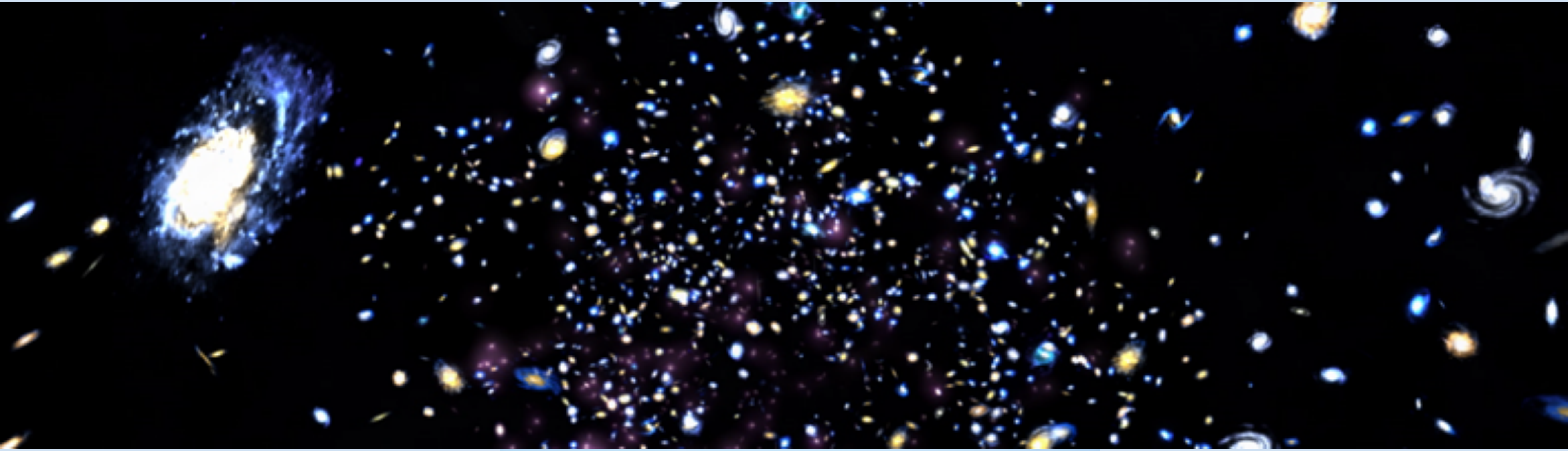
SEARCHES FOR LEPTON-JETS WITH THE ATLAS DETECTOR AT THE LHC



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On behalf of the ATLAS collaboration
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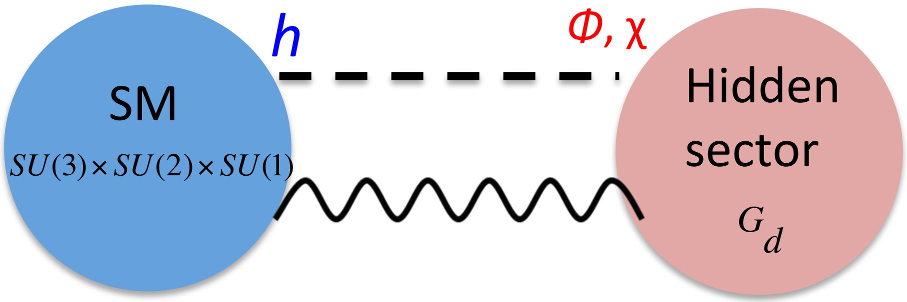
Outline

- **Introduction**
- **Lepton-jets**
  - **Prompt and long-lived**
- **Search strategy**
- **Background**
- **Results and interpretations**

Introduction

Conflicting results from astrophysical experiments inspired interesting models for production and decays of dark sector particles!

Originally proposed by N. A-. Hamed, N. Weiner
arXiv: 0810.0714



$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m_{\gamma_d}^2 b^2$$

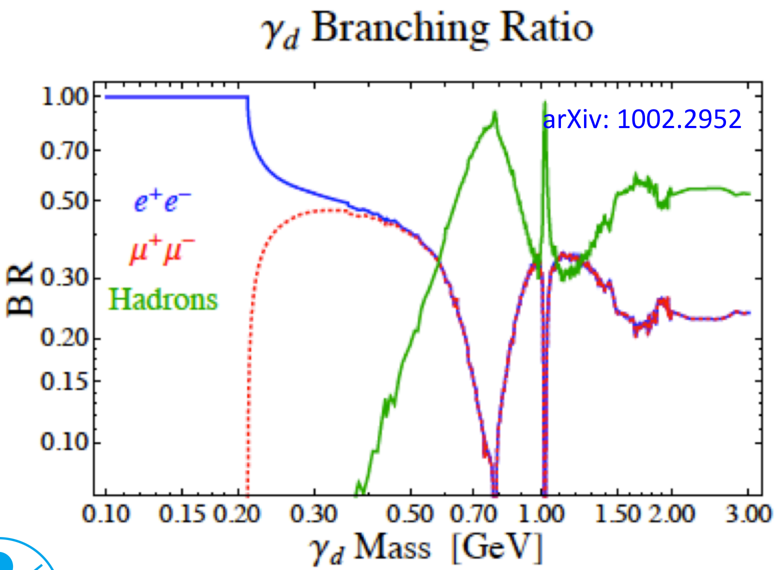
- SM particles could couple to hidden sector via Higgs portal or kinetic mixing
- The lightest unstable particle (γ_d) in the hidden sector could couple back to SM via kinetic mixing
- Search at LHC for γ_d production could constrain kinetic mixing (ε), and mass ($m_{\gamma d}$) parameters

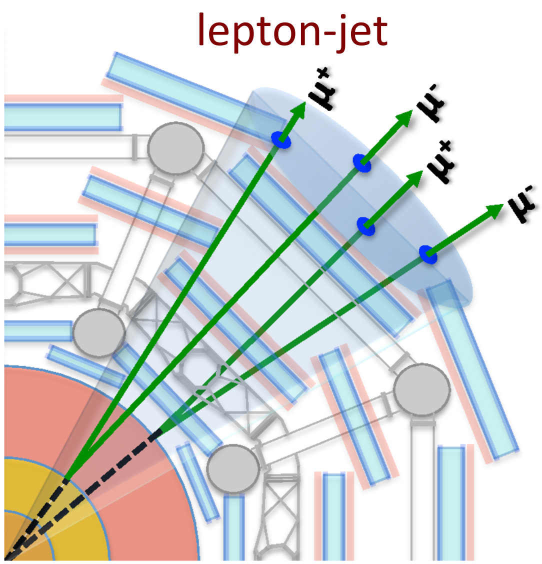
Lepton-jets

- Low mass (O(1) GeV) dark photons, γ_d, may be produced with large boost in the decay chain of heavier states
- γ_d can decay mostly into SM leptons (***e^+e^-***, or ***$\mu^+\mu^-$***), and also into light mesons
  → collimated collection of energetic leptons form a "**lepton-jet**"
  - depending on the size of kinetic mixing (ε) and masses of γ_d and leptons, the decay could be **prompt** or **long-lived** (typically $\varepsilon > 10^{-5}$ for prompt)

$$\Gamma_l = \frac{1}{3}\alpha\varepsilon^2 m_{\gamma_d}\sqrt{1-\frac{4m_l^2}{m_{\gamma_d}^2}}\left(1+\frac{2m_l^2}{m_{\gamma_d}^2}\right)$$

  - γ_d decay branching fractions and lifetime are model-dependent





Analysis strategy

- ATLAS search is performed for events containing at least two lepton-jets (LJs) considering both prompt and displaced productions
  - most models predict at least two lepton-jets in the final states (arXiv:0901.0283, arXiv: 0909.0290, arXiv: 1002.2952, etc…)

- Search strategy is nearly model independent selection
  - no restrictions on other objects of event
  - study the γ_d mass in [0.1, 2] GeV range

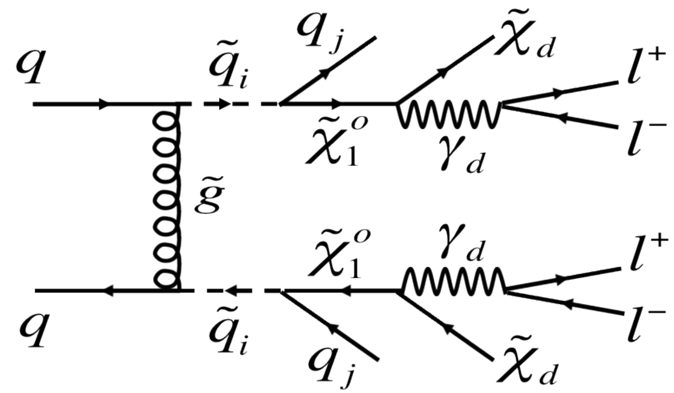
- Prompt and displaced LJs have somewhat different reconstruction methods
  - displaced LJ search covers upto 7 m (first muon-trigger plane) transverse distance range of γ_d decay position from interaction point
    - γ_d decay into e^+e^- only within hadronic calorimeter to reduce background

- Results are interpreted for various topologies, such as Higgs → N γ_d +X, or squark + squark → N γ_d + X, where N>=2

Lepton-jets signal models

SUSY-mediated:

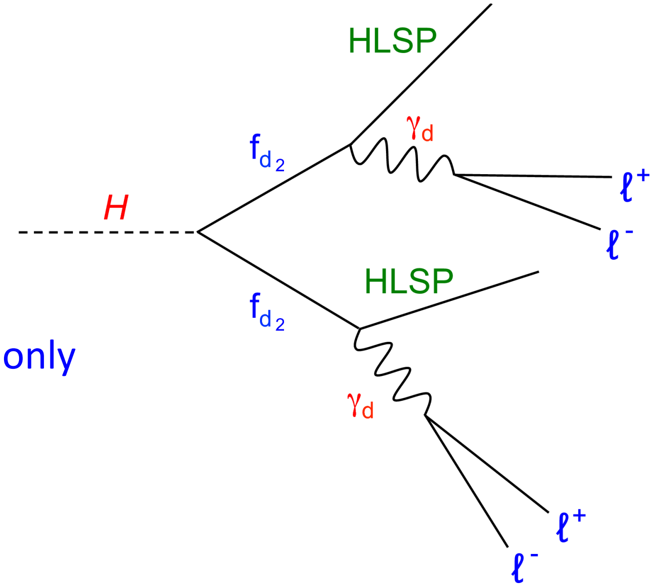
Due to smaller cross section of squark pair production, this model is yet more interesting for prompt LJ search



Higgs-mediated:

γ_d production via SM Higgs portal has good sensitivity for both prompt and displaced LJ searches

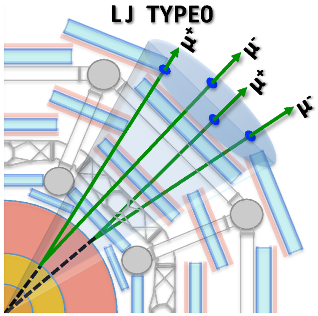
However, this talk considers this model for displaced LJ only

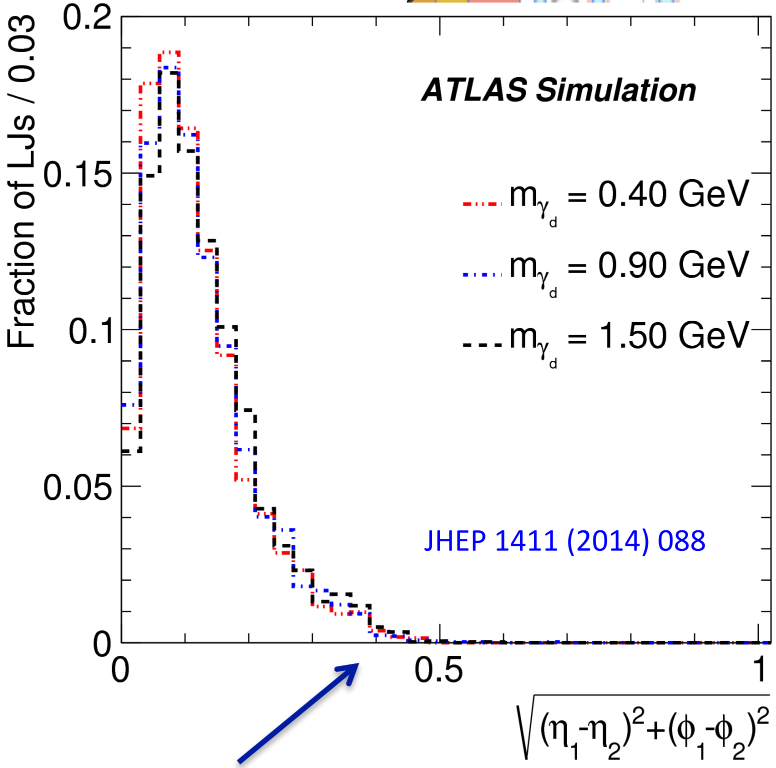


HLSP = Hidden sector Lightest Stable Particle

Lepton-jets reconstruction

- Prompt LJs reconstructions are based on clustering tracks ($p_T \geq 10$ GeV) in a narrow cone, and pointing them to energy deposited in the calorimeter or to the tracks in muon spectrometers
  - overlapped tracks and energy clusters due to limited intrinsic resolution of ATLAS sub-detectors
    - reconst. eff upto ~60%
  - overwhelming QCD background in *e*-channel
  - challenge in the calibrations



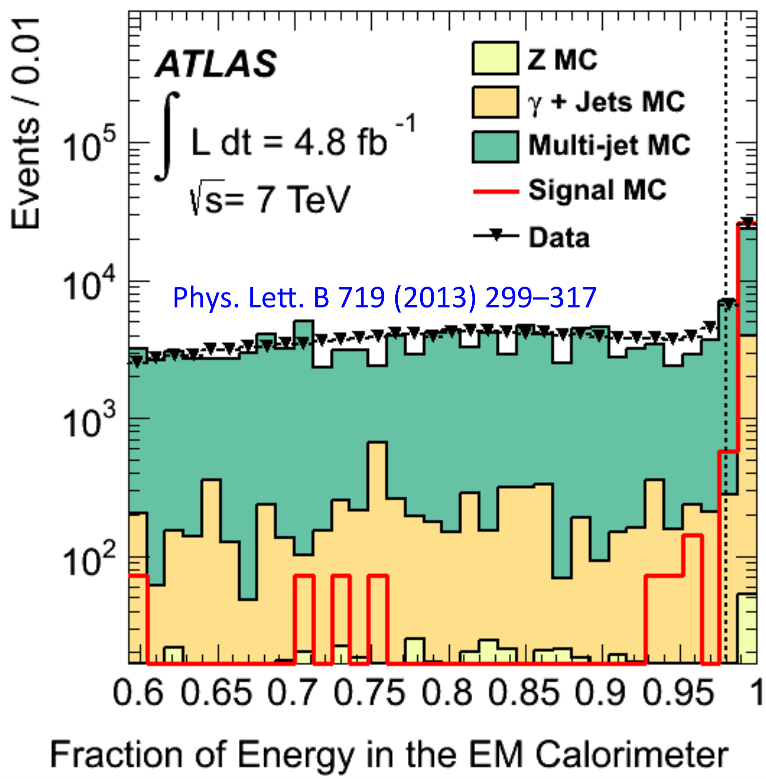


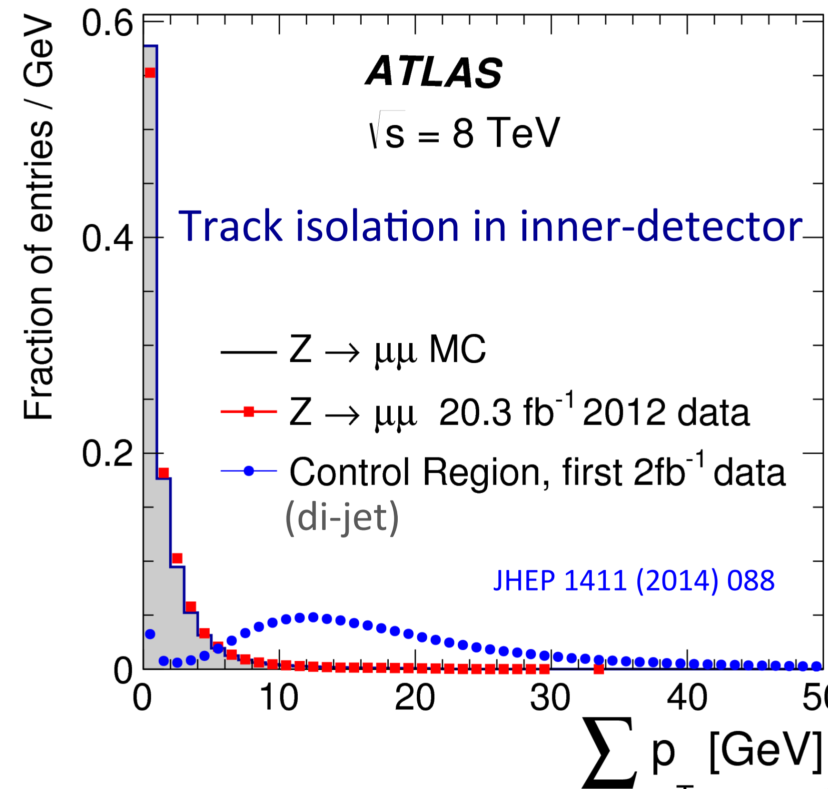
ΔR between two muons of a reconstructed LJ from γ_d

- Similar clustering technique for displaced LJ reconstruction, but veto against inner detector tracks to suppress bkg
  - reconst. eff upto ~20%
  - substantial multi-jet and cosmic-ray bkg contributions
  - additional challenge in trigger and decay vertices reconstruction beyond precision tracking volume
    - this analysis ignores vertices reconstruction

Lepton-jets selection

- Discriminating LJ variables against the QCD bkg and cosmic-ray
  - e.g high-p_T tracks multiplicity, isolation in inner detector and calorimeter, profile of energy deposition of electrons in the calorimeters, timing
    - displaced LJ can have different shower profile compared to prompt LJ if γ_d decayed in the middle of calorimeter
  - requirement of ≥ 2LJs per event suppresses all other backgrounds such as W/Z/γ*+jets, di-bosons, and ttbar processes

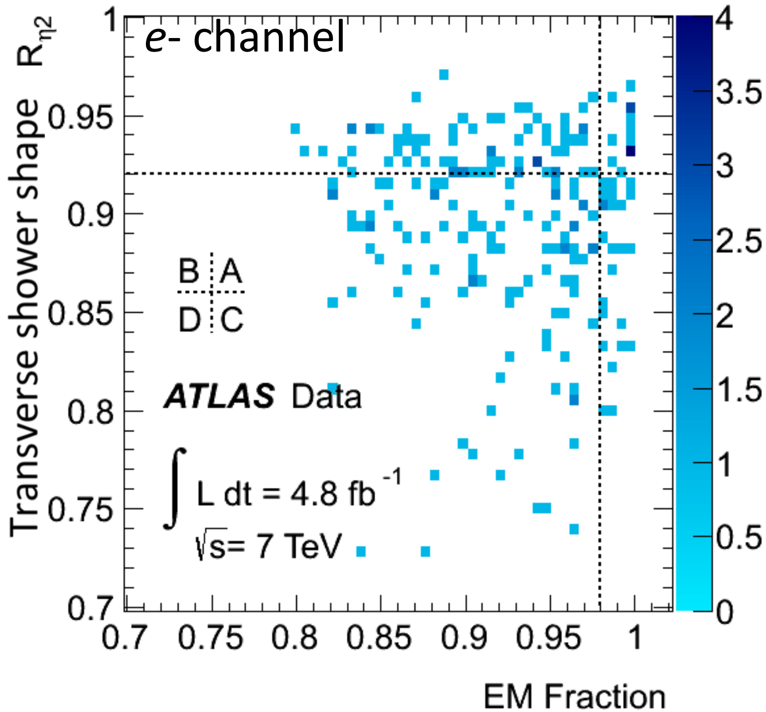




Background (prompt LJ)

- Background due to QCD jet faking as lepton-jet is determined from two nearly uncorrelated discriminating variables using data-driven ABCD likelihood method
  - region A represents signal region
  - likelihood fit to all four regions to estimate background in region A
- Other backgrounds (e.g ttbar, diboson) tiny, and estimated via MC simulation

