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RECENT RESULTS FROM THE FASER EXPERIMENT AT THE LHC [1]

The ForwArd Search ExpeRiment (FASER), is an LHC experiment that aims to: (1) detect and study TeV-energy neutrinos, the most energetic neutrinos ever detected from a human-made source and (2) search for new light and very weakly interacting particles. The FASER detector is located 480 m downstream of the ATLAS p-p interaction point, along the beam collision axis. FASER was designed, constructed, installed, and commissioned during 2019–2022 and has been taking physics data since the start of LHC Run 3 in July 2022. Recently, FASER reported the first measurement of ν_e and ν_μ interaction cross sections at the LHC with its sub-detector FASERν, FASER's emulsion detector, first results on Axion-Like Particles at FASER and dark photons limits. These results will be reported in this article.

Keywords: dark photons, Axion-like-particles, 3 neutrino flavor.

1. Introduction

FASER (ForwArd Search ExpeRiment) is a particle physics experiment located at CERN, designed to detect light, weakly interacting particles that are produced in proton-proton collisions at the Large Hadron Collider (LHC). These particles, such as dark photons or other dark sector candidates, travel in the forward direction with minimal interaction, making them difficult to detect with traditional LHC detectors like ATLAS or CMS. FASER'*s* main goal is to detect new physics phenomena, particularly those related to dark matter and other particles beyond the Standard Model, such as dark photons, axion-like particles, or long-lived particles, but flavors emulsion detector. The experiment is positioned 480 meters downstream of the ATLAS interaction point (IP1), in the forward direction along the beam line, where a significant number of high-energy particles are produced in proton-proton collisions. This location maximizes the probability of detecting certain types of rare particles that other LHC experiments might miss. Unlike the main detectors at the LHC (like ATLAS or CMS), which focus on a wide range of particles and physics processes, FASER'*s* unique placement and design make it highly specialized for detecting light, weakly interacting particles that tend to travel along the beamline. This makes FASER experiment complementary to the larger LHC experiments. FASER started its official data-taking in 2022 during LHC's Run 3, which will continue through 2025. During this period, FASER will collect data as the LHC operates at its highest energy levels.

2. FASER Detector

FASER detector [1] is a compact detector, about 7 meters long and 20 centimeters wide, optimized to fit within the LHC infrastructure (see Fig. 1). Despite its small size, it is highly sensitive to specific types of particles. It has a suite of detectors which includes a front scintillator veto system, FASERν emulsion-detector, interface tracker (IFT), FASER scintillator veto station, decay volume, timing scintillator station, FASER tracking spectrometer, preshower scintillator system, and EM calorimeter. The detector includes three 0.57 T dipole magnets, one surrounding the decay volume and the other two incorporated the tracking spectrometer. The first two scintillator stations are needed to veto charged particles entering the detector:

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[1] This work is based on the results presented at the 2024 "New Trends in High-Energy and Low-x Physics" Conference.

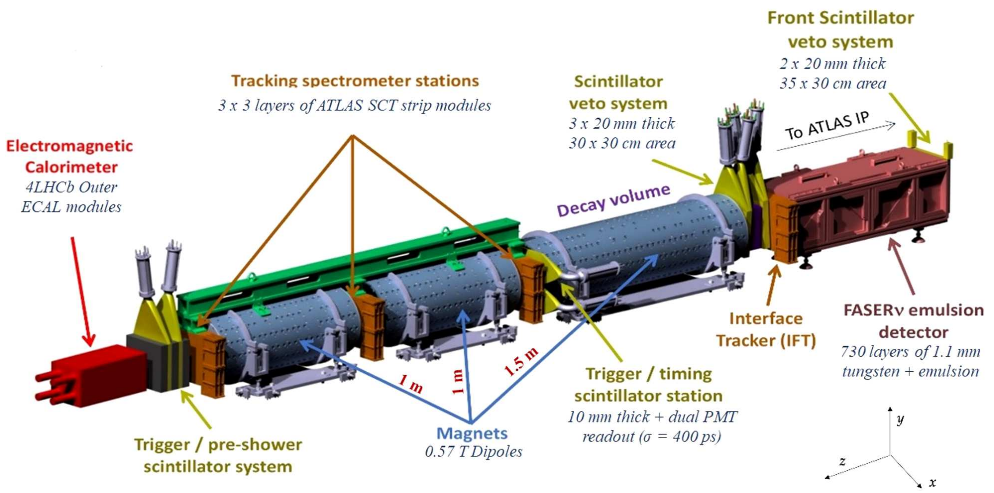


Fig. 1. Experimental set-ups for FASER from LHC

• one is placed in front of the FASERν emulsion detector and consists of two scintillator counters;

