INELASTIC DARK MATTER AT COLLIDERS

E. Izaguirre, G. Krnjaic, BS, arXiv:1508.03050

Brian Shuve

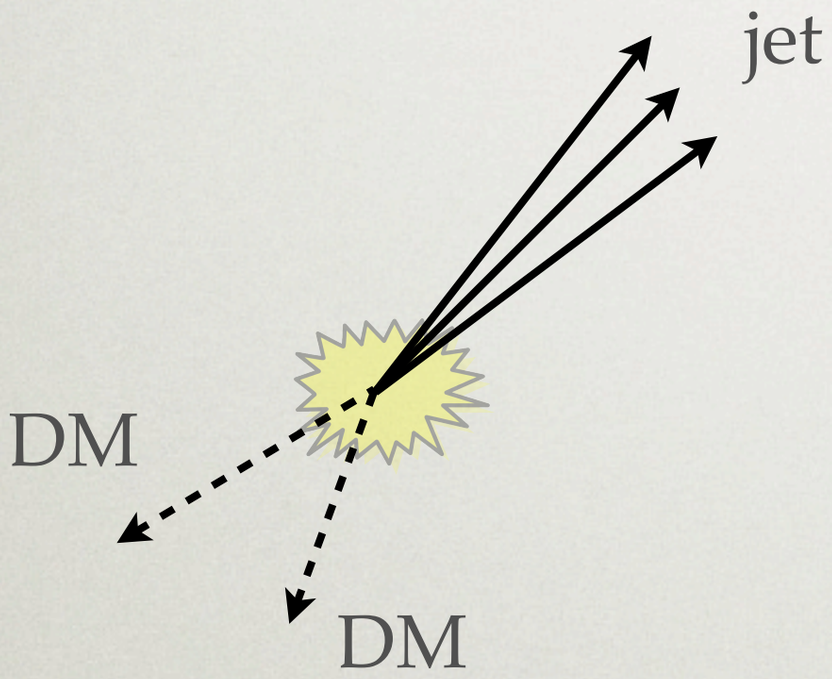
SLAC

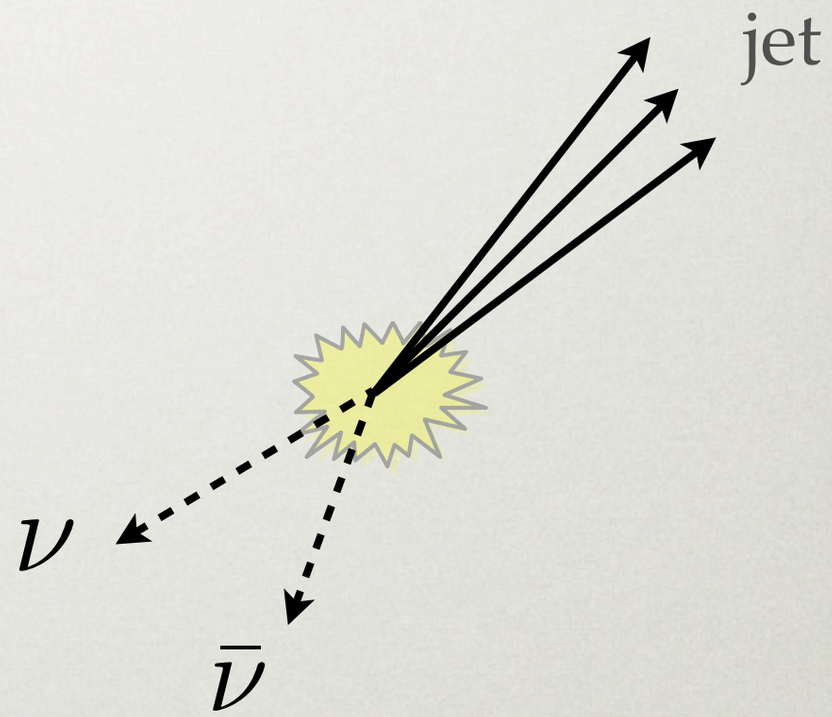
ATLAS Dark Sector Workshop, Cosenza

9 February 2016

Discovering Dark Matter

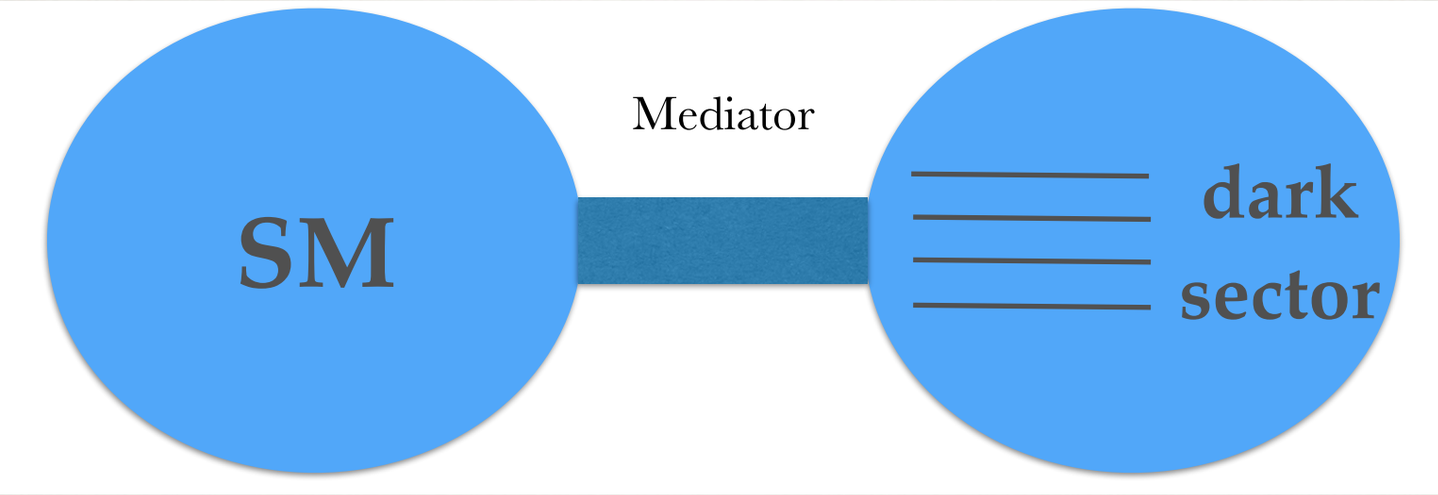
- MET searches are model-independent, but suffer large backgrounds





Discovering Dark Matter

- When there are more dark particles, there are more probes



- Can be whole new sector with confining forces (*c.f.* hidden valley)

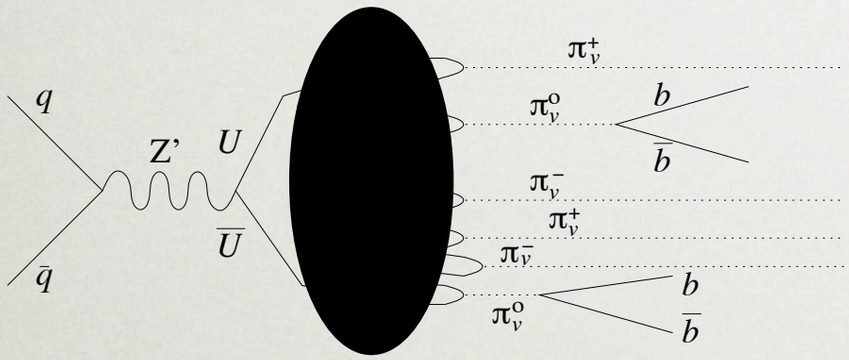
Strassler, Zurek, hep-ph/0604261; Strassler, Zurek, hep-ph/0605193;
Strassler, hep-ph/0607160; Han *et al.*, 0712.2041

- Can be simple with just a few new particles

Holdom, 1986; Pospelov, Ritz, Voloshin, 0711.4866; Arkani-Hamed *at al.*, 0810.0713;
Cheung *et al.*, 0909.0920; Falkowski *et al.*, 1002.2952; and many more...

Dark Sector Collider Signals

- If most dark sector energy dumped back to **visible particles**:



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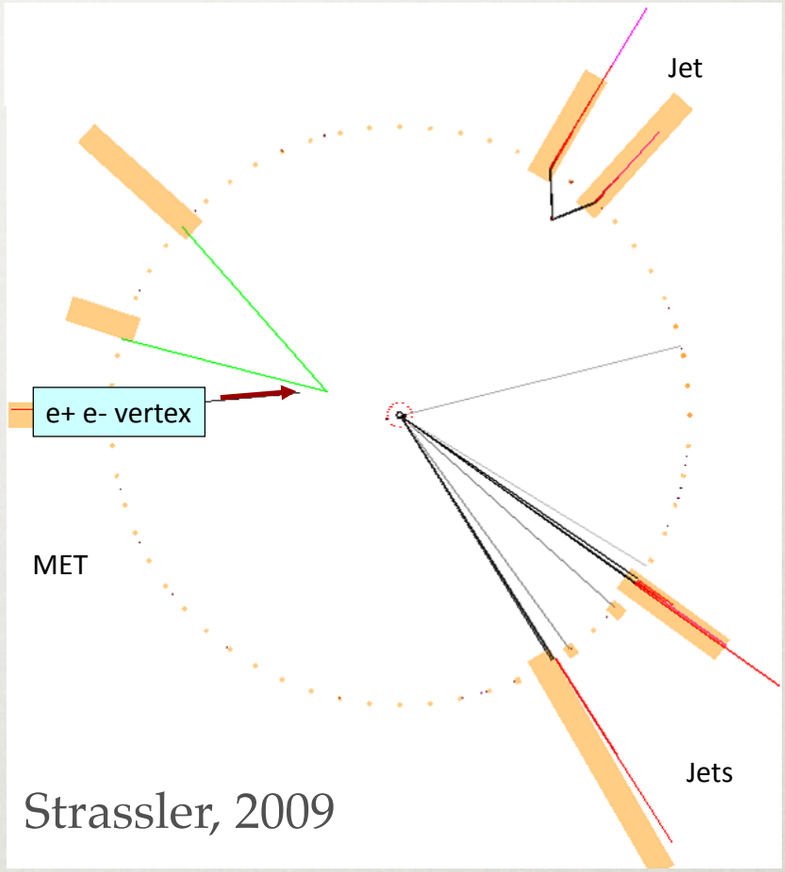
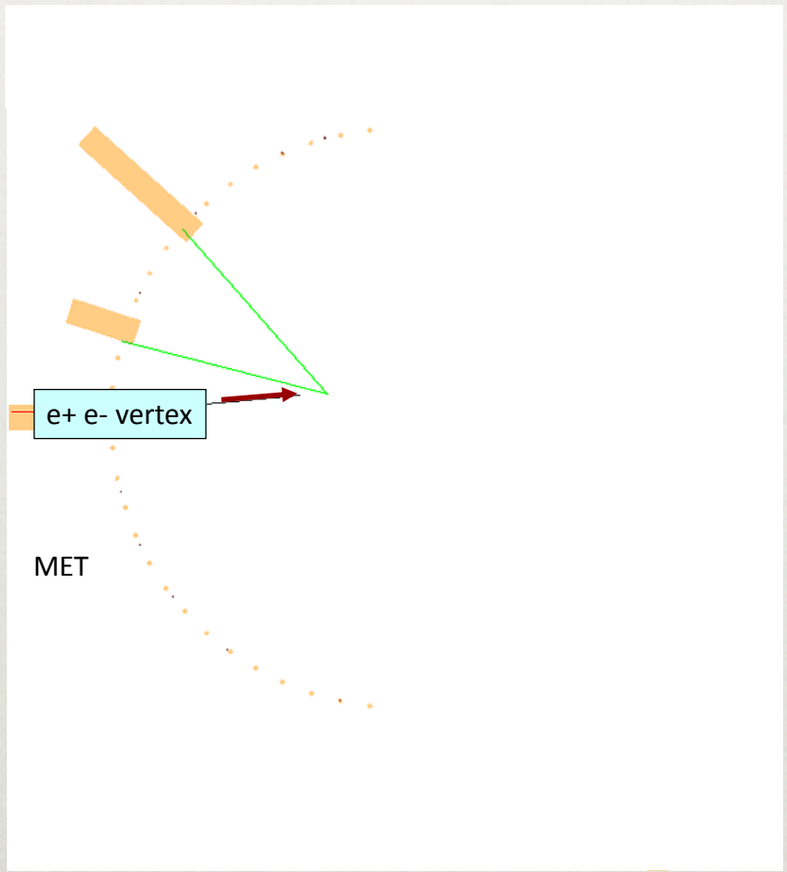


Strassler, 2009

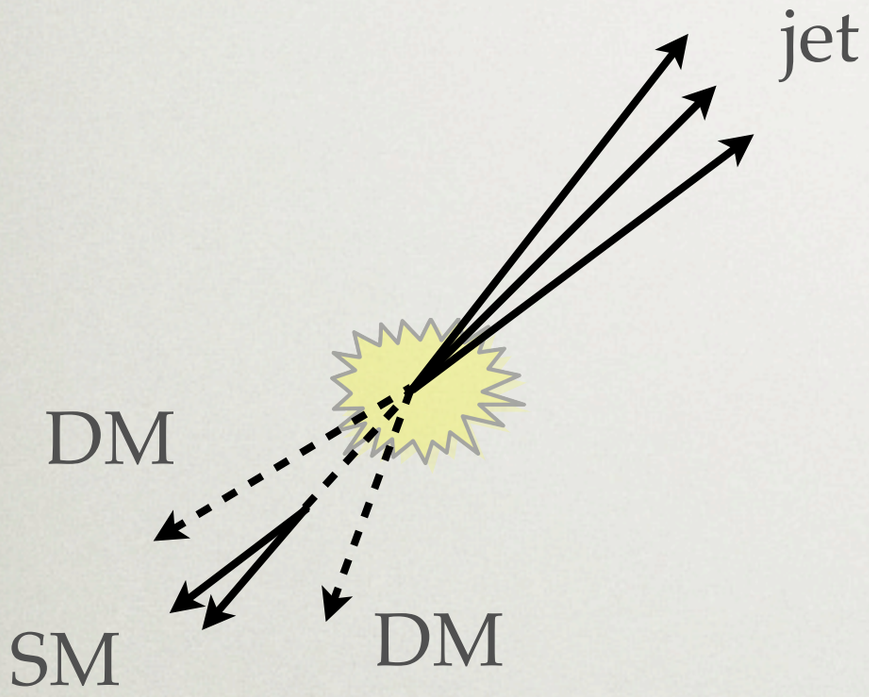
- Get many hard objects: displaced vertices, “emerging jets”, “semi-visible jets”, lepton jets, photon jets, ...

