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A new Scattering and Neutrino Detector at the LHC

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The Scattering and Neutrino Detector (SND@LHC) is a compact and stand-alone experiment to perform measurements with neutrinos produced at the LHC in a hitherto unexplored pseudo-rapidity region of $7.2 < \eta < 8.4$, complementary to all the other experiments at the LHC. The experiment is located 480 m downstream of IP1 in the unused TI18 tunnel. The detector is composed of a hybrid system based on a 800 kg target mass of tungsten plates, interleaved with emulsion and electronic trackers, followed downstream by a calorimeter and a muon system. The configuration allows efficiently distinguishing between all three neutrino flavours, opening a unique opportunity to probe physics of heavy flavour production at the LHC in the region that is not accessible to ATLAS, CMS and LHCb. This region is of particular interest also for future circular colliders and for predictions of very high-energy atmospheric neutrinos. The physics programme includes studies of charm production, and lepton universality tests in the neutral sector. The detector concept is also well suited to searching for Feebly Interacting Particles via signatures of scattering in the detector target. The first phase aims at operating the detector throughout LHC Run 3 to collect a total of 250 fb^{-1}. We report the results from the data taken in 2022, namely the measurement of the muon flux at TI18 and the observation of muon neutrino interactions.

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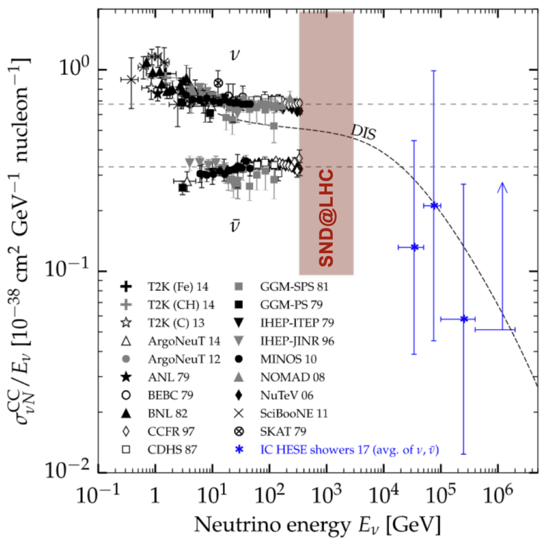


Figure 1: Overview of the neutrino cross-section measurement at different energies [13].

1. Introduction

Studies about neutrino physics at colliders are dated back to 80s [1, 2] hinting at the physics potential of a detector to study neutrinos, examined in Reference [3], in a forward region from b and c decays. As a matter of fact, SND@LHC [4, 5], is a compact experiment designed to perform measurements with high-energy neutrinos, in the energy range between 100 GeV and few TeV, produced at the LHC in the pseudorapidity region $7.2 < \eta < 8.4$. In such a particular pseudorapidity range, currently unexplored, a significant portion of neutrinos come from the decay of charmed-hadrons [6], allowing the exploration of heavy-flavor production in a region not covered by other LHC experiments.

2. The physics program

Neutrinos can provide precise tests of the Standard Model (SM) [7–10], and thus can be used as a probe for new physics [11, 12]. In the last decades, measurements of neutrino interactions have been performed at low and very-high energies, leaving a wide unexplored region between hundreds of GeV and about 10 TeV [13], as shown in Figure 1. The SND@LHC experiment is therefore aiming to provide neutrino measurements in such a currently unexplored domain up to a few TeV using LHC as neutrino factory, in particular in Figure 2 the energy spectra of neutrinos making charged-current deep inelastic scattering (DIS) within the SND@LHC acceptance range are shown.

Nonetheless the SND@LHC experiment offers a wide physics program which includes the study charmed hadron production from pp collision in a forward region, tests of the lepton flavour universality in neutrino interactions measuring the ratio of ν_e/ν_τ and ν_e/ν_μ and the measurement of the ratio between charged current (CC) and neutral current (NC) interactions as internal consistency check.

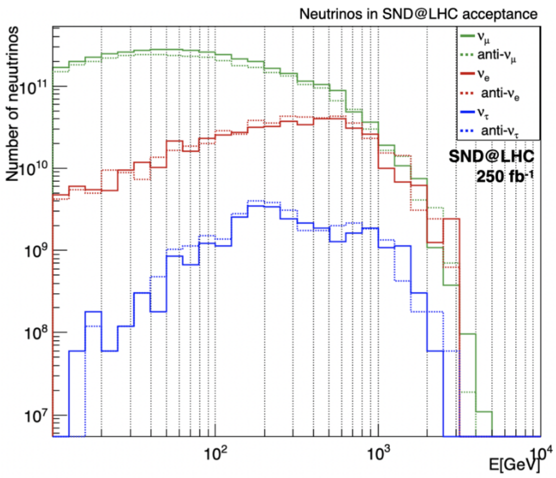


Figure 2: Energy spectrum of different flavours of neutrinos in the SND@LHC acceptance as predicted by DPMJET [14, 15]/FLUKA [16, 17] simulation. The spectrum has been normalised to 250 fb^{-1} [18].

Moreover, SND@LHC proposes a model-independent direct search for Feebly Interacting Particles (FIPs) using a recoil signature combined with a time-of-flight measurement to disentangle it from neutrinos [5].

3. The SND@LHC detector

The SND@LHC detector [18] is located at about 480 m away of the ATLAS interaction point (IP1) [19] in the TI18 unused LEP transfer tunnel shielded from most of charged particles by about 100 m of rock and concrete. The detector was installed in the tunnel in 2021, after the approval of March 2021, and has collected data since the beginning of the LHC Run 3 in April 2022.
The detector has been designed to identify the three neutrino flavours with high efficiency, alongside their energy measurement and to provide the direct search for FIPs. It foresees a modular structure made up of three key elements, i.e. a vertex detector with a high resolution allowing for an efficient tracking of the tau lepton and its decay vertex, a calorimeter capable of providing both electromagnetic and hadronic energy measurement and a muon system designed for the identification of the outgoing muon from either the ν_τ charged current interactions or from the τ lepton muonic decay. Furthermore, a veto system is located upstream of the vertex detector and comprises two parallel planes of scintillating bars to tag muons and other charged particles entering the detector from the IP1 direction.
The vertex detector is made up of five walls of four Emulsion Cloud Chamber (ECC) units [20] interleaved by five Scintillating Fibre (SciFi [21]) planes for tracking and electromagnetic calorimetry. Each ECC unit consists of 60 nuclear emulsion films interleaved with 59 tungsten plates as passive material, weighting approximately 41.5 kg for a total target weight of about 830 kg. Each SciFi station, consisting of $40 \times 40\,\mathrm{cm}^2$ planes, provides event timestamps and suitable time and position resolutions for time-of-flight measurement of particles from IP1 ($\sim$ 150 μm and 250 ps respectively).

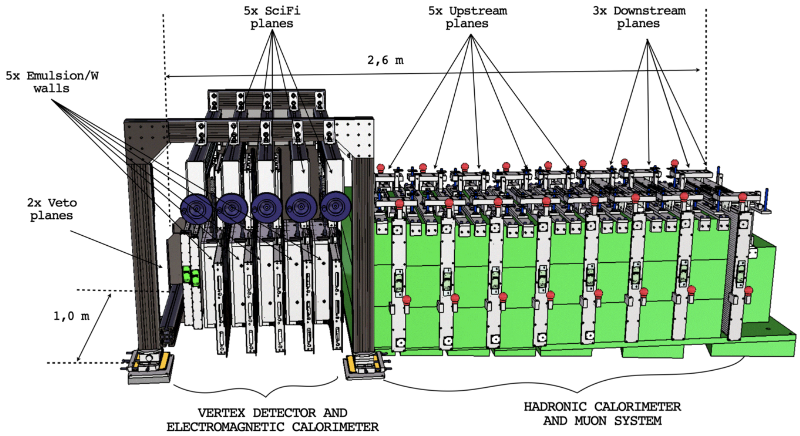


Figure 3: The SND@LHC detector layout [18]

The vertex region is surrounded by a borated polyethylene/acrylic box which can shield against low-energy neutrons and provides a temperature and humidity controlled environment for emulsion films.

The muon system and hadronic calorimeter foresees an upstream section (US) consisting of five stations instrumented with 10 stacked horizontal scintillator bars and a downstream section (DS) in which the granularity is increased consisting of 3 stations instrumented with 60 thinner scintillator bars. The eight scintillator planes are interleaved by 20 cm thick iron slabs. The above presented configuration acts as a sampling calorimeter with ~ 9.5 interaction lengths (λ_{int}) and approximately $11\,\lambda_{\text{int}}$ if the target region is considered which allows a comprehensive coverage of the hadronic showers [5], in Figure 3 the layout of the detector is shown.

4. Event reconstruction

The event reconstruction foresees two phases: the first one performed online makes use of the response of the electronic detectors; in the second phase, performed offline, the information provided by the nuclear emulsion data is then added up.

As far as the *online* phase is concerned, neutrino interaction or FIP scattering will be first detected with the Muon System and the SciFi tracker. The latter is expected to identify electromagnetic showers as well as they develop and get absorbed within the target region, while muons in the final state will be reconstructed by the Muon System. Furthermore, since the detector is acting as a sampling calorimeter, the combination of data taken from both systems will be used to measure hadronic as well as electromagnetic energy of the event. On the other hand, as far as the *offline* phase is concerned, once the emulsion target is extracted (every $20\,\text{fb}^{-1}$), emulsion films are scanned with optical microscopes and tracks as well as vertices are reconstructed with suitable algorithms. Neutrino interaction vertices are thus found basing on their topologies, as seen in Figure 4 in which examples respectively of ν_μ, ν_τ and ν_e charged-current interactions in SND@LHC bricks are shown.

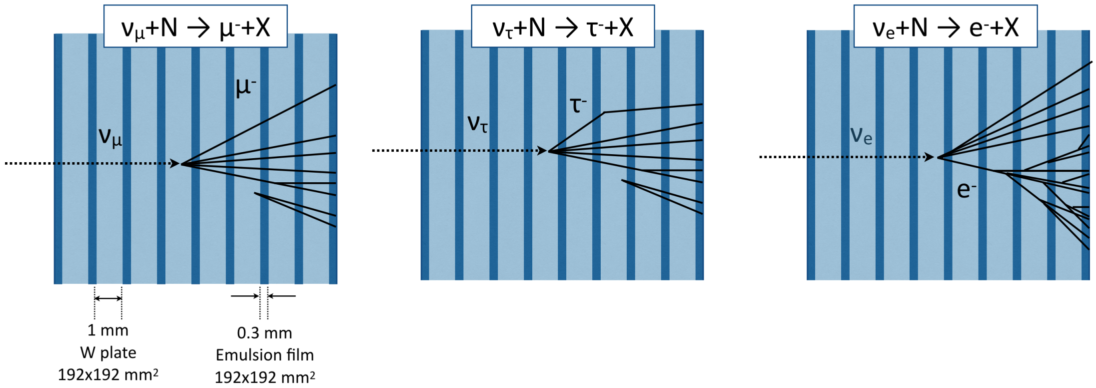


Figure 4: Topologies of signal event that can be reconstructed in SND@LHC emulsion bricks.

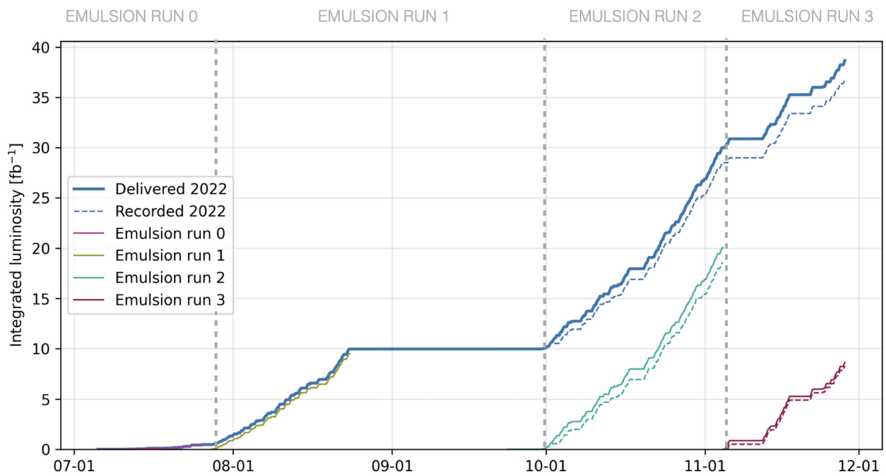
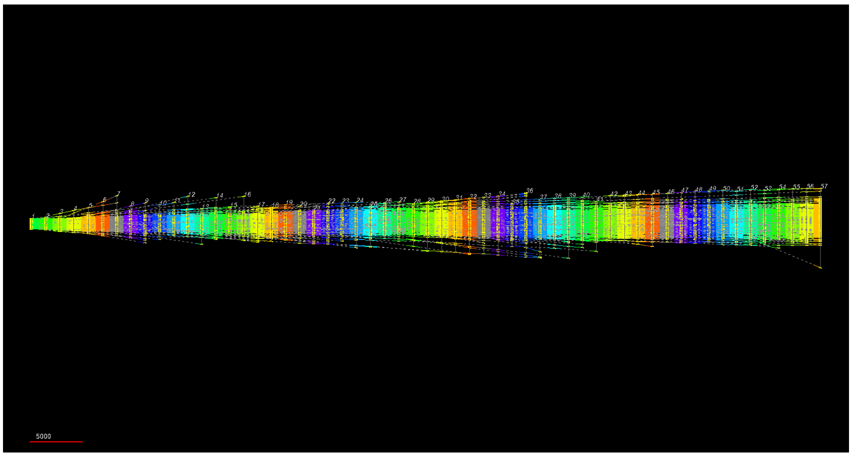
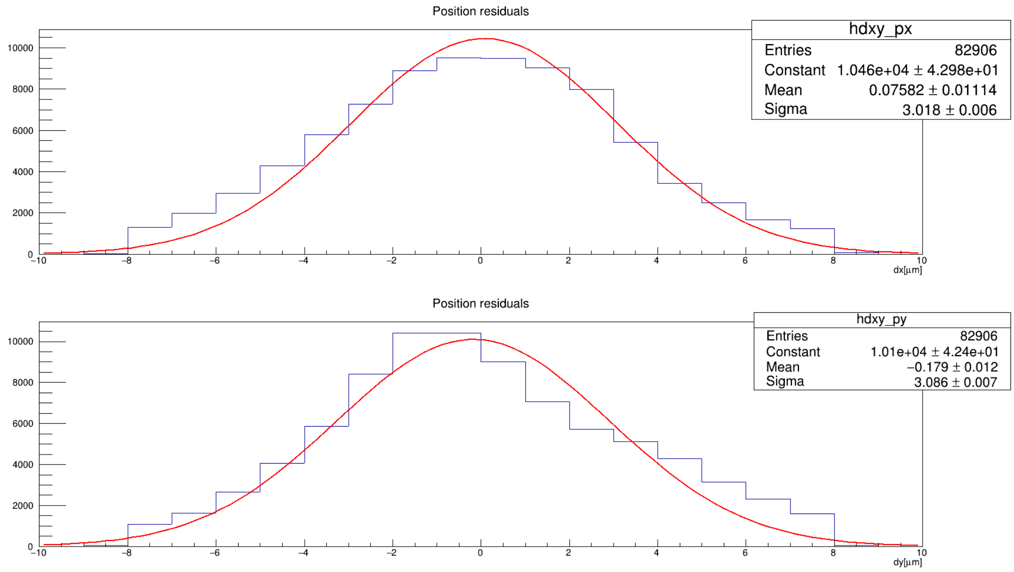


Figure 5: Timeline of the 2022 data-taking emulsion runs.

The matching with the adjacent SciFi tracker plane will be performed by aligning the centre-of-gravity of events reconstructed in the two detectors, thus assigning timing information to interactions reconstructed in the brick.
During the LHC Run 3 data-taking of the 2022 the SND@LHC detector has achieved a remarkable uptime efficiency (95%), collecting about 36.8 fb^{-1}out of 38.7 fb^{-1}delivered to ATLAS at IP1. There have been four *emulsion runs* with different target masses and integrated luminosities, starting from Emulsion Run 0 with 0.45 $\text{fb}^{-1}$to Emulsion Run 3 with 8.6 fb^{-1}. The time-sequence of the above mentioned emulsion runs and the recorded luminosity can be found in Figure 5.



(a)



(b)

Figure 6: Reconstructed tracks in 1 mm^2 (a) developing through all 57 emulsion films of one brick and position resolution of nuclear emulsion achieved in emulsion run 1 (b).

5. Physics results

The muon flux measurement is one of the earliest results of the experiment. Its aim is to provide first information about the muon flux in a forward rapidity range where SND@LHC is and to have a characterisation of one of the main background sources for the neutrino search. The measurement has been performed using data from electronic detectors, SciFi and Muon System, and rates have been reported per fb^{-1}and cm^2. The measured muon flux using the SciFi is $2.06 \pm 0.01(\text{stat}) \pm 0.11(\text{sys}) \times 10^4$ fb/cm^2, while for the DS it is $2.35 \pm 0.01(\text{stat}) \pm 0.08(\text{sys}) \times 10^4$ fb/cm^2 [22]. The systematic uncertainty takes into account different sources such as the tracking method used, the luminosity measurement as well as tracking efficiency fluctuations in different $x - y$ detector regions.

Nevertheless the data/Monte Carlo agreement is at the level of $20-25\%$ and a 10% agreement is observed when comparing early data from SciFi and Emulsion run 0 data. As a matter of fact, as far as emulsion run 1 data is concerned, early results are shown in Figure 6, i.e. a display of reconstructed tracks in nuclear emulsions in 1 mm^2 in all emulsion films of one brick can be found in Figure 6a whereas in Figure 6b a $\sim 3\,\mu$m position resolution in both coordinates is achieved within the same emulsion run.

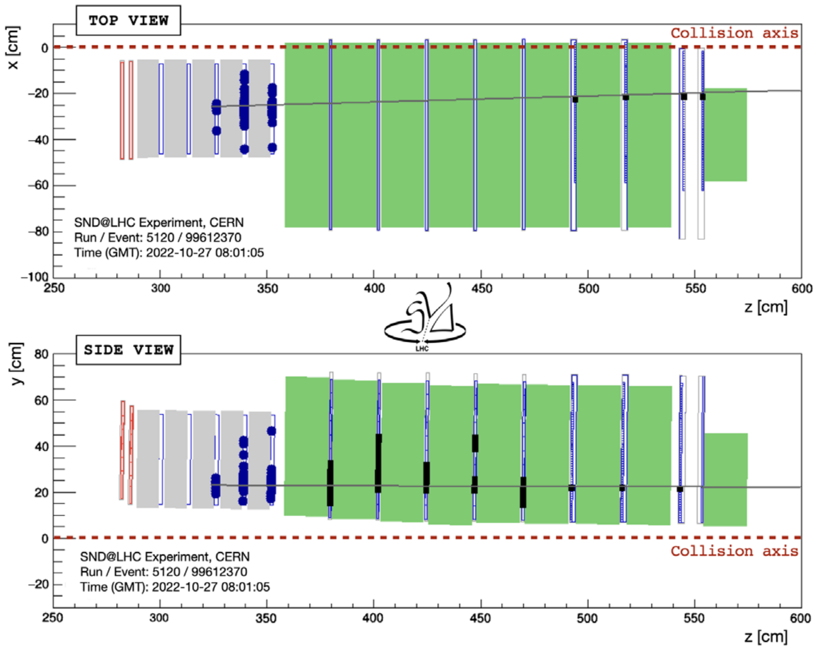


Figure 7: Display of a ν_μ CC candidate event [23].

In addition, the search for high-energy muon neutrinos at the SND@LHC is the most recent study and its aim is to find a high-purity sample of ν_μ CCDIS interaction events in the full 2022 recorded data. This has recently resulted in a paper, reported as Reference [23]. The study adopted a cut-based selection with strong rejection power being the rare neutrino signal overwhelmed by the background, mainly provided by muons ($O(10^9)$). Two main phases can be identified in the signal selection strategy. The first phase, aiming at rejecting background from charged particles entering from the front and the sides of the detector, identifies a fiducial region of the target exploiting the hit multiplicity in Veto and SciFi planes and the very-high rejection power offered by the 1st and 2nd SciFi planes used as veto as well. The second phase, on the other hand, is devoted to the search for signal-like signature patterns, typical of ν_μ CCDIS interactions such as large hadronic activity in the calorimetric system, a clean reconstructed muon track as well as hit time distribution consistent with an event originating from the IP1. The main source of background is provided by muons, either making interactions without being vetoed or interacting strongly in the concrete or rock surrounding the detector and thus generating neutral particles, mainly neutrons and K^0_Ls, which can in turn mimic the neutrino signal when interacting within the detector. In particular the background induced by muons entering the fiducial volumes is taken as negligible when the combined inefficiency of the Veto system and the two most upstream SciFi planes is considered, i.e.

5.3×10^{-12} whereas the background provided by neutrals, estimated with muon DIS simulations, is considered as negligible as well for a total background yield of $(8.6 \pm 3.8) \times 10^{-2}$ after the selection. With that given, the Collaboration reports the observation of 8 candidate events consistent with ν_μ CC interactions as an excess over the background-only hypothesis of 6.8 standard deviations. A display of one of the selected candidates can be found in Figure 7.

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