Exotic Prompt and Non-Prompt Leptonic Decays as a Window to the Dark Sector with ATLAS

SUSY 2016, Melbourne

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… or, using the Dark Side of the Force

Outline

- Search Motivations
- Search Strategies
- Low-mass ("Dark γ") Searches
  - Challenges and Analysis Handles
  - Displaced Lepton-Jets Analysis (Run 1 results + Run 2 preliminaries)
  - Prompt Lepton-Jets Analysis (Run 1 results)
- Higher-mass ("Dark Z") Searches
  - Challenges and Analysis Handles
  - $h \rightarrow Z_D Z^*$ Analysis (Run 1 results)
  - $h \rightarrow Z_D Z_D$ Analysis (Run 1 results)
- Potential Future Extensions

All results referenced here are available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Dark Boson 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

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

My convention :
γ_d low-mass
Z_D higher-mass

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

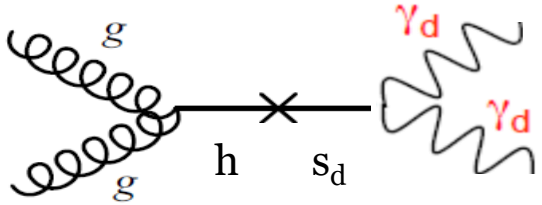
$$\mathcal{L} \supset (A\varphi + \lambda\varphi^2)H^\dagger H$$

Higgs mixing parameter

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

  - Trilinear term induces mixing after EWSB

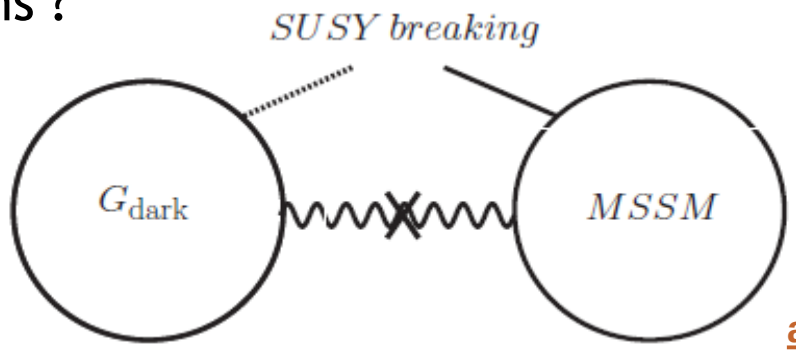
- Hidden Abelian Higgs: Higgs Portal + dark boson



Dark Boson Search Motivations

- "Hidden Valley": dark boson our best candidate for collider detection amongst hidden zoo?
  - High dark boson multiplicity in long decay chains?
- Dark matter models
  - Inelastic Dark Matter
  - Radiating Dark Matter

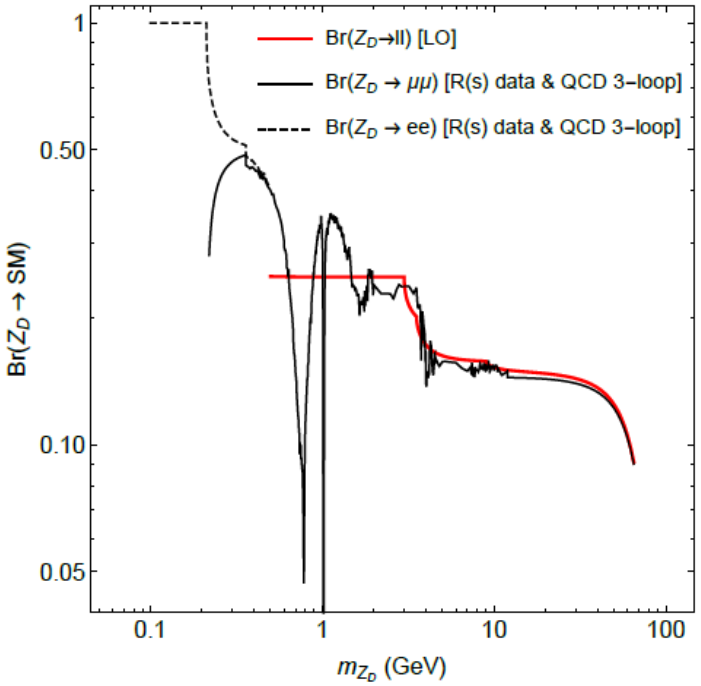
  … etc
- Dark boson as mediator between dark gauge group and (N)MSSM ?
  - "Standard" production of superpartners @LHC → dark sector → dark bosons ?

