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Dark Sectors and Dark Photons search decaying into collimated leptons with the ATLAS experiment(*)

B. Ricci([1])([2])(**) on behalf of the ATLAS Collaboration

([1]) *INFN Sezione di Trieste, Gruppo Collegato di Udine - Udine, Italy*
([2]) *Università degli Studi di Udine - Udine, Italy*

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Summary. — Several extensions of the Standard Model predict the existence of a Dark Sector weakly coupled to the Standard Model via the vector portal. The simplest extension of the Standard Model foresees the addition of a U(1) gauge group and therefore of a new vector boson, the Dark Photon. At the Large Hadron Collider it is also possible to study Higgs portal models, which allows for the Higgs boson to decay into Dark Sector particles. These models results in Higgs decay processes that have two Dark Photons as their final state, which then decay into Standard Model particles, with highly collimated decay products. This work presents the ongoing search for the Dark Photon, with a mass between 17 MeV and 10 GeV, decaying promptly in the ATLAS detector into jets of collimated electrons and/or muons (Lepton-Jets). The analysis is performed by studying the entire Run-2 dataset at a center-of-mass energy of 13 TeV in proton-proton collisions.

1. – Motivation and Dark Sectors

Several extensions of the Standard Model (SM) predict a Dark Sector weakly coupled to the SM [1-4]. The minimal extension of the SM is obtained with the addition of a U(1) gauge group. This leads to create an electromagnetic-like force mediated by a new vector boson, the Dark Photon γ_d (DP). Depending on the Dark Sector's structure and its SM coupling, unstable Dark States might be produced at colliders and decay into SM particles via the *vector portal*, parametrized by the kinetic mixing coupling ϵ. These scenarios introduce a Dark Higgs boson to give mass to the γ_d. This Dark Higgs can also lead to an exotic decay of the SM Higgs boson (H) due to the mixing between the two Higgs sectors via the *Higgs portal*, a decay that can be investigated at the Large Hadron Collider (LHC).

This work presents the case where the two sectors couple via both the vector portal and the Higgs portal, searching for the γ_d in the full Run-2 dataset with the ATLAS

(*) IFAE 2024 - "Energy Frontier" session
(**) E-mail: `bernardo.ricci@cern.ch`

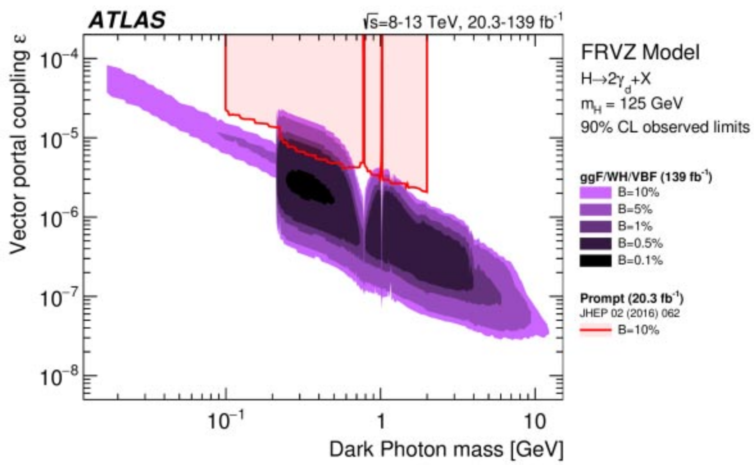

Fig. 1. – The 90% CL exclusion contours regions of the SM Higgs boson as a function of the γ_d mass and of the kinetic mixing parameter ϵ for the $H \to 2\gamma_d + X$ process. These limits are obtained assuming the FRVZ model (sect. **2**) [6] with decay branching fractions of the Higgs boson into γ_d which range between 0.1% and 10%, and the NNLO Higgs boson production cross-sections via gluon–gluon fusion. The figure also shows excluded regions from the early Run-2 prompt searches (in red) [7].

detector [5]. The kinetic mixing term ϵ, which can vary over a wide range of values ($\epsilon \sim 10^{-11}$–10^{-2}), determines the lifetime of the DP, since is proportional to the inverse square of the kinetic mixing coupling ($\tau_{\gamma_d} \propto \epsilon^{-2}$). For a large ϵ the γ_d decays *promptly*, *i.e.*, in the Inner Detector (ID).

This analysis focuses on large values of the kinetic mixing term, $\epsilon > 10^{-5}$, for different values of BR($H \to 2\gamma_d$), and it is optimised for DP masses ranging from a few MeV up to $\mathcal{O}(10)$ GeV. The most-updated exclusion plot with both the Higgs portal and the vector portal is shown in fig. 1.

