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Results from TeV Neutrinos at the FASER Experiment

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FASER, the ForwArd Search ExpeRiment, has successfully taken data at the LHC since the start of Run 3 in 2022. With 2022 data alone, FASER directly detected the first muon and electron neutrinos at the LHC, opening the window on the new subfield of collider neutrino physics. In this paper, we will give a full status update of the FASER and FASERnu experiments and their latest results, with a particular focus on our very first measurements of neutrino cross sections in the TeV-energy range, along with its implications for far forward hadron production.

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1. Introduction

The Forward Search Experiment (FASER) is a small LHC based experiment designed to search for light, weakly interactive particles produced in the far-forward region of pp collisions at the ATLAS interaction point. These particles include the neutrinos of the Standard Model, as well as proposed new particles. The FASER [1] detector is located ~480 m from the ATLAS interaction point along the beam collision axis line-of-sight (LOS). To study high-energy neutrinos, a specialized tungsten/emulsion sub-detector FASERν [2] is used, which is located in front of the FASER spectrometer. With FASERν, charged particle tracks produced by neutrino interactions in the detector can be reconstructed with sub-micron precision. This allows us to identify leptons and measure the energies of electrons and momenta of muons, enabling the identification of electron and muon charged-current (CC) neutrino interactions and the measurement of neutrino interaction cross sections in the currently unexplored TeV energy range. Since neutrinos only interact weakly, they are not affected by the 100 m of rock or by the magnetic fields between the collision point and the detector. These, however, substantially reduce the rate of background particles.

2. The FASERν emulsion detector and the analysed dataset

The FASERν detector (module) is made of 730 layers of interleaved tungsten plates and emulsion films [3], with a total target mass of 1.1 tonnes. The tungsten plates are 1.1 mm thick, and each emulsion film is 0.34 mm thick. The detector is 1.05 m long and has a transverse area with respect to the neutrino beam of 25×30 cm^2. The detector is aligned with the LOS and placed in front of the FASER spectrometer, 480 m away from the pp collision point within the ATLAS experiment (IP1). A more detailed description of the FASERν detector is provided in Ref. [4].

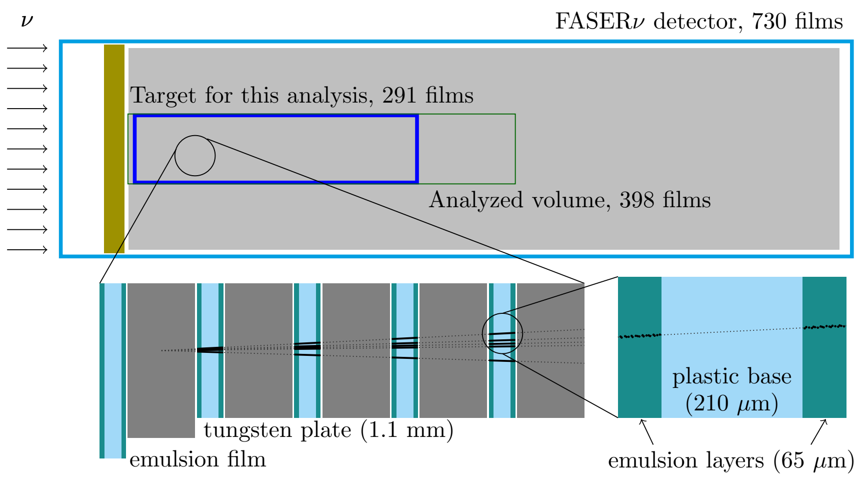

Figure 1: Schematic view of the analysed detector volume (side view). The FASERν box contains a total of 730 emulsion films and is shown in grey. The thin green box outlines the reconstructed volume, and neutrino interactions are searched for within the fiducial volume defined by the blue box.

