PROCEEDINGS OF SCIENCE

First results of LHC neutrinos with FASERν

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FASER is aiming to detect neutral Beyond Standard Model particles and neutrinos from LHC ATLAS p-p collision point. Studies of hadron production with high-energy proton beams have been basic inputs to understand the cosmic-ray spectra observed on the earth. While the Ultra-High-Energy Cosmic Ray (UHECR) studies gave discrepancy in number of muons or cosmic ray composition from expectation and it have been a hot topics in the field and called Muon Puzzle. The FASER detector located at 480 m away in the forward direction of 14 TeV p-p collision point. As it corresponds to 100 PeV proton interactions in fixed target mode, a precise measurement by FASER would provide information relevant to PeV-scale cosmic rays. Study with three flavours neutrinos with the dedicated neutrino detector (FASERν) would shed light on the unresolved Muon Puzzle. FASER has started taking data in Run 3 of the LHC operation (2022-2025). Here the first results on neutrino analysis from the 2022 run and its prospects are reported.

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1. Introduction

FASER experiment is aiming to detect neutral particles from LHC ATLAS collision point (see Figure1 and [1]). One of the physics target is Beyond the Standard Model (BSM) particles such like dark photons or axion like particles who may decay in the decay volume in FASER detector. Another target is Standard Model (SM) particles, high energy and unexplored energy region neutrinos at several 100 GeV to several TeV.

At the LHC collision point, large detectors, ATLAS / CMS / LHCb analyse large transverse momentum events and small transverse momentum events are not analysed. The LHC p-p collision centre of mass energy 14 TeV would be equivalent to 100 PeV proton interaction at fixed target. The energy of 100 PeV proton interaction is smaller than the energy region where muon puzzle is reported at UHECR ($10^9 \leq$ E/GeV $\leq 10^{11}$), while it is a approaching or entrance energy region to the puzzle. Neutrino analysis in FASER or extended FASER would give a hint on the puzzle [2]. Mesons produced into forward direction at the collision point will decay into neutrinos. Three flavours of neutrinos are produced from different composition of their mother mesons, π, K, charms. So through the measurement of three flavours neutrino energy distributions, one can extract information of mother meson production differential cross section at the centre of mass energy of 14 TeV or 100 PeV fixed target proton interactions.

Apart from the possible contribution to UHECR muon puzzle, analysis of three flavour neutrinos will be a test of Lepton Flavour Universality where an anomaly is reported in B meson decays by LHCb or BelleII experiments[3]. The charm production rate in neutrino Charge Current (CC) interactions in three neutrino flavour will be measured for that.

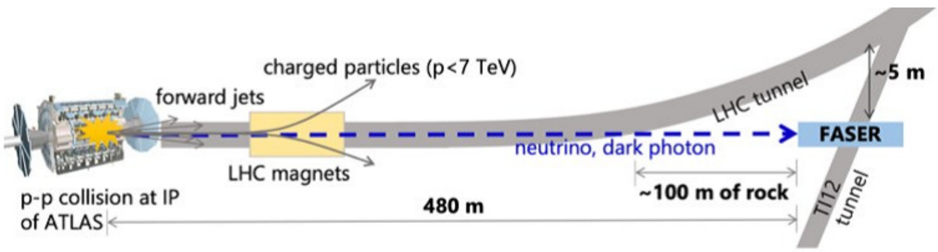

Figure 1: The schematic view of the FASER experiment cite

2. FASER detector

FASER detector is made by two major components (see Figure2). An Emulsion Cloud Chamber (ECC) made by 1.1mm thick tungsten plates and nuclear emulsion films. 730 nuclear emulsion films are interleaved with tungsten plates with 25cm × 30cm cross-section become a 1.1 ton active target. This part is massive target and tracking detector for neutrino interaction products and called as FASERν detector. Spectrometer behind the FASERν detector, three air core magnets with 0.6 T magnetic filed are followed and the air core parts are the decay volume for BSM neutral particles. The length of magnet is about 1m each and a set of silicon stripe detectors (SCTs) and scintillators between magnets will record the tracks and their momentum and the charge will be measured. At the end part of FASER detector is a set of calorimeters to measure the energy of the particle. At

