PROCEEDINGS OF SCIENCE

Searches for new physics with the FASER experiment

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FASER, the ForwArd Search ExpeRiment, is an LHC experiment located 480 m downstream of the ATLAS 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. FASER is designed to search for signatures of physics beyond the Standard Model, in particular new light and very weakly-interacting particles. This talk will briefly present the status of the experiment, including the detector design and performance, before summarising the first results of a search for dark photons. The search uses Run 3 data corresponding to an integrated luminosity of 27.0 fb^{-1}, and provides constraints on dark photons with masses $\sim 17-70$ MeV and couplings $\epsilon \sim 2\times10^{-5}-1\times10^{-4}$. The results are also interpreted in the context of a $\text{U}(1)_{\text{B-L}}$ model, where gauge bosons with masses in the range $\sim 15-40$ MeV and couplings $g_{\text{B-L}} \sim 5\times10^{-6} - 2\times10^{-5}$ are excluded.

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1. The FASER detector

FASER, the ForwArd Search ExpeRiment [1–4], is a relatively new detector designed to search for new light and weakly-interacting long-lived particles (LLPs) produced in collisions at the LHC. The detector is ~ 7 m long with an active transverse area given by a circle of radius 10 cm [4]. It is located in the unused TI12 service tunnel, 480 m away from the ATLAS [6] interaction point (IP1) along the collision axis. Charged particles originating from IP1 are deflected by the LHC magnets, whilst an additional shielding of 100 m of rock and concrete between the LHC beampipe and the FASER detector helps to further reduce potential backgrounds.

1.1 FASER design

A schematic of the FASER detector is shown in Figure 1. It consists of an emulsion detector for neutrino detection[1], a series of scintillator stations for triggering and rejection of events containing high energy muons, a tracking spectrometer for reconstruction of charged particle tracks, and a calorimeter system for electromagnetic (EM) energy measurements. A 1.5 m long decay volume is immersed together with the tracking spectrometer in a 0.57 T dipole magnetic field [4].

1.2 FASER performance

Data-taking was continuous and largely automatic throughout 2022. The trigger rate, dominated by signals from high energy muons in the scintillator and calorimeter systems, averaged around 1 kHz with a maximum of 1.3 kHz. An average deadtime of 1.3%, combined with a couple of system crashes, limited the recorded luminosity to 96.1% of the delivered value. A total luminosity of 27.0 fb^{-1} is used for the dark photon analysis, corresponding to data collected with calorimeter optical filters installed [5].

2. Dark photons at FASER

Dark photons are hypothesised spin-1 vector bosons that are a general feature of so-called "hidden sector" models. In such models, dark photons may act as mediators between a dark sector, containing a dark matter particle, and the Standard Model (SM). The dark photon A' could couple to SM fermions with a coupling strength determined by the kinetic mixing ϵ, with the Lagrangian given by [1]

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f, \tag{1}$$

where $m_{A'}$ is the dark photon mass and q_f is the charge of the SM fermion f. If the dark photon is additionally light and weakly-interacting, it would be an LLP and would travel a macroscopic distance before decaying. For dark photon masses in the range $2m_e < m_{A'} < 2m_\mu$, the branching ratio for decays to electron-positron pairs is $\sim 100\%$. The sensitivity of FASER is largely determined by its location, and for TeV dark photons covers the parameter space with $m_{A'} \sim 10 - 100$ MeV and $\epsilon \sim 10^{-5} - 10^{-4}$. The dominant production mechanism in this parameter space is via neutral pion decay, although contributions from η decay and dark bremsstrahlung can also be significant [1, 5].

[1] The emulsion detector is not directly used in the dark photon search, but provides additional background suppression via its eight interaction lengths of tungsten.

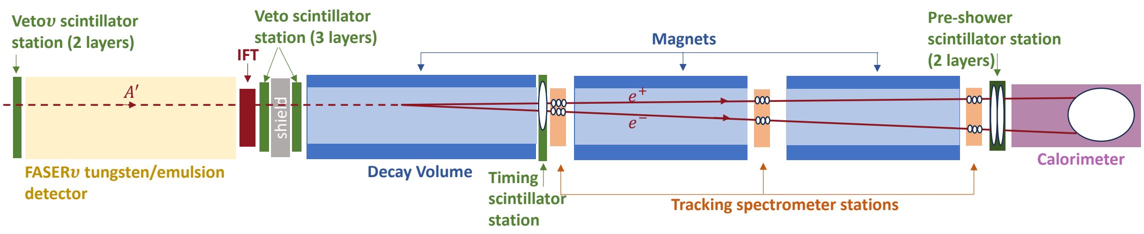

Figure 1: Schematic of the FASER detector showing the signature of a dark photon. The white areas indicate where detector signals would be expected, whilst the red lines correspond to reconstructed tracks.

