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Detection of High-Energy Neutrinos at the Large Hadron Collider with the Scattering and Neutrino Detector †

Masahiro Komatsu for the SND@LHC Collaboration

Institute of Liberal Arts and Sciences, Nagoya University, Furo-cho Chikusa-ku, Nagoya J-464-8602, Japan; komatsu@flab.phys.nagoya-u.ac.jp

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Abstract: SND@LHC is designed to perform measurements with neutrinos produced at the LHC in the pseudo-rapidity range of $7.2 < \eta < 8.4$. The experiment is located 480 m downstream of the ATLAS interaction point in the TI18 tunnel. The detector is a hybrid system composed of an 830 kg target made from 1 mm thick tungsten plates interleaved with nuclear emulsion films, electronic trackers also acting as an electromagnetic calorimeter, a hadronic calorimeter and a muon identification system. The detector is able to distinguish three neutrino flavours using the emulsion detector which can identify primary electrons and taus in charged current neutrino interactions. This capability allows probing heavy flavour forward production at the LHC, which even LHCb cannot access. The LHC CM energy corresponds to the 10^{17} eV astronomical energy region, which is of interest for future detectors. The SND@LHC's capabilities and current status are reported in this document.

Keywords: neutrino; LHC; tau neutrino

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1. Overview

SND@LHC is an experiment proposed to exploit the high-energy neutrinos of all three flavours from the ATLAS interaction point (IP) at the LHC [1]. It covers the unexplored energy region in the pseudo-rapidity range of $7.2 < \eta < 8.4$, in which a large fraction of neutrinos originate from charmed hadron decay. These neutrinos can be used as a probe for heavy flavour production in a very forward region that is not accessible even by LHCb experiments. The FASERν [2] and the SND@LHC experiments will observe neutrinos produced by the LHC.

In order to shield the detector from charged particles produced at ATLAS IP, the SND@LHC detector is located in the TI18 tunnel, 480 m downstream of the ATLAS interaction point. A large fraction of charged particles is deflected by the LHC bending magnets and neutral particles are shielded by 100 m of rock. The TI18 tunnel is a suitable location to place the detector. FASERν is also located in the TI12 tunnel symmetric to TI18. The SND@LHC detector was installed in TI18 in 2021 during Long Shutdown 2 and is expected to collect 290 fb^{-1} of data from 2022 to 2025 during Run 3 of the LHC.

2. Detector

Lepton flavour identification has paramount importance in distinguishing three neutrino flavours. The main detector is equipped with five walls of Emulsion Cloud Chambers (ECCs) of 830 kg, followed by Scintillating Fibre (SciFi) planes. The ECCs are composed of emulsion films as a micrometric tracking detector and a passive material acting as the neutrino target. Tungsten is used as a passive material to maximize the number of events. The ECC technology provides electron and tau lepton flavour identification. Electron identification is achieved through electromagnetic shower detection with high granularity every

1 mm and extreme two particle separation to distinguish single electrons through converted electron–positron pairs. Tau lepton identification is achieved through detecting its decay within a few mm, with a typical impact parameter of around 90 µm. This electron and tau neutrino identification was proven in the DONUT [3] and OPERA [4,5] experiments. The SciFi planes provide the timestamp for the reconstructed events. The combination of the ECC and the SciFi planes also acts as an electromagnetic calorimeter, with an average radiation length of 40.

The hadronic calorimeter and muon identification system are located downstream of the target. They consist of eight iron slabs in total with 9.5 interaction lengths, followed by one or two planes of scintillating bars. The hadronic shower develops in the target region, which adds on average 1.5 interaction lengths, totalling 11 interaction lengths on average. The whole detector layout is shown in Figure 1.

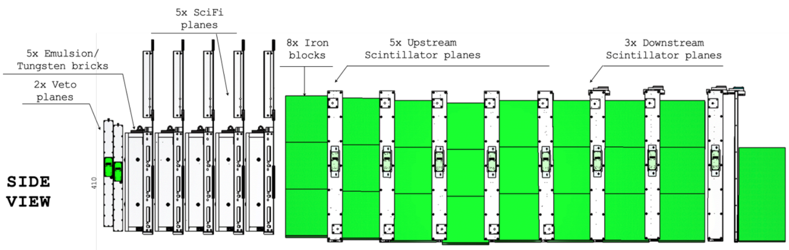

Figure 1. Layout of the SND@LHC experiment.

3. Neutrino Events and Physics Program in Run 3

Figure 2 shows the interacted energy spectrum of neutrinos and anti-neutrinos in the pseudo-rapidity range covered by the SND@LHC detector for 290 fb^{-1}. Table 1 summarizes the expected number of events for both neutrinos and anti-neutrinos for all flavours with their mean energy.

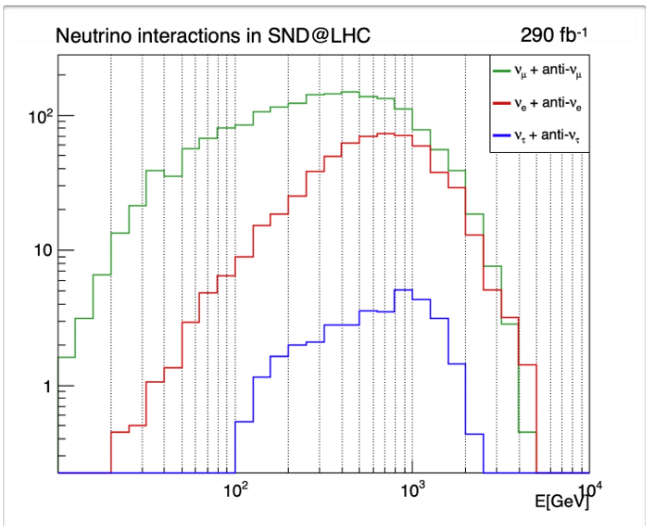

Figure 2. Interacted neutrino energy spectrum of the three neutrino flavours for 290 fb^{-1}.

Since the three neutrino flavours can be identified based on ECC technology for electrons and tau neutrinos, and with the muon system placed downstream of the ECC target, the lepton flavour universality in the neutrino sector can be tested by measuring the ratio of ν_τ/ν_e and ν_μ/ν_e interactions. Both ν_e and ν_τ are mostly produced through semi-leptonic and fully leptonic decays of charmed hadrons. Therefore, the ν_τ/ν_e ratio depends only on the charm hadronization ratio and its branching fractions. The uncertainties of the charm production cross-section and beam flux cancel out. Then, the ratio is sensitive to the ν-nucleon interaction cross-section of the two neutrino flavours. The estimated remaining systematic uncertainty is about 22%; the statistical uncertainty of ν_τ dominates this measurement due to the low statistics of the ν_τ sample. In total, we expect a 30% uncertainty in this measurement.

Table 1. Expected neutrino event yields.

	CC Interactions		NC Interactions	
Flavour	**<E> (GeV)**	**Yield**	**<E> (GeV)**	**Yield**
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

On the other hand, ν_μ has the largest statistics but is highly contaminated by π and K decays. However, this contamination is mostly populated in the low energy region due to the smaller gamma factor of its parent particles. Above the 600 GeV region, the contamination is expected to be 35%. Electronic and muonic decay branching ratios are essentially the same. Therefore, the ν_μ/ν_e ratio is not affected by the uncertainty of the branching fractions, but by the uncertainty due to π and K production in the SND@LHC η range. The ν_μ/ν_e ratio provides a test of the lepton flavour universality with an uncertainty of 15% and with 10% statistical and systematic contributions.

LHC neutrinos are also important to investigate heavy flavour production in ultra-high-energy cosmic ray interactions for the future neutrino radio telescopes. The LHC CM energy (13 TeV) is equivalent to the 10^{17} eV cosmic ray interaction. Furthermore, in ultra-high-energy cosmic neutrino detection, tau neutrinos play an important role because only tau leptons produce energetic air showers. In the case of tau neutrinos, not only ice but also rock can be used as the neutrino interaction target. Therefore, for both heavy flavour production at ultra high energy and in tau neutrinos, interaction properties are important. Both physical phenomena can be achieved using LHC neutrinos.

Further details are presented in the technical proposal [6].

4. Installation and Run Status

The detector installation started on 1 November 2021 and electronic detector installation was completed by 3 December 2021. Then, the installation of the neutron shield was completed on 15 March 2022, just before LHC commissioning started. Muons from p–p collisions at 13.6 TeV were successfully recorded by the SND detector on 6 July 2022. See Figures 3 and 4.

Figure 3. Detector installation in the TI18 tunnel.

Detector commissioning was also successfully performed before pilot ECC target 0, 1/4 of one wall, was installed on 7 April 2022. All emulsion films for the target 0 were produced at an emulsion production facility at Nagoya University, Japan. Full target 1 (44% Nagoya and 56% Slavich films) installation was performed on 26 July 2022 and extracted on 13 September. The integrated luminosity for target 1 was 10.5 fb^{-1}. Target 2 (100% Nagoya film) was installed on 13 September and extracted on 4 November. The integrated luminosity for target 2 was 21.4 fb^{-1}. Target 3 (77% Nagoya and 23% Slavich films) was installed on November 4th. It took four hours for target exchange.

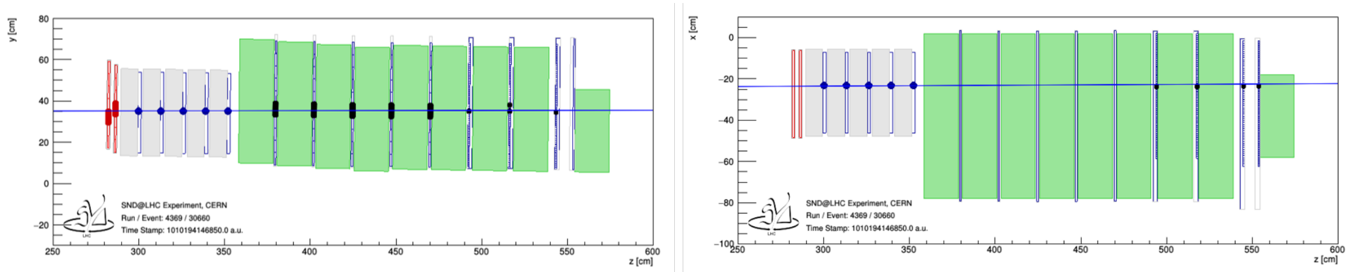

Figure 4. Muons from p–p collisions at 13.6 TeV recorded on 6 July 2022.

5. Summary

SND@LHC is designed to perform measurements with neutrinos produced at the LHC in the pseudo-rapidity range of $7.2 < \eta < 8.4$ and perform neutrino measurements in the unexplored energy region with all three neutrino flavours suitable to study lepton universality in the neutrino sector. It is also important to measure heavy flavour production in very forward regions which are unreachable even by LHCb experiments using neutrinos as a probe.

The experiment was approved by the CERN Research Board in March 2021. Detector installation started in November 2021 and was completed by December 2021. The first emulsion films were installed on 7 April 2022. A physics run with a full ECC target started on 26 July. Three targets have been used so far. The integrated luminosities for the first and second target were 10.5 and 21.4 fb^{-1}, respectively.

Emulsion films were developed for these targets. The first results will be presented in 2023.

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