PROCEEDINGS OF SCIENCE

Neutrinos at the LHC - Results from FASER

Jeremy Atkinson[a,*] **on behalf of the FASER Collaboration**

[a] *Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*

E-mail: jeremy.atkinson@unibe.ch

The goal of FASER, the ForwArd Search ExpeRiment, at the CERN LHC, is to investigate light, weakly-interacting particles. Aligned with the collision axis line-of-sight of the ATLAS interaction point, it is located 480 m downstream, and covers the previously unexplored pseudorapidity range of $\eta > 8.8$. Sitting in front of the main electronic detector, the passive FASERν neutrino detector focuses on high-energy collider neutrino interactions in the TeV regime, extending current cross-section measurements. The FASER collaboration announced in August 2023 the first direct observation of electron neutrino interactions in a particle collider experiment, using only a sub-volume of data collected so far with the FASERν detector. Made up of alternating emulsion films and tungsten plates, it has a target mass of 1.1 tonnes. Sub-micron position resolution is achieved, allowing for all three neutrino flavours to be distinguished by their vertex topology in charged current interactions. FASER plans to run throughout the LHC Run 3, collecting 250 fb^{-1} of data. By probing forward hadron production and deep inelastic scattering of high-energy neutrinos, FASER results will provide important insights in QCD. In this presentation, recent FASERν results, as well as the status of data taking and analysis, will be presented.

ArXiv ePrint: 2403.12520

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

PoS(DIS2024)056

1. The ForwArd Search ExpeRiment

The ForwArd Search ExpeRiment, FASER, is a small experiment located at the LHC at CERN, taking data throughout the LHC Run 3 (2022 - 2025). It's primary goal is to investigated light, long-lived, weakly-interaction particles and study collider neutrinos in the currently unexplored TeV regime.

At the ATLAS interaction point (IP1), proton-proton collisions with a center-of-mass energy of 13.6 TeV produce a multitude of hadrons in the far-forward region. Many of these decay producing neutrinos of all three flavours, resulting in a highly-collimated neutrino beam. FASER is located 480 meters away from IP1 in TI12, an unused service tunnel coming off the main LHC tunnel, covering the $\eta > 8.8$ pseudorapidity range. This is an ideal location for both neutrino studies and BSM searches due to its large background suppression - the majority of charged particles are swept away by the LHC magnets, and 100 meters of rock and concrete between where the LHC tunnel turns and the position of FASER absorbs most surviving particles. The only particles reaching FASER from the LHC are therefore neutrinos, high energy muons, and potential BSM candidates.

The detector is compact, comparatively cheap and was rapidly approved and assembled, from a proposal in 2018 to taking data in 2022. It is composed both by spare parts from other experiments as well as new dedicated components. Sitting in front of the main electronic detector components, the FASERν detector is a passive emulsion-tungsten neutrino detector.

FASER can observe neutrinos using two complementary methods, the first of which is the dedicated FASERν detector mentioned above. The second is using the electronic components of the main FASER detector to observe muon neutrinos - this method led to the first direct observation of ν_μ CC interactions at the LHC [1].

To maximise both the number and energy of neutrino interactions of all three flavours, the detector is aligned with the collision axis light-of-sight (LoS). Throughout the LHC Run 3, equivalent to 250 fb^{-1}, the expected numbers of neutrinos interacting with the FASERν detector are $\nu_e \sim 1700$, $\nu_\mu \sim 8500$, and $\nu_\tau \sim 30$. More details on the neutrino flux can be found in [2]. FASER's strong neutrino programme makes it the first collider neutrino experiment.

2. The FASERν detector

The FASERν detector is made up of 730 alternating FASERν emulsion films and 1.1 mm thick tungsten plates (both of dimensions of 25×30 cm^2). This results in a target mass of 1.1 tonnes and a length of 1.1 meters, equivalent to 220 X_0 and 8 λ. To keep track occupancy in emulsion below 10^6 cm^{-2}, 3 modules are irradiated each year, collecting approximately 20 fb^{-1} each. The temperature of the module is kept constant at the 0.1°C level with a dedicated cooling system, and the entire module position can be adjusted to compensate for the changing ATLAS IP crossing angle.

The advantage of using emulsion for a neutrino detector is its ability to flavour tag events using topological and kinematic variables: for a ν_e CC interaction, the daughter electron produces a very clear electromagnetic shower; in a ν_μ CC interaction, a high-energy daughter muon leaves the interaction vertex; for a ν_τ CC interaction, the daughter tau will travel a distance of order 1 cm before decaying, leaving a clear kink in the track.

