Dark Photon Searches with ATLAS

February 2017

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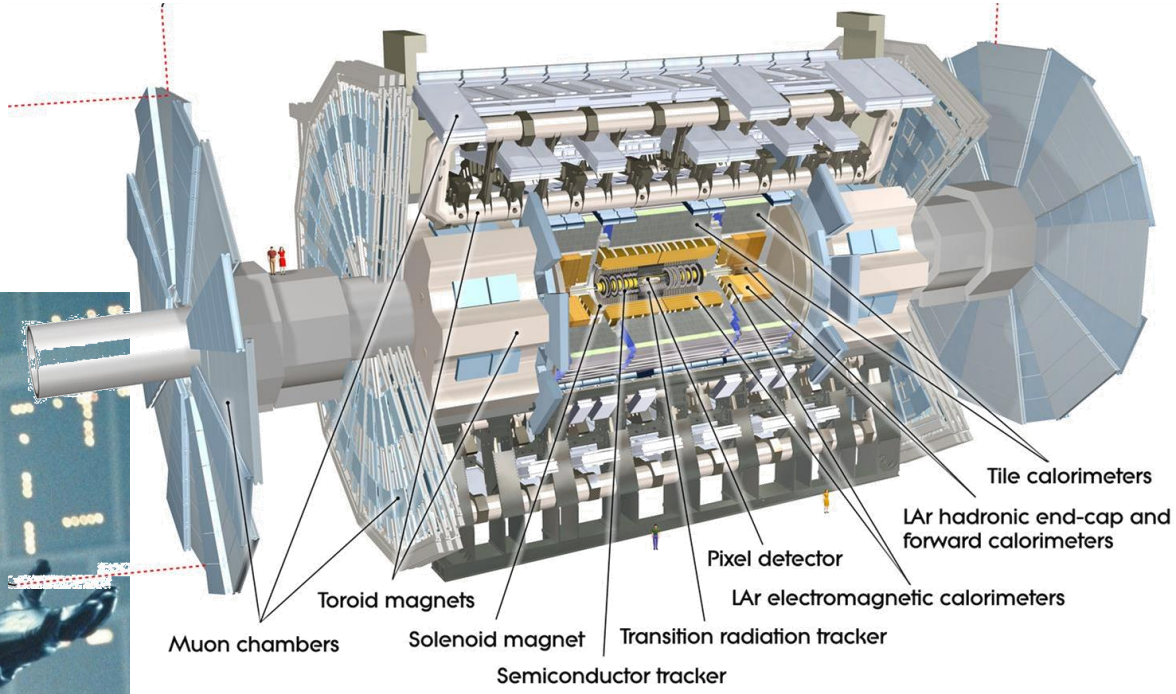
… or, using the Dark Side of the Force



Dark Boson Models

- Vector Portal: Add a U(1)' whose massive "dark" gauge boson (A' / Z_D / γ_d) mixes kinetically with SM photon

kinetic mixing parameter

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

My convention :
γ_d low-mass
Z_D higher-mass
A' agnostic

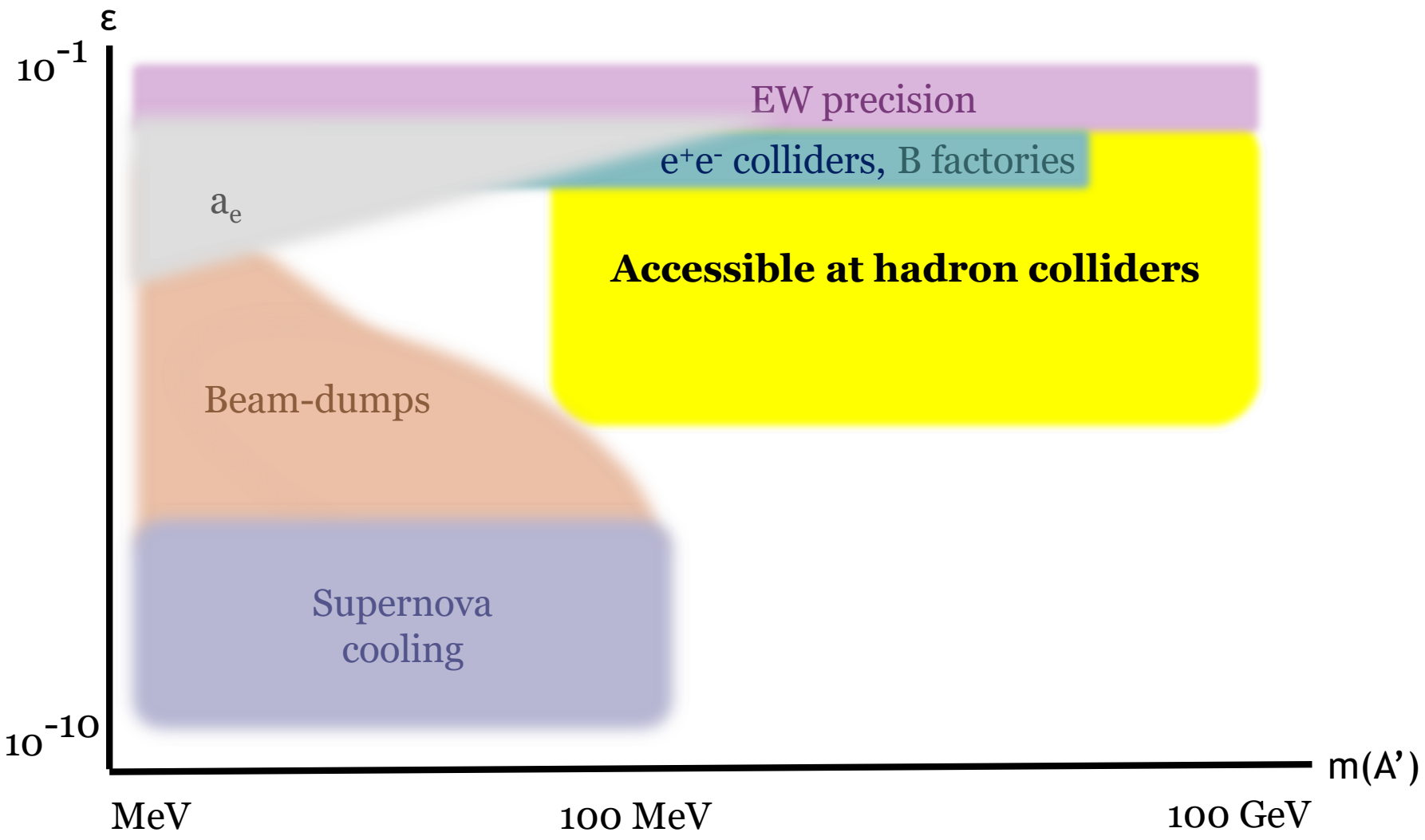
- + Higgs Portal: Add dark scalar singlet (φ / S) that spontaneously breaks U(1)' and mixes with SM Higgs

Higgs mixing parameter

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

- Hidden Valley: sector of dark particles, interacting amongst themselves, weakly coupled to SM through loops of TeV-scale particles or marginal operators
  - Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
  - "Portal", coupling both to SM and Valley operators, can be A' [+ S]

Dark Boson Models

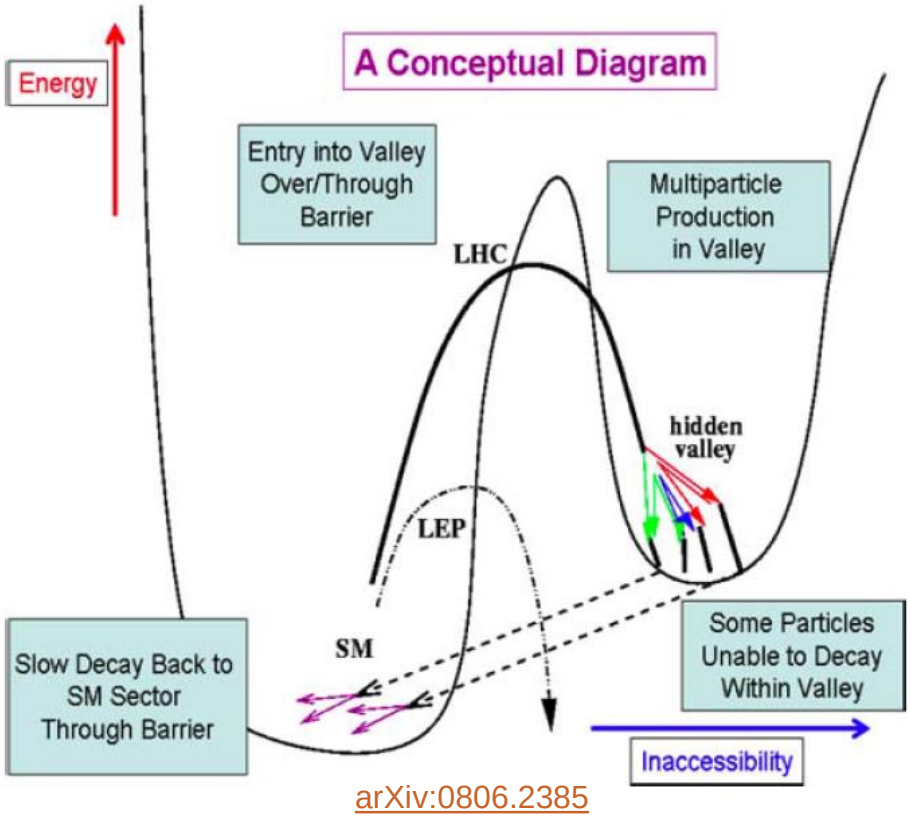


Search Motivations

Look for the Portal

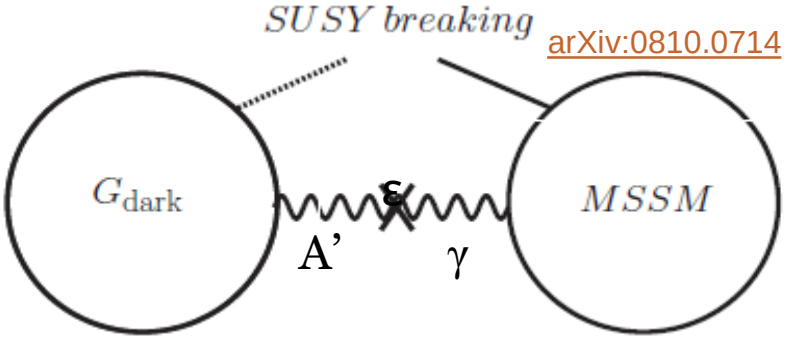
Collider Search Motivations

- Hidden Valley: A' best candidate for collider detection amongst hidden zoo?
  - High A' multiplicity in decay chains?



arXiv:0806.2385

- A' mediator between dark gauge group and (N)MSSM ?



arXiv:0810.0714

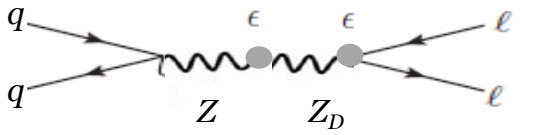
- A' contribution to h → inv ?
- "Bottom-up" DM models

- Final-state dileptons: promising if A' decays back to SM
  - Assume A' lowest-mass dark state
  - BRs vary with mass
    Lifetime varies with mass, ε

Collider Search Strategies

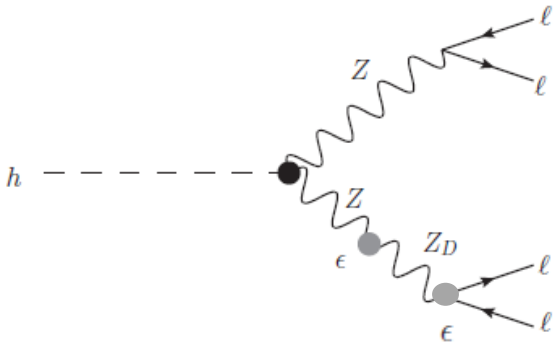
$pp \rightarrow Z_D \rightarrow l^+l^-$

- only requires vector portal



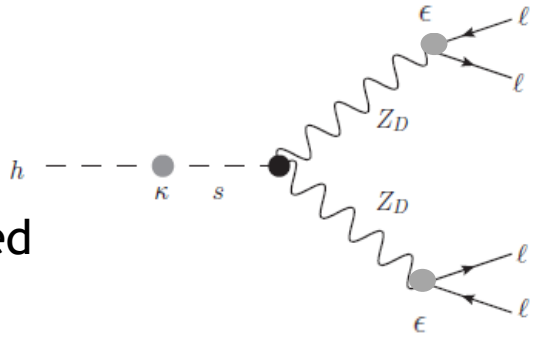
$pp \rightarrow h \rightarrow Z\ Z_D \rightarrow 2l^+\ 2l^-$

