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First results from FASER at the LHC

Daiki Hayakawa[a,*] **, on behalf of the FASER collaboration**

[a] *Department of Physics, Chiba University, 1-33 Yayoi-cho Inage-ku, 263-8522 Chiba, Japan*

E-mail: daiki.hayakawa@cern.ch

The ForwArd Search ExpeRiment (FASER) is a new experiment at the Large Hadron Collider (LHC) designed to search for light, weakly-interacting particles. Placed 480 m downstream from the ATLAS interaction point along the beam collision axis, FASER detects particles that travel hundreds of meters. This paper presents the first physics results from FASER using data collected during LHC Run 3 in 2022-2023. We report on searches for dark photons decaying into electron-positron pairs and axion-like particles (ALPs) decaying into photon pairs, both of which can provide insights into physics beyond the Standard Model. We discuss the first direct observation of collider neutrinos with FASER and measurements of electron neutrino and muon neutrino interaction cross-sections in the unexplored TeV energy range using the FASERν emulsion detector. These results provide new opportunities for exploring both Standard Model and Beyond the Standard Model physics in the forward region of LHC proton-proton collisions. We also discuss future prospects, including an upgrade of a preshower calorimeter detector and plans for the Forward Physics Facility in the High-Luminosity LHC era.

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*Speaker

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1. Introduction

The ForwArd Search ExpeRiment (FASER) [1–4] is an experiment at the Large Hadron Collider (LHC) designed to search for light, weakly-interacting particles. These particles include Standard Model (SM) neutrinos [5, 6] and new particles associated with physics beyond-the-SM (BSM). The FASER detector is positioned at 480 m downstream from the ATLAS interaction point (IP1) along the beam collision axis, or line of sight (LOS). Many of charged particles are deflected by the LHC magnets before reaching the FASER detector, while neutral hadrons are absorbed by a hundred meters of concrete and rock in front of the FASER detector. The detector is in an ideal location to study light, weakly-interacting particles produced in the forward direction, offering a relatively large acceptance and efficiency for long-lived particle (LLP) decays and neutrinos.

One of the primary physics goals of FASER is to search for LLPs that could provide insights into BSM physics. These LLPs include new particles in a hidden sector that weakly interacting with SM particles. Such new particles are of great interest in both particle physics and astrophysics, as they could provide key insights into the nature of dark matter. The region probed by FASER offers unique sensitivity to the light, weakly-interacting new particles that might be produced in the decay of mesons, which are abundantly created in the forward direction at the LHC. A search for dark photons, decaying into electron-positron pairs, was performed using data collected in 2022 [7]. Subsequently, a search for Axion-like particles (ALPs), decaying into photon pairs, was reported using data collected in 2022 and 2023 [8].

FASER also aims to study SM particles produced in the forward direction. In particular, FASER includes a dedicated component, FASERν, designed to detect and study high-energy neutrinos at the unexplored TeV ranges. In 2021, the FASER Collaboration reported the first evidence of neutrino interaction candidates produced at the LHC, using a 29 kg pilot emulsion detector, highlighting the potential of discovering collider neutrinos [9]. For the first time, neutrinos from colliders were directly observed using the electronic component of FASER in 2022 data [10]. The FASER Collaboration recently reported the first measurement of the muon neutrino interaction cross section and flux as a function of energy [11]. The interactions of all three neutrino flavours can be measured by identifying leptons generated through neutrino charged-current (CC) interactions with the FASERν emulsion detector [4]. For the first time, FASER measured electron neutrino and muon neutrino interaction cross sections using a 128 kg subset of the FASERν detector after exposure of 9.5 fb^{-1} of 13.6 TeV proton-proton (pp) collisions [12].

In this paper, we present the FASER detector, followed by detailed descriptions of these first physics results from LHC Run 3. We also discuss future prospects, including an upgrade of a preshower calorimeter detector and plans for the Forward Physics Facility in the High-Luminosity LHC era.

