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Puzzling out neutrino mixing through golden measurements

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"....una estudiante de Físicas, una entre los $\sim \mathcal{O}(400)$ *jóvenes estudiantes que se matriculan cada año en la Universidad Autónoma de Madrid, UAM para los amigos. Durante su tercer y cuarto año de estudios, cursó ciertas asignaturas que realmente le impactaron, como la Mecánica Cuántica y la Mecánica Teórica. Un año antes de licenciarse, acudió al despacho de la que había sido su profesora de Mecánica Cuántica, Belén Gavela, y le preguntó acerca de seguir investigando en Física Teórica con su ayuda. Belén la apoyó y animó, la escuchó y discutió con ella cada tema que estudiaba, le cedió libros, artículos y trató de desnudar la Física ante sus ojos. Cuando esta estudiante se licenció, decidió continuar, pese a no saber con certeza hacia dónde le dirigiría todo aquello. Pero Belén, su supervisora ("a la english") de tesis, le siguió brindando un sinfín de oportunidades, como trabajar con ella y con gente increíble, Pilar, Stefano, Andrea y Juanjo, todos ellos geniales y brillantes, con los que colaborar, aprender, y, muy importante, también divertirse, disfrutar trabajando y estudiando.*

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Colorín, Colorado,... Este cuento no se ha acabado...

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"Lo demás no importa, no importaba, no había aliciente que nos distrajera ni amenaza que nos disuadiera. Así vivimos, con esa única meta, y así luchamos a nuestro modo[...]"
Rosa Regás, "Luna Lunera",(1999).

En fin....también hay toda una vida por "explorar" mas allá de la Física (no sólo Beyond the SM) (¿es esto lo que llaman deformación profesional?)..
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Y ahora, por fin, este cuento llega a su final. Ojalá este "viaje" lo realizara muchas veces y pudiera estar junto a todos vosotros ¿de nuevo?."

Introducción y motivaciones

Nuestro conocimiento experimental de las masas fermiónicas y de los parámetros de mezcla entre los distintos sabores está continuamente recibiendo datos cada vez más precisos. Sin embargo, el entendimiento teórico del origen de estas masas y de estos parámetros de mezcla permanece aún oscuro. Las tres constantes gauge de acoplo adimensionales e independientes del sabor en el Modelo Estándar (SM) [1], son del orden de la unidad. En dicho modelo, las masas de los quarks y de los fermiones cargados están determinadas por sus respectivos acoplos de Yukawa con el campo bosónico de Higgs. Estos parámetros de acoplo han de ser especificados en el SM, es decir, el SM no predice ningún valor para ellos. El problema es que, a diferencia de las constantes de acoplo, estos parámetros de sabor presentan un amplio espectro jerárquico, es decir, existen varios órdenes de magnitud entre unos y otros. Por lo tanto, las masas de los quarks, excepto en el caso del quark *top*, tambieén presentan un espectro similar al de los acoplos de Yukawa, existiendo diferencias de varios órdenes de magnitud entre ellas y también respecto de la escala electrodébil$\sim \mathcal{O}(250)$ GeV. Esta situación es usualmente denominada *puzzle de sabor*: ¿por qué las masas de los quarks presentan esta estructura jerárquica?, ¿qué determina el valor preciso de los ángulos de mezcla entre las diferentes familias?. Uno podría profundizar aún mas en la situación, y formular la siguiente cuestión: ¿cuál es la razón de la existencia de tres familias de fermiones ligeros?.

Este espectro tan peculiar puede integrarse en el contexto del actual Modelo Estándar. Sin embargo, aún no ha sido explicado. En paralelo al problema de las jerarquías existentes en las masas de los quarks y fermiones cargados, se encuentra el de la masa del bosón de Higgs, que yace como un problema persistente, ya que no es posible asignarle un valor *natural*. Con *natural*, nos referimos a un valor no *ajustado* finamente, no *arreglado* respecto al valor que se obtendría después de considerar las correcciones radiativas a la masa de dicho bosón. Ambos problemas sugieren la búsqueda de un modelo mas potente, ya que el SM no presenta una descripción completa del espectro de las partículas elementales.

En el SM, los neutrinos son partículas sin masa. Los neutrinos son introducidos como fermiones para los cuales en el marco de este modelo no es posible construir un término de masa invariante gauge y renormalizable. De este modo, en el sector leptónico del SM no es posible observar fenómenos de mezcla de sabores ni tampoco fenómenos asociados a la violación de la simetría CP.

No obstante, los datos obtenidos en el experimento Super Kamiokande [2] muestran agudas evidencias experimentales de la existencia de oscilaciones de neutrinos atmosféricos. Estas claras señales de fenómenos de mezcla entre distintos sabores de neutrinos, junto con con los resultados recientes del experimento SNO [3, 4, 5], que corroboran firmemente la existencia de fenómenos de oscilación en lo que respecta a los neutrinos solares, indican la existencia de Física más allá del SM, dado que los fenómenos de mezcla entre los distintos sabores de las partículas son sólo posibles si éstas son masivas, y los neutrinos en el contexto del SM no poseen dicha propiedad. Esta observaciones experimentales han cambiado nuestra perspectiva del problema de las jerarquías de sabor, sugieriendo la existencia de una nueva escala de Física, todavía inexplorada: la determinación de las masas de los neutrinos y de los parámetros de mezcla entre sus distintos sabores suponen un primer paso obligatorio y necesario para poder acercarnos a esta nueva escala. Además, la existencia de neutrinos masivos y de violación de CP en el sector leptónico han sido considerados como ingredientes clave en la generación de la asimetría materia-antimateria del universo.

En esta tesis nos hemos centrado en la determinación de los parámetros de mezcla presentes en los fenómenos de oscilaciones de sabor de los neutrinos y en la medida del efecto de violación de la simetría CP en el sector leptónico. Dicha determinación requiere, de un modo imprescindible, un avance en la precisión de las medidas experimentales.

Los futuros experimentos LBL (del inglés *Long BaseLine*) son proyectos en los cuales un haz de neutrinos de un determinado sabor es detectado tras propagarse cientos o miles de kilómetros. Los fenómenos de oscilación tendrían lugar en dicha propagación, y estos experimentos LBL podrían determinar los parámetros de mezcla, y, con fortuna, medir los efectos de violación de la simetría CP en el sector leptónico.

Uno entre ellos es el experimento llevado a cabo con *Superbeams* [6, 7, 8], es decir, con los llamados Super-haces de neutrinos, y otro es el llevado a cabo en una *Neutrino Factory* [9, 10, 11, 12, 13], o Factoría de neutrinos, que ahora describiremos.

¿En qué consiste un *Superbeam*? Un *Superbeam* de neutrinos es un haz de neutrinos convencional pero dotado de una intensidad y pureza notablemente superior a los haces de neutrinos hoy existentes. Un haz de neutrinos convencional es obtenido mediante el decaimiento de piones y kaones procedentes de las interacciones de un haz primario de protones acelerados que se hacen chocar contra un blanco. Si se eligen piones y kaones cargados positivamente, el haz de neutrinos obtenido contendrá, de un modo mayoritario, neutrinos muónicos, producidos en los decaimientos a dos cuerpos $\pi^+ \to \mu^+\nu_\mu$ y $K^+ \to \mu^+\nu_\mu$. El haz de neutrinos también contendrá, en pequeña proporción, neutrinos electrónicos producidos en los decaimientos de muones secundarios y en los decaimientos a tres cuerpos $K^+ \to e^+\pi^0\nu_e$. Además, si el haz de protones inicial es lo suficientemente energético habrá también una pequeña cantidad de neutrinos tauónicos (prodecentes, mayoritariamente, de los decaimientos tauónicos de los mesones D_s). Los haces de antineutrinos se pueden producir de manera exacta pero partiendo de piones y kaones cargados negativamente.

Se espera que la próxima generación de experimentos, en aceleradores, reactores y experimentos empleando *Superbeams*, confirmen rigurosamente en experimentos llevados a cabo en laboratorios en su totalidad, la existencia de oscilaciones de estas partículas y aumenten nuestro conocimiento de los parámetros de la oscilación.

Sin embargo, la composición de estos haces de neutrinos no es la idónea para los experimentos de oscilaciones, ya que sólo contienen neutrinos electrónicos en una pequeñísima proporción (lo cual también supone un problema, ya que constituye la fuente principal de errores sistemáticos en los experimentos de neutrinos).

La medida precisa de la existencia de violación de CP en el sector leptónico requiere, muy probablemente, un experimento basado en una *Neutrino Factory*.

¿En qué consiste una *Neutrino Factory*? En este experimento, los haces de neutrinos, altamente energéticos, proceden del decaimiento de muones mediante el proceso $\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ en la sección recta de un anillo de almacenamiento de los mismos. Esta factoría de neutrinos formaría parte de un gran proyecto: un collider de muones de alta luminosidad. El haz de neutrinos producido mediante este mecanismo tendría una composición perfectamente conocida y una intensidad cuatro órdenes de magnitud superior a los haces actuales: estaría compuesto de un 50% de ν_μ y un 50% de $\bar{\nu}_e$ (si almacenamos μ^-), y de un 50% de $\bar{\nu}_\mu$ y un 50% de ν_e (si almacenamos μ^+). Si quisiéramos estudiar las oscilaciones de los neutrinos, lo único que tendríamos que buscar y medir en nuestro experimento son **sucesos debidos a muones de signo contrario al que se esperaría en ausencia de oscilaciones, o *"wrong-sign" muons*** [11, 14]. Esta es precisamente la valiosísima medida que se puede llevar a cabo sólo en el marco de una *Neutrino Factory*. Veamos esto más detenidamente:

1. Supongamos que en el anillo de almacenamiento tenemos μ^-. En ausencia de oscilaciones, en nuestro detector aparecerán únicamente μ^- debido a las interacciones por corrientes cargadas de los ν_μ producidos en los decaimientos de los muones negativos. Sin embargo, si existen oscilaciones del antineutrino electrónico del tipo $\bar{\nu}_e \to \bar{\nu}_\mu$, cuando los antineutrinos muónicos lleguen al detector producirán μ^+ vía corrientes cargadas.
2. Supongamos ahora que en el anillo de almacenamiento hubiese μ^+. Si no existieran oscilaciones sólo observaríamos sucesos debidos a μ^+. No obstante, si se produjese la oscilación $\nu_e \to \nu_\mu$, en nuestro detector aparecerían sucesos debidos a μ^-.

Sin embargo, el diseño de una futura *Neutrino Factory* requiere las herramientas esenciales para llevar a cabo un experimento empleando *Superbeams*: en esta tesis hemos considerado el impacto que supondría la combinación de los resultados obtenidos en ambos.

La tesis que aquí presentamos está organizada del siguiente modo: en el Capítulo I narraremos de un modo breve la historia del neutrino y recordaremos al lector por qué los neutrinos no poseen masa en el Modelo Estándar y cómo puede ampliarse dicho modelo para explicar la existencia de neutrinos masivos. También durante dicho capítulo presentamos un estudio sobre la teoría de oscilaciones del neutrino. En el Capítulo II revisaremos las evidencias experimentales procedentes de los experimentos hasta ahora llevados a cabo, y examinaremos las expectativas de los experimentos futuros, en particular, aquellos que están basados en el uso de *Superbeams* de neutrinos. En los Capítulos III, IV y V mostramos nuestro trabajo original, y concluiremos en el Capítulo VI.

Motivations and goals of this work.

"There are still plenty of puzzles left in the universe to solve."
B. Lundberg, Scientific Colloquium at Fermilab July, (2000).

Whereas the measurement of the fermion masses and mixing parameters is continuously improving, their theoretical understanding remains obscure. The dimensionless flavor-blind parameters of the Standard Model (SM) [1], that is, the three gauge couplings, are of order one. The quark and charged lepton masses are determined by the Yukawa couplings with the Higgs boson field, parameters which must be specified when defining the SM. Most of these flavor parameters are largely hierarchical, that is, they have very different magnitudes from each other. As a consequence, the quark masses differ by orders of magnitude among themselves and also with respect to the electroweak scale $\sim \mathcal{O}(250)$GeV, except for the top quark mass. This situation is the usually dubbed *flavor puzzle*: why this hierarchical structure of fermion masses and the associated quark mixings, and why three generations of light fermions? This spectrum can be accommodated in the SM, but it is not explained. In parallel to these facts, the lightness of the Higgs mass is puzzling as well from a naturalness (non fine-tuned) perspective. Both sets of problems suggest that the SM is not the complete picture of Nature.

Neutrinos are massless within the SM: in the absence of any direct indication for their mass, they were introduced as fermions for which no gauge invariant renormalizable mass term can be constructed. As a consequence, in the SM there is neither mixing nor CP violation in the lepton sector.

The strong evidence for atmospheric neutrino oscillations reported by the Super Kamiokande experiment [2] and the recent results of solar neutrino oscillations from the SNO Collaboration [3, 4, 5], have meant the first departure from the SM theory, as they indicate non-zero neutrino masses, and have thus opened up a new perspective of the *flavor puzzle*. These observations suggest the existence of an underlying *New Physics*, with a new scale associated to it.

The determination of the fermion masses and mixings parameters is a mandatory first step that is essential for an understanding of the origin of flavor. Furthermore, neutrino masses point to leptogenesis as the source of the matter-antimatter asymmetry of the universe, provided CP is violated in the leptonic sector. In the present work we concentrate on the determination of neutrino oscillation parameters and on the measurement of leptonic CP Violation.

A quest for physics answers evidently requires an increase in the precision on the experimental measurements. Much research has been devoted to study the possibilities of future long baseline experiments (LBL)[1] to measure the neutrino oscillation param-

[1]These experiments are projected to detect neutrinos at distances of hundreds of km from its source.

eters and hopefully leptonic CP violation, which are the final physics goals of these experiments. Among them, one is the Superbeam facility [6, 7, 8] and another one is the Neutrino Factory complex [9, 10, 11, 12, 13].

What is a Superbeam experiment? It consists, basically, in a higher intensity and higher purity version of a conventional neutrino (antineutrino) beam, the next step in accelerator-based neutrino physics. A conventional neutrino beam is produced by a primary proton beam which hits a target and creates secondary beams of charged pions and kaons. If positive charged pions and kaons have been selected for the decay channel, the resulting beam will contain mostly muon neutrinos produced in the two body decays $\pi^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\nu_\mu$. We shall present the different Superbeam projects and their expected sensitivities with some detail along the present work.

However, despite the expected progress from several experiments that use neutrino beams from particle accelerators and nuclear reactors that will take data over the next few years, and from Superbeam planned experiments, the ultimate precision appropiate for the discovery of leptonic CP Violation should come from a Neutrino Factory, by using the golden signature [11, 14] of *"wrong sign muons"*.

What is a Neutrino Factory? It consists, essentially, in a muon storage ring[2] with long straight sections along which the muons decay. These muons provide high intensity neutrino beams (the neutrino flux is approximately 10^4 times the flux of existing neutrino beams), which have a precise neutrino flavor content, making them extremely superior to the conventional beams. Hence, compared to conventional neutrino beams from pion decay, the Neutrino Factory provides ν_e and $\overline{\nu}_e$ beams in addition to ν_μ and $\overline{\nu}_\mu$ beams, with minimal systematic uncertainties on the neutrino flux and spectrum.

What is a "wrong sign muon" event? Suppose, for example, that positive charged muons have been storaged in the ring. These muons will decay as $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$. The muon antineutrinos will interact in the detector to produce positive muons. Then, any "wrong sign muon" (negative muon) detected is a clean proof of electron neutrino oscillations, in the $\nu_e \to \nu_\mu$ channel. This is, precisely, the golden channel, which will be shown to be essential for the goals of the present study.

The Neutrino Factory design requires the essentials of a Superbeam facility. In this work we have considered the combination of their physics results.

The work that we present here is organized as follows. In Chapter I we start with a short history of the neutrino. We also recall why neutrinos are massless within the SM, how can the latter be enlarged to accommodate those masses and we discuss as well the theory of neutrino oscillations. In Chapter II we review the results from the oscillation experiments already performed and we present the current status of our understanding of neutrino masses and mixings, discussing what are the present unknowns. The future oscillation experiments are examined as well: we describe in particular the experiments at a Superbeam facility. From Chapter III to Chapter V

[2]This muon storage ring is an essential stepping-stone towards possible muon colliders.

our original work is described. In Chapter III we introduce the golden measurements at the Neutrino Factory complex [14], where we present both analytical and numerical studies. In Chapter IV we refine the analysis performed in Chapter III by exploring the full range of the unknown parameters and by including the expected uncertainties on the remaining neutrino oscillation parameters [15]. In Chapter V we show the potential of the combination of Superbeam and Neutrino Factory results [16]. In Chapter VI we conclude.

Contents

Chapter 1

The neutrino: mass and Oscillation Physics

1.1 A bit of History

"Neutrinos [...] are different than any other particles. They are sort of pure. It is very hard to do neutrino experiments, but I think they may be the first ones to show unexpected interactions."
(Martin Perl, 1995 Nobel Prize winner for the discovery of the tau lepton).

The first to assume the existence of the neutrino as an elementary particle was W. Pauli in 1930 [17], as a solution to a frustrating problem in the β spectrum: the examination of the products indicated that some energy was missing. Pauli postulated a third neutral particle, companion of the electron and the final nucleus. This particle was supposed to have spin 1/2 (to solve the "*nitrogen catastrophe*"), mass smaller than the electron mass and a mean free path much larger than the mean free path of the photon [18]. Pauli named this new particle "*neutron*".

Soon after Pauli's postulate, E. Fermi proposed the first theory of β-decay of nuclei [19], and he baptized this new particle with the name of neutrino (Chadwick had discovered the neutron -as we know it today- in 1932), maybe implying something small about it.

Despite Pauli's pessimistic words, "*I made a prediction which can never be tested, ever, because this particle is so weakly interacting that it may never be seen*", twenty-six years after neutrino's birth, Cowan and Reines first observed electron antineutrinos [20] through the reaction $\overline{\nu}_e + p \rightarrow e^+ + n$ in an experiment done at the Savannah River reactor in USA (1954-56). B. Pontecorvo, also influenced by the contemporaneous work of Gell-Mann and Pais [21], theorized that an antineutrino produced in the Savannah detector could oscillate into a neutrino and be detected [22]: The idea of neutrino oscillations was born.

After the neutrino detection, the most important physics goals were to determine its spin and mass. In 1956, an experiment changed the understanding of the weak interaction and the recent detected neutrino: C. S. Wu *et al.* [23] discovered the non conservation of parity in the β-decay. Landau, Lee and Yang proposed then the theory of two-component neutrino [24]: this mysterious particle was not as the other elementary particles, which have both left-handed and right handed components, but it is purely left-handed. In fact, the helicity of the neutrino was determined in 1957 in an experiment developed by Goldhaber *et al.* [25].