- only requires vector portal



$pp \rightarrow h \rightarrow Z_D\ Z_D \rightarrow 2l^+\ 2l^-$

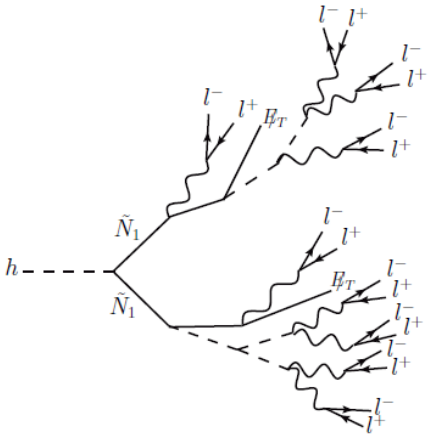
- suppressed in vector portal
- significant if Higgs portal added



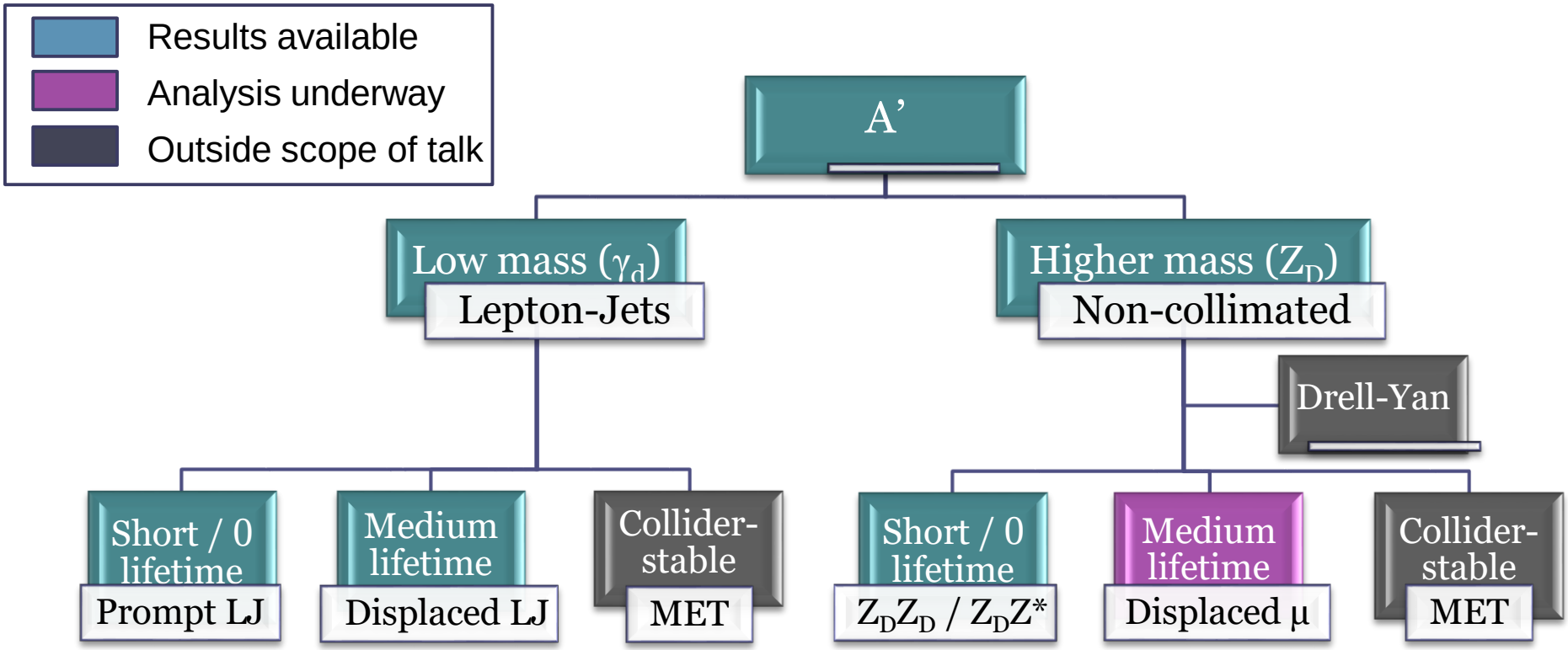
arXiv:1412.0018

Hidden Valley / SUSY

- Various combinations of dark vertices, decay chains



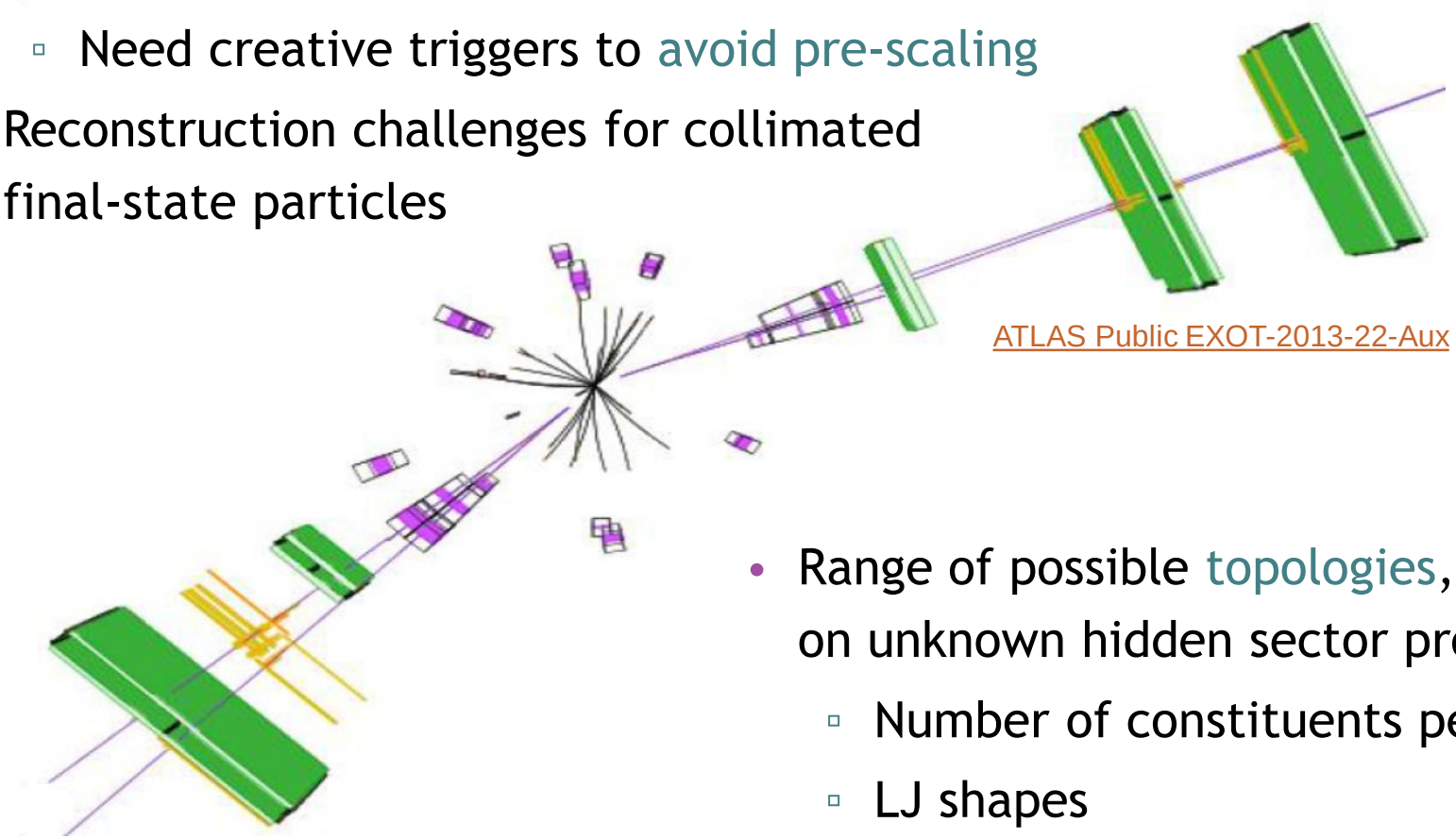
Collider Search Strategies



- Lepton-Jet (LJ): collimated jet-like structure containing pair(s) of muons and/or electrons *(and/or light hadrons)*
- Non-collimated: sufficiently far apart for standard reconstruction

Low-Mass Searches: 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



ATLAS Public EXOT-2013-22-Aux

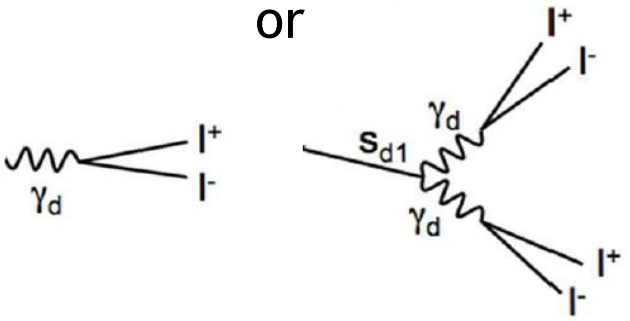
- Range of possible topologies, depending on unknown hidden sector properties
  - Number of constituents per LJ
  - LJ shapes

Low-Mass Searches: Strategy

- Categorize LJs by:
  - Particle species
  - Prompt vs displaced
- Key properties:
  - Angular aperture of constituents
  - Isolation (Σp_T of charged tracks within cone)
- LJ-building: cone-based clustering
- Require two LJs in event
  - Minimum $\Delta\varphi$ separation

- Use "Lepton-Jet Gun" MC tool to simulate detector response to

or

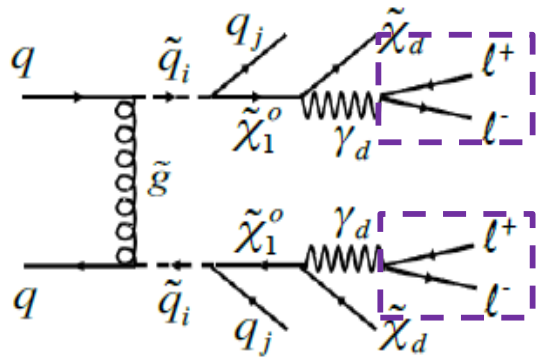


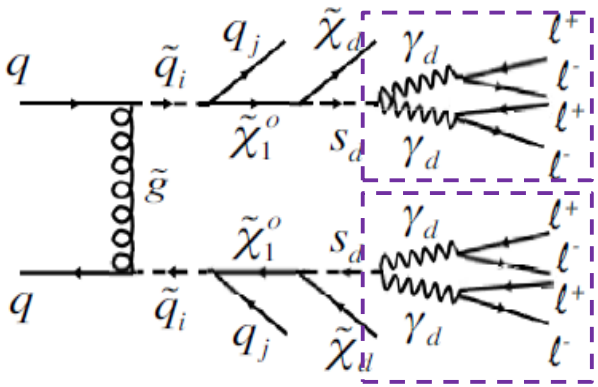
  - Model-independent trigger & reco efficiency for LJs as function of γ_d {$c\tau$, p_T}
  - Allows easy recasting