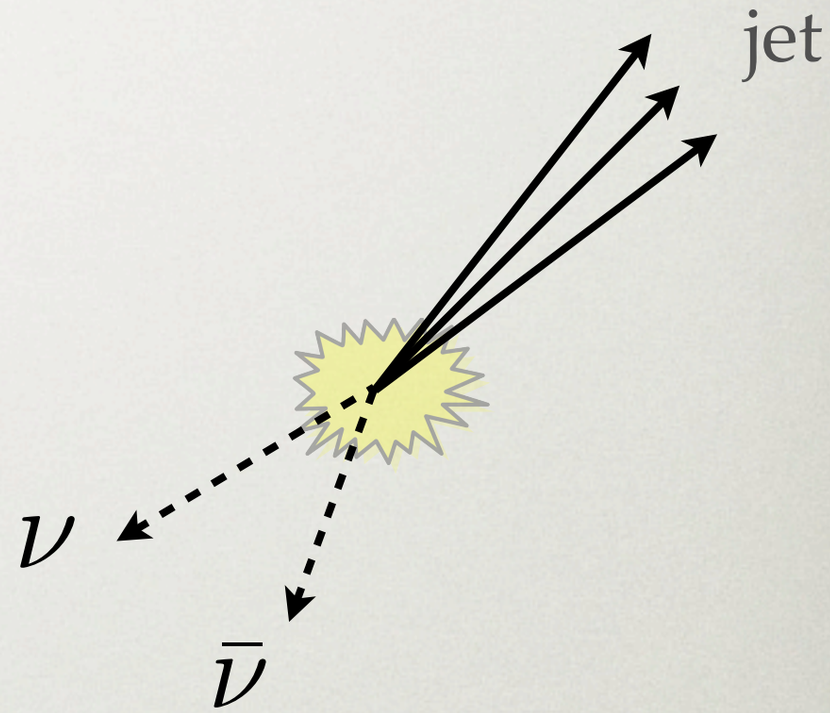
Dark Sector Collider Signals

- If dark sector decays mostly into **invisible** particles...



Dark Sector Collider Signals





Outline

- **Model: Inelastic Dark Matter**
    - An iDM Benchmark Model

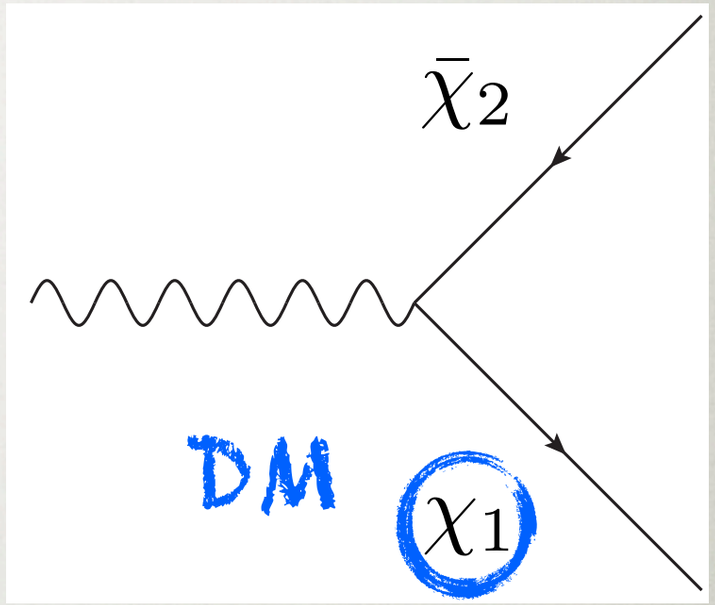
- **Proposals for iDM Searches**
    - Dark Photon
    - Magnetic iDM
    - Other Applications (if time)

Inelastic Dark Matter

- In **Inelastic Dark Matter** (iDM) scenarios, interactions always involve two **different** dark sector particles

Tucker-Smith, Weiner, hep-ph/0101138

$$\Delta \equiv M_2 - M_1 > 0$$



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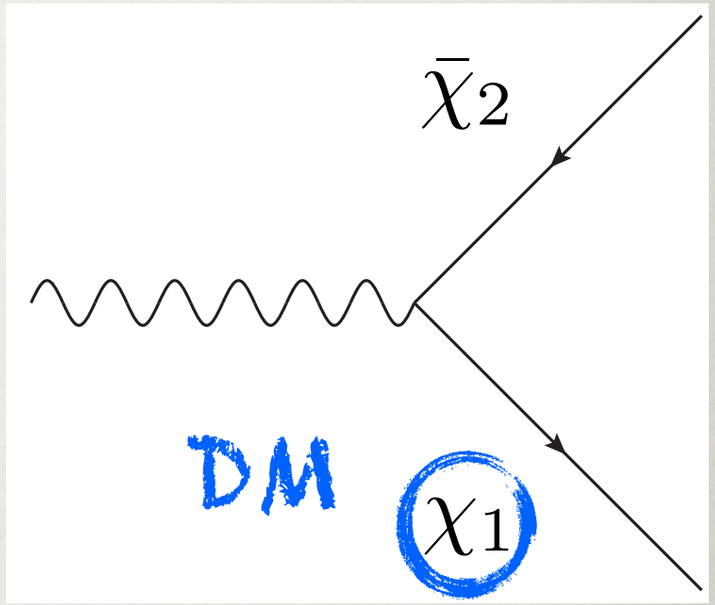
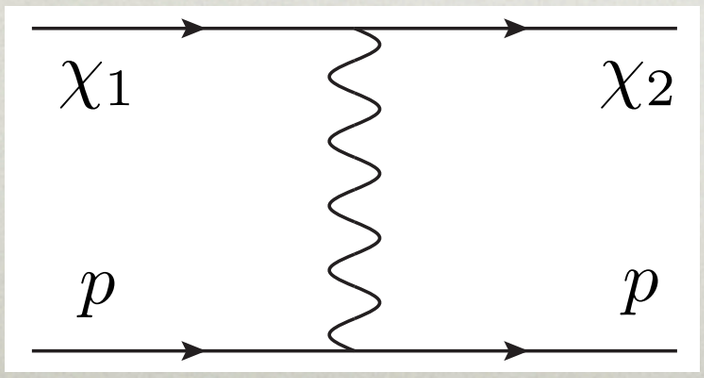
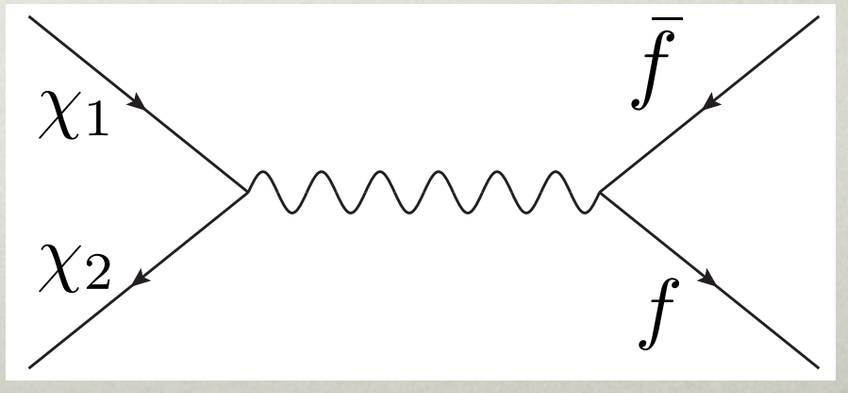


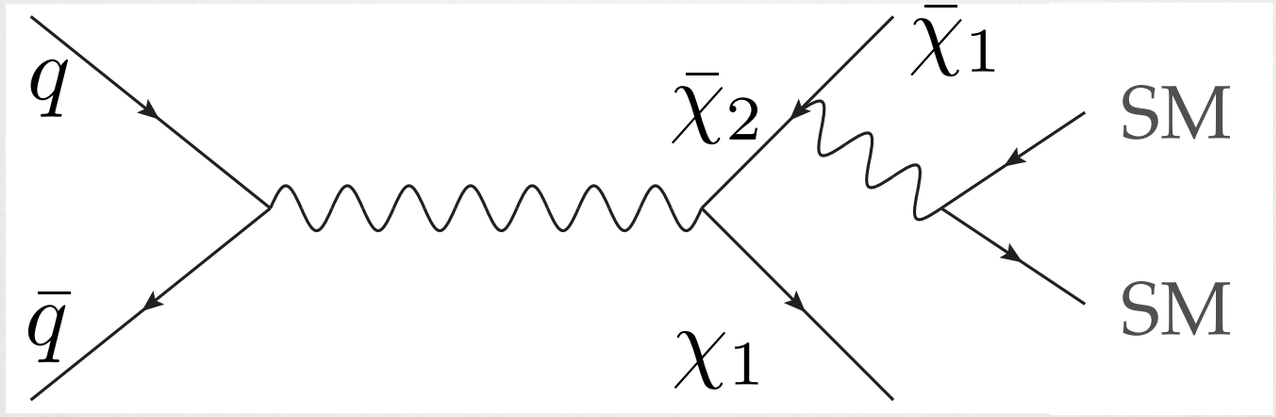
- Can greatly suppress DM signals today!





Inelastic Dark Matter

- By contrast, colliders can easily produce both $(\Delta \lesssim \mathrm{TeV})$



Weiner, Yavin, 1206.2910; Primulando *et al.*, 1503.04204

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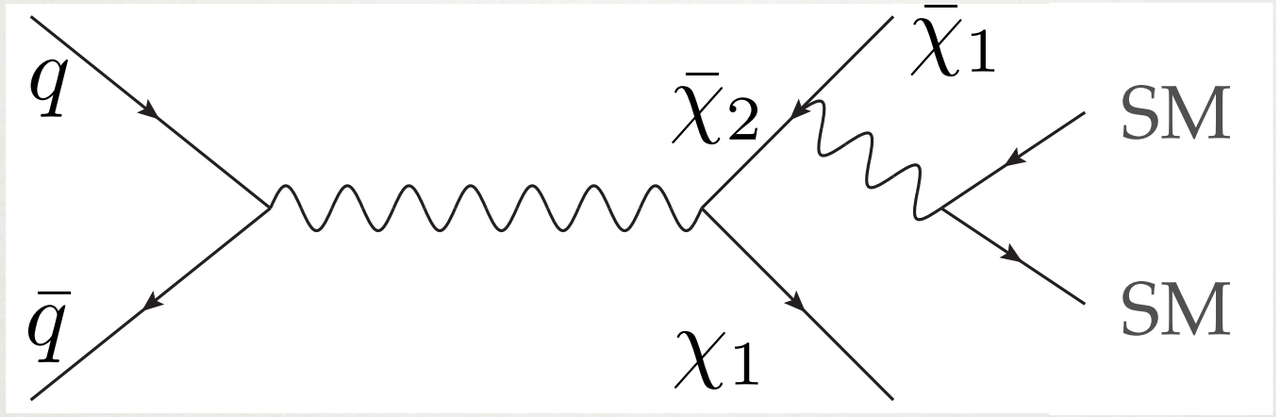
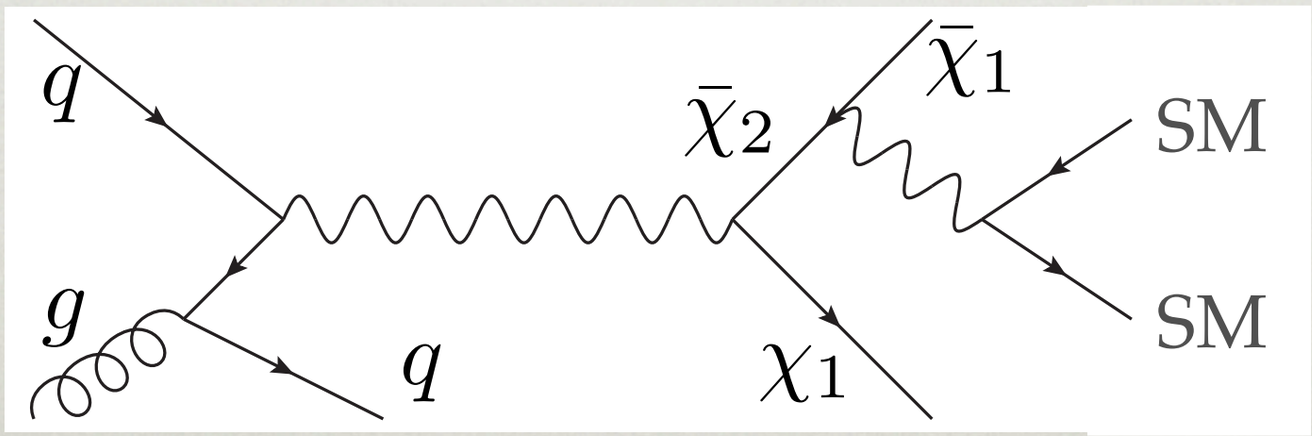


Weiner, Yavin, 1206.2910; Primulando *et al.*, 1503.04204

- If decay products too soft, use monojet + MET

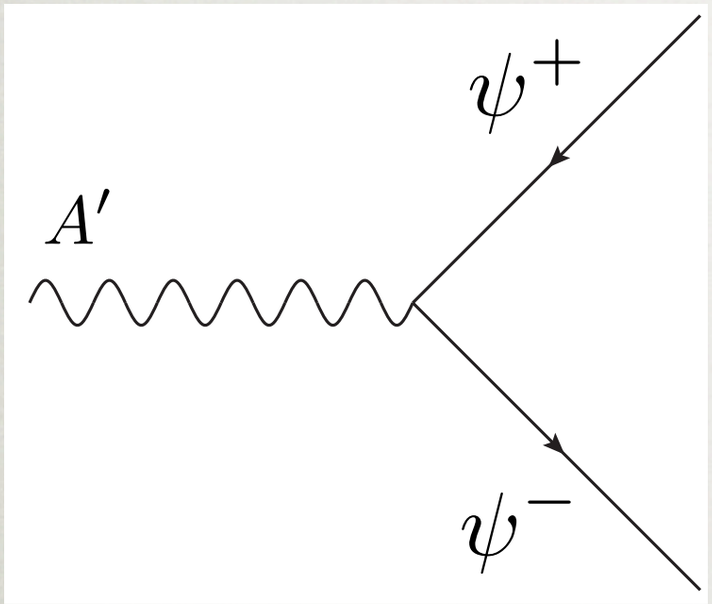


Bai, Tait, 1109.4144; Izaguirre, Krnjaic, BS, 1508.03050

An Inelastic Benchmark

Tucker-Smith, Weiner, hep-ph/0101138; Izaguirre, Krnjaic, BS, 1508.03050

- Higgsed dark QED



$$\mathcal{L} \supset ig'\bar{\psi}\gamma^\mu\psi A'_\mu - M_\psi\bar{\psi}\psi$$