The discovery of parity non conservation in the weak interactions and the confirmation of the theory of a two-component neutrino stimulated the theoretical research, resulting in the formulation of the V-A theory [26], a successful description of the weak processes. In the late sixties, the consistency problems of the V-A theory led to formulate the Glashow-Weinberg-Salam (GWS) model, wherein electromagnetic and weak interactions were unified [1].

The second neutrino, the muon neutrino, was discovered in 1962 [27], although its existence was postulated approximately twenty years before by the theorists Inouë and Sakata. The same year, Maki, Nakagawa and Sakata proposed that these two types of detected neutrinos could mix [28]. But this mixing could only happen if the neutrinos were massive and these masses were different.

In the early sixties, Bahcall and his collaborators at Caltech proposed a detailed program for studying the theoretical aspects of solar neutrinos [29]. Neutrinos escape from natural sources as the Sun and the stars, carrying crucial information about its structure and evolution. Then, its study and detection is an important test of existing theoretical models for the structure and evolution of the Sun and other stars, and its understanding helps to better understand the universe. In 1964, Davis and his co-workers started the solar neutrino observation at the Homestake mine. Four years later, R. Davis *et al.* [30] reported a deficit in the solar neutrino flux, that Gribov and Pontecorvo interpreted as a proof of neutrino oscillations [31]. The evidence was reinforced over the years.

By the middle 1980's, several large, underground detectors were constructed to detect proton decay. They failed in such a detection, but a burst of neutrinos from a Supernova was detected. These detectors started the measurement of the flux of neutrinos produced by cosmic ray collisions [32, 33].

In 1998, Super-Kamiokande (SK) data confirmed an anomaly in the atmospheric neutrino flux, implying muon neutrino oscillations into another neutrino flavor which was not the electron neutrino[1]. In particlar, the evidence for an azimuthal asymmetry in the distribution of the flux of atmospheric neutrinos was flabbergasting evidence for

[1]In July 2000, The DONUT experiment [34] at Fermilab found the *missing puzzle piece*: they reported the first evidence for the tau neutrino, whose existence was mandatory after the LEP data on the number of light neutrino generations [35, 36, 37]. In fact, the helicity of the tau neutrino had been accurately measured at LEP[38].

neutrino masses and neutrino oscillations. The same experiment also obtained data which supported the evidence of solar neutrino deficit. Altogether, the SK data have opened a new -very exciting- era in Particle Physics.

Thanks to the compelling evidence for neutrino oscillations from SK and SNO data, we now know that there exist, at least, two massive neutrinos, as required by the two distinct squared mass differences measured [2, 3, 4, 5]

$$|\Delta m^2_{\rm atm}| \sim 1 \times 10^{-3} \text{ eV}^2 \ , \tag{1.1}$$

$$|\Delta m^2_{\rm sun}| \sim 1 \times 10^{-4} \text{ eV}^2 \ . \tag{1.2}$$

The SK experiment, as well as the SNO experiment -which has nailed down the case for solar neutrino oscillations- will be treated in the text in further detail, together with other presently running or planned experiments.

In the next section we shall describe the neutrino within the SM and deal with the question of its mass.

1.2 The neutrino in the Standard Model

The SM is based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group, with only one doublet scalar, which is responsible for charged fermion masses.

Neutrinos (antineutrinos) are neutral particles of spin 1/2 which only interact via electroweak processes. The number of different active light neutrino flavors α was measured at LEP from the decay width of the Z^0 boson (that is, $m_\nu \leq m_Z/2$), resulting in 2.994 ± 0.012 different neutrino species [36, 37], in very good agreement with the three flavors of the charged current (CC) processes. Within the SM, the three active light neutrinos reside in lepton doublets,

$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ \ell^-_\alpha \end{pmatrix}_L \ , \tag{1.3}$$

where $\alpha = e, \mu, \tau$. In what follows we shall use the convention of greek indices for flavor eigenstates and latin ones for mass eigenstates.

Neutrinos (antineutrinos) thus interact with charged leptons through reactions mediated by the W^+ (W^-) boson. These interactions are described by the CC Lagrangian:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{\nu_{\alpha L}} \gamma^\mu \ell^-_{\alpha L} \ W^+_\mu + \text{h.c.} \ , \tag{1.4}$$

where g is the electroweak coupling constant.

Neutrinos (antineutrinos) also interact with themselves through neutral current (NC) processes mediated by Z^0 bosons, described by the following Lagrangian:

$$-\mathcal{L}_{NC} = \frac{g}{2\cos\theta_W}\, \overline{\nu_{\alpha L}}\, \gamma^\mu\, \nu_{\alpha L}\, Z^0_\mu\ , \tag{1.5}$$

where θ_W is the Weinberg angle.

The SM Lagrangian, with its gauge symmetry and its particle content, possesses accidental symmetries related to flavor. Because of the quark masses and mixings, only global baryon number is conserved in the Lagrangian, $U(1)_B$, while, with massless neutrinos, the leptonic L_e, L_μ and L_τ quantum numbers are independently conserved: the CC and the NC interactions given by Eq. (1.4) and Eq. (1.5) conserve L for each leptonic flavor (see Tab. (1.1)). When non-perturbative effects are taken into account, only $U(1)_{(B-L)}$ remains unbroken at the quantum level.

	L_e	L_μ	L_τ
$(\nu_e\,,\,e^-)$	+1	0	0
$(\nu_\mu\,,\,\mu^-)$	0	+1	0
$(\nu_\tau\,,\,\tau^-)$	0	0	+1

Table 1.1: *Assignment of lepton numbers. The corresponding antiparticles have opposite lepton numbers.*

The vacuum expectation value (v.e.v.) of the Higgs doublet ϕ breaks spontaneously the original $SU(2)_L \times U(1)_Y$ symmetry,

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}\ . \tag{1.6}$$

resulting in massive $W^\pm$, Z^0. Fermions masses arise as well through Yukawa interactions,

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{\alpha\beta}\overline{Q_{\alpha L}}\phi d_{\beta R} + Y^u_{\alpha\beta}\overline{Q_{\alpha L}}\tilde{\phi} u_{\beta R} + Y^\ell_{\alpha\beta}\overline{L_\alpha}\phi e_{\beta R} + \text{h.c.}\ , \tag{1.7}$$

where $\tilde{\phi} = i\tau_2\phi^\star$, $Q_{\alpha L}$, L_α are left handed quark and lepton doublets, $u_{\beta R}$, $d_{\beta R}$ and $e_{\beta R}$ are the $SU(2)_L$ singlet right handed fields of up-type quarks, down-type quarks and charged leptons, respectively, and $Y^{d,u,\ell}_{\alpha\beta}$ are the corresponding Yukawa fermion couplings.

Only one helicity state of the neutrino per generation is present and the only scalar is the doublet ϕ. After spontaneous symmetry breaking (SSB), the Yukawa interactions lead to quark masses and charged lepton masses:

$$(m_\ell)_{\alpha\beta} = \frac{Y^\ell_{\alpha\beta}\, v}{\sqrt{2}}\ , \tag{1.8}$$

while the neutrinos remain massless.

1.3 Neutrino mass and Extensions of the SM

Direct information on neutrino masses can be extracted from kinematic studies of reactions in which a neutrino and antineutrino is involved. These direct searches of neutrino mass are the tritium beta decay and the neutrinoless double beta decay experiments (in the ν_e mass case) and the investigation of the kinematics of the charged lepton products from weak decays (in the ν_μ and ν_τ case). From these measurements, the upper limits on neutrino masses are:

$$\begin{array}{rcl} \mathrm{m}_{\nu_e} & < & 2.2 \text{ eV (C.L.= 95\%) [39]} , \\ \mathrm{m}_{\nu_\mu} & < & 0.19 \text{ MeV (C.L.= 90\%) [37]} , \\ \mathrm{m}_{\nu_\tau} & < & 18.2 \text{ MeV (C.L.= 95\%) [40]} , \end{array}$$

Table 1.2: *Present upper bounds on neutrino masses.*

where for the bound on m_{ν_e} the latest limit from the Mainz experiment [41] is taken.

From the astrophysical and cosmological perspectives, massive neutrinos contribute to the mass density of the universe, leading to the constraint [42].

$$\sum_i m_i < 28 \text{ eV .exit}$$

(1.9)

A lower robust bound is indicated from the 2df galaxy redshift [42]:

$$\sum_i m_i < 3 \text{ eV (C.L. = 95\%)} . \tag{1.10}$$

Nevertheless, from atmospheric neutrino oscillations experiments, Eq. (1.1) indicates that at least one type of neutrino has a lower bound on its mass

$$m_\nu \sim \sqrt{|\Delta m^2_{\rm atm}|} \geq 0.05 \text{ eV} . \tag{1.11}$$

It is then necessary to extend the SM to accommodate massive neutrinos. This implies a new energy scale Λ, as we shall argue.

There is an a priori simple way to obtain neutrino masses if the new physics scale Λ is much smaller than the electroweak SSB scale $\Lambda \ll v$: the SM fermion content (that is, with only left-handed neutrinos) is unchanged while the Higgs sector is enlarged by adding just a triplet Higgs scalar Φ with $Y = 1$, with gauge invariant Yukawa interactions [43, 44],

$$-\mathcal{L}_\Phi = Y^\Phi_{\alpha\beta}\, L_\alpha \Phi (L_\beta)^c + \text{h.c.} . \tag{1.12}$$

$Y^{\Phi}_{\alpha\beta}$ are new Yukawa couplings. When Φ develops a non zero v.e.v, Λ, neutrinos acquire a Majorana mass $(m_\nu)_{\alpha\beta} \sim Y^{\Phi}_{\alpha\beta}\Lambda$. For $\Lambda \leq$ a few GeV there is no contradiction with the experimental measurement of the ρ parameter. The theoretical problem with this small scale model is that it introduces a new hierarchy problem, that is, $\Lambda \ll v$, or $Y^{\Phi}_{\alpha\beta}$ extremely fine-tuned. The experimental aspect of this idea is very constrained as well. We shall not exploit thus this trivial extension of the SM Higgs sector since it is highly unnatural to have additional fine-tuning in a new scale $\Lambda \ll v$, in order to avoid a grossly wrong value of the ρ parameter.

Another way to provide very small neutrino masses are large extra dimensions models [45], in which isosinglet neutrinos appear in the bulk and couple to SM neutrino fields. The new scale in this case is the extra-dimensional one. For instance, a possibility is that the neutrino mass is suppressed because it is inversely proportional to the volume of the extra dimensions. We shall not discuss here this model-building in higher dimensions.

1.3.1 Naturalness criterion

In the previous paragraph, we have argued in terms of naturalness.
What do we mean precisely by natural? We shall specify further, for the sake of discussions below.

A Lagrangian has to include all terms compatible with its gauge symmetries for a given matter content, except for terms forbidden by some symmetry. In other words, all dimensionless parameters are expected to be of $\mathcal{O}(1)$, or ~ 0 if protected by some symmetry.

Equivalently, all dimensionful parameters are expected to be of the order of the scale of the theory to which the fields are sensitive, unless, once again, a symmetry forces them to be lighter.

1.3.2 A new physics scale, $\Lambda \gg v$

Assume instead that there exist in Nature a theory beyond the SM which is defined by a energy scale $\Lambda \gg v$. The SM can be regarded then as an effective low energy theory. Effects of this *new physics* below the scale Λ will be represented by adding to the SM a tower of operators of dimension > 4, and suppressed by powers of $1/\Lambda$. The lowest dimensional term made out of the SM fields and also consistent with its gauge symmetries is a five dimensional operator and it reads [46, 47]

$$\frac{c_{\alpha\beta}}{2\Lambda}\,\overline{L_\alpha}\;\tilde{\phi}\;\tilde{\phi}^T\;(L_\beta)^c + \text{h.c}\;, \tag{1.13}$$

where L_α, L_β are the left handed lepton doublets, α, β are the generation indices, and the index T refers to the transpose matrix. The effective operator in Eq. (1.13) violates lepton number L, (and thus $B - L$), by two units. After SSB, this term leads to Majorana neutrino masses

$$(m_\nu)_{\alpha\beta} = \frac{c_{\alpha\beta}}{2}\frac{v^2}{\Lambda} \ . \tag{1.14}$$

For natural values of the coefficients $c_{\alpha\beta} \sim \mathcal{O}(1)$, the magnitude of neutrino masses is then suppressed with respect to the charged fermions by the factor $\frac{v}{\Lambda}$. Since $\Lambda \gg v$, the smallness of neutrino masses is naturally (i.e., in a non-fine-tuned way) explained. For instance, imagine that the mass of the heaviest neutrino is given by the equality Eq. (1.11), which, together with the solar oscillation, see Eq. (1.2), would indicate:

$$0.05 \text{ eV} \geq m_\nu \geq 0.01 \text{ eV} \ .$$

From Eq. (1.14), this implies:

$$10^{11} \text{ GeV} \leq \Lambda \leq 10^{15} \text{ GeV} \ .$$

It is striking that present neutrino oscillation data point to a new scale Λ that is comparable to the scale at which the SM gauge couplings are converging [48].

The neutrino mass eigenstates corresponding to Eq. (1.13) are Majorana neutrinos. Let us recall that if both chirality components of ψ field are related, then ψ is a Majorana field:

$$\psi = \eta\, \psi_L + \eta^*\, {\psi_L}^c \ , \tag{1.15}$$

where $\eta = e^{i\beta/2}$ is an arbitrary phase and ${\psi_L}^c$ is the $\tilde{C}$-conjugated of ψ_L. The operator $\tilde{C}$ is defined as

$$(\psi)^c \equiv \tilde{C}\psi \equiv C\overline{\psi}^t \ , \tag{1.16}$$

where $C \equiv i\gamma_0\gamma_2$ is the charge conjugation operator. Whereas C only flips the charge-like quantum numbers of a field, $\tilde{C}$ also flips the chirality, converting a particle in its own antiparticle.

A Majorana neutrino is thus its own antiparticle and coincides with its $\tilde{C}$-conjugated apart from the η phase factor

$$(\nu)^c = \eta^* \nu \ . \tag{1.17}$$

An experimental signal of the putative Majorana character of the neutrinos would be the observation of *neutrinoless* $\beta\beta$ *decay*. Double beta decay is a rare spontaneous nuclear transition in which the charge of two isobaric nuclei changes by two units with the simultaneous emission of two electrons. The dominant mode is

$$(A, Z) \to (A, Z + 2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e \ , \tag{1.18}$$

which conserves the lepton number and it is thus allowed in the SM framework. The double beta decay without antineutrino emission,

$$(A, Z) \to (A, Z + 2) + e^- + e^- \ , \tag{1.19}$$

Figure 1.1: *Neutrinoless $\beta\beta$ transition: the cross in the ν_e exchanged line depicts the Majorana mass contribution.*

is the *neutrinoless $\beta\beta$ decay*, see Fig. 1.1, and its detection would be a major discovery. The non-observation of neutrinoless $\beta\beta$ processes provides at present bounds on the so-called *"effective Majorana mass"* of the electron neutrino [49],

$$\langle m_{\text{eff}} \rangle < 0.35 \text{ eV (C.L.} = 90\%) \ , \tag{1.20}$$

where $\langle m_{\text{eff}} \rangle$ is a combination of the Majorana neutrino mass eigenvalues weighted by leptonic flavor mixing effects, to be discussed in next sections. New projects [50] expect to improve the sensitivity up to one order of magnitude. If these expected sensitivities are going to be closer or not to the $\langle m_{\text{eff}} \rangle$ best-fit value from oscillation experiments depends on the neutrino mass spectrum [51].

1.3.3 Adding a right-handed neutrino to the SM

Why have we discussed previously the possible extensions of the SM to account for neutrino masses instead of simply add a right-handed neutrino, ν_R, to the SM fermion content? A priori, this does not seem to imply a *new physics scale*. If the SM is extended only through the addition of singlet neutrinos, (i.e., right-handed neutrinos), the neutrino masses are generated via the standard Higgs mechanism,

$$-\mathcal{L}^{\nu}_{\text{mass}} = Y^{\nu}_{\alpha\beta} \ \overline{L_\alpha} \ \tilde{\phi} \ \nu_{\beta R} + \text{h.c.} \ , \tag{1.21}$$

where $Y^{\nu}_{\alpha\beta}$ are the Yukawa neutrino couplings, respectively. After SSB, the neutrinos get masses,

$$(m_\nu)_{\alpha\beta} = \frac{Y^{\nu}_{\alpha\beta} \ v}{\sqrt{2}} \ . \tag{1.22}$$

In order to account for the experimental data, one would need $Y^\nu \sim 10^{-5} Y^\ell$ which would be highly unnatural. The unexplained smallness of neutrino Yukawa couplings would lead to a large hierarchy even in the same family.

1.3.4 The complete model with right-handed neutrinos

The discussion above is not complete. Following the naturalness criterion mentioned in subsection 1.3.1, once a neutrino right is added to the SM field content all possible terms compatible with the $SU(2)_L \times U(1)_Y$ gauge symmetry have to be included in the Lagrangian, Eq. (1.21). Besides the Yukawa interactions, Eq. (1.21), there is another possible term which fulfills this criterion:

$$\overline{\nu_R} M_R \, {\nu_R}^c \ , \tag{1.23}$$

where M_R is a new scale. This term is a **Majorana mass term** and it is gauge invariant since ν_R have $Y = 0$. The Majorana mass term violates the leptonic number, L, by two units. Barring an *ad-hoc* imposition of L conservation, this term has to be present.

In resume, the addition of a ν_R per generation to the SM fermion content results in the general neutrino mass Lagrangian

$$-\mathcal{L}^{\nu}_{\text{mass}} = Y^{\nu}_{\alpha\beta} \ \overline{L_\alpha} \ \tilde{\phi} \ \nu_{\beta R} + \frac{1}{2} \overline{\nu_{\alpha R}} (M_R)_{\alpha\beta} \, {\nu_{\beta R}}^c + \text{h.c.} \ . \tag{1.24}$$

After electroweak SSB, Eq. (1.24) takes the form

$$-\mathcal{L}^{\nu}_{\text{mass}} = \frac{1}{2} \overline{{n_L}^c} \mathcal{M}^* n_L + \text{h.c.} \ , \tag{1.25}$$

where for simplicity we have omitted the generation indices and n_L is the vector of the 6 left-handed neutrinos,

$$n_L = \begin{pmatrix} \nu_L \\ {\nu_R}^c \end{pmatrix} \ . \tag{1.26}$$

$\mathcal{M}$ is the 6×6 neutrino mass matrix

$$\mathcal{M} = \begin{pmatrix} 0 & \left(\frac{Y^\nu v}{\sqrt{2}}\right) \\ \left(\frac{Y^\nu v}{\sqrt{2}}\right)^T & M_R \end{pmatrix} \ , \tag{1.27}$$

where Y^ν is the 3×3 complex matrix containing the Yukawa neutrino couplings.