2. The FASER Detector

Figure 1 shows a sketch of the FASER detector. On the detector upstream side, the right side in the sketch, there is a neutrino detection part (FASERν). FASERν consists of a front scintillator veto system, an emulsion detector with approximately 1-tonne tungsten target, and the interface tracker (IFT) for muon charge separation. On the downstream side, the left side in the sketch, there is a detector part to search for new particles. The part is composed of the scintillator veto station, the decay volume, the timing scintillator station, the FASER tracking spectrometer, the preshower scintillator system and the electromagnetic (EM) calorimeter system. The detector includes three 0.57 T dipole magnets, one surrounding the decay volume and the other two embedded in the tracking spectrometer.

3. Search for Dark Photon Decays with FASER

FASER reported a search for dark photons (A'), decaying into electron-positron pairs, using data collected in 2022 (27.0 fb^{-1}) [7]. If dark photons are light and has a feeble interaction, it becomes a LLP and can be produced in large quantities in pp collisions at the LHC. The production in the dark photon analysis is the decay mode of neutral pions, which are abundantly produced in the forward direction, $\pi^0 \rightarrow A'\gamma$.

The event topology for dark photon detection in FASER requires capturing the electron-positron pair resulting from the dark photon decay (Figure 2). The selection criteria were: (1) high-quality data from physics runs, (2) no signals in any of the five layers of Veto detectors ($<$ 40 pC, $\sim$ 0.5 MIP) to exclude background events mainly from charged particles like muons from upstream, (3) signals visible in Timing and preshower detectors ($>$ 1 MIP), (4) two reconstructed tracks with momentum $>$ 20 GeV within the effective volume of 95 mm radius, and (5) energy deposit $>$ 500 GeV in the calorimeter. These criteria maintained a 40-50% signal efficiency.

The Veto detector can eliminate charged particles from upstream with 99.9998% efficiency, leaving two main types of background events. The first is secondary particles from neutrino interactions in the detector, estimated using MC samples equivalent to 300 ab^{-1} and scaled to the 27 fb^{-1} used in the dark photon search, yielding $1.5 \pm 0.5_{\text{stat.}} \pm 1.9_{\text{syst.}} \times 10^{-3}$ events. The second is neutral hadron decays from muon interactions with rock upstream of the FASER detector. While most neutral hadrons are suppressed by muon detection and the tungsten in the FASERν detector,

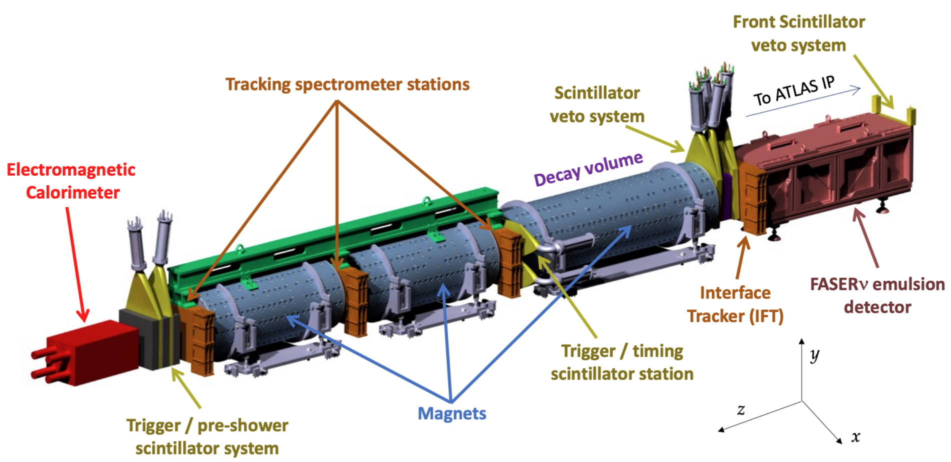

Figure 1: A sketch of the FASER detector, showing the different sub-detector system. The detector coordinate is also shown [4].

some survive and leave 2-track or 3-track signatures. Using 3-track events as a control region, the 2-track background in the signal region was estimated to be $8.4 \pm 11.9 \times 10^{-4}$ events. The total estimated background was $2.3 \pm 2.3 \times 10^{-3}$ events.

