PROCEEDINGS OF SCIENCE

Neutrino Physics at CERN

Giovanni De Lellis[a,*]

[a] *University "Federico II" and INFN,*
via Cintia, 80126, Naples, Italy

E-mail: giovanni.de.lellis@cern.ch

At CERN there has been recently a revival of neutrino physics. In 2018 a feasibility study was conducted which paved the way to the proposal of two neutrino experiments at the LHC, studying for the first time neutrinos with energies up to a few TeV. The FASER and SND@LHC experiments started their data taking with the Run3 of the LHC in 2022 and provided the first observation of collider neutrinos already one year after the start of data taking. This has set off the birth of a new era of collider neutrinos. In March 2024, CERN approved the construction of the Beam Dump Facility with the SHiP experiment to search for sterile neutrinos and to study all three neutrino flavours. SHiP will explore neutrino properties in an energy domain complementary to the LHC and will search for feebly interacting particles with unprecedented sensitivity as possible candidates to solve the open problems of the Standard Model.

NOW 2024,
2-8 September 2024
Otranto (Lecce), Italy

PoS(NOW2024)089

---

[*] Speaker

©Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) All rights for text and data mining, AI training, and similar technologies for commercial purposes, are reserved. ISSN 1824-8039 . Published by SISSA Medialab.

1. The SND@LHC experiment

The use of the Large Hadron Collider (LHC) as a neutrino factory was first envisaged long ago [1–3] in particular for the then undiscovered ν_τ [4]. Those studies suggest a detector intercepting the very forward flux ($\eta > 7$) of neutrinos (about 5% have τ flavor) from b and c decays [5]. The physics potential of a detector to study neutrinos was underlined in Ref.[6]. The role of an off-axis setup, which enhances the neutrino flux from charmed particle decays, was emphasized in Ref.[7]. Proton-proton (pp) collisions at a center-of-mass energy of 13.6 TeV during LHC run 3, with an expected integrated luminosity of 250 fb^{-1}, will produce a high-intensity beam yielding the order of 10^{12} neutrinos in the far forward direction with energies up to a few TeV [8]. Neutrinos allow precise tests of the standard model (SM) [9–14] and are a probe for new physics [15, 16]. Measurements of the neutrino cross section in the last decades were mainly performed at low energies. The region between 350 GeV and 10 TeV is currently unexplored [17]. SND@LHC [18] was designed to perform measurements with high-energy neutrinos (100 GeV to a few TeV) produced at the LHC in the pseudo-rapidity region $7.2 < \eta < 8.4$. It is a compact, stand-alone experiment located in the TI18 unused LEP transfer tunnel (480 m away of the ATLAS interaction point, IP1 [19]) where it is shielded from collision debris by around 100 m of rock and concrete. The detector is capable of identifying all three neutrino flavors with high efficiency. The off-axis location of the detector results in contributions of charmed hadron decays to the fluxes of all neutrino flavors. This enables measurements of charm production using electron neutrino events, and the partial cancellation of production uncertainties when measuring ratios of different flavor neutrino cross sections to search for lepton flavor universality violation [8]. The detector was installed in TI18 in 2021 during the long shutdown 2 and has collected data since the beginning of the LHC run 3 in April 2022. The experiment will run throughout the whole run 3, during which a total of two thousand high-energy neutrino interactions of all flavors are expected to occur in the detector target.

The SND@LHC detector consists of a hybrid system with a ~ 830 kg target made of tungsten plates interleaved with nuclear emulsions and electronic trackers, followed by a hadronic calorimeter and a muon system. The electronic detectors provide the time stamp of the neutrino interaction, preselect the interaction region, tag muons and measure the electromagnetic and hadronic energy, while the emulsion detectors provide excellent vertex reconstruction.

