

New Results from a Search for Dark Photons with the FASER Detector at the LHC

FASER Collaboration

FASER is an experiment at the LHC designed to search for light, feebly-interacting particles produced in proton-proton collisions at the ATLAS interaction point that travel in the far forward direction. Here we present results from a search for dark photons decaying to electron-positron pairs using a dataset corresponding to an integrated luminosity of 177 fb^{-1} . This dataset was collected at a center-of-mass energy $\sqrt{s} = 13.6 \text{ TeV}$ in 2022, 2023, and 2024 during LHC Run 3. No events are seen in a nearly background-free analysis, resulting in world-leading constraints on dark photons with couplings $\epsilon \sim 10^{-5} - 10^{-4}$ and masses $\sim 10 \text{ MeV} - 150 \text{ MeV}$.

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1. INTRODUCTION

There is significant evidence that a large fraction of the matter content of our universe is composed of an unknown non-baryonic form of matter known as dark matter (DM), which is thus far only known to interact with Standard Model (SM) particles through gravity. Understanding the particle nature of dark matter is one of the most important open questions in physics, and answering it requires a diverse set of complementary approaches. Various extensions to the SM posit a “dark sector” composed of various particles in addition to the one or more particles that make up cosmological dark matter. One could search for production of dark sector particles and other such beyond-the-standard-model (BSM) signatures in high-energy collisions, which is possible if DM interacts with SM particles through renormalizable couplings. A common benchmark is to introduce a dark sector with a $U(1)$ symmetry with a corresponding gauge boson. A well-known class of such models are dark photons, which interact with the SM through kinetic mixings with SM fermions [1]. This remains a key benchmark search target for many experiments.

In the case of thermal freeze-out dark matter production, cosmological constraints favor a dark photon with mass $m_{A'} \in [1, 1000]$ MeV and coupling $\epsilon \in [10^{-6}, 10^{-3}]$ [2–4]. Dark photons satisfying these constraints can be produced in large numbers in proton-proton collisions at the Large Hadron Collider (LHC) and then travel hundreds of meters before decaying into charged particles [5]. The ForwArD Search ExpeRiment (FASER) is an experiment at the LHC designed to search for signals of such particles and other light, long-lived particles (LLPs) produced in collisions at the ATLAS interaction point (IP1) [5–7]. For a more detailed discussion of the sensitivity of FASER to dark photons, see [8].

In this work we present results from a significantly expanded search for dark photons decaying to e^+e^- pairs using the FASER detector and a combined dataset from 2022, 2023 and 2024 corresponding to an integrated luminosity of 177 fb^{-1} . We improve the signal efficiency of our original analysis [8], which had an integrated luminosity of 27 fb^{-1} , and introduce a brand new analysis strategy to gain sensitivity to signal events that decay anywhere in our detector prior to the EM calorimeter.

2. THE FASER DETECTOR

The FASER detector, described in detail in Ref. [7], is located in the TI12 tunnel about 5 m away from the LHC tunnel and ~ 480 m away from the ATLAS IP1. It is aligned with the collision axis line-of-sight (LOS); however, due to the crossing angle in IP1¹, the LOS is offset vertically with respect to the center of the detector. Most background particles are absorbed by the 100 m of rock in between IP1 and FASER or deflected by the LHC magnets. The detector, loosely sketched in Fig. 1, consists of a front scintillator veto system, the passive FASER ν emulsion detector, the interface tracker, a scintillator veto station, the decay volume, the timing scintillator station, the tracking spectrometer [9], the preshower (PS) scintillator system, and the EM calorimeter system. The tracking spectrometer is made up of three stations, with each station comprised of three planes of eight double-sided ATLAS semiconductor tracker (SCT) barrel modules [10]. To separate oppositely-charged particles in the decay volume and to measure the momentum in the tracking spectrometer the system includes three 0.57 T dipole magnets. All systems with the exception of the FASER ν emulsion detector are relevant for this analysis. Events are triggered by signals from the scintillator stations and the calorimeter. We also note that FASER underwent hardware upgrades in early 2024. A dual readout system for the FASER calorimeter was installed, which

¹ The half crossing angle was fixed at $-160 \mu\text{rad}$ in 2022, varied slightly between $-165 \mu\text{rad}$ and $-135 \mu\text{rad}$ in 2023, and varied around $+160 \mu\text{rad}$ in 2024. See Sec. 3.

enables the high- and low-gain channels to be read out simultaneously. The high-gain channel is not relevant for this analysis, and was only used for the calibration of the low-gain channel [11]. Additionally, due to this upgrade, we were able to add a sixth veto scintillator layer to our readout, improving our background rejection.

3. DATASET AND SIMULATED SAMPLES

This analysis uses data collected from $\sqrt{s} = 13.6$ TeV center-of-mass collisions provided by the LHC in 2022, 2023 and 2024. The combined data corresponds to an integrated luminosity of 177 fb^{-1} after data quality selections. We use ATLAS luminosity measurements and calibrations described in [12–14]. Events are triggered [15] by signals from the scintillator or calorimeter system [15], with a typical trigger rate of 1 kHz. This trigger rate is dominated by high-energy muons. We have certain requirements to ensure high trigger efficiency and rejection of non-collision backgrounds. We require that the event time is consistent with stable beams and a colliding bunch at IP1. We trigger on events that are coincident between scintillator stations or deposit energy in the calorimeter. To ensure the efficiency of this trigger, we require that neither our timing nor the first preshower scintillator layer are saturated. The average detector deadtime is measured to be 1.3%.

For signal, Monte-Carlo (MC) simulated samples are used to optimize selections and study signal yields. The dominant sources of dark photons from proton-proton collisions at IP1 for FASER are from SM meson decays (primarily from π^0, η) and dark bremsstrahlung [5, 6, 8], which we simulate using **FORESEE** [16]. For each signal model, samples are simulated for a 2-dimensional grid in the mass-vs-coupling plane. Similar to the previous Axion-Like-Particles search [17], we adopt a method of parameterizing the efficiency of $A' \rightarrow e^+e^-$ as a function of energy and decay radius, which overcomes the computing resource constraints of generating a large grid and facilitates a more accurate statistical analysis. Our simulation accounts for dark photons decaying within a 110 mm radius around our detector axis for the decay volume and full tracking spectrometer.

To study backgrounds we use various dedicated MC samples, described in detail in Sec. 5. Data and simulation reconstruction largely follows the same procedure as in [8, 17] with significant improvements in accuracy and performance.

We also note significant differences between 2024 running conditions and those of 2022 and 2023. The crossing angle changed from $-160 \mu\text{rad}$ to $+160 \mu\text{rad}$, which impacts our signal yields by $\sim 10\%$. Second, a change in the LHC optics nearly doubled the rate of muons seen by FASER, which impacted our background estimations. We account for this in our simulation and correctly weight our signal and background samples to ensure an accurate result.

4. ANALYSIS STRATEGY AND EVENT SELECTION

The sensitivity of FASER to dark photons depends on their lifetime, which is inversely proportional to the coupling ϵ and the mass $m_{A'}$. The dominant processes producing dark photons for the region of parameter space to which FASER is sensitive are SM meson decays and dark bremsstrahlung [5]. These processes produce a high-intensity beam of dark photons in the far forward direction. Because dark photons are extremely weakly interacting, they are long-lived and typically decay hundreds of meters after they were produced. From the standpoint of the detector, this means we are interested in events that pass through our upstream veto scintillators without depositing charge (as the A' will not interact) followed by signals of charged particles in the downstream scintillators and tracking station. This topology coupled with TeV-scale calorimeter energy deposits is strong evidence of a boosted LLP produced at IP1. There are no known SM processes