BSM particle analysis, detecting neutral particles decays into two charged particles at the decay volume and the reconstructed mass of the in-coming neutral particle candidates are analysed. The momentum measured by the spectrometer will be also used for neutrino analysis where muons produced at muon neutrino CC interactions and emit from FASERν detector.

Fro the tracking device at FASERν, nuclear emulsion films are adapted. Silver bromide crystals of 200 nm diameter are immersed in gelatine layer by high occupancy and each of the crystals are mini detector to detect charged track. Crystals hit by charged track become a silver metal grains similar size of original crystal after chemical development. So a track is made by a straightly aligned silver grains with such a spatial resolution and recorded as full 3-dimensional track in gelatine binder. Nuclear emulsion layers of 70 μm thick are coated on both side of 200 μm thick plastic base and a connected track between track segments recorded in two emulsion layers will be used as a representative of track recorded in a nuclear emulsion film for further analysis. Thanks to the micro metric resolution and full 3D tracking, the nuclear emulsion films interleaved with metal plate structure, ECC succeeded the first observation of tau neutrinos in DONuT experiment [4]. So FASER can detect tau neutrinos by the ECC technique. However the tau neutrino cross-section or its properties are least studied. It is worth to say that FASER will give results on that too.

So all the three neutrino flavours can be identified using track information stored in ECC as illustrated in Figure3. The electron neutrino case, an electron from neutrino interaction vertex will make electro magnetic shower thanks to a short radiation length X0$\sim$ 3.5mm of tungsten. The muon neutrino case, a muon from neutrino interaction vertex will penetrate the ECC and the spectrometer will measure the muon momentum and its charge. So muon neutrino case, one can distinguish neutrino and anti-neutrino and analyse them separately. The tau neutrino case, a tau particle from neutrino interaction vertex will decay immediately in a short flight of several mm or so. And the decay branching ratio in charged daughter multiplicity is 85% into one charged daughter and 15% into three charged daughters.

The FASERν detectors are exchanged every 20-30 fb^{-1}. So FASERν ECC is counted as a module and three or four modules are exposed to beam per year from 2022 to 2025. The nuclear emulsion are produced at Nagoya University and 730 films per one module corresponding to a total surface of emulsion is about 55m^2.

Neutrino events corresponding to about 80 fb^{-1} LHC p-p collisions are accumulated into five module so far. After a module was exposed to the beam, it is dis-assembled and nuclear emulsion films are photo-chemical developed at CERN emulsion facility. These developed films are sent to Nagoya University, Japan. The films are scanned by automated high speed scanning system HTS [5]. HTS readout all the charged track's position and angle (up to 1 radian) in 60-80 min from a film area of 25cm $\times$ 30 cm. One can make detector alignment of nuclear emulsion films using high density and high energy penetrating tracks and the alignment accuracy reach to 0.2 μm.

3. Neutrino analysis with nuclear emulsion

3.1 Expected number of neutrino interactions

The number of expected neutrino interactions in LHC run3 period , 2022-2025 is estimated. The neutrino energy reconstruction resolution is estimated by Monte Carlo simulation as about

