Prompt Lepton-Jets from Decays of Low-Mass Dark Gauge Bosons

LHC Dark Matter Working Group
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Introduction

- Many BSM theories predict dark gauge boson as mediator between hidden and visible sectors
- Collider production of **low-mass** dark gauge boson mediator?
  - **Low-mass** → boosted → highly-collimated decay products
  - Decaying back to SM with sizeable BR → dileptons (and/or light hadrons) in final state
  - Short-lived → prompt decay (no displaced vertex)

Prompt "Lepton-Jet" Signature

Smoking Gun

Lepton-Jet (LJ): collimated jet-like structure containing pair(s) of muons and/or electrons (and/or light hadrons)

Outline

- Low-Mass Dark Gauge Boson Search Motivations
- Low-Mass Dark Gauge Boson Decays
- Lepton-Jet Search Challenges
- Lepton-Jet Search Strategies
- Prompt Lepton-Jet Search Results, Run 1
  - ATLAS
  - CMS
- Potential For Run 2

Search Motivations

- Possible portals to dark sector: Higgs, Neutrino, Vector, (Axion)
- Vector portal: add U(1)' whose massive gauge boson (A' / Z_D / γ_d) mixes kinetically with SM photon

kinetic mixing parameter

$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu}$$

- Higgs portal: add "dark scalar" (φ / s_d) that mixes with SM Higgs

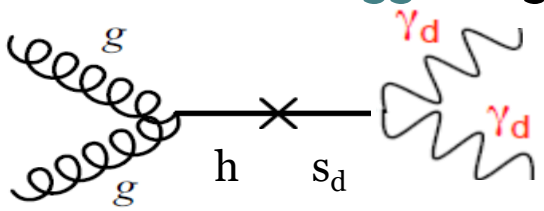
$$\mathcal{L} \supset (A\varphi + \lambda\varphi^2)H^\dagger H$$

Higgs mixing parameter

$$\kappa = \frac{Av}{m_h^2 - m_\varphi^2}$$

  - Trilinear term induces mixing after EWSB

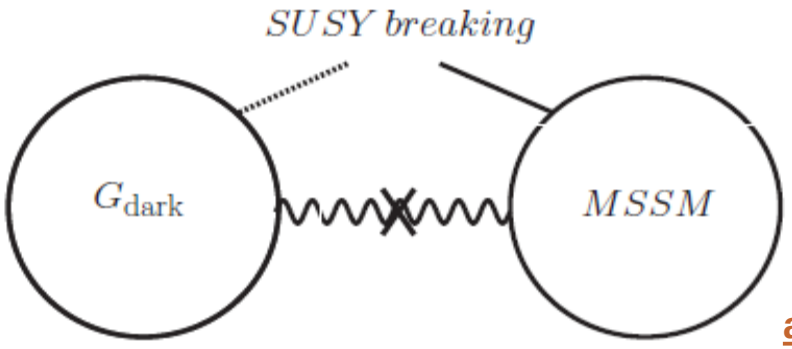
- Hidden Abelian Higgs: Higgs Portal + dark gauge boson



- **Large unexplored areas of parameter space with low-mass γ_d**

Search Motivations

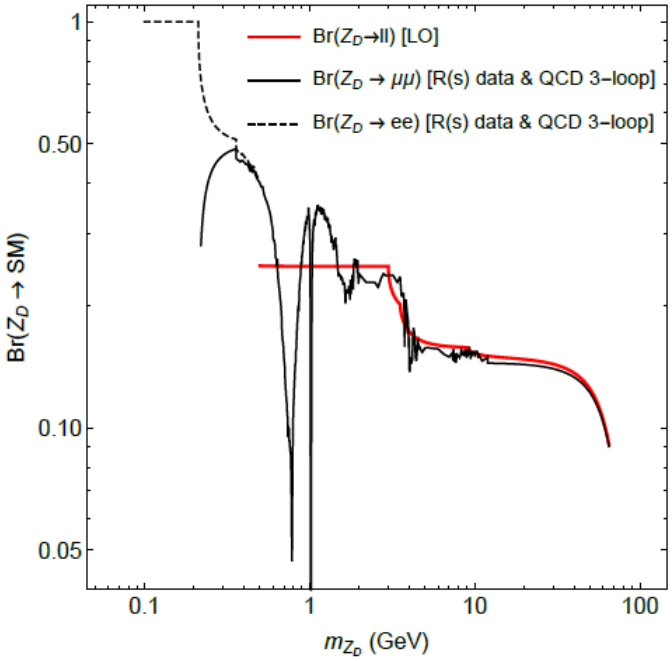
- "Hidden Valley": γ_d our best candidate for collider detection amongst hidden zoo?
  - High γ_d multiplicity in long decay chains?
- Many dark matter models require γ_d to satisfy astrophysical constraints
  - Inelastic Dark Matter
  - Radiating Dark Matter
- γ_d as mediator between dark gauge group and (N)MSSM ?
  - Production of superpartners @LHC → dark sector → γ_d's ?

