PROCEEDINGS OF SCIENCE

Performance overview of SND@LHC and Faser

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Since 2022, the LHC physics programme has been expanded into new areas by two experiments studying collider neutrinos and searching for long-lived weakly interacting particles produced in the collisions: SND@LHC and FASER. These experiments, located symmetrically about 500 m away from the ATLAS interaction point, aim to provide measurements of neutrino interactions in previously unexplored energy ranges between $E_\nu \in [10^2, 10^3]$ GeV, as well as to extend the experimental sensitivity to long-lived dark sector particles into new areas previously inaccessible at the LHC. The SND@LHC and FASER detectors utilise a combination of emulsion cloud chambers for neutrino identification via precise vertexing, and electronic detectors used for tracking, timing and calorimetry. This document presents a short review of the key aspects of detector design and performance of the two experiments.

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1. Introduction

The Large Hadron Collider at CERN, unique for its high energies and intensities, has a lesser-known function as a source of neutrinos. At the LHC, high fluxes of neutrinos of all flavours are produced in the decays of various products of the pp collisions. The energy spectrum of these neutrinos spans a range of $E_\nu \in [10^2, 10^3]$ GeV, covering a region previously unexplored by other experiments [1].

In addition to neutrinos, new physics in the form of light, weakly interacting particles could also be produced abundantly in the pp collisions at the LHC [2]. In the past, New Physics searches have largely focused on heavy particles produced in the high-p_T regions of high-energy collisions. More recently, increasing interest is seen in models predicting long-lived, feebly interacting particles. Such particles, if produced at the LHC, could be collimated very close to the beam axis in the forward region , and travel large distances before decaying or interacting, therefore evading detection by the large experiments at the interaction points.

Since 2022, two dedicated experiments, the Scattering and Neutrino Detector at the LHC (SND@LHC), and the ForwArd Search ExpeRiment (FASER), have been extending the LHC physics program to the previously inaccessible topics of neutrinos and long-lived particles (LLPs). Located symmetrically about 500 m away from the ATLAS interaction point IP1, the two experiments measure collider neutrinos at complementary pseudorapidity ranges, and offer sensitivity to new long-lived particles via their scattering and decay. This document aims to provide a brief overview of the detector design and performance of the two experiments.

2. SND@LHC

SND@LHC [3, 4] is a compact, standalone experiment designed for the study of collider neutrinos from the LHC in the pseudorapidity range of $7.2 < \eta < 8.4$, and the search for dark-sector LLPs via scattering [5]. The detector design, illustrated in Fig. 1, is optimised for the detection and identification of all three neutrino flavours, and consists of a scintillator veto, a target region acting as a vertex detector and electromagnetic calorimeter, and a combined muon system and hadronic calorimeter.

In its location in the TI18 tunnel, the SND@LHC detector is shielded from the charged particles generated at IP1 by LHC magnets and about 100 m of bedrock. The main background comes from muons originating either directly from IP1 or from interactions of secondary particles with the LHC machine elements, that have a flux of around $10^4 \mathrm{fb}/\mathrm{cm}^2$ [6] at the detector location. To mitigate this background contribution, a veto detector consisting of staggered planes of scintillating bars is placed upstream of the target region. The scintillating bars have dimensions $(1 \times 6 \times 42)$ cm^3 and are read out with (6×6) mm^2 silicon photomultipliers (SiPMs). In studies performed in 2023 with two veto planes, the inefficiency of the veto was found to be approximately 9×10^{-8}. In 2024, a third veto plane was added, and improvement in the inefficiency from ongoing studies is expected.

The SND@LHC target is a hybrid system that combines emulsion cloud chambers (ECCs) used for neutrino flavour identification via precise vertexing with scintillating fibre (SciFi) technology used for timing and calorimetry. It consists of five ECC walls alternating with five SciFi stations. Each ECC wall is made of 60 layers of 0.31 mm nuclear emulsions interleaved with 59 1 mm tungsten plates, making up a total thickness of 17 radiation lengths per wall, and a total target mass

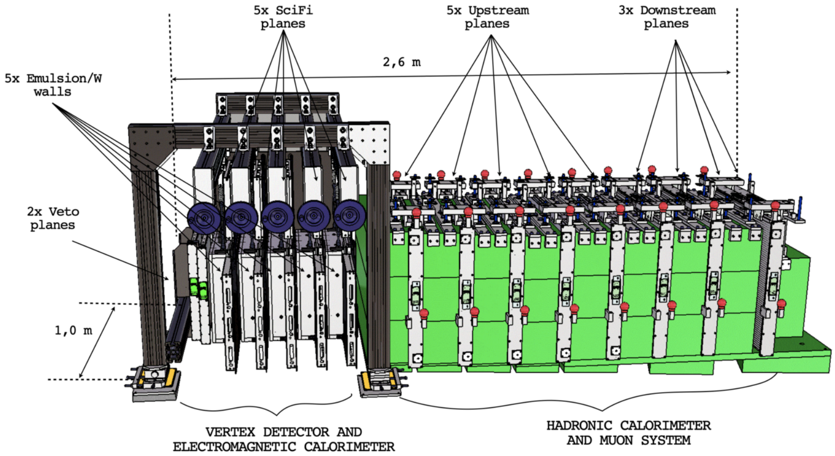

Figure 1: Illustration of the SND@LHC detector design. Reproduced from [3].