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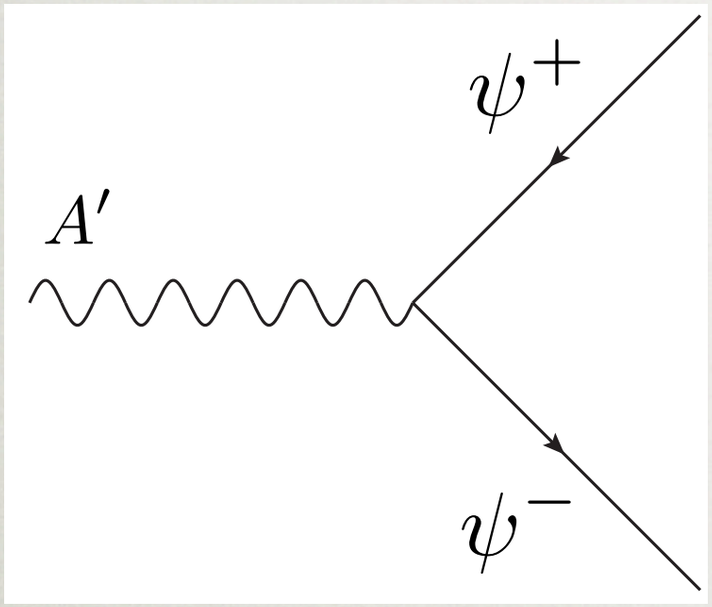

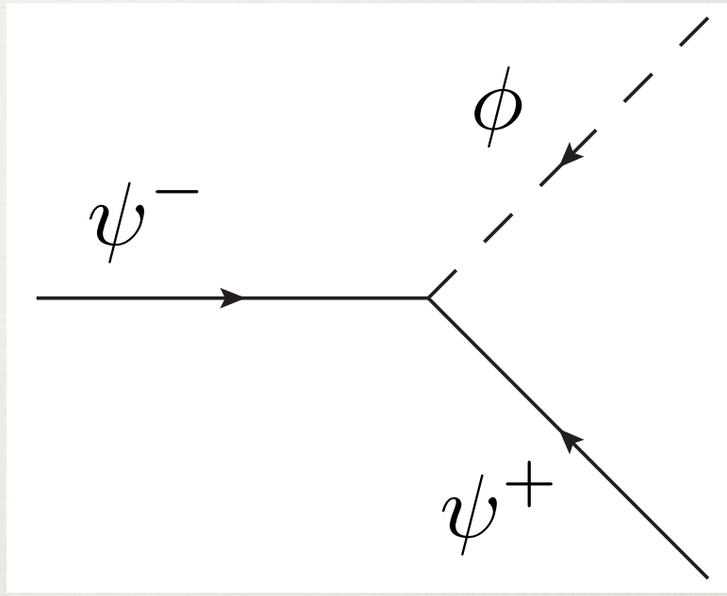

$$\mathcal{L} \supset i g' \bar{\psi} \gamma^\mu \psi A'_\mu - M_\psi \bar{\psi} \psi + y \phi \bar{\psi}^c \psi$$

An Inelastic Benchmark

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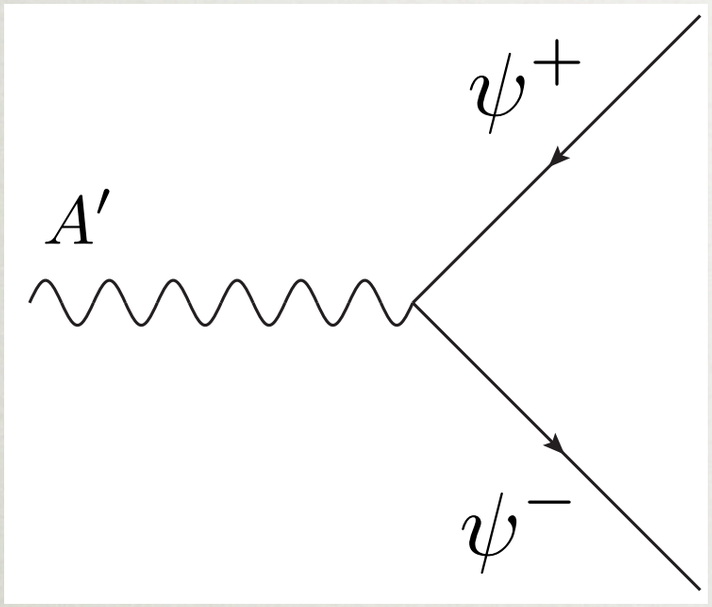

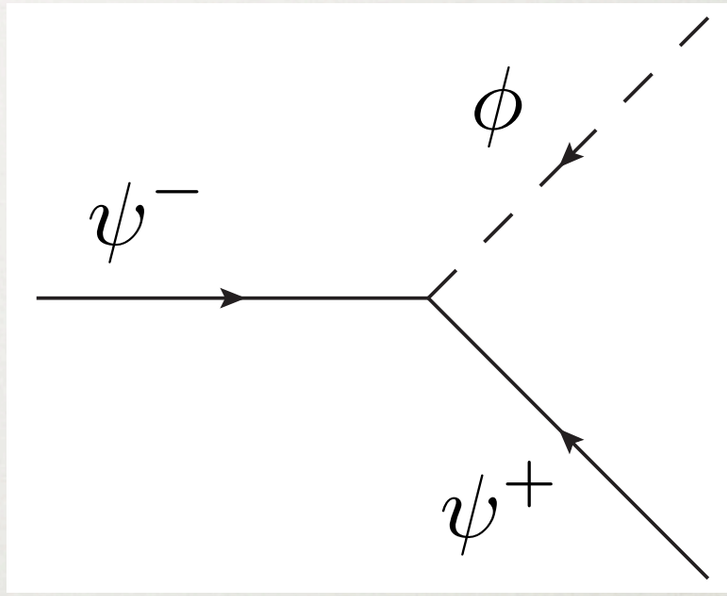

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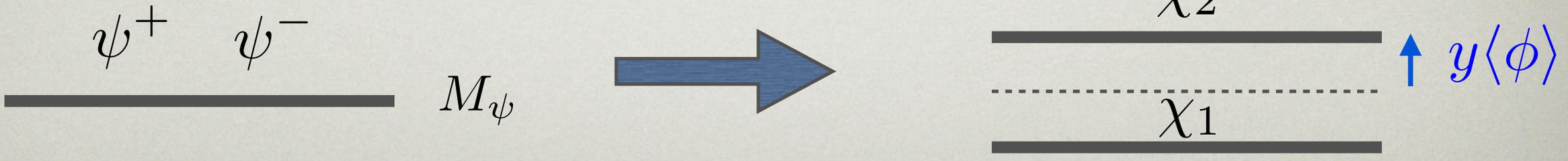
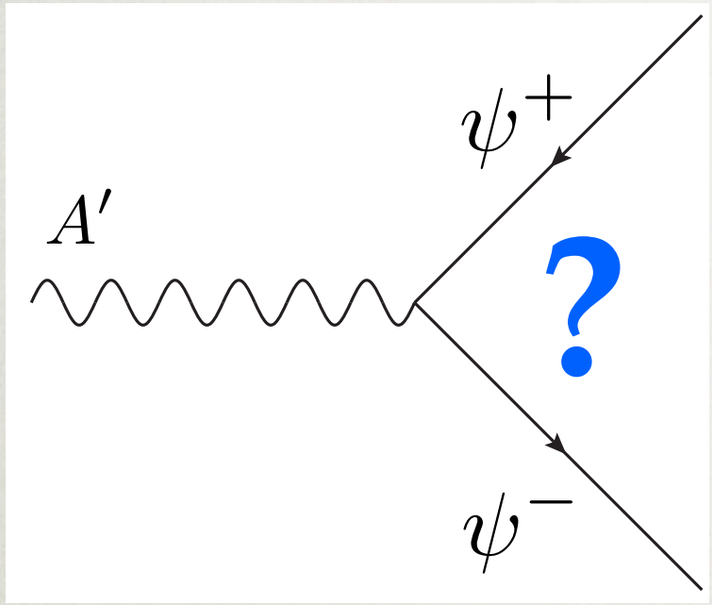


An Inelastic Benchmark

- How do $\chi_{1,2}$ interact under force?



$\chi_{1,2}$ are Majorana (particle = antiparticle):

$$\bar{\chi}_i \gamma^\mu \chi_i A'_\mu = 0$$

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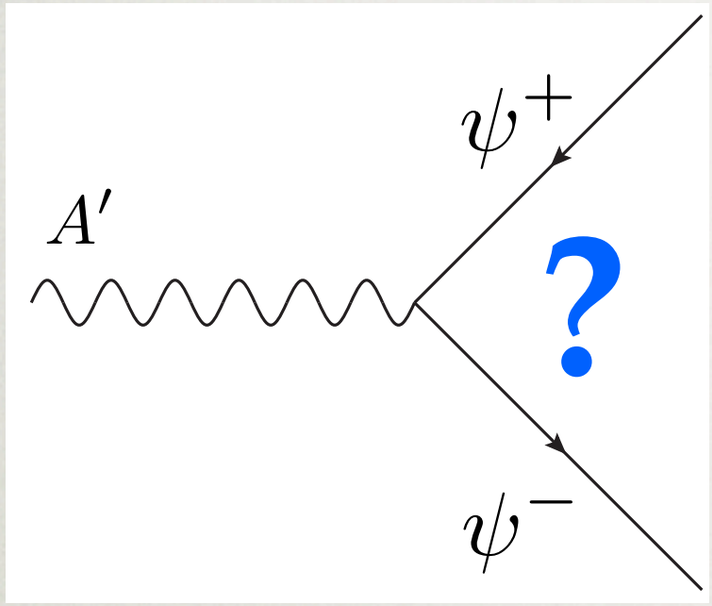
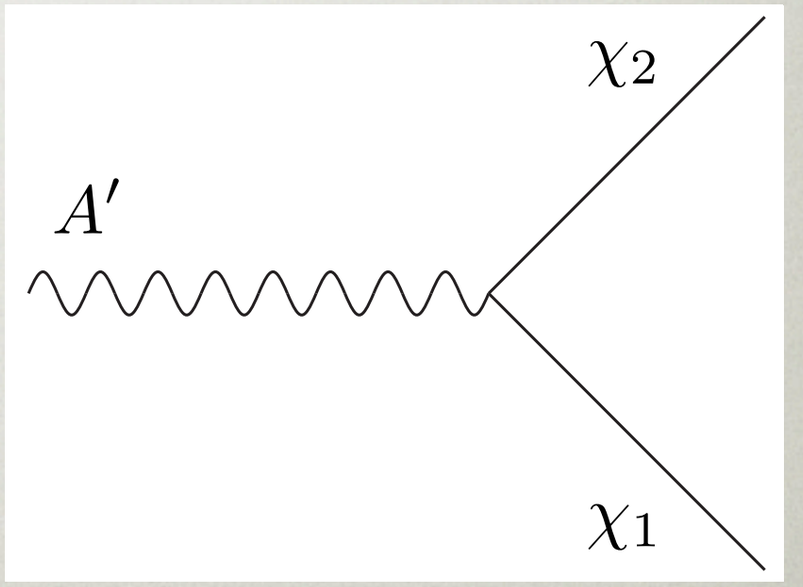


$\chi_{1,2}$ are Majorana (particle = antiparticle):

$$\bar{\chi}_i \gamma^\mu \chi_i A'_\mu = 0$$

- If parity conserved, only **inelastic** interaction allowed

$$\mathcal{L} \supset i g' \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu$$



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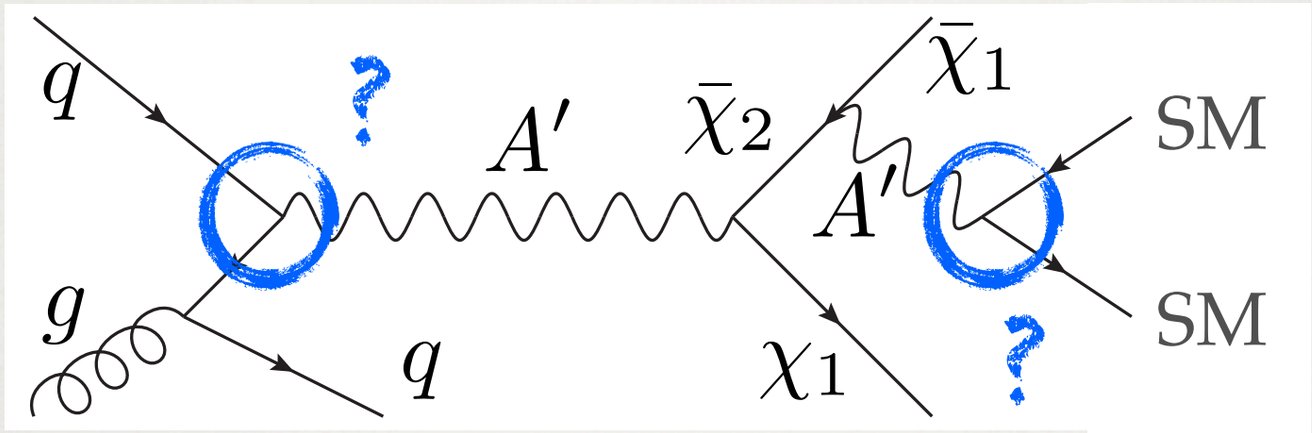

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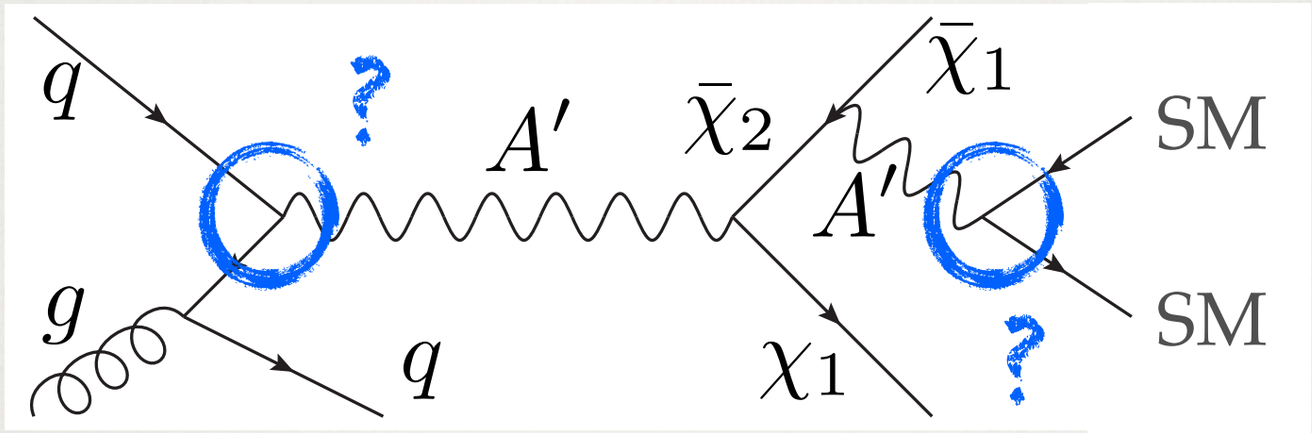
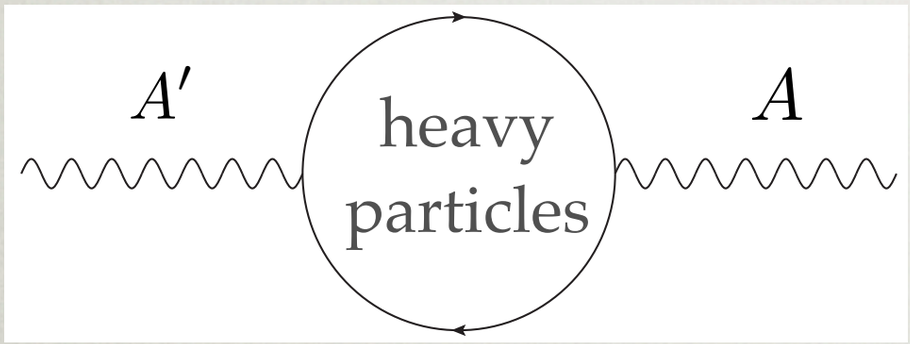
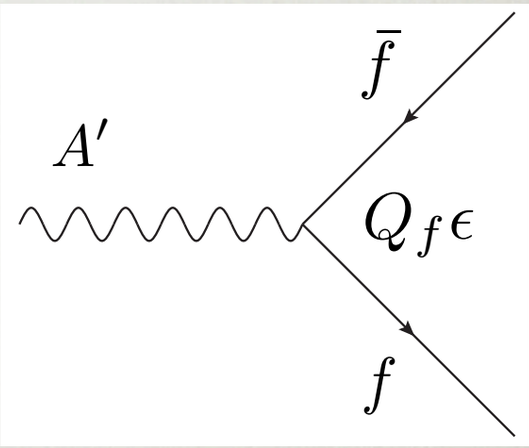