Low-Mass Searches: Strategy

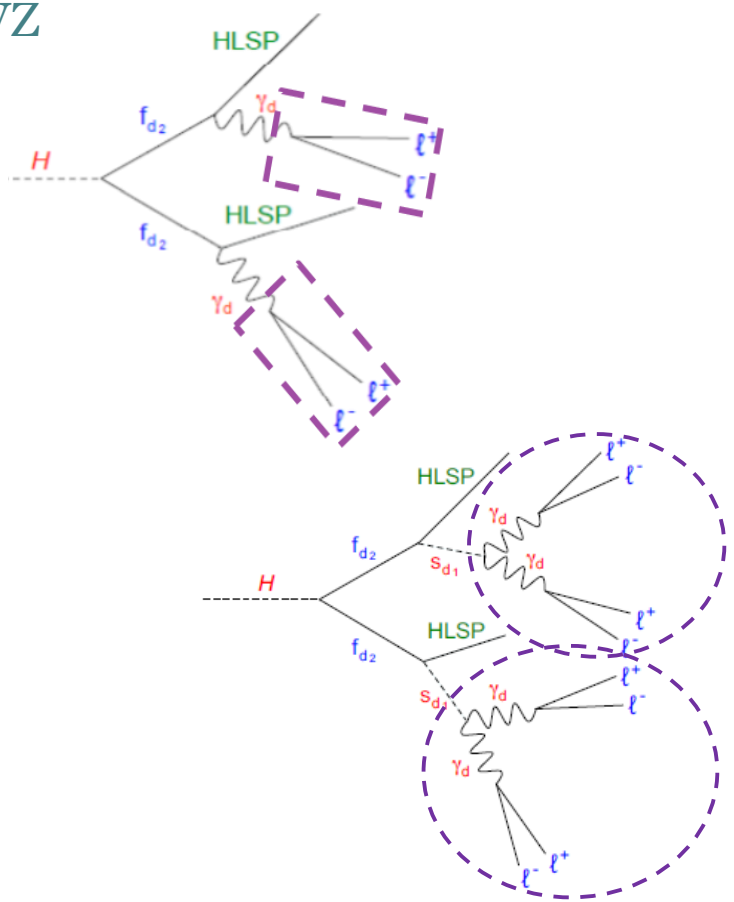
- Benchmark models for limit-setting:

Dark SUSY





FRVZ

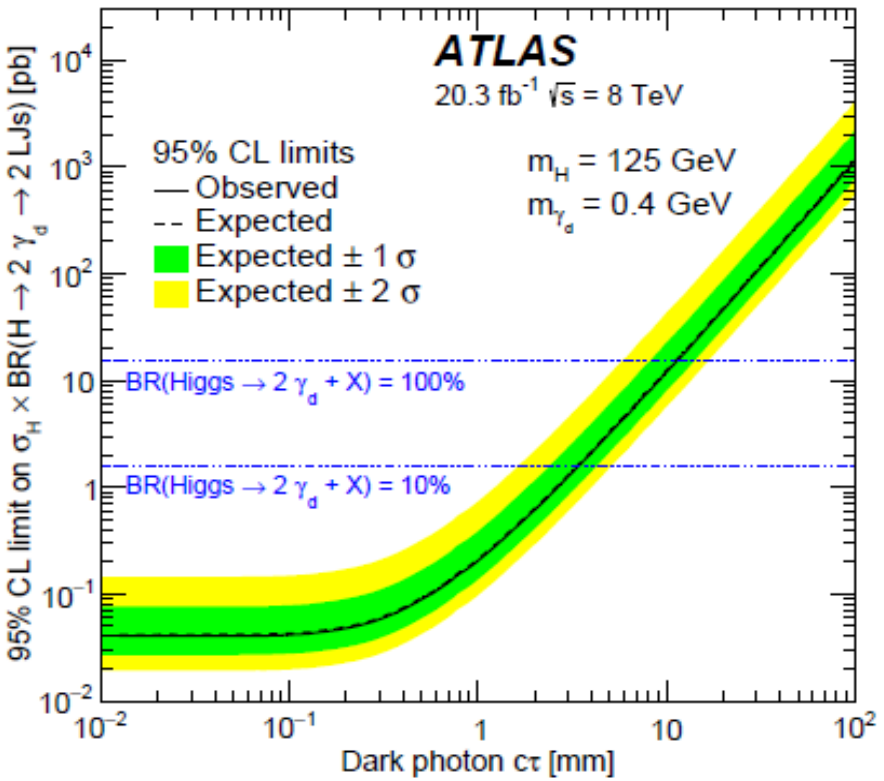


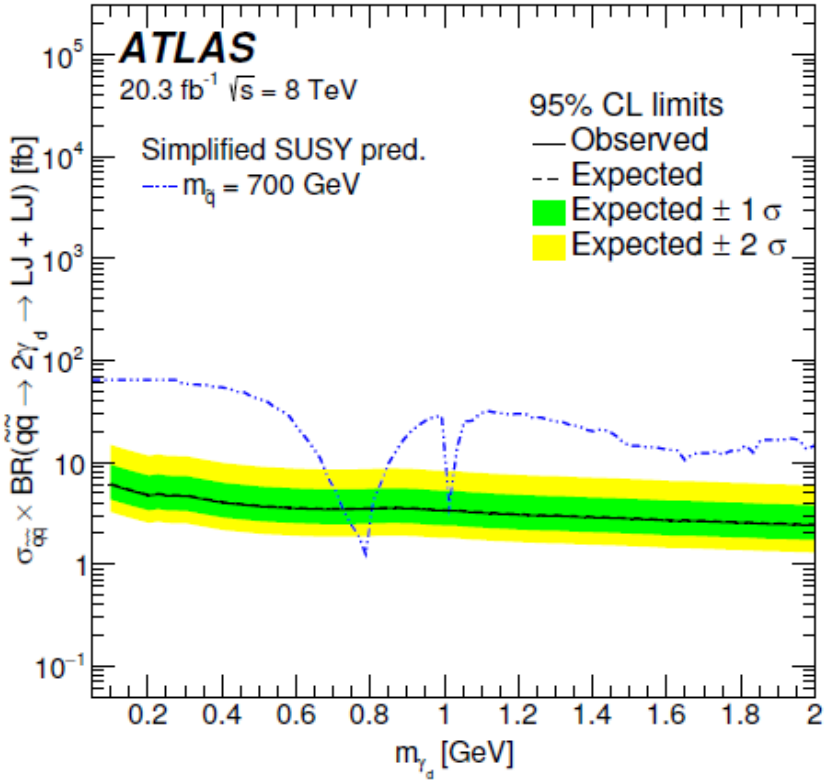
Low-Mass Searches: Prompt LJs

Run 1 Results

Run 1 (20.3 fb^{-1})
JHEP **62**, 02 (2016)

- Limits in Benchmark Models:





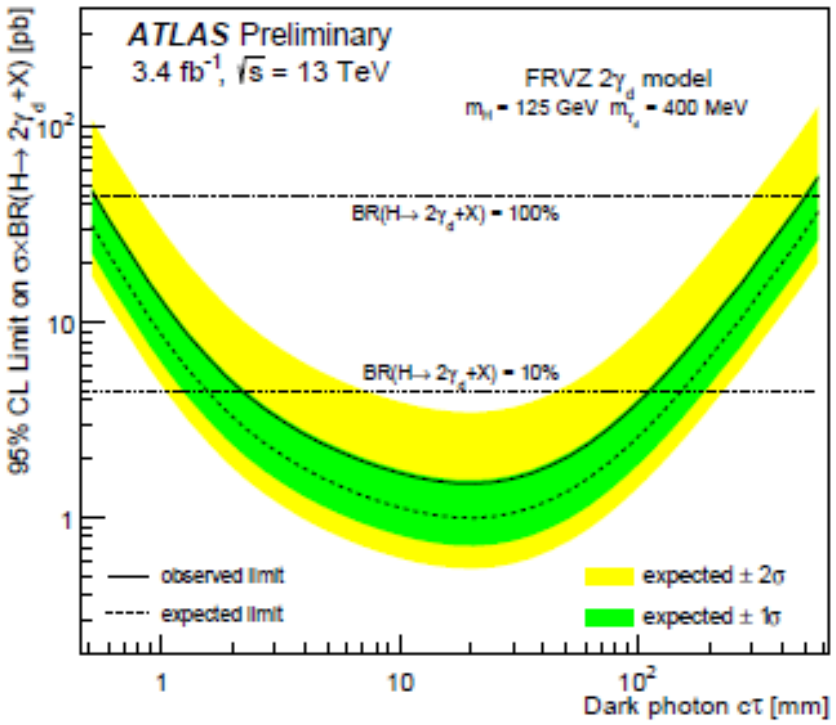
Low-Mass Searches: Displaced LJs

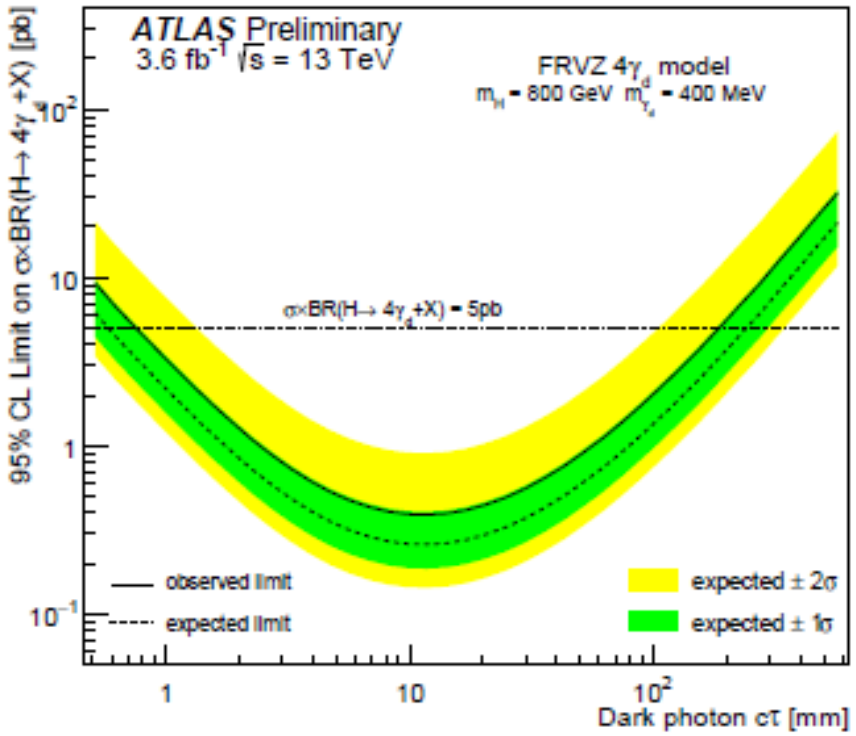
Run 1 (20.3 fb^{-1})
JHEP **11**, 088 (2014)

Run 2 (3.6 fb^{-1})
ATLAS-CONF-2016-042

Run 2 Results

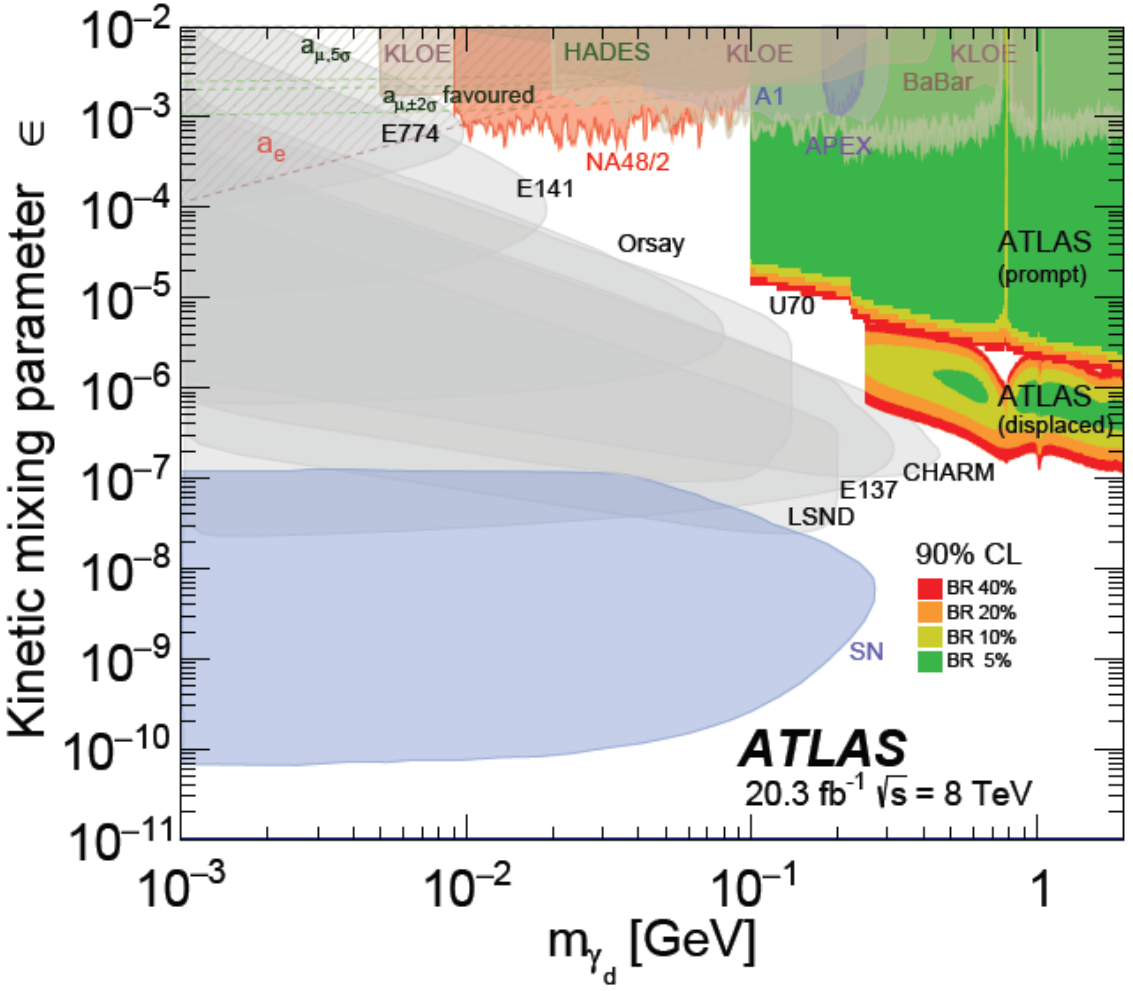
- Limits in Benchmark Models:





Low-Mass Searches: Combined Results

- ATLAS Displaced + Prompt provide complementary coverage in γ_d parameter space
- In regions other experiments unable to reach!
  - ATLAS limits have extra parameter (BR for h → hidden)



Higher-Mass Searches

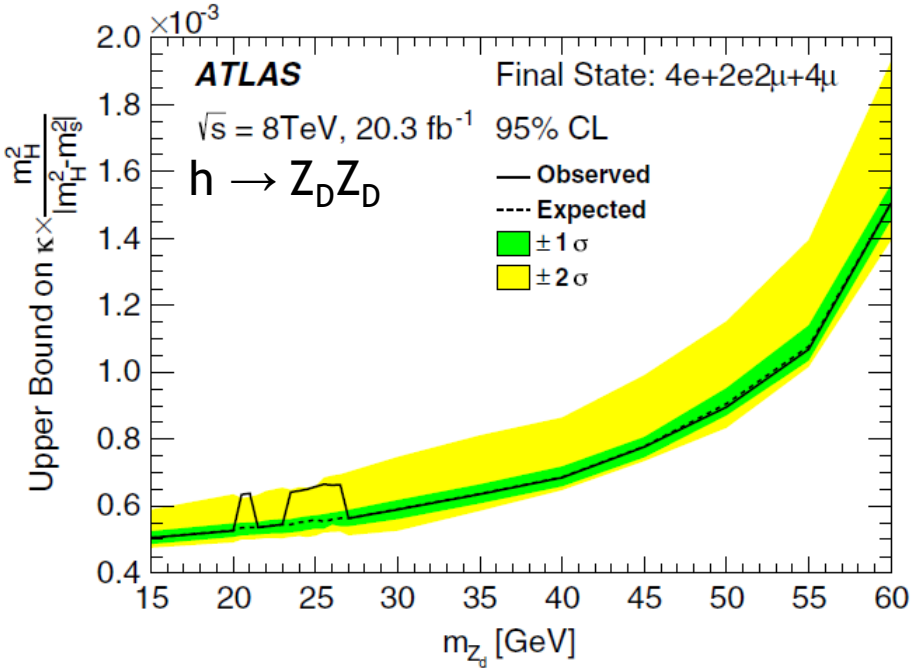
Run 1 (20.3 fb^{-1})
PhysRevD **92**, 001 (2015)

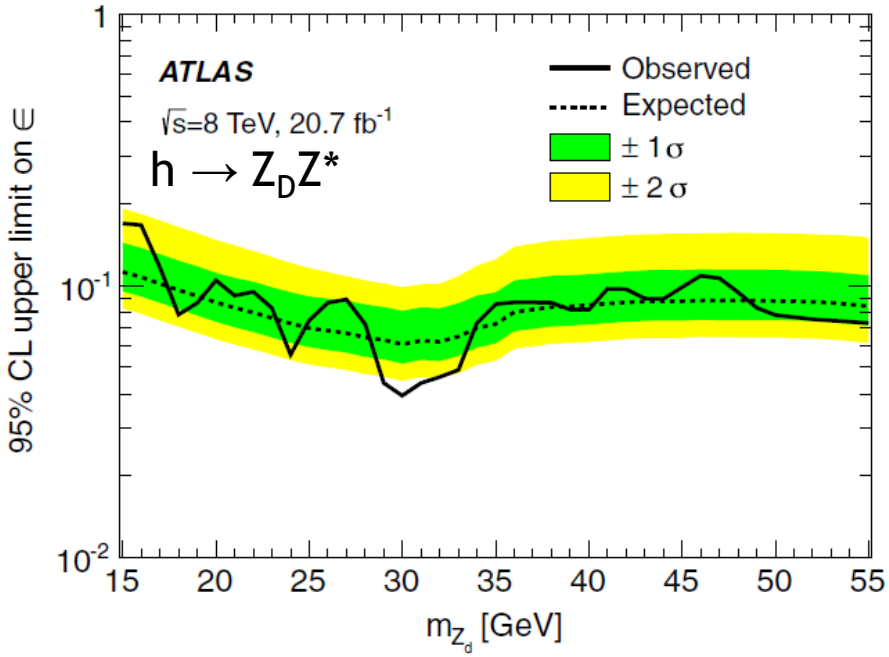
- Assume Z_D on-shell, from decay of 125 GeV Higgs → use invariant mass
- All same-flavor opposite-sign combinations of 4l final state
  - 4μ, 2μ2e, 4e channels
- Combination of various triggers
  - Single-electron, single-muon, di-electron, di-muon, electron+muon
- Overlap removal for close-together leptons
- Impact-parameter cuts reject cosmic-ray muons and non-prompt leptons

- **$h \rightarrow Z_D Z_D$** Higgs to 2 equal-mass intermediates
- **$h \rightarrow Z_D Z^*$** resonance in Z* mass spectrum

Higher-Mass Searches

Run 1 Results





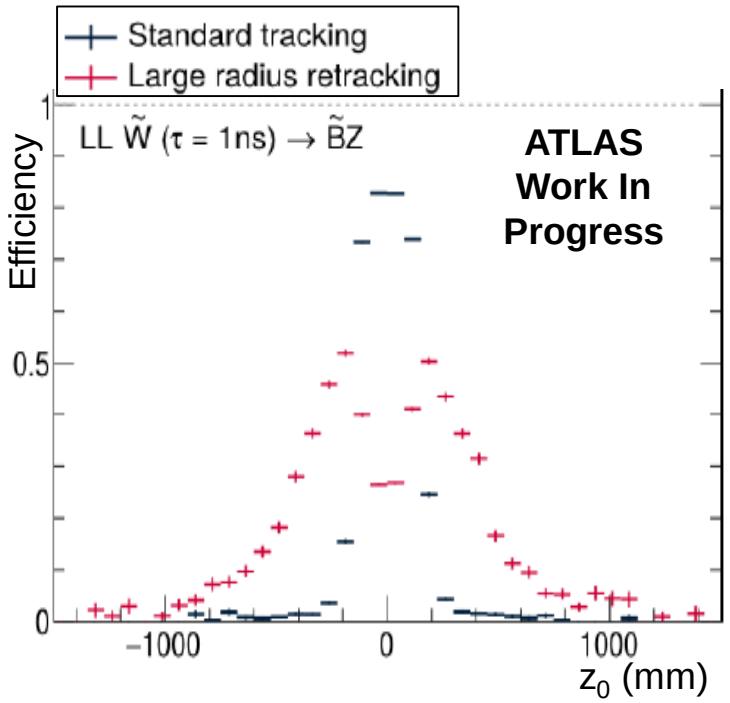
Also placed limits, as a function of m_{Z_D}, on:

- BR($h \rightarrow Z_D Z \rightarrow 4l$) / BR($h \rightarrow 4l$)
- BR($h \rightarrow Z_D Z \rightarrow 4l$) [using SM BR($h \rightarrow Z_D Z^*$)]
- $Z_D Z_D$ signal strength $\dfrac{\sigma \times BR(h \rightarrow Z_D Z_D \rightarrow 4l)}{[\sigma \times BR(h \rightarrow Z_D Z_D \rightarrow 4l)]_{SM}}$

Future Prospects: LJs

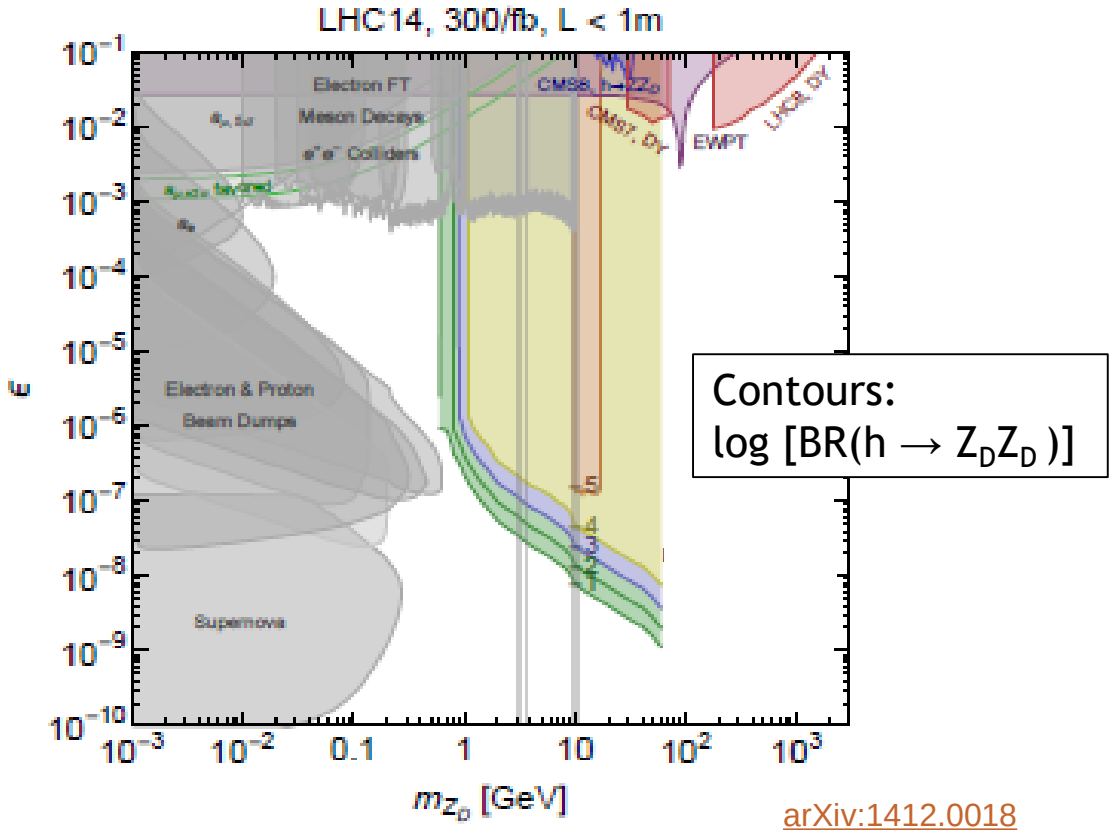
- Specialized reconstruction of displaced Inner Detector tracks: to address gap between Prompt and Displaced analyses, at lifetimes of tens of mm (partway through ID)
- Tricky because standard ATLAS ID tracking algorithms only reconstruct tracks pointing back to IP
- Large Radius Retracking project aims to recover displaced ID tracks:

Max	Standard ATLAS Tracking	Large-Radius Retracking
d_0	10 mm	300 mm
z_0	250 mm	1.50 m



Future Prospects: LJs

- New ATLAS "displaced non-collimated muons" analysis planned, extending $Z_D Z_D$ search to lower masses and merging with LJ analyses