2.1 The FASERν process

Emulsion films used in FASERν are produced in Nagoya University, Japan, at a dedicated facility, and to improve the film quality, a resetting procedure is conducted either at Nagoya University or at Kyushu University, Japan, before being shipped to CERN. The Emulsion Facility (EF) at CERN is shared among the FASER, DsTau/NA65, SND@LHC and SHiP Collaborations. Here 73 FASERν sub-modules are assembled, each containing 10 emulsion films and 10 tungsten plates, and are installed into the main module ready for irradiation in TI12. After irradiation, the module is disassembled in the EF, and the films are labelled and chemically developed. Surface silver on the developed films must be removed before scanning using the Hyper-Track Selector (HTS) in Nagoya University, a high-resolution digital microscope, which scans each film to extract track data. A-Film alignment, track reconstruction, vertex reconstruction and event selection follow, readying the data for the final analysis.

2.2 FASERν Performance and Kinematic Measurements

Performance

Position resolution in FASERν is determined using the position displacement between a hit in the emulsion and the linear fit of a track using two films on either side. A hit resolution of 300 nm has been achieved after dedicated film alignment using high-momentum muon tracks ($O(10^5)$ tracks/cm^2). From this, for a track of length of approximately 1 cm, the angular resolution can be calculated to be around 0.04 mrad. Investigating background muons reaching FASER, the angular spread of muon peaks is about 0.4 mrad.

Momentum measurement and EM shower energy reconstruction

In emulsion, particle momenta can calculated using Multiple Coulomb Scattering (MCS) via various methods; in light of the TeV-scale momenta of particles in FASERν, the Coordinate Method is used, which works well even above 1 TeV. The current resolution for the muon momentum measurement is $\Delta P^{RMS}/P \approx 0.3$ at 200 GeV.

Electromagnetic shower reconstruction is critical in FASERν for ν_e identification. Due to the short radiation length of tungsten (3.5 mm), EM showers develop within approximately 5 cm. The energy of an EM shower is proportional to the track multiplicity of the shower, and therefore this can be used to estimate the energy of the daughter electron. The current resolution for EM shower energy reconstruction is $\Delta E/E \approx 0.25$ at 200 GeV.

3. Results from FASERν

The first analysis of the FASERν emulsion detector [3] was conducted on a sub-volume of the second module in 2022. As shown in Figure 3, the two zones nearest to the LoS, using 291 emulsion films and tungsten plates as a target, were analysed, corresponding to a target mass of 128.6 kg and an integrated luminosity of 9.5 fb^{-1}. 7 films upstream of the analysed volume were used to check for the absence of charged parent tracks, and 100 films downstream were analysed to measure the momentum or energy of the particle tracks.

The selection criteria for ν_e and ν_μ CC events is defined as follows: vertex reconstruction requires $N_{track} \geq 5$ and $N_{\tan\theta \leq 0.1} \geq 4$; the lepton requirements are E_e or $p_\mu > 200$ GeV and

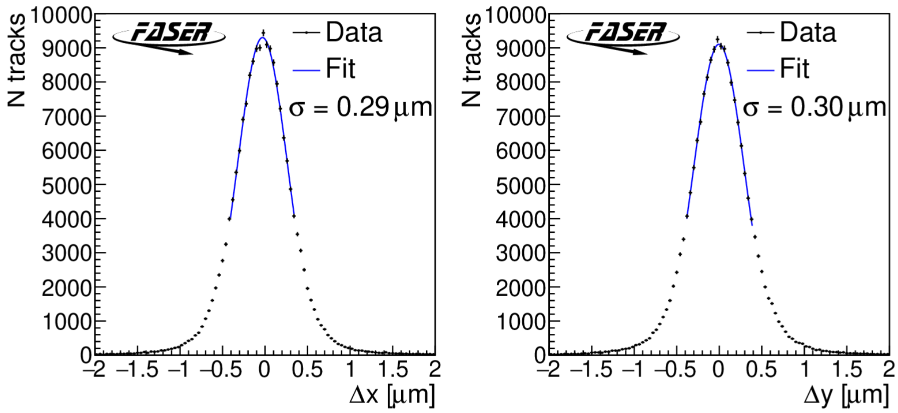

Figure 1: Distributions of the position deviation of the track hits with respect to a linear-fit line for the reconstructed tracks, measured in a typical sub-volume of the FASERν data.