3. Search for dark photons with FASER

FASER searches for dark photons that decay to an electron-positron pair [5]. Data with no signal in the VetoNu and Veto scintillator stations and a calorimeter energy larger than 100 GeV are blinded during the optimisation of the analysis selection.

3.1 Signal generation

Signal events are generated using `FORESEE` [7] with the `EPOS-LHC` generator [8] to model very forward pion and η production. The subdominant contribution from dark bremsstrahlung is also included. Systematic uncertainties on the number of signal events decaying in the FASER detector volume are estimated by comparing predictions using different generators to model forward hadron production. The envelope of the estimates is used to parameterise the uncertainty as a function of the energy. This parameterisation also encompasses the uncertainty on the dark bremsstrahlung prediction, as shown for an example signal point in Figure 2a.

3.2 Event selection

Events are selected to maximise the potential for discovery. The event time is required to be consistent with a colliding bunch at IP1. Backgrounds from high energy muons are effectively removed by requiring a signal in the VetoNu and Veto scintillators no larger than half of that expected from a MIP. The signal in the Timing and Pre-shower scintillators is required to be larger than or equal to that expected from two MIPs. Only events with exactly two tracks of high quality with a momentum larger than 20 GeV and a radius extrapolated to all scintillator and tracking stations smaller than 95 mm are considered. Finally an energy larger than 500 GeV is required in the calorimeter. The efficiency of the selection for signal events decaying in the decay volume is around 50% over the parameter space FASER is sensitive to.

3.3 Backgrounds

Potential inefficiencies in the VetoNu and Veto scintillator stations are investigated as a potential cause of backgrounds. The inefficiency is measured in data using muon events with tracks pointing back to the scintillator layers. The fraction of events with scintillator signals smaller than threshold is found to be $\mathcal{O}(10^{-5})$ per layer. The high efficiency of the scintillator layers combined with the signal region selection reduces the expected $\mathcal{O}(10^{8})$ muons to a negligible level.

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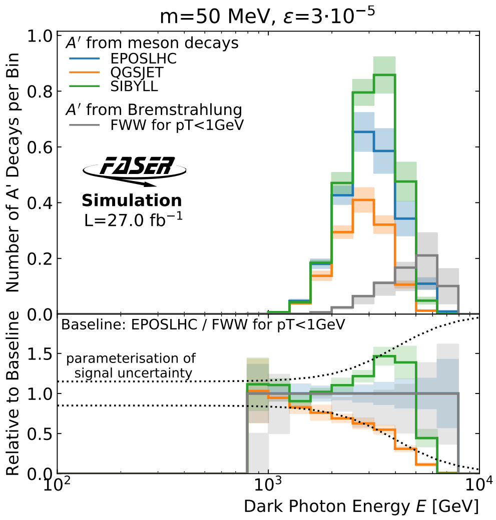
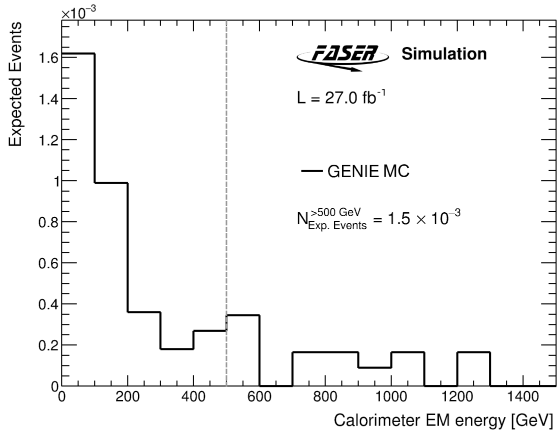


(a)



