SEARCH FOR LONG-LIVED NEUTRAL PARTICLES DECAYING INTO LEPTON-JETS WITH THE ATLAS DETECTOR IN PROTON-PROTON COLLISION DATA

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

MOTIVATION

A wide range of Beyond the Standard Model (BSM) theories predict a hidden sector, weakly coupled to the visible sector. One particularly promising, yet challenging, collider search strategy targets processes with:

- 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 $\pi^+\pi^-$ in final state
- Non-negligible lifetime → decay vertex displaced relative to primary vertex of event

dLJs IN DARK PHOTON MODELS

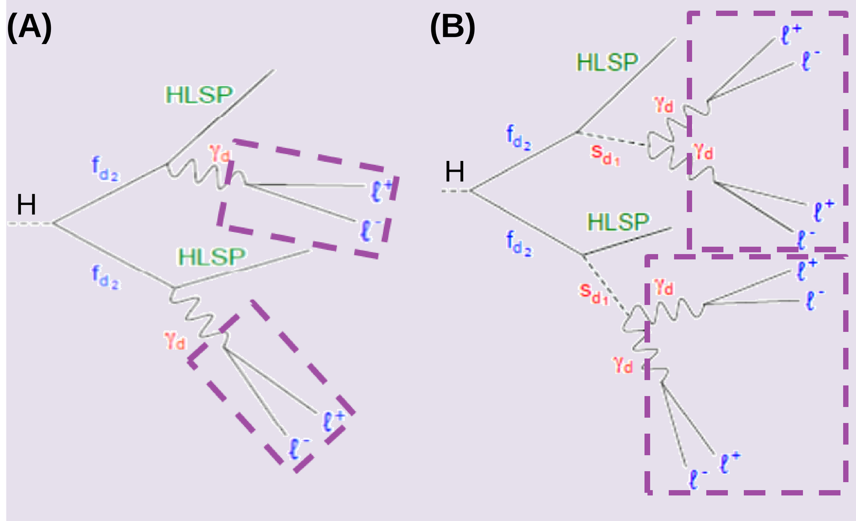
dLJs are a particularly distinctive "smoking gun" signature of the dark photon (A' or γ_d), the heavy gauge boson of an additional U(1)'. In "vector portal" models, the γ_d can kinetically mix with the SM photon:

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} A_{\mu\nu} + m_{\gamma_d}^2 A'^2$$

Smaller mixing parameter ϵ yields longer γ_d lifetime. BRs of the γ_d depend on its mass. Much of the parameter space in such models features long-lived, boosted low-mass $\gamma_d \rightarrow l^+l^-$ yielding final-state dLJs.

BENCHMARK MODELS

As benchmarks, we take two hidden sector models (Falkowsky-Ruderman-Volansky-Zupan, FRVZ):



H (SM-like Higgs or a BSM heavy neutral variety) decays to heavy hidden fermions f_{d2}. Each f_{d2} may decay directly to a γ_d and Hidden Lightest Stable Particle (left), or through a hidden scalar s_{d1} (right). The γ_d's decay to LJs, which usually come off back-to-back. [1]

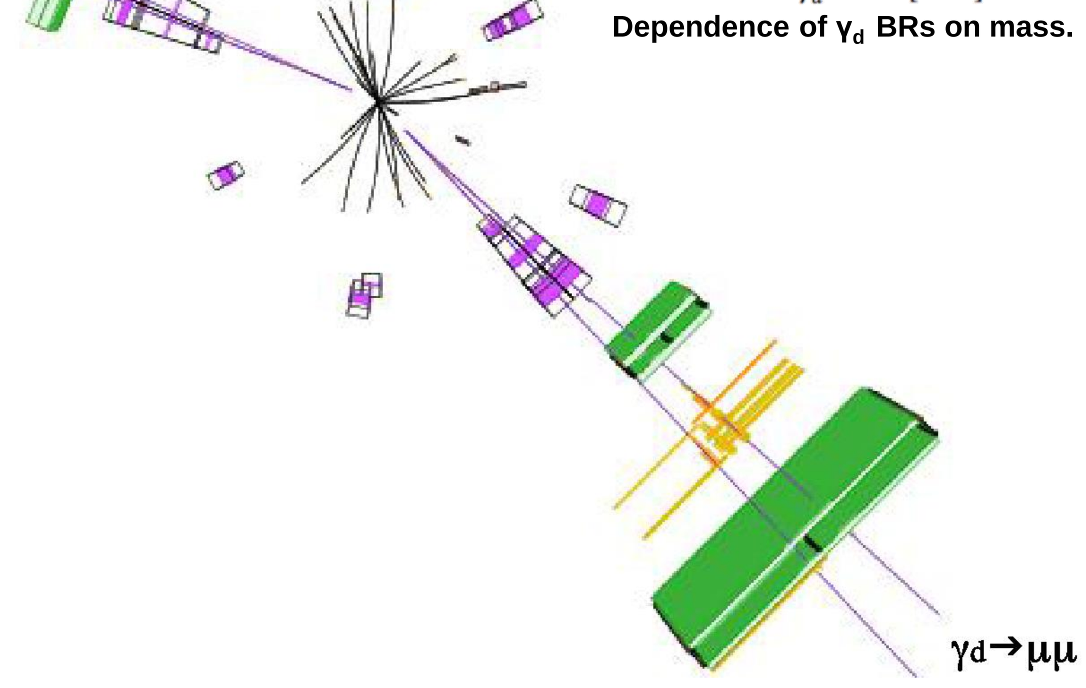
dLJ SEARCH STRATEGY

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

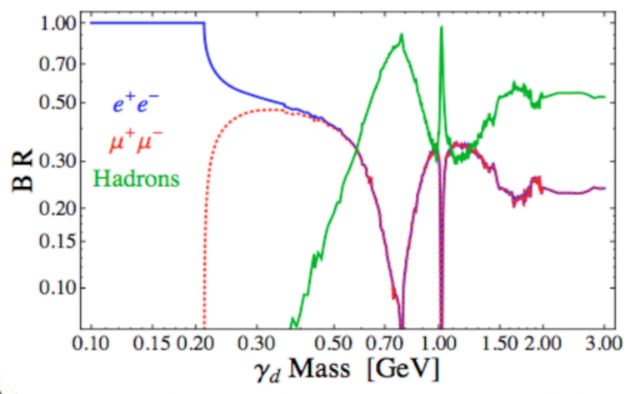
- Muon pairs appear in spectrometer as "MSonly" tracks (no associated ID tracks)
- Electron / pion pairs appear in calorimeters as "LJCalTracks" (narrow isolated jets, with much less energy deposition in EMCal than in HCal)

LJ-finding uses a clustering algorithm with $\Delta R = 0.5$ cone, and special reconstruction considerations:

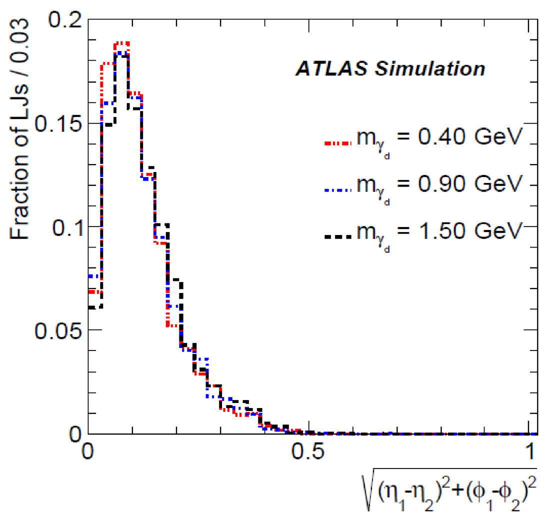
- Collimated final-state particles difficult to reconstruct due to detector granularity
- Reconstruction of tracks with displaced decay vertices require removal of primary vertex constraints used in standard algorithms, and is especially difficult outside ID



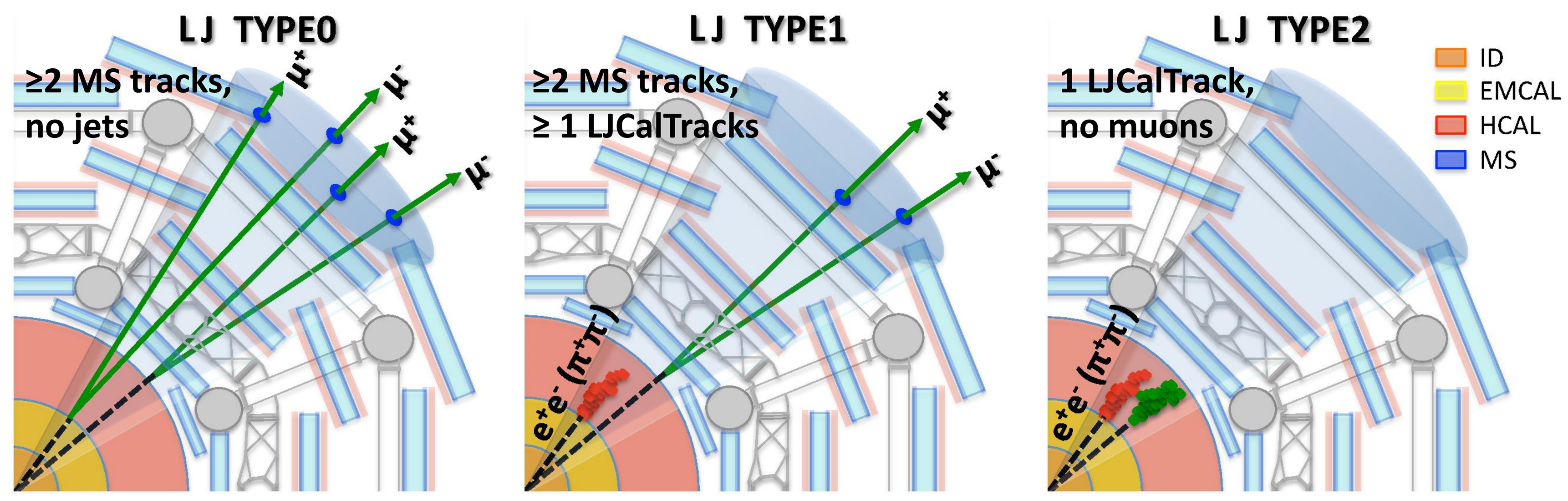
Event display of a simulated dLJ. [3]

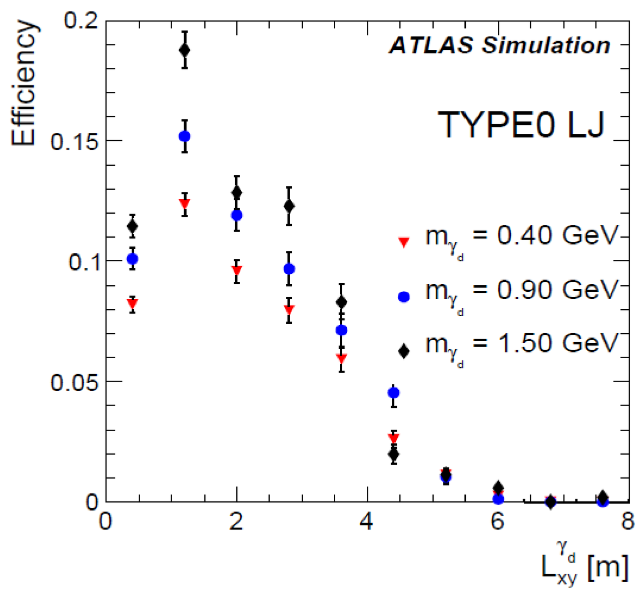


Dependence of γ_d BRs on mass. [1]

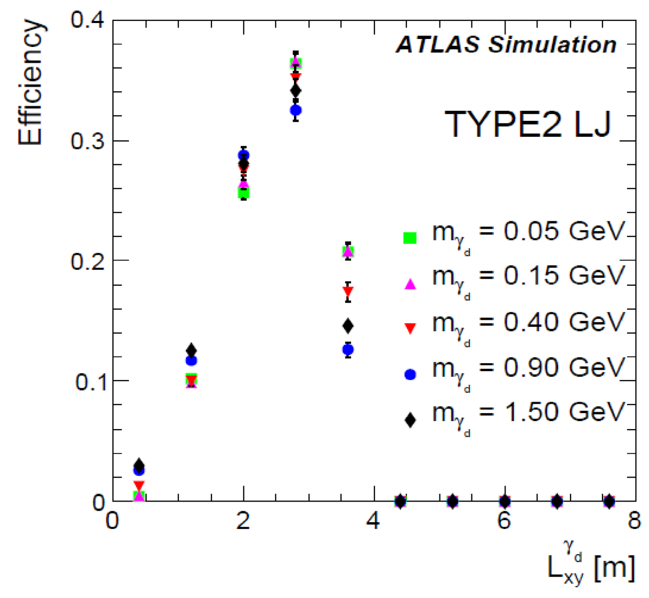


Opening angle of constituents of dLJs from $\gamma_d \rightarrow \mu^+\mu^-$. Evaluated in MC samples for Run 1 ($\sqrt{s}$ = 8TeV). [2]





dLJs are categorized into three types (above) for ease of search and analysis. Reconstruction efficiency for dLJs, Type 0 (left) and Type 2 (right), varies as a function of the transverse decay length of the γ_d. Evaluated in MC samples of $\gamma_d \rightarrow \mu^+\mu^-$ (left), $\gamma_d \rightarrow e^+e^-$ / $\pi^+\pi^-$ (right), for Run 1 ($\sqrt{s}$ = 8TeV). [2]



BACKGROUND SOURCES

- QCD multi-jet: γγ, γ+jets, $t\bar{t}$, single top, Drell-Yan e^+e^- / $\mu^+\mu^-$, Z/W+jets, diboson
- Cosmic-ray muon energy deposits in calorimeters (for Types 1, 2 dLJs): mis-reconstructed as jets
- Cosmic muon bundles (for Types 0, 1): mainly concentrated in barrel
- Beam-induced background (for Type 2): high-energy muon longitudinally crossing detector, with bremsstrahlung in HCal barrel

TRIGGERS

The ATLAS trigger system has multiple levels. L1 is hardware-based, using the calorimeters and MS to define regions-of-interest. The next two levels, combined into a High-Level Trigger (HLT) in Run 2, are software-based and are fed from all sub-detectors.

The following HLT triggers are used for dLJs:

- Tri-muon: 3 MSonly tracks, p_T > 6 GeV (for pair of Type 0 dLJs)
- Narrow-scan: 2 MSonly tracks in ΔR = 0.5 cone, leading p_T > 20 GeV, sub-leading > 6 GeV (for Type 0, 1 dLJs). New in Run 2
- CaloRatio: jet p_T > 30 GeV with low EM fraction (for Type 1, 2 dLJs)

$H \rightarrow 2\gamma_d + X$	m_H=125GeV		m_H=800GeV
	Run 2	Run 1	Run 2
Tri-muon	2.0%	2.9%	2.4%
Narrow-scan	10.6%	--	23.0%
CaloRatio	0.3%	2.3%	9.7%
OR of all	11.9%	4.6%	32.0%
$H \rightarrow 4\gamma_d + X$	m_H=125GeV		m_H=800GeV
	Run 2	Run 1	Run 2
Tri-muon	4.9%	5.8%	7.8%
Narrow-scan	8.3%	--	38.4%
CaloRatio	0.1%	0.5%	7.4%
OR of all	11.8%	6.2%	44.8%

High-Level Trigger efficiencies for dLJs in MC samples of two benchmark processes.

SELECTION REQUIREMENTS

Cuts defined to optimize signal significance, with variables ordered by separation power:

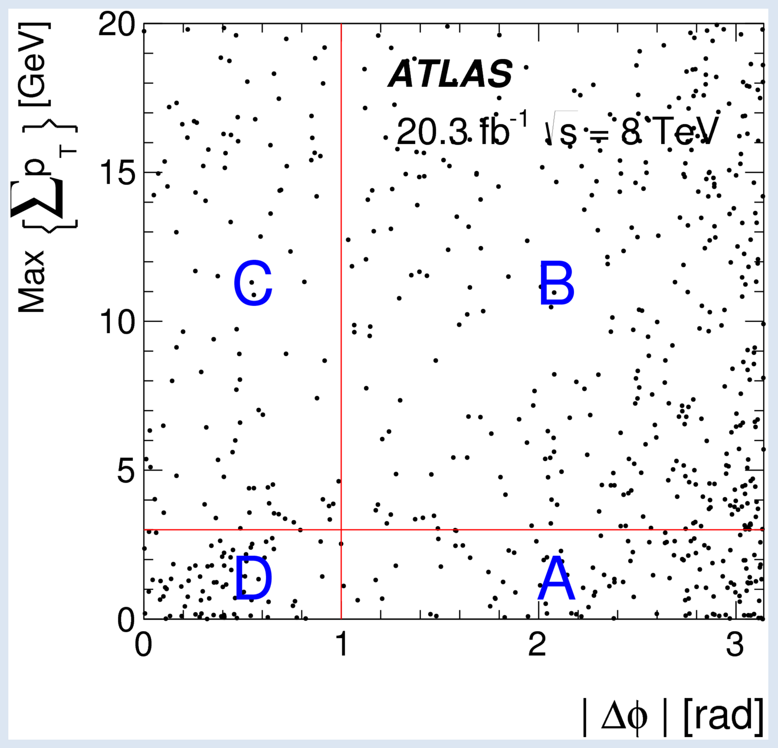
- Jet Vertex Tagger: Rejects QCD jets (Type 2 dLJs)
- Jet Width: Rejects QCD (Type 2)
- Jet EM Fraction: Rejects QCD (Type 2)
- Muon timing (Δt between RPC layers): Rejects muon bundles (Types 0, 1)
- Jet timing: Rejects mis-reconstructed cosmics (Types 1, 2)
- Beam-Induced Background tagging: Rejects fake BIB jets accompanied by φ–matched muon segments parallel to beampipe (Type 2)

Cuts defined using data-driven method for QCD multi-jet contamination:

Simplified matrix (ABCD) method assumes multi-jet background factorizable in 2D plane

- $\sum p_T$: Scalar sum of transverse momentum of ID tracks (pT>0.5 GeV belonging to primary vertex of event) in ΔR = 0.5 cone around LJ centre
- max(|φ|): between leading LJ in event and LJ that is farthest from it in φ

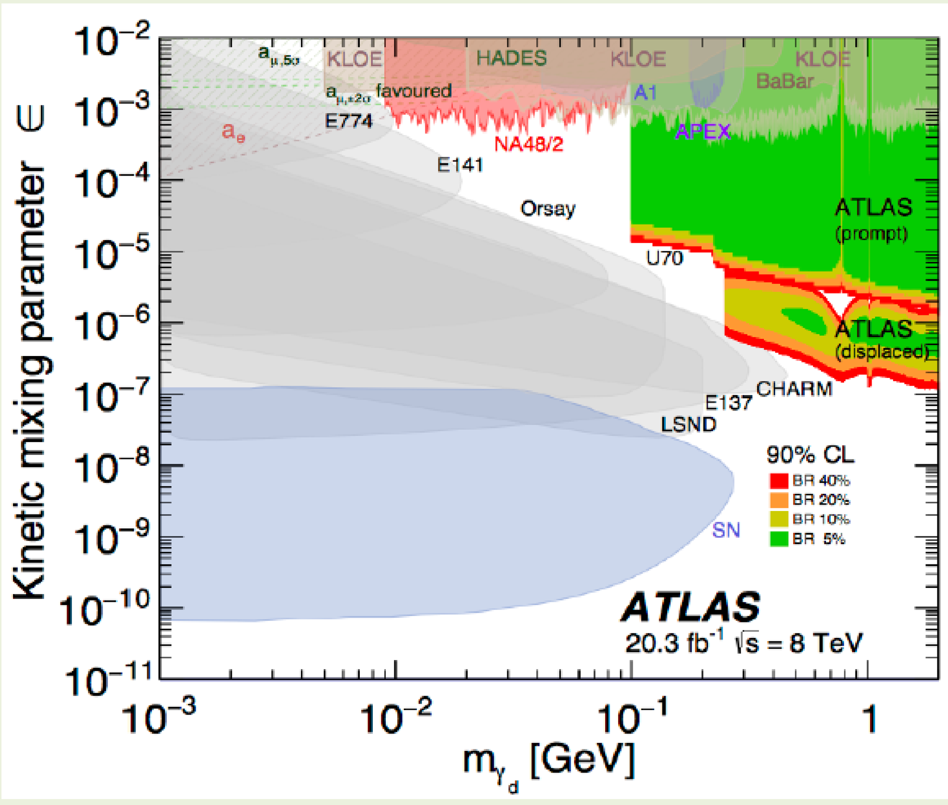
dLJs back-to-back from FRVZ processes have high |φ| and low $\sum p_T$



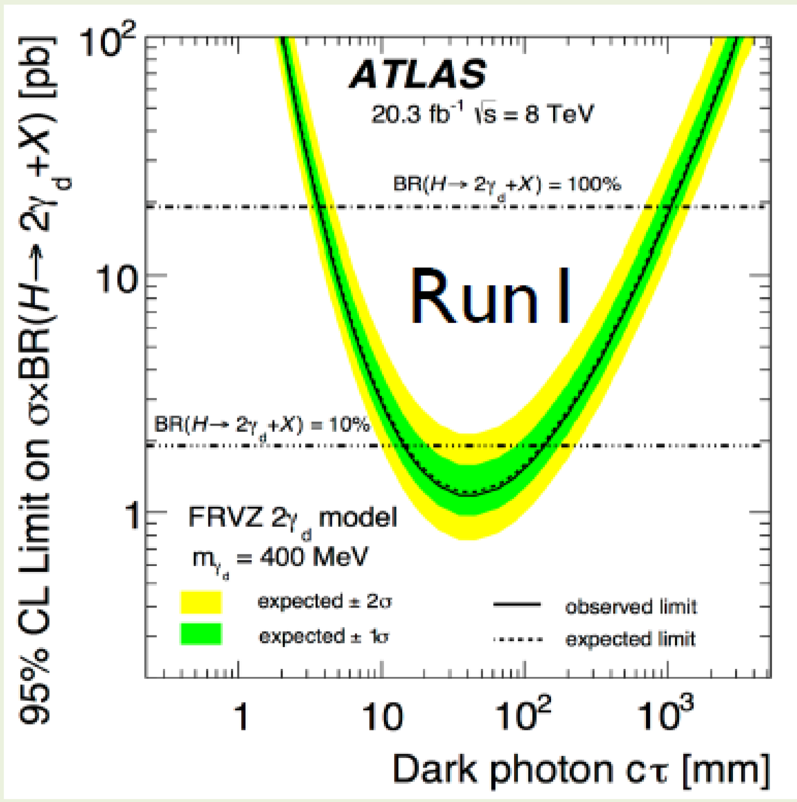
Simultaneous counting experiment in control and signal regions, with $N_A = N_D \times N_B/N_C$, provides estimate of background contamination in signal region A. [2]

RESULTS

A search for dLJ pairs was performed using the full 2012 ATLAS dataset at $\sqrt{s}$ = 8 TeV (20.3 fb^{-1}). The search was kept largely model-independent until the limit-setting stage. To facilitate re-casting of the results, trigger and reconstruction efficiency tables were produced as a function of dark photon cτ and p_T using a dedicated "LJ gun" Monte Carlo tool. A similar, complementary search for "prompt" LJ pairs (where γ_d has small or zero cτ, and therefore decay vertex compatible with the event's primary vertex) was also performed.



Exclusion contours were established in the plane of kinetic mixing parameter vs γ_d mass, in the context of vector portal models. The prompt and displaced LJ contours cover an area of parameter space untouched by other experiments, although they do depend upon an additional parameter, BR(H → γ_d + X). [2]



With the FRVZ models (assuming SM Higgs produced via gluon-gluon fusion) as benchmarks, limits were established on σ x BR(H → xγ_d + X), thereby setting BR-dependent exclusion bounds on cτ(γ_d) in these models. Bounds for FRVZ process (A), H → γ_d γ_d +X , shown here. [2]

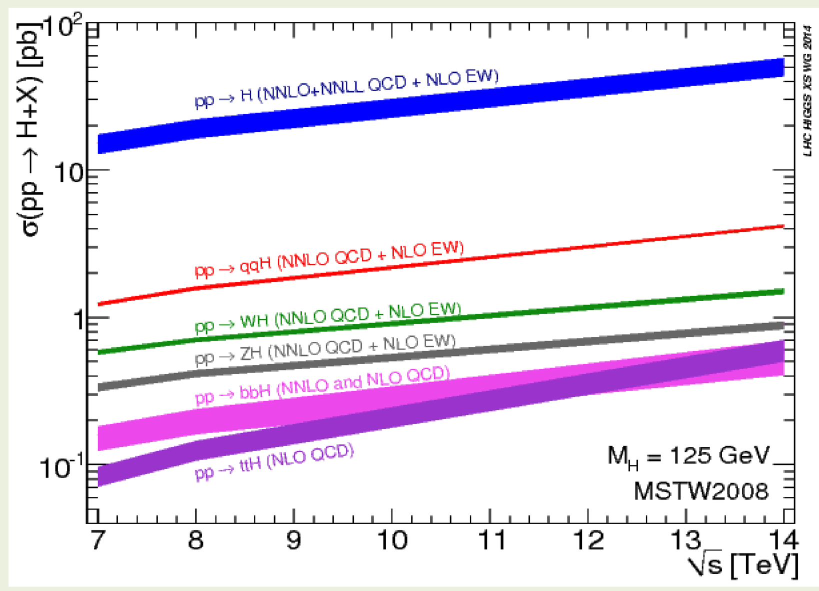
For Run 2 (13 TeV), the analysis will be extended to:

- Additional topologies, e.g. new narrow-scan trigger will enable searches for only one LJ in the final state
- Higher γ_d masses
- Higher Higgs masses (for BSM extended Higgs sectors) and associated Higgs production

SYSTEMATIC UNCERTAINTIES

(In order of Run 1 importance)

- Cosmic ray background estimation
- QCD multijet background estimation
- Trigger efficiency
- γ_d detection efficiency and p_T resolution
- Higgs production $\sigma_{gg\ fusion}$
- Muon reconstruction efficiency
- Effect of pile-up on $\sum p_T$
- Normalization of integrated luminosity
- Jet energy scale



Higher Higgs production cross-sections at 13 TeV, which will greatly benefit dLJ search sensitivity. [4]

[1] A. Falkowski *et al*, *Hidden Higgs Decaying to Lepton Jets*, JHEP **05** (2010) 077 [arXiv:1002.2952]
[2] ATLAS EXOT-2013-22 [3] ATLAS EXOT-2013-22 Aux [4] LHC Higgs Cross Section Working Group 2014

Miriam Diamond, University of Toronto, on behalf of the Exotics Group of the ATLAS Collaboration

ATLAS EXPERIMENT