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Search for Beyond Standard Model Physics with FASER at the LHC

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FASER (the Forward Search Experiment) is a compact detector located about 480 m downstream of the ATLAS interaction point at CERN's Large Hadron Collider (LHC). It is designed to explore new Beyond the Standard Model (BSM) physics by searching for light, weakly interacting, and long-lived particles (LLPs) produced in the far-forward region. This unique setup—shielded by approximately 100 m of rock and concrete—enables FASER to perform highly sensitive searches for exotic states such as dark photons (A) and axion-like particles (ALPs), potentially mediating interactions between the visible and dark sectors. During Run 3 (2022–2024), FASER has recorded 190 fb of data with over 97% efficiency, and A dark photon and ALP searches are performed. We will present these physics results, probing previously unexplored mass and coupling ranges. FASER is now planning an upgrade of its preshower sub-detector to improve diphoton resolution and background discrimination, aiming for enhanced sensitivity in upcoming ALP and other new physics searches. With continued data collection through Run 3 and a substantially increased data set during the High-Luminosity LHC era (Run 4), FASER will further extend its discovery potential for long-lived particles and other novel BSM signatures. In this talk, we will present the status of the experiment, including detector design, detector performance, and physics results of new particle searches from Run 3 data.

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1. Introduction

The search for new physics beyond the Standard Model remains one of the central goals of high-energy particle physics. While traditional collider experiments have focused primarily on heavy particles with strong or electroweak-scale interactions, a growing framework of theoretical and experimental work has highlighted the importance of exploring the light and weakly coupled frontier [1]. In particular, long-lived particles (LLPs) with masses in the MeV to GeV range and feeble interactions may have escaped detection in conventional detectors due to their long lifetimes and forward kinematics. The FASER (ForwArd Search ExpeRiment) experiment at the LHC [2] is designed to address this gap by targeting light LLPs produced in the far-forward region of proton-proton collisions. Located 480 m downstream from the ATLAS interaction point, FASER leverages a low-background environment and high luminosity to search for new particles such as dark photons [3] and axion-like particles [4]. These particles are motivated by extensions to the Standard Model involving hidden sectors, which could play a crucial role in dark matter, or the hierarchy problem [5].

2. New Particle Searches at FASER

FASER is uniquely sensitive to new light particles produced with low transverse momentum and high boost in the forward direction. Many theoretically motivated models predict such signatures [6]. Among these, two prominent benchmark cases are dark photons (A') and axion-like particles (ALPs), which appear in a wide range of hidden sector and UV-completion scenarios. Dark photons are massive gauge bosons associated with a hypothetical $U(1)_D$ gauge symmetry. They can kinetically mix with the Standard Model photon via a small dimensionless parameter ϵ, allowing them to be produced in meson decays or bremsstrahlung processes. If long-lived, dark photons can decay into visible final states such as e^+e^- within the FASER detector volume. The experiment is thus sensitive to dark photons in the mass range from ~10 MeV to ~1 GeV and mixing parameters as small as $\epsilon \sim 10^{-5}$. Axion-like particles are pseudoscalar bosons that couple to gauge boson field strengths [7]. In models where the ALP couples to electroweak gauge bosons, the primary production mechanism at the LHC involves flavor-changing decays of heavy mesons such as B hadrons. These ALPs can subsequently decay into photon pairs, producing a distinctive di-photon signature in the FASER calorimeter. FASER's geometry and granularity enable efficient detection of such events, even for masses in the sub-GeV range. Together, these searches allow FASER to explore previously inaccessible regions of parameter space and provide complementary coverage to other experiments. The results presented here are based on data collected during Run 3 and represent significant steps toward discovering physics beyond the Standard Model through forward LLP searches.

3. FASER Detector

The FASER detector is a cylindrical apparatus with a diameter of approximately 20 cm and a length of around 7 m, as illustrated in Fig. 1. It is composed of the following key components:

1. **FASERν Emulsion Detector**
   This module serves as the neutrino target and consists of 730 layers, each made of 1.1 mm thick tungsten plates interleaved with nuclear emulsion films [8]. The total mass of this component is approximately 1.1 tons.

2. **Veto Scintillator System**
   Positioned at the front of the detector, this system is designed to suppress background events by identifying and rejecting incoming charged particles, such as cosmic muons.

3. **Tracking Stations**
   The detector contains four tracking stations. Each station includes three layers, with every layer composed of eight ATLAS Semiconductor Strip Tracker (SCT) modules [9, 10]. These layers enable precise measurement of the momentum and trajectories of charged particles produced in the decay of long-lived particles (LLPs). The tracker station immediately downstream of FASERν is known as the Interface Tracker (IFT), and it links tracks from the emulsion detector to the downstream spectrometer.

4. **Permanent Dipole Magnets**
   Two magnets generate a uniform magnetic field of 0.55 T. These fields bend charged particle tracks, allowing for the separation of oppositely charged decay products of LLPs.

5. **Timing and Trigger Scintillators**
   Scintillator layers provide precise timing information and are used to trigger events. They ensure that LLP decays occur within the detector's fiducial volume [11].

6. **Electromagnetic Calorimeter (ECAL)**
   The ECAL consists of four modules originally developed for the LHCb experiment's outer ECAL [12]. It serves to distinguish electrons from muons by measuring the energy deposited by particles.

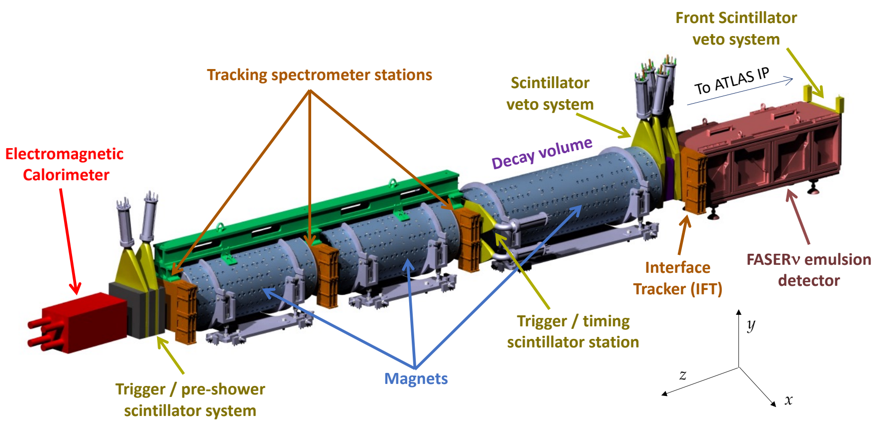

Figure 1: A schematic view of the FASER detector [2]

4. Data Analysis

4.1 Axion-like Particles (ALPs)

The analysis targeting axion-like particles (ALPs) focuses on the decay channel $a \to \gamma\gamma$, motivated by models in which the ALP couples to electroweak gauge bosons. The dataset corresponds to an integrated luminosity of 57.7 fb^{-1} recorded during LHC Run 3 at a center-of-mass energy of $\sqrt{s}$ = 13.6 TeV. Signal events are expected to manifest as highly collimated di-photon showers without associated charged tracks shown in Fig. 2. Such events yield a large electromagnetic energy deposit in the calorimeter while producing minimal activity in the tracking and scintillator systems. To suppress backgrounds, events are selected to have no significant signals (below 0.5 MIP) in the VetoNu, Veto, and Timing scintillators. The preshower response must be consistent with an electromagnetic shower profile, based on the charge collected in each layer and their ratio. Additionally, the ECAL energy is required to exceed 1.5 TeV, and the event timing must be consistent with a valid bunch crossing at the ATLAS interaction point. The dominant background arises from neutrino interactions in the preshower layers, particularly from electron and muon neutrinos. This background was estimated using a combination of POWHEG+Pythia and EPOS-LHC to model forward hadron production, while GENIE was used to simulate neutrino interactions. The total expected background in the signal region is 0.42 ± 0.38 events. Other potential sources, such as neutral hadrons, cosmic rays, and detector inefficiencies, were studied and determined to be negligible.

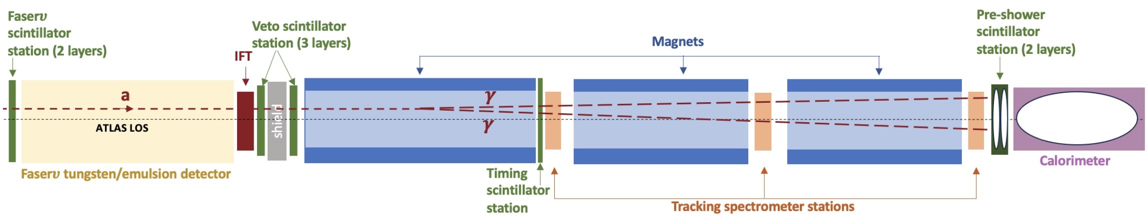

Figure 2: Sketch of an ALP traversing through the FASER detector [4].

4.2 Dark Photons

The dark photon analysis is based on a dataset of 27.0 fb^{-1} collected during the latter half of 2022. The analysis targets the decay mode $A' \to e^+e^-$, where the resulting electron and positron produce two high-momentum tracks and a large electromagnetic deposit in the calorimeter as shown in Fig. 3. Candidate events are selected by requiring two well-reconstructed tracks with momentum greater than 20 GeV, both fully contained within the fiducial tracking volume. To ensure no missed veto activity, the extrapolated positions of the tracks must also fall within the acceptance of the upstream veto detectors. A minimal ECAL energy of 500 GeV is required, and no significant activity must be present in the veto scintillators. A blind analysis strategy was implemented, with the signal region defined as events having ECAL energy above 100 GeV and no veto signals. All selection criteria were finalized before unblinding the data. The expected backgrounds primarily consist of neutrino-induced interactions and neutral hadrons entering the detector from upstream. Neutrino backgrounds were estimated using a large simulation sample equivalent to 300 ab^{-1}, yielding an expectation of 0.0018 ± 0.0024 events. The contribution from neutral hadrons, largely originating from muon-induced showers in upstream rock, was estimated to be $(2.2 \pm 3.1) \times 10^{-4}$ events. The total background expectation is 0.0020 ± 0.0024 events.

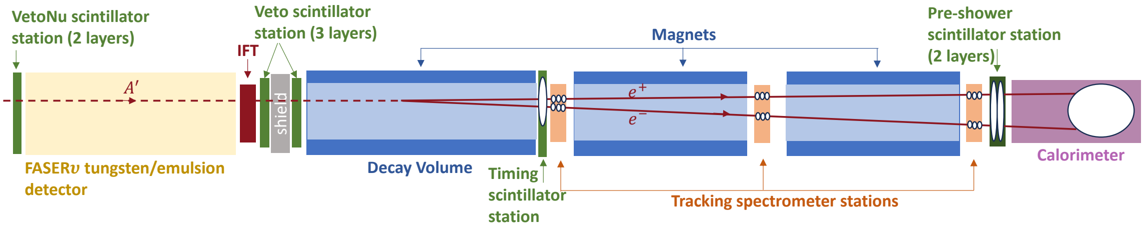

Figure 3: A sketch presenting a side view of the FASER detector [3].

5. Results

5.1 Axion-like Particles (ALPs)

After unblinding the signal region, one candidate event with an ECAL energy of 1.6 TeV was observed. This is consistent with the background expectation and does not constitute a significant excess. As a result, exclusion limits were set at 90% confidence level in the m_a–g_{aWW} parameter space. The analysis excludes previously unexplored ALP masses between 60 and 300 MeV and coupling strengths down to $g_{aWW} \sim 10^{-4}$ GeV^{-1}. The results were also reinterpreted in the context of alternative new physics scenarios involving final states with multiple photons, including ALPs coupled to photons or gluons, $U(1)_B$ gauge bosons, and scalar particles coupling to up-quarks, extending the reach of the FASER experiment into new theoretical territory, as shown in Fig. 4.

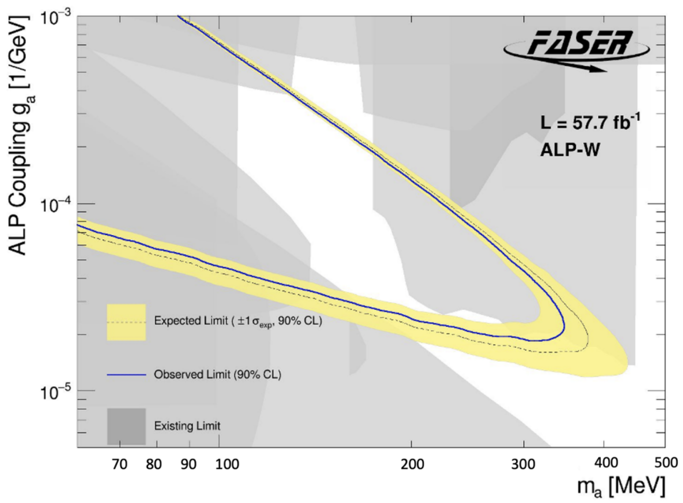

Figure 4: The 90% confidence level exclusion contour on the ALP model parameter space. [4].

5.2 Dark Photons

In the dark photon analysis, no events were observed in the blinded signal region after applying all selection criteria. Given the extremely low expected background, this null result allows the setting of strong exclusion limits at 90% confidence level. The analysis excludes dark photons with masses between 10 and 80 MeV and kinetic mixing parameters ϵ in the range of 10^{-5} to 2×10^{-4}. These constraints probe new regions of parameter space and provide complementary coverage to other existing experiments, as shown in Fig. 5. The excluded region also intersects with theoretically motivated scenarios involving thermal relic dark matter, demonstrating the relevance of FASER's forward physics program in the broader context of dark sector searches.

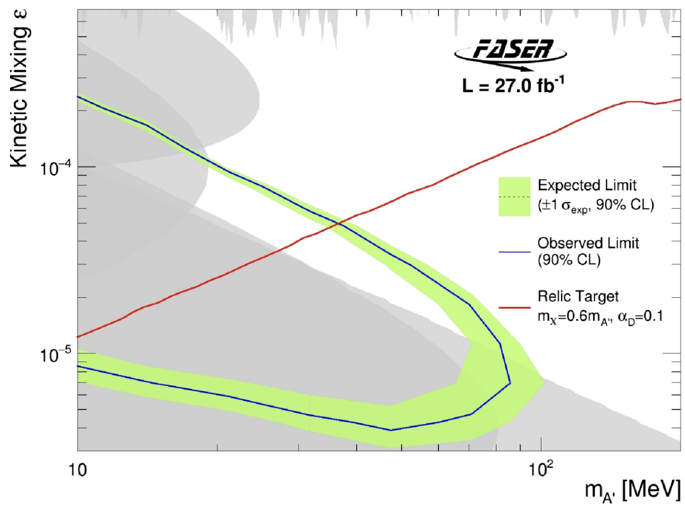

Figure 5: The 90% confidence level exclusion contour on the dark photon model parameter space. The red line represents the parameter space of the thermal relic dark matter model [3, 13].

6. Summary

We presented searches for axion-like particles and dark photons using FASER Run 3 data. The ALP analysis, based on 57.7 fb^{-1}, observed one event consistent with background and excluded new regions in the m_a–g_{aWW} plane. The dark photon search, using 27.0 fb^{-1}, found no events and set strong constraints in the $m_{A'}$–ϵ parameter space. Both analyses probe unexplored territory and demonstrate FASER's capability to search for long-lived particles in the forward region. Future data and upgrades will further enhance sensitivity to dark sector physics.

Acknowledgments

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