√s = 7 TeV @ 4.8 fb^{-1}	e-channel	μ-channel
Data	15	3
Background	15.2 ± 2.7	0.5 ± 1.5



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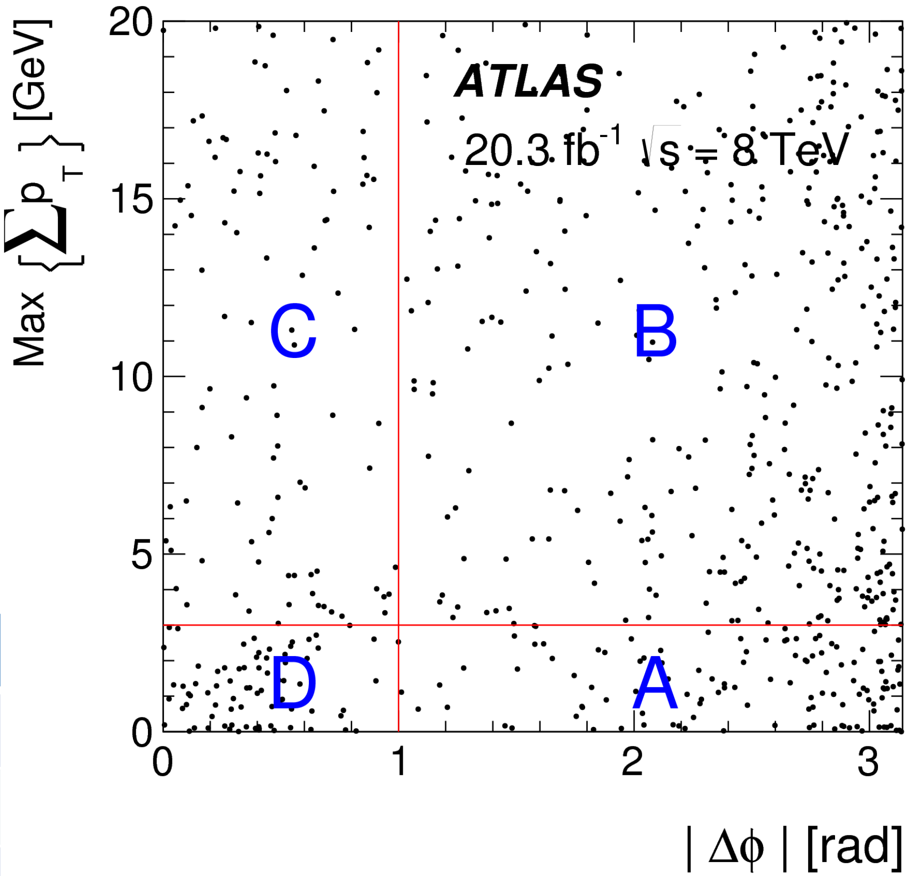
Background (displaced LJ)

- Same data-driven technique for multi-jet bkg estimation
  - choice of ABCD variables is independent of lepton-jet type
- Cosmic-ray is additional source of background
  - determined from empty bunch crossings data



8 TeV data @ 20.3 fb^{-1}	119
Cosmic-ray	40 ± 11 ± 9
Multi-jet	70 ± 58 ± 11
Total background	110 ± 59 ± 14

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Interpretations (prompt LJ)

- No significant excess is found in 7 TeV data compared to background prediction
- 95 %CL limits are placed on the cross section x BR of two lepton-jets
  - limits are extracted for lepton-jet production via SUSY mediator

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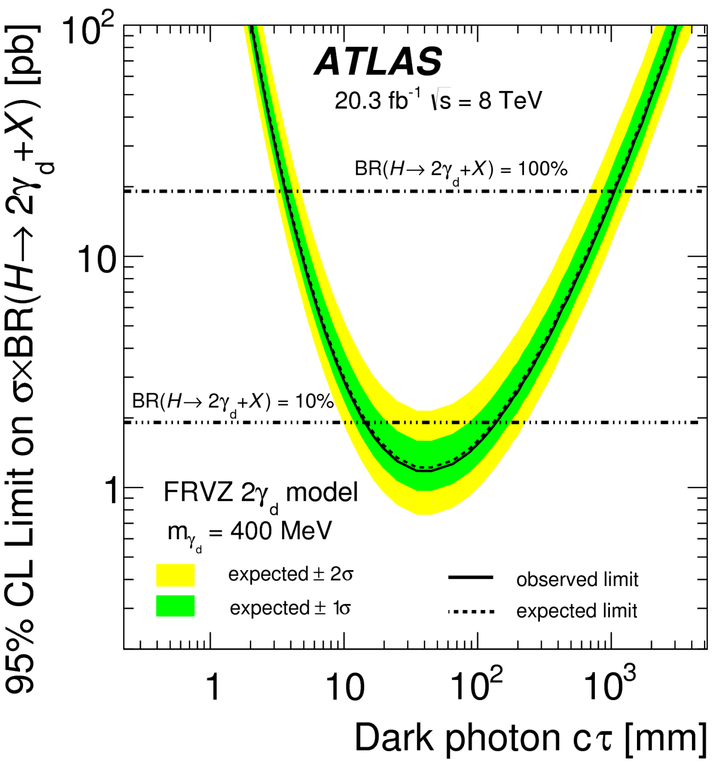
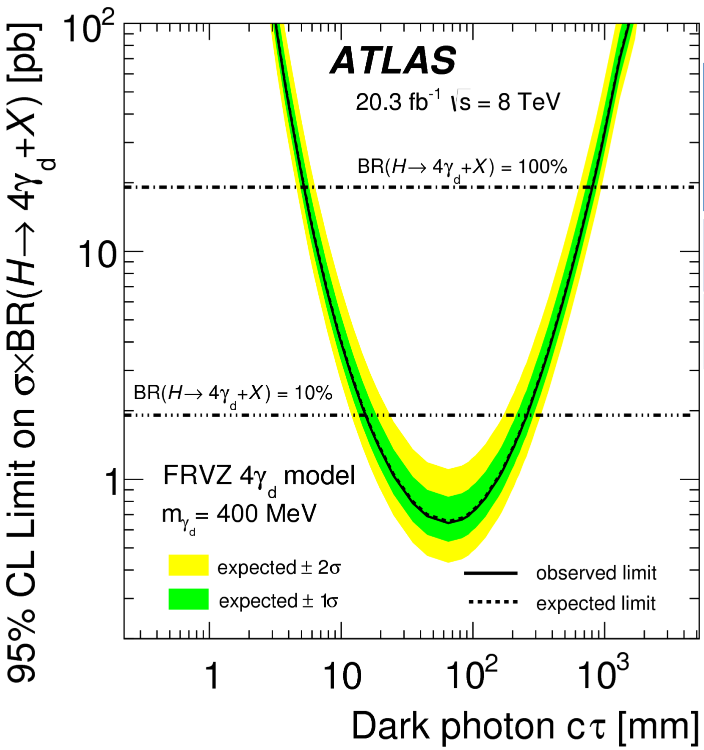
Dark photon mass [MeV]	≥ 2 electron jets Obs (Exp) [pb]	≥ 2 muon jets Obs (Exp) [pb]
150	0.082 (0.082)	--
300	0.11 (0.11)	0.017 (0.011)
500	0.20 (0.21)	0.019 (0.012)

- Constraints on the Higgs portal topology could also be established based on search results
  - higher production cross section of gg → H
- Extension of constraints for other masses of γ_d upto 2 GeV are possible with relatively detailed studies on calibration
- Results with 8 TeV data are imminent with extended studies!

Interpretations (displaced LJ)

- No significant excess is found in 8 TeV data compared to background prediction
- 95 %CL limits are placed on the cross section x BR
  - limits are extracted for lepton-jet production via Higgs portal (H→ 2 γ_d + X or H → 4 γ_d+ X) for 0.4 GeV γ_d





m_H = 125 GeV BR = 10%	95% CL excluded cτ [mm]
H→ 2γ_d +X	14 < cτ < 140
H→ 4γ_d +X	15 < cτ < 260

95%CL excluded kinetic mixing:
$7.7\times10^{-7} \leq \varepsilon \leq 2.7\times10^{-6}$

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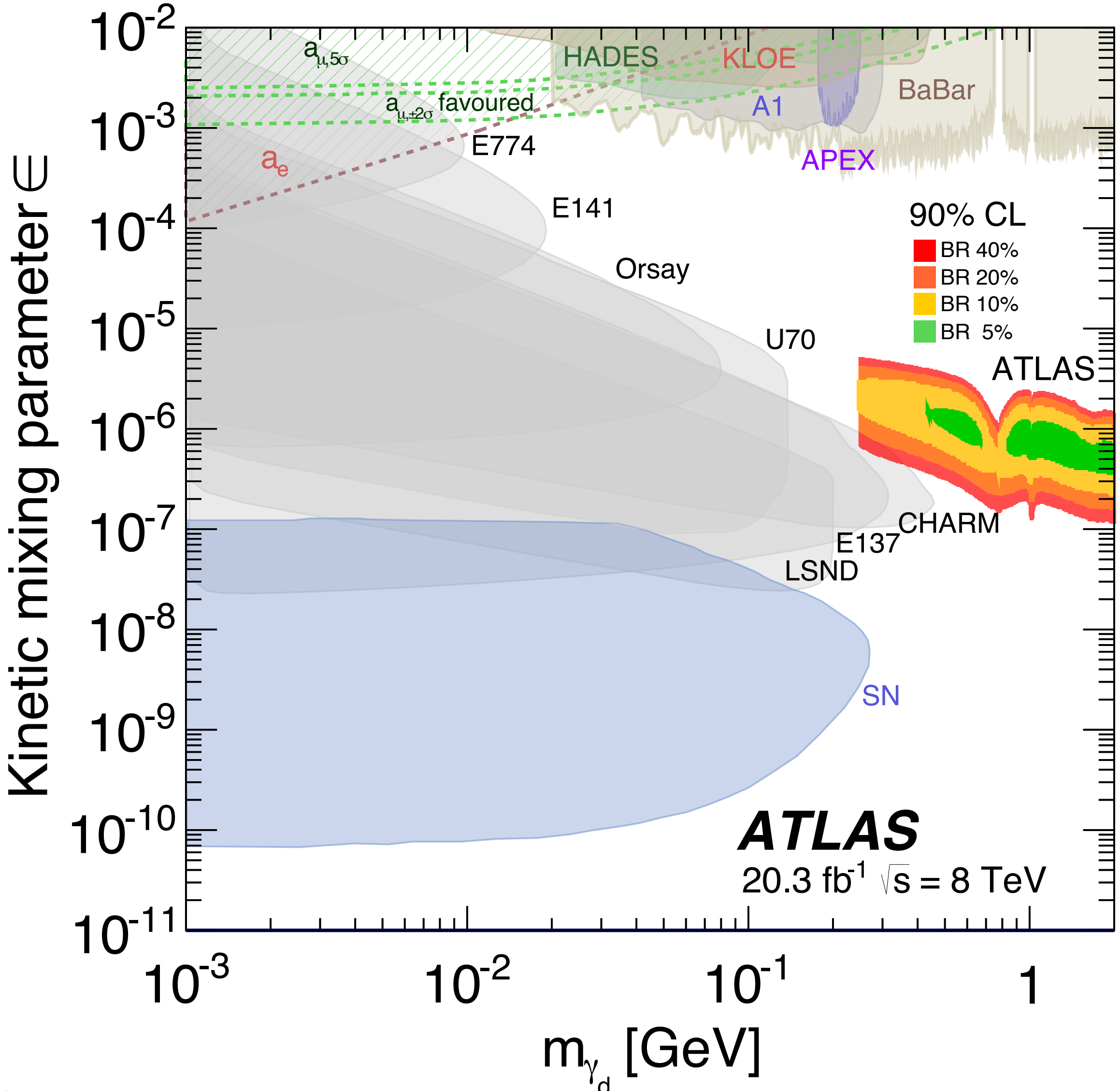
Kinetic mixing vs mass exclusion



90%CL exclusion regions in kinetic mixing ε and dark photon mass plane

- derived from $H \rightarrow 2\gamma_d + X$ process
- Higgs BR = 5%/10%/20%/40%

Excludes regions unconstrained by earlier experiments

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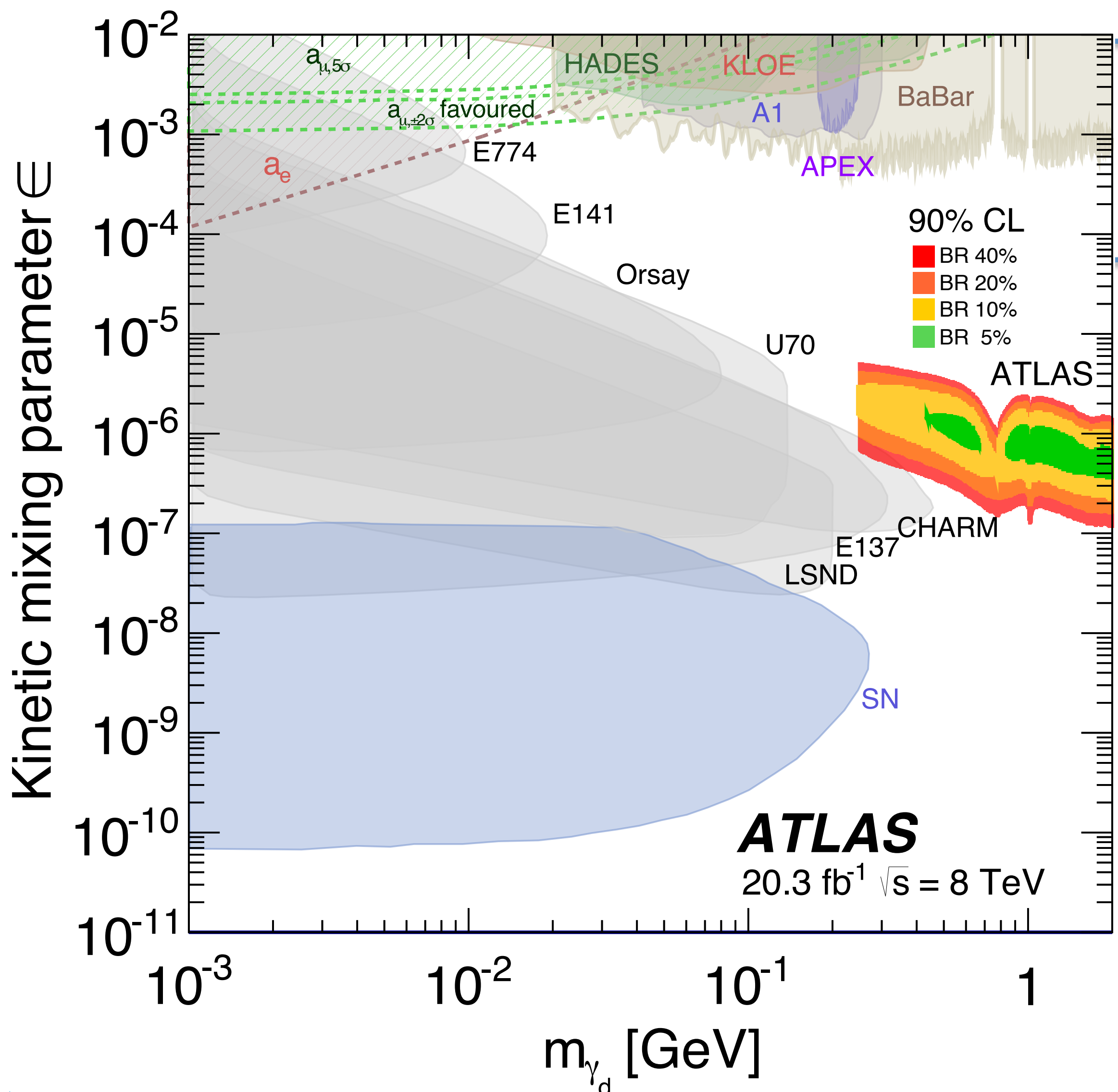
Kinetic mixing vs mass exclusion



prompt LJ search with 8 TeV ATLAS data has potential to constrain this region.
Stay tuned!

90%CL exclusion regions in kinetic mixing ε and dark photon mass plane

- derived from $H \rightarrow 2\gamma_d + X$ process
- Higgs BR = 5%/10%/20%/40%

Excludes regions unconstrained by earlier experiments

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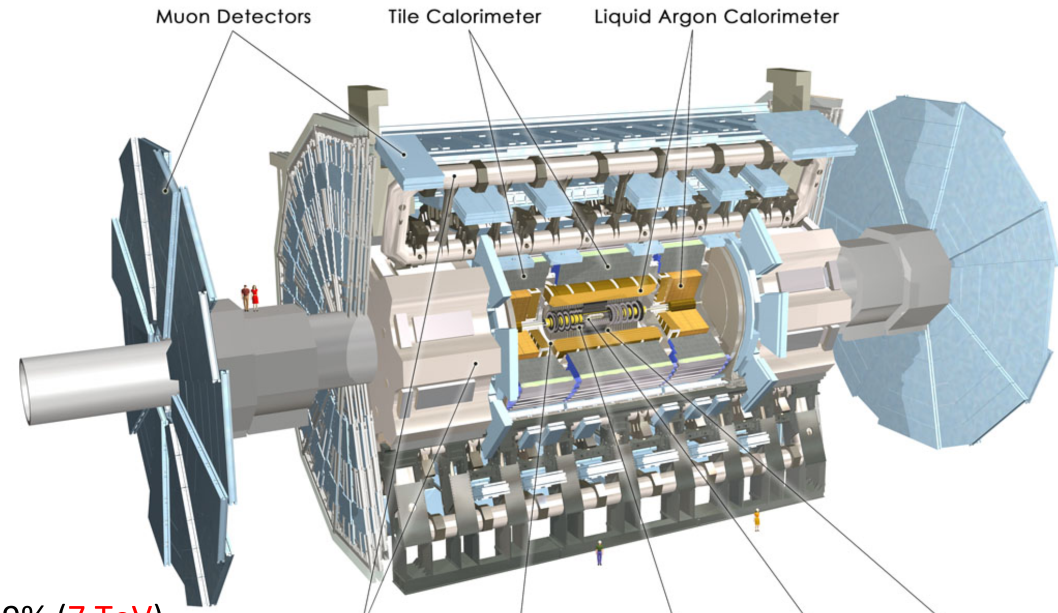
Conclusions

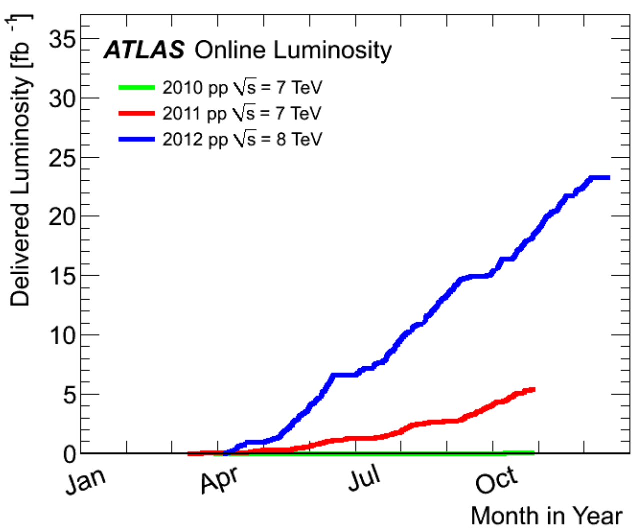
- Lepton-jets in the final states are distinct signatures for various models of dark sector
- We have conducted a nearly model independent search for lepton-jets using Run I data at ATLAS.
  - prompt lepton-jets search results with 8 TeV data will be released soon!
- The observed number of lepton-jets are consistent with the background prediction.
  - 95%CL upper limits are established on γ_d production in Higgs-mediated and SUSY-mediated topologies and 90%CL exclusions are extracted for γ_d mass and lifetime.
- Continue with the lepton-jet searches in Run II with further improvement in strategies!

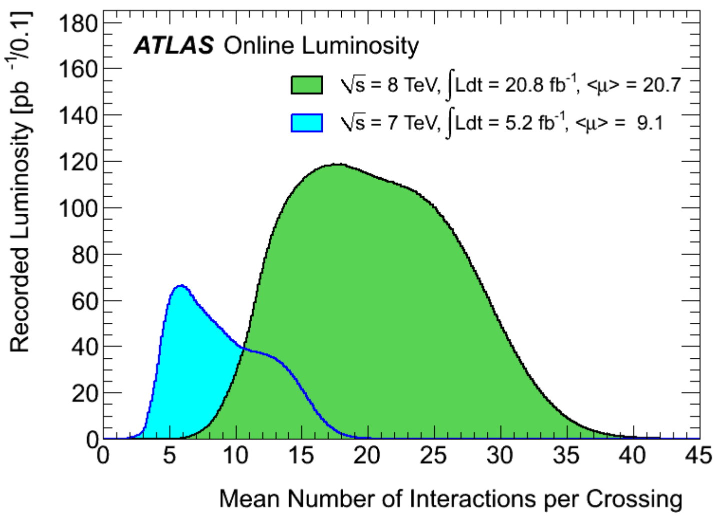
Thanks

The ATLAS detector



Lumi. Uncertainty = 3.9% (7 TeV)
= 2.8% (8 TeV)





Few facts about ATLAS Run I sub-detectors

- **Pixels:**

  Barrel radial distance from IP: 5 cm < R < 12 cm

  Pixel granularity: 50 μm x 400 μm in rΦ x Z

  Intrinsic resolution: 10 μm x 115 μm in rΦ x Z

- **SCT:**

  Barrel radial distance from IP: 12 cm < R < 52 cm

  strips with 80 μm pitch and 40 mrad stereo angle

  Intrinsic resolution: 17 μm x 580 μm in rΦ x Z

- **TRT:**

  Barrel radial distance from IP: 56 cm < R < 108 cm

  Intrinsic resolution: 130 μm in rΦ

- **Calorimeter:**

  Barrel radial distance from IP: 120 cm < R < 230 cm

  Spatial granularity in 2nd sampling: 0.025 x 0.025 in Δη x ΔΦ

- **Muon spectrometer:**

  Barrel radial distance from IP: 500 cm < R < 1200 cm

  EC longitudinal distance: 750 cm < rZ < 2250 cm

  Spatial size of L1 trigger ROI: 0.2x 0.2 in Δη x ΔΦ for barrel and 0.1x 0.1 in Δη x ΔΦ for end-cap.

Dark photons

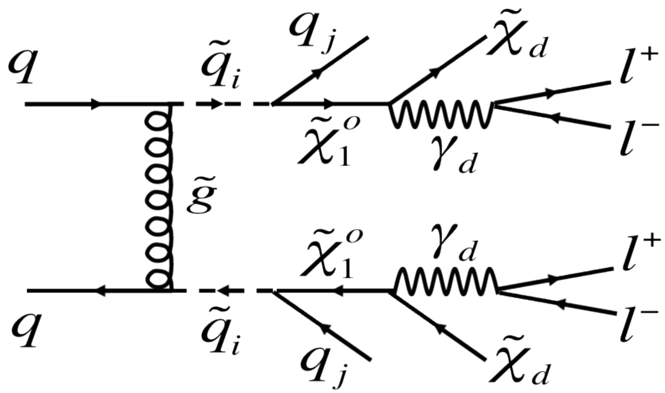
- Existence of dark matter (DM) is supported by astrophysical measurements
  - one of the greatest mysteries unexplained by SM

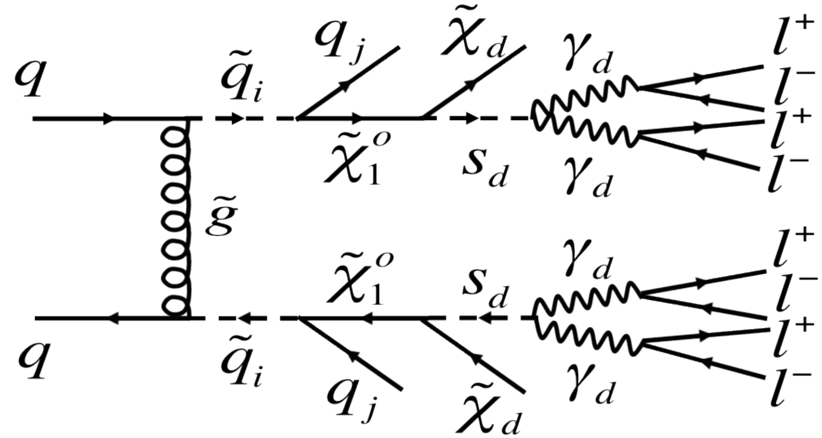
- DM could be composed of massive particles that interact very weakly with ordinary matter
  - most theories predict mass range between a few MeV to a few TeV

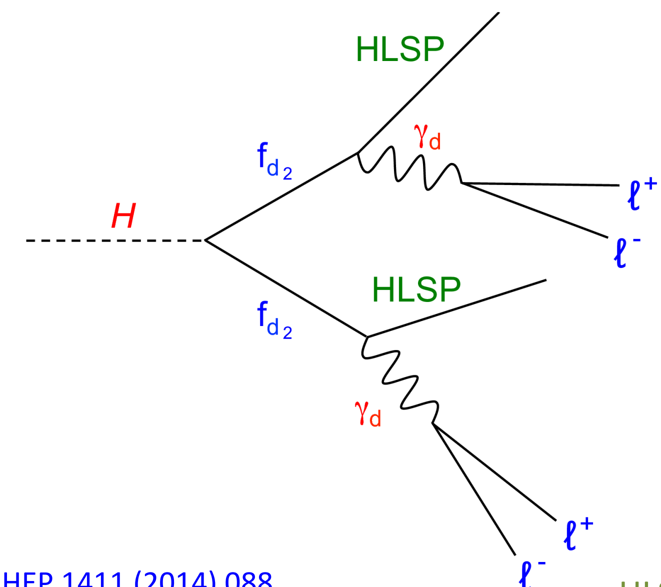
- Possible candidates:
  - lightest SUSY stable particles, stable Kaluza-Klein modes, sterile neutrinos, dark sector particles predicted by hidden sector particle theories, WIMPs, etc..

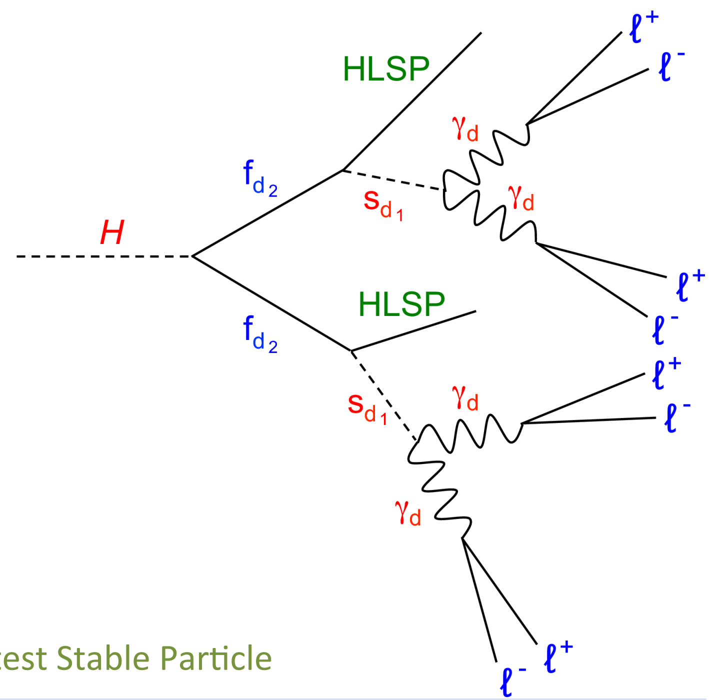
This talk is focused on ~ 1 GeV mass dark photon

Lepton-jets signal models









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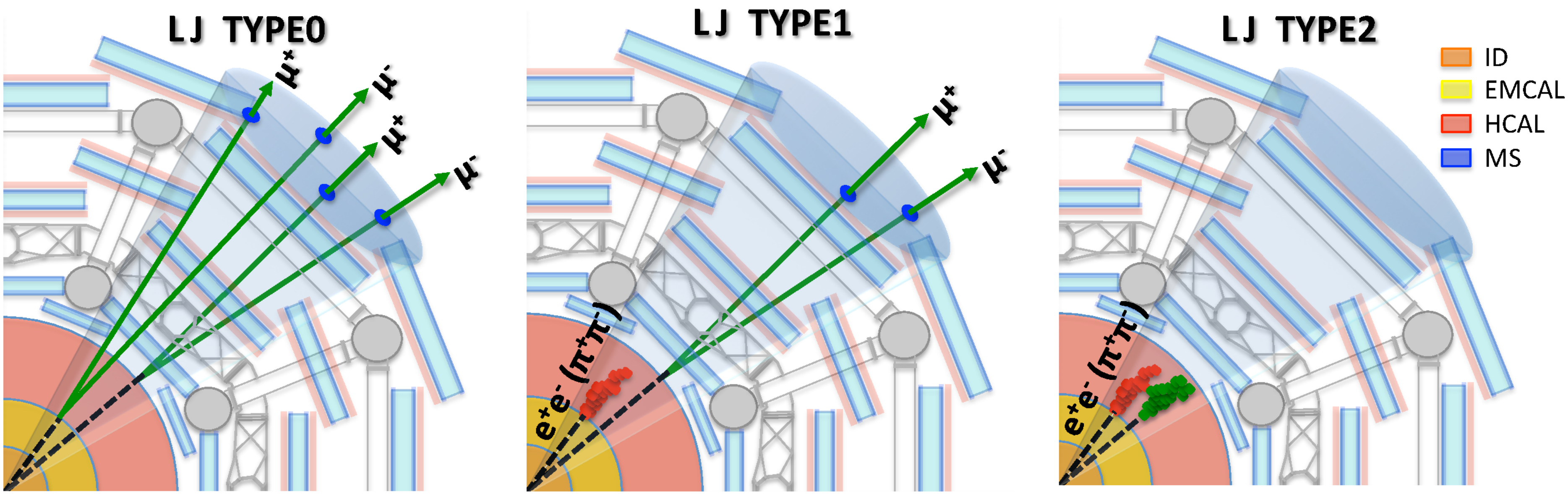
HLSP = Hidden sector Lightest Stable Particle

Displaced lepton-jets types



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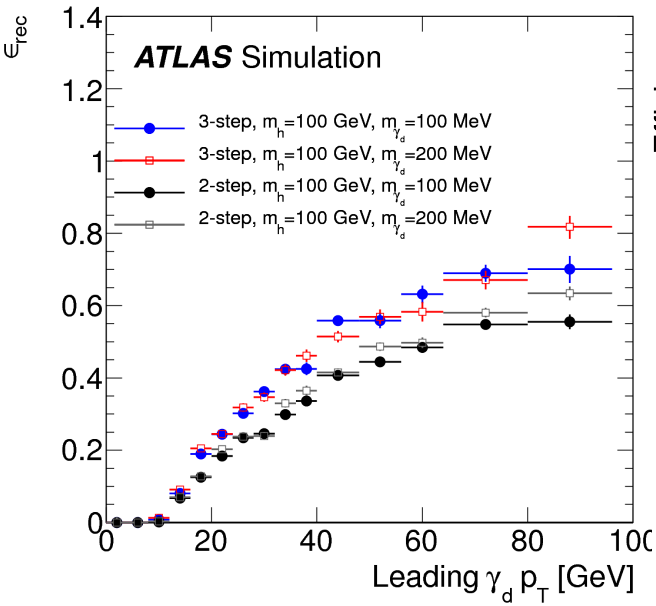
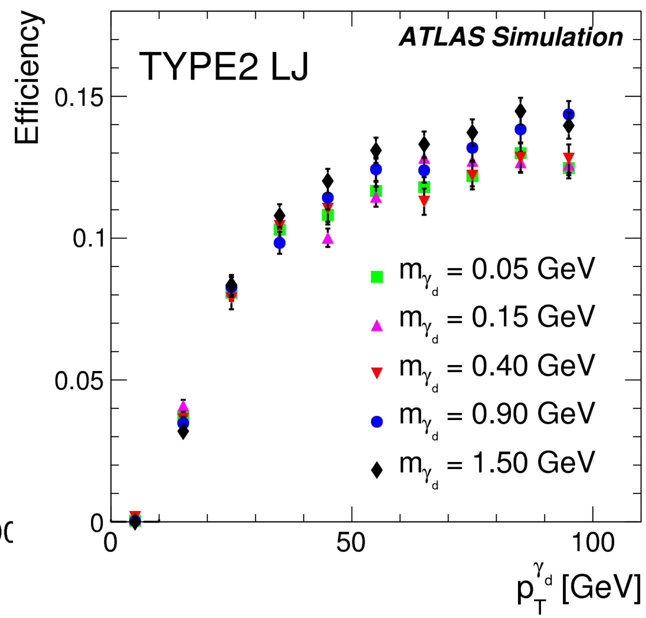
Lepton-jets reconstruction efficiencies (I)

Reconstruction efficiencies for a few lepton-jet types as a function of γ_d p_T

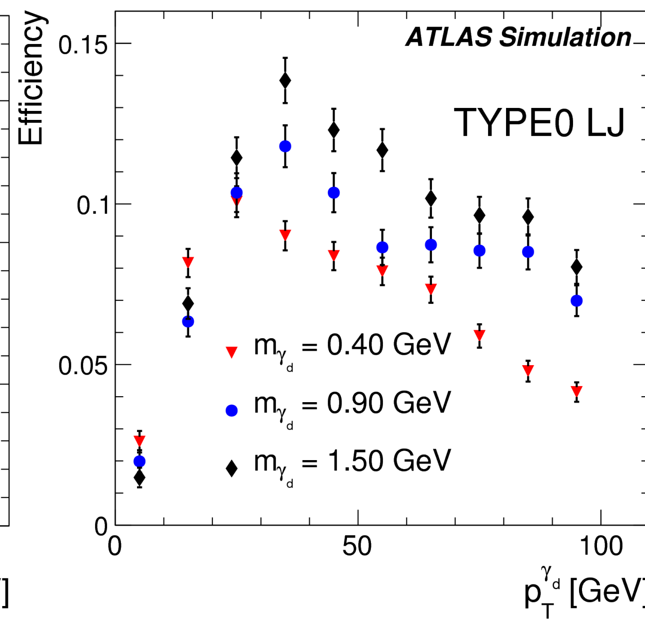
prompt electron LJ



displaced electron/pion LJ



displaced muon LJ



|d0| < 200 mm and |z0| < 270 mm cuts on muon tracks in displaced LJ to suppress cosmic-ray by a factor of 200, while reducing signal efficiencies by 25-50%

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Lepton-jets reconstruction efficiencies (II)

Reconstruction efficiencies for a few lepton-jet types as a function of γ_d decay length

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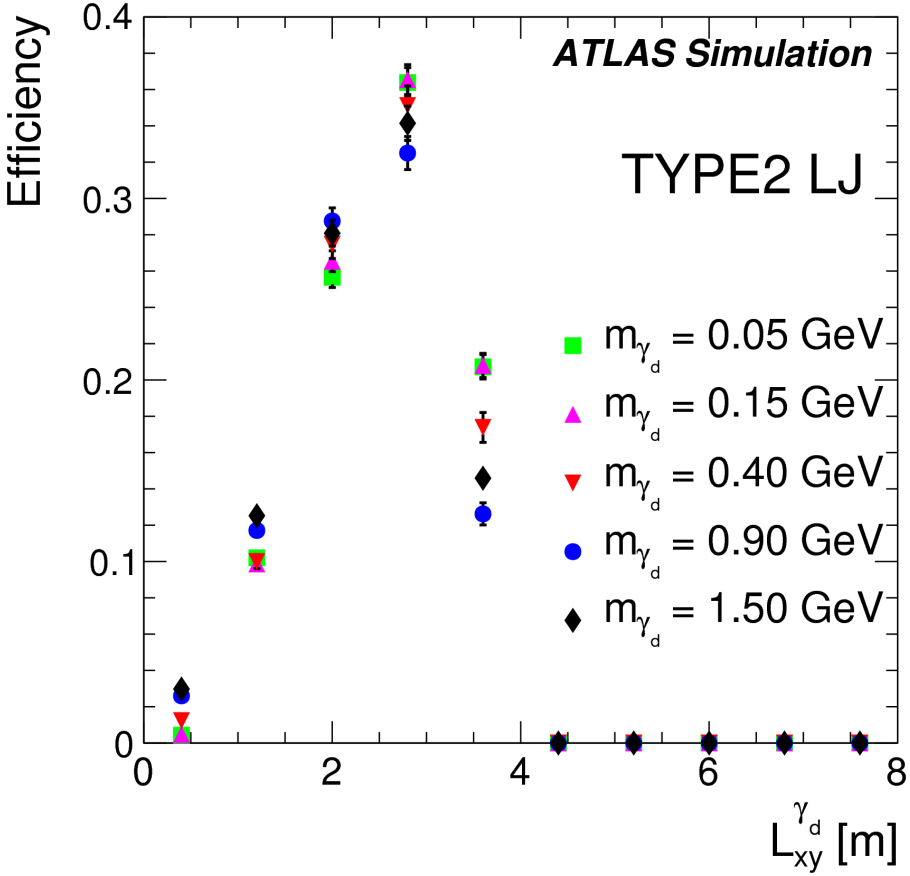
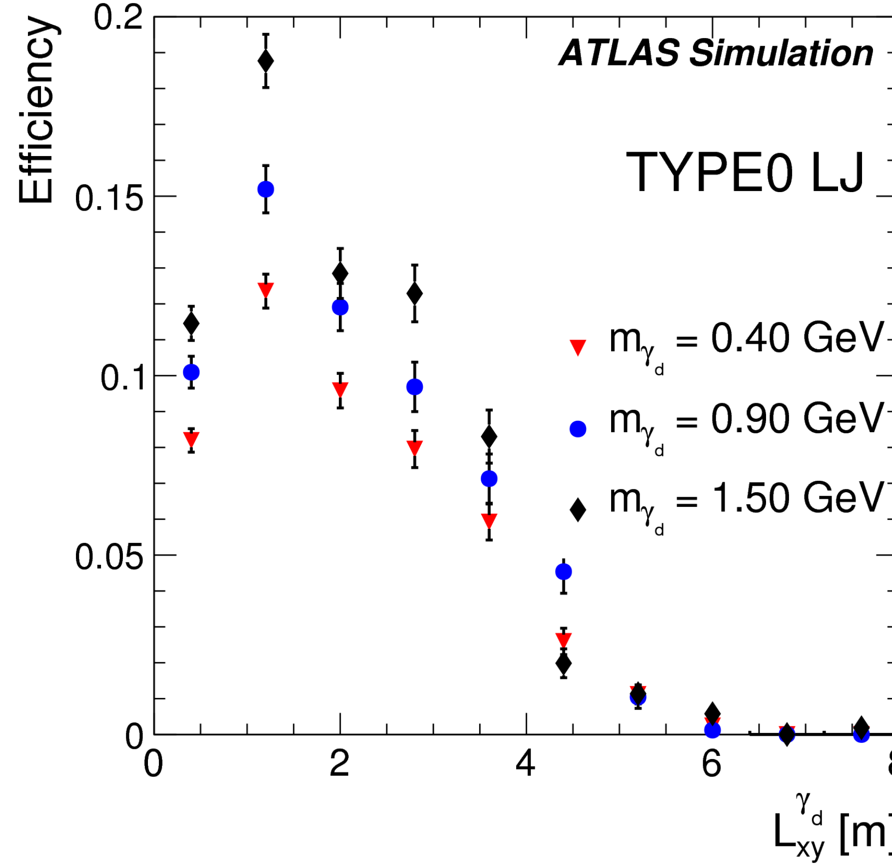
displaced electron/pion LJ



displaced muon LJ



Prompt lepton-jets have constant efficiency below decay length of 50 mm, and drops to zero afterwards

Trigger efficiencies

Trigger efficiencies for long-lived γ_d as a function of γ_d p_T

Electron channel suffers from loss in efficiency for γ_d decaying well before calorimeter that fail to pass trigger cut on electromagnetic to hadronic energy ratio.