of 830 kg. The emulsion walls are exchanged every 10 to 20 fb^{-1} depending on the muon rate that varies with the beam crossing angle at IP1, to keep the density of tracks accumulated on the emulsions manageable. The data is extracted by developing and scanning the emulsion films in a dedicated laboratory with optical microscopes. The tracking resolution of the SND@LHC ECCs has been evaluated and found to be about 0.7 µm for the x/y position.

The five SciFi stations placed in between the ECC walls complement the tracking data from the emulsions by providing timing and calorimetric information. Each station has two perpendicular planes made from stacked layers of 250 µm scintillating fibre to measure x and y coordinates. The fibres are read out with SiPMs of $(0.25 \times 1.62)\ \mathrm{mm}^2$ channel size, chosen to match the width of the scintillating fibre and the thickness of the fibremat. The single-hit efficiency of the SciFi has been evaluated using TI18 data, and was found to be approximately 98% in each plane, and 99% in the active area of each plane. The time resolution, also evaluated on data collected at TI18, reaches 320 ps for a single scintillating fibre layer, 230 ps for a plane, and 100 ps for the full SciFi detector. The spatial resolution, estimated using muon testbeam data, is approximately 100 µm.

The last section of the SND@LHC detector is made of 20 cm iron slabs interleaved with scintillating bar stations, and is used as a combined muon detector and hadronic calorimeter. It consists of five upstream stations with coarse bar segmentation, and three downstream stations with finer bar segmentation for improved muon tracking. Each upstream station contains 10 scintillating bars of size $(1 \times 6 \times 81)\ \mathrm{cm}^3$ in horizontal orientation, read out by a combination of large (6×6) mm^2 SiPMs with 50 $\mu\mathrm{m}^2$ pixels and small $(3 \times 3)\ \mathrm{mm}^2$ SiPMs with 10 $\mu\mathrm{m}^2$ for a better dynamic range. In contrast, each downstream station contains 60 $(1 \times 1 \times 81)\ \mathrm{cm}^3$ horizontal bars and 60 $(1 \times 1 \times 60)\ \mathrm{cm}^3$ vertical bars, all read out by the larger $(6 \times 6)\ \mathrm{mm}^2$ SiPMs. The energy resolution of the system used as a hadronic calorimeter has been studied in a dedicated testbeam campaign with pions, and was found to be 14% at 300 GeV.

The data acquisition of the electronic subsystems of SND@LHC [7] is implemented in a triggerless manner, by sending all hits of sufficient signal amplitude to a server for processing and event building. During 2022-2024, the detector has been operated with high efficiency, reaching an integrated luminosity of 138.67 fb^{-1} in the emulsions and collecting more than 95% of the delivered luminosity with the electronic subdetectors.

3. FASER

The FASER experiment [8] is an experiment dedicated to the search of of light, extremely weakly interacting particles produced at the LHC. The detector design, illustrated in Fig. 2, is optimised in particular for the search of the decay of such long-lived particles [9], and it features a decay volume followed by a spectrometer and an electromagnetic calorimeter. Included in the design is also FASERν [10, 11], a subdetector designed for measuring collider neutrinos at a pseudorapidity range of $\eta > 8.8$ that is complementary to the SND@LHC acceptance.

Similarly to SND@LHC, the FASER detector, situated in the TI12 tunnel, is shielded from the collision products from IP1 by LHC magnets and about 100 m of rock, and receives a background consisting mainly of muons. To tag the charged particles entering the detector, a veto station made of two plastic scintillator modules of size (30×35) cm^2 is placed in front of the FASERν subdetector. A second scintillator veto with four smaller (30×30) cm^2 modules and a 10 cm lead plate for absorbing bremsstrahlung photons is placed between FASERν and the decay volume. The veto inefficiency, as evaluated from TI12 data, is less than 10^{-6} for each scintillator, and less than 10^{-20} for the whole system.

In addition to the veto system, scintillator stations are used in FASER for trigger and timing purposes. The first trigger station is placed after the decay volume and in front of the first spectrometer tracker, and is used to detect charged particle pairs coming from LLPs decaying within the decay volume. This station provides the primary trigger for physics analysis, as well as a precise timestamp of the signal with respect to the pp interaction at IP1. The time resolution of the station has been evaluated with TI12 data, and found to be 420 ps. The trigger provided by the first trigger and timing station can optionally be combined in coincidence with a second trigger station placed between the spectrometer and the ECAL, to reduce the rate of non-physics triggers. This station, consisting of two scintillator modules interleaved with tungsten and graphite absorbers, serves a secondary purpose as a pre-shower station used to distinguish between pairs of energetic photons and neutrinos that would otherwise leave a similar signal in the ECAL.

The FASERν subdetector extends the physics reach of FASER from LLP searches to neutrino interactions. Like SND@LHC, it uses ECCs to identify all three neutrino flavours via precise reconstruction of the interaction vertices. The detector consists of 77 vacuum packed ECC modules compressed inside a box to guarantee sub-micrometric alignment. Within each module, 10 emulsion films of thickness 0.34 mm and size (20×6) cm^2 are interleaved with 10 1.1 mm tungsten plates, resulting in a thickness of 200 radiation lengths or 7.7 nuclear interaction lengths and a mass of 1100 kg for the entire FASERν system. The tracking resolution of the detector has been measured to be 0.3 µm. An additional tracking station placed immediately downstream of FASERν, called the Interface Tracker, allows the matching of the precisely reconstructed ECC tracks to the electronic detector information.

A key element of the FASER detector design is the tracking spectrometer [12], which allows the separation of two collimated oppositely charged particles coming from an LLP decay. It consists of three tracking stations made from silicon double strip modules that were originally designed for

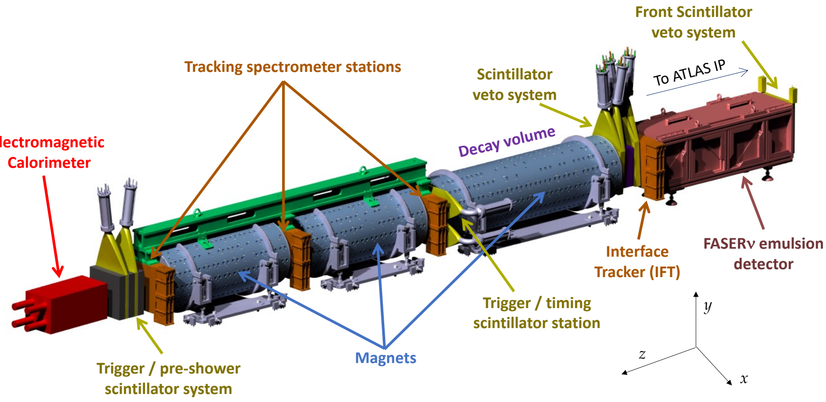

Figure 2: Illustration of the FASER detector design. Reproduced from [8].

use in the ATLAS SCT barrel detector. The tracking stations are separated by two permanent dipole magnets of 0.57 T, with a third magnet placed upstream inside the decay volume. The hit efficiency of the tracker has been measured using dedicated runs taken in TI12, and found to be approximately 99.6%. The alignment of the trackers has been validated and spatial resolution measured to be 30 µm in the precision coordinate.

The last section of the FASER detector is the electromagnetic calorimeter. It consists of four repurposed LHCb outer ECAL modules, placed in a (2×2) configuration. Each module is 25 radiation lengths thick, and is made of 66 layers of lead and plastic scintillator and read out with a photomultiplier tube via wavelength shifting fibres. The ECAL has been calibrated using electrons and muons during a testbeam campaign, and the energy resolution has been measured with high energy electrons up to 300 GeV to be about 1%.

The FASER data acquisition [13] operates with a trigger that uses the different scintillator systems of the detector. In the so-called physics coincidence trigger mode, events with signal in the front veto station and the preshower station are selected. This trigger has a dead time of around 2%, and a rate of the order of 500 Hz. The rate of the coincidence trigger is about 4 times smaller than the individual trigger rate, suggesting that the dominant triggered background comes from particles triggering individual station rather than energetic muons. During its operation between 2022 and 2024, FASER has collected 190 fb^{-1} of data, recording more than 97% of the delivered luminosity.

4. Conclusion

The LHC offers a unique environment for neutrino physics and long-lived dark sector particle searches. Since 2022, two complementary experiments studying these topics, SND@LHC and FASER, have been in operation, and have already provided the first ever observation of collider neutrinos from the LHC [14, 15] along with other physics results. These proceedings have presented a brief overview of the experimental design of the SND@LHC and FASER detectors, and performance highlights of their various subdetector systems. During the few years of commissioning and operation, both experiments have measured and characterized their detector systems in detail, and plans for future upgrades are already underway.

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