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Neutrino Experiments at the LHC

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Abstract. The LHC neutrino experiments, FASER and SND@LHC were approved by the CERN Research Board in 2019 and 2021, respectively, to operate during LHC Run 3. Both experiments began taking physics data in July 2022 and have since recorded approximately 70 fb^{-1} of data from proton-proton collisions with a center-of-mass energy of 13.6 TeV. These experiments achieved the first direct observation of neutrino interactions at the LHC, using the active electronic components of their detector. Additionally, FASERν, using 2% of its data sample, detected the highest-energy ν_e and ν_μ interactions ever observed from an artificial source and made the first measurements of neutrino interaction cross-sections over energy ranges of 560–1740 GeV for ν_e and 520–1760 GeV for ν_μ.
Additionally, both experiments are actively searching for physics beyond the Standard Model, with FASER already publishing initial results on Dark Photons and Axion-like Particles. In this report, we will discuss the status of the experiments, including the detector concept, performance, and the first physics results from Run 3 data.

1 Introduction

Neutrinos have been intensely studied since their discovery, being detected from various natural and artificial sources. These include the Sun, cosmic ray interactions in the Earth's atmosphere, nuclear reactors, the Earth's crust, supernovas, and even extragalactic origins, allowing to study from particle physics to astrophysics and cosmology. Particle accelerators have played a crucial role in neutrino research, allowing the precise tuning of beam energies to study neutrino interactions in great detail. Figure 1 provides an overview of the existing neutrino nucleon charged current (CC) scattering cross-section measurement for ν_e, ν_μ and ν_τ. As illustrated in Figure 1, ν_τ remains the least studied among the neutrino flavors. While there are several measurements of ν_e cross-sections, particularly in the low energy region, ν_μ has been intensively studied in the accelerator-based experiments, with measurements extending up to energies of 360 GeV. Furthermore, the IceCube experiment has made significant progress in constraining the neutrino cross-section at ultra-high energies, particularly for atmospheric muon neutrinos above 6.3 TeV. The gap in the energy range of 360 GeV to 6.3 TeV remains largely unexplored.

The concept of using particle colliders, such as the Large Hadron Collider (LHC), as a source of neutrinos was considered in the 1980s and 1990s [1, 2], but it was only realized in 2017 with the proposal of the ForwArd Search ExpeRiment (FASER) [3–5]. FASER was designed to study high-energy neutrinos and search for light, feebly interacting, and long-lived

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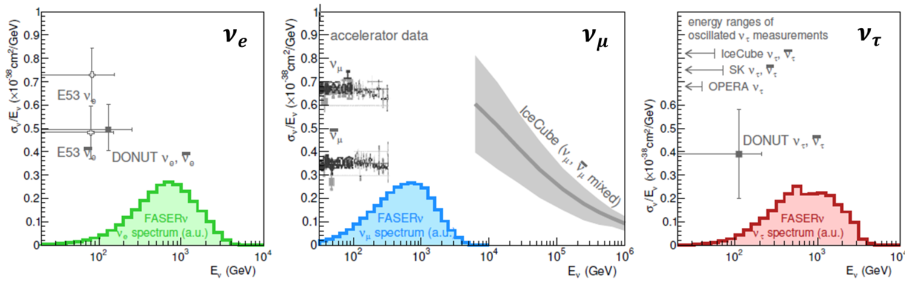

Figure 1. Experimental constraints on the neutrino charged current interaction cross sections and expected energy spectra of neutrino interactions in FASERν for all neutrino flavors [5]

particles beyond the Standard Model, which are produced in the forward region at the LHC. The experiment was approved by CERN in 2019. In 2018, the FASER collaboration installed a small pilot emulsion detector in the LHC TI18 tunnel to measure the muon background and demonstrate the feasibility of neutrino detection at the LHC. The analysis of the pilot detector data led to the first observation of neutrino interaction candidates at the LHC [6], thereby confirming the potential for LHC-based neutrino experiments.

In addition to FASER, the Scattering and Neutrino Detector @ LHC (SND@LHC) was proposed to study high-energy neutrinos and investigate feebly interacting particles produced in the forward region and then approved by CERN in 2021 [7, 8].