• the other is located in front of the FASER decay volume and is made up of four scintillator counters. Timing scintillator station is placed after the decay volume and it consists of two scintillator counters, each read out by two photomultiplier tubes PMTs. A pre-shower scintillator station is placed at the back of the tracking spectrometer and is composed of two scintillator counters, each read out by a single PMT, interleaved with two tungsten absorbers, and graphite blocks. The electromagnetic (EM) calorimeter consist of four spare modules from the LHCb experiment's outer electromagnetic calorimeter (ECAL) and is designed to measure the energy of high-energy electrons and photons. FASERν emulsion-detector is an Emulsion Cloud Chamber (ECC) made by 1.1 mm thick tungsten plates and nuclear emulsion films, designed to search for muonic, electronic and tauonic neutrinos.

3. Dark Photons Search in FASER Experiment

Dark matter particles search is a great field of interest of BSM physics. The most promising candidates is (A'), a hypothetical light and weakly interacting particle. Unlike regular photons, dark photons interact very weakly with ordinary matter, which makes them hard to detect. The dark photon is characterized by it's mass, (A') and coupling parameter, (ϵ). Since weakly interacting particles like dark photons are often produced in the forward direction (along the beam axis), FASER is ideally placed to detect them. By being positioned far from the main interaction point, FASER operate in a low-background environment, increasing its sensitivity to new physics signals, including dark photons. If produced, the dark proton would travel through the FASER detector and its decay into charged particles (such as electrons and positrons).

3.1. Event selection

The discovery of dark photons with FASER detector is significant due to the simple event selection optimized for the detection of the signature, Fig. 2. The signal region event selection requires the following:

• event time is consistent with a colliding bunch at IP1;

• no signal in any of the five veto scintillators, required to be less than half that expected from a minimal ionizated particle (MIP);

• signal in the scintillators that are downstream of the decay volume, required to be compatible with or larger than expected for two MIPs;

• two fiducial reconstructed tracks of good quality, the cuts on the number of hits, fit χ^2 and reconstructed momentum are applied;

• total calorimeter energy greater than 500 GeV [4].

The efficiency of this selection on a representative signal model in the parameter space, where the analysis is most sensitive $\epsilon = 3 \times 10^{-5}$, $mA' = 25.1$ MeV

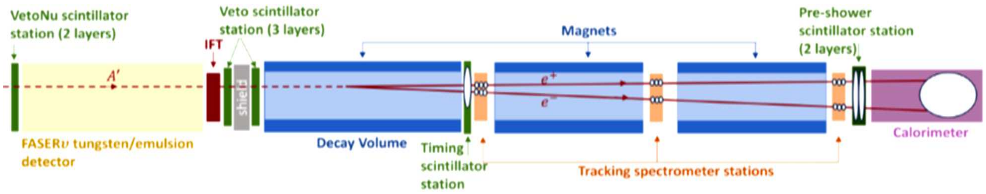
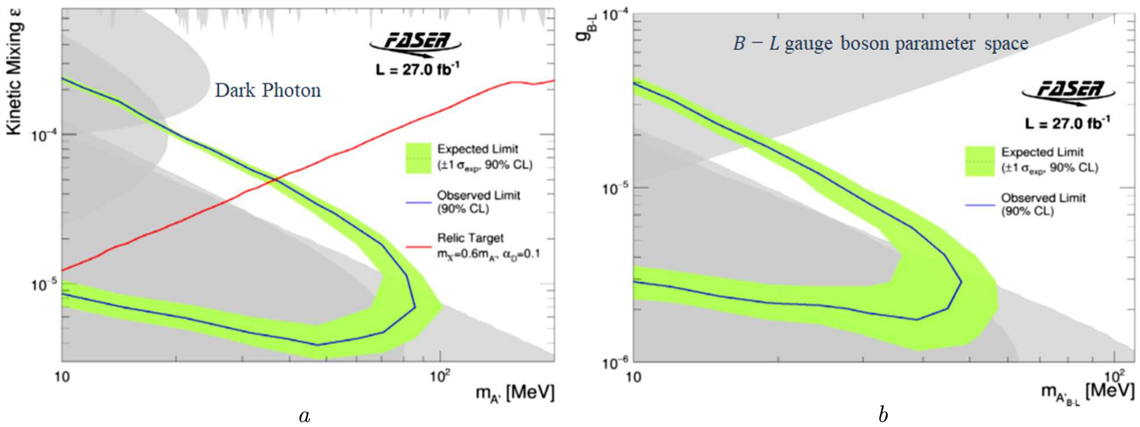


