Prompt and non-prompt leptonic decays as a window into the dark sector with ATLAS

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ATLAS EXPERIMENT

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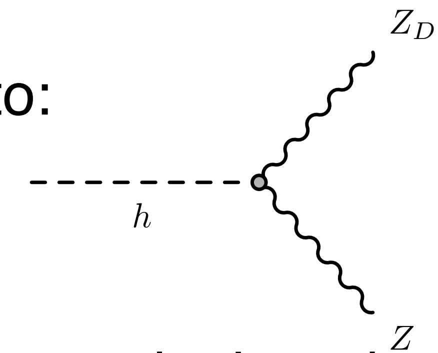
U(1) dark – a simplified dark photon model

U(1)$_{dark}$ is a simple extension to the Standard Model (SM) that adds a vector boson, Z_d (also know as: A', Z', γ_d)

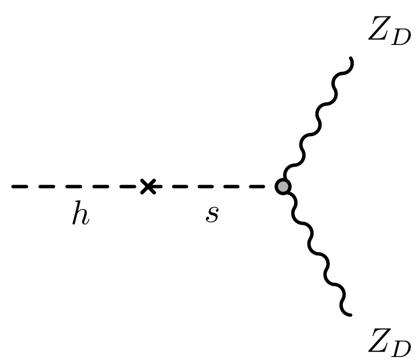
- *Kinetic mixing* between SM and dark sector: $\frac{1}{2}\,\epsilon\, F'_{\mu\nu} B^{\mu\nu}$

Z-Z_d mixing leads to:



- Can generate Z_d mass by introducing a dark scalar

Allows for decays:



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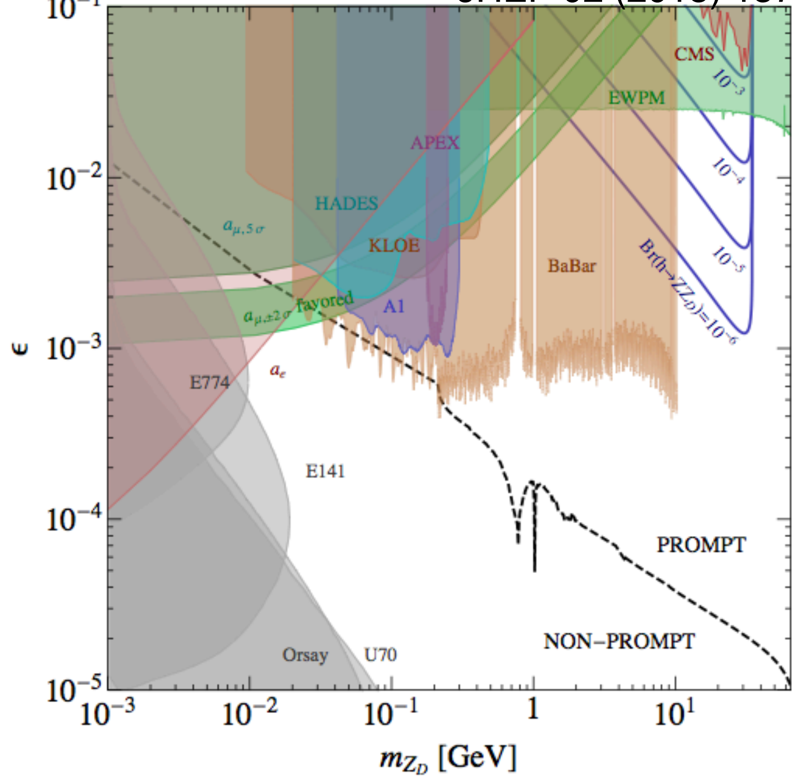

Not discussed in this talk: Drell-Yan production (pp → Z_d → l^+l^-)
See JHEP 02 (2015) 157 for a discussion of DY prospects

How does the Z_d decay?

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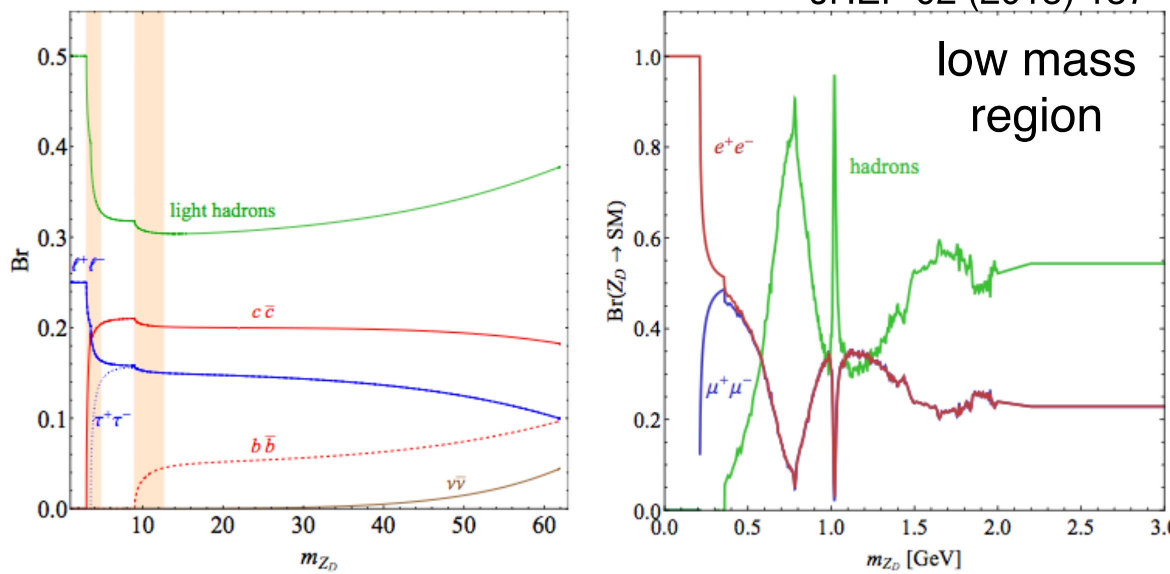
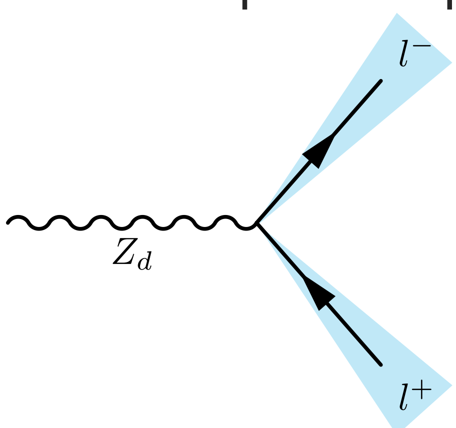
- Depending on the Z_d mass, to leptons or quarks
- Leptons provide a distinct, clean search channel with low backgrounds