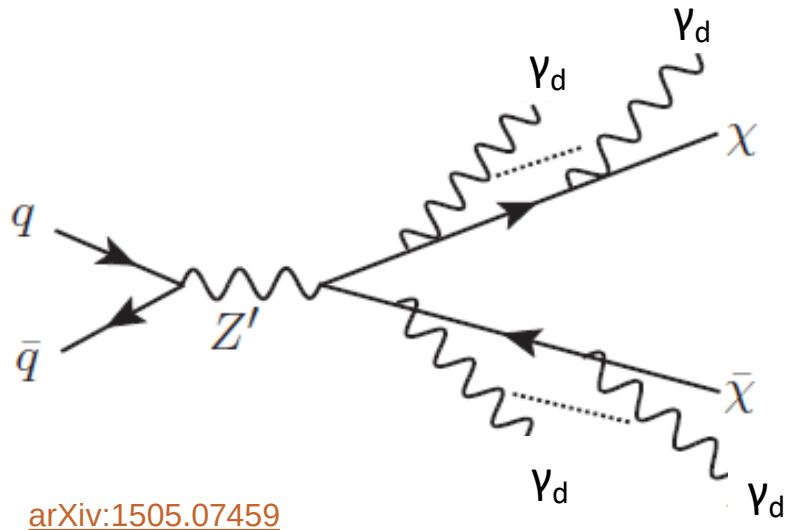


Contours:
log [BR(h → $Z_D Z_D$)]

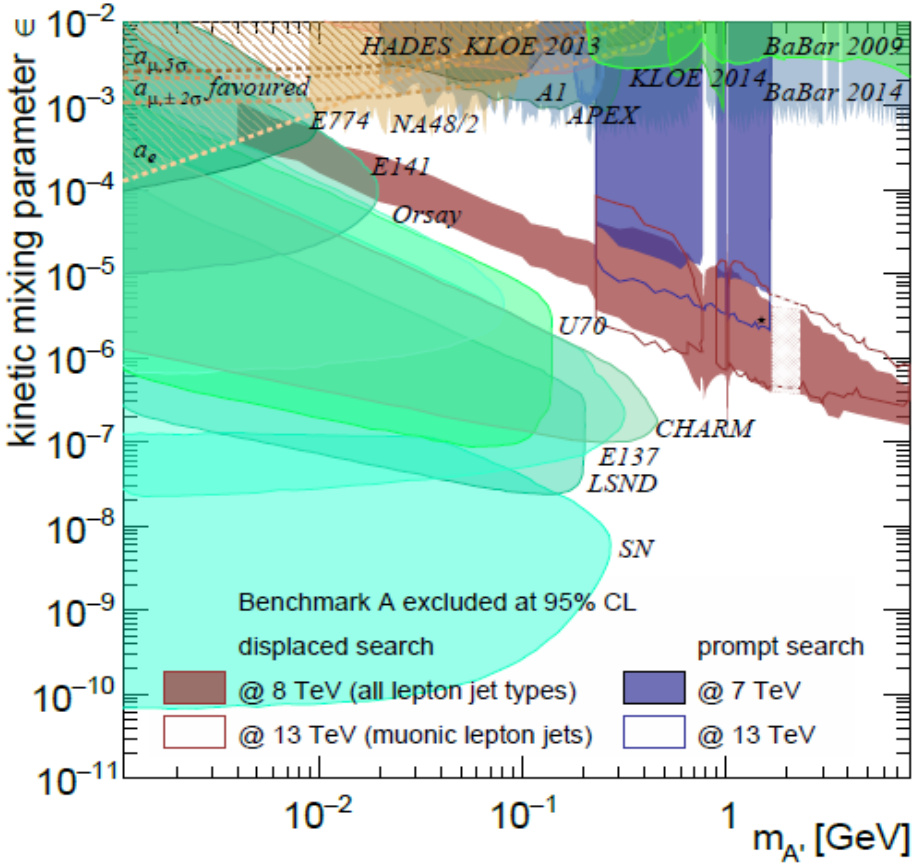
arXiv:1412.0018

Future Prospects: LJs

- Radiating DM: WIMP χ gives off copious γ_d's due to high α_D
- Phenomenologists used Pythia dark-showering + re-casting of ATLAS 7TeV Prompt and 8TeV Displaced results



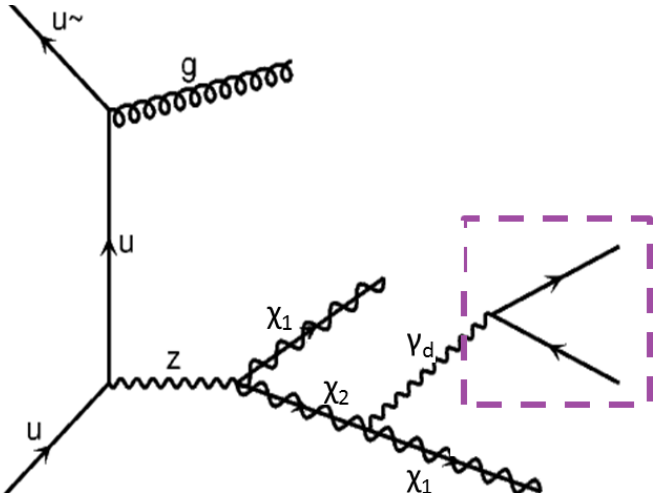
arXiv:1505.07459

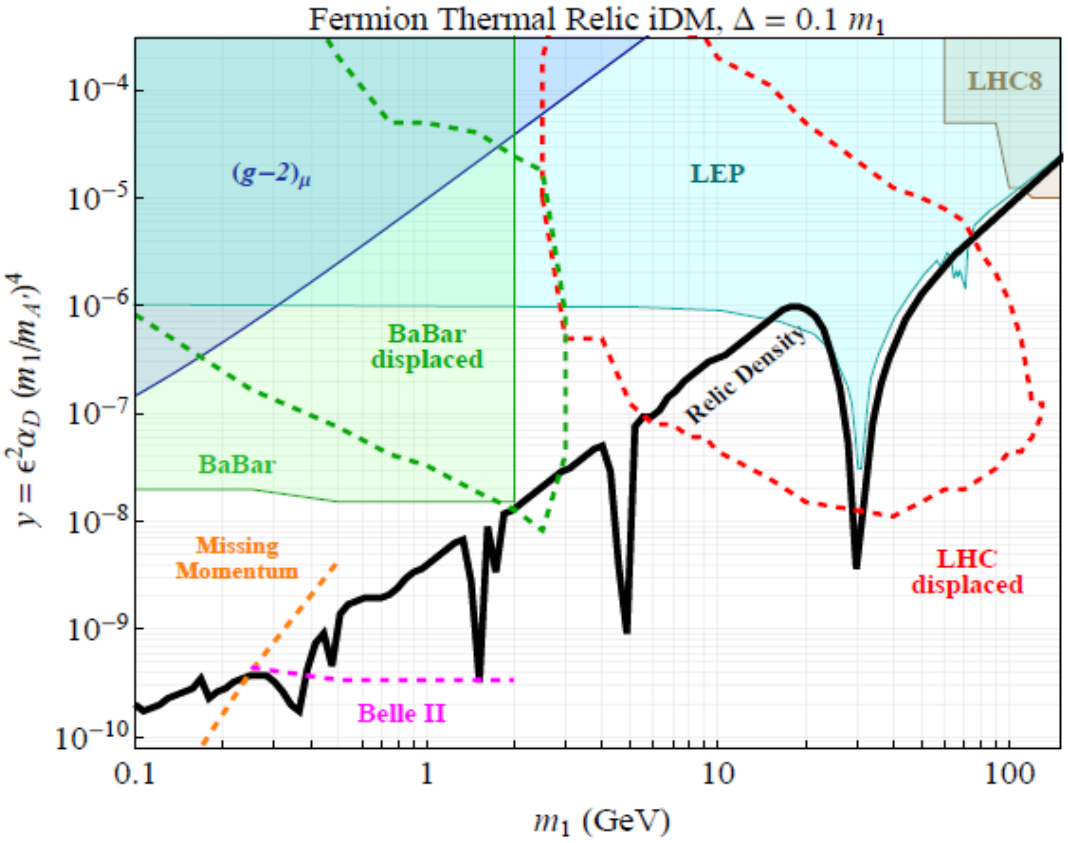


Work with phenomenologists for improved limits at 13TeV?

Future Prospects: LJs

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



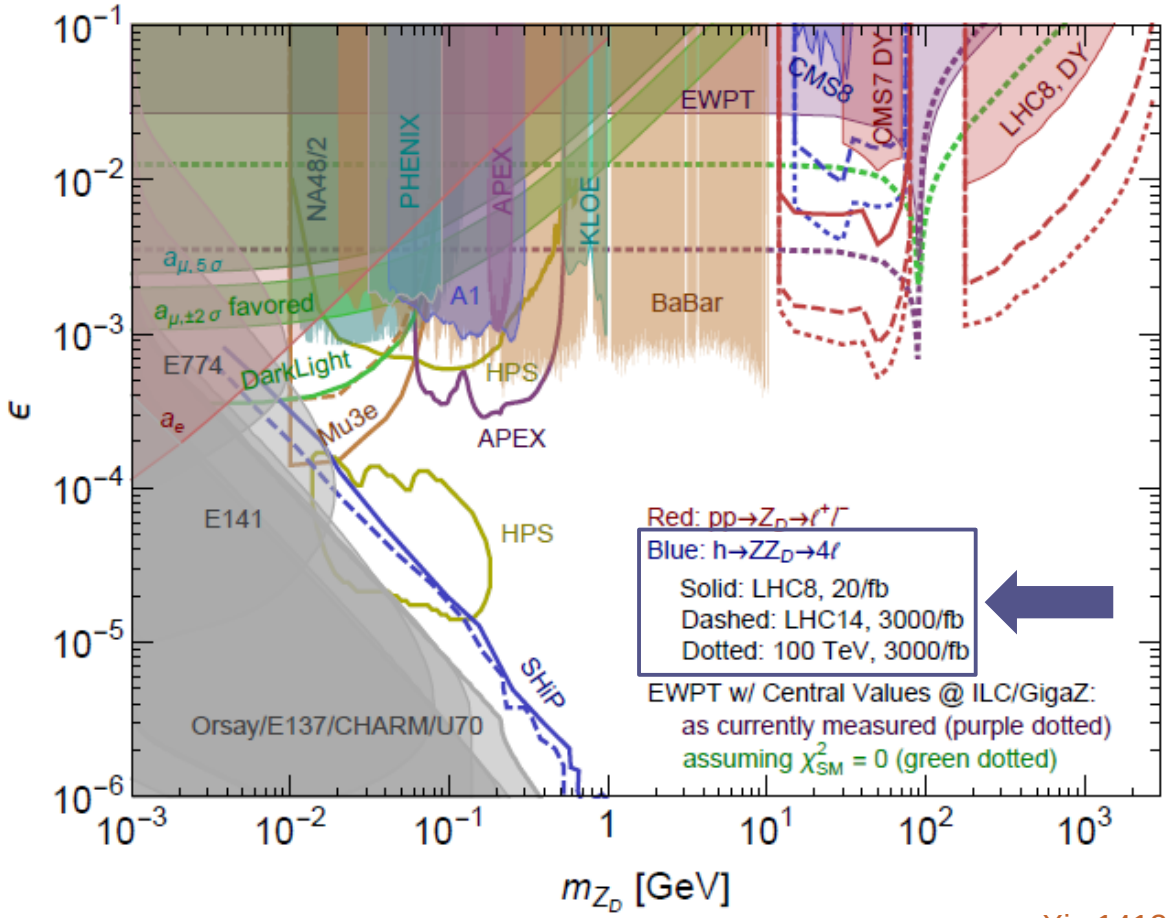


Challenging: only one LJ in final state!