- The dark photon can kinetically mix with visible photon



$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

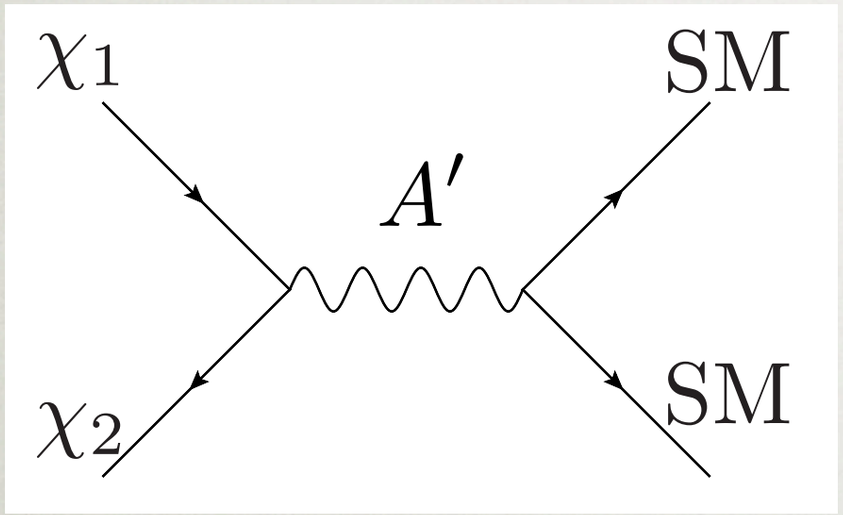


- We consider the spectrum hierarchy $\Delta \ll M_{1,2} \lesssim M_{A'}$

For other hierarchies, see: "Secluded DM", Pospelov, Ritz, Voloshin, 0711.4866; Autran *et al.*, 1504.01386; Bai *et al.*, 1504.01395; Buschmann *et al.*, 1505.07549

Inelastic Freeze-out

- Many parameters -- we want to connect DM freeze-out to lab probes



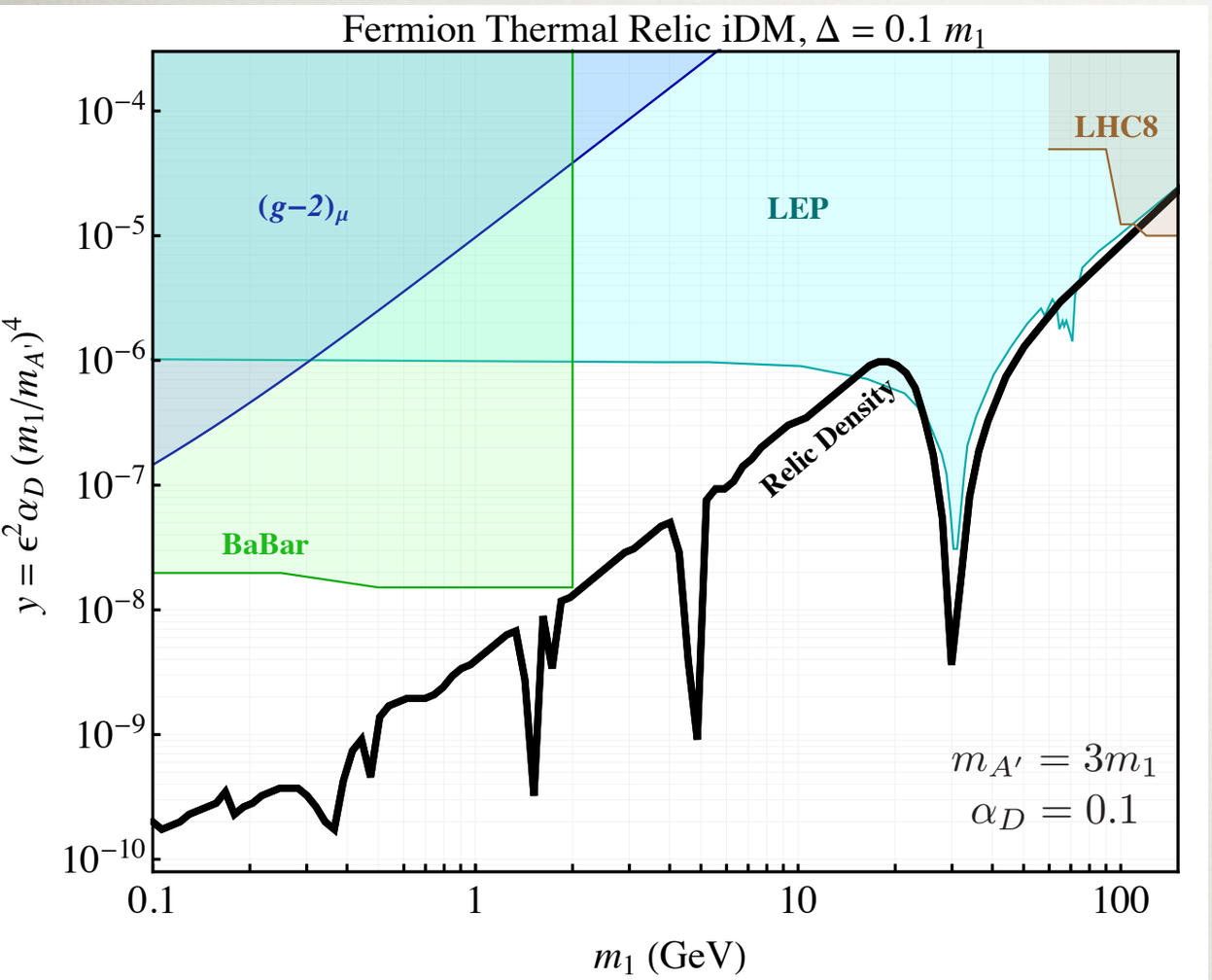
$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_{\rm D} M_1^2}{M_{A'}^4} = \frac{y}{M_1^2} \qquad (M_{A'} \gg M_1)$$

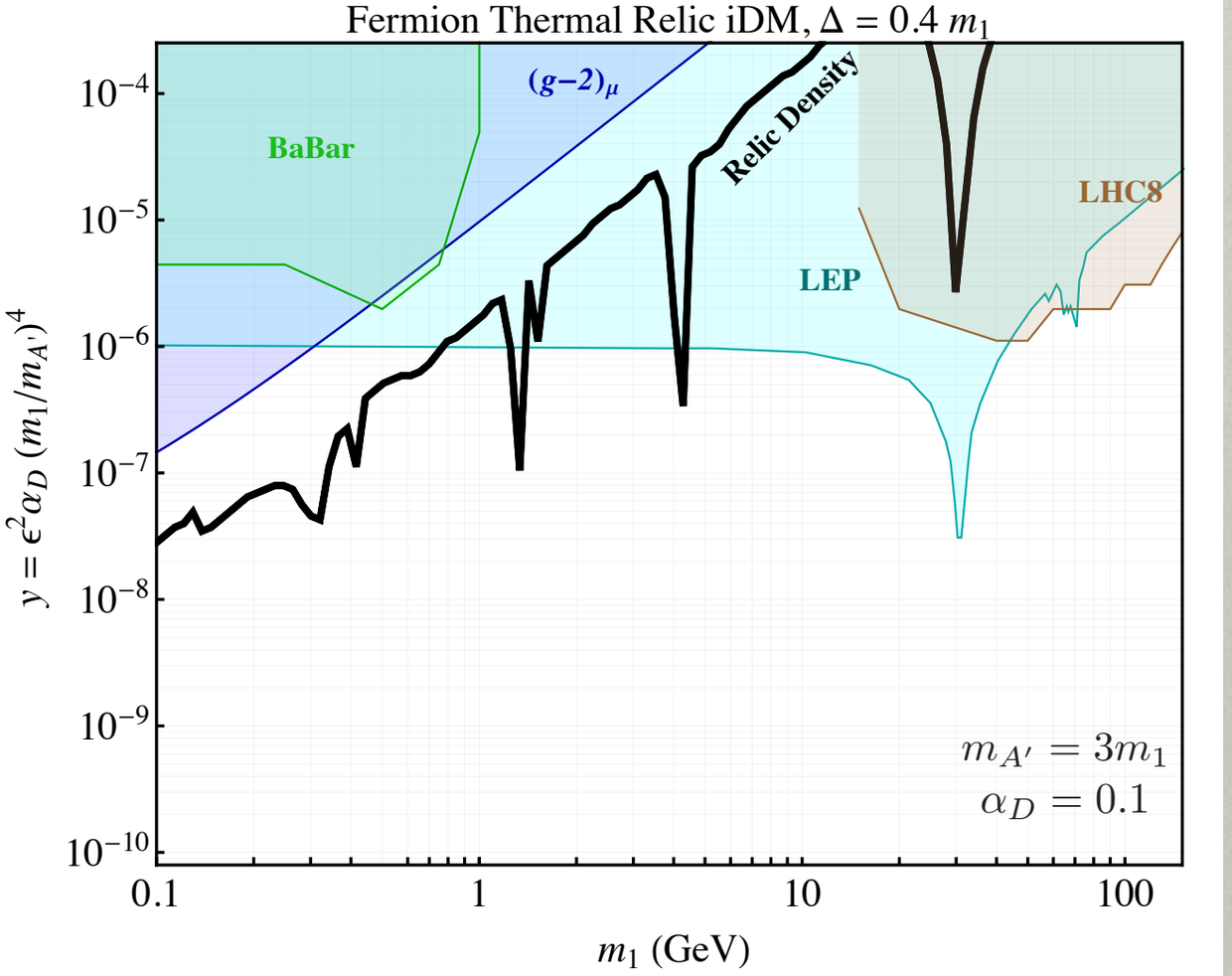
$$y \equiv \epsilon^2 \alpha_{\rm D} \left(\frac{M_1}{M_{A'}} \right)^4$$

- Choose large value of $\alpha_{\rm D}$ to avoid over-stating bounds

(Izaguirre *et al.*, 1505.00011)

An Inelastic Benchmark



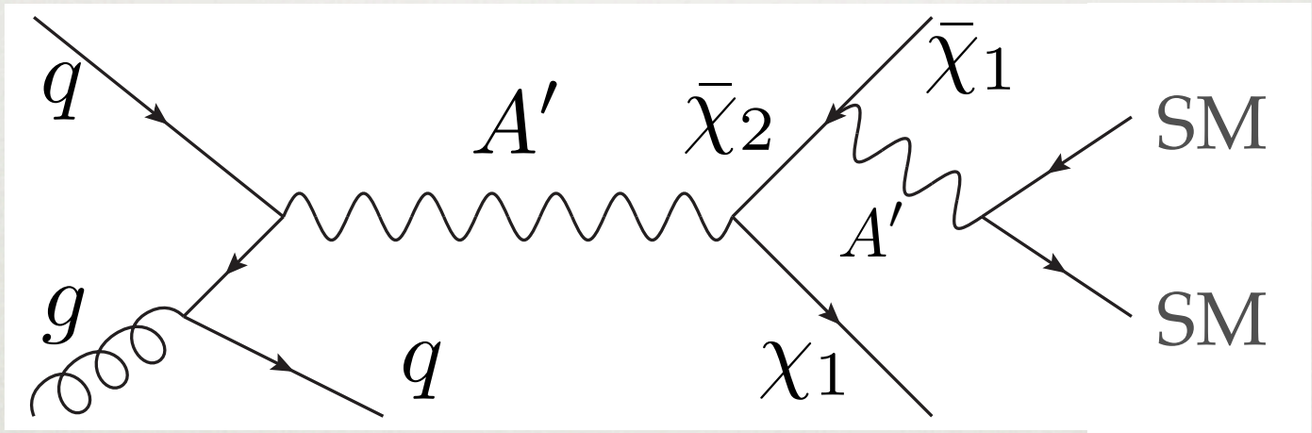


Proposals for iDM Searches

Dark Photon

E. Izaguirre, G. Krnjaic, BS, arXiv:1508.03050

Improving the Searches



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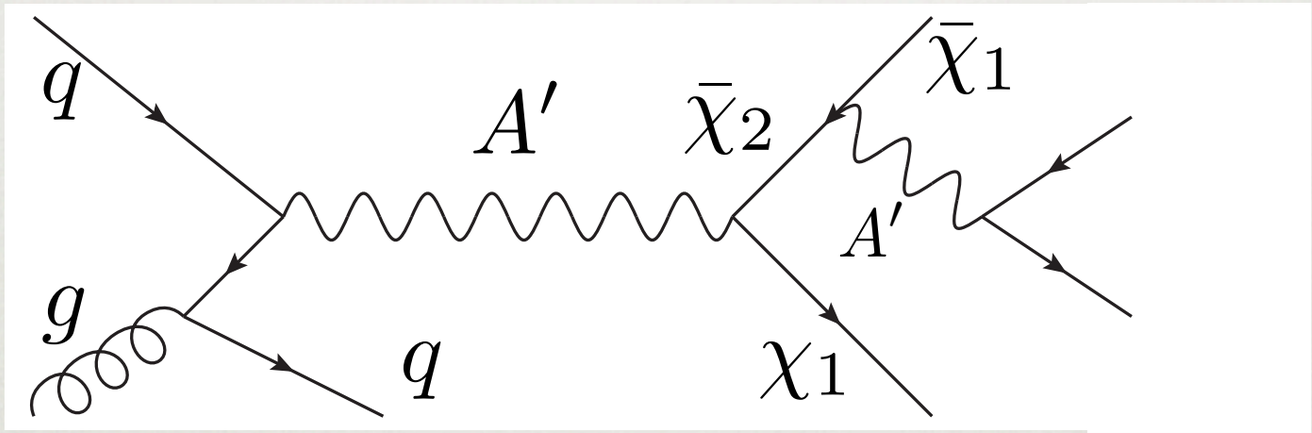