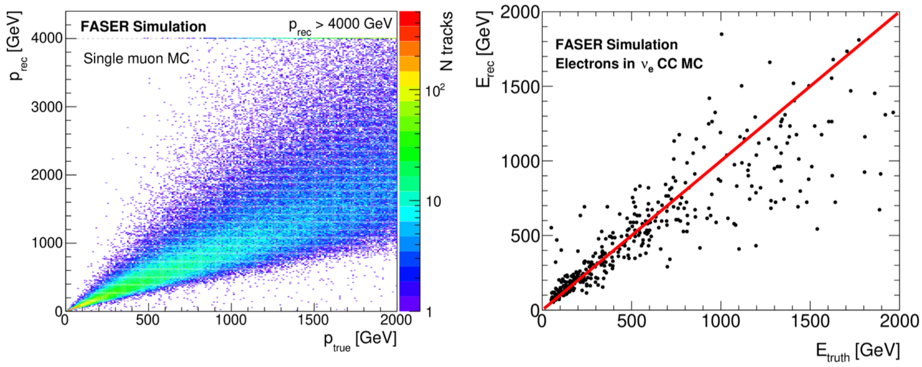

Figure 2: *Left:* Reconstructed momenta versus true momenta in simulated muon tracks with a flat momentum distribution from 1 to 2000 GeV. *Right:* The reconstructed electron energy versus the true energy in ν_e CC MC simulation.

$\tan\theta_e$ or $\tan\theta_\mu > 0.005$; the event must have a back-to-back topology: $\Delta\phi > 90$ deg. The selection efficiencies for ν_e and ν_μ CC events are approximately 30% for a 1 TeV neutrino.

3.1 Neutral Hadron validation study

The dominant backgrounds to the neutrino search in the FASERν detector are neutral hadrons interactions. High energy muons from the IP interact with the rock and concrete before the FASERν module, producing neutral hadrons that travel into the detector. This results in a neutral vertex similar to that from a neutrino, but can be rejected by using topological and kinematic cuts, particularly the momentum and angular cuts on the daughter lepton. Before these cuts are applied, the number of neutral vertices are dominated by neutral hadron interactions (K_S, K_L, n, $\overline{n}$, Λ, $\overline{\Lambda}$). A validation study was conducted using 150 tungsten plates, corresponding to a target mass of 68.2 kg. 246 vertices were expected, and 139 vertices were detected, which lies within the 50% uncertainty.

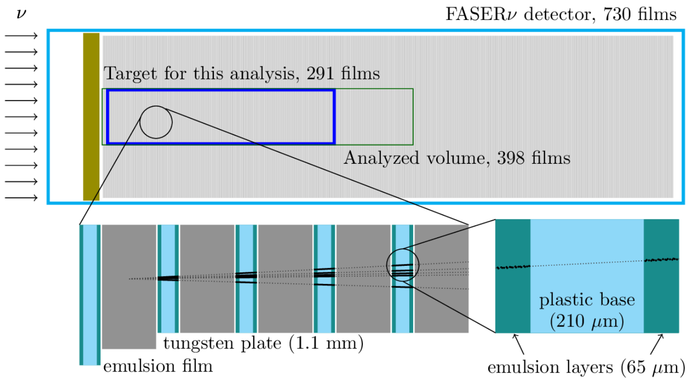

Figure 3: Schematic view of the analysed detector volume (side view). The FASERν box contains a total of 730 emulsion films and is shown in grey. The thin green box outlines the reconstructed volume, and neutrino interactions are searched for within the fiducial volume defined by the blue box.

3.2 Neutrino observation and cross-section measurements

Following the analysis outlined above, 1.1 - 3.3 ν_eCC events were expected, with a background of $0.025^{+0.015}_{-0.010}$, and 6.5 - 12.4 ν_μ CC events were expected, with a background of $0.22^{+0.09}_{-0.07}$. 4 electron neutrino and 8 muon neutrino charged current events were observed, corresponding to a significance of 5.2σ and 5.7σ respectively. This is the first direct observation of electron neutrinos at a particle collider. Out of the 4 ν_e events, the highest reconstructed energy for a daughter electron was 1.5 TeV, making it the highest-energy ν_e interaction observed at accelerator-based experiments. The interaction cross-section per nucleon was measured in single energy bins (560 - 1740 GeV for ν_e and 520 - 1760 GeV for ν_μ) with respect to the theoretical curve. For ν_e, $\sigma_{obs}/E_\nu = (1.2^{+0.8}_{-0.7}) \times 10^{-38}$ cm^2 GeV^{-1}. For ν_μ, $\sigma_{obs}/E_\nu = (0.5 \pm 0.2) \times 10^{-38}$ cm^2 GeV^{-1}. These results are consistent with the Standard Model predictions for the cross-section.

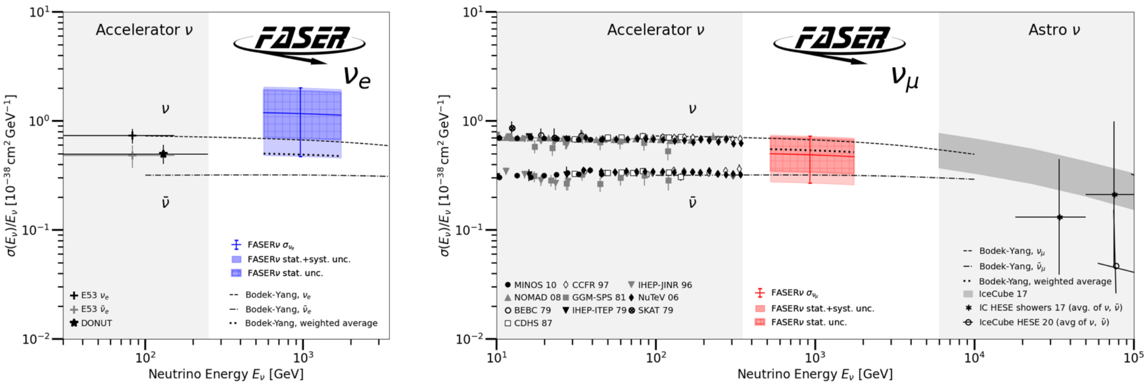

Figure 4: The measured cross section per nucleon for ν_e (*left*) and ν_μ (*right*). The dashed contours labelled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, as implemented in GENIE.

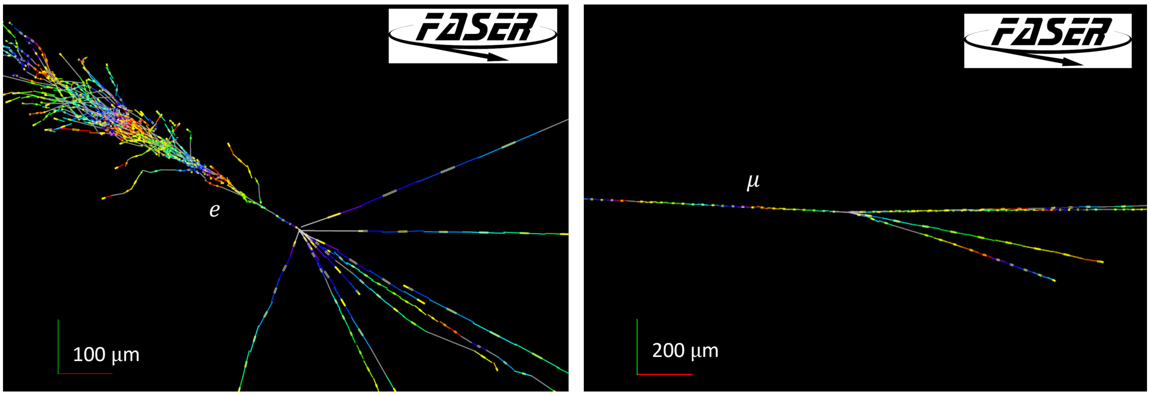

Figure 5: Event displays of one of the ν_e CC candidate events (*left*) and one of the ν_μ CC candidate events (*right*). The views are transverse to the beam direction. The right-handed coordinate axes are shown in the bottom left, with red, green, and blue axes indicating the x (horizontal), y (vertical), and z (beam - not visible) directions, respectively. Yellow line segments show the trajectories of charged particles in the emulsion films. The other coloured lines are interpolations, with the colours indicating the longitudinal depth in the detector.

References

[1] FASER Collaboration et al. *First Direct Observation of Collider Neutrinos with FASER at the LHC*. July 2023. DOI: 10.1103/PhysRevLett.131.031801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.131.031801.

[2] FASER Collaboration et al. *Neutrino rate predictions for FASER*. July 2024. DOI: 10.1103/PhysRevD.110.012009. URL: https://link.aps.org/doi/10.1103/PhysRevD.110.012009.

[3] FASER Collaboration et al. *First Measurement of ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector*. July 2024. DOI: 10.1103/PhysRevLett.133.021802. URL: https://link.aps.org/doi/10.1103/PhysRevLett.133.021802.