The detector consists of three parts: the veto system, the target section, and the hadronic calorimeter and muon system. The veto system is located upstream of the target region and comprises two parallel planes, located 4.3 cm apart, of scintillating bars read out on both ends by silicon photomultipliers (SiPMs). Each plane consists of seven $1 \times 6 \times 42$ cm^3 stacked bars of EJ-200 scintillator. This system is used to tag muons and other charged particles entering the detector from the IP1 direction. The target section contains five walls. Each wall consists of four units of emulsion cloud chambers (ECC [20]) and is followed by a scintillating fiber (SciFi [21]) station for tracking and electromagnetic calorimetry. The muon system and hadronic calorimeter consists of two parts: upstream (US), the first five stations, and downstream (DS), the last three stations. Each US station consists of 10 stacked horizontal scintillator bars of $82.5 \times 6 \times 1$ cm^3, similar to the veto detector, resulting in a coarse y view. A DS station consists of two layers of thinner $82.5 \times 1 \times 1$ cm^3 bars arranged in alternating x and y views, allowing for a spatial resolution in each view of less than 1 cm. The time resolution for a single DS detector bar is ~ 120 ps. The

PoS(NOW2024)089

eight scintillator planes are interleaved with 20 cm thick iron blocks. In combination with SciFi, the muon system and hadronic calorimeter acts as a coarse sampling calorimeter ($\sim 9.5\ \lambda_{int}$ in the US detector), providing the energy measurement of hadronic jets with an expected resolution around 20% [8]. The finer spatial resolution of the DS detector allows for the identification of muon tracks exiting the detector.

All signals exceeding preset thresholds are read out by the front-end electronics and clustered in time to form events. A software noise filter is applied to the events online, resulting in negligible detector deadtime or loss in signal efficiency. Events satisfying certain topological criteria, such as the presence of hits in several detector planes, are read out at a rate of around 5.4 kHz at the highest instantaneous luminosity achieved in 2022 of 2.5×10^{34} cm^{-2} s^{-1}.

PoS(NOW2024)089

2. Observation of collider neutrinos

The search for collider neutrinos was first made with the data collected in 2022, with an integrated recorded luminosity of 36.8 fb^{-1} [19]. The dataset comprises a total of 8.3×10^9 events.

The signal selection proceeds in two steps. The first step aims at identifying events happening in a fiducial region of the target, while rejecting backgrounds due to charged particles entering from the front and sides of the detector. Cuts are applied on the hit multiplicity in the veto and SciFi planes to select events that are located in the 3rd or 4th target wall and consistent with a neutral particle interaction. The exclusion of events starting in the two most upstream target walls enhances the rejection power for muon-induced backgrounds while reducing the expected signal by around 60%. Excluding events starting in the most downstream wall ensures the neutrino-induced showers are sampled by at least two SciFi planes. The efficiency of fiducial region cuts on simulated neutrino interactions in the target is 7.5%. The second step selects signal-like signature patterns using a cut-based procedure. ν_μ CCDIS interactions are associated to a large hadronic activity in the calorimetric system, with a clean outgoing muon track reconstructed in the muon system, and hit time distribution consistent with an event originating from the IP1 direction. The muon track is defined by a set of muon system hits in a straight-line pattern spanning at least three detector planes in both zx and zy views. Events with a large number of hits in the muon system are rejected to ensure cleanly reconstructed tracks.

The achieved reduction factor on the data for the total selection (fiducial and neutrino identification cuts) amounts to 1.0×10^9, while the overall efficiency on the ν_μ CCDIS Monte Carlo sample is 2.7%. As a result of the full selection, 8 ν_μ CCDIS candidates are identified, while 4.2 are expected. Neutral particles (mainly neutrons and K^0_L's) originating from primary muons interacting in rock and concrete in front of the detector can potentially mimic a neutrino interaction since they do not leave any incoming trace in the electronic detectors, and can create a shower in the target associated with a DS track produced by punchthrough or decay-in-flight $\pi^\pm$ and $K^\pm$. Although they are mainly rejected due to accompanying charged particles originating from the primary muon interaction, they constitute the main background source for the neutrino search. The background yield after the selection amounts to $(8.6 \pm 3.8) \times 10^{-2}$ and is dominated by neutrons and K^0_Ls. Given this level of background, the exclusion of the background-only hypothesis at the level of 6.8 standard deviations was provided, thus supporting the first observation of collider muon neutrinos[22].

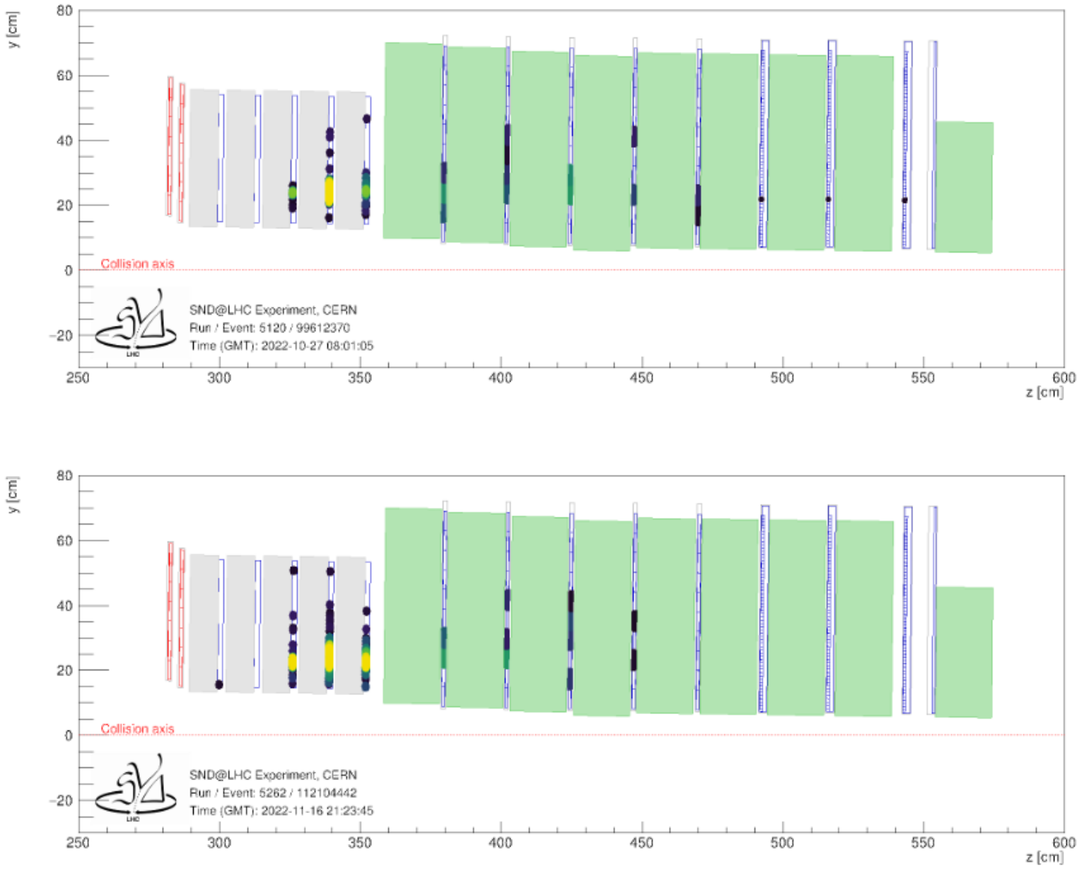

Figure 1: Representative example of signal-like events. The top panel shows one of the eight ν_μ candidates while the bottom panel shows a ν_e candidate event. The coloured circles represent the local density of hits in the SciFi detector, corresponding to the number of hits within 1 cm of each hit. The coloured rectangles represent the amplitude, in arbitrary units, of hits in the US hadron calorimeter. Lighter shades correspond to higher values.