After unblinding, no significant excess was observed. A 90% confidence level upper limit was set as shown in Figure 3. The results exclude a wide parameter space with $\epsilon \sim 4 \times 10^{-6}$ to 2×10^{-4} and $m_{A'} \sim 10 - 80$ MeV. Particularly for dark photons with masses around 30-40 MeV, the results exclude models where dark photons could mediate between Standard Model particles and dark matter in the thermal freeze-out scenario, as represented by the "Relic target" curve in Figure 3.

4. Search for ALPs Decays with FASER

ALPs (a) is a general term for pseudoscalar particles, including axions. Here, we consider a scenario where ALPs interact with $SU(2)_L$ gauge bosons and, after electroweak symmetry breaking, interact with photons and weak gauge bosons. The Lagrangian $\mathcal{L}$ is expressed as

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu} , \tag{1}$$

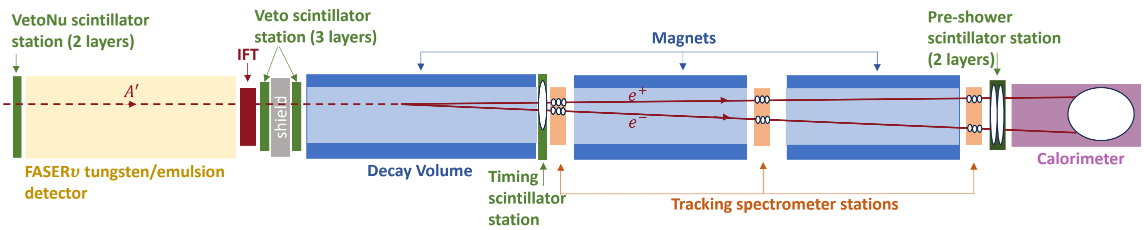

Figure 2: Sketch of a dark photon (A') decaying into an electron position pair in the FASER detector [7].

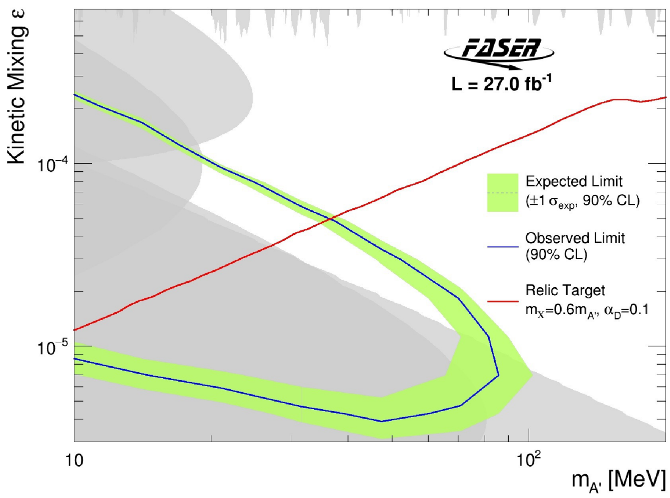

Figure 3: Dark photon limit curve [7]. The Relic target in the figure is the theoretical prediction curve when the current amount of dark matter can be explained. The gray area is the area excluded by previous researches, and the green band is the area newly excluded.

where m_a and a represent the mass and field of the ALP, respectively, g_{aWW} is the coupling constant between the ALP and weak gauge bosons, and $W^{\mu\nu}$ represents the $SU(2)_L$ field strength.

Using data collected in 2022 and 2023 (57.7 fb^{-1}), FASER searched for ALPs decaying into two photons [8]. The decay event of ALPs in the FASER detector is illustrated in Figure 4. Since ALPs have no electric charge, they leave no signal in the veto stations and the tracking detectors. High-energy photon pairs emitted from ALP decays interact in the preshower and are observed as EM showers in the calorimeter. Due to the collimated pair of photons, they cannot be resolved by the FASER detector. Events observed as a single EM shower with the energy of at least 1.5 TeV in the calorimeter are required. The signal region was defined to require the energy deposited in the second layer of the preshower scintillator exceeded 10 MIPs, and more than 4.5 times larger than the energy deposited in the first layer.