Fig. 2. A side view of the FASER detector, showing the different detector systems as well as the signature of a dark photon (A') decaying to an electron-positron pair inside the decay volume



a *b*

Fig. 3. 90% confidence level exclusion contours for dark photons (a) and B-L gauge boson parameter space (b). The expected limits are shown with green, red line shows the region of parameter space that yields the correct dark matter relic density and the regions excluded by previous experiments are shown in grey

was found to be about 50% for dark photons that decay in the decay volume [4].

3.2. Background

Several sources of background are considered in the analysis. The dominant background arises from neutrino interactions in the detector. Other processes such as neutral hadrons, or muons that enter the detector volume without firing the veto scintillator systems, either by missing the scintillators or due to scintillator inefficiencies, also contribute to the background. Inefficiencies in the veto scintillators can lead to an instrumental background from unvetoed muons entering the detector volume. At the end, non-collision backgrounds from cosmic rays or nearby LHC beam interactions are also considered. The analysis is done using the dataset corresponding to an integrated luminosity of 27 fb^{-1}. Expected background total is estimated for this statistics by combining just the neutrino and neutral hadron estimates, leading to a total background of $(2.3 \pm 2.3) \times 10^{-3}$ [3]. At the 90% confidence level, FASER excludes the region of $\epsilon \approx 4 \times 10^{-6}$–$2 \times 10^{-4}$ and $m_{A'} \approx 10$–80 MeV in the dark photon parameter space, as well as the region of $g_{\text{B-L}} \approx 3 \times 10^{'6}$–$4 \times 10^{-5}$ and $m_{A'_{\text{B-L}}} \approx 10$–50 MeV in the B-L gauge boson parameter space. In both the dark photon and B-L gauge boson models, these results are one of the first probes of these regions of parameter space since the 1990's, and they exclude previously-viable models motivated by dark matter [4].

3.3. Results

After we apply the signal selection are applied to 27 fb^{-1} data sample, no events are observed in the data. This is compatible with the expected background. As no significant excess of events over the background is observed, the results are used to set exclusion limits in the signal scenarios considered. Figure 3 shows the (A') exclusion limit in the signal parameter.

4. Axion-Like-Particles (ALPs) Search in FASER Experiment

Axion-like particle (ALP) is a particle that looks like axion particle. It appears from a quark bottom

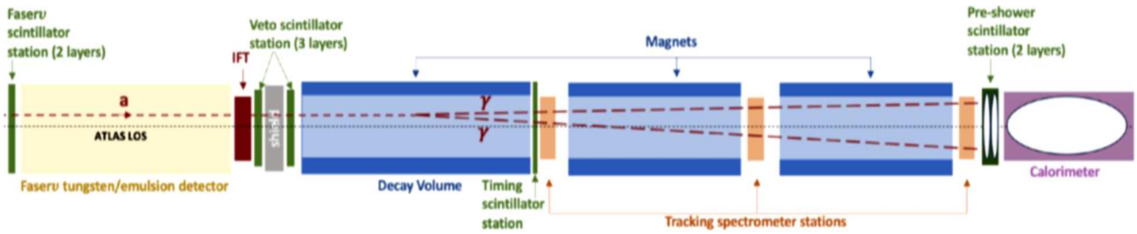


Fig. 4. An ALP event traversing through the FASER detector sketch. Dotted lines show that the ALP is leaving no signal in the detector and the white blobs in the preshower layers and the calorimeter depict energy deposits

that decays into a quark strange and axion-like particle. This decay into 2 protons (gamma – gamma) that appear out of nowhere and can decay anywhere in the FASER. The corresponding Lagrangian for the ALPs is:

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{2}g_{aWW}\, a W^{a,\mu\nu}\widetilde{W^a_{\mu\nu}}, \qquad (1)$$

where m_a is the ALP mass, g_{aWW} is the ALP coupling parameter, and $W^{\mu\nu}$ is the SU(2)L field strength tensor.