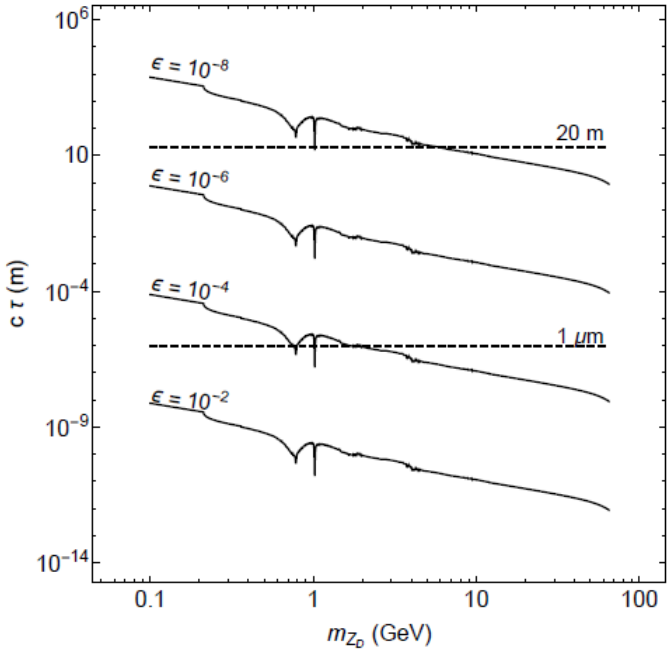


arXiv:0810.0714

Low-Mass Dark Gauge Boson Decays

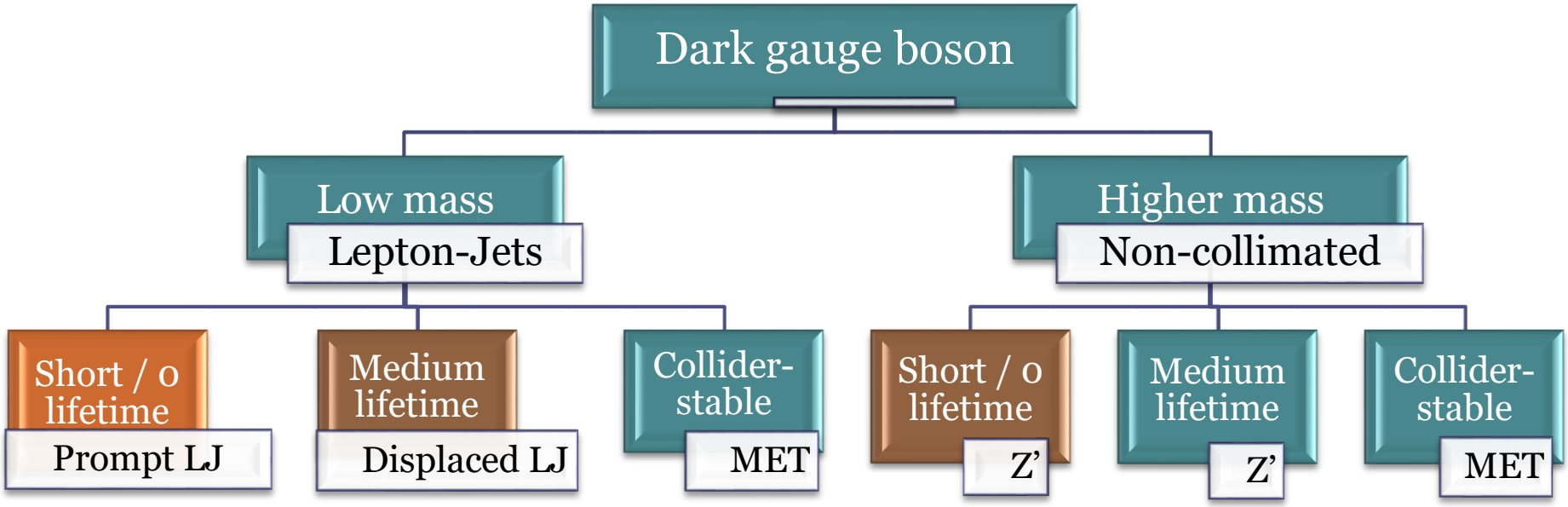
- Final-state collimated dilepton signatures: promising but challenging search prospects if γ_d decays back to SM with sizeable BR
- BRs vary with mass
- Lifetime ($c\tau$) varies with mass and ε
  - Displaced decays: in domain of planned Long-Lived Particles WG





arXiv:1412.0018

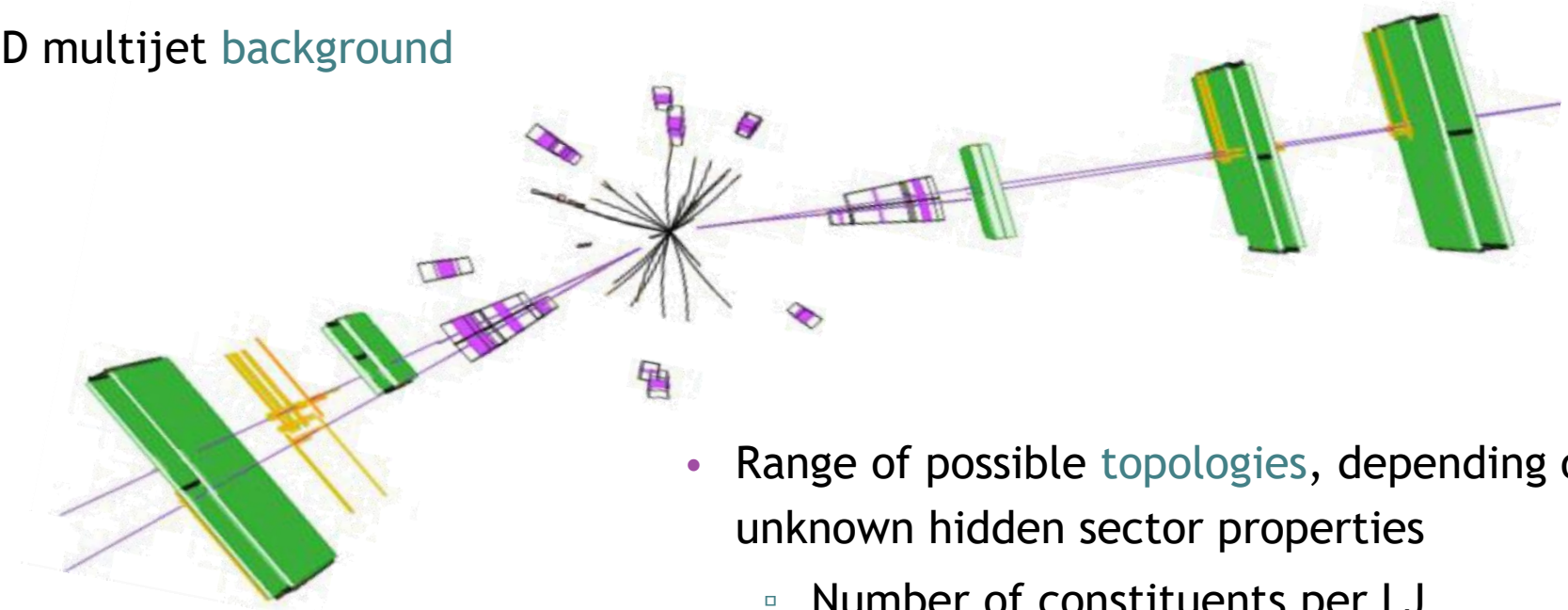
Low-Mass Dark Gauge Boson Decays



- Prompt LJ search: meets short-lifetime limit of Displaced LJ searches, and low-mass limit of Z' searches

Lepton-Jet Search Challenges

- Low signal rate and no obvious triggers
  - Low lepton-p_T thresholds for sufficient efficiency
  - Need creative triggers to avoid pre-scaling
- Reconstruction challenges for collimated final-state particles
- QCD multijet background



ATLAS Public EXOT-2013-22-Aux

- Range of possible topologies, depending on unknown hidden sector properties
  - Number of constituents per LJ
  - LJ widths

Lepton-Jet Search Strategies

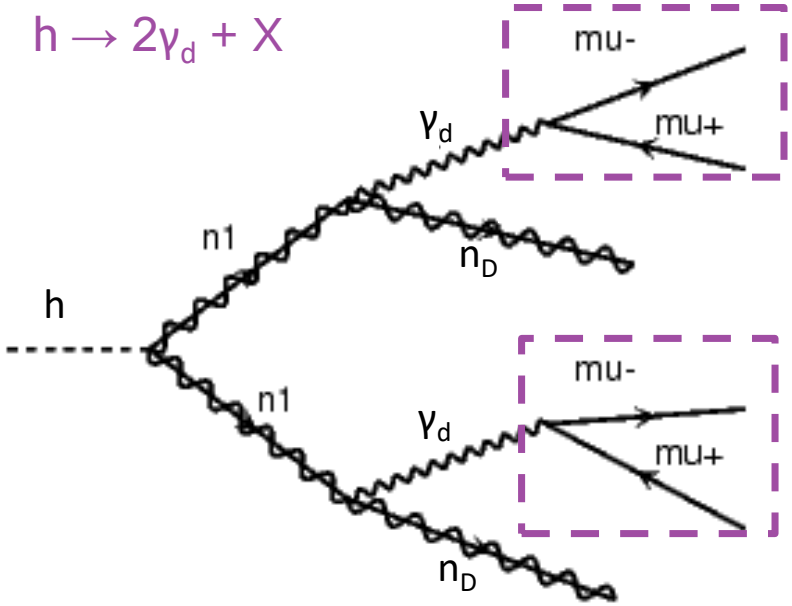
Green: ATLAS analyses
Orange: CMS analyses
Black: both

- Key properties:
  - Particle species of decay products (CMS: μ only)
  - Angular aperture of decay products
  - Decay distance (ATLAS: two separate analyses, Prompt and Displaced)
- LJ constituent selection:
  - Clustering algorithm using ΔR cone
  - Vertex fit
  - Invariant mass window
- LJ isolation
  - Σp_T of tracks within ΔR cone, excluding tracks of LJ constituents
- Require two LJs, consistent with same pp interaction
  - Small $|z_{1LJ} - z_{2LJ}|$ (z_{LJ} = projected z at point of closest approach to beamline)
  - Large Δϕ between LJs

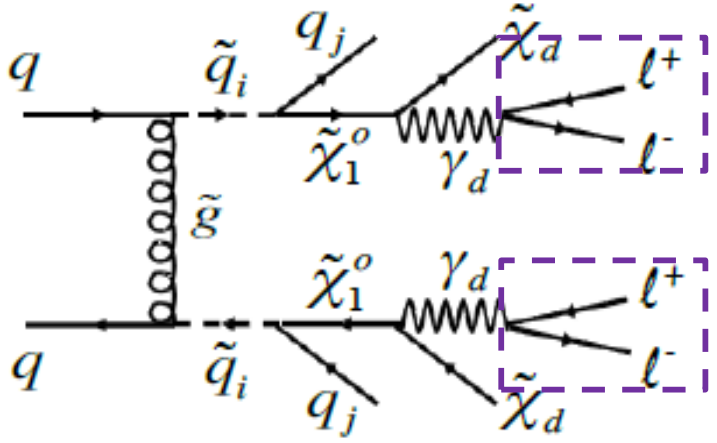
Lepton-Jet Search Strategies

- For limit-setting, need benchmark models, e.g.

$h \rightarrow 2\gamma_d + X$



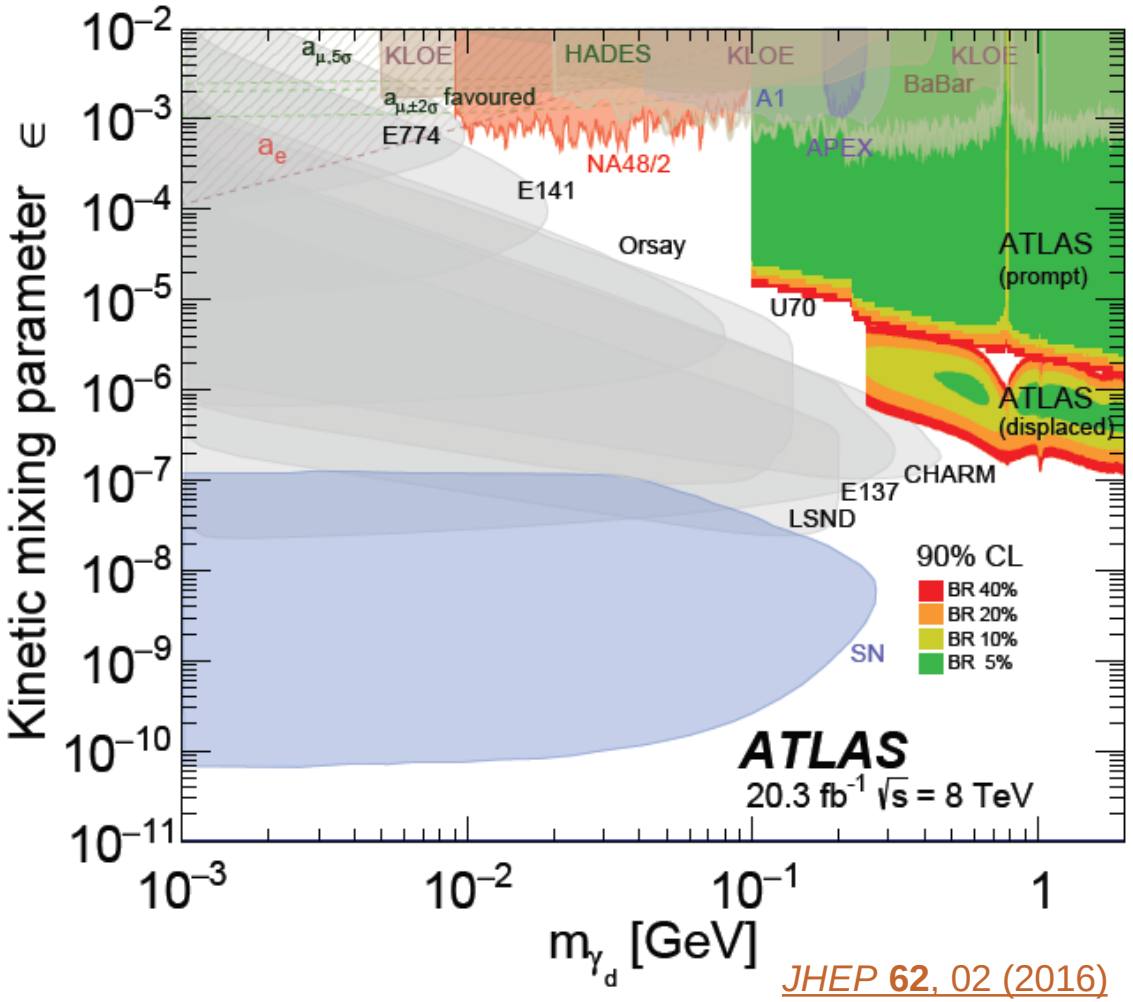
Dark SUSY



- ATLAS: to allow easy re-casting, tables of trigger and reconstruction efficiency as a function of γ_d {cτ , p_T} produced using "Lepton-Jet Gun" MC tool

Run 1 Results: ATLAS

- Prompt search targets decays at primary vertex
- Complementary coverage to ATLAS Displaced LJs search in γ_d parameter space
- In regions other experiments are unable to reach!
  - But, an extra parameter (BR for h → hidden)



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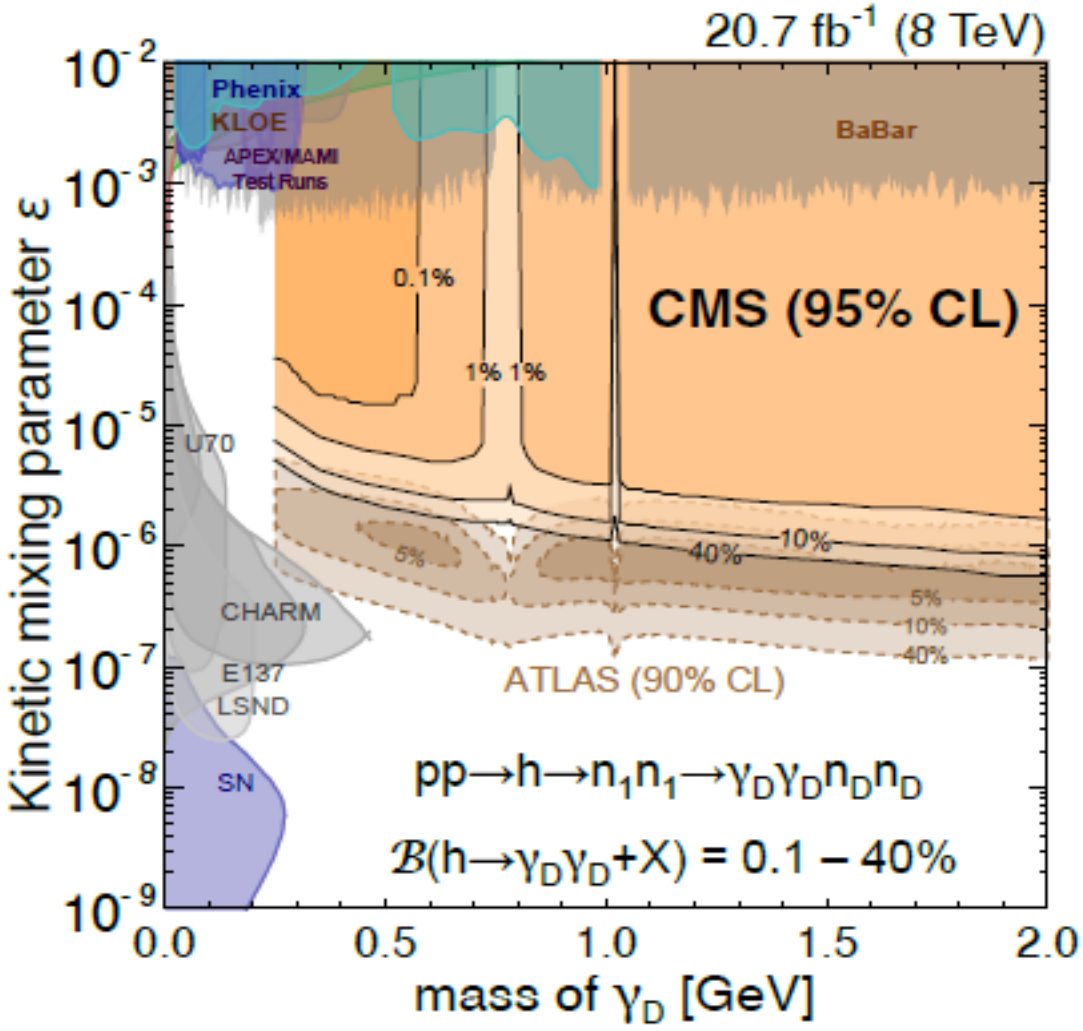
Run 1 Results: CMS

- Targets decays within pixel detector
- Only muon LJs
- Similar coverage to ATLAS Prompt LJs analysis in γ_d parameter space
- In regions other experiments are unable to reach!
  - But, an extra parameter (BR for h → hidden)



