Searches with Displaced Lepton-Jet Signatures

LHC Searches for Long-Lived BSM Particles: Theory Meets Experiment
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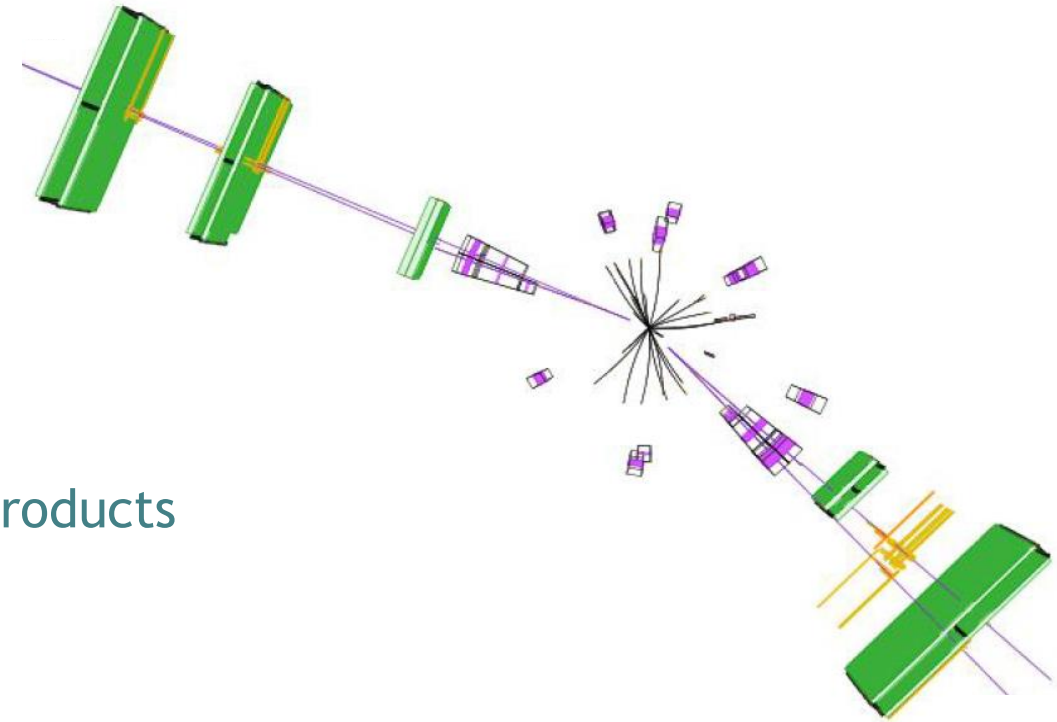
Outline

- What is a Displaced Lepton-Jet?
- Signatures of What?
  - Dark Photons
  - Hidden Sector
  - BSM Higgs
  - SUSY
  - Inelastic Dark Matter
- Challenges for Displaced LJ Searches
- Potentially Useful Handles
- Results from LHC Run 1 Searches
- Plans for Run 2 Searches

What is a Displaced LJ?

- LJ: Collimated jet-like structure containing pair(s) of muons and/or electrons (and/or pions)
- Displaced: Produced far from primary interaction vertex of event

- Defined using
  - Basic clustering algorithm with ΔR cone, or
  - Displaced vertex-finding
- Key properties:
  - Type of decay products
  - Angular aperture of decay products
  - Invariant mass
  - Vertex displacement



[ATLAS EXOT-2013-22 Aux]

Signatures of What?

- Many BSM theories predict some sort of hidden sector, weakly coupled to visible sector
- Collider production of unstable hidden states?
  - Low-mass → boosted → highly-collimated decay products
  - Decaying back to SM with sizeable BR → dileptons (and/or pions) in final state
  - Long-lived → displaced vertex

Displaced Lepton-Jet Signature

"Smoking Gun"

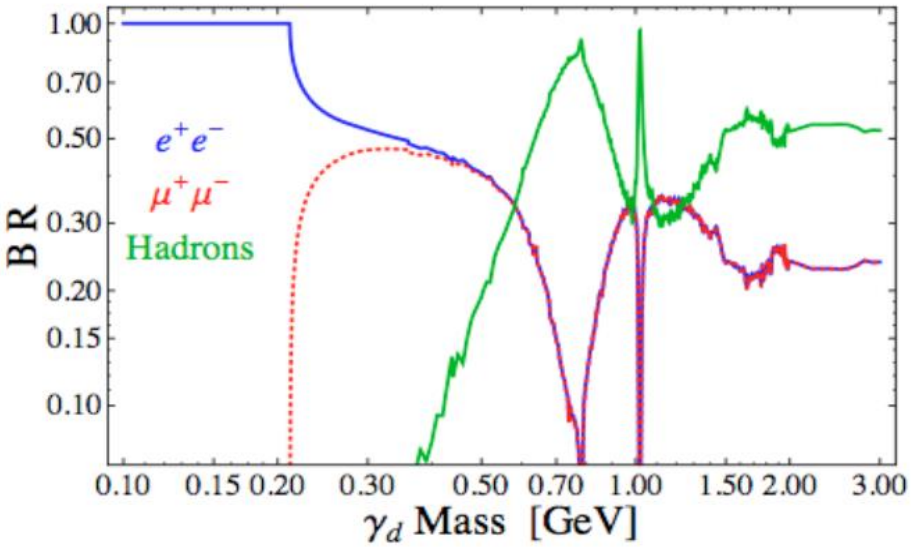
Dark Photons

- Vector portal: add U(1)' whose massive gauge boson (A' or z_d or γ_d) mixes kinetically with SM photon

$$\mathcal{L} \supset \frac{\epsilon_Y}{2} F^{Y,\mu\nu} F_{D,\mu\nu} - \frac{1}{4} F_D^{\mu\nu} F_{D,\mu\nu} + \frac{m_{A'}^2}{2} A'^{\mu} A'_{\mu} + g_D J^{\mu}_{A'} A'_{\mu}$$

  - Field re-definition removes kinetic mixing term, generates coupling $\epsilon e A'_{\mu} J^{\mu}_{\mathrm{EM}} \quad (\epsilon \equiv \epsilon_Y \cos\theta_W)$

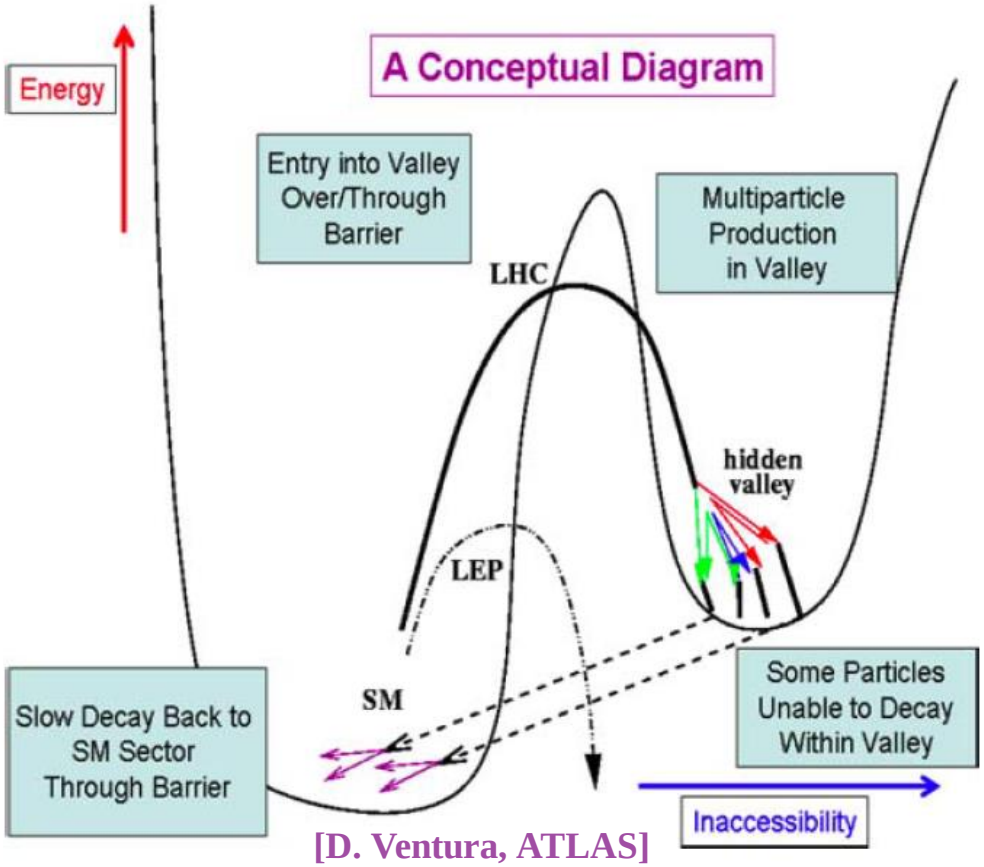
- Much parameter space for long-lived boosted low-mass $\gamma_d \rightarrow l^+l^-$
  - Lifetime varies with ε
  - BRs vary with mass

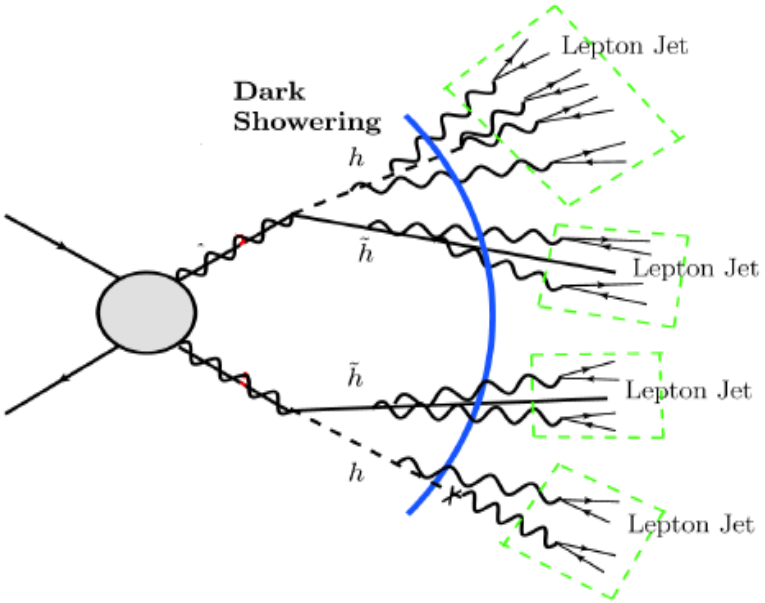


[arXiv:1002.2952]

Hidden Sector

- γ_d accompanied by zoo of other "hidden" particles?
- G_{dark} bigger than U'(1)?