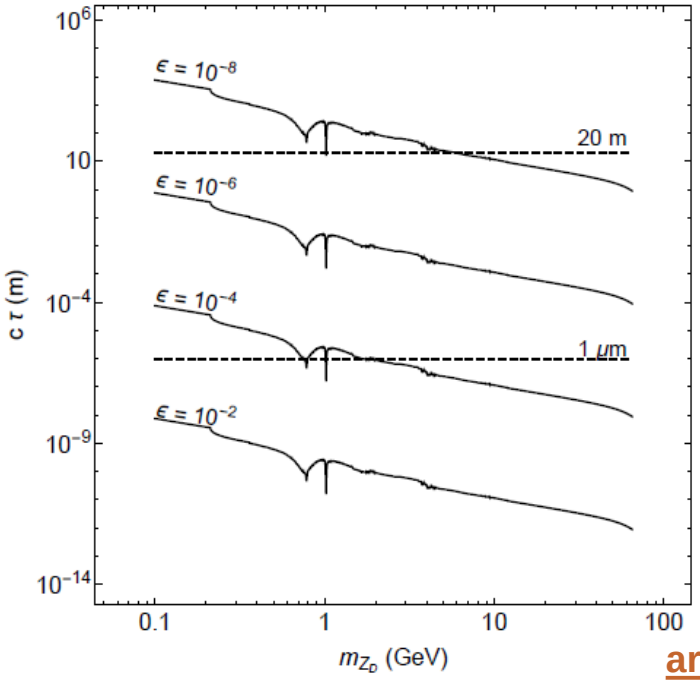


arXiv:0810.0714

Search Strategies

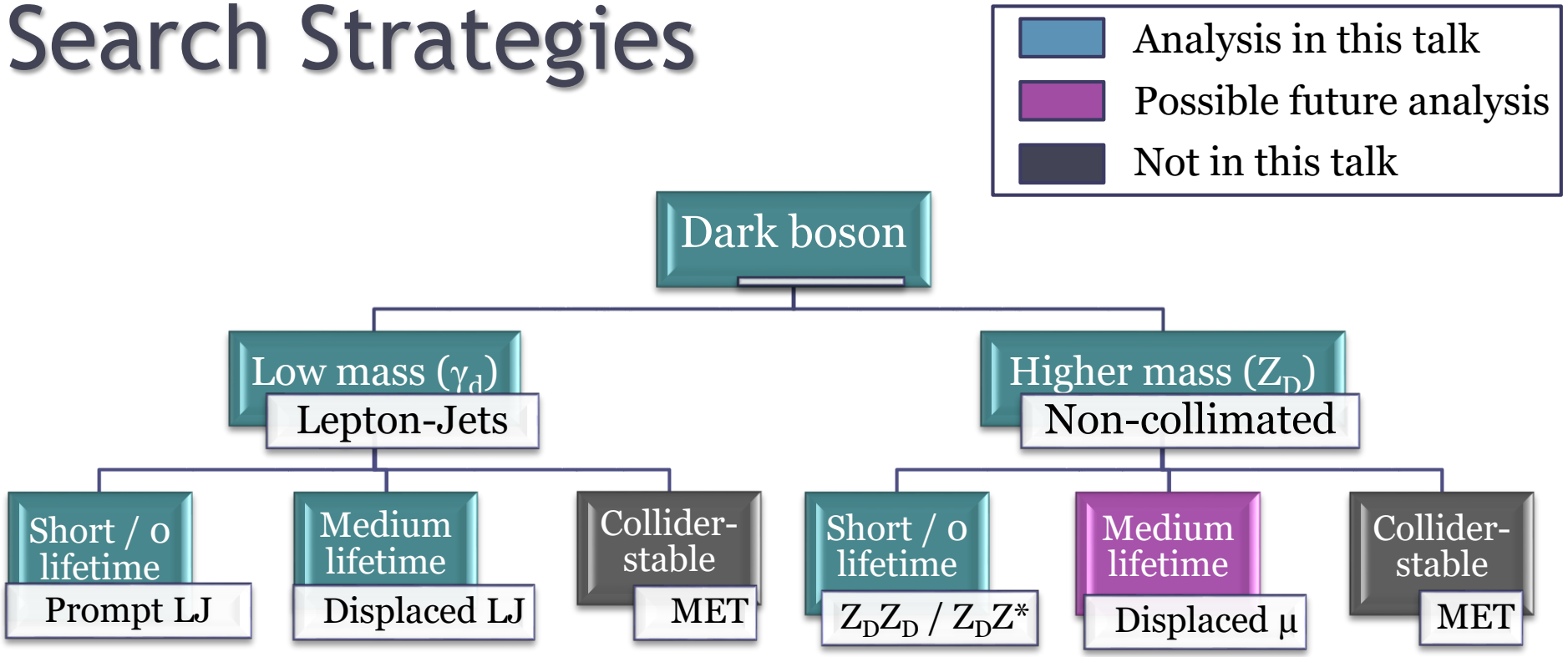
- Final-state dilepton signatures: promising search prospects if Z_D/γ_d decays back to SM with sizeable BR
  - BRs vary with mass
  - Lifetime varies with mass and ε