The analysed dataset was collected between July 26 and September 13, 2022, corresponding to 9.5 fb^{-1} of pp collisions at a centre-of-mass energy of 13.6 TeV. The integrated luminosity is measured by the ATLAS experiment with an uncertainty of 2.2%. For the analysis described here, only 14% of the detector volume, shown in Figure 1, was considered as the target region for neutrino interaction vertices. In the transverse[1] (x-y) plane, a region of 23.4 cm × 9.0 cm was analysed, and in the longitudinal direction, 41.5 cm, including 31.6 cm of tungsten (291 tungsten plates), was considered. The corresponding target mass was 128.6 kg. Data from seven films upstream of the target region were used to check the absence of charged parent tracks. Data from an additional 100 plates immediately downstream of the target region were used to measure the energy or the momentum of the particle tracks. The LOS passed through the centre of the analysed volume in the horizontal plane and about 2 cm from the bottom in the vertical plane.

3. Simulation samples

Monte Carlo (MC) samples for neutrino and background processes were used to define the event selection criteria, to estimate the backgrounds, and to assess systematic uncertainties [5].

The main background contributions arose from neutral hadrons produced in the photo-nuclear interactions of muons within the rock in front of the FASER detector or within the FASERν module material. The muon flux was measured to be $(1.43 \pm 0.07) \times 10^4$ tracks/cm^2/fb^{-1}, as estimated from the reconstructed tracks within an angle of $\Delta\theta$ <10 mrad from the beam direction in the FASERν module. Simulation of the background was done through a multi-step process. First, the energy spectrum of muons was simulated using the `FLUKA` package, which included a detailed model of the LHC infrastructure between IP1 and FASER. `GEANT4` was then used to simulate the interactions of these muons within the rock in front of FASER or in the tungsten of the FASERν detector. Finally, high-statistics samples of the individual neutral-hadron species (K_S, K_L, n, Λ, $\bar{n}$, and $\bar{\Lambda}$) were produced and weighted to follow the expected energy spectra estimated by the previous step.

The simulated events were reconstructed in the same way as the data. Corrections were applied to the simulated samples to reproduce the hit efficiencies, position and angular resolutions of the data. Also the MC samples were normalized to the equivalent luminosity of the data by using the number of observed and simulated muons. The final neutral-hadron samples were equivalent to ~400 times the size of the data.

The total background estimates were $0.025^{+0.015}_{-0.010}$ and $0.22^{+0.09}_{-0.07}$ for the ν_e and ν_μ selections, respectively.

4. Event selection and vertex reconstruction

Candidate ν_e and ν_μ CC interactions were selected based on reconstructed charged particle tracks, forming a neutral vertex in FASERν. The number of neutral hadrons drops quickly with increasing energy. Since neutrinos are more energetic than the neutral-hadron background, the tracks associated to the vertex were boosted in the forward direction. A CC interaction produced a high-energy electron or muon, well separated in azimuthal angle from the other particles associated with the vertex.

[1] A Cartesian coordinate system is used with the z-axis running along the LOS from the ATLAS collision point to FASER, the y-axis pointing vertically upwards, and the x-axis pointing horizontally to the centre of the LHC ring.

Using the reconstructed tracks passing through at least three plates, the vertex reconstruction was performed by searching for converging track patterns with an impact parameter less than 5 μm. Tracks with $\tan\theta \leq 0.5$ were retained, and converging patterns with more than four tracks were selected as vertices. The tracks were required to start within three films downstream of the vertices. The number of tracks with $\tan\theta \leq 0.1$ relative to the beam direction was also required to be greater than three to suppress the neutral-hadron background. Furthermore, the vertices were required to not have a parent track.

4.1 Electron identification and energy measurement

Candidate ν_e CC interactions were selected from the initial set of vertices by requesting an associated high-energy electromagnetic (EM) shower with a reconstructed energy above 200 GeV and $\tan\theta > 0.005$. The latter requirement was used to reduce the neutral-hadron background. It improved the signal-to-noise ratio because leptons from neutrino CC interactions had larger angles, due to higher transverse momenta, than high-energy particles from the neutral hadron background.

EM shower energy reconstruction algorithm is described in Ref. [5]. Its performance was tested for electrons in the ν_e MC simulation, showing a resolution of around 25% at 200 GeV and between 25-40% at higher energies.

4.2 Muon identification and momentum measurement

Candidate ν_μ CC interactions were selected from the initial set of vertices by requiring that one of the reconstructed charged particle tracks associated with the vertex was a muon candidate. Muon candidates were defined as tracks that penetrate more than 100 tungsten plates without exhibiting secondary hadron interactions consisting of at least two daughter tracks. Furthermore, the muon reconstructed momentum p had to be greater than 200 GeV with $\tan\theta > 0.005$. Simulation studies showed that the probability for a charged hadron with $p > 200$ GeV to satisfy the muon candidate requirements was about 20%. The muon candidate track was then required to have an azimuthal angle in the (x-y) plane $\Delta\phi > \pi/2$.

The track momentum was estimated by measuring multiple Coulomb scattering using the so-called coordinate method [6]. The performance of the momentum evaluation algorithm was studied using simulated muon tracks with a flat momentum distribution from 1 to 2000 GeV, including position and angular smearing to account for residual misalignments between the emulsion films. The resolution, as quantified by the RMS of the distribution of the difference between the true and reconstructed momentum, was around 30% at 200 GeV and reached 50% at higher energies.

5. ν_e and ν_μ candidate events

Four events were selected by the ν_e selection on data. The highest reconstructed electron energy from the selected ν_e CC candidates was 1.5 TeV. It was therefore the highest-energy ν_e interaction ever detected by accelerator-based experiments. Eight events were selected by the ν_μ selection on data. The highest reconstructed muon momentum from the selected ν_μ CC candidates was 864 GeV, meaning that the ν_μ sample included neutrinos with energy likely above 1 TeV, far higher than from previous accelerator-based neutrino studies.

The expected number of neutrino signal events satisfying the selections were in the range 1.1–3.3 (for ν_e CC) and 6.5–12.4 (for ν_μ CC). The observed number of interactions was consistent with Standard Model predictions.

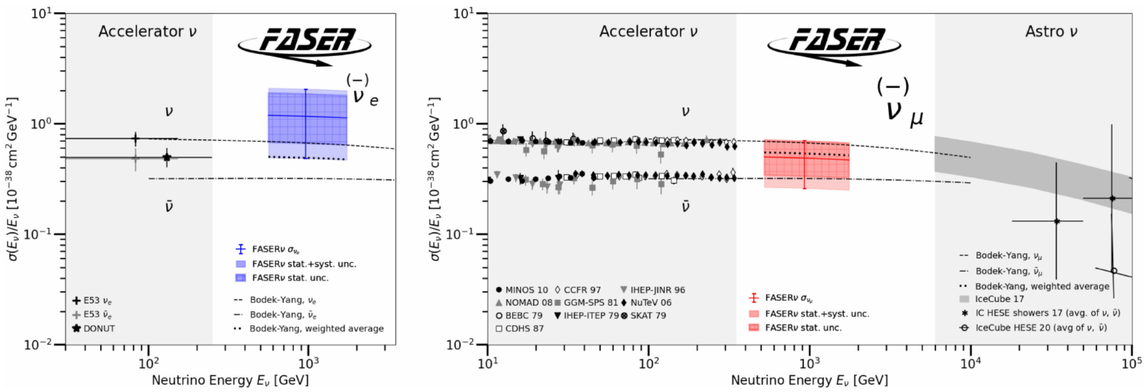

Figure 2: The measured cross section per nucleon for ν_e (left) and ν_μ (right). The dashed contours labelled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, implemented in simulations. Note that the displayed experiments do not all use the same targets.

The statistical significance of the observation of ν_e and ν_μ was estimated by considering the confidence level for excluding the null hypothesis (background-only). Based on the Probability Density Function (PDF) for the background, 10^{10} pseudo-experiments were generated. The neutral-hadron background was generated following separate Poisson distributions for each neutral hadron species considered, with a Gaussian-distributed systematic uncertainty of 100% included. The background from neutrino NC events was generated from a Poisson distribution, with systematic uncertainties included via Gaussian-distributed nuisance parameters (separately for the uncertainties from the light hadron and charm hadron neutrino flux, and the experimental uncertainties).

A random value, N, was calculated following the total background PDF, and the number of pseudo-experiments with $N \geq N_{\text{obs}}$ was counted, where N_{obs} is the number of observed neutrino events. Based on the fraction of cases with $N \geq N_{\text{obs}}$, observed p-values of 8.8×10^{-8} for ν_e and 5.7×10^{-9} were obtained, corresponding to significances of 5.2 σ for ν_e and 5.7 σ for ν_μ for the exclusion of the null hypothesis. The expected significance was estimated with pseudo-experiments with the signal expectation from the baseline flux model to be 3.3 σ for ν_e and 6.4 σ for ν_μ.

6. ν_e and ν_μ cross section measurements

The number of observed neutrino events can be described as

$$N_{\text{obs}} = \frac{L\,\rho\,l}{m_{\text{nucleon}}} \int \sigma(E)\,\phi(E)\,\varepsilon(E)\,\mathrm{d}A\,\mathrm{d}E,$$

where L is the luminosity, ρ is the density of tungsten (19.3 g/cm^3), l is the thickness of the tungsten plates, m_{nucleon} is the mass of the nucleon, $\sigma(E)$ is the cross section, $\phi(E)$ is the neutrino flux at the detector integrated over the transverse area A and the energy E, and $\varepsilon(E)$ is the detection efficiency.

The ν_e and ν_μ CC cross sections were measured in a single energy bin. The ratio between the cross sections evaluated with simulated events (σ_{theory}) and with the observed data was defined as a factor α as described by $\sigma_{\rm obs} = \alpha \cdot \sigma_{\rm theory}$, assuming that α was common for neutrino and anti-neutrino interactions. The energy range for $\sigma_{\rm theory}$ was defined to contain 68% of reconstructed neutrinos using the baseline models, which was 560–1740 GeV and 520–1760 GeV for ν_e and ν_μ, respectively.

The energy-independent part of the interaction cross sections per nucleon, $\sigma_{\rm obs}/E_\nu$, was measured over the considered energy ranges to be $(1.2^{+0.8}_{-0.7}) \times 10^{-38}$ cm^2 GeV^{-1} for ν_e and $(0.5 \pm 0.2) \times 10^{-38}$ cm^2 GeV^{-1} for ν_μ. Figure 2 shows the measured cross sections, together with those obtained by other experiments. The measured value of $\sigma_{\rm obs}$ is shown as the blue curved line for ν_e and the red curved line for ν_μ. The weighted average of the predicted cross section is also shown, assuming the ratio of the incoming neutrino to anti-neutrino fluxes to be 1.04 for ν_e and 0.61 for ν_μ.

7. Conclusions

First results from the search for high-energy electron and muon neutrino interactions in the FASERν tungsten/emulsion detector of the FASER experiment have been presented. The analysis used a subset of the FASERν volume, corresponding to a target mass of 128.6 kg, exposed to 9.5 fb^{-1} of LHC pp collisions during the summer of 2022. Selections were applied to retain reconstructed vertices consistent with high-energy ν_e and ν_μ CC interactions, while minimizing the background from neutral-hadron interactions. Statistical significances of observation of the ν_e and ν_μ interaction candidate events were 5.2 and 5.7 standard deviations, correspondingly. The interaction cross section per nucleon measured over previously unexplored energy ranges were both consistent with those predicted by the Standard Model. These results demonstrated the capability to study flavour-tagged neutrino interactions at TeV energies with the FASERν emulsion-based detector at the LHC.

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