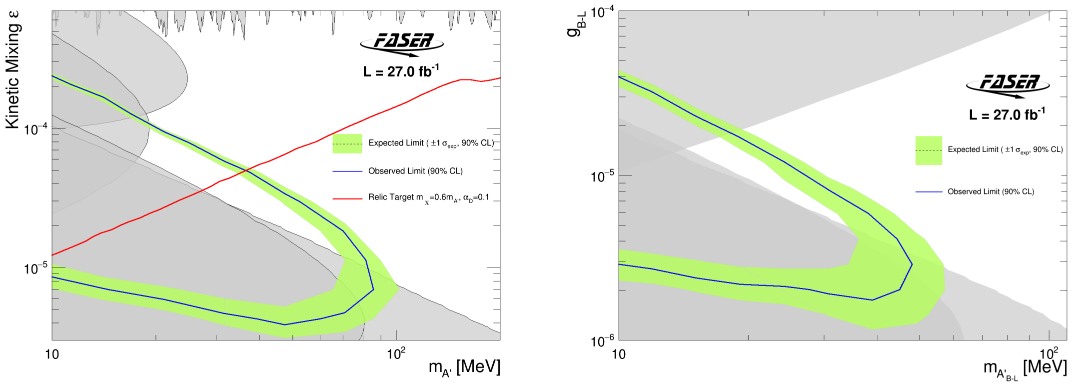
(b)

Figure 2: **(a)** An example of the signal yield uncertainty parameterisation based on differences in the generator used to model forward hadron production [5]. **(b)** Calorimeter EM energy for the neutrino simulation before the 500 GeV signal region selection.

The number of events from cosmic ray candidates is measured in runs without beams in the LHC, for a running time similar to the 2022 data-taking period. Background from nearby beam debris from beam-1, the incoming beam to ATLAS at the FASER location, is measured in events with no colliding bunch at IP1. For both cosmic ray and beam-1 background, there are no events with energies in the range relevant for the dark photon search and so such non-collision backgrounds are considered to be negligible.

Neutrino interactions in the Timing layer and tracking stations can produce signatures similar to those of a dark photon. The contribution of such a background in the signal region is estimated using simulation. This is based on calculations of the expected neutrino flux, energy spectrum and flavour composition [9], with neutrino interactions modelled by `GENIE` [10, 11]. The calorimeter energy distribution is shown in Figure 2b. When scaled to 27.0 fb^{-1}, the neutrino background in the signal region is predicted to be $(1.5 \pm 2.0) \times 10^{-3}$, where conservative uncertainties are applied to account for variations in the flux and interaction modelling.

Neutral hadrons may be produced from muons interacting in the rock upstream of FASER. In order to be considered a background for the dark photon search, the accompanying muon must be scattered such that it does not pass through the VetoNu or Veto stations. The hadron must also pass through eight interaction lengths of tungsten before decaying into high energy charged particles. For these reasons, such a background is expected to be heavily suppressed. An estimate is provided by dividing events into categories with differing requirements on the number of tracks and scintillator signals. The number of events in data in the different regions is combined and extrapolated to give the expected number of events in the signal region. The resulting estimate of $(0.8 \pm 1.2) \times 10^{-3}$ is considered a conservative upper limit, where the uncertainties account for data statistics and the assumptions of the method.



(a) (b)

Figure 3: Expected and observed limits for **(a)** dark photon and **(b)** B-L parameter spaces. Shown in red is an example thermal relic contour. Grey areas indicate exclusions from other experiments [5].

4. Results

No events are observed in the unblinded signal region, consistent with the total background expectation of $(2.3 \pm 2.3) \times 10^{-3}$ events. Exclusion limits at 90% confidence level are instead set according to the CLs prescription [12, 13] as shown in Figure 3a. These limits probe previously unexplored regions of the dark photon parameter space, including a significant fraction able to reproduce the observed dark matter thermal relic density under certain assumptions. The result is also interpreted in the context of a $\mathrm{U}(1)_{\mathrm{B-L}}$ model, where the associated gauge boson decays to an electron-positron pair. New regions of this parameter space are also excluded as shown in Figure 3b.

5. Conclusion

The FASER detector successfully took data throughout the first year of Run 3. The recorded data was used to provide constraints on previously unexplored regions of dark photon and $\mathrm{U}(1)_{\mathrm{B-L}}$ parameter space. An additional $\sim 30\ \mathrm{fb}^{-1}$ of data has been collected during 2023, which is expected to be used in further searches for particles beyond the SM. In addition, a large scale upgrade to FASER is planned for the high-luminosity LHC (HL-LHC) as part of the Forward Physics Facility (FPF) [14], which is expected to provide a significant improvement in the sensitivity for such searches.

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