PROCEEDINGS OF SCIENCE

Muon neutrino interaction studies with SND@LHC detector

Giulia Paggi[a,b,*] **for the SND@LHC collaboration**

[a] *Università di Bologna,*
Via Zamboni, Bologna, Italia
[b] *INFN Bologna section*
Viale C. Berti Pichat, Bologna, Italia

E-mail: giulia.paggi@cern.ch

The Scattering and Neutrino Detector at LHC (SND@LHC) is a compact, standalone experiment located in the TI18 tunnel, 480 meters downstream of the ATLAS interaction point, designed to observe neutrinos produced in LHC proton-proton collisions. The SND@LHC detector allows for the identification of all three flavours of neutrino interactions in the pseudorapidity region $7.2 < \eta < 8.4$ within an unexplored energy range of $100\,\mathrm{GeV} < \mathrm{E} < 1\,\mathrm{TeV}$. The SND@LHC detector comprises three main sections: an instrumented target, a hadron calorimeter, and a muon system. This talk presented the status of the most interesting activities of the collaboration, with a focus on muon neutrino seach in 2024 data. Compared to the 2022-23 dataset, which enabled the first observation of accelerator neutrinos, this analysis benefits from several significant improvements. The recorded luminosity in 2024 is more than three times larger than in 2022, leading to an expected number of neutrino interactions in the detector of the order of thousands. Additionally, the installation of a veto plane during the 2023–2024 Year-End Technical Stop enhanced target coverage and significantly improved background rejection. Another key advancement is the calibration of the calorimeter, made possible by a dedicated test beam campaign. This calibration not only enables precise energy estimation for recorded events but also provides an additional tool for background suppression, allowing better exploitation of the instrumented volume.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

[*] Speaker

PoS(EPS-HEP2025)144

1. The Detector

The SND@LHC detector [1] consists of a hybrid system with an ~ 830 kg target made of tungsten plates interleaved with nuclear emulsions and electronic trackers, followed by a hadronic calorimeter and a muon system (see figure 1).

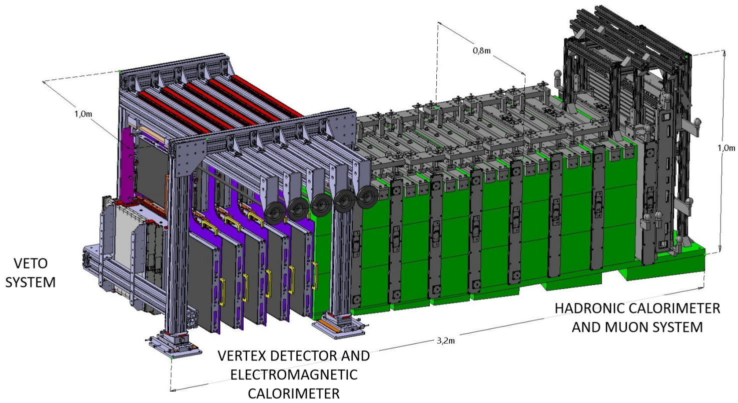

Figure 1: The SND@LHC detector geometry of 2025.

The veto system is located upstream of the target region and comprises three planes of scintillating bars. The veto system configuration is further discussed in section 1.1. The target section contains five walls, each made of four units, called bricks, of emulsion cloud chambers (ECC). Each ECC unit is a sequence of 60 nuclear emulsion films, $19.2 \times 19.2\,\text{cm}^2$ and $\sim 300\,\mu$m thick, interleaved with 59 tungsten plates, 1 mm thick. An ECC wall is followed by a scintillating fibre (SciFi) station for tracking and electromagnetic calorimetry (ECAL). Each SciFi station consists of two $40 \times 40\,\text{cm}^2$ planes, alternating x and y views. Each view comprises six densely packed staggered layers of 250 μm diameter polystyrene-based scintillating fibres read out by SiPM arrays. The muon system and hadronic calorimeter (HCAL) include two parts: upstream (US), the first five stations, and downstream (DS), the last three stations. Each US station consists of 10 stacked horizontal $82.5 \times 6 \times 1\,\text{cm}^3$ scintillator bars, equipped with SiPMs at both left and right edges. A DS station consists of two layers of thinner $82.5 \times 1 \times 1\,\text{cm}^3$ bars arranged in alternating x and y views, allowing for a spatial resolution in each view of less than 1 cm. The eight scintillator planes are interleaved with 20 cm-thick iron blocks. In combination with SciFi, the muon system and hadronic calorimeter act as a $10\,\lambda$ deep sampling calorimeter to measure the energy of hadronic jets. As of March 2025, two additional drift chambers have been installed in the muon system. This upgrade is further discussed in 1.3.