4.1. Event selection

By summing the digitised pulse values post-pedestal subtraction, the total charge of the calorimeter and scintillator signals is extracted. In Fig. 4, we show a typical signature of a signal event in the detector and can be summarised:

- no signal is observed in the veto scintillators, since ALPs are electrically neutral;
- preshower charge deposits (measured charge in the photomultiplier tube (PMT) when particles lose energy and generate light in the scintillators) consistent with an EM shower arising from the decay photons;
- a large energy deposit in the calorimeter left by the high-energy photon pairs.

A blinding methodology was implemented, to avoid any bias in the analysis. In any of the veto scintillators and calorimeter energy surpassing 100 GeV, a "blinded" region was defined as events with a limited deposited charge. To investigate this blind region, were completed with priority the event selection, background estimation, and consideration of systematic uncertainties. The event selection requires events triggering the calorimeter and the collision timing in the same time. We select only events corresponding to colliding bunches, with a requirement on the calorimeter timing to be >5 ns and <10 ns to ensure consistency with collision timing. No veto signal is expected from the ALPs signal, the charge deposited in each of the five veto stations is required to be less than half that expected from a MIP.

4.2. Background estimation

In the analysis, various sources of background are considered. The dominant background is expected to result from neutrino interactions within the detector. Other backgrounds may appear from neutral hadrons that enter the detector, muons that bypass the veto scintillator systems as they enter the detector at an angle, or veto inefficiencies, this are negligible.

The neutrino background is evaluated in MC simulations [5] and validated in regions designed to target neutrinos interacting in different areas of the detector. MC predictions for the number of signal events in 57.7 fb^{-1} in the signal region are in Table. One event was observed in the signal region after unblinding, with the background exception of 0.42 ± 0.38, probing new parameter space of this ALPs model, Figure 5. In Figure 6 is show the energy distribution in the preshower and signal region.

5. Neutrino Studies in FASER Experiment

The LHC p-p collisions are the source of huge number of (anti)neutrinos of all flavors with the high energies belonging to the unexplored region. They are

Summary of the MC estimate of the neutrino background in the signal region

	>1.5 Tev signal region
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	$\mathbf{0.42 \pm 0.38}$ **(90.6%)**

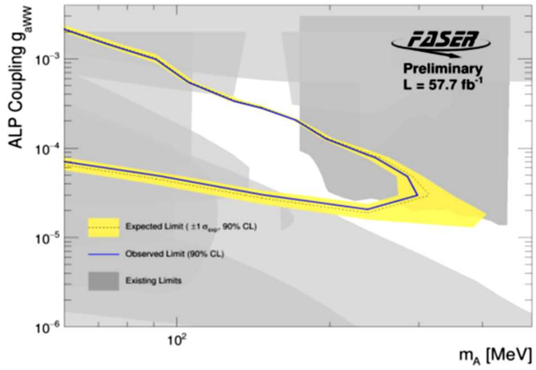


Fig. 5. Interpretation of the signal region yield as ALP exclusion limits with the assumption of 0.42 neutrino background events [5]

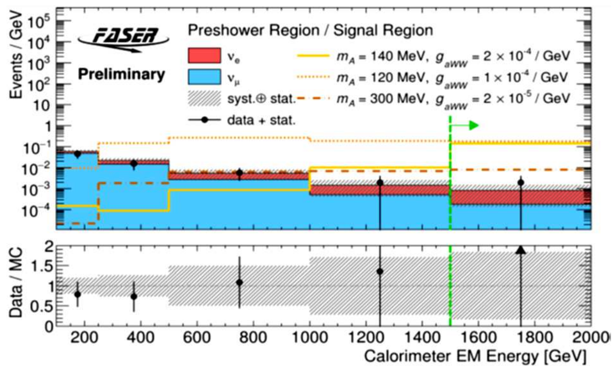


Fig. 6. Calorimeter energy distribution in the preshower and signal region, showing the neutrino background composition, separated according to neutrino flavor [5]

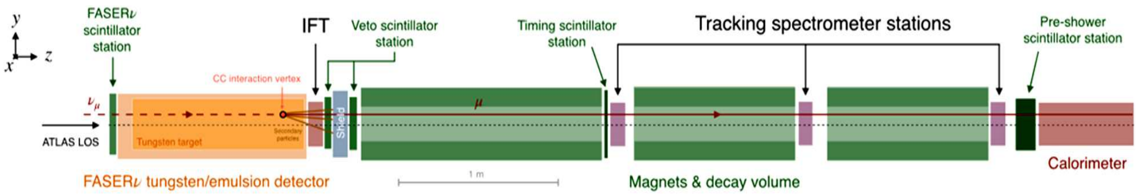


Fig. 7. Schematic side view of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion-tungsten target

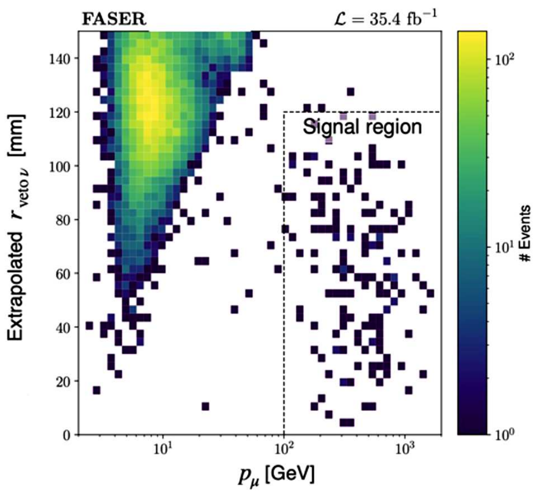


Fig. 8. Signal region in extrapolated radius $r_{\text{veto}\,\nu}$ and reconstructed track momentum p_μ is depicted is selected. The region with lower momenta and larger radii is dominated by background events consisting of charged particles that miss the FASERν scintillator station [7]

weekly interacting and escape registration nearby the p-p IP. Huge number of neutrinos pass through the FASERν detector and, during Run 3, it is expected to register about 103 ν_e, 104 ν_μ and 50 ν_τ which open the possibility to measure neutrino cross section at the high energies [3, 6].

5.1. Silicon tracker data analysis

For the first study, we have focused on ν_μ, $\bar{\nu}_\mu$ charged current (cc) interactions at FASERν with silicon tracker data usage. It is done for the statistics corresponding to the luminosity of 35.4 fb^{-1}. The event selection criteria are the following:

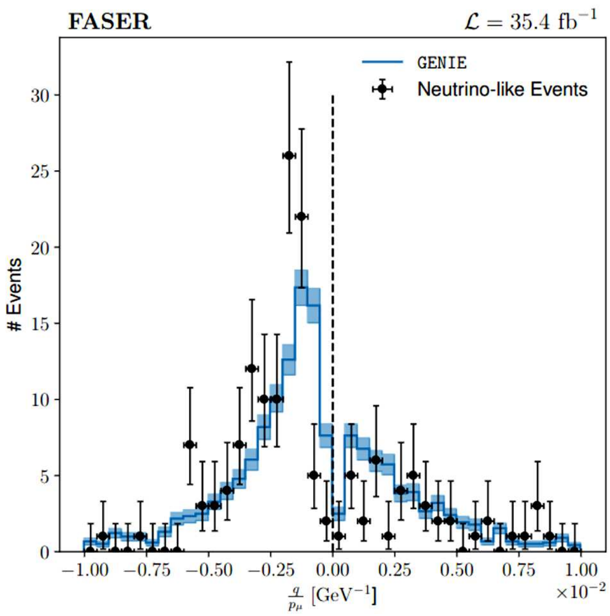
• event time is consistent with a colliding bunch at IP;

• no signal in FASERν scintillator detector any of the five veto scintillators, required to be less than half expected from a MIP;

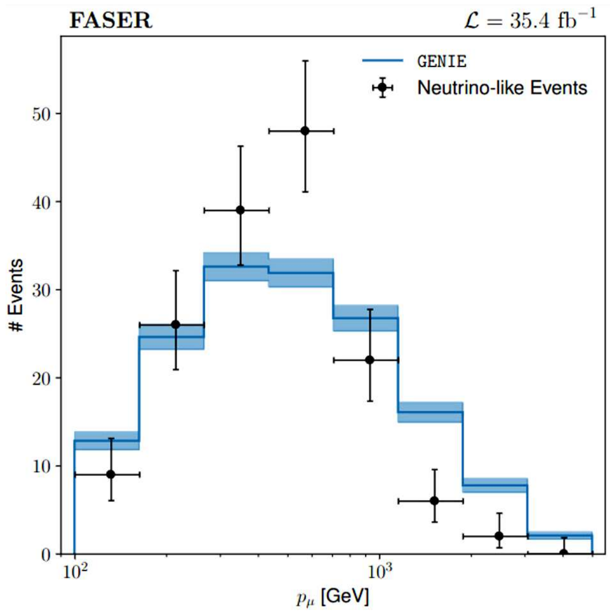
• exactly one track with more than 11 silicon hits in the tracking stations is reconstructed with the three tracker stations;

• a reasonable track fit quality of the reconstructed 203 tracks;

• the track's extrapolation to the IFT must lie with in 95 mm of the detector's central axis, and its extrapolation to the FASERν scintillator must be at a



a



b

Fig. 9. The variables, q/p_μ (*a*) and the reconstructed momentum, p_μ (*b*), for events in the signal region (black markers) and a comparison to the expectation from GENIE (blue)

distance of $r_{\text{veto}\,\nu} < 120$ mm from the FASERν scintillator center;

• reconstructed track momentum to fulfill $p_\mu >$ > 100 GeV [7].

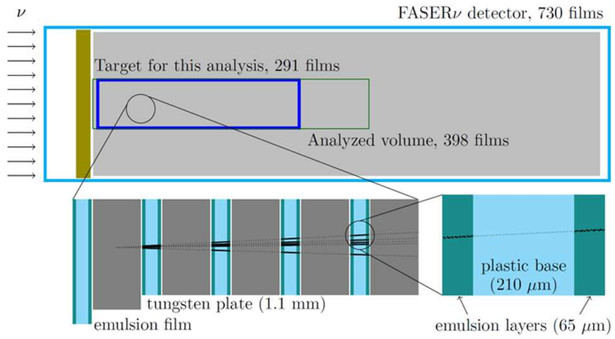
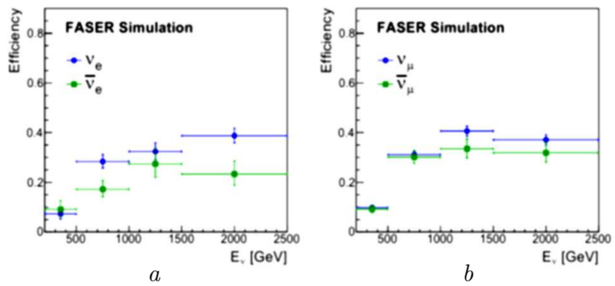


Fig. 10. Schematic view of the analyzed detector volume (side view). The FASERν box is shown in gray, contains a total of 730 emulsion films. The thin green box outlines the reconstructed volume, and neutrino interactions are searched within the fiducial volume defined by the blue box



a *b*

Fig. 11. Selection efficiencies for ν_e CC and $\bar{\nu}_e$ CC interactions (*a*) and for ν_μ CC and $\bar{\nu}_\mu$ CC interactions (*b*)

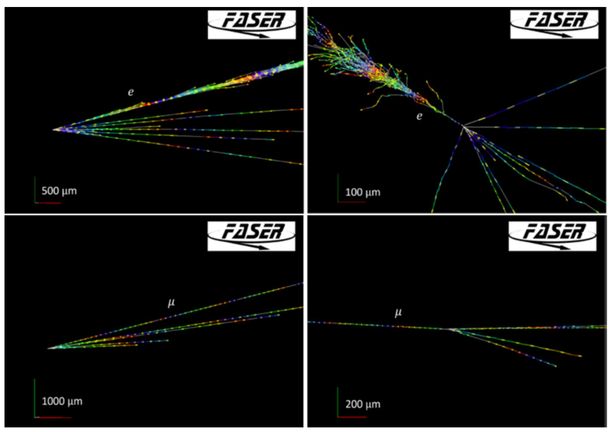


Fig. 12. Event displays of one of the ν_e CC candidate events (top) and one of the ν_μ CC candidate events (bottom). In each panel, the right handed coordinate axes are shown in the bottom left, with red, green, and blue axes indicating the x (horizontal), y (vertical), and z (beam) directions, respectively

A blind analysis was done where the event selection, background estimations, and systematic uncertainties were fixed before looking at data in the signal-

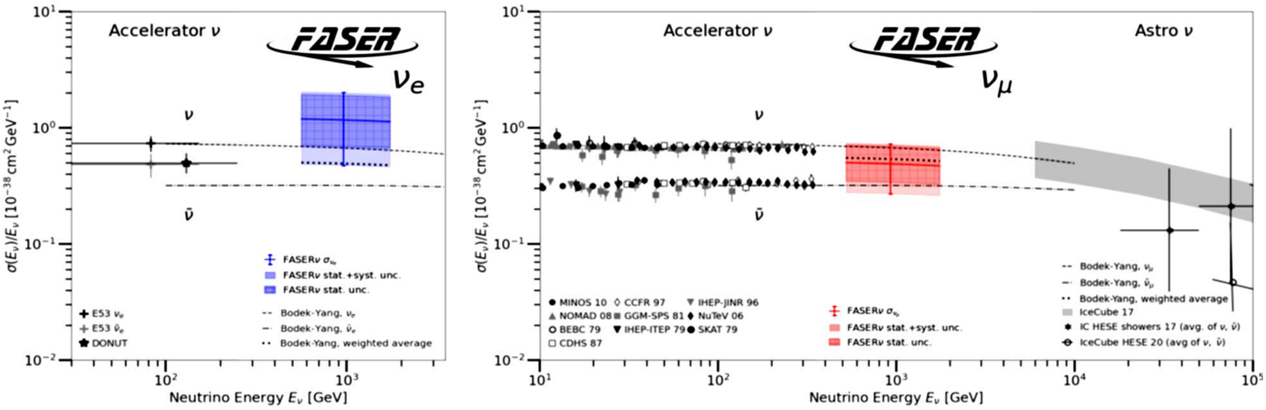


Fig. 13. The measured cross section per nucleon for ν_e (*a*) and ν_μ (*b*)

enhanced region. The main background to ν_μ came from high-momentum muons. Two additional sources of backgrounds are relevant: neutral hadrons produced by muon interactions in the concrete in front of the FASERν detector and geometric backgrounds from charged particles missing the FASER scintillator. The backgrounds from cosmic rays and LHC beam background have been studied using events occurring when there are no collisions, and are found to be negligible. The expected number of neutral hadron background for the analyzed statistics is $n_{\rm had} = 0.01 \pm 0.06$, with the uncertainty denoting the statistical error and a total geometric background estimate of 0.08 ± 1.83 events. The selected events, as well as the background-enriched regions with lower momentum or $r_{\rm vetov} > 120$ mm it is show in Fig. 8. 153 events passing all selection steps are observed. Figure 9 summarizes additional properties of the signal category event. A clear charge separation in q/p_μ for the reconstructed tracks, with q denoting the assigned track charge. In total, 40 events with a positively-charged track candidate are observed, showing the presence of $\bar{\nu}_\mu$ in the dataset. There were found:

$$n_\nu = 153^{+12}_{-13}(\text{start})^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot}), \qquad (2)$$

with a significance of 16 standard deviations over the background-only hypothesis and based on the asymptotic distribution of the test statistics. The excess is compatible with the expected number of ν_μ events $n_\nu^{\rm exp} = 151 \pm 41$ [7].

5.2. FASERν emulsion detector data analysis

FASERν detector have a 1.1 tons with the size of 30×25 cm^2 in the transverse plane to the beam and it is 1 m in length. It consists of 1.1 mm tungsten plates thick interleaved with emulsion films. Give the possibility to distinguish all neutrino flavors because his excellent space and angular emulsion resolution. The detector is aligned with the LOS and placed in front of the FASER spectrometer. The emulsion-tungsten detector has to be replaced every 30–50 fb^{-1} to have manageable track density, three time per year. FASERν box is replaced during every LHC technical stops [8].

For vertex reconstruction, we use the reconstructed tracks passing through at least 3 plates with an impact parameter less than 5 μm. The number of tracks with tan $\theta \leq 0.1$ relative to the beam direction is also required to be more than 3 to suppress the neutral-hadron background. ν_e CC interactions candidate are selected from the initial set of vertices by requesting an associated high-energy electromagnetic (EM) shower with a reconstructed energy more than 200 GeV and tan $\theta > 0.005$. For the ν_μ CC interactions candidate require that one of the reconstructed charged particle tracks is a muon candidate, the muon reconstructed momentum has to be more than 200 GeV with tan $\theta > 0.005$. Selection efficiency cross section are shown in fig. 11 for neutrino and antineutrino electron and muon, the efficiency of antineutrino events that pass the vertex selection is slightly lower that neutrino events [8].

5.3. ν_e and ν_μ candidate events

Four events are selected by the ν_e selection on data. The highest reconstructed electron energy from the selected ν_e CC candidates is 1.5 TeV. It is therefore the highest-energy ν_e interaction ever detected by accelerator-based experiments. Eight events are selected by the ν_μ selection on data. The highest reconstructed muon momentum from the selected ν_μ CC candidates is 864 GeV, meaning that the ν_μ sample includes neutrinos with energy likely above 1 TeV, far higher than from previous accelerator-based neutrino studies. In Figure 12 are show an example event displays of ν_e and ν_μ candidates. Both events exhibit a back to back topology between the lepton candidate and the other tracks in the vertex.

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

The energy independent part of the interaction cross sections per nucleon, $\sigma_{obs}/E\nu$, is measured over the considered energy ranges to be for $\nu_e 1.2^{+0.07}_{-0.08} \times 10^{-38}$ cm^{2}GeV^{-1} and for $\nu_\mu(0.5\pm0.2) \times 10^{-38}$ cm^{2}GeV^{-1}. The measured cross sections, together with those obtained by other experiments [8] are show in figure 10. The blue curved line for ν_e and the red curved line for ν_μ are represent σ_{obs} measurement value [8].

The average of the GENIE predicted cross section, assuming the ratio of the incoming neutrino to antineutrino fluxes is 1.04 for ν_e and 0.61 for ν_μ and is also represented in Figure 13.

5.4. Results

Four electron neutrino interaction candidate events are observed, with an expected background of $0.025^{+0.015}_{-0.010}$, that lead to a statistical significance of 5.2 standard deviations. This represents the first direct observation of electron neutrinos produced at a particle collider. Eight muon neutrino interaction candidate events are found, with an expected background $0.22^{+0.09}_{-0.07}$, leading to a statistical significance of 5.7 standard deviations.

6. Summary

FASER is a small experiment but with good potential of discovery for new physics. The experiment is continuing to operate successfully in Run 3 of LHC approximately 140 fb^{-1} were collected.

The first search for dark photons by the FASER experiment has been presented, providing a proof of principle that very low background searches for long-lived particles (LLPs) in the very forward region are possible at the LHC [4].

FASER searched for axion-like particles (ALPs) using data collected in 2022 and 2023. The dominant backgroud source was neutrinos interacting the preshower detector of FASER. One event was observed in the signal region, with a background expectation of 0.42 ± 0.38 [5].

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 and also first results about ν_e, ν_μ interaction cross sections at TeV energies with FASERν using the 2022 data [7, 8].

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ОСТАННІ РЕЗУЛЬТАТИ
ЕКСПЕРИМЕНТУ FASER НА КОЛАЙДЕРІ LHC

ForwArd Search ExpeRiment (FASER) – це експеримент на колайдері LHC, який має на меті: (1) детектувати і вивчати нейтрино в області енергій порядка ТеВ – нейтрино найвищих енергій, коли-небудь зареєстрованих з джерела, створеного людиною, і (2) пошук нових легких і дуже слабко взаємодіючих частинок. Детектор FASER розташований на відстані 480 м після точки p-p взаємодії в детекторі ATLAS уздовж напрямку зіткнення протонів. Установка FASER була розроблена, виготовлена, встановлена і введена в експлуатацію протягом 2019–2022 років і збирає експериментальні дані з моменту запуску LHC Run 3 у липні 2022 року. Нещодавно з FASER повідомили про перше вимірювання перерізів взаємодії ν_e і ν_μ на LHC за допомогою субдетектора FASERν – емульсійного детектора FASER та про перші результати щодо аксіоноподібної частинки і щодо меж для темних фотонів. Ці результати обговорюються в даній роботі.

К л ю ч о в і с л о в а: темні фотони, аксіоноподібні частинки, 3 аромати нейтрино.