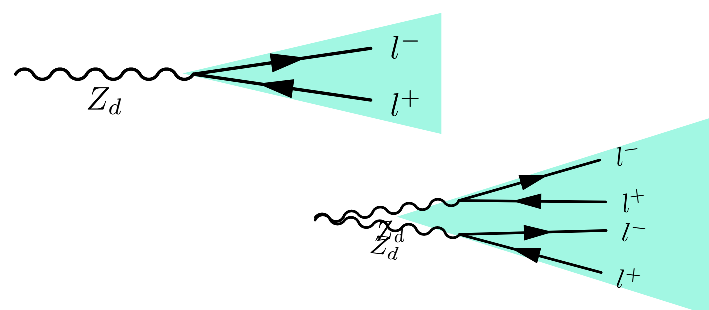


(a) (b)

- Collimation of leptons depends on the Z_d boost/mass:



resolved leptons



lepton jets

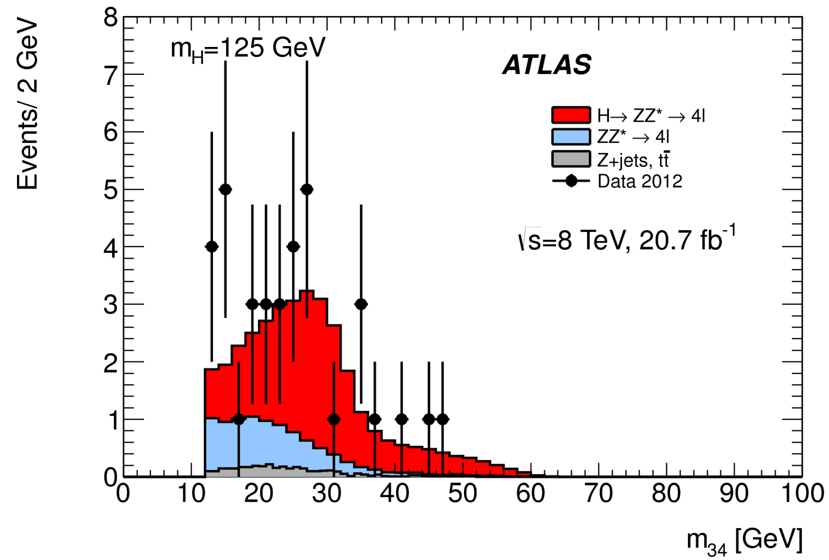
H→Z Z_d

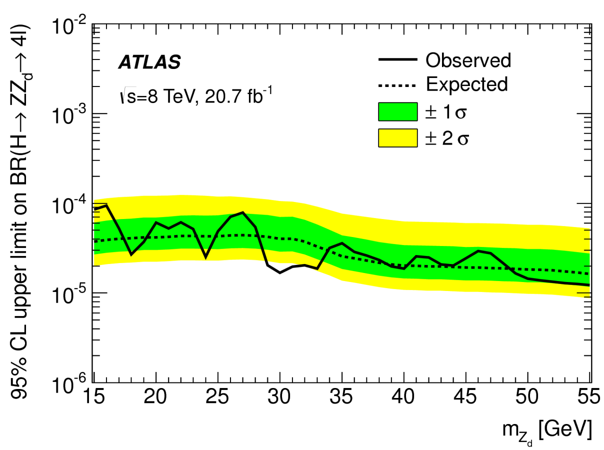
Very similar analysis to H→ZZ*, except now H→ZZ* is an irreducible background!

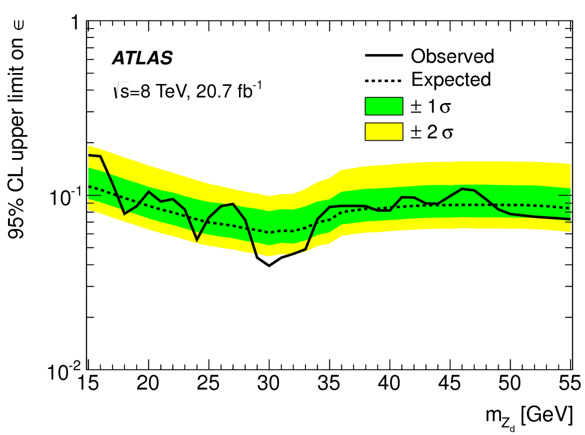
- Two pairs of same flavour, opposite sign (SFOS) leptons:
  - $50 < m_{12} < 106$ GeV
  - $12 < m_{34} < 115$ GeV
- Mass of 4 leptons required to be consistent with the SM Higgs:
  - $115 < m_{4l} < 130$ GeV

Z_d would present as a peak in m_{34}:

- scan for signal peak in 1 GeV steps (15 GeV – 55 GeV)







No excess of events: set limits on branching ratio for H → Z Z_d or kinetic mixing parameter

$H \rightarrow Z_d Z_d$: analysis

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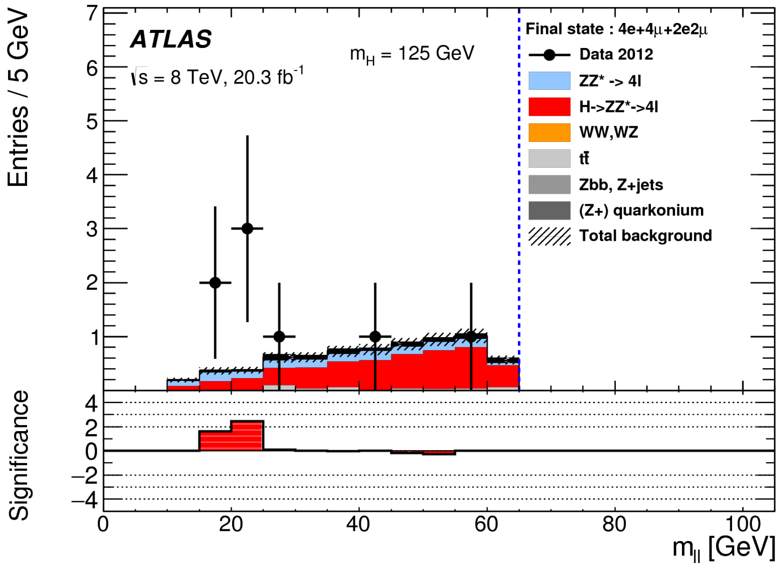
No distinction between lepton pairs: both Z_d are on-shell, and both Z_d have the same mass

➔ same 4l mass requirement as $H \rightarrow ZZ_d$: $115 < m_{4l} < 130$ GeV

➔ select e, μ lepton pairs to minimize $\Delta m = |m_{12} - m_{34}|$

- Veto J/ψ, Y by requiring $m_{ll} > 12$ GeV, veto Z with $|m_{ll} - m_Z| > 10$ GeV, where m_{ll} is *any* SFOS lepton pair



- Loose selection requires $m_{ij} < m_H / 2$, four events pass loose selection

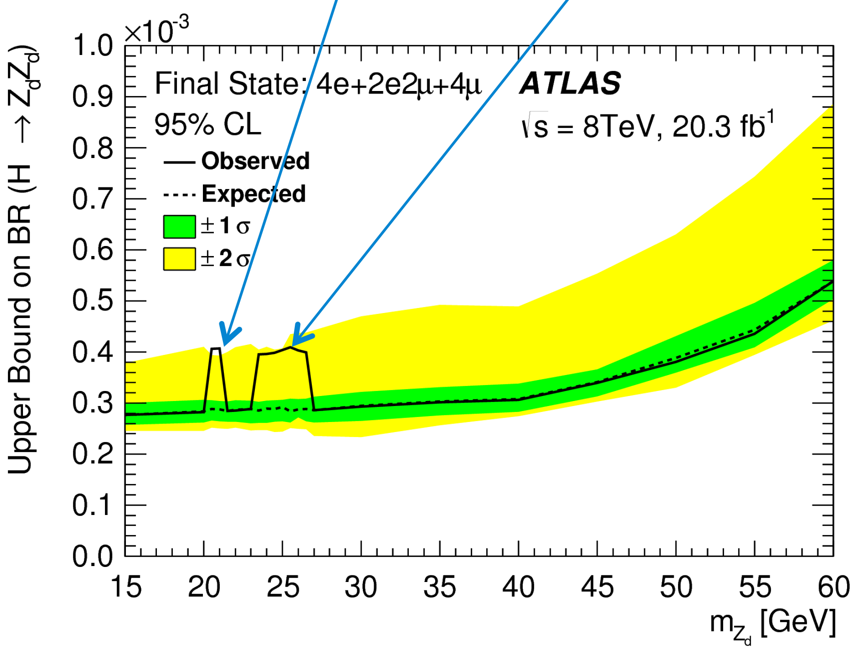
- Final event selection restricts lepton pair invariant mass depending on flavour and m_{Zd}:

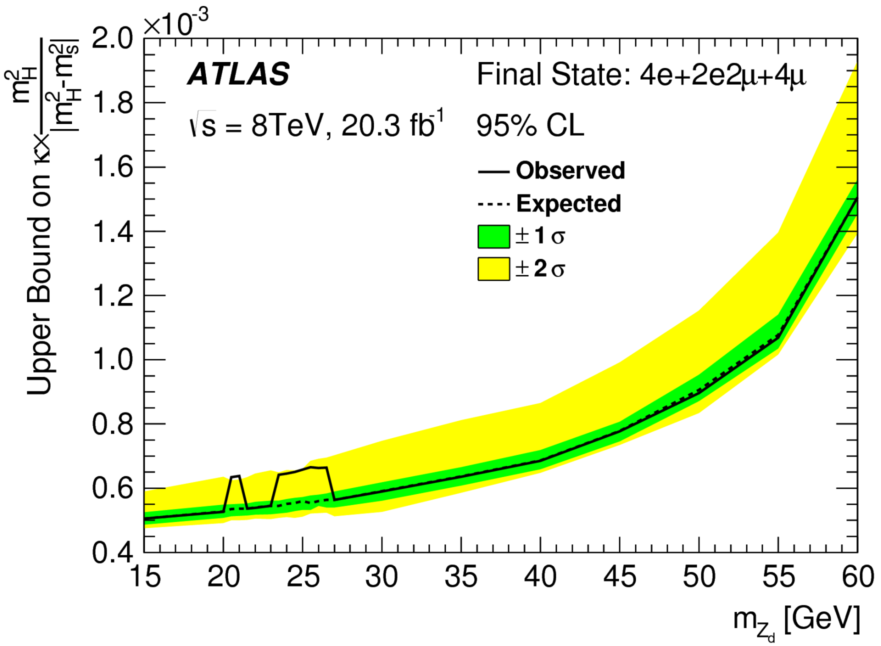
$\|m_{Zd} - m_{ij}\|$	channel
5 GeV	4e
3 GeV	4μ
4.5 GeV	2e2μ

Total background is < 0.1 event in all channels

Two events pass final signal selection:

m_{12}	m_{34}	consistent m_{Zd}	channel
18 GeV	23.2 GeV	20.5 – 21.0 GeV	4μ
21.8 GeV	28.1 GeV	23.5 – 26.5 GeV	4e





Limits can be set on $BR(H \rightarrow Z_d Z_d)$ or the kinetic mixing parameter, κ

Prompt lepton jets

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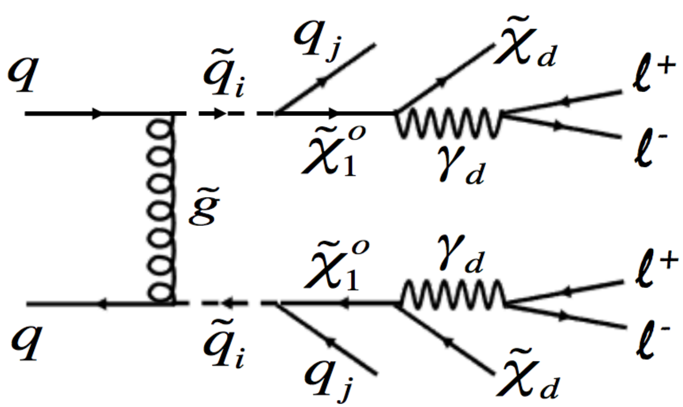
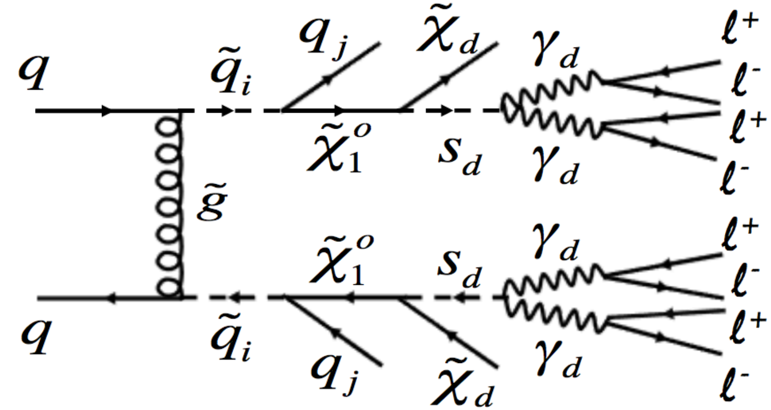
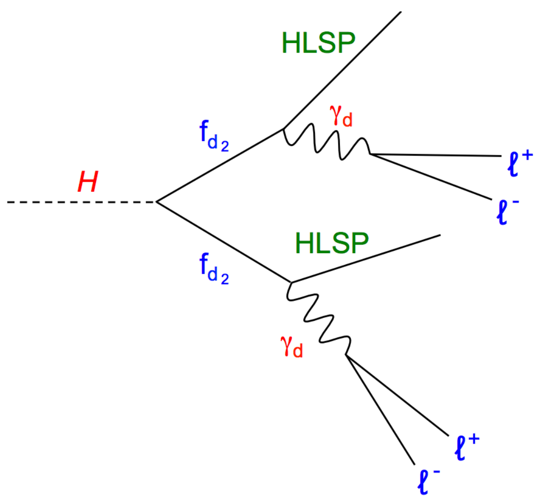
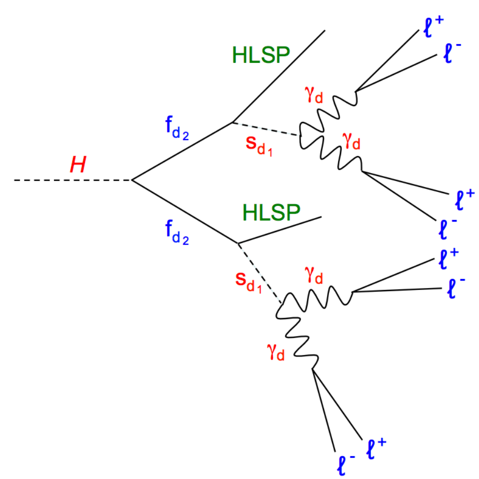
SUSY production of lepton jets, with dark sector candidate X_d:





and Higgs-portal production in Falkowski-Ruderman-Volansky-Zupan (FVRZ) models:

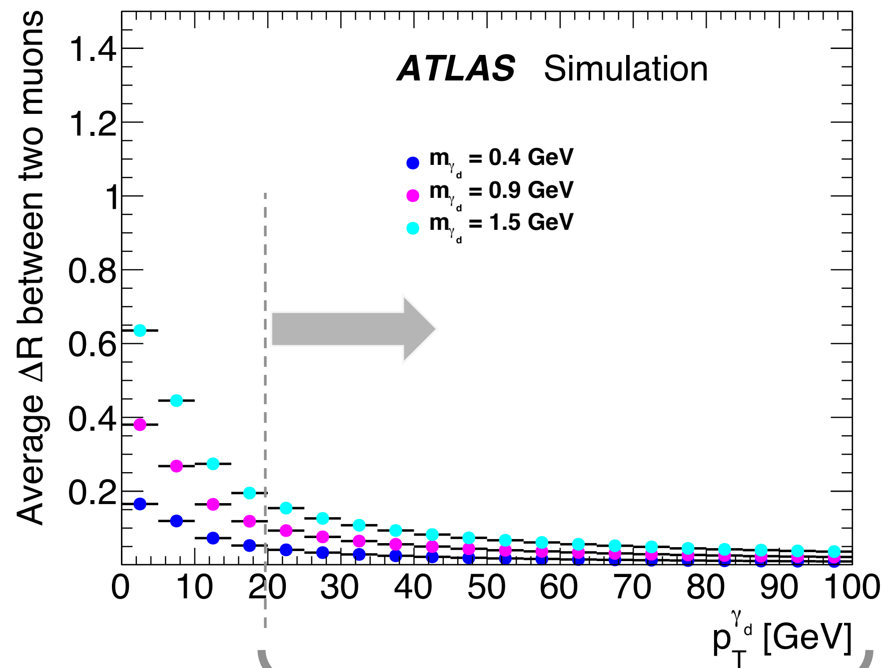




HLSP:
Hidden lightest stable particle (simulated mass is 2 GeV)

High dark photon boost

Very collimated leptons



analysis signal region

Reconstruction:

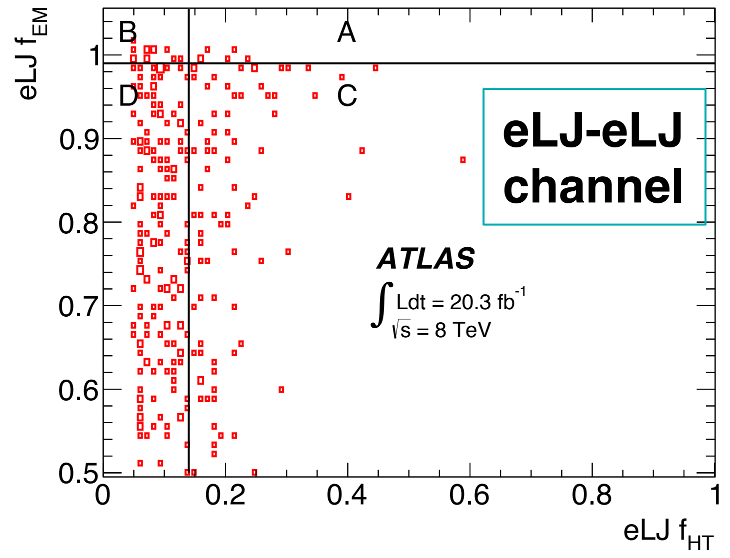
1. Cluster tracks in ΔR = 0.5 cone
2. Search for leptons within ΔR = 0.5 of track axis
3. Can find three types of lepton jet:
   - electron (**eLJ**):
     - ≥ 1 electron, **no** muons, ≥ 2 tracks
   - muon (**muLJ**):
     - ≥ 2 muons, **no** electrons, ≥ 2 tracks
   - electron+muon (**emuLJ**):
     - ≥ 1 muon, ≥ 1 electron, ≥ 2 tracks

Six possible 2-LJ event topologies:

eLJ-eLJ	eLJ-muLJ
muLJ-muLJ	eLJ-emuLJ
emuLJ-emuLJ	muLJ-emuLJ

Prompt lepton jets: results

- Dominant background is QCD jets faking lepton jets
  → estimate with ABCD likelihood method using pairs of approximately uncorrelated variables for each 2-LJ topology
- Diboson (includes γ*), $t\bar{t}$ backgrounds estimated from MC



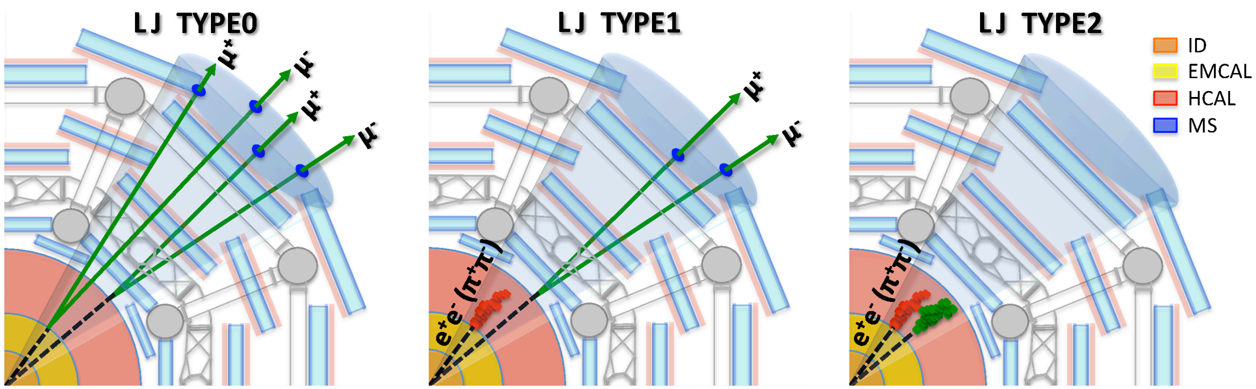
<u>No significant excess of events in any topology:</u>

Channel	Background (ABCD-likelihood method)	Background (total)	Observed events in data
eLJ–eLJ	2.9 ± 0.9	4.4 ± 1.3	6
muLJ–muLJ	2.9 ± 0.6	4.4 ± 1.1	4
eLJ–muLJ	6.7 ± 1.4	7.1 ± 1.4	2
eLJ–emuLJ	7.8 ± 2.0	7.8 ± 2.0	5
muLJ–emuLJ	20.2 ± 4.5	20.3 ± 4.5	14
emuLJ–emuLJ	1.3 ± 0.8	1.9 ± 0.9	0

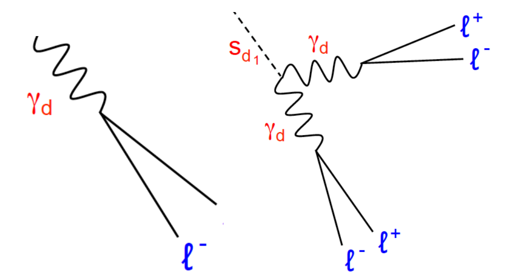
Displaced lepton jets

What if the dark photons have a non-zero proper lifetime?

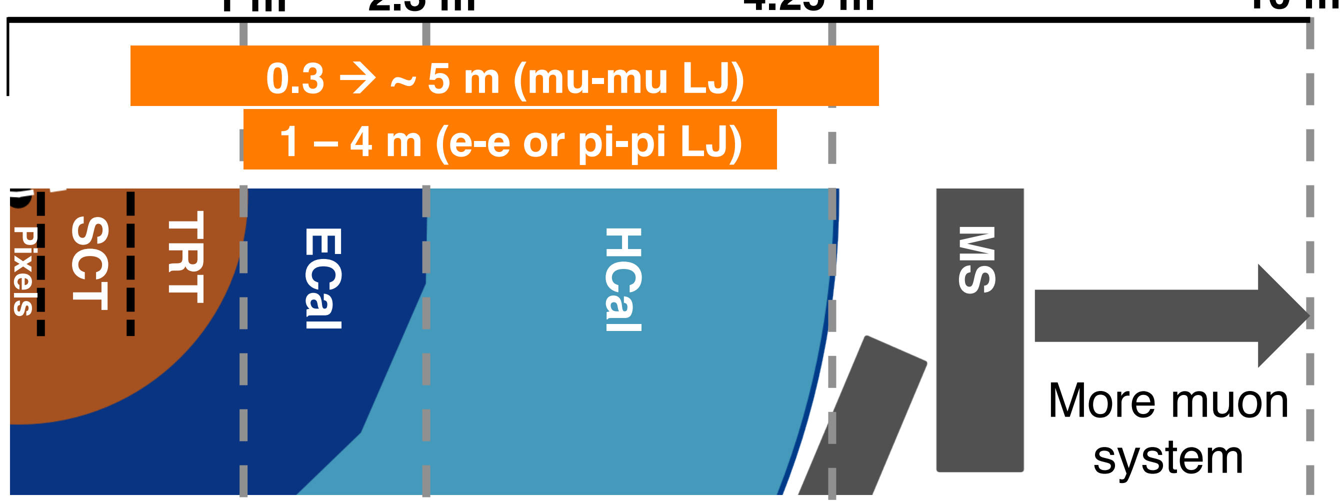
Higgs portal model gives three types of LJs:



From two types of decays:



Sensitivity regions:



Displaced lepton jets: reconstruction

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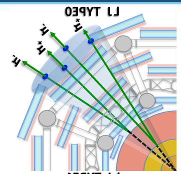
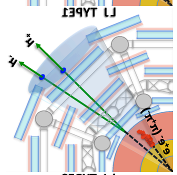
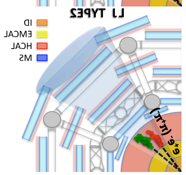