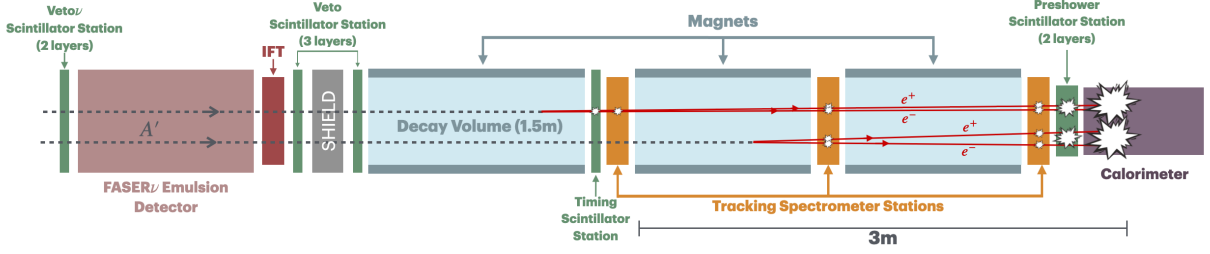


FIG. 1: A sketch of the FASER detector with two $A' \rightarrow e^+e^-$ signals that the previous analysis would have rejected. The top signal would have been rejected as the dark photon tracks would be too close-by to be reconstructed as two tracks, and the bottom signal would have been rejected as it had no reconstructed tracks. The One Track region is designed to maximize sensitivity to the dark photon decaying in the decay volume, and the Segment Signal Region is designed to maximize acceptance for downstream decays.

that can mimic this signal. The first dark photon search with FASER targeted this signal by requiring exactly two high momentum tracks. While conservative, this track requirement was the largest source of signal inefficiency [8]. The source of this inefficiency was investigated, and found to be largely due to either removing events with more than two tracks (from EM showers or other interactions), or removing events that were reconstructed as only having a single track, which can occur if the tracks are highly boosted and have very small separation.

In addition to resolving the two-track inefficiency, we were also motivated to improve our signal acceptance. Previously, we only searched for dark photons that decay in the 1.5 m decay volume; however, there remains an additional 2.5 m of potential decay volumes prior to the EM calorimeter contained inside the tracking spectrometer. We have added a second signal region designed to study downstream decays, which improves sensitivity to dark photons with larger masses. A sketch of these signals is shown in Fig. 1.

To target events of interest, we require no signal in either of our veto scintillator stations. Then we implement two orthogonal signal regions in addition to the common data quality requirements described in Sec. 3. The first is a modification of the first FASER dark photon search with relaxed tracking requirements, which we refer to in the following as the “One Track Signal Region,” and the second is a new signal region that uses track segment information from individual tracking stations in the tracking spectrometer, which we designate as the “Segment Signal Region.” For the latter signal region we refer to tracking stations by number, where tracking station 1 is the station closest to the decay volume, station 2 is in the middle, and station 3 is at the end near the preshower station.

To avoid unconscious bias affecting the analysis, we blind events where there is no signal in any veto scintillator and where there are either exactly two tracks or a calorimeter energy above 100 GeV. We then finalize the event selection and background estimation prior to studying the signal region in our full dataset. We briefly describe the event selection criteria below.

4.1. One Track Signal Region

This signal region is identical to the signal region described in [8], with the following modifications. The definition of a good quality track has been modified. We define a good track as one with a track fit $\chi^2/\text{number of degrees of freedom} < 25$, at least 12 hits on track, and has a minimum momentum requirement of 100 GeV. This high momentum requirement was chosen to

ensure that our tracks are straight to mitigate non-fiducial background events. A fiducial track has an extrapolated radius $r < 95$ mm at all scintillators and tracking stations. We modify the exactly two good fiducial track requirement, relaxing it to at least one good fiducial track. This is due to the inefficiency of requiring exactly two tracks, for the reasons discussed earlier.

4.2. Segment Signal Region

This signal region is designed to target A' particle decays in the tracking spectrometer after the decay volume. In order to be sensitive to charged particle tracks without using all three stations, we study reconstructed track segments in individual tracking stations. Signals from charged particles interacting in the silicon strips of the tracking station are combined into clusters. These clusters are then directly combined into track segments, which are then used to seed the reconstruction of full tracks. The electron-positron decay products from A' will separate and each deposit charge in a tracking station, and each track will be partially reconstructed as an event with ≥ 1 track segments. Thus to identify the charged particle pairs produced from A' decays in between the first and second (second and third) tracking station we look for events with ≥ 2 track segments in tracking station 2 (3).