[arXiv:1506.00424]

Potential For Run 2

- Repeat Prompt LJ search with 2015-2016 data
  - Expect better limits in [$h \rightarrow 2\gamma_d + X$] benchmark models due to higher Higgs production cross-section
  - A Displaced LJ search with 2015 data has been done: ATLAS-CONF-2016-042

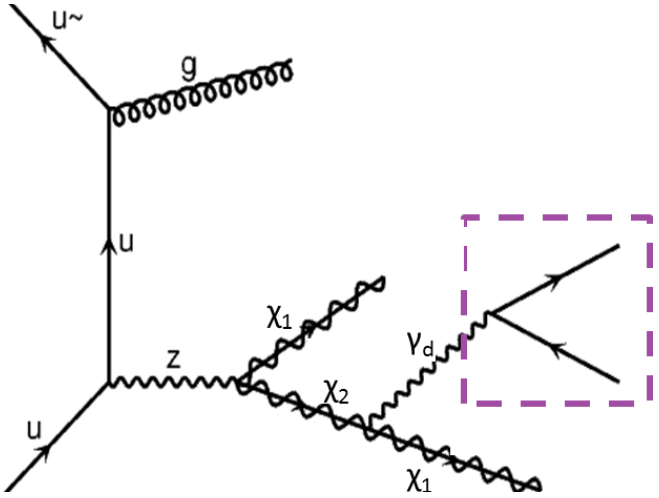
- Extended m_h, m_{γ_d} coverage
- Additional LJ types (ATLAS: converted photons, CMS: electrons)
- ATLAS: Better coverage of short (non-zero) lifetimes via specialized reconstruction of displaced inner detector tracks
- CMS: Improved dimuon vertex reconstruction, in broader fiducial region

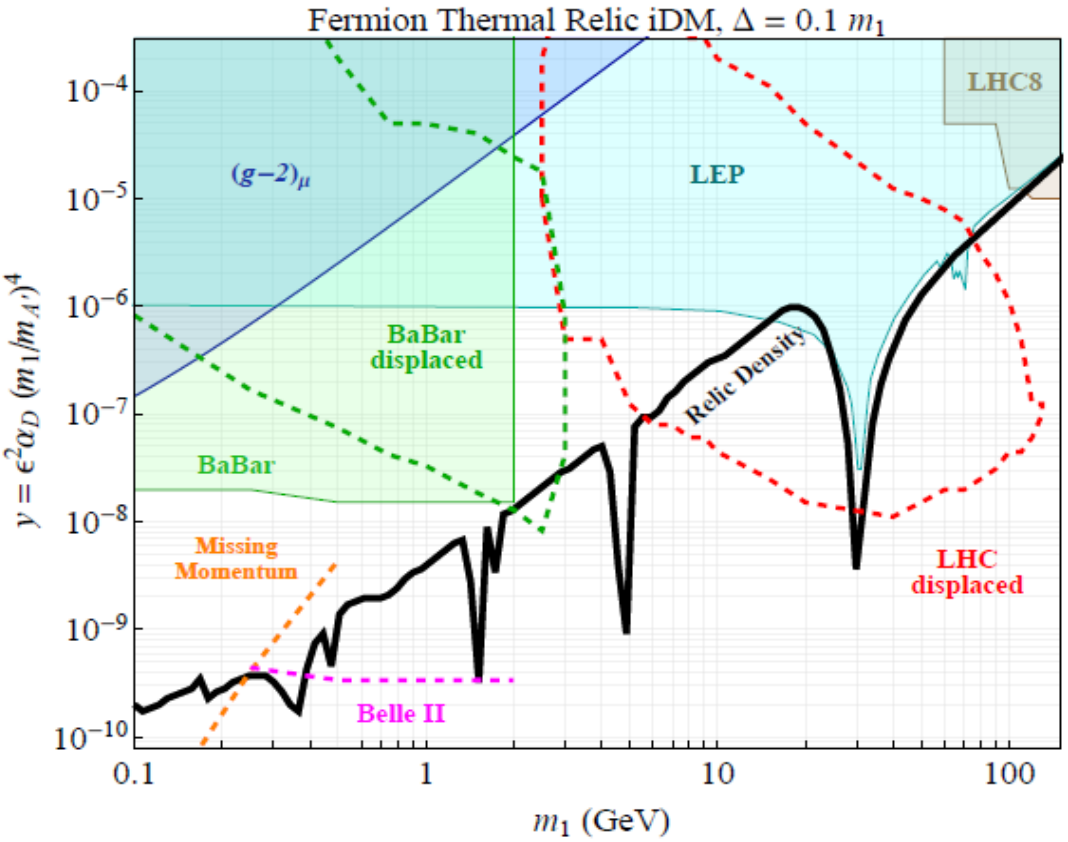
- Additional benchmark models …

Potential For Run 2

- iDM (inelastic dark matter): Dirac fermion DM, mass eigenstates χ_1 and χ_2 with dominantly off-diagonal interactions