The primary background events are charged current interactions of neutrinos in the preshower calorimeter. Neutrino background events were estimated using Monte Carlo simulations (MC) and checked with the data, confirming the consistency of the MC estimates. Other background considerations included inefficiencies in the veto detectors, muons, neutral hadrons, cosmic rays, and beam background arriving at the FASER detector, all of which were estimated to be negligible. The most significant systematic uncertainties were the flux uncertainties of forward hadrons production, followed by uncertainties in the energy scale calibration of the calorimeter. The neutrino background events in the signal region are summarized in Table 1. One event was observed in the signal region after unblinding, and an exclusion limit was set as shown in Figure 5, successfully excluding regions not previously ruled out.

5. First Direct Observation of Collider Neutrinos with FASER

High-energy neutrinos produced at particle colliders had never been directly detected until FASER's observation in 2023. FASER reported the first direct observation of neutrino interactions

Table 1: Summary of the MC estimate of the neutrino background in the signal region. Uncertainties on the flux, as well as experimental uncertainties, are also given. The MC events are normalised to 57.7 fb^{-1}, and MC statistical uncertainties are given [8].

	> 1.5 TeV signal region
Light	0.34 ± 0.33 (flux) $\pm$ 0.11 (exp.) $\pm$ 0.05 (stat.)
Charm	0.10 ± 0.05 (flux) $\pm$ 0.05 (exp.) $\pm$ 0.02 (stat.)
Total	**0.44 ± 0.39 (88.6%)**

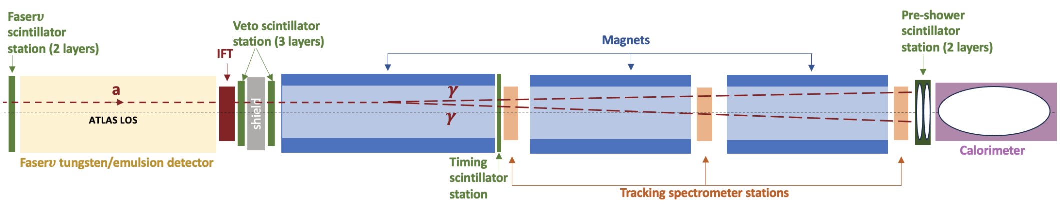

Figure 4: Sketch of an ALP (a) traversing and decaying into two photons in the FASER detector [8].

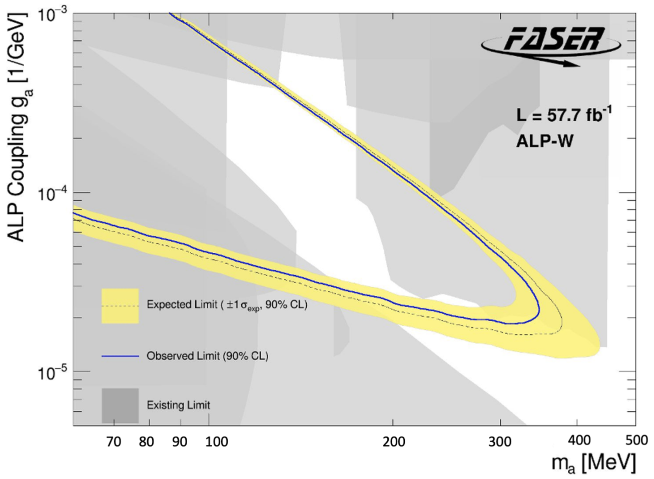

Figure 5: Interpretation of the signal region yield as ALP-W exclusion limits. Limits are provided at 90% confidence level in the ALP -W mass (m_a) and coupling (g_{aWW}) plane [8].

at a collider experiment, using data collected in 2022 (35.4 fb^{-1}).

The detection method takes advantage of unique configuration of FASER. Muon neutrinos (ν_μ) that reach the detector can undergo charged-current (CC) interactions in the tungsten target, producing hadrons and a muon. This muon passes through the Interface Tracker (IFT) and Veto detector, leaving signals, while any hadrons are absorbed by the absorber material. A single high-energy muon is then detected in the spectrometer and calorimeter.