1.1 Veto System Upgrade

Following the results of the 2022 and 2023 data analysis, the SND@LHC Collaboration decided in the autumn of 2023 to upgrade the Veto system by lowering the Veto by ≈ 27 cm to provide better coverage of the bottom edge of the target, and by adding a third plane (Veto 3) of scintillating bars to improve the Veto efficiency for incoming charged particles. To minimise the probability that, after the detection of a muon in Veto 1 or 2, whose bars are aligned horizontally, the dead time coincides with the passage of a second muon through the same bar, Veto 3 bars were aligned vertically. From the collected data, it was possible to compute an upper limit of $(8.7 \pm 3.5) \times 10^{-9}$ total system inefficiency on the whole target area, resulting in an expected increase of 56% of observable neutrinos. The construction of the third Veto station and its performance during commissioning, the relocation of the Veto system in TI18 during the 2023-2024 YETS, and its performance assessment using passing-through muons from LHC pp collisions are reported in [2].

1.2 HCAL Calibration

Reconstructing energy and direction of hadronic showers is crucial in SND@LHC to fully understand neutrino interactions and estimate the energy of the incoming neutrino. For this reason, a dedicated test beam was carried out in August 2023. These constants have been computed and validated [3] with the data collected using hadron beams, with energy from 100 to 300 GeV, achieving an energy resolution ranging from $\sim$ 12% to 22% depending on the incoming hadron energy. A poster was dedicated to this topic [4].

1.3 Muon System Upgrade

In March 2025, two Mini Drift Tube (MiniDT) modules, scaled-down versions of CMS Drift Tubes, were added to the SND@LHC muon system to enhance muon identification. These modules deliver high-resolution position and direction measurements, improving track reconstruction. This upgrade will enable more precise muon flux measurement and enhance discrimination between background events and muon neutrino interactions in the target.

2. The Analyses

Between 2022 and 2024, the SND@LHC electronic detectors recorded a total integrated luminosity of $\sim$ 187 fb^{-1} with a 96% uptime, while the emulsion detector collected $\sim$ 170 fb^{-1}, corresponding to 14 exposed targets and 5700 developed films ($\sim$ 210 m^2). In 2024, an unexpected increase in the muon flux doubled the target replacement rate, and only the lower half of the target was instrumented, resulting in about 65% of neutrino interactions being retained. Despite improvements in 2025, muon rates remain $\sim$ 40% higher than in 2022–2023.

2.1 Emulsion Progress

The emulsion analysis achieved a position resolution of 0.2 μm, and vertex reconstruction is ongoing for muon and electron neutrinos, as well as muon deep inelastic scattering events, which are crucial for background studies. Preliminary reconstructed events and simulations demonstrate the capability to identify neutrino candidates and disentangle complex topologies.

2.2 Muon Analyses

Muon analyses at SND@LHC address both detector performance and background characterisation, as well as rare processes of physics interest.

Muon flux measurements are a key component of SND@LHC operations, as muons represent the dominant experimental background and provide an essential handle for detector calibration,

PoS(EPS-HEP2025)144

performance validation, and background modelling. Results using 2022 data [5] showed excellent agreement across all sub-detectors. Heavy-ion runs provide an independent check of detector performance and background models, as the different LHC optics yield a softer muon spectrum.

Beyond their role in background characterisation, muons provide a probe for rare processes of physics interest. One example currently under investigation by the SND@LHC collaboration is the search for the muon trident process, in which a muon scattering off a nucleus produces an additional $\mu^+\mu^-$ pair. The first observation of muon trident events at the LHC has been achieved, and the current goal is to measure the cross section. More information can be found in the dedicated poster [6].

