PROCEEDINGS OF SCIENCE

Overview of neutrino studies at FASER

Daniela Koeck on behalf of the FASER Collaboration[a,*]

[a] *University of Oregon, Department of Physics, Eugene, Oregon*

E-mail: dkoeck@cern.ch

This contribution discusses the first neutrino studies performed with the FASER experiment. This includes the first neutrino observation from colliders with the electronic components of the FASER detector, as well as the first electron neutrino observation from colliders using FASER's emulsion detector, FASERν. Both analyses are based on proton-proton collision data collected in 2022, the first year of FASER operation.

12th Edition of the Large Hadron Collider Physics conference,
3rd-7th June 2024
Northeastern University, Boston, USA

*Speaker

PoS(LHCP2024)055

1. Introduction

FASER [1–4] is an experiment designed to detect long-lived, weakly interacting particles produced in proton-proton collisions delivered by the LHC inside of ATLAS. Such long-lived, weakly interacting particles can either be long-lived new particles discussed in a separate conference contribution, or Standard Model neutrinos, discussed here in more detail.

The FASER detector is installed in the Tl12 transfer line tunnel previously connecting the SPS and the LEP accelerators at CERN. Its located about 480 meters from IP1, the LHC interaction point housing the ATLAS experiment. The detector is aligned with the collision axis line of sight (LOS). FASER is composed of an emulsion detector, FASERν [5], consisting of 730 layers of interleaved emulsion and tungsten layers, adding up to 8 interaction lengths of material. Infront of this emulsion box towards IP1 are two scintillator planes, referred to as the FASERν (veto) scintillator station. Following the dedicated neutrino detector emulsion films are the electronic components of FASER. An interface tracker (IFT) and veto scintillator system located downstream of FASERν preface the decay volume, surrounded by a 0.57 T permanent dipole magnet. Timing scintillators after the decay volume are followed by two additional magnets, with three SCT tracking stations in between. Furthermost downstream the detector is a pre-sower scintillator system as well as four electromagnetic calorimeter modules. FASER has been taking data since July 2022 and collected around 35 fb^{-1} at the time of this conference contribution. Studying neutrinos produced in proton-proton collisions opens a window into exploring TeV energy neutrinos and probing forward-hadron productions. These forward hadron productions provide input into QCD calculations and simulations, mainly for light or charm hadron decays into neutrinos. FASER offers two ways of measuring collider neutrinos, through the dedicated neutrino part, FASERν or with the electronic components of FASER. Both methodologies and first results will be discussed in the following.

2. First collider neutrino observation with FASER's electronic components

FASER's first analysis of neutrinos produced in proton-proton collisions has been performed using the electronic components of the FASER detector. This analysis presents the first observation of collider neutrinos and is published as Ref. [6], based on data collected between July and November 2022. The FASERν emulsion and tungsten films serve as 1.1 t target for muon neutrino interactions. An event selection (illustrated in Fig. 1) requires a muon track crossing FASER with a location extrapolated back to be within the veto scintillator systems volume. No activity in the FASERν scintillator station, but increased activity in the IFT, from secondary particles in the charged current neutrino interaction. The timing and pre-shower scintillator stations show signals in the scintillator equivalent to a traversing muon.

Within the analysed dataset; a total of $n_{\nu}^{exp} = 151 \pm 41$ muon neutrino events are expected. Backgrounds that could lead to a similar detector signature include neutral hadrons interacting in the FASER*nu* material; potentially leading to muons from neutral hadron interactions entering the electronic detector components. This background is estimated through simulation to make up 0.11 ± 0.06 events in the dataset and is significantly reduced through most neutral hadrons being absorbed within the material. Muons from IP1 could pass the Vetoν scintillator veto requirement through an inefficiency of the Vetoν scintillators or by entering FASER through a large angle,