2. – Signature and benchmark models

Two different benchmark models are studied. The Falkowski-Ruderman-Volansky-Zupan (FRVZ) model [8, 9] where a pair of Dark Fermions (f_d) are produced by the Higgs boson with the Higgs portal. In this model, shown in fig. 2(a), Dark Fermions then decay into a γ_d and a lighter Dark Fermion, assumed to be the hidden lightest stable particle (HLSP). The Hidden Abelian Higgs Model (HAHM) [4] instead predicts a direct decay of the Higgs boson into a pair of γ_d, as shown in fig. 2(b). Then, in both models, each γ_d decays, via the vector portal, in a pair of SM fermions.

The analysis described here considers γ_d decaying in $\mu^+\mu^-$ and e^+e^- pairs. Due to their small mass, DP are expected to be produced with large boosts at LHC, resulting in collimated groups of leptons in a jet-like structure, hereafter referred to as *Lepton-Jets* (LJs). The collimation of leptons is shown in the ΔR (1)

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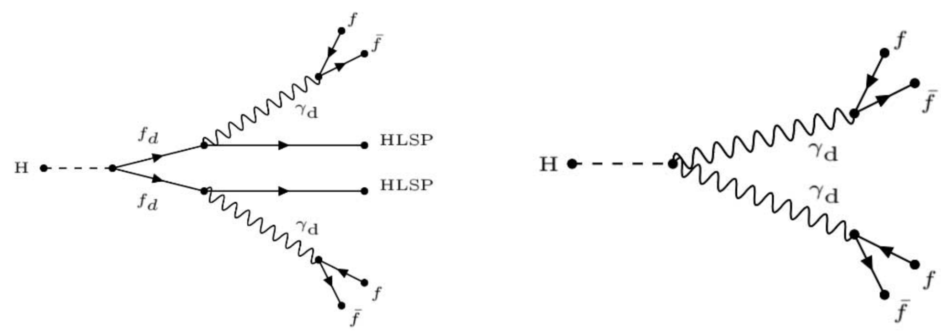
(1) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates



(a) (b)

Fig. 2. – (a) FRVZ process with the Dark Fermion f_d decaying into a γ_d and an HLSP. (b) HAHM process with the two γ_d directly produced by the Higgs boson. The γ_d decays into SM fermions, denoted by f and $\bar{f}$.

3. – Lepton Jets

Electrons are reconstructed in the ATLAS detector by matching an energy deposit in the electromagnetic calorimeter with (at least) an ID track. Muons are reconstructed using the ID and the Muon Spectrometer (MS). LJs are then built from close-by leptons, and classified depending on the number of muons and electrons within a fixed ΔR=0.4 cone. If the cone contains at least two muons and no electrons (with muons referring both to μ^+ or μ^- and electrons both to e$^+$ or e$^-$), the LJ is classified as a muon-LJ (μLJ). If it contains at least one electron with at least two associated tracks and no muons, it is classified as an electron-LJ (eLJ). These requirements make the two categories exclusive, as shown in fig. 4.

For the eLJ case it can happen that, since e^+e^- pairs are highly collimated, the electromagnetic clusters in the electromagnetic calorimeter (ECAL) of the two electrons are overlapped, making an only electromagnetic cluster with two tracks associated. The two possible cases are shown in fig. 5.

4. – Analysis strategy

The search described here is based on the full dataset collected by ATLAS during Run-2 at $\sqrt{s}$=13 TeV, from 2015 to 2018. Events are categorized into orthogonal channels based on the LJs constituent particles: the electronic channel, in which both γ_d decays in electrons and so in which 2 eLJ are reconstructed, the muonic channel, where both γ_d decays in muons and 2 μLJ are reconstructed, and the mixed channel, with one γ_d decaying in muons and one γ_d in electrons and 1 eLJ + 1 μLJ are reconstructed. The electronic chanel is optimized for γ_d masses below 240 MeV, instead the muonic and

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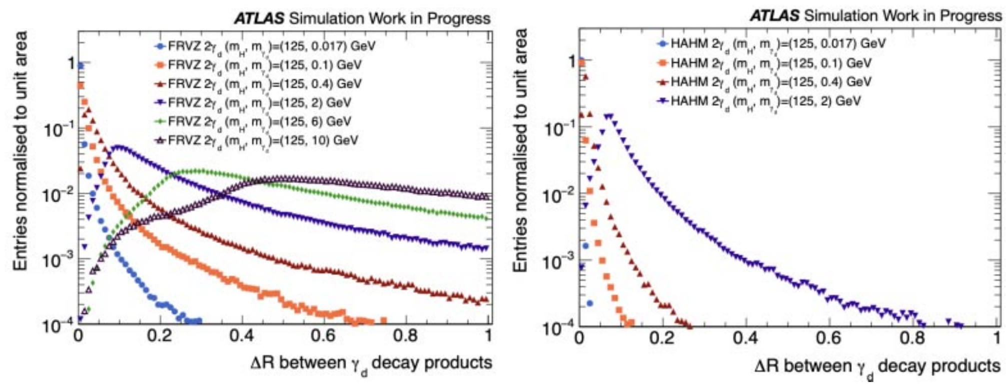
(r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_zc}{E-p_zc}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.



(a) (b)

Fig. 3. – ΔR opening of the two decay products for different γ_d masses generated according to the FRVZ (a) and HAHM (b) models.

mixed channel are searching for masses above 240 MeV. The three channels are studied with MonteCarlo (MC) simulations in three different orthogonal Signal Regions (SR), *i.e.*, regions where the γ_d is expected to be observed, one for each channel.

Background sources include collimated lepton pairs from the decay of light SM resonances (such as J/ψ, $\psi(2S)$ and $\phi(1020)$), and a non-resonant component where virtual photons convert to leptons. Misidentified LJs can also arise from a prompt lepton crossed by a random track, where the prompt lepton is produced in processes such as Z+jets. The background evaluation is performed with *data-driven* techniques in three different Control Regions (CR), with different methods depending on the channel to be studied. For the electronic channel the *ABCD* method is performed, while for the muonic and mixed channel is performed the *bump-hunting*.

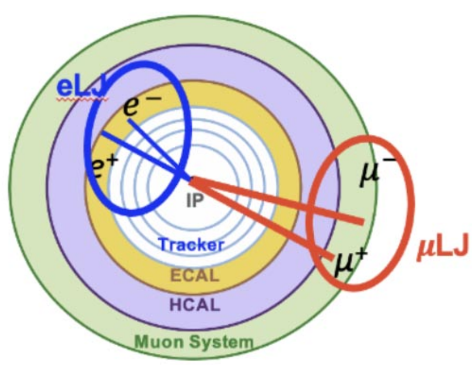


Fig. 4. – Scheme of reconstruction of the two types of LJs: the eLJ and μLJ.

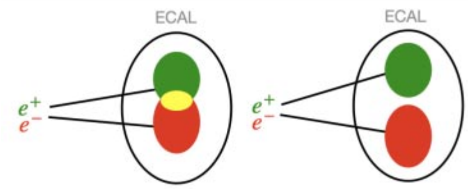
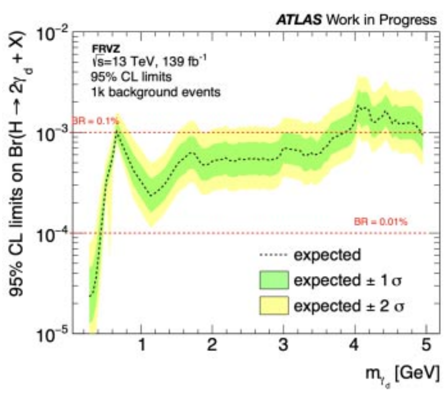


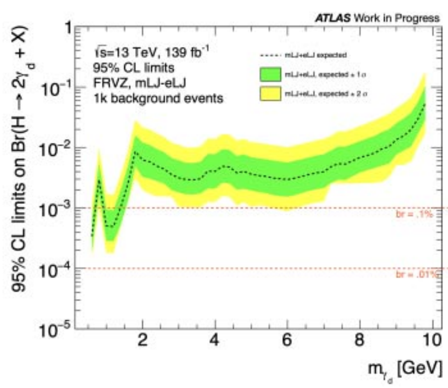
Fig. 5. – eLJ reconstruction: it can happen that the electromagnetic clusters in the ECAL of the e^+e^- pairs are overlapped with at least two associated tracks (left). Also the case in wich two electrons are separately reconstructed in a $\Delta R = 0.4$ cone (right).

5. – Expected limits

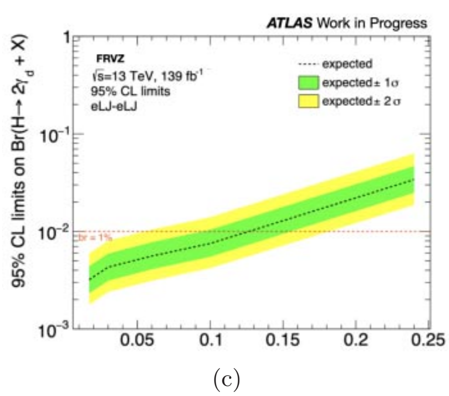
With a study on the MC simulations in SRs and a background studies on real data in the CRs, it's possible to obtain the expected limits on the $BR(H \to 2\gamma_d + X)$ at 95% CLs for the different channels. The expected limits for the FRVZ model for all channels are shown in fig. 6.



(a)



(b)



(c)

Fig. 6. – Expected limits at the 95% confidence level (CL) on the branching ratio for the process $BR(H \to 2\gamma_d + X)$ FRVZ model in the full γ_d mass range in the 2 μLJ channel (a), in the 1 eLJ + 1 μLJ channel (b) and in the 2 eLJ cahnnel (c).

6. – Conclusions

In this report the Lepton-Jets signature is explained and the expected upper limits on the $BR(H \rightarrow 2\gamma_d + X)$ obtained on the full Run-2 dataset with the ATLAS detector for the FRVZ model are presented. The analysis on real data is in progress.

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