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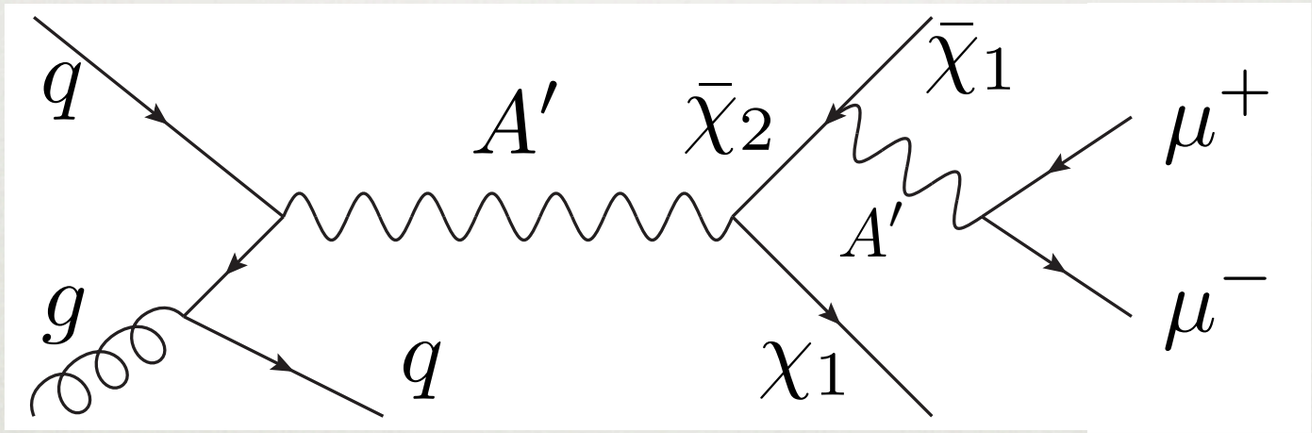

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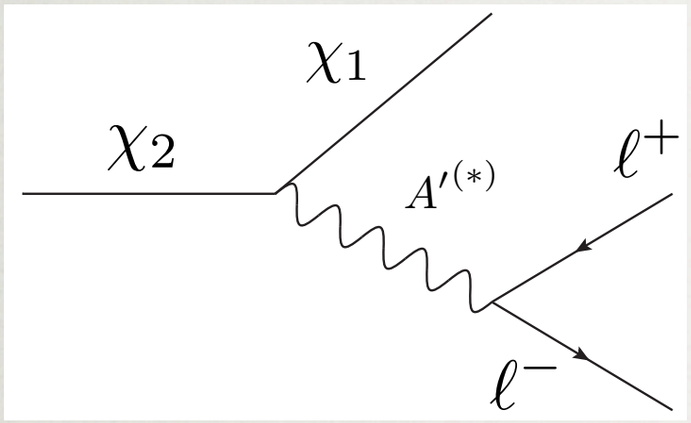
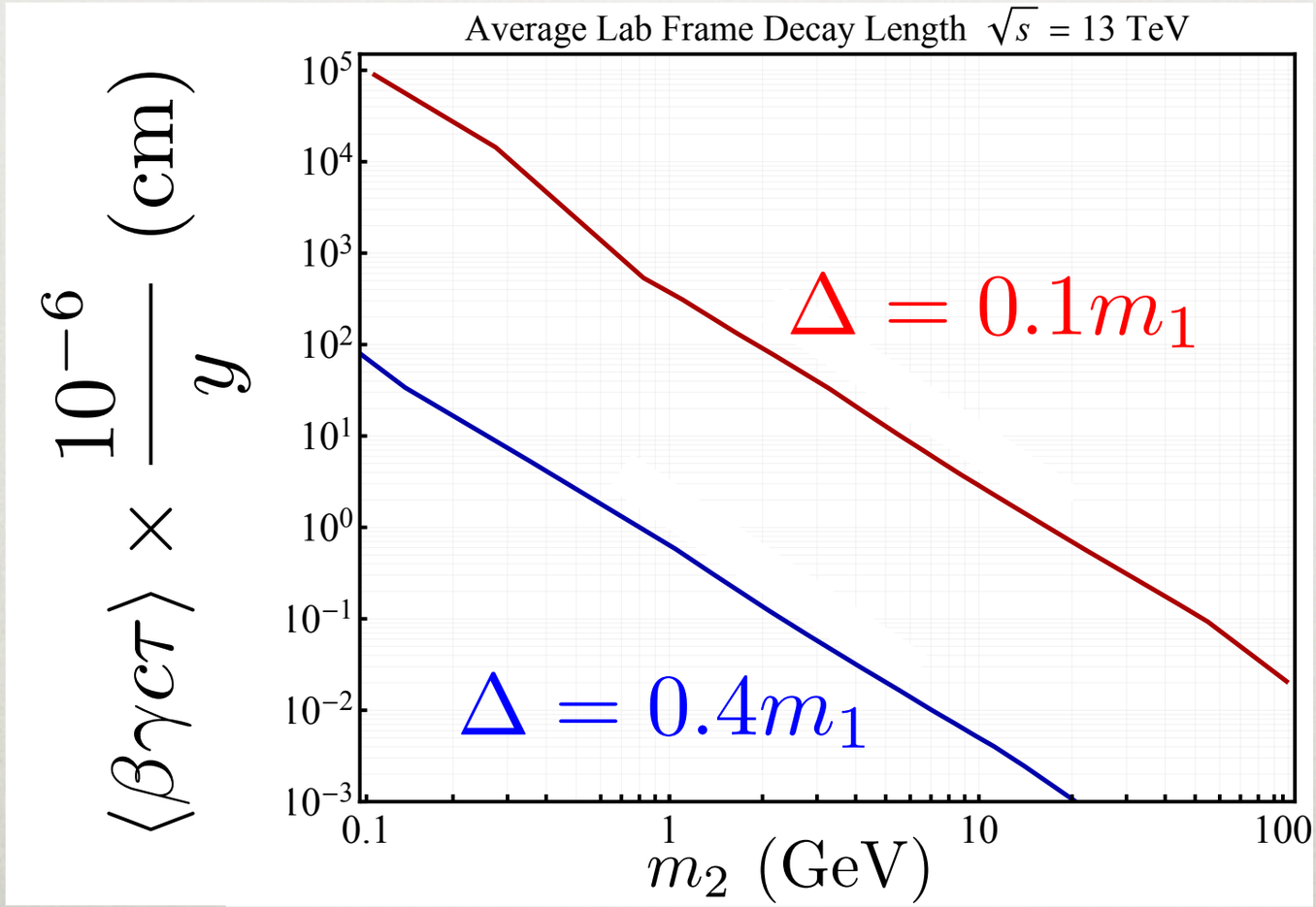


$$\Gamma_{\chi_2} \sim \frac{\alpha \alpha_D \epsilon^2 \Delta^5}{M_{A'}^4}$$

- Get displaced decay!



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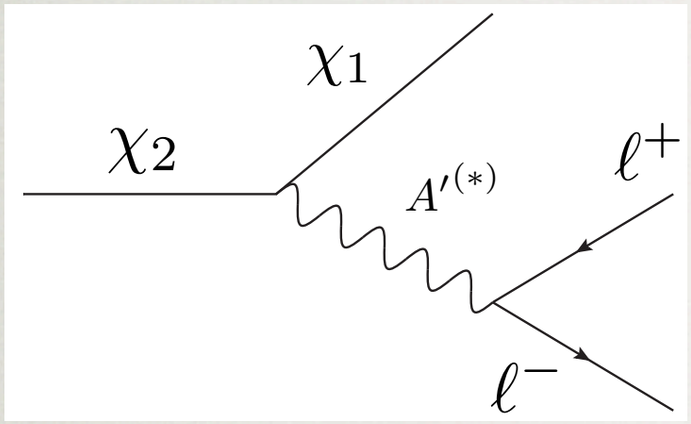
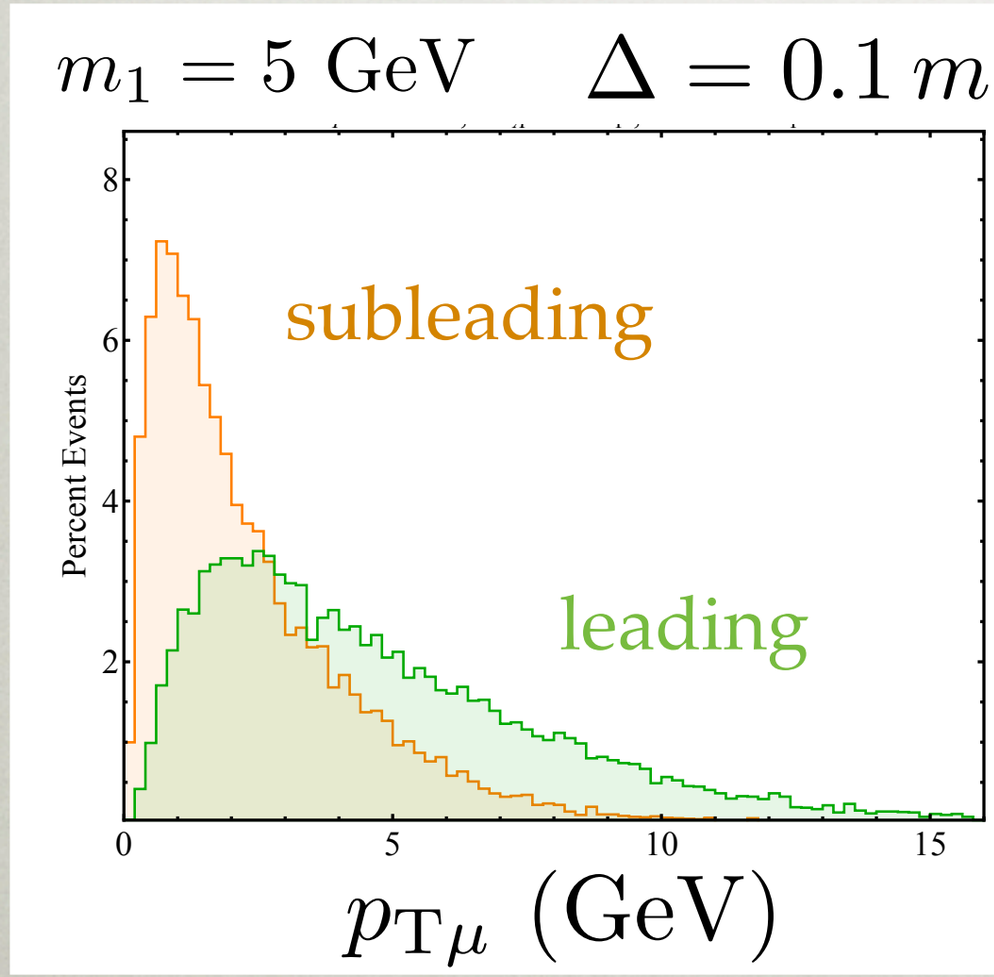
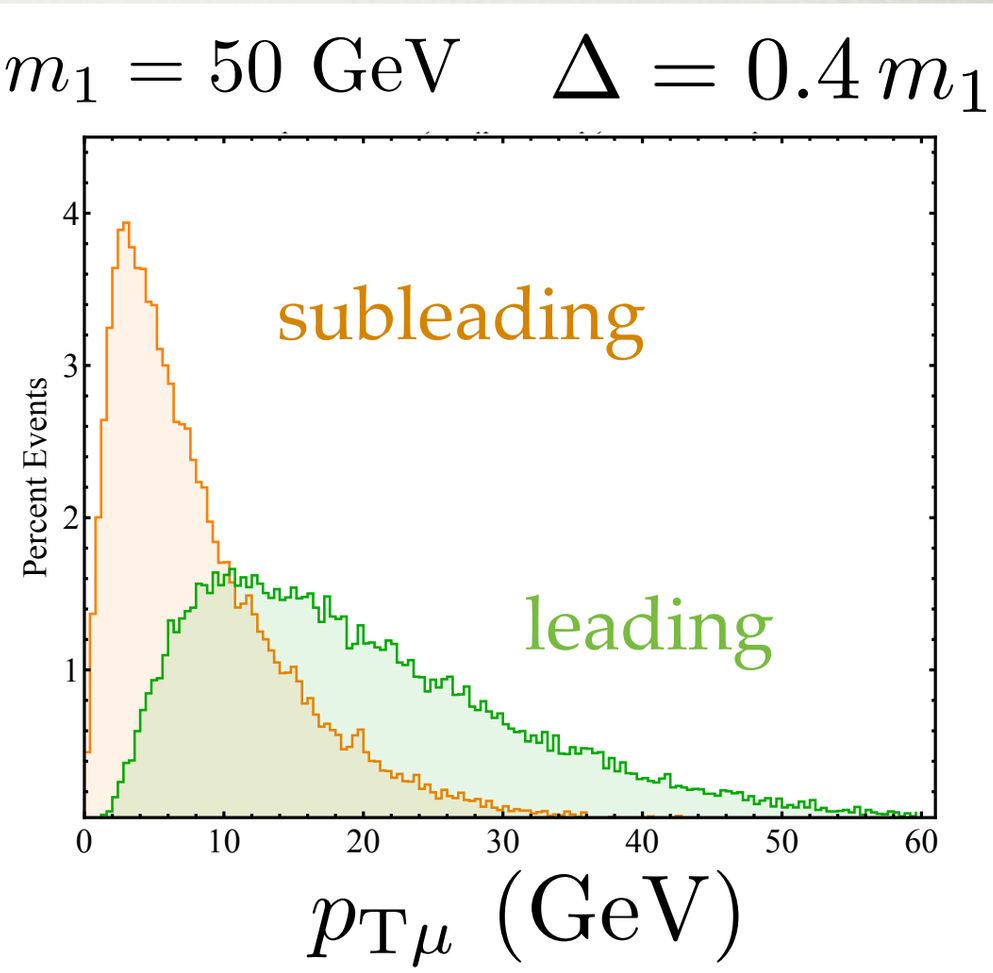


- For small splittings, leptons are soft, so trigger on monojet + MET

$m_1 = 5$ GeV $\quad \Delta = 0.1\, m_1$



$m_1 = 50$ GeV $\quad \Delta = 0.4\, m_1$



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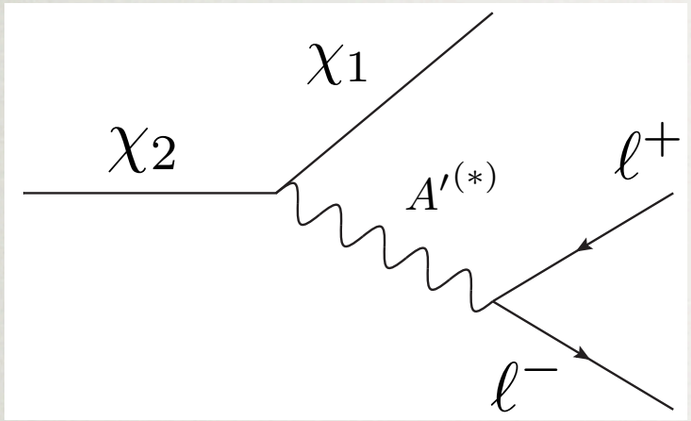
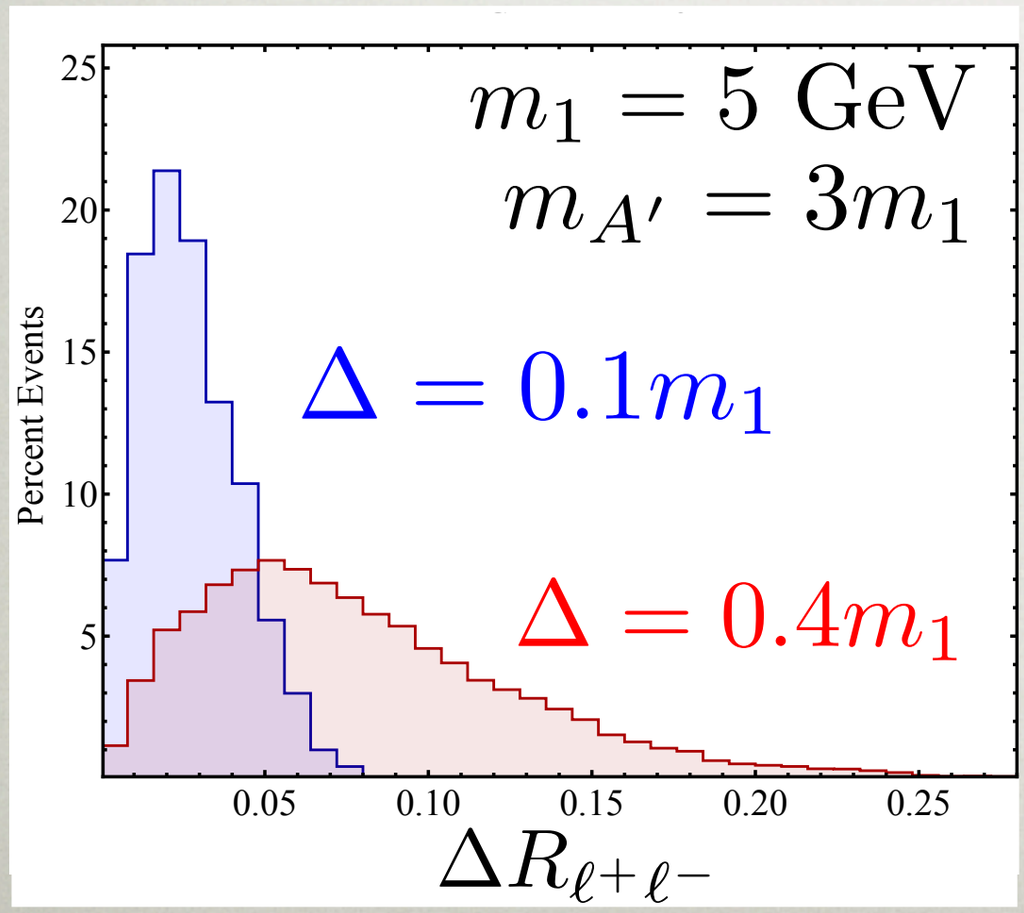
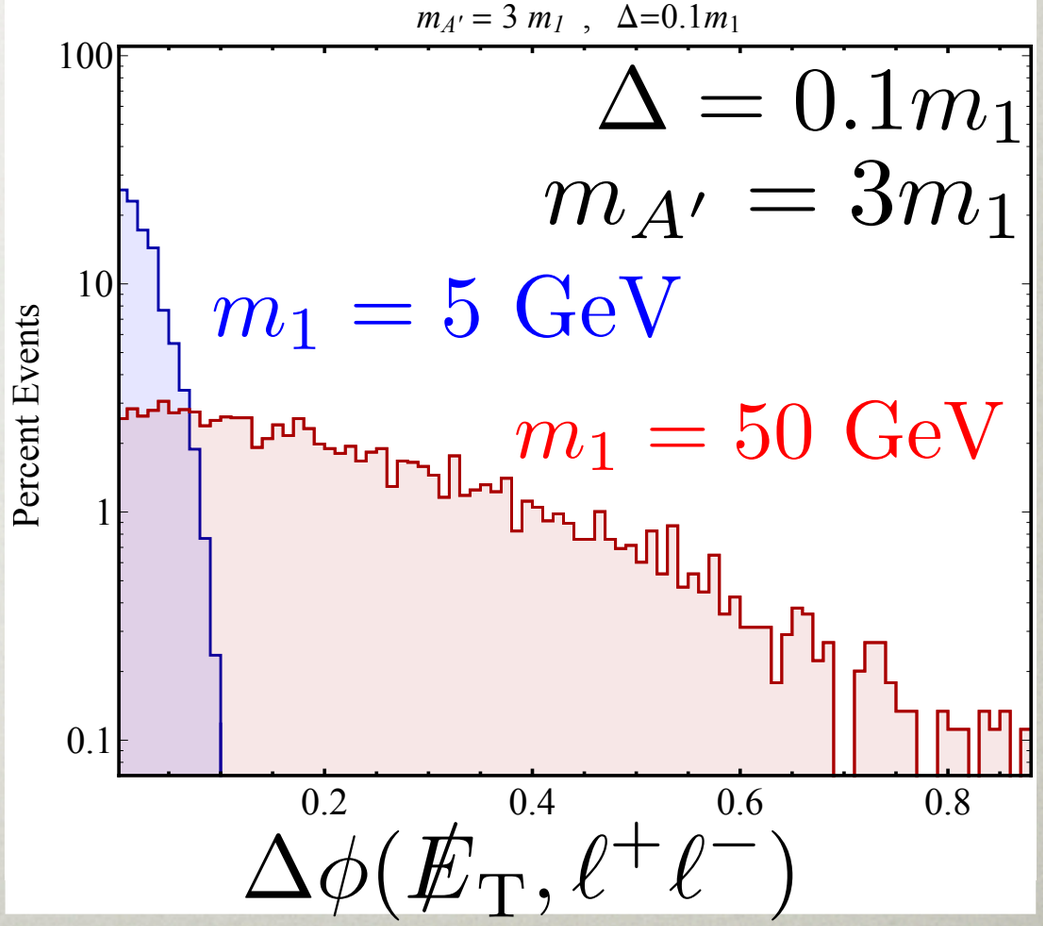


- DM recoils off monojet, so typically **boosted**





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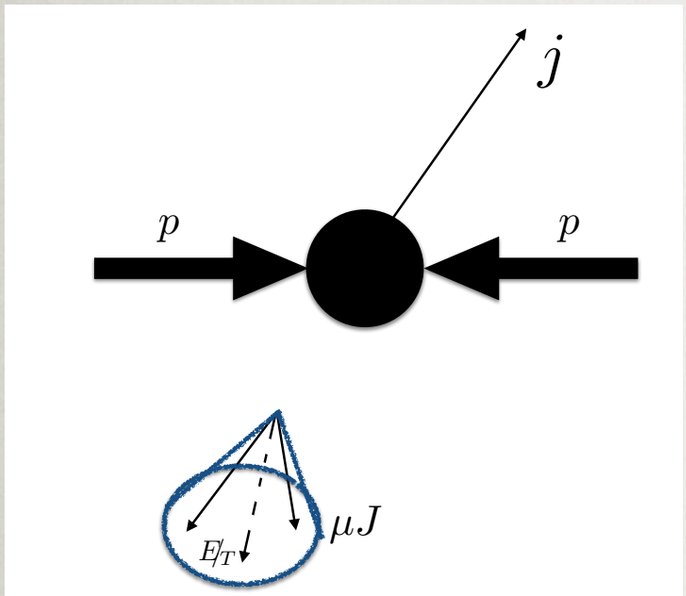


- $\not{H}_{\mathrm{T}} > 120$ GeV

- Leading jet $p_{\mathrm{T}} > 120$ GeV, veto 3rd jet $p_{\mathrm{T}} > 30$ GeV

- Two displaced muon tracks, $p_{\mathrm{T}} > 5$ GeV, with impact parameter between 1 mm and 30 cm

- **One DV:** Closest distance of approach of muons < 1 mm

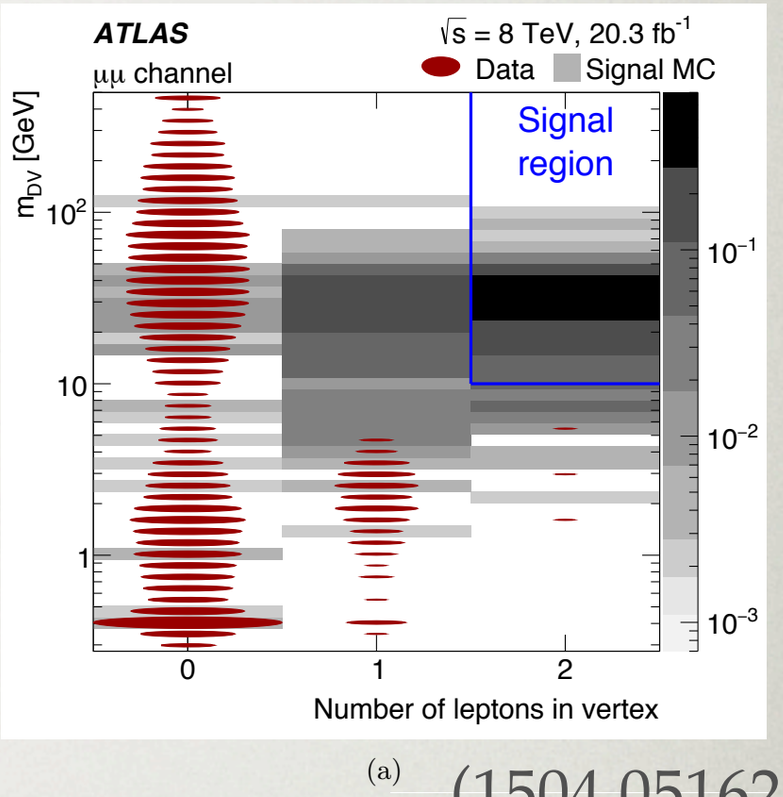
- $\Delta R < 0.4$ between muons

- $|\Delta\phi| < 0.4$ between lepton jet and MET

Improving the Searches

Backgrounds:

- Hard to simulate, should be small



(a) (1504.05162)

Improving the Searches

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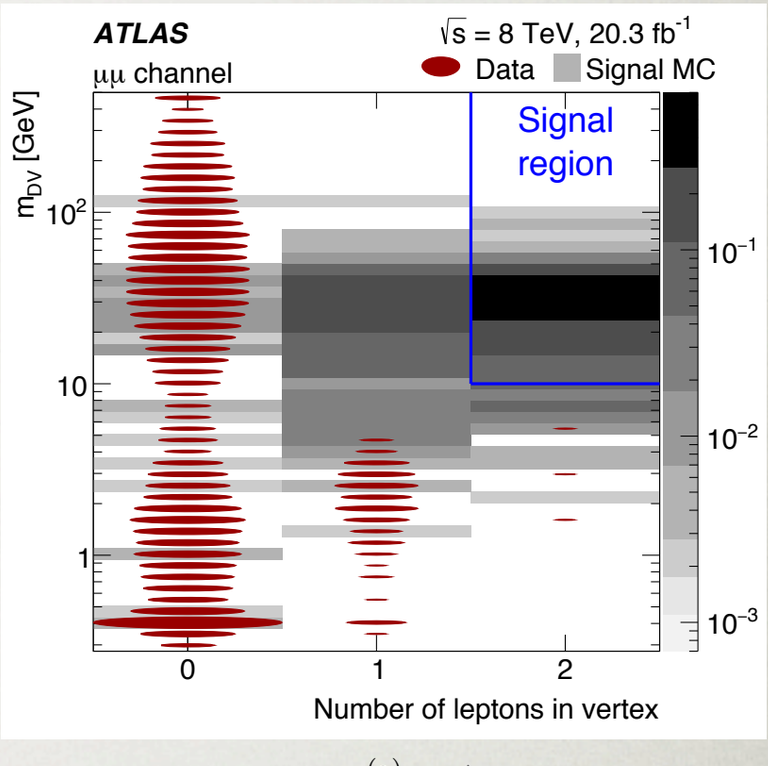

(a) (1504.05162)

We considered:

- Heavy flavour (coincidental crossing)
- Taus
- Pile-up

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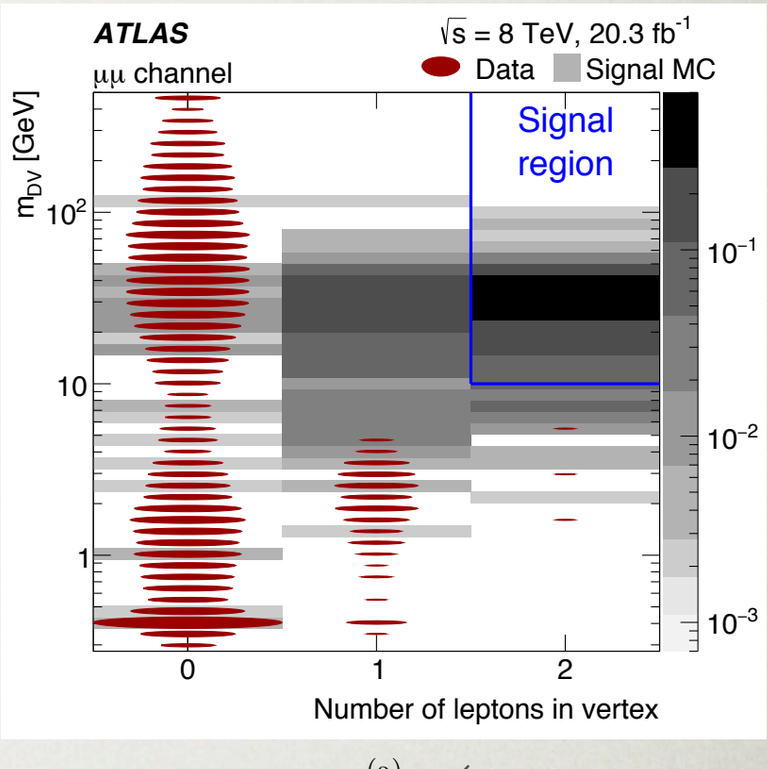

(a) (1504.05162)

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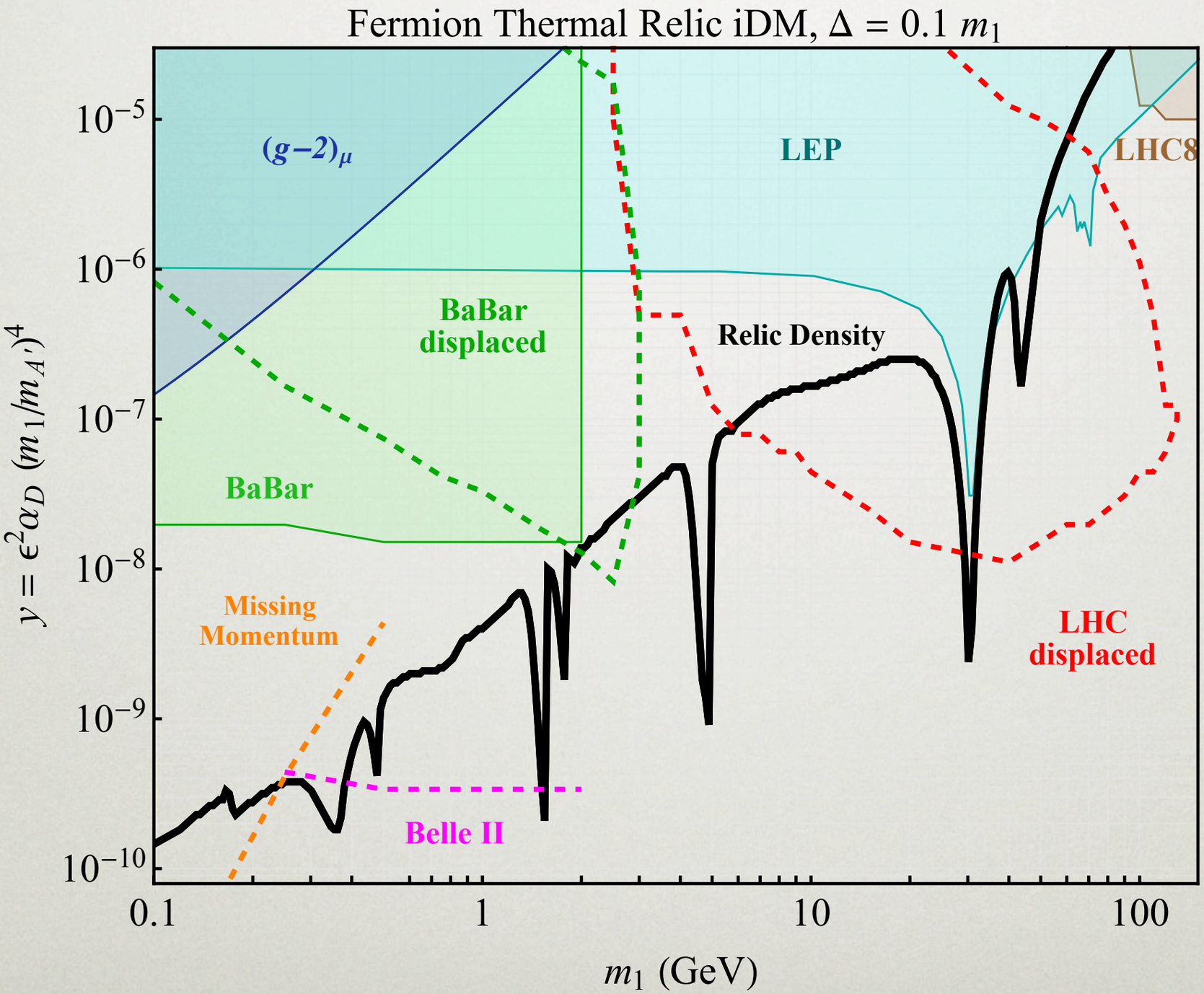
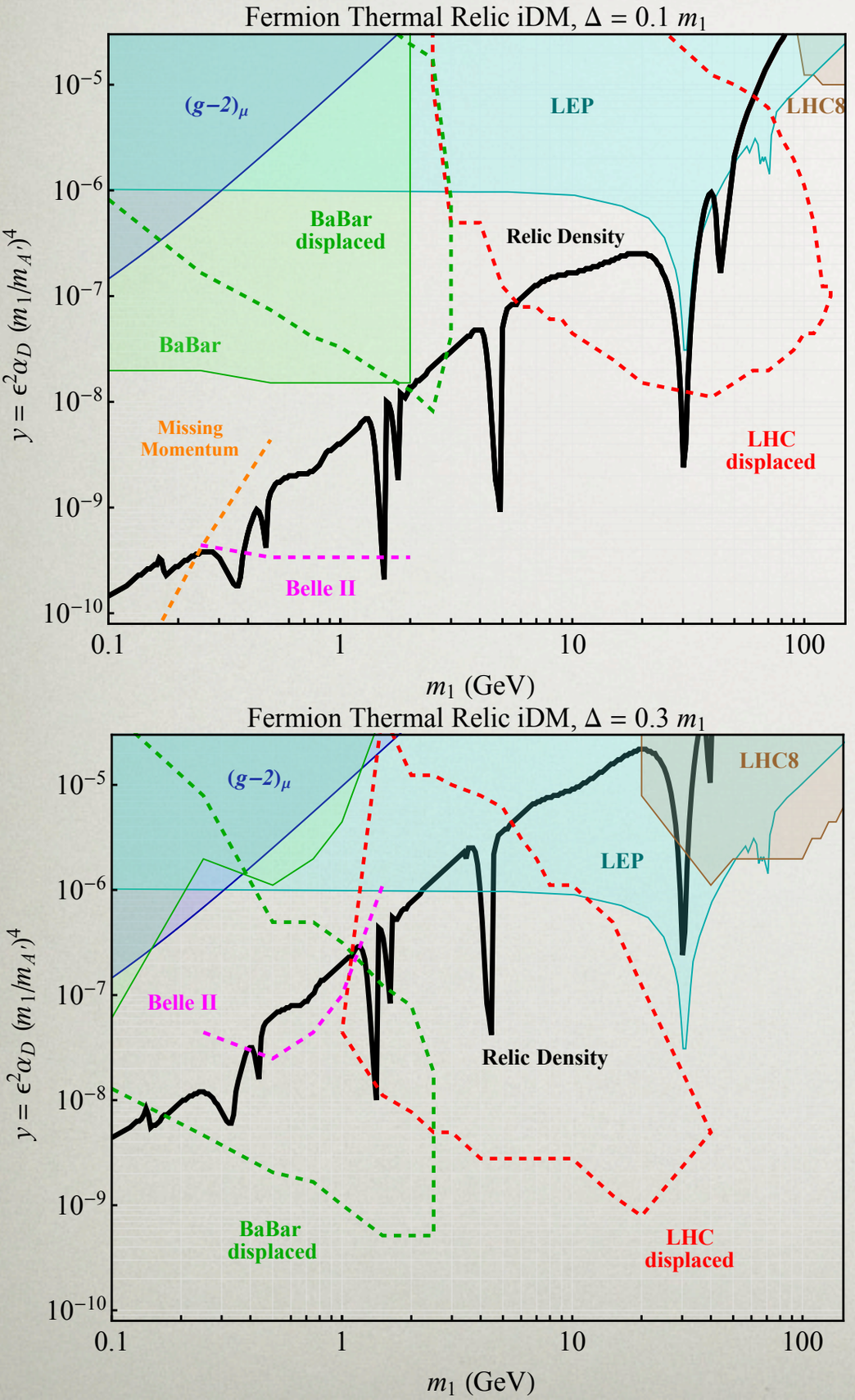
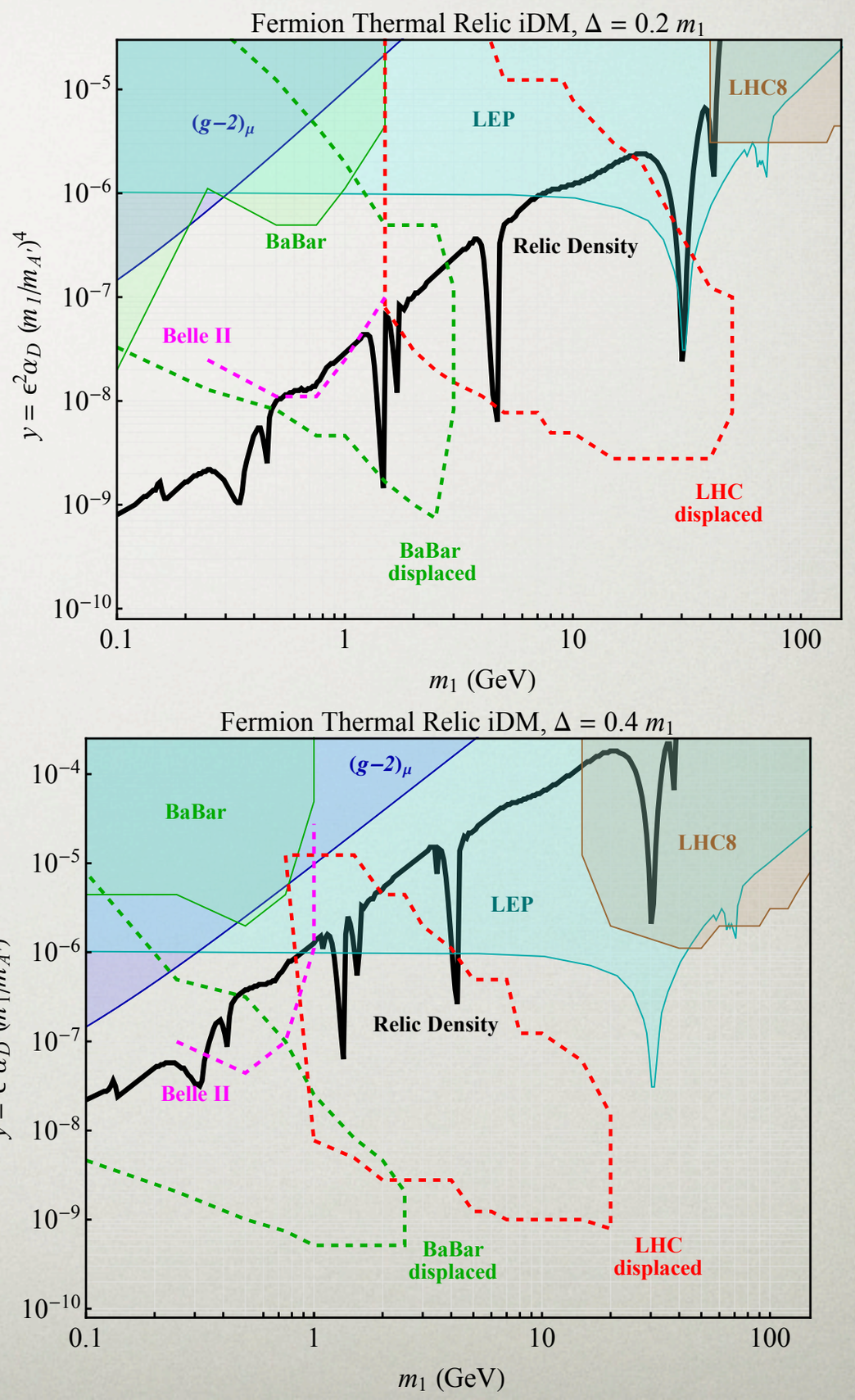
Show sensitivity for 10 signal events

LHC Results


Fermion Thermal Relic iDM, Δ = 0.1 m_1
$(g-2)_\mu$
LEP
LHC8
BaBar displaced
Relic Density
BaBar
Missing Momentum
LHC displaced
Belle II
$y = \epsilon^2\alpha_D\,(m_1/m_{A'})^4$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100
m_1 (GeV)

LHC Results


Fermion Thermal Relic iDM, Δ = 0.1 m_1
$(g-2)_\mu$
LEP
LHC8
BaBar displaced
Relic Density
BaBar
Missing Momentum
LHC displaced
Belle II
$y = \epsilon^2 \alpha_D \, (m_1/m_{A'})^4$
m_1 (GeV)


Fermion Thermal Relic iDM, Δ = 0.2 m_1
$(g-2)_\mu$
LEP
LHC8
BaBar
Relic Density
Belle II
LHC displaced
BaBar displaced
$y = \epsilon^2 \alpha_D \, (m_1/m_{A'})^4$
m_1 (GeV)

Fermion Thermal Relic iDM, Δ = 0.3 m_1
$(g-2)_\mu$
LHC8
LEP
Belle II
Relic Density
BaBar displaced
LHC displaced
$y = \epsilon^2 \alpha_D \, (m_1/m_{A'})^4$
m_1 (GeV)

Fermion Thermal Relic iDM, Δ = 0.4 m_1
$(g-2)_\mu$
BaBar
LHC8
LEP
Relic Density
Belle II
BaBar displaced
LHC displaced
$y = \epsilon^2 \alpha_D \, (m_1/m_{A'})^4$
m_1 (GeV)

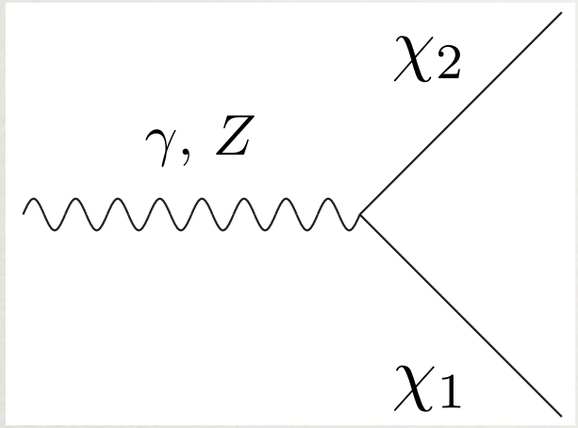
Proposals for iDM Searches

Magnetic iDM

E. Izaguirre, G. Krnjaic, BS, arXiv:1508.03050

Magnetic iDM

- We can (and should!) consider monojet + MET + other objects, such as photons:



$$\mathcal{L} = \frac{\mu_\gamma}{2} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$$

Masso, Mohanty, Rao, 0906.1979; Chang, Weiner, Yavin 1007.4200

1. **Lifetime (2-body) decay:**
   - Decays promptly **or** too boosted to see non-pointing photon

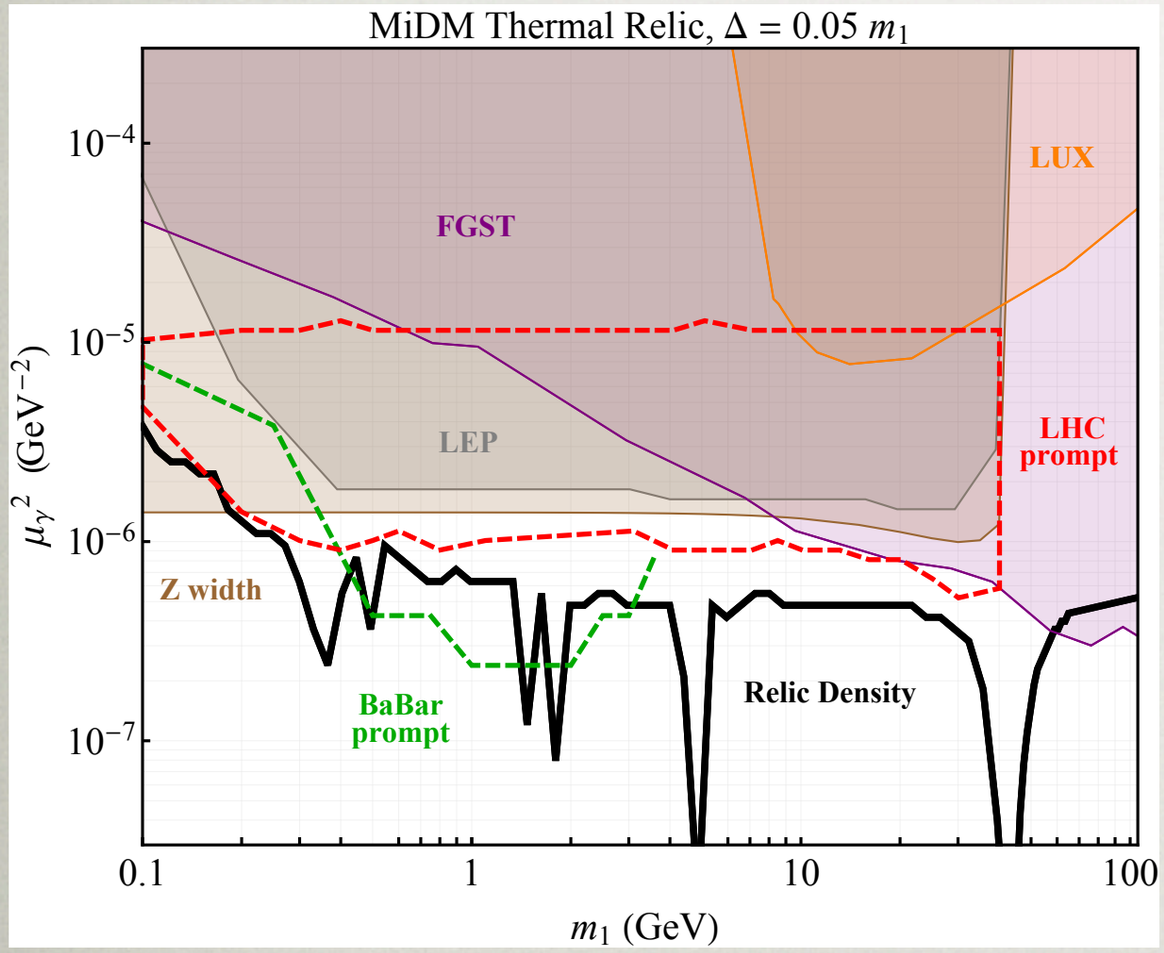
2. **Photon reconstruction:**
   - Must be harder ($E_T > 15$ GeV), cut tighter to reject fakes

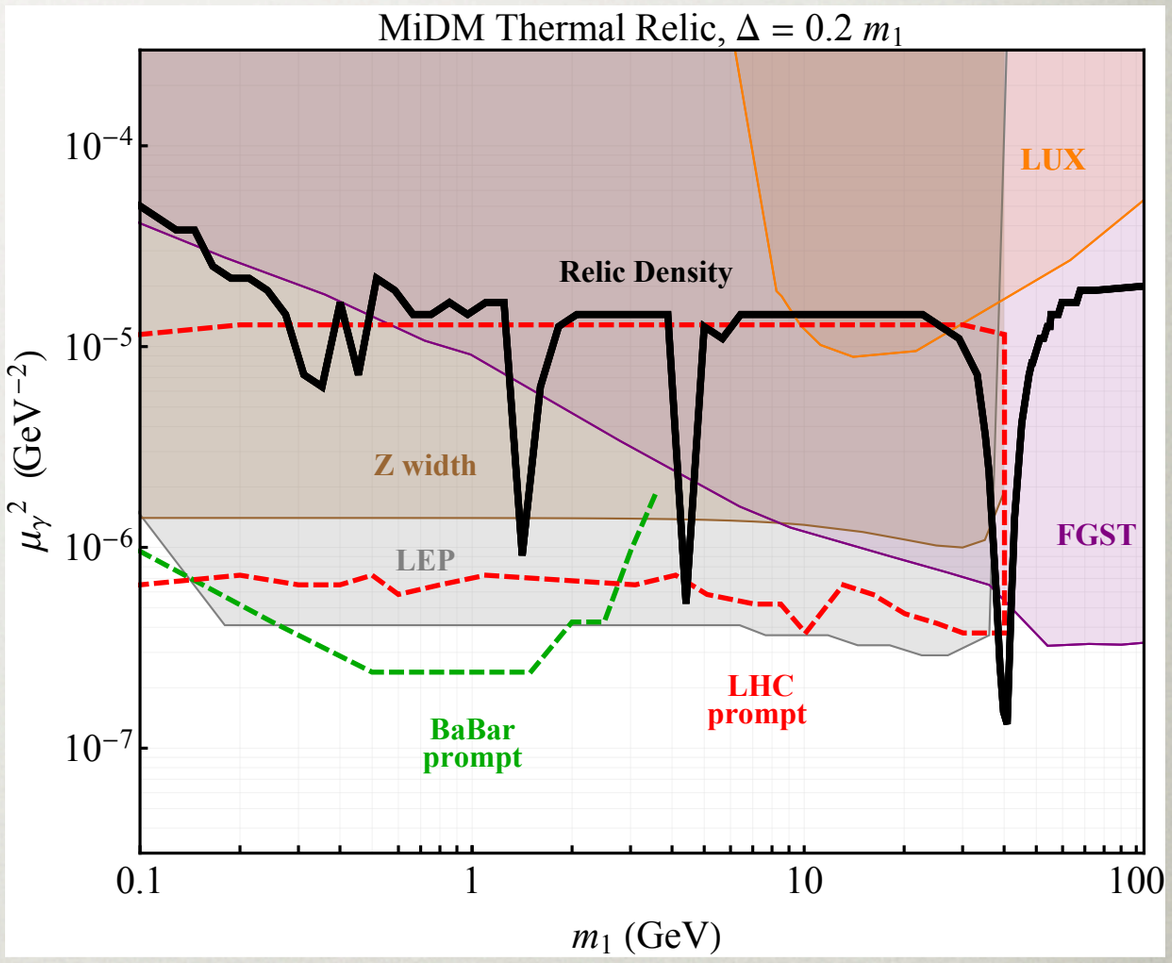
3. **Large, irreducible backgrounds:**
   - Large W + jet background with W $\rightarrow \ell$ + MET + gamma

Magnetic Dipole iDM

- Assume 10% systematic

(events truncated within EFT validity)





Other Possibilities for Photons

- Can use monojet + soft object tagging for non-iDM scenarios

- *E.g.,* "pure Higgsino"

$$\tilde{H}^{\pm}$$

$$\tilde{H}^{0}$$

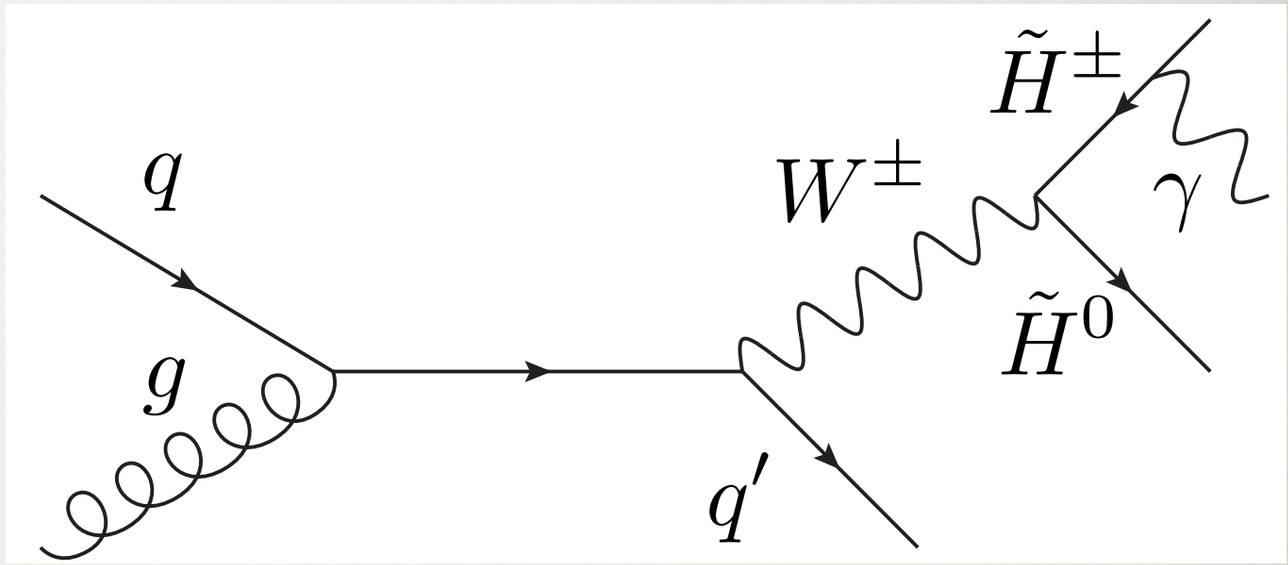
$$c\tau(\tilde{H}^{\pm} \to \tilde{H}^{0}\pi^{\pm}) \sim 5 \text{ mm}$$

- Disappearing charged track, but **too short!**

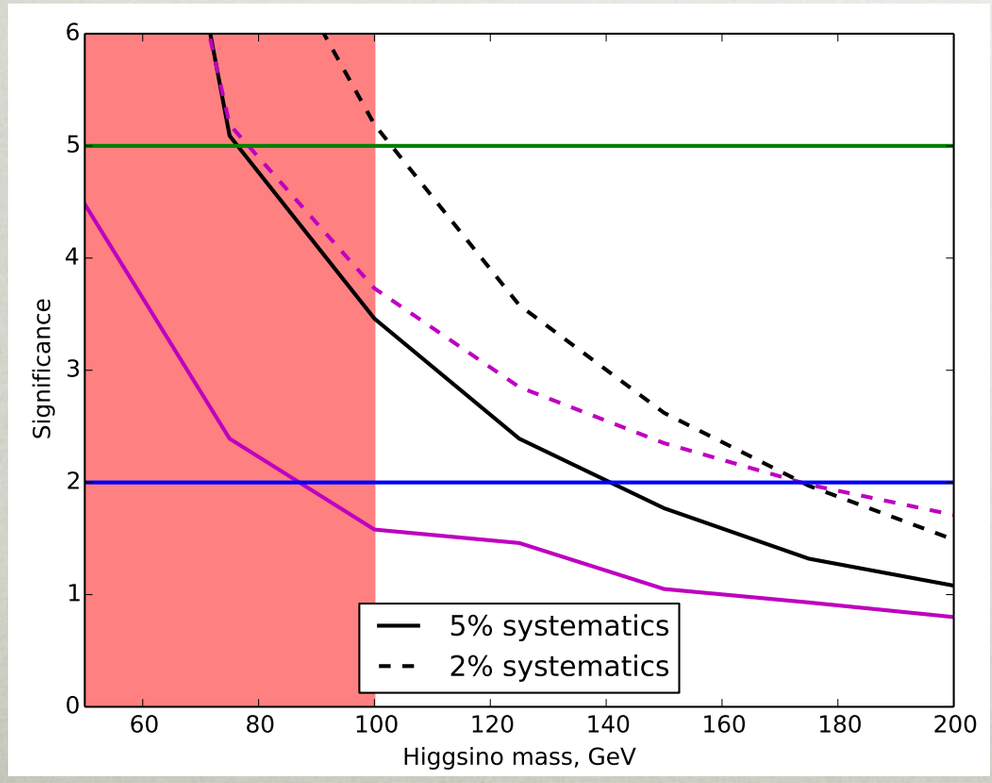
Thomas, Wells, hep-ph/9804359, ...

Other Possibilities

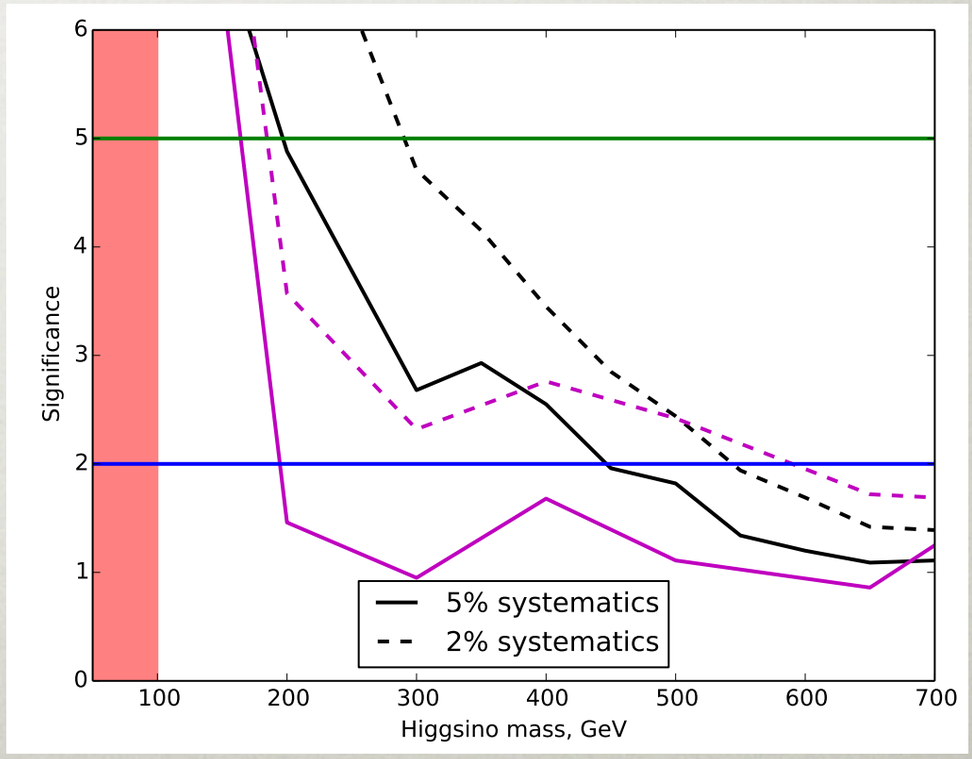
- Instead, use photon FSR
- Helps when systematics dominated



HL-LHC



100 TeV, 3/ab



(Ismail, Izaguirre, BS, preliminary!)

Summary

- iDM is a simple benchmark exhibiting soft signatures characteristic of hidden sectors

- It is sometimes better to use associated objects (monojet+MET) for trigger + background suppression (also true for Higgs portal!)

- iDM can predict **one** displaced vertex!

- Dedicated searches can have good sensitivity to thermal DM & other scenarios