The fiducial requirements are very powerful for rejecting backgrounds in the One Track Signal Region. We can enforce similar fiducial requirements for the reconstructed segments by cutting on their position and angle. The final selections, in addition to the common data quality selections, are summarized as follows:

- No signal in any of the five (six)² veto scintillators.
- No signal in the timing scintillator, to act as an additional veto
- ≥ 2 Track Segments in tracking station 2 or 3. This ensures sensitivity to dark photon decays in between tracking station 1 and 2, and in between station 2 and 3.
- All segments in station 2 and 3 are fiducial (within a 95 mm radius from the center of the detector)
- All segments are pointed straight, with segment angle within ± 0.02 radians with respect to the precision coordinate.
- Total calorimeter energy exceeding 500 GeV

The probability to veto an event, due to the presence of an uncorrelated beam-background muon in the same or neighboring bunch crossing is estimated using flux measurements to be less than 2 per mille for the total dataset. With the scintillator saturation requirements, our trigger efficiency is 100% for the phase space of interest.

While these two signal regions are relatively straightforward extensions to the original signal region, as a result of these changes, FASER is more than twice as sensitive to dark photons compared to our previous analysis strategy. This improvement is highlighted in Fig. 2, which shows the expected number of dark photon events for FASER in our updated signal regions.

5. BACKGROUNDS

We consider several sources of background in our analysis, largely the same set presented in [8]. The contributions of each source are described and quantified below.

² A sixth veto station was added to the readout due to upgrades, this applies to 2024 data only, see Sec. 2.

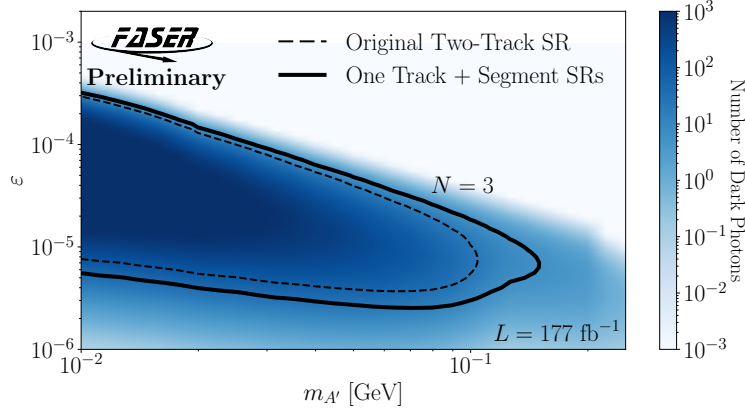


FIG. 2: Expected number of dark photons events in FASER for 177 fb^{-1} in the new signal regions. In blue are the number of signal events for the One Track + Segment Signal Regions. In solid black we plot the contour where expect 3 signal events, which corresponds to the 95% confidence level for zero background, in the Segment SR + One Track SR. We also plot the same expectation for the original two track signal region [8] as a dashed contour.

5.1. Neutrinos

FASER sees a large flux of high-energy neutrinos from the ATLAS IP1, which constitute an important background since the neutrinos interacting in material downstream of the veto systems and upstream of the preshower do not leave any signal in the veto scintillators and can interact to produce high-energy particles. The neutrino background is estimated using flux predictions from [18, 19] and Monte-Carlo samples generated with GENIE [20, 21]. These samples simulate 100 ab^{-1} ($\sim 500\times$ more luminosity than our collected dataset) of neutrino interactions in the FASER detector. Following Ref [19], we use EPOS-LHC [22] and POWHEG+Pythia [23] to obtain our central prediction, and the envelope of different generator predictions as a systematic uncertainty. After scaling to 177 fb^{-1} , the simulation shows that $0.050^{+0.024}_{-0.039}$ events pass our one track signal region and 0.025 ± 0.014 events pass our segment signal region. Our simulation studies show backgrounds from neutrino interactions are primarily suppressed by the energy requirement and fiducial requirements.