arXiv:1508.03050

Future Prospects: Higher-Mass

- $h \rightarrow Z_D Z^*$ will soon begin to encroach on open parameter space

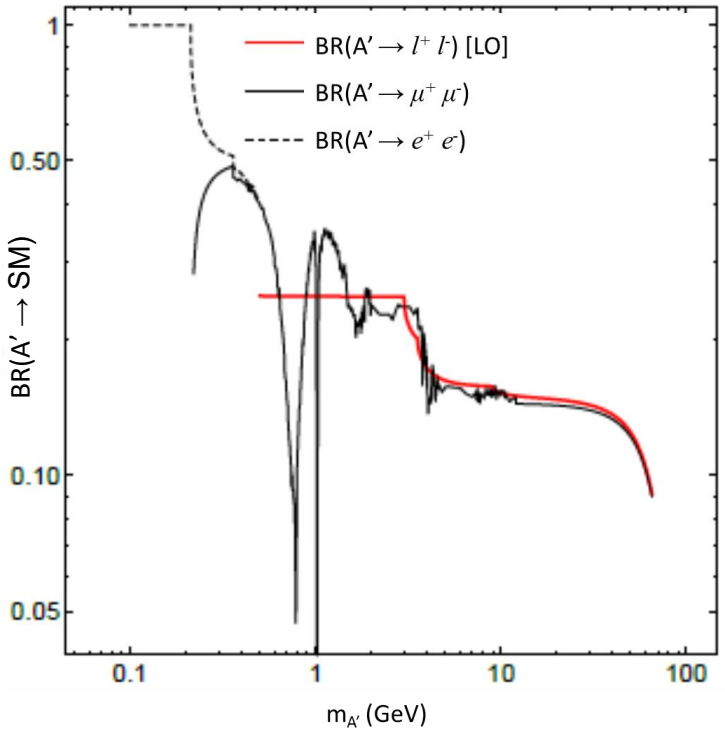


arXiv:1412.0018

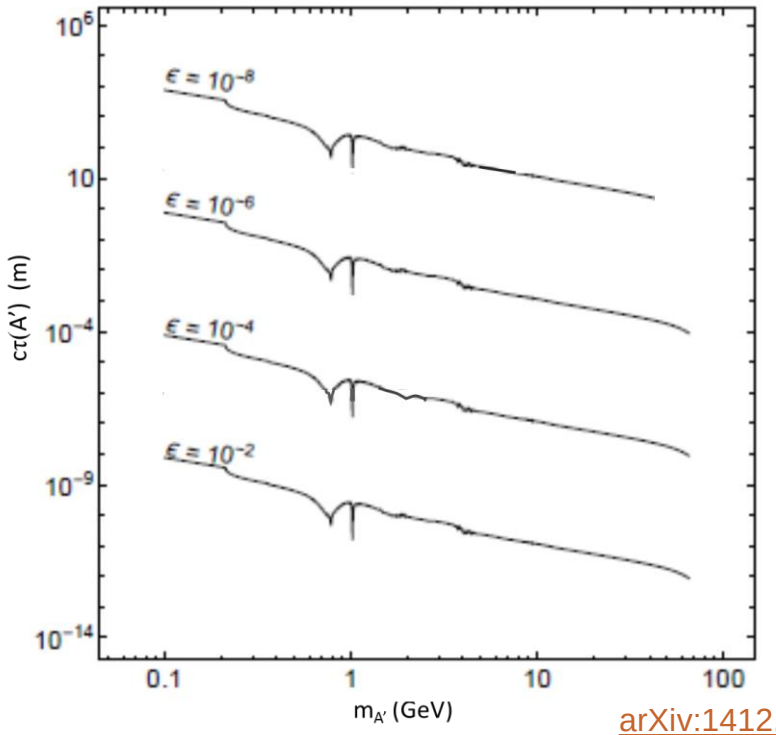
BACKUP

Branching Ratios & Lifetimes

- Final-state dilepton signatures: promising search prospects if A' decays back to SM with sizeable BR
  - Assume A' lowest-mass dark state
  - BRs vary with mass

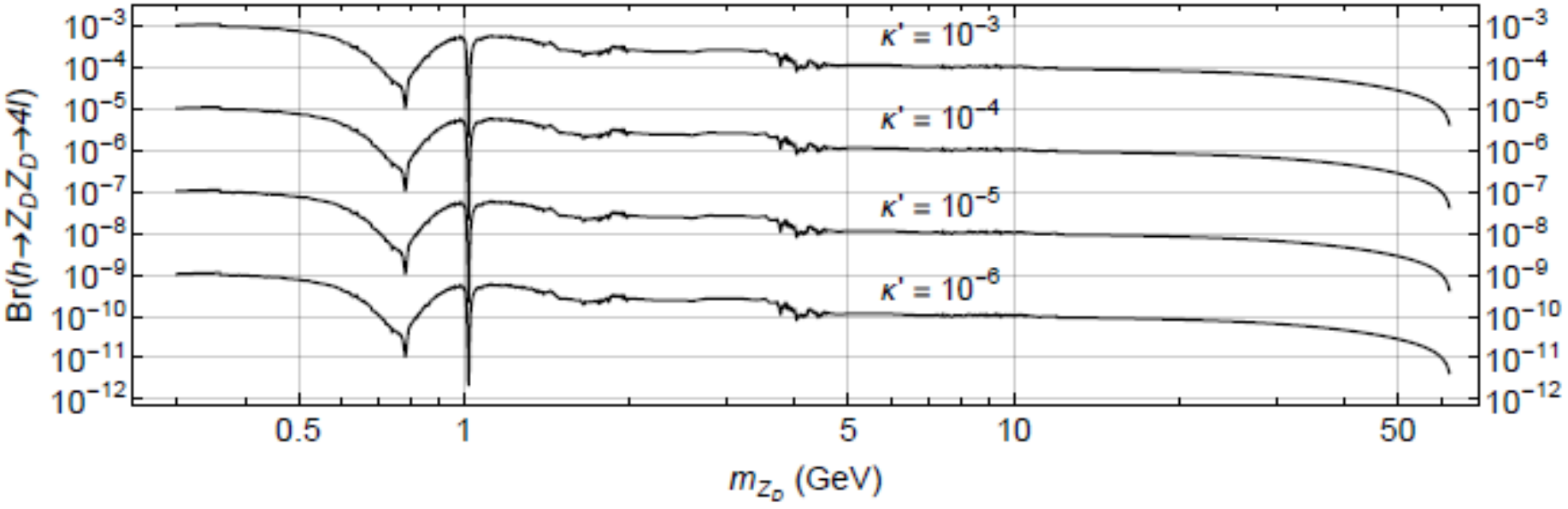


Lifetime varies with mass, ε



arXiv:1412.0018

Branching Ratios



$$\Gamma(Z_D \to \bar{f} f) = \frac{N_c}{24\pi m_{Z_D}} \sqrt{1 - \frac{4m_f^2}{m_{Z_D}^2}} \left(m_{Z_D}^2 \left(g_L^2 + g_R^2 \right) - m_f^2 \left(-6 g_L g_R + g_L^2 + g_R^2 \right) \right)$$

$$g_{Z_D f \bar{f}} \equiv \frac{g}{\cos\theta} \left(-\sin\alpha \left(t^3 \cos^2\theta - Y \sin^2\theta \right) + \eta \cos\alpha \sin\theta \, Y \right)$$

$$\Gamma(h \to Z_D Z_D) = \kappa'^2 \frac{1}{32\pi} \frac{v^2}{m_h} \sqrt{1 - \frac{4m_{Z_D}^2}{m_h^2}} \frac{(m_h^2 + 2m_{Z_D}^2)^2 - 8(m_h^2 - m_{Z_D}^2) m_{Z_D}^2}{m_h^4}$$

$$\kappa' = \kappa \frac{m_h^2}{|m_h^2 - m_s^2|}$$

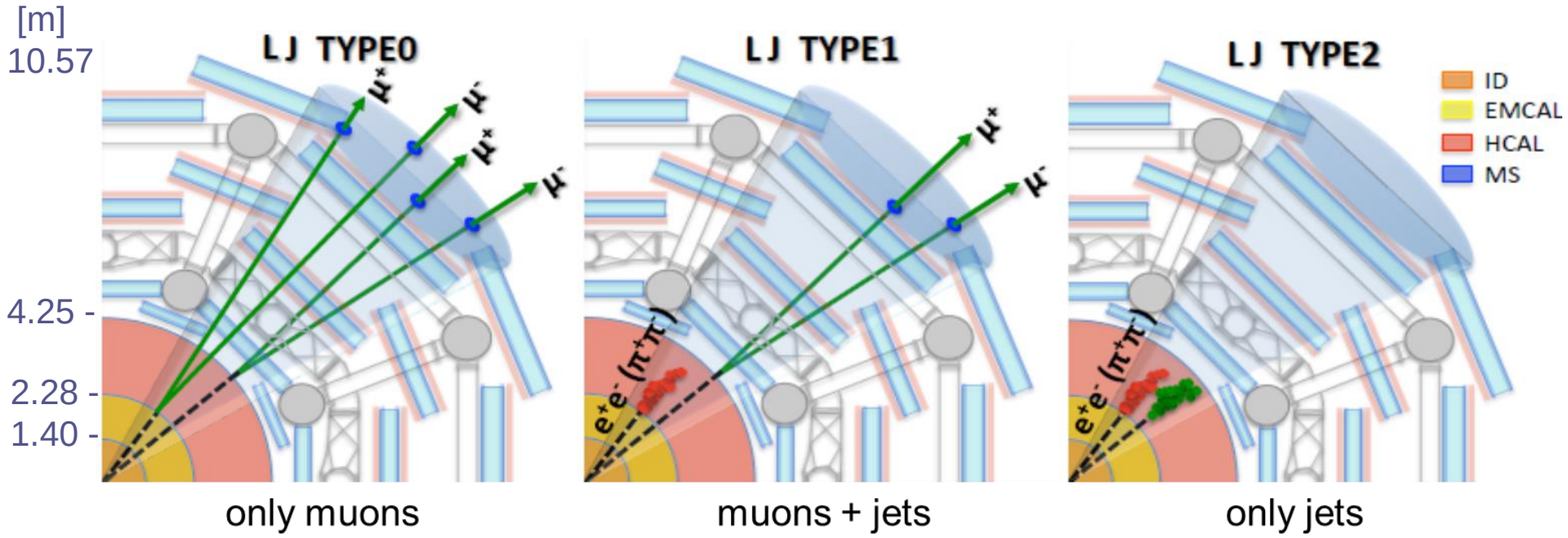
Low-Mass Searches: Displaced LJs

Run 1 (20.3 fb^{-1})
JHEP **11**, 088 (2014)

Run 2 (3.6 fb^{-1})
ATLAS-CONF-2016-042

Targets long-lived γ_d decays

- Decay volume: beyond pixel detector, out to muon spectrometer (MS)
- LJ consists of at least one muon and/or electron pair in cone
  - Muon pairs: MS tracks with no corresponding ID tracks
  - Electron pairs: appear as jets in calorimeters



Low-Mass Searches: Displaced LJs

Triggers:

- 3 MS tracks without ID tracks
- 2 close-together MS tracks without ID tracks

  (NEW IN RUN 2: ~3x gain in trigger efficiency)
- Jet with low fraction of energy deposition in EM calorimeter

Efficiency (in %)				
Trigger	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 800$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 800$ GeV
Tri-muon MS-only	2.0	2.4	4.9	7.8
Narrow-Scan	10.6	23.0	8.3	38.4
CalRatio	0.3	9.7	0.1	7.4
OR of all	11.9	32.0	11.8	44.8

Main backgrounds:

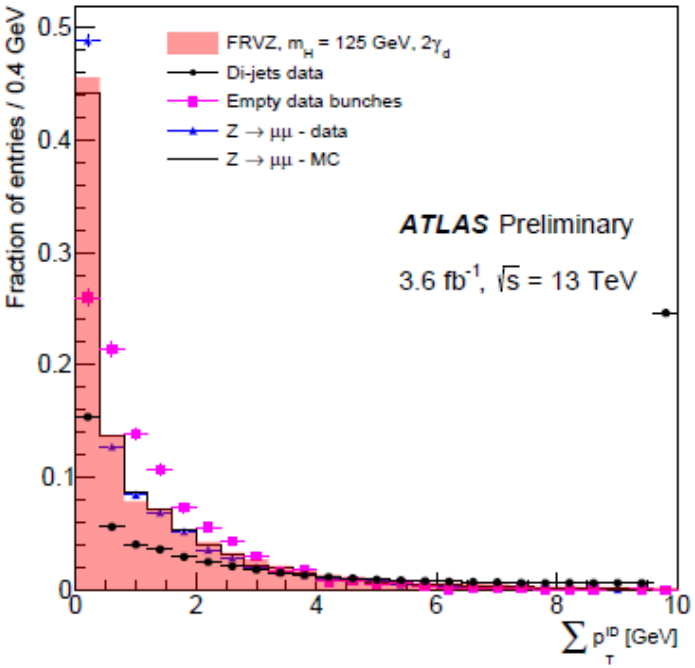
- QCD multijet
- Cosmic-ray muons
- Beam-Induced Backgrounds (BIB) (NEW IN RUN 2: dedicated BIB tagging)

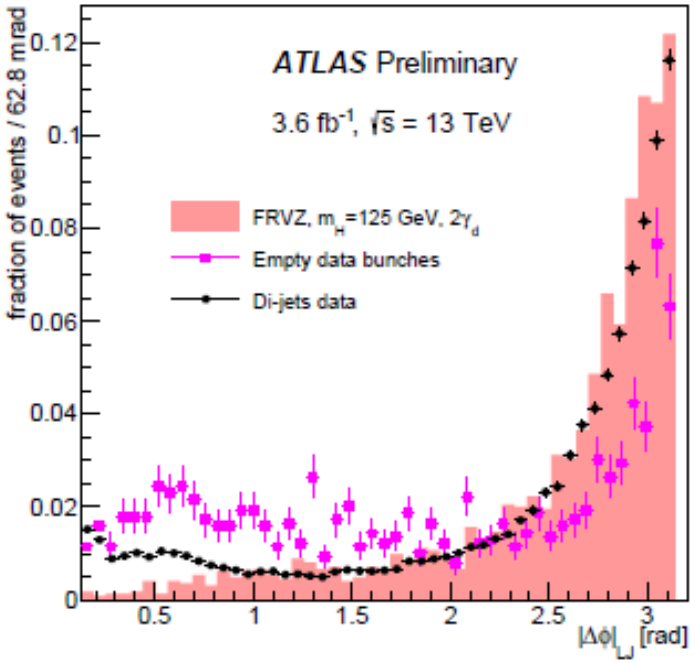
Low-Mass Searches: Displaced LJs

- Requirements on LJ constituents:
  - Muon impact parameters
  - Jet timing & width
  - EMcal/Hcal energy deposition
  - Veto on prompt muons & BIB

Build LJs

- Event-level selection:
  - ≥2 LJs
  - ID track isolation ($\sum p_T$ of ID tracks within cone of each LJ)
  - $|\Delta\varphi|$ between LJs

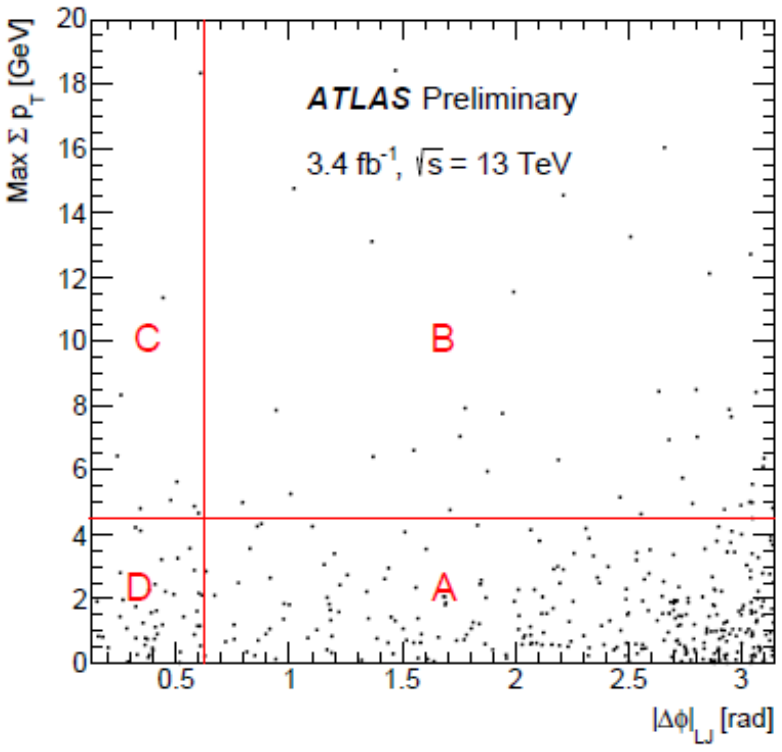




Low-Mass Searches: Displaced LJs

- Likelihood-based method to minimize Cosmics and QCD bg in signal region A, using control regions B, C, D
  - Two uncorrelated variables
  - Simultaneous data-driven bg estimation & signal hypothesis test
  - Also yields estimate of residual bg contamination in signal region
- Systematic uncertainties:

Luminosity	2.1%
Trigger: Narrow Scan	6.0%
Trigger: Tri-muon-MS-only	5.8%
Trigger: CalRatio	11.0%
Reconstruction efficiency of single γ_d	15.0%
Effect of pile-up on Σp_T^{ID}	5.1%
Reconstruction of the p_T of the γ_d	10.0%

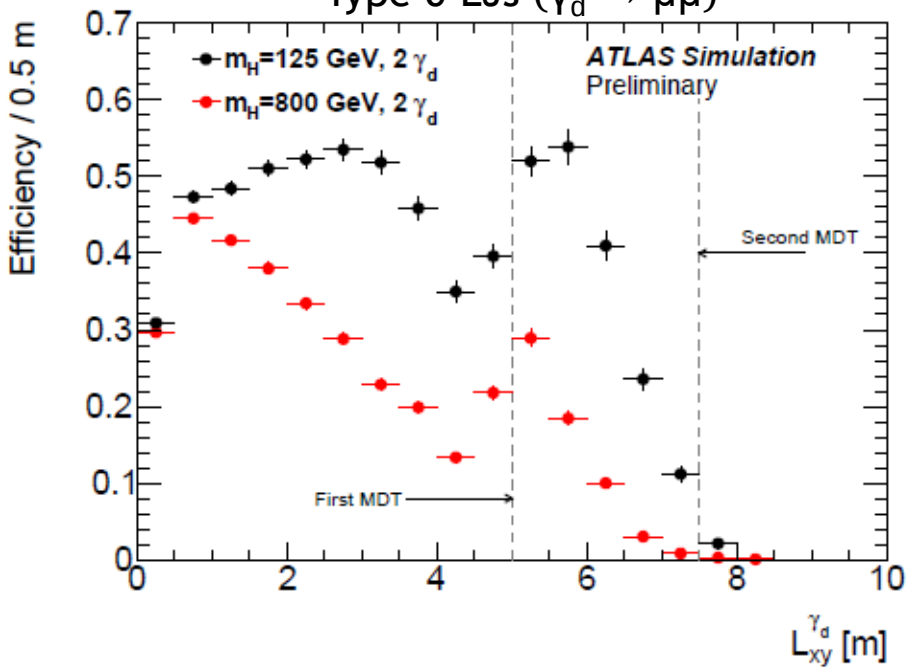


Low-Mass Searches: Displaced LJs

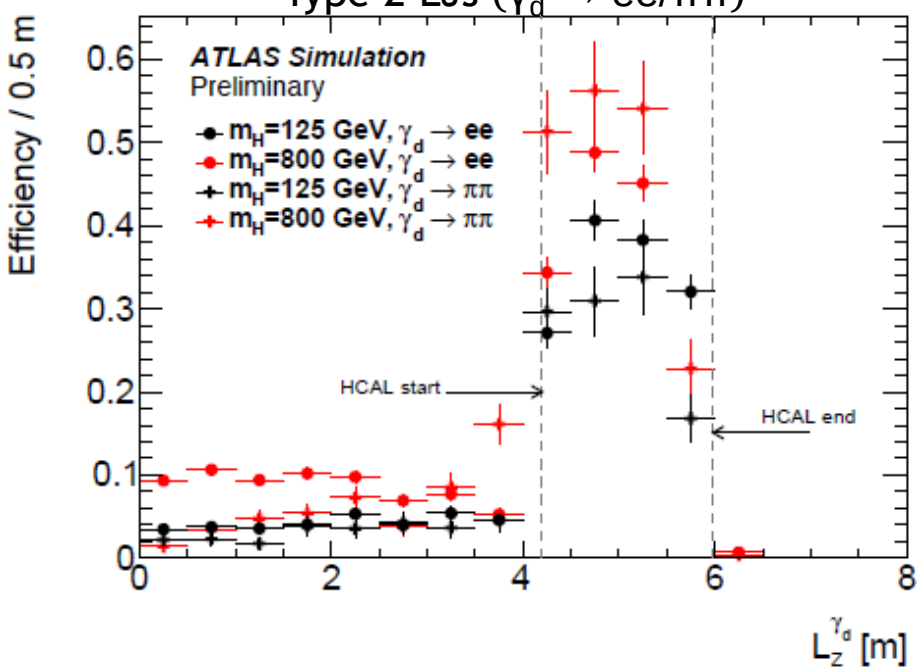
Run 2 Results

- Efficiency x Acceptance (also available in recasting-friendly table form)
  - m_H = 800 GeV: BSM extra Higgs at start of decay chain?

Type 0 LJs ($\gamma_d \rightarrow \mu\mu$)



Type 2 LJs ($\gamma_d \rightarrow ee/\pi\pi$)



Low-Mass Searches: Displaced LJs

Run 2 Results

- (Fairly) Model-Independent:

Category	Observed events	Expected background
All channels	285	231 ± 12 (stat) ± 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) ± 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) ± 65(syst)

  - Type2: Electron/pion LJs (higher backgrounds than muon LJs)

- No signal seen above expected background, so set limits in Benchmark Models:

FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow 2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow 4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow 2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow 4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$

Low-Mass Searches: Prompt LJs

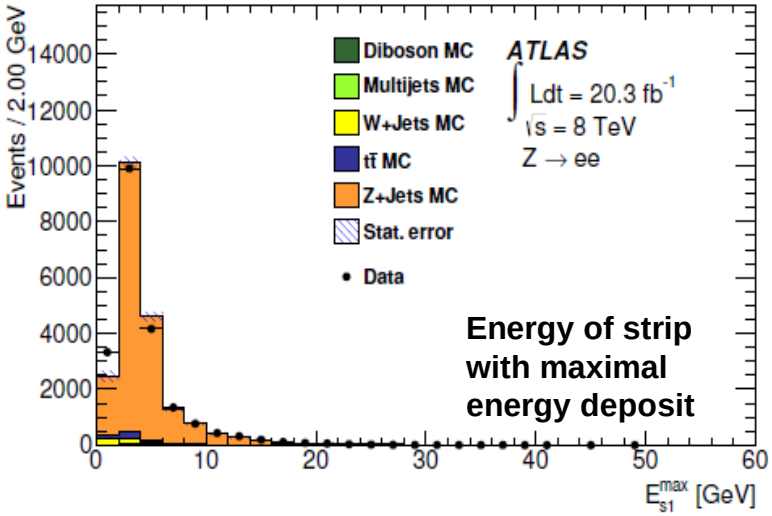
Triggers: single-electron, di-EM, single-muon, di-muon

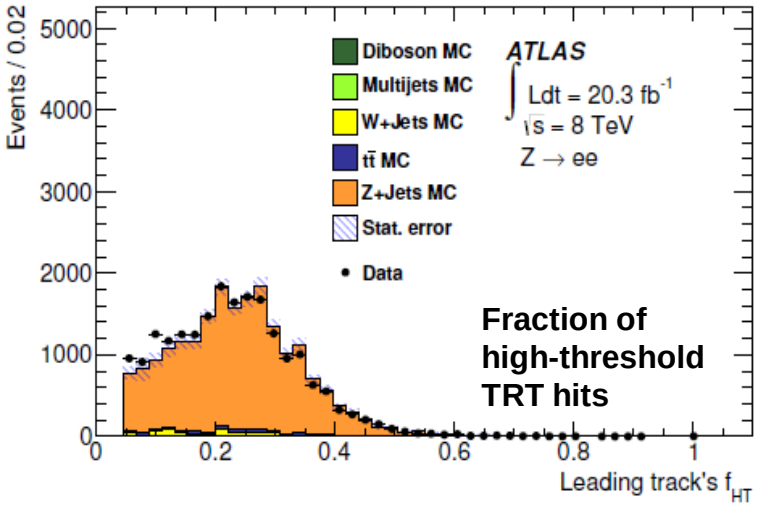
Main backgrounds: QCD multijet

- More problematic than in Displaced case

LJ constituents selection:

- Calorimeter isolation
- Jet EM fraction
- EM Calorimeter hit properties and hadronic leakage
- Transition Radiation Tracker hit properties



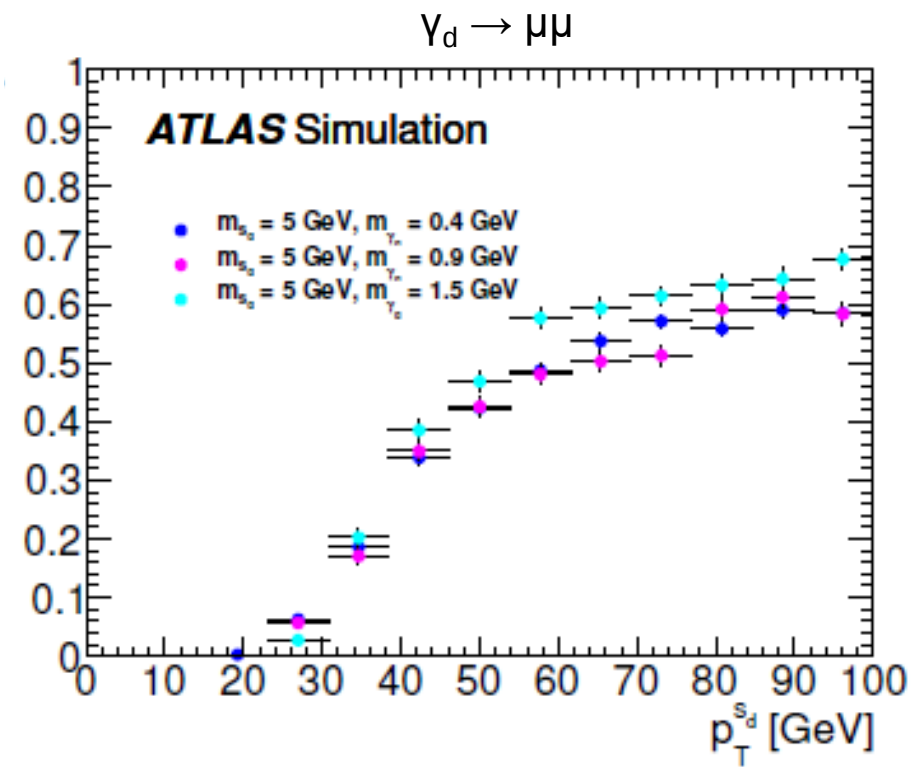


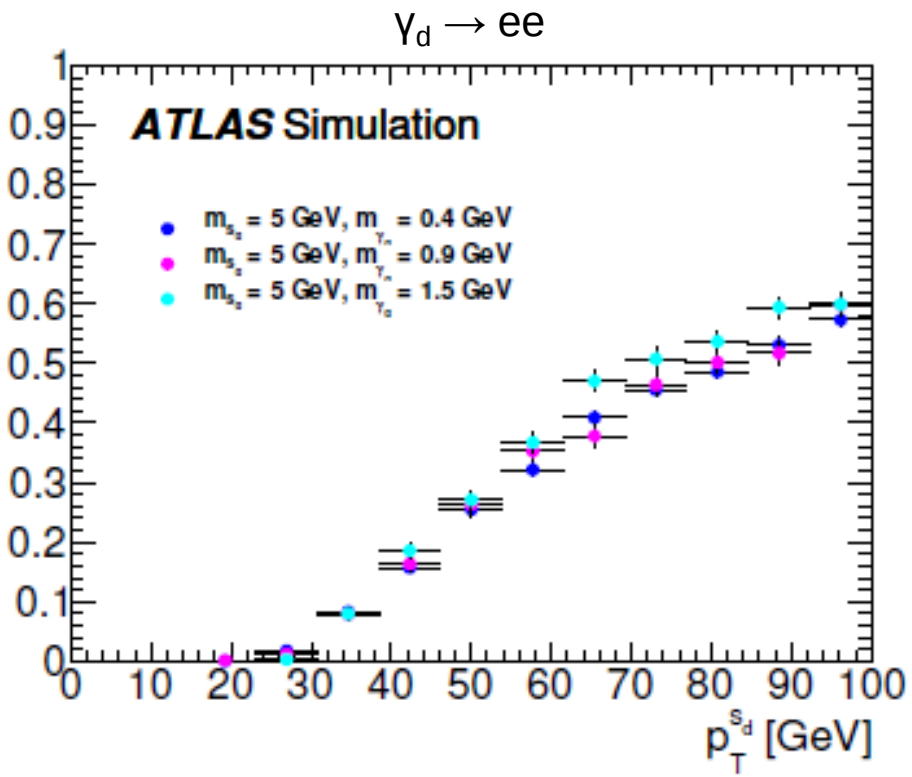
Run 1 (20.3 fb^{-1})
JHEP **62**, 02 (2016)

Low-Mass Searches: Prompt LJs

Run 1 Results

- Efficiency x Acceptance (also available in recasting-friendly table form):





Low-Mass Searches: Prompt LJs

Run 1 Results

- (Fairly) Model-Independent:

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

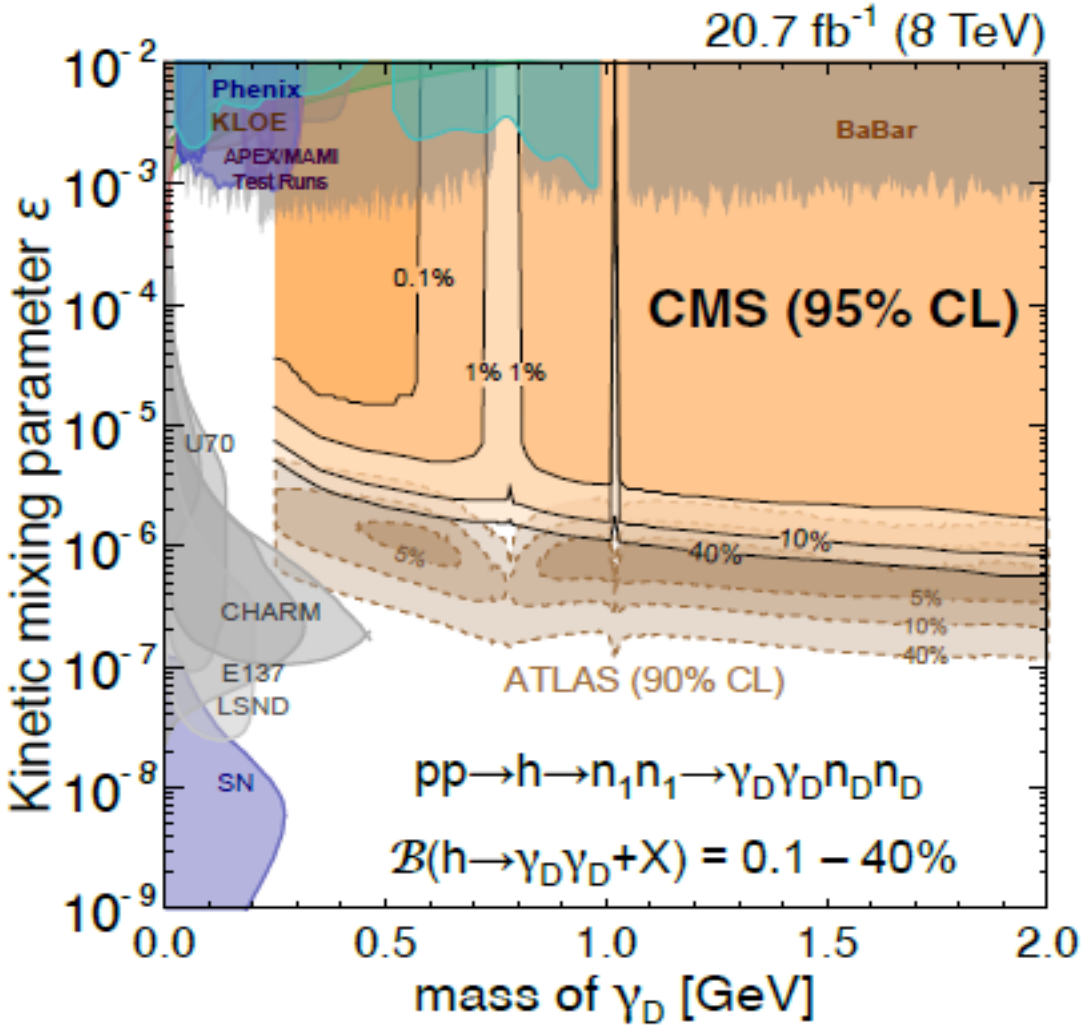
- No signal seen above expected background, so set limits in Benchmarks:

SUSY (m_q = 700 GeV) ($m_{\gamma d}$ = 0.4 GeV)	$2\gamma_d$ + X # Events		$2(s \rightarrow \gamma_d\gamma_d)$ + X #Events	
	Obs.	Exp.	Obs.	Exp.
eLJ-eLJ	8.4	6.6	9.0	7.1
muLJ-muLJ	5.9	6.5	6.3	6.9
eLJ-muLJ	3.9	8.0	4.1	8.6
eLJ-emuLJ	--	--	7.3	11.7
muLJ-emuLJ	--	--	8.8	16.5
emuLJ-emuLJ	--	--	2.9	5.1

FRVZ (m_h = 125GeV) ($m_{\gamma d}$ = 0.4 GeV)	$2\gamma_d$ + X # Events		$2(s \rightarrow \gamma_d\gamma_d)$ + X #Events	
	Obs.	Exp.	Obs.	Exp.
eLJ-eLJ	8.5	6.7	8.5	6.7
muLJ-muLJ	5.9	6.5	6.5	7.0
eLJ-muLJ	3.9	8.1	4.5	9.2
eLJ-emuLJ	--	--	5.9	9.7
muLJ-emuLJ	--	--	11.5	20.8
emuLJ-emuLJ	--	--	3.9	6.1

Low-Mass Searches: Combined Results

- ATLAS Displaced + CMS provide complementary coverage in γ_d parameter space
- In regions other experiments unable to reach!
  - ATLAS & CMS limits have extra parameter (BR for $h \rightarrow$ hidden)



arXiv:1506.00424

Low-Mass Searches: Muonic LJs (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:

Requirement	Description
4 offline muon candidates	Particle Flow algorithm
Muon p_T , $\|\eta\|$	$p_T > 8$GeV, $\|\eta\| < 2.4$
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

Low-Mass Searches: Muonic LJs (CMS)

Run 1 Results

(Fairly) Model-Independent 95% CL:

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

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

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

α = kinematic & geometrical acceptance

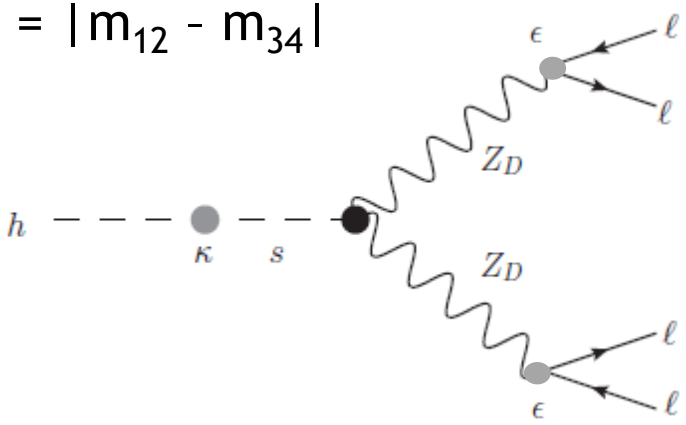
ε = selection efficiency

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

Higher-Mass Searches

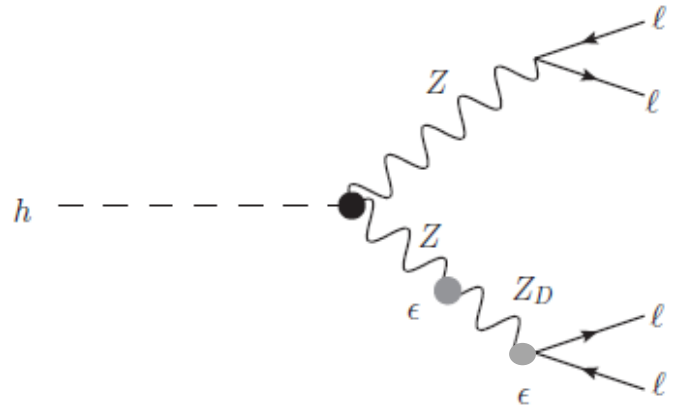
$h \rightarrow Z_D Z_D$:

- Lepton quadruplet selected by minimizing $\Delta m = |m_{12} - m_{34}|$
- Sensitivity to κ, ε
- Main backgrounds: ZZ*
- Invariant mass cuts:
  - m_{4l} , $|m_{pair1} - m_z|$
  - m_{pair2} within δm of hypothesized m_{Z_D}



$h \rightarrow Z_D Z^*$:

- For Z* mass spectrum, use opposite-sign same-flavor l pair closest to m_z
- Sensitivity to ε
- Main backgrounds: ZZ*, Z+jets, $t\bar{t}$
- Invariant mass cuts: m_{4l} , m_{12} , m_{34}



Higher-Mass Searches

Run 1

- Invariant mass distributions for data and expected backgrounds: