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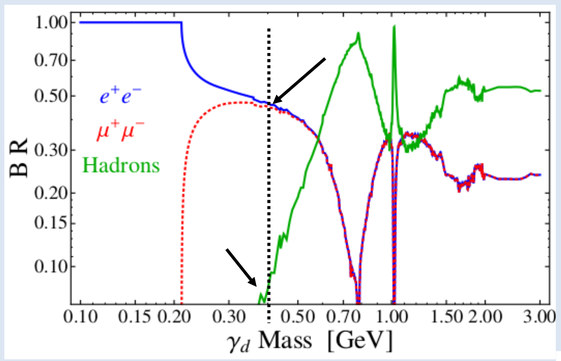
Search for long-lived neutral particles decaying into Lepton-Jets with the ATLAS detector in proton-proton collision data at √s= 13 TeV

Abstract

Several extensions of the Standard Model (SM) predict the existence of a dark sector weakly coupled to the visible one, via vector portal, i.e, through a long lived dark photon with mass in the MeV to GeV range, which mixes kinetically with the SM photon. If the dark photon is the lightest state in the dark sector, it will decay to SM particles.
At the LHC, these dark photons would typically be produced with large boost resulting in collimated jet-like structures containing pairs of leptons and/or light hadrons: lepton-jets (LJs).
This work is focused on the search for Displaced LJs, produced far away from the interaction point. The most recent ATLAS results based on samples collected at a center of mass energy of 13 TeV and integrated luminosity of 3.4 fb^{-1}, are presented. The results are interpreted in terms of the Falkowsky-Ruderman-Volansky-Zupan models where dark photons are generated through the decay of a Higgs boson, produced via gluon-fusion.

1 Hidden Valley

The **Hidden Valley** (HV) is a new sector weakly coupled to the Standard Model (SM). New heavy particles (or even H/W/Z/t) produced at the LHC may decay to HV and some hidden particles like **dark photon** γ_D may decay back to SM particles on measurable time scale. The γ_D lifetime is given by the kinetic mixing parameter ε (10^{-3}–10^{-4}) and can become large, producing decays far away from the interaction point. Moreover, due to the small mass, the γ_D is highly boosted and it decays to collimated jet-like structures containing pairs of e^-e^+, $\mu^-\mu^+$, $\pi^-\pi^+$: the **displaced Lepton-Jets** (dLJ).[1]



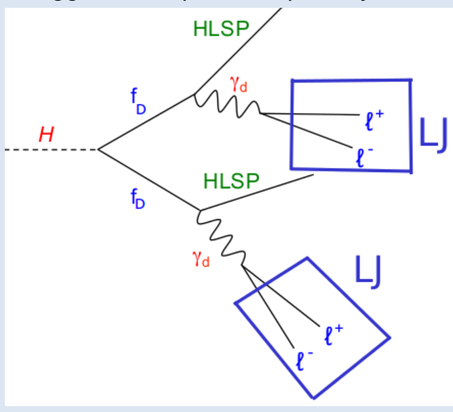
Branching ratio of γ_D as a function of its mass

$$L \supset \frac{\epsilon}{2} F^{\pi\mu} A_{\mu\nu} + m^2_{\gamma_D} A^2$$

SM – HV coupling

2 Falkowsky-Ruderman-Volansky-Zupan models

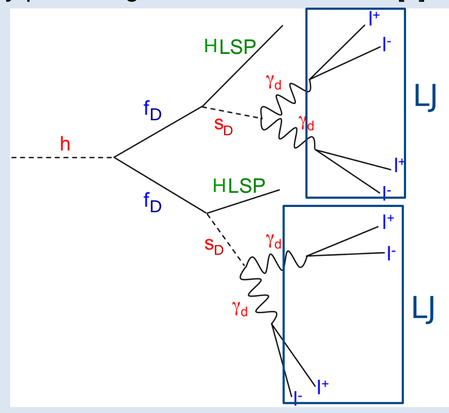
The **FRVZ models** describe a general interaction between SM and HV sectors, in which Higgs (125 GeV) or BSM Higgs boson (800 GeV) decays in a hidden sector fermion, finally producing two back-to-back LJs.[2]