TYPE0: ≥ **2** *displaced* muons and no jet

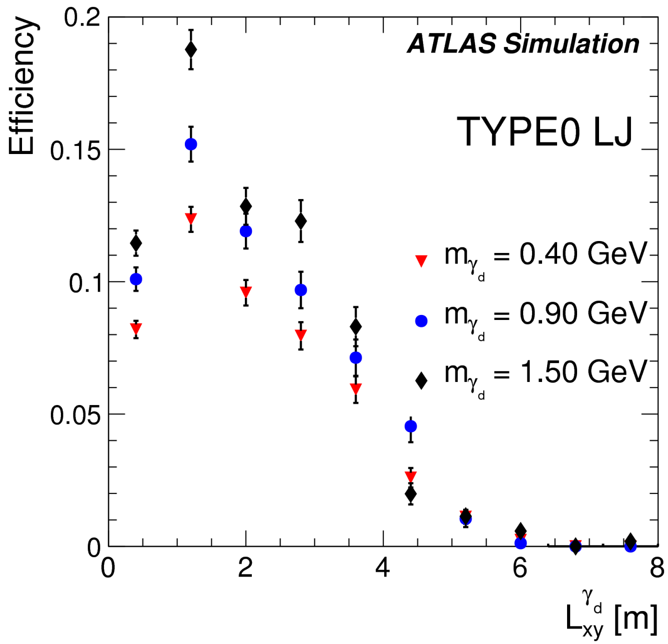


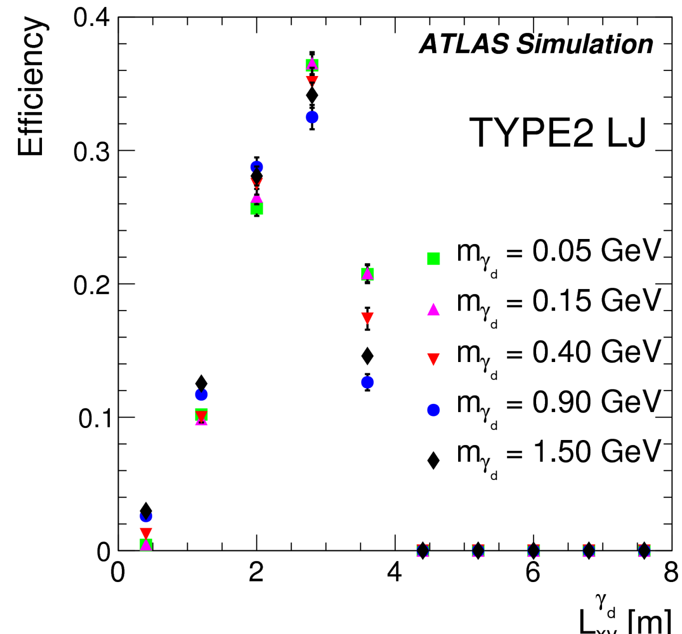
TYPE1: ≥ **2** *displaced* muons and one jet



TYPE2: one low-EMF jet

Reconstruction efficiency depends on *where the dark photon decays:*





Displaced lepton jets: results

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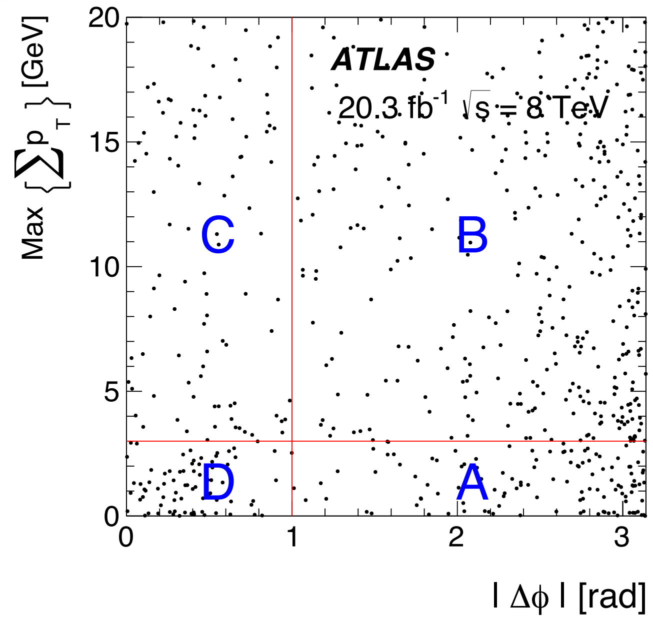
Main backgrounds are cosmic rays and QCD jets

- Estimate QCD background using ABCD likelihood method (same region for *all* LJ topologies):

- Cosmic ray background estimated using data collected in *empty bunches* during collision runs



No significant excess of events in any topology:

	All LJ pair types	TYPE2-TYPE2 LJs excluded
Data	119	29
Cosmic rays	$40 \pm 11 \pm 9$	$29 \pm 9 \pm 29$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$	$12 \pm 9 \pm 2$
Total background	$110 \pm 59 \pm 14$	$41 \pm 12 \pm 29$

Background from TYPE2-TYPE2 (2 low-EMF jets) topology largest – signal contribution is not → better limits *without* TYPE2-TYPE2 signal region.

Combined lepton jet limits

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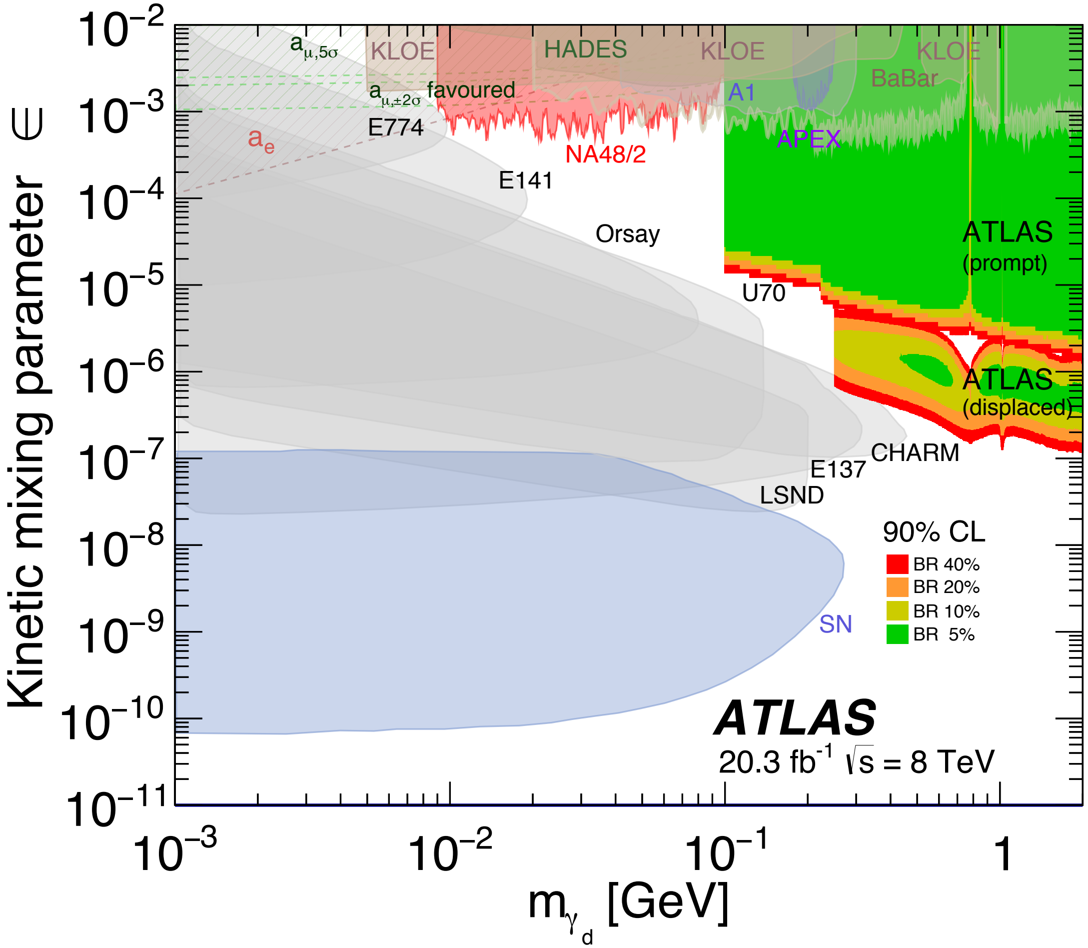
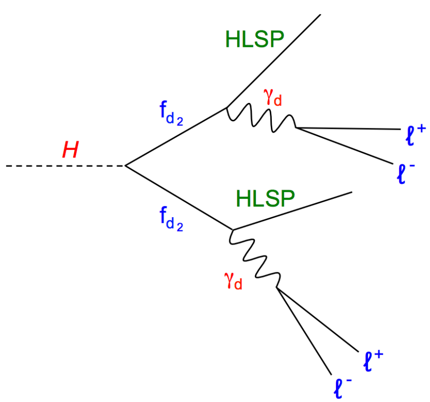
- Dark photon lifetime depends on kinetic mixing parameter
- Small ε → long lifetime
- Limits here are *model dependent* – based on FRVZ model H→2γ_D + *X*. Other limits are from direct searches (beam dump, etc.)





Many channels investigated in Run 1:

	one Z_d	two Z_d	four Z_d
prompt, non-collimated Z_d	✓ $H \to Z Z_d$	✓ $H \to Z_d Z_d$	
displaced, non-collimated Z_d			
prompt, collimated Z_d		✓ $H \to Z_d Z_d + X$	✓ $H \to s_D s_D + X$, $s_D \to Z_d Z_d$
displaced, collimated Z_d		✓ $H \to Z_d Z_d + X$	✓ $H \to s_D s_D + X$, $s_D \to Z_d Z_d$

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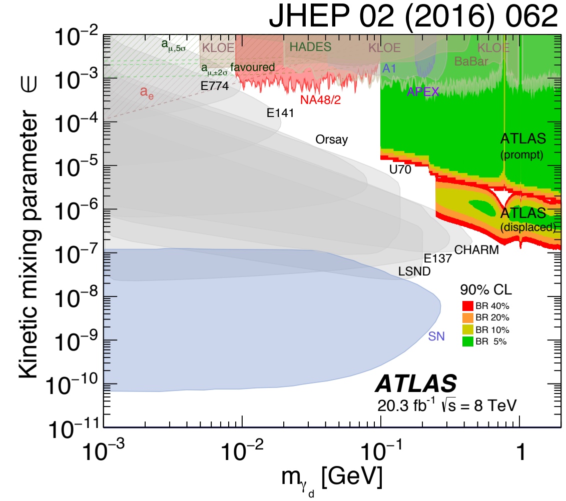

No excesses found, but parameter space is still open:

Will fill in the gaps and push the boundaries with Run 2!

All ATLAS Exotics public results can be found here:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults