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FASER experiment and first results from LHC run 3

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Abstract

FASER is designed to search for light, extremely weakly interacting and long-lived beyond standard model particles at the CERN Large Hadron Collider. Such particles, e.g., dark photons, may be produced in the high-energy proton-proton collisions at the ATLAS interaction point and then decay to visible particles in FASER, which is placed 480 m downstream and aligned with the collision axis line-of-sight. The detector covers a previously unexplored range of pseudorapidity larger than 8.8, which allows it to have sensitivity to new physics in the far-forward region. FASER also has a sub-detector called FASERν, which is specifically designed to detect and investigate high-energy collider neutrino interactions in the TeV regime, extending current cross-section measurements. In this proceeding, the FASER detector and present recent results obtained during LHC Run 3 will be introduced.

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1 Introduction

Proton-proton (pp) collisions at the Large Hadron Collider (LHC) can provide unprecedented access to exploring high-energy neutrinos and dark sectors including dark photons and other long-lived particles (LLPs). Such collisions produce a large number of hadrons with low transverse momentum along the beam direction, carrying a substantial fraction of the proton's energy. These hadrons upon decaying, generate an intense, narrowly focused beam of high-energy neutrinos of various flavors, propagating in the forward direction. Consequently, the LHC functions as a TeV-scale neutrino beamline. Moreover, if dark photons interact with Standard Model (SM) particles, they could potentially be produced in high-energy pp collisions at the LHC, establishing it as a dark photon factory.

The ForwArd Search ExpeRiment, FASER, is designed to search for light, extremely weakly interacting and long-lived beyond standard model particles and study the interactions of high energy neutrinos at the CERN LHC [1]. The FASER detector is strategically positioned about

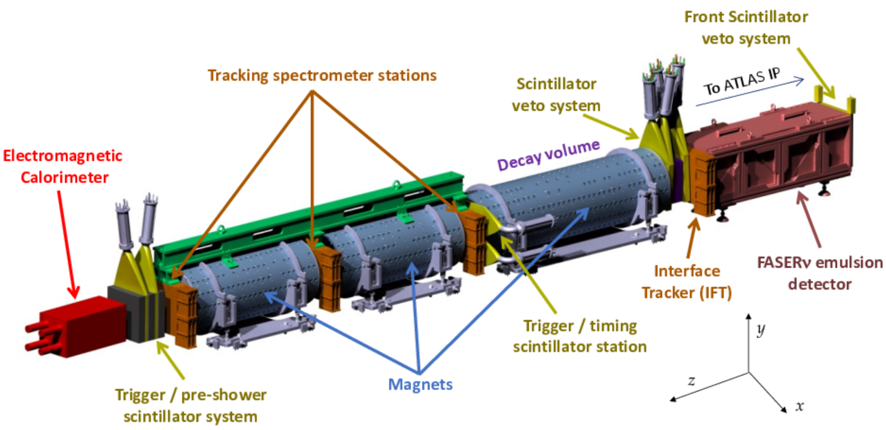

Figure 1: A schematic view of the FASER detector [2].

480 meters away from the ATLAS interaction point (IP), aligned precisely with the beam collision's line-of-sight. Most SM particles generated at the ATLAS IP, with the exception of muons and neutrinos, are either diverted by the LHC's powerful magnets or stopped in the 100 m of rock and concrete. This location provides unique opportunities to access the neutrino beam and study its properties as well as detecting dark photons and other LLPs that are hypothesized to be produced at IP.

1.1 FASER detector

The FASER detector system is composed of FASERν neutrino detector and the main spectrometer as depicted in Figure 1. The FASERν detector consists of 730 layers of emulsion films interleaved with 1.1 mm-thick 25 cm by 30 cm tungsten plates, with a total mass of 1.1 tons. It is followed by a magnetic system that includes three dipole magnets generating a 0.57 T magnetic field, three tracking stations, and electromagnetic calorimeter, placed at the back of the detector to measure the energy of particles traversing the detector. The initial 1.5 m-long magnet serves as a decay volume for long-lived particles. In addition, the so-called timing scintillator station, located between the decay volume and the front of the first tracking station, is used primarily for triggering. An interface silicon tracker links the emulsion and electronic components of the detectors, allowing a combined analysis as well as the muon charge identification, hence allowing to distinguish ν_μ and $\bar{\nu}_\mu$ interactions. Moreover veto station located at the upstream of FASERν detector helps to identify incoming muons and distinguish muon induced background from neutrino interaction events. A detailed description of the FASER detector can be found elsewhere [2].

1.2 FASER performance

In 2022, FASER's data acquisition was consistently automated, with a trigger rate of 1 kHz dominated by signals from high-energy muons. The system's efficiency was slightly compromised by an average deadtime of 1.3% and a few system crashes, leading to a recorded luminosity that was 96.1% of the expected total. From June 2022 to August 2023, nearly 70 fb^{-1} of data was collected. To mitigate high track densities (O(10^6) tracks/cm^2), the FASERν detectors were replaced every 20-30 fb^{-1} during the LHC's technical stops. This maintenance strategy was critical in managing the data quality. Throughout this period, the FASER spectrometer successfully captured over 350 million single muon events.

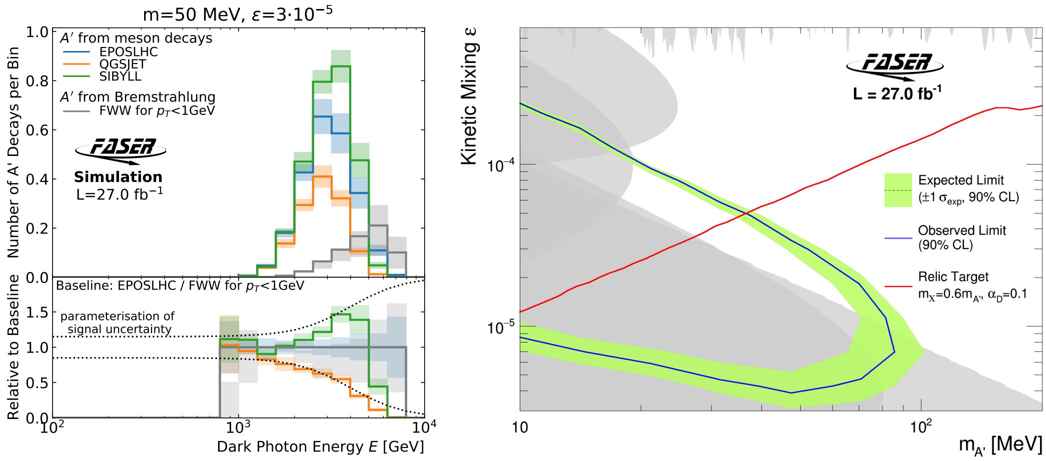

Figure 2: Left: Energy spectrum of dark photons in FASER. Right: 90% confidence level exclusion countours in the dark photon parameter space [3].

2 Dark photons search in FASER

Dark photons, envisioned as lightweight, weakly (or feebly) interacting spin-1 vector bosons, are theorized within hidden sector models, acting as mediator between the dark sector and the SM through kinetic mixing, ϵ. Potentially produced in large numbers (up to 10^8) in pp collisions at the LHC, these long-lived particles could travel hundreds of meter of distances before decaying into charged particle pairs. At the LHC, the dominant source of dark photons is SM meson decay ($\pi^0 \to A'\gamma$, $\eta \to A'\gamma$) and dark bremsstrahlung ($pp \to ppA'$). For the dark photon masses in the range of $2m_e < m_{A'} < 2m_\mu$, they exclusively decay into e^+e^- pairs, with $Br(A' \to e^+e^-) \approx 100\%$.

Thanks to FASER's detection capabilities and its precise location, largely determine its sensitivity, it covers the parameter space with $m_{A'} \sim 10-100$ MeV and $\epsilon \sim 10^{-5} - 10^4$ for TeV dark photon. Figure 2 shows the energy spectrum of dark photons in FASER estimated by modelling meson production in different generators.

Data collected in 2022 during LHC Run 3, corresponding to an integrated luminosity of 27.0 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 13.6$ TeV, used for dark photons search [3]. The search strategy involved stringent event selection criteria, including the absence of signals in the veto scintillator systems, the presence of two high-quality reconstructed charged particle tracks, and a minimum of 500 GeV energy deposition in the calorimeter. No events were detected in the unblinded signal region that met the selection criteria, with an expected background of $(2.3 \pm 2.3) \times 10^{-3}$ events. Consequently, FASER was able to set exclusion limits at the 90% confidence level, ruling out dark photon models in the range of $\epsilon \sim 4 \times 10^{-6} - 2 \times 10^{-4}$ and $m_{A'} \sim 10-80$ MeV as illustrated in Figure 2.

3 Neutrino physics in FASER

Positioning the FASER detector along the beam collision axis, covering pseudorapidity larger than 8.8, maximizes the flux of all three neutrino flavors. It allows FASERν to comprehensively explore neutrino production mechanism, their propagation, and interactions at the energy frontier [4]. In Run 3, with 250 fb^{-1} integrated luminosity, FASERν is expecting to collect about 3000 ν_e, 10000 ν_μ, and 70 ν_τ. It will significantly expand the neutrino cross-section measurements to higher energies for both electron and tau neutrinos. Additionally, FASERν

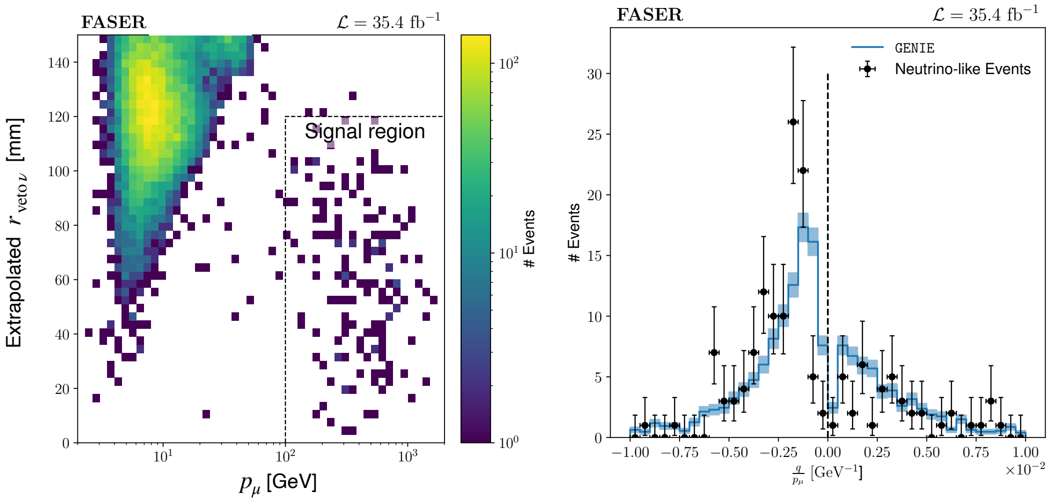

Figure 3: Left: Signal region [5].

will fill the gap in muon neutrino cross-section data between existing accelerator experiments (E_ν < 350 GeV) and IceCube observations (E_ν > 6.3 TeV). Furthermore, comparing cross-sections across all three flavors will provide a crucial test of lepton universality in neutrino interactions. Further details are available elsewhere [4].

3.1 Neutrino search using FASER spectrometer

A subsample of a data, corresponding to a total luminosity of (35.4±0.8) fb^{-1}, collected at $\sqrt{s}$=13.6 TeV between July and November 2022 were analysed to detect charged-current (CC) interactions of ν_μ and $\bar{\nu}_\mu$ by studying muon tracks reconstructed by the spectrometer [5]. FASERν detector is used as a target for CC neutrino interactions, and the active electronic detector components of FASER is used to identify muon neutrino candidates. Selection criteria were stringent: no activity in the initial scintillator station and at least one MIP's energy deposition in two additional stations, with consistent timing and pre-shower counter readings. The tracks were required to be within a 95 mm radius from the magnet center, with momentum over 100 GeV/c and an angle under 25 mrad from the beam center.

The interaction with the tungsten-emulsion detector is simulated using the GENIE event generator using the neutrino energy spectra. About 151±41 neutrino events $\nu_\mu(\bar{\nu}_\mu)$CC interactions expected, where the uncertainty is given by the difference between generators (DPMJET and SIBYLL). The main background to neutrino signatures originates from the high energy muons scattering in the tungsten and/or bending in the magnetic field, estimated to be 0.08±1.83 events. Additionally, neutral hadron interactions in FASERν producing charged particles with a momentum of more than 100 GeV, estimated to be 0.11±0.06 events. Figure 3 shows the selected events, as well as the signal region. A clear charge separation in q/p_μ for the reconstructed tracks is also observed. A total of 153 neutrino event are observed by opening blind analysis with a significance of 16 standard deviations over the background only hypothesis.

3.2 Neutrino search in FASERν

FASERν aims to explore neutrino interactions in a high-energy domain that has not been extensively studied before. Using high-resolution capabilities of its emulsion detector, FASERν can accurately identify electron and muon leptons from neutrino interactions. Electrons are

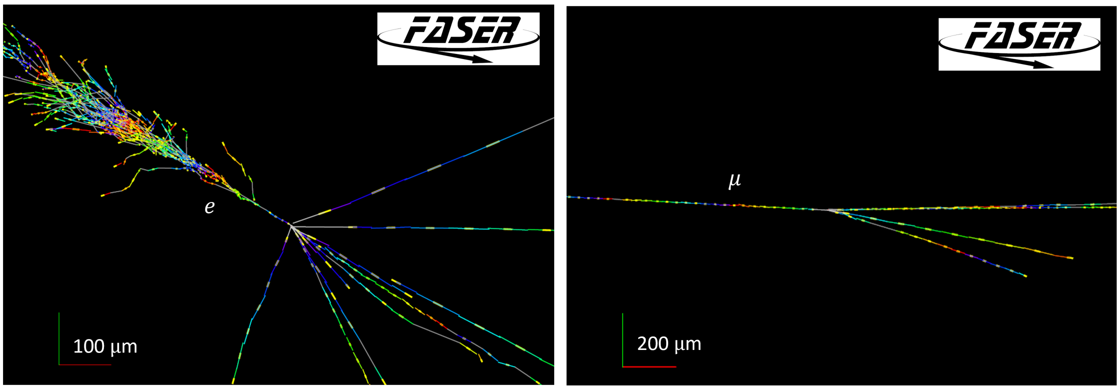

Figure 4: Event displays of ν_e and ν_μ candidates [6].

detected through their associated electromagnetic showers. Thanks to Tungsten's short radiation of 0.35 cm, these shower remains compact and ease their reconstruction by detecting track segments within a 100μm radius cylinder around it's axis. The electron energy is estimated by counting track segments at the shower maximum with a resolution of about 25% at 200 GeV and between 25-40% at higher energies. Muons are identified by their extended tracks in the detector, and their momentum is estimated by multiple Coulomb scattering, with a resolution of 30% at 200 GeV, increasing to 50% at higher energies [6].

During the LHC Run3 from July to September 2022, FASERν accumulated data equivalent to 9.5 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 13.6$ TeV, used to search for neutrino vertices. Neutrino search was performed on a subset of the FASERν detector volume, corresponding to a target mass of 128.6 kg. Within this analyzed volume, the expected numbers of neutrino interaction events without any selection cuts are 8.5, 43.6 and 16.5 events for ν_eCC, ν_μCC, and NC, respectively [6].

After applying stringent selection criteria, such as requiring electrons with reconstructed energy above 200 GeV, four high energy electron neutrino candidates were found, with a background expectation of 0.025±0.015. This resulted a statistical significance of 5.2σ, marking the first direct observation of high energy electron neutrino interactions at a particle collider. Furthermore, eight muon neutrino interaction candidates were detected, with a background expectation of 0.22±0.09, leading to a statistical significance of 5.7σ. Figure 4 illustrates the event displays for ν_e and ν_μ candidates, both showing a back-to-back topology between the lepton candidate and other tracks at the interaction point.

4 Conclusion

The FASER experiment at the LHC is designed to explore forward physics, enabling the search for long-lived particles like dark photons and the study of TeV neutrinos from *pp* collision with 13.6 TeV in the center-of-mass energy. During the first year of the LHC Run 3, the FASER detector operated efficiently and successfully collected data. Subsamples of the recorded data were used to search for dark photons and to study LHC neutrinos both using the FASER spectrometer and FASERν neutrino detector. FASER has provided constraints on previously unexplored dark photon parameter space; ruling out models in regions of low mass and kinetic mixing, probing new territory in the interesting thermal relic region. Furthermore, FASER has achieved the first direct detection of neutrinos produced at the LHC utilizing the FASER spectrometer and FASERν detector. These results represent the beginning of FASER's extensive physics program, which targets both beyond the Standard Model physics and neutrino physics.

Moreover, a significant upgrade to FASER is planned as a part of the Forward Physics Facility (FPF), proposed at the high-luminosity LHC [7]. By upgrading to ten-tonne-scale detectors, FASER2 and FASERν2 will be able to improve the sensitivity for beyond Standard Model particles, feebly interacting, dark photons, ALPs, as well as neutrino physics by increasing statistics for all flavor; $\mathcal{O}(10^5)$ ν_e, $\mathcal{O}(10^6)$ ν_μ and $\mathcal{O}(10^4)$ ν_τ interactions with energies from $\mathcal{O}$(100GeV) to a few TeV.

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