arXiv:1412.0018

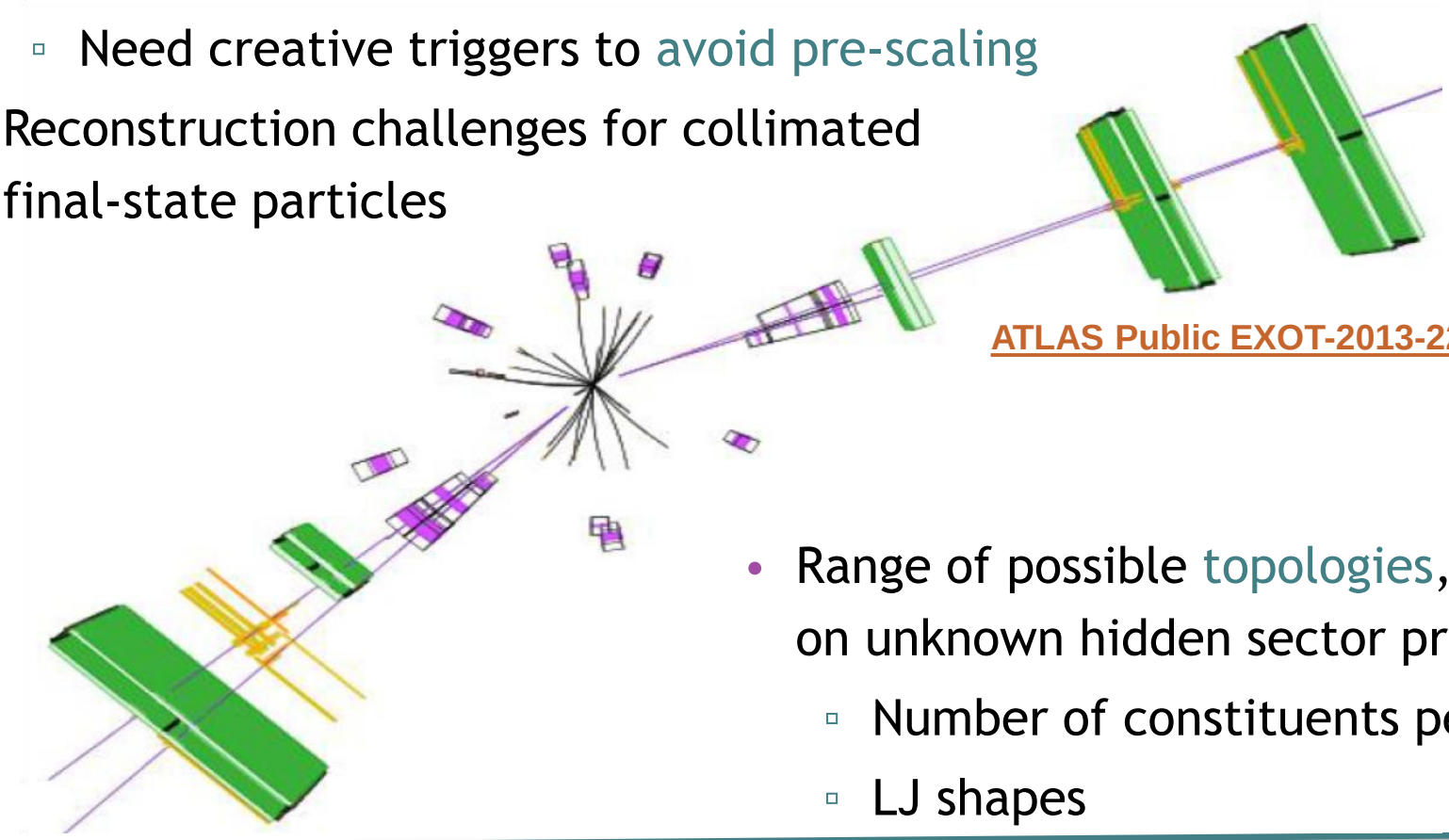
Search Strategies



- Lepton-Jet (LJ): collimated jet-like structure containing pair(s) of muons and/or electrons *(and/or light hadrons: not discussed here)*
- Non-collimated: final state leptons far enough apart to pass standard reconstruction criteria

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

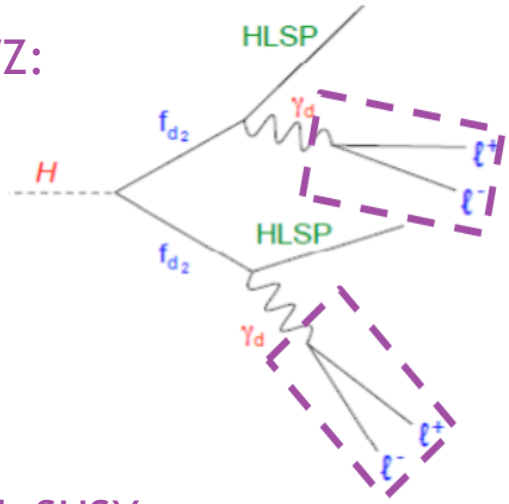
Low-Mass Searches: Handles

JHEP **62**, 02 (2016) *JHEP* **11**, 088 (2014)
ATL-PHYS-PUB-2016-010

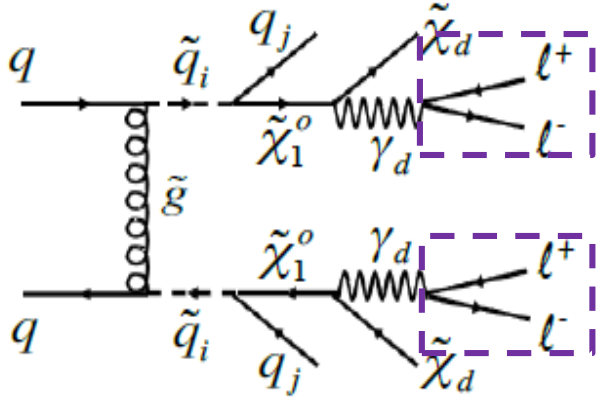
- Categorize LJs by:
  - Particle species
  - Prompt vs displaced
- Key properties:
  - Angular aperture of constituents
  - Isolation (Σp_T of charged tracks within cone)
- LJ-building: cone-based clustering
- Require two LJs in event
  - Minimum $\Delta\varphi$ separation
- To allow easy re-casting: trigger & reco efficiency tables as function of γ_d {$c\tau$, p_T}
  - "Lepton-Jet Gun" MC tool

Benchmark Models

FRVZ:



Dark SUSY:



Low-Mass Searches: Displaced LJs

Targets γ_d decays beyond pixel detector, out to muon spectrometer (MS)

- Muon pairs: MS tracks with no corresponding ID tracks
- Electron pairs: appear as jets in calorimeters

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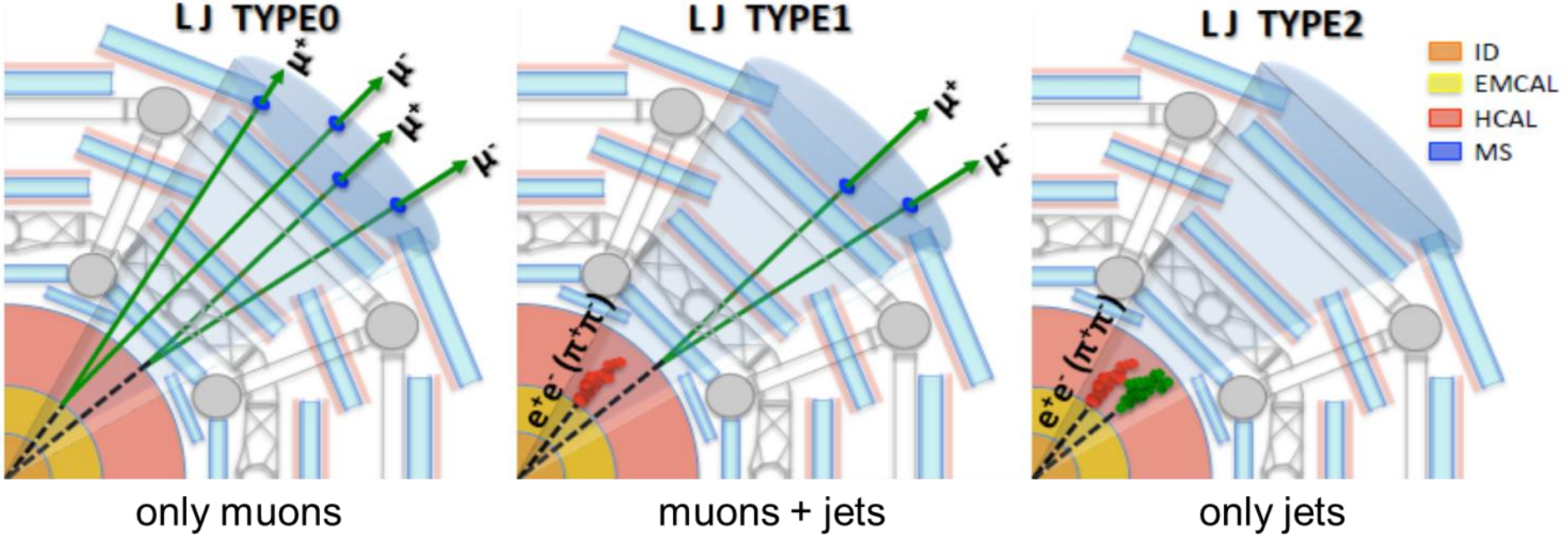
LJ categorization:



Low-Mass Searches: Displaced LJs

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Main backgrounds:

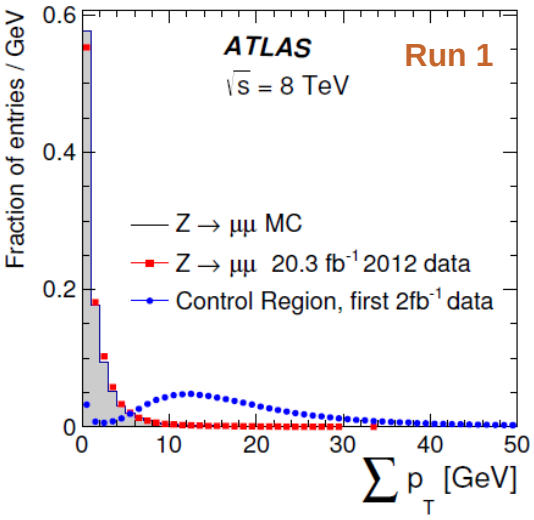
- QCD multi-jet
- Cosmic-ray muons
- Beam-induced

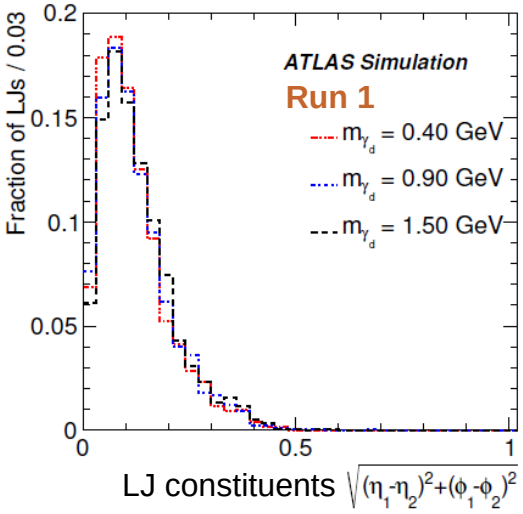
Triggers:

- 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

Additional discriminating variables:

- Jet width and timing
- Beam-induced BG tagging NEW IN RUN 2





Low-Mass Searches: Prompt LJs

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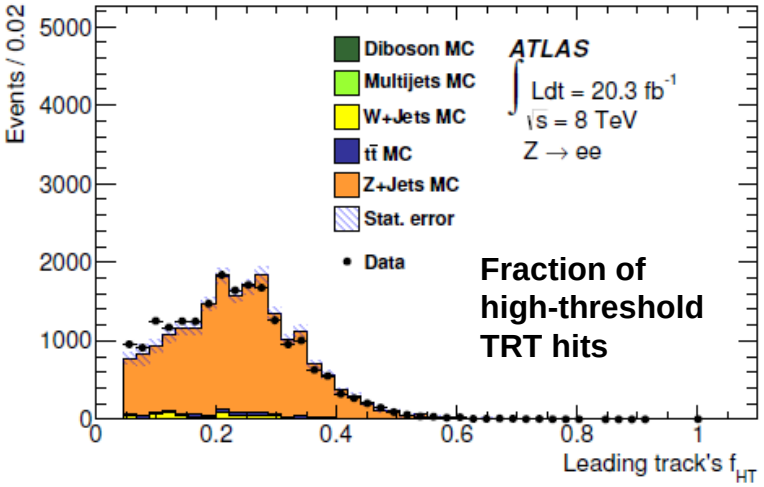
LJ Categories:
Muon, electron, mixed

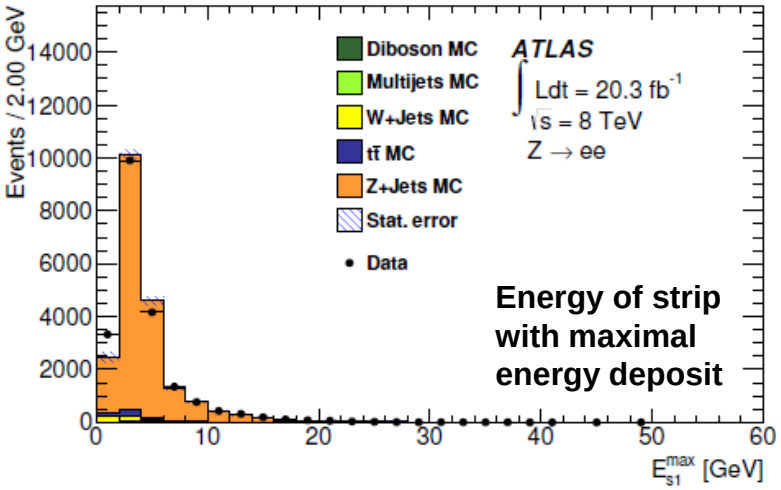
Main backgrounds: QCD multi-jet

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

Additional discriminating variables:

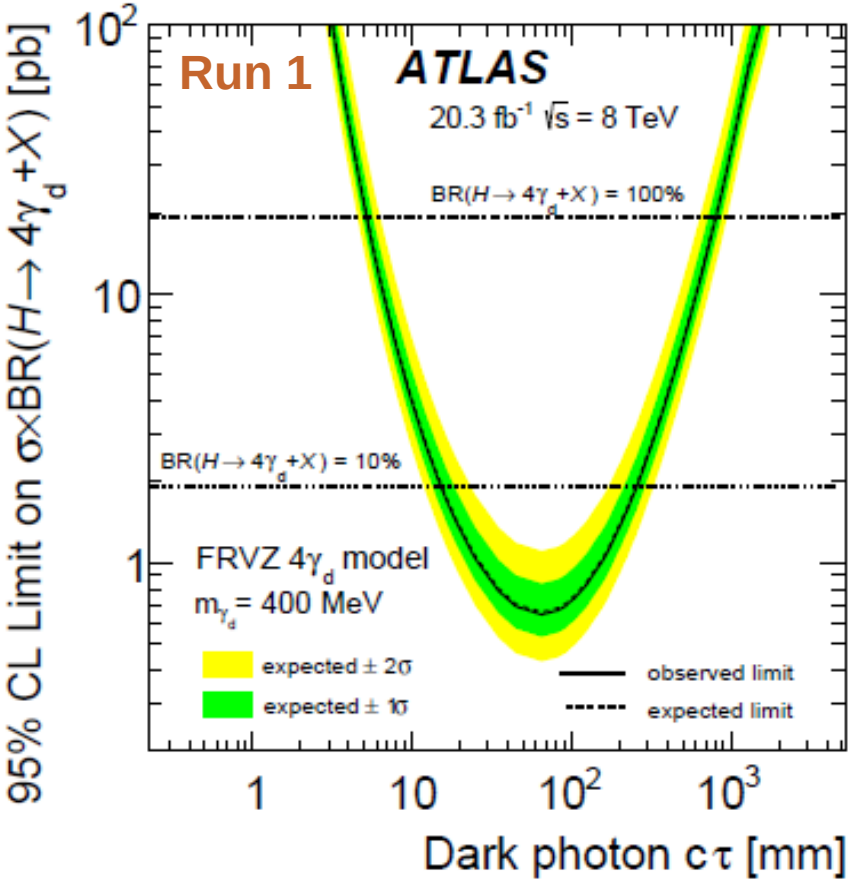
- Calorimeter isolation
- Jet EM fraction
- EM Calorimeter hit properties and hadronic leakage
- Transition Radiation Tracker hit properties





Low-Mass Searches: Run 1 Results

Displaced:



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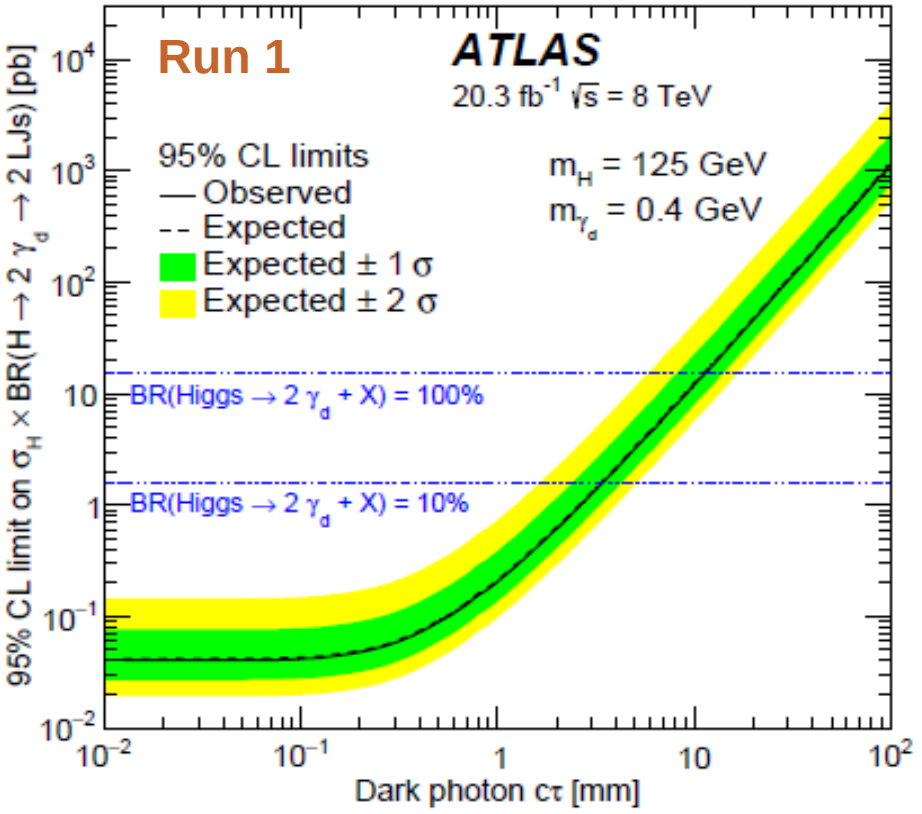
Prompt:



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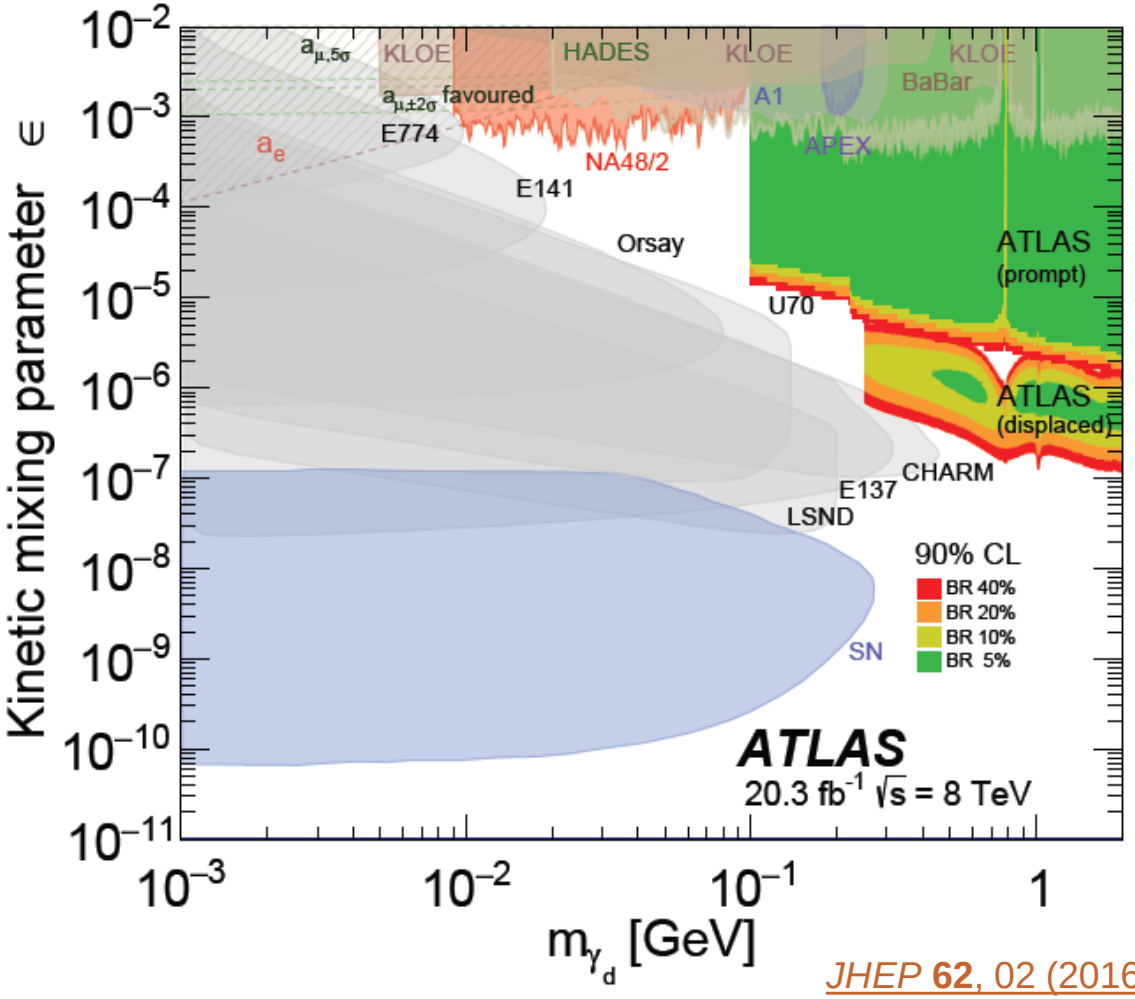
Low-Mass Searches: Run 1 Results

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



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Higher-Mass Searches: Challenges & Handles

PhysRevD **92**, 001 (2015)

- Assumption of Z_D on-shell → use of 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

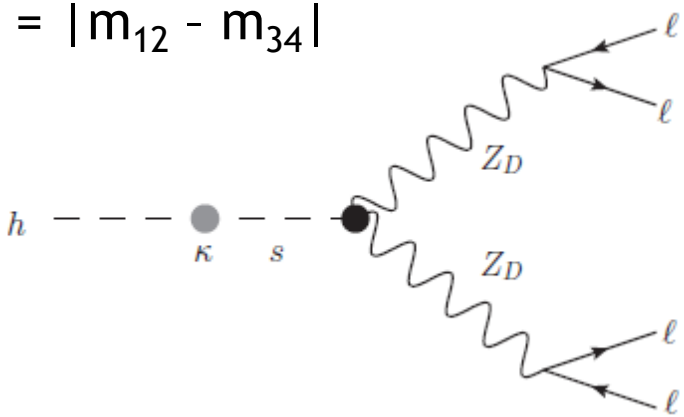
- **$h \rightarrow Z_D Z_D$** targets Higgs decay to 2 equal-mass intermediate particles
- **$h \rightarrow Z_D Z^*$** scans for resonance in Z* mass spectrum

Higher-Mass Searches

PhysRevD **92**, 001 (2015)

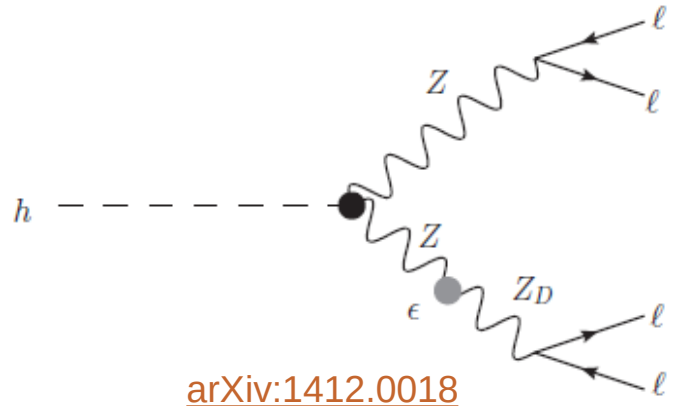
$h \rightarrow Z_D Z_D$:

- Lepton quadruplet selected by minimizing $\Delta m = |m_{12} - m_{34}|$
- Sensitivity to κ
- Main backgrounds: ZZ*
- Invariant mass cuts:
  - m_{4l} , $|m_{pair} - m_z|$
  - m_{pair} 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}

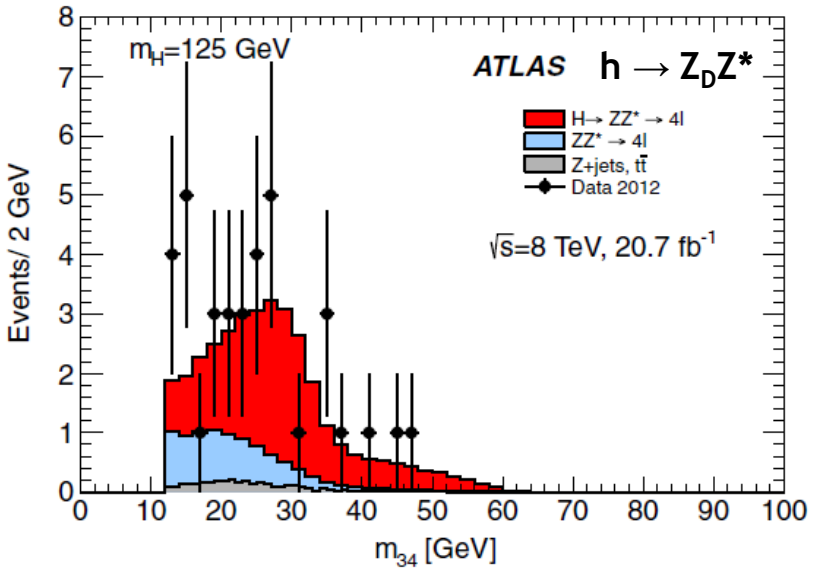


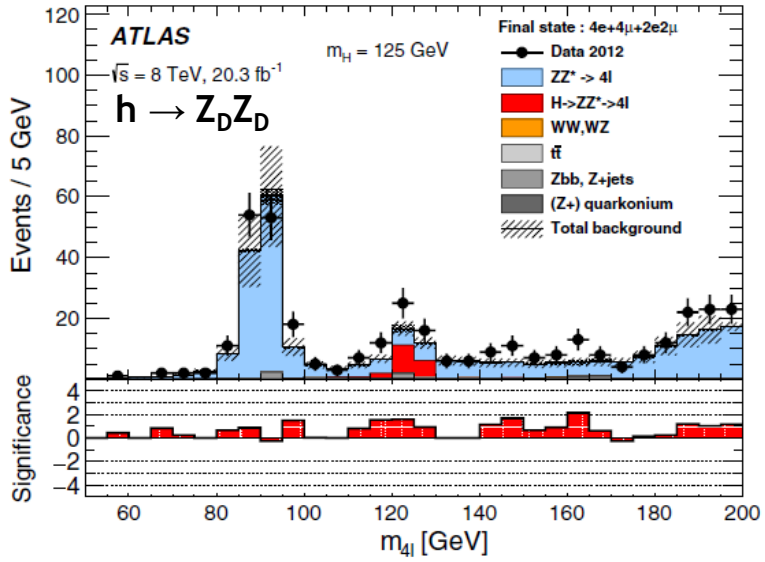
arXiv:1412.0018

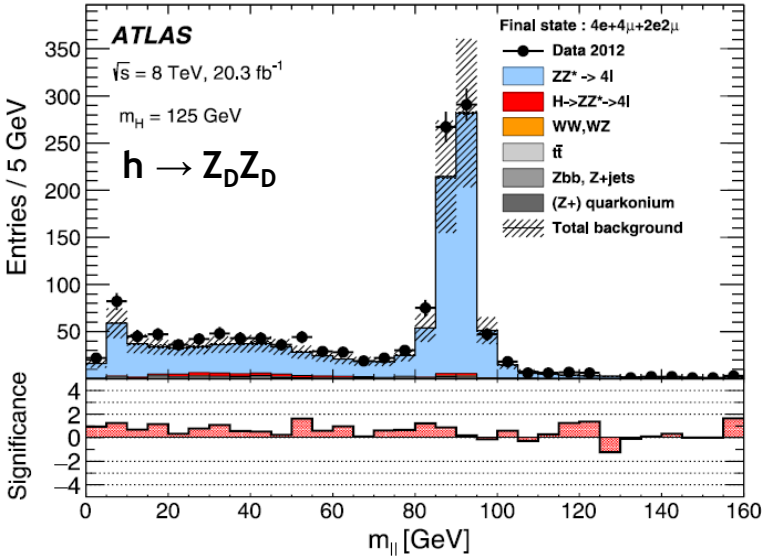
Higher-Mass Searches

PhysRevD **92**, 001 (2015)

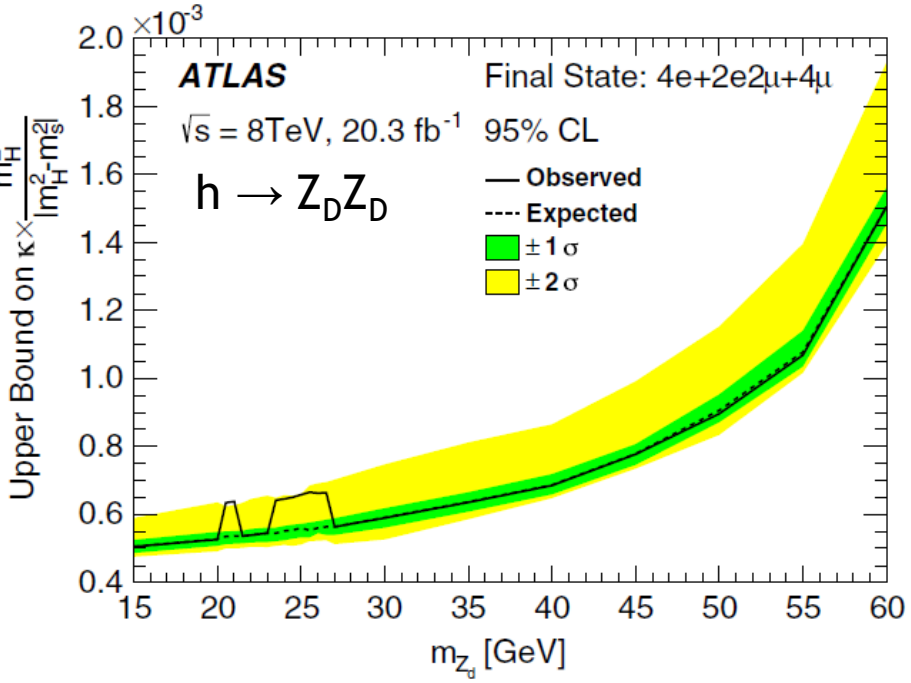
Invariant mass distributions for data and expected backgrounds:

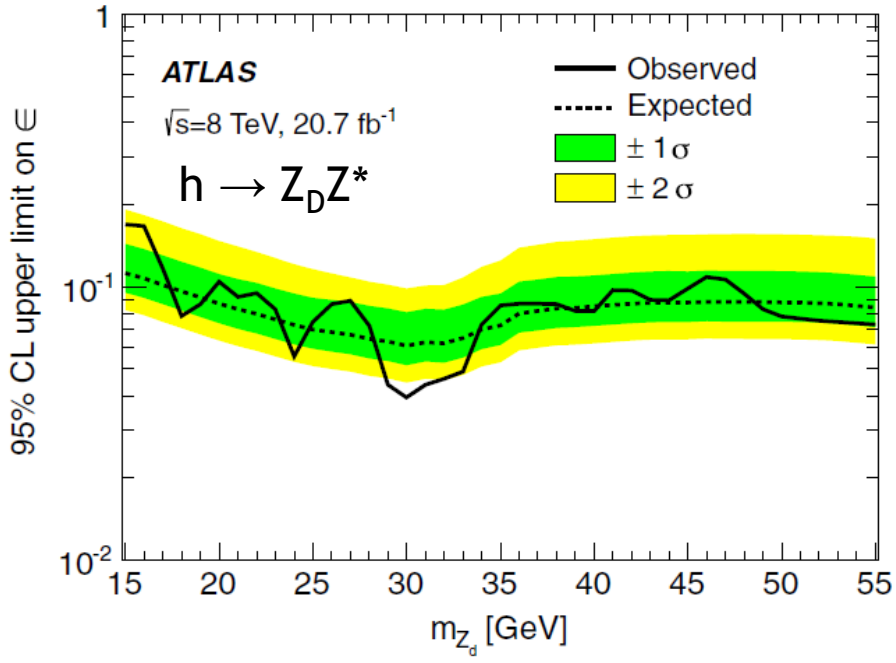






Higher-Mass Searches: Run 1 Results





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

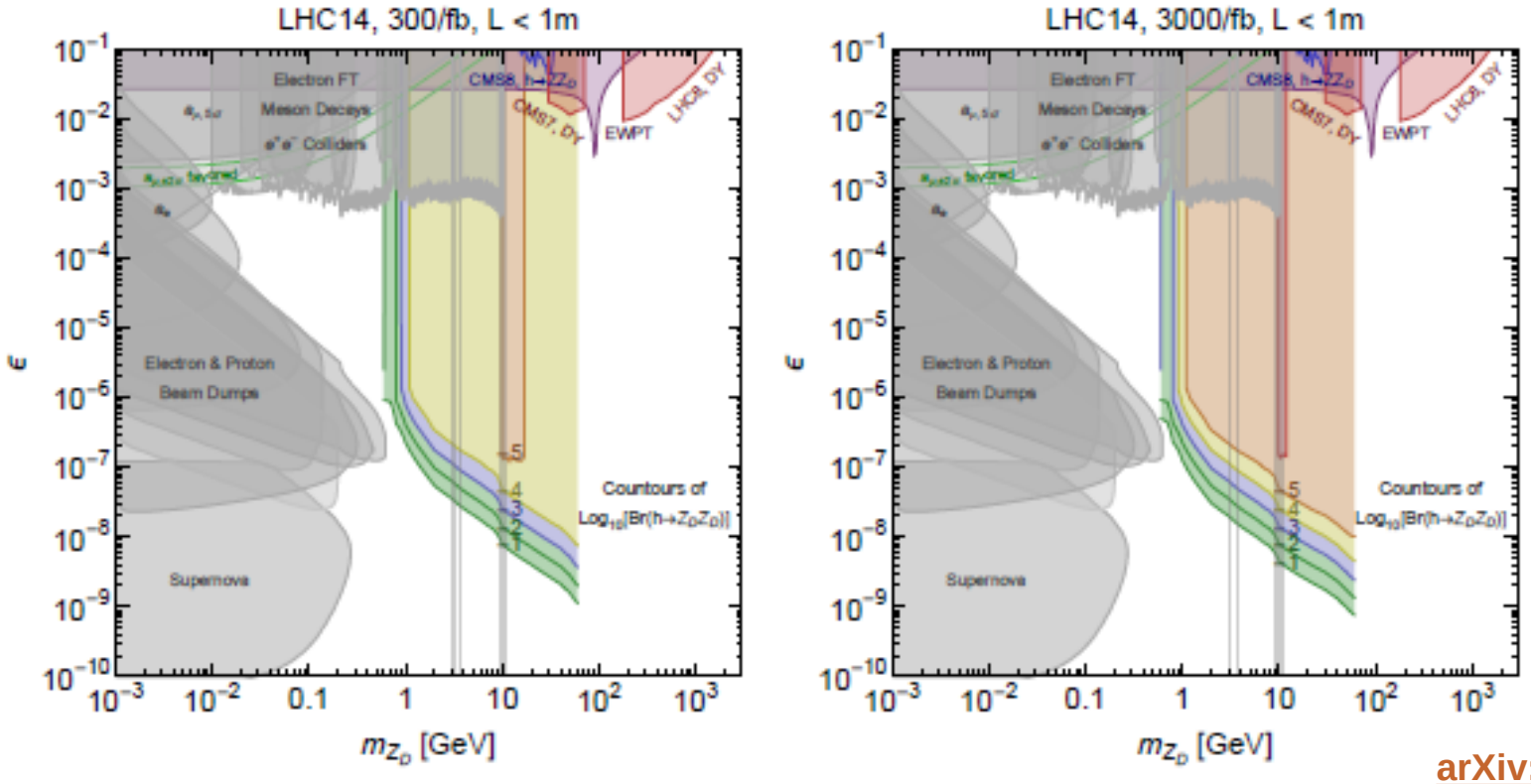
PhysRevD **92**, 001 (2015)

Potential Future Extensions

- Diphoton 750 GeV bump: contribution from h → γ_d's ?
  arXiv:1606.03833
- Nuclear transitions 17 MeV bump: "protophobic boson" not exactly our Z_D / γ_d, but perhaps detectable?
  arXiv:1604.07411
- Lepton-Jets:
  - Additional benchmark models (e.g. inelastic DM)
  - Additional LJ types (e.g. converted photons)
  - Extended m_H, m_{γ_d} coverage
  - For short lifetimes: specialized reconstruction of displaced inner detector tracks
- Non-collimated:
  - Combination with LJ analysis
  - For extended angular aperture coverage: overlap removal adjustments

Potential Future Extensions

- New “displaced non-collimated muons” analysis for Run 2, extending $Z_D Z_D$ search to longer lifetimes



arXiv:1412.0018

Conclusions

- Dark bosons appear in a wide range of BSM models
  - Vector Portal, Higgs Portal, Hidden Valley, SUSY, DM …
- Rich phenomenology of leptonic final states presents challenges …
  - Widely-varying topologies
  - Non-standard reconstruction
  - Tricky to trigger on
- … but also opportunities for discoveries in ATLAS!
  - Multiple complementary analyses with distinct strategies
  - Lepton-Jet (Prompt + Displaced) and $Z_D Z_D$ / $Z_D Z^*$ analyses cover large swaths of previously-unexplored parameter space
- Building on successes of 8TeV analyses for even wider-reaching 13TeV versions