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Looking Forward to New Physics at Dark Sectors with the FASER experiment at the LHC

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FASER, the ForwArd Search ExpeRiment, is the newest experiment at CERN's Large Hadron Collider (LHC) and it is designed to be complementary to the LHC's ongoing physics program, extending its discovery potential to light and weakly-interacting particles that may be produced at the LHC in the far-forward region. It is uniquely situated around 480 m from the ATLAS detector and will be able to detect the decays of long-lived dark photons or axion-like particles with masses in the MeV to GeV range, which are thought to act as a mediator between the particles that make up ordinary matter and a new dark sector. Such a new particle of a dark sector has attracted growing interest because it can yield dark matter with the correct relic density. 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. In the first year of run3, we have already collected data delivered from 40 fb^{-1} (inverse femtobarns) of proton-proton collisions with a center-of-mass energy of 13.6 TeV. We will present the status of the experiment, including detector design, detector performance, and first physics results of new particle searches from Run 3 data.

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1. Introduction

New particles with light masses from MeV to GeV that interact feebly with the standard model particles have been attracting attention in recent years as candidates for new physics beyond the standard model. The FASER (ForwArd Search ExpeRiment) is a new experiment aiming at the search for light, long-lived new particles generated in the forward direction from proton-proton collisions at the LHC (Large Hadron Collider) of CERN, and research into the TeV neutrinos [1]. The detector is installed 480 meters downstream from the LHC proton-proton beam collision point Fig. 1.

Dark matter particles with a mass of GeV - TeV energies that interact with standard model particles at the level of weak interactions are referred to as WIMPs. If dark matter is made up of WIMPs, it can successfully reproduce the amount of residual dark matter obtained from cosmic observations. This is known as the WIMP miracle [2]. On the other hand, even if the mass of dark matter is less than the GeV-scale, new light particles with masses ranging from MeV to GeV could exist as mediated particles for dark matter. If they mix weakly with standard model particles, such as photons, through mixing parameters, they can generate the observed density of dark matter, which is called “WIMP-less miracle [3]". There are several candidates for new particles that can realize the WIMP-less miracle. The benchmark model for the FASER experiment is a dark photon A', which is predicted by introducing the dark sector containing a U(1) electromagnetic force. Dark photons can decay into standard model particles by mixing with photons. Dark photons are characterized by their mass $m_{A'}$ and coupling parameter ϵ.

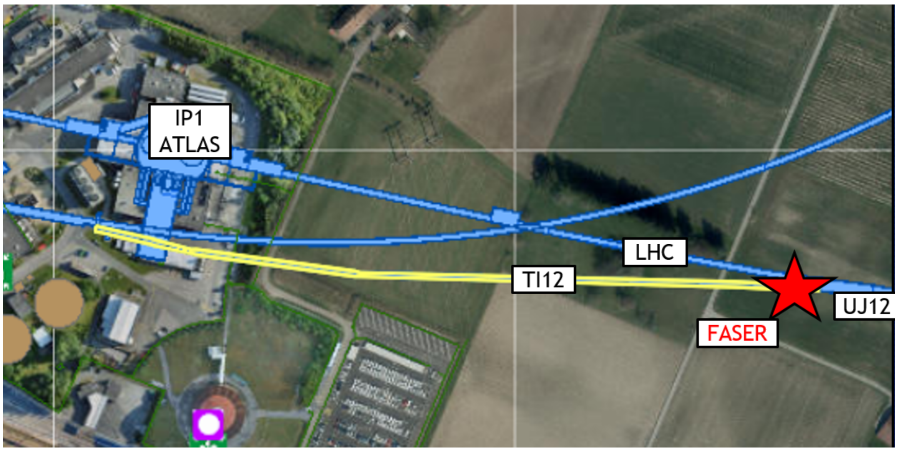

Figure 1: The FASER detector is located at TI12 tunnel in the LHC, which is 480 m downstream from the ATLAS interaction point [4].

2. FASER detector

The FASER detector is approximately 20cm in diameter and 7m in length as shown in Fig. 2. The detector components are as follows: (1) the FASERν emulsion detector [5]. This consists of 730 layers of 1.1 mm tungsten + emulsion neutrino target and its weight is 1.1 tons. (2) the veto scintillator system. This provides background rejection arising from charged particles like muons coming to the detector. (3) Four tracker stations. 3 layers per station with 8 ATLAS semiconductor strip tracker modules (SCT) [6, 7] in each layer. These provide the position and momentum measurements of charged particles from Long-lived particle decay. The station behind the FASERν is referred to as the interface tracker (IFT), and it is supposed to match tracks between the FASERν and the following spectrometer. (4) permanent dipole magnets. Their field strength is 0.55 T, and they separate the pair of charged particles originating from the decay of LLPs. (5) timing, and preshower scintillator system. These provide a trigger and ensure that LLPs decay inside the decay volume of the detector. (6) An electromagnetic calorimeter. They are consisted of 4 LHCb outer ECAL modules [8]. This makes a separation between muons and electrons by measuring the energy of the particles.

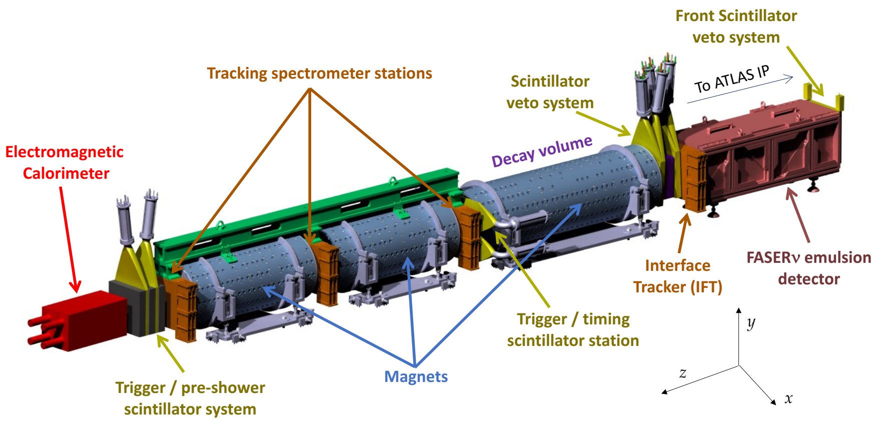

Figure 2: A schematic view of the FASER detector [4]

3. Datasets and Analysis

The LHC run 3 started in July 2022 and FASER has been taking data smoothly from the beginning with up to 1.3 kHz of the trigger rate. For this study, we used 27.0 fb^{-1} of collision data between September and November 2022. The ATLAS experiment provided the luminosity of the dataset. Event reconstruction was processed in FASER's Calypso offline software [9], based on the Atheta framework of the ATLAS experiment [10]. The range of FASER is typically between 10 and 100 MeV of the masses and between 10^{-5} and 10^{-4} of a coupling ϵ. Dark photons in the MeV-scale are expected to be produced by meson decays at the LHC tunnel though the process $\pi \rightarrow A'\gamma$, and also $\eta \rightarrow A'\gamma$ decays and dark bremsstrahlung $pp \rightarrow ppA'$ can contribute. For $E_{A'} \gg m_{A'} \gg m_e$ which represents the energy and mass of a dark photon and the mass of an electron, the decay length of the dark photon can be written as [11]:

$$d = c\beta\tau\gamma \sim (80\ m)\ B_e \left[\frac{10^{-5}}{\epsilon}\right]\left[\frac{E_{A'}}{\text{TeV}}\right] \tag{1}$$

In case the mass of the dark photon is 1 MeV$< m_{A'} <$ 211 MeV, the dark photn will decay into $e+e-$ pair with 100 % of the branching ratio. In this study, we searched for a pair of electrons inside the decay volume with trackers and a large energy deposit in the calorimeter. For this analysis, we used the simple and robust selection criteria for the performed blind analysis, which means we fixed and optimized the event selection before looking at the signal region of the data. Analysis was blinded events for $E > 100$ GeV where E is the deposited energy in the calorimeter without any veto signals. The selection criteria are as follows: (1) events in collision crossing, during good physics data period, (2) no signal in any of veto scintilators (< 40pC ~ 0.5 MIP. (3) timing and preshower scintillators consistent with ≥ 2MIPs, (4) Two good quality tracks with momentum p > 20 GeV, which requires both tracks should be in the fiducial tracking volume (r<95 mm) and both tracks should be extrapolated to r<95 mm in veto scintillators, (5) energy deposit inside the calorimeter E > 500 GeV. After all selections were applied, we found there are two major backgrounds, neutrino interaction in the detector and neutral hadron entering and decaying in the detector. The contribution from neutrino interaction is estimated with a large simulation sample, corresponding to 300 ab^{-1} and the estimated number is 0.0018±0.0024. The other contribution from neutral hadrons mainly originated from muon interactions in the rock upstream of the FASER detector and the majority of those events are suppressed by the FASERν tungsten. The estimated number of this background component is (2.2±3.1) $\times 10^{-4}$. In the end, the total expected background event is 0.0020±0.0024 events.

4. Results

After the background is estimated, no events are observed and Fig.3 shows that the energy distribution is measured by the calorimeter with the expected signals. We set constraints on the parameter space of dark photons at a 90 % confidence level. Fig. 4 shows the exclusion limits on the signal parameter space. In this analysis, we excluded models in the range $\epsilon \sim 1 \times 10^{-5}$ - 2×10^{-4} and masses ~ 10 MeV - 80 MeV, including the unexplored parameter regions ever. In the Fig. 4, an example of thermal relic dark matter is shown, assuming the dark photons couple to a light complex scalar dark matter field [12], which is interesting in terms of cosmological dark matter models.