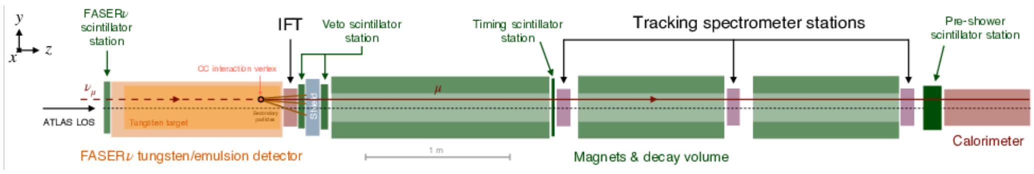

Figure 1: Signature of a muon neutrino interacting in the FASERν emulsion films with the produced muon crossing the electronic components of FASER. [6]

geometrically missing the scintillators. The former background is negligible due to the very high scintillator efficiencies. The later, large-angle muon background, was estimated in control regions to be 0.08 ± 1.83. All events passing the signal region selections are entered into a likelihood, classifying the events to be signal like or background like. This results in $n_\nu = 153^{+12}_{-13}$(tot) observed neutrino events, leading to a signal significance of 16σ over the expected background. Based on the reconstructed muon track and its curvature in the FASER magnet, the charge and momentum of the muon can be reconstructed. This in turn can be compared to simulations of neutrino interactions and the consecutive expected muon momentum and charge. The observed events and their charge to momentum ratio is compared to `GENIE` simulation in Fig. 2. Through the muon charge, neutrino and anti-neutrino interactions can be distinguished, showing 40 anti-neutrino interactions as positively charged muon tracks. Also shown in Fig. 2 are events in a muon momentum and radial extrapolated position plane, highlighting the background events missing the veto scintillator stations through large angles and not entering the signal region selections.

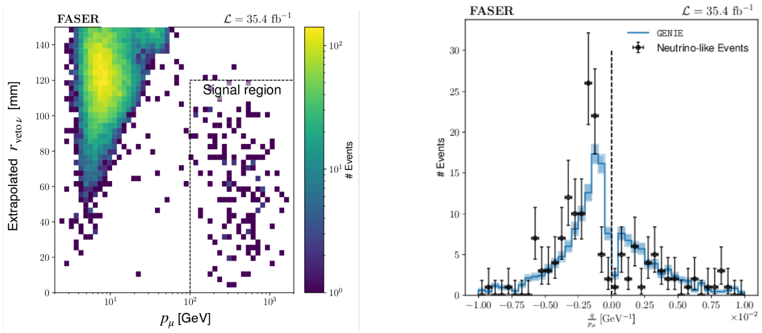

Figure 2: Visualisation of the signal region selections and measured momentum over charge ratio of the signal region events observed in the electronic components of FASER in comparison to *GENIE* simulations of neutrino interactions [6].

3. First collider electron neutrino measurements with FASERν emulsion films

Measurements of neutrino interactions with the electronic components of FASER are restricted to muon neutrino interactions, whereas an analysis of the FASERν emulsion films can reconstruct and distinguish electron, muon and tau neutrinos. Since the FASERν emulsion films are not within a magnetic field, no separation of neutrinos and anti-neutrinos (through the leptons created in charged current interactions) is possible. A first analysis of parts of the emulsion films installed

PoS(LHCP2024)055

between July 26th and September 13th 2022 with a total target mass of 128.6kg has led to the first observation of electron neutrinos from a collider [7]. After the development and scanning of the emulsion films in detail described in [7]; neural vertices in the emulsion are selected. These neutral vertices should have no incoming track, boosted outgoing tracks with leptons well separated from other tracks. Muon tracks are required to cross over 100 tungsten plates. The momentum of outgoing muons is measured through multiple Coloumb scatterings in the emulsion films, whereas the electron energy is measured through the segments associated with the electromagnetic shower. Neutral vertices require a muon momentum of over 200 GeV and electron energy of over 200 GeV. Potential backgrounds emulating charged current neutrino events can happen through neutral hadron interactions or neutral current events, both estimated through Monte Carlo simulation. An overall background of 0.025 ± 0.015 from neutral hadrons mimicking electron neutrino interaction vertices and 0.22 ± 0.09 from neutral hadrons or neutral current interactions mimicking muon neutrino charged current vertices is expected within the analyses dataset. Four electron neutrino events and eight muon neutrino events have been observed, leading to a significance of 5.2σ and 5.7σ respectively over the background expectation.

