Recent results from SND@LHC

The SND@LHC Collaboration

represented by G.M. Dallavalle
Istituto Nazionale Fisica Nucleare, Sezione di Bologna - Bologna, Italy

Summary. — SND@LHC is a new experiment at the LHC, designed to study laboratory-produced neutrinos in the unexplored TeV-energy range. It is installed 480 m from the proton-proton collision point IP1 in the secondary tunnel TI18, where only muons, neutrinos, and possible unknown feebly interacting particles arrive, forward emitted in the pseudo-rapidity range between 7.2 and 8.4. The system is capable of distinguishing between the three species of neutrinos which allows for testing their production ratios. As well, SND@LHC can perform measurements on heavy quarks in a kinematic region, not accessible to ATLAS, CMS and LHCb, of interest for the design of a hadronic Future Circular Collider and for atmospheric neutrino experiments. SND@LHC has been taking data since 2022. The first measurements confirm the experiment potential. The detector is going to undergo a major upgrade to continue running in the LHC High Luminosity phase.

1. – Introduction

In an era preceding the Large Hadron Collider (LHC) construction at CERN, in the early '80s, it took ground the idea of using proton-proton interactions at the collider to produce high-energy neutrino "beams" ($pp \to \nu\ X$) [1, 2, 3, 4]. However, the predicted backgrounds were prohibitive for real experiments. About thirty years later, specific measurements were conducted in the LHC tunnel in search of locations where the background radiation fields were low enough to observe neutrino interactions [5, 6, 7]. Then, two experiments, SND@LHC [9] and FASERν [10], were proposed and are taking data at the CERN LHC since 2022. They are located on either side of LHC Intersection Point 1 (IP1) in secondary tunnels that were used for injecting beams in the Large Electron Positron collider (LEP) and are unused in LHC (figure 1). Both experiments use a hybrid technology: they exhibit a target (0.8 T for SND@LHC, 1.1 T for FASERν) instrumented with nuclear emulsions, for precisely locating neutrino interaction vertexes, together with a full electronic detector for on-line data taking and event reconstruction. The pseudo-rapidity η ranges are complementary: SND@LHC is slightly off-axis $7.2 < \eta_\nu < 8.4$ (optimized for neutrinos from charm quark decays), while FASERν is on-axis $\eta_\nu > 8.8$ (maximizing the neutrino flux) [6, 11].

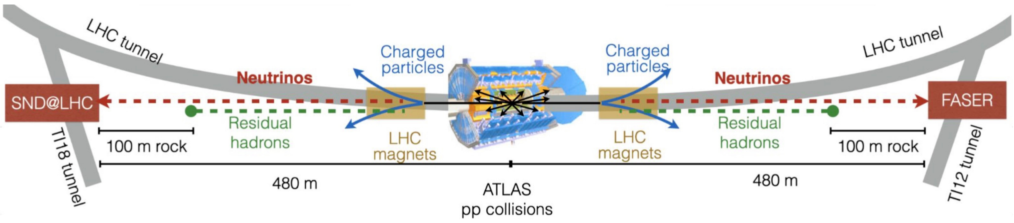

Fig. 1. – SND@LHC and FASERν locations in LHC. The figure is not to scale.

2. – SND@LHC

2˙1. *Physics goals*. – The physics program of SND@LHC addresses both the production mechanism of neutrinos in pp collisions and the interaction of neutrinos with matter.

High energy neutrinos reaching SND@LHC from the LHC IP1 mainly originate in the decay of $c\bar{c}$ pairs that, in LHC proton-proton collisions, are likely created by gluon-gluon scattering, in which a high momentum gluon interacts with a very-low-x (of about 10^{-6}) gluon [6]. The gluon Particle Density Function (PDF) for such low x values is a major uncertainty in the QCD calculations. This affects directly the predictions for the Physics program of a $\sim$ 100 TeV hadronic collider, such as the future FCChh being planned at CERN, and also, indirectly, the characterization of the high-energy neutrino flux in astrophysical observations. The measurement of the neutrino rate in SND@LHC provides a constrain to the very-low-x gluon PDF and lowers the uncertainty of QCD predictions.

The cross section of muon and electron neutrino interactions on nucleons have been intensively studied in fixed target experiments up to neutrino energies of $\sim$ 350 GeV; recently the interaction cross section of $\sim$ 10 TeV astrophysical neutrinos have been derived from IceCube data [8]. Measurements with forward emitted LHC neutrinos bridges the energy range from a few 100 GeV to a few TeV, for all three neutrino flavors.

2˙2. *Detector*. – The SND@LHC detector [12] uses a hybrid technology: within an 800 kg target, composed of tungsten plates alternating with nuclear emulsions, are interspersed electronic detectors for tracking charged particles and for measuring electromagnetic showers. The apparatus is completed by a hadronic calorimeter [13] and detectors for muon identification. Scintillator planes upstream the target are used to veto charged particles that enter the target acceptance [14].

The target is replaced after collecting $\sim 20\ fb^{-1}$, and the emulsions undergo thorough scanning. The track density is high, up to a few 10^5 tracks/cm^2, three orders of magnitude higher than in any previous application. The emulsion data analysis required a full revision of alignment, tracking, vertexing procedures. An excellent tracking performance is achieved, with position and angular resolutions of 0.2 μm and 1.2 $mrad$ per track.

2˙3. *First results*. – SND@LHC recorded 187 fb^{-1} in 2022-2024, 96% of the total luminosity that LHC delivered to IP1.

Muons from IP1 constitute the main source of backgrounds to neutrino signals. They can interact in the rock and tunnel walls and produce neutral hadrons (n, K^0) that enter the detector acceptance and interact in the target volume, mimicking neutrino interactions. Moreover, in spite of a veto inefficiency of $\sim 10^{-9}$, muons at the border of

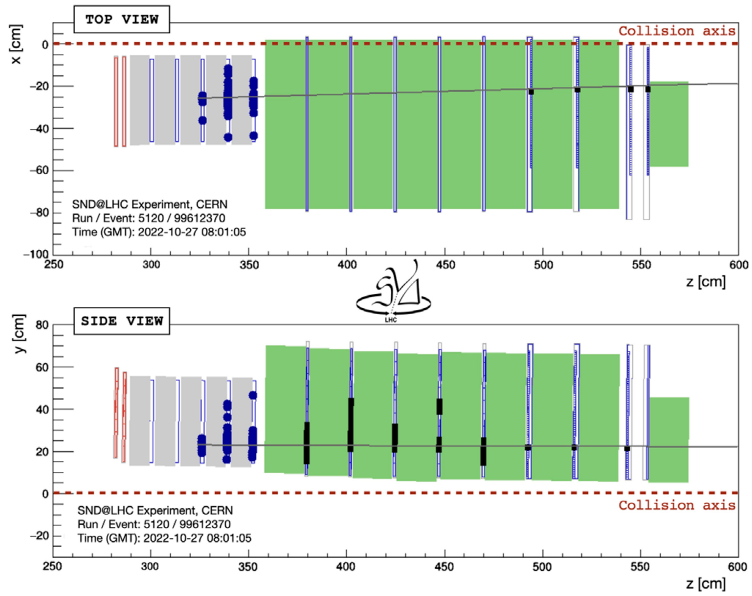

Fig. 2. – SND@LHC display of a ν_μ CC candidate event [16].

the acceptance can go undetected and produce EM showers or, by DIS, hadronic showers, that partially enter the detector. Therefore a precise measurement of the muon flux is primary to validate the background calculations. Independent stand-alone measurements using either the electronic tracker in the target, or the emulsions, or the downstream muon system were carried out and found highly consistent with the LHC simulations [15].

Already with the 2022 data a very clean direct observation of muon neutrinos was performed [16] with a significance of 6.8 σ with respect to the background; an updated measurement using the full 2022-2023 data sample is going to be released. A display of a muon neutrino interaction is shown in figure 2.

Neutrino interactions without final state muons, due to neutral-current and electron neutrino charged-current interactions in the detector, have also been clearly observed [17] with a significance of 6.4 σ.

2·4. *Upgrade for High-Luminosity-LHC*. – Running the emulsion detector at the HL-LHC is unfeasible, since the replacement necessity would become too frequent. Then, silicon-strip modules are going to be used for tracking and calorimetry in the target area. The strip modules are taken from the current CMS outer barrel tracker, which will be dismantled during the 2027-2029 LHC shut-down. Four layers of fast-timing detectors will provide a trigger signal for reading out the data. The target mass will be increased to 1.3 T of tungsten.

The SND@LHC calorimeter region as well will be refurbished with silicon strip modules; besides, it will be embedded in an iron-core solenoid to provide momentum and charge measurement of muon tracks. The detector will be moved upstream and upward to fit in the existing space in TI18. SND@HL-LHC will detect neutrinos in the pseudo-rapidity range $6.9 < \eta_\nu < 7.7$. Table I reports the expected charged-current interactions for an integrated luminosity of 3000 fb^{-1}, with the estimation of those due to neutrinos from charm meson decays.

More information can be found in the technical proposal [18].

Table I. – *CC DIS νN interactions expected in SND@HL-LHC (3000 fb^{-1})*

flavor	total	from $c\,\bar{c}$
$\nu_\mu + \bar{\nu}_\mu$	$1.5\ 10^4$	$2.4\ 10^3$
$\nu_e + \bar{\nu}_e$	$3.4\ 10^3$	$2.7\ 10^3$
$\nu_\tau + \bar{\nu}_\tau$	$2.8\ 10^2$	$2.8\ 10^2$
total	$1.9\ 10^4$	$5.4\ 10^3$

3. – Summary

Since 2022 two experiments at the CERN LHC are dedicated to study ν_e , ν_μ , ν_τ from pp collisions: SND@LHC in $7.2 < \eta_\nu < 8.4$, FASERν in $\eta_\nu > 8.8$

Those experiments extend the Physics reach at LHC: (i) they allow for studying neutrino-Nucleon interactions at neutrino energies in the TeV range, bridging laboratory neutrino measurements and astrophysical results; (ii) they probe parton fractional momenta down to 10^{-6} and can constrain QCD uncertainties, improving the physics predictions for FCChh.

SND@LHC collected 187 fb^{-1} in 2022-2024 and published first results on the observation of collider muon neutrinos and on the observation of neutrino-Nucleon interactions without final state muons.

For the High-Luminosity-LHC phase, the SND@HL-LHC experiment will be instrumented with silicon strip modules, recycled from the dismissed outer tracker of the CMS barrel, in both target and calorimetry sections, and equipped with a solenoid for separating ν_μ and $\bar{\nu}_\mu$ interactions.

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