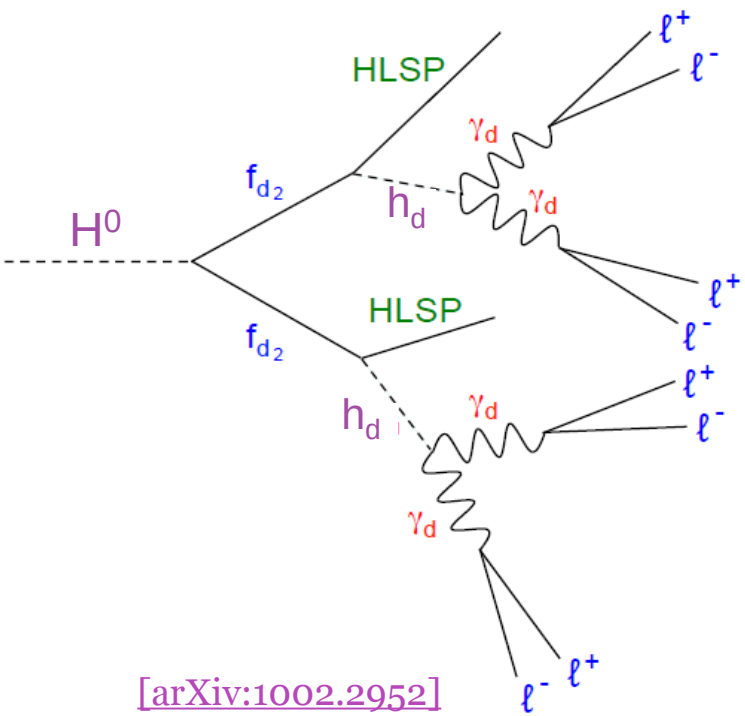




- Production of multiple boosted γ_d from long decay chains → multiple displaced LJs

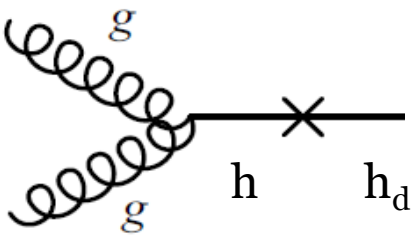
BSM Higgs

- In some BSM models with additional neutral heavy Higgses, can have $H^0 \rightarrow$ dark sector $\rightarrow$ LJs
- Or dark Higgs in decay chain ending with LJs



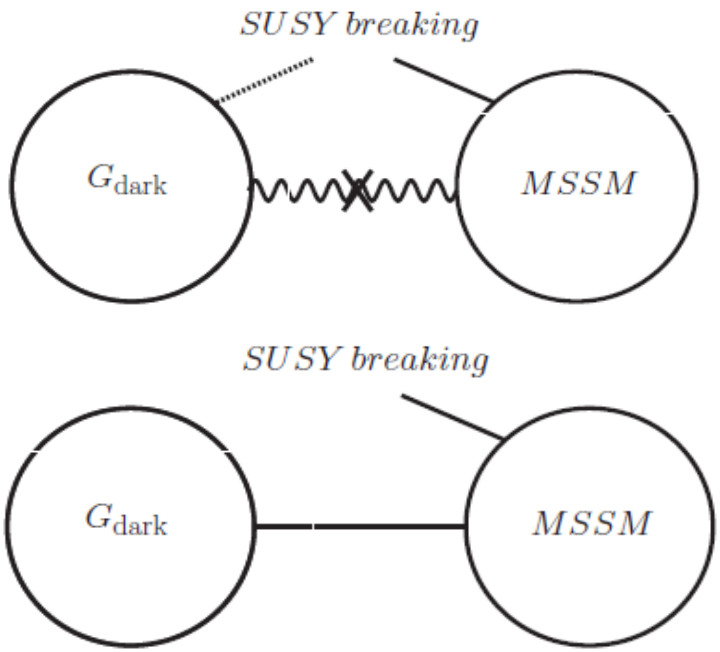
[arXiv:1002.2952]

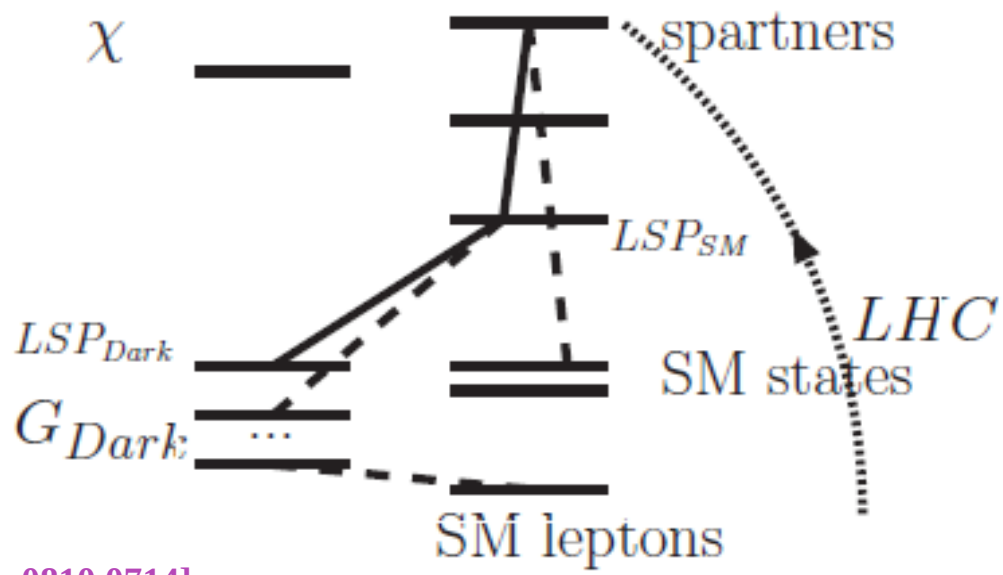
- Hidden Abelian Higgs models (Higgs Portal):



SUSY

- Can embed range of discrete dark symmetries (accidental or exact, global or gauged) within SUSY
- Standard SUSY production at LHC, followed by sparticles → dark sector → LJs

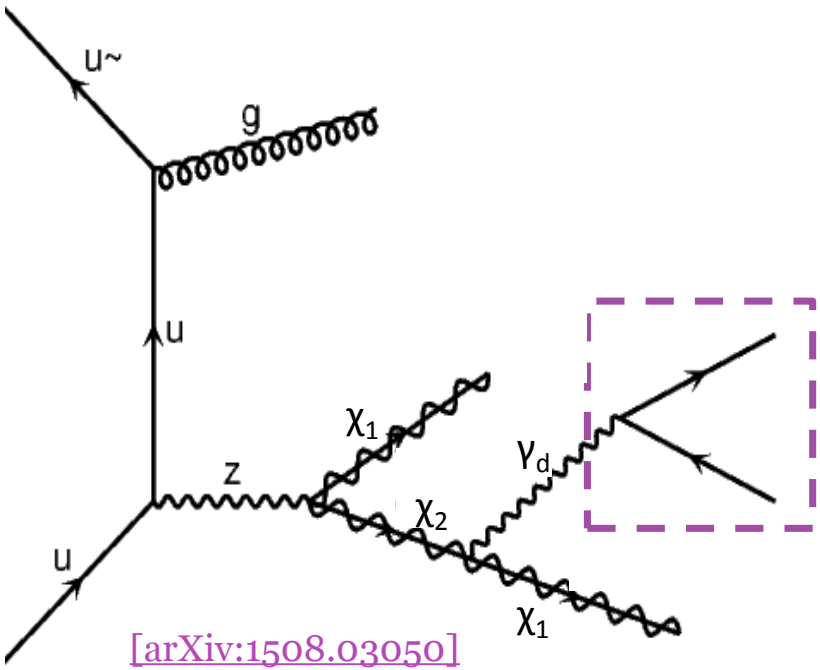




[arXiv:0810.0714]

Inelastic Dark Matter

- Dirac fermion charged under G_{dark}
- Spontaneously broken symmetry allows Majorana masses, yielding mass eigenstates χ_1 and χ_2 with dominantly off-diagonal interactions



[arXiv:1508.03050]

- γ_d and χ_2 with $c\tau \sim \mathcal{O}$(metre) in much of parameter space relevant for "thermal target"
- Displaced LJ + ISR jet + MET

Challenges for Displaced LJ Searches

Detector issues:

- No particularly convenient trigger object
  - Want low lepton p_T thresholds to cover low-mass phase space
  - But, in the face of low signal rate, also want to avoid pre-scaling
- Collimated final-state particles difficult to reconstruct (detector granularity)
- Tracks with displaced decay vertices difficult to reconstruct (no primary vertex constraint)
  - Even more difficult if displaced past inner detector
- Electron/pion LJs generally more difficult than muon LJs
  - Close-together energy deposits in calorimeters, without Muon Spectrometer information to aid reconstruction, are messy

Challenges for Displaced LJ Searches

Range of possible LJ topologies:

- Varying number of constituents
  - "Dense" LJ (e.g. hidden cascade decays)
  - "Sparse" LJ (e.g. lone dark photon)
- Unknown dynamics in hidden sector
  - QCD-like broadening of LJs?
- LJ shape influenced by boost
  - Depends upon unknown hidden particle masses

Challenges for Displaced LJ Searches

Potential backgrounds:

- 4 muons from $b\bar{b}$: via semileptonic decays, or via resonances
- Cosmic-ray muon bundles
- Combinatorics of prompt muons, mis-reconstructed/pileup: W+jets, Z+jets, ttbar, single-top, WW, WZ, ZZ, etc.
- QCD multi-jet (for electron/pion LJs)
- 4 muons from electroweak production (small)
- 4 muons from direct J/ψ pair production (small)

Potentially Useful Handles

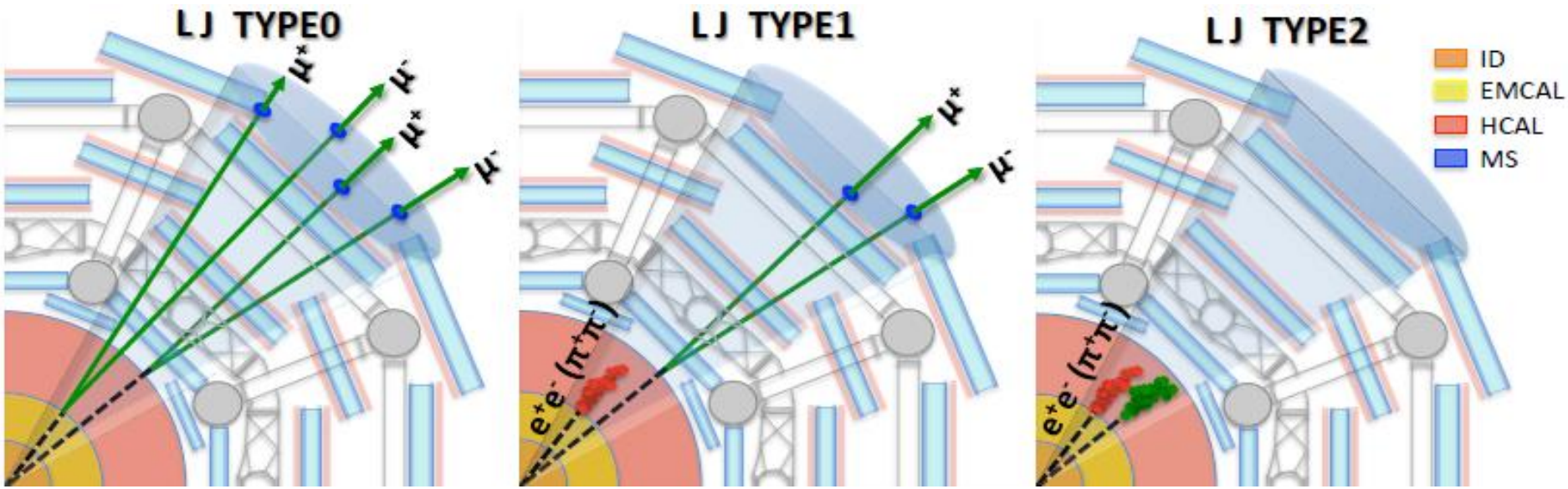
- LJ constituent selection:
  - Clustering algorithm using ΔR cone
  - Displaced vertex fit
  - Invariant mass window
- LJ isolation
  - Maximum $\sum p_T$ of charged tracks within ΔR cone centered on momentum vector of candidate LJ, excluding tracks of LJ constituents
- Require two LJs, consistent with same pp interaction
  - Small $|z_{1LJ} - z_{2LJ}|$ (nearby projected z coordinates at point of closest approach to beamline)
  - Cut on azimuthal angle $\Delta\phi$ between LJs

Run 1 Results: ATLAS

Targets γ_d decays beyond pixel detector, up to muon spectrometer

- Muon pairs: have only spectrometer information
- Electron / pion pairs: appear as jets in calorimeters
- LJ categorization:

[arXiv:1409.0746]



only muons | muons + jets | only jets

Run 1 Results: ATLAS

- Trigger for muon LJs: tri-muon MSonly, p_T > 6GeV, not pre-scaled
- Trigger for electron/pion LJs: single-jet, low E_T threshold, low EM fraction, isolated energy deposition in narrow region, not pre-scaled
- LJ-finding: clustering algorithm with ΔR = 0.5 cone
- Selection criteria: [arXiv:1409.0746]

Requirement	Description
Two reconstructed LJs	select events with at least two reconstructed LJs
η range (TYPE1)	remove jets with $\lvert\eta\rvert > 2.5$
η range (TYPE2)	remove jets with $\lvert\eta\rvert > 2.5$ and $1.0 < \lvert\eta\rvert < 1.4$
EM fraction (TYPE2)	require EM fraction of the jet < 0.1
Jet width W (TYPE2)	require width of the jet < 0.1
Jet timing (TYPE1/TYPE2)	require jets with timing -1 ns $< t < 5$ ns
NC muons (TYPE0/TYPE1)	require muons without ID track match
ID isolation	require $\max\{\Sigma p_T\} \leq 3$ GeV
$\Delta\phi$	require $\lvert\Delta\phi\rvert \geq 1$ rad between the two LJs

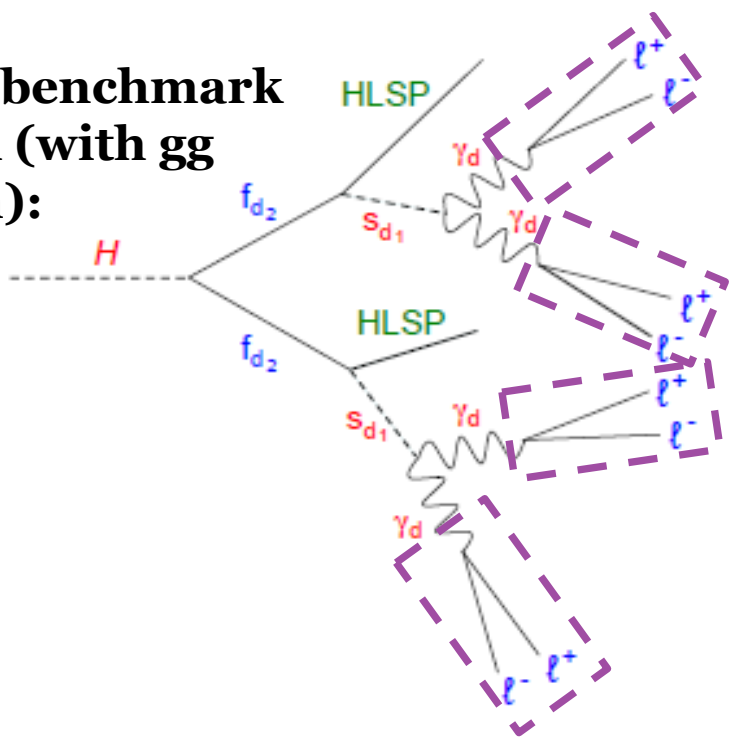
Run 1 Results: ATLAS

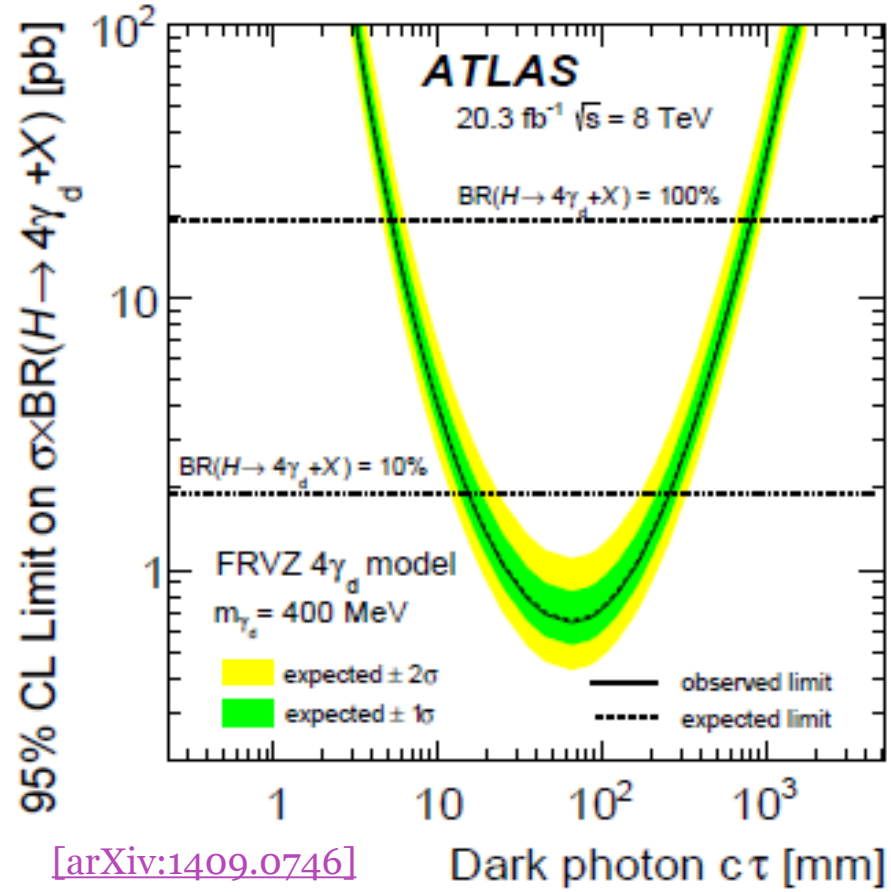
Events (+/- stat. +/- sys.)

Data	119
Cosmic rays	$40 \pm 11 \pm 9$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$
Total background	$110 \pm 59 \pm 14$

FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \to 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \to 4\gamma_d + X$	$15 \leq c\tau \leq 260$

FRVZ benchmark model (with gg fusion):





[arXiv:1409.0746]

Run 1 Results: ATLAS

- To allow easy re-casting: trigger & reco efficiency tables as a function of dark photon $c\tau$ and p_T
- Produced using "LJ Gun" MC tool, which simulates detector response to LJs of one or two dark photons

L_{xy} (cm)	$\gamma_d \to \mu\mu$ with $m_{\gamma_d} = 0.4$ GeV in the ATLAS barrel ($\lvert \eta \rvert \leq 0.9$)						
580-780	0.021 ± 0.006	0.005 ± 0.002	0.005 ± 0.001	0.005 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0.001 ± 0.001
500-580	0.095 ± 0.014	0.072 ± 0.008	0.040 ± 0.005	0.026 ± 0.009	0.017 ± 0.004	0.013 ± 0.003	0.003 ± 0.002
420-500	0.158 ± 0.014	0.085 ± 0.008	0.047 ± 0.005	0.047 ± 0.011	0.027 ± 0.005	0.015 ± 0.003	0.007 ± 0.002
340-420	0.208 ± 0.012	0.133 ± 0.008	0.090 ± 0.007	0.056 ± 0.012	0.041 ± 0.006	0.026 ± 0.004	0.017 ± 0.004
275-340	0.240± 0.012	0.198 ± 0.010	0.139 ± 0.008	0.099 ± 0.016	0.076± 0.008	0.037 ± 0.005	0.029 ± 0.005
210-275	0.210 ± 0.009	0.215± 0.009	0.159± 0.008	0.111 ± 0.016	0.118 ± 0.010	0.072± 0.006	0.036 ± 0.006
145-210	0.215 ± 0.007	0.217 ± 0.008	0.190 ± 0.008	0.159 ± 0.017	0.114 ± 0.009	0.076 ± 0.006	0.042 ± 0.006
80-145	0.210± 0.006	0.231 ± 0.007	0.200 ± 0.008	0.160± 0.016	0.130 ± 0.009	0.098 ± 0.007	0.070 ± 0.007
14-80	0.117 ± 0.003	0.152 ± 0.005	0.145 ± 0.006	0.117 ± 0.011	0.102 ± 0.007	0.070 ± 0.005	0.062 ± 0.007
$p_T$interval (Gev)	10-20	20-30	30-40	40-50	50-60	60-80	80-100

[ATLAS EXOT-2013-22 Aux]

Run 1 Results: CMS

Targets γ_d decays within the pixel detector, into muon LJs only

- Trigger: dimuon, p_T > 17 GeV (leading), p_T > 8 GeV (subleading)
- Selection criteria: [arXiv:1506.00424]

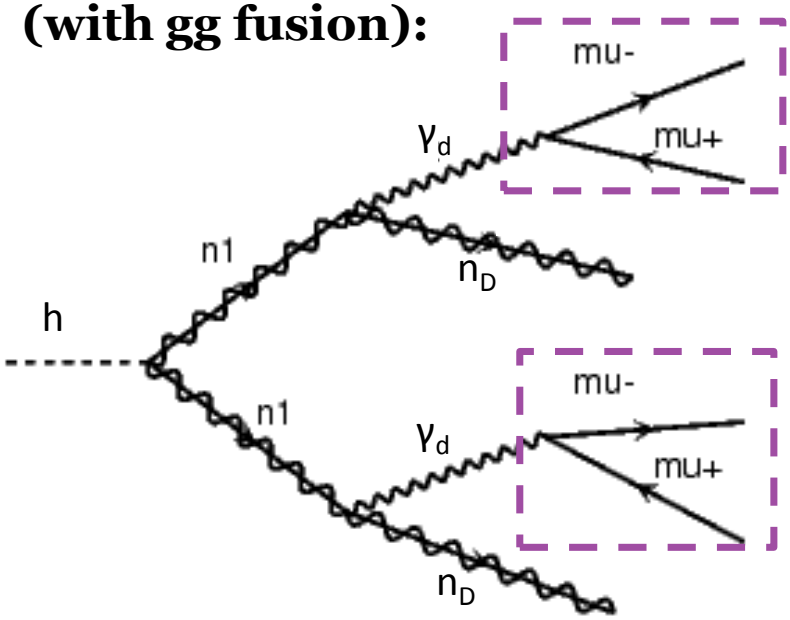
Requirement	Description
4 offline muon candidates	Particle Flow algorithm
Muon p_T , $\|\eta\|$	p_T > 8GeV, $\|\eta\|$ < 2.4
High-energy muon	At least one muon with p_T > 17 GeV, $\|\eta\|$ < 0.9
Dimuon pair	Two oppositely-charged pairs
Dimuon invariant mass	$m(\mu+\mu-)$ < 5 GeV
Dimuon common vertex	$P_v(\mu+\mu-)$ > 1% or $\Delta R(\mu+\mu-)$ < 0.01
Dimuon fiducial	≥1 hit in first layer of pixel barrel or endcaps
Dimuon isolation	I_{sum} < 2 GeV
Dimuons from same interaction	$\|z_{1\mu\mu} - z_{2\mu\mu}\|$ < 1 mm

Run 1 Results: CMS

Model-independent 95% CL:

$$\sigma(\mathrm{pp} \to 2\mathrm{a} + \mathrm{X})\, \mathcal{B}^2(\mathrm{a} \to 2\mu)\, \alpha_{\mathrm{gen}} \leq 0.24 + 0.09 \exp\left(-\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2}\right)$$
$$= \bar{N}(m_{\mu\mu}) / (\mathcal{L}\bar{r})$$

Dark SUSY benchmark model (with gg fusion):



α = kinematic & geometrical acceptance
ε = selection efficiency
r = $\varepsilon_{\mathrm{data}} / \alpha_{\mathrm{gen}}$

m_{γ_D} [GeV]	0.25		
$c\tau_{\gamma_D}$ [mm]	0	0.5	2
ϵ_{sim} [%]	8.85 ± 0.12	1.76 ± 0.05	0.23 ± 0.03
α_{gen} [%]	14.32 ± 0.14	2.7 ± 0.06	0.31 ± 0.03
$\epsilon_{\mathrm{sim}} / \alpha_{\mathrm{gen}}$	0.62 ± 0.01	0.65 ± 0.02	0.74 ± 0.13

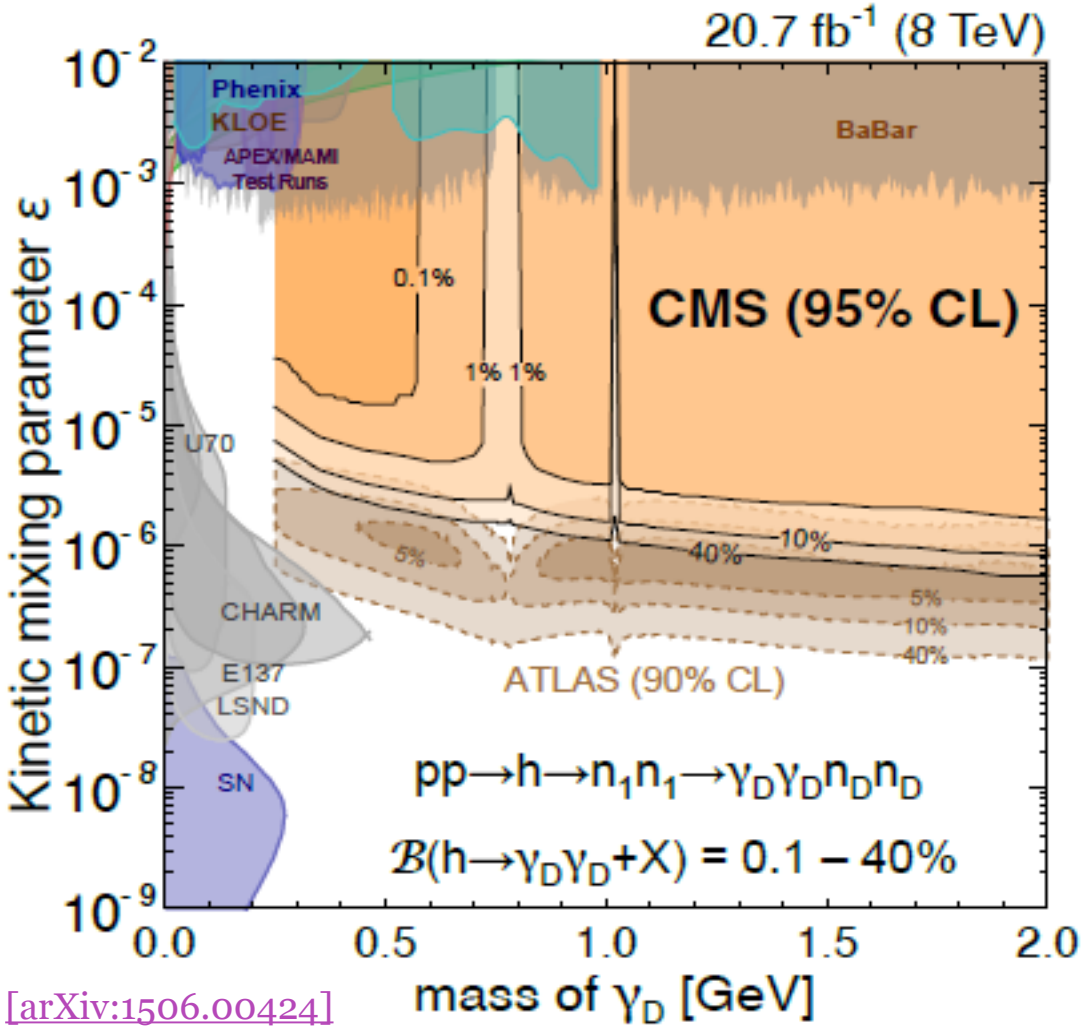
m_{γ_D} [GeV]	1.0		
$c\tau_{\gamma_D}$ [mm]	0	0.5	2
ϵ_{sim} [%]	6.13 ± 0.23	4.73 ± 0.07	1.15 ± 0.04
α_{gen} [%]	8.89 ± 0.28	6.98 ± 0.09	1.68 ± 0.05
$\epsilon_{\mathrm{sim}} / \alpha_{\mathrm{gen}}$	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