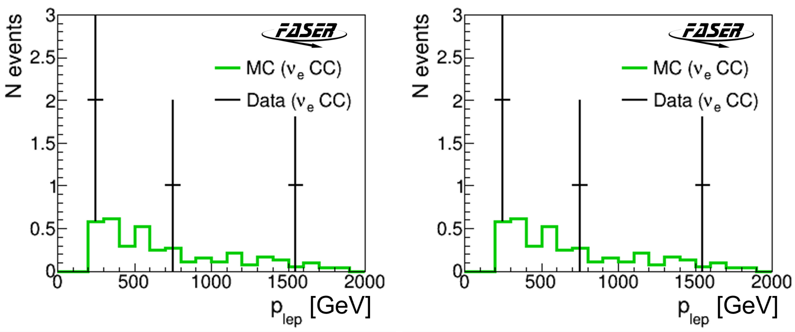

Figure 3: Observed electron and muon momentum connected with selected neutral vertices compared with MC simulation of neutrino interactions [7]

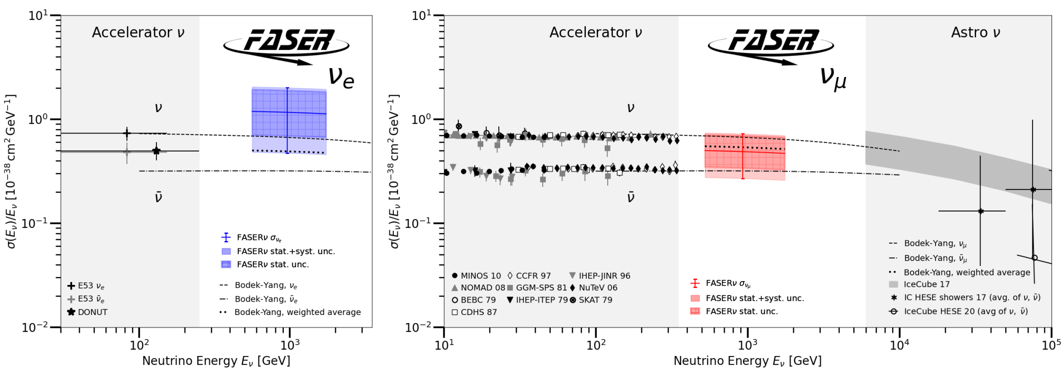

Figure 4: Measurement of the electron and muon neutrino cross section with FASERν events. Also shown are previous measurements from beam-dump experiments and astronomical neutrinos [7].

The kinematic properties of the observed events can be studied, such as the momentum distribution of the outgoing electron or muon as shown in Fig. 3. This offers an indirect measurement

PoS(LHCP2024)055

of the incoming neutrino energy. With the observed neutrino interaction vertices, a measurement of the electron and muon neutrino interaction cross section can be performed at unprecedented energies. The measurement is performed separately for electron and muon neutrinos, using a single energy bin containing 68% of reconstructed neutrinos. This reflects a range from 560–1740 GeV for ν_e and 520–1760 GeV for ν_μ. The measured cross section is highlighted in Fig. 4.

Also displayed are previous measurements, constrained by the accelerator beam momentum towards higher energies for electron and muon neutrinos. For muon neutrinos measurements of neutrinos from astronomical origins are also shown. This highlights the unique energy range of neutrinos FASER is able to probe.

4. Conclusion and Further prospects

This contribution has presented two latest observations of collider neutrinos by the FASER experiment, among this a first cross section measurement of neutrinos from colliders. The results presented here showcase the capabilities of the FASER detector to study collider neutrinos at unprecedented energies and mark only the beginning of the exploration of collider neutrinos with the FASER experiment. The analysed data leading to the two breakthrough observations described only include the first year of data-taking with the electronic FASER detector components and only a fraction of the recorded emulsion data.