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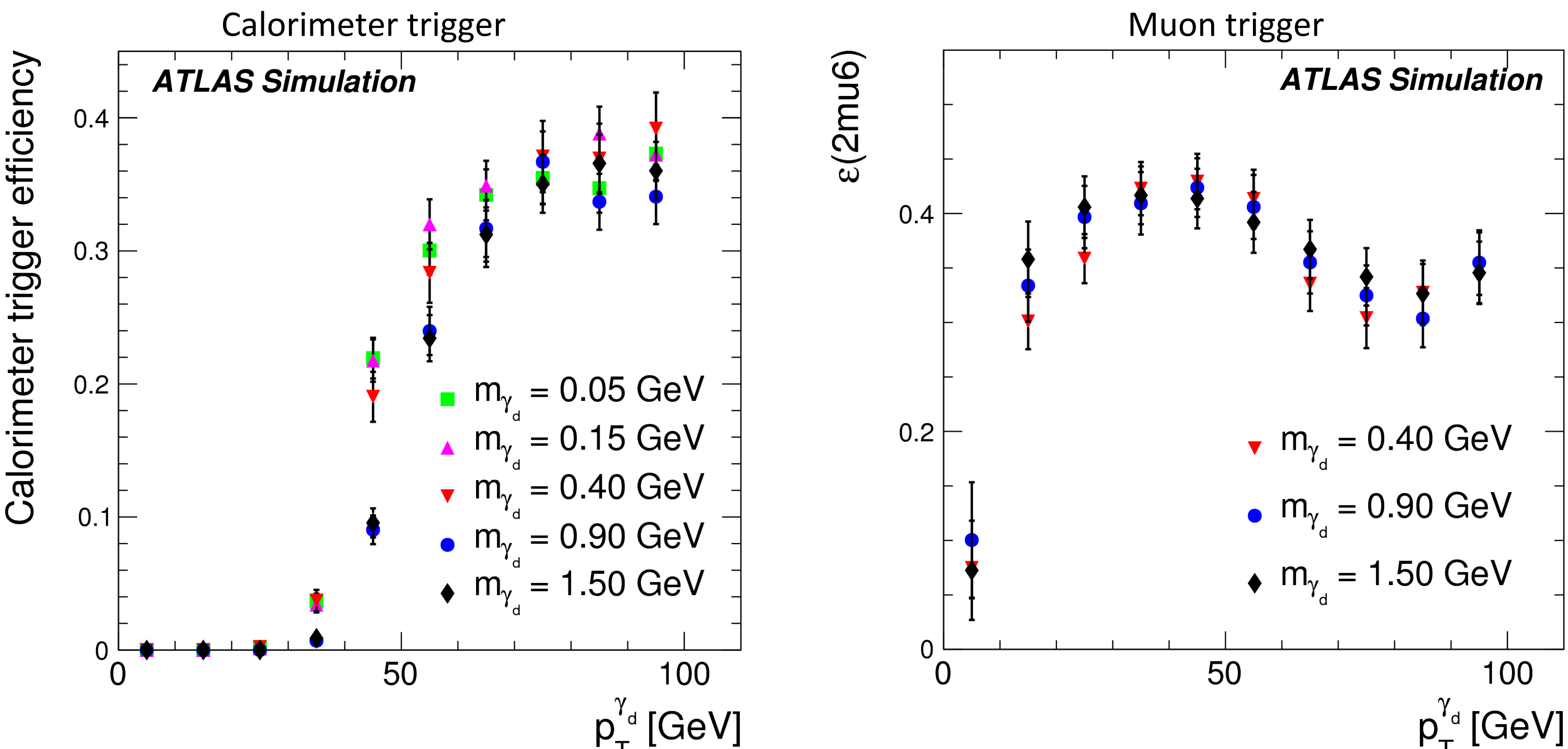
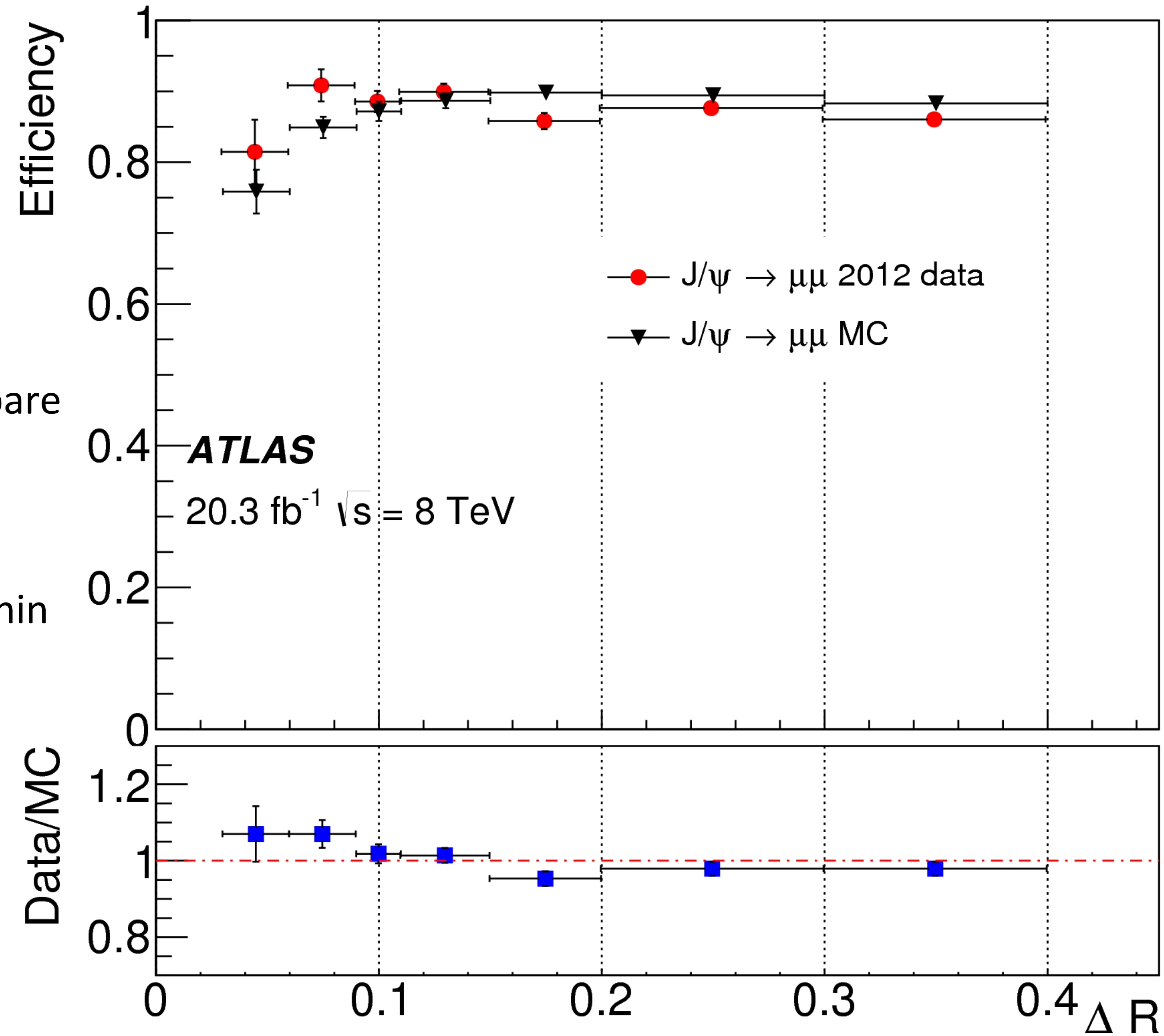


Track reconstruction at small opening angle

Employ usual tag and probe method with J/ψ ->μμ to compare the reconstruction at small opening angle

agreement in data and MC within 5.4%



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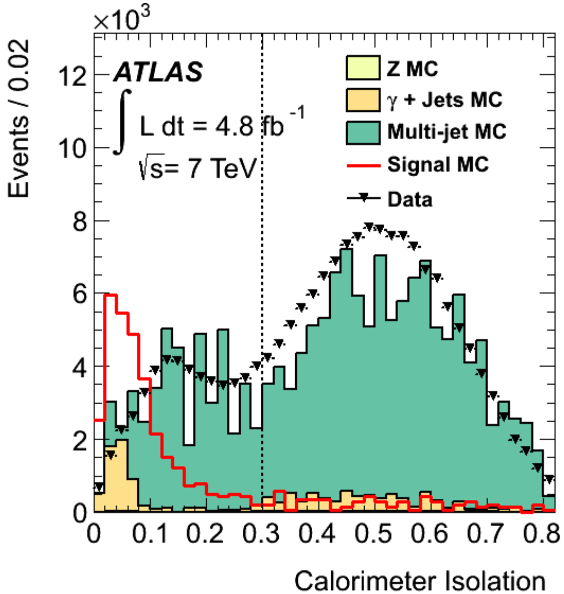
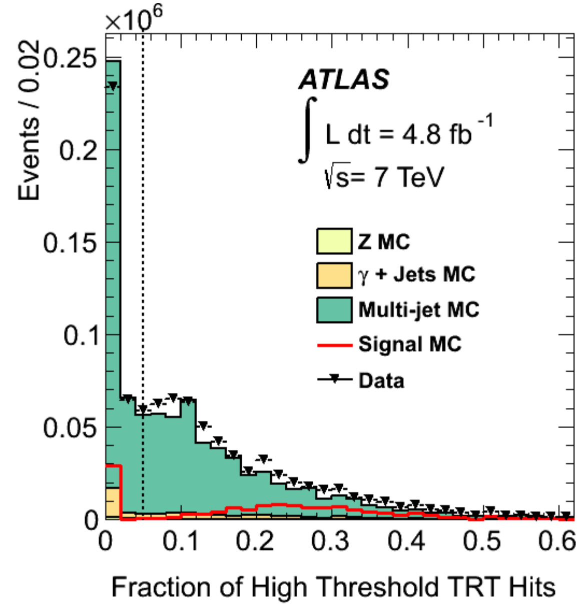
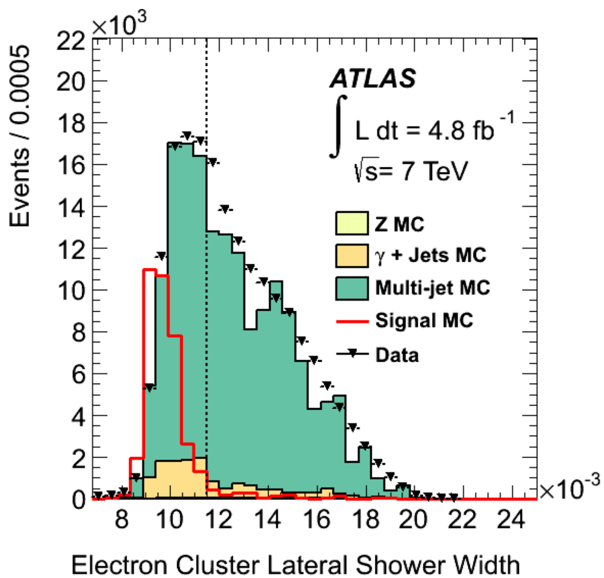
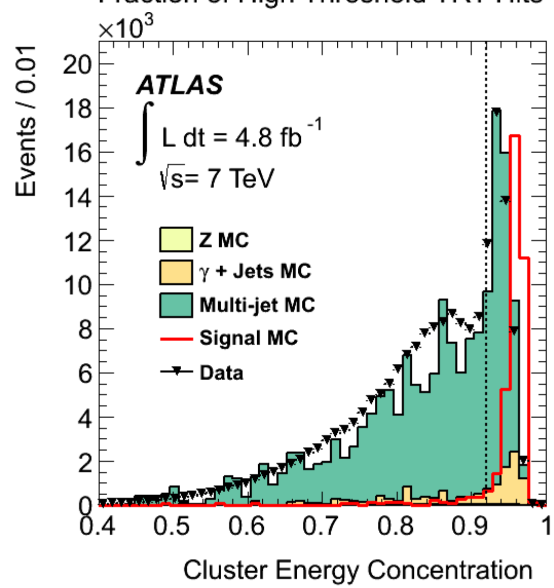
Discriminating variables distributions of LJs









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ABCD likelihood method for background estimation

$$\mu_A = \mu^U + \mu + \mu_A^K$$

$$\mu_B = \mu^U \tau_B + \mu b + \mu_B^K$$

$$\mu_C = \mu^U \tau_C + \mu c + \mu_C^K$$

$$\mu_D = \mu^U \tau_B \tau_C + \mu d + \mu_D^K$$

μ : signal strength

μ^U : background strength

b, c, d : signal contaminations

τ_B, τ_C : ratio of the background in side-bands

$\mu_A^K, \mu_B^K, \mu_C^K, \mu_D^K$: bkg estimate from MC

Minimize the likelihood $\prod_{i=A,B,C,D} \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i!}$ to extract the background μ^U.

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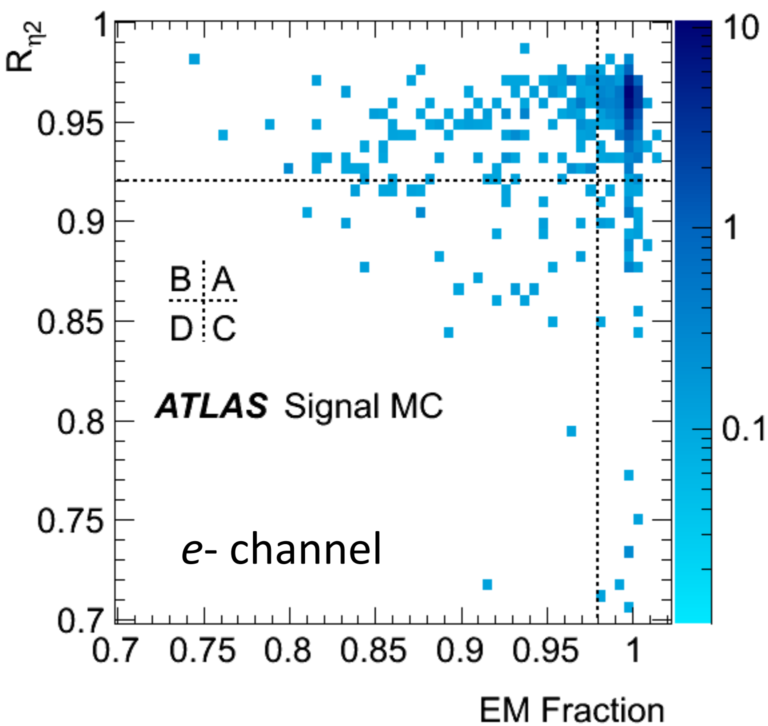
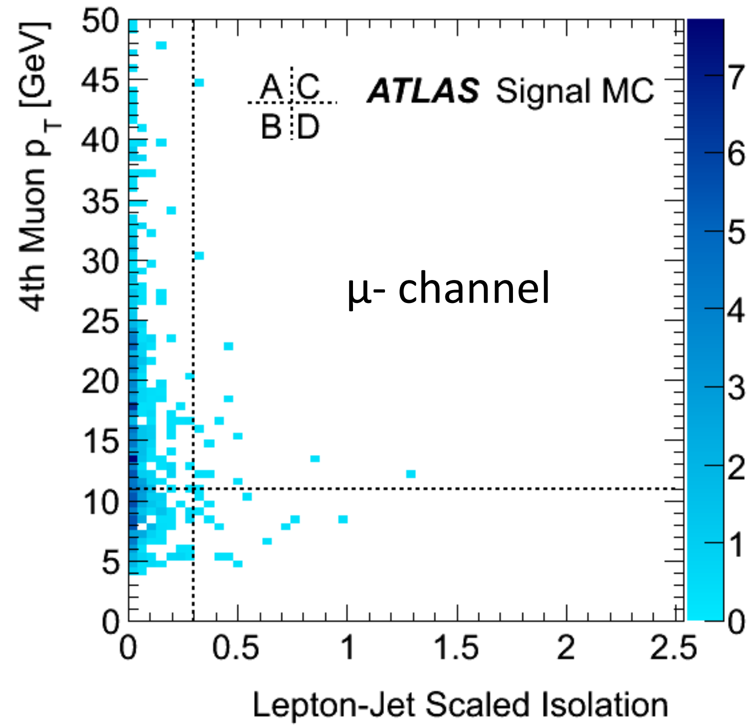
Signal MC (prompt LJ)

- Background due to QCD processes is determined from two nearly uncorrelated discriminating variables using data-driven ABCD method
  - Region A is denoted as signal region





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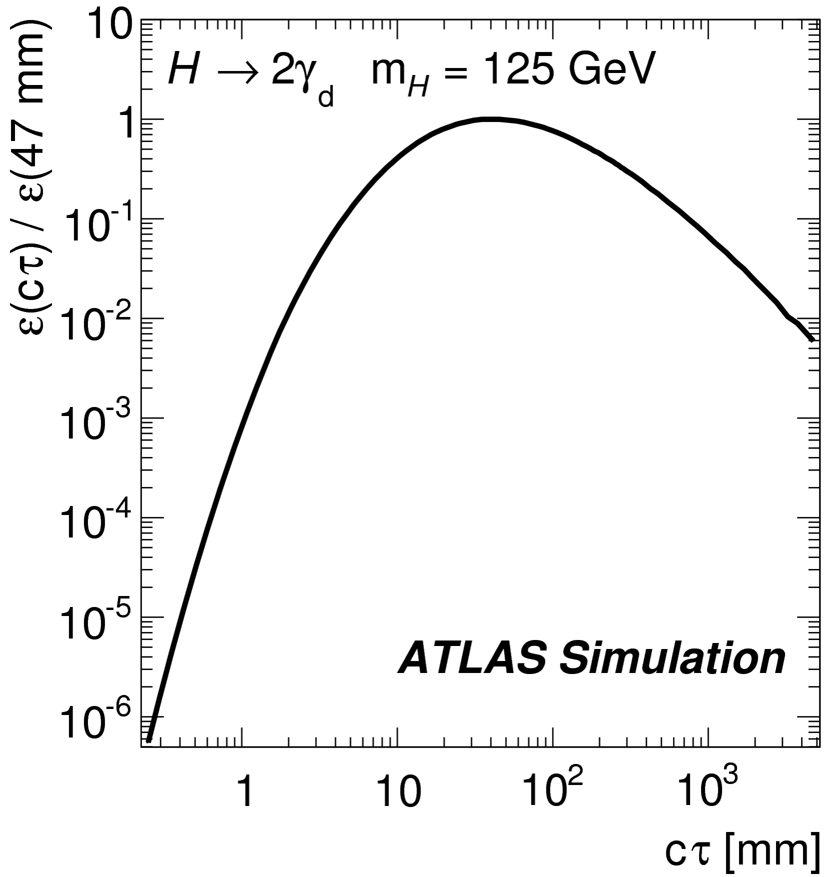
Displaced LJ signal detection efficiency vs cτ

- LJs are reconstructed that decayed after pixel and before muon trigger plane
- Detection efficiency depends on mean lifetime cτ



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Signal efficiencies

For prompt LJ search the signal efficiency ranges from 1.8% to 9.2% depending on γ_d mass and channel

γ_d mass MeV	Acceptance x eff (%) e-channel	Acceptance x eff (%) μ-channel
150	3.01 ± 0.30	--
300	2.7 ± 0.5	9.2 ± 0.9
500	1.8 ± 0.5	8.5 ± 1.1

The overall detection efficiency for two displaced LJs for signal selection is 0.15%

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Prompt LJ 7 TeV data analysis systematics

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Source	Systematics uncertainty
Luminosity	3.9%
Trigger	1.5% - 2%
ID track or muon reconstruction at small ΔR	11% - 13%
Muon momentum scale/resolution	1%
Electron energy scale	0.6%
Discriminating variables efficiency	1% - 10%

Displaced LJ 8 TeV data analysis systematics

Source	Systematics uncertainty
Luminosity	2.8%
Trigger	5.8% - 11%
Muon reconstruction at small ΔR	5.4%
Muon momentum scale/resolution	1.0%
Jet energy scale	0.9% - 1.7%
Effect of pile-up	4.1%
Multi-jet background	15%
Cosmic-ray background	22%

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