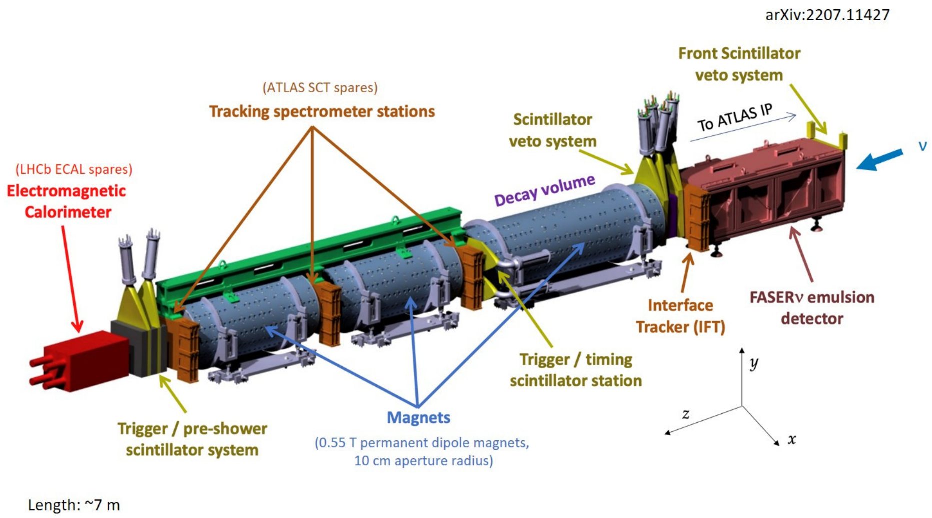

Figure 2: The schematic view of the FASER detector

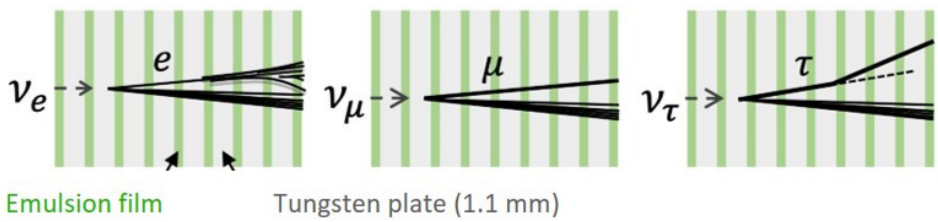

Figure 3: The schematic view of ECC

30%. It is summarized in table 1 since some difference in expectation are seen among used hadron generators. Looking at the table1, the differences are larger in the expectation for tau neutrinos and electron neutrinos, where the charm mesons and K mesons will be the main source of them (see Figure4 and [6]). It is a remarkable feature that tau neutrino case only charm meson can be their mother. The deviation is smaller in the muon neutrino case where especially π and then K contribution is larger. Higher energy spectrum from K mesons in muon neutrino than electron neutrino is expected. And the contribution of mother meson ratio or value of charm contribution differ among the hadron generators. So the difference among generators can be tested by the results from FASER three flavour neutrino analysis.

Table 1: Expected number of CC interactions (250fb^{-1}) base on PhysRevD.104.113008

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu_e}$	$\nu_\mu + \bar{\nu_\mu}$	$\nu_\tau + \bar{\nu_\tau}$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Phythia8 (Hard)	2521	9841	57
QGSJET	Phythia8 (Soft)	1616	8918	26.8
Combination (all)		$2850\,^{+2910}_{-1348}$	$9636\,^{+2176}_{-1663}$	$67.5\,^{-94}_{-43}$
Combination (w/o DPMJET)		$1880\,^{+641}_{-378}$	$8910\,^{+930}_{-938}$	$36\,^{-20.8}_{-11.5}$

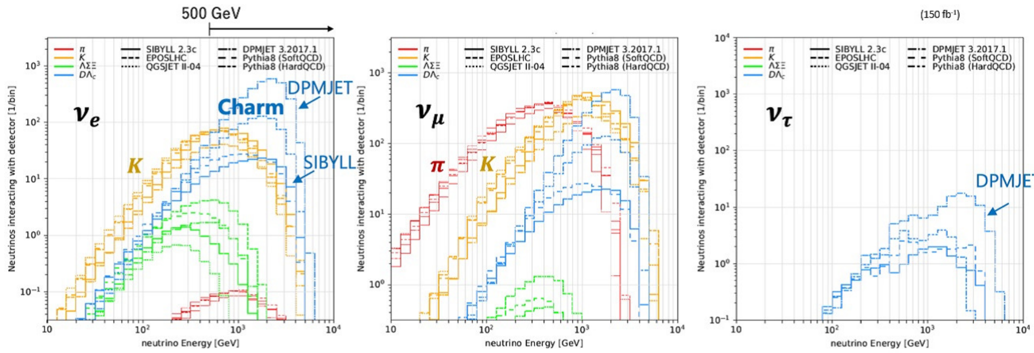

Figure 4: Expected energy spectra of neutrino interactions with mother meson information.

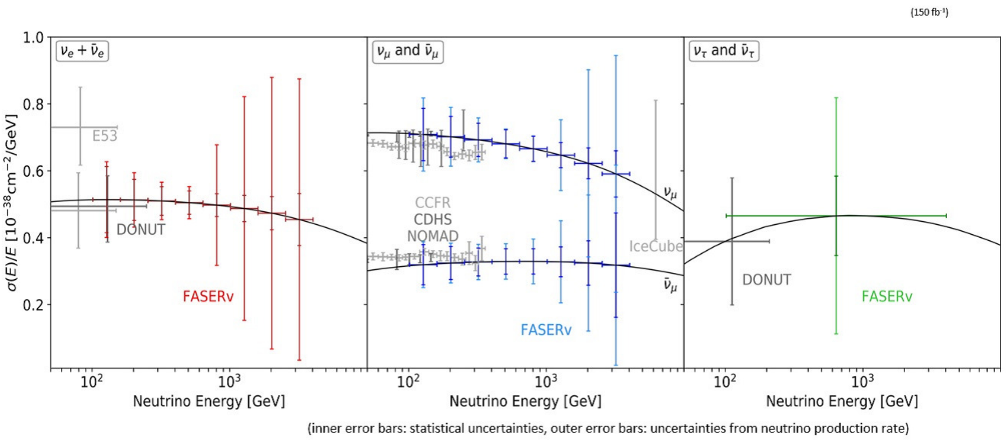

Figure 5: Expected result on neutrino cross-section accuracy.

3.2 ECC analysis status

Now the analysis on a subsample of FASERν ECCs exposed in 2022 is on going. There are several neutrino candidates found in the ECC. Figure 6 is an example of an electron neutrino candidate's event viewer where an electron track emit from a vertex at a tungsten and development of electro-magnetic shower is seen in downstream. Other tracks from the vertex emit in the opposite direction in ϕ from beam direction and it is nature of neutrino CC interaction. The energy of neutrino events are analysed to measure momentum of all the charged tracks by detecting the size of Multiple Coulomb Scattering. For electron case, electron energy can be estimated by electro-magnetic shower growth shape and number of track segments count. Muon case we can use momentum and charge measured by the spectrometer. For tau neutrino case momentum of tau daughter and other tracks from neutrino vertex will be measured and reconstruct event energy. So far, the number of analysed films is limited by first 255 out of 730 plates and muon identification purity is not satisfactory yet. A much better purity about hadron and muon separation can be achieved with a full set of 730 nuclear emulsion films information. Even though we have several muon neutrino CC interaction candidate and also some neutral current neutrino interaction candidate so far. The analysis will be summarized soon. The processing to combine a muon track in ECC and electronic detector will be done and neutrino and anti-neutrino will be analysed separately.

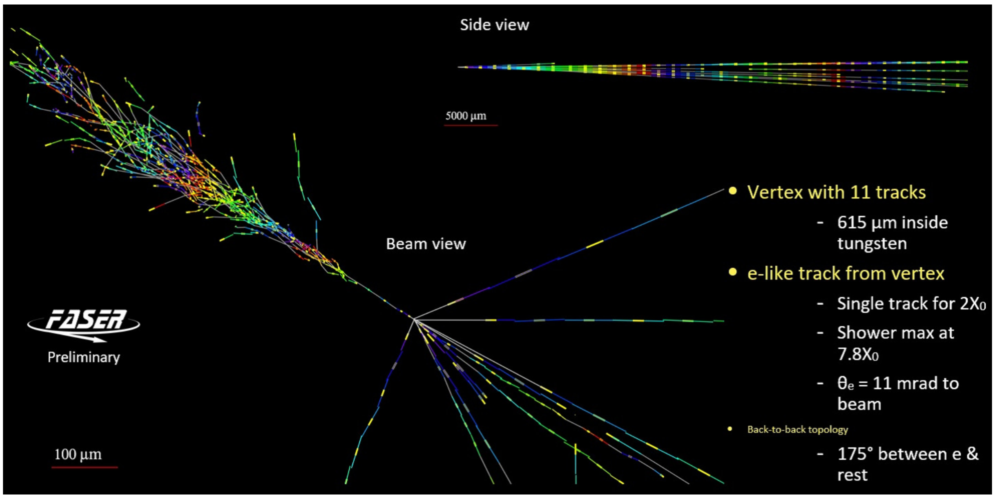

Figure 6: An electron neutrino interaction detected in 2022 2nd module

4. Neutrino interaction analysis by the electronic detector

The neutrino analysis is currently on-going by FASERν detector where three neutrino flavour analysis is available. On the other hand, a muon will penetrate the interacted FASERν detector and one can detect muon by electronic detector alone. So a sub sample of a data recorded in 2022 were analysed to detect neutrino interactions by electronic detector.

The beam exposure operations in LHC run3 is going well and the first year 2022 FASER detector recorded 37.0 fb^{-1} corresponding to 96% of delivered luminosity. The operation in 2023 went well too and more than 30 fb^{-1} of data are recorded so far. The neutrino interaction analysis using only electronic detector is advanced.

Here the results from the analysis using good data quality 35.4 fb^{-1} in 2022 are presented. The strategy is that neutrino interactions with 1.1 ton FASERν detector with a long track, ie. muons are reconstructed by the spectrometer. And the main event selection to enhance neutrino events is followings. No activity in FASERν scintillator station and activity corresponding to more or equal to one MIP energy deposition in two scintillator stations on front and on back of the first spectrometer magnet is required and the timing and pre-shower counter consistent with more or equal to one MIP. The track reconstructed in the spectrometer should be well inside of fiducial volume in radius from the centre of magnet r less than 95mm. The reconstructed momentum should be larger than 100 GeV/c and its angle respect to beam centre should be smaller than 25 mrad. By this condition with GENIE simulation gave the expected number of events as 151 ± 41 events. The uncertainty come from mainly by the difference between the expectation from DPMJET and SIBYLL generators.

A total of 153 events are observed by opening blind analysis [7]. This corresponding to event significance of 16 σ. The observed number of events and event features such like muon momentum distribution etc. (see Figure9) are well consistent with expectation. It is about 14% of statistics and then more accurate analysis will be done in near future. And the three neutrino flavour analysis in FASERν combined with muon momentum will come soon.

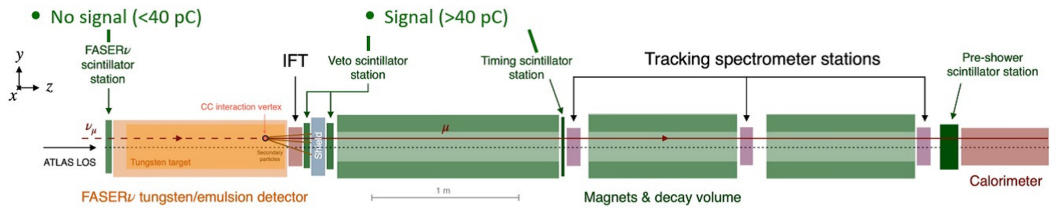

Figure 7: Neutrino event search by the electronic detector information.

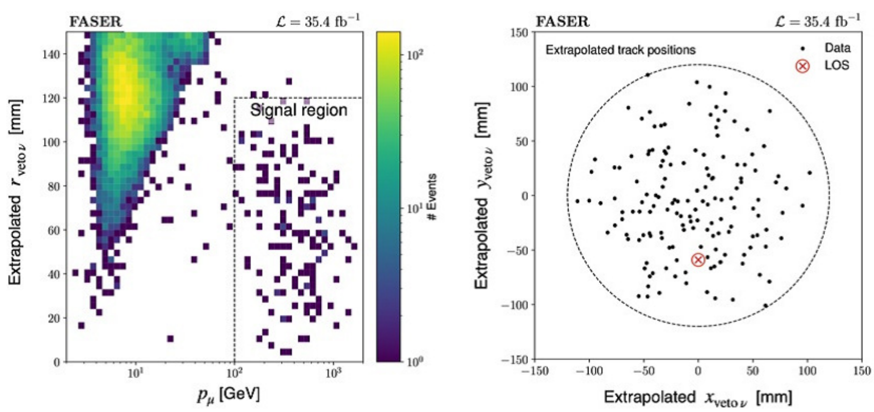

Figure 8: Result of neutrino event search with only electronic detector

5. Summary and Future

FASER is aiming to detect neutral particles products from 480m away from LHC p-p collision. One of the target neutral particle is BSM particles such like dark photon or axion like particles who decay into two particles at the decay volume of FASER detector. Another target is high energy neutrinos whose energy region from a few hundred GeV to a few TeV is unexplored yet. The FASER detectors are exposed to the beam from p-p collisions during 2022 to 2025 of LHC run3 period.

Here the neutrino interaction analysis part and its results are presented. Thanks to the micro-metric spatial resolution and full three dimensional tracking capability, nuclear emulsion films

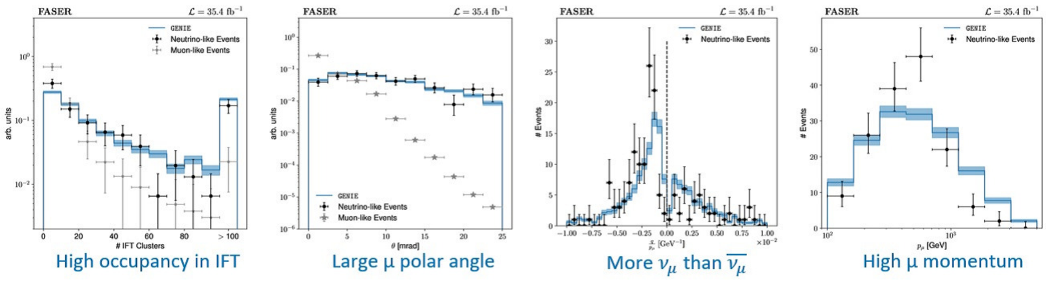

Figure 9: The event properties of neutrino event candidates

interleaved with tungsten target plates ECC are able to detect and identify three type of neutrino flavours. The expected number of neutrino interactions in LHC run3 period is about 10,000 events. The neutral lepton, ie. neutrino flavour universality test sensitivity with three flavours is limited due to small statistics especially in number of tau neutrino events. High luminosity LHC will start after LHC run3 shutdown and it is good occasion to extend FASER analysis with upgrade detector. The new experimental site of Forward Physics Facility [8] is discussing and upgraded and enlarged FASER like detector is under considered. A total of 20 tons of the neutrino interaction target mass will collect a total of 2,300 (SIBYLL) or 20,000 (DPMJET) tau neutrino events. It will give a few percent accuracy test for the lepton flavour universality and also such accuracy of knowledge on mother meson components will be available.

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