PoS(NOW2024)089

The 2023 run was interrupted by an issue in the LHC machine which prevented operating it beyond July. Nevertheless, the data taking of SND was successful and achieved its record performance with 99.7% efficiency in the recorded luminosity. An integrated luminosity of 68.6 fb^{-1} was achieved over the first two years of data taking. This data was used to search for neutrino interactions without a muon in the final state: this sample consists essentially of neutral current neutrino interactions and charged-current electron neutrinos. Electron neutrinos produce typically an electron in the final state with more than 300 GeV energy on average, thus producing a large density of the energy deposited in the neutrino target. The selection could therefore be tuned to enrich the sample of electron neutrinos by using the energy density. The data accumulated in a test beam carried out at the SPS in 2023 for the calorimeter calibration were used to validate the Monte Carlo simulation. A control region outside of the signal selection cuts was defined which showed a good agreement between data and simulation. As a result of the selection, 9 candidate events were found with an expected background of 0.3 events, dominated by muon neutrinos where the muon is not identified. This has led to the observation of neutrino interactions without a muon in the final state with a significance above 6σ and to the evidence for electron neutrinos with 3.7σ[23].

The observation of neutrino interactions was at the same time reported with the analysis of the 2022 data by the FASER Collaboration [24–26] at a complementary pseudorapidity range, $\eta > 8.5$. We note that a significant component of the flux of muon neutrinos at the SND@LHC off-axis location originates in the decay of promptly produced charmed hadrons, while this contribution is negligible at the FASER on-axis location [27]. Taken together, these highly complementary observations herald a new era of physics measurements using LHC neutrinos.

3. The SHiP experiment at the SPS Beam Dump Facility

In spite of the remarkable achievements of the Standard Model (SM) of particle physics, substantial evidence supports the existence of new physics that goes beyond its scope. The SM as-is cannot account for neutrino flavor oscillations, dark matter, and generation of the matter-antimatter asymmetry in the early Universe. However, new particles capable of resolving the problems of the SM can have masses from sub-eV to Planck scale and coupling constants with SM particles ranging many orders of magnitude. If the mass of a new particle is below the electroweak (EW) scale, it can be generated at accelerators, not only as a resonance but also through the decay processes of Standard Model (SM) particles, such as the heavy bosons W, Z, H^0, as well as mesons like π, D and B. The reason that such new particles have not yet been detected may not be due to their exceedingly rare production rate. This is why new particles of this nature are often referred to as feebly interacting particles, or FIPs. The strategy employed by the recently approved SHiP experiment at CERN hinges on the high-intensity proton beam of the SPS, dumped onto a heavy target to produce FIPs, with search for decays within an isolated fiducial volume, distinct from Standard Model background. The experimental signature of these FIPs is a reconstructed isolated vertex pointing back towards the proton target. Details of the SHiP detector and of its implementation at the Beam Dump Facility (BDF) can be found in [28]. The high intensity and high energy proton beam at BDF produces a high intensity neutrino and antineutrino flux of all flavours. The presence of a hadron absorber and a muon shield that clear the forward region from hadrons and muons makes the SHiP experiment ideally suited to perform neutrino physics studies. A compact detector, located immediately downstream of the muon shield allows the detection of all neutrino flavours and measurement of their energy. This enables SHiP to perform tau neutrino studies with unprecedented statistics, as well as measuring the relevant kinematical variables of the deep inelastic scattering (DIS) processes for both the charged and neutral current (CC and NC) interactions for all neutrino flavours. At the SPS, the optimal conditions for BDF/SHiP are obtained with a 400 GeV proton beam and slow extraction of the proton spills over one second, effectively 1.2s flat top over a cycle length of 7.2s. The design of the BDF is based on the full exploitation of the CERN accelerator complex with the SPS at its present performance, delivering 4×10^{19} PoT to BDF/SHiP per year while ensuring 1.25×10^{19} protons to the other SPS beam facilities. With 6×10^{20} PoT, SHiP will integrate an unprecedented number of detected neutrino interactions: in particular of the order of one million of ν_e and $\bar{\nu}_e$ and of the order of ten thousands of ν_τ and $\bar{\nu}_\tau$. The rich physics program of the SHiP experiment is highlighted in Ref. [13]. The plots in Figure 2 report the unprecedented SHiP sensitivity to Heavy Neutral Leptons for a given benchmark model

PoS(NOW2024)089

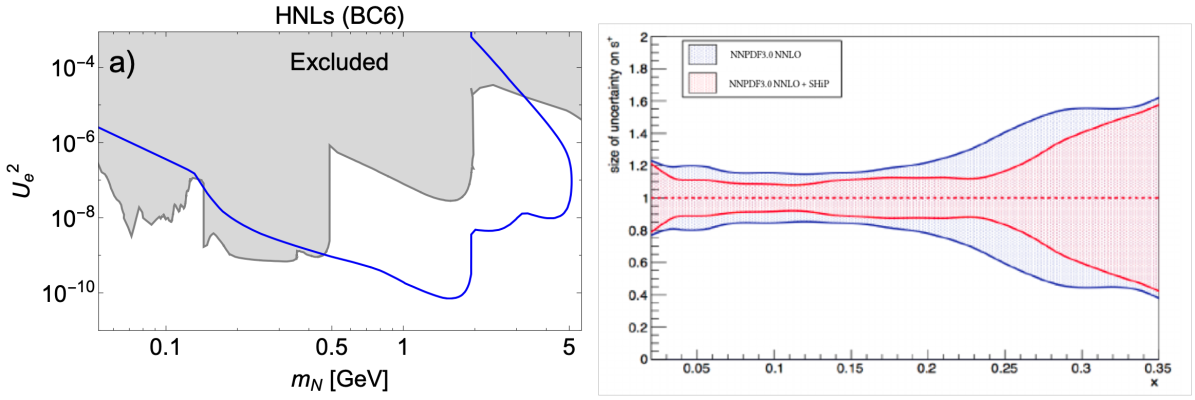

Figure 2: Left: SHiP's sensitivity to HNLs coupled to the electron neutrino flavour. Right: improvement in the strange quark content from the SHiP neutrino physics program.

and the potential improvement in the uncertainty of the strange quark content of the nucleon [28]. SHiP and SND@LHC altogether will explore neutrino properties in the energy range from 10 GeV to a few TeV. The SHiP data taking will start in 2032.

References

[1] A. De Rújula and R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators, in Proceedings of the SSC Workshop: Superconducting Super Collider Fixed Target Physics (1984) pp. 571–596, 10.5170/CERN-1984- 010-V-2.571; Report No. CERN-90-10-V-2.

[2] A. De Rújula, E. Fernandez, and J. Gomez-Cadenas, Neutrino fluxes at future hadron colliders, Nucl. Phys. B405, 80 (1993).

[3] F. Vannucci, Neutrino physics at LHC/SSC, Technical Report No. LPNHE-93-03, University of Paris, Paris, 1993, https://cds.cern.ch/record/253670.

[4] Large Hadron Collider Workshop: Aachen, Germany 1990, edited by G. Jarlskog and D. Rein (CERN, Geneva, 1990), 10.5170/CERN-1990-010-V-2.

[5] S. Buontempo et al., CMS-XSEN: LHC neutrinos at CMS. Experiment feasibility study, Technical Reports No. CMS NOTE 2018/001, No. CMS-NOTE-2018-001, No. CERN-CMS-NOTE-2018-001, CERN, Geneva, 2018, https://cds .cern.ch/record/2309742.

[6] N. Beni et al., Physics potential of an experiment using LHC neutrinos, J. Phys. G 46, 115008 (2019).

