PROCEEDINGS OF SCIENCE

SND@LHC and AdvSND: a roadmap for neutrino detection at LHC and HL-LHC

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SND@LHC is a forward experiment measuring neutrinos produced at the LHC. The detector was installed in 2021-2022. The first physics data yielded the first observation of neutrinos produced at a collider.

The detector is a hybrid system based on a 830 kg target with tracking capabilities, followed by a calorimeter and a muon system. Its configuration allows to identify all three neutrino flavours, opening a unique opportunity to probe heavy flavour production in a region not accessible to ATLAS, CMS and LHCb.

An upgrade is foreseen for Run 4: the new detector will replace the nuclear emulsions embedded in the target with silicon sensors, and use a magnetised HCAL.

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1. THE SND@LHC DETECTOR

The SND@LHC detector [1] 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 (see figure 1).

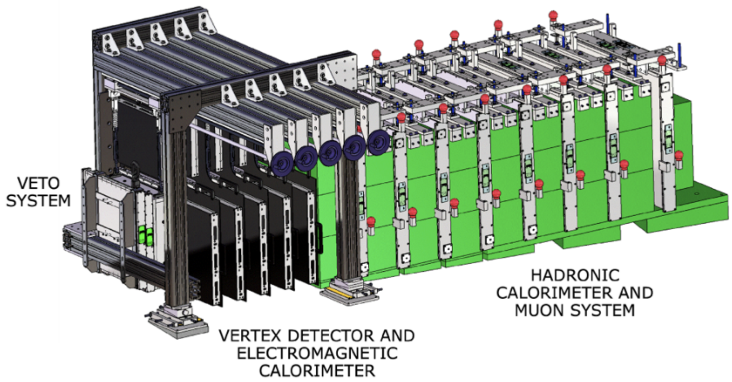

Figure 1: The SND@LHC detector.

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 2.1. The target section contains five walls, each made of four units, called bricks, of emulsion cloud chambers (ECC) and is followed by a scintillating fibre (SciFi) station for tracking and electromagnetic calorimetry (ECAL). Each ECC unit is a sequence of 60 nuclear emulsion films, $19.2 \times 19.2\,\text{cm}^2$ and approximately 300 µm, interleaved with 59 tungsten plates, 1 mm thick.

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) 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 $82.5 \times 6 \times 1\,\text{cm}^3$ 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 acts as a coarse sampling calorimeter to measure hadronic jets energy. Together with the target the hadronic system is ten interaction lengths deep.

2. Run 3 Operation

2.1 Veto system upgrade

To identify neutrino interactions it is crucial to have efficient tagging of incoming charged particles within the detector volume. In data collected in 2022, the veto performance [2][3] required the use of the first two SciFi planes to fully reject the muon background, significantly reducing the fiducial volume. Consequently, the SND@LHC Collaboration decided in the autumn of 2023 [4] to lower the veto system by ~ 27 cm in order to provide better coverage of the bottom edge of the neutrino tungsten target, and to add a third layer (Veto 3, V3) of scintillating bars to improve the veto efficiency for incoming charged particles. The Veto planes 1 and 2 (V1 and V2) each have seven scintillating bars $42 \times 6 \times 1\,\text{cm}^3$, stacked horizontally. Each bar, made of plastic Eljen EJ 200 [7] is tightly wrapped in 20 µm thick aluminized mylar foils. The bars are read out with 56 SiPMs (Hamamatsu Photonics MPPC S14160-6050HS [8]) at both left and right ends. Bars in Veto 3 are aligned vertically, to minimize the probability that the readout dead time, after a bar has detected a muon in V1 or 2, coincides with the passage of a second muon through the same bar. Veto 3 bars are identical to the other planes except for the lenght of 46 cm, extending by 2 cm above and below the V1 and V2 range. The bars are read just from the top to meet the geometrical constraints imposed by the Veto 3 position, shown in figure 2, as this was proven not to affect the readout efficiency [4].

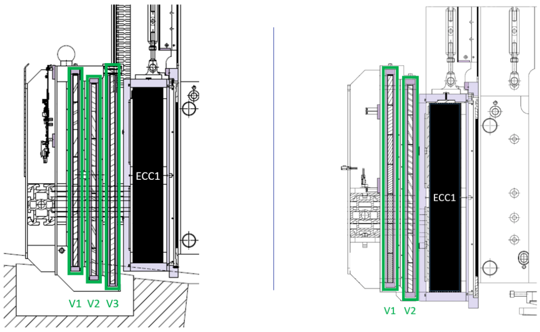

Figure 2: Current (left) and previous (right) Veto system configuration. Planes are highlighted in green.

2.2 Emulsion target optimization

Since the restart of LHC operation in March 2024, due to the change of the machine configuration, the muon background at the SND@LHC detector position increased by a factor 2. This strongly affects the ECC, since the emulsion films can only be exposed to a finite integrated luminosity. Given the impossibility to double the amount of films available due to production time, the SND@LHC collaboration decided to instrument only the lower part of each ECC module. Indeed the neutrino flux is expected to be larger in the lower part of the instrumented area, and the muon flux has been measured to be larger in the top part [5]. This partially compensates the loss of neutrino events, which is expected to be 65% of the fully instrumented target.

2.3 HCAL calibration

Reconstructing energy and direction of hadronic showers is crucial in SND@LHC to fully understand the neutrino interaction and estimate the energy of the incoming neutrino. For this reason a dedicated test beam was carried out in August 2023. With the data collected using hadrons beam with energy ranging from 100 to 300 GeV, the aim is to calibrate the energy response of SND@LHC detector HCAL composed of the Scifi modules and the US (described in 1). The test beam setup, shown in figure 3, is similar to that of the SND@LHC detector but slighly different in the target region with smaller $13 \times 13\,\mathrm{cm}^2$ Scifi modules and only 4 of them. Also the passive material in the test beam was iron instead of the tungsten used in the SND@LHC setup.

In the data collected, the digitized value of the integrated charge (QDC) in the shower events follows the relation:

$$E_{incoming} = k \times QDC_{SciFi} + \alpha \times QDC_{US} \tag{1}$$

where $E_{incoming}$ is the incoming particle energy, QDC_{SciFi} and QDC_{US} are the detector responses respectively in the SciFi and US modules, k and α are the calibration constants under study. These constant have been computed and validated, as shown in figure 4, using test beam data achieving an energy resolution ranging from $\sim$ 12% to 22% depending on the incoming hadron energy. The work is still ongoing to optimize the computed values to apply the calibration to data collected in the SND@LHC detector.

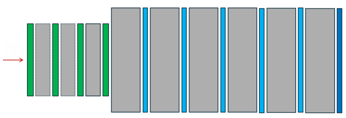

Figure 3: Test beam setup scheme. In green the SciFi modules, in light blue the US stations, in dark blue the DS module, in gray the iron. The red arrow shows the incoming hadron beam.

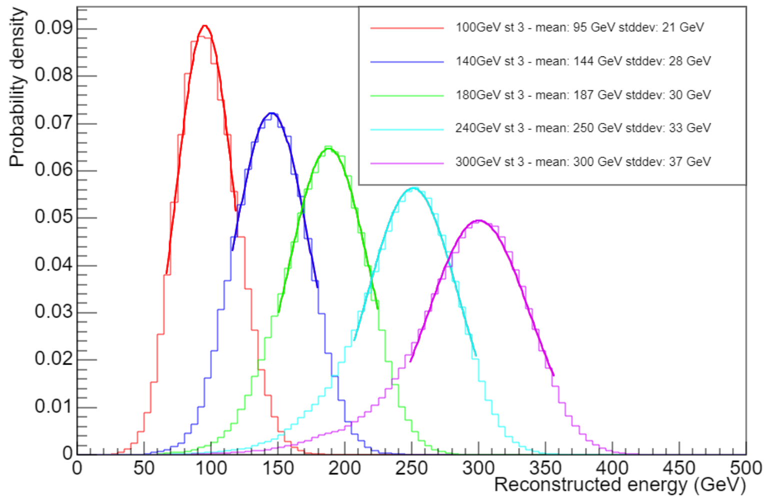

Figure 4: Reconstructed energy in the test sample for showers starting in the third SciFi modules, with different hadron beam energies.

2.4 Muon system upgrade

A feasibility study is just started to improve the muon track resolution in SND@LHC. Currently, muon tracking is done using the DS modules (described in 1) which have a resolution of $\sim$ cm. These scintillator modules may be replaced or complemented by small size replicas of CMS Drift Tubes chamebers, called MiniDTs, which will provide a point resolution of $\sim 150\,\mu\mathrm{m}$. These new modules should be installed during the 2024 – 2025 year end technical stop and take data for the rest of Run 3. Improving muon tracking will not only help in vertex identification for muonic neutrinos interaction, but also in background rejection, helping to discriminate those events entering the instrumented volume from the side without crossing the veto system.

3. Run 4 Upgrade

The results which will be obtained from Run 3 will provide the first measurement of neutrinos in an unprecedented energy range and will constrain the gluon Parton Distribution Function using neutrinos as a probe of charm production in an unexplored pseudo-rapidity domain. Nevertheless, Run 3 measurements will be statistically limited, given the geometrical constraints of the current detector and the expected integrated luminosity. For this reason an upgrade is being proposed for HL-LHC. Civil ingeneering will be needed to optimize the detector acceptance for the crossing angle configuration proposed in Run 4 and 5, but a compact upgrade is being proposed to limit the intervention only to floor excavation. The main new feature of the upgraded AdvSND will be a magnetized HCAL that can lead to the first experimental direct observation of $\bar{\nu}_\tau$.

3.1 Vertex detector upgrade

The vertex detector will need to be replaced since HL-LHC collisions will produce a muon flux too intense to use Emulsion Cloud Chambers efficiently. The passive material will be tungsten as in the current configuration but emulsion films will be replaced by silicon detector planes. These will be made reusing CMS Tracker Outer Barrel (TOB) strip modules that will be uninstalled from CMS for its Phase 2 upgrade. Strips will be arranged in different configurations, shown in figure 5 to have four possible active layer geometries to be alternated in the final setup to achieve the best acceptance possible. The final result, in figure 6, will be a target and vertex detector made by 50 to 100 of these modules interleaved by tungsten for a total mass of 1.3 to 1.75 tons, doubling the current target mass.

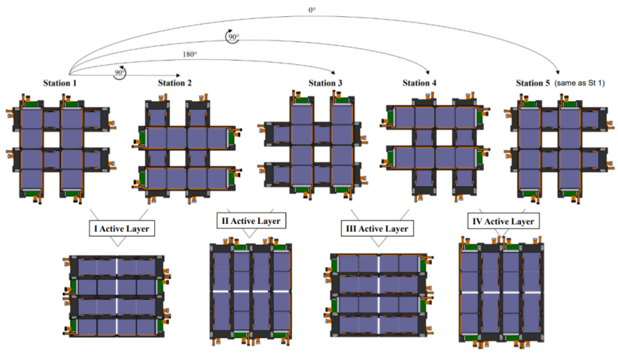

Figure 5: Possible TOB strips arrangement to compose active layers.

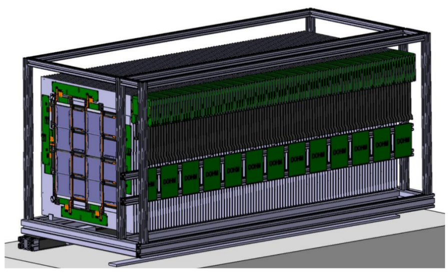

Figure 6: Scheme of the AdvSND target and vertex detector.

3.2 Magnetized HCAL

As mentioned in 3, the main feature of the AdvSND will be a magnetized HCAL. This will be made by adding a coil around the detector and magnetizing the iron used as passive material. This technique will allow for a magnetic field of 1.75 T that will increase the detector sensitivity to charge, in order to discriminate neutrinos and antineutrinos interactions. AdvSND will aim to have a $\sim 20\%$ momentum resolution for muons up to 1 TeV, needing a point resolution in the HCAL section of ~ 30 μm. The final detector layout is still under study but this requirement is met by CMS TOB strips. The total number of CMS microstrip sensor available will allow for the construction of several planes to be equipped also in the HCAL section of the detector.

4. CONCLUSION

The SND@LHC experiment is dedicated to the detection of very high energy neutrinos from proton-proton collisions at the LHC. To achieve the best possible performances, different upgrades are being performed exploiting the information collected since the start of its data taking in 2021. The collaboration is also looking at the future opportunities that HL-LHC will open for neutrino physics, in particular for ν_τ and $\bar{\nu}_\tau$.

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