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Long-lived dark photons at ATLAS: a search for unconventional signatures at the LHC

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Long-lived particles represent a well motivated approach for beyond-Standard Model (SM) physics searches. An interesting scenario at the LHC is the one in which light vector mediators (dark photons), weakly coupled to the SM photon, can be produced by an exotic decay of the SM Higgs boson and decay back to SM particles after travelling a macroscopic distance. This study presents a search for light, neutral long-lived particles decaying in collimated jet-like structures containing pairs of leptons or quarks. The search is performed on 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$ collected by ATLAS during the Run-2. Both the gluon-gluon fusion and associated production with a W boson are considered for the Higgs production. Dark photon decays are identified among the overwhelming QCD and non-collision background using a selection involving dedicated triggers and deep-learning based classifiers. The results obtained are interpreted in the context of simplified long-lived particle models such as the Hidden Abelian Higgs Model and the Falkowski-Ruderman-Volansky-Zupan model.

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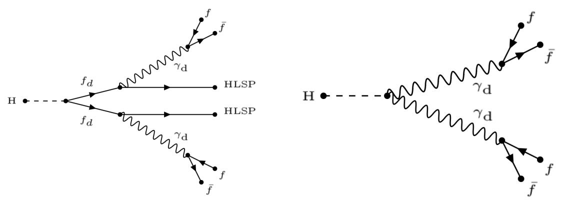
1. Dark photons at ATLAS

A simple extension of the Standard Model (SM) can predict the existence of light vector mediators known as dark photons (γ_d), which can be produced in proton–proton collisions at the LHC, assuming an exotic decay of the SM Higgs boson as described in [1, 2]. Dark photons produced in this way can be detected by the ATLAS Experiment [3] if they mix kinetically with a SM photon and consequently decay in pairs of leptons and hadrons.

Recent results from the ATLAS Collaboration [4] have probed the existence of these dark photons analysing 139 fb^{-1} of data, collected between 2015 and 2018. In this search the kinetic mixing parameter (ε), responsible of the lifetime of the γ_d, is assumed to be smaller than 10^{-5}, while the dark photon mass ranges between $O(10\,\text{MeV})$ and $O(10\,\text{GeV})$. For such values of ε and γ_d mass, and thanks to their large Lorentz boosts, dark photons produced in the LHC interaction point can travel a macroscopic distance in the detector before decaying in collimated pairs of particles, referred to as Dark-Photon-Jets (DPJs).

Simulated Monte Carlo events are used to define the signal regions of the analysis. Two different signal models are considered by the search, where pairs of dark photons are produced in each event. In the *Falkowski–Ruderman–Volansky–Zupan* (FRVZ) model [5], a pair of dark fermions (f_d) is obtained from a Higgs boson decay, producing two γ_d and a pair of *Hidden Lightest Stable Particles* (HLSP) in the final state (Figure 1a). The *Hidden Abelian Higgs Model* (HAHM) instead, predicts the production of a pair of γ_d directly from a Higgs boson decay (Figure 1b). In the following, the results and challenges of the aforementioned search will be summarised.



(a) **(b)**

Figure 1: Diagrams of the production of two γ_d from an exotic decay of a SM Higgs, as predicted in the FRVZ (a) or in the HAHM (b) model. Figures adapted from [4].

2. Dark photon signature and search strategy

The search for displaced dark photon decays, in an environment like ATLAS, represents a challenge from the points of view of the trigger capabilities and the background rejection strategy. In order to maximise the signal sensitivity, two exclusive search categories are defined: the *gluon-gluon fusion* (ggF) selection and the *WH associated production* selection, both targeting the corresponding Higgs boson production modes. For the former, the only possible way to trigger an event is to make use of dedicated triggers, searching for narrow jets with a small fraction of energy released in the electromagnetic calorimeters or highly collimated tracks in the muon spectrometer. For the latter, the possibility of triggering on the prompt lepton originating from the W boson decay allows to exploit single-lepton triggers. After the trigger is applied to the events, two mutually-exclusive types of DPJs are defined to better identify the dark photon decay products:

- **Muonic DPJs (μDPJs)** are defined from at least two tracks in the muon spectrometer, found in a narrow cone where neither jets nor tracks from the inner detector are present.
- **Calorimeter DPJs (cDPJs)** are narrow jets, whose fraction of energy released in the electromagnetic calorimeter is below 40% of the total and do not match neither muons nor tracks from the inner detector.

The main source of background is the production of hadronic jets, resulting in mis-identified DPJs, originating from multi-jet and W+jet events. The reduction of this background represents a major challenge for this search. It is achieved by using a dedicated discriminator (QCD tagger), based on a convolutional neural network, for which the input is a three-dimensional representation of the energy deposits associated with the jet (jet image). The QCD tagger score is reported in Figure 2 for a set of signal scenarios and multi-jet events.

Calorimeter DPJs can also be reconstructed in events where high-energy muons are produced by the interaction of the LHC beams with the accelerator components (Beam-Induced-Background, BIB). This background is suppressed thanks to a second tagger based on jet images (BIB tagger), trained to discriminate signal cDPJs from cDPJs found in BIB-enriched events.

A third background source is represented by cosmic-ray muons, which can yield mis-identified DPJs of both types. This background is strongly reduced, for cDPJs, thanks to a selection based on the jet timing. On the other hand, the presence of μDPJs due to cosmic-ray muons is reduced thanks to a dense neural network (Cosmic-ray tagger), trained on muon track parameters and on the timing information of the muon hits in the RPC detectors.

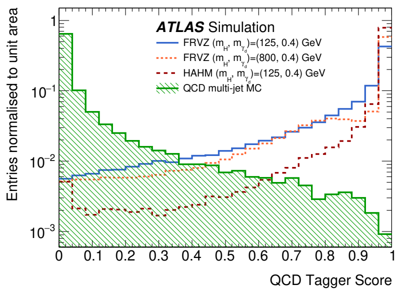
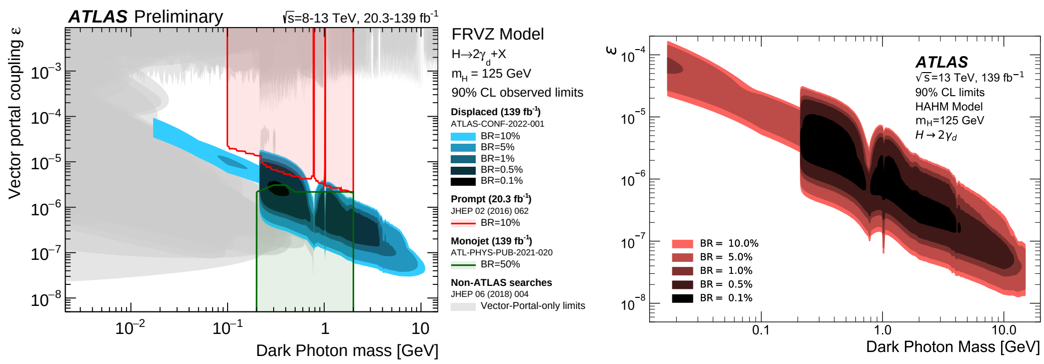


Figure 2: Distribution of the QCD tagger score for three different signal benchmark models and for cDPJs found in a multi-jet Monte Carlo dataset. Figure from [4].

In total, six statistically-independent signal regions are identified by imposing requirements on the number of DPJs and their type. The background component in each signal region is reduced thanks to a selection on the score of the aforementioned taggers, as well as with a selection on other variables helpful in maximising the signal sensitivity. Events of the ggF category can be classified in three of these signal regions, respectively by the presence of at least two μDPJs, two cDPJs or one μDPJ and one cDPJ. On the other hand, the WH selection category features one signal region where the requirement on the number of DPJs is fixed to exactly one cDPJ, plus two additional signal regions requiring at least two cDPJ, or at least one cDPJ and one μDPJ. The amount of multi-jet background in each region is estimated with a data-driven method (ABCD). This technique relies on the assumption that two variables defining the signal region (A) are uncorrelated for background events. Reversing the selection on one or both variables defines three additional regions (B, C and D), which allow to estimate the number of background events in the signal region as $N_A = N_B \times N_D / N_C$. Eventual contributions from cosmic-ray muons are subtracted from the observed yields, while the presence of BIB is reduced to a negligible level.

3. Interpretation of the results

No significant disagreement is observed with respect to the predicted background. A likelihood fit is performed to get the final background estimation and to set upper limits on the production cross section times branching ratio of the Higgs-mediated dark photon production. Exclusion limits are initially obtained for a single choice of the dark photon mass and mean proper lifetime. These results are then extended to a two-dimensional exclusion contour thanks to a weighting method, allowing to put limits on the plane of the kinetic mixing parameter and dark photon mass. The 90% CL exclusion regions are shown, in Figure 3a and Figure 3b for the FRVZ model and the HAHM model, respectively.



(a) (b)

Figure 3: 90% CL exclusion regions of the Higgs boson decay branching ratio (BR), as function of the kinetic mixing parameter and the dark photon mass. In (a) the results for the FRVZ model are reported, where darker blue tones correspond to smaller values of the $H \to 2\gamma_d + X$ BR. This excluded region is complementary to the ones obtained by previous ATLAS searches (in red [6] and green [7]) and to non-ATLAS results (in gray), where the latter do not consider γ_d production via the Higgs boson decay [8]. In (b) the corresponding result for the HAHM model is reported. Figure (a) is reported from [9], while figure (b) is adapted from [4].

4. Conclusion

A search for long-lived neutral particles which decay in collimated pairs of fermions in the ATLAS detector, based on a dataset corresponding to 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV, has been presented. SM Higgs branching fractions above 1% are excluded at 95% CL, for dark photons with mean proper decay lengths between 10 mm and 250 mm and masses between 0.4 GeV and 2 GeV.

References

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