MUON NEUTRINO CHARGED CURRENT QUISSI-ELASTIC INTERACTIONS IN THE T2K OFF-AXIS NEAR DETECTOR

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T2K (Tokai-to-Kamioka) is a long-baseline neutrino oscillation experiment, currently operating in Japan, built to precisely measure the mixing angle $\theta_{13}$, using the $\nu_e$ appearance channel, and to refine the measurement of the atmospheric parameters, $\Delta m^2_{23}$ and $\theta_{23}$, using the $\nu_\mu$ disappearance channel. An intense high purity muon neutrino beam, produced at the J-PARC facility, is directed toward the Super-Kamiokande (SK) water Cherenkov detector, located 295 km away. The off-axis near detector, ND280, measures the neutrino beam properties and the neutrino interaction cross-section and kinematics before the oscillation, in order to predict the neutrino flux and the relevant neutrino interactions at SK.

This thesis work provides a strategy for selecting muon neutrino-induced charged current quasi-elastic (CCQE) interactions in ND280. The results of the analysis with real data and a comparison with the NEUT Monte Carlo (MC) prediction are provided. A brief qualitative study on the impact of proton final state interactions (FSI) on the selection is also presented.

Different CCQE topologies, depending on whether only the muon or both the muon and the proton have been reconstructed and on the detectors crossed by the selected tracks, have been studied. The relevant detector systematic uncertainties have been estimated for each selected sample. A total of 11026 CCQE candidate events have been selected in the real data sample (corresponding to a total of $1.58 \times 10^{20}$ protons on target): 7629 events correspond to the one-track sample; 3397 events correspond to the two-track samples. The number of selected events predicted by the MC for the one-track sample is slightly higher than that obtained when the study was performed on real data. On the other hand, the MC prediction is slightly lower than the data result for the two-track samples. These results, together with the study on the impact of proton FSI on the selection, suggest discrepancies between the FSI simulation in NEUT and real data, causing the proton produced in the neutrino-nucleus interaction to escape from the nucleus less frequently in the MC than in data.

The results of this thesis work have been used to extract a CCQE cross-section on Carbon.
Resumen

En la última década el fenómeno mecánico-cuántico denominado oscilaciones de neutrinos, cuya señal experimental es la existencia de transiciones entre los distintos sabores de los tres tipos de neutrinos que participan en las interacciones débiles, ha sido probado por más de una decena de experimentos en todo el mundo, usando tanto neutrinos atmosféricos y solares como neutrinos producidos por aceleradores y reactores nucleares. Su existencia implica que los neutrinos tienen masa, contrariamente a lo que postula el Modelo Estándar de la física de partículas.

En el panorama actual, el experimento de oscilaciones de neutrinos a larga distancia T2K (Tokai-to-Kamioka), situado en Japón, ocupa un papel de primer orden a nivel mundial en la investigación de las propiedades de los neutrinos. T2K ha sido construido para medir el ángulo de mezcla $\theta_{13}$ mediante el estudio de la aparición de neutrinos electrónicos en un haz de neutrinos muónicos, y para mejorar la medida de los parámetros atmosféricos $\Delta m^2_{23}$ y $\theta_{23}$ utilizando el canal de desaparición del neutrino muónico. T2K consiste en un haz muy puro de neutrinos muónicos producidos por el acelerador del centro de investigación JPARC y dirigidos hacia el detector Super-Kamiokande (SK), situado a 295 km de la fuente, y desplazado 2.5° con respecto a la dirección del haz de neutrinos. El detector cercano, ND280, está localizado a 280 m del blanco en la dirección de SK y mide las propiedades del haz de neutrinos, la sección eficaz de interacción y la cinemática de los neutrinos antes de oscilar, para predecir el flujo de neutrinos y las interacciones de neutrinos relevantes en SK.

T2K ha sido el primer experimento en observar la aparición de neutrinos electrónicos, en 2011, proporcionando la primera indicación de un valor no nulo de $\theta_{13}$, seguidos por experimentos de oscilaciones de neutrinos producidos en reactores nucleares. Actualmente $\theta_{13}$ está medido por los experimentos con reactores con una precisión del 5% [3] y la significancia de la señal de aparición de T2K es mayor de 7 sigmas [4]. Este resultado implica que es posible investigar la asimetría materia-antimateria a través de la búsqueda de la violación de CP en el sector leptónico. T2K ha proporcionado recientemente el primer indicio
de violación de CP [4]. Sin embargo, el conocimiento de las propiedades de las interacciones de neutrinos en la región de energía del orden del GeV (que es la región usada por T2K y por la mayoría de los experimentos de oscilaciones de neutrinos a larga distancia) limita la precisión de estas medidas. La interacción cuasi-elástica de corriente cargada (CCQE), caracterizada por un estado final sencillo con solo un muón y un protón emitidos, típicamente proporciona la contribución más grande a la señal a estas energías y constituye el canal más limpio para caracterizar el haz de neutrinos antes de oscilar.

Los resultados obtenidos en las últimas décadas por diferentes experimentos con diferentes técnicas muestran que la interacción CCQE es más complicada de lo esperado: hay discrepancias en la sección eficaz medida a diferentes energías y entre los modelos teóricos y las medidas experimentales. Gracias a su alta estadística y su excelente resolución espacial, ND280 es capaz de medir con gran precisión la sección eficaz de interacciones CCQE y contribuir al conocimiento de este proceso.

ND280 es un detector con una segmentación fina inmerso en un campo magnético de 0.2 Tesla creado por el imán usado anteriormente en los experimentos UA1 y NOMAD. ND280 está constituido por un detector de piones neutros (P0D), un sistema de trazado formado por un sandwich de tres cámaras de proyección temporal (TPCs) y dos detectores de alta granularidad (FGDs), un calorímetro electromagnético (ECAL) que rodea P0D, TPCs y FGDs, y un detector de muones (SMRD) insertado en los huecos del imán, que envuelve a todos los demás subdetectores. El sistema de trazado está optimizado para estudiar las interacciones de neutrinos que producen partículas cargadas en el estado final. Las TPCs proporcionan una medida de alta resolución del momento y la carga de las partículas cargadas que las atraviesan, así como la discriminación entre diferentes partículas por medio de la medida de la pérdida de energía. La alta segmentación de las FGDs permite una medida muy precisa del vértice de la interacción. Además los FGDs proporcionan informaciones cruciales para la reconstrucción de las trazas y la identificación de los productos de la interacción antes de que lleguen a la TPC.

Esta tesis doctoral presenta un método para seleccionar eventos producidos por interacciones CCQE de neutrinos muónicos en el sistema de trazado de ND280. A través del estudio de las propiedades de los eventos simulados por el generador de Monte Carlo (MC) NEUT, se ha desarrollado un criterio para la selección de eventos CCQE cuando una traza (solo el muón) o dos trazas (el muón y el protón) han sido reconstruidas (Capítulo [4]). La selección está enfocada a interacciones que ocurren en el primer FGD y usa principalmente el sistema de trazado de ND280 para reconstruir la trayectoria de partículas cargadas. Cuatro muestras de eventos, dependiendo de los detectores en los cuales se reconstruyen
el muón y el protón, han sido seleccionadas. Los errores sistemáticos asociados al detector y sus efectos sobre la selección han sido estudiados para cada una de las muestras (Capítulo 5).

El estudio separado de topologías con una o dos trazas es importante para entender los detalles de los procesos cuasi-elásticos. La caracterización de las interacciones de neutrinos con núcleos se basa en la identificación del estado final hadrónico, que puede cambiar por efecto de las interacciones del protón primario en el interior del núcleo (FSI). Por esta razón la muestra de dos trazas es especialmente interesante, pues permite acceder a la cinemática total del evento. Además, el estudio de esta topología y la comparación con los resultados obtenidos con datos reales puede ayudar a discriminar entre diferentes modelos de interacciones de neutrinos.

Datos reales correspondientes a un total de $1.578169 \times 10^{20}$ protones impactando en el blanco y los correspondientes datos simulados por NEUT se han usado en este análisis. Según la predicción del Monte Carlo (MC), el número esperado de eventos seleccionados es $8691 \pm 46 \pm 210 \pm 420$ para la muestra de una traza, $1573 \pm 19 \pm 72 \pm 78$ para la muestra de dos trazas con ambos el muón y el protón reconstruidos en la TPC, $1064 \pm 16 \pm 31 \pm 53$ para la muestra de dos trazas con el muón reconstruido en la TPC y el protón en el FGD, $531 \pm 11 \pm 53 \pm 31$ para la muestra con el protón reconstruido en la TPC y el muón en el FGD y en los otros detectores que rodean la TPC. El error estadístico (primer valor), el error sistemático debido al detector (segundo valor) y el error sistemático debido al flujo del haz de neutrinos (tercer valor) han sido calculados para cada muestra de datos simulados. Un total de 11026 eventos han sido seleccionados en la muestra de datos reales:

1. $7629 \pm 87$ eventos en la muestra de una traza;
2. $1572 \pm 40$ eventos con ambos el muón y el protón reconstruidos en la TPC;
3. $1210 \pm 35$ eventos con el muón reconstruido en la TPC y el protón en el FGD;
4. $615 \pm 25$ eventos con el protón reconstruido en la TPC y el muón en el FGD y en los otros detectores que rodean la TPC.

En todos los casos el ruido está altamente dominado por interacciones de corriente cargada con un pión en el estado final (CC1\(\pi\)), en las que éste no se reconstruye.

En general, el acuerdo entre los resultados del análisis con datos reales y simulados es bueno para todas las muestras seleccionadas excepto en la distribución angular del protón (Capítulo 6), lo cual sugiere que la simulación de FSI en
NEUT no es realista. También se ha llevado a cabo un estudio cualitativo del efecto de FSI sobre la selección del protón, descrito en el Capítulo 6.

El método de selección así como la propagación de errores sistemáticos, desarrollados en este trabajo de investigación, han sido utilizados para calcular la sección eficaz de interacciones cuasi-elásticas de corrientes cargadas en Carbón (el material principal del que está hecho el FGD) [1,2]. Este estudio ha sido llevado a cabo por nuestro grupo de investigación en colaboración con otros grupos extranjeros de T2K y se encuentra en fase de publicación. Sin embargo queda fuera del ámbito de esta tesis doctoral.
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Introduction

The last decade has been a turning point in the field of neutrino physics. The evidence for neutrino flavour change among the three neutrino types participating in weak interactions (electron, muon, and tau neutrinos) has been established beyond any doubts by more than a dozen experiments worldwide, using solar and atmospheric neutrinos as well as man-made neutrinos from nuclear reactors and accelerators. This implies that mixing among neutrino weak and mass states occurs and that neutrinos are massive particles, providing the first direct evidence for physics beyond the Standard Model of particle physics.

In this panorama, the T2K (Tokai-to-Kamioka) experiment \[47\] occupies a prime role, within the world context, for the experimental exploration of neutrino properties. T2K is a long baseline neutrino oscillation experiment installed in Japan. It was built to precisely measure the last unknown neutrino mixing angle describing the quantum mechanical phenomenon of neutrino oscillations, \(\theta_{13}\), by the observation of the \(\nu_\mu \rightarrow \nu_e\) appearance and to refine the measurement of the atmospheric parameters, \(\Delta m^2_{32}\) and \(\theta_{32}\), using the \(\nu_\mu\) disappearance channel. T2K uses an intense high purity accelerator muon neutrino beam, which is produced at the J-PARC facility in Tokai and is directed \(2.5^\circ\) off-axis toward the Super-Kamiokande (SK) water Cherenkov detector, located 295 km away in the Kamioka Observatory. The off-axis near detector (ND280), located 280 m from the target, measures the neutrino beam properties and the neutrino interaction cross-section and kinematics before the oscillation, in order to predict the neutrino flux and the relevant neutrino interactions at SK.

T2K was the first experiment to observe the appearance of the electron neutrinos providing the first hint for a non-zero value of \(\theta_{13}\) in 2011 \[51\], followed by reactor experiments \[65, 66\]. Currently \(\theta_{13}\) is measured with a precision of 5\% by reactor experiments \[3\] and the significance of the T2K appearance signal exceeds the 7 sigma significance \[4\]. This result strongly affects the future program of neutrino physics as it allows to investigate the matter-antimatter asymmetries through the search for CP-violation in the leptonic sector. Unlike reactor experiments, T2K is sensitive to the CP-violation phase and has pro-
vided recently the first hint towards CP-violation [4]. However, the precision of such measurements in current and future experiments is limited, among others, by the knowledge of the neutrino interaction properties at energies in the GeV region, which is the energy range used by T2K and by most long baseline neutrino oscillation experiments. The charged current quasi-elastic (CCQE) neutrino-nucleus interaction typically gives the largest contribution to the signal samples at these energies and constitutes the cleanest channel to characterize the neutrino beam before it oscillates. It is characterized by a simple final state (with only a muon and a proton emitted) and has the advantage of providing a simple method to reconstruct the neutrino energy using only the primary lepton kinematics. In the last decades several experiments have studied the neutrino charged current quasi-elastic scattering using different techniques, showing that the CCQE channel is more complicated than expected. Specifically, recent data have shown a significant discrepancy in this cross-section measured at different energies (by the MiniBooNE [87] and NOMAD [88] experiments). In addition, a comparison between theoretical models describing the CCQE process and modern measurements reveals several discrepancies. Thanks to its high statistics and excellent spatial resolution, ND280 is able to provide precise CCQE cross-section measurements and contribute to improve the understanding of this channel.

ND280 is a large, highly segmented detector located inside the refurbished UA1/NOMAD magnet, which has a magnetic field of $\sim 0.2$ Tesla. It consists of a Pi-Zero Detector (P0D), optimized for measuring the rate of neutral current $\pi^0$ production, followed by a tracker, made of a sandwich of three Time Projection chambers (TPCs) and two Fine Grain Detectors (FGDs), an electromagnetic calorimeter (ECAL) in front of the tracker and surrounding the P0D, and the tracker, and a Side Muon Range Detector (SMRD) to measure the range of muons that exit the sides of ND280. The ND280 tracker is optimized to study neutrino interactions with charged particles in the final state. The TPCs are the main tracking and particle identification device and provide a very precise measurement of momentum and angle. The fine segmentation of the FGDs allows a precise measurement of the interaction vertex. In addition, the FGDs provide tracking and particle identification information.

This thesis presents a method to select muon neutrino-induced CCQE interactions in the tracker of the T2K ND280 off-axis near detector. By studying the properties of events generated by the ND280 NEUT Monte Carlo simulation, a criterion to select muon neutrino-induced CCQE events in the ND280 tracker was developed. Both the one-track (only the muon is reconstructed) and the two-track (both the muon and the proton are reconstructed) cases have been addressed. The selection focuses on interactions occurring in the most upstream FGD and uses mainly the tracker region of ND280 to reconstruct trajectories.
of charged particles. Exclusive topologies as the ones studied in this thesis are very important to understand the details of the CCQE process. As the characterization of a neutrino-nucleus interaction is based on the hadronic final state of the reaction, which can be altered by proton final state interactions (FSI), the two-track sample is especially interesting because it allows to access the full kinematics of the CCQE events. The study of such kind of topologies could help also in discriminating between different neutrino interaction models.

Chapter 1 presents a brief overview of neutrino physics. The history, theory and current state of neutrino oscillations are outlined, as well as the main neutrino interactions expected at T2K, with an emphasis on the CCQE process.

Chapter 2 is a brief summary of the T2K experiment. The physics goals, the general measurement principle and technique are presented. The T2K accelerator and the neutrino beamline, together with the near detector suite and the far detector Super-Kamiokande (SK) are described. A brief description of the ND280 subdetectors and the magnet surrounding them is also given. The TPCs and FGDs, which are extensively used in this analysis, are described in more detail.

The off-line software and event reconstruction in ND280, which is used extensively in the analysis presented in this thesis, is described in Chapter 3 with an emphasis on the reconstruction in the tracker as a whole and in the individual subdetectors (TPC and FGD). The global reconstruction, which combines the information of all the ND280 detectors, is briefly discussed too. This chapter is essential to understand some of the systematic errors affecting the analysis.

Chapter 4 describes in detail the work conducted by the author to select $\nu_\mu$ CCQE interactions in the ND280 tracker. The selection criteria, based on the results and performance of the ND280 NEUT Monte Carlo (MC) simulation, and the efficiency and purity of the CCQE selected samples are discussed.

In Chapter 5 the detector systematic uncertainties and the beam flux systematics affecting the analysis described in this thesis are presented and discussed.

Chapter 6 shows the results obtained using Runs 1, 2, 3 and 4 of T2K data and the corresponding NEUT MC simulations. Kinematic distributions, including momentum and angular distributions of the muon and proton candidates as well as distributions of reconstructed neutrino energy and squared four-momentum transferred to the nuclear system under the hypothesis of CCQE interaction, and
a comparison between data and MC results are presented for each of the selected CCQE samples. The effect of final state interactions (FSI) on the selection of the proton track, based on MC studies, is briefly discussed too.

In Chapter 7 a conclusion of the thesis as a whole is provided.
Author’s contribution

Contribution to T2K

Since 2007, when I joined the experimental neutrino physics group of IFIC (Instituto de Física Corpuscular) in Valencia as a PhD student, my research activity has been completely dedicated to the T2K experiment. I have been involved in several aspects of the experiment, but mainly in the calibration of the ND280 Time Projection Chambers (TPCs) and in the data analysis.

In 2007 I participated to a cosmic ray test performed at CERN to study the performance of a prototype of readout plane for the TPCs of the ND280 tracker [5]. The HARP TPC was instrumented with a GEM and a Micromegas (MM) module and immersed in a magnetic field of about 0.2 Tesla, like the one used by ND280. The study of the response of the detector to both modules led to the choice of the MM technology for the ND280 TPCs. I participated in the data taking and also in the data analysis. In particular, I was involved in the study of the pedestal and noise levels of the MM modules, that are fundamental parameters to obtain a good spatial resolution. I participated also in the calibration of the MM modules that took place at CERN using a test-bench with a movable $^{55}\text{Fe}$ radioactive source [121]. The goal was to provide a map of gain and energy resolution for each MM module. I contributed to the data taking and to the creation of a data base to store the results of the calibration and of the analysis of these data. These studies are reported in [5] and [7].

Until 2010 I was involved in the analysis of events produced by the MC simulation (the so called “cheating analysis”). This study provided a method to simulate the effect of the ND280 detector using a simple smearing of the true kinematic variables provided by the MC. The results of this analysis helped to optimize the reconstruction algorithms and to understand better the detector’s performance. These results were presented at several internal T2K meetings and set the basis for the CCQE analysis presented here.

Since the beginning of the data taking, in 2010, I have been involved in the analysis with real data. I contributed to previous studies on the selection of charged current (CC) and CCQE interactions in the ND280 tracker, which
Author’s contribution

provided the main body of the CC event selection used in the analysis presented in this thesis and were a valuable tool to check and improve the reconstruction algorithm. These studies are discussed in the internal technical notes T2K-TN-023 [8] and T2K-TN-044 [9].

I was involved also in the estimation of the systematic uncertainties associated with both the inclusive CC and the exclusive CCQE analyses [152]. In more detail, I computed the systematic error due to the TPC cluster efficiency (see Section 5.2.2 and Appendix B) and contributed to the investigation of some other systematic uncertainties.

Afterwards, I focussed on the selection of one- and two-track CCQE events and I provided an algorithm, based on MC studies and described in Chapter 4, to perform the selection in the ND280 tracker. The results obtained with real data are presented in Chapter 6. These studies are the main topic of this thesis.

Contribution to this thesis

I was entirely responsible of providing the CCQE selection algorithm and the corresponding results with real data (Chapters 4 and 6).

Regarding the systematics, I estimated the TPC cluster efficiency in data and MC, explained in detail in Section 5.2.2 and in Appendix B.

As I was the first one in using the new ND280 analysis framework for the systematic propagation, I took care of debugging, validating and improving all methods. Therefore, my work on the systematics will be useful for many other analysis in ND280, which will use the same systematic propagation.

A differential CCQE cross-section study, based on the event samples and systematic propagation described in this thesis, has been conducted in collaboration with other T2K groups form other institutions [1][2] and will be published shortly. However, this study is beyond the scope of this thesis.
Neutrino physics is among the most exciting and active areas of research in high energy physics, both experimentally and theoretically.

The existence of the quantum mechanical phenomenon of neutrino oscillations opened a window to new physics beyond the Standard Model (SM) of elementary particles, which describes the building blocks of matter and the fundamental interactions. In the Standard Model neutrinos are massless particles but the existence of neutrino oscillations, which violate the lepton number conservation, proves they are massive and provides the first strong evidence for physics beyond the SM. Nevertheless, it is not yet understood how their masses are generated. If a non-zero complex phase in their mixing matrix will be measured, neutrinos would violate the CP symmetry. That could be the first step towards the understanding of the matter-antimatter asymmetry observed in the Universe. However, despite the great progress in neutrino physics over the last 20 years, there is still a lack of knowledge on their intrinsic properties. Only recently we are observing phenomena which are sensitive to neutrino masses as well as to the mixing among the various neutrino species. We still do not know whether neutrinos are Dirac or Majorana particles, with neutrinos and antineutrinos as different particles or as a unique neutral particle free of all kinds of charges, or whether sterile neutrinos exist, implying there are more than three neutrino families.

Neutrinos play a very important role in many fields of subatomic and subnuclear physics, as well as in astrophysics and cosmology.

Neutrino-nuclear reactions provide a clean probe of nuclear and nucleon structure; on the other hand, from neutrino detection rates nuclear physics can compute the reaction cross-sections needed for calculating neutrino fluxes.

Neutrino reactions play a crucial role in the mechanism of supernova explosions and are copiously produced in thermonuclear reactions which occur in
the stellar interior (in particular in our Sun). Solar neutrinos carry information about the core of the Sun which is unaccessible to direct optical observations. At the same time, cosmic rays in the atmosphere, supernovae and the Sun allow us to study neutrino properties over extremely long baselines and high matter densities.

Produced naturally in the Sun, in supernovae, in the Earth or artificially in accelerator beams or nuclear reactors, neutrinos are one of the most interesting subjects in modern physics.

1.1 The discovery of neutrinos

The neutrino physics history is strictly related to the history of weak interactions, which dates back to 1896, when Becquerel discovered that some chemical elements naturally emit radiation even in the absence of an outside stimulus. In the early 1900’s, detailed analysis of this natural radioactivity revealed that different elements emitted different types of radiation, baptized as $\alpha$, $\beta$, and $\gamma$ radiation, or rays, by Lord Rutherford.

The history of neutrinos begins with the study of the $\beta$ decay, the decay of a neutron into a proton and an electron. Observation of the particles after decay pointed to a lack of conservation of energy and momentum in the observed process. In December, 1930 Wolfgang Pauli postulated the existence of the neutrino $[10]$, theorizing that an undetected particle was carrying away the observed difference between the energy and angular momentum of the initial and final particles, explaining in this way the continuous energy spectrum of $\beta$ decays.

Because of their "ghostly" properties, neutrinos were experimentally detected for the first time about 25 years after they were first postulated. It was only in 1956 that C. Cowan and F. Reines detected the electron antineutrinos ($\bar{\nu}_e$) produced by the Savannah River reactor (South Carolina, USA) using a detector filled with water and cadmium chloride through the $\bar{\nu}_e + p \rightarrow e^+ + n$ reaction, proving the neutrino existence $[11]$. Their result was rewarded with the 1995 Nobel Prize.

In 1962 L. M. Lederman, M. Schwartz and J. Steinberger showed that more than one type of neutrino exists by detecting the muon neutrino ($\nu_\mu$) while studying pion decays at the Brookhaven National Laboratory $[12]$, in the first accelerator neutrino experiment.

When a third type of lepton, the tau, was discovered in 1975 at the Stanford Linear Accelerator, it was expected to have an associated neutrino. First evidence for this third neutrino type ($\nu_\tau$) came from the observation of missing energy and momentum in $\tau$ decays analogous to the $\beta$ decay that had led to the discovery of the electron neutrino. The first detection of tau neutrino in-
teractions was announced in summer of 2000 by the DONUT collaboration at Fermilab [13].

1.2 The discovery of neutrino oscillations

The evidence for neutrino oscillations was solidly established during the last decades by more than a dozen experiments around the world using solar and atmospheric neutrinos as well as man-made neutrinos from nuclear reactors and accelerators.

The concept of neutrino oscillation was first proposed by B. Pontecorvo in 1957 [15] using an analogy with the neutral kaon system [14]. In 1967 he presented the first intuitive understanding of two-neutrino mixing and oscillation in vacuum [16], which he later completed with V. N. Gribov in 1969 [17]. The theory of neutrino oscillations was finally developed in 1975-76 by W. Eliezer and A. R. Swift [18], H. Fritzsch and P. Minkowski [19], S. M. Bilenky and B. Pontecorvo [20,21].

In 1985 S. Mikheyev and A. Smirnov (expanding on 1978 work by L. Wolfenstein [22]) noted that flavour oscillations can be modified when neutrinos propagate through matter. This so-called MSW effect [23] is important to understand neutrinos emitted by the Sun, which pass through its dense core on their way to detectors on Earth.

The first experiment to measure the flux of neutrinos produced in the fusion reactions that take place in the Sun was proposed and realized by R. Davis and J.N. Bahcall in the late 60s in the Homestake mine [24]. The measured flux showed a deficit with respect to the expected number of solar neutrinos, as predicted by B. Pontecorvo as a consequence of the transition from $\nu_e$ to $\nu_\mu$ or to a sterile neutrino (a neutral fermion which does not take part in weak interactions, that was proposed by B. Pontecorvo in the late 1950s in order to discuss neutrino oscillation, since at that time only one active neutrino, $\nu_e$, was known). The solar neutrino deficit was confirmed by several other experiments using different techniques: GALLEX [25], Sage [26], GNO [27], using radiochemical techniques, and Kamiokande [28] and Super-Kamiokande (SK) [33], using water Cherenkov detectors.

In 2002, the Sudbury Neutrino Observatory (SNO) experiment [29], a heavy water Cherenkov detector, provided a strong evidence for the flavour transformation of electron neutrinos into muon and tau neutrinos [30], providing a solution to the problem of the solar neutrino deficit.

The first evidence of oscillation of reactor neutrinos was found by the long-baseline KamLAND (Kamioka Liquid-scintillator AntiNeutrino Detector) experiment [31] in 2002. The KamLAND results confirmed the $\nu_e$ disappearance ac-
1. Neutrino physics

The atmospheric neutrino anomaly was discovered in the late 1980s in the Kamiokande and IMB \[32\] experiments, both based on large water Cherenkov detectors. The atmosphere is constantly being bombarded by cosmic rays, mainly composed of protons, which hit nuclei in the Earth’s upper atmosphere and shower, setting up a cascade of hadrons. The decay of these hadrons during flight produces the atmospheric neutrinos. A detector looking at atmospheric neutrinos is, necessarily, positioned on the Earth’s surface or just below it. Consequently flight distances for neutrinos detected in these experiments can vary from 15 km for neutrinos coming down from an interaction above the detector, to more than 13000 km for neutrinos coming from interactions in the atmosphere below the detector on the other side of the planet. Both Kamiokande and IMB observed that the measured ratio between the upward and downward going $\nu_\mu$ was different from the expected value.

In 1998, forty one years after B. Pontecorvo postulated neutrino oscillations, the Super-Kamiokande experiment in Japan showed an unambiguous and statistically significant evidence for neutrino oscillations in their atmospheric neutrino data \[34\], solving the atmospheric neutrino puzzle. The deficit of the detected neutrino flux compared to expectations was demonstrated to depend on the neutrino pathlength (baseline), $L$, and energy, $E$, in the way it is expected to depend in the case of neutrino oscillations (see Eq. 1.6).

The high precision measurements of SK, confirmed by the Soudan2 \[39\] and MACRO \[40\] experiments, and later by MINOS \[41\], provide precise information on the values of the atmospheric neutrino oscillation parameters, which are in good agreement with the independent results of K2K \[42\], the first accelerator long-baseline experiment.

1.3 The theory of neutrino oscillations

The results of the atmospheric, solar, accelerator and reactor experiments are nicely explained by neutrino oscillation in the framework of the three-neutrino mixing model, in which the three flavor neutrinos $\nu_e$, $\nu_\mu$ and $\nu_\tau$ are unitary linear combinations of three massive neutrinos $\nu_1$, $\nu_2$ and $\nu_3$.

A neutrino produced in a weak charged current (CC) interaction\[1\] is described by the flavor state expressed by the following equation:

$$|\nu_\alpha\rangle = U_{\alpha i}^* |\nu_i\rangle$$ (1.1)

\[1\] Neutrinos produced in weak CC interaction processes can be produced from a charged lepton $l^-_\alpha$ (i.e $l^-_\alpha \rightarrow \nu_\alpha$ transitions) or together with a charged antilepton $l^+_\alpha$ (i.e. creation of $l^+_\alpha \nu_\alpha$ pair)
1.3. The theory of neutrino oscillations

where:

- $|\nu_\alpha\rangle$ and $|\nu_i\rangle$ (with $i = 1, 2, 3$) are weak, or flavour, eigenstates and mass eigenstates, respectively;
- $\alpha$ corresponds to the flavour of the neutrino $e, \mu, \tau$;
- $U_{\alpha i}$ is the $3 \times 3$ unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix, given by Eq. 1.2.

\[ U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{32} & s_{32} \\ 0 & -s_{32} & c_{32} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \] (1.2)

In Eq. 1.2 $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ are mixing angles and $\delta$ is a CP violating phase. The angles $\theta_{12}$, $\theta_{32}$ and $\theta_{13}$ are often referred to as the solar, atmospheric and reactor/accelerator parameters, respectively.

Since neutrinos have a non zero mass and the mass eigenstates do not correspond to the flavor eigenstates, then neutrinos can mix, analogously to what happens in the quark sector.

It is worth noting that, if the number of massive neutrinos is greater than three, the additional neutrinos in the flavor basis must be sterile (i.e. they do not participate in weak interactions but interact with matter through gravitational or exotic interactions beyond the ones in the SM).

Let us consider a neutrino produced by a weak interaction at initial time $t_0 = 0$ in a flavor eigenstate $|\nu(0)\rangle = |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$, which is a particular linear combination of states of definite mass. Suppose we let it propagate in a free space towards a detector some distance $L$ away. The initial state mass components will evolve independently with the time, according to the time-dependent Schrodinger equation, acquiring a phase $e^{-im_i\tau_i}$, where $m_i$ is the mass of the mass state $\nu_i$ and $\tau_i$ is the time in the $\nu_i$ rest frame (natural units, $\hbar = c = 1$, are used). Since the phase factor is Lorentz-invariant, it can be written in terms of the laboratory-frame distance, $L$, that the neutrino travels between its source and the detector, and the laboratory-frame time, $t$, that elapses during the trip:

\[ e^{-im_i\tau_i} = e^{-i(E_i t - p_i L)} \] (1.3)

where $E_i$ and $p_i$ are the energy and momentum of the mass eigenstate $\nu_i$ in the laboratory frame.
Since neutrinos are highly relativistic, we can assume that the neutrino masses $m_i$ are sufficiently small compared with the momentum ($m_i \ll p_i$) so that we can make the approximation:

$$m_i \ll p_i \Rightarrow m_i \ll E_i \Rightarrow p_i = \sqrt{E_i^2 - m_i^2} \approx E_i \left(1 - \frac{m_i^2}{2E_i^2}\right) \quad (1.4)$$

Furthermore, we can make the approximation $t \sim L$ for all mass eigenstates, where $L$ is the propagation distance. This step is based on the fact that, in neutrino oscillation experiments, the propagation time is not measured, while the distance $L$ is known.²

The different mass eigenstate components of a beam which have the same energy, $E$, contribute coherently to the oscillation signal.²

Therefore, after travelling the distance $L$ between the source and the detector, the neutrino will be in the state:

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}^* |\nu_i(t)\rangle = \sum_i U_{\alpha i}^* e^{-im_i^2 L/2E} |\nu_i\rangle \quad (1.5)$$

If at this point the neutrino is detected, the probability of observing a neutrino that was in flavor state $\alpha$ at time $t_0$ in flavor eigenstate $\beta$ at time $L$ is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha (L) \rangle|^2 = |U_{\alpha i}^* e^{-im_i^2 L/2E} U_{\beta i}|^2 \quad (1.6)$$

Using the properties of the complex exponential and the unitarity of the PMNS matrix, and defining $W_{\alpha \beta}^{ij} = U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*$, Eq. 1.6 can be rewritten in this way:

$$P(\nu_\alpha \rightarrow \nu_\beta)(L, E) = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re(W_{\alpha \beta}^{ij}) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$
$$+ 2 \sum_{i>j} \Im(W_{\alpha \beta}^{ij}) \sin \left(\frac{\Delta m_{ij}^2 L}{2E}\right) \quad (1.7)$$

where $\Delta m_{ij}^2 = m_i^2 - m_j^2$ is the difference of the squared-masses of the two eigenstates. The probability of flavor change in vacuum oscillates with $L/E$. The source-detector distance and the neutrino energy, which are quantities depending on the experiment, and the squared-mass differences $\Delta m_{ij}^2$, which are physical constants, determine the phase $\phi$ of the neutrino oscillation. The amplitude of

²The value of $L$ is chosen by the experimenters through their choices for the location of the source and the location of the detector. Thus, $L$ is defined by the experiment and is common to all $\nu_i$ components of the beam.
The oscillation is specified only by the elements of the PMNS mixing matrix, which are constants of nature. Measurements of neutrinos oscillation allows to determine the values of the squared-mass differences and of the matrix elements. However, they do not provide information on the absolute values of neutrino masses, except, obviously, that \( m_i^2 \) or \( m_j^2 \) must be larger than \( \Delta m_{ij}^2 \).

The oscillation probabilites of the channels with \( \alpha \neq \beta \) are usually called “transition probabilites” while the one of channels with \( \alpha = \beta \) are called “survival probabilites”.

It is worth noting that if neutrinos are massless, so that all \( \Delta m_{ij}^2 = 0 \), then \( P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} \). Thus, the observation that neutrinos can change from one flavor to a different one implies neutrino mass.

1.3.1 Two-neutrino mixing case

Two-neutrino mixing is an approximation in which only two massive neutrinos are considered. The oscillation formulas in this case are much simpler and depend on less parameters. Furthermore, the data of experiments that are not sensitive to the influence of three-neutrino mixing can be analyzed using a model with two-neutrino mixing.

In this simplest case the mixing matrix can be written as a rotation:

\[
U = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\]  

(1.8)

In the case of two-neutrino mixing there is only one squared-mass difference. For neutrino oscillations to occur, at least one of the mass states must be non-zero. Furthermore, the masses of the mass states must be different.

The mixing angle \( \theta \), which defines how different the flavour states are from the mass states, has a value in the interval \( 0 \leq \theta \leq \pi/2 \). If \( \theta = 0 \), the flavour states are identical to the mass states and oscillations cannot happen.

The probability of \( \nu_\alpha \to \nu_\beta \) transitions is:

\[
P(\nu_\alpha \to \nu_\beta)(L, E) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)
\]  

(1.9)

Since \( \sin^2(2\theta) \) is symmetric under the exchange \( \theta \leftrightarrow \pi/2 - \theta \) and \( \theta \) ranges from 0 to \( \pi/2 \), then there is a degeneracy of the transition probability for \( \theta \) and \( \pi/2 - \theta \). However, these two situations correspond to different mixings (a different \( \nu_1 \) and \( \nu_2 \) composition of the flavor state).

Neutrino oscillation experiments aim to measure the squared-mass difference \( \Delta m^2 \) and the mixing angle \( \theta \).
There are two types of experiments one could think of doing in order to measure neutrino oscillations. The first one consists in starting with a pure beam of known flavour $\nu_\alpha$ and in looking to see how many neutrinos of a different flavour $\nu_\beta$ are detected (appearance experiments). The second one consists in starting with a pure beam of known flavour $\nu_\alpha$ and looking to see how many have disappeared (disappearance experiments). More in detail:

- **Appearance experiments**: they measure transitions between different neutrino flavors. They can be sensitive to very small values of mixing angles if in the initial beam there is a very small background of neutrinos of the final flavor.

- **Disappearance experiments**: they measure the survival probability of a neutrino flavor by counting the number of interactions in the detector and comparing it with the expected one. Such experiments are not sensitive to small values of the mixing angle due to statistical fluctuations in the number of detected events.

By choosing appropriately the value of the ratio $L/E$, different experiments can be designed in order to be sensitive to different values of $\Delta m^2$.

### 1.3.2 Antineutrino case

An antineutrino produced in a weak CC interaction\(^3\) is described by the flavor state expressed by the following equation:

\[
|\bar{\nu}_\alpha\rangle = U_{\alpha i} |\bar{\nu}_i\rangle
\]  

(1.10)

which is analogous to Eq.1.5 but here the elements of the mixing matrix are the complex conjugated with respect to the flavor neutrino states.

Since massive antineutrinos have identical kinematical properties to those of massive neutrinos, the probability of $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ oscillations can be computed in the same way as the $\nu_\alpha \rightarrow \nu_\beta$ oscillation probability discussed in Section 1.3. Applying the same steps described in Section 1.3 we obtain the following

\(^3\)Antineutrinos produced in weak CC interaction processes can be produced from a charged antilepton $l^+_\alpha$ (i.e. $l^+_\alpha \rightarrow \bar{\nu}_\alpha$ transitions) or together with a charged lepton $l^-_\alpha$ (i.e. creation of $l^-_\alpha \bar{\nu}_\alpha$ pair)
expression for the antineutrino oscillation probability:

\[
P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(W_{ij}^{\alpha\beta}) \sin^2 \left[ \frac{1.27 \Delta m_{ij}^2 L}{E} \right] - 2 \sum_{i>j} \Im(W_{ij}^{\alpha\beta}) \sin \left[ \frac{2.54 \Delta m_{ij}^2 L}{E} \right] \tag{1.11}
\]

which differs from the corresponding neutrino oscillation probability (Eq. 1.7) only in the sign of the terms depending on the imaginary part of \(W_{ij}^{\alpha\beta}\). Thus, if the mixing matrix is complex, \(P(\nu_\alpha \to \nu_\beta)\) and \(P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)\) differ, meaning that CP, the transformation that interchanges neutrinos with antineutrinos and reverses the helicity, is violated. CP-violation requires all mixing angles to be nonzero and is proportional to the sine of the \(\delta\) phase (the CP-violating effects vanish in the limit \(\delta = 0\)). In addition, as the mass squared differences satisfy \(\Delta m_{21}^2 + \Delta m_{32}^2 + \Delta m_{13}^2 = 0\) it follows that the CP-violating effects vanish if any of the neutrino masses are degenerate, i.e. that any of \(\Delta m_{ij}^2\) are equal to zero. CP-violation can be revealed in oscillation experiments by measuring different values of the oscillation probabilities \(P(\nu_\alpha \to \nu_\beta)\) and \(P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)\). CP asymmetry can be measured only in transitions between different flavors since for \(\alpha = \beta\) the imaginary parts in Equations 1.7 and 1.11 vanish. So far, CP-violation has been seen only in the quark sector.

As shown schematically in Figure 1.1, physical neutrinos and antineutrinos are related also by CPT and T transformations. T interchanges the initial and final states; CPT interchanges the \(\nu_\alpha \to \nu_\beta\) and \(\bar{\nu}_\alpha \to \bar{\nu}_\beta\) channels.
In the framework of a local quantum field theory, in which the neutrino oscillation theory described here is formulated, CPT is a symmetry of the oscillation probabilities. That means that:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) \]  

(1.12)

Thus, small violations of the CPT symmetry, possible if local quantum field theory does not perfectly describes nature, can be revealed in neutrino oscillation experiments by measuring different values of \( P(\nu_\alpha \rightarrow \nu_\beta) \) and \( P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) \).

It is worth noting that, in the case of the survival probabilities of neutrinos and antineutrinos, Eq. [1.12] implies:

\[ P(\nu_\alpha \rightarrow \nu_\alpha) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha) \]  

(1.13)

which has important phenomenological implications.

If CPT is a symmetry of nature, the violation of the CP symmetry implies the violation of the T symmetry. It is possible to observe T violation in neutrino oscillation experiments by measuring a non zero value of \( P(\nu_\alpha \rightarrow \nu_\beta) - P(\nu_\beta \rightarrow \nu_\alpha) \) or \( P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) - P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) \).

If only two neutrino families are included, there are no CP nor T violations (it can be seen from the absense of any phase in the mixing matrix given by Eq. [1.8]). Thus the following probabilities are all equal:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = P(\nu_\beta \rightarrow \nu_\alpha) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) \]  

(1.14)

### 1.3.3 Neutrino oscillations in matter

When neutrinos propagate in matter (e.g. the Earth, the Sun or a supernova), they are subject to a potential due to the coherent forward elastic scattering with the particles in the medium (electrons and nucleons) which modifies the mixing between flavour states and mass states, leading to a different oscillation probability with respect to vacuum. The Feynman diagrams of charged and neutral current interactions of neutrinos with matter are shown in Figure 1.2.

A neutrino in matter can undergo coherent forward scattering in two ways:

- Electron neutrinos can exchange a \( W \) boson with an electron. Coherent forward scattering by electrons via \( W \) exchange gives rise to an extra interaction potential energy, \( V_W \), which is proportional to \( G_F \), the Fermi coupling constant, and to the number of electrons per unit volume \( (N_e) \):

\[ V_W = +\sqrt{2}G_F N_e \]  

(1.15)

\( V_W \) changes sign if we replace \( \nu_e \) by \( \bar{\nu}_e \). Neutrinos with other flavors are not affected by this kind of interaction.
1.3. The theory of neutrino oscillations

Figure 1.2: Feynman diagram of charged (left) and neutral (right) current interactions of neutrinos with matter.

- Neutrinos of all flavors can exchange a $Z$ boson with an electron or nucleon in the medium. The amplitude for this $Z$ exchange is flavor independent. Assuming the matter through which neutrinos travel is electrically neutral, the number density of protons equals that of electrons. Thus, the neutral current potential of electrons and protons cancel each other and only neutrons contribute. The $Z$ exchange, then, gives rise to a neutrino-flavor-independent extra interaction potential energy, $V_Z$, which depends only on the number of neutrons per unit volume ($N_n$):

$$V_W = -\frac{\sqrt{2}}{2}G_F N_n \quad (1.16)$$

As for $V_W$, $V_Z$ changes sign if we replace neutrinos by antineutrinos.

Let us consider the simplest case of two-neutrino mixing. The neutral current contribution is the same for all flavor eigenstates and can be neglected, as it does not modify the oscillation probability if only active neutrino flavors exist. The mass eigenstates in matter can be written as a function of a new mixing angle $\theta_M$ and a new squared mass splitting $\Delta m^2_M$ that include matter effects. The new mixing matrix will be given by:

$$U_M = \begin{pmatrix} \cos \theta_M & \sin \theta_M \\ -\sin \theta_M & \cos \theta_M \end{pmatrix} \quad (1.17)$$

$\theta_M$ and $\Delta m^2_M$ can be expressed as a function of the mixing angle and the squared mass splitting in vacuum:

$$\sin^2 (2\theta_M) \equiv \frac{\sin^2(2\theta)}{\sin^2(2\theta) + (\cos(2\theta) - x)^2} \quad (1.18)$$

$$\Delta m^2_M = \Delta m^2 \sqrt{\sin^2(2\theta) + (\cos(2\theta) - x)^2} \quad (1.19)$$
where the parameter $x$ is a measure of the importance of the matter effect relative to that of the neutrino squared-mass splitting and is given by:

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$  \hspace{1cm} (1.20)

The following remarks should be made:

- The behaviour of neutrino oscillations in matter is different from that in vacuum. The two-neutrino oscillation probability in vacuum is symmetric under the exchange $\theta \rightarrow \pi/2 - \theta$, while there is an asymmetry between antineutrino oscillation and neutrino oscillation that is induced by matter effects (the sign of $x$ is different for neutrinos and antineutrinos). This asymmetry has nothing to do with genuine CP-violation, and must be disentangled from the antineutrino-neutrino asymmetry that does come from genuine CP-violation in order for us to be able to study the latter phenomenon.

- The effective mixing angle for neutrinos in matter, $\theta_M$, depends on the absolute value of $\Delta m^2$. Thus, experiments sensitive to the matter effect will also be sensitive to the sign of the mass difference $\Delta m^2$.

- if $x \ll \cos (2\theta)$, $\theta_M \approx \theta$ and we recover the vacuum case.

- if $x \gg \cos (2\theta)$, matter effects dominate and oscillations are suppressed.

- if $x = \cos (2\theta)$, there is a resonance: $\theta_M = \pi/4$, $\Delta m^2_M$ has its minimum value (given by Eq. 1.21) and the mixing is maximal.

$$\Delta m^2_N|_R = \Delta m^2 \sin (2\theta)$$  \hspace{1cm} (1.21)

Thus, even if the vacuum mixing is tiny, there is the possibility of total transition between the two neutrino flavors if the resonance region is wide enough. This mechanism is called Mikheyev-Smirnov-Wolfenstein (MSW) effect.

- If the matter density is constant (a good approximation for oscillations in the Earth crust), the transition probability in matter has the same structure as the two-neutrino transition probability in vacuum (see Eq. 1.9), except for the replacement of the vacuum parameters by their equivalents in matter:

$$P(\nu_e \rightarrow \nu_\mu)(x) = \sin^2 (2\theta_M) \sin^2 \left( \frac{\Delta m^2_M L}{4E} \right)$$  \hspace{1cm} (1.22)
Due to the high matter density of the Sun and to the variable electron density profile in the neutrino path, matter effects are not negligible in the case of solar neutrinos.

In the case of terrestrial neutrino oscillation experiments, matter effects might have an impact on the search for $\nu_e$ appearance. In general, since the neutrino beam is close to the Earth’s surface, the electron density can be considered constant along the neutrino path and the contribution of matter effects depends on the neutrino propagation distance and on the neutrino energy range. Matter effects are very small for T2K.

1.4 Neutrino oscillations state of the art

In the case of three-neutrino mixing, there are three flavor transition channels for neutrinos:

$$\nu_e \leftrightarrow \nu_\mu, \quad \nu_e \leftrightarrow \nu_\tau, \quad \nu_\mu \leftrightarrow \nu_\tau$$  \hspace{1cm} (1.23)

and the corresponding three channels for antineutrinos, and there are three squared-mass differences:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2, \quad \Delta m_{31}^2 \equiv m_3^2 - m_1^2, \quad \Delta m_{32}^2 \equiv m_3^2 - m_2^2$$  \hspace{1cm} (1.24)

However, since:

$$\Delta m_{32}^2 + \Delta m_{21}^2 - \Delta m_{31}^2 = 0$$  \hspace{1cm} (1.25)

only two of them are independent.

The observed hierarchy:

$$\Delta m_{21}^2 \ll \Delta m_{32}^2$$  \hspace{1cm} (1.26)

can be accommodated in the two types of mixing schemes, referred to as the “normal” ($\Delta m_{31}^2 > 0$) and “inverted” ($\Delta m_{31}^2 < 0$) hierarchies, corresponding to different mass orderings (see Figure 1.3):

- Normal hierarchy: $m_3 > m_2 > m_1$
- Inverted hierarchy: $m_2 > m_1 > m_3$  \hspace{1cm} (1.27)

Neutrino oscillations are insensitive to the absolute scale of the three masses and only mass differences can be measured.
The solar neutrino parameters, $\theta_{12}$ and $\Delta m^2_{21}$, have been constrained by solar neutrino oscillation experiments, which are sensitive to $\nu_e$, and the long-baseline KamLAND experiment. The combination of the results of all solar neutrino experiments and KamLAND provides the following values: $\theta_{12} \sim 32^\circ$ and $\Delta m^2_{12} = (8.0 \pm 0.6) \times 10^{-5}$ eV$^2$. The sensitivity of solar experiments to matter effects allowed to determine the sign of $\Delta m^2_{21}$.

The atmospheric neutrino parameters, $\theta_{32}$ and $\Delta m^2_{32}$, have been measured by SK and the K2K and MINOS long-baseline experiments, sensitive to the $\nu_\mu \rightarrow \nu_\tau$ oscillation. Measurements are done through $\nu_\mu$ disappearance. The limits on the oscillation parameters provided by the MINOS experiment are $\sin^2 2\theta_{32} > 0.90$ (90% C.L.) and $\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}$ eV$^2$. Recently also T2K provided a precise measurement of the atmospheric neutrino mixing parameters [53]: the 68% confidence limit on $\sin^2 (\theta_{32})$ is $0.514^{+0.055}_{-0.056}$ (0.511 $\pm$ 0.055) assuming normal (inverted) hierarchy; the best-fit mass-squared splitting is $\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}$ eV$^2$ ($\Delta m^2_{32} = (2.48 \pm 0.10) \times 10^{-3}$ eV$^2$) for normal (inverted) hierarchy. Oscillations in matter with long baselines can allow to discriminate the sign of $\Delta m^2_{32}$ and establish the mass hierarchy of neutrinos.

Recently, accelerator (T2K [47], MINOS [60], in the $\nu_\mu \rightarrow \nu_e$ appearance channel) and reactor (Double Chooz [62,63], RENO [64,65], Daya Bay [66] in the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance channel) neutrino experiments provided a very significant evidence of non-zero $\theta_{13}$, completing the current knowledge of the three neutrino mixing angles. Currently $\theta_{13}$ is measured with a precision of 5% by reactor experiments [3] and the T2K appearance signal has a 7.3 sigma significance [4].
as discussed below.

The indication of a non-zero value of $\theta_{13}$ strongly affects the future program of neutrino physics because a zero element in the mixing matrix would have eliminated the possibility of leptonic CP-violation. On the contrary, a large value of $\theta_{13}$ increases the reach of experiments to reveal the ordering of the neutrino masses (the “mass hierarchy”), and to discover matter-antimatter asymmetries (CP or T reversal violation) in the neutrino sector.

The CP-violating phase $\delta$ can be measured in long baseline experiments, studying differences in the oscillation probabilities for neutrinos and antineutrinos, $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. It will be necessary to be able to disentangle the real CP-violation due to the $\delta$ phase from the matter effects.

Recently, T2K has released its first measurement of muon-antineutrino disappearance [54] and performed its first antineutrino appearance search [55–57], observing three candidate electron antineutrino events at Super-Kamiokande in the muon antineutrino beam from J-PARC. Although bigger statistics is needed to make a significant observation, this result is compatible with the $\theta_{13}$ measured value. These results confirm the potential of the T2K experiment to perform a powerful antineutrino oscillation search and CP violation studies.

$\theta_{13}$ measurements

The measurement of $\theta_{13}$ can be performed either through $\nu_e$ appearance experiments using muon neutrinos from an accelerator and a long baseline of several hundred km, or through $\bar{\nu}_e$ disappearance experiments using electron antineutrinos from a reactor and a modest baseline of the order of 1 km.

Accelerator long baseline experiments are characterized by a muon neutrino or antineutrino beam produced by the decay in flight of pions and kaons created by shooting a proton beam to a target. The kaons and pions are allowed to decay in a tunnel of length of the order of 100 m. The beam is composed of $\nu_\mu$’s or $\bar{\nu}_\mu$’s depending on the polarity of the horn which focuses the pions and kaons. The typical energy of neutrinos is of the order of a few GeV, but can be larger depending on the energy of the proton beam. The typical source-detector distance is about $10^2 - 10^3$ km.

Fission reactors are abundant sources of $\bar{\nu}_e$ produced by the $\beta$ decays of neutron-rich nuclei (such as the isotopes $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu). The total rate of antineutrino production of a typical nuclear power plant is very high. However, reactor antineutrinos have low energy (of the order of few MeV), which implies a relatively short oscillation length, and the antineutrino flux (which is isotropic) decreases rapidly with distance. Thus, only $\bar{\nu}_e$ disappearance can be investigated in reactor anti-neutrino experiments. In fact the energy in not sufficient to produce, in a detector, muons and taus through charged-current
interactions. Reactor $\bar{\nu}_e$ are detected through the inverse $\beta$-decay reaction ($\bar{\nu}_e + p \to e^+ + n$). The antineutrino events are distinguished from the background by the coincidence of a prompt positron signal (which can be seen in scintillator detectors) with the delayed signal produced by the nuclear capture of the neutron (a very clear signal is obtained by using materials with high neutron capture cross section, such as Gadolinium).

Until the new reactor and accelerator experiments provided their results, the best constraint to $\theta_{13}$ came from the CHOOZ \cite{48} reactor anti-neutrino experiment: $\sin^2(2\theta_{13}) < 0.2$ at 90\% confidence level (C.L.), for $\Delta m^2_{32} = 2.0 \times 10^{-3}$ eV$^2$ \cite{49}.

The CHOOZ detector was a liquid scintillation calorimeter located in France, about 1 km away from two nuclear reactors which generate a total thermal power of $\sim 8.5$ GW and was designed to detect reactor $\bar{\nu}_e$’s of average energy of 3 MeV. CHOOZ was characterized by the average value of $L/E_{\nu} \sim 300$ ($L \sim 1$ km, $E_{\nu} \sim 3$ MeV) and an intense and nearly pure neutrino flavour composition ($\sim 100\%$ $\bar{\nu}_e$).

In June 2011 the T2K collaboration has reported indications of $\nu_\mu \to \nu_e$ appearance with 2.5\% significance \cite{52}. The existence of electron-neutrino appearance in a muon neutrino beam has been definitely confirmed by the latest T2K results, at the moment of this writing, based on data taken from January 2010 to May 2013. A total of 28 electron neutrino events were detected with an energy distribution consistent with an appearance signal, corresponding to a significance of 7.3\% when compared to 4.92$\pm$0.55 expected background events. In the PMNS mixing model, a best-fit value of $\sin^2(2\theta_{13}) = 0.140^{+0.038}_{-0.032}(0.170^{+0.045}_{-0.037})$ is obtained for normal (inverted) hierarchy and for $\delta = 0$ \cite{4}.

T2K uses a conventional neutrino beam produced at the accelerator centre J-PARC (located in Tokai, Japan) and directed 2.5$^\circ$ off-axis to the Super-Kamiokande (SK) water Cherenkov detector at a distance $L = 295$ km. This configuration produces a narrow-band $\nu_\mu$ beam \cite{130}, tuned at the first oscillation maximum ($E_{\nu} \simeq 0.6$ GeV), reducing backgrounds from higher energy neutrino interactions (such as neutral current interactions). T2K makes use of a near detector complex, located 280 m downstream from the target. It hosts two detectors: the on-axis Interactive Neutrino GRID (INGRID) accumulates neutrino interactions with high statistics to monitor the beam intensity, direction and profile; the off-axis detector (ND280) reconstructs exclusive final states to study neutrino interactions and beam properties corresponding to those expected at the far detector. A detailed description of the T2K experimental set-up can be found in Chapter \ref{Chapter2}.

Figure \ref{Fig:1.4} shows the first electron-neutrino candidate observed after the recovery from the earthquake on the east coast of Japan in 2011.
1.4. Neutrino oscillations state of the art

Figure 1.4: A candidate electron-neutrino event in Super Kamiokande. The image shows the first electron-neutrino candidate observed after the recovery from the earthquake on the east coast of Japan in 2011. Image taken from [50].

The T2K first result was soon followed by the MINOS collaboration which reported also indication of non-zero $\theta_{13}$. MINOS is a two-detector long-baseline neutrino oscillation experiment situated along the NuMI neutrino beamline (which uses protons from the Main Injector accelerator to produce an intense beam of neutrinos) at Fermilab, near Chicago. MINOS uses a 0.98-kton near detector located at Fermilab, 1.04 km downstream of the NuMI target, and a 5.4-kton far detector located 735 km downstream in the Soudan Underground Laboratory, in northern Minnesota. The two detectors have nearly identical designs, each consisting of alternating layers of steel and plastic scintillator. The $\theta_{13} = 0$ hypothesis is disfavored by the MINOS data at the 89% C.L. [61].

Three new reactor experiments turned on in 2011: Double Chooz (France), RENO (South Korea), Daya Bay (China). The three of them have a very similar basic design and use a near detector to reduce systematics.

Double Chooz is based on the CHOOZ-B Nuclear Power Station. The experiment is a double detector apparatus (each detector with a fiducial volume of 10.3 m$^3$) based on liquid scintillator, though up to the moment of this writing they took data only with their far detector located at 1.05 km from the two 4.27 GWth reactor cores. Double Chooz presents an indication of reactor electron antineutrino disappearance consistent with neutrino oscillations. The value of $\theta_{13}$ is measured to be $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ [63].

In the RENO experiment antineutrinos from six 2.8 GWth reactors at the Yonggwang Nuclear Power Plant in Korea, are detected by two identical de-
tectors located at 294 m and 1383 m, respectively, from the reactor array center. RENO has observed the disappearance of reactor electron antineutrinos, consistent with neutrino oscillations, with a significance of 4.9 standard deviations. A rate-only analysis at RENO obtains $\sin^2(2\theta_{13}) = 0.113 \pm 0.013$(stat.)$ \pm 0.019$(syst.) [65].

In the Daya Bay experiment electron antineutrinos from six reactors of 2.9 GWth were detected in six antineutrino detectors located in two near (flux-weighted baselines of 470 m and 576 m) and one far (1648 m) underground experimental halls. Daya Bay excludes a zero value for $\sin^2(2\theta_{13})$ with a significance of 7.7 standard deviations [66]. An analysis of the relative rates in six detectors finds $\sin^2(2\theta_{13}) = 0.089 \pm 0.010$(stat.)$ \pm 0.005$(syst.) in a three-neutrino framework.

### 1.4.1 Future neutrino projects

The next generation of long-baseline neutrino oscillation experiments aims to improve the precision on the already measured oscillation parameters, to measure the neutrino mass hierarchy and search for CP-violation in the lepton sector. In order to achieve these goals the neutrino beam production must be enhanced and detectors must be upgraded. Several projects are currently being actively developed. The main ones are briefly presented in this section.

In the USA, the proposed LBNE (Long-Baseline Neutrino Experiment) neutrino project [71], at Fermilab, would send a high-intensity neutrino beam from Fermilab to a particle detector in South Dakota. Construction of the experiment could be underway in 2023. The LBNE experiment would determine whether neutrinos break the matter-antimatter symmetry, which could be the explanation for the dominance of matter over antimatter across the universe. The experiment’s capabilities would far exceed those of the NO$\nu$A (NuMI Off-Axis Electron-neutrino Appearance Experiment) [67] experiment. NO$\nu$A is a long-baseline accelerator based neutrino oscillation experiment which uses the upgraded Fermilab NuMI beam and measures electron-neutrino appearance and muon-neutrino disappearance at its far detector in Ash River, Minnesota. The main goals of NO$\nu$A are to measure the neutrino mass hierarchy and the CP-violating phase and to improve the $\theta_{13}$ measurement. NO$\nu$A has begun to take data in 2014. The NO$\nu$A collaboration has announced the NO$\nu$A’s first oscillation results in 2015 [68–70].

nuSTORM (Neutrinos from STORed Muons) [72] is based on the idea of using a muon storage ring to produce a high-energy (50 GeV) neutrino beam. It would use 3-4 GeV/c muon storage ring to study eV-scale oscillation physics and, in addition, could contribute significantly to the understanding of the $\nu_e$ and $\nu_\mu$ cross-sections.
1.5. Neutrino-nucleus interactions

The PINGU (Precision IceCube Next Generation Upgrade) experiment, to be placed with the IceCube DeepCore detector in the deep Antarctic glacier, is being designed to provide a first definitive measurement of the mass hierarchy.

The LBNO (Long Baseline Neutrino Oscillation) experiment consists of a far detector, situated at 2300 km from CERN and a near detector based on a high-pressure argon gas TPC. Its main goals are to discover CP-violation in the leptonic sector and determine the neutrino mass hierarchy. The strategy of LBNO is to exploit the L/E dependence of the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance probabilities with a wide-band beam at a baseline of 2300 km. Separate information on neutrinos and antineutrinos can be obtained by changing the horn focusing polarity of the beam. The disappearance channels ($\nu_\mu \nu_\mu$ and $\bar{\nu}_\mu \bar{\nu}_\mu$) will constrain the atmospheric parameters and the muon charge identification will independently determine the $\nu_\mu/\bar{\nu}_\mu$ fluxes at the far distance. The $\nu_\mu \nu_\tau$ and $\bar{\nu}_\mu \bar{\nu}_\tau$ appearance channels will also be accessible with an unprecedented precision.

In Japan, projects exploring the lepton sector CP symmetry both with a 100kt detector based on a liquid Argon time projection chamber and a 560kt water Cherenkov detector (Hyper-Kamiokande), both using a high-intensity neutrino beam that would be provided by J-PARC, are being planned. Hyper-Kamiokande (Hyper-K) will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC, and as a detector capable of observing - far beyond the sensitivity of the Super-Kamiokande (Super-K) detector - proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology. Hyper-K presents unprecedented potential for precision measurements of neutrino oscillation parameters and discovery reach for CP-violation in the lepton sector. In addition, a high statistics data sample of atmospheric neutrinos will allow to access the information on the mass hierarchy and the octant of $\theta_{32}$.

1.5 Neutrino-nucleus interactions

The precision of the current and next generation of neutrino experiments is limited by the knowledge of how neutrinos interact with matter, thus an accurate understanding of neutrino-nucleus interactions is required.

Neutrinos are un-coloured and electrically neutral particles of spin 1/2 which interact with matter only through the weak force, i.e. by exchanging a $Z^0$ or $W^\pm$ boson with a lepton, a nucleon or a nucleus. Their detection is done through interactions with the nuclei present in the detector and, since it is impossible to directly observe the neutrino path, details of the interaction must be inferred.
from the observable particles produced.

Although neutrino interactions are accurately described by the standard model for point-like particles, most neutrino cross-sections come from interactions of neutrinos with nucleons (which are bound states of quarks) or with nuclei (which are bound states of nucleons), meaning that other effects must be taken into account and that the precision of any measurement involving interactions with a nucleus is greatly affected by the theoretical model chosen to describe the nucleus and nucleon-nucleon interactions (see Section 1.6).

1.5.1 Neutrino-nucleus interactions at T2K

The main neutrino-induced interactions expected at T2K will be briefly discussed in this section. Charged current quasi-elastic (CCQE) scattering, which is of interest to this thesis, will be extensively discussed in Section 1.6.

**Charged current interactions**

In charged current (CC) interactions the neutrino exchanges a $W^\pm$ boson with a nucleon or a nucleus, and turns into its corresponding charged lepton partner after the interaction.

Figure 1.5 shows the charged current neutrino cross sections as a function of neutrino energy. In the region of interest to T2K (the peak neutrino energy at T2K is 0.6 GeV) the cross-section is dominated by quasi-elastic and single pion production (CC1π) interactions. At larger neutrino energies the dominant interaction is deep inelastic scattering (DIS).

![Figure 1.5: Charged current neutrino cross sections as a function of energy (in GeV). Shown are the contributions from quasi-elastic (dashed), single pion (dot-dash) and deep inelastic scattering (dotted) processes.](79)
In a CCQE interaction the target nucleus does not break up. The neutrino interacts with a neutron in the nucleus to produce a charged lepton and a proton in the final state:

\[ \nu_l + n \rightarrow l^- + p \quad (l = e, \mu, \tau) \]  

(1.28)

The interaction is called “quasi-elastic” because of the need to create a massive charged lepton. CCQE interactions will be extensively discussed in Section 1.6.

CC1\(\pi\) interaction refers to any reaction producing a charged lepton and one pion, either through a neutrino-nucleon interaction with an intermediate resonance (resonant reaction):

\[ \nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+ \]  

(1.29)

\[ \nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + n + \pi^+ \]  

(1.30)

or through a coherent reaction in a nucleus (coherent pion production):

\[ \nu_\mu + A \rightarrow \mu^- + A + \pi^+ \]  

(1.31)

Resonant production is the dominant mechanism at low neutrino energy. The produced baryon resonance is determined by the neutrino’s energy, resulting in a variety of final states, including multiple pions and kaons. However, at the T2K neutrino energy usually the resonances decay to a nucleon and a single pion. In coherent pion production the nucleus is left in its ground state after scattering; the neutrino interacts with the whole nucleus and transfers little energy to produce a forward-going pion.

If the final state pion is not detected (it can be absorbed by the nuclear medium) the signal mimics a CCQE event. This is one of the main backgrounds in the \(\nu_\mu\) disappearance analysis at T2K. The strategy adopted to reduce the CC1\(\pi\) background in the analysis presented in this thesis is discussed in Section 4.8.

At high energy (above a few GeV, corresponding to the high energy tail of the neutrino energy distribution at T2K) deep inelastic scattering is the dominant interaction: the neutrino is able to transfer sufficient momentum to break the nucleus up and scatter off any of the quarks inside the nucleon (\(\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'\)), producing hadronic showers.

**Neutral current interactions**

In neutral current (NC) interactions the neutrino exchanges a \(Z^0\) with a nucleon or a nucleus. Multiple hadrons can be produced and there is no outgoing charged lepton.
Neutral current interactions with a neutral pion in the final state:
\[ \nu_l + n(p) \rightarrow \nu_l + n(p) + \pi^0 \quad (l = e, \mu, \tau) \] (1.32)
are one of the main backgrounds to the \( \nu_e \) signal in the T2K appearance analysis. The \( \pi^0 \) decays to produce two photons which are expected to produce two e-like rings in the SK detector. Since showering electrons appear almost identical to showering photons, if one of these two rings is not observed (due to the small opening angle, in the laboratory frame, between the two photons, or because one photon is not reconstructed), the signal can mimic a \( \nu_e \) CC interaction.

Single \( \pi^\pm \) from NC interactions:
\[ \nu_l + n(p) \rightarrow \nu_l + p(n) + \pi^-(\pi^+) \quad (l = e, \mu, \tau) \] (1.33)
are estimated as another important contribution to the background in \( \nu_e \) appearance analyses, as sometimes they leave e-like rings at SK.

Neutrinos can interact with nucleons also through neutral current elastic scattering, the neutral current equivalent to CCQE. In this process, the neutrino interacts with a nucleon in the nucleus to produce a neutrino and a nucleon (with the same isospin as the original nucleon) in the final state:
\[ \nu_l + n(p) \rightarrow \nu_l + n(p) \quad (l = e, \mu, \tau) \] (1.34)

1.6 CCQE interactions

As mentioned in Section 1.5, CCQE \( (\nu_\mu + n \rightarrow p + \mu^-) \) typically gives the largest contribution to the oscillation search signal samples at energies in the GeV region, which is the energy range used by most long baseline experiments. In more detail, CCQE is the signal sample used at T2K to investigate neutrino oscillations and, due to its two-body nature, it constitutes the cleanest channel to characterise the neutrino beam before it oscillates (this is the main goal of the ND280 detector, see Section 2.2.3) since it provides a robust method to reconstruct the neutrino energy using only the primary lepton kinematics. In fact, if the target nucleon is at rest (this is a reasonable approximation for high neutrino energy), then the momentum and angle of the outgoing lepton with respect to the neutrino are sufficient to calculate the neutrino energy, \( E_\nu(\mu) \):

\[ E_\nu(\mu) = \frac{1}{2} \frac{(M_p^2 - m_\mu^2) + 2E_\mu(M_n - V) - (M_n - V)^2}{-E_\mu + (M_n - V) + p_\mu \cos \theta_\mu} \] (1.35)

In the above formula \( M_p, M_n \) and \( m_\mu \) are the proton, neutron and muon mass, respectively; \( V \) is the nuclear potential; \( p_\mu \) and \( \cos \theta_\mu \) are the momentum and angle of the outgoing muon with respect to the neutrino, respectively.
Neutrino energy distributions obtained using this procedure for CCQE candidate events in the ND280 tracker are shown in Section 6.2. The muon momentum and angle with respect to the neutrino are measured by the time projection chambers (TPCs), while the fine grained detectors (FGDs) provide the target material to reconstruct the neutrino interaction vertices (see Section 2.2.3). As the FGDs are mainly made of plastic scintillator bars (Carbon nuclei mainly), the value of the binding energy in Eq. 1.35 is set to 25 MeV [83].

The event selection criteria used to define the CCQE sample varies from experiment to experiment because it is strongly influenced by both the target material and the detector technology. The capabilities of the detector strongly affect also the efficiency and purity of the selection.

The first neutrino experiments were performed with bubble chambers, which are characterized by deuterium fills and low energy thresholds for protons (typically, $\geq 100$-200 MeV/c in momentum) which allow the detection of the spectator proton (i.e. the proton initially in the deuteron) in the CCQE scattering event: $\nu_\mu d \rightarrow \mu^- pp_s$. The event selection was based on the identification of two (the muon and the proton) or three (the muon, the proton and the spectator proton) final-state tracks. Bubble chambers allow to reach very high sample purities (from 97% to 99%). The lowest $Q^2$ region ($Q^2$ is the squared four-momentum transferred to the nuclear system) was often excluded in the analysis of these data in order to avoid regions with poor identification efficiency, nuclear effects, and larger backgrounds.

Most experiments built during the modern era were designed primarily for neutrino oscillation measurements. Thus, they employed heavy targets and a variety of different detector technologies. Furthermore, the use of extremely intense neutrino beamlines allowed much larger event samples to become available. These experiments fall into two broad categories: tracking detectors (typically drift chambers or segmented scintillation elements) and Cherenkov detectors (large tanks of water or mineral oil as a target with photodetectors lining the inner surface of the tank to collect the light emitted by relativistic charged particles).

Tracking experiments attempt to identify charged particles as they traverse the active elements of the detector. The quasi-elastic event selection is based on the analysis of both one-track (muon plus no proton) and two-track (muon plus proton) event samples. Thus, the detection thresholds for protons play a significant role in tracking detectors. On the other hand, the final-state proton emitted in neutrino quasi-elastic interactions is typically below Cherenkov threshold and hence is undetected in Cherenkov detectors. It is worth noting that the one-track samples were never considered in bubble chamber experiments.

Typical quasi-elastic purities in modern detectors range from 60% to 70%. 

The main reasons for modern experiments to obtain purities lower than those achieved in deuterium-filled bubble chambers are that they cannot rely on the identification of the full interaction (muon plus proton plus spectator proton) and use heavy nuclear targets (where nuclear effects are large). In more detail, the fundamental process we seek to measure occurs in a nuclear environment, while our event selection is based on what is visible in the detector after intranuclear processes have occurred. The largest sources of background contamination and inefficiency stem from nuclear effects associated with “final state interactions” (FSI, i.e. rescattering of hadrons produced in the initial neutrino interaction before they have had a chance to exit the target nucleus). FSI lead to topological changes in the final state that can influence both signal and background processes. There may also be limitations posed by the detector itself, such as the inability to detect low-energy particles (particularly nucleons) emerging from the target nucleus or the misidentification of observed particles. Such effects vary from detector to detector.

Table 1.1 summarizes the detector techniques employed in the experimental study of neutrino-induced CCQE scattering.

The criteria used to select CCQE event samples in the T2K ND280 tracker is the topic of this thesis and is discussed in detail in Chapter 4.

1.6.1 The relativistic Fermi gas model

Although CCQE is very well characterized when occurring on a single nucleon, its description becomes very complicated when occurring on nuclei:

\[ \nu_l + \frac{A}{2} X \rightarrow l^- + p + \frac{A}{2-1} X \]  
(1.36)

as mentioned in Section 1.5.

The kinematics and cross-section of any neutrino-nucleus interaction are affected by the motion of the nucleons inside the nuclear potential. The simplest model describing the most important features of nuclear dynamics is the relativistic Fermi gas model (RFG) \[80\] \[81\], in which the nucleus is considered as an ideal gas composed of weakly interacting fermions, i.e. particles obeying Fermi-Dirac statistics.

The binding potential is generated by all nucleons, considered as moving freely within the nuclear volume. Neutrons and protons are distinguishable fermions and are therefore situated in two separate potential wells (see Figure 1.6). Each energy state can be occupied by two nucleons with different spin projections and all available energy states are filled. The energy of the highest occupied state is the Fermi energy \(E_F\). The Fermi level of the protons and neutrons in a stable nucleus have to be equal, otherwise the nucleus would enter
1.6. **CCQE interactions**

<table>
<thead>
<tr>
<th>experiment</th>
<th>detector technology</th>
<th>years</th>
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<tbody>
<tr>
<td>ANL</td>
<td>Spark chamber, bubble chamber</td>
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<tr>
<td>BEBC</td>
<td>Bubble chamber</td>
<td>1990</td>
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<td>BNL</td>
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<td>FNAL</td>
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<td>Sepurkov</td>
<td>Spark chamber</td>
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<td>K2K</td>
<td>Tracking detectors (solid scintillator strips plus scintillating fiber tracker)</td>
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<tr>
<td>SciBooNE</td>
<td>Tracking detector (solid scintillator strips plus electromagnetic calorimeter)</td>
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<td>MINOS</td>
<td>ND and FD: Tracking calorimeter (iron plates plus solid scintillator strips)</td>
<td>2004-present</td>
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<td>Tracking detector (solid scintillator strips plus electromagnetic and hadronic calorimetry)</td>
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<td>ND and FD: Tracking detector (liquid scintillator cells)</td>
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<td>ND: Tracking detectors (solid scintillator plus time-projection chambers plus electromagnetic calorimeters)</td>
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<tr>
<td></td>
<td>FD: Cherenkov detector</td>
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</table>

Table 1.1: Summary of detector techniques employed in the experimental study of neutrino charged current quasi-elastic scattering ($\nu_\mu + n \rightarrow \mu^- + p$) [86]. ND stands for Near Detector, FD for Far Detector.

a more energetically favourable state through $\beta$-decay. Thus for heavy nuclei, which have a surplus of neutrons, the depth of the potential well as it is experienced by the neutron gas has to be larger than the one of the proton gas. Protons are therefore on average less strongly bound in nuclei than neutrons. This may be understood as a consequence of the Coulomb repulsion of the charged protons.

The difference $E_B$ between the top of the well and the Fermi level is constant for most nuclei and is just the average binding energy per nucleon (of the order of 7-8 MeV).
At temperature $T = 0$, i.e. for the nucleus in its ground state, the lowest states will be filled up to a maximum momentum, called the Fermi momentum $p_F$. Assuming the proton and the neutron potential wells have the same radius, we find that for a nucleus with $Z=N=A/2$ the Fermi momentum $p_F$ is of the order of 250 MeV/c.

Due to Pauli-blocking, the nuclear potential limits the final-state kinematics available to interactions producing a nucleon because the resulting nucleon cannot be in a state which is already occupied. Thus the available phase space, and hence the cross-section, is reduced. In the framework of the RFG model the quasi-elastic process is only allowed if the momentum of the final-state nucleon exceeds the Fermi momentum.

Most CCQE models (including many Monte Carlo codes and particularly NEUT [109], which is used in the analysis presented in this thesis) are based on the RFG model (in particular, on the Smith and Moniz model [80], which is the most commonly used version of the RFG model) and assume that the incoming neutrino interacts with only one nucleon, which is subsequently emitted, while the remaining nucleons in the target are spectators (impulse approximation approach). However, in reality, nucleons are not independent particles and more complex nuclear dynamics are involved.

In most experiments exploring high neutrino energies the RFG model is a good approximation since at large $Q^2$ the effects of the nucleon motion on the kinematics and cross-section of neutrino-nucleus interactions can be neglected, but alternative models, such as “spectral functions” [82], are being investigated for the current and future generation of experiments exploring lower energy regions (where those effects are not negligible).
1.6. CCQE interactions

1.6.2 Final state interactions

Another effect that must be taken into account when dealing with neutrino-nucleus interactions is that the final-state hadrons can undergo strong interactions with the nucleons inside the nucleus while propagating out through the nucleus (FSI), as mentioned above. Consequently, their momentum and direction can be significantly altered.

1.6.3 CCQE cross-section

The CCQE cross section is usually written according to the Llewelyn-Smith formalism \[84\], which assumes the neutrino to be massless and the neutron to be at rest, and parametrizes the cross section in terms of several Lorentz-invariant form factors (vector, pseudoscalar and axial-vector form factors) which are functions of \(Q^2\). Form factors encapsulate information about the nucleon structure. In more detail, they describe the spatial distribution of the electric charge and current inside the nucleon.

The pseudoscalar form factors to a good approximation are negligible due to kinematics; the vector form factors can be extracted from electron scattering measurements on proton and deuteron targets with great accuracy; the axial form factor, \(F_A\), must be measured by neutrino scattering experiments and is the only free parameter. An often used parametrization for \(F_A\) is a dipolar form:

\[
F_A(Q^2) = g_A \left[ 1 + \frac{Q^2}{M_A^2} \right]^{-2}
\]

where \(M_A\) is the axial mass parameter. It defines the axial nucleon radius, which is expected to be of the order of 1 GeV. The \(Q^2\) dependence of \(F_A\) has to be determined experimentally. Thus, the cross section, to a good approximation, can be considered as a function of a single parameter, the axial mass \(M_A\). Therefore in first approximation the problem of the determination of the quasi-elastic cross section can be indentified with the measurement for \(M_A\). However, a comparison between theoretical models and modern measurements of these quantities reveals several discrepancies, discussed below.

Axial mass puzzle

Recent data have shown that the CCQE channel is more complicated than expected, since a significant discrepancy in this cross section measured at different energies (by the MiniBooNE and NOMAD experiments) has been observed, as shown in Figure 1.7.

MiniBooNE is a 800 ton, spherical mineral oil Cherenkov detector, uses a carbon target and a neutrino beam of \(\sim 1\) GeV. NOMAD is a tracking detector
Neutrino physics

It is composed of drift chambers situated in a magnetic field complemented with electromagnetic and hadronic calorimeters as well as muon detectors. It uses a carbon target and operates at higher neutrino energy (∼24 GeV).

Figure 1.7: Measurements of the absolute $\nu_\mu$ quasi-elastic (QE) scattering cross section on carbon as a function of neutrino energy from the MiniBooNE [87] and NOMAD [88] experiments. Also shown is a representative collection of theoretical calculations from a recent compilation [102]. The theoretical curves are from References [103], [104] and [105] (spectral functions) and from [106, 107] and [108] (Martini et al.). Figure and caption taken from [86].

The NOMAD experiment measures results for both $M_A$ and the CCQE cross section that are consistent with those expected from the historical value of the axial mass obtained in previous deuterium filled bubble chamber experiments, $M_A = 1.03$ GeV, while the comparison of the MiniBooNE result with the same model prediction reveals a substantial discrepancy. A modification of the axial mass from the standard value to a larger value, $M_A = 1.35$ GeV, is needed to account for MiniBooNE data. A similar conclusion holds for the $Q^2$ distribution (Figure 1.8).

In more detail, the neutrino CCQE cross sections obtained by MiniBooNE are ∼30% larger. Several representative calculations, including the RFG model and the spectral function approach [80, 82], that have been very successful at describing electron scattering data over a wide range of kinematics do not reflect the MiniBooNE result. This has to be understood. However, Figure 1.7 shows that
1.6. CCQE interactions

the prediction from a model allowing the multinucleon emission channel \[106,107\] can account for the unexpected behaviour of the MiniBooNE quasi-elastic cross section. In more detail, according to \[106,107\], as the nuclear medium is not a gas of independent nucleons, correlated only by the Pauli principle, but there are additional correlations, thus the ejection of a single nucleon is only one possibility and events involving correlated nucleon pairs (n particle-n hole, \(np - nh\), states) from which the partner nucleon is also ejected must be considered too. At present, such events are not easily experimentally distinguishable from the genuine quasi-elastic events and must be considered simultaneously.

Furthermore, it is worth noticing that NOMAD selects events with only one track (a muon) or two tracks (a muon plus a proton), while MiniBooNE selects events with a muon and no pions. Thus, it is not clear how many events accepted by MiniBooNE are rejected by the NOMAD selection.

Low \(Q^2\) and \(Q^2\) shape

Modern measurements show a suppression of events at low \(Q^2\) (\(Q^2 < 0.2\ GeV^2\)) when the shape of the \(Q^2\) distribution is compared with standard predictions. This effect is clearly evident in MiniBooNE data (Figure 1.8) because of their high statistics, but it has also been observed in other low-energy neutrino experiments \[89,97\]. To address the discrepancy between the prediction and the data (which can be ascribed to the inadequacy of the impulse approximation at such low \(Q^2\) values) a rescaling of the amount of Pauli blocking in the impulse-approximation calculations \[98\] has been introduced. Recently improved modelling of the non-QE backgrounds, which are large in this region, also greatly improves the agreement at low \(Q^2\) \[99\].

In addition to discrepancies at low \(Q^2\), the overall distribution of the events is shifted to higher \(Q^2\) values in many of the experimental data (Figure 1.8). As a result, this “harder” data spectrum requires a higher \(M_A\) value than the prior world average (\(M_A \sim 1.0\ GeV\)). The \(M_A\) values determined by MiniBooNE, K2K and MINOS show similar trends. \(M_A\) values determined from these experiments range anywhere from \(M_A = 1.14\) to 1.35 GeV (\[98,101\]). In contrast, the NOMAD experiment measures a lower value of \(M_A = 1.05\ GeV\) \[89\] for high energy neutrinos (4-70 GeV) on carbon. The source of this difference is not fully understood at present.

Recently, the MINER\(\nu\)A collaboration reported a study \[91\] of \(\nu_\mu\) charged current quasi-elastic events in the segmented scintillator inner tracker of the MINER\(\nu\)A experiment \[90\] running in the NuMI neutrino beam \[92\] at Fermilab. The MINER\(\nu\)A detector consists of a fine-grained scintillator tracker surrounded by electromagnetic and hadronic calorimeters. The detector enables reconstruction of the neutrino interaction point, the tracks of outgoing charged
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Figure 1.8: Flux-integrated single differential cross-section per target neutron for the $\nu_\mu$ CCQE process. The measured values are shown as points with the shape error as shaded bars. Calculations from the nuance RFG model with different assumptions for the model parameters are shown as histograms. Figure and caption taken from [150].

Figure 1.9: Neutrino quasi-elastic cross-section as a function of $Q^2$ compared with several different models of the interaction. Figure and caption taken from [91].

particles, and the calorimetric reconstruction of other particles produced in the interaction. MINER$\nu$A is located 2 m upstream of the MINOS near detector [93], which is used to reconstruct the momentum and charge of muons. A measurement of the flux-averaged differential cross-section, $d\sigma/dQ^2$, shown in Figure 1.9 and studies of the low energy particle content of the final state have showed deviations from the expectations of a model of independent nucleons in a rela-
tivistic Fermi gas. Different models of nuclear effects in quasi-elastic scattering lead to significant variations in the shape of $d\sigma/dQ^2$ from the expectation of the RFG model. Figure 1.9 shows a comparison between the MINERνA data, the RFG model in the GENIE event generator 175 and a set of calculations made with the NuWro generator 95,96. MINERνA data are in best agreement with a transverse enhancement model (TEM) 94 with $M_A = 0.99$ GeV. This model implements an enhancement of the magnetic form factors of bound nucleons that has been extracted from electron-carbon scattering data.

MINERνA observes also an excess of energy near the interaction vertex consistent with multiple protons in the final state 91.
Chapter 2

The T2K experiment

Figure 2.1: The T2K experiment, from Tokai to Kamioka (Japan).

The T2K (Tokai to Kamioka) experiment is a long-baseline neutrino oscillation experiment, located in Japan, aiming at measuring several parameters that describe the neutrino mixing.

T2K began accumulating neutrino beam data for physics analysis in January 2010 and provided its first results in 2011. Its main goals were the measurement of the mixing angle $\theta_{13}$, using the $\nu_e$ appearance channel [4, 52], and the improvement of the measurement of the atmospheric parameters, $\Delta m^2_{32}$ and $\theta_{32}$, using the $\nu_\mu$ disappearance channel [53, 58]. As the $\theta_{13}$ oscillation parameter has been probed to be non-zero by T2K and by reactor experiments (see Section 1.4), the second phase of the T2K experiment aims at a search for CP-violation in the leptonic sector by measuring the CP-violation phase $\delta$. Recently, T2K has released its first measurement of muon-antineutrino disappearance.
and performed its first antineutrino appearance search \cite{55-57}. Other goals of the experiment include various neutrino cross-section measurements and sterile neutrino searches.

T2K uses a high purity off-axis muon-neutrino beam that is sent from the J-PARC (Japan Proton Accelerator Research Center, see Section 2.1) proton accelerator complex at Tokai, Ibaraki, to Super Kamiokande (SK, see Section 2.3), a cylindrically shaped water Cherenkov detector located in the Kamioka Observatory, 295 km away from the neutrino source.

The neutrino energy spectrum, flavor content and interaction rates of the unoscillated beam are measured by the near detector complex (see Section 2.2), located 280 m downstream of the target, which hosts two detectors: the on-axis Interactive Neutrino GRID (INGRID \cite{116}), described in Section 2.2.2, and the off-axis detector (ND280), described in Section 2.2.3. INGRID records neutrino interactions with high statistics to monitor the beam intensity, direction and profile. ND280 measures the muon neutrino flux and energy spectrum, intrinsic electron neutrino contamination in the beam in the direction of the far detector, and rates for exclusive neutrino reactions.

The strategy used to measure the oscillation parameters is the one typical of long baseline neutrino oscillation experiments. As mentioned in Section 1.6 the energy region covered by T2K (below 1 GeV) is dominated by CCQE interactions \((\nu_l + n \rightarrow l + p, \text{with } l = \mu, e)\). Assuming the CCQE hypothesis for all of the detected neutrinos, the neutrino energy spectrum at both the near and far detectors can be precisely reconstructed by two body kinematics for both \(\nu_\mu\)'s and \(\nu_e\)'s. The off-axis far detector, SK, measures the oscillated \(\nu_\mu\) and \(\nu_e\) energy spectra, while the off-axis near detector, ND280, measures the unoscillated \(\nu_\mu\) and intrinsic \(\nu_e\) energy spectra \cite{117}. The spectra measured at the near detector are extrapolated and compared to the ones obtained with the far detector, to measure the oscillation parameters.

\section{2.1 The J-PARC accelerator}

J-PARC consists of three accelerators:

- a linear accelerator (LINAC), which boosts \(H^-\) ions up to a kinetic energy of 181 MeV before they are converted into an \(H^+\) beam by charge-stripping foils;
- a rapid-cycling synchrotron (RCS) where the \(H^+\) beam is accelerated up to 3 GeV;
- the main ring (MR) synchrotron, which accelerates the proton beam (used to produce the neutrino beam) up to 30 GeV every 2 to 3 seconds;
2.1 The J-PARC accelerator

Figure 2.2: The J-PARC facilities at Tokai Mura, Japan.

and three experimental facilities: Materials and Life Science, Neutrino and Hadron, as shown in Figure 2.2.

There are two extraction points in the MR: slow extraction for the hadron beamline and fast extraction for the neutrino beamline. In the fast extraction mode, for each acceleration cycle, the beam is extracted to the T2K neutrino beamline as a “spill” of 5.6 $\mu$s to produce the neutrino beam. In each spill there are 8 bunches (limited at 6 for the 2010 run) each of a length of 58 ns.

2.1.1 The T2K neutrino beamline

The neutrino beamline (shown in Figure 2.3) is composed of two sequential sections: the primary and secondary beamlines. In the primary beamline the extracted proton beam is transported to point in the direction of the secondary beamline (toward Kamioka) and focussed to have the desired profile at the target. In the secondary beamline the proton beam impinges on a graphite target to produce secondary pions and other hadrons which are focussed by magnetic horns and decay into neutrinos. The arrangement of the secondary beamline’s components is shown in Figure 2.4.

The primary beamline consists of three parts: the preparation section, the arc section and the final focussing section. In the preparation section the extracted proton beam is tuned with a series of normal conducting magnets so that it can be accepted by the arc section, where it is bent towards Kamioka. In the final focussing section the beam is guided and focussed onto the target and directed downward by 3.64 degrees with respect to the horizontal.

The intensity, position and profile of the proton beam in the primary sections are precisely monitored in order to have a well-tuned proton beam. This is essential for stable neutrino beam production, to minimize beam loss and to
achieve high-power beam operation.

The secondary beamline consists of three sections: the target station, the decay volume and the beam dump. After the final focusing section, protons from the primary beamline are directed to the target station, installed 12 meters underground, where the T2K target and the horn system are installed. After entering the target station the beam passes through a baffle, to reduce the exposure of the horn to beam loss, and then through the optical transition radiation monitor (OTR), which measures the beam profile. The beam then impinges on the target, which consists of a 91.4 cm long (corresponding to 1.9 interaction length) graphite rod with a diameter of 2.6 cm and a density of 1.8 g/cm$^3$ [1]. The secondary pions generated by the interaction of the primary protons with the target are focussed by three magnetic horns and enter the decay volume (a 96 m long steel tunnel) where the decay in flight of positive pions into muons and muon neutrinos (through $\pi^+ \rightarrow \mu^+ + \nu_\mu$) produces the main component of the beam. The intrinsic $\nu_e$ contamination of the beam is generated mainly by the decay of few charged kaons, which are also produced by the primary proton interaction, and by the muon decay through $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, which also adds a $\bar{\nu}_\mu$ component to the beam. However, most of the $\bar{\nu}_\mu$'s are created by the decay of negative pions surviving the defocussing induced by the horns.

Only muons above $\sim5$ GeV/c and $\nu_\mu$'s pass through the beam dump. As muons are mainly produced along with neutrinos from the pion two-body decay, 

---

[1] Graphite has a high melting point and good thermal stress resistance. The intensity of the beam is so high that materials with higher $Z$ than graphite would be strongly damaged by the high temperature due to the energy deposited by the protons.
they are monitored to characterize the neutrino beam. In more detail, the muon monitor is located just behind the beam dump and is designed to measure the neutrino beam direction with a precision better than 0.25 mrad and to monitor the stability of the neutrino beam intensity with a precision better than 3%.

![Figure 2.4: Side view of the secondary beamline. The length of the decay volume is ∼96 m.](image)

2.1.2 Off-axis technique

Unlike previous long-baseline neutrino oscillation experiments, T2K uses the off-axis technique, with ND280 and SK positioned 2.5 degrees off-axis from the centre of the T2K neutrino beam. Such configuration yields a narrow band neutrino beam, peaked at ∼600 MeV [129], in both detectors due to the correlation of off-axis angle and neutrino energy. In addition, the off-axis technique allows to reduce the high-energy components of the beam that limit the precision of the oscillation parameters. In particular, the background to electron-neutrino appearance detection is minimized.

Let us consider a muon neutrino produced in the pion decay process \( \pi^+ \rightarrow \mu^+ + \nu_\mu \), with the high-energy pion moving, in the laboratory frame, along the \( z \) axis. The dependence of the neutrino energy, \( E_\nu \), from the small off-axis angle of displacement of the detector, \( \theta \), with respect to the pion direction of flight can be written as:

\[
E_\nu = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{E_\pi m_\pi^2}{m_\pi^2 + E_\pi^2 \theta^2} \tag{2.1}
\]

where \( E_\pi \) and \( m_\pi \) are the pion energy and mass, respectively, and \( m_\mu \) is the muon mass.
2. The T2K experiment

Figure 2.5: Left: muon neutrino survival probability at SK and neutrino fluxes for different off-axis angles. Image taken from [129]. Right: Neutrino energy $E_\nu$ as a function of pion energy $E_\pi$ for different off-axis angles. Image taken from [130].

For an on-axis detector, $\theta = 0$ and the neutrino energy is proportional to the pion energy, leading to a wide beam if the pion energy range is wide. On the other hand, for an off-axis detector, both the numerator and the denominator in Eq. 2.1 increase with the pion energy, leading to a suppression of the dependence of $E_\nu$ from $E_\pi$. More in detail, it can be seen that, if $\theta \neq 0$, the derivative of $E_\nu$ (given by Eq. 2.1) with respect to $E_\pi$ vanishes for $\theta = m_\pi/E_\pi$, which corresponds to a maximum neutrino energy, $E_{\nu,max}$, given by:

$$E_{\nu,max} = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{m_\pi}{2\theta} = \frac{29.79 \text{ MeV}}{\theta} \quad (2.2)$$

Thus, a detector at off-axis angle $\theta \simeq m_\pi/\langle E_\pi \rangle$ (where $\langle E_\pi \rangle$ is the average energy of the pion beam) receives an almost monochromatic neutrino beam with an average energy given by Eq. 2.2. The peak energy of the neutrino beam can be varied by changing the off-axis angle (see Figure 2.5-right).

At T2K, the narrow-band neutrino energy spectrum is tuned to the value of $L/E$ that maximizes the neutrino oscillation effect due to $\Delta m_{32}^2$, the mass splitting observed in atmospheric neutrinos. In more detail, the off-axis angle is set at $2.5^\circ$ (corresponding to $E_{\nu,max} \simeq 683$ MeV) so that the neutrino beam at SK has a peak energy near the expected first oscillation maximum, as shown in Figure 2.5-left. The design of the T2K beam line is such that the off-axis angle can be reduced to $2.0^\circ$, allowing variation of the peak neutrino energy, if
necessary. The neutrino beam direction with respect to SK and the distance between the target and SK are obtained by GPS survey.

2.2 The near detector suite

The T2K near detector site is located 280 m away from the target in the direction of Super-Kamiokande and is housed in a pit with a depth of 37 m and a diameter of 17.5 m (see Figure 2.6).

![Image of the near detector complex](image)

Figure 2.6: Near detector complex. The off-axis detector and the magnet are located on the upper level; horizontal INGRID modules are located on the level below; and the vertical INGRID modules span the bottom two levels.

The pit hosts the on-axis INGRID detector (an array of detectors made from iron and plastic scintillator) and the 2.5° off-axis ND280 detector. ND280 is made up of several subdetectors contained within the refurbished UA1/NOMAD magnet: a $\pi^0$ detector, a tracker, a calorimeter and a side muon range detector.

The same right handed coordinate system is used for all detectors: $z$ is along the nominal neutrino beam axis, $x$ and $y$ are horizontal and vertical respectively.

2.2.1 Scintillator-based detectors

Both the INGRID and the ND280 detectors extensively use scintillator detectors and embedded wavelength-shifting (WLS) fibers.

The operation and readout principle is the same for all the near detector scintillator-based detectors: scintillation light produced by charged particles
passing through the scintillator material is collected by 1 mm diameter Y11 Kuraray WLS fibers and then transported to Hamamatsu Photonics Multi-Pixel Photon Counters (MPPCs [112]) which convert it into an electrical signal. All INGRID and ND280 scintillator bars are polystyrene bars infused with PPO (1%) and POPOP (0.03%) and coated with a layer of TiO$_2$ to provide light reflection and isolation.

MPPCs, consisting of an array of avalanche photo-diodes operating in Geiger mode, have been chosen to detect scintillation light because they are compact, well matched to the spectral emission of WLS fibers, and insensitive to magnetic fields. Each T2K MPPC, shown in Figure 2.7, consists of 667 pixels and have a sensitive area of 1.3 $\times$ 1.3 mm$^2$. The signals from all pixels are summed together on one output. A Geiger discharge is initiated in a pixel when a photon is absorbed and a hot carrier is released and accelerated by the high electric field present in the depletion region. The MPPC gain is determined by the charge, $Q_{\text{pixel}}$, accumulated in a pixel capacitance, $C_{\text{pixel}}$: $Q_{\text{pixel}} = C_{\text{pixel}} \cdot \Delta V$, where the overvoltage $\Delta V$ is the difference between the applied voltage and the breakdown voltage of the photodiode. For MPPCs the operational voltage is about 70 V, which is 0.8 - 1.5 V above the breakdown voltage. The pixel capacitance is 90 fF, which gives a gain in the range 0.5 - 1.5 $\times 10^6$. All the scintillator-based near detectors use identical electronics (based on the Trip-T ASIC [114, 115] developed at Fermilab) to read out the MPPCs.

In case of the ECal, P0D, SMRD, and INGRID, the electronic signal from the MPPCs is integrated and digitized by Trip-t Front-end Boards (TFB), each of them serving up to 64 MPPCs. In the FGD, the MPPCs are coupled to AFTER ASIC chips [113] which were originally designed for the ND280 TPCs. Each ASIC reads out 32 MPPCs.
2.2.2 The INGRID on-axis near detector

As mentioned above, T2K uses an off-axis beam configuration. As the neutrino energy varies as a function of the off-axis angle, it is important to monitor and control the beam direction precisely. In addition, it is important to monitor the beam intensity in order to ensure stable neutrino beam production. Although the muon monitor downstream of the beam dump measures the beam direction and stability (by detecting muons from pion decay for every bunch), it covers a phase space of the parent pions which is very different from the one of pions which produce neutrinos to the near or far detectors.

INGRID is designed to measure the on-axis neutrino beam profile at the 280 m site by means of neutrino interactions in iron, with sufficient statistics to provide daily measurements at nominal beam intensity. The phase space of the parent pions covered by INGRID is much closer to the one for the off-axis neutrino detectors than the muon monitor. The neutrino beam direction is measured by INGRID with accuracy better than 0.4 mrad from the measured profile center. The normalized event rate is measured with 4% precision.

![INGRID on-axis detector](image)

Figure 2.8: INGRID on-axis detector.

The INGRID detector (shown in Figure 2.8) consists of 16 identical modules: 14 of them are arranged as a cross in horizontal and vertical arrays (each arm contains 7 modules) around the beam center (i.e. the centre of the cross is at 0° with respect to the direction of the primary proton beamline); 2 separate modules are located at off-axis directions outside the main cross in order to
monitor the axial asymmetry of the neutrino beam.

Each module (shown in Figure 2.9-left and centre) consists of a sandwich structure of nine iron plates (serving as a neutrino interaction target) and eleven tracking scintillator planes surrounded by veto scintillator planes (to help in rejecting interactions occurring outside the module). The modules are perpendicular to the nominal beam direction defined by the primary proton beam direction. The dimensions of each iron plate are $124 \, \text{cm} \times 124 \, \text{cm} \times 6.5 \, \text{cm}$ in $x$, $y$, $z$ respectively. The total iron mass is 7.1 tons per module. No iron plate was placed between the 10$^{th}$ and 11$^{th}$ tracking planes due to weight restrictions.

Each tracking plane consists of one layer of 24 scintillator bars in the horizontal direction glued to one layer of 24 perpendicular bars. The dimensions of each scintillator bar are $1.0 \, \text{cm} \times 5.0 \, \text{cm} \times 120.3 \, \text{cm}$. Each veto plane consists of 22 scintillator bars segmented along the beam direction with dimensions $1.0 \, \text{cm} \times 5.0 \, \text{cm} \times 111.9 \, \text{cm}$ (for the bottom/top veto planes) and $1.0 \, \text{cm} \times 5.0 \, \text{cm} \times 129.9 \, \text{cm}$ (for the right/left veto planes).

**Figure 2.9:** An INGRID module (left and central images). The left image shows the tracking planes (blue) and iron plates. The central image shows veto planes (black). In the right image the Proton Module is shown. It is similar to the INGRID modules, but with finer grained scintillator and without the iron plates.

An additional module, called the Proton Module (shown in Figure 2.9-right), consisting of scintillator planes without any iron plate and surrounded by veto planes, is positioned in the centre of the INGRID cross (between the vertical and horizontal modules). This module was added in order to detect with good efficiency muons and protons produced by the neutrino beam in INGRID.

Neutrino interaction events are selected by reconstructing the track of charged particles generated by interactions in the iron target. The horizontal and vertical profiles (see Figure 2.10) are reconstructed from the number of observed events.

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$^2$This has been shown to have no effect on the tracking performance.
2.2. The near detector suite

in each module. The beam center is estimated to be at the center of the profile. A typical neutrino event detected by INGRID is shown in Figure 2.11.

![Figure 2.10](image1.png)  
Figure 2.10: Neutrino beam profiles for $x$ (left) and $y$ (right) directions measured in April 2010. The error bars are the statistical errors and the error size is about 1%. Image and caption taken from [116].

![Figure 2.11](image2.png)  
Figure 2.11: A typical neutrino event in an INGRID module. A neutrino enters from the left and interacts within the module, producing charged particles. One of them makes a track which is shown as the red circles. Each of the green cells in this figure is a scintillator, and the size of the red circles indicates the size of the observed signal in that cell. Blue cells and gray boxes indicate veto scintillators and iron target plates, respectively.

2.2.3 The ND280 off-axis near detector

In order to measure the neutrino oscillation parameters it is fundamental to characterize the unoscillated neutrino beam. The major role of the ND280 off-axis
The T2K experiment

detector (shown in Figure 2.12) is to measure the $\nu_\mu$ and $\nu_e$ fluxes and their energy spectrum through charged current quasi-elastic (CCQE) processes, and to study processes that could mimic the $\nu_\mu$ or $\nu_e$ signals and could be background in the far detector. Other crucial measurements that can be provided by ND280 concern processes producing pions in the final states, which constitutes the dominant backgrounds to the $\nu_\mu$ disappearance measurement at SK. In addition to contributing to the oscillation physics goals of T2K, ND280 is able to provide dedicated cross-section measurements thanks to its high statistics and excellent spatial resolution.

Figure 2.12: An exploded view of the ND280 off-axis detector. The ND280 coordinate system is shown too. The origin of the axes is located in the middle of the basket.

ND280 (see Figure 2.12) is a large, highly segmented detector and consists of several elements, described below: a Pi-Zero Detector (P0D), located at the most upstream end of the ND280 and optimized for measuring the rate of neutral current $\pi^0$ production; a tracker, located downstream the P0D, optimized for studying neutrino interactions that produce charged particles; an electromagnetic calorimeter (ECal), which surrounds the P0D and the tracker and whose main purpose is to detect photons from $\pi^0$ produced in neutral current interactions; and a Side Muon Range Detector (SMRD) to measure the range of muons that exit the sides of the detector.

The analysis presented in this thesis is based on information from the tracker. It consists of a sandwich of three identical time projection chambers (TPCs) interleaved with two fine grained detectors (FGDs). It allows very precise measurements of momentum and angle of charged particles and is intended to measure
the $\nu_\mu$ and $\nu_e$ fluxes and spectra and various charged current cross sections. The TPCs play a critical role in the ND280 detector, measuring the momentum, charge, and identity of penetrating charged particles. The FGD modules, placed after the first and second TPC, provide the target mass for neutrino interactions. They provide also spatial and particle identification information and allow momentum by range measurements (see Section 4.4.1). One FGD module consists entirely of plastic scintillators, while the second consists of plastic scintillator and water to allow the separate determination of exclusive neutrino cross-sections on carbon and on water.

**Pi-Zero Detector (P0D)**

The P0D sits at the upstream end of ND280 and is optimized for measuring the neutral current process $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X$ on a water (H$_2$O) target. This measurement is fundamental since neutral current processes that produce a $\pi^0$ in the final state constitute one of the main backgrounds in the $\nu_e$ appearance search at the far detector.

![Figure 2.13: A schematic of the pi-zero detector. The beam is coming from the left and going right.](image)

The schematic in Figure 2.13 shows the main features of the P0D. It consists of $x$ and $y$ planes of triangular (isosceles, with a 33 mm base and 17 mm height) scintillator bars interleaved with fillable water target bags and sheets of lead.
and brass. There are 40 scintillator modules (P0Dules) in the P0D, each one containing 134 vertical bars (2200 mm long) and 126 horizontal bars (2340 mm long).

The most upstream and downstream sections of the P0D contain electromagnetic calorimeters (the “upstream ECal” and the “central ECal”). Each Ecal is a sandwich of 7 P0Dules alternating with 7 stainless steel clad lead sheets (4 mm thick). This layout improves the containment of electromagnetic showers and provides a veto region before and after the water target region to provide effective rejection of particles entering from interactions outside the P0D.

The central section of the P0D is composed of the “upstream water target” and the “central water target”. The upstream target is a sandwich of 13 P0Dules alternating with 13 water bag layers (each 28 mm thick) and 13 brass sheets (each 1.5 mm thick). The central target has the same structure but contains only 12 water bags and 12 brass sheets.

The dimensions of the active target of the entire P0D are 2103 mm × 2239 mm × 2400 mm (width × height × length) and the mass of the detector with and without water is 16.1 tons and 13.3 tons respectively. The water bags can be filled or emptied, enabling to measure water-only cross sections by examining the difference in event rates between the “water-in” and “water-out” modes of operation. The scintillator bars provide sufficiently fine segmentation to reconstruct charged particle tracks (muons and pions) and electromagnetic showers (electrons and photons from π⁰’s).

Detailed information about the P0D can be found in [118].

Time Projection Chambers (TPCs)

The ND280 tracker contains three TPCs (named TPC1, TPC2, TPC3 from the most upstream to the most downstream) located on each side of the FGDs. The TPCs provide the basis for the selection of high purity samples of different types of neutrino interactions as, thanks to their excellent imaging capabilities in three dimensions, they enable 3-dimensional reconstruction of charged particles traversing the detectors. Furthermore, as they operate in a magnetic field, the TPCs can provide measurements of the momentum of charged particles produced by neutrino interactions, allowing to compute the event rate as a function of neutrino energy for the neutrino beam prior to oscillation. Identification of different types of charged particles can also be made by the TPCs using the amount of ionization left by each particle combined with the measured momentum. Particle identification by the TPCs is a crucial tool to determine the relative abundance of electron neutrinos in the beam.

Each TPC consists of two boxes, one inside the other, as shown in the simplified drawing in Figure 2.14. The walls of the inner box, which holds an argon-
2.2. The near detector suite

Figure 2.14: Simplified cut-away drawing showing the main aspects of the TPC design. The outer dimensions of the TPC are approximately $2.3 \text{ m} \times 2.4 \text{ m} \times 1.0 \text{ m}$.

Based drift gas and is divided into two sections by a central cathode panel, form the field cage. The walls of the outer box, which holds CO$_2$ as an insulating gas between the inner box and ground and excludes atmospheric oxygen from entering the inner volume, are at ground potential.

The inner box supports twelve $342 \text{ mm} \times 359 \text{ mm}$ micromegas (MM) modules located in a plane parallel to the cathode at each end. The walls joining the cathode and the micromegas are covered with a series of conducting strips joined by precision resistors, forming a voltage divider that creates the uniform electric field along the drift direction. The MMs are arranged on the readout plane into two vertical columns that are offset so that the small inactive regions between modules are not aligned. There are 72 MMs in total, each one made of 1728 $7.0 \text{ mm} \times 9.8 \text{ mm}$ (vertical × horizontal) anode pads on 48 columns and 36 lines (see Figure 2.15-right), providing an active surface of nearly $9 \text{ m}^2$ for the three TPCs.

The MM principle is simple. Charged particles passing through the TPCs ionize the gas and produce ionization electrons that drift away from the central cathode and toward one of the readout planes. The gas volume is separated by a thin micromesh in two regions, one where the conversion and drift of the ionization electrons occurs and one, $128 \mu\text{m}$ thick, where the amplification takes place. Twelve pillars over each pad support the mesh to maintain a constant gap (see Figure 2.15-left). In the amplification region, a very high field (about $30000 \text{ V/cm}$), created by applying a voltage of a few hundred volts between the
mesh and the anode plane, allows the multiplication of the primary electrons. The avalanche is then collected by the pads on the anode plane. The anode segmentation into pads allows 3-dimensional track reconstruction of the traversing charged particle by means of the combination of the pattern of signals in the pad plane and of the arrival time of the signals.

Figure 2.15: Left: Schematic view of a micromegas. The ionization electrons drift towards the micromesh that is placed above the anode. The micromesh is supported by short cylindrical pillars. Between the mesh and the anode an avalanche is produced. The time structure of the signal is shown on the right-hand side of the padplane. Right: Micromegas plane close up. The holes at the bottom are for the gas inlet.

Six front-end electronics cards, each containing four custom ASICs called “AFTER”, plug into the connectors on the back side of the MM printed circuit boards and digitize signals from the 1728 pads. Each AFTER ASIC shapes the signals and buffers 72 pad signals into 511 time-bin switched capacitor arrays. The six front-end cards connect to a single front-end mezzanine card that aggregates the data, performs zero suppression, and sends data out of the detector with optical links.

The gas system is designed to maintain a stable mixture in the inner volume and a constant positive pressure with respect to the outer volume. The inner gas mixture, Ar : CF$_4$ : iC$_4$H$_{10}$ (95:3:2), was chosen for its high speed, low diffusion, and good performance with micromegas detectors. Each of the three TPC volumes contains 3000 liters, and each of the three CO$_2$ filled gap volumes contains 3300 liters. The TPC gas system was designed for an operating flow of 10 L/min/TPC (30 L/min total flow).

The performance of the TPCs have been deduced from measurements with particle beams, cosmic rays, and the calibration system.

As at 700 MeV neutrino energy estimation in CCQE events is limited at
about the 10% level due to the Fermi motion of the struck nucleons, the TPC momentum resolution goal is set to be \( \delta(p_{\perp})/p_{\perp} < 0.1 \) \( p_{\perp} \) [GeV/c], where \( p_{\perp} \) is the momentum component perpendicular to the magnetic field direction. The TPC track reconstruction has shown good tracking performance with a spatial resolution (~0.7 mm per column of pads) sufficient to achieve that goal (see Figure 2.16-left).

Figure 2.16: Left: Momentum resolution for a single TPC is shown as a function of momentum perpendicular to the magnetic field as predicted by the MC simulation of muons generated with the standard neutrino event generator of T2K. The tracks are selected to cross at least 50 out of the 72 pad columns of the TPC volume. The dashed lines represents the momentum resolution goal. Images taken from [119]. Right: Distribution of the energy loss for negatively charged particles with momenta between 400 and 500 MeV/c.

The TPC is the main particle identification (PID) tool of the ND280 detector. PID in the TPC is based on the measurement of the deposited energy by particles passing through it (see Section 3.4.1). The ionization energy loss of electrons in 1 atm Argon gas is roughly 45% larger than for muons over the momentum range of interest in T2K (0.5 - 1.0 GeV/c). In order to achieve a 3 \( \sigma \) separation between the electron and the muon tracks and, indeed, measure the \( \nu_e \) contamination of the beam, the resolution in ionization energy loss needs to be better than 10%. The distribution of the deposited energy (obtained using the method explained is Section 3.4.1) is shown in Figure 2.16-right. The resolution is of 7.8 ± 0.2\% for minimum ionizing particles, better than the 10\% requirement for the T2K TPCs. This resolution allows muons to be distinguished from electrons in the TPCs.

More information about the design, construction, and performance of the
Fine Grained Detectors (FGDs)

The ND280 tracker contains two FGDs, which provide target mass for neutrino interactions and tracking of charged particles emerging from the interaction vertex.

As mentioned in Section 1.5, CC1$\pi$ interactions constitute one of the main backgrounds in the $\nu_\mu$ disappearance analysis at T2K because they can be mis-reconstructed as CCQE events causing a smearing of the energy spectrum measurement. Thus, it is very important to exclude CC1$\pi$ interactions from the energy spectrum analyses in both the near and far detectors. In particular, the rates of CCQE interactions and backgrounds from the T2K beam must be well determined in the ND280 tracker so that a satisfactory prediction of the un-oscillated event rates at SK can be made. The FGDs play a key role in the detection of events containing pions at ND280, allowing to search for additional charged tracks near the vertex (thanks to their capability of detecting charged particles produced at the interaction vertex with good efficiency) and identify Michel electrons produced by pions stopping in an FGD through the $\pi \rightarrow \mu \rightarrow e$ decay chain (thanks to the ability of their electronics to provide acceptance of late hits such as those due to Michel electrons). In addition the FGDs are thin enough ($\sim$30 cm) to allow charged particles such as leptons to penetrate into the TPCs, where their momenta and flavour can be determined, and are able, thanks to their fine granularity, to measure the direction of short-ranged particles such as recoil protons. Particle identification from energy loss measurements is also possible in the FGDs, as explained in Section 3.4.2.

Each FGD (see Figure 2.17) is made of 186.4 $\times$ 186.4 $\times$ 2.02 cm$^3$ (width $\times$ height $\times$ depth in beam direction) modules, each consisting of a layer of 192 bars of extruded polystyrene scintillator in the horizontal direction ($x$) glued to 192 bars in the vertical direction ($y$). The bars are oriented perpendicular to the beam and have dimensions 9.61 mm $\times$ 9.61 mm $\times$ 1864.3 mm. The scintillator bars provide the target mass for neutrino interactions; their orientation makes full three dimensional reconstruction possible.

Each FGD has outer dimensions of 2300 mm $\times$ 2400 mm $\times$ 365 mm and contains 1.1 tons of target material, allowing sufficient statistical sample of events. The most upstream FGD (named FGD1) contains 15 modules; the other FGD (named FGD2) contains 7 such modules alternating with 6 layers of water (each 2.5 cm thick). Comparing the interaction rates in the two FGDs allows the study of exclusive cross-sections on carbon and on water. This separation is crucial to account for nuclear effects (such as Pauli blocking and pion rescattering and absorption inside the nucleus) in SK (which contains water), since they cannot be
2.2. The near detector suite

Figure 2.17: View of an FGD with the front cover removed. XY scintillator modules (green) hang perpendicular to the direction of the neutrino beam. Along the top, six mini-crates with electronics can be seen without their cooling lines, while on the right side the cooling lids covering the mini-crates are shown.

reliably corrected for from theory.

The FGDs must have good timing resolution in order to reliably separate the activity due to the background of neutrino interactions occurring in the surrounding magnet from that initiated in the FGD scintillators. Good timing resolution is also necessary to determine the particle direction by comparing the time of hits in FGD1 and FGD2. Studies showed that the FGDs have a timing resolution of the order 3 ns for each hit, satisfying the above requirements.

More information about the FGDs can be found in [122].

Electromagnetic Calorimeter (ECAL)

An electromagnetic calorimeter surrounds the P0D and the tracker. The ECal is optimized to measure the energy and direction of any charged particle leaving or entering the inner volume of ND280 through the detection of photons, and to provide information relevant for the identification of charged particles (electromuon-pion separation). The ECal plays a key role in the reconstruction of $\pi^0$'s produced in neutrino interactions inside the tracker detectors and it can also be used as target material to determine neutrino interaction cross-sections on lead.

The ECal is made of 13 independent modules arranged as in Figure 2.12:

- 6 modules surround the tracker volume on the four sides parallel to the beam axis (Barrel-ECal);
2. The T2K experiment

- 1 module is placed downstream the tracker (Ds-ECal);

- 6 modules surround the P0D detector volume on its four sides parallel to the beam axis (P0D-ECal).

The Ds-ECal is located inside the basket carrying the inner ND280 subdetectors. The Barrel-ECal and the P0D-ECal are attached to the magnet and have 2 top and 2 bottom modules in order to allow for the opening of the ND280 magnet. Each Ecal module is made of consecutive layers of active plastic scintillator bars glued to a sheet of lead converter. A drawing of a completed module is shown in Figure [2.18].

Both the Barrel-ECal and the Ds-Ecal were designed as a tracking calorimeter to complement the charged particle tracking and identification capabilities of the TPCs by providing detailed reconstruction of electromagnetic showers. This allows the energy of neutral particles to be measured, providing useful information for particle identification in the ND280 tracker. To this end, there are 31 scintillator-lead layers in the Barrel-ECal and 34 layers in the Ds-ECal (with the lead sheets having a thickness of 1.75 mm), corresponding to approximately 10 and 11 radiation lengths, respectively. The number of layers was determined by the requirement to have sufficient radiation lengths of material to contain electromagnetic showers of photons, electrons and positrons with energies up to 3 GeV. At least 10 electron radiation lengths are required to ensure that more than 50% of the energy resulting from photon showers initiated by a $\pi^0$ decay is contained within the ECal. The direction of the scintillator bars in alternate layers is rotated by $90^\circ$ for 3-dimensional track and shower reconstruction purposes. In the Barrel-ECal module, the bars running in the $z$ direction are 3.84 m long while bars running in the $x$ ($y$) directions in the top/bottom (side) modules are 1.52 m (2.36 m) long. The Ds-ECal bars are each 2.04 m long.

The P0D-ECal modules are not intended for $\pi^0$ reconstruction as this takes place inside the dedicated P0D detector which they surround. The role of the P0D-ECal is to complement the P0D reconstruction with information on escaping energy and distinguish between photons and muons. The construction of the P0D-ECal therefore is simpler, with only 6 scintillator layers separated by 4 mm-thick lead sheets, corresponding to approximately 4.3 radiation length, and all bars (2.34 m long) running parallel to the beam direction. The thickness of the lead sheets was chosen in such a way to ensure that photons are detected with high efficiency, that showers are well contained, and that photon showers can be distinguished from muon deposits.

Detailed information on the ECal can be found in [126].
2.2. The near detector suite

Figure 2.18: External view of one ECal module. The scintillator bars run horizontally inside the module. The readout electronics, signal and power cables, and cooling pipes can be seen mounted on the aluminum plates on the sides of the module. The gray surface at the top is the carbon fiber sandwich front plate, which in the final module position is facing towards the inner subdetectors (P0D, FGDs and TPCs). Image taken from [47]

Magnet

ND280 uses the refurbished UA1/NOMAD magnet operated with a magnetic field of 0.2 T to enable subdetectors enclosed in the magnet to measure the momenta with good resolution and determine the sign of penetrating charged particles produced by neutrino interactions in the near detector.

The magnet consists of water-cooled aluminum coils (with 5.45 cm $\times$ 5.45 cm square cross sections, with a central 23 mm diameter bore for water to flow), which create the horizontally oriented dipole field, and a flux return yoke. The dimensions of the inner (external) volume of the magnet are 3.5 m $\times$ 3.6 m $\times$ 7.0 m (7.6 m $\times$ 5.6 m $\times$ 6.1 m) and the total weight of the yoke is 850 tons.

As shown in Figure 2.19, the magnet is made up of two mirror-symmetric halves which allow access to the inner detectors. The coils are mechanically supported by the return yoke but electrically insulated from it, and are split into 4 elements, 2 for each half. The yoke consists of 16 C-shaped elements which are grouped in pairs to form a ring surrounding the inner detectors on four sides. Each yoke element consists of 16 low-carbon steel plates (each 4.8 cm thick, with 15 air gaps each 1.7 cm thick) fitted on rails operated by hydraulic movers, so that each half magnet can be separately moved to an open or closed position.
The SMRD consists of 440 scintillator modules (192 horizontally and 248 vertically oriented) placed in the innermost air gaps in between the iron plates which make up the magnet yokes.

The main purpose of the SMRD is to detect muons which escape from the inner volume of the ND280 detector with large angles with respect to the beam direction and measure their momenta. In order to achieve very high detection efficiency, the active detector medium has to enclose the inner detectors nearly hermetically and provide uniform efficiency across the entire sensitive area. The SMRD also helps to identify events generated in the magnet yoke and surrounding walls and provides a veto for events entering the detector from the outside. In addition it provides a cosmic trigger signal for calibration purposes of the ND280 detector. Through-going cosmic ray muons can be used for the calibration of the inner detectors, as they provide a sample of muon tracks that are, apart from their direction, very similar to the muons created in neutrino beam interactions.

The SMRD horizontal modules (shown in Figure 2.20-top) measure 9 mm $\times$ 686 mm $\times$ 955 mm (height $\times$ width $\times$ depth) while the vertical modules measure 9 mm $\times$ 892 mm $\times$ 955 mm, according to the dimensions of the slits in the yokes. Horizontal (vertical) modules are composed of four (five) scintillation counters with dimensions 7 mm $\times$ 167 mm $\times$ 875 mm (7 mm $\times$ 175 mm $\times$ 875 mm). The counter sizes have been optimized to maximize the active area in each magnet gap. A key feature of the individual SMRD counters is the usage of a serpentine-shaped fiber (see Figure 2.20-bottom), which provide near uniform
response across the surface of the scintillation counter and minimize the number of photosensors and electronics channels compared to more conventional designs with multiple straight fibers.

A more detailed description of the SMRD can be found in [127].

Figure 2.20: Top: Completed SMRD horizontal module equipped with photosensors and combined power and signal cables. Bottom: SMRD scintillator slabs with a serpentine-routed Y11 WLS fiber. Images and captions taken from [127].

2.3 The far detector system

Super-Kamiokande (SK), the largest water Cherenkov detector in the world, serves as T2K far detector. It is located at 295 km from the neutrino beam source and is built 1 km deep within the center of Mt. Ikenoyama. The depth at which Super-Kamiokande is buried reduces the cosmic ray flux by five orders of magnitude with respect to the Earth’s surface.

SK has been taking data since 1996 and has produced a large number of important results including the first unambiguous evidence of neutrino oscillation in atmospheric neutrinos [34]; confirmation of the solar neutrino flux deficit and first measurement of the solar neutrino energy spectrum above 5 MeV [35, 36]; and limits on partial lifetimes for nucleon decay [37, 38]. Over this time there have been four running periods: SK-I, SK-II, SK-III, and SK-IV, which is still in progress (it is the period in which the T2K experiment takes place) and features upgraded PMT readout electronics.

Since SK has been used in several experiments, its behavior is very stable and well understood. The energy scale is known to the percent level, and the
software for modeling events in the detector matches calibration samples to the percent level.

Figure 2.21: A schematic view of the Super-Kamiokande detector site, under Mt. Ikenoyama. The detector is mainly comprised of two segments, the inner and outer detectors. The boundary between the two segments is defined by a cylindrical scaffold used to mount photomultiplier tubes and optically separate the segments. The figure is taken from [47].

The SK detector (see Figure 2.21) consists of a cylindrical tank (39 m diameter, 41 m tall) filled with 50 ktons of pure water and containing approximately 13000 photomultiplier tubes (PMTs), allowing to image neutrino interactions.

The SK geometry consists of two major volumes: an inner and an outer detector which are separated by a 50 cm wide cylindrical stainless steel structure. The inner detector (a cylindrical space 33.8 m in diameter and 36.2 m in height) houses 11129 inward facing 50 cm diameter PMTs providing 40% surface coverage. The outer detector (a cylindrical space approximately 2 m thick radially) surrounds the inner detector and is instrumented along its inner walls with 1885 outward facing 20 cm diameter PMTs. It serves as an active veto of cosmic ray muons and other backgrounds and as a radioactivity shield.

In order to measure the flavor composition of the T2K neutrino beam at SK, and thereby observe neutrino oscillations and extract neutrino oscillation parameters for $\nu_e$ appearance ($\nu_\mu$ disappearance), T2K counts the number of electrons (muons) produced in $\nu_e$ ($\nu_\mu$) CCQE interactions in SK. Charged particles produced by neutrino interactions in the inner SK detector create a Cherenkov light...
2.3. The far detector system

cone as they cross the water when moving faster than light in that medium. When the photons reach the PMTs on the detector walls they produce a ring-shaped hit pattern which is used to extract information about the interaction such as the event vertex position and momenta of product particles. The type of neutrino that induced the interaction can be inferred by studying the ring shape produced by the Cherenkov light. The light rings produced by muons can be easily distinguished from the ones produced by electrons. Electrons undergo multiple scattering in the water and almost always induce electromagnetic showers at the energies relevant to SK, resulting in a “fuzzy” ring pattern seen by the PMTs, which can be thought of as the sum of many overlapping Cherenkov light cones. On the other hand, muons are highly penetrating particles and produce rings with much sharper, well-defined edges. The typical electron-like and muon-like Cherenkov rings seen in the SK detector are shown in Figure 2.22.

A much more detailed description of the Super-Kamiokande detector can be found in [128].

Figure 2.22: Example of reconstructed T2K events in Super-Kamiokande for (a) a muon-like ring and (b) an electron-like ring. Both figures show the cylindrical detector, unrolled onto a plane. Each colored point represents a PMT, with the color corresponding to the amount of charge, and the reconstructed cone is shown as a white line. The second figure in the upper right corner shows the same hit map for the OD. The white crosses indicate the location of the reconstructed vertex. The diamond marks the location where a ray starting from the event vertex and heading in the direction of the beam would intersect the detector wall. Image and caption taken from [47].
2. The T2K experiment
Chapter 3

ND280 offline software: simulation, calibration and reconstruction

This chapter presents a general overview of the ND280 simulation, calibration and reconstruction tools relevant to the analysis presented in this thesis.

As information from the FGDs and TPCs plays a primary role in the selection of $\nu_\mu$ CCQE interactions in the ND280 tracker, which is the topic of this thesis, this chapter is focussed on the reconstruction in the tracker region of the ND280 detector. Reconstruction details not discussed here can be found in [170].

In what follows the coordinate system is defined as shown in the Figure 2.12. Inside the basket the magnetic field is mostly $x$ oriented. Horizontal and vertical tracks are referred to depending on their angle with regard to the beam ($z$) axis.

3.1 ND280 offline software overview

The ND280 offline software is used for processing of both data measurements and MC simulations. Its purpose is to apply the appropriate calibration chain and reconstruction algorithms to both raw data and MC events and then save the output in a format suitable for the high level analysis. The underlying framework and the data storage model are both based on ROOT [172], while Geant4 [173] is used as the basic simulation library. The general structure of the software suite is shown in Figure 3.1.

For data, the “oaRawEvent” library interfaces with the readout data format and allows the raw data output (in the MIDAS [174] format) to be read directly by the offline software in a file format defined by the “oaEvent” library. This
library provides the basic ROOT-based I/O functions for ND280 software and the format used for storing the simulation, calibration and reconstruction output as well as ND280 geometry information. Calibration constants for the detectors are stored on a centralized MySQL database, and are applied by “oaCalib” and its sub-packages at processing time. After the events have been reconstructed, the “oaAnalysis” package saves the full event information contained in the oaEvent format files in pure ROOT objects which can be used by the analyser.

For MC simulations, interfaces have been built between the neutrino beam simulation, the neutrino interaction generation packages and the ND280 software. The JNUBEAM simulation package provides the kinematic information for particles emerging from the target and hence the neutrino flux simulation at the near and far detectors, as explained in Section 3.2.1. Both the GENIE [175] and NEUT [109] neutrino event generators are used to simulate the interaction of neutrinos with different nuclei in the ND280 detector. Interactions of final state particles (i.e. particles, produced in neutrino-induced interactions, which escape the nuclear environment) inside the near detector are simulated by “nd280mc” using the Geant4 package. The “elecSim” package simulates the response of active detector components and readout electronics in the ND280 detector. At this point the MC output is converted in the oaEvent format, calibration and recon-

Figure 3.1: Schematic of the package structure of the ND280 Software Suite. Only the most representative packages are included. Image taken from [47].
3.2 Simulation

In this section the NEUT event generator and the beam flux simulation used at T2K are briefly discussed.

3.2.1 Neutrino flux prediction

Measurements at both the near and far detectors rely heavily on the neutrino flux prediction. To achieve the T2K physics goals, the ratio of fluxes at ND280 and SK as a function of energy must be known to better than 3%. Furthermore, to study the neutrino-nucleus interactions at ND280 and to make neutrino cross-section measurements a small absolute flux uncertainty is required. It is difficult to predict accurately the flux due to uncertainties in the underlying physical processes, particularly hadron production in proton-nucleus interactions. The MC simulation used to predict the flux and spectrum of neutrinos at T2K is briefly described in this section.

The MC simulation is driven by experimental data: proton beam profile measurements, studies of the horn magnetic field and results from the NA61/SHINE experiment (a dedicated hadron production experiment that covers the whole kinematic region of interest for T2K) are used.

In the MC simulation protons with a kinetic energy of 30 GeV are injected into the graphite target. Secondary particles are produced and focussed in the horn magnets. The secondaries and any surviving protons are tracked until they decay into neutrinos or are stopped at the beam dump. Then the neutrinos trajectories are extrapolated to the near and far detectors, providing the predicted fluxes and energy spectra at both detector sites. The primary proton interactions are simulated based on NA61/SHINE data. Other hadronic interactions in the target and baffle are simulated by FLUKA. Kinematic information for particles emitted from the target is saved and transferred to the JNUBEAM simulation, which is a GEANT3 MC simulation of the baffle, target, horn magnets, helium vessel, decay volume, beam dump, and muon monitor. JNUBEAM also includes the INGRID, ND280, and SK detectors. The interactions outside the target are simulated using GEANT3/GCALOR with the interaction cross sections tuned to experimental data.

The predicted unoscillated neutrino flux by flavour at ND280 and SK can be seen in Figure 3.2. The neutrino beam is predicted to contain mainly muon
neutrinos, with a small contamination of electron neutrino and very small anti-neutrino components.

Figure 3.2: Flux prediction by flavour at ND280 (left) and SK (right) broken down into the neutrino type and as a function of energy [131].

3.2.2 The NEUT event generator

The neutrino interaction simulation programs (event generators) play an important role in all neutrino experiments. They are used to provide information about the signal and background events observed in the detectors. Therefore, each generator is expected to simulate all the possible interactions occurring in the detectors and the interaction simulation must cover the entire experimental kinematical region. In order to get a reliable simulation, appropriate models must be used and, as it is not possible to simulate all neutrino interactions perfectly, a number of reasonable simplifications and assumptions must be done in the implementation of the simulation programs. Therefore, different event generator can provide slightly different results. There are several neutrino event generators available in the market. The one used in this analysis is NEUT [109].

NEUT was initially developed for the Kamiokande experiment and continuously updated for the Super-Kamiokande, K2K, SciBooNE and T2K experiments. One of the main applications of NEUT is to simulate interactions of atmospheric neutrinos in a water Cherenkov detector. Thus, this program library covers a wide neutrino energy range, from several tens of MeV to hundreds of TeV. The primary target materials for neutrino interactions are Hydrogen, Oxygen and Carbon.

NEUT uses the Llwellyn-Smith [84] formalism to describe CCQE scattering off a single nucleon. The relativistic Fermi gas model by Smith and Moniz [80] is used to calculate the cross-section off nucleons in the nucleus. The nuclear potential is characterized by two parameters which are nucleus dependent, $p_F$,
3.3 Calibration

the Fermi momentum of the nucleus, and $E_B$, the binding energy. The uncertainties on $p_F$ and $E_B$ are determined from electron scattering data [111] and summarized in Table 3.1.

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<th>Nonimal value</th>
<th>Uncertainty</th>
<th>Fractional uncertainty</th>
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<td>$E_B$ (Oxygen)</td>
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<td>33.33%</td>
</tr>
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Table 3.1: Value and uncertainty for $p_F$ and $E_B$ from electron scattering data. Table taken from [110].

Both the Llwellyn-Smith and Smith-Moniz models use vector and axial-vector form factors of nucleons. Dipole form factors are used by NEUT at the moment of this writing, although comparisons with electron scattering data suggest that a more complicated model of the nuclear potential, called the “spectral function” (SF) [147], is a more correct representation of the nuclear potential. The SF defines the probability distribution of nucleon momenta and removal energies within the nucleus. It is more realistic than the Fermi Gas formalism in which nucleons are assumed to be distributed uniformly inside the Fermi sphere and a constant value of the binding energy is assumed in the energy balance. The axial mass in the CCQE cross section calculation, $M_{QE}^A$, which appears in the axial vector form factor, in NEUT has a default value of 1.21 GeV/c².

The quasi-elastic scattering is identified by a final state with a proton and a muon emitted and reconstructed in the tracking detectors. As the nucleon rescattering in the nucleus can alter the event final state, it affects the identification of the neutrino interaction mode. Therefore, the understanding of the nucleon interactions is important. NEUT uses the cascade model [148] [149] to simulate the nucleon rescattering inside the nucleus. The interaction probabilities are extracted from the existing data of differential cross-sections from nucleon-nucleon scattering experiments [145]. The considered interactions are elastic scattering and a single or two $\Delta$’s production. For delta productions, the isobar model by Lindenbaum et al is used [146].

3.3 Calibration

The calibration depends on the subdetector and is discussed in detail somewhere else. It includes calibration of the electronics, energy calibration and corrections related to charge attenuation, spatial distortions, magnetic field and geometrical
alignment. In addition, the time offsets between the subdetectors require an additional time calibration using tracks passing through several subdetectors.

The calibration procedure of the scintillator detectors (P0D, FGD, ECal and SMRD) is described extensively in [171] while the TPC calibration is described in [119] and [121]. Specifically, a dedicated test bench was used at the T2K Micromegas production laboratory at CERN to characterize each MM, validate its performance and provide energy calibration. A photoelectron calibration system was also incorporated into the TPC design to generate a control pattern of photoelectrons from the cathode. Data from this system are used to precisely determine the electron drift velocity and to measure distortions in the electron drift due to inhomogeneities in the electric and magnetic fields and misalignment.

3.4 Reconstruction

The analysis presented in this thesis is based on the so-called global ND280 reconstruction, which represents the final step of the N280 reconstruction chain. Its main goal is to create multi-detector objects based on the information provided by the individual sub-detectors. For event information reconstruction in individual sub-detectors, dedicated packages (which are part of the ND280 software) have been designed. To perform different reconstruction tasks, such as matching, merging and (re)-fitting of sub-detector objects, the RecPack [177] external library is interfaced with the ND280 software. RecPack provides various tracking tools (e.g. track state propagation, Kalman Flitering [178], etc.) and allows taking into account magnetic field, ND280 geometry information, multiple scattering and energy loss.

A brief overview of the TPC and FGD reconstruction is given below, as well as a brief description of the tracker and global reconstruction. For further details and information about the reconstruction in other sub-detectors, one should refer to [170].

3.4.1 TPC reconstruction

The TPC reconstruction is performed for each single TPC volume. The first step of the TPC reconstruction is the application of the gain calibration constants and the removal of dead and noisy channels. The output of this process is a collection of waveforms. A waveform represents the charge acquired in a single pad as a function of time (hit).

The next step is the search for clusters of waveforms. A cluster is the basic element for track reconstruction and particle identification in the TPCs. Signals in neighboring MM pads consistent with arising from the same particle (wave-
forms must overlap in time and be consecutive in space) are grouped together to form a track of ionization. Then the clusters are connected to form a track segment following a pattern recognition algorithm. The current implementation of the track pattern recognition is based on a cellular automaton algorithm (SBCAT [179]). This code is adapted from the 2D algorithm implemented for the SciBar detector in K2K [42] and SciBooNE [180] to a 3D algorithm. Initial clustering and the subsequent pattern recognition deal with so-called vertical clusters (grouping inside MM vertical pad columns), since it is preferred by the main direction of the particles from the neutrino interactions in ND280. However prior to the track creation and fitting all possible vertical and horizontal clusters are built. Clusters consisting of neighboring pads within a column (row) for roughly horizontal (vertical) tracks are shown in Figure 3.3.

The track properties (coordinates, angles and curvature) are estimated by maximizing the likelihood of the observed charge sharing between the pads in the clusters. Prior to the likelihood fit, when the seed has been prepared, the starting time of the track, $T_0$, is estimated by matching the $yz$ projection of the TPC track to hits in the adjacent detectors (FGD, ECal and P0D; FGD hits, when available, are preferred by default). This information allows to extract the $x$ coordinates and is used to reconstruct the drift distance and predict the size of the electron cloud due to the transverse and longitudinal diffusion. During the likelihood fit, the local angle from the seed is used to make the decision whether to use horizontal or vertical clusters (see Figure 3.4). This allows dealing with the tracks that have high-angles with regard to beam axis. For later use it is important to note that the total energy of the cluster is computed from the sum of the charge of all the hits composing it. A horizontal track traversing the whole TPC (i.e. two entire MM modules) has 72 clusters.

Figure 3.3: Schematic drawing of a TPC cluster. Image taken from [170].
The final part of the reconstruction computes the ionization energy deposited in the TPC gas by charged particles passing through it as a function of the track length for the purpose of particle identification (see below).

**Particle identification in the TPC**

The particle identification (PID) in the TPC is based on the energy loss signature of the tracks in the TPC gas.

The distributions of the energy loss as a function of the momentum for data taken during the first T2K physics run are shown in Figure 3.5 for negatively and positively charged particles respectively. These events mainly contain through-going muons and neutrino interactions in ND280. The data are compared to the expected energy loss curves for muons, electrons, pions and protons; the different particle species are clearly visible in the TPC. For negatively charged particles, mainly muons with few low momentum electrons are observed while in the positively charged sample protons, pions and positrons are seen. Muons and pions are very difficult to separate as they have similar energy loss curves. In the momentum region where the proton and muon curves cross each other, protons can be misidentified as muons if the track charge is not well reconstructed.

The selection of the exclusive CCQE channels studied in this thesis (see Section 4.1) depends heavily on the unambiguous tagging of a muon and a proton in the event. The main tool for this tagging is the TPC PID. A brief description of the TPC PID algorithm is given here. For further details one should refer to [151].
3.4. Reconstruction

Figure 3.5: Distribution of the energy loss as a function of the momentum for negatively (left) and positively (right) charged particles produced in neutrino interactions, compared to the expected curves for muons, electrons, protons, and pions. Images taken from [119].

The lower energy fraction of the charge distribution in a TPC segment, set to 70%, is selected. This procedure of discarding the measurements with the largest energy deposition (which could cause inhomogeneities) defines the “truncated fraction” and corresponds to measure a quantity closely related to the peak of the cluster energy distribution. An ionization estimator with an expectation value which does not depend on the track length and on the number of clusters is built by calibrating the energy of each cluster of a track. In order to do that, the measured energy loss of each track is normalized to the corresponding energy that a horizontal track with 72 clusters would have had. The mean energy of the calibrated cluster in the truncated sample defines the ionization estimator $C_{meas}^T$:

$$C_{meas}^T = \frac{1}{xNf(N)} \sum_{i}^{xN} g(d_i)C_C(i) \quad (3.1)$$

where:

- $C_C(i)$ is the energy in cluster $i$, ordered according to increasing energy. Prior to $C_C(i)$ measurements, the charge deposited in the MM pads is corrected for variation of the gas temperature and pressure as explained in [119]. In addition, clusters at the edge of the MM or close to the central cathode are rejected as an unknown fraction of the charge in these clusters has not been collected on the sensitive area.
- $N$ is the number of cluster energy measurements in the TPC.
- $x$ is the truncation fraction.
• $f(N)$ and $g(d_i)$ are calibration factors that depend on the number of clusters and on the sample length (defined as the path length traversed by the track passing from one pad column to the next), respectively, and are equal to unity for an horizontal track traversing the whole TPC.

The energy loss is a function of $\beta\gamma$ only so, once the track momentum has been measured, knowing the mass of the particle and given a parametrization of the energy loss curve (which can be found in [151]), the expected energy loss can be computed for each reconstructed track in the TPC for different particle hypotheses (electron, muon, pion and proton). By comparing the measured energy loss with the expected one for different particle hypotheses it is possible to perform the particle identification for a track.

Given the measured mean energy of the calibrated clusters in the truncated sample, $C_{T}^{\text{meas}}$, and the expected energy loss as a function of momentum for a given particle type $\alpha$, $C_{T}^{\text{exp,}\alpha}(p)$, a “pull”, $\text{Pull}_{\alpha}(p)$, providing the number of standard deviations the measurement is away from the expected value for particle type $\alpha$ at the observed momentum, can be computed for each TPC segment of a global track in this way:

$$\text{Pull}_{\alpha}(p) = \frac{C_{T}^{\text{meas}} - C_{T}^{\text{exp,}\alpha}(p)}{\sqrt{\sigma_{C_{T}^{\text{meas}}}^2 + \sigma_{C_{T}^{\text{exp,}\alpha}(p)}^2}}$$

where $\sigma_{C_{T}^{\text{meas}}}$ and $\sigma_{C_{T}^{\text{exp,}\alpha}(p)}$ are the uncertainty on $C_{T}^{\text{meas}}$ and on $C_{T}^{\text{exp,}\alpha}(p)$ (which is dominated by the uncertainty on the momentum measurement), respectively.

In order to combine PID information from different TPCs and different hypotheses, the “likelihood”, $L_{\alpha}$, which is (assuming equal priors) the probability for a particle of measured momentum $p_k$ and pull $\text{Pull}_{\beta,k}$ (defined by Eq. 3.2) in TPC $k$ to be of type $\alpha$, has been introduced:

$$L_{\alpha} = L(\alpha|\{p_k\}, \{\text{Pull}_{\beta,k}\}) = \prod_k P_k(\text{Pull}_{\alpha,k}|p_k, \alpha) / \sum_{\beta} \prod_k P_k(\text{Pull}_{\beta,k}|p_k, \beta)$$

where $P_k(\text{Pull}_{\alpha,k}|p_k, \alpha)$ is the probability to measure a value $\text{Pull}_{\alpha,k}$ in TPC $k$ for a particle of type $\alpha$ and measured momentum $p_k$ (in the same TPC), $\beta$ runs over all particle type hypotheses, and $k$ runs over TPCs. The $P_k(\text{Pull}_{\alpha,k}|p_k, \alpha)$ distribution can be assumed to be Gaussian.

### 3.4.2 FGD reconstruction

The FGD reconstruction is done after the TPC reconstruction and is divided in several parts. The first part consists in performing “time binning” on the hits of an event in order to reconstruct clusters (i.e. collections of hits in space)
separated in time. A FGD time bin is defined as a cluster of hits from tracks which are passing through the detector at the same time. Particles passing through the FGDs with some energy and direction are represented as a set of hits, which record point-like information based on the position of the FGD bars which are hit. All hits are sorted in time and the times between each neighboring pair of hits are compared, starting from the first hit. If the time difference is less than 100 ns, the two hits are put together in a bin. If the time difference is larger than 100 ns, the later hit is put into the next bin, as shown in Figure 3.6. Further FGD reconstruction deals with individual time bins.

The main reconstruction algorithm is the TPC-based incremental FGD hit matching. Since FGD reconstruction follows the TPC one, TPC objects are used to seed track finding in the detector. The incremental matching is based on the Kalman Filter implemented in RecPack. For each TPC the following algorithm is used:

1. For each TPC and FGD time bin, only TPC tracks having their time stamps matching the time bin of the FGD hits being examined are considered.

2. FGD hits are sorted in increasing or decreasing $z$, depending on the topology, to go outwards the TPC track.

3. The RecPack package is used to propagate the state of the TPC track to each subsequent FGD layer.

4. A $\chi^2$ filtering is performed using the hit position and the extrapolated state. If the resulting $\chi^2$ is below a given cut value, the hit information is used to update the overall seed state used by the Kalman Filter.
5. If there are multiple hits in a given layer, then the $\chi^2$-based ordering is applied and the matching starts with the hit corresponding to the smallest $\chi^2$ value.

6. The matching is stopped if more than a single FGD layer is skipped (with some exception for very “flat” tracks).

7. At the final step of the procedure successfully filtered FGD hits are combined together with the TPC object in a single track which is subject to a final refit so to get a fully consisted reconstructed state in all the points.

Hits which were not used in the FGD-TPC matching process are saved and reconstructed separately, identifying tracks that are not matched to TPC objects. First, pattern recognition is done and the input hits are divided into sets that look like a track. Tracks are assumed to be well described by a straight-line approximation and Radon Transform is used to extract the most likely tracks out of the group of given hits. Pattern recognition is done separately for the XZ and YZ projections; it is followed by track cleaning which is run to remove duplication and make sure that track hits are connected. Then, candidate tracks from XZ and YZ projections are matched together to form three-dimensional reconstructed objects. It may be worth noting that there is also SBCat based pattern recognition developed for the FGDs but the Radon transform one was shown to have better performance especially for the tracks that have high-angle with regard to the beam $z$ axis. For further details one may refer to [124].

As the TPC-FGD matching is done first, some hits of the FGD track reconstructed in this way can be incorrectly associated with a nearby TPC track, producing a shift of the reconstructed FGD track.

Finally, the FGD track time calculation (a time stamp of each hit is corrected for light propagation in WLS fiber and the weighted average is taken using the charge dependent uncertainties) is done and the FGD PID algorithm (explained below) is applied.

**Particle identification in the FGD**

PID in the FGDs is based on the same principles as that in the TPCs. In more detail, it is based on the different energy deposition in the scintillator bars for different particle types as a function of the associated track length. The FGD PID algorithm was primarily designed for stopping fully contained tracks which deposit all their kinetic energy in the FGD. A brief description of the method is given below. For further details one should refer to [125].

The energy associated to each of the hits forming a FGD track (corrected for light attenuation inside WLS fiber and Birk’s affect [123]) is used to compute the
total energy deposited by the corresponding particle in the detector, \( E \), while the distance between the outermost hits is used to compute the track length \( x \). On the other hand, the expected deposited energy for a given particle type, \( E_i(x) \), and its error, \( \sigma_i(x) \) (where \( i = \mu, \pi, p \)), can be computed as a function of \( x \). Given these quantities, the pull, \( \text{Pull}_i(x) \), can be calculated in this way:

\[
\text{Pull}_{i,FGD} = \frac{E - E_i(x)}{\sigma_i(x)}
\]  \hspace{1cm} (3.4)

\( E_i(x) \) and \( \sigma_i(x) \) for each hypothesis are determined by the MC studies. Assuming that the energy deposited in the FGDs follows a gaussian distribution around the expected energy deposited, the distribution of the pull variable is supposed to be a gaussian with zero mean around the expected value and unit standard deviation for the correct hypothesis. There are several factors that can produce deviations from that behavior, such as the dependence on the track angular distribution of the different amount of dead material crossed by different particles. However, it can be shown that a gaussian can reasonably describe the distribution in a first approximation \[125\].

A scatter plot of deposited energy as a function of range for particles produced by neutrino interactions and stopping in FGD1 is shown in Figure 3.7. The solid, dashed and dot-dashed lines show the expected locations of protons, muons, and pions, respectively.

![Figure 3.7: Deposited energy vs range for particles stopping in FGD1. The scatter-plot shows stopping particles in neutrino beam data, while the curves show the MC expectations for protons, muons, and pions. Figure and caption taken from \[122\]](image)

The FGD PID is a crucial tool for the analysis presented in this thesis, as it uses FGD-only tracks and relies heavily on the muon and proton tagging.
3.4.3 Tracker reconstruction

The initial TPC/FGD matching described in Section 3.4.2 creates tracks that span a single TPC. The tracker reconstruction involves matching together tracks that cross multiple TPCs. In order to do that, a loop over all pairs of tracks in adjacent TPCs is done. The closest states of the two tracks of the pair are selected. Then, one of them (that corresponds to the track with more TPC hits) is propagated to the second and the matching $\chi^2$ is calculated using the kinematic parameters of the two tracks and the corresponding covariances. All parameters are matched: position, direction and momentum ($q/p$). If the resulting $\chi^2$ is below a given cut value, then the two tracks are merged together and further re-fitted with the RecPack Kalman Filter so to combine the information. The merging procedure starts with the pair that has the lowest matching $\chi^2$.

The final set of FGD-TPC or FGD-only tracks from the matching stage are re-fitted with the RecPack Kalman Filter to ensure that all the tracks have been fitted in a similar way and use an appropriate correction to take into account the energy loss in the detector material. However, despite the refit, the momentum estimate of FGD-only tracks is not reliable, as the TPC curvature information is not available. The analysis presented in this thesis in based on the selection of FGD-only tracks and relies on the good momentum reconstruction for these tracks in order to get reliable kinematic distributions. For this reason, a method to estimate by range the momentum of these tracks has been developed, as explained in Section 4.4.1.

By default tracks coming from the TPC and FGD reconstruction are assumed to be directed downstream. The tracker reconstruction allows the direction of tracks that cross both FGDs to be flipped based on the FGD time difference, $\Delta t_{FGD}$:

$$\Delta t_{FGD} = t_{FGD2} - t_{FGD1}$$ (3.5)

where $t_{FGD1}$ and $t_{FGD2}$ are the track time computed in FGD1 and FGD2, respectively. If $\Delta t_{FGD} < -3$ ns the track direction is switched to go backwards. As the population of forward going tracks is much larger than that of backward going tracks and the FGD time difference measurement has some significant intrinsic resolution, the condition $\Delta t_{FGD} < 0$ ns is not used in order to ensure that forward going tracks are not accidently flipped.

As tracks not crossing two FGDs are extensively used in the analysis presented in this thesis, a method to improve the track direction reconstruction for these tracks has been developed, as explained in Section 4.4.2.

---

1In the initial TPC-FGD incremental matching the energy loss correction is switched off. Thus, a final refit of all tracks with the energy loss correction is needed
3.4.4 Global reconstruction

As mentioned at the beginning of this chapter, the global reconstruction involves combining together the results from the individual sub-detectors to form reconstructed objects that span all of ND280. This basically includes matching of the tracker objects with the ones from P0D, ECAL and SMRD. First, one tries to match reconstructed tracks in the tracker to objects in the adjacent detectors: P0D and ECAL. To make the decision whether two objects belong to the same global track, the closest state of the tracker track is extrapolated into the neighboring sub-detector in concern and the matching $\chi^2$ is built using the position and direction (and the corresponding covariance matrices) of the propagated state and the one of the sub-detector. If the $\chi^2$ is smaller than a given cut value the matching is considered to be successful. All possible matches between available track pairs are tried and the reconstruction proceeds with the output matched pairs starting with the one corresponding to the smallest $\chi^2$. In addition to the $\chi^2$-based criteria, a time cut is applied: a 300 ns window is used to associate tracks. The window is wide to account for possible problems in the inter-detector time calibration. After the matching step, two tracks of a pair are merged together to build a new track and the latter is fitted with the RecPack Kalman Filter so to combine the information of the sub-detectors involved. As two successfully combined tracks are removed from further merging and fitting procedure, each individual track can correspond to only one global object. Figure 3.8 shows the example of the track built with the information from various sub-detectors. A simplified ND280 geometry used by RecPack is also shown.

In addition to tracker tracks matching, global reconstruction also combines objects that do not have tracker components (e.g. tracks passing through P0D and ECAL). When all the matching between the “inner” detectors is finished the available tracks are used to seed SMRD reconstruction, which is based on the FGD-like incremental hit matching. This allows creating objects with SMRD constituents and is the last step of the ND280 reconstruction flow.

As already mentioned, global tracks are used in the analysis presented in this thesis.

$^2$Note that direction information is not used in case of matching to showers.
Figure 3.8: Example of a global reconstruction event display. The upper plot shows the inputs to the global reconstruction which are the P0D track, the tracker track and the DsECAL track. The lower plot shows the results after the global reconstruction has been run.
Chapter 4

$\nu_\mu$ CCQE event selection in the ND280 tracker

The peak energy of the narrow-band neutrino beam that the T2K experiment uses is selected in such a way that the majority of neutrino interactions seen in ND280 is CCQE interactions. The ND280 tracker combines a significant fiducial mass, track and particle identification information from the FGDs with the excellent tracking and PID capabilities of the TPCs, allowing the detailed measurement of CCQE interactions in the ND280 detector.

By studying the properties of events generated by the ND280 NEUT MC simulation, a criterion to select $\nu_\mu$ CCQE events in the ND280 tracker was developed. The final results of this study are presented in this chapter. The systematic error estimation and the results obtained with real data are presented in Chapters 5 and 6 respectively.

4.1 CCQE topologies

For a $\nu_\mu \ n \rightarrow \mu^- \ p$ event one would expect two tracks originating from the reconstructed primary vertex (see Figure 4.1), one of them identified as a muon, the other one as a proton. Events with such a topology will be referred to as 2-track events. However, the reconstruction of the proton can fail due to either its kinematics (too low momentum or too large emission angle) or nuclear re-interactions. In this case only the muon track is reconstructed. Such an event will be referred to as a 1-track event.

Only interactions happening in FGD1 are included in this analysis. Consequently, all selected tracks are required to have their reconstructed start position in FGD1. Furthermore, only FGD-TPC tracks (i.e. tracks with both FGD and TPC segments) and FGD tracks (i.e. tracks with at least one FGD segment and...
Figure 4.1: Typical CCQE event detected in the ND280 tracker.

no TPC segments) are considered. Two different kinds of FGD tracks have been taken into account:

- **FGD1 fully contained tracks**: their start and end positions are inside FGD1 and they do not have segments of other detectors. They correspond to topology 1 in Figure 4.2 and will be called “FGD-only tracks” in the following.

- **FGD tracks with reconstructed start position in FGD1 but not fully contained**: they have segments of other detectors (ECAL and/or SMRD). They correspond to topologies 2, 3 and 4 in Figure 4.2.

Four different topologies of CCQE events have been studied (see Figure 4.3):

1. $\mu_{\text{TPC}}$: the muon candidate is a FGD-TPC track, the proton candidate is not reconstructed.

2. $\mu_{\text{TPC}}$-$p_{\text{TPC}}$: both the muon and proton candidates are FGD-TPC tracks.

3. $\mu_{\text{TPC}}$-$p_{\text{FGD}}$: the muon candidate is a FGD-TPC track, the proton candidate is a FGD-only track.

4. $\mu_{\text{FGD}}$-$p_{\text{TPC}}$: the muon candidate is a FGD track, the proton candidate is a FGD-TPC track.

A detailed description of the event selection criterion corresponding to each topology is given in the next sections.
4.2 Monte Carlo and real data sets

The ND280 NEUT MC simulated data for Runs 1, 2, 3 and 4 of official production 5E and the corresponding real data for Runs 1, 2, 3 and 4 of the official production 5F have been used in this analysis. Table 4.1 summarizes the protons on target (POT) values corresponding to each run period for data and MC.

The default Monte Carlo simulation used for ND280 contains only interactions that occur within the magnet. In order to take into account interactions originating outside the magnet, an independent dedicated MC simulation of so-
called “sand muons” (particles produced by beam neutrino interactions occurring in the sand and pit walls surrounding the detector) \(^{160}\) has been used. The sand muon sample, which corresponds to \(2.1475 \times 10^{20}\) POT, has been scaled to the POT of the standard MC.

<table>
<thead>
<tr>
<th>POT data</th>
<th>Run1</th>
<th>Run2</th>
<th>Run3</th>
<th>Run4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1</td>
<td>2.9602 \cdot 10^{19}</td>
<td>7.8778 \cdot 10^{19}</td>
<td>1.5978 \cdot 10^{20}</td>
<td>3.34583 \cdot 10^{20}</td>
</tr>
<tr>
<td>POT MC</td>
<td>3.8 \cdot 10^{20}</td>
<td>8.825 \cdot 10^{20}</td>
<td>1.1425 \cdot 10^{21}</td>
<td>10^{21}</td>
</tr>
</tbody>
</table>

Table 4.1: POT values for data beam runs and for the corresponding NEUT MC runs.

All results and plots presented in this chapter, apart from the data plots in Figure 4.4, refer to Run 4 of the NEUT MC production 5E plus the sand muon NEUT MC sample. The sand muon sample is scaled to the standard MC by POT.

4.3 Beam bunching

As shown in Table 4.2 and mentioned in Section 2.1, the neutrino beam has a structure of six or eight bunches per spill, with a separation in time of about 580 ns (see Figure 4.4). The bunch width is \(\approx 7.0\) ns in Monte Carlo and \(\approx 15.0\) ns in real data.

In the analysis presented in this thesis every beam bunch defines an event, meaning that all tracks coming from the same bunch are associated with the same event regardless of the number of true interactions occurring in that bunch. In more detail, only tracks that deviate from the mean bunch position less than 60 ns (i.e. 4 times the data bunch width) are considered. With the tracks being grouped together in this way, neutrino interactions in two different bunches within the same beam spill are treated as two different events, minimizing accidental pile-up of events. The probability of having two interactions in the same bunch is negligible. Thanks to this procedure, the background of tracks produced in non-beam interactions (mainly cosmics) is minimized.

4.4 Reconstruction improvements at analysis level

Some important reconstruction tools to be used at analysis level have been developed in order to increase the phase space available for the analysis:

- The momentum of FGD tracks, for which the TPC curvature information is not available, has been estimated by range, taking advantage of the detector
4.4. Reconstruction improvements at analysis level

Figure 4.4: Bunch position for data run 1 (first line), run 2 (second line), run 3 (third line), run 4 (fourth line), and NEUT MC (fifth line). Run2 and run3 have two sub-periods corresponding to different data taking periods with different beam intensity.

gallery knowledge and of the particle energy loss in the detector material (see Section 4.4.1).
Table 4.2: Bunch position in ns units for different ND280 run periods.

<table>
<thead>
<tr>
<th>Run Period</th>
<th>MC</th>
<th>Run1</th>
<th>Run2</th>
<th>Run3</th>
<th>Run4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 6000</td>
<td>[6000, 7000]</td>
<td>[7000, 8000]</td>
<td>[8000, 8550]</td>
</tr>
<tr>
<td>bunch 1</td>
<td>2750.2</td>
<td>2839.7</td>
<td>2853.95</td>
<td>3019.11</td>
<td>3024.22</td>
</tr>
<tr>
<td>bunch 2</td>
<td>3322.0</td>
<td>3423.5</td>
<td>3444.15</td>
<td>3597.74</td>
<td>3606.11</td>
</tr>
<tr>
<td>bunch 3</td>
<td>3914.7</td>
<td>4005.4</td>
<td>4030.41</td>
<td>4180.73</td>
<td>4188.01</td>
</tr>
<tr>
<td>bunch 4</td>
<td>4497.0</td>
<td>4588.6</td>
<td>4620.34</td>
<td>4763.93</td>
<td>4769.90</td>
</tr>
<tr>
<td>bunch 5</td>
<td>5078.4</td>
<td>5172.2</td>
<td>5180.28</td>
<td>5346.49</td>
<td>5351.79</td>
</tr>
<tr>
<td>bunch 6</td>
<td>5659.7</td>
<td>5754.6</td>
<td>5770.12</td>
<td>5927.83</td>
<td>5933.68</td>
</tr>
<tr>
<td>bunch 7</td>
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<td>6343.77</td>
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<td>6515.58</td>
</tr>
<tr>
<td>bunch 8</td>
<td>6824.2</td>
<td>————</td>
<td>6924.67</td>
<td>7093.56</td>
<td>7097.47</td>
</tr>
</tbody>
</table>

- The sense determination for FGD tracks has been improved by comparing the distance of their starting and ending points from the reconstructed vertex of the event (see Section 4.4.2).

### 4.4.1 Momentum by range of FGD tracks

As the TPC curvature information is not available for FGD tracks, it is not possible to reconstruct the momentum of these tracks using the standard reconstruction algorithm. However, the momentum can be computed by range at analysis level\(^1\) taking advantage of the detector geometry knowledge and of the particle energy loss in the detector material. In more detail, assuming that the track loses all its energy inside the ND280 detector, the momentum by range is computed by adding step by step the momentum lost inside the detector volume to the track final momentum (assumed to be almost zero), as shown schematically in Figure 4.5, taking into account the properties of the traversed material (considering also the dead material between detectors) and the length traversed by the particle at each step. The trajectory is assumed to be a straight line. The step size is chosen at each step in such a way that the momentum variation is smaller than 10%. The energy loss at each step is computed for each particle type based on the energy reached at the previous step.

Figure 4.6 shows the difference between the true and the reconstructed momentum when the latter is computed by range for true protons and true muons fully contained in FGD1. The momentum by range reproduces quite well the

\(^1\)For production 5 (the one used when this thesis work was performed) the momentum by range algorithm was not available in the reconstruction. It is available for production 6.
4.4. Reconstruction improvements at analysis level

Figure 4.5: Schematic drawing showing how the momentum by range is computed for a FGD-only track. The same procedure is used for other kinds of FGD tracks stopping inside the active part of the ND280 detector.

Figure 4.6: Momentum by range minus true momentum for true muons (left) and true protons (right) fully contained in FGD1.

true momentum for muons, while it is slightly overestimated for protons.

Thanks to this procedure it is possible to reconstruct the final state kinematics of CCQE 2-track events in which one of the two tracks has no TPC segments (i.e. events with $\mu$TPC-pFGD and pTPC-$\mu$FGD topologies).

\footnote{The same behaviour is expected in real data}
4.4.2 Track sense reconstruction using the event vertex

With the time information from both FGD1 and FGD2 not being available, it is not possible to reconstruct the direction of FGD-only tracks and of FGD tracks with segments in other detectors but crossing only one FGD\(^3\), so the reconstruction defines those tracks as forward going by default. As FGD tracks have in general larger emission angles than FGD-TPC tracks (which correspond mainly to forward going particles), the probability of those tracks to be produced by a backwards going particle is higher. For this reason the track sense correction algorithm is especially important for FGD tracks.

![Diagram of track sense correction](image)

**Figure 4.7:** Track sense correction: the distance \(\text{dist}_{\text{start}}\) of the starting point of the FGD track (\(\text{pos}_{\text{start}}\)) from the reconstructed vertex (\(\text{pos}_{\text{vtx}}\)) is compared to the distance \(\text{dist}_{\text{end}}\) of the ending point (\(\text{pos}_{\text{end}}\)) from the reconstructed vertex; if \(\text{dist}_{\text{end}} < \text{dist}_{\text{start}}\) the track is reversed because it is very likely that its reconstructed sense is wrong.

In order to improve the reconstruction (by assigning the correct sense to backwards going FGD tracks) and extend the phase space available for the analysis (by recovering events rejected due to wrong FGD track direction reconstruction), a check of the track direction, done by comparing the distance of the starting and ending points of the FGD track from the reconstructed vertex (as shown in Figure 4.7), has been introduced. As tracks are grouped in bunches according to their time (see Section 4.6), the probability of pile-up is negligible. Consequently, if the end position of the track is closer to the reconstructed vertex than its start

\(^{3}\)The time difference between detectors other than FGDs was not available for the data production used in this analysis so it couldn’t be used to determine the track direction at reconstruction level.
position, it can be assumed that the track is backwards going and its sense is reversed.

This improvement affects both the $\mu$TPC-pFGD and the pTPC-$\mu$FGD 2-track topologies because one of the two candidates (the proton in the $\mu$TPC-pFGD topology, the muon in the pTPC-$\mu$FGD topology) is a FGD track. In more detail, due to the so-called “common vertex” cut (see Sections 4.10 and 4.11), which requires the distance between the starting points of the muon and proton candidates to be below a given threshold, good events with a mis-reconstructed backwards going FGD-only track would be rejected by the CCQE selection, as shown in the schematic drawing of Figure 4.8-left. The case of a FGD track not completely contained in FGD1 affects only the pTPC-$\mu$FGD topology. In this case, if the track is originated in FGD1 but its start and end positions are exchanged, the track starting point is reconstructed outside the FGD1 volume, as shown in the central and right panels of Figure 4.8, causing the event to be rejected because the muon and proton candidates would appear as originated in different detectors (see Section 4.11).

Figure 4.8: Schematic drawing showing the effect of the FGD track sense correction on the selection of CCQE events with $\mu$TPC-pFGD and pTPC-$\mu$FGD topologies. Case 1: the FGD track is a FGD-only track. Case 2: the FGD track reaches the ECAL. Case 3: the FGD track reaches the SMRD. Case 1 affects both the $\mu$TPC-pFGD and pTPC-$\mu$FGD topologies, while cases 2 and 3 affect only the pTPC-$\mu$FGD topology.

Figures 4.9 and 4.10 show the effect of the tracks sense correction for events with $\mu$TPC-pFGD and pTPC-$\mu$FGD topologies, respectively. Backwards going FGD-only tracks are reconstructed as forward going when the track sense correction is not applied while their direction is correctly reconstructed when the track

4. $\nu_\mu$ CCQE event selection in the ND280 tracker

Figure 4.9: Top: Reconstructed (red) and true (black) polar angle of FGD-only tracks when the sense correction is applied (left) and when it is not (right), for events with $\mu$TPC-pFGD topology. Bottom: True minus reconstructed polar angle of FGD-only tracks when the sense correction is applied (left) and when it is not (right), for events with $\mu$TPC-pFGD topology.

Figure 4.10: Top: Reconstructed (red) and true (black) polar angle of FGD tracks when the sense correction is applied (left) and when it is not (right), for events with pTPC-$\mu$FGD topology. Bottom: True minus reconstructed polar angle of FGD tracks when the sense correction is applied (left) and when it is not (right), for events with pTPC-$\mu$FGD topology.
4.5 Efficiency and purity definition

The CCQE purity and efficiency have been computed after each cut, in order to study the effect of each step of the selection. The CCQE purity is defined as the fraction of selected events originated by a true CCQE interaction in the FGD1 fiducial volume (FV) defined in Table 4.5:

\[
\text{CCQE PURITY} = \frac{\text{selected true CCQE events in FGD1 FV}}{\text{selected events}}
\]  

(4.1)

The true reaction type of the interaction is checked by looking at the MC truth information of the true vertex associated with the reconstructed one. Consequently it makes no sense to compute the purity before the reconstructed vertex of the event has been defined.

The CCQE efficiency is defined as the fraction of true CCQE interactions with true vertex in the FGD1 FV that are selected:

\[
\text{CCQE EFFICIENCY} = \frac{\text{selected true CCQE events in FGD1 FV}}{\text{true CCQE events in FGD1 FV}}
\]  

(4.2)

In this case the true vertex is defined by the interacting neutrino, regardless of the reconstructed vertex.

When computing the CCQE efficiency, one should take into account that in real data there can be sometimes pile up of a good event inside FGD1 FV and a sand muon crossing TPC1, causing the event to be rejected by the so-called “external veto” cut (see Section 4.7). The probability of such coincidence grows with the beam intensity. In Monte Carlo such event would be accepted, because the sand muon and the standard NEUT MC samples are separated. So, in the efficiency calculation one should take into account the probability of having a sand muon in TPC1 in the same bunch (see Section 4.3) as the candidate CCQE event. The correction that should be applied to the efficiency in order to take into account this effect is discussed in Section 5.5.4. This effect, which is of the order of 1% or less, is not taken into account in this chapter, as it does not affect the definition of the cuts.

---

4The reconstruction of backwards going tracks when the track sense correction is not applied (Figure 4.10-top right) is due to an artefact of the reconstruction algorithm.
4.6 Pre-selection

As explained in Section 4.3, every beam bunch defines an event.

The first part of the selection consists of a preliminary set of cuts (see Table 4.3) common to all topologies and designed to select good quality events containing at least one track with TPC segments.

<table>
<thead>
<tr>
<th>CUT</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>good spill and data quality (DQ)</td>
</tr>
<tr>
<td>2</td>
<td>at least one TPC track</td>
</tr>
</tbody>
</table>

Table 4.3: List of pre-selection cuts.

CUT 1: Data quality cut

Good quality events are selected according to the standard data quality cuts recommended by the ND280 data quality group [138]–[142]. More in detail, beam spills triggered by the near detector are required to satisfy the good quality assessment criteria by the beam group [143]. In addition, several criteria based on checks on the hardware status of the ND280 detector and on some reconstructed variables are used to assess the quality of the data in each beam run. Beam runs and beam spills which are not considered to be of enough good quality to be analyzed are rejected. This cut is applied only to data events, not to the MC.

CUT 2: At least one TPC track

Only events containing at least one reconstructed track with one or more TPC segments, regardless of the track start position, are selected and used in this analysis. The TPC track multiplicity of events passing the data quality cut is shown in Figure 4.11. Most of the times only one TPC track is reconstructed.

4.7 Inclusive $\nu_\mu$ CC selection

The selection of CCQE samples with $\mu$TPC, $\mu$TPC-pTPC and $\mu$TPC-pFGD topologies (i.e. all topologies whose muon candidate is a FGD-TPC track) is based on the inclusive selection of $\nu_\mu$ CC events.

Events with at least one negative FGD-TPC track are selected. The muon candidate is defined as the highest momentum negative (HMN) track in the event among all negative FGD-TPC tracks starting in the FGD1 fiducial volume (FV) with good reconstruction quality (with a minimum length). The reconstructed
4.7. Inclusive $\nu_\mu$ CC selection

Figure 4.11: TPC track multiplicity. Only the data quality cut has been applied. Events with at least one TPC track are selected, as indicated by the arrow.

The start position of the muon candidate defines the reconstructed vertex of the event. Part of the external background (i.e. background due to events generated by interactions occurring outside of the FGD1 FV but reconstructed inside) is removed by requirements on the position of other TPC tracks in the event (the so-called “external veto cut”). Finally, the TPC PID (see Section 2.2.3) is used to check the muon candidate identity and select tracks compatible with the muon hypothesis.

Table 4.4 summarizes the CC selection cuts and the order in which they are applied. Cuts 1 and 2 have been already discussed in Section 4.6. The rest of the cuts are explained in detail below.

<table>
<thead>
<tr>
<th>CUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.4: List of CC selection cuts.

CUT 3: Fiducial Volume and TPC track quality cuts

The combination of the so-called “TPC track quality” and “fiducial volume” cuts aims at selecting good quality tracks originated in FGD1 FV. In addition it defines the reconstructed vertex as the start position of the HMN track in the
event, chosen among all negative FGD-TPC tracks having their start position in FGD1 FV and having good reconstruction quality. The HMN negative track selected in this way defines the muon candidate.

Figure 4.12: Reconstructed position of the HMN track along the x, y, z axes before (left) and after (right) the fiducial volume cut (the quality cut has been applied). The arrows and the red contour indicate the FGD1 fiducial volume regions.

The fiducial volume cut requires the reconstructed vertex to be inside the fiducial volume of FGD1. The starting point of the reconstructed track is in general based on where the fitted 3D track intercepts the vertical plane of the most upstream matched FGD hit, except when the track has both FGD1 and FGD2 segments and the time difference between those is compatible with a backwards going particle (see Section 3.4.3). In this case the intersection with
4.7. Inclusive $\nu_\mu$ CC selection

the plane associated to the most downstream matched hit defines the starting point.

<table>
<thead>
<tr>
<th>FGD1 fiducial volume</th>
<th>min (mm)</th>
<th>max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>-874.51</td>
<td>874.51</td>
</tr>
<tr>
<td>$y$</td>
<td>-819.51</td>
<td>929.52</td>
</tr>
<tr>
<td>$z$</td>
<td>136.875</td>
<td>446.955</td>
</tr>
</tbody>
</table>

Table 4.5: Definition of the FGD1 fiducial volume in the ND280 coordinate system.

The fiducial volume cut is defined by: $|x| < 874.51$ mm, $|y-55| < 874.51$ mm, and $136.875 < z < 446.955$ mm (see Table 4.5). The cuts along $x$ and $y$ match the outer boundaries of the central 182 scintillator bars in the $x$ and $y$ layers. Each layer contains a total of 192 bars, so 5 bars on either end of each layer are excluded from the fiducial volume. The 55 mm offset in the $y$ cut reflects the fact that the XY modules are displaced 55 mm upwards with respect to the centre of the ND280 coordinate system (see Figure 2.12). The upstream $z$ cut places the fiducial volume just after the first XY module, but includes the remaining 14 XY modules.

Figure 4.12 shows the reconstructed start position of the HMN track with good quality before (left) and after (right) the application of the FV cut. The FGD segmentation is clearly visible along $z$ (Figure 4.12-bottom-right).

The TPC track quality cut defines the criterion used to select well reconstructed tracks and is based on the number of TPC clusters associated with the track (see Section 2.2.3 for the cluster definition). Only tracks with more than 18 clusters (corresponding to a half of the MM module) in the closest TPC to their own starting point are selected and used in this analysis, while short tracks, for which the reconstruction is less reliable, are rejected. The cut value was chosen based on detailed dedicated studies which showed that the rate of charge mis-reconstruction decreases for long tracks with high number of TPC clusters [161] and that the TPC track finding efficiency is $\sim$99.8% for tracks with more than 18 TPC clusters and decreases considerably for track with less clusters [156].

As shown in Figure 4.13-left, the muon candidate is normally forward going and the closest TPC to its start position is in general TPC2, except a few cases in which the track is backwards going and crosses TPC1. Only few tracks have less than 19 clusters, as shown in Figure 4.13-right. The two peaks at 36 and 72 correspond to tracks passing through one or two entire MM modules respectively.
Figure 4.13: Left: Muon candidate reconstructed polar angle (top) and closest TPC (bottom). Right: Distribution of reconstructed TPC2 clusters for the HMN FGD-TPC track in the event. Cuts 1 and 2 of Table 4.4 plus the fiducial volume cut have been applied. The TPC track quality cut accepts only events with more than 18 reconstructed clusters, as indicated by the arrow.

CUT 4: External veto cut

The purpose of this cut is to remove mis-reconstructed events entering the FGD1 fiducial volume from the upstream edge of the detector.

Figure 4.14: Schematic drawing showing examples of event topologies rejected by the external veto cut: a track entering the detector from the P0D (case a) or magnet (cases b, c) region.

The start position of the highest momentum track with a TPC segment other than the muon candidate (the so-called “veto track”) is required to be less than 150 mm upstream of the muon candidate’s start position. If this condition is not
Figure 4.15: Left: Distance between the muon candidate and the veto track computed as the veto track reconstructed start position along $z$ minus the muon candidate reconstructed start position along $z$. Right: The same in logarithmic scale. If the veto track’s start position is less than 150 mm upstream of the muon candidate’s start position the event is accepted, as indicated by the arrow. Cuts 1, 2 and 3 of Table 4.4 have been applied.

satisfied the event is rejected because it is likely that there is a track in the event which probably entered the detector from the P0D or magnet region. Figure 4.14 shows topology examples of events rejected by the external veto cut. As shown in Figure 4.15 in most of the events rejected by this cut the muon candidate comes from an interaction occurring outside of the FGD1 FV.

**CUT 5: Muon TPC PID cut**

In order to select muon-like particles the TPC PID based on the likelihood, $L_\alpha = L(\alpha|\{p_k\}, \{Pull_{\beta,k}\})$ (where $k$ runs over TPCs and $\beta$ over particle hypotheses: $\mu$, $\pi$, $e$, $p$) is used, which gives the probability (assuming equal priors) for a particle of measured momentum $p_k$ and pull $Pull_{\beta,k}$ in each of the three TPCs to be of type $\alpha$ (see Section 3.4.1). The following cuts are applied:

$$L_{\text{MIP}} = \frac{L_\mu + L_\pi}{1 - L_p} > 0.8 \quad \text{if } p < 500 \text{ MeV/c}$$  \hspace{1cm} (4.3)

$$L_\mu > 0.05$$  \hspace{1cm} (4.4)

where $L_\mu$, $L_\pi$ and $L_p$ are computed according to Eq. 3.3 taking into account four particle types ($\mu$, $e$, $\pi$, $p$) and correspond to the probability of being a muon, a pion or a proton, respectively.

$L_{\text{MIP}}$ can distinguish only between muons/pions and electrons\(^5\). The cut

\(^5\)To subtract $L_p$ in the denominator of Eq. 4.3 is equivalent to not consider the proton
on $L_{\mu}$ (Eq. 4.4) allows to separate muons from pions and muons/pions from electrons and protons.

Figure 4.16: MIP likelihood (as defined by Eq. 4.3) of the muon candidate after the external veto cut has been applied, for tracks with reconstructed momentum $< 500$ MeV/c (left) and for tracks with reconstructed momentum $> 500$ MeV/c (right). The arrow indicates the region accepted by the cut on $L_{MIP}$.

Figure 4.17: Left: Muon likelihood (defined by Eq. 3.3) of the muon candidate after the cut on $L_{MIP}$ (Eq. 4.3) has been applied. The arrow indicates the region accepted by the cut on $L_{\mu}$. Right: Detail of the rejected region for muon candidate momentum $< 500$ MeV/c (top) and $> 500$ MeV/c (bottom).

The cut on $L_{MIP}$ is applied only to particles with momentum lower than 500 MeV/c, allowing to remove the electron background, which is concentrated in hypothesis at all as $1 - L_{p} = L_{\mu} + L_{\pi} + L_{e}$. On the other hand, since $L_{\mu}$ is added to $L_{\pi}$ in the numerator, no discrimination between muons and pions is possible with $L_{MIP}$.
4.7. Inclusive $\nu_\mu$ CC selection

this region (see Figure 4.16 left). It is not worth applying the cut on $L_{MIP}$ to particles with momentum higher than 500 MeV/c because in that region there are few electrons and a significant amount of muons (see Figure 4.16 right).

As the energy loss curves of $\mu^-$ and $\pi^+$ are well separated at low momentum, as well as those of $\mu^-$ and $e^-$ at high momentum (see Figure 3.5), both the residual background of positive pions at low momentum ($<500$ MeV/c) and the electron contamination at high momentum are reduced by the cut on $L_{\mu}$ (see Figure 4.17 right-top and -bottom). Low momentum ($<1$ GeV/c) protons are also removed as the energy loss curves of muons and protons differ significantly at low momentum, while high momentum protons cannot be separated from muons (see Figure 3.5).

After the muon TPC PID cut has been applied the muon purity (computed as the fraction of selected events whose muon candidate is a true muon) increases by $\sim 20\%$ (passing from 67.6\% to 89.9\%).

### 4.7.1 CC and CCQE efficiency and purity after selection

The CC efficiency and purity after each selection cut can be defined analogously to the CCQE ones by requiring CC instead of CCQE interactions in Eq. 4.2 and 4.1 respectively.

![Figure 4.18: CC (dashed lines) and CCQE (continuous line) efficiency (Eq. 4.2) and purity (Eq. 4.1) as a function of the CC selection cuts listed in Table 4.4. The purity has been computed when sand muons are taken into account (red line) and when they are not (green line). The numerical results are given in Table 4.6.](image)

The evolution of the CC and CCQE efficiency and purity is shown in Figure 4.18 and summarized in Table 4.6. The final efficiency is 54.6\% for CC and
49.6% for CCQE. As the sand muon background at the end of the CC selection is negligible (see Table 4.7), also the change in the final purity when taking sand muons into account is negligible (the purity changes by 0.5% for CC and by 0.2% for CCQE). At this point of the selection, considering the total MC (magnet interactions plus sand muons), the CC purity is 89.1%, while the CCQE purity is 42.2%. The main background to CCQE interactions at the end of the CC selection is due to resonance and deep inelastic scattering (see Table 4.7). This background will be reduced by applying the dedicated CCQE cuts discussed in
4.8 CCQE 1-track sample: µTPC topology

The selection of CCQE single track events is based on the CC selection plus additional cuts. In more detail, events with only one negative FGD-TPC track are selected and events in which the presence of Michel electrons is detected are rejected. In addition, the requirement of no other tracker tracks in the event must be satisfied, where “tracker track” stands for any track containing TPC and/or FGD segments, regardless of their length.

The CCQE 1-track cuts are summarized in Table 4.8. The CC cuts have already been discussed in Section 4.7. The CCQE 1-track specific cuts are explained in detail below.

<table>
<thead>
<tr>
<th>CUT</th>
<th>Description</th>
<th>CC selection</th>
<th>µTPC CCQE selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>good spill and DQ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>at least one TPC track</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>fiducial volume and track quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>external veto</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>muon TPC PID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>one negative FGD-TPC track</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>no Michel electrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>one tracker track</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8: List of CCQE selection cuts for the single track sample (µTPC topology). Cuts from 1 to 5 aim at selecting an inclusive CC sample; 6 and 7 are CCQE specific cuts; cut 8 aims at selecting 1-track events.

**CUT 6: One negative FGD-TPC track**

In order to reduce the background due to other kind of neutrino-nucleus interactions producing a muon plus other particles in the final state, events with only one negative FGD-TPC track with good quality in FGD1 FV are selected.

As shown in Figure 4.19-left, the fraction of selected CCQE events is very low when more than one negative FGD-TPC track is reconstructed, as expected.

**CUT 7: No Michel electrons**

The second most probable interaction at 1 GeV corresponds to charged current single pion (CC1π) interactions, which are one of the main backgrounds for the
CCQE selection at both the near and far detectors. The identification of pions is crucial for the discrimination between CCQE and CC1π interactions. The typical single pion production reactions at T2K are summarized in Eq. 1.29, 1.30, 1.31.

In ND280, the pion produced in a CC1π interaction often stops in the FGDs and decays to a muon and a neutrino:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]  

(4.5)

The decay muon usually stops in the same FGD as the pion by decaying to an electron and neutrinos:

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]  

(4.6)

The electron produced in the muon decay is known as Michel electron. Due to the decay time of the pion and the muon, Michel electrons come from a vertex separated in time from the primary vertex. In addition they usually produce electromagnetic showers in the FGD, meaning that the presence or lack of delayed clusters in the FGD can be used for tagging the presence of a pion.

In more detail, Michel electrons are identified by searching for isolated time bins (see Section 3.4.2) of at least 200 photoelectrons in FGD1 and delayed of at least 100 ns with respect to the initial neutrino interaction. If there is at least one of such delayed time-bins, the event is classified as background and rejected. The time window of 100 ns ensures that the additional charge is not produced in the primary neutrino interaction. Detailed dedicated studies have been done [144], showing that eliminating events with delayed time bins having charge deposit above the threshold allows to reduce the CC1π contamination without removing CCQE events. The effect of this cut can be seen in the middle panel of Figure 4.19.

CUT 8: One tracker track

Events with more than one tracker track are rejected. That means that the only allowed tracker track in the event is the muon candidate. As pile-up is negligible due to the bunching, this cut rejects events in which also the proton has been reconstructed (these events are included in the event samples with µTPC-pTPC and µTPC-pFGD topologies) and background due to other kind of interactions producing a muon plus other particles (see Figure 4.19-right).

---

6 No Michel electrons come from the muon produced in the primary neutrino interaction, since it reaches the TPC and therefore is not stopping in FGD.
4.8.1 CCQE efficiency and purity after selection

The CCQE purity and efficiency after each cut are summarized in Figure 4.20 and Table 4.9. The final CCQE purity of the selected sample is \( \sim 85\% \) and the sand muon background is negligible. The last three cuts improve the CCQE purity by \( \sim 40\% \) with respect to the CC selection.

By requiring only one tracker track in the event most of the background due to resonance production, deep inelastic scattering and interactions occurring outside of the FGD1 FV is removed, causing the CCQE purity to improve by more than 30%. On the other hand, the efficiency decreases by 18%. Part of the rejected CCQE events will be included in the 2-track CCQE samples and recovered. The dominant background at the end of the selection is due to an irreducible contamination of pions originated by resonance production (Table 4.10).

4.9 CCQE 2-track sample: \( \mu \)TPC-pTPC topology

As the \( \mu \)TPC, \( \mu \)TPC-pTPC and \( \mu \)TPC-pFGD topologies are all based on the CC selection and have the same muon topology, cuts from 1 to 7 of Table 4.8 apply to all of them. In addition, in order to select 2-track events with \( \mu \)TPC-pTPC topology, one must define a criterion to select the proton candidate. As both the muon and the proton are required to be reconstructed, only events with two tracker tracks are selected.

The definition of the proton candidate is analogous to the one of the muon candidate: the highest momentum positive (HMP) FGD-TPC track in the event with good reconstruction quality whose reconstructed start position is in FGD1.
CCQE event selection in the ND280 tracker

Figure 4.20: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) after each of the CCQE selection cuts listed in Table 4.8. The purity has been computed when sand muons are taken into account (red line) and when they are not (green line). Cuts from 1 to 5 are inclusive CC selection cuts. The numerical results are given in Table 4.9.

<table>
<thead>
<tr>
<th>CUT</th>
<th>CCQE eff (%)</th>
<th>CCQE pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with sand μ</td>
<td>w/o sand μ</td>
</tr>
<tr>
<td>1 good spill and DQ</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>64.3</td>
<td>—</td>
</tr>
<tr>
<td>3 FV and track quality</td>
<td>51.6</td>
<td>23.4</td>
</tr>
<tr>
<td>4 external veto</td>
<td>50.1</td>
<td>31.2</td>
</tr>
<tr>
<td>5 muon TPC PID</td>
<td>49.6</td>
<td>42.4</td>
</tr>
<tr>
<td>6 one negative FGD-TPC track</td>
<td>49.1</td>
<td>47.4</td>
</tr>
<tr>
<td>7 no Michel electrons</td>
<td>48.6</td>
<td>50.9</td>
</tr>
<tr>
<td>8 one tracker track</td>
<td><strong>30.6</strong></td>
<td><strong>85.3</strong></td>
</tr>
</tbody>
</table>

Table 4.9: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) after each of the CCQE selection cuts listed in Table 4.8. The values refer to Figure 4.20.

FV. A cut on the distance between the reconstructed start positions of the muon and proton candidates is applied to minimise the presence of events with bad kinematics. Finally, the TPC PID information is used to select proton-like particles.

The selection cuts are summarized in Table 4.11. Cuts from 1 to 5 define the
4.9. CCQE 2-track sample: $\mu$TPC-pTPC topology

<table>
<thead>
<tr>
<th>background type</th>
<th>total fraction (%)</th>
<th>bkg fraction (%)</th>
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</thead>
<tbody>
<tr>
<td>RES</td>
<td>8.6</td>
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</tr>
<tr>
<td>DIS</td>
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<td>9.3</td>
</tr>
<tr>
<td>COH</td>
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<td>7.4</td>
</tr>
<tr>
<td>NC</td>
<td>0.9</td>
<td>6.3</td>
</tr>
<tr>
<td>out FGD1 FV</td>
<td>2.6</td>
<td>17.5</td>
</tr>
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<td>other</td>
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<td>0.8</td>
</tr>
<tr>
<td>TOTAL</td>
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<td>100</td>
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</tbody>
</table>

Table 4.10: Background summary. First column (total fraction): fraction of selected events which are background to CCQE interactions. Second column (bkg fraction): fraction of background due to each background type. Background types considered: resonance production (RES); deep inelastic scattering (DIS); coherent pion production (COH); neutral current interactions (NC); events whose true start position is not in FGD1 FV (out FGD1 FV); sand muons (sand $\mu$); any other interaction type (other).

inclusive CC selection (see Section 4.7), while cuts 6 and 7 have been explained in Section 4.8. The other cuts, specific of the $\mu$TPC-pTPC topology, are discussed below.

<table>
<thead>
<tr>
<th>CUT</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>good spill and DQ</td>
</tr>
<tr>
<td>2</td>
<td>at least one TPC track</td>
</tr>
<tr>
<td>3</td>
<td>fiducial volume and track quality</td>
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<td>external veto</td>
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<td>muon TPC PID</td>
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<td>6</td>
<td>one negative FGD-TPC track</td>
</tr>
<tr>
<td>7</td>
<td>no Michel electrons</td>
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<td>two tracker tracks</td>
</tr>
<tr>
<td>9</td>
<td>one FGD-TPC positive track</td>
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<td>common vertex</td>
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<td>proton TPC PID</td>
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<table>
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<td>$\mu$TPC-pTPC CCQE selection</td>
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</tbody>
</table>

Table 4.11: List of CCQE selection cuts for the 2-track sample, $\mu$TPC-pTPC topology. Cuts from 1 to 5 aim at selecting an inclusive CC sample; 6 and 7 are CCQE specific cuts; from 8 to 11 are $\mu$TPC-pTPC specific cuts.
**CUT 8: Two tracker tracks**

Only events with two tracks in the tracker are selected. Despite having high CCQE purity, events with only one reconstructed tracker track cannot be accepted as the proton has not been reconstructed (they are already included in the event sample with $\mu$TPC topology). On the other hand, by rejecting events with more than two tracker tracks, the contamination due to resonant interactions and deep inelastic scattering producing a muon plus other particles is reduced (see Figure 4.21-left).

It is worth noting that with an event being defined as a beam bunch and all tracks being grouped into bunches, an implicit time cut is applied to the second track as it must come from the same bunch as the muon candidate.

**CUT 9: One positive FGD-TPC track**

Events with one and only one positive FGD-TPC track with good quality and starting in FGD1 FV. The track selected in this way defines the proton candidate.

This cut rejects events in which the proton produced in the neutrino-induced CCQE interaction is not well reconstructed (has bad quality), does not reach the TPC (this case is included in the $\mu$TPC-pFGD topology), or is not reconstructed at all (these events correspond to the $\mu$TPC topology). In addition, the background due to interactions occurring outside the FGD1 FV is considerably reduced. The contamination of resonant interactions is still high in the selected sample (see Figure 4.21-right) but it will be reduced by subsequent cuts explained below.

**CUT 10: Common vertex cut**

A safety cut on the distance between the starting points of the muon and proton candidates has been introduced. Thanks to the bunching and to the selection of tracks having their reconstructed start positions in the same detector, the risk of selecting two particles produced in different interactions is negligible. However this cut helps to minimise reconstruction failures and the selection of events with bad reconstructed kinematics.

This cut rejects events in which the distance between the starting point of the two tracks is larger than 50 mm along $x$ or $y$, or larger than 30 mm along $z$. As the cut regions are very poorly populated (see Figure 4.22), the effect of this cut is very small.

---

7In more detail, the track must have more than 18 TPC clusters in the closest TPC to its own start position and the track start position must be reconstructed in FGD1 FV.
4.9. CCQE 2-track sample: $\mu$TPC-pTPC topology

Figure 4.21: Left: Number of reconstructed tracker tracks after all cuts prior to cut 8 have been applied (see Table 4.11). Right: Number of reconstructed positive FGD-TPC tracks with more than 18 reconstructed TPC clusters starting inside the fiducial volume of FGD1 after the tracker track multiplicity cut has been applied. The selected regions are indicated by the arrows.

Figure 4.22: Muon candidate reconstructed start position minus proton candidate reconstructed start position along the three coordinates, after the positive track multiplicity cut (cut 9) has been applied. The distance along $z$ is shown in logarithmic scale. If the distance is not contained in the safety region indicated by the arrows the event is rejected.

**CUT 11: Proton TPC PID cut**

In order to select proton-like particles a cut on the proton TPC PID likelihood of the proton candidate is applied. If the likelihood, $L_p$, is less than 0.5 the event
is rejected:

\[ L_p > 0.5 \]  \hspace{1cm} (4.7)

\( L_p \) is computed according to Eq. 3.3 taking into account four particle types (\( \mu \), \( e \), \( \pi \), \( p \)) and corresponds to the probability (assuming equal priors) for a particle whose momentum and pulls have been measured in each of the three TPCs of being a proton (see Section 3.4.1).

Figure 4.23: Proton TPC PID likelihood of the proton candidate after the common vertex cut has been applied. The arrow indicates the region selected by the proton TPC PID cut.

The cut on \( L_p \) allows to remove the pion background, as shown in Figure 4.23. When the proton TPC PID cut is applied the proton purity (computed as the fraction of selected events whose proton candidate is a true proton) increases by almost 30% (passing from 71.3% to 99.4%).

4.9.1 CCQE efficiency and purity after selection

The CCQE purity and efficiency after each cut are summarized in Figure 4.24 and Table 4.12. As mentioned in Section 4.8, cuts from 1 to 7 are common to the \( \mu \)TPC topology. When requiring two tracker tracks and when selecting the proton candidate the purity decreases a bit and the efficiency drops, as single track CCQE events (included in the \( \mu \)TPC topology) are rejected and background due mainly to resonance production is selected together with the signal. However, as the TPC PID is very effective in separating pions from protons, when applying the proton TPC PID cut the purity rises again up to 59.1% and the efficiency remains almost stable at \( \sim 4\% \).

No sand muons are left at the end of the selection cut chain and the main background is due to resonance production (see Table 4.13).
4.9. CCQE 2-track sample: $\mu$TPC-pTPC topology

<table>
<thead>
<tr>
<th>CUT</th>
<th>CCQE eff (%)</th>
<th>CCQE pur (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>with sand $\mu$</td>
<td>w/o sand $\mu$</td>
</tr>
<tr>
<td>1 good spill and DQ</td>
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<td>2 at least one TPC track</td>
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<tr>
<td>3 FV and track quality</td>
<td>51.6</td>
<td>23.4</td>
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<tr>
<td>4 external veto</td>
<td>50.1</td>
<td>31.2</td>
</tr>
<tr>
<td>5 muon TPC PID</td>
<td>49.6</td>
<td>42.4</td>
</tr>
<tr>
<td>6 one negative FGD-TPC track</td>
<td>49.1</td>
<td>47.4</td>
</tr>
<tr>
<td>7 no Michel electrons</td>
<td>48.6</td>
<td>50.9</td>
</tr>
<tr>
<td>8 two tracker tracks</td>
<td>13.7</td>
<td>48.6</td>
</tr>
<tr>
<td>9 one positive FGD-TPC track</td>
<td>4.7</td>
<td>40.9</td>
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<td>10 common vertex</td>
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<td>41.9</td>
</tr>
<tr>
<td>11 proton TPC PID</td>
<td><strong>3.8</strong></td>
<td><strong>59.1</strong></td>
</tr>
</tbody>
</table>

Table 4.12: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) as a function of the CCQE selection cuts listed in Table 4.11. The values refer to Figure 4.24.

Figure 4.24: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) after each of the CCQE selection cuts listed in Table 4.11. The purity has been computed when sand muons are taken into account (red line) and when they are not (green line). Cuts from 1 to 5 are inclusive CC selection cuts. The numerical results are given in Table 4.12.
4. \( \nu_\mu \) CCQE event selection in the ND280 tracker

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<tr>
<th>background type</th>
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<th>bkg fraction (%)</th>
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<td>NC</td>
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</tr>
<tr>
<td>out FGD1 FV</td>
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<td>5.2</td>
</tr>
<tr>
<td>sand ( \mu )</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>other</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>40.9</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.13: Background summary. First column (tot fraction): fraction of selected events which are background to CCQE interactions. Second column (bkg fraction): fraction of background due to each background type. Background types considered: resonance production (RES); deep inelastic scattering (DIS); coherent pion production (COH); neutral current interactions (NC); events whose true start position is not in FGD1 FV (out FGD1 FV); sand muons (sand \( \mu \)); any other interaction type (other).

4.10 CCQE 2-track sample: \( \mu \)TPC-pFGD topology

Although the proton candidate has a different topology in the \( \mu \)TPC-pFGD and \( \mu \)TPC-pTPC samples, the muon topology is the same: a negative TPC-FGD muon-like track starting in FGD1. In addition, both samples contain 2-track events and in both cases the CC1\( \pi \) background can be reduced by tagging the presence of Michel electrons. Thus, the selection algorithms of the \( \mu \)TPC-pFGD and \( \mu \)TPC-pTPC topologies share a few cuts (from 1 to 8 in Tables 4.11 and 4.14). Furthermore, the \( \mu \)TPC-pFGD selection uses a cut similar to the common vertex cut of the \( \mu \)TPC-pTPC topology in order to minimise reconstruction failures.

The proton candidate selection for events with \( \mu \)TPC-pFGD topology has specific cuts different from the ones used in the other CCQE samples. In more detail, events with a FGD-only track completely contained in FGD1 are selected; the FGD PID information is used to select proton-like particles; an additional check on the end position of the proton candidate must be done in order to ensure that it stopped in the FGD1 volume. This last requirement is mandatory for a correct estimation of the momentum by range (see Section 4.4.1) of the proton candidate, but it can be avoided in analyses not using the proton kinematics.

The selection cuts are summarized in Table 4.14. Cuts from 1 to 5 aim at selecting an inclusive CC sample (see Section 4.7); 6 and 7 are CCQE specific cuts and have been extensively explained in Section 4.8; cut 8 is common to the \( \mu \)TPC-pTPC topology and has been explained in Section 4.9. The remaining
### 4.10. CCQE 2-track sample: $\mu$TPC-pFGD topology

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<tr>
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</tr>
</thead>
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<td>1.</td>
<td>good spill and DQ</td>
</tr>
<tr>
<td>2.</td>
<td>at least one TPC track</td>
</tr>
<tr>
<td>3.</td>
<td>fiducial volume and track quality</td>
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<tr>
<td>4.</td>
<td>external veto</td>
</tr>
<tr>
<td>5.</td>
<td>muon TPC PID</td>
</tr>
<tr>
<td>6.</td>
<td>one negative FGD-TPC track</td>
</tr>
<tr>
<td>7.</td>
<td>no Michel electrons</td>
</tr>
<tr>
<td>8.</td>
<td>two tracker tracks</td>
</tr>
<tr>
<td>9.</td>
<td>one FGD-only track</td>
</tr>
<tr>
<td>10.</td>
<td>common vertex</td>
</tr>
<tr>
<td>11.</td>
<td>proton FGD PID</td>
</tr>
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<td>12.</td>
<td>stopping proton</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>$\mu$TPC-pFGD CCQE selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. One FGD-only track</td>
</tr>
</tbody>
</table>

Table 4.14: List of CCQE selection cuts for the $\mu$TPC-pFGD topology. Cuts from 1 to 5 aim at selecting an inclusive CC sample, 6 and 7 are CCQE specific cuts, from 8 to 12 are $\mu$TPC-pFGD specific cuts.

Cuts, specific of the $\mu$TPC-pFGD topology, are discussed below.

**CUT 9: One FGD-only track**

This topology requires the proton candidate not to cross the TPC. As in general the proton does not have enough energy to leave the FGD, events with one FGD-only track in FGD1 are selected.

As the TPC reconstruction is done first, the FGD reconstruction strongly depends on it. In particular, if during the TPC-FGD matching process (see Section 3.4.2) some hits of the FGD-only track are incorrectly associated with a nearby FGD-TPC track, the reconstructed start position of the FGD-only track can be shifted towards the FGD border, as shown schematically in Figure 4.25. In order to take into account this effect, the start position of the FGD-only track is not required to be inside the FGD1 FV but just inside the FGD1 volume.

Figure 4.26 shows the number of events with a single FGD-only track (1) or none (0). As cut 8 requires the presence of only two tracker tracks, there cannot be more than one FGD-only track. It is worth noting that part of the CCQE events rejected by this cut correspond to the second track being a FGD-TPC track and are included in the event sample with $\mu$TPC-pTPC topology.
Figure 4.25: Schematic drawing showing how the reconstructed position of a FGD-only track can be moved towards the border of the FGD due to incorrect hit matching during the reconstruction process. Some hits of the FGD-only track can be incorrectly associated with a nearby FGD-TPC track, producing a shift of the reconstructed start position of the FGD-only track. The analogous case for a FGD track starting in FGD but not completely contained is shown in Figure 4.36.

Figure 4.26: Number of FGD-only tracks after events with two tracker tracks have been selected. The arrows indicate the selected regions.

CUT 10: Common vertex cut

As for the $\mu$TPC-pTPC topology (see Section 4.9), a cut on the distance between the starting points of the muon and proton candidates has been introduced. Figure 4.27 shows the corresponding distributions, which are wider than those for the $\mu$TPC-pTPC topology. In particular, the spatial resolution in $x$ and $y$ is a bit worse in this topology because FGD-only tracks are in general less collimated with the neutrino beam than FGD-TPC tracks and the extrapolation to a vertical plane has a larger error. For this reason a looser cut has been chosen: events in which the distance between the starting points of the two tracks is larger than
100 mm along $x$ or $y$, or bigger than 50 mm along $z$, are rejected.

The shift of the distance distribution along $z$ towards negative values is due to incorrect hit matching during the reconstruction process (see Section 3.4.2), which causes a shift of the reconstructed start position of the FGD-only track along $z$ (see Figure 4.25). As the shift can be equally towards bigger or smaller values with respect to the position in $x$ and $y$, two peaks are visible along the $x$ and $y$ axes.

Figure 4.27: Muon candidate reconstructed start position minus proton candidate reconstructed start position along the three coordinates, after cuts from 1 to 9 (see Table 4.14) have been applied. The distance along $z$ is shown in logarithmic scale. If the distance is not contained in the region indicated by the arrows, the event is rejected.

CUT 11: Proton FGD PID cut

The particle identity of the proton candidate is checked by using the FGD PID (see Section 3.4.2). Only events whose proton candidate satisfies the following condition on the proton FGD pull are selected:

$$\text{Pull}_p > -4$$

$\text{Pull}_p$, defined according to Eq. 3.4, is shown in Figure 4.28. Assuming that the track loses all its energy in FGD1, $\text{Pull}_p$ is expected to be a Gaussian distribution with zero mean and unit standard deviation for true protons. The small proton
peak at negative $Pull_p$ values is due to FGD-only tracks whose true start or end position is not inside FGD1. As the FGD PID algorithm was optimized for tracks depositing all their kinetic energy in the FGD, the $Pull_p$ distribution is not expected to be centered at zero for protons not fully contained in FGD1.

![Proton candidate FGD proton pull distribution after cuts from 1 to 10 (see Table 4.14) have been applied. The arrow indicates the region selected by the proton FGD PID cut.](image)

The $\mu^-$ background visible in Figure 4.28 is due to “broken-tracks”, i.e. tracks that have been broken into two or more pieces due to a reconstruction failure and whose pieces have been reconstructed as single separate tracks (see Figure 4.29). Both the muon and proton candidates are in this case two reconstructed segments produced by the same particle. This cut removes a big fraction of events whose proton candidate is not a true proton. In particular, almost all the pion and muon background is rejected, as shown in Figure 4.28-left. The proton purity increases by $\sim 20\%$ (passing from 72.6\% to 92.7\%). It is also worth noting that most of the rejected events correspond to OOFV interactions (see Figure 4.28-right).

**CUT 12: Stopping proton cut**

As explained in Section 4.4.1, the momentum by range reconstruction algorithm works correctly only for particles losing all their kinetic energy inside the active part of the detector. To ensure that the proton candidate stops inside the FGD1, it is required to have its end position inside a reduced FGD1 FV volume, defined in Table A.1. Along the $x$ and $y$ coordinates this reduced volume coincides with the FGD1 FV defined in Table 4.5. Along $z$ two scintillator layers are removed (1 would not be enough due to the FGD hit inefficiency). Figure 4.30 shows the proton candidate end position distribution along the three coordinates for not
4.10. CCQE 2-track sample: $\mu$TPC-pFGD topology

The largest population corresponds to the outermost layers in the three coordinates. This additional cut is recommended only if one wants to make use of the proton kinematics for further studies.

4.10.1 CCQE efficiency and purity after selection

The CCQE purity and efficiency after each cut are summarized in Figure 4.31 and Table 4.15. As mentioned above, the first eight cuts are common with the $\mu$TPC-pTPC topology. Among the cuts specific of the $\mu$TPC-pFGD topology, the most effective one is the FGD PID cut (it improves the CCQE purity by $\sim 10\%$). As it reduces the background of pions, most events coming from resonance production and deep inelastic scattering are rejected by this cut, although a considerable amount of this background is still present at the end of the selection. After all selection cuts have been applied, the sand muon background is completely removed (see Table 4.16).

Requiring the proton candidate to stop inside the detector (cut 12) produces a drop in the efficiency while the gain in purity is marginal. As mentioned in Section 4.10, this cut is not needed if the proton kinematics is not used. The final

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4.11 CCQE 2-track sample: $\mu$FGD-pTPC topology

The selection criterion of events with $\mu$FGD-pTPC topology is not based on the inclusive CC selection described in Section 4.7, as it was for the other CCQE topologies, because in the $\mu$FGD-pTPC topology the muon candidate is a FGD track. In addition, as the reconstruction of tracks containing TPC segments is more precise, the reconstructed vertex will be defined in this case by the proton candidate (instead of the muon candidate as it is for the other topologies).

Table 4.17 lists the selection cuts for this topology. The first two cuts are common to all topologies (they are explained in Section 4.6). Cuts from 3 to 6 are similar to the CC ones but are applied to the proton candidate instead of the muon candidate. In addition only events with two reconstructed tracks in the tracker are accepted, as for the other 2-track topologies. Cuts from 8 to 12 aim at selecting the muon candidate among all FGD tracks starting in the FGD1 volume. If the FGD track is completely contained in FGD1 it is required to be
### 4.11. CCQE 2-track sample: $\mu$FGD-pTPC topology

<table>
<thead>
<tr>
<th>CUT</th>
<th>CCQE eff (%)</th>
<th>CCQE pur (%)</th>
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<td>1 good spill and DQ</td>
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<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>64.3</td>
<td>—</td>
</tr>
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<td>51.6</td>
<td>23.4</td>
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<td>31.2</td>
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Table 4.15: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) as a function of the CCQE selection cuts listed in Table 4.14. The values refer to Figure 4.31.

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<tr>
<th>background type</th>
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<th>bkg fraction (%)</th>
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</tr>
<tr>
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</table>

Table 4.16: Background summary. First column (tot fraction): fraction of selected events which are background to CCQE interactions. Second column (bkg fraction): fraction of background due to each background type. Background types considered: resonance production (RES); deep inelastic scattering (DIS); coherent pion production (COH); neutral current interactions (NC); events whose true start position is not in FGD1 FV (out FGD1 FV); sand muons (sand $\mu$); any other interaction type (other).

long and the FGD PID is used to select muon-like particles. A common vertex cut similar to the one of the other 2-track topologies is applied too. Finally, an additional check on the end position of the muon candidate (analogous to cut 12 in Section 4.10) is done to ensure that the momentum by range is correct (see
Figure 4.31: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) after each of the CCQE selection cuts listed in Table 4.14. The purity has been computed when sand muons are taken into account (red line) and when they are not (green line). Cuts from 1 to 5 are inclusive CC selection cuts. The numerical results are given in Table 4.15.

Section 4.4.1). It should be noticed that this last cut is mandatory for events with this topology as the muon kinematics is needed to reconstruct the neutrino energy (see Section 6.2). Cuts from 3 to 12 are discussed below.

<table>
<thead>
<tr>
<th>CUT</th>
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<td>fiducial volume and track quality</td>
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<td>external veto</td>
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<td>one positive FGD-TPC track</td>
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<td>7</td>
<td>two tracker tracks</td>
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<td>8</td>
<td>one FGD track</td>
</tr>
<tr>
<td>9</td>
<td>long FGD track</td>
</tr>
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<td>10</td>
<td>muon FGD PID</td>
</tr>
<tr>
<td>11</td>
<td>common vertex</td>
</tr>
<tr>
<td>12</td>
<td>stopping muon</td>
</tr>
</tbody>
</table>

Table 4.17: List of CCQE selection cuts for the 2-track sample, $\mu$FGD-pTPC topology.
4.11. CCQE 2-track sample: $\mu$FGD-$p$TPC topology

CUT 3: Fiducial volume and TPC track quality cuts

The fiducial volume and the TPC track quality cuts have the same structure as the corresponding ones used for the CC selection (see Section 4.7) but aim at selecting the proton candidate instead of the muon candidate. In more detail, the proton candidate is defined as the highest momentum positive (HMP) track in the event, chosen among all positive FGD-TPC tracks having their start position reconstructed in the fiducial volume of FGD1 (see Table 4.5) and having more than 18 TPC clusters (corresponding to a half of the MM module) in the closest TPC to their own start position (TPC2 in general, as shown in Figure 4.32-left-bottom). The reconstructed start position of the proton candidate defines the reconstructed vertex of the event.

As shown in Figure 4.32, the proton candidate is usually forward going and only a small fraction of the selected tracks have less than 19 clusters. The effect of the fiducial volume cut is shown in Figure 4.33. At this level there is a large background contribution from interactions occurring outside the FGD1 FV.

Figure 4.32: Left: Proton candidate reconstructed polar angle (top) and closest TPC (bottom). Right: Distribution of reconstructed TPC2 clusters for the HMP FGD-TPC track in the event. The two peaks at 36 and 72 clusters correspond to tracks traversing, respectively, one or two entire MM modules. Cuts 1 and 2 of Table 4.17 plus the fiducial volume cut have been applied. The TPC track quality cut accepts only events with more than 18 reconstructed clusters, as indicated by the arrow.
Figure 4.33: Reconstructed position of the HMP track along the $x$, $y$, $z$ axes before (left) and after (right) the fiducial volume cut (the quality cut has been applied in both cases). The FGD segmentation is clearly visible along $z$. The arrows and the red contour indicate the FGD1 fiducial volume regions.

CUT 4: External veto cut

This cut is analogous to the one explained in Section 4.7, with the muon candidate replaced by the proton candidate. Rejected events correspond mainly to interactions occurring outside the FGD1 FV, as shown in Figure 4.34.
4.11. CCQE 2-track sample: $\mu$FGD-pTPC topology

Figure 4.34: Distance along the z axis between the reconstructed start position of the proton candidate and that of the highest momentum TPC track in FGD1 volume other than the proton candidate in linear (left) and logarithmic (right) scale. Cuts 1, 2 and 3 of Table 4.17 have been applied. The region indicated by the arrow is accepted by the external veto cut.

**CUT 5: Proton TPC PID cut**

In order to select proton-like particles the TPC PID (see Section 3.4.1) is used. A cut on the proton TPC PID likelihood, analogous to the one used to select proton-like particles in events with $\mu$TPC-pTPC topology, is applied: if the likelihood is smaller than 0.5 the event is rejected (see Eq. 4.7). As shown in Figure 4.35, thanks to this cut the background of other particle types is significantly reduced and the proton purity increases by 43% (passing from 55.0% to 99.3%).

Figure 4.35: Proton TPC PID likelihood of the proton candidate after all cuts prior to the TPC PID cut have been applied (see Table 4.17). The arrow indicates the region accepted by the proton TPC PID cut.


**CUT 6: One positive FGD-TPC track**

To reduce the background due to interactions in which more than one positive track is expected in the final state (like resonance production and deep inelastic scattering), events with only one positive FGD-TPC track in the FGD1 FV are selected\(^9\). As shown in Figure 4.37-left, the fraction of CCQE interactions is negligible when more than one track is reconstructed.

**CUT 7: Two tracker tracks**

Only events with two tracks in the tracker are selected. The same cut is applied also for selecting events with \(\mu\)TPC-pTPC and \(\mu\)TPC-pFGD topologies (see Section 4.9 and 4.10).

When more than two tracker tracks are reconstructed the contamination due to other kind of interactions and to interactions occurring outside the FGD1 fiducial volume is very high, as shown in Figure 4.37-middle. If the proton candidate is the only tracker track to be reconstructed the background fraction is even bigger, as expected because in a CCQE interaction normally the muon is energetic enough to be reconstructed. In this case the fraction of neutral current interactions is significant.

Analogously to the other 2-track topologies, the requirement of two tracker tracks in the event implies an implicit time cut on the second track as an event is defined as a beam bunch and both the selected tracks must be in the same bunch. In addition, it implies an implicit constraint on the number of FGD tracks, as events with more than one of such tracks are rejected.

**CUT 8: One FGD track**

Even if the previous cut implicitly requires no more than one FGD track, it does not imply the presence of such FGD track, as the second track (besides the proton candidate) could be another FGD-TPC track. Therefore, an explicit cut is needed: if the second selected track is a FGD track starting in the FGD1 volume (either fully contained in FGD1 or not), the event is accepted. As for the \(\mu\)TPC-pFGD topology, the start position of the FGD track is required to be inside the FGD1 volume but not necessarily inside the fiducial volume in order to take into account the reconstruction issue discussed in Section 4.10 (see Figures 4.36, 4.25), which can cause the reconstructed start position of FGD tracks to be shifted towards the FGD border. The FGD track selected in this way defines

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\(^9\)In more detail, events with only one track having more than 18 TPC clusters in the closest TPC to its own start position and having the start position reconstructed inside the FGD1 FV are selected. Thus, the allowed positive track coincides with the proton candidate.
the muon candidate. In all other cases the event is rejected as it is likely that the second track does not correspond to the muon candidate or is badly reconstructed or the event corresponds to a different topology. In particular, if the second track is a negative FGD-TPC track with good quality and its start position is in FGD1 FV, the event has already been taken into account in the \( \mu \text{TPC-pTPC} \) topology.

Figure 4.37 right shows the FGD track multiplicity before the application of this cut.

Figure 4.36: Schematic drawing showing how the reconstructed position of a FGD track starting in FGD but non fully contained can be moved towards the border of the FGD due to incorrect hit matching during the reconstruction process. Some hits of the FGD track can be incorrectly associated with a close FGD-TPC track, producing a shift of the reconstructed start position of the FGD track. The analogous case for a FGD-only track is shown in Figure 4.25.

Figure 4.37: Left: Multiplicity of reconstructed positive tracks with more than 18 reconstructed TPC clusters in the closest TPC and having their reconstructed start position in the FGD1 FV. Cuts from 1 to 5 (see Table 4.17) have been applied. Middle: Multiplicity of reconstructed tracker tracks after the positive track multiplicity cut. Right: Number of FGD tracks after events with two tracker tracks have been selected. The arrows indicate the selected regions.
CUT 9: Long FGD track

Most muons produced in neutrino-induced CCQE interactions at T2K energies are MIP’s (i.e. have mean energy loss rates close to the minimum). Therefore, they tend to travel long distances. For this reason the muon candidate is required either to escape the FGD1 (in this case it can leave the detector and contains segments of ECAL and/or SMRD) or, when it is a FGD-only track, to be long enough (>500 mm). No cut on the length of FGD tracks exiting the FGD1 is applied since they are long by definition.

Figure 4.38 shows the muon candidate angular distribution before the track length cut has been applied. The two cases in which the track is fully contained or escapes from FGD1 have been separated. The muon purity is equal to 43.7% when the muon candidate is a FGD-only track and doubles (85.2%) when it exits the FGD. This is expected because, as mentioned above, the muon is likely to travel a long distance. The high contamination of protons (due mainly to short tracks coming from interactions occurring outside the FGD1 FV and corresponding to broken tracks - see Figure 4.29) in the sample of FGD-only tracks (Figure 4.38, bottom) is significantly reduced by requiring FGD-only tracks to be long, as shown in Figure 4.39. Although a big fraction of true muons and true CCQE interactions is removed as well, the amount of removed background is bigger than that of signal.

CUT 10: Muon FGD PID cut

If the muon candidate is fully contained in FGD1, the FGD PID (see Section 3.4.2) can be reliably used to check the particle identity and select muon-like particles. Only events whose muon candidate has a muon FGD pull bigger than $-5$ are selected:

$$Pull_\mu > -5$$ (4.9)

$Pull_\mu$ is defined according to Eq. 3.4 and is expected to be a Gaussian distribution with zero mean and unit standard deviation for true muons losing all their kinetic energy in FGD1.

Figure 4.40 shows the FGD muon pull distribution for long FGD-only tracks. As most of the contamination of particles other than muons was removed by requiring the FGD-only track to be long (cut 9), the muon FGD PID cut has a small effect. However, it allows to remove part of the residual background due to other particle types and increases the muon purity by 5% for FGD-only tracks (it passes from 84.9% to 89.9%).
CUT 11: Common vertex cut

As for the other 2-track topologies (see Sections 4.9 and 4.10), a cut on the distance between the reconstructed start positions of the muon and proton candidates has been introduced. Events in which the distance is bigger than 200 mm along $x$ or $y$, or bigger than 60 mm along $z$ are rejected (see Figure 4.41).
Figure 4.40: Muon candidate FGD muon pull distribution after cut 9 of Table 4.17 has been applied. The arrow indicates the accepted region.

Figure 4.41: Muon candidate reconstructed start position minus proton candidate reconstructed start position along the three coordinates, after cuts from 1 to 10 (see Table 4.17) have been applied. The arrows indicate the accepted region.

CUT 12: Stopping muon cut

As for the proton candidate in the $\mu$TPC-pFGD topology, in order to make the momentum by range reconstruction algorithm (see Section 4.4.1) work correctly, the FGD track must stop inside the active region of the ND280 detector. To ensure that this condition is satisfied a requirement on the reconstructed end
position of the muon candidate is done: FGD-only tracks are required to have their reconstructed end position inside the reduced FGD1 volume defined in Table [A.1] while FGD tracks escaping FGD1 must stop inside the reduced Barrel ECAL or SMRD volumes defined in Tables [A.2] and [A.3]. The reduced volumes remove the last layers of the FGD1, ECAL and SMRD because there is a probability that some hits have been lost, causing a track stopping outside the detector to have its end position reconstructed inside.

Figure 4.42 shows the muon candidate end position after the stopping muon cut has been applied.

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Figure 4.42: Muon candidate reconstructed end position along the three coordinates after cut 12 was applied, in the case in which the muon candidate is a FGD track with its start position in FGD1 but not completely contained (left) and when it is a FGD-only track completely contained in FGD1 (right).
4.11.1 CCQE efficiency and purity after selection

The CCQE purity and efficiency after each cut are summarized in Figure 4.43 and Table 4.18. The final efficiency is 6.8% while the purity is 76.7%. Cuts 7 and 9 are the most effective ones (the purity increases by $\sim20\%$ and $\sim27\%$, respectively) as the muon produced in a neutrino-induced CCQE interaction usually is energetic enough to be reconstructed and travels a long distance, as already mentioned in Section 4.11. On the other hand, the efficiency drops when applying the track multiplicity cuts (cuts 7 and 8) because CCQE events with both the muon and the proton reconstructed in TPC (i.e. events with $\mu$TPC-pTPC topology) as well as CCQE events in which proton re-interactions produced additional particles are rejected. The last cut has a negligible effect on the purity but, as mentioned in Section 4.11, it is needed for the momentum by range calculation.

The main background to CCQE interactions at the end of the selection is due to interactions occurring outside the FGD1 FV and resonance production. Sand muons are completely removed (see Table 4.19).

![Figure 4.43: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) after each of the CCQE selection cuts listed in Table 4.17. The purity has been computed when sand muons are taken into account (red line) and when they are not (green line). The numerical results are given in Table 4.18.](image-url)
### 4.12 Selection efficiency

Summary plots comparing the efficiencies of the selected CCQE samples as a function of the true values of simulated kinematic variables are shown in Figures

<table>
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<th>CUT</th>
<th>CCQE eff (%)</th>
<th>CCQE pur (%)</th>
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<tr>
<td>good spill and DQ</td>
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<td>—</td>
</tr>
<tr>
<td>at least one TPC track</td>
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<tr>
<td>stopping muon</td>
<td>1.8</td>
<td><strong>76.7</strong></td>
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Table 4.18: CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) as a function of the CCQE selection cuts listed in Table 4.17. The values refer to Figure 4.43.

<table>
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<th>bkg fraction (%)</th>
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</tr>
<tr>
<td>COH</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>NC</td>
<td>2.3</td>
<td>10.0</td>
</tr>
<tr>
<td>out FGD1 FV</td>
<td>9.2</td>
<td>39.7</td>
</tr>
<tr>
<td>sand µ</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>other</td>
<td>1.0</td>
<td>4.2</td>
</tr>
<tr>
<td>TOTAL</td>
<td><strong>23.3</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 4.19: Background summary. First column (tot fraction): fraction of selected events which are background to CCQE interactions. Second column (bkg fraction): fraction of background due to each background type. Background types considered: resonance production (RES); deep inelastic scattering (DIS); coherent pion production (COH); neutral current interactions (NC); events whose true start position is not in FGD1 FV (out FGD1 FV); sand muons (sand µ); any other interaction type (other).
The overall efficiency of all the samples together is shown too (black points). In order to get bins with similar statistics, the following binnings have been chosen:

- \{0, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1250, 1500, 2000, 3000, 5000\} for momentum (in MeV/c) and neutrino energy (in MeV);
- \{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.25, 1.5, 2\} for transferred quadri momentum (in GeV$^2$/c$^4$);
- \{0.000, 0.142, 0.200, 0.284, 0.348, 0.403, 0.451, 0.555, 0.644, 0.795, 0.927, 3.142\} for the polar angle (in rad).

Due to the difficulties in reconstructing the proton produced in a CCQE interaction (as the proton has high ionization rate, it tends to travel a short distance in the detector and most times it does not satisfy the minimum requirements to be reconstructed), the 1-track sample has in general higher selection efficiency than the 2-track samples (see Figures 4.44, 4.45, 4.48, 4.49).

Muon tracks with high momentum are favoured in the topologies in which the muon track is required to reach the TPC (the efficiency is peaked around 700 MeV/c in the $\mu$TPC sample and becomes basically flat above 1 GeV/c in the $\mu$TPC-pTPC and $\mu$TPC-pFGD samples), while in the $\mu$FGD-pTPC topology the efficiency is peaked at low momentum (about 300 MeV/c) as the muon track is required to not cross the TPC (see Figure 4.44). Forward going muon tracks with small angles are favoured in all samples (see Figure 4.45).

The efficiency is lower at low momenta, where it is difficult to reconstruct the proton due to its high ionization rate. The lower proton momentum threshold in the $\mu$TPC-pFGD topology (due to the fact that the reconstruction algorithm requires an higher number of FGD hits for fully contained FGD tracks than for FGD-TPC tracks to be reconstructed) is clearly visible (see Figure 4.46). The efficiency drops in the last angular bin (containing backwards going proton tracks) in the topologies with the proton reconstructed in the TPC (as the proton has to reach the TPC, it has to be forward going), while it does not for events with $\mu$TPC-pFGD topology, as in this case the proton is fully contained in the FGD and there are no constraints due to the detector geometry (see Figure 4.47).

The efficiency is higher at high true neutrino energy in the topologies with the muon track in the TPC, while smaller values of the neutrinos energy are favoured in the $\mu$FGD-pTPC topology (see Figure 4.48).

The efficiency distribution as a function of the transferred quadri-momentum, $Q^2$, is shown in Figure 4.49. Small $Q^2$ values are favoured by the $\mu$TPC topology. For the 2-track samples with the muon reconstructed in the TPC the efficiency as a function of $Q^2$ is peaked around 0.3 GeV$^2$/c$^4$, while the $\mu$FGD-pTPC topology
favours higher $Q^2$ values (the peak is around $0.5 \text{ GeV}^2/c^4$). In these first three cases the efficiency becomes stable at high $Q^2$ values, while it seems to decrease for events with $\mu$FGD-TPC topology. However, it is difficult to conclude as the last sample has small statistics in this region.

The overall efficiency is dominated by the 1-track sample, as it is the one with higher statistics.

Figure 4.44: Selection efficiency as a function of the true muon momentum for all topologies together (black) and for the $\mu$TPC (pink), $\mu$TPC-TPC (red), $\mu$TPC-pFGD (green), $\mu$FGD-TPC (blue) individual samples.

Figure 4.45: Selection efficiency as a function of the true muon polar angle for all topologies together (black) and for the $\mu$TPC (pink), $\mu$TPC-TPC (red), $\mu$TPC-pFGD (green), $\mu$FGD-TPC (blue) individual samples.
Figure 4.46: Selection efficiency as a function of the proton muon momentum for all topologies together (black) and for the \( \mu \text{TPC} \) (pink), \( \mu \text{TPC-TPC} \) (red), \( \mu \text{TPC-FGD} \) (green), \( \mu \text{FGD-TPC} \) (blue) individual samples.

Figure 4.47: Selection efficiency as a function of the true proton polar angle for all topologies together (black) and for the \( \mu \text{TPC} \) (pink), \( \mu \text{TPC-TPC} \) (red), \( \mu \text{TPC-FGD} \) (green), \( \mu \text{FGD-TPC} \) (blue) individual samples.
4.12. Selection efficiency

Figure 4.48: Selection efficiency as a function of the true neutrino energy for all topologies together (black) and for the $\mu$TPC (pink), $\mu$TPC-pTPC (red), $\mu$TPC-pFGD (green), $\mu$FGD-pTPC (blue) individual samples.

Figure 4.49: Selection efficiency as a function of the true transferred quadri-momentum for all topologies together (black) and for the $\mu$TPC (pink), $\mu$TPC-pTPC (red), $\mu$TPC-pFGD (green), $\mu$FGD-pTPC (blue) individual samples.
4. $\nu_\mu$ CCQE event selection in the ND280 tracker
Chapter 5

Detector systematic uncertainties

In this chapter the systematic uncertainties relevant for the analysis presented in this thesis (detector and beam flux systematics) are discussed. As no cross-sections will be calculated in this thesis work, cross-section modelling uncertainties are not taken into account. A brief description of the systematics calculation and an overview of the error propagation methods are presented.

The work presented here is based on the internal technical note T2K-TN-152 \[152\] and the included references, which incorporate studies done by many groups inside the T2K collaboration.

5.1 Detector systematics overview

The relevant subdetectors and the corresponding systematic uncertainties affecting the analysis presented in this thesis are summarized in Figure 5.1. Propagating the systematics consists in studying the effect of those inaccuracies on the final number of selected events (integrated or in bins of a given observable). Ideally, one should study the effect of varying basic parameters in the MC (such as the gas density or pressure in the TPC, or the light speed in scintillators) in order to take properly into account the correlations between all systematic parameters. Sometimes this is possible, as in the following cases:

- The model of pion secondary interactions (SI) is only approximate in the MC. The uncertainties on pion SI cross-sections must be properly propagated, as they will alter the event topology and kinematics, and therefore the selection.
Figure 5.1: Sketch of the sub-detectors relevant for this analysis and the corresponding associated systematics.

- The density of the FGD1 detector, which affects directly the FGD1 mass and therefore the neutrino interaction rate, is not known with infinite precision. Thus, its uncertainty must be taken into account and propagated to the final number of selected events.

However, this procedure is in general very complicated, as it requires a very detailed knowledge of the detector and all physics processes involved, in both data and MC. Thus, in practice, some derived parameters (such as reconstruction efficiencies or the mean and resolution for some reconstructed observables) which affect directly the event selection can be computed for data and MC and used to propagate the systematic uncertainties.

As mentioned above, one of the effects of an imperfect MC can be a difference in the reconstruction efficiency, both at track and event level, which, in general, will affect directly the number of events passing the selection cuts. For example, dissimilarities in the TPC or FGD tracking efficiency or in the TPC-FGD matching efficiency in data and MC will result in a different number of events passing the track multiplicity cuts in the two samples. In the same way, the efficiency of selecting a sand or cosmic muon as the muon candidate (these are examples of event-level reconstruction efficiencies) might be different in data and MC.

MC imperfections can also produce a different mean and resolution of reconstructed observables with respect to data, as in the case of the momentum scale and resolution. As will be discussed below, if the TPC gas density is not the
same in data and MC there will be dissimilarities in the space point resolution, resulting in a different momentum resolution. The gas density could also have an effect on the mean and resolution of the mean energy loss of charged particles passing through the TPCs, which would alter the effect of the TPC PID cuts. If an observable is reconstructed with a different mean or resolution in data and MC, two effects may arise:

- As some cuts depend on the value of the reconstructed observable, their effect can change. For example, the TPC and FGD PID cuts select muon and proton-like tracks by using the pull values for different hypotheses (see Sections 3.4.1 and 3.4.2). A different pull mean or width in data and MC will result in a different effect of the TPC and FGD PID cuts.

- The variation of a reconstructed observable can produce a migration of events from one bin to another in differential distributions. For example, the muon and proton candidate momentum distributions in the MC will be altered by the momentum scale, momentum resolution and magnetic field distortion systematics.

In the following sections the systematic error sources are grouped according to the detector they are related to (TPC, FGD or both) or to the source of the uncertainty (background and basic MC modeling parameter). A brief overview of the method and control samples used to compute each systematics is provided. Once the source of systematic error is understood, the systematics has to be propagated. Several methods, depending on the nature of the uncertainties, have been used to propagate the systematics:

- **efficiency-like method** (see Section 5.1.1), used for propagating the systematics associated with track-level reconstruction efficiencies;

- **reconstructed observable variation method** (see Section 5.1.2), used to propagate the systematics associated with differences in mean or resolution for some reconstructed observables;

- **normalisation method** (see Section 5.1.3), used to propagate all event-level efficiency uncertainties, the pion SI and FGD mass systematics.

As will be explained below, systematics using the reconstructed observable variation method are propagated repeating the selection several times for different variations of the observable. In the other two methods only an event weight is applied at the end of the selection.

In all cases a Probability Density Function (pdf) must be assumed: all systematic sources are assumed to be Gaussian except the B field distortions, for
which a uniform PDF is used. Table 5.1 gives a list of the systematic uncertainties considered as well as the corresponding error propagation model and probability density function (pdf) and whether a correction has been applied or not\(^1\) (see Sections 5.1.2 and 5.1.3).

In the following, the relative systematic error distributions are shown as a function of the muon and proton candidates’ momentum. In order to get bins with similar statistics, the following momentum binning (in MeV/c) is used:

- \{0, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1250, 1500, 2000, 3000, 5000\}.

It is worth noting that the muon and proton candidate momenta are computed by range for events with \(\mu\)FGD-pTPC and \(\mu\)TPC-pFGD topologies, respectively.

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\(^1\)When a discrepancy between data and MC is observed in the resolution or in the mean value of the observable, a correction to take into account this difference is applied when the systematics is propagated.
Table 5.1: Systematic error propagation model and probability density function (pdf) used for each of the systematic uncertainties considered [152]. In the last column it is indicated whether a correction is applied when the systematics is propagated.
5. Detector systematic uncertainties

5.1.1 Efficiency-like systematics propagation method

The way efficiency-like systematics are computed is based on studies comparing data and MC predictions in well known control samples. Tracking and matching efficiencies can be easily computed using the redundancy between detectors. For example, the TPC2 track efficiency can be computed using tracks with segments in FGD1 and FGD2. Similarly, the FGD1 track efficiency can be computed using tracks with segments in TPC1 and TPC2. As these special requirements in general are not satisfied in the analysis sample, control samples are necessary. As will be shown below, a very useful control sample is the one of throughgoing muons, consisting of events in which a single muon track crosses the entire tracker. These muons, emerging from interactions in the sand surrounding the detector (sand muons), in the P0D or in the magnet, cover a limited phase space (in general they have small angle and high energy). Furthermore, as only a single track is present in those events, the effect of other tracks that may vary the efficiency cannot be taken into account (this will be the case in three of the CCQE topologies under study). For these reasons it is possible that the efficiencies computed using those control samples do not correspond to the ones of the analysis samples. Thus, a model to extrapolate the control sample efficiency to the analysis sample is needed. The simplest model is the one assuming that the ratio between the efficiencies in data and MC is the same in both the analysis and control samples. This is a reasonable assumption and will be used in this chapter. The efficiency in the MC analysis sample can be computed using the truth information (given a true GEANT4 trajectory, it is always possible to know whether it has been reconstructed or not), while the predicted efficiency in the analysis data sample can be computed as follows:

$$
\varepsilon_{data} = \frac{\varepsilon_{CS}^{data}}{\varepsilon_{CS}^{MC}} \varepsilon_{MC}
$$

(5.1)

where $\varepsilon_{CS}^{data}$ and $\varepsilon_{CS}^{MC}$ are efficiencies in the control samples and $\varepsilon_{MC}$ is the efficiency in the MC analysis sample. The statistical error of the efficiency computed using the control samples ($\sigma_{\varepsilon_{data}}^{CS}$ and $\sigma_{\varepsilon_{MC}}^{CS}$ for data and MC, respectively) must be taken into account when propagating the systematic error. Thus, the variation for the predicted data efficiency ($\varepsilon'_{data}$) is given by:

$$
\varepsilon'_{data} = \frac{\varepsilon_{CS}^{data} + \delta_{data} \cdot \sigma_{\varepsilon_{data}}^{CS}}{\varepsilon_{CS}^{MC} + \delta_{MC} \cdot \sigma_{\varepsilon_{MC}}^{CS}}
$$

(5.2)

where $\delta_{data}$ and $\delta_{MC}$ are the variations in number of standard deviations in the data and MC control samples, respectively, and can assume both positive and negative values.
In order to convert the track-level efficiencies mentioned above into event-level efficiencies, which could be directly applied as event weights, the following method is used. For each MC event a loop over all relevant GEANT4 truth trajectories is done. If the trajectory is successfully reconstructed it contributes to the efficiency calculation and therefore it is weighted by the ratio between data and MC efficiencies, in such a way that the corrected efficiency is the one of the data. The weight to be applied in this case is:

$$W_{\text{eff}} = \frac{\varepsilon'_{\text{data}}}{\varepsilon_{\text{MC}}}$$  \hspace{1cm} (5.3)

where $\varepsilon'_{\text{data}}$ is given by Eq. 5.2. If, on the contrary, the truth trajectory is not successfully reconstructed, it contributes to the inefficiency and is weighted by the ratio of data and MC inefficiencies. In this case the weight to be applied is given by:

$$W_{\text{ineff}} = \frac{1 - \varepsilon'_{\text{data}}}{1 - \varepsilon_{\text{MC}}}$$  \hspace{1cm} (5.4)

### 5.1.2 Reconstructed observable variation propagation method

The reconstructed observable variation method applies to variables which might have different mean or resolution in data and MC. In general, the observable value is varied in this way:

$$x' = x + \Delta x + \delta \cdot \sigma_{\Delta x}$$  \hspace{1cm} (5.5)

where $x$ is the original value of the observable; $\Delta x$ is the correction that should be applied to the MC to match the mean value in the data, $\sigma_{\Delta x}$ is the statistical uncertainty on $\Delta x$ and $\delta$ is the variation in number of standard deviations.

The different cases will be discussed separately in the corresponding sections. In all cases the event selection is run again on the new observable.

### 5.1.3 Normalization systematics propagation method

If the systematic uncertainty is associated with the total event normalisation the event is re-weighted according to the variation suggested by the systematic error studies, in accordance with:

$$W = W_0(1 + \delta \cdot \sigma_W)$$  \hspace{1cm} (5.6)

where $W$ is the weight to be applied to the MC due to the systematics, $W_0$ is the nominal weight in the absence of systematics (it is different from 1 if some corrections have been applied), $\sigma_W$ is the systematic error on the normalisation and
δ is the variation in number of standard deviations. Since a single normalization factor per event is applied, the event selection does not have to be redone.

5.1.4 Covariance matrix calculation

Systematic errors are propagated using toy experiments. The covariance for the bins $i$ and $j$ reads:

$$ C_{ij} = \sum_{t=1}^{N_{\text{toys}}} [(N_i^t)^W - N_i^{\text{avg}}][(N_j^t)^W - N_j^{\text{avg}}] \cdot w^t $$

(5.7)

where:

- $w^t$ is the toy experiment weight (i.e. the probability of this toy to occur). When random throws are used to generate the toy, it is just:

$$ w^t = \frac{1}{N_{\text{toys}}} $$

(5.8)

- $(N_i^t)^W$ is the number of selected events for toy $t$ and bin $i$ once weight systematics (efficiency-like and normalization systematics, described above) have been applied (hence the superindex “W”):

$$ (N_i^t)^W = \sum_{e=1}^{N_{\text{events}}} (W^t)_e \cdot (\delta^t_i)_e $$

(5.9)

being $(W^t)_e$ the systematic weight for toy $t$ and event $e$. $(\delta^t_i)_e$ is 1 or 0 depending on whether the selection was passed for event $e$ and toy $t$ and the event fell in bin $i$.

- $N_i^{\text{avg}}$ is the average number of events for bin $i$ when no weight systematics where applied:

$$ N_i^{\text{avg}} = \sum_{t=1}^{N_{\text{toys}}} w^t \cdot N_i^t = \sum_{t=1}^{N_{\text{toys}}} w^t \cdot \sum_{e=1}^{N_{\text{events}}} (\delta^t_i)_e $$

(5.10)

5.2 TPC related systematics

In this section the systematic uncertainties related to the TPC detectors are discussed. Since the middle TPC (TPC2) is the most important for the analysis presented in this thesis, results for this TPC will be shown as an example.
5.2. TPC related systematics

5.2.1 TPC Particle ID

The TPC PID systematics for muons and protons are obtained by comparing the data and MC predictions for high purity muon and proton samples, respectively [152,153]. The high purity (98%) proton sample has been obtained by selecting events with vertex in the FGD1 FV and whose most energetic positive track has momentum between 300 MeV/c and 1.1 GeV/c and deposits a large amount of charge in the TPCs (see Figure 3.5). A sample of sand muons has been used to compute the systematics for muons.

The muon (proton) pulls (see Eq. 3.2) have been computed for data and MC tracks for each TPC and run period independently and have been grouped in momentum bins. The resulting distributions have been fitted to a Gaussian. Two systematic error sources have been extracted from those fits: the difference in the mean between data and MC and the difference in the standard deviation. The comparison between data and MC for muons shows that the difference in the mean of the pulls is small (see Figure 5.2-top-left) and that the width is slightly narrower in the MC (see Figure 5.2-top-right). For protons, the mean is always lower in data in all TPCs (see Figure 5.2-bottom-left), probably due

![Figure 5.2: Top: mean (left) and width (right) of the TPC muon pull in data and MC as a function of the momentum for tracks in the TPC2. Bottom: mean (left) and width (right) of the TPC proton pull in data and MC as a function of the momentum for tracks in the TPC2. Images taken from [152].](image-url)
to the simulation of charge saturation which needs to be improved. The effect
is bigger at lower momentum, where the deposited charge is larger. As for the
muons, the width is slightly narrower in the MC (see Figure 5.2-bottom-right).

**Error propagation**

Both the pull mean and width systematics are propagated through the recon-
structed observable variation method (see Section 5.1.2). The observable to be
varied track by track is, in this case, the truncated mean of the ionisation loss by
charged particles crossing the TPC gas, $C_T$, defined in Eq. 3.1. For each TPC
segment in every track, the $C_T$ value is varied twice, according to Eq. 5.5 to
account for:

- the systematics on the pull mean: $x = C_T$, $\Delta x = \langle \text{Pull} \rangle \cdot \sigma(C_T - C_T^{\text{exp}})$,
  $\sigma_x = \sigma_{\langle \text{pull} \rangle} \cdot \sigma(C_T - C_T^{\text{exp}})$;

- the systematics on the pull width: $x = C_T$, $\Delta x = (C_T - C_T^{\text{exp}}) \cdot \langle \sigma_{\text{pull}} \rangle$,
  $\sigma_x = (C_T - C_T^{\text{exp}}) \cdot \sigma_{\langle \sigma_{\text{pull}} \rangle}$.

where $\langle \text{pull} \rangle$ and $\sigma_{\langle \text{pull} \rangle}$ are the fitted pull mean and its error, respectively; $\langle \sigma_{\text{pull}} \rangle$ and $\sigma_{\langle \sigma_{\text{pull}} \rangle}$ are the mean value of the fitted pull width and its error, respectively.

The systematic error source parameter, available for muons/pions, electrons and
protons, is chosen based on the true particle type.

The overall effect of the TPC PID uncertainty on the CCQE samples studied
in this thesis can be seen in Figure 5.3. The relative error is higher for the CCQE
samples using the proton TPC PID, as expected (see Figure 5.2).

![Relative systematic error induced by the TPC particle identification uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.](image-url)
5.2.2 TPC cluster efficiency

The method used to compute the cluster efficiency systematic error is described in detail in Appendix B. The TPC cluster efficiency is defined as the probability to find a reconstructed cluster at a given MM pad column when the particle should have produced one. It is expected to be the dominant source of the systematic uncertainty induced by the TPC track quality cut (see Sections 4.7 and 4.11), as the effects of MM modules mis-alignment and pattern recognition are expected to be small.

A sample of events passing the data quality cut (see Section 4.6) and with a single track crossing TPC2 (mainly muons) has been selected and used to compute this systematics. If an extra cluster inefficiency is added to the nominal MC in order to match the data, the events in the distribution of the number of clusters and in that of the track start position along \( z \) are expected to migrate from one bin to another. The value of the extra inefficiency has been found by weighting the nominal MC, to take into account the different inefficiency in the inner and outer pad columns and by fitting it to the data (see Figure B.2). The extra MC inefficiency given by the fit is \( 0.00097 \pm 0.00001 \) for inner columns and \( 0.0283 \pm 0.0002 \) for outer columns. As a cross-check the study has been repeated using different track samples and in all cases results of the same order have been found. No spatial, angular and momentum dependence has been found.

The effect of such small differences in cluster efficiencies on the MC selection has been studied and found to be negligible. This is somehow expected, as the fraction of events rejected by the track quality cut is small (see Sections 4.7 and 4.11). Thus, this systematic has not been propagated.

5.2.3 TPC track-finding efficiency

The TPC track finding efficiency has been computed for two different topologies: events with a single track in the TPC under study and events with two tracks nearly overlapping (see [155] and [156]). The double tracking efficiency was found to be compatible with 100% [155] and its associated systematics has been neglected. For the single tracking efficiency two different samples were used in order to cover as much phase space as possible. A sample of throughgoing muons was used to evaluate the efficiency for long tracks crossing the entire TPC: the upstream and downstream detectors around a TPC were used to select events in which a single muon crossed the tested TPC. The results of this study showed no visible dependency on angle or momentum and a good match between data

\[ \text{tracks with few clusters normally cross only one Micromegas (MM) module (except tracks crossing the cathode, but the contribution from this kind of tracks is expected to be small)} \]

\[ \text{As the outermost pad columns are subject to border effects, they have different inefficiency.} \]
and MC within the statistical uncertainties. The efficiency for shorter tracks was measured by selecting events with a clean track (for example in TPC2 and a BarrelECAL module) such that a short track is expected in TPC3. Comparing the track length prediction from the TPC2 track propagation and the MM geometry to the presence of a reconstructed track, the reconstruction efficiency versus the number of TPC track clusters was computed. The TPC track finding efficiency is very high (statistically compatible with 100%) and shows no dependency on the number of clusters for tracks with 16 clusters or more, for both data and MC. The efficiency starts to drop but remains above 97% for tracks with more than 10 clusters and the data and MC efficiencies are still consistent within errors [156].

As none of the two analyses simultaneously covers all angles, momenta, and track lengths with high statistics, it was decided to use a conservative estimate of the efficiency and its systematic uncertainty to account for potential small dependencies. The TPC track-finding efficiency for all angles, momenta, and track lengths is found to be $0.998^{+0.002}_{-0.004}$ in both the MC and data control samples. The corresponding efficiency in the analysis samples is 0.974.

**Error propagation**

The TPC track-finding efficiency systematics is propagated according to the efficiency-like propagation method explained in Section 5.1.1. The effect of this uncertainty on the CCQE selection is shown in Figure 5.4. This systematics affects the selection through the TPC track multiplicity cuts. Also the selection of the HMN and HMP tracks is affected by this systematics. The error is in general below 1% in all cases, except for the $\mu$FGD-TPC topology, for which the probability of having more than one not reconstructed trajectory is higher. The statistics of this sample is very small for muon candidate momentum above 1000 MeV/c.

**5.2.4 TPC momentum resolution**

The momentum resolution for data and MC was studied [154] for both single TPC segments and global tracks (see Section 3.4.3). The samples used for this study consist of events with a single throughgoing negative muon crossing several TPCs. In this way, the momentum measurement in different TPCs can be used to estimate the systematic error. Using the inverse of the momentum transverse to the magnetic field, $1/p_T$, the distribution of its difference between TPC1 and TPC2 corrected by energy loss in the intermediate FGD, $\Delta(1/p_T)$, is approximately Gaussian, with mean close to 0 and standard deviation $\sigma_{\Delta(1/p_T)}$. The energy loss and multiple scattering in the intermediate FGD, the intrinsic
5.2. TPC related systematics

Figure 5.4: Relative systematic error induced by the TPC track efficiency uncertainty for events with $\mu_{\text{TPC}}$ (blue), $\mu_{\text{TPC-pTPC}}$ (black), $\mu_{\text{TPC-pFGD}}$ (red), $p_{\text{TPC-}\mu_{\text{FGD}}}$ (green) topology as a function of the muon (left) and proton (right) candidate momentum.

momentum resolutions of the involved TPCs and the correlations between these two effects contribute to $\sigma_{\Delta(1/p_T)}$.

This study has been extended to global tracks passing through several FGDs and TPCs. In this case the comparison is done between two different momentum measurements for the same track. In more detail the momentum at the upstream end of TPC1 using different combination of detectors (TPC1-FGD1-TPC2-FGD2-TPC3 and TPC1-FGD1-TPC2-FGD2 for the same global track) in the Kalman filter fit has been used.

The difference in resolution between data and MC is obtained by smearing the momentum of all MC tracks, using different smearing factors ($\alpha$), until the difference in $\sigma_{\Delta(1/p_T)}$ between data and MC is minimised. The values of the smearing factor obtained for different ranges of $p_T$ are summarized in Table 5.2. The difference in resolution is attributed mainly to electric field distortions. Unfortunately, a satisfactory model to account for it is not available at the moment of this writing. For this reason an error of 10% for all $p_T$ bins has been used, despite the fact that the statistical errors on the determination of $\alpha$ were much smaller.

<table>
<thead>
<tr>
<th>$p_T$ range (MeV/c)</th>
<th>$\alpha \pm \sigma_{\alpha}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:500</td>
<td>$0.113 \pm 0.10$</td>
</tr>
<tr>
<td>500:1400</td>
<td>$0.242 \pm 0.10$</td>
</tr>
<tr>
<td>1400:10^6</td>
<td>$0.306 \pm 0.10$</td>
</tr>
</tbody>
</table>

Table 5.2: Smearing factor for different $p_T$ ranges.
### 5. Detector systematic uncertainties

#### Error propagation

The systematic uncertainty is propagated according to the reconstructed observable variation method (see Section 5.1.2) by rescaling the difference between the true and the reconstructed $p_T$, according to Eq. 5.5 with: $x = 1/p_T$, $\Delta x = (1/p_T - 1/p_T^{true}) \cdot \alpha$, and $\sigma_{\Delta x} = (1/p_T - 1/p_T^{true}) \cdot \sigma_\alpha$ (where $p_T^{true}$ is the true transverse momentum). The effect of the momentum resolution uncertainty on the CCQE selection is shown in Figure 5.5. The relative error is negligible when computed as a function of the momentum by range, as the momentum resolution systematics does not affect tracks not crossing the TPCs. The complicated peak structure visible in Figure 5.5-left is due to the interplay between the chosen binning and the systematic source parameter dependence on the momentum.

![Figure 5.5: Relative systematic error induced by the momentum resolution uncertainty for events with $\mu$TPC (blues), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.](image)

#### 5.2.5 TPC charge confusion

The method used to compute the systematic error associated with wrong charge reconstruction is described in detail in [161]. The charge confusion probability has been extracted by comparing the reconstructed charges in the different TPCs by using global tracks (see Section 3.4.3) with segments in all three TPCs. A sample populated mainly by muons that start in the P0D and cross the whole detector, and containing a negligible fraction of mismatched tracks and backwards going particles has been used. Assuming the three TPC segments were produced by the same particle and the charge confusion probability ($P_{wrong}$) is the same in all TPCs, $P_{wrong}$ is given by:

$$P_{wrong} = 0.5 \times (1 - \sqrt{1/3(4P_{same} - 1)})$$  \hspace{1cm} (5.11)
where $P_{\text{same}}$ is the probability of reconstructing the same charge in all three TPCs. The difference between the charge confusion rates (computed based on Eq. 5.11) in the data and MC control samples, gives the final systematic uncertainty.

Table 5.5 summarizes the charge identification efficiency in the analysis sample and in the control samples for different momentum bins.

<table>
<thead>
<tr>
<th>momentum range (MeV/c)</th>
<th>$\alpha$ (%) (AS)</th>
<th>$\alpha \pm \sigma_\alpha$ (%) (MC CS)</th>
<th>$\alpha \pm \sigma_\alpha$ (%) (data CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:300</td>
<td>0.875</td>
<td>0.882 ± 0.025</td>
<td>0.764 ± 0.025</td>
</tr>
<tr>
<td>300:600</td>
<td>0.990</td>
<td>0.9984 ± 0.0013</td>
<td>0.9954 ± 0.0013</td>
</tr>
<tr>
<td>600:900</td>
<td>0.992</td>
<td>0.99649 ± 0.00099</td>
<td>0.9934 ± 0.00099</td>
</tr>
<tr>
<td>900:1200</td>
<td>0.990</td>
<td>0.9967 ± 0.0011</td>
<td>0.9935 ± 0.0011</td>
</tr>
<tr>
<td>1200:1500</td>
<td>0.988</td>
<td>0.9904 ± 0.0017</td>
<td>0.9864 ± 0.0017</td>
</tr>
<tr>
<td>1500:1800</td>
<td>0.983</td>
<td>0.9870 ± 0.0017</td>
<td>0.9779 ± 0.0017</td>
</tr>
<tr>
<td>1800:2100</td>
<td>0.978</td>
<td>0.9851 ± 0.0023</td>
<td>0.9697 ± 0.0023</td>
</tr>
<tr>
<td>2100:2400</td>
<td>0.982</td>
<td>0.9840 ± 0.0023</td>
<td>0.9729 ± 0.0023</td>
</tr>
<tr>
<td>2400:2700</td>
<td>0.971</td>
<td>0.9756 ± 0.0028</td>
<td>0.9662 ± 0.0028</td>
</tr>
<tr>
<td>2700:3000</td>
<td>0.965</td>
<td>0.9764 ± 0.0026</td>
<td>0.9727 ± 0.0026</td>
</tr>
<tr>
<td>3000:4000</td>
<td>0.970</td>
<td>0.9666 ± 0.0019</td>
<td>0.9500 ± 0.0019</td>
</tr>
<tr>
<td>4000:5000</td>
<td>0.971</td>
<td>0.9550 ± 0.0029</td>
<td>0.9118 ± 0.0029</td>
</tr>
<tr>
<td>5000:10000</td>
<td>0.947</td>
<td>0.9205 ± 0.0032</td>
<td>0.8468 ± 0.0032</td>
</tr>
<tr>
<td>10000:15000</td>
<td>0.896</td>
<td>0.858 ± 0.014</td>
<td>0.729 ± 0.014</td>
</tr>
<tr>
<td>15000:20000</td>
<td>0.712</td>
<td>1.000 ± 0.079</td>
<td>0.667 ± 0.079</td>
</tr>
</tbody>
</table>

Table 5.3: Charge identification efficiency in the analysis sample (AS) and in the MC and data control samples (CS) with the corresponding statistical errors in different momentum bins.

**Error propagation**

This uncertainty is propagated as an efficiency-like systematics (see Section 5.1.1) using the efficiency values of Table 5.5. The effect of this systematics on the CCQE selection is shown in Figure 5.6. As expected, the systematic error is larger at low momentum, where the data-MC differences are larger. It can also be noticed that the error is larger for the $\mu$TPC-pTPC topology, as both the muon and the proton candidates are affected by this systematics. The peak visible for the $\mu$FGD-pTPC sample is spurious (it is due to the small statistics in that area).
5. Detector systematic uncertainties

Figure 5.6: Relative systematic error induced by the charge confusion uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.

5.2.6 TPC magnetic field distortions

The treatment of the magnetic field (B field) distortions in the TPC and the associated errors is based on the analysis described in [164]. Particles entering a TPC create a track of primary ionization. Electrons from the ionization drift towards the detector readout plane. In an ideal TPC with the magnetic and electric fields oriented parallel to each other, electrons drifting in the gas travel in the direction of the field lines, known as the drift direction. However, due to imperfections in the magnetic and electric fields, the path of the drift electrons can be distorted. Deflections in the plane transverse to the drift direction distort the image of the track at the readout plane, leading to a bias in the reconstructed momentum of the track.

The design and construction of the detectors is done in such a way as to minimize the electric and magnetic field distortions. However, not all imperfections can be removed and the remaining inhomogeneities in the electric and magnetic fields must be calibrated for. In order to do that, a dedicated TPC photoelectron calibration system [119] and a MC simulation of electrons drifting in the TPCs have been used. The photoelectron calibration system is designed to produce a control sample of photoelectrons by means of a laser flashing aluminium targets placed on the surface of the central cathode of the TPCs. For all three TPCs the MC simulation reproduces the main features of the target displacements, but in some regions there are significant differences in the direction and magnitude. Using those differences a map of empirical corrections can be computed. Since the source of the distortions is not fully understood, these corrections were not applied to the nominal data. They are used to estimate a systematic error by comparing in the MC, on a track by track basis, the momentum measured with
and without the distortion correction.

**Error propagation**

The systematics is propagated through the reconstructed observable variation method (see Section 5.1.2) according to Eq.5.5 with \(x = p\), \(\Delta x = 0\) and \(\sigma_{\Delta x} = p - p_{\text{dist}}\), where \(p_{\text{dist}}\) and \(p\) are the TPC track momentum values with a without distortion correction, respectively. The effect of this systematic uncertainty on the CCQE selection is shown in Figure 5.7. As the B field distortions do not affect tracks not crossing the TPCs, this systematics is negligible when computed as a function of the momentum by range. For the other topologies the fractional uncertainty is of the order of 1% around the muon candidate momentum peak.

![Figure 5.7: Relative systematic error induced by the B field distortions for events with \(\mu\)TPC (blue), \(\mu\)TPC-pTPC (black), \(\mu\)TPC-pFGD (red), pTPC-\(\mu\)FGD (green) topology as a function of the muon (left) and proton (right) candidate momentum.](image)

**5.2.7 TPC momentum scale**

The systematic uncertainty on the TPC momentum scale is strictly related to the knowledge of the magnetic field scale. The relation between the momentum and the magnetic field (B field) is given by:

\[
p_T = \frac{0.3 B}{\rho}
\]

where \(p_T\) is the transverse momentum of the particle in MeV/c, B the magnetic field in Tesla and \(\rho\) the inverse of the radius in mm\(^{-1}\), e.g the curvature.

The B field measurement and its systematic errors are provided in [162]. The mapping of the ND280 magnetic field was done through a set of measurements performed in September 2009 using a dedicated device designed and built...
at CERN. The measurement map consists of a 3D grid with measurement distances of 5 cm in the region of the ND280 tracker at a coil current of 1000 A, corresponding to a magnetic field of 712.6 G in the center of the magnet. During the mapping campaign a series of measurements with different granularity and at different coil currents was done. Furthermore, two dedicated magnet ramp-ups to higher field values at a coil current of 2600 A and 2900 A were performed in April and November 2010. After the mapping, the data were calibrated and corrected for non-linearities in the magnetic field and for the misalignment between the Hall probes, and extrapolated from 1000 A up to the nominal values of 2600 A, 2700 A and 2900 A.

The systematic errors on the mean magnetic field measurement can be divided into three categories:

- **Resolution.** It is the combination of the intrinsic resolution of the Hall probes and the error of the offset correction.

- **Misalignment.** It combines three effects: uncertainties of the skewing of the mapping device with the mapping device reference frame; the remaining error on the misalignment between the probes; the uncertainty of the survey which connects the mapping device reference frame with the ND280 reference frame.

- **Non-linearities of the B field.** Non-linearities are due to the uncertainty of the magnet yoke properties. The mean value of the non-linear parameter for all Hall probes at 1000 A differs from the mean value for the permanent probes retrieved from the ramp-ups to 2600 A and 2900 A.

For the main component of the magnetic field ($B_x$) the non-linearities are the main source of uncertainty, while for the transverse components ($B_y, B_z$) the misalignment of the probes with respect to the main B field direction dominates the systematic error. However, when extrapolating to higher field values, uncertainties on the non-linear part of the B field become the dominant source of systematic errors.

The overall systematic uncertainty on the momentum scale, inferred from the field map and the extrapolation to the full magnet current, has been found to be 0.57%. This result has been cross-checked and confirmed by using a sample of stopping muons in FGD1 from FGD-triggered cosmics and comparing the TPC momentum with the momentum by range in the FGD [152].

**Error propagation**

The propagation of the momentum scale systematics is done according to the reconstructed observable variation method (see Section 5.1.2) taking into account
that the effect of the systematics is a scaling of the original momentum. Thus, Eq. 5.5 is used, with: \( x = p, \Delta x = 0 \) and \( \sigma_{\Delta x} = p \cdot 0.0057 \), where \( p \) is the original momentum. Figure 5.8 shows the effect of the momentum scale uncertainty on the CCQE samples selection. As for other TPC related systematics, the relative error is negligible when computed as a function of the momentum by range, as tracks not crossing the TPCs are no affected directly.

![Figure 5.8: Relative systematic error induced by the momentum scale uncertainty for events with \( \mu \)TPC (blue), \( \mu \)TPC-pTPC (black), \( \mu \)TPC-pFGD (red), \( \mu \)FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.](image)

### 5.3 FGD1 related systematics

In this section the systematic uncertainties related to the FGD1 detector are discussed. Since only neutrino interactions occurring in the FGD1 volume are taken into account in this analysis, no FGD2 systematics have been considered.

#### 5.3.1 FGD-only track Particle ID

The FGD PID algorithm (see Section 3.4.2) works for stopping non-interacting particles and is based on measuring the energy deposited along the track and comparing it to the expected energy deposit for a given reconstructed range in the FGD and a given particle type. To study the muon and proton FGD PID systematics, the FGD1 segments of protons and muons stopping in FGD1 and crossing TPC1 have been analyzed. The momentum of the identified particles has been reconstructed using the TPC1 information.

Muon and proton FGD pulls (defined in Eq. 3.4) have been computed for the muon and proton samples respectively. As shown in Figure 5.9, the largest contribution at low muon pull values comes from muons crossing the FGD. The
tail at low values of the proton pull is due mainly to interacting protons. Gaussian functions were fitted to the central part of the distributions to estimate the peak position and width. The fitted parameters are listed in Table 5.4.

Figure 5.9: Distributions of the pull for the proton hypothesis for the selected proton sample (left) and the pull for the muon hypothesis for the selected muon sample (right). The upper plots show the comparison of the MC to the data and the Gaussian fits. The lower plots are for MC-only and show the contribution from the different types of particles. Red: stopping non-interacting protons (left) or muons (right), green: protons/muons interacting in the FGD, blue: FGD-crossing protons/muons, black: not protons/muons. Image and caption from [152].

**Error propagation**

The FGD PID systematic errors are propagated through the reconstructed observable variation method (see Section 5.1.2), analogously to the TPC PID systematics (see Section 5.2.1). The overall effect of the FGD PID systematic uncertainty on the $\mu$TPC-pFGD CCQE sample can be seen in Figure 5.10. As the FGD PID cut is not used to select $\mu$TPC or $\mu$TPC-pTPC events, this systematics has no effect on these two topologies. As the FGD PID cut is applied only to FGD-only tracks and the majority of the muon candidate tracks exit the FGD in events with $\mu$FGD-pTPC topology, the effect of this cut is very small for
### 5.3. FGD1 related systematics

#### 5.3.1 Muon systematics

<table>
<thead>
<tr>
<th></th>
<th>Muon Sample</th>
<th>Proton Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data mean</td>
<td>-0.02 ± 0.03</td>
<td>0.15 ± 0.03</td>
</tr>
<tr>
<td>MC mean</td>
<td>0.25 ± 0.02</td>
<td>-0.05 ± 0.03</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.71 ± 0.02</td>
<td>0.75 ± 0.03</td>
</tr>
<tr>
<td>MC sigma</td>
<td>0.15 ± 0.03</td>
<td>1.18 ± 0.03</td>
</tr>
</tbody>
</table>

Table 5.4: Fitted parameters for the data and MC pull distributions for the proton hypothesis in case of the selected proton sample and for the muon hypothesis for the selected muon sample. A Gaussian function was fitted in the range from $-1.5$ to $+3$ for the proton sample and proton hypothesis and from $-1$ to $+2$ for the muon sample and muon hypothesis.

**For the muon sample**, the effect of the associated systematics is negligible for the $\mu_{\text{FGD-pTPC}}$ topology.

![Relative systematic error induced by the FGD particle identification uncertainty for events with $\mu_{\text{TPC-pFGD}}$ topology as a function of the muon (left) and proton (right) candidate momentum.](image)

Figure 5.10: Relative systematic error induced by the FGD particle identification uncertainty for events with $\mu_{\text{TPC-pFGD}}$ topology as a function of the muon (left) and proton (right) candidate momentum.

#### 5.3.2 FGD-only track-finding efficiency

This efficiency was estimated in data and MC using a control sample of events with a proton-like track in TPC1 that exits the downstream end of this TPC (surface $S_1$) and extrapolates to the upstream end of the FGD1 active region (surface $S_2$). To avoid ambiguities a single TPC1 track within 20 cm from the exit position in $S_1$ is allowed. The FGD-only reconstruction is considered successful when there is a FGD-only track starting in $S_2$ within a radius of 10 cm (in XY) from the extrapolated position of the TPC1 track. Since no obvious dependency on momentum was found, this systematic is assumed to depend only on the track polar angle (see Table 5.5). Given the low statistics at large angles ($\cos \theta < 0.3$), values for that region were found by extrapolating the mean and
sigma values obtained for the other angular regions. The systematics is assumed to be specular for backward going tracks.

<table>
<thead>
<tr>
<th>$\cos \theta$ range</th>
<th>$\alpha$ (AS)</th>
<th>$\alpha \pm \sigma_\alpha$ (MC CS)</th>
<th>$\alpha \pm \sigma_\alpha$ (data CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0:0.1</td>
<td>0.566</td>
<td>0.188 ± 0.087</td>
<td>0.31 ± 0.17</td>
</tr>
<tr>
<td>0.1:0.2</td>
<td>0.613</td>
<td>0.303 ± 0.063</td>
<td>0.40 ± 0.14</td>
</tr>
<tr>
<td>0.2:0.3</td>
<td>0.657</td>
<td>0.405 ± 0.046</td>
<td>0.48 ± 0.12</td>
</tr>
<tr>
<td>0.3:0.4</td>
<td>0.690</td>
<td>0.494 ± 0.035</td>
<td>0.553 ± 0.095</td>
</tr>
<tr>
<td>0.4:0.5</td>
<td>0.732</td>
<td>0.576 ± 0.025</td>
<td>0.621 ± 0.078</td>
</tr>
<tr>
<td>0.5:0.6</td>
<td>0.757</td>
<td>0.633 ± 0.022</td>
<td>0.671 ± 0.058</td>
</tr>
<tr>
<td>0.6:0.7</td>
<td>0.789</td>
<td>0.698 ± 0.020</td>
<td>0.708 ± 0.048</td>
</tr>
<tr>
<td>0.7:0.8</td>
<td>0.810</td>
<td>0.723 ± 0.018</td>
<td>0.733 ± 0.035</td>
</tr>
<tr>
<td>0.8:0.9</td>
<td>0.831</td>
<td>0.756 ± 0.013</td>
<td>0.763 ± 0.029</td>
</tr>
<tr>
<td>0.9:1.0</td>
<td>0.840</td>
<td>0.773 ± 0.010</td>
<td>0.770 ± 0.023</td>
</tr>
</tbody>
</table>

Table 5.5: FGD-only track reconstruction efficiency in the analysis sample (AS) and in the MC and data control samples (CS) with the corresponding statistical errors in different angular bins.

**Error propagation**

The error propagation method is the one common to all efficiency-like systematics (see Section 5.1.1). The effect of the FGD-only track efficiency uncertainty on the CCQE selection is shown in Figure 5.11. This systematics affects the selection through the tracker track multiplicity cut. The selection of the muon and proton candidates in events with $\mu$TPC-pFGD and $\mu$FGD-pTPC topologies is also affected by this cut. It is worth noting that in events with $\mu$FGD-pTPC and $\mu$TPC-pFGD topologies the muon and the proton candidates, respectively, can be backward going.

**5.3.3 Michel Electron tagging efficiency**

The Michel electron tagging efficiency is evaluated using a sample of cosmic muons stopping in FGD1, selected by requiring a single TPC2-FGD1 track with its outermost FGD1 hits in the FV and no track in TPC1. A residual electron contamination is removed by requiring the momentum by range measurement for the muon hypothesis to be compatible with the TPC2 momentum. Using this sample, the Michel electron cut was applied to evaluate the efficiency, which
5.3. FGD1 related systematics

was measured to be 58.6±5.5% for data and 61.9±1.1% for MC. The efficiency in the MC analysis sample was found to be 61.6%.

Error propagation

This uncertainty is propagated as an efficiency-like systematics (see Section 5.1.1). The effect of this systematics on the CCQE selection is shown in Figure 5.12. The effect of the Michel electron cut on the selection is small, as shown in Section 4.8; thus, the associated relative error is small. As the Michel electron cut is not used to select events with \( \mu \)FGD-\( \mu \)TPC topology, this systematics has not been propagated for this sample.
5.4 TPC-FGD matching

The technique used to evaluate the TPC-FGD matching systematics is described in [155]. The TPC to FGD matching algorithm matches the TPC track to individual FGD hits using a Kalman Filter, as explained in Section 3.4.2. The matching algorithm may fail to match some of the FGD hits, producing two distinct effects:

- For a particle with true vertex in FV, if none of the FGD hits is matched the efficiency will decrease.

- For a particle with true vertex outside the FV (mainly upstream), if not all the FGD hits are matched, the reconstructed vertex, which is defined by the most upstream matched hit, could migrate into the FV volume. Such an event will contribute to the OOFV background.

In order to study the first kind of failure, a control sample of throughgoing muons was used; in particular, a sample of events with long tracks in TPC1 and TPC2 was selected. The TPC-FGD matching efficiency was calculated by checking for the presence of a TCP2-FGD1 reconstructed track, under the assumption that if tracks in TPC1 and TPC2 are found they probably correspond to a long track that also crossed FGD1. This study showed that for momenta above 200 MeV/c the TPC-FGD matching efficiency is very high and agrees well for data and MC, while below 200 MeV/c the matching efficiency is substantially reduced and there is a larger data/MC difference, as shown in Table 5.6.

The second failure type is studied using TPC-FGD tracks originated outside the FV and checking whether the reconstruction is able to associate all the FGD hits such that the start position of the track is kept outside the FV. Two different samples were used: throughgoing muons to study the efficiency at low angles, and FGD-triggered cosmic muons with a segment in TPC2 and no segments in TPC1/TPC3 (this ensures large angles). In both cases the failure rate is higher in data than in MC. For low angles it has been estimated to be 25%. For large angles, since the problem is not fully understood, a 150% systematic error is assumed.

As the systematics associated with the second type of TPC-FGD matching affects the OOFV background, but not the signal efficiency, its propagation is discussed in Section 5.5.1.

Error propagation

The error propagation method is the one common to all efficiency-like systematics and explained in Section 5.1.1. The effect of the TPC-FGD matching efficiency uncertainty on the CCQE selection is shown in Figure 5.13.
### 5.5 Background related systematics

In this section the background related systematics are discussed. Each background source has been considered separately and the corresponding systematic uncertainty has been calculated.

#### 5.5.1 Out of fiducial volume background

Out of fiducial volume (OOFV) background refers to neutrino interactions that occur outside of the FGD fiducial volume (see Table 4.5) but are reconstructed inside and selected.

---

#### Table 5.6: TPC-FGD matching efficiency in the analysis sample (AS) and in the MC and data control samples (CS) with the corresponding statistical errors in different momentum bins.

<table>
<thead>
<tr>
<th>momentum range (MeV/c)</th>
<th>$\alpha$ (%) (AS)</th>
<th>$\alpha \pm \sigma_\alpha$ (%) (MC CS)</th>
<th>$\alpha \pm \sigma_\alpha$ (data CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:100</td>
<td>0.791</td>
<td>$0.731^{+0.019}_{-0.019}$</td>
<td>$0.662^{+0.021}_{-0.021}$</td>
</tr>
<tr>
<td>100:200</td>
<td>0.935</td>
<td>$0.9903^{+0.0019}_{-0.0022}$</td>
<td>$0.9904^{+0.0021}_{-0.0024}$</td>
</tr>
<tr>
<td>200-100000</td>
<td>0.903</td>
<td>$0.999683^{+0.000052}_{-0.000058}$</td>
<td>$0.999642^{+0.000051}_{-0.000056}$</td>
</tr>
</tbody>
</table>

---

#### Figure 5.13: Relative systematic error induced by the TPC-FGD matching efficiency uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.

---

4 Including interactions in the active parts of the FGD outside of the FV, in the FGDs’ and TPCs’ dead material and in the P0D, ECAL, magnet, or surrounding material. Cosmic rays
with the OOFV background can be found in [157].

Two kinds of systematic uncertainties have been considered for each source of OOFV background:

- **Rate uncertainty.** A large fraction of the OOFV backgrounds are due to interactions on lead, iron, or aluminum, which are present in the P0D, ECAL, magnet and the tracker’s dead materials. A 20% overall uncertainty on the rate of neutrino interactions that produce this background has been assigned to OOFV events when the initial neutrino interaction was outside the tracker region, to reflect the uncertainty on how well NEUT models the cross-sections on these metals.

- **Reconstruction uncertainty.** OOFV events can be misidentified as interactions inside the FGD FV due to reconstruction failures. Differences in the failure rate between data and MC result in systematic uncertainties.

Several categories of OOFV background sources have been identified:

1. Neutral particles entering the FGD from outside the tracker. They create secondary charged particles inside the FGD. As the reconstruction alone can never reject such events, no reconstruction systematics is applied.

2. Interactions in the downstream tracker dead material. Backwards going hadrons produced by interactions in the downstream dead material can stop in the FGD, while forward going tracks from the same event can enter the TPC. The two tracks can be matched as a single track starting in the FGD FV and entering TPC2.

3. Interactions in the upstream tracker dead material. If an event occurs in dead material in the upstream-most XY module of FGD1, the hit may be missing. In this case the upstream-most hit will appear inside the FV.

4. Interactions in FGD1 scintillators outside the FV.

5. Bad first hit in the TPC-FGD matching. If the TPC-FGD matching picks the wrong hit to start the extrapolation into the FGD, the track may fail to match properly all the way through to the upstream-most hits, causing matching for a throughgoing track to stop inside the FGD FV\(^5\). This case has been discussed in Section 5.4.

\(^5\)This category contains also events in which the muon had a hard scattering in the FGD, as this kind of events are difficult to reconstruct and separate from the bad first hit category. No reconstruction systematics is assigned to this kind of events, provided that GEANT4 does a good job of modelling the probability of such hard scatters.
5.5. Background related systematics

6. Backwards going tracks created outside the tracker. Backwards going tracks stopping in the FGD1 are reconstructed as forward going due to the limitation of the reconstruction in determining the track direction. As this case does not reflect a reconstruction failure, but only the reconstructions limited ability to distinguish between forward and backward going tracks, no reconstruction systematics is assigned.

7. Layer 28/29 failure. When the drift velocity or time offset of the TPC track is not well reconstructed, the track is matched to FGD hits only in the YZ projection, not in the XZ projection. In this case the track gets reconstructed as being in layer 28 or 29.

8. High-angle tracks. These tracks are usually not well reconstructed, as hits are generally missing at the end of the FGD part of the track that extends outside of the FGD preventing the matching between the TPC and the FGD. This kind of TPC-FGD matching failure has been discussed in Section 5.4.

9. Doubled skipped layers. If two layers in a row lack FGD hits, the matching of FGD hits to TPC tracks fails and the track is broken. Then the track appears to start inside the FGD FV even if there are further upstream hits. This failure generally happens for tracks almost parallel to the beam direction and passing through the dead coating material between scintillator bars.

A skimmed sample containing only OOFV events was used as control sample to compute the systematics associated with each category. Table 5.7 summarizes the rate and reconstruction related uncertainties assigned to each OOFV background type.

Error propagation

The OOFV systematics is treated as a normalization systematics. Two independent weights, associated with the rate and reconstruction uncertainties, are computed using Eq. 5.6 and multiplied to obtain the total event weight. The effect of the OOFV uncertainty on the CCQE selection is shown in Figure 5.14. The relative error is larger for the $\mu$FGD-pTPC (as the OOFV is the dominant background for this topology) and is in general significant for all topologies at low momenta (as in this region the OOFV background is larger).

---

6Tracks are assumed to be forward going in the reconstruction, unless they cross two FGDs. In this case the track direction can be flipped by using the timing of both FGDs.
Table 5.7: OOFV background types and corresponding cross-section (second column) and reconstruction related (third column) uncertainties.

<table>
<thead>
<tr>
<th>Background type</th>
<th>Rate uncertainty (%)</th>
<th>Reconstruction uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Neutral particles from outside tracker</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>2 Interactions in downstream tracker material</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>3 Interactions in upstream tracker dead material</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4 Interactions in OOFV FGD scintillator</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5 Bad first hit in the TPC-FGD matching</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>6 Backwards-going tracks</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>7 Layer 28/29 failure</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>8 High-angle tracks</td>
<td>20</td>
<td>150</td>
</tr>
<tr>
<td>9 Doubled skipped layers</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 5.14: Relative systematic error induced by the OOFV uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.

5.5.2 Sand muon background

As explained in Section 4.2, the analysis concerning the events originating from neutrino interactions outside the ND280 detector has been performed using a dedicated MC simulation [160]. The expected contribution from sand interactions can be verified by comparing the absolute rate per POT observed in MC and in data. To perform such analysis, tracks entering through the front wall of P0D were selected. A set of simple cuts (see [160] for details), mostly concerning the track start position, which should be very close to the P0D borders, allows to obtain a sample enriched in sand muons. However, in data there can still be
tracks originating from neutrino interactions in the P0D casing, coil and basket supporting structure. Since such interactions are simulated in the default MC, the cuts are applied to the default MC as well, and the obtained rate is added to the rate from sand MC.

The discrepancy in the total rate of events passing the front wall cuts between data and MC (which is about 10%) is included as a systematic uncertainty to the predicted number of sand events.

However, as in the CCQE analysis samples the amount of sand muon background is negligible or null (see Tables 4.9, 4.12, 4.15, 4.18), this systematics can be considered negligible. Thus, it was decided to not propagate it.

5.5.3 Cosmic ray background

Cosmic muons, continuously crossing ND280, can mimic interactions of muon neutrinos from the beam, and thus contribute to the background of the selected CC and CCQE samples. A detailed explanation of the systematic error associated to the cosmic muon background is given in [158].

In order to estimate the cosmic muon background contribution, dedicated simulated samples of cosmic muons and a data sample taken with the beam trigger, when the beam was off, have been used. The effect on the CC sample (see Section 4.7) was studied by applying the standard inclusive CC selection to both the data and cosmic MC samples and calculating the corresponding rates (defined as the number of tracks divided by the corresponding integrated time). The rate of MC events passing the cuts was found to be in the range (0.07-0.08) \( \pm 0.01 \) Hz. As no tracks passed the cuts in the data sample, a set of simpler cuts was used to check the data/MC agreement: no tracks in TPC1 and at least one track with more than 18 clusters in TPC2 or TPC3. The rate of such events in data was found to be 1.13-1.41 times higher than in the simulation. Taking into account this data/MC ratio, the predicted number of cosmic muons passing the CC cuts in the data sample was found to be 0.64 \( \pm 0.08 \), corresponding to about 0.01% of the total number of events passing the selection.

Cosmic muons crossing the TPC1 volume can also produce a false veto signal for neutrino events. The rate of cosmic events with a segment in TPC1 has been computed and the probability of such events has been found to be 0.0055%.

As both effects produce very small errors compared to the other systematics, they can be safely neglected for the inclusive CC sample. As the CCQE 1- and 2-track samples with the muon reconstructed in the TPC use the CC selection plus additional cuts which further suppress these results, and taking into account that the probability of having a coincidence of two cosmic muons in the same bunch window with one of them identified as a proton is very small, this systematics can be considered negligible also in these cases. Regarding the \( \mu \)FGD-pTPC
sample, the procedure described above has been used to compute the number of single cosmic muon tracks with the same topology as the proton and muon candidates. It was found that the expected number of cosmics mimicking the proton (muon) candidate is 1 (15). With the additional requirements of the two tracks being in the same bunch and having their reconstructed start positions in the FGD1 FV, this final result is further suppressed, showing that the cosmic muon background is negligible also in this case. In addition, dedicated studies [155] have shown that the probability of having broken tracks (see Figure 4.29) is negligible. Consequently the probability of a broken track coming from a cosmic muon mimicking a CCQE 2-track event is negligible as well. Thus, the systematic uncertainty associated with cosmic muons can be safely neglected.

5.5.4 Event pile-up

Pile-up refers to the probability of having two interactions in the same beam bunch (see Section 4.3). There are several categories of possible pile up, but only the effect of sand muons is significant for this analysis. The external veto cut (see Section 4.7) rejects most events with activity in TPC1 since in most cases the TPC1 activity is due to tracks from interactions occurring upstream of the detector (sand muons) or outside the tracker fiducial volume. As discussed in Section 4.5, since sand muons are not included in the standard NEUT simulation, the MC does not reproduce the coincidence of a candidate CCQE event with a sand muon and a correction must be made to account for this effect. Thus, a weighting factor, \((1 - C_{\text{pileup}})\), is applied to all MC events in the analysis, where \(C_{\text{pileup}}\) is defined as the fraction of TPC1 sand muon events per bunch in a given data set. As the correction to be applied to the MC should depend on the beam intensity, it is evaluated for each data set (see Section 4.2) separately.

The systematic error source is given by the difference, \(\Delta_{\text{data:MC}}\), of the number of TPC1 events/bunch between data and MC, with the sand muon contribution added to the MC (the MC is also weighted by the data intensity). In order to take into account the 10% uncertainty on the sand muons (described previously) and to avoid double counting the two uncertainties, the larger value among \(\Delta_{\text{data:MC}}\) and \(0.1 \times C_{\text{pileup}}\) is taken as the pile-up systematic error, \(\sigma_{\text{pileup}}\).

Table 5.8 summarizes the values of the pile-up correction and systematic uncertainty for each data set. The \(C_{\text{pileup}}\) value increases with the run number as the probability of a coincidence with sand muons grows with the beam intensity.

Error propagation

This uncertainty is propagated as a normalisation systematic error (see Section 5.1.3) according to Eq. 5.6 with \(W_0 = 1 - C_{\text{pileup}}\) and \(\sigma = \sigma_{\text{pileup}}/(1 - C_{\text{pileup}})\).
Table 5.8: Pile-up correction and systematic uncertainty for each data set. P0D water-in and water-out configurations have been separated. Run3b and Run3c refer to different data taking periods with the same detector configuration but different beam intensity.

The effect of the pile-up uncertainty on the CCQE selection is shown in Figure 5.15. A MC sample corresponding to Run3 of data taking (with a dominant component corresponding to Run3c) has been used. The overall relative error is of the order of 0.1%, as expected according to Table 5.8. The relative error fluctuations for events with $\mu$FGD-pTPC topology are due to the small statistics of this sample above 1000 MeV/c.

Figure 5.15: Relative systematic error induced by the pileup uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum. The NEUT MC simulation corresponding to Run3 of data taking have been used.

5.6 MC modeling related systematics

In this section the systematic errors associated with inaccuracies of basic MC modelling parameters are discussed.
5.6.1 Pion secondary interactions

Pion secondary interactions (SI) refer to interactions that a pion undergoes outside of the nucleus that it was produced in. Only the three most significant SI types were considered in this study:

- **Absorption.** The incident pion is completely absorbed by the nucleus, and there are no pions in the final state.

- **Charge Exchange.** The incident pion interacts with a nucleus to produce a pion with one less unit of charge.

- **Quasi-Elastic scattering.** The pion interacts with the nucleus, and one pion of the same charge exits the interaction (amongst other non-pion particles).

Absorption and charge exchange can cause a charged pion to disappear before it could be detected. In this case, should the neutrino interaction and the pion SI occur inside the FGD1 FV, there is a good chance that the event could be mistaken for a CCQE interaction. On the other hand, the reconstruction of events from quasi-elastic scatters can be complicated due to the sudden change in direction and momentum of the pion. Furthermore, a pion that was headed for detection in the TPC could be redirected towards the ECAL instead, where it could be undetected by the selection described in this thesis. In addition, the outgoing pion will be of lower momentum, and therefore may have a higher absorption cross-section.

These processes are modelled in GEANT4 but the simulation differs significantly from the available external data. In addition, the uncertainty on the existing data is large and must be taken into account. Both effects are responsible for a systematic uncertainty that affects the selection. Figure 5.16 shows a comparison of the GEANT4 and data cross-sections for an absorption process on Carbon. As in the momentum region below 100 MeV/c and above 550 MeV/c there was no data, the data was extrapolated using weighted GEANT4 values and conservative uncertainties were applied, as explained in [165]. Although the extrapolated uncertainties are large at high momenta, they do not contribute significantly to this systematic because the number of pions at these momenta is small.

**Error propagation**

In order to compute the systematics associated with pion SI, the impact of varying the secondary interaction cross-section on the total number of events was estimated taking into account both effects (the discrepancy between data
Figure 5.16: A comparison of the $\pi^+$ Absorption on Carbon-12 data and extrapolations (black) with the GEANT4 cross section (blue). The extrapolated data points begin when the points get much denser, below and above the data region. Image taken from [165].

and MC and the uncertainty on the available data), as described in detail in [165] and summarized below.

Since only neutrino interactions occurring in the FGD1 FV are considered in this analysis, then the $\pi^+$ and $\pi^-$ tracks may be missed if one of the relevant SI described above occurs inside the FGD1 FV. Thus, to estimate the effect of varying the SI cross-section, two sets of weights are generated and applied to events where a pion SI occurred in the FGD1 FV:

- correction weight, to bring the MC into agreement with the pion SI data;
- variation weight, to account for the uncertainty on the pion SI data.

The procedure used to generate the weights is explained in detail in Appendix [C]. The overall event’s interaction probability is computed as the product of the individual probabilities of all the pion trajectories in the event. Such probabilities depend on the particle momentum, the density of the material and the interaction type, and are proportional to the product of the three SI cross-sections described above. Thus, the correction weight is given by the ratio of a quantity proportional to the interaction probabilities in data and MC. The variation weight is obtained by varying the data cross sections by a fraction of the cross-section uncertainty for each interaction type. The final weight, given by the product of the two individual weights, is treated as a normalization weight (see Section 5.1.3). The effect of this uncertainty on the CCQE selection is shown in Figure 5.17.
5. Detector systematic uncertainties

![Graphs showing relative systematic error induced by the pion SI uncertainty for events with different topologies as a function of the muon (left) and proton (right) candidate momentum.]

Figure 5.17: Relative systematic error induced by the pion SI uncertainty for events with μTPC (blue), μTPC-pTPC (black), μTPC-pFGD (red), μFGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.

5.6.2 FGD Mass Uncertainty

As described in [169], this systematics is generated by the uncertainty on the MC FGD1 material density, as this produces an error on the number of simulated interactions. This uncertainty is found to be 0.67%, while the mean value differs by only 0.09% from the value recommended in [169], meaning that no rescaling of the MC output is necessary on account of the detector density.

Error propagation

The FGD mass systematics is a normalisation systematic uncertainty (see Section 5.1.3) and is propagated to a sub-sample of events with true interaction vertex in FGD1 according to Eq. 5.6. The effect of this uncertainty on the CCQE selection is shown in Figure 5.18. The relative error is of the same order as the uncertainty on the total FGD XY module mass (0.67%) for all samples, as expected. The smaller error at low momentum is due to the large contamination from OOFV events in this region (most of them do not contribute to this systematics since they correspond to interactions occurring outside the FGD1).

5.7 Beam flux systematics

A brief summary of the different sources contributing to the beam flux systematic uncertainty is given in this section. A detailed description is given in [129] and in the internal technical notes T2K-TN-039 [181], T2K-TN-054 [182] and T2K-TN-99 [183].

The uncertainties on the flux prediction are studied by varying underlying inputs to the flux simulation (the hadron production model, the proton beam...
5.7. Beam flux systematics

profile, the horn currents, etc.) and evaluating the effect on the predicted flux. Two approaches are used. Where an error source includes a number of correlated underlying parameters, re-weighting methods are used. The underlying parameters are varied (typically 500 or more throws are done) and the flux prediction is re-weighted. The effect on the flux is evaluated by constructing a covariance matrix from the throws. The second method for evaluating uncertainties is applied for uncertainties represented by variations of the flux due to changes in a single underlying parameter. In this case the flux is typically re-simulated for variations of the parameter at $\pm 1\sigma$ (corresponding to two throws. A covariance matrix is then constructed using these two throws. The combined uncertainty on the flux prediction is represented by the sum of the covariances from each independent source of uncertainty.

The neutrino flux uncertainty can be ascribed to several sources:

- **Hadron interaction uncertainties**
  The uncertainty in the modelling of the pion and kaon production multiplicity arises from several sources: the uncertainties associated with the experimental production data used to reweight the pion and kaon production multiplicity in the MC; the uncertainty on the incident particle momentum scaling for different incident beam energies, used to apply the data to interactions with lower momentum incident nucleons; the uncertainty from extrapolating the data into the phase space that contribute to the T2K neutrino flux which is not covered by the available data points. In addition, the uncertainty on the kaon production from interactions in the Al around the target must be taken into account for kaons. The pion and kaon production data of the NA61/SHINE collaboration [132, 133], Eichten et al. [184], and Allaby et al. [185] have been used to estimate these
systematic uncertainties.

Interactions of secondary nucleons (i.e. protons and neutrons produced by the initial incident primary proton beam) inside the target contribute about 16% (protons) and 5% (neutrons) to the neutrino flux. The high momentum protons are produced in quasi-elastic scattering or scattering where soft pions are produced. Due to the lack of relevant data in this momentum region, a 100% uncertainty is assigned on the proton production multiplicity in this region, but the effect on the flux is still relatively small since these nucleons are forward-going and carry most of the original proton momentum. The contribution from low momentum protons is due to hadronic production. In the low momentum region the uncertainty for the secondary proton production is evaluated based on the discrepancy between the FLUKA model and the proton production measurements of Eichten et al. [184] and Allaby et al. [185]. Only low momentum neutrons contribute significantly to the flux. The same error as that of low momentum protons is assigned to low momentum neutrons.

The systematic uncertainty in the production cross-section is conservatively taken to be represented by the magnitude of the quasi-elastic correction applied to the total inelastic cross-section for a given particle and at given beam energy. This systematic uncertainty arises from an apparent discrepancy between cross-section measurements for protons, which may result from the difficulty in understanding whether experiments measure the inelastic or production cross-sections.
In summary, at low energy, the largest sources of uncertainty in the $\nu_\mu$ flux are from the secondary nucleon production and production cross-sections. At high energy, the flux uncertainty is instead dominated by the experimental errors on the kaon production. New measurements from NA61/SHINE are expected to reduce the overall uncertainty on the neutrino flux prediction.

• **Proton beam and off-axis angle uncertainties.**
  
  The proton beam is generated in the simulation according to the measured primary proton orbit and optics parameters. Studies found that only the systematic errors for the vertical center position and center angle of the beam have a sizable effect on the neutrino flux prediction, as these parameters effectively change the off-axis angle at the far detector. A 2% absolute flux normalization uncertainty arises from the errors on the proton beam intensity measured by the proton beam monitor.

  The neutrino beam direction is measured by INGRID. The neutrino flux uncertainty due to the uncertainty in the off-axis angle is evaluated by looking at a variation of the neutrino flux when the SK and ND280 detectors are moved by 0.44 mrad in JNUBEAM.

• **Target and horn alignment uncertainties.**
  
  The effects of the target alignment were studied by rotating the target in JNUBEAM by 1.3 (0.1) mrad in the horizontal (vertical) plane. This configuration results in a few percent change in the predicted neutrino flux. To determine the horn position alignment uncertainties, the effects of horn movements along each coordinate axis were studied. Only the uncertainty in $y$ results in a sizable change (a few percent) in the predicted flux. The effects of horn rotations in both the horizontal and vertical plane by 0.2 mrad were studied. Only rotations of the first horn showed any significant effect on the predicted neutrino flux.

  In summary, for neutrinos with energies below 7 GeV the fractional uncertainties due to these sources are under 3%.

• **Horn current and magnetic field uncertainties.**
  
  The total uncertainty of the horn current measurement is 1.3% and the measured magnetic field strength is consistent with the expected one within 2%. This results in an overall 2% uncertainty on the neutrino flux.

  The total flux uncertainty for $\nu_\mu$ at ND280 as a function of neutrino energy is shown in Figure 5.19. The uncertainty is dominated by the hadron interaction uncertainties, with a significant contribution from the off-axis angle and proton
beam uncertainties at the flux peak. Shifts in the off-axis angle and proton beam tend to shift the peak position of the flux in energy.

**Error propagation**

The beam flux uncertainty is propagated as a normalization systematics (see Section 5.1.3). As expected, the relative error is of the order of $\sim 10\%$.

![Figure 5.20: Relative systematic error induced by the beam flux uncertainty for events with $\mu$TPC (blue), $\mu$TPC-pTPC (black), $\mu$TPC-pFGD (red), $\mu$FGD-pTPC (green) topology as a function of the muon (left) and proton (right) candidate momentum.](image)

**5.8 Total systematic uncertainty**

The total systematic uncertainty must take into account the effect of all systematics on the selection. A list of the integrated and differential systematics (individual and total) for all CCQE topologies is given in Table 5.9.

The differential systematic error corresponds to the weighted average value of the systematics in the considered bins of the chosen observable.\(^7\) Due to the way it is defined, the differential systematics depends on the chosen observable and binning. The differential values in Table 5.9 correspond to the muon candidate momentum with the binning defined in Section 5.1. The total differential systematic uncertainties induced by all systematics, when correlations between systematics are taken into account (i.e. when all the systematics are propagated simultaneously), are 3.4\%, 6.6\%, 7.5\%, 11\% when the beam flux systematics is not taken into account (see Figure 5.21-top-right and Table 5.9) and 8.7\%, 9.7\%, 11\%, 12\% when the beam flux is included, for the $\mu$TPC, $\mu$TPC-pTPC, $\mu$TPC-pFGD, $\mu$FGD-pTPC topologies, respectively (see Figure 5.21-top-left and Table 5.9).

\(^{7}\)The fractional number of events in each bin is used.
The differential relative error distributions as a function of the proton candidate momentum are shown in Figure 5.21-bottom.

Figure 5.21: Total differential relative error induced by all the systematic uncertainties as a function of the muon (top) and proton (bottom) candidate momentum, for the $\mu_{\text{TPC}}$ (blue), $\mu_{\text{TPC}}$-$\mu_{\text{TPC}}$ (black), $\mu_{\text{TPC}}$-$\mu_{\text{FGD}}$ (red), $\mu_{\text{FGD}}$-$\mu_{\text{TPC}}$ (green) topologies, when the beam flux systematics is taken into account (left) and when it is not (right).

The total integrated systematic uncertainties, taking correlations into account, are 2.6%, 4.6%, 4.2%, 11% when the beam flux is not taken into account and 5.4%, 6.4%, 6.5%, 12% when the beam flux is included, for the $\mu_{\text{TPC}}$, $\mu_{\text{TPC}}$-$\mu_{\text{TPC}}$, $\mu_{\text{TPC}}$-$\mu_{\text{FGD}}$, $\mu_{\text{FGD}}$-$\mu_{\text{TPC}}$ topologies, respectively (see Table 5.9). The total systematics is smaller for the $\mu_{\text{TPC}}$ topology, as there are no constraints on the proton candidate, while it is higher for the $\mu_{\text{FGD}}$-$\mu_{\text{TPC}}$ topology, which relies strongly on the selection of the proton candidate.

Larger values of the differential and integrated total relative errors are obtained when the individual systematics are considered independent and summed in quadrature (i.e. when the total error is computed as the quadratic sum of all the terms in each column of Table 5.9). The systematic errors shown in the tables and final kinematic distributions in the next chapter are computed taking into account correlations.

Looking at the differential values of the individual systematics as a function
of the muon candidate momentum (see Table 5.9), one can see that the dominant contribution to the total differential systematic uncertainties comes from pion secondary interactions for all topologies. The TPC related systematics and the FGD track-finding efficiency systematics are important for all topologies with the muon candidate reconstructed as a TPC track. For the $\mu_{TPC}$-$p_{FGD}$ topology the systematic uncertainty due to TPC-FGD matching efficiency is also significant. For the $\mu_{FGD}$-$p_{TPC}$ topology, the main systematics are the ones due to TPC track-finding efficiency and to the OOFV background (one of the dominant backgrounds for this topology). The systematics associated with FGD track-finding and TPC-FGD matching efficiencies are also important for this topology.

When integrated systematics uncertainties are considered (see Table 5.9), the dominant contribution to the overall integrated systematics is given by pion secondary interactions, followed by the FGD track-finding efficiency and charge confusion systematics for the $\mu_{TPC}$, $\mu_{TPC}$-$p_{FGD}$ and $\mu_{TPC}$-$p_{TPC}$ topologies. For the topologies with one of the two candidate tracks reconstructed as FGD tracks, the systematics due to the TPC-FGD matching is also important. For the $\mu_{FGD}$-$p_{TPC}$ topology the main systematics are the ones induced by the TPC track-finding efficiency and by the OOFV background.

The FGD PID systematics, which affects only the $\mu_{TPC}$-$p_{FGD}$ and the $\mu_{FGD}$-$p_{TPC}$ topologies, has a small effect (both the differential and integrated relative errors associated with this systematics are small or negligible), as expected (the effect of the FGD PID on the selection is small, as shown in Section 4.10 and 4.11).

It is worth noting that the momentum scale, momentum resolution and B field distortions systematics cause a migration of events among bins of momentum. As shown in Table 5.9, this effect is relatively large if one considers differential distributions (the differential uncertainties are relatively large for these systematics) while is relatively small if one considers the integrated relative errors.

Finally, as at the moment of this writing some systematic studies are still ongoing, some considerations should be taken into account. More in detail:

- The systematic error associated with the TPC-FGD matching efficiency is optimized for muons. It has been assumed that the results discussed in Section 5.4 are valid also for protons. This is a reasonable assumption, although the energy loss rate in the FGDs is different for muons and protons.

- The systematic error associated with TPC track-finding efficiency is optimized for muons but the results discussed in Section 5.2.3 can be assumed to be a reasonable approximation for protons, except at very low momen-
tum, where one could expect some discrepancies. However, in the analysis presented in this thesis the low momentum region has very low statistics, so its effect on the systematics should not be important. The same argument is valid for the momentum resolution systematics.

- The systematics associated with the momentum by range has not been included in the analysis presented in this thesis because at the moment of this writing its study is still in a very preliminary phase, but its effect is expected to be small.

- The systematics associated with the FGD track-finding efficiency is optimized for protons. Due to the different energy loss rate of muons and protons, this systematics may be slightly different for muons. Unfortunately, the study for stopping muons is not available at the moment of this writing and the results obtained with protons have been used as an approximation.

- The systematics associated with the proton FSI has not been included in this study because an appropriate parametrization to characterize this kind of processes is not available at the moment of this writing. However, a qualitative study attempting to understand the effect of proton FSI on data and MC has been done (see Section 6.3.3).

---

8The different energy loss rate of muons and protons may affect differently the track curvature and the multiple scattering effects.
Table 5.9: Integrated and relative systematic error for each of the systematic error sources considered, for all CCQE topologies. The differential systematic error corresponds to the average value of the systematics and is defined as the sum of the relative error’s values in all the considered bins of the chosen observable. Due to the way it is defined, the differential systematics depends on the chosen observable and binning. In the last four lines the value of the total systematic error is given when the correlations between the individual systematics are taken into account (total correlated) and when the individual systematics are considered independent and summed in quadrature (total in quadrature). The results are given when the beam flux is taken into account and when it is not. No value of the relative error is given when the systematics is not applied or when its effect on the selection is negligible.
Chapter 6

Results

The results obtained with real data using the selection criteria described in Chapter 4 and the comparison with the corresponding NEUT MC simulation are presented in this chapter. As mentioned in Section 4.2, real data Runs 1, 2, 3 and 4 of the official production 5F and the corresponding NEUT MC 5E production (both magnet and sand muon simulations) have been used.

6.1 CCQE event rates

Table 6.1 summarizes the main features of the selected CCQE samples, including the statistical error in data and MC and the detector and beam flux systematic uncertainties in MC.

As mentioned in Section 1.6.2, the characterization of a neutrino-nucleus interaction often depends on the hadronic final state. The proton produced in a neutrino-nucleus CCQE interaction (called “primary proton” in the following) can suffer final state interactions (FSI), which can produce additional final state particles and cause migrations among the selected CCQE samples. Thus, the exclusive data/MC ratios could be distorted if FSI are not correctly simulated.

The data/MC ratio results in Table 6.1 show that in the event sample with \( \mu \)TPC topology the number of selected events predicted by the MC is higher than that obtained when the study was performed on real data. On the other hand, the data/MC ratio is compatible with 1 for the event sample with \( \mu \)TPC-pTPC topology, while in the \( \mu \)FGD-pTPC and \( \mu \)FGD-pTPC samples the MC

\footnote{As some systematic uncertainties involve applying a correction to the MC (see Chapter 5), taking into account systematic errors can change slightly the number of MC selected events. For this reason, the values of the data/MC ratio given in Table 6.1 are slightly different from those given in Tables 6.2, 6.3, 6.4, and 6.5 as the latter are based on the results presented in Chapter 4 and do not take into account systematic errors.}
Table 6.1: Summary of the main features of the CCQE samples after the corresponding selection cuts have been applied: number of selected events in data and MC samples (both magnet and sand muon simulations, normalized to data by POT) with the corresponding errors; data/MC ratio and corresponding errors; fraction of selected events corresponding to each topology; CCQE efficiency (Eq. 4.2) and purity (Eq. 4.1) of the MC samples. Only the statistical error is given for data, while for MC and for the data/MC ratio the statistical error (first value) and the detector (second value) and beam flux (third value) systematic errors are given.

<table>
<thead>
<tr>
<th>sample</th>
<th>selected events</th>
<th>data/MC ratio</th>
<th>fraction (%)</th>
<th>eff (%)</th>
<th>pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>data</td>
<td>MC</td>
<td></td>
<td>data</td>
<td>MC</td>
</tr>
<tr>
<td>$\mu$TPC</td>
<td>7629 ± 87</td>
<td>8691 ± 46 ± 210 ± 420</td>
<td>0.88 ± 0.01 ± 0.02 ± 0.04</td>
<td>69.0</td>
<td>73.3</td>
</tr>
<tr>
<td>$\mu$TPC-pTPC</td>
<td>1572 ± 40</td>
<td>1573 ± 19 ± 72 ± 78</td>
<td>1.00 ± 0.03 ± 0.05 ± 0.05</td>
<td>14.1</td>
<td>13.2</td>
</tr>
<tr>
<td>$\mu$TPC-pFGD</td>
<td>1210 ± 35</td>
<td>1064 ± 16 ± 31 ± 53</td>
<td>1.14 ± 0.04 ± 0.03 ± 0.06</td>
<td>11.3</td>
<td>9.0</td>
</tr>
<tr>
<td>$\mu$FGD-pTPC</td>
<td>615 ± 25</td>
<td>531 ± 11 ± 53 ± 31</td>
<td>1.16 ± 0.05 ± 0.11 ± 0.06</td>
<td>5.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The suppression, in both data and MC, of events with 2-track topologies with respect to single-track events (less than 30% of the selected events has 2-track topology, see Table 6.1) most of the times is related to the difficulties in reconstructing the proton produced in a CCQE interaction. As the proton tends to travel a short distance in the detector (mainly FGD) due to its high ionization rate, most times it does not produce enough FGD hits to be reconstructed. This explains the low efficiency (<4%) of the 2-track samples. It should be noticed that, as the muon usually is energetic enough to reach the TPC, the fraction of selected events with $\mu$FGD-pTPC topology and the corresponding efficiency are even lower than those corresponding to the other 2-track topologies. The lower purity of the 2-track samples with respect to the single-track sample (see Table 6.1) is due to the higher background of resonance production interactions, as it is quite probable that the pion from the resonance decay (see Eqs. 1.29 and 1.30) is not reconstructed. On the other hand, it is very unlikely that both the pion and the proton from the resonance decay are not reconstructed. Thus, the purity is higher in the $\mu$TPC sample.

It is interesting to compare the main features of the selected CCQE samples cut by cut. Tables 6.2, 6.3, 6.4, 6.5 summarize the data event reduction, data/MC...
6.1. CCQE event rates

ratio, efficiency and purity after each selection cut for each topology

<table>
<thead>
<tr>
<th>CUT</th>
<th>data evts</th>
<th>data/MC ratio</th>
<th>eff (%)</th>
<th>pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 good spill and DQ</td>
<td>1119379</td>
<td>1.02</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>1046000</td>
<td>1.05</td>
<td>64.3</td>
<td>—</td>
</tr>
<tr>
<td>3 fiducial volume and track quality</td>
<td>48331</td>
<td>0.88</td>
<td>51.6</td>
<td>23.4</td>
</tr>
<tr>
<td>4 external veto</td>
<td>35627</td>
<td>0.87</td>
<td>50.1</td>
<td>31.2</td>
</tr>
<tr>
<td>5 muon TPC PID</td>
<td>26273</td>
<td>0.90</td>
<td>49.6</td>
<td>42.4</td>
</tr>
<tr>
<td>6 one negative FGD-TPC track</td>
<td>23237</td>
<td>0.90</td>
<td>49.1</td>
<td>47.4</td>
</tr>
<tr>
<td>7 no Michel electrons</td>
<td>21530</td>
<td>0.90</td>
<td>48.6</td>
<td>50.9</td>
</tr>
<tr>
<td>8 one tracker track</td>
<td>7629</td>
<td>0.85</td>
<td>30.6</td>
<td>85.3</td>
</tr>
</tbody>
</table>

Table 6.2: Number of events with μTPC topology passing each selection cut for data and MC.

<table>
<thead>
<tr>
<th>CUT</th>
<th>data evts</th>
<th>data/MC ratio</th>
<th>eff (%)</th>
<th>pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 good spill and DQ</td>
<td>1119379</td>
<td>1.02</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>1046000</td>
<td>1.05</td>
<td>64.3</td>
<td>—</td>
</tr>
<tr>
<td>3 fiducial volume and track quality</td>
<td>48331</td>
<td>0.88</td>
<td>51.6</td>
<td>23.4</td>
</tr>
<tr>
<td>4 external veto</td>
<td>35627</td>
<td>0.87</td>
<td>50.1</td>
<td>31.2</td>
</tr>
<tr>
<td>5 muon TPC PID</td>
<td>26273</td>
<td>0.90</td>
<td>49.6</td>
<td>42.4</td>
</tr>
<tr>
<td>6 one negative FGD-TPC track</td>
<td>23237</td>
<td>0.90</td>
<td>49.1</td>
<td>47.4</td>
</tr>
<tr>
<td>7 no Michel electrons</td>
<td>21530</td>
<td>0.90</td>
<td>48.6</td>
<td>50.9</td>
</tr>
<tr>
<td>8 two tracker tracks</td>
<td>7218</td>
<td>1.02</td>
<td>13.7</td>
<td>48.6</td>
</tr>
<tr>
<td>9 one positive FGD-TPC track</td>
<td>2728</td>
<td>0.95</td>
<td>4.7</td>
<td>40.9</td>
</tr>
<tr>
<td>10 common vertex</td>
<td>2486</td>
<td>0.96</td>
<td>4.3</td>
<td>41.9</td>
</tr>
<tr>
<td>11 proton TPC PID</td>
<td>1572</td>
<td>0.96</td>
<td>3.8</td>
<td>59.1</td>
</tr>
</tbody>
</table>

Table 6.3: Number of events with μTPC-pTPC topology passing each selection cut for data and MC.

The first thing one can notice is that the fiducial volume and track quality cuts are responsible for making the data/MC ratio decrease by 16% in all topologies with the muon in TPC and 18% in the $\mu$FGD-pTPC sample. As the simulation of the detector volumes is reliable and the TPC track efficiency is close to 1 in both data and MC, the different effect of these cuts on the simulated and real data is probably due to sand muons. It should be noticed that

\(^2\)The values given in Tables 6.2, 6.3, 6.4, 6.5 refer to the results presented in Chapter ???. Systematics uncertainties are not taken into account.
### Table 6.4: Number of events with $\mu$TPC-pFGD topology passing each selection cut for data and MC.

<table>
<thead>
<tr>
<th>CUT</th>
<th>data evts</th>
<th>data/MC ratio</th>
<th>eff (%)</th>
<th>pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 good spill and DQ</td>
<td>1119379</td>
<td>1.02</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>1046000</td>
<td>1.05</td>
<td>64.3</td>
<td>—</td>
</tr>
<tr>
<td>3 fiducial volume and track quality</td>
<td>48331</td>
<td>0.88</td>
<td>51.6</td>
<td>23.4</td>
</tr>
<tr>
<td>4 external veto</td>
<td>35627</td>
<td>0.87</td>
<td>50.1</td>
<td>31.2</td>
</tr>
<tr>
<td>5 muon TPC PID</td>
<td>26273</td>
<td>0.90</td>
<td>49.6</td>
<td>42.4</td>
</tr>
<tr>
<td>6 one negative FGD-TPC track</td>
<td>23237</td>
<td>0.90</td>
<td>49.1</td>
<td>47.4</td>
</tr>
<tr>
<td>7 no Michel electrons</td>
<td>21530</td>
<td>0.90</td>
<td>48.6</td>
<td>50.9</td>
</tr>
<tr>
<td>8 two tracker tracks</td>
<td>7218</td>
<td>1.02</td>
<td>13.7</td>
<td>48.6</td>
</tr>
<tr>
<td>9 one FGD-only track</td>
<td>2824</td>
<td>1.11</td>
<td>5.3</td>
<td>52.4</td>
</tr>
<tr>
<td>10 common vertex</td>
<td>2438</td>
<td>1.14</td>
<td>4.7</td>
<td>55.7</td>
</tr>
<tr>
<td>11 proton FGD PID</td>
<td>1969</td>
<td>1.13</td>
<td>4.3</td>
<td>66.2</td>
</tr>
<tr>
<td>12 stopping proton</td>
<td>1210</td>
<td>1.13</td>
<td>3.1</td>
<td>67.3</td>
</tr>
</tbody>
</table>

### Table 6.5: Number of events with $\mu$FGD-pTPC topology passing each selection cut for data and MC.

<table>
<thead>
<tr>
<th>CUT</th>
<th>data evts</th>
<th>data/MC ratio</th>
<th>eff (%)</th>
<th>pur (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 good spill and DQ</td>
<td>1119379</td>
<td>1.02</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>2 at least one TPC track</td>
<td>1046000</td>
<td>1.05</td>
<td>64.3</td>
<td>—</td>
</tr>
<tr>
<td>3 fiducial volume and track quality</td>
<td>50997</td>
<td>0.86</td>
<td>19.4</td>
<td>8.1</td>
</tr>
<tr>
<td>4 external veto</td>
<td>33912</td>
<td>0.88</td>
<td>17.2</td>
<td>11.0</td>
</tr>
<tr>
<td>5 proton TPC PID</td>
<td>15644</td>
<td>0.84</td>
<td>15.1</td>
<td>20.1</td>
</tr>
<tr>
<td>6 one positive FGD-TPC track</td>
<td>13116</td>
<td>0.85</td>
<td>14.5</td>
<td>23.5</td>
</tr>
<tr>
<td>7 two tracker tracks</td>
<td>5354</td>
<td>0.95</td>
<td>9.9</td>
<td>44.0</td>
</tr>
<tr>
<td>8 one FGD track</td>
<td>2501</td>
<td>0.98</td>
<td>4.6</td>
<td>45.4</td>
</tr>
<tr>
<td>9 long FGD track</td>
<td>1096</td>
<td>1.04</td>
<td>3.2</td>
<td>72.5</td>
</tr>
<tr>
<td>10 muon FGD PID</td>
<td>1077</td>
<td>1.05</td>
<td>3.1</td>
<td>73.9</td>
</tr>
<tr>
<td>11 common vertex</td>
<td>968</td>
<td>1.06</td>
<td>2.9</td>
<td>76.9</td>
</tr>
<tr>
<td>12 stopping muon</td>
<td>615</td>
<td>1.10</td>
<td>1.8</td>
<td>76.7</td>
</tr>
</tbody>
</table>

At this point of the selection the sand muon contamination is quite high, as no requirements on the track start position have been done yet. As sand muons have been simulated at a given beam intensity, which does not perfectly match the real one, the fiducial volume cut could have a different effect on MC and data and be responsible of the observed MC deficit.
Despite being the less abundant sample, the event sample with $\mu$FGD-pTPC topology has quite high purity (76.7%), mainly thanks to the successful selection of the muon candidate (see Table 6.5) which allows to remove most of the background due to interactions occurring out of the FGD1 FV, resonance production and deep inelastic scattering.

The first five cuts of the CCQE samples with the muon in TPC (see Tables 6.2, 6.3 and 6.4) define the CC sample. As in the inclusive CC selection criterion there are no requirements on the proton, the CC sample is not affected by proton FSI. Thus, the MC excess observed after these first 5 selection cuts is ascribed partially to a not very well known neutrino flux, which, in the neutrino energy region of interest for this analysis, has a systematic uncertainty between 5% and 10% [176], as shown in Figure 6.1. When comparing the data/MC ratio after the first four selection cuts of the $\mu$FGD-pTPC sample (see Table 6.5) with the data/MC ratio after the first four cuts of the other samples (see Tables 6.2, 6.3 and 6.4), very similar results, indicating a data deficit, are obtained. Cuts 1 and 2 are exactly the same for all samples while the only difference in cuts 3 and 4 is that when selecting events with $\mu$FGD-pTPC topology they are applied to the HMP track in the event instead of the HMN one. As there are no specific requirements on the muon and proton candidates, this result supports the hypothesis that the observed data deficit mentioned above is due mainly to the beam flux.

Looking at the data/MC ratios after each cut, one can notice that in the event samples with $\mu$TPC topology the ratio decreases by about 5% and gets smaller than that of the inclusive CC sample (i.e. the event sample corresponding to cuts 1 to 5 in Tables 6.2, 6.3 and 6.4) when one and only one tracker track in
the event is required (see Table 6.2). On the other hand, when events with two tracker tracks are selected the data/MC ratio of all 2-track samples increases by more than 10% (see Table 6.3, 6.4, 6.5), supporting the hypothesis that the proton reconstruction is responsible for the suppression (enhancement) of the 2-track (1-track) samples in MC with respect to data. The subsequent requirement of one positive FGD-TPC track in the event makes the data/MC ratio of the \( \mu \)TPC-pTPC event sample decrease by about 7% (see Table 6.3) while the ratio of the \( \mu \)TPC-pFGD sample increases by \( \sim 9\% \) and that of the \( \mu \)FGD-pTPC sample by \( \sim 3\% \) when selecting events with one FGD-only track (see Tables 6.4 and 6.5). These results show that the topologies with FGD-TPC tracker tracks are suppressed with respect to those with FGD tracks in data, in agreement with the results shown in Table 6.1.

### 6.2 Final kinematic distributions

It is interesting to compare the final kinematic distributions of the CCQE samples, as they cover different regions of the phase space. As discussed briefly in Section 6.1, the large discrepancies between data and MC for both the CC inclusive and the CCQE exclusive samples (shown in Table 6.1 and Figure 6.1) can be partially ascribed to an incomplete neutrino flux description. In order to disentangle possible kinematical discrepancies from a pure normalisation effect caused by the beam flux, in the following, the MC has been normalized to data by area and the beam flux systematic uncertainty has not been included. The error bars in data represent the statistical error in the data samples, while in the MC the error bars contain both the statistical and detector systematic uncertainties. In all cases the MC reproduces the data reasonably well.

#### 6.2.1 Momentum and angular distributions

As shown in the first three plots of Figure 6.2, the topologies with the muon in TPC have similar momentum (left panels) and angular distributions (right panels) for the muon candidate. The momentum distributions are peaked around 500 MeV/c and forward going particles are usually selected due to the detector geometry (the muon candidate is required to be produced in FGD1 and pass through TPC2). However, more forward tracks are favoured in the single track topology (see first plot of Figure 6.2-right) while the requirement of the proton to be reconstructed makes the muon candidate angular distribution slightly wider in the \( \mu \)TPC-pTPC and \( \mu \)TPC-pFGD topologies (see second and third plots of Figure 6.2-right).

When the muon candidate does not pass through the TPC (\( \mu \)FGD-pTPC
6.2. Final kinematic distributions

Figure 6.2: Muon candidate momentum (left) and angular (right) distributions for events with $\mu$TPC (first line), $\mu$TPC-pTPC (second line), $\mu$TPC-pFGD (third line) and $\mu$FGD-pTPC (fourth line) topology. The MC is normalized to data by area.

topology) its momentum distribution changes significantly due to the detector geometry: as the muon must have high angle in order to reach the ECAL/SMRD without passing through the TPC, less forward (see Figure 6.2-bottom-right) and less energetic (see Figure 6.2-bottom-left) tracks are favoured. Thanks to the
Figure 6.3: Proton candidate momentum (left) and angular (right) distributions for events with $\mu$TPC-pTPC (first line), $\mu$TPC-pFGD (second line) and $\mu$FGD-pTPC (third line) topology. The MC has been normalized to data by area.

track sense correction (see Section 4.4.2), backwards going muons are recovered and selected in events with $\mu$FGD-pTPC topology (the muon candidate angular distribution covers the whole phase space). It should be noticed that the muon candidate momentum in this case has been computed by range (see Section 4.4.1).

The proton candidate momentum and angular distributions for the 2-track topologies are shown in Figure 6.3. Analogously to the muon candidate, when the proton candidate is reconstructed in the TPC, it is usually forward going (see first and third panels of Figure 6.3-right) and more energetic (see first and third panels of Figure 6.3-left) than in the $\mu$TPC-pFGD topology (see second panels of Figure 6.3). The suppression of very high (>1500 MeV/c) proton momentum values in the topologies with the proton in TPC is due to the TPC PID cut: as
protons, muons and pions have similar energy loss curves above 1 GeV/c, the cut on the proton TPC PID rejects most protons above this threshold. One should notice that, despite of the proton candidate being a FGD-TPC track in both the $\mu$TPC-pTPC and $\mu$FGD-pTPC topologies, its kinematics is slightly different in the two samples because of the different muon candidate topology: in events with $\mu$TPC-pTPC topology the muon candidate crosses the TPC (consequently smaller muon angles are preferred), while in those with $\mu$FGD-pTPC topology the muon candidate is a FGD track (as the muon candidate usually reaches the ECAL and SMRD, higher muon angles are favoured). This affects the proton candidate kinematics and favours higher proton angles with respect to the neutrino direction in the $\mu$TPC-pTPC topology.

In the $\mu$TPC-pFGD topology the proton candidate momentum has been computed by range as the TPC information is not available for the proton candidate. As the proton is required to stop in the FGD volume, higher momenta are suppressed (see middle panel of Figure 6.3-left) and the proton candidate momentum is lower than in the other 2-track topologies. The momentum threshold (no tracks are reconstructed below $\sim 400$ MeV/c) is due to an intrinsic momentum cut, applied at reconstruction level (see Section 3.4), favouring protons with higher momentum: in order to be reconstructed, a FGD-only track must have at least six FGD hits, while to reconstruct a FGD-TPC track a single FGD hit (plus a signal in TPC) is enough. Furthermore, FGD-only tracks are in general less collimated with the neutrino direction than FGD-TPC tracks due to the detector geometry. Also in this case the track sense correction allows to recover some backwards going tracks (see middle panel of Figure 6.3-right). However, forward going tracks with high polar angle are favoured by the kinematics of the process (see Section 6.3.1). It is interesting to notice that there is a high background of resonant interactions for events with backwards going proton candidate (see Figure 6.4).

6.2.2 Neutrino energy and $Q^2$ distributions

As the muon candidate is reconstructed and its kinematics is known for all topologies, the neutrino energy, $E_\nu$, can be computed using the standard formula based on the muon kinematics:

$$E_\nu(\mu) = \frac{1}{2} \left( \frac{M_p^2 - m_\mu^2}{E_\mu} \right) + 2E_\mu(M_n - V) - \left( M_n - V \right)^2 - E_\mu + \left( M_n - V \right) + p_\mu \cos \theta_\mu$$

(6.1)

where $M_p$, $m_\mu$, $M_n$ are, respectively, the proton, muon and neutron masses; $V$ is the nuclear potential, whose value is set to 25 MeV (which is the known value for Carbon, the main FGD1 material); $E_\mu$ and $p_\mu$ are the energy and momentum of
the muon; \( \cos \theta_\mu \) is the cosine of the angle between the muon and the neutrino. Eq. 6.1 is valid under two assumptions:

- the process is a CCQE interaction. Interactions other than CCQE will distort the reconstructed neutrino energy distribution.

- The neutron is at rest (i.e. the Fermi motion is not taken into account); this approximation will smear and bias the reconstructed neutrino energy distribution, as discussed in Appendix D.

Once the reconstructed neutrino energy is known, the reconstructed transferred quadri-momentum, \( Q^2 \), can be computed as:

\[
Q^2 = 2E_\nu (E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2
\]  \hspace{1cm} (6.2)

where \( E_\nu \) is given by Eq. 6.1 and \( E_\mu, p_\mu, \cos \theta_\mu \) and \( m_\mu \) have the same meaning as in Eq. 6.1.

The reconstructed \( E_\nu \) and \( Q^2 \) distributions for the selected data and MC samples are shown in Figure 6.5. All topologies reproduce the neutrino energy peak around 0.6 GeV (see Figure 6.5-left). The high energy region is suppressed in the \( \mu \)FGD-pTPC topology (see fourth panel of Figure 6.5-left) because, as explained in Section 6.2.1, the detector geometry favours events with less energetic muon candidates while the proton TPC PID suppresses high momentum protons (above 1 GeV/c protons, muons and pions have similar energy loss curves).

Regarding the \( Q^2 \) distributions, shown in Figure 6.5-right, the agreement is remarkable for the 1-track sample, while for the 2-track samples some discrepancies are observed.
Figure 6.5: Left: Reconstructed neutrino energy computed according to Eq. 6.1. Right: Reconstructed transferred quadri-momentum computed according to Eq. 6.2. First line: \( \mu\)TPC topology; second line: \( \mu\)TPC-pTPC topology; third line: \( \mu\)TPC-pFGD topology; fourth line: \( \mu\)FGD-pTPC topology. The MC is normalized to data by area.
The discrepancies between data and MC are ascribed mainly to the approximation of the neutron inside the target nucleus at rest. The effect of Fermi motion on the reconstructed $E_\nu$ and $Q^2$ distributions is briefly discussed in Appendix D.

6.3 Effect of FSI on the proton candidate selection

The hadronic final state of a neutrino-nucleus interaction can be modified by final state interactions (FSI) which, in general, stand for subsequent strong interactions between the product of the electroweak vertex and the other nucleons in the nucleus. FSI can involve processes such as absorption, charge exchange, redistribution of energy and production of new particles and influence the number, momenta and angular distribution of hadrons exiting the nucleus.

Even though FSI often play a key role in understanding particular reactions and are crucial in the reconstruction of the kinematics of neutrino-induced interactions, little experimental work has been done in this area, given the difficulty of calculating the great number of possible final states in such kind of processes. For this reason FSI represent a challenge in MC development and different neutrino generators use slightly different models. The comparison of the MC prediction from different generators with the data from current and future neutrino experiments can help to discriminate between different models.

In this section a brief qualitative study on the effect of proton FSI on the proton candidate selection in both the 1- and 2-track samples is presented.

It should be noticed that, while FSI can have a big impact on the proton candidate selection, they do not affect the muon candidate selection because the muon cannot suffer such kind of interactions. On the other hand other nuclear effects can alter the kinematics of the final state muon:

- Pauli blocking: as nucleons are fermions and, consequently, obey Fermi-Dirac statistics, which allows only two nucleons per energy level, scatterings which would take the nucleon to a state already occupied by other nucleons are not allowed.

- Fermi motion: as the nucleon is confined in a region of the order of 10 fm, it must have some momentum from the uncertainty principle (typically 100-200 MeV/c), causing the center of mass energy where the reaction takes place to change. In Carbon target the neutron can have a momentum up to $\sim 220$ MeV/c.

- binding energy: part of the incoming neutrino energy is needed to remove the nucleon from the nucleus.
All these effects are taken into account in the NEUT MC simulation, which has been used in this analysis.

As mentioned above, the characterization of a neutrino-nucleus interaction often depends on the hadronic final state. If the proton produced in a neutrino-nucleus CCQE interaction, which will be called “primary proton” in the following, suffers FSI and does not escape from the nucleus, another proton produced in subsequent strong interactions in the nucleus, which will be called “secondary proton” in the following, can escape from the nucleus and be selected as the proton candidate. In this case the reconstructed proton kinematics will differ from that of the primary proton, and the information about the initial CCQE interaction carried by the primary proton will be lost. On the other hand, if the primary proton suffers only elastic scattering, it has a chance to be reconstructed and selected as the proton candidate, but its kinematics will be slightly different from that at the interaction vertex.

As the muon produced in a CCQE interaction cannot suffer strong interactions in the nucleus, it is usually correctly reconstructed.

In order to study the effect of FSI on the proton candidate selection in the 1- and 2-track samples, a MC-only study has been done. Events with $\mu$TPC, $\mu$TPC-pTPC, $\mu$TPC-pFGD, $\mu$FGD-pTPC topologies have been selected and, in addition, the following requirements have been applied:

- the selected events must be generated by a true CCQE interaction;
- in the 2-track samples the muon and proton candidates must be, respectively, a true muon and a true proton. In events with 1-track topology, as there is no proton candidate, the only requirement is that the muon candidate must be a true muon.

The fraction of events whose primary proton (i.e. the proton produced in the neutrino-nucleus interaction) escapes from the nucleus for the CCQE samples selected according to the criteria described above, is summarized in Table 6.6. According to NEUT, if the primary proton undergoes elastic scattering only, it usually escapes from the nucleus, while if it undergoes other kind of interactions producing secondary protons, it does not, as will be seen in the following.

In the CCQE samples with the muon in TPC about half of the times the proton candidate exits the nucleus. This fraction is about 10% higher for events with $\mu$FGD-pTPC topology.

### 6.3.1 2-track topologies

In this section the case of events with 2-track topologies is treated. The 1-track sample is discussed separately in Section 6.3.2.
### Table 6.6: Fraction of selected true CCQE events whose primary proton escaped from the nucleus, computed for each CCQE 1- and 2-track topology. The additional selection requirements described above have been applied.

<table>
<thead>
<tr>
<th>topology</th>
<th>$P_{\text{primary escaped (%)}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$TPC</td>
<td>53.5</td>
</tr>
<tr>
<td>$\mu$TPC-pTPC</td>
<td>55.4</td>
</tr>
<tr>
<td>$\mu$TPC-pFGD</td>
<td>52.3</td>
</tr>
<tr>
<td>$\mu$FGD-pTPC</td>
<td>62.7</td>
</tr>
</tbody>
</table>

Figure 6.6 shows the momentum and angular distributions of the candidate and primary protons, when the latter (in red) exits the nucleus. In this case the primary proton is usually reconstructed and selected as the proton candidate. The small discrepancies are due to elastic scattering suffered by the primary proton in the nucleus.

![Figure 6.6: Top: Primary proton momentum (red) and proton candidate true momentum (black) when the primary proton escapes from the nucleus. Bottom: Primary proton angle (red) and proton candidate angle (black) with respect to the neutrino true direction when the primary proton escapes from the nucleus. Left: $\mu$TPC-pTPC topology. Middle: $\mu$TPC-pFGD topology. Right: $\mu$FGD-pTPC topology. The additional selection requirements described in Section 6.3 have been applied.](image)

Figure 6.7 shows the momentum and angular distributions of the candidate (black) and primary (red) protons when the latter does not exit the nucleus (and, consequently, is not reconstructed). In this case the proton candidate

...
6.3. Effect of FSI on the proton candidate selection

corresponds to a secondary, less energetic, proton, as shown in Figure 6.7-top.

![Figure 6.7](image)

Figure 6.7: Top: Primary proton momentum (red) and proton candidate true momentum (black) when the primary proton does not escape from the nucleus. Bottom: Primary proton angle (red) and proton candidate angle (black) with respect to the neutrino true direction when the primary proton does not escape from the nucleus. Left: $\mu$TPC-pTPC topology. Middle: $\mu$TPC-pFGD topology. Right: $\mu$FGD-pTPC topology. The additional selection requirements described in Section 6.3 have been applied.

In addition one should notice that in the $\mu$TPC-pTPC topology (Figure 6.7-bottom-left) the secondary proton is more forward than the primary one as it has to reach the TPC. In the $\mu$FGD-pTPC topology (Figure 6.7-bottom-right) both the secondary and primary proton angular distributions are constrained by the muon topology and the angle of the primary proton with respect to the neutrino direction is smaller than in the $\mu$TPC-pTPC topology. In the $\mu$TPC-pFGD topology (Figure 6.7-bottom-middle) the proton candidate covers a larger region of the phase space than the primary one because of less angular constraints (the proton candidate has to be contained in the FGD1 volume and does not have to reach the TPC). In addition, it should be noticed that the primary proton is always forward going while some proton candidates are backwards going. That means that the reconstructed proton kinematics in the events with backwards going proton candidate does not correspond to the kinematics at the interaction vertex (it either corresponds to a secondary particle produced by FSI or to a particle produced by resonances or other backgrounds, see Figure 6.4).
6.3.2 1-track topology

In the 1-track topology the primary proton is not reconstructed at all because either it does not escape from the nucleus or it escapes from the nucleus but it does not satisfy the minimum requirements to be reconstructed. In addition, no other secondary proton is reconstructed.

Figure 6.8: Top: Primary proton (left) and primary muon (right) momentum (top) and angle with respect to the neutrino true direction (bottom) when the primary proton exists the nucleus (green) and when it does not (black). The additional selection requirements described in Section 6.3 have been applied.

Figure 6.8 shows the primary proton momentum and angle (left panels) with respect to the neutrino true direction when it escapes from the nucleus (green) and when it does not (black), and the corresponding primary muon momentum and angular distributions (right panels). Although the proton angular distributions are very similar in the two cases (see Figure 6.8-bottom left), protons exiting the nucleus are usually less collimated with the neutrino direction than those stopping inside the nucleus (and the corresponding primary muon is more forward, as shown in Figure 6.8-bottom right). The fraction of backwards going particles is higher when the primary proton exists the nucleus. As no proton candidate is reconstructed in events with 1-track topology, primary protons escaping the nucleus must have low momentum (as shown in Figure 6.8-top left): as they lose their energy very rapidly in the detector material, they do not leave enough hits to be reconstructed. On the other hand, when the primary proton
6.3. Effect of FSI on the proton candidate selection

does not exit the nucleus (and consequently, is not reconstructed) no secondary protons are reconstructed probably due to reconstruction failures, the detector geometry or the kinematics of the event.

6.3.3 Data vs MC comparison

By comparing the proton candidate kinematic distributions predicted by the MC with the results obtained with real data, it is possible to perform a qualitative study and try to infer some conclusions about the simulation of FSI in NEUT. Figures 6.9 and 6.10 show the proton candidate momentum and angular distributions, respectively, for the 2-track topologies for both data and MC. In the MC, the two cases in which the primary proton exits the nucleus (left panels) and in which it does not (right panels) have been separated for true CCQE interactions. The data are the same on both panels.

The agreement between data and MC is reasonably good in all momentum distributions for all topologies, apart from shift in data towards higher momentum values for the $\mu$FGD-pTPC topology when the primary proton does not escape from the nucleus (see Figure 6.9-bottom-right).

The main differences between data and MC can be observed in the angular distributions (see Figure 6.10). When the primary proton exits the nucleus (left panels), small discrepancies can be observed for the $\mu$TPC-pTPC and $\mu$TPC-pFGD samples (top and middle panels, respectively). The agreement between data and MC is quite good for events with $\mu$FGD-pTPC topology (bottom panel).

When the primary proton does not exit the nucleus (in this case for true CCQE interactions the proton candidate is a secondary particle produced by proton FSI in the nucleus) the agreement between data and MC gets worse for all the 2-track topologies (right panels of Figure 6.10). In the $\mu$TPC-pTPC topology (top panel) the proton candidate polar angle seems to be shifted towards smaller angles in the MC. For events with $\mu$TPC-pFGD (middle panel) and $\mu$FGD-pTPC (bottom panel) topologies there is a data deficit at small angles and a data excess in the intermediate region for forward going tracks. In addition, there is a MC excess of backward going tracks in the $\mu$TPC-pFGD sample (middle panel). For the topology with the muon in the FGD ($\mu$FGD-pTPC, bottom panel) the angular distribution is wider in the MC. Those data-MC discrepancies (in the case in which the primary proton does not escape from the nucleus), can be attributed either to a wrong description of the secondary proton kinematics in the MC or to an excess of events with FSI in the MC. Given the reasonable agreement of the proton kinematics for events in which the primary proton escapes from the nucleus, the second hypothesis is favoured: it seems that the fraction of times the proton does not escape the nucleus is overestimated in the MC. It should be
Figure 6.9: Proton candidate reconstructed momentum. Events with $\mu$TPC-pTPC (top), $\mu$TPC-pFGD (middle), $\mu$FGD-pTPC (bottom) topologies have been selected in both data and MC. In addition, the MC events satisfy also the following requirements: they must have been generated by a true CCQE interaction; the muon and proton candidates must be, respectively, a true muon and a true proton; the primary proton escaped from the nucleus (left) or the primary proton did not exit the nucleus (right). MC is normalized to data by area.

noticed that the first hypothesis would imply similar kinematics for the primary and secondary protons, which is very unlikely. This is, however, a qualitative statement; more studies are needed to clarify the situation.
6.3. Effect of FSI on the proton candidate selection

Figure 6.10: Proton candidate polar angle. Events with $\mu$TPC-pTPC (top), $\mu$TPC-pFGD (middle), $\mu$FGD-pTPC (bottom) topologies have been selected in both data and MC. In addition, the MC events satisfy also the following requirements: they must have been generated by a true CCQE interaction; the muon and proton candidates must be, respectively, a true muon and a true proton; the primary proton escaped from the nucleus (left) or the primary proton did not exit the nucleus (right). MC is normalized to data by area.
Chapter 7

Summary and prospects

The T2K experiment is a long baseline neutrino oscillation experiment, whose main purpose was to discover the $\nu_\mu \rightarrow \nu_e$ oscillations ($\nu_e$ appearance) and refine the measurement of the atmospheric parameters, $\Delta m^2_{32}$ and $\theta_{32}$, using the $\nu_\mu$ disappearance channel. T2K was the first experiment providing a hint for a non-zero value of $\theta_{13}$, by exploring the $\nu_e$ appearance channel, in 2011. T2K uses one of the most intense accelerator muon neutrino beam ever built, produced at the J-PARC facility and sent toward the Super-Kamiokande (SK) water Cherenkov detector, located 295 km away in the Kamioka Observatory. The neutrino beam properties and interactions before the oscillation are studied at the near detector suite (ND280 and INGRID), located 280 m from the target. Specifically, ND280 measures the neutrino beam properties and the neutrino interaction cross-section and kinematics before the oscillation, in order to predict the neutrino flux and the relevant neutrino interactions at SK. Provided that $\theta_{13}$ is not null, it is possible to investigate the matter-antimatter asymmetries through the search for CP-violation in the leptonic sector, which implies different oscillation probabilities for neutrinos and antineutrinos. To reach this goal more precise measurements using long baseline accelerator neutrino and antineutrino experiments are needed. However, the precision of such measurements is limited, among others, by the knowledge of the neutrino properties and interactions at energies in the GeV region, where the charged current quasi-elastic (CCQE) neutrino-nucleus interaction typically gives the largest contribution to the signal samples. In the last decades several experiments have studied this channel, showing that it is more complicated than expected. Thus, new measurements are needed. Thanks to its high statistics and excellent spatial resolution, ND280 is able to provide precise CCQE cross-section measurements and contribute to improve the understanding of this channel.

The analysis presented in this thesis provides a method to select CCQE inter-
actions in the tracker of the T2K ND280 off-axis near detector, based on studying the properties of events generated by the ND280 NEUT Monte Carlo (MC) simulation. In a $\nu_\mu$ CCQE interaction, the neutrino interacts with a neutron in the nucleus to produce a muon and a proton in the final state. Both the 1-track (only the muon is reconstructed) and 2-track (both the muon and the proton are reconstructed) cases have been addressed. Four different topologies, depending on the detector in which the muon and the proton are reconstructed and on the number of selected tracks, have been identified and studied. Only interactions happening in the most upstream FGD (FGD1) have been taken into account. The 1- and 2-track topologies which rely on the reconstruction of the muon in the TPC (the $\mu$TPC, $\mu$TPC-pTPC, $\mu$TPC-pFGD topologies) are based on the selection of an inclusive sample of charged current (CC) events. The reconstructed vertex of the event is defined as the start position of the muon candidate. Next, the selection is split into three categories based on whether the proton is reconstructed or not and, in the case it is reconstructed, on the detectors crossed by the proton. The selection criteria of events with $\mu$FGD-pTPC topology, in which the muon does not cross the TPC and the reconstructed vertex is defined by the start position of the proton candidate, is based on a different set of cuts. In all cases the selection of CCQE events relies heavily on the selection of muon- and proton-like tracks and makes extensive use of the TPC and FGD particle identification (PID).

The global reconstruction, combining the results of the track reconstruction from each sub-detector taking into account the ND280 geometry, the momentum loss and multiple scattering, is used in this analysis. The resulting global tracks cross several sub-detectors. First, the reconstruction in the TPC is performed. Then, TPC tracks are extrapolated into the FGDs and matched to FGD hits identified using the Kalman filter. The tracker tracks obtained in this way are extrapolated into the other subdetectors. FGD hits which were not used in the FGD-TPC matching process are saved and reconstructed separately, resulting in short tracks fully contained in the FGDs. The curvature of tracks passing through the TPC are used to compute the track momentum and charge. For fully contained FGD tracks, for which the curvature information is not available, the momentum is estimated by range. The particle identification in the TPCs and FGDs is performed based on the energy loss signature of the tracks in the detectors (the TPC gas and the FGD scintillator bars).

The exclusive topologies studied in this thesis are very important to understand the details of the CCQE process. As the characterization of a neutrino-nucleus interaction is based on the hadronic final state of the reaction, which can be altered by proton final state interactions (FSI), the two-track sample is especially interesting because it allows to access the full kinematics of the CCQE
events.

Runs 1, 2, 3 and 4 of official production 5F of T2K data (comprising a total of $1.578169 \times 10^{20}$ protons on target) and the ND280 NEUT MC simulated data for Runs 1, 2, 3 and 4 of official production 5E were used in this analysis. The relevant systematic uncertainties affecting the selection were measured. In the following, the statistical error (first value), the detector systematic error (second value) and the beam flux systematic error (third value) are given for the MC. Only the statistical error is given for data. Based on the MC prediction, the expected number of events for the accumulated POT was $8691 \pm 46 \pm 210 \pm 420$ for the one-track sample and $1573 \pm 19 \pm 72 \pm 78$, $1064 \pm 16 \pm 31 \pm 53$, $531 \pm 11 \pm 53 \pm 31$ for the two-track samples ($\mu$TPC-pTPC, $\mu$TPC-pFGD, $\mu$FGD-pTPC topologies, respectively). The purities of the selected event samples are $85.3\%$ in the one-track case and $59.1\%$, $67.3\%$, $76.7\%$ in the two-track cases ($\mu$TPC-pTPC, $\mu$TPC-pFGD, $\mu$FGD-pTPC topologies, respectively). The corresponding efficiencies are $30.6\%$, $3.8\%$, $3.1\%$, $1.8\%$, respectively. When analysing real data, a total of 11026 CCQE candidate events were selected:

- $\mu$TPC topology: $7629 \pm 87$ events;
- $\mu$TPC-pTPC topology: $1572 \pm 40$ events;
- $\mu$TPC-pFGD topology: $1210 \pm 35$ events;
- $\mu$FGD-pTPC topology: $615 \pm 25$ events;

The obtained data/MC ratios are $0.88\pm0.01\pm0.02\pm0.04$ for the $\mu$TPC sample and $1.00 \pm 0.03 \pm 0.05 \pm 0.05$, $1.14 \pm 0.04 \pm 0.03 \pm 0.06$ and $1.16 \pm 0.05 \pm 0.11 \pm 0.06$ for the $\mu$TPC-pTPC, $\mu$TPC-pFGD and $\mu$FGD-pTPC samples, respectively. These results suggest that there is a difference in the reconstruction rate of the primary proton produced by the neutrino-nucleus interaction in data and MC, probably due to a not realistic simulation of proton FSI in the NEUT MC causing the primary proton to escape from the nucleus less frequently in the MC than in data. A brief qualitative study on the effect of proton FSI on the proton candidate selection, presented in this thesis, supports this hypothesis. Further studies of such kind of topologies, not addressed in this thesis work, could help in discriminating between different neutrino interaction models.

The selection criterion, as well as the propagation of the systematic uncertainties, developed in this thesis work has been used to extract a CCQE cross-section on Carbon $^{12}$. This study, which will be published shortly, has been conducted by the IFIC T2K group in collaboration with other T2K groups from other institutions. However, this work is out of the scope of this thesis and is not addressed here.
Appendix A

Reduced FGD1, Barrel ECAL and SMRD volumes

As explained in Section 4.4.1, in order to properly compute the momentum by range, non-TPC tracks must stop inside the ND280 detector.

In the analysis presented in this thesis non-TPC tracks not completely contained in FGD1 (such as the muon candidate in the pTPC-μFGD topology) are required to have their reconstructed end position inside a reduced Barrel ECAL or SMRD volume. The Barrel ECAL surrounds the P0D and the tracker (as shown in Figure A.1). In order to define the reduced volume, the Barrel ECAL volume has been split up in six parts and each of them has been tagged as Left, Right, Top Left, Top Right, Bottom Left, Bottom Right depending on their position with respect to the P0D+tracker system. The SMRD surrounds the Barrel ECAL, the P0D and the tracker (see Figure A.1) and is made up of eighth modules. In order to define the reduced SMRD volume, the central parts of modules from 1 to 5 have been grouped together, as well as modules 7 and 8, while module 6 has been considered separately, according to the distribution of the SMRD scintillation counters in the magnet gaps. The position of the left and right sides are defined separately for each group of modules. The reduced volumes defined by the Left Top, Right Top, Left Bottom and Right Bottom SMRD modules are grouped together, as shown in Figure A.2.

FGD-only tracks (such as the muon candidate in the pTPC-μFGD topology and the proton candidate in the μTPC-pFGD topology) are required to stop inside a reduced FGD1 volume. The only difference between the standard FGD1 FV (defined in Table 4.5) and the reduced volume is that in the latter also the last FGD1 layers along z are removed.

The reduced detector volumes used in the analysis are summarized in Tables A.1, A.2, A.3.
Figure A.1: Schematic drawing of the ND280 detector. The ND280 coordinate system is shown too. The origin of the axes is located in the middle of the basket. The eight SMRD modules are tagged with numbers from 1 to 8. The Right, Top Right, Bottom Right parts of the Barrel Ecal, used to define the reduced Barrel Ecal volume in Table A.2 are indicated. The Left, Top Left, Bottom Left Barrel Ecal parts are specular to them. The SMRD parts used to define the reduced SMRD volume are shown in Figure A.2.

<table>
<thead>
<tr>
<th>FGD1</th>
<th>min (mm)</th>
<th>max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>-874.51</td>
<td>874.51</td>
</tr>
<tr>
<td>$y$</td>
<td>-819.51</td>
<td>929.52</td>
</tr>
<tr>
<td>$z$</td>
<td>136.875</td>
<td>426.005</td>
</tr>
</tbody>
</table>

Table A.1: Position of the reduced FGD1 volume with respect to the ND280 coordinate system. The only difference with respect to the standard FGD1 FV, defined in Table 4.5 is that also the last FGD1 layers are removed.
<table>
<thead>
<tr>
<th></th>
<th>min (mm)</th>
<th>max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>1385.03</td>
<td>1756.27</td>
</tr>
<tr>
<td>(y)</td>
<td>-1023.47</td>
<td>1196.47</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
<tr>
<td><strong>Right Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>-1776.27</td>
<td>-1385.03</td>
</tr>
<tr>
<td>(y)</td>
<td>-1023.47</td>
<td>1197.47</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
<tr>
<td><strong>Top Left Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>76.03</td>
<td>1535.97</td>
</tr>
<tr>
<td>(y)</td>
<td>1310.53</td>
<td>1681.77</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
<tr>
<td><strong>Top Right Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>-1535.97</td>
<td>-76.03</td>
</tr>
<tr>
<td>(y)</td>
<td>1310.53</td>
<td>67</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
<tr>
<td><strong>Bottom Left Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>176.03</td>
<td>1635.97</td>
</tr>
<tr>
<td>(y)</td>
<td>-1721.77</td>
<td>-1330.53</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
<tr>
<td><strong>Bottom Right Barrel ECAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x)</td>
<td>-1635.03</td>
<td>-176.03</td>
</tr>
<tr>
<td>(y)</td>
<td>-1721.77</td>
<td>-1330.53</td>
</tr>
<tr>
<td>(z)</td>
<td>-623.97</td>
<td>3175.97</td>
</tr>
</tbody>
</table>

Table A.2: Position of the reduced Barrel ECAL volume with respect to the ND280 coordinate system.
<table>
<thead>
<tr>
<th></th>
<th>min (mm)</th>
<th>max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left 1-5 SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>1832.03</td>
<td>1961.97</td>
</tr>
<tr>
<td>$y$</td>
<td>-2029.98</td>
<td>2009.98</td>
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<td>$z$</td>
<td>-3688.98</td>
<td>790.47</td>
</tr>
<tr>
<td>Right 1-5 SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-2081.97</td>
<td>-1832.02</td>
</tr>
<tr>
<td>$y$</td>
<td>-2029.98</td>
<td>2009.98</td>
</tr>
<tr>
<td>$z$</td>
<td>-3688.98</td>
<td>790.47</td>
</tr>
<tr>
<td>Left 6 SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>1832.03</td>
<td>2026.97</td>
</tr>
<tr>
<td>$y$</td>
<td>-2029.98</td>
<td>2009.98</td>
</tr>
<tr>
<td>$z$</td>
<td>1121.03</td>
<td>1746.97</td>
</tr>
<tr>
<td>Right 6 SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-2146.97</td>
<td>-1832.02</td>
</tr>
<tr>
<td>$y$</td>
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<td>$z$</td>
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<td>Left 7-8 SMRD</td>
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<td>2156.97</td>
</tr>
<tr>
<td>$y$</td>
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<td>2009.98</td>
</tr>
<tr>
<td>$z$</td>
<td>2077.03</td>
<td>3688.48</td>
</tr>
<tr>
<td>Right 7-8 SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-2276.97</td>
<td>-1832.02</td>
</tr>
<tr>
<td>$y$</td>
<td>-2029.98</td>
<td>2009.98</td>
</tr>
<tr>
<td>$z$</td>
<td>2077.03</td>
<td>3688.47</td>
</tr>
<tr>
<td>Top Left SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>32.02</td>
<td>1896.98</td>
</tr>
<tr>
<td>$y$</td>
<td>2010.02</td>
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<tr>
<td>$z$</td>
<td>-3938.98</td>
<td>3693.98</td>
</tr>
<tr>
<td>Top Right SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-1896.98</td>
<td>-32.02</td>
</tr>
<tr>
<td>$y$</td>
<td>2010.02</td>
<td>2137.48</td>
</tr>
<tr>
<td>$z$</td>
<td>-3938.98</td>
<td>3693.98</td>
</tr>
<tr>
<td>Bottom Left SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-1896.98</td>
<td>1896.98</td>
</tr>
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<td>$y$</td>
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<td>$z$</td>
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<td>3688.98</td>
</tr>
<tr>
<td>Bottom Right SMRD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-1896.98</td>
<td>-32.02</td>
</tr>
<tr>
<td>$y$</td>
<td>-2282.48</td>
<td>-2030.02</td>
</tr>
<tr>
<td>$z$</td>
<td>-3938.98</td>
<td>3688.98</td>
</tr>
</tbody>
</table>

Table A.3: Position of the reduced SMRD volume with respect to the ND280 coordinate system.
Figure A.2: Schematic drawing of the left SMRD side. The SMRD portions (Top, Bottom, 1-5, 6 and 7-8) used to define the reduced SMRD volume in Table A.3 are shown. The central parts of modules from 1 to 5 have been grouped together, as well as modules 7 and 8. Module 6 has been considered separately. The reduced volumes of the Top and Bottom SMRD parts are given as a whole (all SMRD modules grouped together). The right SMRD side is specular to the left one.
A. Reduced FGD1, Barrel ECAL and SMRD volumes
Appendix B

TPC cluster efficiency systematics

As explained in Section 3.4.1, a cluster in the TPC is defined as a collection of contiguous hits. The TPC cluster efficiency is defined as the probability to find a reconstructed cluster at a given MM pad column when the particle should have produced one.

A different cluster efficiency in data and MC induces a systematic uncertainty mainly due to the application of the so-called “TPC track quality” cut (see Sections 4.7 and 4.11), which requires the HMN and HMP tracks in the event to have more than 18 TPC clusters. The TPC cluster efficiency is expected to be the dominant source of the systematic uncertainty induced by this cut, as the effects of MM modules mis-alignment and pattern recognition are expected to be small.

A sample of events passing the data quality cut (see Section 4.6) and with a single track crossing TPC2 has been selected and used to compute this systematics. The cutes are listed in Table B.1. This sample contains mainly muons (there is an intrinsic excess in the data due to sand muons, which are not present in the standard MC).

The cluster efficiency is strictly related to the amount of deposited charge in a given pad column. As the outermost columns are subject to border effects, one can assume that the efficiency is different in the outermost columns. In order to study the outer efficiency the TPC2 track start position along z ($z_{\text{start}}$) has been used. Figure B.1 shows the $N_{\text{cluster}}$ and $z_{\text{start}}$ distributions when sand muons

---

1 tracks with few clusters normally cross only one Micromegas (MM) module (except tracks crossing the cathode, but the contribution from this kind of tracks is expected to be small)

2 The binning of the $z_{\text{start}}$ distribution as been chosen in such a way that the effect of mis-alignment in real data is avoided.
Table B.1: List of cuts used to select the TPC2 track sample.

<table>
<thead>
<tr>
<th>CUT NAME</th>
<th>CUT DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>good spill and DQ</td>
<td>good quality event in good quality beam spill (according to the data quality flag)</td>
</tr>
<tr>
<td>bunching</td>
<td>tracks are grouped together in bunches according to their times</td>
</tr>
<tr>
<td>total track multiplicity</td>
<td>at least one FGD or TPC track</td>
</tr>
<tr>
<td>TPC2 tracks multiplicity</td>
<td>only one track crossing TPC2</td>
</tr>
</tbody>
</table>

are not taken into account in the MC. In this case the intrinsic excess in the data due to sand muons, which are not present in the MC, is clearly visible.

Figure B.1: Distribution of the number of TPC2 clusters (left) and TPC2 track start position along \( z \) (right) for the track candidate, for both data and MC samples after all selection cuts listed in Table B.1 have been applied. The contribution from sand muons is not taken into account in the MC.

Let \( \alpha_{\text{in}} \) and \( \alpha_{\text{out}} \) be the extra cluster inefficiencies to be added to the MC in order to match the data, for inner and outer columns respectively. Two mathematical expressions for the expected number of events in the distributions of \( N_{\text{cluster}} \) (see Eq. B.3 and Table B.2), and \( z_{\text{start}} \) (see Eq. B.6), taken into account the effect of \( \alpha_{\text{in}} \) and \( \alpha_{\text{out}} \), have been found (see Sections B.0.4 and B.0.5) under several assumptions:

- the probability of losing one cluster is given by the cluster inefficiency in a single column multiplied by the number of columns (i.e. \( 68 \cdot \alpha_{\text{in}} \) and \( 4 \cdot \alpha_{\text{out}} \) for inner and outer columns respectively);
- only tracks losing one or two clusters have been taken into account, as the probability of losing more than two is negligible;
• $\alpha_{out}$ is the same for all outer columns.

Those expressions depend on three free parameters ($\alpha_{in}$, $\alpha_{out}$ and a global data-MC normalization factor) and on the input distributions, $N_{cluster}^{MC}$ and $N_{z}^{MC}$, corresponding to the number of events in the $N_{cluster}$ and $z_{start}$ distributions respectively, for the nominal MC. Values of $\alpha_{in}$ and $\alpha_{out}$ have been obtained by fitting those two expressions to data. The fit has been restricted to regions of $N_{cluster}$ and $z_{start}$ with large statistics, where the sensitivity to $\alpha_{in}$ and $\alpha_{out}$ is enhanced ($N_{cluster} \geq 62$ and $z_{start} < 713$).

![Figure B.2: Cluster (left plot) and start position (right plot) fits respectively, using the TPC2 tracks sample.](image)

The values of the inner and outer efficiencies obtained by the fit (see Figure B.2) are:

• $\alpha_{in} = 0.00097 \pm 0.00001$, i.e. for inner columns only a $\sim 0.1\%$ extra inefficiency has to be added to the MC to match the data.

• $\alpha_{out} = 0.0283 \pm 0.0002$, i.e. the nominal MC has $\sim 3\%$ larger efficiency for outer columns.

It can be noticed that the agreement between data and MC is much better when the extra cluster inefficiency is introduced in the MC (red line in Figure B.2). No spatial, angular and momentum dependence has been found, as $\alpha_{in}$ and $\alpha_{out}$ have been computed also for different spatial, angular and momentum ranges and in all cases values of the same order of the ones given above have been found.

The presence of sand muons only in the data could introduce an artificial difference in cluster efficiency due to the different phase space of the selected sample. As a cross-check the study has been repeated for two other samples in
which the presence of sand muons is minimized: i) applying an extra cut on the start position of the global track ($z < 3000$ cm, $|x| < 950$ cm, $|y| < 950$ cm) and ii) the $\nu_\mu$ CC inclusive sample without the track quality cut. In both cases $\alpha_{in}$ and $\alpha_{out}$ are of the same order as in the other sample.

As mentioned above, the TPC cluster efficiency systematics affects the TPC track quality cut. However, as discussed in Sections 4.7 and 4.11, the effect of the track quality cut is small, as only a small fraction of the selected tracks has less than 19 clusters (see Figures 4.13-right and 4.32-right). Thus, the effect of the systematic error associated with it is expected to be small as well. In more detail, its effect has been estimated to be negligible in the CC selection. On the other hand, it has been observed that the TPC track quality cut has not effect on the final number of selected events in the CCQE 1- and 2-track samples. Thus, it was decided to not propagate this systematics in the analysis presented in this thesis.

B.0.4 Expected number of events in the $N_{\text{cluster}}$ distribution

Let $x$ be the number of clusters in the closest TPC of the track. A track traversing two entire MM modules will have 4 clusters in the edges of the MM and $(x - 4)$ clusters inside the MM, as shown in the schematic picture in Figure B.3.

![Schematic view of a track traversing 2 MM modules. The red points correspond to the clusters in the edges of the MMs.](image)

In general the probability of losing one cluster is given by the cluster inefficiency in a single column multiplied by the number of columns. The probability for a track in bin $x$ of losing one cluster in the inner MM pads is then given by:

$$P_{1}^{\text{in}} = (x - 4)\alpha_{in} \quad (B.1)$$

while the probability of losing one cluster in the edges of the MM is:

$$P_{1}^{\text{out}} = 4\alpha_{out} \quad (B.2)$$
It is a good approximation to consider only tracks losing one or two clusters due to the extra MC cluster inefficiency since the probability of losing more than two clusters is negligible. In the case of tracks loosing two clusters one should consider different cases:

- the track loses two clusters in the outer pads;
- the tracks loses two clusters in the inner pads;
- the track loses one cluster in the outer pads and one in the inner pads.

The two probabilities of losing a single cluster can be multiplied since they are independent. The number of different combinations of two clusters will be given by the binomial coefficient.

Since a MC track losing one cluster (two clusters) will migrate to the previous (second previous) bin, the number of entries $N_x$ in bin $x$ will be increased by the number of events migrating from the bins $x+1$ and $x+2$ and will be decreased by the number of events migrating to the bins $x-1$ and $x-2$. The function to fit the data must take into account all these terms and is given by:

$$f(\alpha_{in}, \alpha_{out}, x) = N_x \left[ 1 - \alpha_{in}(x-4) \left( 1 + \frac{x-5}{2} \alpha_{in} + 4\alpha_{out} \right) - 4\alpha_{out} \left( 1 + \frac{3}{2} \alpha_{out} \right) \right]$$

$$+ N_{x+1} [ (x-3)\alpha_{in} + 4\alpha_{out} ] + N_{x+2} \left[ \frac{(x-2)(x-3)}{2} \alpha_{in}^2 + 4\alpha_{out}^2 \left( x - \frac{1}{2} \right) \right]$$

(B.3)

Tables B.2 summarize all terms contributing to the number of clusters in bin $x$.

### B.0.5 Expected number of events in the $z_{\text{start}}$ distribution

The track start position along $z$ in TPC2 should correspond to the first pad column if a cluster is found on it and to the second pad column when the cluster in the outer pad is not reconstructed.

Since a MC track losing one cluster will migrate to the next bin of right plot of Figure B.1, the number of entries $N_x$ in bin $x$ will be increased by the number of events migrating from the previous bin $x-1$ and will be decreased by the number of events migrating to the next bins $x+1$.

Taking into account that inner and outer pads have different hit efficiency, one can find a mathematical expression, depending on the extra inner and outer MC cluster inefficiencies and on the number of events in each MC bin, giving the number of events in each MC bin. Also in this case the probability of losing one cluster is given by the cluster inefficiency in a single column multiplied by the number of columns (see Eq. B.1 and B.2). Furthermore the assumption that
Table B.2: List of terms contributing to the fit function. The terms listed in the first two tables must be subtracted to the number of entries in bin \( x \) \((N_x)\) while the terms listed in the third and fourth tables must be added. The combination of all these terms gives Eq. B.3. \( \alpha_{in} \) and \( \alpha_{out} \) are the extra MC cluster inefficiencies in the inner and outer pad columns respectively; \( x \) is the bin number; \( N_x \) is the number of entries in bin \( x \); \( N_{x+1} \) is the number of entries in bin \( x + 1 \); \( N_{x+2} \) is the number of entries in bin \( x + 2 \).

\[ \alpha_{out} \] is the same for all outer columns has been made. The number of events migrating from the first to the second bin, \( N_{12} \), will be given by:

\[ N_{12} = \alpha_{out} N_1 \quad (B.4) \]

where \( N_1 \) is the number of MC events in the first bin. The number of events migrating from the second to the third bin, \( N_{23} \), will be given by:

\[ N_{23} = \alpha_{in}(N_2 + N_{12}) \quad (B.5) \]

where \( N_2 \) is the number of MC events is the second bin, and so on.

In general, the number of events migrating from bin \( i \) to bin \( j \) will be then given by:

\[ N_{ij} = \alpha_{in}(N_i + N_{i-1,i}) \quad (B.6) \]
where $N_{i-1,i}$ is the number of events migrating from bin $i-1$ to bin $i$, taking into account that the number of events migrating from the first to the second bin depends on $\alpha_{out}$ and is given by Eq. B.4.
B. TPC cluster efficiency systematics
Appendix C

Propagation of the pion secondary interactions systematics

In order to compute the systematics associated with pion SI, the impact of varying the secondary interaction cross-section on the total number of events was estimated taking into account both effects (the discrepancy between data and MC and the uncertainty on the available data), as described in detail in [165] and summarized below.

Since only neutrino interactions occurring in the FGD1 FV are considered in this analysis, then the $\pi^+$ and $\pi^-$ tracks may be missed if one of the relevant SI described above occurs inside the FGD1 FV. So, in order to estimate the effect of varying the SI cross-section, two sets of weights are generated and applied to events where a given secondary interaction occurred in the FGD1 FV:

- correction weight, to bring the MC into agreement with the pion SI data;
- variation weight, to allow variations based on the uncertainty in the data, for systematic calculations.

The procedure used to generate the weights is the following one.

The trajectory of each charged pion in the event is divided into steps based on the pion position, momentum and secondary interaction undergone. A momentum dependent interaction probability is associated with each step: $P_{NI}$ (probability of no interaction), or $P_{int}$ (probability of interaction), where $int = \{\text{Absorption, Charge Exchange, Quasi-Elastic}\}$. Considering all charged pion trajectories in the event, the overall interaction probability of the event is $P_{evt} = \prod_{traj} P_{traj}$, where $P_{traj} = \prod_{step} P_{step}$ is the probability of each pion trajectory.
(\( P_{\text{step}} = \{ P_{NI}, P_{int} \} \)). A different cross-section will correspond to different probabilities \( P'_{NI}, P'_{int} \), which result in a different event probability, \( P'_{\text{evt}} \). The weight for the event is therefore \( w_{\text{evt}} = \frac{P'_{\text{evt}}}{P_{\text{evt}}} \).

It can be shown that \( \frac{P'_{\text{evt}}}{P_{\text{evt}}} = \frac{Q'_{\text{evt}}}{Q_{\text{evt}}} \), where \( Q'_{\text{evt}} \) and \( Q_{\text{evt}} \) are quantities depending on the particle type undergoing the interaction at each step, the momentum, the density of the material and the interaction type, and are proportional to the product of the individual interaction cross-sections \([152, 165]\). Thus, \( w_{\text{evt}} = \frac{Q'_{\text{evt}}}{Q_{\text{evt}}} \).

The correction weight is then given by \( \frac{Q_{\text{data}}}{Q_{\text{MC}}} \), where \( Q_{\text{data}} \) and \( Q_{\text{MC}} \) are proportional to the event’s interaction probabilities in data and MC respectively. The variation weight is equal to \( \frac{Q_{\text{varied}}}{Q_{\text{data}}} \), where \( Q_{\text{varied}} \) uses the data cross-sections varied by a fraction of the uncertainty for each interaction type individually, i.e. :

\[
Q_{\text{varied}} \propto \prod_{\text{int}} (X_{\text{data}}^{\text{int}} + \sigma X_{\text{data}}^{\text{int}} \cdot \delta)
\]  

(C.1)

where \( X_{\text{data}}^{\text{int}} \) and \( \sigma X_{\text{data}}^{\text{int}} \) are the individual cross-section and the corresponding uncertainty in the external data for the interaction type \( \text{int} \), and \( \delta \) is the variation in number of standard deviations. The overall event’s weight is given by the product of the two weights.

For cross-sections of interactions in different materials, this study uses the data sets prepared for the work described in \([168]\), and values taken from Geant4. For the external data, if there is no \( \pi^- \) data, the \( \pi^+ \) data is used. If no data are available on the cross-section in a given element, its nearest tabulated neighbour in atomic number is used. If interactions occurred in composite materials, both an average data cross-section and an average Geant4 model cross-section are calculated. In momentum regions where there is no data, an extrapolation is done.
Appendix D

Neutrino energy and transferred quadri-momentum bias

As mentioned in Section 6.2.2, Eq. 6.1 does not take into account the neutron motion inside the nucleus (the neutrino energy is reconstructed under the assumption of the target neutron being at rest). To neglect the Fermi motion in Eq. 6.1 produces a smear and a bias in the reconstructed neutrino energy, $E_\nu$, distribution. In addition, also the transferred quadri-momentum, $Q^2$ (see Eq. 6.2), will be distorted as the neutrino energy is needed to compute it.

The $E_\nu$ and $Q^2$ pulls (computed as the difference between the true and reconstructed values, divided by the true value) for all the selected CCQE samples are shown in Figure D.1. The corresponding neutron momentum and angular distributions are shown in Figure D.2. It can be seen that the CCQE selection criteria favour a particular phase-space of the neutron Fermi momentum. As the target neutron moves inside the nucleus and its angular distribution is not flat in the selected samples, neglecting the Fermi motion in the neutrino energy calculation results in an underestimation of both $E_\nu$ and $Q^2$.

The neutron momentum can reach values up to $\sim 250$ MeV/c (see Figure D.2-right), affecting both the $E_\nu$ and $Q^2$ intrinsic resolutions. The phase space corresponding to more forward neutrons is clearly favoured (see Figure D.2-left), producing the bias and the tail observed in Figure D.1. As the neutron angular distribution is more flat for events with $\mu$TPC topology (because there are no constraints on the proton topology), the bias is smaller in the 1-track sample. On the other hand, in the $\mu$TPC-pTPC topology, in which the neutron angular distribution is less flat, the bias is bigger. The biggest $E_\nu$ and $Q^2$ bias corresponds to events with $\mu$FGD-pTPC topology but in this case also the estimation of the
muon candidate momentum by range is responsible for part of the bias, because it is less precise than the estimation based on the TPC information and does not work properly for tracks not stopping in the detector volume.
Figure D.1: Left: Neutrino energy bias (i.e. reconstructed minus true neutrino energy, divided by true neutrino energy) and $Q^2$ bias (i.e. reconstructed minus true $Q^2$, divided by true $Q^2$) of the MC samples for true CCQE interactions. First line: $\mu$TPC topology; second line: $\mu$TPC-pTPC topology; third line: $\mu$TPC-pFGD topology; fourth line: $\mu$FGD-pTPC topology.
Figure D.2: Cosine of the neutron polar angle for events with $\mu$TPC (top left), $\mu$TPC-pTPC (top right), $\mu$TPC-pFGD (bottom left), $\mu$FGD-pTPC (bottom right) topology. CCQE true interactions have been selected.
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