2.3 Neutrino Analyses

Neutrino analyses, the main focus of SND@LHC, use the electronic detector to identify interaction vertices, reconstruct kinematics, and study different flavours and interaction channels.

2.3.1 $0\,\mu$ final state

The collaboration reported the observation of neutrino interactions without final state muons at the LHC [7], with a significance of $6.4\,\sigma$. The whole dataset collected by SND@LHC in 2022 and 2023 is used, corresponding to an integrated luminosity of $68.6\,\text{fb}^{-1}$. Neutrino interactions without a reconstructed muon are selected by using the sum of hit-density weights in Scifi. This method rejects a large number of events in the data resulting from the debris of muon interactions in the detector surroundings, which consist of small hit clusters scattered in the detector. This selection produces an event sample consisting mainly of neutral-current and electron neutrino charged-current interactions in the detector. After selection cuts, 9 neutrino interaction candidate events are observed with an estimated background of 0.32 events, see figure 2.

2.3.2 ν_μ interactions

In early 2023, the SND@LHC collaboration reported the first observation of collider muon neutrinos [8]: 8 ν_μ Charged Current (CC) events with significances of about $6.8\,\sigma$, using 2022 data with $36.8\,\text{fb}^{-1}$. The updated analysis, using the combined 2022+2023 dataset ($68.8\,\text{fb}^{-1}$) and an expanded fiducial volume, raising the acceptance from 7.5% to 18%, increased the number of neutrino candidates to 32, corresponding to a significance of $12\,\sigma$. This dataset enabled the first measurement of reconstructed hadronic energy spectra, using the calibration constants previously described in section 1.2, shown in figure 3.

A search for CCν_μ is ongoing also on 2024 data. The whole dataset collected is $\sim 119 fb^{-1}$, $\sim$ 1.75$\times$ the available data from 2022+2023, so the collaboration decided to blind most of it, allowing $\sim 20 fb^{-1}$ to be used to develop a new, even if still cut-based, approach.

The analysis focuses on selecting a clean CCν_μ sample. Events showing activity in the veto system are rejected, while those selected are required to contain a hadronic shower and a muon that produces a signal across all detector planes. A key enhancement to this study is the use of a larger fiducial area in the SciFi detector, thanks to the improved efficiency of the veto system and a different strategy in using the muon reconstructed track. Although the analysis is still in progress, once unblinded, the available statistics will be sufficient to enable a detailed study of the distributions of the main properties of CCν_μ events up to the TeV scale.

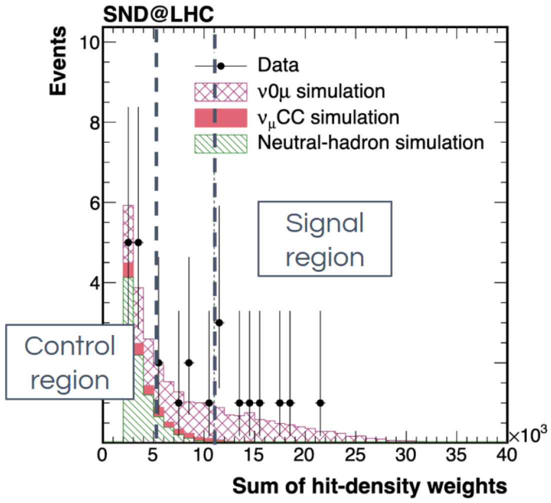

Figure 2: Distribution of the sum of SciFi hit-density weights for events selected into the analysis sample. The events from the data are shown alongside the expected signal and background.

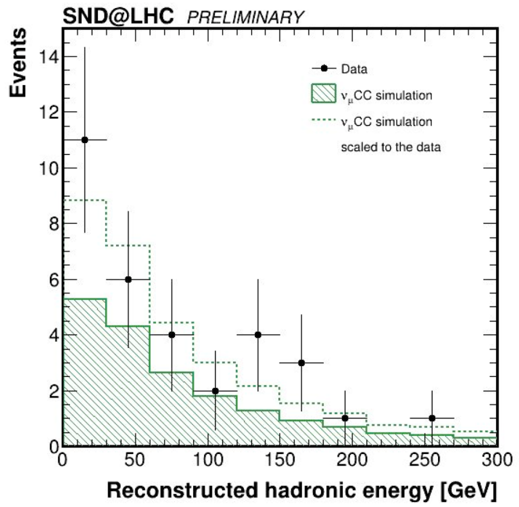

Figure 3: Reconstructed hadronic energy for the CCν_μ candidates in 2022-2023 dataset.

