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High-energy neutrino measurements with FASERν

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FASER is an experiment to search for light weakly-interacting particles and measure neutrino interactions with Large Hadron Collider at CERN and started in 2022 spring. The FASERν is sub-detector of FASER that works as dedicated neutrino detector consisting of a front scintillator veto system, the emulsion and silicon strip detectors. This paper describes target of neutrino measurement with the FASERν as well as the construction and commissioning. In addition, the results of neutrino measurements with a pilot emulsion detector, that was performed at TI18 tunnel at CERN in 2018, is presented.

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1. Introduction

The ForwaArd Search ExpeRiment (FASER) is an experiment to search for light weakly-interacting particles and measure neutrino interactions with Large Hadron Collider (LHC) at CERN. The detector is placed on the beam collision axis line-of-sight (LOS) 480 m from the ATLAS collision point in an unused service tunnel (TI12) as shown in Figure 1 [1, 2]. Figure 2 is a sketch of the FASER detector. From the upstream of the beam axis, the detector consists of FASERν, the FASER scintillator veto station, the decay volume, the timing scintillator station, the FASER tracking spectrometer [3], the pre-shower scintillator system, and the electromagnetic (EM) calorimeter system. The detector also includes three 0.57 T dipole magnets, one surrounding the decay volume and the other two embedded in the tracking spectrometer.

The experiment started in 2022 spring, synchronizing LHC Run 3, and aims to accumulate more than 150 fb^{-1} of data. This paper describes target of neutrino measurement with the FASERν as well as the construction and commissioning. In addition, the results of neutrino measurements with a pilot emulsion detector, that was performed at TI18 tunnel at CERN in 2018, is presented.

2. FASERν detector

The FASERν is a detector dedicated for neutrino measurements, consisting of a front scintillator veto system, the emulsion detector and the InterFace Tracker (IFT) (see Fig. 2). The scintillator veto system is placed in front of the emulsion detector to veto charged particles entering the detector. It is constructed from two modules placed back-to-back with a 30 cm × 35 cm, 2 cm thick EJ-200 plastic scintillator connected by a 1.5 cm × 1.5 cm × 37.5 cm EJ-280 plastic wavelength shifting rod to a Hamamatsu H11934-300 PMT.

The emulsion detector consists of 770 emulsion films interleaved with 1-mm-thick tungsten plates with the dimensions of 25 cm × 30 cm. The total tungsten mass is 1.1 tons corresponding to 220 radiation lengths and 7.8 hadronic interaction lengths. The emulsion film is composed of two emulsion layers with 65 μm thickness, that are poured onto both sides of a 210-μm-thick plastic base. The emulsion detector with 200 nm crystals has a spatial resolution of 50 nm, and accordingly the

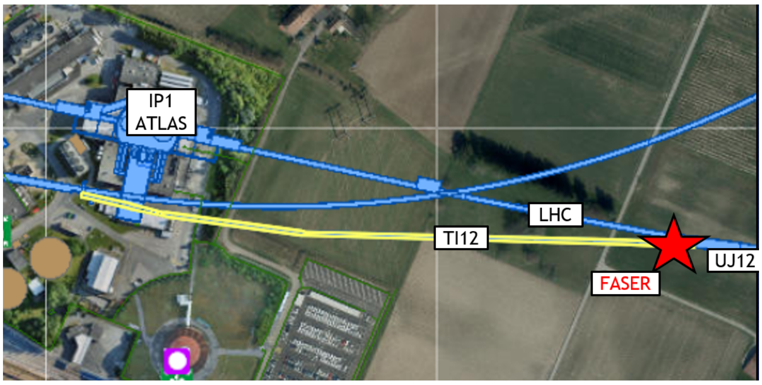

Figure 1: The FASER location: TI12 tunnel, 480 m downstream of the ATLAS interaction point. The detector is located along the beam collision axis LOS.

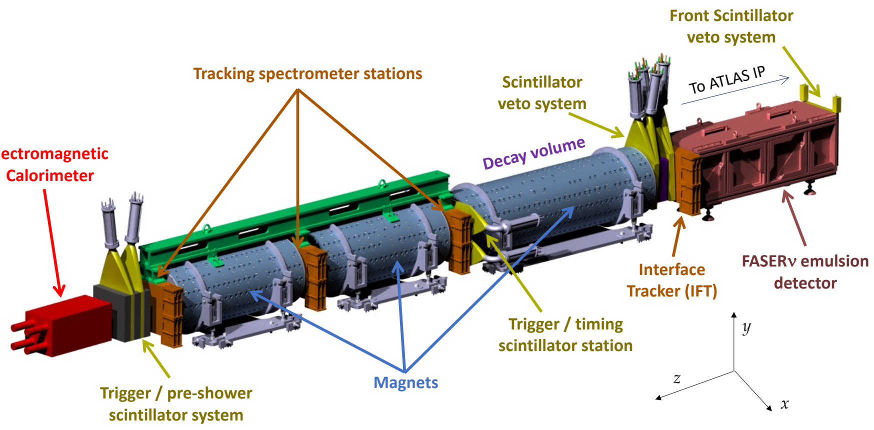

Figure 2: A sketch of the FASER detector, showing the different sub-detector systems.

two-dimensional intrinsic angular resolution is 0.35 mrad with a double-sided emulsion film. The emulsion detector has the ability to identify different lepton flavours by using the event topology of the final states in the Charged Current (CC) interactions. In addition, it can measure the momentum of muons and hadrons as well as the energy of electromagnetic showers. That allows us to estimate the energy of neutrinos.

The IFT adopts the same design as the FASER tracking spectrometer station which is composed of three planes of silicon strip modules that were originally the spare for the ATLAS SCT barrel detector [4]. Each sensor has strips with 80 μm pitch and 12.4 cm long. The module consists of two sensors placed with 40 mrad stereo angle so that the hit position can be identified with about 16 μm resolution in the precision coordinate (the y-axis in Fig. 2), and 816 μm in the other coordinate (the x-axis in Fig. 2). The same readout electronics, detector control system (DCS) and cooling system are used both for the tracking spectrometer and IFT, that were newly developed for FASER.

3. Neutrino measurements at FASERν

The FASERν measures the neutrino cross-section at TeV region which is uncovered by existing experiments. All neutrino flavors in CC interactions can be identified including ν_τ, thanks to the excellent position resolution of the emulsion detector. The numbers of CC interactions with 150 fb^{-1} of data are expected to be 1128, 5346 and 21.6 for ν_e, ν_μ and ν_τ, respectively, in average over the prediction of three different generators (SIBYLL, EPOSLHC and QGSJET) [5]. Figure 3 shows the expected sensitivity to neutrino cross-sections at FASERν with 150 fb^{-1}. FASER is the first experiment to measure the cross-section of CC τ neutrino interactions. The anomaly of the coupling strength in the third generation of the quark-sector is reported in the measurement of a branch ratio between B→ $D^{(*)}\tau\nu_\tau$ and B→ $D^{(*)}\ell\nu_\ell$ where ℓ denotes an electron or muon [6]. FASER can explore the anomaly of the third generation of the neutrino sector. The cross-section for ν_μ and $\bar{\nu}_\mu$ also can be measured separately, identifying charge of μ with magnetic field in the

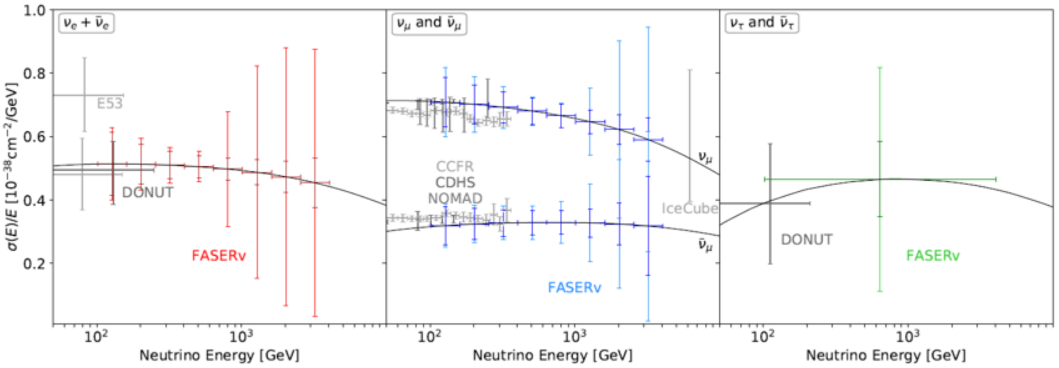

Figure 3: The expected sensitivity to ν-nucleaon CC cross-section for ν_e (left), ν_μ (middle) and ν_τ (right) with 150 fb^{-1} of data-taking at FASERν in LHC Run 3.

tracker spectrometer behind FASERν. In addition to CC interactions, FASERν also can measure the inclusive cross-section of the neutral current interactions of all neutrino flavours.

There are large number of difference between generator predictions, especially for ν_e and ν_τ from large uncertainties in the forward charm production. The FASERν will explore the energy region above 500 GeV in which the cross-section of ν_e and ν_τ is determined by the forward charm production, therefore, can give constraint on it.

4. Results of pilot beam test

The pilot runs took place for neutrino detection and flux measurement of charged particles at TI12 and TI18 at CERN in 2018 [7], where TI18 is the tunnel at the same distance from ATLAS IP as TI12 but the opposite side. The neutrino measurement was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 fb^{-1} of data. The interactions contained in a 10 kg volume were used for the analysis. 18 candidates of the neutral vertex were detected, that are the first candidates of the neutrino interactions at a collider. 2.7σ excess of neutrino-like signal above muon-induced background was measured.

5. Construction and commissioning

The integration and installation of the FASER detector started in 2020 with preparation of the TI12 tunnel and engineering work on the detector support. The civil engineering works was necessary to place the FASER detector on the LOS. The main trench is about 5.5 m long and 1.4 m wide, and is 60 cm deep at the front of the FASER detector and 20 cm deep at the back. After the installation of the services in TI12, the FASER detector except for FASERν was installed until March 2021.

The mechanical support for the emulsion detector was built in the end of 2020. The emulsion films are produced in Nagoya University. Since the emulsion films are sensitive to light, the dark room facility at CERN is used for an assembly of the sub-modules with tungsten plates and the emulsion films, chemical development of the emulsion films, and vacuum-pack. The first emulsion

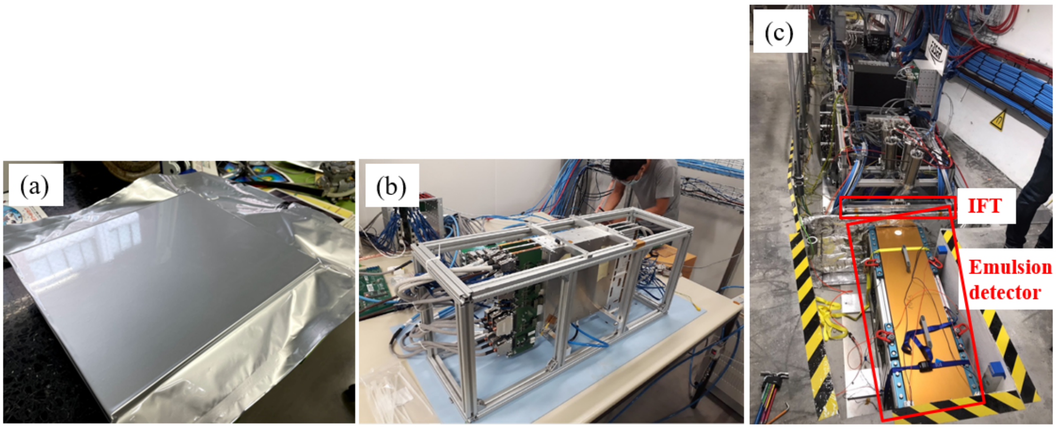

Figure 4: (a) The emulsion sub-module, (b) IFT, and (c) both in FASER site.

detector was prepared in March 2022 as shown in Fig. 4(a, c). 22 emulsion sub-modules were housed in the emulsion box with tungsten plates for the remaining volume. This is about 30% of the full emulsion for commissioning. The scintillator veto system is also mounted in front of the emulsion detector. The emulsion films were replaced with a full detector for the first physics in July 2022. The emulsion films will be replaced eleven times every 30-50 fb^{-1}. Scanning the extracted emulsion films and the event reconstruction are done at Nagoya University. The emulsion readout system takes a sequence of tomographic images, changing the focal plane on each emulsion layer. The images are analyzed to find sequences of grains of a track segment.

The candidates of the single strip modules used for the FASER tracking spectrometer and IFT were electrically tested, and those with the best quality were selected for the detectors. The IFT was assembled with the 24 modules as shown in Fig. 4(b), and the electrical tests were performed to evaluate the performance on surface by using the same readout system as the real detector. The installation of the IFT in the FASER site was done in December 2021 (Fig. 4(c)).

The commissioning of the scintillator veto system and IFT was performed with other FASER sub-systems by using cosmic rays and pp collision events during the LHC commissioning for LHC Run 3. Figure 5 (left) shows an event display of high energy muons originated from pp collisions at the ATLAS experiment, that was obtained during the commissioning. Hits by two muons are seen on the scintillator veto station, IFT and FASER tracking spectrometer. This shows that data are taken with synchronization of all FASER sub-detectors. Figure 5 (right) shows the simulated CC interactions of ν_e and ν_μ in the emulsion detector, that are expected to be observed in the event reconstruction after extracting the emulsion films.

6. Summary and conclusion

The FASERν is a detector dedicated for neutrino measurements in FASER, consisting of a front scintillator veto system, the emulsion detector and the IFT. FASERν will measure cross-sections of CC interactions of all neutrino flavors at TeV region, where this is the first time to measure that of ν_τ directly. The detector was successfully constructed and commissioned before starting the physics

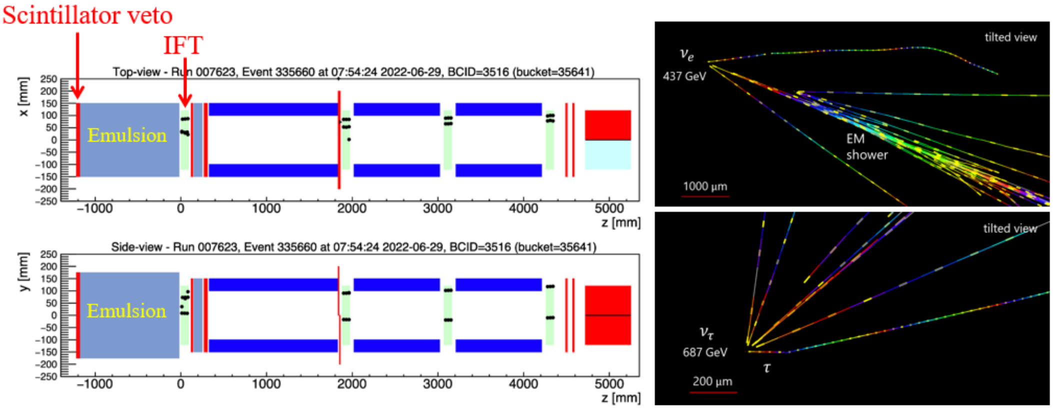

Figure 5: Event display of high energy muons originated from pp collisions (left) and simulated CC interactions of ν_e and ν_μ in the emulsion detector (right).

data-taking in 2022. The FASERν will collect more than 150 fb^{-1} of data during LHC Run 3. The emulsion films will be replaced eleven times every 30-50 fb^{-1} until the end of the data-taking in 2025.

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