Search for displaced “Lepton-Jets” with the ATLAS experiment

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1. MOTIVATIONS

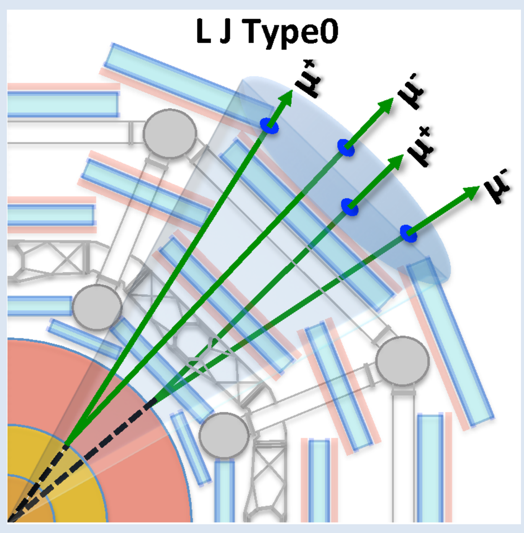
A wide range of Beyond the Standard Model (BSM) theories predict a hidden sector, weakly coupled to the visible sector.

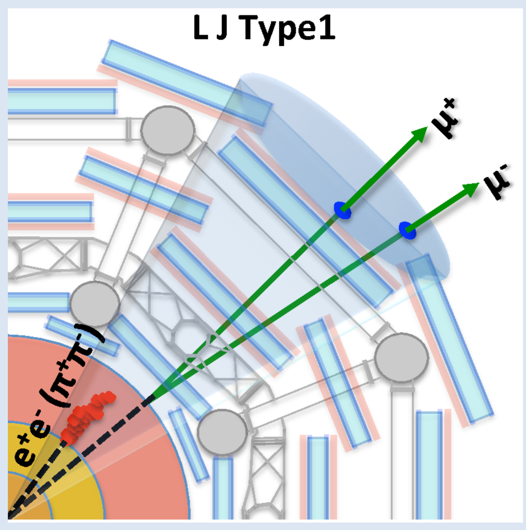
Discovery processes with peculiar signatures:

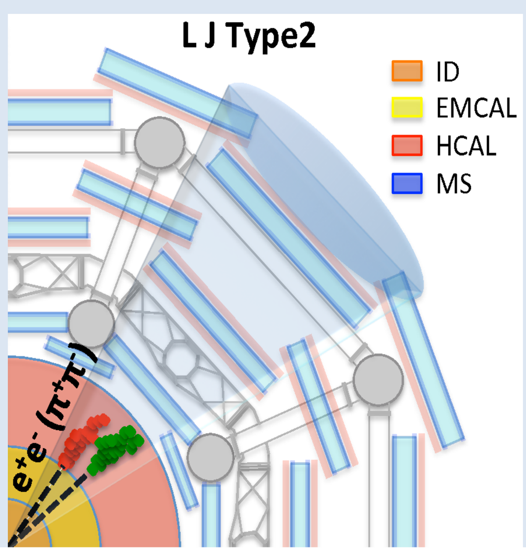
- Lightest unstable hidden states in MeV to GeV range typically produced with large boost → highly-collimated decay products
- Decay back to SM with high branching fraction → e^+e^-, $\mu^+\mu^-$, or light hadrons in final state
- Non-negligible lifetime → displaced decay vertex with respect to primary vertex of event

3. Categorisation of LJs into 3 types for ease of search & reconstruction:

TYPE0: ≥2 MS tracks, no jets
TYPE1: ≥2 MS tracks, ≥ 1 jet
TYPE2: 1 jet with low EM fraction, no muons

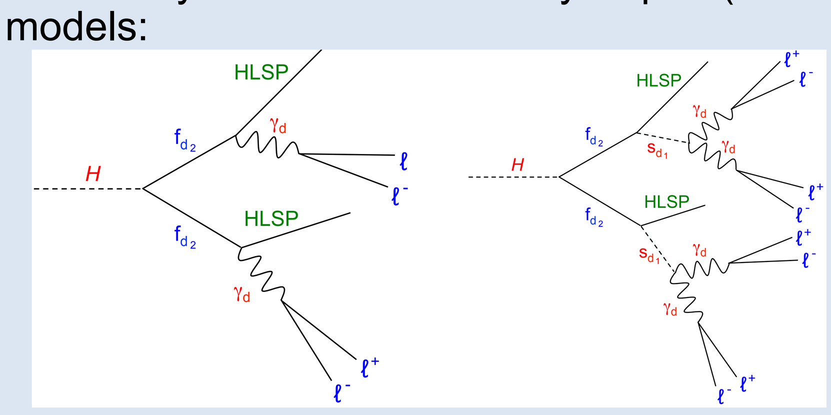






5. BENCHMARK MODELS

Falkowsky-Ruderman-Volansky-Zupan (FRVZ) models:



- SM Higgs or BSM additional heavy Higgs decays to hidden sector fermions f_{d2}
- Hidden shower ends with γ_d’s and Hidden Lightest Stable Particles
- γ_d’s produces LJs, which usually come off back-to-back

2. DISPLACED LEPTON-JETS (dLJs)

Collimated jet-like structures, produced far from the primary vertex, containing pair(s) of muons, electrons, and/or light hadrons.

dLJs IN DARK PHOTON MODELS

dLJs are signature of the dark photon (γ_d) decay, the heavy gauge boson of an additional U(1). In “vector portal” models, the γ_d kinetically mix with the SM photon:

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m_{\gamma_d}^2 b^2$$

Smaller ε yields longer γ_d lifetime. Branching ratios of the γ_d depend on its mass.

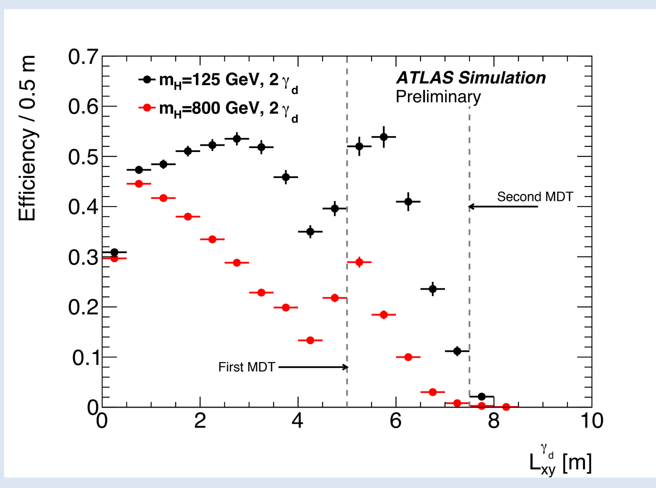
4. dLJ RECONSTRUCTION and dedicated TRIGGERS

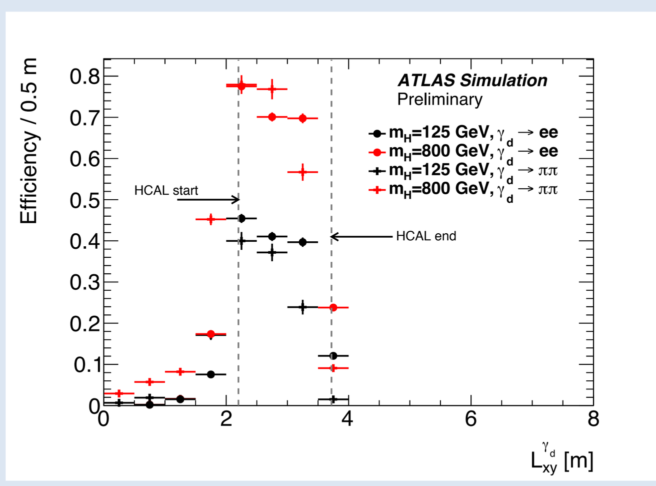
Target:

γ_d decays beyond the Inner Detector (ID) up to the Muon Spectrometer (MS)

- Muon pairs appear in spectrometer as “MSonly” tracks (no associated ID tracks)
  - Tri-muon trigger: 3 MSonly tracks, p_T > 6 GeV (for pair of TYPE0 dLJs)
  - Narrow-scan trigger: 2 MSonly tracks in ΔR = 0.5 cone, leading p_T > 20 GeV, sub-leading > 6 GeV (for TYPE0 and TYPE1 dLJs)
- Electron/pion pairs appear in calorimeters as narrow isolated jets, with much less energy deposition in EM Calorimeter (EMCAL) than in Hadronic Calorimeter (HCAL)
  - CaloRatio trigger: jet p_T > 30 GeV with low EM fraction of the energy (for TYPE 2 dLJs)
- **A LJ-finding clustering algorithm is used with ΔR = 0.5 cone (fully contains decay products).**

Efficiency dependent on muons separation due to the magnetic field.

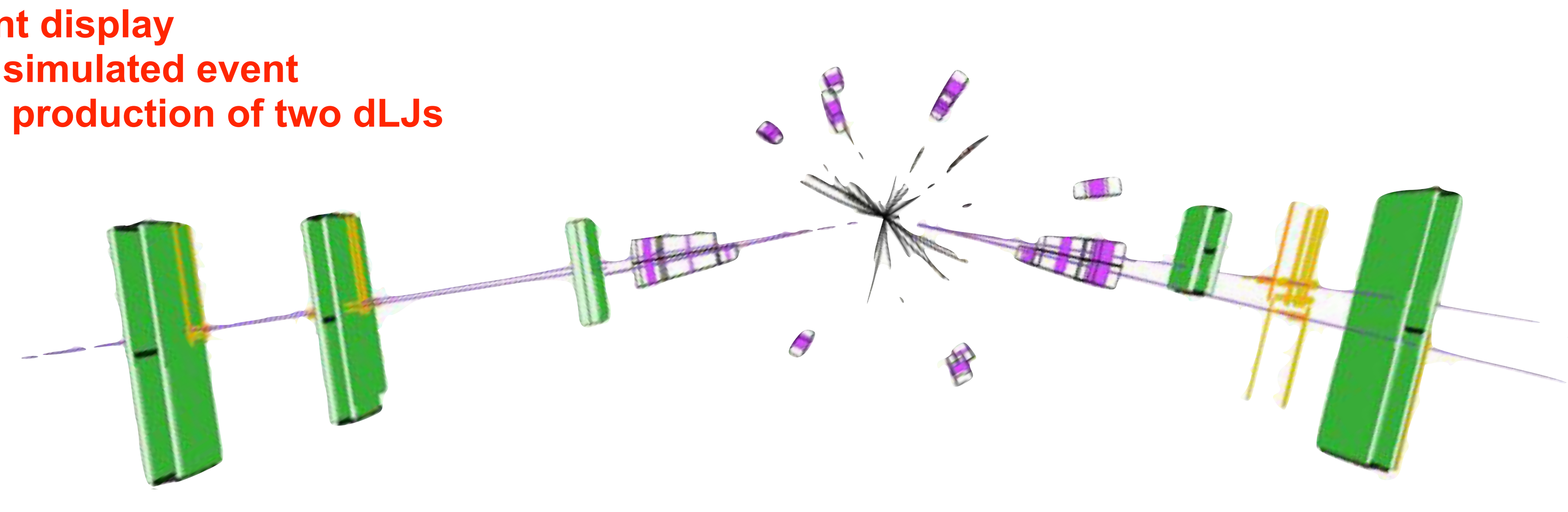




6. SEARCH STRATEGY

- Two LJs are expected to be produced back-to-back in the azimuthal plane.
- All the possible combinations of pairs of LJ types are taken into account.
- If >= 2 LJs are reconstructed, the leading LJ and the farthest LJ in φ are chosen.

Event display of a simulated event with production of two dLJs



7. BACKGROUND ESTIMATION

- Cosmic-ray muon energy deposits in calorimeters (for TYPE1 and TYPE2 dLJs): mis-reconstructed as jets
- QCD multi-jet production (for TYPE 2): evaluated with the ABCD method
- Beam-induced background (BIB) (for TYPE2): high-energy muon longitudinally crossing detector, with bremsstrahlung in HCAL barrel
- Cosmic muon bundles (for TYPE 0, TYPE1): mainly concentrated in barrel
- SM processes which lead to real prompt muons and muons plus jets in the final state such as W+jets, Z+jets, tt, single-top, Drell-Yan e^+e^- / $\mu^+\mu^-$, WW, WZ, and ZZ: estimated in MC and removed by requiring muons to be non-Combined.

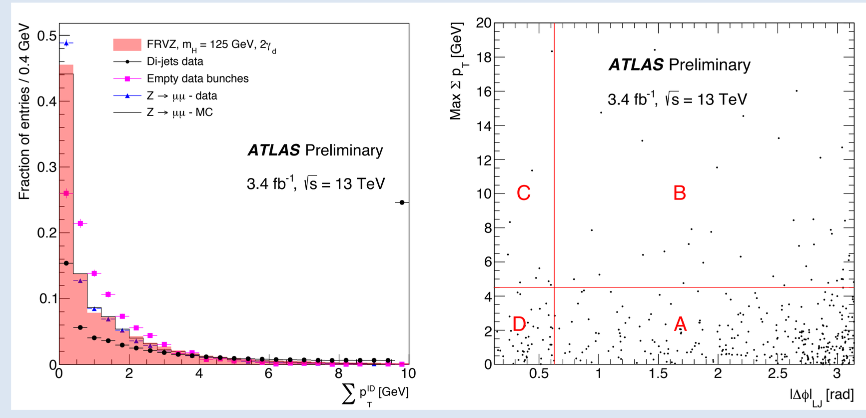
Cuts applied at dLJ level, to optimize signal significance, ordered by separation power:

- Jet Width: rejects QCD (TYPE2)
- Jet EM Fraction: rejects QCD (TYPE2)
- Loose requirement on muon impact parameter: rejects muon cosmics (TYPE0 and TYPE1)
- Jet timing: rejects mis-reconstructed cosmics and BIB (TYPE1 and TYPE2)
- BIB tagging: rejects BIB jets accompanied by φ–matched muons parallel to beam pipe (TYPE2)

Cuts applied at event level, using data-driven method (QCD multi-jet + cosmics):

Matrix (ABCD) method assumes background factorizable in 2D plane

- Require 2 dLJs per event (any possible combination between TYPES 0,1,2)
- $\sum p_T$: Scalar sum of transverse momentum of ID tracks belonging to the primary vertex of the event in ΔR = 0.5 cone around LJ centre (all dLJ types, dLJs are highly isolated in ID, variable validated using muons form Z boson decays)
- |Δφ| between leading LJ and farthest LJ in φ



Simultaneous (signal+data) counting experiment in control and signal regions, with $N_A = N_D \times N_B / N_C$, provides estimate of background contamination in **signal region A**, taking into account signal contamination in B, C and D regions.

8. SYSTEMATIC UNCERTAINTIES

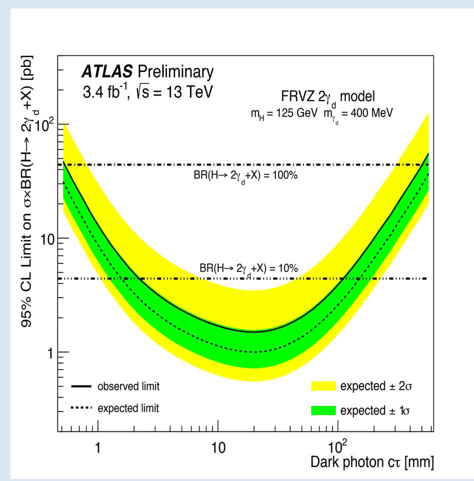
- Overall normalization of integrated luminosity
- Muon trigger efficiency using a tag and probe method with J/ψ from data and Monte Carlo
- CaloRatio trigger
- Close-by muon track reconstruction efficiency using a tag and probe method with J/ψ from data and Monte Carlo
- Effect of pile-up on $\sum p_T$
- ABCD background estimation

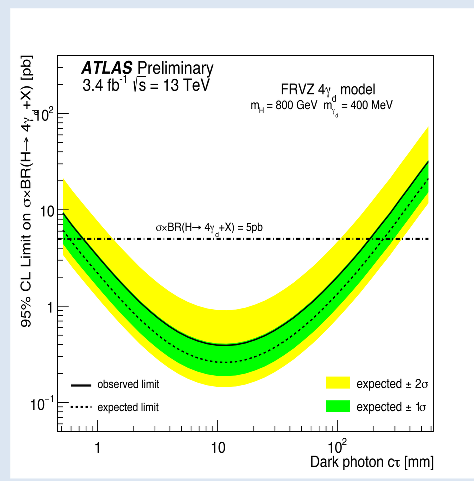
9. RESULTS

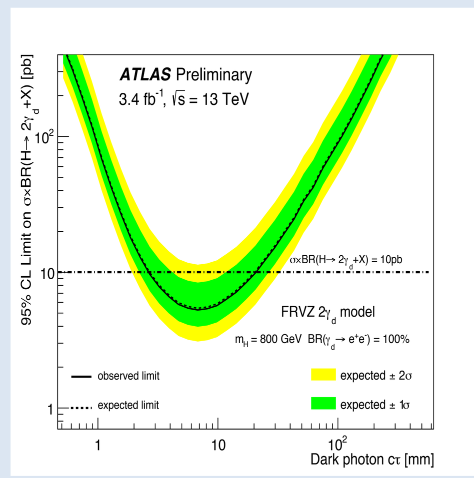
- Search for dLJ pairs performed using 3.57 fb^{-1} of 2015 pp data collected by ATLAS at $\sqrt{s}$ = 13 TeV
- Starting from a general definition of dLJs, a set of selection criteria able to isolate their signature from the SM, BIB and cosmic-rays backgrounds were defined
- Observed data consistent with the experimental background expectations
- Results of the search used to 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
- Limits set on the σ×BR for Higgs → $2(4)\gamma_d + X$ as a function of the long-lived particle 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.

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] $\sigma \times BR = 5$ pb
800 GeV Higgs → $2\gamma_d + X$	$0.6 \le c\tau \le 63$
800 GeV Higgs → $4\gamma_d + X$	$0.8 \le c\tau \le 186$







10. WHAT’S NEXT?

- Analysis of full 2015 + 2016 dataset (36 fb^{-1}) already ongoing, then will be extended with 2017 sample too.
- New strategies based on BDT selection have been optimised.
- Other production mechanisms of the Higgs boson will be explored, i.e. W/Z associated production
  - better trigger performance are expected.