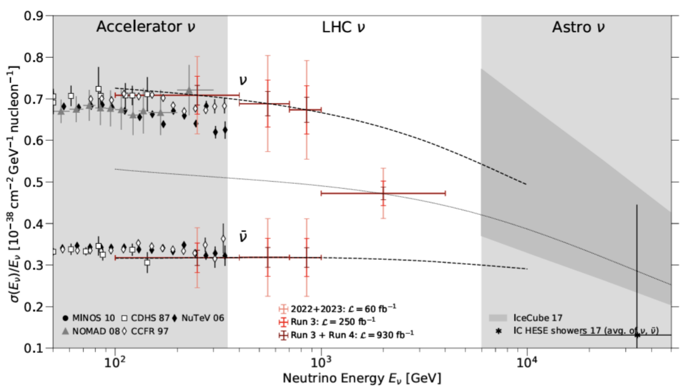

Figure 5: Projection of the muon neutrino interaction cross section measurements and its anticipated statistical uncertainty with the electronic components of FASER in 2022 and 2023 data; full Run-3 expected luminosity and Run 3 and 4 combined projected luminosity [8].

Fig. 5 showcases the vast potential for neutrino cross section measurements still open for FASER, here only considering the electronic detector component analysis. FASER has recently been approved to operate during LHC Run-4, with projections of integrated Luminosity collected with FASER reaching over 900 fb^{-1}. This offers a multitude of possibilities for FASER to study highly energetic, TeV-level neutrinos with increasing precision.

5. Acknowledgements

We thank CERN for the excellent performance of the LHC and the technical and administrative staff members at all FASER institutions for their contributions to the success of the FASER experiment. This work was supported in part by Heising-Simons Foundation Grant Nos. 2018-1135, 2019-1179, and 2020-1840, Simons Foundation Grant No. 623683, U.S. National Science Foundation Grant Nos. PHY-2111427, PHY-2110929, and PHY-2110648, JSPS KAKENHI Grant Nos. 19H01909, 22H01233, 20K23373, 23H00103, 20H01919, and 21H00082, the joint research program of the Institute of Materials and Systems for Sustainability, ERC Consolidator Grant No. 101002690, BMBF Grant No. 05H20PDRC1, DFG EXC 2121 Quantum Universe Grant No. 390833306, Royal Society Grant No. URF\R1\201519, UK Science and Technology Funding Councils Grant No. ST/ T505870/1, the National Natural Science Foundation of China, Tsinghua University Initiative Scientific Research Program, and the Swiss National Science Foundation.

References

[1] J. L. Feng, I. Galon, F. Kling, and S. Trojanowski, "ForwArd Search ExpeRiment at the LHC," *Phys. Rev. D* **97** (2018) no. 3, 035001, arXiv:1708.09389 [hep-ph].

[2] **FASER** Collaboration, "Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC," arXiv:1812.09139 [physics.ins-det].

[3] **FASER** Collaboration, "Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC," arXiv:1811.10243 [physics.ins-det].

[4] **FASER** Collaboration, "The FASER detector," *JINST* **19** (2024) no. 05, P05066, arXiv:2207.11427 [physics.ins-det].

[5] **FASER** Collaboration, "Technical Proposal: FASERnu," arXiv:2001.03073 [physics.ins-det].

[6] **FASER** Collaboration, "First Direct Observation of Collider Neutrinos with FASER at the LHC," *Phys. Rev. Lett.* **131** (2023) no. 3, 031801, arXiv:2303.14185 [hep-ex].

[7] **FASER** Collaboration, "First Measurement of ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector," *Phys. Rev. Lett.* **133** (2024) no. 2, 021802, arXiv:2403.12520 [hep-ex].

[8] J. Boyd and J. L. Feng, "Request to run FASER in Run 4," Tech. Rep. CERN-LHCC-2023-009, LHCC-I-039, CERN, Geneva, 2023. https://cds.cern.ch/record/2882503.