Several selection criterias were: (1) high-quality data from physics runs, (2) no signals in the two FASERν Veto detector layers ($<$ 40 pC, $\sim$ 0.5 MIP), (3) particle detection in at least two of the three Veto detector layers, (4) calorimeter signal consistent with $\geq$ 1 MIP, (5) exactly one good quality track with momentum $>$ 100 GeV in the spectrometer, (6) track within the fiducial volume with radius $<$ 95 mm, and (7) track extrapolation to $<$ 120 mm in the front Veto scintillator.

The background events for this analysis included: muons produced by neutral hadrons colliding in the tungsten, and muons entering outside the FASERν Veto detector's range and scattering in the tungsten. The former was estimated using GEANT4 simulations to be 0.11 $\pm$ 0.06 events. The latter was estimated using data-driven methods by examining low-momentum muon events and extrapolating to higher momenta, resulting in an estimate of 0.08 $\pm$ 1.83 events.

153 events passed all selection criteria, representing a 16σ significance for the detection of muon neutrinos. This result constitutes the first detection of neutrinos at a collider experiment. Figure 7 shows the momentum distribution of the ν_μ candidate events, with the data points showing statistical errors only and the blue line representing GENIE simulation results.

Recently, FASER also reported the first measurement of the muon neutrino interaction cross section and flux as a function of energy [11], using data collected in 2022 and 2023 (65.6 fb^{-1}) data. In this analysis, 338.1 $\pm$ 21.0 ν_μ interaction events were identified and the contributions of neutrinos from pion and kaon decays were extracted.

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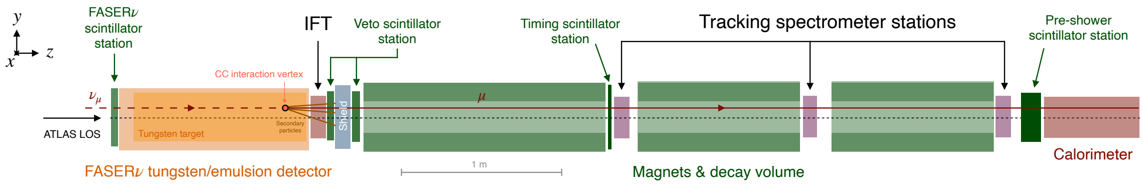

Figure 6: Schematic side view of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion-tungsten target [10].

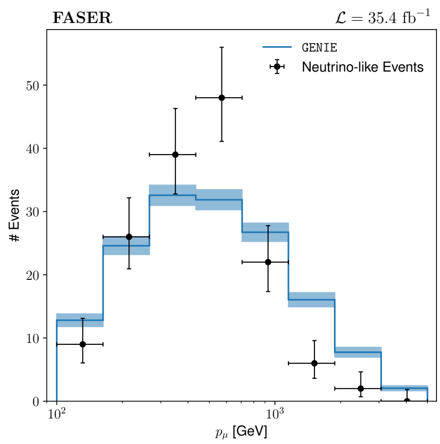

Figure 7: Reconstructed momentum p_μ for events in the signal region (black markers) and the expectation from GENIE (blue) [10]. The blue band corresponds to the statistical error of the simulated samples and is luminosity scaled.

6. First Measurement of ν_e and ν_μ Interaction Cross Sections with FASERν

The FASERν detector is a dedicated component of FASER designed specifically for neutrino detection and measurements. It consists of 730 tungsten plates (1.1 mm thick each) interleaved with emulsion films, providing a high-density target with a total tungsten mass of approximately 1.1 tonnes. The emulsion detector offers precise tracking capabilities for charged particles produced in neutrino interactions, with position resolution of approximately 0.3 μm as demonstrated by the position deviation distribution of muon tracks.

The emulsion detector enables the study of all three neutrino flavors. The detector reconstruct interaction vertices where five or more tracks converge within 5 μm, and distinguish neutrino flavors by identifying muons, electrons, and tau decay products based on their characteristic signatures. Neutrino events are identified using multivariate analysis of the angles and momenta of particles from the interaction vertices.

For the first cross-section measurement, the analysis focused on the central region of the first 398 layers of the second emulsion module exposed in 2022. To distinguish CC interactions from hadronic interactions and neutral-current interactions, electron or muon candidates with energies above 200 GeV from the interaction vertices are required, along with specific angular conditions.

This analysis resulted in the observation of 4 electron neutrino (ν_e) CC interaction candidates with 5.2σ significance and 8 ν_μ CC interaction candidates with 5.7σ significance (Figure 8). This also represents the first direct observation of electron neutrinos at the LHC.

FASERν also performed the first measurements of neutrino interaction cross sections in the TeV energy range. The interaction cross section per nucleon is measured over an energy range of 560-1740 GeV for ν_e and 520-1760 GeV for ν_μ. In these energy ranges, the neutrino-antineutrino combined cross sections, $\sigma_{\mathrm{obs}} E_\nu$, are constrained 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. The measured cross sections were consistent with SM predictions. This analysis is based on only ~1.7% of the data collected and demonstrates the capabilities of FASERν for precision neutrino physics at the LHC.

7. Future Prospects

In the search for ALPs with FASER, given that neutrinos are the main background and considering the uncertainties of the neutrino flux in the forward direction, background will be dominant for the future analysis. Therefore, the preshower detector is being updated with a new design incorporating tungsten plates and four detection layers based on Monolithic Active Pixel Sensors (MAPS) produced in 130 nm SiGe BiCMOS technology [13]. The high position resolution of the new preshower detector will allow the separation of collimated photon pairs, previously observed as single electromagnetic showers, significantly reducing neutrino background events. Figure 10 shows the expected sensitivity with the upgraded detector. Thanks to the photon pair separation capabilities, the sensitivity to ALPs can be significantly enhanced in future analysis.

Building on the success of FASER in demonstrating the physics potential of the forward region, the Forward Physics Facility (FPF) at the High-Luminosity LHC is proposed to construct a dedicated

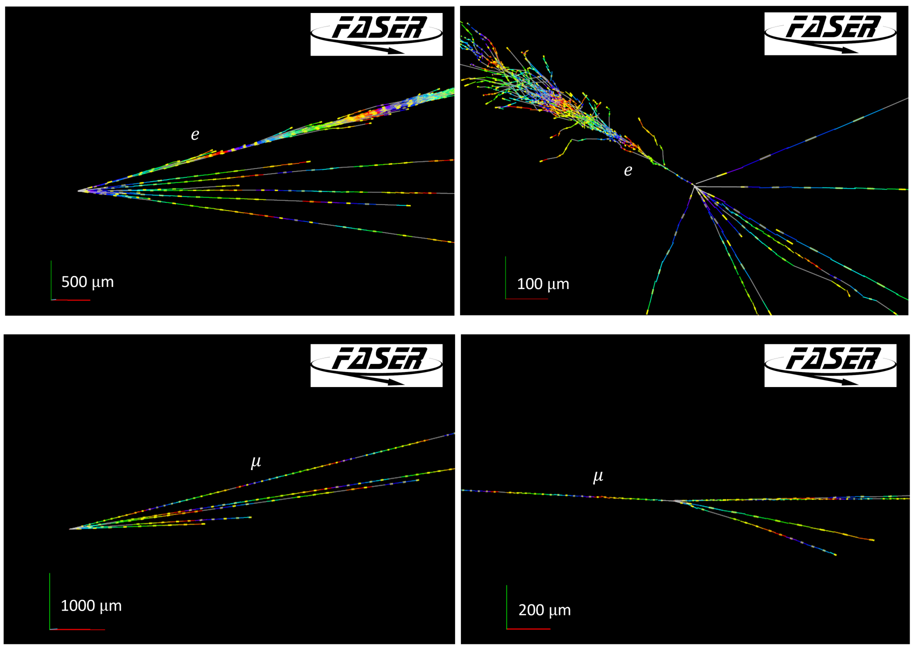

Figure 8: Event displays of one of the ν_e CC candidate events (top) and one of the ν_μCC candidate events (bottom) [12]. In each panel, the right-handed coordinate axes are shown in the bottom left, with red, green, and blue axes indicating the x (horizontal), y(vertical), and z (beam) directions, respectively.

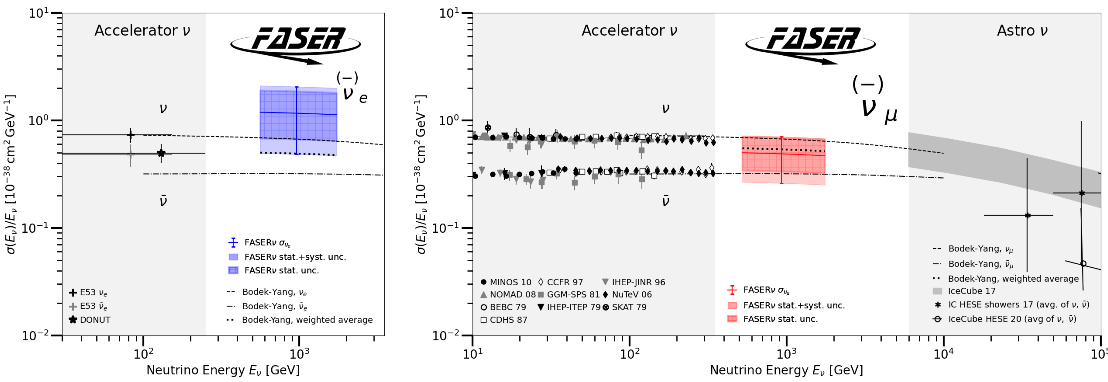

Figure 9: The measured cross section per nucleon for ν_e (left) and ν_μ(right) [12]. The dashed contours labeled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, as implemented in GENIE. Note that the displayed experiments do not all use the same targets.

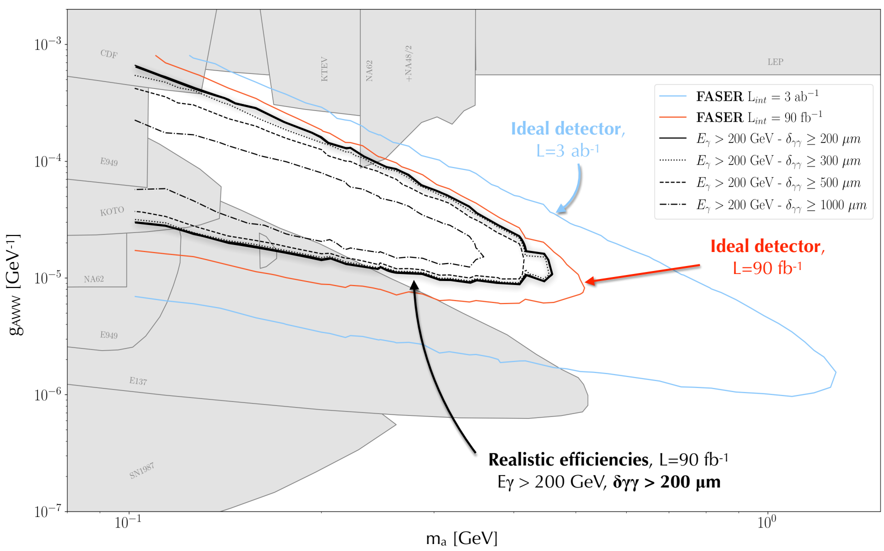

Figure 10: Sensitivity reach of the FASER W-Si preshower in the ALP parameter space [13]. The blue and red lines show the sensitivity reach for an ideal detector with 100% photon-pair reconstruction efficiency for the Run 3 (90 fb^{-1}) and HL-LHC (3 ab^{-1}) expected integrated luminosities for 14 TeV collision energy. The black lines show the sensitivity reach for 90 fb^{-1} of data including simulated efficiencies for photon-pairs with $E_\gamma > 200$ GeV and various values of the diphoton separation δ_γ. The grey-shaded regions represents the parameter space currently excluded by the other experiments.

facility to host multiple experiments aimed at exploiting physics opportunities in the far-forward region [14]. Figure 11 shows the sketch of the proposed FPF. It will provide a larger space with improved infrastructure, allowing for more sophisticated and large detector systems and expanded physics programs.

The FPF neutrino detectors (FASERν2 and FLArE) study interactions of all three neutrino flavors in the TeV energy range. $\mathcal{O}\left(10^3\right)$ tau neutrino (ν_τ) and anti-tau neutrino($\bar{\nu}_\tau$) interactions are expected in the neutrino detectors. The measurement of the neutrino flux at the FPF provides unprecedented access to both the very low-x gluon parton distribution function (PDF) regions, which are sensitive to BFKL effects and non-linear dynamics in Quantum Chromodynamics, and very high-x PDF regions, including investigation of intrinsic charm. Furthermore, the FPF acts as a neutrino-induced deep-inelastic scattering (DIS) experiment, offering valuable complementary data on the partonic structure of nucleons and nuclei to the upcoming Electron-Ion Collider. The FPF facilitates interdisciplinary studies by improving the modeling of high-energy hadronic interactions in the atmosphere, reducing uncertainties in air shower measurements and aiding in the understanding of cosmic ray properties. Additionally, it helps to understand the atmospheric neutrino flux, which is a crucial background for astrophysical neutrino searches in multi-messenger astrophysics.

The proposal for the FPF is being developed through a collaborative effort involving members of the FASER collaboration and other physicists interested in forward physics. The facility would represent a significant addition to the LHC physics program, complementing the physics potential of the LHC experiments.

8. Conclusions

FASER has successfully demonstrated its capabilities for both new physics searches and high-energy neutrino measurements at the LHC. The first results presented in this paper include searches

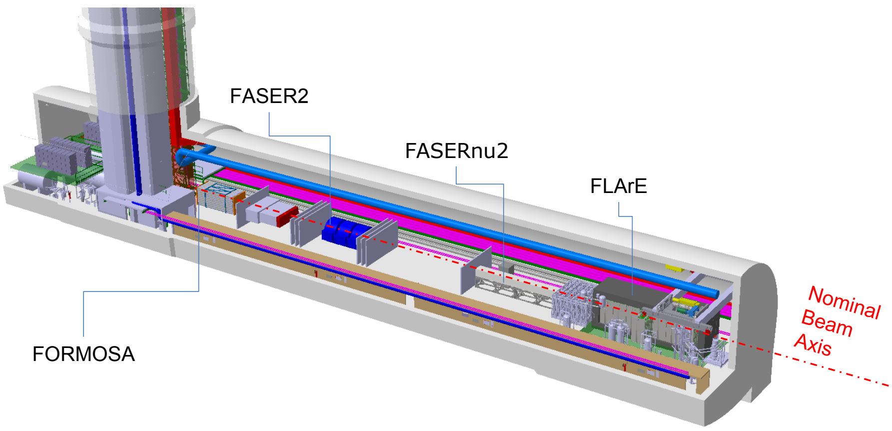

Figure 11: A sketch of the FPF, which houses multiple experiments (FASER2, FASERν2, FLArE and FORMOSA). The FPF is excavated with a new shaft and new cavern, providing 65 m of space along the beam collision axis.

for dark photons and axion-like particles, which have set new constraints on these potential mediators to dark sectors. FASER achieved the first direct observation of collider neutrinos, including both muon and electron neutrinos. The FASERν detector provided the first measurements of electron neutrino and muon neutrino interaction cross sections in the TeV energy range. These results establish techniques for studying forward neutrino production at hadron colliders.

The FPF at the High-Luminosity LHC is a proposed dedicated facility building on FASER's success in the far-forward region to host multiple experiments, exploiting physics opportunities in the far-forward region . The FPF will enable crucial studies of neutrino interactions, fundamental QCD and weak interaction investigations, and provide complementary data for nucleon structure studies. Moreover, it will foster interdisciplinary research in astroparticle physics. The FPF represents a significant enhancement to the LHC physics program, expanding our understanding of fundamental physics.

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