As an illustration, consider the simplest case with only one generation. $\mathcal{M}$ is thus a real 2×2 matrix. Upon diagonalization, the following eigenvalues are found

$$m_{1,2} = \frac{M_R}{2} \mp \sqrt{\left(\frac{M_R}{2}\right)^2 + \left(\frac{Y^\nu v}{\sqrt{2}}\right)^2} \ . \tag{1.28}$$

As the Majorana mass term Eq. (1.23) is not protected by the $SU(2)_L \times U(1)_Y$ gauge symmetry, it is natural to assume that M_R is close to whatever physics scale may exist at high energies, and to which ν_R may be sensitive, that is $M_R \gg v$. In this case, the mass eigenvalues simplify to

$$|m_1| \simeq \frac{(Y^\nu v)^2}{2M_R} \, , \qquad |m_2| \simeq M_R \, . \tag{1.29}$$

It results in one very light mass eigenstate and a heavy mass one. This is the so-called *seesaw* mechanism [52].

Realize that if we integrate out the heavy ν_R, the effective operator obtained at low energies is, for natural values $c_{\alpha\beta} \sim Y^\nu_{\alpha\beta} \sim 1$, precisely that in Eq. (1.13) with

$$M_R \simeq \Lambda \, . \tag{1.30}$$

1.4 Neutrino Oscillations

We shall review now an experimental signal which is generically present if neutrinos have non-vanishing masses, independently of the possible Dirac or Majorana neutrino character: neutrino oscillations.

Neutrino oscillation phenomenon occurs when an original neutrino of flavor α with $\alpha = e, \mu, \tau$ is detected after traveling a distance L as a neutrino of different flavor β.

Neutrino flavor metamorphosis implies leptonic mixing: the mass eigenstates may not coincide with the eigenstates of the weak Hamiltonian,

$$\nu_\alpha = \sum_j U_{\alpha j} \nu_j \, , \tag{1.31}$$

where U is a 3×3 unitary matrix [22, 28], similar to the quark mixing matrix [53], and it will be further studied in the next subsection. Particle mixing is thus not a peculiarity of the quark sector. The CC leptonic weak interactions Eq. (1.4) are given by

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{\nu_{iL}} \gamma^\mu U^\dagger_{i\alpha} \ell^-_{\alpha L} \, W^+_\mu + \frac{g}{\sqrt{2}} \overline{\ell^+_{\alpha L}} \gamma^\mu U_{\alpha i} \nu_{iL} \, W^-_\mu \, . \tag{1.32}$$

Consider now an experiment where a neutrino of flavor α is born with its associated charged lepton, Eq. (1.4). To explain the evolution of ν_α we shall use the standard approximation in which $|\nu\rangle$ is a plane wave [54] with a sharp energy E. Let us explain why to do so.

In all oscillation experiments the size of the neutrino source is very much smaller than the distance between source and detector. The neutrino emitted from the point source must therefore be described by a wave packet which satisfies a simple general boundary condition [55]: the probability amplitude for finding a particle having the wrong flavor at the source vanishes at all times, or, in other words, there is no flavor mixing at the source.

Assume then that the produced flavor at $x = 0$, $t = 0$ is α, see Eq. (1.31). The wave packet will be generally characterized by a certain energy and momentum spread, (ΔE) and (Δp) respectively. In practice, in real experiments, $(\Delta p) \gg (\Delta E)$ [2]. It is thus a very good approximation to describe the neutrino states through plane waves with well defined energy E, (i.e., $E_j = E_k = E$ [57]) and different momenta (instead of the wave packet treatment), then

$$\begin{aligned} p_j^2 &= E^2 - m_j^2 \ , \\ p_k^2 &= E^2 - m_k^2 \ . \end{aligned} \tag{1.33}$$

A flavor state with a sharp energy E is a mixture of mass eigenstates with different momenta. It will oscillate in *space* with a well-defined oscillation wave length. Indeed, present experiments always measure oscillations *in space* [58] [3]. The transition amplitude for an initial $|\nu_\alpha\rangle$ state to be detected as a $|\nu_\beta\rangle$ state, after propagating through a distance L, reads

$$\mathcal{A} \equiv \langle \nu_\beta \ (L,t) | \nu_\alpha \ (0,0) \rangle = \sum_{i,j} \langle \nu_i | U^*_{\beta i} e^{i(p_i L - Et)} U_{\alpha j} | \nu_j \rangle \ , \tag{1.34}$$

where we have explicitely considered only one space dimension in the source-detector direction. The corresponding transition probability reads, in the same energy prescription,

$$P\left(\nu_\alpha \to \nu_\beta\right) = |\langle \nu_\beta \ (x, L) | \nu_\alpha(0,0) \rangle|^2 = \sum_{k,j} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \, e^{-i(p_j - p_k)L} \ , \tag{1.35}$$

where, from Eq. (1.33), and for relativistic neutrinos (that is, $p_j \simeq p_k \simeq E$):

$$|p_j - p_k| = \frac{(m_k^2 - m_j^2)}{(p_j + p_k)} \simeq \frac{(m_k^2 - m_j^2)}{2E} \ . \tag{1.36}$$

Finally,

$$P\left(\nu_\alpha \to \nu_\beta\right) = -4 \sum_{k>j} Re \left[W^{jk}_{\alpha\beta} \right] \sin^2 \left(\frac{\Delta_{jk} L}{2} \right) \pm 2 \sum_{k>j} Im \left[W^{jk}_{\alpha\beta} \right] \sin \left(\Delta_{jk} L \right) \ , \tag{1.37}$$

where the positive (negative) sign is referred to neutrino (antineutrino) oscillations and

$$W^{jk}_{\alpha\beta} \equiv \left[U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \right] \ , \qquad \Delta_{jk} \equiv \frac{\Delta m^2_{jk}}{2E} \ , \qquad \Delta m^2_{jk} \equiv m_k^2 - m_j^2 \ . \tag{1.38}$$

---

[2] For instance, for a conventional neutrino beam from secondary muons from pion decay, $(\Delta p) = \frac{1}{A} \sim 2 \times 10^3$ eV and $(\Delta E) \sim \frac{1}{\tau_\mu} \sim 3 \times 10^{-10}$ eV [56].

[3] An hypothetical flavor eigenstate produced with sharp momentum would be a mixture of mass eigenstates with different energies. It would oscillate in time with a well defined oscillation period. Such a description does not represent accurately the present physics measurements, that measure the distance between the production and the detection processes, and not time differences.

The Jarlskog determinant J [59], is defined through

$$J \sum_{\gamma,l} \epsilon_{\alpha\beta\gamma}\epsilon_{jkl} \equiv Im\left[W_{\alpha\beta}^{jk}\right] = Im\left[U_{\alpha j}U_{\beta j}^{*}U_{\alpha k}^{*}U_{\beta k}\right] \ . \tag{1.39}$$

The transition probability given by Eq. (1.37) has an oscillatory behavior, with oscillation length

$$L_{jk}^{\rm osc} = \frac{4\pi E}{\Delta m_{jk}^2} \ , \tag{1.40}$$

and amplitude which is proportional to the mixing matrix elements. An experiment is characterized by the neutrino energy, E, and by the distance between the source and the detector, L, Eq. (1.37). In order to be sensitive to a certain Δm_{jk}^2, the experiment has to be set up with $E/L \sim \Delta m_{jk}^2$, ($L \sim L_{jk}^{\rm osc}$). The typical values of E and L for different types of neutrino sources and experiments, that we shall describe with some detail in Chapter II, are shown in Tab. (1.3).

It is customary to classify terrestrial (accelerator and reactor) neutrino oscillation experiments as *Short BaseLine experiments* (SBL) and *Long BaseLine experiments* (LBL). SBL experiments have detection distances L of the order of hundred of meters, while LBL experiments are characterized by distances $L \sim$ several hundred or thousand of km.

Experiment	$L(km)$	E (MeV)	Δm^2
Solar	10^7	1	10^{-10}
Atmospheric	$10 - 10^4$	$10^2 - 10^5$	$10^{-1} - 10^{-4}$
Reactor	$10^{-1} - 10$	1	$10^{-2} - 10^{-3}$
Accelerator	10^{-1}	$10^2 - 10^4$	≥ 0.1
LBL Accelerator	$10^2 - 10^3$	10^4	$10^{-2} - 10^{-3}$

Table 1.3: *Values of E and L for different sources and experiments.*

1.4.1 The Leptonic mixing matrix and the three-family scenario

In general, an unitary matrix $N \times N$ depends on N^2 parameters [60]. From these, $N(N-1)/2$ are moduli and the remaining $N(N+1)/2$ are phases [61]. However, a number of phases in the U mixing matrix can be absorbed by redefining the neutrino mass eigenstates leaving invariant the Lagrangian of the model. For Dirac neutrinos, $2N-1$ phases can be absorbed by the left handed fields, leaving $(N-1)(N-2)/2$ physical (measurable) phases [59], and the resulting mixing matrix is alike to that in the quark sector. Otherwise, more phases remain.

The mixing matrix U for three generations is called the MNSP matrix, U_{MNSP} (*Maki-Nakagawa-Sakata-Pontecorvo*) [22, 28][4]:

$$U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} P_\eta \ , \tag{1.41}$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$. For Dirac neutrinos, $P_\eta \equiv I$, while for Majorana neutrinos,

$$P_\eta = \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \ . \tag{1.42}$$

Notice that the presence of the "CKM-like" phase δ is independent of the Dirac or Majorana neutrino character.

The propagation of the neutrino flavor system is given by:

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} U_{MNSP} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{12} & 0 \\ 0 & 0 & \Delta m^2_{13} \end{pmatrix} U^\dagger_{MNSP} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \ , \tag{1.43}$$

where the m_2^2, m_3^2 eigenvalues have been normalized[5] to m_1^2: oscillation physics is only sensitive to mass differences; not to the absolute mass scale. The action of the three rotation angles is illustrated in the Fig. 1.2 with approximate values of the three mixing angles θ_{12}, θ_{23} and θ_{13}, as known from experiments. The Jarlskog determinant, given by Eq. (1.39), can be expressed in terms of the mixing parameters as

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta \ . \tag{1.44}$$

It is important to notice as well that P_η, which is the tell-tale of Majorana character, does not play any role in neutrino oscillations [63]. In Eq. (1.43) only $U_{MNSP} D U^\dagger_{MNSP}$ is involved in oscillation experiments, and since D, the squared mass differences matrix, is diagonal, it commutes with the P_η matrix. It is thus always possible to eliminate these extra Majorana phases.

P_η will have physical consequences in other transitions, though, as for instance, neutrinoless double beta-decay, that was briefly described in subsection 1.3.2. Let us recall that the amplitude of this process provides information on the "effective Majorana mass", which, in a 3-family scheme, reads

$$\langle m_{\rm eff}\rangle \equiv \left|\sum_i U^2_{ei}\, m_i\right| = |U_{e1}|^2\, e^{i\alpha_1/2}\, m_1 + |U_{e2}|^2\, e^{i\alpha_2/2}\, m_2 + |U_{e3}|^2 e^{-i\delta} m_3 \ , \tag{1.45}$$

[4]Notice, though, that our convention for the sign of δ is opposite to the one used in Ref. [37].

[5]This is equivalent to add in the propation equation of the three flavor states a global phase factor, which has not physical importance.

Figure 1.2: *Rotation between the mass and flavor eigenstates in the three-family neutrino oscillation scheme. Figure extracted from Ref. [62].*

where m_i are the mass eigenvalues and $|U_{ei}|$ are the moduli of the MNSP matrix elements. The phases α_i are exclusively due to the Majorana character, whereas δ is the Dirac phase. If the values of m_i were known from experiments such as tritium beta decay, an observation of neutrinoless double beta decay would allow us in principle to extract information on the Majorana phases[6].

In resume, oscillations in vacuum in a three generation scenario are described by six parameters: two mass differences (Δm^2_{12} and Δm^2_{13}), three Euler angles (θ_{12}, θ_{23} and θ_{13}) and one Dirac phase δ. Neither the absolute value of the neutrino masses nor the additional phases (due to the possible Majorana neutrino character) can be determined through neutrino oscillation experiments, though.

[6]For a recent pessimistic appraisal of the practical possibility of extracting them in the future, see Ref. [64].

1.4.2 Oscillation probabilities in a 3-flavor scheme

The present experimental knowledge on neutrino mixing parameters indicates $\Delta m^2_{12} \ll \Delta m^2_{13}$, $\theta_{23} \sim \theta_{12} \sim 45^\circ$ (that is, they are nearly maximal) and a small value for the mixing angle θ_{13}, as we shall further explain in the next chapter. As an illustrative example, we show here the corresponding approximate probability expressions in vacuum.

One mass gap dominance: Δm^2_{13}

At terrestrial or atmospheric distances (that is, $L \sim$ thousand of kilometers) and neutrino energies of several GeV, it is possible to neglect the Δm^2_{12} effects ($\Delta m^2_{12} L/4E \ll 1$), setting it to zero. The neutrino oscillation probabilities are thus accurately described by only three parameters, θ_{23}, $\Delta m^2_{13} \simeq \Delta m^2_{23}$ and θ_{13} (provided $\theta_{13} \neq 0$) [11]:

$$P_{\nu_e\nu_e(\bar{\nu}_e\bar{\nu}_e)} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;, \tag{1.46}$$

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = \sin^2 2\theta_{13}\, \sin^2\theta_{23}\, \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;, \tag{1.47}$$

$$P_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)} = \sin^2 2\theta_{13}\, \cos^2\theta_{23}\, \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;, \tag{1.48}$$

$$P_{\nu_\mu\nu_\mu(\bar{\nu}_\mu\bar{\nu}_\mu)} = 1 - \cos^4\theta_{13} \sin^2\theta_{23}(1 - \cos^2\theta_{13} \sin^2\theta_{23})\, \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;, \tag{1.49}$$

$$P_{\nu_\mu\nu_\tau(\bar{\nu}_\mu\bar{\nu}_\tau)} = \cos^4\theta_{13}\, \sin^2 2\theta_{23}\, \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) \;, \tag{1.50}$$

where we have used the conventional notation, $\Delta_{jk} \equiv \frac{\Delta m^2_{jk}}{2E}$.

One mass gap dominance: Δm^2_{12}

For solar distances, much larger than terrestrial distances, and energies of few MeV, $\Delta m^2_{13} L/4E \gg 1$ and the corresponding oscillatory term, averages[7] to 1/2. However, for these particular conditions, $\Delta m^2_{12} L/4E \sim \mathcal{O}(1)$. Neglecting the small mixing angle θ_{13}, the dominant mass gap now is Δm^2_{12}, and the oscillation probabilities, in vacuum, are given by

$$P_{\nu_e\nu_e(\bar{\nu}_e\bar{\nu}_e)} \simeq 1 - \sin^2 2\theta_{12}\, \sin^2\left(\frac{\Delta_{12}\, L}{2}\right) \;, \tag{1.51}$$

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} \simeq \cos^2\theta_{23}\, \sin^2 2\theta_{12}\, \sin^2\left(\frac{\Delta_{12}\, L}{2}\right) \;, \tag{1.52}$$

$$P_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)} \simeq \sin^2\theta_{23}\, \sin^2 2\theta_{12}\, \sin^2\left(\frac{\Delta_{12}\, L}{2}\right) \;. \tag{1.53}$$

[7] In practice, neutrino beams are not monochromatic. Neutrino oscillation experiments measure thus the energy averaged probability, that is, the probability weighted with the neutrino spectra, the neutrino cross-sections, and the detector efficiencies and resolutions.

In the next chapter we shall exploit all these probability expressions, in order to accommodate the experimental data in the 3-family scenario.

1.4.3 Matter effects in neutrino oscillations

We have described neutrino oscillations in vacuum. However, when neutrinos travel through matter (e.g. in the Sun, Earth, or a Supernova), their coherent forward scattering with particles along the way can significantly modify their propagation [65, 66]. As a result, the probability for changing flavor can be rather different than in vacuum.

The reason is simple: matter contains electrons but not muons or taus at all. Neutrinos of the three flavors interact with the electrons, the protons and the neutrons of the matter via neutral currents, Eq. (1.5). Electron neutrinos in addition interact with electrons via charged current processes, Eq. (1.4), see Fig. 1.3. The matrix accounting for the potentials in the flavor basis is thus diagonal, $V_f = diag(V_e + V_{NC}, V_{NC}, V_{NC})$. Once again, only differences in the diagonal elements will have physical consequences in oscillations.

(40,50)(70,25) (40,-50)(70,-25) (70,25)(70, -25)3 4 (95,0)[r]$W^{\pm}$ (95,35)[r]e (100,-35)[r]ν_e (40,-3

Figure 1.3: *Neutrino scattering diagrams. Figure extracted from Ref. [67].*

The effective potential V_e can be derived from the following charged current weak Hamiltonian, which is a good approximation at low energies $\ll M_W$,

$$H_{CC} = \frac{G_F}{\sqrt{2}} \, (\overline{e}_L \gamma_\mu e_L)(\overline{\nu}_{eL} \gamma^\mu \nu_{eL}) \ , \tag{1.54}$$

where G_F is the Fermi constant. In order to obtain the matter-induced potential for ν_e we integrate over all the variables corresponding to the electron. We consider here an unpolarized medium (for a calculation of the effective potentials in polarized and magnetized media see Ref. [68]). For nonrelativistic electrons, only the γ_0 component of the vector current gives a non-negligible contribution, and $\langle \overline{e}_L \gamma_0 e_L \rangle = \langle e^\dagger e \rangle = n_e$, where by $\langle \ \rangle$ we denote the averaging over electron spinors and summing over all the electrons in the medium. The effective potential V_e reads

$$V_e = \pm\sqrt{2}\, G_F \, n_e \ , \tag{1.55}$$

where the positive (negative) sign refers to ν_e ($\overline{\nu}_e$), and $n_e = N_A F_e \rho$ is the electron density. N_A is the Avogadro's number, F_e is the electron fraction and ρ is the matter density.

The propagation of neutrinos is thus affected if matter is present. In the three family scenario one obtains,

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E}U_{MNSP}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{12} & 0\\ 0 & 0 & \Delta m^2_{13}\end{pmatrix}U^\dagger_{MNSP} + \begin{pmatrix}2AE & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \tag{1.56}$$

where the term $2AE$ provides an effective contribution to ν_e and $\overline{\nu}_e$ energy. The matter parameter A is defined through $A \equiv \pm\sqrt{2}\, G_F\, n_e$, and the sign plus (minus) refers to neutrinos (antineutrinos). Its presence in the evolution of flavor eigenstates modifies the effective mixing parameters [69], and can lead to an enhancement (depletion) of neutrino (antineutrino) oscillations in media. This effect is known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect [66]. The MSW effect has been applied to solar neutrinos[8] and to neutrinos from Supernovae.

This effect also modifies the transition probability of neutrinos from different sources traveling through the Earth [70]. In fact, if matter effects are large enough, as in LBL experiments with a setup of thousand of kilometers between the source and the detector, the sign of Δ_{13} [71] could be determined, providing then very valuable information on the neutrino mass pattern. Indeed, the effective $\sin^2 2\theta_{13}$ in matter reads

$$(\sin^2 2\theta_{13})_{\text{matter}} = \sin^2 2\theta_{13}\, \frac{\Delta^2_{13}}{[\Delta_{13}\, \cos 2\theta_{13} \mp A]^2 + [\Delta_{13}\, \sin 2\theta_{13}]^2}\,, \tag{1.57}$$

where the sign minus (plus) refers to neutrinos (antineutrinos). If Δ_{13} is positive (negative) and matter effects are important, the probability of neutrinos is enhanced (depleted).

The knowledge of the matter density is thus very important for future LBL experiments [72]. A very convenient representation of the Earth's density profile is given by the *Preliminary Earth Model* [73, 74]. However, present geophysical studies leave uncertainties of $\sim$ 5% [75] on the matter density which affect the determination of neutrino oscillation parameters. The effect of these uncertainties will be discussed in detail later.

1.5 CP-δ Violation

CP symmetry interchanges particles with antiparticles and its violation implies for instance that $P\,(\nu_\alpha \to \nu_\beta) \neq P\,(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ [76]. These two oscillation probabilities may

[8] We shall describe the different solutions that arise from MSW effect for the solar neutrino oscillations in the next chapter.

differ if the mixing matrix, U, is complex, see Eq. (1.37). We have pointed out that only one phase in U, δ, is measurable in neutrino oscillation experiments. One example of a CP-related observable is the asymmetry [11, 77, 78, 79, 14]:

$$A^{\mathrm{CP}} \equiv \frac{P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)}{P\left(\nu_\alpha \to \nu_\beta\right) + P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)} \; . \tag{1.58}$$

A T-odd asymmetry can be also defined [80, 81], [11, 77], [82]-[85]:

$$A^{\mathrm{T}} \equiv \frac{P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\nu_\beta \to \nu_\alpha\right)}{P\left(\nu_\alpha \to \nu_\beta\right) + P\left(\nu_\beta \to \nu_\alpha\right)} \; , \tag{1.59}$$

where T denotes time reversal and it interchanges the initial and final states. If CPT if conserved, both asymmetries defined above are equivalent. We shall assume CPT invariance through all the present work.

CP or T violation effects can be identified only in appearance experiments[9], that is, $\alpha \neq \beta$ [77]: for disappearance experiments, $\alpha = \beta$, T invariance is automatic. The probability for $\bar{\nu}_\alpha \to \bar{\nu}_\alpha$, in the notation used in section 1.4, is

$$P\left(\bar{\nu}_\alpha \to \bar{\nu}_\alpha\right) \equiv |\mathcal{A}(\bar{\nu}_\alpha \to \bar{\nu}_\alpha; x, t)|^2 \; . \tag{1.60}$$

According to CPT conservation, $\mathcal{A}(\bar{\nu}_\alpha \to \bar{\nu}_\alpha; x, t) = \mathcal{A}^*(\nu_\alpha \to \nu_\alpha; -x, -t)$, and, from Eq. (1.34) it follows that

$$\mathcal{A}^*(\nu_\alpha \to \nu_\alpha; -x, -t) = \mathcal{A}(\nu_\alpha \to \nu_\alpha; x, t) \; . \tag{1.61}$$

Therefore, CP-Violation effects vanish in disappearance experiments.

Consider now appearance experiments ($\alpha \neq \beta$) and the CP-odd observable given by Eq. (1.58), whose numerator reads

$$D_{\alpha\beta} = \sum_{k>j} I_{\alpha\beta jk} \sin \frac{\Delta m^2_{jk} L}{2E} \; , \tag{1.62}$$

where

$$I_{\alpha\beta jk} = 4J \sum_{\gamma,l} \epsilon_{\alpha\beta\gamma}\epsilon_{jkl} = 4Im\left[U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}\right] \; . \tag{1.63}$$

Leptonic CP-Violation effects in vacuum are thus proportional to the Jarslog factor, J, as in the quark sector. In order to have a non-zero CP-odd observable, it is necessary that [77]

- All the mass differences of leptons of the same charge have to be non-zero.

[9] An appearance experiment searches for a flavor β non present (except as background) in the original beam of flavor α while a disappearance experiment looks for the remaining original α flavor, as we shall describe before.

- All the mixing angles and the CP phase-δ must have values for which the Jarlslog factor, Eq. (1.44), should not vanish.

According to the requirements depicted above, the CP-observable given by Eq. (1.58) will thus vanish if the appearance experiment considered here is only sensitive to one of the squared mass differences $\Delta m^2_{jk} \sim \Delta m^2_{13}$, see subsection 1.4.2. For instance, in SBL experiments and for neutrino energies of $\mathcal{O} \sim$ few GeV, $\Delta m^2_{12} L/2E \ll 1$ and Eq. (1.62) reads [77]

$$D^{(\mathrm{SBL})}_{\alpha\beta} \simeq (I_{\alpha\beta 13} + I_{\alpha\beta 23}) \sin \frac{\Delta m^2_{13} L}{2E} , \tag{1.64}$$

that vanishes due to the unitarity of the mixing matrix. The measurement of leptonic CP-Violation effects requires an appearance experiment sensitive to both $\Delta m^2_{13} L/2E$ and $\Delta m^2_{12} L/2E$: this will lead us to a LBL experiment with a typical distance $L \sim \mathcal{O}(1000)$ km for the neutrino energies considered above. Such an experiment has also to be equipped with a detector capable to identify the lepton charge, since the neutrino and antineutrino interactions produce negative and positive charged leptons, respectively.

CP-Violation effects involve thus subleading transitions not considered in subsection 1.4.2 that include small effects due to θ_{13} and Δm^2_{12}. We have developed a good and simple approximation for the transition probabilities by expanding to second order in the small parameters, $\theta_{13}, \Delta_{12}/\Delta_{13}$ and $\Delta_{12} L$ [14],

$$\begin{aligned} P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} &= \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{13}\, L}{2} \right) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta_{12}\, L}{2} \right) \\ &+ \tilde{J} \cos \left(\pm\delta - \frac{\Delta_{13}\, L}{2} \right) \frac{\Delta_{12}\, L}{2} \sin \left(\frac{\Delta_{13}\, L}{2} \right) , \end{aligned} \tag{1.65}$$

where the plus (minus) sign in the formulae refers to neutrinos (antineutrinos), and J is the Jarlslog factor defined in Eq. (1.44). Eq. (1.65) has three very different terms: the first one, which is dominant if we neglect Δm^2_{12} effects but not θ_{13} (that we shall dub the *atmospheric regime*), the second term, which is the dominant one when θ_{13} is very small or Δm^2_{12} effects are large (that we shall call the *solar regime*), and the third term, which contains the δ phase and is the *interference term*, which is relevant only if both Δm^2_{12} and θ_{13} are non-negligible.

The above discussion was for vacuum oscillations: in many situations, when neutrinos oscillate from the production source to the detector, they cross the Earth, and as argued in subsection 1.4.3, the Earth is a CP-odd medium. Matter induces thus a fake CP-Violation, since ν_e and $\overline{\nu}_e$ are differently affected by the ambient electrons [11, 77, 78, 14], [86]-[88]. To extract the value of the phase δ from the CP-observable given by Eq. (1.58), it is necessary to subtract the matter effects from that asymmetry. Else, a complete fit of all data, taking into account matter effects, can also extract the value of δ without theoretical subtractions and can be more complete, as it will be shown in Chapter III.

The T-odd asymmetry, Eq. (1.59), is not contaminated by the Earth CP-asymmetry. Its experimental measurement is extremely difficult, though, since one needs to produce two distinct neutrino flavors, not available in present neutrino experiments. This would be possible in future neutrino factories which produce neutrino beams composed by a 50% of ν_μ's ($\overline{\nu}_\mu$'s) and a 50% of $\overline{\nu}_e$'s (ν_e's) from μ^-'s (μ^+'s) decays. In practice, the measurement of the T-odd asymmetry in a neutrino factory would require to identify the electron charge, a truly difficult measurement [11].

The measurement of leptonic CP-Violation is thus a very difficult task. The CP-phase δ is highly correlated with other neutrino oscillation parameters, in particular, with the mixing angle θ_{13} [14, 15], see the U_{e3} element of the U_{MNSP} matrix given in Eq. (1.41). Also the uncertainties on the remaining parameters (two mass differences, two mixing angles and the matter effects, expressed through the A parameter) hide the extraction of δ. In fact, the measurement of δ is only foreseeable if Nature has selected large values for Δm^2_{12}, as can be observed from Eq. (1.65). We are lucky since this seems to be the case as indicated by recent results of the SNO experiment. In the next chapter it will be shown how the determination of the leptonic mixing parameters and the detection of CP-Violation effects start to be disentangled thanks to the experimental data from past, present and future neutrino oscillation experiments.

Chapter 2

Neutrino Oscillation Experiments

2.1 Introduction

As it has been shown in the last chapter, the oscillation probabilities for three light neutrino generations are described by two squared mass differences (Δm^2_{12} and Δm^2_{13}), three Euler angles (θ_{12}, θ_{23} and θ_{13}) and one CP-violating phase (δ). We have also pointed out that the present experimental data indicate that there exists a hierarchy in the neutrino mass spectrum $|\Delta m^2_{12}| \ll |\Delta m^2_{13}|$.

Different present and possible future experiments focus into the determination of these parameters, to wit:

Δm^2_{13}, θ_{23}	Atmospheric and LBL experiments,
	Superbeam projects and Neutrino Factory.
Δm^2_{12}, θ_{12}	Solar and Reactor experiments.
θ_{13}	Reactor, Atmospheric and LBL experiments,
	Superbeam projects, Neutrino Factory and BetaBeams projects.
CP-phase δ	Superbeam projects, Neutrino Factory and BetaBeams projects.

Consider the oscillation probabilities given in subsection 1.4.2. In *disappearance* experiments, one looks for the attenuation of the initial flavor in a neutrino beam due to the mixing with other flavors. Such an experiment tries to measure, for example, the oscillation probabilities $P_{\nu_e\nu_e(\bar{\nu}_e\bar{\nu}_e)}$ or $P_{\nu_\mu\nu_\mu(\bar{\nu}_\mu\bar{\nu}_\mu)}$, given at terrestrial or atmospheric distances by Eqs. (1.46) and (1.49) respectively, in the vacuum approximation.

In *appearance* experiments, one searches for neutrino interactions of a flavor not present in the original neutrino beam. For example, if one would like to measure the ν_μ events from an initial pure ν_e beam, the oscillation probability, at terrestrial or atmospheric distances is given by $P_{(\nu_e\nu_\mu)}$, see as an example Eq. (1.47), in the vacuum approximation.

Two principal sources of neutrinos are involved in performing the above neutrino oscillation experiments:
Nature neutrinos: Since the early sixties, neutrinos produced in the Sun have been observed [30]. From 1987 to now, thanks to the development of large and deep underground detectors, extensive measurements of the atmospheric neutrino flux have been also carried out.
Laboratory neutrino beams, produced at either accelerators or nuclear reactors. Nuclear reactors produce $\overline{\nu}_e$ beams in the β decay of neutron-rich fission fragments. The neutrino flux and spectra depend on the composition of the core, in terms of the four isotopes ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu being fissioned in the reactor. From the knowledge of reactor parameters the $\overline{\nu}_e$ flux is predicted with an uncertainty of 2.7%. The typical neutrino energies are $E \sim$ MeV. Due to the low neutrino energy, positrons are the only charged lepton which can be produced in the neutrino CC interaction at the far detector. Therefore oscillation experiments at reactors are *disappearance* experiments, i.e., they measure $P_{\bar{\nu}_e \bar{\nu}_e}$.

Traditional neutrino beams in particle accelerators from charged pion and kaons decays will be studied in some detail in subsection 2.2.2.

In the following sections we shall describe the above experiments and summarize the status on the knowledge of the neutrino mixing parameters deduced from the present experimental information. We shall also describe future planned experiments and its expected sensitivity to the oscillation parameters that they would measure.

2.2 $(\Delta m^2_{13},\, \theta_{23})$

2.2.1 Atmospheric neutrinos

When primary cosmic ray protons and nuclei enter the atmosphere their interactions produce secondary, -"atmospheric"- cosmic rays, including all the hadrons and their decays products [89]. The weakly interacting neutrinos are the last component of this secondary cosmic radiation. They have a very important role for neutrino oscillation experiments, covering a range of the parameter space unexplored up to now by terrestrial (i.e. laboratory) neutrino beams. The very recent accelerator-based K2K LBL experiment [90] is also sensitive to this region, as it will de described in subsection 2.2.2.

Atmospheric neutrinos are $\nu_e(\overline{\nu}_e)$, $\nu_\mu, (\overline{\nu}_\mu)$ neutrinos characterized by a wide L/E spectrum, from about 1 km/GeV to 10^5 km/GeV. The flight length of atmospheric neutrinos ranges from ~ 15 km to ~ 13000 km. This range, as we have pointed out in subsection 1.4.2, is such that $\Delta m^2 L/E \ll 1$ for the smaller mass gap Δm^2_{12}, but not for the larger mass gap, that is, Δm^2_{13}. The oscillation probabilities are then given, with a good approximation, by Eqs. (1.46), (1.47), (1.48), (1.49) and (1.50). We know from CHOOZ reactor data [91][1] that the mixing angle θ_{13} has a small value. Neglecting θ_{13}, one can describe the atmospheric oscillation phenomenom in a 2-family neutrino scenario. The relevant oscillation probabilities in vacuum for atmospheric neutrino experiments are:

$$\begin{aligned} P_{\nu_e\nu_e(\bar{\nu}_e\bar{\nu}_e)} &\simeq 1, & (2.1)\\ P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} &\simeq 0, & (2.2)\\ P_{\nu_\mu\nu_\tau(\bar{\nu}_\mu\bar{\nu}_\tau)} &\simeq \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) , & (2.3)\\ P_{\nu_\mu\nu_\mu(\bar{\nu}_\mu\bar{\nu}_\mu)} &\simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{13}\, L}{2}\right) . & (2.4) \end{aligned}$$

Atmospheric neutrino oscillation experiments then provide us information on the $(\Delta m^2_{13},\, \theta_{23})$ sector.

Atmospheric neutrino flux

The atmospheric neutrino flux was measured in the 1980's and early 1990's by the following experiments: Kamiokande [32], IMB [33], Soudan2 [92], MACRO [93], Fréjus [94] and Nusex [95]. Kamiokande and IMB were Cherenkov detectors while the other experiments were iron calorimeter detectors which detected the tracks of the charged particles.

The neutrinos come primarily from the two-body decay modes of pions and kaons and the subsequent muon decays:

$$\begin{aligned} Cosmic\, Rays + Atmosphere \;&\rightarrow\; \pi^\pm\,(K^\pm) \;+\; X\ , \\ \pi^\pm\,(K^\pm) \;&\rightarrow\; \mu^\pm + \nu_\mu\,(\overline{\nu}_\mu)\ , \\ \mu^\pm &\rightarrow e^\pm + \nu_e\,(\overline{\nu}_e) + \overline{\nu}_\mu\,(\nu_\mu)\ . \end{aligned} \qquad (2.5)$$

We have displayed only the dominant channels. When conditions are such that all particles decay, we expect:

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \sim 2\ . \qquad (2.6)$$

That is, one would expect to have two $\nu_\mu(\overline{\nu}_\mu)$ for each $\nu_e(\overline{\nu}_e)$. However, the different lifetimes and spectra of the decay particles modify this naive composition of the fluxes. In fact, the calculation of the atmospheric flux is a difficult task which considers factors such as geomagnetic effects, the cross section of π and K production or the solar activity and so on. Schematically, the flux of neutrinos of flavor i coming form the direction Ω can be written as [96]

$$\phi_{\nu_i}(\Omega) = \sum_A \Phi_A \otimes R_A \otimes Y_{p,n\rightarrow\nu_i}\ , \qquad (2.7)$$

[1]We shall explain the CHOOZ experiment in section 2.4.

where Φ_A is the primary cosmic-ray spectrum, R_A is the geomagnetic cutoff for the protons or light nuclei on the atmosphere from the direction Ω, and $Y_{p,n\to\nu_i}$ is the yield per nucleon of ν_i. The main sources of uncertainties on these quantities are related to:
Cosmic ray spectrum. The most important features are its composition, the energy dependence and the solar modulation. In particular, the solar wind makes the cosmic ray time dependent, specially at low energies (below 10 GeV).
Geomagnetic effects. Low energy cosmic rays are affected by the geomagnetic field which they must penetrate to reach the top of the atmosphere. This effect is stronger near the geomagnetic equator.
The neutrino yield. The decay distributions of the secondary mesons and muons which emerge from the interactions of cosmic rays with air nuclei are extremely well known. The largest source of differences between the various calculations for the neutrino yield is the use of different models for hadronic interactions.
Each of these factors induces some uncertainty on the calculation resulting in an overall uncertainty of $\sim 20\%$ in the knowledge of the atmospheric neutrino fluxes. In the ratio of the muon neutrino flux to the electron neutrino one, given by Eq. (2.6), the large uncertainty on the overall normalization cancels, though, and this ratio is estimated with an error of $\sim 5\%$ [97].

The main source of the uncertainty on the predicted atmospheric neutrino flux is the hadronic interaction model. A detailed knowledge of the hadron production cross-sections at the relevant energies for atmospheric and accelerator-based neutrino oscillation experiments will be soon achieved by the HARP experiment [98]. It will provide the key to a precise calculation of atmospheric neutrino fluxes, with an accuracy $\sim \mathcal{O}(2\%)$ on the prediction of the accepted muons.

Atmospheric neutrino experiments

To report their results, atmospheric neutrino experiments use the double ratio of the number of $\mu-like$ events (or "tracks") and the number of $e-like$ events (or "showers") between data and MC prediction:

$$R = \frac{\left(\frac{N_\mu}{N_e}\right)_{DATA}}{\left(\frac{N_\mu}{N_e}\right)_{MC}} \ . \tag{2.8}$$

The ratio given by Eq. (2.8) has been measured in several experiments such as Superkamiokande (SK) [2], Kamiokande [32], IMB [33], Soudan2 [92] or MACRO [93] and compared to Monte Carlo predictions. All these high statistic experiments[2] have reported that the double ratio measured is smaller than 1. The discrepancy between the observed and the predicted atmospheric neutrino fluxes is the well-known *atmospheric neutrino anomaly*.

[2]Although Fréjus and Nusex presented a double ratio $R \simeq 1$, which agreed with the expectation, the statistical errors of their measurements were large compared with Kamiokande and IMB.

The impressive statistics of the SK collaboration measurements [2], which have also received valuable confirmation from Soudan2 and MACRO [99], have confirmed the existence of the anomaly, which has been best explained in terms of neutrino oscillations.

Figure 2.1: *SK water Cherenkov located at the Mozumi mine in Kamioka, Japan. It is constituted by a 42 m cylindrical tank in height and 39 m in diameter which holds 50 kton of water. Figure taken from Ref. [100].*

The SK detector is a 50 kton water Cherenkov detector surrounded by more than 13,000 photomultiplier tubs, see Fig. 2.1. Atmospheric neutrinos are detected through CC interactions

$$\nu_\alpha + N \to \ell_\alpha + N' \ , \tag{2.9}$$

where $\alpha = e, \mu$. The resulting charged leptons produce rings of Cherenkov light.

The SK Collaboration divides their analysis into neutrino events with energies below the GeV (sub-GeV) and above the GeV (multi-GeV). Their measurement of the ratio given by Eq. (2.8) after 1489 days of contained data taking[3] gives [102]

$$\begin{aligned} R &= 0.638 \pm 0.016(\text{stat.}) \pm 0.05(\text{syst.}) \quad (\text{sub} - \text{GeV}) \ , \\ R &= 0.658^{+0.030}_{-0.028}(\text{stat.}) \pm 0.078(\text{syst.}) \quad (\text{multi} - \text{GeV}) \ , \end{aligned}$$

which deviate from the SM value of 1 by about 3 standard deviations. These effects were previously indicated by the data from the iron calorimeters Soudan2 and MACRO.

The result $R < 1$ implies a deficit of ν_μ, a superavit of ν_e, or both. The goal of the SK large statistics is not only to give a striking evidence of the atmospheric anomaly,

[3] There exist three types of atmospheric neutrino events observed in Kamiokande and subsequently in SK: fully-contained (FC), partially-contained (PC) and upward going muon events. The partially contained events are assumed to be all $\mu - like$ events [101].

but also to explain it in terms of neutrino oscillations, as it has been pointed out. Such an explanation was reinforced after the study of the angular dependence of the atmospheric neutrino flux [2].

The direction of a given neutrino interacting in the detector is described by the zenith angle θ and the azimuth angle ϕ. The zenith angle, parameterized in terms of $\cos\theta$, measures the direction of the reconstructed charged lepton with respect to the vertical of the detector. Vertically down-going (up-going) particles correspond to $\cos\theta = +1(-1)$. Kamiokande results yet seemed to indicate that there was a deficit of $\mu - like$ events mainly due to neutrinos coming below the horizon [103] and this deficit grew with the distance between the production and the detection point. Atmospheric neutrinos are produced isotropically at a distance of about 15 km above the surface of the Earth, but the neutrinos coming from the bottom of the detector have traveled 10^4 km more than those that come from the top (Fig. 2.2).

Figure 2.2: *Zenith angle symmetry of upward and downward going atmospheric neutrinos.*

This effect is more obvious for multi-GeV events since at higher energy the direction of the charged lepton is more aligned with the neutrino direction. The anomaly in the angular dependence can also be described in terms of an up-down asymmetry:

$$\mathcal{A}_\mu = \frac{\mathcal{U}_\mu - \mathcal{D}_\mu}{\mathcal{U}_\mu + \mathcal{D}_\mu} = -0.316 \pm 0.042(\text{stat.}) \pm 0.005(\text{syst.}) \quad (\text{multi} - \text{GeV}) \ , \qquad (2.10)$$

where $\mathcal{U}_\mu$ ($\mathcal{D}_\mu$) are the contained $\mu - like$ events with the zenith angle in the range $-1 \leq \cos\theta \leq -0.2$ ($0.2 \leq \cos\theta \leq 1$). It deviates from the SM value, $\mathcal{A}_\mu = 0$, by 7.5 standard deviations [96].

For the e-like events, a good agreement with $\mathcal{A}_e \simeq 0$, is found.

The SK precision data show consequently evidence for ν_μ oscillations into neutrinos which are not ν_e. The transition $\nu_\mu \to \nu_e$ is also excluded by negative results from the CHOOZ experiment [91], which is sensitive to $\Delta m^2_{13} \sim 10^{-3}$ eV^2 for maximal mixing. Thus, the two remaining possibilities are oscillations into ν_τ or into sterile neutrinos[4]. Sterile neutrino oscillations have been recently reported to be disfavored at the 99% confidence level [105] in a two family scheme, although SK data allows up to a 25% (90% C.L.) contribution from a neutrino sterile as a subdominant oscillation partner, in an analysis assuming more than two neutrino species. Assuming that no sterile component is present, in a 2-flavor generation analysis, see Eq. (2.3), the data fit at the 90% C.L. to oscillation parameters [102]:

$$\sin^2 2\theta_{23} \geq 0.92 \ , \tag{2.11}$$

$$|\Delta m^2_{13}| = (1.6 - 3.9) \times 10^{-3} \ \text{eV}^2 \ . \tag{2.12}$$

The allowed parameter regions at the 68%, 90% and 99% C.L. are shown in Fig. 2.3.

Figure 2.3: *Allowed parameter regions from the SK experiment on atmospheric neutrinos in the context of* $\nu_\mu \to \nu_\tau$ *oscillations in two families. The contours show the allowed parameter region at the* 68%, 90% *and* 99% *C.L., starting from inside. Figure extracted from Ref. [100].*

In November 2001, an explosion occurred in the SK detector which destroyed about 8000 photomultiplier tubs and stopped the data taking. The rebuilding of the 47% photomultiplier tubs by the autumn 2002, will allow to continue the measurements. The full detector is expected to be recovered in 2007.

[4]The sterile neutrino was first introduced by B. Pontecorvo in 1967 [104].

2.2.2 Laboratory Experiments

In particle accelerators, ν_μ's and $\overline{\nu}_\mu$'s are obtained mainly from π decays, with the pions produced by the scattering of accelerated protons on a fixed target:

$$\begin{aligned} p + \text{target} \rightarrow \quad & \pi^\pm \quad +X \\ & \pi^+ \quad \rightarrow \mu^+\nu_\mu \\ & \qquad\quad \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu \\ & \pi^- \quad \rightarrow \mu^-\bar{\nu}_\mu \\ & \qquad\quad \mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu \; . \end{aligned} \tag{2.13}$$

Above the kaon production threshold, some kaons arise from the proton interactions, and they will also produce neutrinos. If positive charged pions and kaons have been selected for the decay channel, the resulting beam will contain mostly muon neutrinos produced in the two body decays $\pi^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \mu^+\nu_\mu$. The neutrino beam will also contain a small contamination of electron neutrinos, electron antineutrinos and muon antineutrinos from muon, kaon and charmed meson decays. If the primary proton energy is large enough, the beam will also contain a small ν_τ component coming from prompt tauonic decays of D_s mesons. Muon antineutrino beams can be made by using a negatively charged meson beam.

There is a one to one correspondence between the energy of the parent pion and the energy of the neutrino at the far detector [106]

$$E_\nu = E_\pi \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{1}{1+\gamma^2\theta^2} \; , \tag{2.14}$$

where m_π and E_π are the mass and the energy of the pion, $\gamma = E_\pi/m_\pi$ and θ is the angle between the pion trajectory and the direction of the detector. In practice, the beam-line is designed to focus pions within a given momentum window. A broader pion momentum acceptance results in a higher neutrino flux, but also in a broader energy spread, which makes difficult to subtract the background events.

The neutrino flux per unit area and per meson decay at the far detector is

$$\Phi_\nu = BR \frac{1}{4\pi L^2} \left(\frac{2\gamma}{1+\gamma^2\theta^2} \right)^2 \; , \tag{2.15}$$

where BR is the branching ratio and L is the distance to the detector. The neutrino flux is thus maximal in the forward direction but the energy spread is large.

Experiments based on pion decay search for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations. The sensitivity of the latter is limited due to the ν_e contamination of the initial beam. The ν_e resulting from three-body decays, has an energy spectrum typically much broader than the ν_μ spectrum: some fraction of the electron neutrino flux overlaps in energy with the muon neutrino flux. Consequently, the narrower the ν_μ spectrum, the less the ν_e background.

The pioneer experiments in searching ν_μ oscillations were the CDHS experiment at CERN [107] and the BNL E776 experiment at the Brookhaven National Laboratory (USA) [108]. The data collected at both experiments, however, did not provide any evidence for neutrino oscillations.

The CERN SBL program has two appearance experiments: CHORUS and NOMAD [109]. The mean distance from the neutrino source is 600 m and 620 m respectively. They are based on a Wide Band Beam of ν_μ and the average energy of the neutrinos is $\sim$ 25 GeV. The muon antineutrino $\overline{\nu}_\mu$ and the electron neutrino ν_e contaminations in the beam are at the level of 6% and 1%. Both of them are mainly appearance experiments, looking for the $\nu_\tau + N \rightarrow \tau^- + X$ charged current process. These two experiments differ in the τ identification technics. While NOMAD uses an indirect search (the detector is an hybrid one: an active emulsion target plus an electronic detector), and the τ lepton is identified by kinematical criteria, CHORUS employs a direct search and the signal is from visual scanning (the detector is a fine grained calorimetry). Their expected sensitivity to Δm^2 is

$$\Delta m^2 \sim E/L \sim 10 \text{ eV}^2 \ . \tag{2.16}$$

More precisely, the range explored is $\Delta m^2 \sim 1 - 10$ eV^2 down to $\sin^2 2\theta \sim \mathcal{O}(10^{-4})$. This range is relevant for cosmology and dark matter (DM) studies. No evidence of neutrino oscillations has been found in any of them.

The K2K (KEK-to-Kamioka) experiment [90] is the first *"all-human-controlled"* experiment that was planned to cover the parameter region suggested by the atmospheric neutrino anomaly and confirmed by SK, free thus from the uncertainties on the neutrino flux calculation. K2K started the data taking in 1999. Neutrinos from pion decay are produced at the KEK proton-synchrotron (PS) with an energy spectrum peaked at $\sim$ 1 GeV. It uses the SK 50 kton water Cherenkov detector located at 250 km from the neutrino source. The K2K sensitivity is

$$\Delta m^2 \sim E/L \sim 4 \times 10^{-3} \text{ eV}^2 \ , \tag{2.17}$$

which overlaps significantly with the atmospheric neutrino region allowed by SK data, see Eq. (2.12) and consequently it provides information in the (Δm^2_{13}, θ_{23}) sector. The 90% C.L. allowed region on the oscillation parameters is $\Delta m^2_{13} = (1.5 - 3.9) \times 10^{-3}$ eV^2 for $\sin^2 2\theta_{23} = 1$ [110]. K2K has reported a probability for null oscillation less than 1% [110]. The rebuilding by autumn 2002 of the SK detector will allow to continue the K2K measurements.

2.2.3 (Δm^2_{13}, θ_{23}): Future

The immediate future of neutrino physics will be LBL experiments based on conventional beams from pion decay. In the next few years, besides K2K, the MINOS and

CERN to Gran Sasso (CNGS) facilities will confirm the hypothesis that neutrino oscillations are the explanation of SK data on atmospheric neutrinos. We briefly describe here the planned projects.

The MINOS experiment at Fermilab is under construction. Its major goals will be the observation, for the first time, of the L/E neutrino oscillation behavior, together with a precise determination of the Δm^2_{13}, θ_{23} parameters. This facility is designed to detect neutrinos from the Fermilab NuMI beam [111]. The source of the neutrino beam is the decay of pions produced by collisions of 120 GeV protons at the 0.4 MW NuMI proton driver. The ν_e contamination is of about 1%. A low, a medium and a high energy neutrino beam can be realized at MINOS by adjusting the focusing horn at the source. The resulting beam energies are peaked at 3.5, 7 and 15 GeV, respectively. The experiment will start to take data in 2005 with the low energy beam since this configuration maximizes the sensitivity to the atmospheric regime.

The MINOS project will have two iron/scintillator detectors: a near detector of 1 kton and a 5.4 kton located 735 km away from the source in the Soudan mine in Minnesota. Its expected sensitivity in the low energy configuration is

$$\Delta m^2 \sim E/L \sim 4 \times 10^{-4}\ \mathrm{eV}^2\ , \tag{2.18}$$

which overlaps the SK region, providing thus information in the (Δm^2_{13}, θ_{23}) sector. With the ν_μ disappearance channel, see Eq. (2.4), and the low energy beam, MINOS can determine the atmospheric parameters $\sin^2 2\theta_{23}$ and $|\Delta m^2_{13}|$ with a precision of about 10% [112] after 10 kton-years data, at the 99% C.L., in the range allowed by SK data.

At present, a new facility (CNGS) [113] is under construction at CERN that will direct a ν_μ beam to the Gran Sasso Laboratory (Italy) at a distance of 732 km, where two detectors (ICARUS and OPERA) will measure neutrino oscillations [114, 115]. Both detectors aim to measure ν_τ appearance, see Eq. (2.3). The average energy of the ν_μ beam is expected to be 17 GeV and the fraction of ν_e/ν_μ and ν_τ/ν_μ in the beam are of 0.8% and 10^{-7}. By exploring then the $\nu_\mu \to \nu_\tau$ channel, they claim to be able to achieve a measurement of $|\Delta m^2_{13}|$ with 10% accuracy [113] after 5 years data taking. Nevertheless, the extremely low statistics means that no real new knowledge, as regards the atmospheric oscillation parameters, will be extracted from τ detection, if MINOS progresses as planned.

2.3 (Δm^2_{12}, θ_{12})

Solar neutrinos are ν_e's with an energy $E \sim 0.2 - 9$ MeV, which travel distances $L \sim 10^7$ km. For these large distances, and neglecting the small mixing angle θ_{13}, see subsection 1.4.2, the analysis reduces to the 2-flavor scenario in Eqs. (1.51), (1.52) and (1.53). After this approximation, the oscillation probability for solar neutrinos, in vacuum, is given by Eq. (1.51):

$$P_{\nu_e\nu_e} \simeq 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) . \tag{2.19}$$

Solar neutrino experiments thus provide information mainly on the $(\Delta m^2_{12}, \theta_{12})$ sector.

2.3.1 Solar neutrinos

Electron neutrinos are produced in thermonuclear reactions which generate the solar energy. These reactions occur via two main chains, the *pp*-chain and the CNO cycle. Both chains result in the fusion of hydrogen into helium:

$$4p \rightarrow^4 He + 2e^+ + 2\nu_e \ + \gamma \ , \tag{2.20}$$

where $\langle E_{2\nu_e}\rangle = 0.59$ MeV. The fusion process is principally contributed by the *pp* cycle, whereas the carbon-nitrogen-oxygen (CNO) is responsible for less than 2% of the solar energy.

Solar Models [116] describe the properties of the Sun based on a set of observational parameters, as the surface luminosity and its age and mass. In Tab. (2.1) we recall the source reactions, the average and the maximum neutrino energies and the predicted neutrino fluxes by the most updated version of the model [117].

Source	Reaction	Average Energy $\langle E\rangle$ (MeV)	Maximum Energy (MeV)	Flux (10^{10} cm^{-2} s^{-1})
pp	$p + p \rightarrow d + e^+ + \nu_e$	0.2668	0.423 ± 0.03	5.95×10^0
pep	$p + e^- + p \rightarrow d + \nu_e$	1.445	1.445	1.40×10^{-2}
^{7}Be	$e^- + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_e$	0.8631	0.8631	4.77×10^{-1}
^{8}B	${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15	5.05×10^{-4}
hep	${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$	9.628	18.778	9.3×10^{-7}
^{13}N	${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$	0.7063	1.1982 ± 0.0003	5.48×10^{-2}
^{15}O	${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_e$	0.9964	1.7317 ± 0.0005	4.80×10^{-2}
^{17}F	${}^{17}\text{F} \rightarrow {}^{17}\text{O} + e^+ + \nu_e$	0.9977	1.7364 ± 0.0003	5.63×10^{-4}

Table 2.1: *Sources of solar neutrinos. The first five reactions belong to the pp cycle and the last three reactions to the CNO cycle.*

Neutrino propagation inside the Sun

As we have seen in subsection 1.4.3, the presence of solar matter in the neutrino propagation can lead to an enhancement of neutrino oscillations. The effective mixing angle in matter is given by Eq. (1.57), interchanging the subindices 13 by 12. Consider electron neutrinos which are produced in a high density solar zone, for example, in the Sun core. From Eq. (1.57) it follows that the mixing angle in matter is zero, since the matter parameter $A \gg \Delta_{12}\cos 2\theta_{12}$. After crossing this high density zone, the dominant component of the neutrino flavor (in terms of mass eigenstates) depends on the relative size of $\Delta_{12}\cos 2\theta_{12}$ versus A.

If $\Delta_{12}\cos 2\theta_{12} \gg A$, solar matter effects are nearly vanishing, and the oscillation phenomena occur in vacuum (VO), with an oscillation length, Eq. (1.40), of the order of the distance between the surface of the Sun and the detector located at the Earth sunny surface. The survival probability, Eq. (2.19), for this particular case reads

$$P_{\nu_e\nu_e} \simeq 1 - \frac{1}{2}\sin^2 2\theta_{12} \ . \qquad (2.21)$$

Now suppose that $\Delta_{12}\cos 2\theta_{12} < A$. Then, the neutrinos will cross the resonance zone, where $\Delta_{12}\cos 2\theta_{12} = A$, during its travel through the Sun surface, where $A = 0$. In the resonance zone the effective mixing angle in matter is maximal even for small mixing angles in vacuum, see Eq. (1.57). Consequently neutrino oscillations are enhanced in the solar interior and $P_{\nu_e\nu_e}$ can be very small. This is the so-called MSW effect [66].

Solar neutrino experiments

There exist several experiments which have measured the solar neutrino fluxes.

Historically, the first one was the Homestake experiment of R. Davis *et.al.* in 1967 [30]. Solar ν_e's are captured via

$$\nu_e +^{37}\mathrm{Cl} \rightarrow^{37}\mathrm{Ar} + e^- \ . \qquad (2.22)$$

The energy threshold is $E = 0.814$ MeV, and consequently the relevant fluxes are the ^{8}B and ^{7}Be neutrinos, see Fig. 2.4. The results obtained by the Davis experiment were really surprising: a deficit on the solar neutrino flux of more than 60% that predicted by the Solar Standard Model (SSM) was found. The Homestake indication was confirmed by similar radiochemical experiments: SAGE [118] at Baksan in Russia and GALLEX/GNO [119, 120] at Gran Sasso in Italy which used gallium instead of chlorine. In these experiments the energy threshold is lowered to $E = 0.233$ MeV and neutrinos from all sources can be detected. This confirmation of the Homestake results gave a strong support to the neutrino oscillation hypothesis and it spurred an increase of the interest for this problem. An essential improvement in the knowledge of solar

Figure 2.4: *Neutrino fluxes from the pp chain reactions as a function of the neutrino energy. Figure extracted from Ref. [96]*

neutrinos came from the advent of water Cherenkov detectors: Kamiokande and its successor SK also studied solar neutrinos [121] mainly through the detection of the scattered electrons by the elastic interaction

$$\nu + e^- \rightarrow \nu + e^- \ . \tag{2.23}$$

The detection threshold in Kamiokande was $E = 7.5$ MeV. The SK experiment started at $E = 6.5$ MeV and it was running at $E = 5$ MeV [96] before the explosion in November 2001. These energy thresholds indicate that both experiments are only able to detect ^{8}B neutrinos, see Fig. 2.4.

The results of the experiments described above are summarized in the Tab. (2.2) with 1σ uncertainties. In all of them, the measured flux is lower than the expected flux by the SSM [117]. This disagreement is known as the *solar neutrino deficit.* Since the Standard Solar Models have had notable successes, as noted from the excellent agreement between its calculations and helioseismological observations, these large discrepancies cannot be due to errors in the Solar Models.

The solar neutrino deficit can be explained in terms of neutrino oscillations which convert a fraction of solar ν_e's into neutrinos of other flavor or into sterile neutrinos. In the 2-flavor scenario, by assuming neutrino oscillations as the origin of the solar

Experiment	$R = \frac{\text{experimental flux}}{\text{predicted flux}}$
Chlorine	0.337 ± 0.065
Gallium	0.55 ± 0.048
SK	0.465 ± 0.094

Table 2.2: *Ratios of the observed solar neutrino flux to the SSM predictions [96].*

neutrino deficit, there seemed to be multiple solutions in the oscillation parameter space (Δm^2_{12}, θ_{12}) (see Tab. (2.3)):

- The vacuum solution (VO), which explains the solar neutrino deficit with oscillations in vacuum over typical distances of the order of the one between the Earth and the Sun, as it has been mentioned.

- Three additional possible solutions appear if the solar neutrino oscillations happen mainly inside the Sun, and are thus enhanced by the matter present in the solar interior, via the MSW effect explained in section 1.4.3:

  1. LMA (Large Mixing Angle)-MSW solution, if the corresponding mixing angle θ_{12} has a large value.
  2. SMA (Small Mixing Angle)-MSW solution, for which the corresponding mixing angle has a small value.
  3. LOW (low Δm^2_{12}) solution, if the corresponding mass difference has a small value.

- For solar neutrinos with low energies, particularly for *pp* neutrinos, the solar matter effects are nonnegligible for the vacuum oscillation with $\Delta m^2_{12} \geq 5 \times 10^{-10}$ eV^2. This is the quasi vacuum solution (QVO), in which both effects influence the solar neutrino survival probability [123].

Solution	Δm^2_{12} eV^2	$\tan^2 \theta_{12}$
LMA	5.5×10^{-3}	0.42
LOW	7.3×10^{-8}	0.67
QVO	6.5×10^{-10}	1.33
SMA	5.2×10^{-6}	1.1×10^{-3}

Table 2.3: *Best-fit values for the different solar neutrino solutions, for a global fit with all solar neutrino data in the 2-family scheme. Extracted from Ref. [122].*

The latest results of the Sudbury Neutrino Observatory (SNO) have almost unraveled this confusing situation [5]. The SNO experiment was designed to give a solar-model independent test of the solar neutrino flux deficit by having sensitivity to all flavors of active neutrinos and not only to ν_e: it is both an appearance and a disappearance experiment.

The SNO detector is located at Ontario (Canada) and it consists in 1 kton of heavy water D_2O. Electron neutrinos may interact via the CC reaction

$$\nu_e + d \to e^- + p + p \; , \tag{2.24}$$

while all active neutrinos interact via the NC reaction

$$\nu_\alpha + d \to \nu_\alpha + n + p \; , \tag{2.25}$$

and the elastic scattering (ES) process, but with smaller cross section. The detection thresholds of the three reactions are above 2 MeV: SNO only detects ^{8}B neutrinos, see Fig. 2.4.

In June 2001, the SNO Collaboration published its first results, and the CC rates of ν_e were [3]:

$$\phi^{CC}_{SNO} = 1.75 \pm 0.07\,(\text{stat.})^{+0.12}_{-0.11}\,(\text{syst.}) \times 10^6\text{cm}^{-2}\text{s}^{-1} \; . \tag{2.26}$$

The ES rates measured by the SNO experiment were [3]

$$\phi^{ES}_{SNO} = 2.39 \pm 0.34\,(\text{stat.})^{+0.16}_{-0.14}\,(\text{syst.}) \times 10^6\text{cm}^{-2}\text{s}^{-1} \; , \tag{2.27}$$

in agreement with the ES flux measured by SK.

The ratio of the observed SNO-CC flux to the corresponding flux predicted by the authors of Ref. [117] was [96]

$$R_{SNO} \;\; = \;\; 0.348 \pm 0.073 \; , \tag{2.28}$$

confirming the solar deficit and providing the first evidence in favor of the presence of ν_μ and ν_τ in the solar neutrino flux [124, 125].

From the data reported in Eq. (2.26) and Eq. (2.27), it can be seen that the CC flux is smaller than the ES one. The difference between the ratios of the fluxes is consistent with oscillations of ν_e into ν_μ and/or ν_τ, since the ES reaction is sensitive to all neutrino flavors, whereas the CC reaction only to ν_e's. In addition, this measurement disfavors oscillations into a sterile neutrino, which would lead to equal CC and ES ratios.

Recently, the SNO collaboration has published the first results of detection of solar neutrinos by using the NC reaction [4]. New CC and ES data have also been obtained:

$$\begin{aligned}
(\Phi^{CC}_\nu)_{SNO} &= 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\;(\text{syst.}) \times 10^6\;\text{cm}^{-2}\text{s}^{-1} \, , \\
(\Phi^{ES}_\nu)_{SNO} &= 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}\;(\text{syst.}) \times 10^6\;\text{cm}^{-2}\text{s}^{-1} \, , \\
(\Phi^{NC}_\nu)_{SNO} &= 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}\;(\text{syst.}) \times 10^6\;\text{cm}^{-2}\text{s}^{-1} \, .
\end{aligned} \tag{2.29}$$

The excess of the NC flux over the ES and CC implies neutrino flavor transformations in a solar-model independent way. The result for the total active neutrino flux obtained with the NC reaction is in very good agreement with the value calculated by solar models [117]: $5.05 \pm 1.0 \times 10^6$ cm^{-2}s^{-1}.

A simple change of variables resolves the data directly into electron (Φ_{ν_e}) and non-electron (Φ_{ν_μ,ν_τ}) components. The flux of ν_μ and ν_τ is

$$\sum_{l=\mu,\tau} \Phi_{\nu_l}^{NC} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.}) \times 10^6\ \ cm^{-2}s^{-1}\,. \tag{2.30}$$

All in all, it results a 5.3σ evidence of the presence of ν_μ and ν_τ in the flux of the solar neutrinos on the Earth. In a 2-family analysis [122][5], the recent SNO data [5, 122, 126, 127, 128] strongly favor the LMA solution, which is the only viable solution at a level greater than 3σ. LMA best-fit values [122] are shown in Tab. (2.3). Oscillations of solar neutrinos into pure sterile states are disfavored at $\sim 5\sigma$ level due to the difference between the observed CC and NC rates at SNO. In Ref. [122], the authors have found that QVO and LOW solutions are still acceptable at 99% and 99.73%C.L., respectively, while the SMA region is practically ruled out, see Fig. 2.5.

Additional information on the different solar oscillation regimes can be obtained from the analysis of the energy and time dependence data from SK [129], which is currently presented in the form of day-night spectrum. In the SK detector, no distortions were found between the measurements during day and night periods and both of them agreed with the SSM expectations. Thus, a large region of the oscillation parameter space where these variations were expected can be excluded. Finally, SK has also measured the seasonal dependence of the solar neutrino flux, and the data were consistent with the expected annual variation.

Spectra for day and night time periods have also been obtained by SNO [5], showing no statistically significant differences, in agreement with the previous measurements by SK.

All the experiments with data to date plan to continue with solar neutrino measurements. The Chlorine, GNO and SAGE experiments will add to the accuracy of their measurements by further counting and will improve upon the determination of the low energy region of the solar neutrino spectrum. SK is in the process of re-filling the detector following the major implosion in 2001. The SNO experimental plans call for three phases where different techniques are employed for the detection of neutrons from the NC reaction on deuterium.

[5] In Ref. [122] a complete and exhaustive analysis of current solar neutrino data is presented.

Figure 2.5: *Global results of the solar neutrino data analysis in a 2-flavor scenario among active states. Figure extracted from Ref. [122]. The best fit values for the different solutions are given in Tab.(2.3).*

2.3.2 $(\Delta m^2_{12},\, \theta_{12})$: Future

KamLAND and Borexino

The KamLAND reactor experiment, in the Kamioka mine at Japan, has started taking data [130, 131], in January 2002. Alike to the K2K experiment for atmospheric neutrinos, KamLAND may be the first *"all-human-controlled"* experiment showing evidence of neutrino oscillations in the solar range. This experiment is able to check the LMA-MSW solution of the solar neutrino deficit [132]. It is expected that its first results will be presented before the end of the year 2002. Furthermore, if the LMA solution is confirmed, KamLAND would achieve unprecedent precision in the determination of the mass gap Δm^2_{12}, better than 10% [132], if $\sin^2 2\theta_{12} < 0.7$, at the 2σ level.

KamLAND results are crucial as regarding CP-Violation in the leptonic sector, since, as we have pointed out, observable CP-effects require the subleading oscillation given by the smaller gap Δm^2_{12}, which must lay in the LMA region to be large enough to have any real chance of CP-observation in future experiments. The uncertainties on the solar parameters then affect the measurement of δ, as we shall study in Chapter IV.

If KamLAND does not confirm the LMA solution, the next most relevant solar neutrino results are expected to come from Borexino [133], in Gran Sasso (Italy), which is now under construction. Such experiment will be able to test the remaining LOW and QVO solutions by detecting time variations of the event rate [134]. The Borexino experiment, due to its lower energy threshold (~ 0.250 MeV), aims to provide measurements of the monoenergetic solar ^{7}Be neutrinos, see Fig. 2.4.

A new generation of solar neutrino experiments are under study (HELLAZ, HERON and SUPER-MuNu and LENS). The future measurements provide excellent promise for a fuller understanding of solar neutrino [135].

2.4 θ_{13}

We have discussed the experimental evidence for neutrino masses and mixings in a 2-family scenario, neglecting the mixing angle θ_{13}. Only upper bounds exist for this mixing angle. CHOOZ [91] has been fundamental as regards this issue. The CHOOZ reactor experiment (Ardennes, France) has an average ratio $L/E \sim 300$, and tested $\nu_e \rightarrow \nu_x$ neutrino oscillations via the $\overline{\nu}_e$ disappearance channel. It detects $\overline{\nu}_e$'s through the observation of the inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n \; . \tag{2.31}$$

The disappearance probability is well approximated by Eq. (1.46), that we recall here:

$$P_{\bar{\nu}_e \bar{\nu}_e} \;\; \simeq \;\; 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{13}\, L}{2} \right) \quad , \tag{2.32}$$

where we have neglected the Δm^2_{12} solar mass difference. Performing a one mass gap dominance (Δm^2_{13}) oscillation analysis, the 90% CL bound obtained in [91] for large values of Δm^2 is (see Fig. (2.6)):

$$\sin^2 2\theta_{13} < 0.1 \tag{2.33}$$

which means that $\theta_{13} < 9°$.

2.4.1 θ_{13}: Future

Let us recall that the most promising channels to measure or constraint the value of the mixing angle θ_{13} are the $\nu_e \rightarrow \nu_\mu$ and the $\nu_e \rightarrow \nu_\mu$ ones. For instance, for terrestrial

Figure 2.6: *CHOOZ* 90% *C.L. results in the* (Δm^2_{13}, $\sin^2 2\theta_{13}$) *plane, together with other experimental results: those from Bugey reactor experiment [136] and those from SK data analysis for a 3-active flavor scheme [102].*

or atmospheric distances and neutrino energies of several GeV, see subsection 1.4.2, the oscillation probabilities read

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} \simeq \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{13} L}{2}\right) , \tag{2.34}$$

$$P_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)} \simeq \sin^2 2\theta_{13} \cos^2 2\theta_{23} \sin^2\left(\frac{\Delta_{13} L}{2}\right) . \tag{2.35}$$

Experimentally, the channels $\nu_e \to \nu_\mu(\bar{\nu}_e \to \bar{\nu}_\mu)$ and $\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)$ are far superior than $\nu_e \to \nu_\tau(\bar{\nu}_e \to \bar{\nu}_\tau)$, since in the detector they will produce a charged μ (e), which are much easier to identify than a τ lepton.

MINOS [111], by searching for ν_e appearance, see Eq. (2.34), will be sensitive to $\sin^2 2\theta_{13} \geq 0.05$, that is, $\theta_{13} \geq 6°$, for $\Delta m^2_{13} \sim 3 \times 10^{-3}$ eV^2, maximal $\nu_\mu \to \nu_\tau$ mixing and an exposure of 10 kton-years, at the 90% C.L..

A better performance could be reached with the use of an *off-axis* beam at MINOS [137] (Fig. 2.7).

Figure 2.7: *Neutrino spectra from the low-energy MINOS beam recorded at a different transverse positions of the detector. The spectrum is much narrower at the* off-axis *detectors than the one at the central detector. Figure extracted from Ref. [137]*

What is an off-axis beam?
A neutrino beam with a narrow energy spectrum can be produced by placing the detector *off-axis*, i.e. at some angle with respect to the forward direction $\theta = 0$ [137, 138], see Eq (2.14) and Eq (2.15). By using *off-axis* beams, one manages a kinematical suppression of high energy neutrino component, whereas the low energy flux is kept approximately the same as that of *on-axis* beams. Since the neutrino flux is nearly monochromatic, the off-axis technique enables to reduce more effectively the ν_e background from the signal peak, the main problem of conventional beams.

In the off-axis beam case, the medium energy configuration together with a detector located at a transverse distance of 10 km from the central detector offer the best opportunity for the measurement of $\sin^2 2\theta_{13}$, since the ν_e background is strongly suppressed. With this set up, MINOS could be sensitive to a value of $\sin^2 2\theta_{13} \geq 0.0024$ ($\theta_{13} \geq 1.5°$) provided that $|\Delta m^2_{13}| \simeq 3 \times 10^{-3}$ eV^2 and with an exposure of 20 kton·yr, at the 3σ level[6].

[6] For a recent study, see Ref. [139].

Recently, it has been also investigated the sensitivity of the CNGS beam to the sub-dominant $\nu_\mu \to \nu_e$ oscillations in the region indicated by the atmospheric neutrino experiments. By combining both experiments, ICARUS and OPERA, the current limit of the CHOOZ experiment could be significantly improved (about a factor 5) [140]: $\sin^2 2\theta_{13} < 0.03$, that is, $\theta_{13} < 5°$ at 90% C.L., (assuming that $|\Delta m^2_{13}| \simeq 2.5 \times 10^{-3}$ eV^2 and maximal mixing) after 5 years of data taking.

A recent project which utilizes the CNGS in off-axis geometry is an underwater Cherenkov detector with 1 Mt mass located at the Gulf of Taranto [141]. The dominant beam component would consist of monochromatic ν_μ's of energy 0.8 GeV. The originality of this idea is to consider the possibility of a movable experiment, which exploits three different baselines around 1200 km, where the oscillatory pattern of ν_μ is fully developed. In such a facility, the atmospheric parameters could be precisely measured, and a sensitivity to a value of $\sin^2\theta_{13}$ as small as 0.006 ($\theta_{13} \sim 4.5°$) could be achieved.

2.5 LSND and KARMEN

Let us dedicate a few words to an experimental result that could imply that a 3-family neutrino setup is an excessively restricted scenario to encompass all oscillation present data. The LSND [142] scintillator detector is located at 30 m from the neutrino source in Los Alamos (USA). It is an accelerator-based experiment. Most of the produced π^+'s come to rest and decay through the sequence $\pi^+ \to \mu^+\nu_\mu$, followed by $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$. The muon antineutrino flux is used to study $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. A little fraction of the π^+'s decay in flight. This ν_μ flux is used to study $\nu_\mu \to \nu_e$ oscillations. After a global analysis, an evidence of neutrino oscillations was claimed by LSND, with the best fit point in $\sin^2\theta = 0.003$ and $\Delta m^2 = 1.2$ eV^2.

Taken at face value, the atmospheric, solar, and LSND data require three independent Δm^2 scales, that is, there must exist four neutrinos and at least three of them are required to be massive. The Z-boson width requires that one of these four neutrinos has to be a sterile $SU(2) \times U(1)$ electroweak singlet [144].

The LSND results are explored at present in the accelerator experiment KARMEN in the Rutherford Appleton Laboratory (UK) which searches for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations [145]. So far, KARMEN has not found electron antineutrino events, excluding part of the $\Delta m^2 - \sin^2 2\theta$ LSND allowed region. The MiniBooNE experiment [146] at Fermilab (USA), which aims to check all LSND parameter space, is running at present and recently has observed its first neutrino events.

In contrast to solar and atmospheric neutrino indications, in which several experiments have found compelling evidence for neutrino oscillations, the LSND results are presently found only in this experiment. As the LSND oscillation evidence requires confirmation, we shall consider neutrino oscillations in the framework of three families by neglecting LSND data. For the present study this is a conservative attitude.

2.6 Status of neutrino mixing and pending questions

According to the results presented above, the current status on neutrino mixing parameters is, in a scenario with three neutrino generations:

1. SK data on atmospheric neutrinos can be interpreted as neutrino oscillations $\nu_\mu \to \nu_\tau$. In a 2-family analysis, the data fit at the $90\% C.L.$ to oscillation parameters [102]:

$$\begin{aligned} 1.6\times10^{-3}\mathrm{eV}^2 &\leq |\Delta m^2_{23}| \leq 3.9\times10^{-3}\mathrm{eV}^2 \ , \\ 0.92 &\leq \sin^2 2\theta_{23} \leq 1 \ . \end{aligned}$$

2. The solar neutrino deficit is interpreted as matter enhanced neutrino oscillations $\nu_e \to \nu_\mu,\ \nu_\tau$ with two possible solutions for the parameter space. The most favored is the LMA solution with a best fit value [122] (before KamLAND):

$$\begin{aligned} \Delta m^2_{12} &= 5.5\times10^{-5}\mathrm{eV}^2 \ , \\ \tan^2\theta_{12} &= 0.42 \ . \end{aligned}$$

   The LOW and QVO solution are not totally excluded [122], as can be noticed from Fig. 2.5. Recently, the authors of Ref. [134] have studied in detail the 3-family perturbations to the 2-family solutions in solar neutrino analysis including the CHOOZ, SK and K2K constrains. They have found that the best fit is reached in the LMA region for the subcase of 2-family mixing, and, consequently, the additional admixture with the third neutrino is severely limited.

3. From the CHOOZ reactor experiment, we have an upper bound on θ_{13}:

$$\sin^2 2\theta_{13} < 0.1 \ , \tag{2.36}$$

   as recalled above.

Our knowledge of the leptonic mixing matrix MNSP can thus be resumed into:

$$U_{MNSP} = \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\ e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix} \ , \tag{2.37}$$

As a comparison, our knowledge of the CKM matrix, the analogous mixing matrix in the quark sector, is [37]

$$|U_{CKM}| = \begin{pmatrix} \sim 1 & \sim 10^{-1} & \sim 10^{-2} \\ \sim 10^{-1} & \sim 1 & \sim 10^{-2} \\ \sim 10^{-2} & \sim 10^{-2} & \sim 1 \end{pmatrix} , \tag{2.38}$$

The leptonic mixing matrix is rather different from its quark counterpart. In the CKM matrix, the diagonal elements are essentially unity, and all the off-diagonal elements are small. But in the MNSP matrix, given by Eq. (2.37), *all* the elements are fairly large, except U_{e3}. This difference between leptonic and quark mixing matrix may contain a clue about the origin of mixing and lepto-quark symmetries. It is mandatory to determine the MNSP matrix elements exactly. This implies that future neutrino experiments are necessary in order to measure the unknown parameters δ and θ_{13}.

Much is still unknown, and may remain unknown with the presently planned experiments for the forthcoming ten years, regarding fundamental issues such as:

1. The absolute value of neutrino mass.
   Direct determination of the neutrino mass would be the best way to tackle (if any) the new energy scale Λ, see Eq. (1.14). The bound from the tritium beta decay at present is $m_{\nu_e} = \sum_i |U_{ei}|^2 m_i < 2.2$ eV (95% C.L.) [39] . A future project, KATRIN [147], is being prepared to reach a sub-eV sensitivity for the ν_e mass.

2. The Majorana or Dirac character of neutrino field.
   The most promising search for elucidating the neutrino character is the neutrinoless double beta decay experiment. This experiment gives information about the effective Majorana neutrino mass, and its actual limit is $\langle m_{\rm eff} \rangle < 0.35$ eV (90% C.L.) [49]. Several planned projects are expected to improve the sensitivity up to one order of magnitude [50].

3. The value of θ_{13}.
   The determination or a severe constrain of θ_{13} must thus be the first priority of future experiments, in order to discover leptonic CP-Violation.

4. The existence of CP-Violation in the lepton sector.
   The Dirac phase δ may remain unknown. If neutrinos are Majorana, there are two further CP violating phases, only measurable in $\beta\beta$ experiments.

5. The ordering of the mass spectrum.
   The lack of knowledge on the sign of Δm^2_{13} prevents from distinguishing between the two possible patterns of neutrino masses compatible with the result $|\Delta m^2_{12}| \ll |\Delta m^2_{13}|$:

$$\begin{array}{rl} \text{normal hierarchy:} & |m_1| \simeq |m_2| \ll |m_3| \\ \text{inverted hierarchy:} & |m_3| \ll |m_2| \simeq |m_1| \end{array}$$

The matter effects present in future LBL experiments [71] will help to disentangle the two possible neutrino eigenstates mass patterns. This requires to be sensitive to θ_{13}, see Eq. (1.57).

Figure 2.8: *Mass patterns consistent with neutrino oscillation explanations of the atmospheric and solar neutrino data.*

Oscillation experiments can shed much light on the last three questions. Solving all of them will require precision experiments beyond the presently planned ones.

2.7 Future Laboratory Experiments

2.7.1 The BetaBeams project

Recently, an alternative source of neutrinos has been proposed: the nuclear β-decay $^6He^{++} \rightarrow^6 Li^{+++}\, e^- \,\overline{\nu}_e$ [149]. The well-known energy spectrum and the pure ν_e composition suggest *BetaBeams* as an appropriate tool to carry out precision measurements. The attainable physics exploiting BetaBeams facilities is already under study [13].

2.7.2 The Superbeam facilities

A main step on neutrino oscillation physics could be provided by the so-called Superbeams which, based on traditional neutrino beams, can achieve better precision thanks to a higher statistics and other improvements. Superbeam experiments aim to measure the atmospheric parameters at the 1% level. Their main goal, though, will be the measurement or severe constraint of the angle θ_{13} and, in very optimistic conditions, to provide a hint of the CP-phase δ.

The first neutrino Superbeam will be a LBL projected experiment which uses the SK detector: The Japanese Hadron Facility (JHF) [148]. The JHF facility is already under construction and its first phase of 5 years running will start in 2007. It will be provided by three beam configurations: a wide band beam (WBB), a narrow band beam (NBB) and an off-axis beam (OAB) with corresponding peak energies of 1 GeV, 0.95 GeV and 0.7 GeV .The NBB and the OAB designs expect ν_e contamination at the peak energy of 0.2%, while that of the WBB option is 0.3%. The low ν_e background will allow to measure, from ν_μ disappearance, $\sin^2 2\theta_{23}$ with an expected precision of 1% and $|\Delta m^2_{13}|$ with a precision better than 10^{-4}eV^2. Assuming that $|\Delta m^2_{13}| \simeq 3 \times 10^{-3}$ eV^2, JHF will be sensitive to $\sin^2 2\theta_{13} \geq 0.01$ ($\theta_{13} \geq 3°$), in the WBB option, see Fig. 2.9.

Figure 2.9: *Oscillation sensitivity for the JHF wide band beam (WBB), narrow band beam (NBB) and off-axis beam (OAB) at the* 90% *C.L. for 5 years exposure. Notice that the plotted quantity is* $\sin^2 2\theta_{\mu e} = 0.5 \cdot \sin^2 2\theta_{13}$. *Figure extracted from Ref. [148].*

The JHF program has an upgrade proposal, where both the beamline and the detector would be increased. The proton power would be risen to 4 MW and the new detector would be the so-called Hyper Kamiokande [148], a water Cherenkov with 20 times the fiducial mass of the SK detector. With this increase in exposure (in terms of kton-year), JHF would be able to observe $\nu_\mu \to \nu_e$ oscillations at 3σ over the background if $\sin^2 2\theta_{13} \geq 0.001$ ($\theta_{13} \geq 1°$).

Another Superbeam facility at Fermilab has been proposed in Ref. [106]. High intensity neutrino beams would be produced with a proton driver with 1.6 MW which increases the intensity of the NuMI beam by a factor four. In this case the ν_e fractional background is reduced to 0.2%. A range of baselines from 350 km to 2990 km has been considered with corresponding optimal energies from 1 GeV to 8.2 GeV. In this scenario it would be possible to observe ν_e and ν_τ appearance 3σ above the background, provided that $\sin^2 2\theta_{13} \geq 0.002 - 0.003$, an order of magnitude below the reach of the upcoming LBL experiments with lower intensity. A liquid argon detector, an effective 70 kt-year data accumulation for ν_e detection and 3.3 kt per year for ν_τ detection are considered.

The CERN-SPL Superbeam project

The SPL neutrino beam

Mean beam power	4MW
Kinetic energy	2.2 GeV
Repetition rate	75Hz
Pulse duration	2.2 ms
Number of protons per pulse (per second)	$1.5\ 10^{14} (1.1 10^{16})$
Mean current during a pulse	11 mA
Overall lenght	799 m
Bunch frequency (minimum time between bunches)	352.2 MHz (2.84 ns)

Table 2.4: Basic SPL characteristics. Table extracted from Ref. [8]

The planned Super Proton Linac is a proton beam of 4 MW power which will be used as a first stage of the Neutrino Factory complex. Its basic parameters are reported in Tab. (2.4). The resulting neutrino spectra is shown in Fig. 2.10. Notice that the average energy of the neutrinos is around 250 MeV and that the ν_e contamination of the beam is at the level of few per mil. Due to the low energy of protons, kaon production is strongly suppressed, resulting in both less ν_e contamination and better controlled beam systematics.

A very recent new optics design for the CERN-SPL [150] produces a neutrino beam which is much more intense than the one in the first CERN-SPL proposal [8], as can be noticed from Fig. 2.11.

As a baseline, the CERN-SPL proposal [8] considered 130 km, which is near the maximum of the oscillation and equals the distance between CERN and the Modane laboratory in the FREJUS tunnel, where a large neutrino detector could be located [151, 152].

Water Cherenkov detectors

In the CERN-SPL proposal [8], two detector technologies are considered: water Cherenkov and diluted liquid scintillator detectors.

We briefly describe the water Cherenkov detector since its detection techniques will be exploited in Chapter V. The water Cherenkov detector considered was an apparatus

Figure 2.10: *The SPL neutrino spectra, for* π^+ *focused in the horn. The fluxes are computed at 50 km from the target, then scaled to the relevant distances. Figure extracted from Ref. [8].*

of 40 kton fiducial mass and sensitivity identical to the SK experiment. In the absence of neutrino oscillations, the dominant reaction induced by the beam is ν_μ quasi-elastic scattering, leading to a single observed muon ring. To unambiguously identify a potentially small ν_e appearance signal, it is essential to avoid confusion of muons with electrons. Thanks to the low energy of the SPL and its neutrino beam, the Cherenkov threshold itself helps separate muons and electrons, since a muon produced near the peak of the spectrum ($\sim 300\,\mathrm{MeV/c}$) cannot be confused with an electron of comparable momentum; instead it will appear to be a much lower-energy ($\sim 100\,\mathrm{MeV/c}$) electron.

Physics reach

In the CERN-SPL Superbeam facility, the atmospheric parameters could be measured with a precision of $\mathcal{O}(1\%)$ and the sensitivity to $\nu_\mu \to \nu_e$ oscillations would be pinned down to $\sin^2 2\theta_{13} \geq 0.0025$ ($\theta_{13} \geq 1.5^o$), see Fig 2.12, assuming 2 years of neutrino run and ten years of antineutrino run [7].

---

[7] Antineutrino event rates are three to six times lower than neutrino rates, and correspondingly longer running times are required to accumulate comparable number of events

Figure 2.11: *The CERN-SPL neutrino spectra for π^+ focused in the horn. We show the beam with the new beam optics vs. old beam*

In Chapter V we will study the simultaneous measurement of θ_{13} and the CP-phase δ at the CERN-SPL Superbeam facility, but assuming a very large water detector, such as the proposed UNO [153] water Cherenkov apparatus, with a fiducial mass of 400 ktons. Such a detector may be argued to be unrealistic in practice. We shall use it with the purpose of illustrating the far-future physics perspective.

2.7.3 The Neutrino factory complex

A major advance should come from a Neutrino Factory [9, 10, 11, 12] from muon decays, aiming at both fundamental discoveries (regarding the δ and θ_{13} determination) and $\mathcal{O}(1\%)$ precision measurements.

Neutrino Factories provide high energy and very-well known intense neutrino beams resulting from charged muons which decay in the straight sections of a muon storage ring [154]. Present projects consider the production of muon sources of about 10^{20} muons per year. The subsequently neutrino beam is composed by muon antineutrinos (neutrinos) and electron neutrinos (antineutrinos) coming from the decay $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$. The best way to measure the mixing unknowns is through the subleading transitions $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$, which is precisely the clean golden

Figure 2.12: *Oscillation sensitivity for* π^+ *focused neutrino Superbeams at the* 90% *and* 99% *C.L.. Figure extracted from Ref. [8].*

signal at the neutrino factory, that we introduced in our motivations and goals.

An essentially unified design [155], based on a muon accumulator with either a triangular or a bow-tie shape, is shown in Fig. 2.7.3 and Fig. 2.13. Both geometries permit two straight sections pointing in different directions, allowing two different baselines. What is/are the best baseline/s? In the next three chapters we shall study the ideal place to locate the detector, in order to optimize the sensitivity to the mixing parameters. We shall perform both analytical and simulation studies. Our setup consists in neutrino and antineutrino beams coming from the decays of 1×10^{21} positive/negative muons. The muon energy is 50 GeV. The detector considered is an iron magnetized calorimeter of 40 kton, as described in Ref. [156].

In the next two subsections we show the neutrino spectra and charged current event shapes as function of the neutrino energy, for three distinct typical baselines: a short baseline ($L = 732$ km), a medium baseline ($L = 3500$ km) and a large one ($L = 7332$ km).

Neutrino Fluxes

Future neutrino factories aim at an overall flux precision of $\mathcal{O}(1\%)$ or better. In the laboratory frame, the neutrino fluxes are given by:

$$\begin{aligned}
\frac{d^2N_{\bar{\nu}_\mu,\nu_\mu}}{dyd\Omega} &= \frac{4n_\mu}{\pi L^2 m_\mu^6} \cdot E_\mu^4 y^2 (1-\beta\cos\varphi) \cdot \Big\{ \Big[3m_\mu^2 - 4yE_\mu^2(1-\beta\cos\varphi) \Big] \\
&\quad \mp P_\mu \Big[m_\mu^2 - 4yE_\mu^2(1-\beta\cos\varphi) \Big] \Big\} \ , \\
\frac{d^2N_{\nu_e\bar{\nu}_e}}{dyd\Omega} &= \frac{24n_\mu}{\pi L^2 m_\mu^6} \cdot E_\mu^4 y^2 (1-\beta\cos\varphi) \cdot \Big\{ \Big[m_\mu^2 - 2yE_\mu^2(1-\beta\cos\varphi) \Big] \\
&\quad \mp P_\mu \Big[m_\mu^2 - 2yE_\mu^2(1-\beta\cos\varphi) \Big] \Big\} \, . \qquad (2.39)
\end{aligned}$$

where $\beta = \sqrt{1 - m_\mu^2/E_\mu^2}$, m_μ and E_μ are the muon mass and energy, $y = E_\nu/E_\mu$, E_ν is the neutrino energy, n_μ is the number of muon decays, L is the baseline and P_μ is the average muon polarization along the beam direction. The radiative corrections and the angular divergence have been considered in Ref. [158], where we found that the resulting corrections to the neutrino flux turn out to be of order $\mathcal{O}(0.1\%)$, safely below the required precision.

Unlike traditional neutrino beams from charged pion and kaon decays, the fluxes in Eq. (2.39) will increase as $(E_\nu E_\mu)^2$. This implies that the number of neutrinos produced with a given energy $E_\nu < E_\mu$ is independent of E_μ: the oscillation signal does not decrease if E_μ increases, though. In Tab. (2.5) we show the average neutrino and antineutrino energies for different muon polarizations and energies.

In Figs. 2.14, 2.15 and 2.16 we show the neutrino and antineutrino fluxes for the three possible detector locations considered here, and our setup. The angular divergence has been considered constant, $\delta\varphi \sim 0.1$ mr.

$E_\mu (GeV)$	10		20		50	
P_μ	0	-1 (1)	0	-1 (1)	0	-1 (1)
$E_{\bar{\nu}_\mu}(E_{\nu_\mu})(GeV)$	7	6	14	12	35	30
$E_{\nu_e}(E_{\bar{\nu}_e})$ (GeV)	6	6	12	12	30	30

Table 2.5: *Average neutrino and antineutrino energies considering positive (negative) storaged muons with distinct energies and polarizations.*

Charged Current events

The calculation of the number of charged current events in the far detector can be performed in a simple way using the approximate expressions for the neutrino-nucleon cross-sections with an isoscalar target (that is, with the same number of protons than neutrons),

$$\sigma_{\nu N} \approx 0.67 \times 10^{-42} \times \frac{E_\nu}{\text{GeV}} \times \text{m}^2 \ , \qquad \sigma_{\bar{\nu} N} \approx 0.34 \times 10^{-42} \times \frac{E_\nu}{\text{GeV}} \times \text{m}^2. \qquad (2.40)$$

The number of events observed at the far detector will thus grow as E_ν^3. Alike to the neutrino fluxes, we show in Figs. 2.17, 2.18 and 2.19 the number of non-oscillated charged current events for the three possible detector locations.

Figure 2.14: *Neutrino fluxes at $L = 732$ km from the source. The fluxes have been averaged over a central spot with an opening constant angle $\delta\varphi \sim 0.1$ mr. Top (botton) figures correspond to negative (positive) charged storaged muons. Notice the logarithmic scale.*

Figure 2.15: *The same as Fig. 2.14, but for* $L = 3500$ *km.*

Figure 2.16: *The same as Fig. 2.14, but for* $L = 7332$ *km.*

Figure 2.17: *Number of charged current events in a* 40 *kton iron magnetized calorimeter detector located at* $L = 732$ *km from the Neutrino factory complex. Top (bottom) figures correspond to negative (positive) charged storaged muons. Notice the logarithmic scale.*

Figure 2.18: *The same as Fig. 2.17, but for* $L = 3500$ *km.*

Figure 2.19: *The same as Fig. 2.17, but for* $L = 7332$ *km.*

Chapter 3

Golden measurements at a neutrino factory

Chapter 4

On the measurement of leptonic CP violation

Chapter 5

Superbeams plus Neutrino Factory

Chapter 6

Summary and Conclusions

It is a very interesting era for particle physicists. Progressive neutrino data are continously deepening our knowledge of the new physics they unravel. One of our major challenges is to search for a theoretical model to accommodate in a natural way the new physics scale Λ that they suggest.

A measurement of the absolute mass for one neutrino would allow to guide us towards this new physics scale Λ. Neutrino oscillation physics is already able to determine the mass differences and the mixing parameters between neutrino flavors and contribute potentially to the overall understanding of the origin of fermion masses.

Several oscillation experiments that use neutrino beams from particle accelerators and nuclear reactors are taking data and similar future experiments will take data over the next few years. All of them have inaugurated a precision era in Neutrino Physics. In the present work we have concentrated in two important unknowns that, even with all the planned effort, may remain obscure in our knowledge of the leptonic mixing sector: the angle θ_{13} and the CP-phase δ. The former may be at reach if the small parameters θ_{13} and Δm^2_{12} -small when compared with all the relevant energy scales at terrestrial distances- are not so small. The solar parameters are then required to be within the LMA-MSW region, which, in fact, gives the best global fit [134] for solar neutrino data after the SNO recent results, and is expected to be robustly established by the KamLAND data [132]. We have struggled to find a way to determine θ_{13} and δ. This had lead us to consider Superbeam (SB) and Neutrino Factory (NF) facilities.

The most promising way to determine the unknown parameters δ and θ_{13} is through the detection of the subleading transitions $\nu_e \rightarrow \nu_\mu$ and $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ by using the golden signature of wrong sign muons [14]. We have derived an analytical formulae, which constitutes an essential tool to throw much light on the understanding of how to extract δ and θ_{13}. We have also performed an exhaustive numerical treatment. All numerical results have been obtained with the exact formulae for the oscillation probabilities. Realistic background and efficiencies for the detector considered, see Ref. [156], as well as accurate matter effects along the neutrino path, have been included in our numerical analysis. Furthermore, we have also considered the impact of the expected uncertainties on the knowledge of the solar and atmospheric parameters and on the matter density at the time of the NF, and we have found that these uncertainties do not affect dramatically our global fits [15].

We have analyzed the question of whether is it possible the unambiguous determination of δ and θ_{13} by measuring the transition probabilities $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$ at fixed neutrino energy and at just one NF baseline. The answer is no. By exploring the full (allowed) range of the δ and θ_{13} parameters, that is, $-180^\circ < \delta < 180^\circ$ and $0^\circ < \theta_{13} < 10^\circ$, we have discovered, at fixed neutrino energy and at fixed baseline, the existence of degenerate solutions (δ', θ'_{13}), that we have dubbed *intrinsic degeneracies*, which give the same oscillation probabilities than the set (δ, θ_{13}) chosen by Nature [15]. In order to fully resolve these degeneracies with data from only one NF baseline, we suggested to combine the results from the optimal one, that we found to be of the order of $\mathcal{O}(3000)$ km, with other NF baseline [15].

Recently, it also has been pointed out that other fake solutions might appear from unresolved degeneracies in two other oscillation parameters [159], to wit:

1. At the time of the future NF, the sign of the atmospheric mass difference Δm^2_{13} may remain unknown, that is, we would not know if the hierarchy of the neutrino mass spectrum is normal or inverted.

2. Disappearance experiments only give us information on $\sin^2 2\theta_{23}$: is θ_{23} in the first octant, or is it in the second one, $(\pi/2 - \theta_{23})$?

All these ambiguities complicate the extraction strategy of δ and θ_{13}. To illustrate in brief the conclusions obtained in this work, imagine as an example that the values chosen by Nature are $\delta = 54^\circ$ and $\theta_{13} = 2^\circ$, and consider the NF fluxes with a detector of the type discussed in Ref. [156] located at $L = 2810$ km. A global fit of the experimental data using the spectral information would result in a cluster of solutions some of which are depicted in the Fig. 6.1. A constellation of fake solutions (θ'_{13}, δ') surrounds the true one: those induced by the intrinsic degeneracy and by the θ_{23} octant ambiguity are shown, whereas those coming from the ambiguity in the sign of Δm^2_{13} are absent for the particular case analyzed here due to the presence of sizeable matter effects. Finally, the combined degeneracy that would arise when performing a fit with both the wrong choices of the sign(Δm^2_{13}) and of the θ_{23} octant is also not depicted. From the results shown in Fig. 6.1, we see that we would not be able to determine whether $\delta \simeq 54^\circ$ (CP is violated) or $\delta \simeq 180^\circ$ (CP is conserved)!

The degeneracies can be resolved by exploiting the different neutrino energy and baseline dependence of two (or more) LBL experiments. This is precisely the case for the NF and the SPL-SB facilities. The location of the fake solution depends strongly on the baseline and the neutrino energy approximately through the ratio L/E. Since these experiments have different L/E ratio, the fake solutions that appear after a

Figure 6.1: 68.5%, 90% *and* 99% *contours resulting from the fits at* $L = 2810$ *km for* $\delta = 54^\circ$ *and* $\theta_{13} = 2^\circ$*. Three fake solutions appear clustering round the true one. The degeneracy corresponding to the case of a global fit data with the wrong choice of the sign of* Δm^2_{13} *and of the* θ_{23} *octant is not depicted.*

global fit of the data get *opposite displacements* with respect the to the true value. The combination of the results of the two facilities gets then rid of most of them [16]. For the example here, after combining the data obtained at a NF baseline of $L = 2810$ km and the data from the SPL-SB facility, the fit clearly selects the Nature solution, see Fig. 6.2.

Evidently, this example is for a rather high value of $\theta_{13} = 2^\circ$. We have explored in great detail the parameter space down to very low values of θ_{13}, see Chapters III, IV and V. In summary:

- NF and SB experiments are successive steps towards the same physics goals, not two alternative options. It is natural to combine their expected results. This combination is particularly useful to resolve the degeneracies, due to the different neutrino energy and baseline dependence of the signals for these two experiments.

- The intrinsic degeneracies disappear after the combination down to the sensitivity limit, which, if the other degeneracies are not considered, is $\theta_{13} \sim 0.3^\circ$ for the data from a NF medium baseline ($L = 2810$ km) and $\theta_{13} \sim 0.6^\circ$ for the NF short baseline case ($L = 732$ km). These fake solutions are fully resolved even for the data from just one NF short baseline! Although this short distance is below $\sim \mathcal{O}(1000)$ km, which are the required typical distances to be sensitive to CP-Violation effects[1] as we argued in section 1.5, it is a very interesting distance after combining its results from those from the SPL-SB facility.

[1] We are considering neutrino energies of several dozens of GeV.

Figure 6.2: *Fits combining the results from the SPL-SB facility and from a neutrino factory baseline at $L = 2810$ km for $\delta = 54°$ and $\theta_{13} = 2°$. Notice that the fake intrinsic solutions have completely disappeared in the combination.*

- The degeneracies that arise due to the sign(Δm^2_{13}) ambiguity can be resolved by combining the results from a NF with $L = 2810$ km and those from the SPL-SB facilities for $\theta_{13} \geq 1°$. For shorter baselines ($L = 732$ km) these fake solutions can be resolved after the combination for values of θ_{13} near its present limit, given by CHOOZ [91]. At very small θ_{13} the sign remains an ambiguity, but it does not interfere much with the determination of θ_{13} (in this particular case, $\theta^{'}_{13} = \theta_{13}$) and with the measurement of leptonic CP violation, since $\delta^{'} = 180° - \delta$. The former implies that $\sin\delta^{'} = \sin\delta$.

- The degeneracies due to the $(\theta_{23}, \pi/2 - \theta_{23})$ ambiguity are difficult to resolve and they can interfere with the measurement of θ_{13} and δ if θ_{23} is very far from maximal mixing. However, the combination of NF and SB experiments helps enormously in minimizing the bias in the extraction of θ_{13} and δ.

Although the combination of the data from two SB facilities with different $E/L \sim \Delta m^2_{13}$ could also a priori overcome the degeneracies, SB projects are in general planned to exploit data on or nearby the oscillation maximum and, therefore, the differences in their E/L are not large enough to fully resolve them.

An updated version [160] of the work summarize here [16], with new neutrino fluxes from a new optics for the SPL-SB [150] will show that all the degeneracies in the simultaneous determination of the unknown parameters θ_{13} and δ are totally overcome, including those due to the θ_{23} ambiguity, even for the short NF baseline, down to

$\theta_{13} \sim 0.6^\circ$. Furthermore, it has previously been pointed out [161] that a supplementary measurement of the *Silver* channels, i.e. $\nu_e \leftrightarrow \nu_\tau$ ($\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$), could help in removing the intrinsic degeneracy. We have also discussed the expected impact of such measurements on resolving the fake sign and θ_{23} degeneracies. A detailed analysis [162] using these *Silver* channels is mandatory: we expect a big improvement in the dangerous fake solutions associated with the θ_{23} octant ambiguity. If these additional channels are also added to our analysis, the very large detector mass considered here for the SPL-SB analysis (that is, 400 kton) could be lowered, in order to have a more realistic detector.

All the latter improvements have to be explored carefully in order to ascertain the ultimate precision in the determination of the detailed pattern of neutrino mass differences and mixing angles, a prerequisite to understand their origin and their relationship to the analogous parameters in the quark sector. The Neutrino Factory plus its predecessor, the Superbeam experiment, would provide us the key to fulfill this goal.

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Sumario

Los Físicos de Partículas estamos viviendo una era realmente interesante. Los datos procedentes de experimentos con neutrinos nos están permitiendo el acercarnos progresivamente a una nueva escala de Física. Uno de nuestros mayores objetivos, precisamente, es encontrar un modelo teórico para acomodar, de un modo natural, la nueva escala de energía Λ, que estos datos sugieren.

La medida de la masa absoluta de uno de los tres neutrinos activos ligeros nos serviría como guía hacia esta nueva escala. Hoy en día, las oscilaciones del neutrino son ya capaces de proporcionar una medida de las diferencias de masas y de los parámetros de la mezcla entre neutrinos de diferente sabor, facilitando así de un modo extraordinario el entendimiento global del origen de la masa de los fermiones.

Existen varios experimentos que explotarán el potencial de haces de neutrinos producidos en aceleradores y reactores, y que serán operativos en los próximos años. Estos experimentos han inaugurado una era de precisión en el marco de la Física de neutrinos. A pesar de todo el esfuerzo planificado, es posible que, dentro de diez años, dos parámetros de mezcla permanezcan desconocidos: el ángulo θ_{13} y la fase de violación de CP, δ. La medida de esta última puede ser accesible si el valor del ángulo θ_{13}, aunque pequño, no es despreciable, y los parámetros de oscilación solares yacen en la región indicada por la solución LMA-MSW, que, de hecho, surge como favorita tras un ajuste global incluyendo las datos recientes del experimento SNO [134]. Se espera que el experimento con reactores KamLAND [132] establezca firmemente esta solución como la única posible para la explicación de los datos solares.

En esta tesis nos hemos concentrado en la extracción de estos dos parámetros, tarea que nos ha conducido a considerar dos experimentos futuros: el llevado a cabo con *Superbeams*(SB) y la *Neutrino Factory* (NF), ambos previamente descritos.

La manera mas prometedora a la hora de determinar δ y θ_{13} es a través de las transiciones $\nu_e \to \nu_\mu$ y $\overline{\nu}_e \to \overline{\nu}_\mu$ detectando muones de signo contrario del que se esperaría en ausencia de osilaciones [14]. La energía y la distancia de detección se hallan entrelazadas en las oscilaciones en materia del neutrino. Es imprescindible el entender cómo dependen de la energía de los muones que decaen y de la distancia correspondiente a la localización del detector los parámetros que se pretenden determinar. Así, se ha derivado una fórmula analítica aproximada para las probabilidades de oscilación en materia, que constituye una herramienta imprescindible para comprender cómo dependen de ambas cantidades los parámetros a extraer. También se ha realizado un análisis numérico exhaustivo y completo, en el que se han incluído eficiencias, backgrounds, las correspondientes fórmulas exactas de las probabilidades de oscilación y el perfil aproximado de la densidad terrestre a lo largo de la propagación del neutrino. También ha sido estudiado el efecto inducido por el error presente en la medida del resto de los parametros: dichos errores no afectan en gran medida a los ajustes globales realizados [15].

La pregunta que se ha planteado es, si midiendo las probabilidades de transición $\nu_e \to \nu_\mu$ y $\overline{\nu}_e \to \overline{\nu}_\mu$ es posible determinar sin ambigüedad δ y θ_{13} para una energía del neutrino y una única localización del detector fijas. La respuesta es no. Explorando el rango posible de valores permitidos para estos dos parámetros, $-180° < \delta < 180°$ y $0° < \theta_{13} < 10°$, se han descubierto, a una energía y distancia fijas, la existencia de soluciones falsas (δ', θ'_{13}), que hemos denominado *degeneraciones intrínsecas*, que conducen al mismo valor de las probabilidades que las soluciones reales, (δ, θ_{13}), es decir, los valores que la Naturaleza ha elegido para estos dos parámetros [15]. Para resolver estas falsas soluciones con datos obtenidos a partir de los flujos de una NF considerando sólo una distancia, se ha propuesto el combinar los datos procedentes de dos distancias diferentes, siendo una de ellas la que ha resultado ser la óptima, de $\mathcal{O}(3000)$ km [15].

Los autores del artículo dado por la Ref. [159], han señalado recientemente que, otras dos posibles falsas soluciones podrían aparecer debido a:

1. Nuestro posible desconocimiento del signo de la diferencia de masas al cuadrado atmosférica, Δm^2_{13}.

2. Los experimentos de desaparición de ν_μ sólo proporcionan información sobre $\sin^2 2\theta_{23}$: ¿se halla el ángulo θ_{23} en el primer octante, o, por el contrario, está en el segundo cuadrante, es decir, $\pi/2 - \theta_{23}$?

La presencia de estas ambigüedades dificulta la extracción de los parámetros δ y θ_{13}. Para ilustrar brevemente nuestras conclusiones, imagínese, por ejemplo, que los valores elegidos por la Naturaleza para estos dos parámetros son $\delta = 54°$ y $\theta_{13} = 2°$, y considérese un experimento que utiliza los flujos procedentes de una NF con el detector localizado a una distancia $L = 2810$ km de la fuente. Después de realizar un ajuste global de los datos, usando la información espectral, el resultado obtenido se muestra en la Fig. 6.1. En esta figura se puede apreciar que existe toda una constelación de falsas soluciones rodeando al valor elegido por la Naturaleza. En vista de estos resultados, uno no sería capaz de diferenciar dos situaciones tan distintas como $\delta \simeq 54°$ (existe violación de CP en el sector leptónico) o $\delta \simeq 180°$ (no existe violación de CP).

Estas degeneraciones pueden resolverse explotando la dependencia en la energía y en la distancia tan distinta que presentan los datos procedentes de una NF y de un experimento empleando SB. La combinación de ambos experimentos elimina la mayoría de estas falsas soluciones, véase la Fig. 6.2, que muestra el resultado correspondiente al ejemplo anteriormente sugerido, donde la única solución que sobrevive es la elegida por la Naturaleza, es decir, la solución real. Evidentemente, hemos elegido un valor de $\theta_{13} = 2°$ bastante elevado. También hemos explorado valores más pequeños de θ_{13}, veánse los Capítulos III, IV y V.

En resumen,

- Los dos experimentos considerados (NF y SB) son dos pasos sucesivos hacia los mismos objetivos físicos, no dos opciones alternativas. Resulta natural, por lo tanto, combinar los resultados esperados por ambos. Esta combinación resulta ser especialmente útil a la hora de resolver las degeneraciones que surgen en la medida simultánea de δ y θ_{13}, debido a la diferencia existente en el comportamiento de las señales procedentes de ambos experimentos en función de la energía y de la distancia.

- Las *degeneraciones intrínsecas* desaparecen después de combinar los resultados procedentes de NF y de SB hasta valores de θ_{13} tan pequeños como el determinado por su límite de sensitividad, que, en el caso de estar sólo presentes las *degeneraciones intrínsecas* correspondería a $\theta_{13} \sim 0.3°$ para el caso de considerar una NF con el detector localizado a $L = 2810$ km (NF-2810) y $\theta_{13} \sim 0.6°$ si se considera una NF con el detector localizado a $L = 732$ km (NF-732). Lo más interesante es que estas degeneraciones desaparecen incluso considerando una NF con el detector localizado a $L = 732$ km. Si bien esta distancia es inferior a $\sim \mathcal{O}(1000)$ km, que era el orden de distancias requerido para poder ser sensible a los efectos de violación de CP en el sector leptónico (para energías de varios GeV), según ha sido discutido en la sección 1.5, después de la combinación con los datos procedentes del experimento con *Superbeams* aquí considerado, SPL-SB, se convierte en una distancia particularmente interesante para la posible localización del detector.

- Las degeneraciones debidas a la ambigüedad en lo que respecta al signo de Δm^2_{13} se han resuelto combinando los datos procedentes de una NF-2810 y los correspondientes a SPL-SB para valores $\theta_{13} \geq 1°$. Si se consideran distancias más cortas, estas degeneraciones han sido eliminadas satisfactoriamente para valores de θ_{13} cercanos a su actual límite, proporcionado por el experimento con reactores CHOOZ [91]. Para valores del ángulo de mezcla θ_{13} muy pequeños, la ambigüedad en el signo permanece, aunque no interfiere mucho en la extracción de θ_{13}, ya que en este caso $\theta'_{13} = \theta_{13}$, ni tampoco en la medida de violación de CP, ya que $\delta' = 180° - \delta$, y esto implica que $\sin\delta' = \sin\delta$.

- Las degeneraciones debidas a la ambigüedad $(\theta_{23}, \pi/2 - \theta_{23})$ son difíciles de resolver, y pueden interferir en la extracción de δ y θ_{13} si θ_{23} está muy alejado del valor que corresponde a una mezcla máxima, es decir, $\theta_{13} = 45°$. Sin embargo, la combinación de ambos experimentos (NF y SPL-SB) ayuda extraordinariamente en la extracción de δ y θ_{13}.

Se está preparando un nuevo estudio [160] con nuevos flujos más intensos para el experimento SPL-SB [150], en el cual se mostrará que todas estas degeneraciones desaparecen, incluso para el caso de considerar una NF-732, hasta valores de $\theta_{13} \sim 0.6°$. Además, ha sido recientemente señalado que una medida suplementaria de las probabilidades de transición $\nu_e \leftrightarrow \nu_\tau$ y $\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$ ayudaría a eliminar las *degeneraciones* *intrínsecas* [161]. En esta tesis se ha considerado el impacto que tendrían dichas transiciones en el caso de la degeneración debida a la ambigüedad $(\theta_{23}, \pi/2 - \theta_{23})$. Un estudio detallado utilizando también la medida de estas probabilidades [162] se está comenzando a llevar a cabo.

Todos los estudios previamente citados son necesarios con el fin de asegurar la precisión requerida para un conocimiento preciso de las masas de los neutrinos y de sus parámetros de mezcla, un requisito imprescindible para poder ser relacionados con sus análogos en el sector de los quarks. La *Neutrino Factory*, combinada con su predecesor, el experimento que utiliza *Superbeams* de neutrinos, proporciona la clave para alcanzar este objetivo.