[7] N. Beni et al., Further studies on the physics potential of an experiment using LHC neutrinos, J. Phys. G 47, 125004 (2020).

[8] C. Ahdida et al., SND@LHC—scattering and neutrino detector at the LHC, Technical Reports No. CERN- LHCC-2021-003, No. LHCC-P-016, CERN, Geneva, 2021, https://cds.cern.ch/record/2750060/files/LHCC-P- 016.pdf.

PoS(NOW2024)089

[9] R. Brock et al., Handbook of perturbative QCD, Rev. Mod. Phys. 67, 157 (1995).

[10] J. Conrad, M. Shaevitz, and T. Bolton, Precision measure- ments with high-energy neutrino beams, Rev. Mod. Phys. 70, 1341 (1998).

[11] J. A. Formaggio and G. P. Zeller, From eV to EeV: Neutrino cross sections across energy scales, Rev. Mod. Phys. 84, 1307 (2012).

[12] G. De Lellis, P. Migliozzi, and P. Santorelli, Charm physics with neutrinos, Phys. Rep. 399, 227 (2004).

[13] S. Alekhin et al., A facility to search for hidden particles at the CERN SPS: the SHiP physics case, Rep. Prog. Phys. 79, 124201 (2016).

[14] H. Abreu et al. (FASER Collaboration), Detecting and studying high-energy collider neutrinos with FASER at the LHC, Eur. Phys. J. C 80, 61 (2020).

[15] D. Marfatia, D. McKay, and T. Weiler, New physics with ultra-high-energy neutrinos, Phys. Lett. B 748, 113 (2015).

[16] C. Argüelles et al., New opportunities at the next-generation neutrino experiments I: BSM neutrino physics and dark matter, Rep. Prog. Phys. 83, 124201 (2020).

[17] M. Bustamante and A. Connolly, Extracting the Energy- Dependent Neutrino-Nucleon Cross Section above 10 TeV Using IceCube Showers, Phys. Rev. Lett. 122, 041101 (2019).

[18] G. Acampora et al., SND@LHC Collaboration, SND@LHC: The Scattering and Neutrino Detector at the LHC, JINST 19 (2024) 05, P05067.

[19] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C 76 (2016) 653

[20] A. Ariga, T. Ariga, G. De Lellis, A. Ereditato, and K. Niwa, Nuclear emulsions, in Particle Physics Reference Library: Volume 2: Detectors for Particles and Radiation, edited by C. W. Fabjan and H. Schopper (Elsevier, New York, 2020), pp. 383–438.

[21] LHCb Collaboration, LHCb tracker upgrade technical design report, Technical Reports No. CERN-LHCC-2014- 001, No. LHCB-TDR-015, CERN, Geneva, 2014, http://cds .cern.ch/record/1647400.

[22] R. Albanese et al., SND@LHC Collaboration, Observation of Collider Muon Neutrinos with the SND@LHC Experiment, Phys. Rev. Lett. 131 (2023) 3, 031802.

[23] D. Abbaneo et al., SND@LHC Collaboration, Observation of collider neutrinos without final state muons with the SND@LHC experiment, https://arxiv.org/abs/2411.18787.

[24] H. Abreu et al. (FASER Collaboration), First Direct Observation of Collider Neutrinos with FASER at the LHC, Phys. Rev. Lett. 131, 031801 (2023).

PoS(NOW2024)089

[25] H. Abreu et al. (FASER Collaboration), The FASER Detector, JINST 19 (2024) 05, P05066.

[26] R. M. Abraham et al. (FASER Collaboration), First Measurement of ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector, PRL 133 (2024) 2, 021802.

[27] F. Kling and L. J. Nevay, Forward neutrino fluxes at the LHC, PRD 104, 113008 (2021).

[28] C. Ahdida et al. (SHiP Collaboration), BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-2023-033 / SPSC-P-369 https://cds.cern.ch/record/2878604/files/SPSC-P-369.pdf

PoS(NOW2024)089