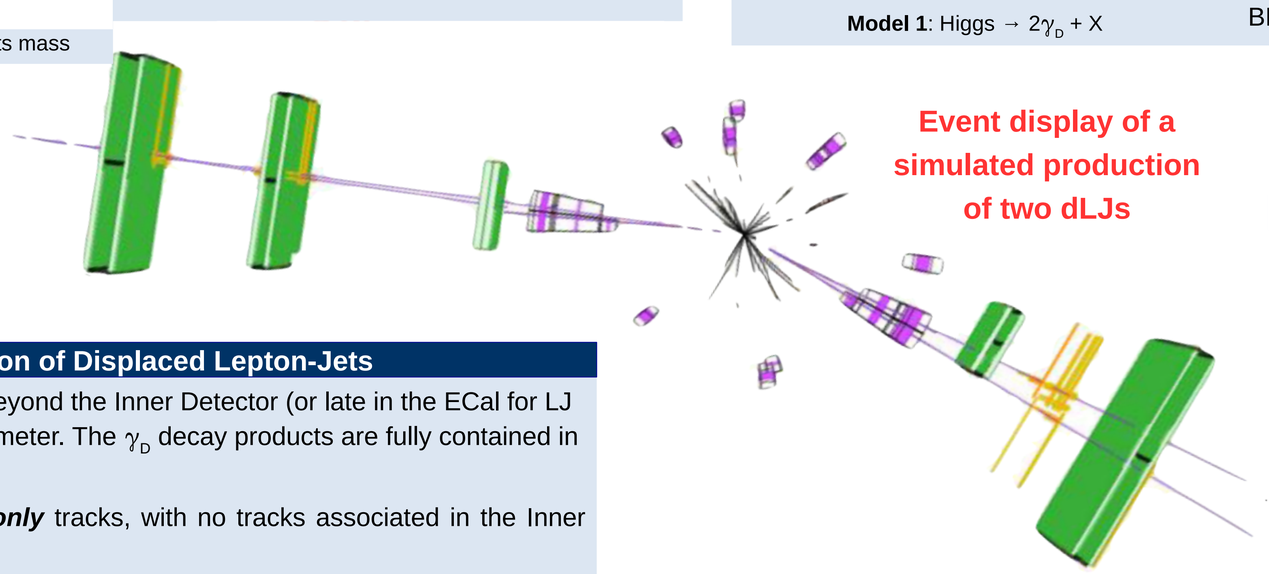
Model 1: Higgs → $2\gamma_D$ + X

Parameters:
m_{fD}= 5 GeV
$m_{\gamma D}$= 0.4 GeV
m_{HLSP} = 2 GeV
m_{SD} = 2 GeV

Branching ratio for γ_D:
BR($\gamma_D \rightarrow \mu^+\mu^-$)= 45%
BR(γ_D->e^+e^-)= 45%
BR(γ_D->$\pi^+\pi^-$)= 10%



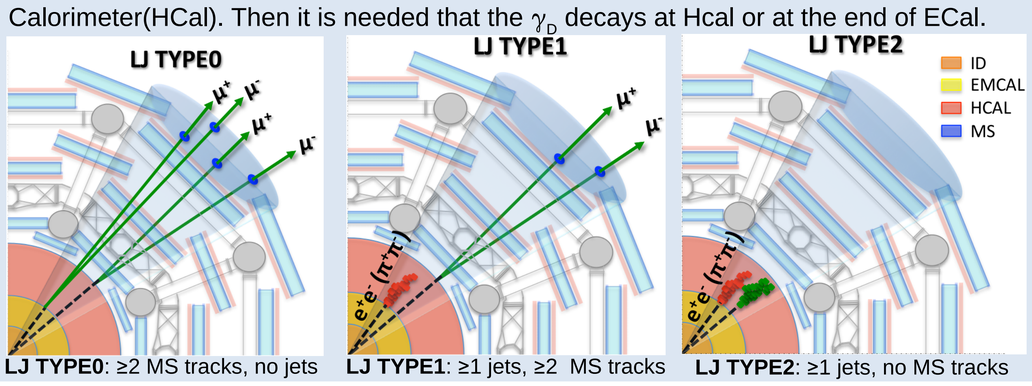
Model 2: Higgs → $4\gamma_D$ + X


Event display of a simulated production of two dLJs

3 Reconstruction of Displaced Lepton-Jets

This analysis only considers decays beyond the Inner Detector (or late in the ECal for LJ TYPE2) and before the Muon Spectrometer. The γ_D decay products are fully contained in a ΔR = 0.5 cone.