[arXiv:1506.00424] $m_{n_1} = 10\,\mathrm{GeV}$, $m_{n_D} = 1\,\mathrm{GeV}$

Run 1 Results: ATLAS + CMS

Combined results for γ_d interpretation:

- Complementary coverage in γ_d parameter space
- In regions other experiments were unable to reach!
  - ATLAS & CMS limits have extra parameter (BR for h → hidden)



[arXiv:1506.00424]

Run 2 Plans

ATLAS

- Extension of search to higher γ_d masses: $\mathcal{O}$(10 GeV)
- Extension to higher BSM H^0 masses: $\mathcal{O}$(TeV)
- New triggers, including "narrow scan" dimuon, to improve efficiency
- More efficient reconstruction of collimated MSonly muons
- More benchmark models (e.g. Higgs Portal, dark SUSY, iDM)

CMS

- New trigger to loosen $|\eta|$ constraints, allowing model-independent search in broader fiducial region
- Improved dimuon vertex reconstruction, to increase sensitivity up to $c\tau \sim 20$ cm
- Inclusion of electron LJs

Conclusions

- Displaced Lepton-Jets: smoking-gun signature of long-lived, boosted, low-mass hidden states decaying to SM
  - Especially dark photons
  - Predicted in wide range of BSM models
- Challenging searches, due to detector limitations and wide range of possible topologies, which aren't background-free
- But have several handles available
- Run 1: complementary ATLAS & CMS searches established limits in large region of dark photon parameter space unexplored by previous experiments
- Run 2: plans underway to extend and enhance displaced LJ searches

References

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2. N. Arkani-Hamed and N. Weiner, *LHC Signals for a SuperUnified Theory of Dark Matter*, *JHEP* **104** (2008) 0812 [arXiv:0810.0714].
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Lepton-Jet Gun

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Table 1:
Reconstruction efficiency table for $\gamma_d \to \mu\mu$ with m_{γ_d} = 0.4 GeV in the ATLAS barrel (midηmid ≤ 0.9) as function of the γ_d p_T and decay distance L_{xy} . The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_T and L_{xy} interval as the ratio between the number of reconstructed $\gamma_d \to \mu\mu$ and the corresponding number of generated ones. The γ_d selection criteria are defined in EXOT-2013-22. Errors are statistical only.

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Table 2:
Reconstruction efficiency table for $\gamma_d \to \mu\mu$ with m_{γ_d} = 0.4 GeV in the ATLAS endcap (1.2 ≤ midηmid ≤ 2.5) as function of the γ_d p_T and decay distance L_z. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_T and L_z interval as the ratio between the number of reconstructed $\gamma_d \to \mu\mu$ and the corresponding number of generated ones. The γ_d selection criteria are defined in EXOT-2013-22. Errors are statistical only.

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Table 3:
Reconstruction efficiency table for $\gamma_d \to ee\ (\pi\pi\pi)$ with m_{γ_d} = 0.4 GeV in the ATLAS barrel (midηmid ≤ 1.0) as function of the γ_d p_T and decay distance L_{xy}. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_T and L_{xy} interval as the ratio between the number of reconstructed $\gamma_d \to ee\ (\pi\pi\pi)$ and the corresponding number of generated ones. The γ_d selection criteria are defined in EXOT-2013-22. Errors are statistical only.

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Table 4:
Reconstruction efficiency table for $\gamma_d \to ee\ (\pi\pi\pi)$ with m_{γ_d} = 0.4 GeV in the ATLAS endcap (1.5 ≤ midηmid ≤ 2.4) as function of the γ_d p_T and decay distance L_z. The reconstruction efficiency is evaluated using a "LJ gun" Monte Carlo generator and processing the generated events through the full ATLAS simulation chain. The reconstruction efficiency is defined in each p_T and L_z interval as the ratio between the number of reconstructed $\gamma_d \to ee\ (\pi\pi\pi)$ and the corresponding number of generated ones. The γ_d selection criteria are defined in EXOT-2013-22. Errors are statistical only.

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L_{xy} (cm)							
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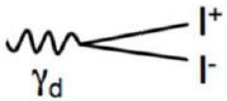
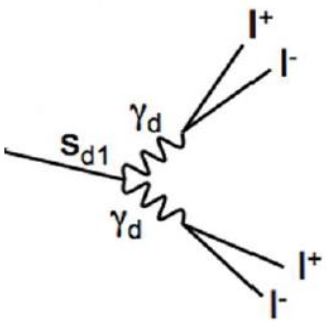
Table 2:
Reconstruction efficiency table for $\gamma_d \rightarrow \mu\mu$ with m_{γ_d} = 0.4 GeV in the ATLAS endcap (1.2 ≤ midηmid ≤ 2.5)

Table 3:
Reconstruction efficiency table for $\gamma_d \rightarrow$ ee (ππ) with m_{γ_d} = 0.4 GeV in the ATLAS barrel (midηmid ≤ 1.0)

Table 4:
Reconstruction efficiency table for $\gamma_d \rightarrow$ ee (ππ) with m_{γ_d} = 0.4 GeV in the ATLAS endcap (1.5 ≤ midηmid ≤ 2.4)

LJ Gun

- "LJ Gun" MC tool: simulates 

or 

- Allows us to determine ATLAS detector response to LJs as a function of: composition, lifetime, opening angle, p_T, η
- γ_d mass determines BRs to {e+e-, μ+μ-, π+π-}
- γ_d polarization state can be set to longitudinal or transverse
- Multiple interactions in same bunch crossing have been added to the simulation, to model pile-up. But, no primary vertex
- Generated events processed through full ATLAS simulation chain based on GEANT4

Using LJ Gun for Displaced Decays

- When using LJ Gun to produce MC samples: γ_d lifetime chosen such that, taking boost into account, 80% of decays occur inside fiducial volume
  - Defined as cylinder 8 m radius and 28 m tall, centred on detector
- All γ_d decaying outside fiducial volume get re-generated, until decay is inside fiducial volume
- This equally populates all detector regions, independent of γ_d p_T

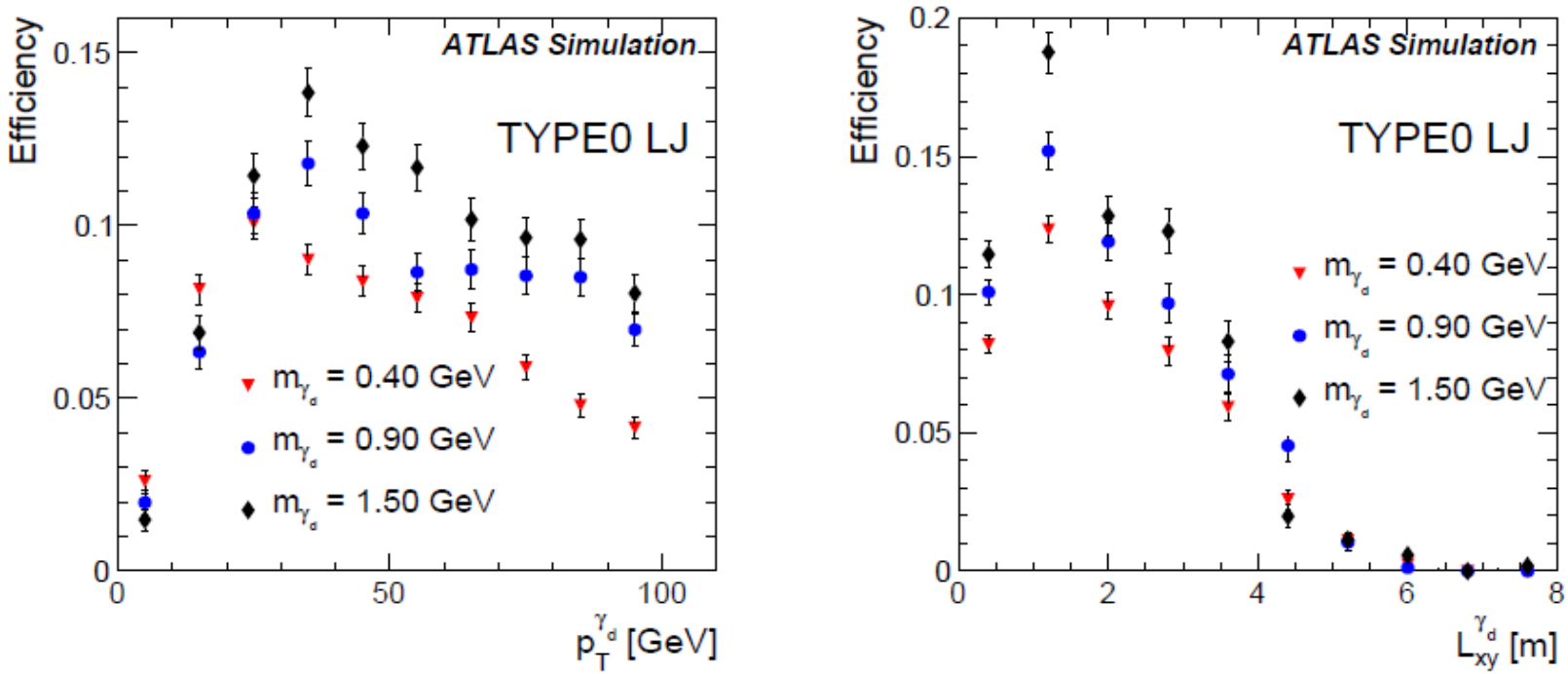


Figure 6. Reconstruction efficiency of TYPE0 LJs as a function of p_{T} (left) and L_{xy} (right) of the γ_{d} for $\gamma_{\mathrm{d}} \to \mu\mu$ obtained from the LJ gun MC samples with γ_{d} masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

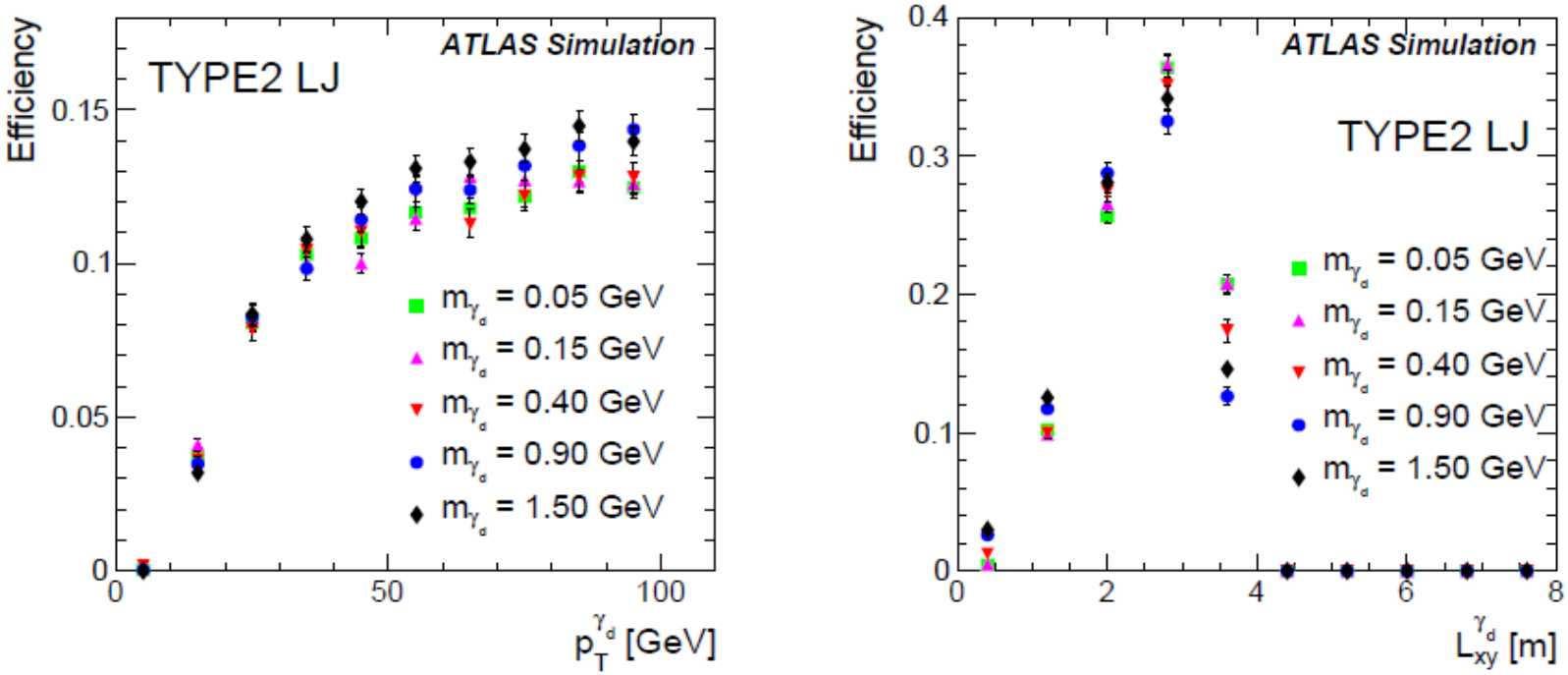


Figure 7. Reconstruction efficiency of TYPE2 LJs as a function of p_{T} (left) and L_{xy} (right) of the γ_{d} for $\gamma_{\mathrm{d}} \to ee/\pi\pi$ obtained from the LJ gun MC samples with γ_{d} masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

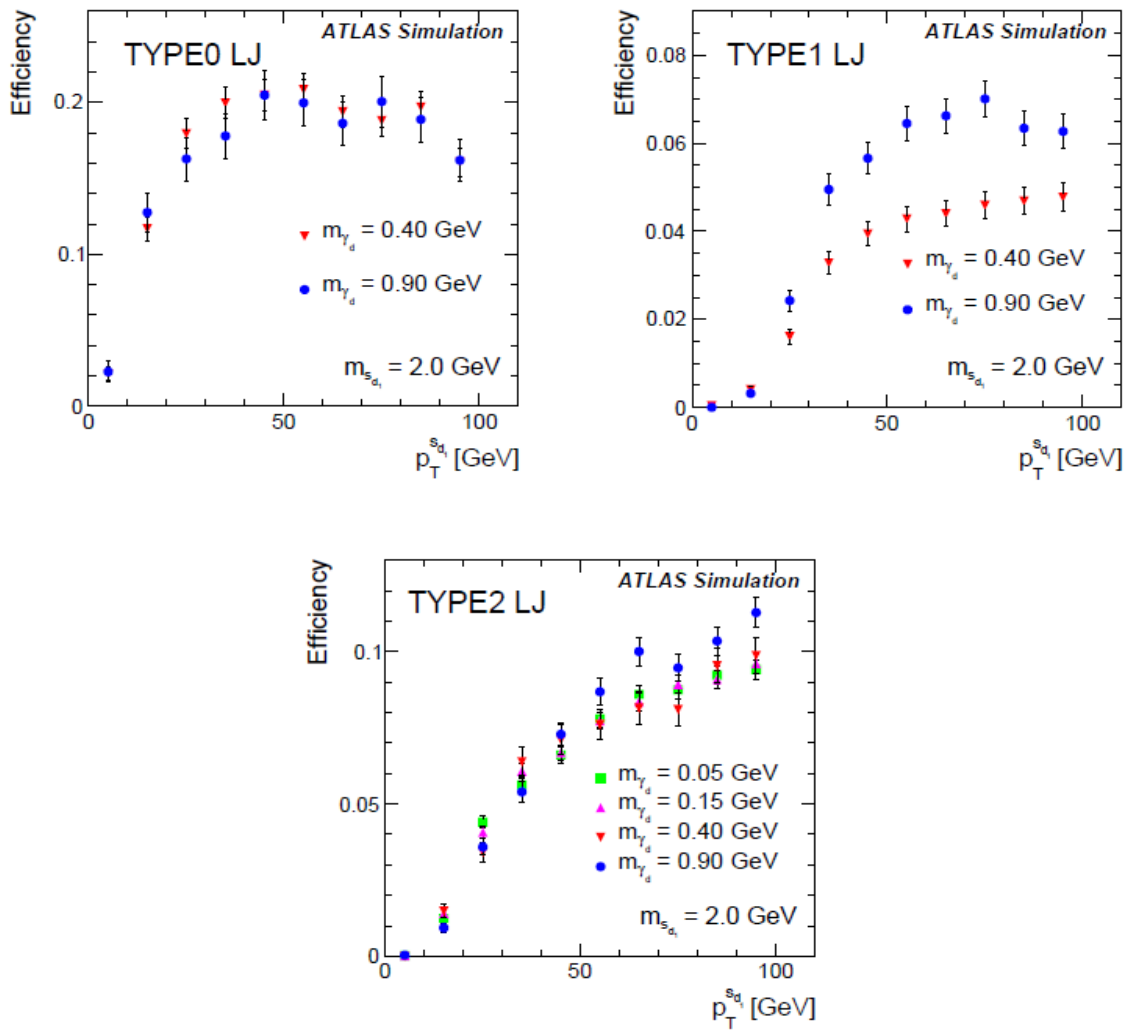
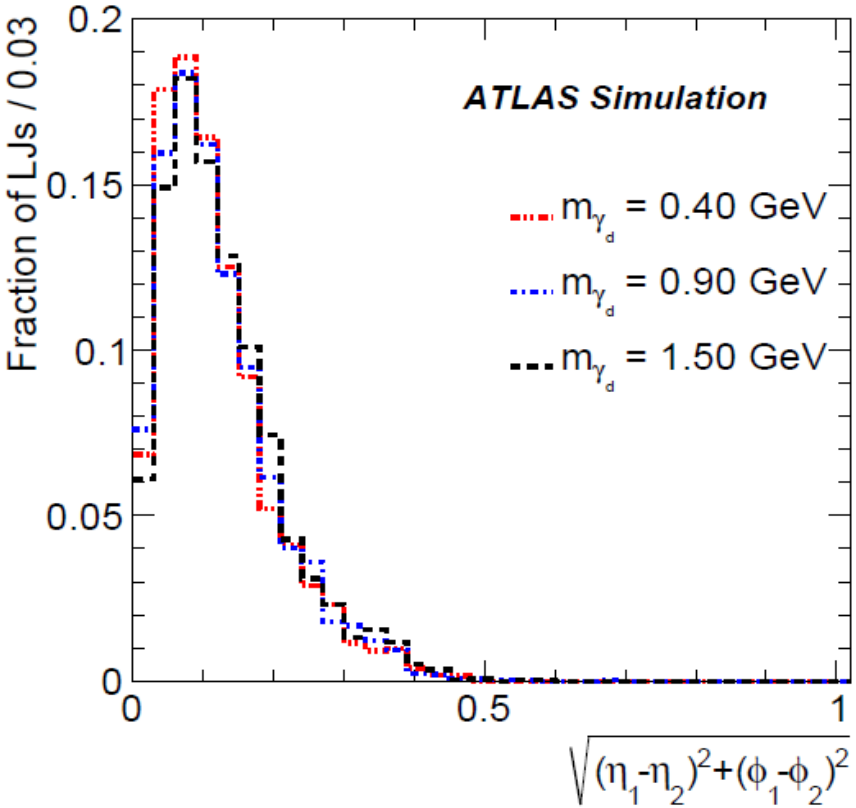


Figure 8. Reconstruction efficiency of TYPE0 (top left), TYPE1 (top right) and TYPE2 (bottom) LJs as a function of the p_T of the s_{d_1} for LJs with two dark photons for an s_{d_1} mass of 2 GeV. For the γ_d, only the kinematically allowed masses are considered. The distributions for the other s_{d_1} masses are very similar. The uncertainties are statistical only.

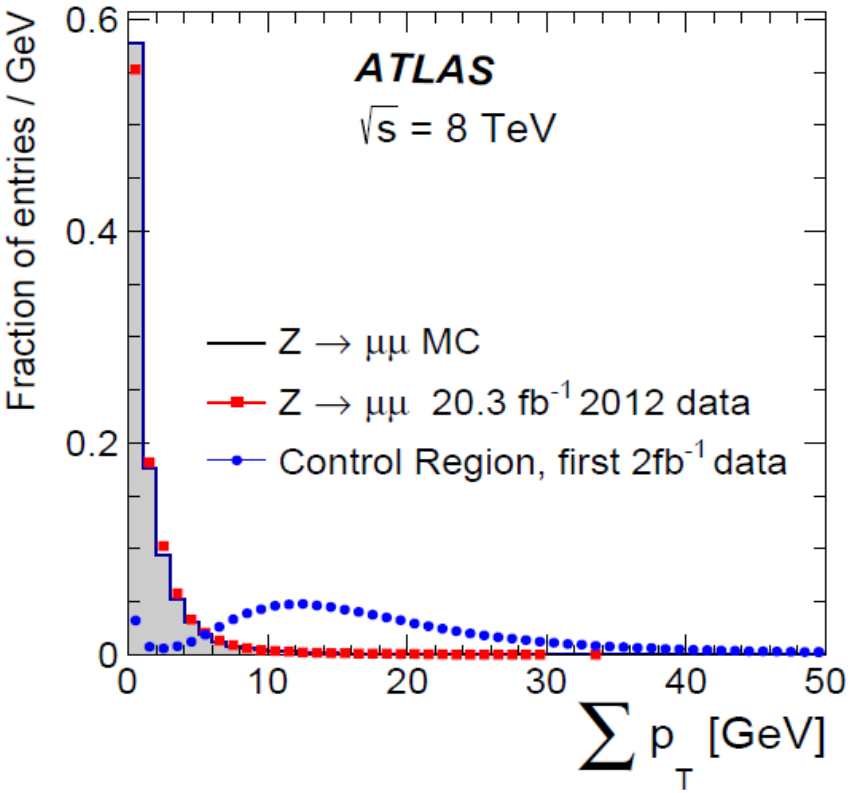
Backup

ATLAS Analysis

LJ ΔR, Σp_T



Single dark photon decaying to muon pair



Multi-jet control region: selected by single-jet triggers, 15 and 35 GeV

Full Analysis Cut-Flow

Requirement	Description
Two reconstructed LJs	select events with at least two reconstructed LJs
η range (TYPE1)	remove jets with $\lvert\eta\rvert > 2.5$
η range (TYPE2)	remove jets with $\lvert\eta\rvert > 2.5$ and $1.0 < \lvert\eta\rvert < 1.4$
EM fraction (TYPE2)	require EM fraction of the jet < 0.1
Jet width W (TYPE2)	require width of the jet < 0.1
Jet timing (TYPE1/TYPE2)	require jets with timing -1 ns $< t < 5$ ns
NC muons (TYPE0/TYPE1)	require muons without ID track match
ID isolation	require $\max\{\Sigma p_{\mathrm{T}}\} \leq 3$ GeV
$\Delta\phi$	require $\lvert\Delta\phi\rvert \geq 1$ rad between the two LJs

Full Analysis Cut-Flow

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Trigger selection	9.226×10^6						
Good primary vertex	9.212×10^6						
Two reconstructed LJs	946	1771	16676	1382	19629	82653	123057
η range (TYPE1/TYPE2)	946	1269	5063	701	3838	25885	37702
EM fraction (TYPE2)	946	1269	393	701	172	4713	8194
Jet width W (TYPE2)	946	1269	350	701	148	3740	7154
Jet timing (TYPE1/TYPE2)	946	1054	216	547	92	578	3433
NC muons (TYPE0/TYPE1)	27	3	42	5	5	578	660
ID isolation	12	0	19	4	3	160	198
$\lvert\Delta\phi\rvert$	11	0	11	4	3	90	119

Table 2. Number of selected data events at different stages of the selection process and for each of the LJ pair types, for the full 2012 data sample.

Backgrounds

- Cosmics (studied using empty bunch crossings sample):
  - Muon LJs: 80% eliminated by NC requirement
  - Muon LJs: reduced by factor of 200 by cut on impact parameters of MS track at PV (|d0| < 200 mm, |z0| < 270 mm)
  - Electron/pion LJs: almost entirely eliminated by jet timing cut

- Multijet (studied using control sample, ABCD method in $\sum p_T$ vs ΔR plane):
  - EM fraction cut provides 99.9% rejection
  - Track isolation cut provides 97% rejection
  - Jet width cut provides 80% rejection

Backgrounds

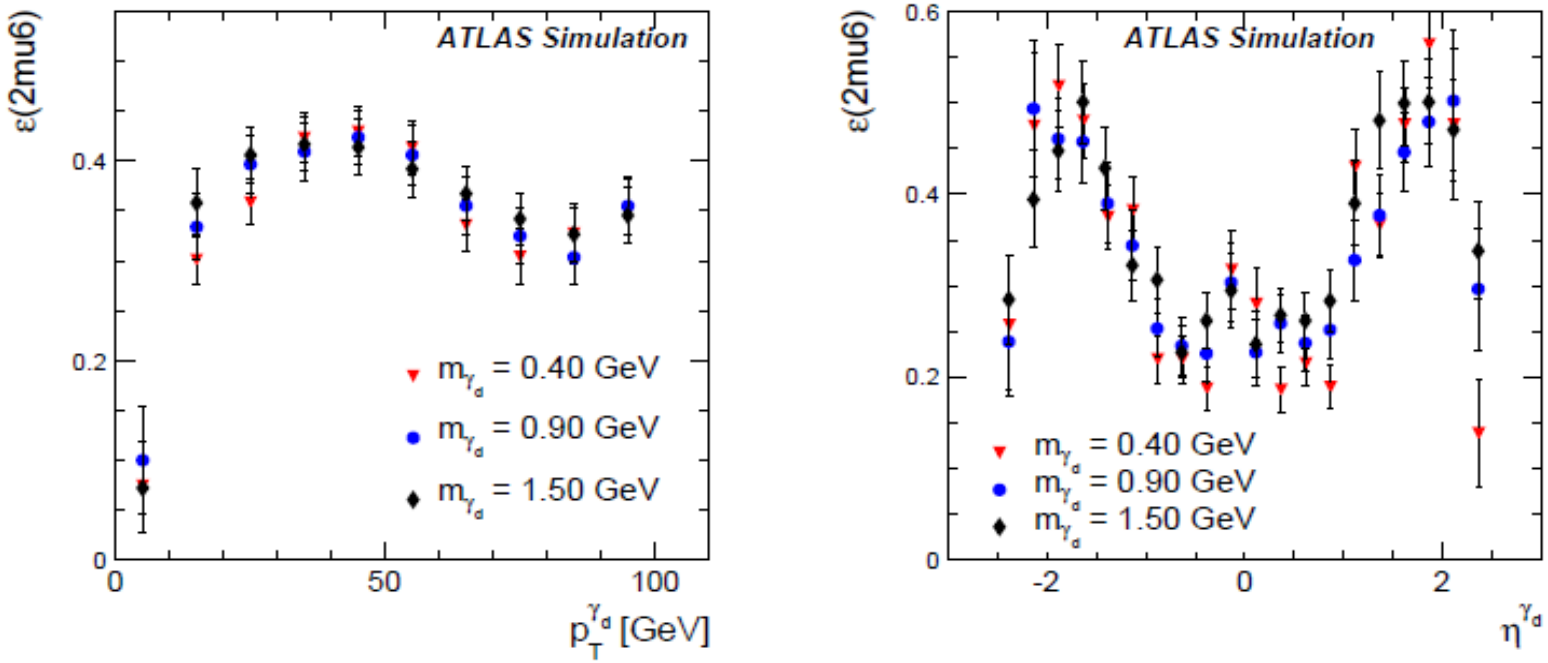
LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Trigger selection	161951						
Good primary vertex	not applicable						
Two reconstructed LJs	6	0	42	0	36	3744	3838
η range (TYPE1/TYPE2)	6	0	29	0	17	2243	2295
EM fraction (TYPE2)	6	0	29	0	17	2190	2242
Jet width W (TYPE2)	6	0	22	0	6	1632	1666
Jet timing (TYPE1/TYPE2)	6	0	6	0	0	24	36
NC muons (TYPE0/TYPE1)	6	0	6	0	0	24	36
ID isolation	6	0	6	0	0	24	36
$\lvert\Delta\phi\rvert$	6	0	5	0	0	4	15
Rescaled to interactions	15 ± 6	$0^{+3.1}_{-0}$	14 ± 6	$0^{+3.1}_{-0}$	$0^{+3.1}_{-0}$	11 ± 7	40 ± 10

Table 3. Result of applying the LJ selection to events triggered in the empty bunch crossings. Number of selected data events at different stages of the selection process and for each LJ pair types. Except for the last row, all these numbers are not rescaled by the ratio of filled to empty bunches in the LHC operation. The quoted uncertainties are statistical only.

Data Type	Events in B	Events in C	Events in D	Expected Events in A
Cosmic-ray data	0	0	60 ± 13	40 ± 10
Data (cosmic rays subtracted)	362 ± 19	99 ± 10	19 ± 16	70 ± 58

Table 4. Event yields in the four ABCD regions used to estimate the multi-jet background with the ABCD method in the LJ signal region. All LJ pair types are used. The quoted uncertainties are statistical only.

Trigger Efficiencies



$$p^{3mu6} = 2 \cdot \varepsilon(1mu6) \cdot \varepsilon(2mu6) - \varepsilon(2mu6) \cdot \varepsilon(2mu6)$$

Figure 9. Muon trigger efficiency, $\varepsilon(2mu6)$, as a function of p_T (left) and η (right) of the γ_d for $\gamma_d \to \mu\mu$ obtained from the LJ gun MC samples with γ_d masses 0.4, 0.9 and 1.5 GeV. The uncertainties are statistical only.

Trigger Efficiencies

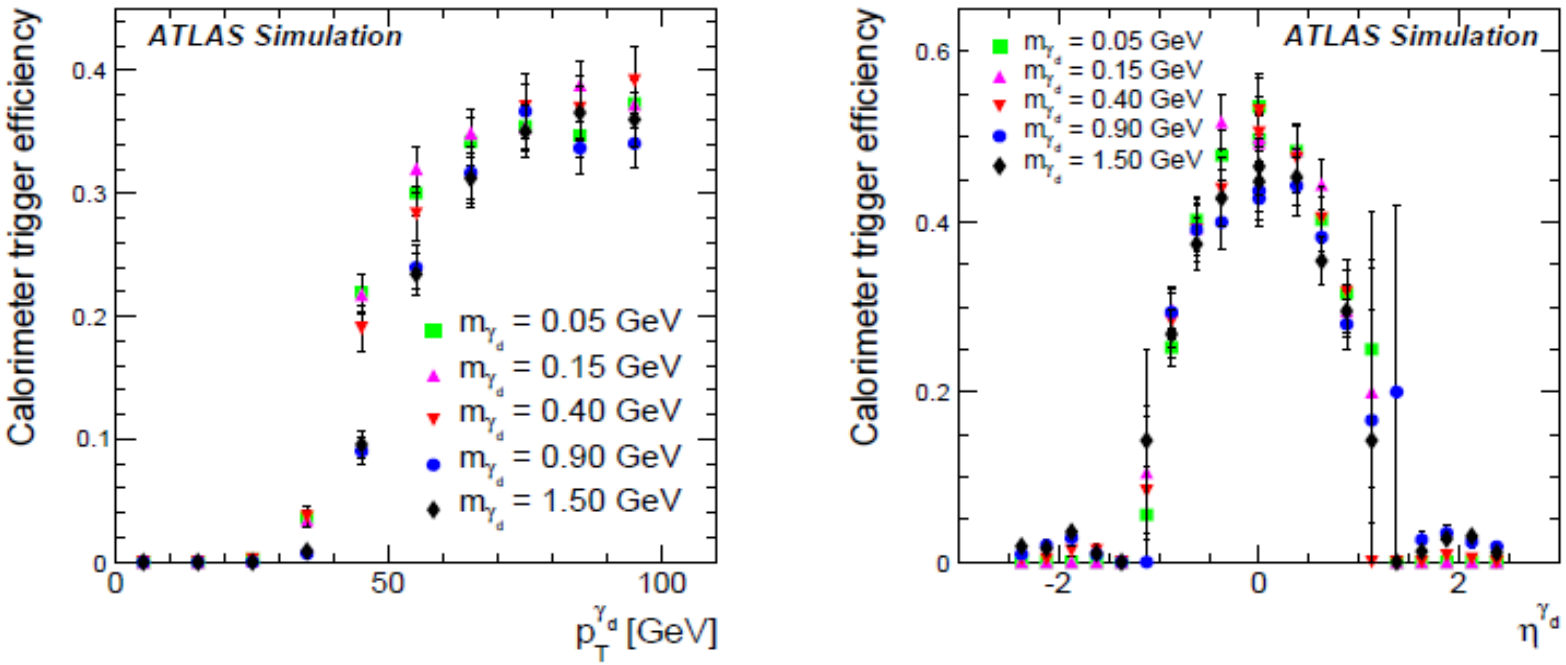


Figure 10. Calorimetric trigger efficiency as a function of p_T (left) and η (right) of the γ_d for $\gamma_d \to ee/\pi\pi$ obtained from the LJ gun MC samples with γ_d masses 0.05, 0.15, 0.4, 0.9 and 1.5 GeV. Similar distributions are obtained for LJs containing two dark photons. The uncertainties are statistical only.

Signal Efficiencies

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Total number of events	39730 ± 100						
Trigger selection	1330 ± 30						
Good primary vertex	1330 ± 30						
Two reconstructed LJs	86	9	40	0	1	39	175 ± 7
η range (TYPE1/TYPE2)	86	8	27	0	1	23	145 ± 6
EM fraction (TYPE2)	86	8	23	0	1	12	130 ± 6
Jet width W (TYPE2)	86	8	23	0	1	12	130 ± 6
Jet timing (TYPE1/TYPE2)	86	6	23	0	1	11	128 ± 6
NC muons (TYPE0/TYPE1)	50	4	17	0	0	11	82 ± 5
ID isolation	37	2	13	0	0	10	63 ± 4
$\lvert\Delta\phi\rvert$	35 ± 3	2 ± 1	12 ± 2	$0^{+0.6}_{-0}$	$0^{+0.6}_{-0}$	10 ± 2	60 ± 4

Table 7. Expected number of LJ events for the two-γ_d FRVZ model, using the parameter values in table 6. The numbers refer to selected signal events at different stages of the selection process and for each LJ pair type. The number of signal events is rescaled to the 20.3 fb^{-1} total integrated luminosity and the quoted uncertainties are statistical only. The detection efficiency is 1.5×10^{-3}.

Signal Efficiencies

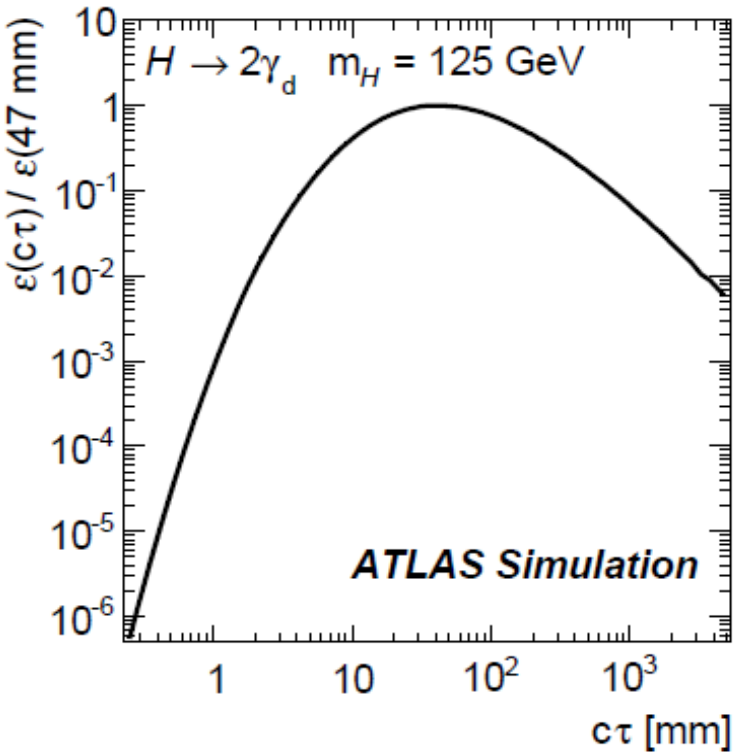


Figure 14. Ratio of the integrated detection efficiency at a given $c\tau$ to the detection efficiency at $c\tau = 47$ mm of the reference $H \rightarrow 2\gamma_d + X$ MC sample.

Systematics

- Luminosity
- Higgs production cross-section
- Trigger efficiency
- Muon reconstruction efficiency
- Muon momentum resolution
- Jet energy scale
- Effect of pile-up on $\sum p_T$
- Multi-jet background
- Cosmics background
- γ_d detection efficiency, p_T resolution