5.2. Geometric Muons

A source of background that is particularly important is the contribution from “large angle” or geometric muons. These refer to muons that are produced in LHC collisions but scatter through the rock and enter FASER through odd angles, coming from below, the side, or above the detector and therefore miss the veto systems. Such muons could interact or radiate to produce large energy in the calorimeter and pass the SR selections. We estimated this background through a data driven approach, isolating events in data that have tracks extrapolated to the edges of the front veto scintillator. The distribution of these events was used to generate an MC sample of geometric muons, which was then validated against all three years of data. An upper bound on the rate of high energy events arising from muons in FASER was estimated through a separate MC sample modeling muons arriving directly from IP1. The results from these two were then combined and scaled to our final luminosity in order to obtain a background estimate. While the fiducial

requirements entirely eliminate this background in our One Track Signal Region, the results of this study were used to estimate a background contribution to the Segment Signal Region, found to be 0.002 ± 0.001 events.

5.3. Neutral Hadrons

Muon-induced production of neutral hadrons upstream of the detector can constitute a potential background since neutral hadron decays can leave reconstructed tracks or track segments without leaving signals in the veto scintillator system [8]. They may then deposit enough energy in our calorimeter to enter our signal regions. Many neutral hadron production modes are possible, but the most likely species are generated by muon interactions in the surrounding rock upstream of FASER. This background is expected to be negligible, due to the low probability of the parent muon scattering and missing the detector coupled with the fact that the neutral hadron must make it through the 8 interaction lengths of the tungsten emulsion detector without interacting. To verify this, we used MC samples studying muon interactions in the rock before FASER. A large number of muons ($\sim 500 \text{ fb}^{-1}$, and thus exceeding our dataset) are simulated using the muon spectra predicted from FLUKA simulations [24–26]. The FLUKA simulations include a detailed description of LHC components and infrastructure between FASER and IP1 at 409 m. Muons are propagated an additional 71 m to FASER, using muon range tables, and then fed into GEANT4 [27] to simulate interactions in the FASER detector. From this sample, we select neutral hadrons produced by muon interactions in the rock and see how many pass baseline selections. After applying the veto requirements we see 0.05 events (corresponding to 177 fb^{-1}) with enough energy to trigger the calorimeter, but none deposit energy exceeding 100 GeV. Out of the total set of neutral hadrons, about 4×10^{-5} pass the 500 GeV calorimeter selection, further scaling down the background estimation. Thus, we are confident this background is negligible, and neglect it.

5.4. Veto Inefficiency

The performance of the FASER veto system has been measured with data and found to be extremely efficient [8]. We remeasure this for the five (six) active veto scintillators in 2023 (2024) data. We do this by choosing events where the scintillator layer being measured records charge below the 40 pC threshold for events where the nearby scintillator layers record charge above the 40 pC threshold. We expect $\mathcal{O}(10^9)$ muons in the total dataset. The measured inefficiencies were found to be $\sim 10^{-4}$ per layer for the Veto ν Scintillators and $\sim 10^{-5}$ per layer for the Veto scintillators, all of which are independent. For the data taken during the 2022/2023 (2024) running conditions where we had two active layers in Veto ν and five (six) active layers in the Veto Station this results in an inefficiency of $\sim 10^{-23}$ (10^{-27}) for charged particles that remain fiducial throughout the detector. Thus this inefficiency remains a negligible contribution to our backgrounds.

5.5. Non-Collision Backgrounds

We consider backgrounds from cosmic rays by studying events when there are no colliding bunches in IP1. Cosmic rays were studied using a dataset of ~ 1900 h compared to the ~ 2100 h of physics data taking. We see zero events that pass any of our tracking or segment requirements, so this background contribution is negligible.

The beam background relevant for FASER is LHC beam 1, which is the incoming beam to ATLAS from the direction of FASER. Beam 1 interactions with gas or tails of the beam interacting

Contribution	Segment SR	One Plus Track SR
Neutrinos	0.025 ± 0.014	$0.050^{+0.024}_{-0.039}$
Geometric Muons	0.002 ± 0.001	0
Neutral Hadrons	0	0
Cosmic	0	0
Beam 1 Background	0	0
Veto Inefficiency	0	0

TABLE 1: Total background contribution for both signal regions. The largest contribution arises from high energy neutrinos, but is well controlled by our selection requirements.

with the beam pipe can be seen in FASER [8]. This beam background is studied by isolating beam 1 events with bunch timing requirements. We see that none of these events have large energy or have reconstructed tracks, and thus the overall contribution is negligible.

