PROCEEDINGS OF SCIENCE

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FASER Results on BSM Physics

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FASER is a small LHC experiment designed to search for light, weakly-interacting, long-lived particles produced in proton-proton collisions at the ATLAS interaction point. The recent BSM physics results from 2023 and 2024 are presented. The search for dark photons uses 27.0 fb^{-1} of data collected by the FASER experiment in 2022. The search sets world-leading exclusion limits for dark photon masses 17 MeV $< m_{A'} <$ 70 MeV and couplings $2 \times 10^{-5} < \epsilon < 1 \times 10^{-4}$ [1]. The results of this analysis are also reinterpreted for the $B - L$ gauge boson model. The search for axion-like particles (ALPs) uses 57.7 fb^{-1} of 2022 and 2023 data. This search provides world-leading exclusion limits for ALP masses $100 < m_a < 250$ MeV and couplings 3×10^{-5} $\mathrm{GeV}^{-1} < g_{aWW} < 5 \times 10^{-4}$ GeV^{-1} [2].

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1. Introduction

FASER is an experiment in the far-forward region of the LHC, 480 m downstream of the ATLAS interaction point. It is designed to search for light, weakly-interacting long-lived particles (LLPs) produced in proton-proton collisions at IP1 and to study collider neutrinos. It is placed along the beam collision axis line-of-sight (LOS) in order to be sensitive to dark photons and axion-like particles (ALPs) that may travel along the LOS for hundreds of metres, passing through LHC infrastructure, rock and concrete without interacting, before decaying to SM final states within the FASER detector decay volume. These proceedings present the search for dark photons decaying to e^+e^- and ALPs with coupling to the $SU(2)_L$ gauge boson decaying to $\gamma\gamma$.

2. The FASER Detector and Datasets

A detailed description of the FASER detector is given in Ref. [3]. FASER is 7 m long with an active radius of 10 cm. The first component of the detector is the "VetoNu" scintillator system, to veto charged particles before they enter the detector, this scintillator sits in front of the FASERν emulsion box. The FASERν box is followed by the interface tracker (IFT), a single tracking station that enables muon tracks in the emulsion to be linked to tracks in the electronic detector. The next component is the veto scintillator station which is followed by a 0.57 T permanent dipole magnet that acts as a decay volume. In the case of highly-collimated particle tracks, the magnet provides a horizontal kick to separate tracks to a detectable distance. There is a third scintillator station for timing and triggering; the timing scintillator sits in front of the tracking spectrometer. FASER's tracker consists of three tracking stations and two 1 m long 0.57 T permanent dipole magnets. The role of the tracking spectrometer is to observe the characteristic signal of two oppositely charged particles pointing back to the IP, and measure their momentum. Immediately following the tracking spectrometer is the preshower detector which contains two scintillator layers. The final component is a sampling electromagnetic calorimeter to measure the total electromagnetic energy of incoming particles.

FASER's trigger and data acquisition system records data with high efficiency [4], data was recorded throughout 2022 and 2023 with an efficiency of 97%. The dark photon analysis presented in these proceedings uses 27.0 fb^{-1} of integrated luminosity recorded by the FASER detector in 2022. The ALPs analysis uses 57.7 fb^{-1} collected in 2022 and 2023. Event reconstruction

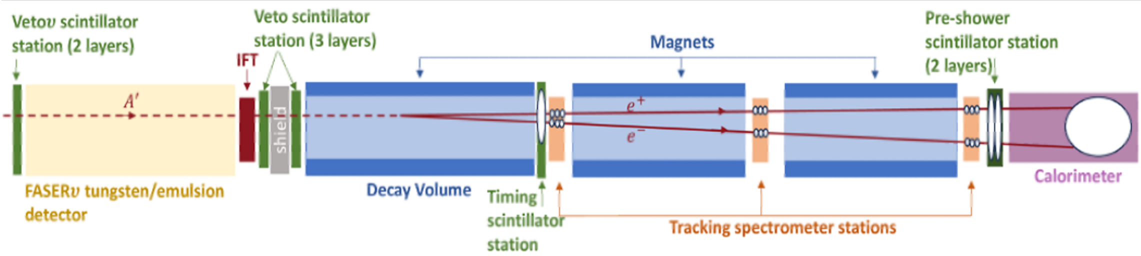

Figure 1: A typical dark photon (A') signal in FASER. The neutral A' (dotted line) enters the detector from the left.

is performed using FASER's Calypso offline software framework, based on the ATLAS Athena framework. Monte Carlo (MC) samples are used in generating the dark photon and ALP signals for the two analyses, additional MC samples are also used to evaluate systematic uncertainties and for background estimation. The MC samples are simulated using GEANT4 [5] and are digitized in order to undergo the same process of reconstruction as data.

3. The Search for Dark Photons

Dark photons, A', are hypothetical particles that could provide a portal to a dark sector that contains a $U(1)'$ electromagnetic force [1]. Interaction between $U(1)'$ and the Standard Model (SM) results in the dark photon that kinematically mixes with the SM photon. The size of the kinetic mixing parameter, ϵ, determines the strength of the interaction, hence the lifetime of the dark photon. A' production in the very forward region takes place predominantly via light meson decays and dark bremsstrahlung. Dark photons produced by these processes are highly-energetic, produced along the LOS with a decay length that is compatible with the location of FASER. Dark photons with masses in the range $2m_e < m_{A'} < 2m_\mu \simeq 211$ MeV decay to e^+e^- pairs with a branching fraction of 100%. FASER has sensitivity to dark photons with couplings $4 \times 10^{-6} < \epsilon < 2 \times 10^{-4}$ and with masses 10 MeV $< m_{A'} <$ 80 MeV.

A typical dark photon signature is shown in Figure 1 [1] in which a neutral A' particle enters the detector and deposits no charge in any of the five veto scintillator layers. It decays within the FASER decay volume to a highly-energetic e^+e^- pair which leaves charge deposits in the timing and preshower scintillators consistent with at least two minimum ionizing particles (MIPs) as well as two highly-collimated tracks within the tracking spectrometer. In addition, there will be an energy deposit of at least 500 GeV in the calorimeter consistent with an EM shower.

The primary source of background in this search arises due to neutrino interactions and neutral hadron interactions. The component of neutrino background is estimated from MC and results in a prediction in the signal region of $(1.5 \pm 2.0) \times 10^{-3}$ neutrino events. The neutral hadrons originate from muon interactions in the rock in front of FASER, the estimate in the signal region is $(0.8 \pm 1.2) \times 10^{-3}$ neutral hadron events. Background from muons is negligible due to the veto scintillator efficiency of 99.9998%.

Once data were unblinded, no events were found to pass the event selection. Exclusion limits can be set on FASER's sensitivity to the dark photon model. In addition, this analysis can be reinterpreted for the $B - L$ gauge boson [7], a well-motivated model that is similar to the dark photon. The contours from evaluating the CLs values at a 90% confidence level for the dark photon model and the $B - L$ gauge boson model are shown in Figure 2.

In the parameter space that is probed by this analysis dark photon signal models with mass 10 MeV $< m_{A'} <$ 80 MeV and coupling $4 \times 10^{-6} < \epsilon < 2 \times 10^{-4}$ are excluded. World-leading constraints are set by FASER for signal models in the mass range 17 MeV $< m_{A'} <$ 70 MeV and coupling $2 \times 10^{-5} - 1 \times 10^{-4}$. The reinterpretation of this analysis probes unconstrained parameter space in the region of $B - L$ gauge boson mass around 15 MeV $< m_{A'_{B-L}} <$ 40 MeV and coupling $5 \times 10^{-6} < g_{B-L} < 2 \times 10^{-5}$.

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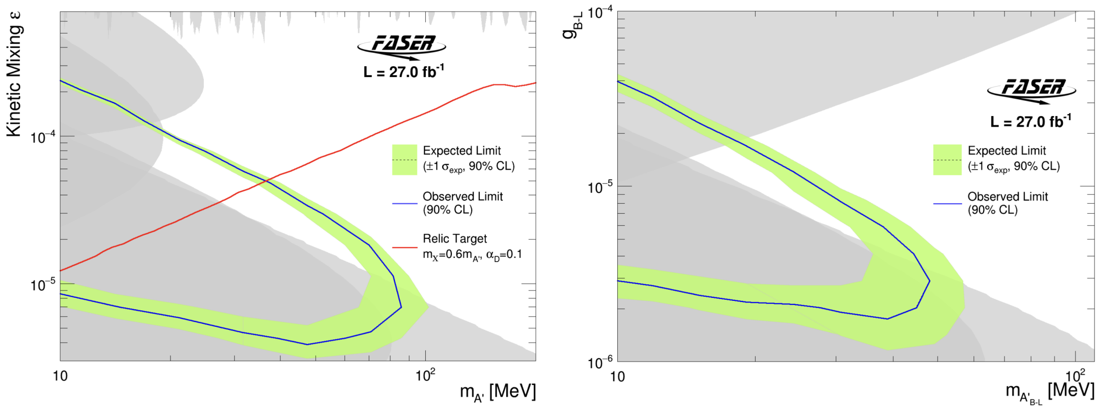

Figure 2: (Left) Interpretation of the signal region yield as A' exclusion limits with the assumption of 2×10^{-3} background events and zero data events. The expected limit with 90% CL is shown by the dashed line and green uncertainty band. The observed limit is shown by the blue line. Existing constraints are shown in grey. The thermal relic density target is shown in red. (Right) Interpretation of the signal region yield as $B - L$ gauge boson exclusion limits.

4. The Search for ALPs

ALPs are defined as pseudoscalar particles coupled to SM particles by dimension-5 couplings to gauge bosons or derivative interactions to fermions. Like the dark photon, ALPs can provide a portal to the dark sector. ALPs can couple to the SM field strength tensor $W^{a}_{\mu\nu}$ from the $SU(2)$ gauge group. In this model, the ALP is primarily produced in B meson decays, although the coupling to the W boson also gives rise to kaon decays at a sub-dominant rate. The leading production processes are $B^0 \to X_s a$ and $B^\pm \to X_s a$. FASER targets ALPs with mass $m_a \sim 50$ MeV and coupling $g_{a\gamma\gamma} \sim 10^{-4}$ GeV^{-1}, which typically have momentum in the TeV range. The decay length is of the order of several hundred metres, which is compatible with FASER's location. ALPs with coupling to the $SU(2)_L$ gauge boson decay to pairs of highly-energetic photons.

A typical ALP signature is shown in Figure 3 [2] in which a neutral ALP particle enters the detector and deposits no charge in any of the veto scintillator stations. It decays within the FASER decay volume to a highly-energetic di-photon pair, depositing no charge in the timing scintillator but significant deposits in the preshower and calorimeter. The event selection requires that a signal equivalent to 10 MIPs is deposited in the second preshower layer, with a ratio greater than 4.5 deposited in the second vs first layer. An EM energy of 1.5 TeV is required in the calorimeter.

The main background in this analysis arises from neutrino interactions in FASER's magnet, preshower and calorimeter. These three regions were used to categorise the neutrino background into validations regions in order to estimate the component of neutrino interactions in the signal region. The MC modeling of the neutrino validation regions agrees well with data. The number of neutrinos expected in the signal region is 0.42 ± 0.38 events [1].

Similar to the dark photon analysis, background from muon events is removed due to the high efficiency of the veto scintillators. Also considered are contributions from neutral hadrons, cosmic ray muons, beam background and potential large-angle muons that could enter FASER by missing

[1] This prediction has been updated since the publishing of the conference note [8].

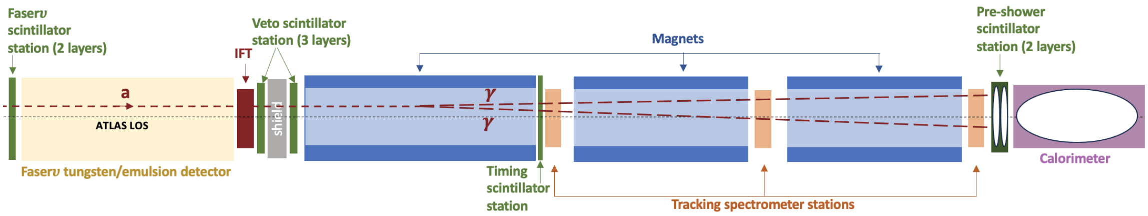

Figure 3: A typical ALP signal event traversing FASER. The neutral ALP (dotted line) enters the detector from the left.

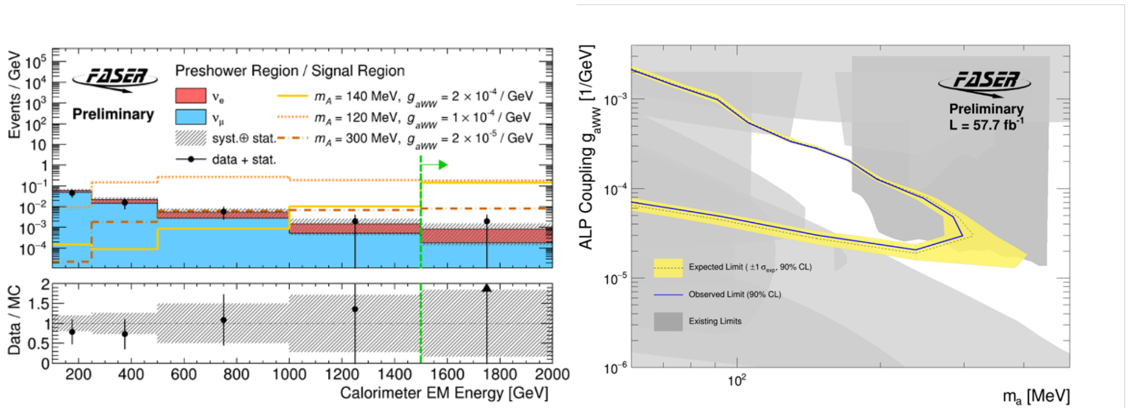

Figure 4: (Left) Calorimeter EM energy distributions in the preshower and signal regions, showing the composition of the neutrino background expectation separated in terms of neutrino type. The final energy bin above 1.5 TeV shows the signal region and is indicated by the green arrow. (Right) Interpretation of the signal region yield as ALP exclusion limits with the assumption of 0.42 neutrino background events. The expected limit with 90% CL is shown by the dashed line and yellow uncertainty band. The observed limit is shown by the blue line. Existing constraints are shown in grey.

the veto scintillators. These contributions were determined to be negligible through a combination of MC and data-driven methods.

Upon unblinding 1 data event was observed in the signal region. This event has a calorimeter energy of 1.6 TeV, a charge deposit in the second preshower layer equal to 146 MIPs, and a preshower ratio of 9.0. Figure 4 shows the unblinded results in terms of calorimeter energy in the signal region and the exclusion limits from evaluating the CLs values at a 90% confidence level. The width of the uncertainty band is driven by the dominant systematic uncertainty, the flux of the MC generators used in signal and background estimation. FASER probes previously unexplored parameter space in this search; ALP masses between 100 and 250 MeV, with coupling between 3×10^{-5} and 5×10^{-4} GeV^{-1} have been excluded by this search.

5. Summary and Outlook

FASER has probed new parameter space with the ALP coupling to the $SU(2)_L$ gauge boson model at mass and coupling previously unexplored by existing experiments. Additionally, FASER presents a reinterpretation of the 2023 dark photon search with the $B - L$ gauge boson model. Looking into the future, FASER plans to install an upgrade to the existing preshower detector

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in YETS 2024, to improve sensitivity to ALP searches and reduce background. The FASER experiment has been approved to operate in Run 4 at the LHC, the projected sensitivity is greatly enhanced with the combined Run 3 and Run 4 dataset for both the dark photon and ALP searches, in addition to other models such as the dark Higgs model.

Acknowledgments

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