3. SND@HL-LHC

Recently, the SND@LHC detector upgrade [9], designed for the HL-LHC era, has been approved. The new geometry is sketched in figure 4. The detector will be modified by replacing its emulsions with reused CMS Outer Barrel strips to create the first-ever silicon-based neutrino vertex detector. This upgrade will also include a new magnetised calorimeter for measuring particle charge and momentum, a crucial step for distinguishing between neutrinos and antineutrinos, that will lead to the first direct observation of the $\bar{\nu}_\tau$. Additionally, a fast-timing detector is being considered to help resolve event pile-up and send a trigger signal to ATLAS, currently under a feasibility study. These enhancements are projected to significantly reduce both the statistical and systematic uncertainties for key measurements, offering a substantial improvement over the performance of Run 3.

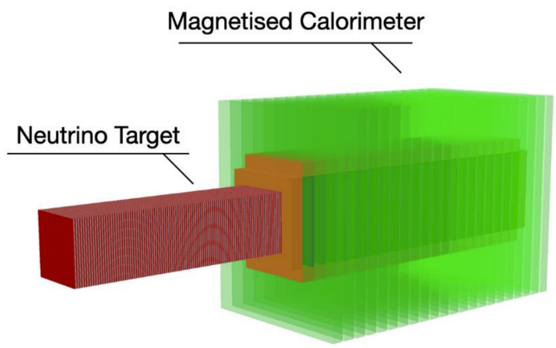

Figure 4: The SND@HL-LHC detector scheme.

4. Conclusions and outlook

The SND@LHC experiment has successfully demonstrated its capability to observe neutrinos in an unexplored pseudorapidity and energy range. With the 2022-2023 datasets, the collaboration reported the first observations of both collider neutrinos without final state muons and collider muon neutrinos, achieving high significance in both cases. The current analysis is leveraging a significantly larger 2024 dataset and benefits from several key detector improvements. These include a more efficient veto system and a calibrated hadronic calorimeter, which together provide enhanced background rejection and precise energy estimation for events. Looking toward the future, an approved detector upgrade for the HL-LHC era will introduce a silicon-based neutrino vertex detector and a new magnetised calorimeter to distinguish between neutrinos and antineutrinos. These and other planned enhancements are projected to reduce measurement uncertainties, enabling SND@LHC to continue its significant contributions to neutrino physics.

References

[1] SND@LHC collaboration, SND@LHC: The Scattering and Neutrino Detector at the LHC. JINST 19 P05067 (2024)

[2] SND@LHC collaboration, Installation and performance of the 3rd Veto plane at the SND@LHC detector. JINST 20 P07011 (2025)

[3] SND@LHC collaboration, Studies of Hadronic Showers in SND@LHC. arXiv:2504.01716 (2025)

[4] F. Mei, "Energy calibration for the SND@LHC hadronic calorimeter", in proceedings of "The European Physical Society Conference on High Energy Physics" PoS(EPS-HEP2025)522, DOI: 10.22323/1.485.0522 (crossref, unregistered)

[5] SND@LHC collaboration, Measurement of the muon flux at the SND@LHC experiment. Eur. Phys. J. C 84: 90 (2024)

[6] A. Murat Guler, "Search for muonic trident production in the SND@LHC detector", in proceedings of "The European Physical Society Conference on High Energy Physics" PoS(EPS-HEP2025)183, DOI: 10.22323/1.485.0183 (crossref, unregistered)

[7] SND@LHC collaboration, Observation of Collider Neutrinos without Final State Muons with the SND@LHC Experiment. PRL 134 231802 (2025)

[8] SND@LHC collaboration, Observation of collider muon neutrinos with the SND@LHC experiment. PRL 131 031802 (2023)

[9] SND@LHC collaboration, SND@HL-LHC, Scattering and Neutrino Detector in Run 4 of the LHC. CERN-LHCC-2025-004 (2025)