5.6. Summary of Expected Backgrounds

Contributions from neutral hadrons, veto inefficiency, non-collision events were found to be negligible for this analysis. The total expected background is obtained by combining the neutrino and geometric muon background estimates. Therefore for the Segment Signal Region we report a final background of 0.027 ± 0.014 events. For the One Track Signal Region this background only arises from neutrinos and is estimated at $0.050^{+0.024}_{-0.039}$ events. The summary of all backgrounds is summarized in Table 1.

6. SYSTEMATIC UNCERTAINTIES

Various sources of systematic uncertainties are considered and apply to both background estimates and signal yields.

There are two sources of systematic uncertainties pertaining to our signal samples that dominate our analysis. The first arises from the uncertainties on the forward flux of mesons, which are obtained using the spread from different generators. The generators used are EPOS-LHC [22], SIBYLL 2.3d [28], QGSJET 2.04 [29], and a dedicated forward physics tune of Pythia 8.3 [30], where EPOS-LHC is taken as nominal. The second is the flux uncertainty from bremsstrahlung, for which we use the quasi-real-approximation [31] with the splitting functions from Ref. [32] and form factor model 1 from Ref. [33]. The largest uncertainties on the modeling of Bremsstrahlung for the masses of interest arise from variations in the parameter Λ_p , used in a kinematic filter to avoid strongly off-shell protons, and a systematic uncertainty is obtained by varying this parameter from 1 to 2 GeV. We ignore any systematic effect from neglecting spin correlations, as this is a negligible effect for FASER [34].

The luminosity uncertainty is provided by ATLAS, and is calculated to be 1.9% [14]. Other uncertainties arise from the modeling of the detector response in MC simulations. We largely repeat the studies detailed in [8, 17] with an improved reconstruction software framework. The systematic uncertainty from our timing and veto scintillators are negligible. The uncertainty on calorimeter energy scale is recalculated from the previous result using a test beam, resulting in an uncertainty of 5.5%. The one track systematic uncertainty was calculated using the same method as in [8], and has been improved from 3% to 0.47%. The momentum scale and resolution remain

Source	Value	Effect on Signal Yield
Dark Photon Generation (from mesons)	15%	15% (8%)
Dark Photon Generation (from dark Bremsstrahlung)	22%	22% (40%)
Luminosity	1.9%	1.9%
Momentum Scale	5%	<0.5%
Momentum Resolution	5%	<0.5%
Single Track Efficiency	0.47%	0.47%
Segment Efficiency	6.07%	6.07%
Calo Energy Scale	5.46%	3% (11%)

TABLE 2: Summary of systematic uncertainties in the two signal regions. The numbers in parenthesis indicate the effect on the signals within the parameter space for which this analysis is sensitive.

the same, at 5% for both. The systematic uncertainty on reconstructing ≥ 2 track segments was studied by examining dark photon and muon Monte-Carlo samples. Track segments and space points are both reconstructed from clusters, and the number of space points reconstructed are highly correlated with the number of expected reconstructed segments. We find that requiring 6 or more space points in a given station correlates with reconstructing two or more segments. We calculate a systematic by checking the efficiency of reconstructing two or more segments after requiring 6 or more space points a given tracking station. We compare muon MC (as most of our data in FASER consists of muons) with data, which results in a systematic uncertainty of 2.8% for tracking station 2 and 6.07% for tracking station 3. We conservatively use the larger number. The results are summarized in Table 2.

7. STATISTICAL ANALYSIS AND RESULTS

After applying our signal selections, we observe zero events in the One Track Signal Region and zero events in the Segment Signal Region, which is compatible with our background estimate of $0.050^{+0.024}_{-0.039}$ events for the former and 0.027 ± 0.014 events for the latter. In Fig. 3 we plot the calorimeter energy distribution for data and two representative signal models at different stages of the signal region selections. As no significant excess of events over background is observed, the results are used to set exclusion limits. The exclusion limits are derived using the `HistFitter` [35] framework, which constructs a parametric model using the nominal predictions of signal, background, and systematic uncertainties and then performs a profile likelihood fit. Following the convention in [36] we derive 90% confidence level exclusion curves. We exclude dark photon signal models with $m_{A'} \sim 10 - 200$ MeV, $\epsilon \sim 3 \times 10^{-6} - 2 \times 10^{-4}$. For dark photons with couplings $\epsilon \sim 10^{-5} - 10^{-4}$ and masses ~ 10 MeV – 150 MeV we set the world-leading exclusion limits as shown in Fig. 4.

We emphasize that an important reason to search for dark photons in particular is their potential for discovering a potential dark sector. They allow for obtaining the correct value of dark matter relic density, $\Omega_{\chi}^{\text{total}} h^2 \simeq 0.12$ [37] via the thermal freeze-out mechanism. Therefore, we plot in Fig. 4 the same example thermal relic contour as detailed in [8]. This contour is obtained for the scenario where the dark photon couples to a light complex scalar dark matter field χ [16]. This line is drawn under the assumptions that the mass ratio $m_{\chi}/m_{A'} = 0.6$ and the coupling constant of the dark photon to dark matter is fixed to $\alpha_D = 0.1$. This guarantees that the dark photon decays into SM species and that dark matter primarily annihilates via $\chi\chi \rightarrow A' \rightarrow ff$, where f refers to a SM fermion. This contour can shift when the coupling and mass ratio are changed. The region

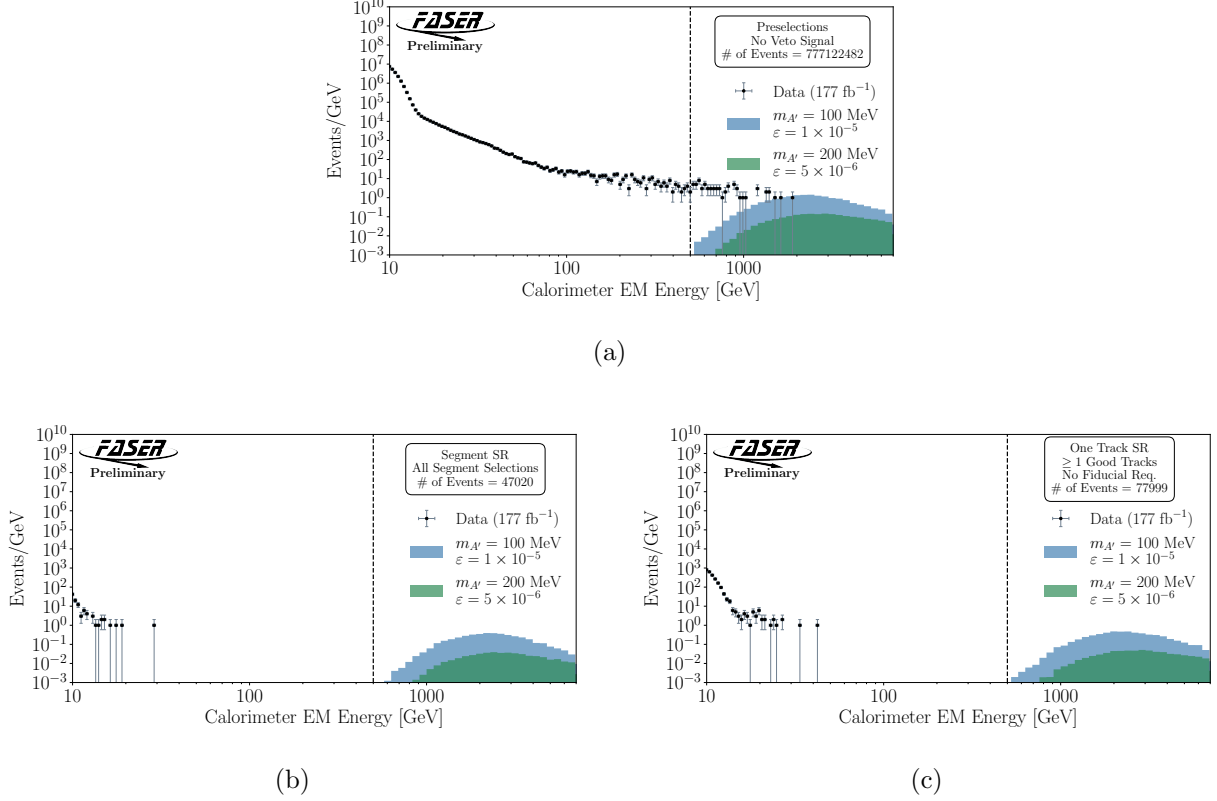


FIG. 3: The calorimeter energy distribution for FASER data and two representative MC dark photon signal samples for both our signal regions. In (a) we show events that have no veto signal and pass our data quality requirements. We show events that have no veto signal and pass all our segment selections in (b), and events that have no veto signal and have at least one good track (without the fiducial requirement) in (c). No events pass the final calorimeter selections for either case.

below the target line corresponds to an over-abundance of dark matter and would therefore be cosmologically-excluded. FASER is therefore making significant progress in probing interesting, cosmologically-allowed regions of this parameter space.

8. CONCLUSIONS

A search for dark photons using 177 fb^{-1} of data collected by the FASER experiment has been presented. Compared to the previous analysis, we have collected $6.5\times$ more data, and the signal yield was improved by a factor of around 2.5. We apply event selections for two orthogonal signal regions. Both require no signal in the veto scintillator systems; the One Track Signal Region targets high energy events with at least one good quality track throughout the entire detector, and the Segment Signal Region uses reconstructed track segments in the downstream tracking stations to search for late decays. No events are observed passing either signal region, with an expected background of 0.027 ± 0.014 events in the Segment Signal Region and $0.050^{+0.024}_{-0.039}$ events in the One Track Signal Region. At the 90% confidence level, FASER sets new constraints for dark photons with couplings $\epsilon \sim 10^{-5} - 10^{-4}$ and masses $\sim 10 \text{ MeV} - 150 \text{ MeV}$, excluding important viable

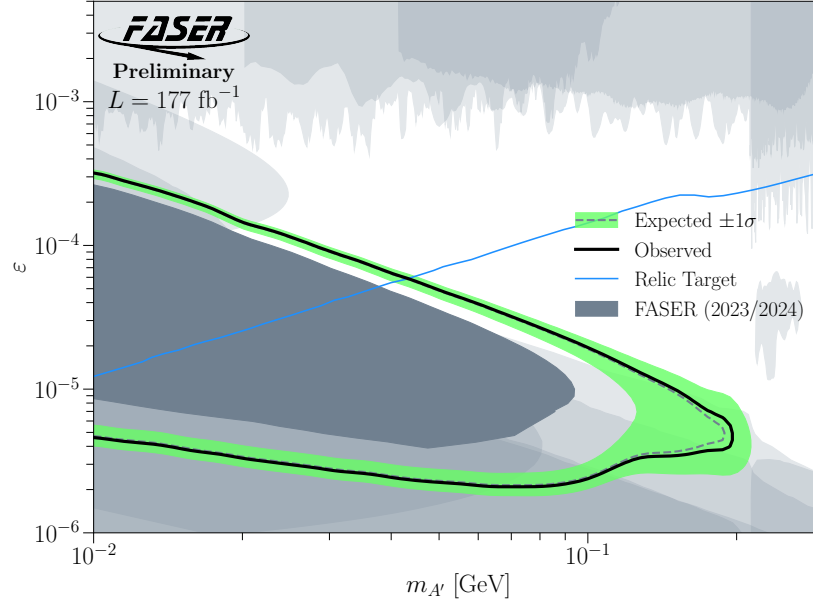


FIG. 4: 90% exclusion contours for dark photons using combination of the Segment and One Track SRs with all systematic uncertainties. The blue line indicates the region of parameter space that yields the correct dark matter relic density under the assumptions discussed in the text. Our previous results [8, 17] are as a combined filled region in dark gray. Shaded light gray contours depict regions excluded by experimental data from various other experiments [38–48].

parameter space motivated by dark matter.

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