2 The LHC as a neutrino beamline

Proton-proton (pp) collisions at the LHC predominantly result in soft interactions, characterized by GeV-scale momentum transfers between the colliding protons. These interactions produce hadrons, such as pions, kaons, and charmed mesons, with a sizable fraction of the proton energy along the beam direction. As these hadrons decay, they generate an intense, and strongly-collimated beam of high-energy neutrinos along the beam collision axis. This makes the LHC not only a powerful collider but also an effective TeV-scale neutrino beamline, enabling the study of high-energy neutrinos in previously inaccessible energy ranges. During LHC Run3, with an integrated luminosity of 250 fb^{-1}, it is expected that approximately 3000 ν_e, 10000 ν_μ and 70 ν_τ events will be collected on axis for a 1-ton target, i.e. in FASERν [9]. The energy spectra for different neutrino flavours is shown in Figure 1.

The existing infrastructure of the LHC offers natural shielding to neutrino detectors located at TI12 and TI18 service tunnels. The neutral beam absorbers efficiently absorb the flux of forward high-energy neutral particles, while the LHC magnets deflect the majority of charged particles away. Additionally, a further layer of protection is provided by 100 m of rock, where the remaining neutral hadrons are absorbed, allowing only neutrinos to pass through.

In addition to neutrinos, the LHC also provides a unique opportunity to search for new physics, including the investigation of dark sectors and long-lived particles, such as dark photons, axion-like particles, etc. Such undiscovered light and weakly interacting particles may be produced in the decays of hadrons generated in the pp collisions, traveling along the beam direction and decaying at experimental sites.

2.1 Physics Potential with LHC Neutrinos

The LHC produces intense, highly collimated beams of neutrinos in all flavors at the highest energy levels ever produced by human-made sources. This enables the FASER and SND@LHC experiments to investigate previously unexplored energy regimes, advancing our understanding of the production, propagation, and interaction of neutrinos at TeV energies.

Forward particle production remains poorly constrained by existing LHC experiments. By focusing on high-energy electron neutrinos, which mainly originate from charm decays, both FASER and SND@LHC can provide the first data on forward charm production. At LHC energies, forward charm particles are predominantly produced through gluon-gluon interactions involving a broad range of momentum fractions, from very low to high. Measuring this production provides a unique opportunity to study and test different aspects of Quantum Chromodynamics (QCD) at small-x, which is crucial for understanding processes like Higgs boson production at the Future Circular Collider. Furthermore, the accurate measurement of neutrino fluxes will provide complementary constraints that can be used to validate and improve Monte Carlo generators. Improved modeling of forward charm production, coupled with new input from the LHC, will improve predictions for prompt atmospheric neutrino production, which is particularly relevant for large-scale neutrino observatories, such as IceCube.

Studying neutrino interactions at the LHC will significantly expand the scope of neutrino cross-section measurements to higher energies, particularly for both electron and tau neutrinos. Additionally, the existing gap in muon neutrino cross-section data will be addressed, allowing a more comprehensive understanding of all three neutrino flavors. Comparing these cross-sections will provide a crucial test of lepton universality in neutrino interactions.

Moreover, the experiments will enable the measurements of not only charged current interactions but also neutral current interactions. These measurements may provide a new limit on nonstandard interactions of neutrinos, offering complementary constraints to the existing limits derived from other experimental tests.

Further details on physics potential can be found elsewhere [10, 11].

3 The LHC neutrino Experiments

As shown in Figure 2, both FASER and SND@LHC detectors are located approximately 480 m away from the ATLAS interaction point (IP). The FASER detector is installed directly on the beam collision axis with a pseudorapidity coverage greater than 8.8, to the east of the ATLAS IP. In contrast, the SND@LHC detector is placed at a symmetric location to the west of the ATLAS IP, slightly off-axis, with a pseudorapity coverage between 7.2 and 8.4. Both detectors began their physics run in 2022 during LHC Run 3, exploiting neutrinos and antineutrinos in all three flavors at TeV energy level.

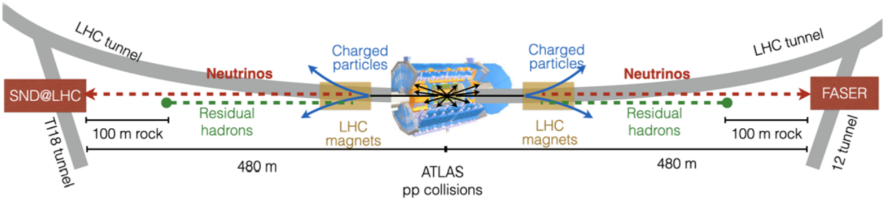

Figure 2. The schematic view of LHC neutrino and experimental sites. Adapted from [12], talk given in Standard Model at the LHC, May 2024.

3.1 FASER Detector

The FASER detector [13] is a compact, and highly specialized instrument with an active volume radius of 10 cm and a length of 7 m. It consists of two scintillator veto systems, a passive tungsten-emulsion neutrino detector (FASERν), and an interface tracker followed by a magnetic system. The magnetic system features three dipole magnets generating a 5.7 T magnetic field, along with three tracking stations, a pre-shower scintillator system, and an electromagnetic calorimeter. The initial 1.5-m long dipole magnet functions as a decay volume for long-lived particles. The tracking stations are positioned before, between, and after two 1-m long dipole magnets, allowing for precise measurement of the position and momentum of charged particles produced from decays occurring within the decay volume.The electromagnetic calorimeter, placed at the back of the detector, measures the energy of the particles passing through the system. Additionally, a scintillator station located between the decay volume and the front of the first tracking station is used for triggering and making precise time measurements of particles in the detector.

The FASER detector reuses the existing spare detector components from other LHC experiments, including ATLAS silicon microstrip detector modules in tracking stations and ECAL modules from LHCb in the electromagnetic calorimeter.

The FASERν neutrino detector [5] is located in front of the main FASER detector, acting as both the target and vertex detector for neutrino interactions. FASERν is composed of 730 layers of 1.1 mm thick tungsten plates sandwiched with emulsion films, and has dimensions of 25 cm in width and 30 cm in height, giving it a total mass of 1.1 metric tons. The FASERν has a total length of approximately 1.35 m, corresponding to 285 radiation lengths and 10.1 hadronic interaction lengths. To keep the occupancy of the tracks in emulsion at an acceptable level for the analysis, the emulsion detectors must be exchanged at every 20-25 fb-1 during LHC technical stops. Once removed, the emulsion films are developed in the darkroom, and then readout using a fast automatic microscope, the Hyper Track Selector system. After the emulsion data is processed to reconstruct the particle tracks, systematic analysis is performed to locate neutrino interactions. By utilizing high-resolution features of its emulsion detector, FASERν can precisely identify electron and muon leptons from neutrino interactions. Electrons are recognized by their associated electromagnetic showers.

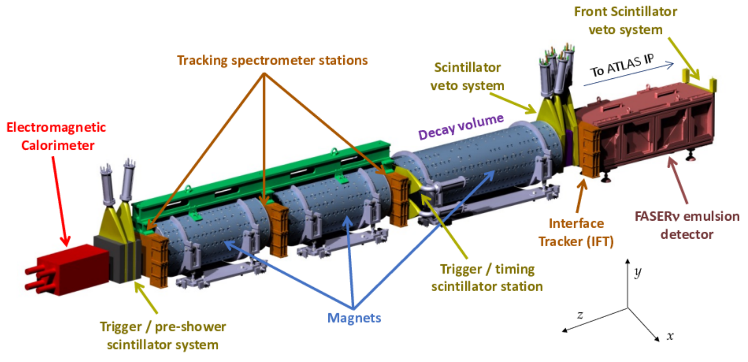

Figure 3. A schematic view of the FASER detector [13].

3.1.1 Neutrino search using FASER Spectrometer

A subsample of data collected at a center-of-mass energy of $\sqrt{s}$ = 13.6 TeV between July and November 2022, corresponding to an integrated luminosity of 35.6±0.8 fb^{-1}, was analyzed for the first direct observation of collider ν_μ and $\bar{\nu}_\mu$ charged current (CC) interactions using FASER detector's electronic components [14]. The FASERν detector served as the primary target for these CC interactions, while the active electronic components of the FASER detector were used to identify neutrino interaction candidates. The signature for these interactions includes the presence of a high momentum muon reconstructed in the FASER spectrometer, alongside increased activity in the veto and timing scintillator stations, as well as the interface tracker station, due to secondary particles produced in the CC interactions.

A blind analysis was performed, with event selection, background estimations, and systematic uncertainties fixed before examining the data in the signal-enhanced region. The selection criteria to identify neutrino interactions were stringent to ensure the reliability of the results. The criteria included the absence of any activity in the initial scintillator station and the requirement of minimum ionizing particle energy depositions in at least two additional stations, with consistent timing and pre-shower counter readings. Moreover, the reconstructed tracks had to be within a 95 mm radius from the magnet center, and their extrapolation to the initial scintillator, $r_{veto\nu}$, had to be within 120 mm of the scintillator center. Furthermore, the reconstructed momentum of the tracks was required to be greater than 100 GeV/c [14].

The neutrino interactions with the tungsten-emulsion detector were simulated using the GENIE event generator and neutrino spectra at the LHC. About 151±41 $\nu_\mu(\bar{\nu}_\mu)$ CC interactions were expected, with the uncertainty arising from differences between event generators (DPMJET and SIBYLL). The main background originated from the high energy muons scattering in the tungsten and/or bending in the magnetic field, estimated to be 0.08±1.83 events. An additional background came from neutral hadron interactions in FASERν, producing charged particles with momentum of more than 100 GeV, estimated to be 0.11±0.06 events [14].

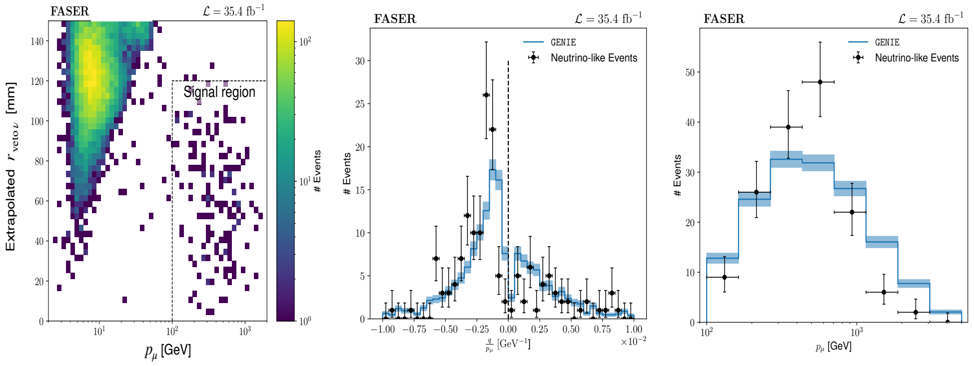

Figure 4. Left: The selected events with the background-enriched regions with a lower momentum, Middle: q/p_μ distributions, Right: the reconstructed momentum p_μ for events in the signal region [14].

Figure 4 shows the selected events, as well as the signal and background enriched regions. In total 153 neutrino events are observed by opening blind analysis with a significance of 16 σ over the background-only hypothesis. A clear charge separation was observed in q/p_μ distribution for the reconstructed tracks, as shown in Figure 4. Among the observed events, 40 positively charged track candidates were identified, indicating the presence of $\bar{\nu}_\mu$ in the data sample. Additionally, the reconstructed momentum distribution indicates that a significant fraction of the neutrino candidates have energies larger than 200 GeV [14].

3.1.2 Neutrino search in FASERν

A dataset collected by the FASERν detector between July and September 2022, corresponding to 9.5 fb^{-1} of pp collisions at a center-of-mass energy of 13.6 TeV, was analyzed to search for neutrino CC interactions [15]. The analysis focused on 14% of the FASERν detector volume, representing a target mass of 128.9 kg. The selected volume aligned with the line-of-sight from the ATLAS interaction point to maximize the likelihood of observing neutrino interactions, including 291 tungsten plates/emulsion films. Data from seven emulsion films upstream of the target region was used to check for the absence of charged parent tracks, while data from an additional 100 plates immediately downstream of the target region was used to measure the energy or the momentum of particle tracks. The electron showers were reconstructed by collecting segments within a 100μm radius cylinder around its axis, with energy estimated by counting track segments at the shower maximum. The energy resolution was about 25% at 200 GeV and between 25-40% at higher energies. Track momentum was estimated using multiple Coulomb scattering, with a resolution of 30% at 200 GeV, increasing to 50% at higher energies.

In a selected target volume, the expected number of neutrino interaction events without any selection cuts were $8.5^{+4.3}_{-1.8}$, $43.6^{+4.7}_{-5.2}$, and $16.5^{+3.0}_{-2.1}$ for $(\nu_e + \bar{\nu}_e)$ CC, $(\nu_\mu + \bar{\nu}_\mu)$ CC, and NC, respectively, with uncertainty from neuttino flux. The event selection involved reconstructing charged particle tracks from neutrino interactions, forming neutral vertices with more than four tracks having angular $\tan\theta \leq 0.5$ and having lepton track candidate azimuthal angle, relative to a hadronic axis, $\Delta\phi > \pi/2$. For ν_e interactions, a high-energy electromagnetic shower with an energy exceeding 200 GeV was required, while ν_μ interactions were identified by tracks penetrating over 100 tungsten plates, with reconstructed momentum greater than 200 GeV.

The main background sources included neutral hadrons, produced through photonuclear interactions of muons within surrounding rock or detector material, which could mimic neutrino signals, as well as neutral current (NC) neutrino interactions. The total background was estimated to be 0.025±0.015 events for ν_e selection and 0.22±0.09 events for ν_μ selection.

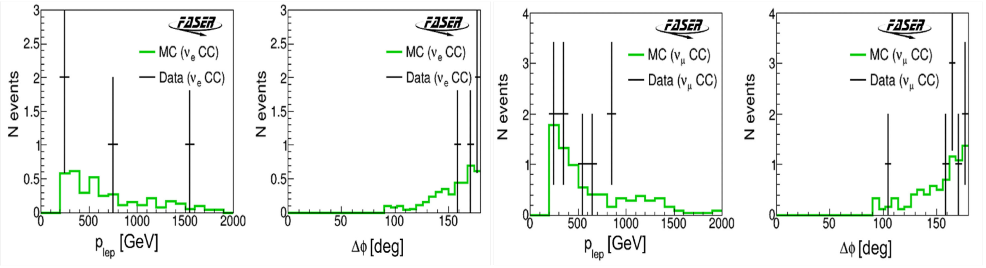

Figure 5. Lepton momentum (p_{lep}) and $\Delta\phi$ distributions for MC simulation and neutrino candidate events in the data sample [15].

In total 246 vertices were identified in the analyzed dataset, with 139 classified as neutral vertices. After applying stringent selection cuts, four ν_e and eight ν_μ CC events were selected. The highest reconstructed electron energy among the ν_e CC candidates was approximately

1.5 TeV, as seen in Figure 5, marking the highest-energy ν_e interaction ever detected by accelerator-based experiments. Similarly, the highest reconstructed muon momentum among the ν_μ CC candidates was around 864 GeV, corresponding to neutrinos with energies likely exceeding 1 TeV, as seen in Figure 5. As shown in Figure 6, ν_e and ν_μ candidate events display a distinct back-to-back topology between the lepton candidate axis and the hadronic axis.

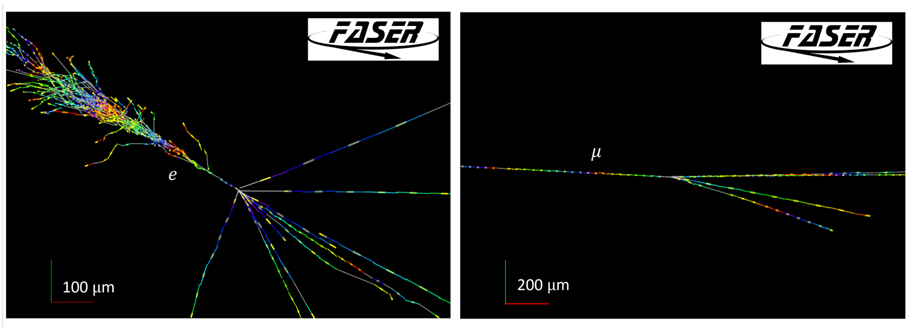

Figure 6. Event displays of ν_e and ν_μ candidates, showing views transverse to the beam direction[15].

The expected number of neutrino signal events satisfying the selection criteria ranged from 1.1 to 3.3 for ν_e CC and 6.5 to 12.4 for ν_μ CC. The observed number of interactions was found to be consistent with Standard Model predictions. The statistical significance of these observations was 5.2 σ for ν_e and 5.7 σ for ν_μ [15].

3.1.3 First measurement of the ν_e and ν_μ interactions cross-sections

Using the same dataset discussed in Section 3.1.2, the cross-section measurements were performed by comparing the observed number of neutrino interactions to the predicted flux of neutrinos using a Bayesian approach to fit the observed data. The measurement involved integrating the expected neutrino flux over the energy range of 560-1740 GeV for ν_e and 520-1760 GeV for ν_μ, adjusting for detection efficiency, and normalizing by the target mass of 128.6 kg and integrated luminosity of 9.5 fb^{-1}. As shown in Figure 7, the cross-sections were measured as $1.2^{+0.8}_{-0.7} \times 10^{-38}$ cm^2 GeV^{-1} for ν_e and $(0.5 \pm 0.2) \times 10^{-38}$ cm^2 GeV^{-1} for ν_μ consistent with Standard Model predictions [15].

3.2 The SND@LHC Detector

The SND@LHC is a hybrid detector [16], featuring an 830 kg of emulsion tungsten target integrated with various electronic detectors. Figure 8 displays the layout of the detector. The target section is segmented into five walls, each composed of four Emulsion Cloud Chambers (ECCs) alternated with a scintillating fiber tracker (SciFi). ECC module contains 60 emulsion films with a dimension of 19.2×19.2 cm^2, interleaved with 1 mm thick tungsten plates, with a total weight of approximately 41.5 kg. The ECC has a total length of 29.5 cm, corresponding to 84 radiation lengths, and a total target length of about 40 cm. The SciFi stations, consisting of 40×40 cm^2 planes, provide event timestamps and offer precise time resolution for measuring the time-of-flight of particles originating from the ATLAS interaction point.

Following the target section, the detector includes a hadron calorimeter and a muon identification system. These components consist of eight layers of scintillating bar planes interleaved with 20 cm-thick iron slabs, providing 9.5 interaction lengths and when combined

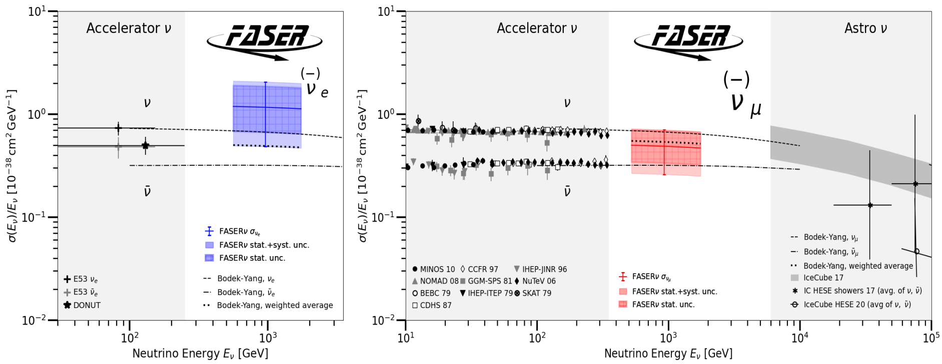

Figure 7. The measured cross section per nucleon for ν_e (left) and ν_μ (right) [15]. The dashed contours labeled "Bodek-Yang" are cross-sections predicted by the Bodek-Yang model, as implemented in GENIE. Note that the displayed experiments do not all use the same targets.

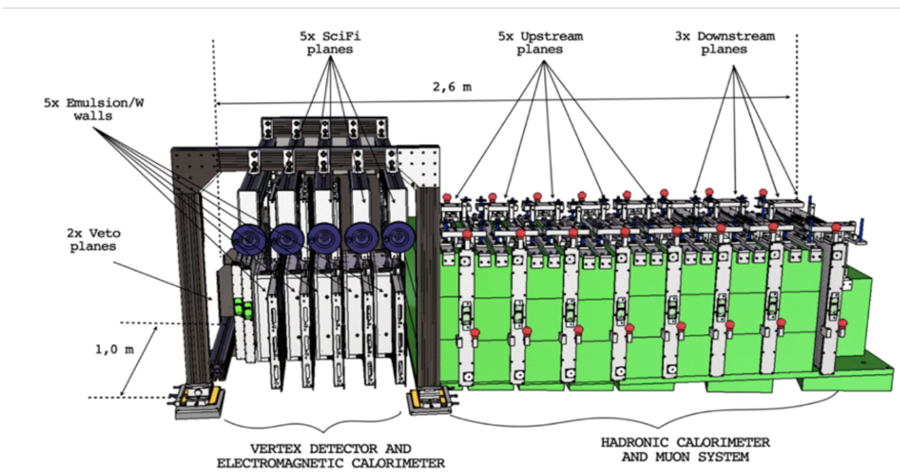

Figure 8. A schematic view of the SND@LHC detector [16]

with the target region, the system totals approximately 11 interaction lengths. The electronics detectors in SND@LHC are crucial for providing timestamps for neutrino interactions, preselecting the interaction region, and identifying muons.

Similar to FASERν, ECC modules are replaced after every 20 fb^{-1} of data collection. About 68.6 fb^{-1} of pp collisions were recorded by the electronic detector, with detector uptime efficiency of 97%.

3.2.1 Observation of Collider Muon Neutrinos

Initially, a dataset of pp collisions at $\sqrt{s}$ = 13.6 TeV, collected by the electronic detector in 2022, corresponding to an integrated luminosity of 36.8, was used to search for muon neutrino charged-current interactions [17]. The signature for these interactions includes an isolated muon track in the muon system, associated with a hadronic shower in the SciFi and hadronic calorimeter. Based on FLUKA and GENIE simulations about 157± 37 ν_μ CC interactions were expected within the full emulsion-tungsten target. Data analysis focused on a fiducial volume within the inner detector region of 25×26 cm^2, as shown in Figure 9 left panel in the orange box, specifically targeting the 3rd or 4th target wall SciFi planes to suppress muon-induced backgrounds. This selection achieved a 7.5% efficiency for simulated neutrino interactions (11.9 out of 157 events). After applying additional selection criteria to identify signal-like patterns characterized by significant hadronic activity and clear muon track in the Muon identification system, 8 neutrino interaction candidates were observed with a significance of 6.8 σ, compared to an expected 4.2 with a background estimation of 0.09 events.

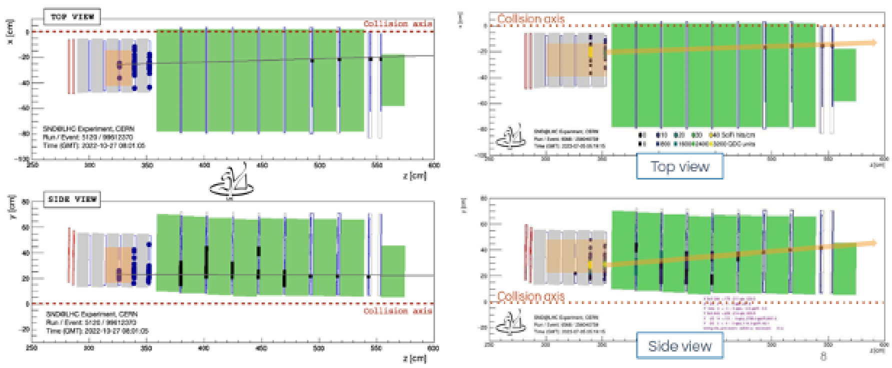

Figure 9. Display of ν_μ CC candidate from 2022 (in left) and 2023 (in right) data samples [17].

Moreover, an expanded analysis combined the 2022 dataset with additional data collected in 2023, reaching a total integrated luminosity of 68.6 fb^{-1}. By extending the fiducial volume and only rejecting events in the first wall, the signal efficiency was increased to 35%. This leads to the observation of 32 ν_μ CC interactions, with an expected 19 events and a background of 0.25 events, yielding a significance of 12 σ. Figure 9 right panel displays an event with a new analysis method. As seen in Figure 10, the kinematics of muon neutrino candidates were found to be in good agreement with the signal predictions. Detailed discussions on the results can be found elsewhere [17].

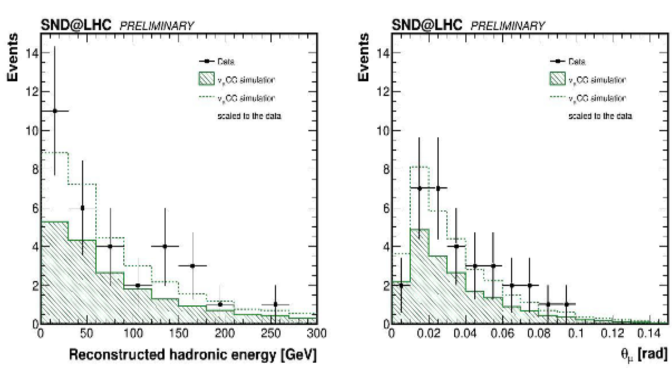

Figure 10. Distribution of reconstructed hadronic energy and slope of μ candidates [17].

3.2.2 Search for shower-like neutrino events

Data collected by SND@LHC was also used to search for shower-like events, focusing on signals from ν_e CC and ν NC interactions [12]. The search criteria included no hits in the veto detector and exclusion of side-entering background events, resulting in a 12% signal acceptance. To identify 0μ neutrino events, the criteria involved significant activity in the scintillating fiber detector and hadronic calorimeter, with no hits in the final two muon system layers. Additionally, the density-weighted number of hits in the most active SciFi station needed to exceed $11{\times}10^3$ as shown in Figure 11 right panel, optimized to maximize expected significance, leading to a signal selection efficiency of 42%.

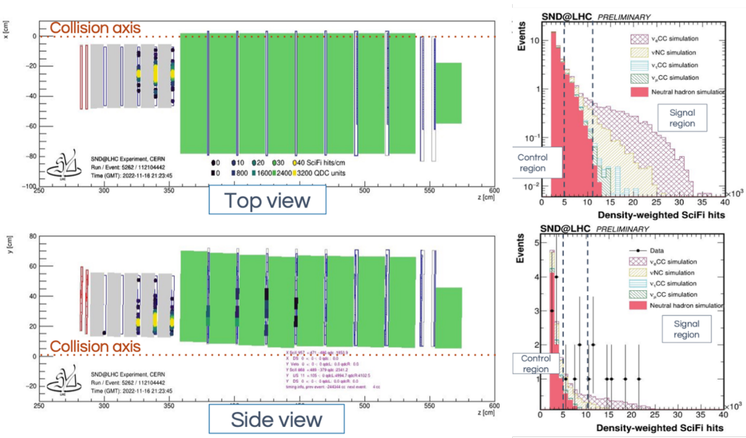

Figure 11. Left: Shower-like event observed in SND@LHC detector, Right: Density-weighted Sci-Fi hits for data, signal, and background in both control and signal region [12].

The neutral hadron background was studied by defining a background-dominated control region and scaling the background prediction to the number of observed events in this region, finding that the observed background was one-third of the predicted value. In the signal region, the expected neutral hadron background was 0.01 events. Muon neutrinos charged current interactions were also considered a dominant background, contributing 0.12 expected events, with tau neutrino CC interactions contributing 0.002 events. The total expected background was 0.13±0.04 events. Observing six events with an expected signal of 4.66 events, the analysis achieved an expected significance of 5.8 σ. Figure 11 left panel displays shower-like (0μ) event.

4 LHC Run 4 Plans for FASER and AdvSND@LHC

FASER [18] and SND@LHC have expressed strong interest in their continuing operations into LHC Run 4, which is scheduled from 2029 to the end of 2032. With an expected total integrated luminosity of 680 fb^{-1}, FASERν anticipates collecting 5000 ν_e, 25000 ν_μ, and 100 ν_τ interactions [9]. This extension will significantly enhance the physics output.

The increased trigger rates and background levels expected during LHC Run 4, especially from muons traversing the detector, will require frequent exchanges of tungsten-emulsion detector in FASERν and ECC modules in SND@LHC, and possible upgrades to handle the higher fluxes. Discussions are ongoing about the use of and upgrading the FASERν neutrino detector, while SND@LHC collaboration has submitted a Letter of Intent for LHC Run 4, proposing an upgrade of their detector, renamed the Advanced Scattering and Neutrino Detector (AdvSND) [19], which would replace the current emulsion and tungsten target with a high precision vertex detector using tungsten as a target.

These upgrades and continued operations are essential to maximize the physics potential of LHC Run 4, particularly in the exploration of neutrino physics and searches for new physics beyond the Standard Model.

5 Conclusions

The successful data taking by FASER/FASERν and SND@LHC during the LHC Run3 marks significant achievements in high-energy neutrino research. Operating at different positions to the LHC beam line, FASER on-axis, and SND@LHC off-axis, each experiment has collected around 70 fb^{-1} of data in 2022 and 2023, with an expected total of 250 fb^{-1} by the end of Run3. This data has led to the first direct observations of collider neutrinos, with FASER detecting 153 $\nu_\mu(\bar{\nu}_\mu)$ CC interactions and SND@LHC 32 ν_μ CC interactions.

Additionally, FASERν has achieved the first measurement of ν_e N and ν_μ N charged current interaction cross-sections, including observation of the highest energy ν_e CC interaction at 1.5 TeV. These groundbreaking observations were made using only a small subset of available data, with four ν_e CC and eight ν_μ CC candidates identified in just 2% of the FASERν data.

In addition to neutrino physics, the experiments are also probing the frontiers of particle physics by searching for long-lived particles beyond the Standard Model, such as Dark Photons and Axion-like Particles. These early results from Run3 highlight the potential of LHC neutrino experiments to continue exploring uncharted territories in high-energy physics during the upcoming LHC Run4.

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