  arXiv:1508.03050





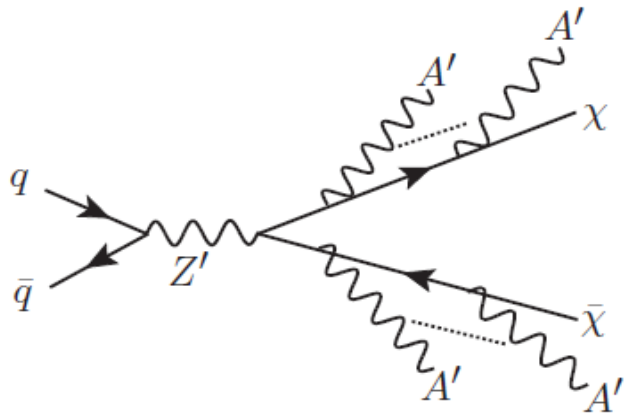
Only one LJ in final state:

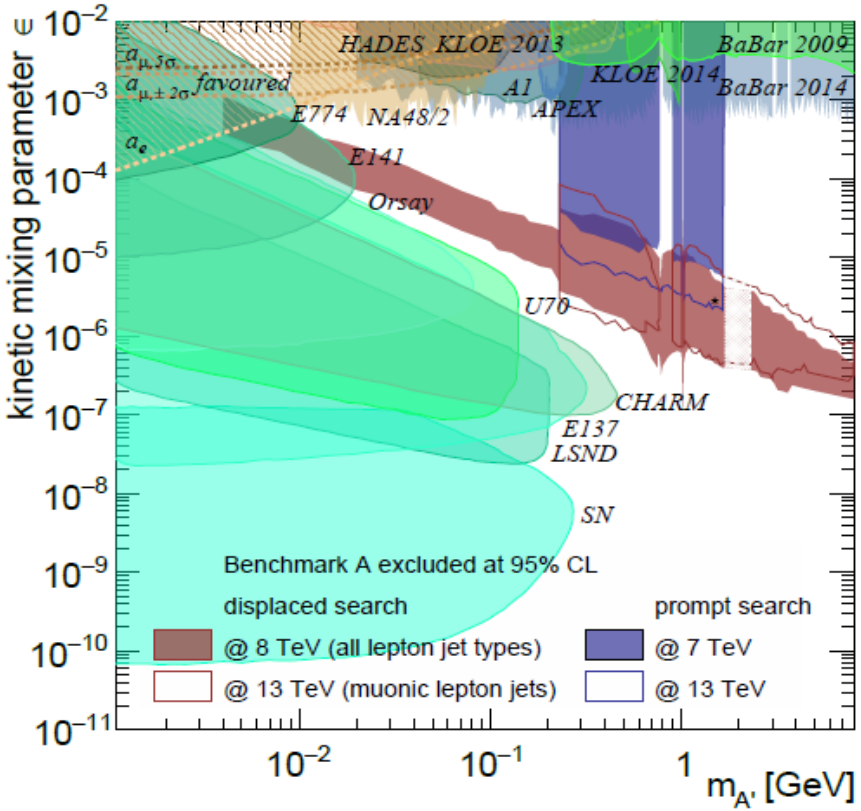
would be new for ATLAS / CMS!

Potential For Run 2

- Radiating DM: Phenomenologists used Pythia dark-showering, and re-casted ATLAS 7TeV Prompt / 8TeV Displaced LJ results

  arXiv:1505.07459





Collaborate with our pheno friends for better re-casting at 13TeV?

Conclusions

- Low-mass dark gauge bosons appear in a wide range of BSM models
  - Vector Portal, Hidden Valley, BSM Higgs, SUSY, …
- Prompt Lepton-Jets: smoking-gun experimental signature
- Presents experimental challenges …
  - Non-standard reconstruction, high QCD multijet background, tricky to find triggers
- … but also big discovery potential!
  - Coverage of large swath of parameter space unexplored by other experiments
- Looking to build on successful 8 TeV Lepton-Jet analyses, at both ATLAS and CMS, for even better 13 TeV versions
  - Expect improved limits on existing benchmark models
  - Potential to explore more models

Backup Slides

Lepton-Jet Search Strategies

ATLAS Prompt

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Lifetime:

Decays at primary vertex

Particle species:

Muon, electron, mixed

Triggers:

OR of {single-electron, di-EM, single-muon, di-muon}

Event Selection:

eLJ	emuLJ
$E_{s1}^{max} > 0.5$ GeV track isolation < 0.04 $f_{HT} > 0.14$ $f_{EM} > 0.99$ $f_{s3} < 0.015$	$E_{s1}^{max} > 3$ GeV track isolation < 0.1 $E_T^{had} < 1$ GeV $f_{s3} < 0.015$

muLJ
track isolation < 0.25 calorimeter isolation < 0.15

CMS

[arXiv:1506.00424]

Lifetime:

Decays within pixel detector

Particle species:

Muon only

Triggers:

Di-muon

Event Selection:

4 offline muon candidates (Particle Flow algorithm)
All muons have $p_T > 8$GeV, $\|\eta\| < 2.4$
At least one muon with $p_T > 17$ GeV, $\|\eta\| < 0.9$
Two oppositely-charged muon pairs, $m(\mu+\mu-) < 5$ GeV
Dimuon vertex: $P_v(\mu+\mu-) > 1\%$ or $\Delta R(\mu+\mu-) < 0.01$
All muons have $\geq$1 hit in pixel layer 1
Dimuon isolation < 2 GeV
$\|z_{1\mu\mu} - z_{2\mu\mu}\| < 1$ mm

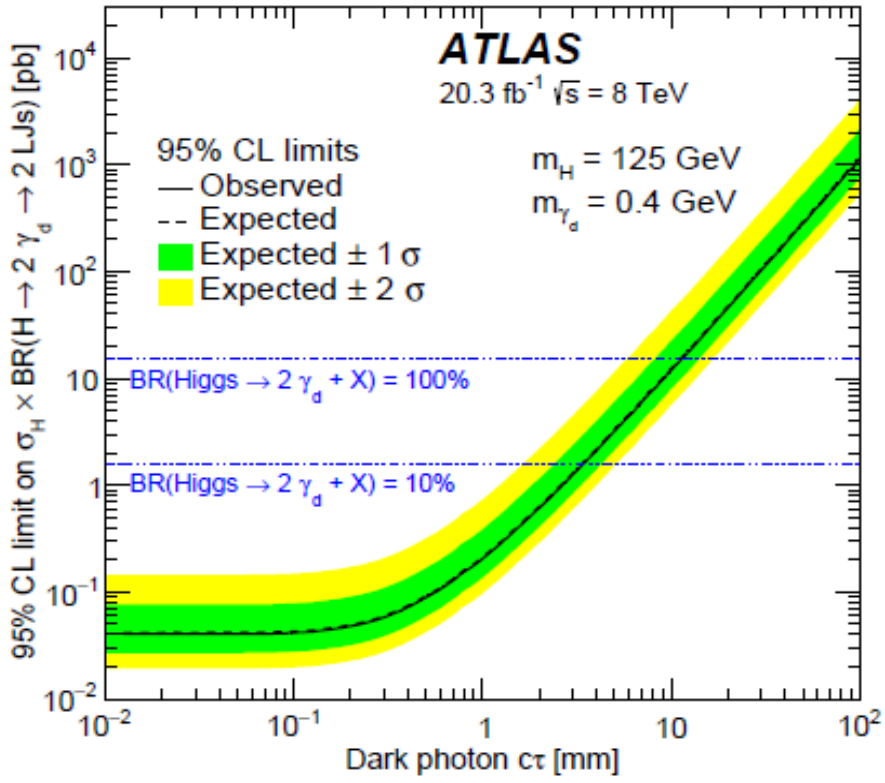
Run 1 Results: ATLAS

Model-independent observations:

Channel	Background (total)	Observed events in data
eLJ–eLJ	4.4 ± 1.3	6
muLJ–muLJ	4.4 ± 1.1	4
eLJ–muLJ	7.1 ± 1.4	2
eLJ–emuLJ	7.8 ± 2.0	5
muLJ–emuLJ	20.3 ± 4.5	14
emuLJ–emuLJ	1.9 ± 0.9	0

Model-specific limits:

Signal bench-marks	$2\gamma_d$ + X					
γ_d mass [GeV]	Obs.	Exp.	-2σ	-1σ	$+1\sigma$	$+2\sigma$
SUSY ($m_{\tilde{q}}$ = 700 GeV)						
0.3	5.9	6.5	2.9	4.1	10.9	18.7
0.4	5.9	6.5	2.9	4.1	10.9	18.7
0.5	5.9	6.5	2.9	4.1	10.9	18.7
0.7	6	6.6	2.9	4.1	11	19
0.9	5.9	6.5	2.9	4.1	10.9	18.7
1.2	5.9	6.5	2.9	4.1	10.9	18.7
1.5	5.9	6.5	2.9	4.1	10.9	18.7
2	5.9	6.5	2.9	4.1	10.9	18.7
Higgs (m_H = 125 GeV)						
0.4	5.9	6.5	2.9	4.1	11	18.8



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Run 1 Results: CMS

Model-independent 95% CL:

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

α = kinematic & geometrical acceptance

ε = selection efficiency

r = $\varepsilon_{data} / \alpha_{gen}$

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
$\epsilon_{sim}/\alpha_{gen}$	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
$\epsilon_{sim}/\alpha_{gen}$	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

$m_{n_1} = 10\,\text{GeV}, m_{n_D} = 1\,\text{GeV}$

[arXiv:1506.00424]