5. Summary

The FASER experiment at the Large Hadron Collider at CERN is aimed for exploring forward physics, which allows searching for long-lived particles like dark photons and also studies TeV neutrinos [1] from a proton-proton collision with 13.6 TeV in the center-of-mass energy. During the LHC run3 starting in 2023, FASER successfully took data, running with fully functional and very good efficiency. With the first data taken in run3, we searched for dark photons and excluded the dark photon models in regions of low mass and kinetic mixing, which probes new territory in the interesting thermal relic region. This result demonstrates the FASER physics programme and more results are expected to come in the next years.

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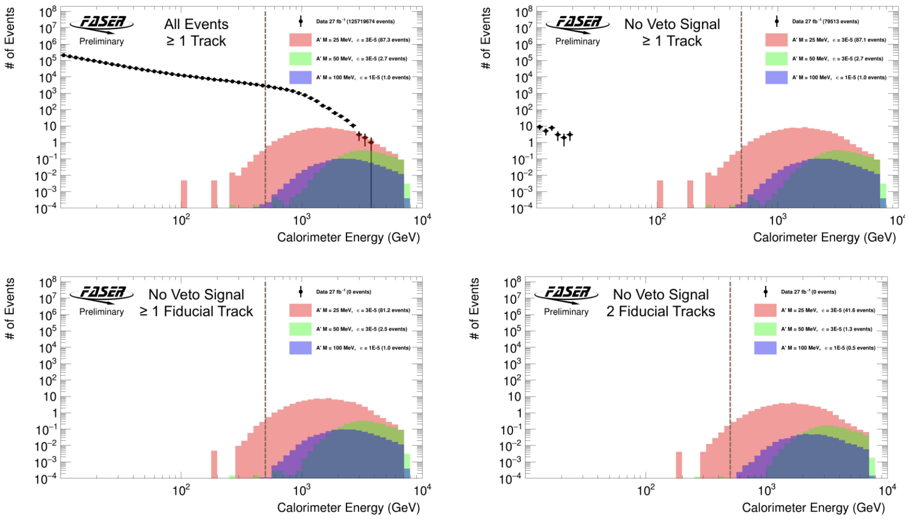

Figure 3: The energy distribution measured by the calorimeter after applying the various selection criteria to data and expected signals. (top left): reconstructed tracks, (top right): reconstructed tracks with no signal in the veto, (bottom left): fiducial tracks with no signal in the veto, (bottom right): two fiducial tracks with no veto signals.

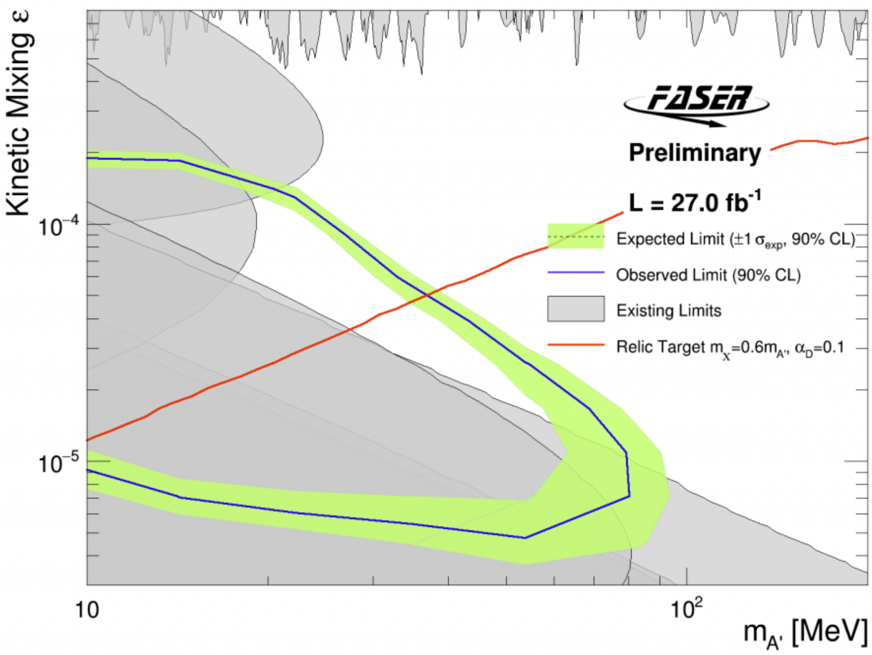

Figure 4: The 90% confidence level exclusion contour on the dark photon model parameter space. The red line represents the parameter space of the thermal relic dark matter model [12].

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