- LJ muons are reconstructed as ***MSonly*** tracks, with no tracks associated in the Inner Detector
- LJ electron and pions are reconstructed as narrow isolated **jets** with much less energy deposition in Electro Magnetic Calorimeter (ECal) than in the Hadronic Calorimeter(HCal). Then it is needed that the γ_D decays at Hcal or at the end of ECal.



LJ TYPE0: ≥2 MS tracks, no jets
LJ TYPE1: ≥1 jets, ≥2 MS tracks
LJ TYPE2: ≥1 jets, no MS tracks

4 Systematics

- CaloRatio trigger
- Effect of pile-up on $\sum p_T$
- ABCD background estimation
- Overall normalization of integrated luminosity
- Narrow-scan trigger efficiency using Tag&Probe method with $J/\psi \rightarrow \mu^+\mu^-$
- Close-by muon reconstruction efficiency in MS, using Tag&Probe method with $J/\psi \rightarrow \mu^+\mu^-$

5 Discriminant variables and Background estimation

Selection requires a logical OR of these ATLAS High Level Triggers:

- **Narrow-scan** (NS): 2 *MSonly* tracks (p_T > 20 GeV, p_T > 6 GeV) in a ΔR=0.5 cone
- **CaloRatio**: jet with p_T > 30 GeV and low EM fraction
- **Tri-muon** (3mu): 3 *MSonly* tracks with p_T > 6 GeV

NS+ 3mu for muon-LJs reconstructed as Msonly tracks (LJ TYPE0)
CaloRatio for e/π-LJs reconstructed as narrow, low EMF jets wo ID tracks (LJ TYPE2)
The search requires a pair of LJs in any of the possible combinations.

Source of **background**:

- Cosmic-ray muon energy deposits in calorimeters (for TYPE1 and TYPE2 dLJs): mis-reconstructed as jets
- Cosmic muon bundles (for TYPE0, 1): mainly concentrated in barrel
- Beam-induced background (BIB) (for TYPE2): high-energy muon longitudinally crossing detector, with bremsstrahlung in HCAL barrel
- QCD multi-jet: γγ, γ+jets, tt, single-top, Drell-Yan e + e - / μ + μ - , Z/W+jets, diboson, heavy flavours

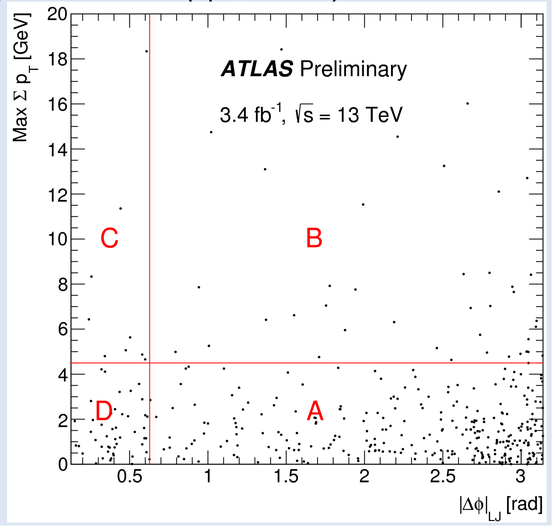
Cuts defined to optimize signal significance:

- **LJ isolation** ($\sum p_T$ of ID tracks belonging to primary vertex in ΔR=0.5 cone around LJ center, with p_T>0.5 GeV)
- **BIB tagging** (Rejects BIB jets accompanied by φ–matched muons parallel to beam pipe, TYPE2)
- **Jet timing** (rejects mis-reconstructed cosmics and BIB, TYPE1, 2)
- **Muon impact parameter**: (rejects cosmic muons, TYPE0, 1)
- **Jet width** (rejects QCD, TYPE2)
- **Jet EM fraction** (Rejects QCD, TYPE2)

The data-driven method used to estimate the QCD multi-jet contribution in region A, is the **simplified matrix method ABCD**, assuming that:

- The multi-jet background is factorizable in 2D plane formed by $\sum p_T$ and $|\Delta\varphi|$
- In the FRVZ models, LJs have high $|\Delta\varphi|$ and low $\sum p_T$

The multi-jet background estimation is given by $N_A = N_D \times N_B / N_C$.



6 Conclusion and results

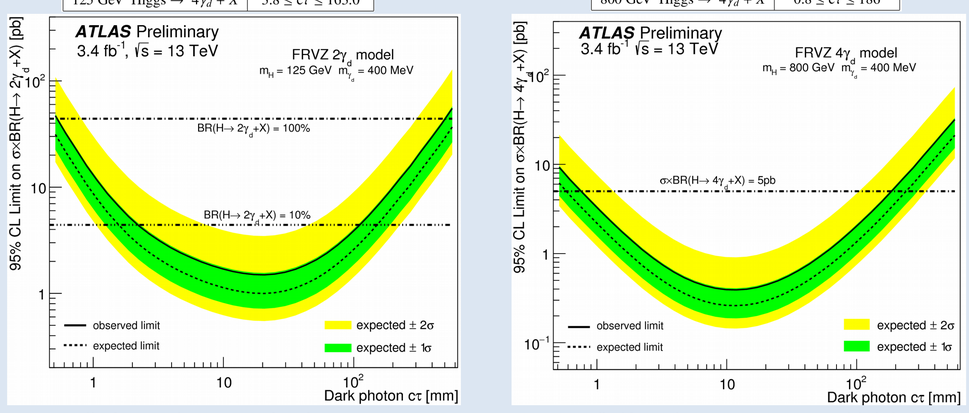
Results with p-p collisions at √s = 13 TeV (3.4 fb^{-1}):

- the search is largely model independent and for a general definition of LJs, found a set of **selection criteria to isolate the LJs signature** from the background
- **set upper limits on non-SM Higgs boson decays to LJs** according to the FRVZ models with a γ_D mass of 0.4 GeV
- **set 95% CL upper limits on the σ×BR for H→ 2(4)γ_D + X** as a function of the γ_D mean lifetime
  - SM gluon fusion production cross section is assumed for the 125 GeV Higgs boson
  - conventional production cross section of 1.0 pb is assumed for the 800 GeV Higgs-like heavy scalar

Recent observation of anomalous internal pair creation in Be8 is interpreted as a possible signature of a light, neutral boson of 16.7 MeV decaying in e^-e^+ pairs from the dark sector.[3] TYPE2-TYPE2 signal can be related to the framework of this "protophobic" boson assuming a 100% 800 GeV heavy scalar decay to $2\gamma_D$ of 16.7 MeV mass

FRVZ model	Excluded cτ [mm] BR(10%)
125 GeV Higgs → $2\gamma_d + X$	$2.2 \le c\tau \le 111.3$
125 GeV Higgs → $4\gamma_d + X$	$3.8 \le c\tau \le 163.0$

FRVZ model	Excluded cτ [mm] σ × BR = 5 pb
800 GeV Higgs → $2\gamma_d + X$	$0.6 \le c\tau \le 63$
800 GeV Higgs → $4\gamma_d + X$	$0.8 \le c\tau \le 186$



95% upper limits on the σ×BR for the FRVZ 125 GeV H→$2\gamma_D$+X (left) and BSM H→$4\gamma_D$+X (right) FRVZ model as a function of the γ_D lifetime with TYPE2-TYPE2 events removed. The simultaneous fit is done taking into account signal contamination in regions B, C and D.

7 Reference and acknowledgement

[1] ATLAS Collaboration, "*Search for long-lived neutral particles decaying into displaced lepton jets in proton-proton collisions at √s= 13TeV with the ATLAS detector*", ATLAS-CONF-2016-042 (2016).
[2] A. Falkowski, J. T. Ruderman, T. Volansky and J. Zupan, "*Discovering Higgs Decays to Lepton Jets at Hadron Colliders*", Phys. Rev. Lett. 105 (2010)
[3] "Observation of Anomalous Internal Pair Creation in 8Be: A Possible Signature of a Light, Neutral Boson", Phys. Rev. Lett. 116 (2016) 042501

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Del Gaudio Michela[1,2] on behalf of the ATLAS Collaboration
[1] University of Calabria, [2] INFN (Italy)