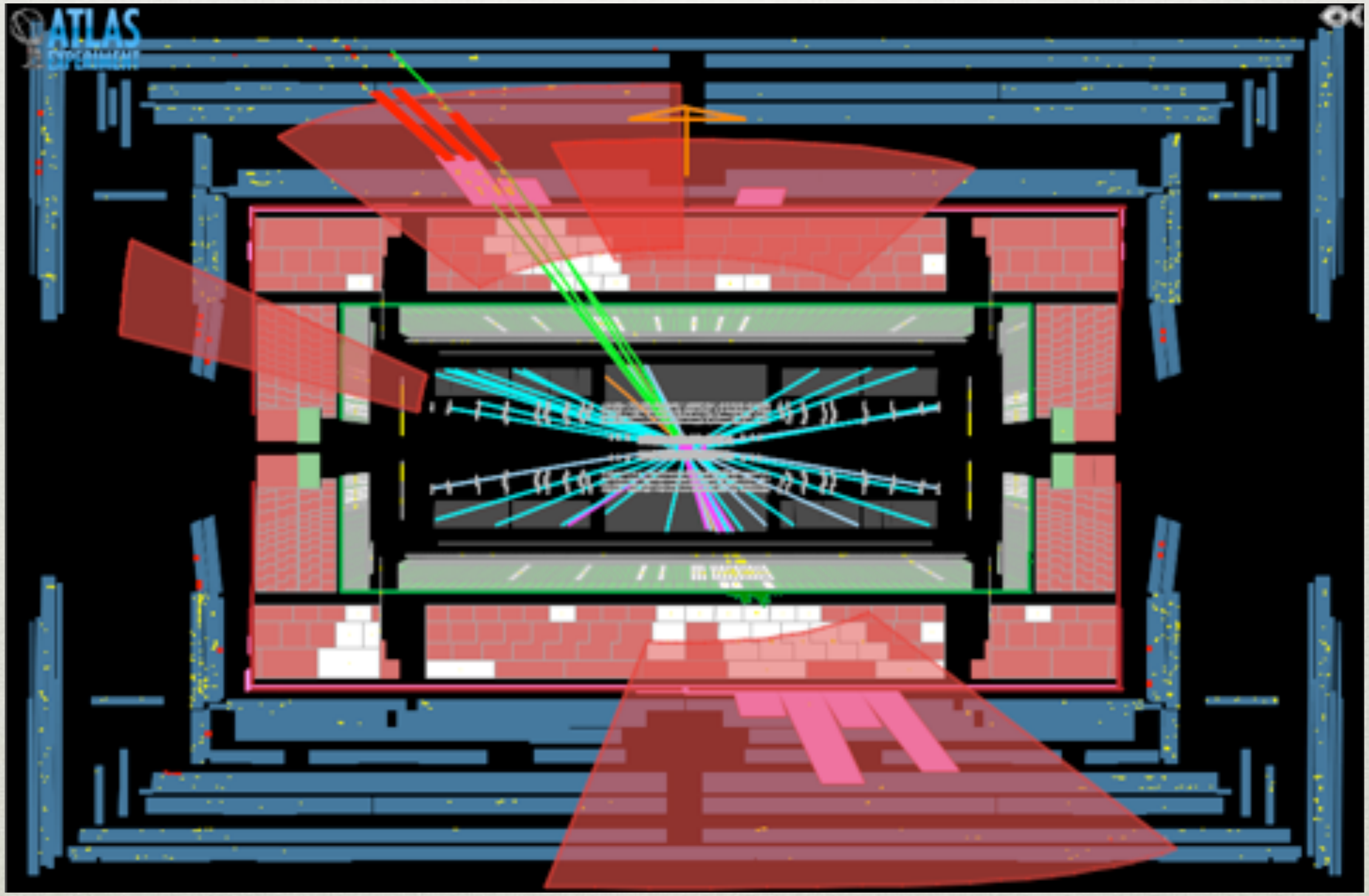
DISCOVERING HIDDEN SECTORS AT COLLIDERS

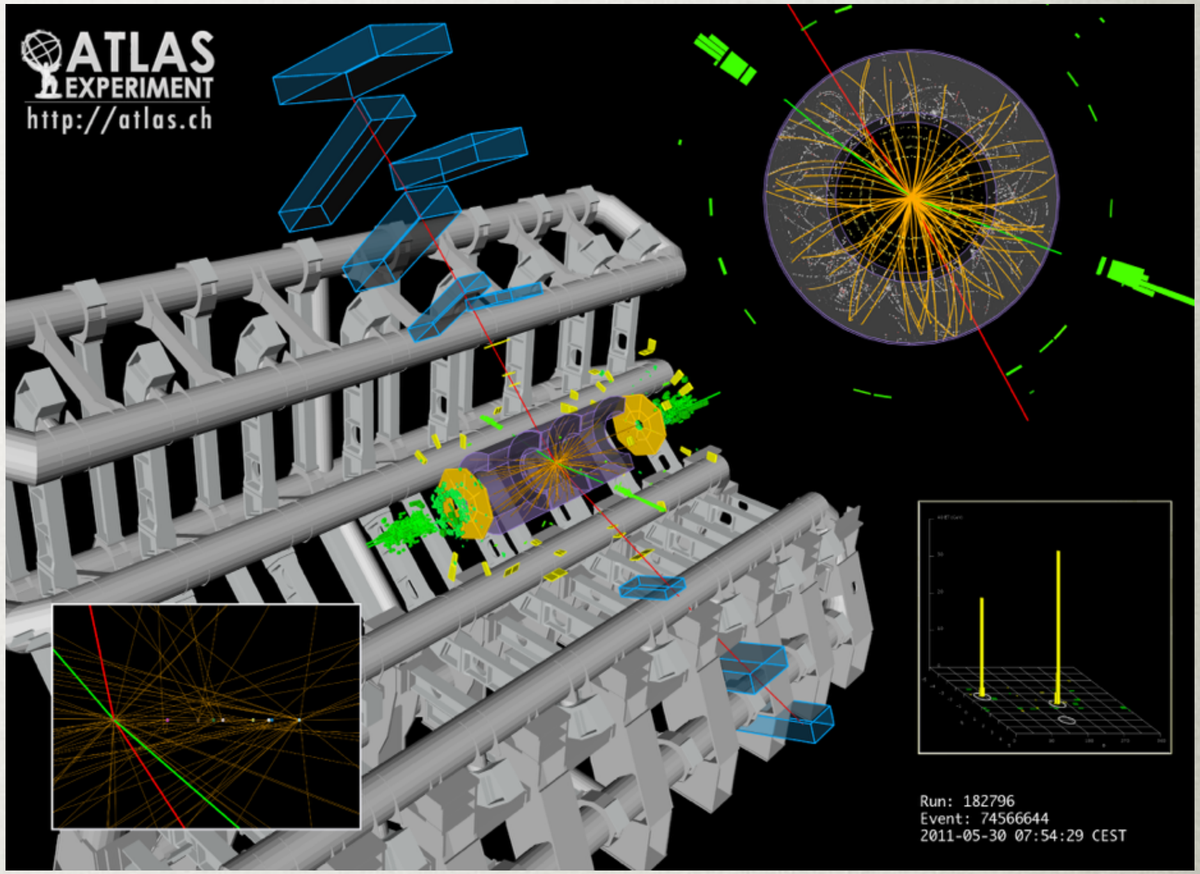


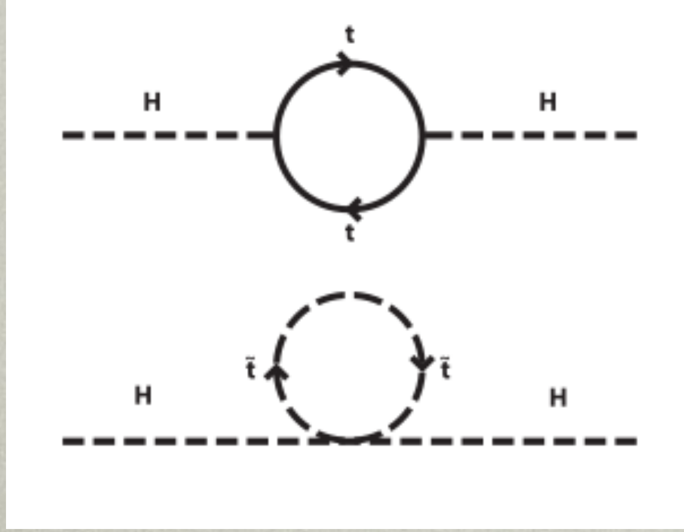
Brian Shuve — SLAC

VIA Seminar — 23 September 2016

Energy Frontier @ LHC

- Main goal of LHC is to discover the **Higgs boson**, measure its properties….





- … and discover new associated states

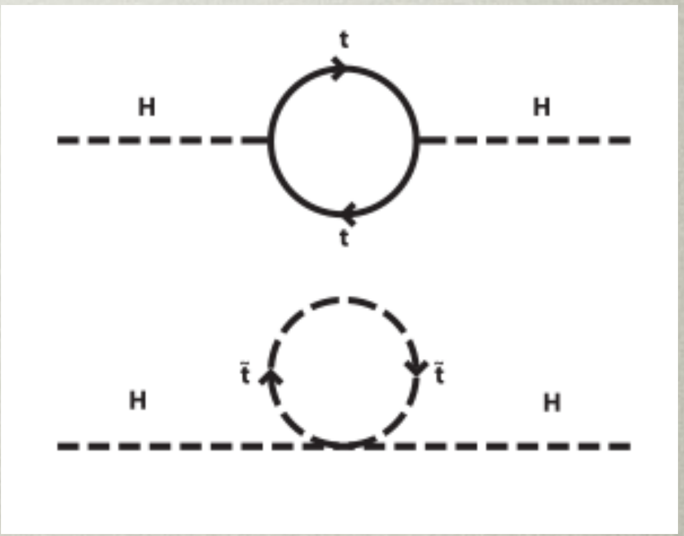
Energy Frontier @ LHC

- Solutions to hierarchy problem like SUSY can resolve other outstanding problems, especially **dark matter** and **baryogenesis**

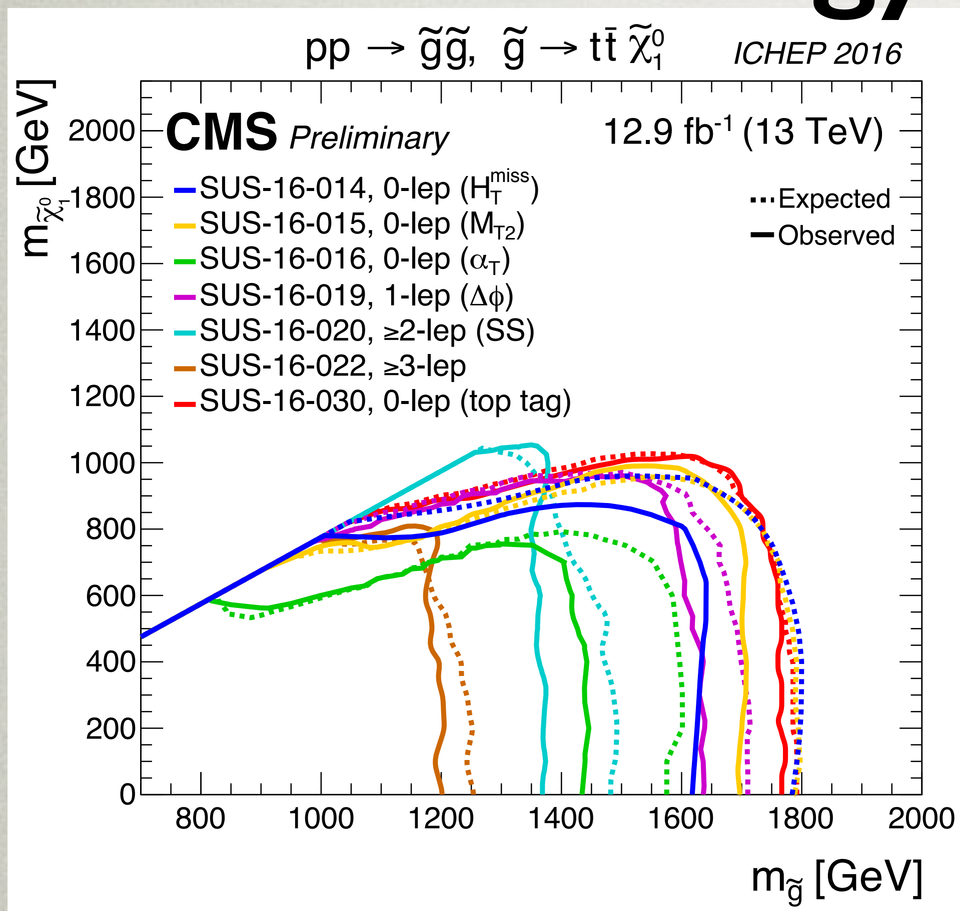
baryons | antibaryons

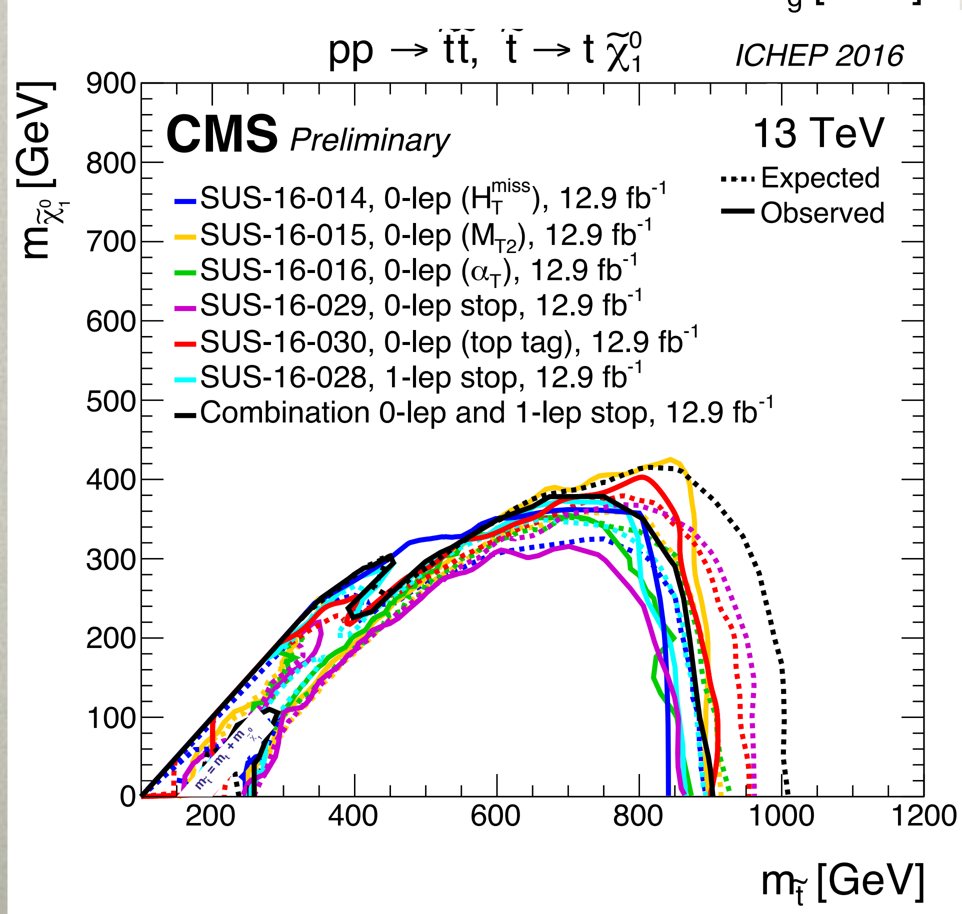
electroweak baryogenesis

WIMP LSPs

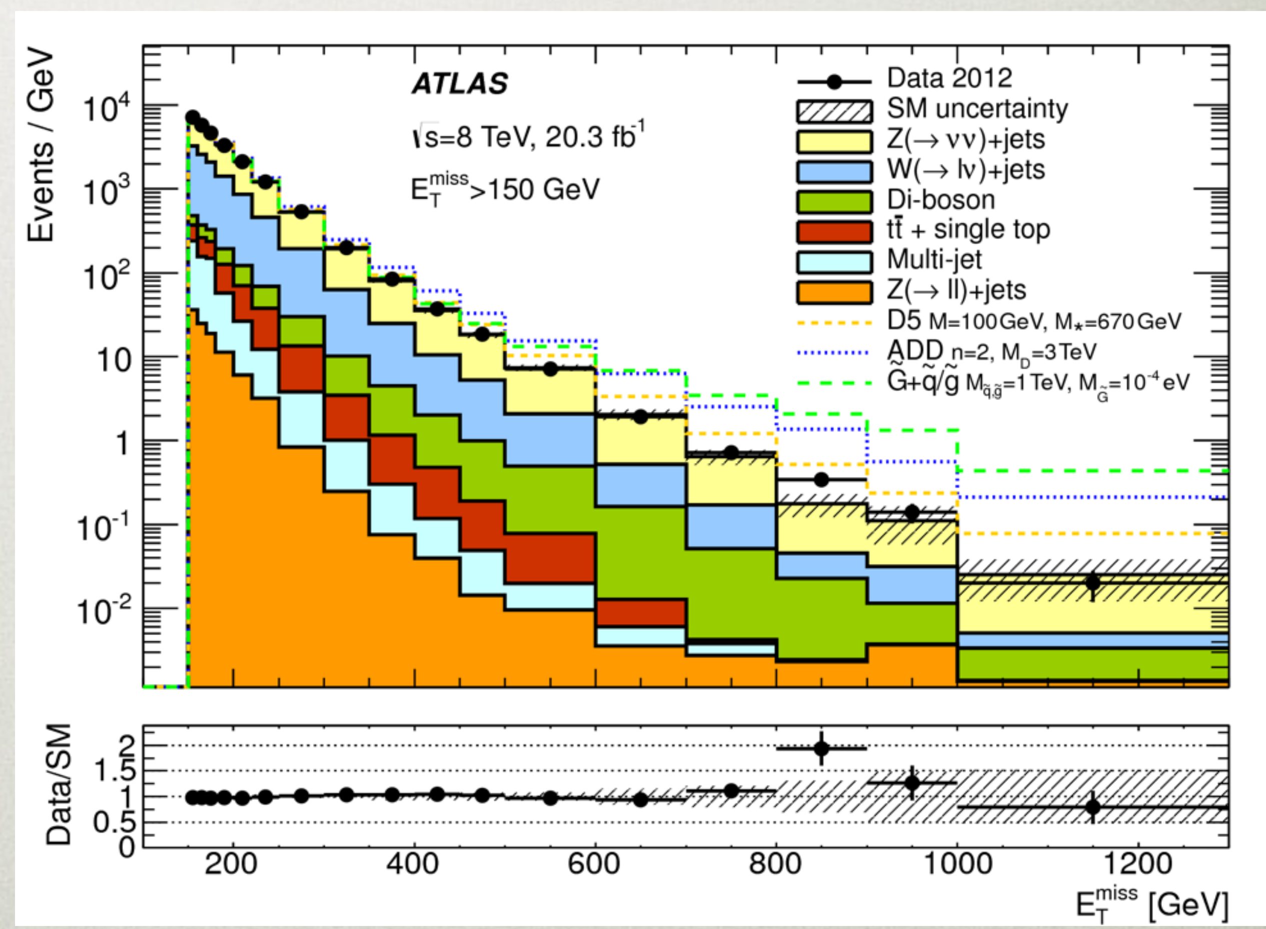


Energy Frontier @ LHC



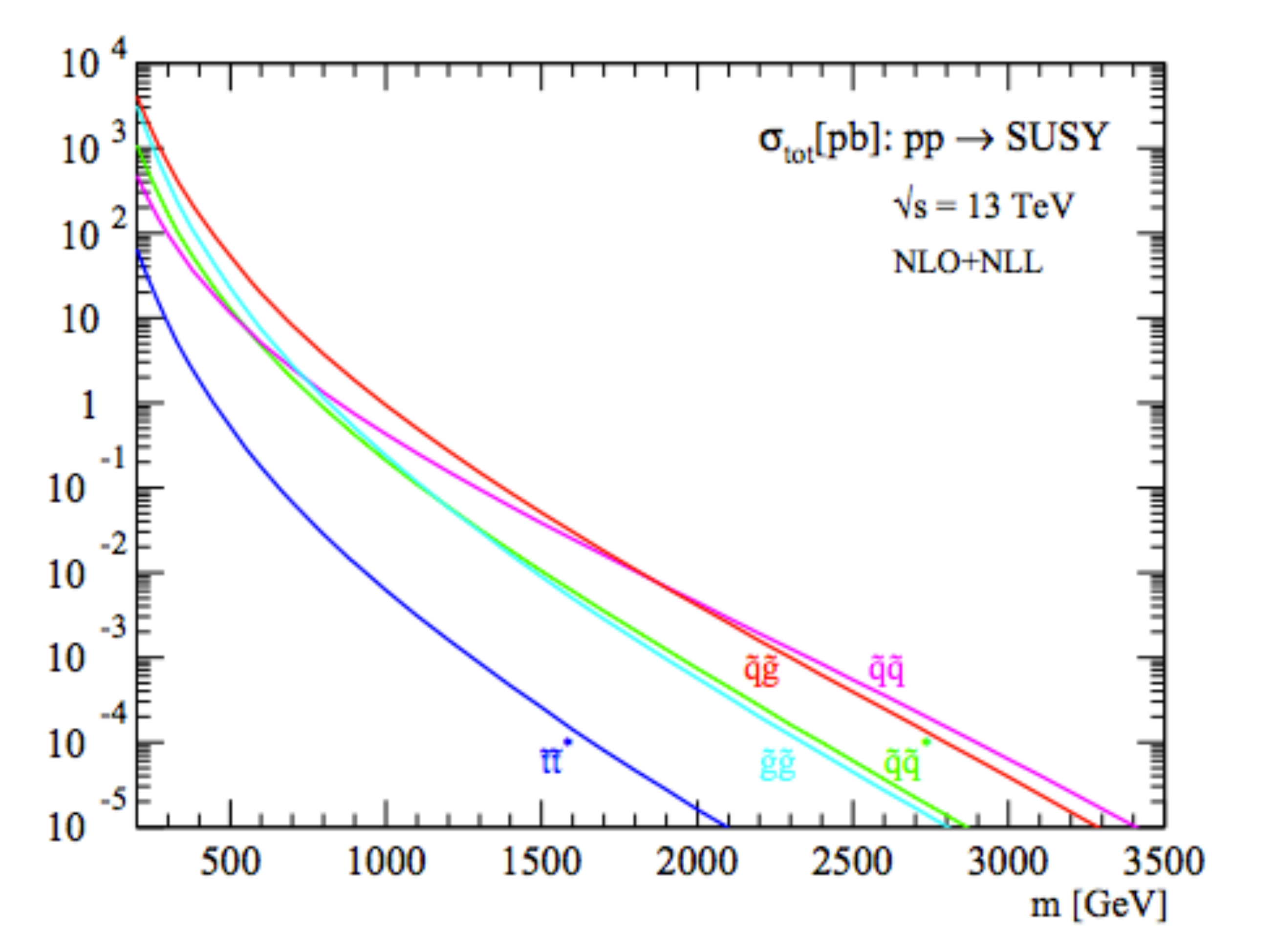


- Comprehensive studies of SUSY, WIMPs, etc. have turned up…



Energy Frontier @ LHC

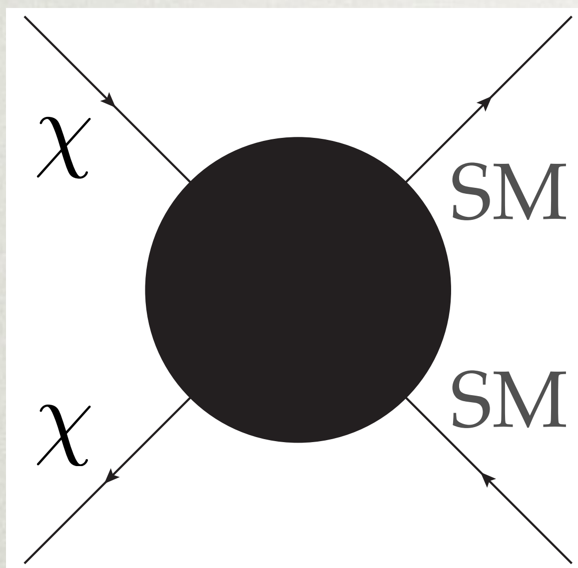
- Still a long way to go (only ~1% of total data collected)…



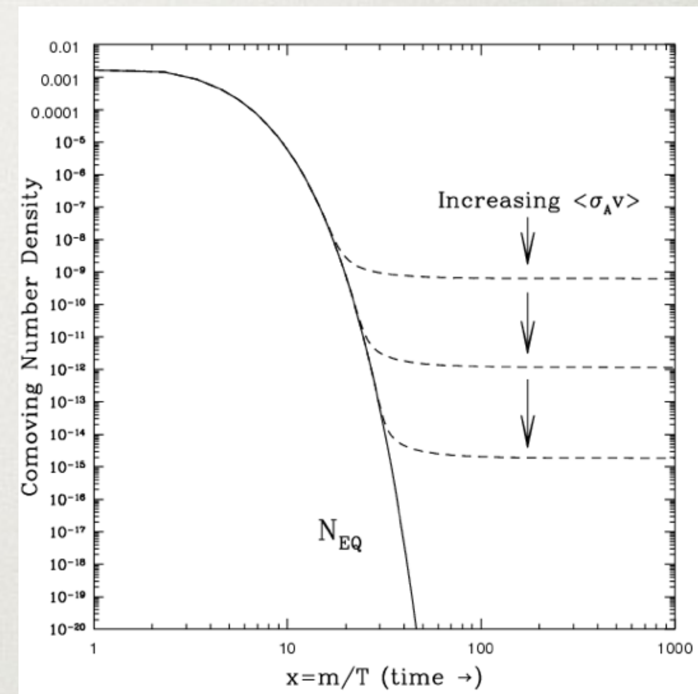
- ...but diminishing returns set in quickly
  - What is missed in the rush to high energy?

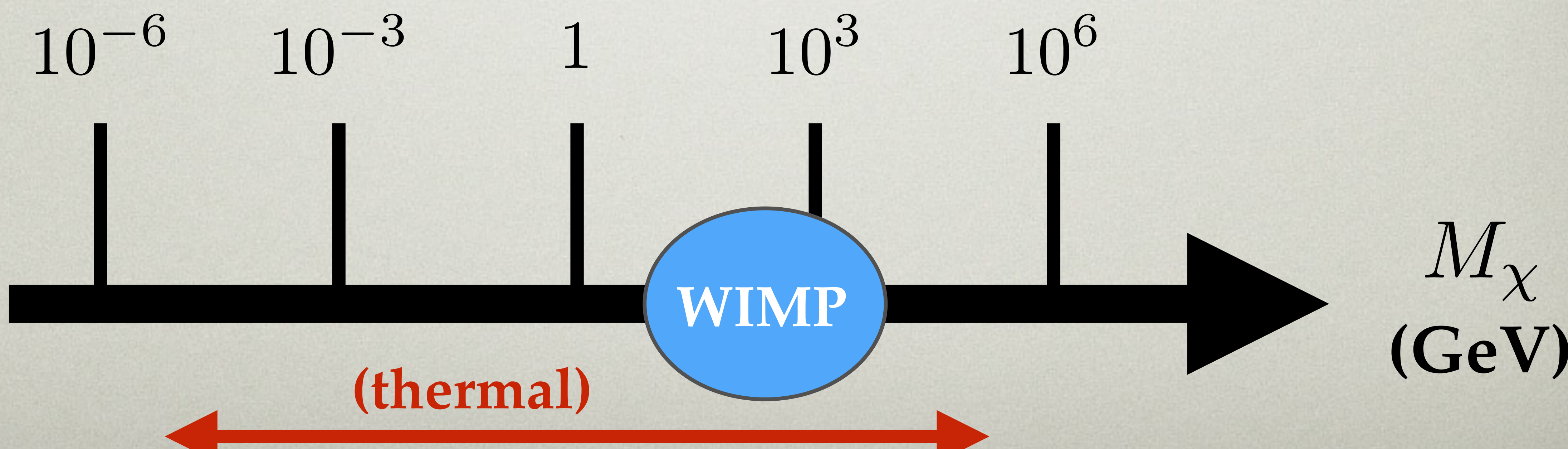
Dark Matter Beyond WIMPs

- Thermal DM (*i.e.*, freeze-out scenarios) can have masses substantially **below** the weak scale



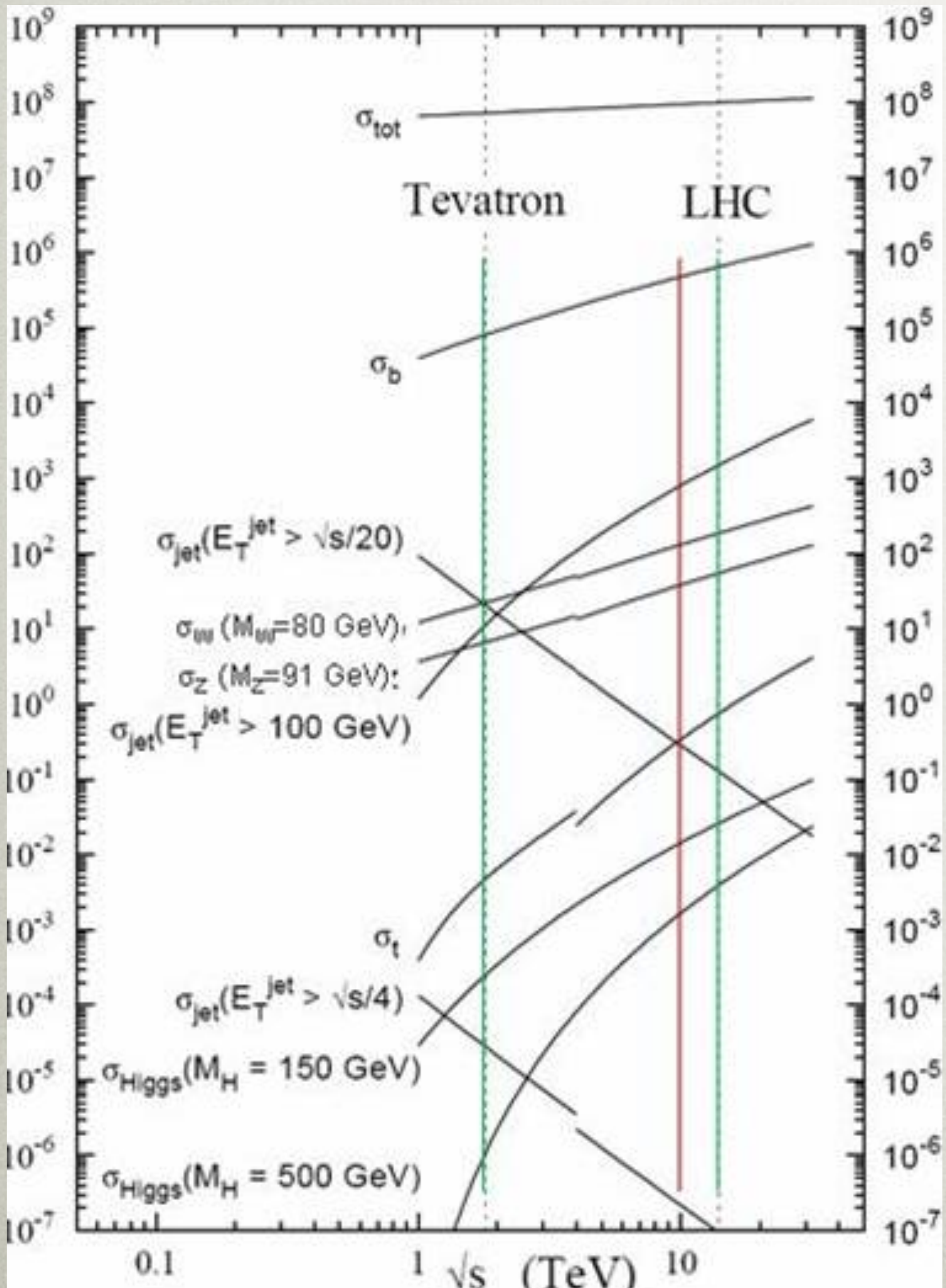
$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/s$$





The LHC is High Intensity

- Kinematically accessible at LHC and other colliders, but signatures may be missed in current searches!



From J. Stirling

With 3000/fb:

- 700 billion *W* bosons
- 100 billion *Z* bosons
- 200 million *H* bosons
- 2000 trillion *B* mesons

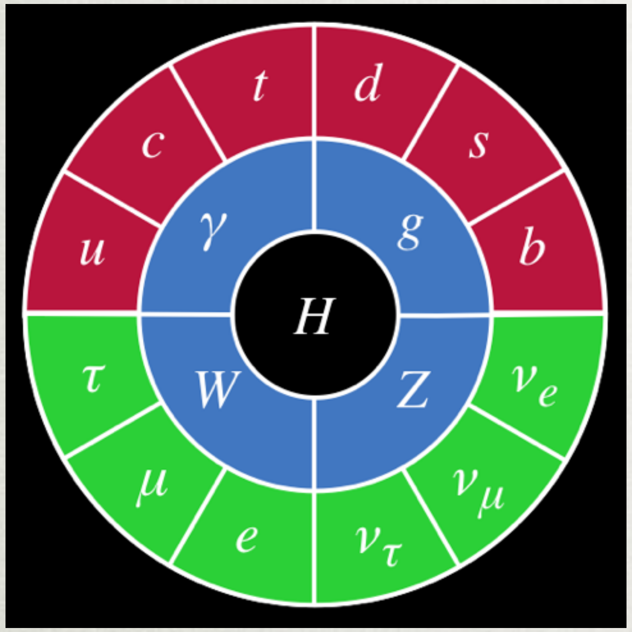
Signatures of Hidden Sectors

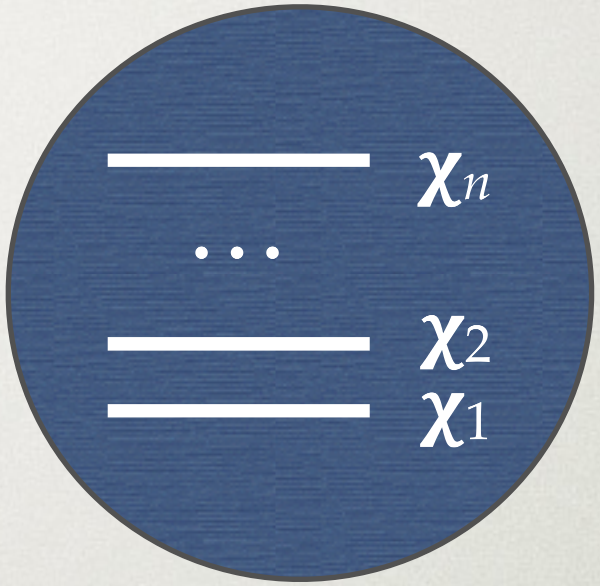
- What can we **realistically discover** that have been missed by existing searches?

- **Multi-Component Hidden Sectors**:
    - Existing searches focus on simplest cases (one new DM particle, missing momentum)
    - Low-mass DM models generically predict **several new particles** with distinctive signatures

- **Non-Minimal Couplings:**
    - Example: lepton flavour non-universality
    - Simple, targeted searches can close remaining gaps

Multi-Component Hidden Sectors





THIS TALK:

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

A. Ismail, E. Izaguirre, BS, arXiv:1605.00658

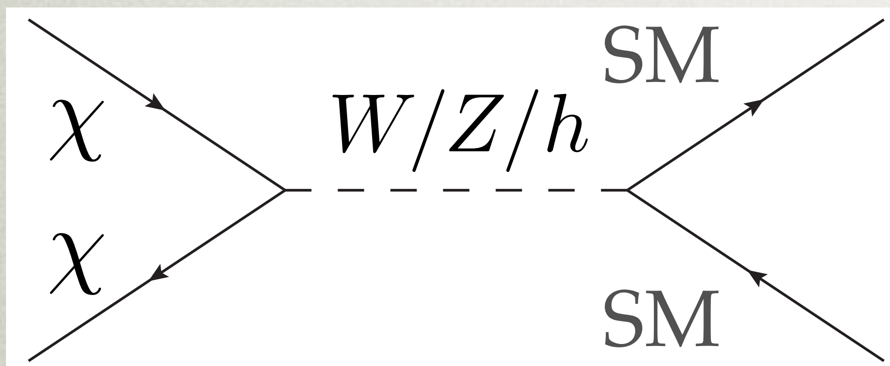
NEUTRINO MASS SCENARIOS:

B. Batell, M. Pospelov, BS, arXiv:1604.06099

B. Batell, M. Pospelov, BS [in progress]

Dark Matter Beyond WIMPs

- Light dark matter implies **more than one** dark particle

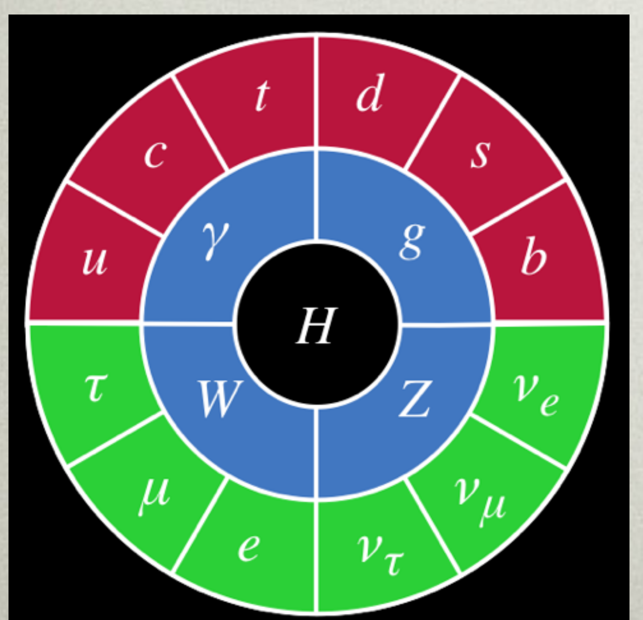


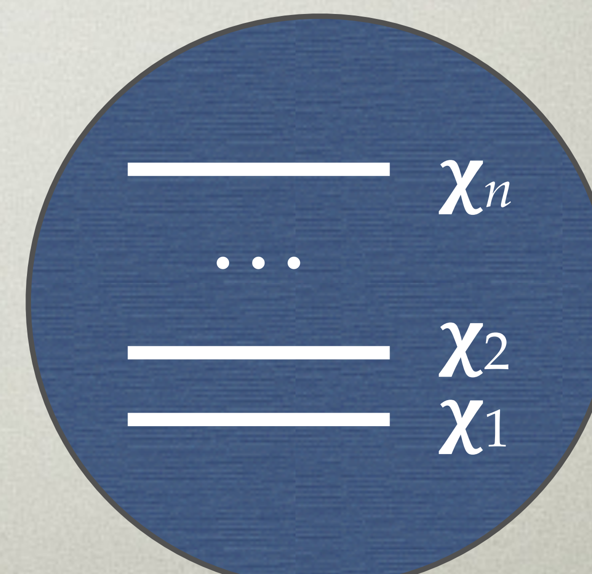
$$\sigma v \sim G_F^2 M_\chi^2 \qquad (M_\chi \ll M_W)$$

$$\Downarrow$$

$$M_\chi \gtrsim \text{few GeV}$$

Lee, Weinberg 1977

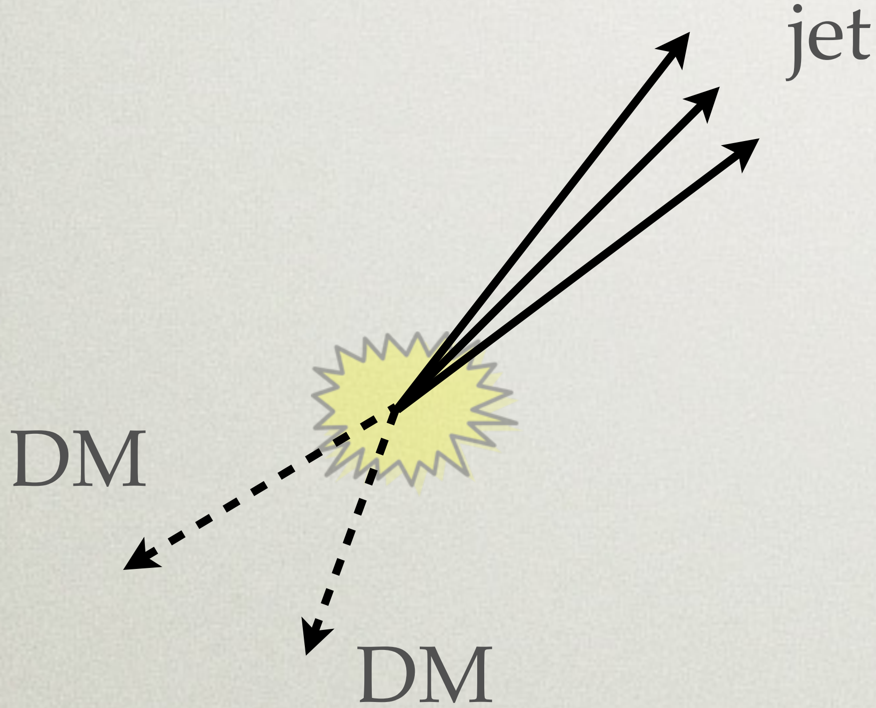


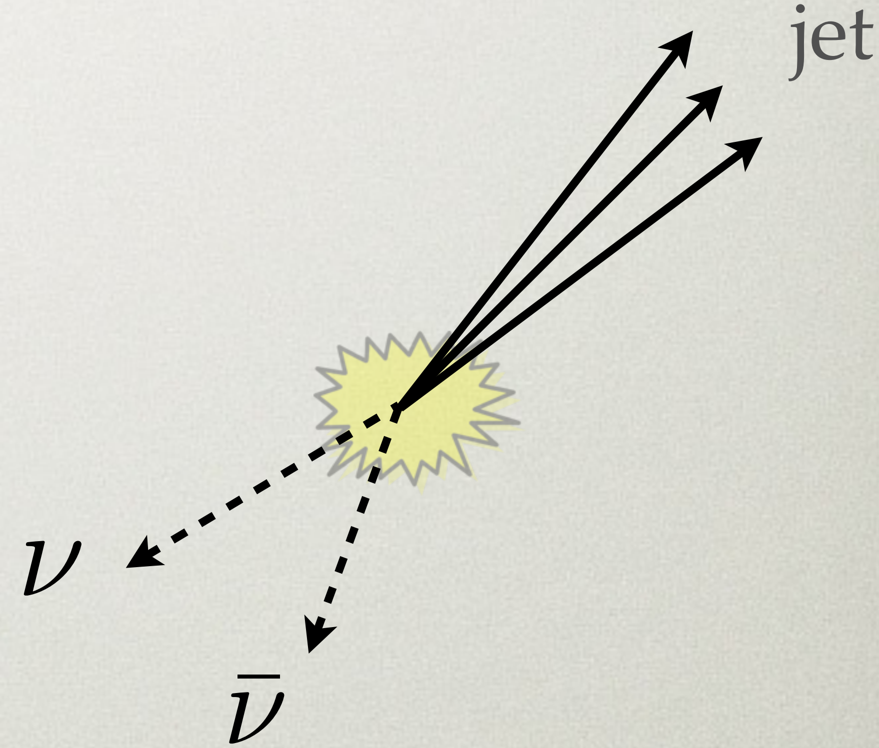


$$\frac{\alpha_{a\chi}\alpha_{a\text{SM}}}{M_\chi^2} \sim \frac{10^{-9}}{\text{GeV}^2}$$

Discovering a Dark Sector

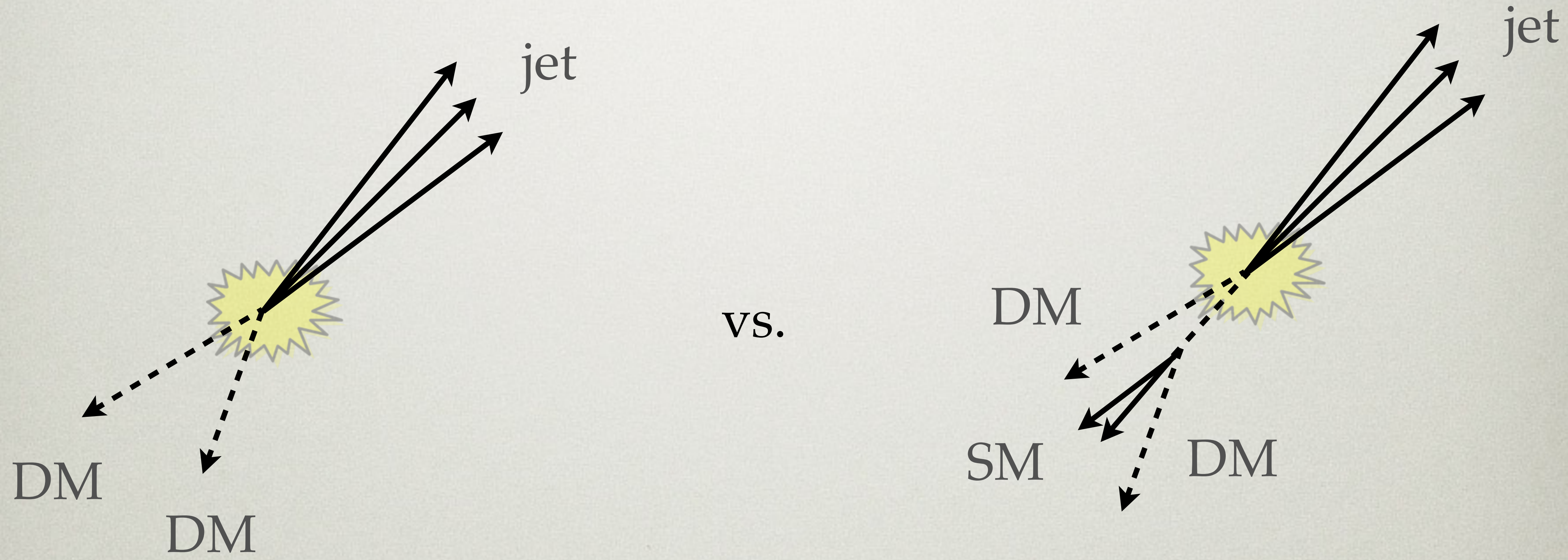
- Why does this help?





Discovering a Dark Sector

- With a dark force (or multiple DM particles), dark matter **isn't invisible** if produced at a collider



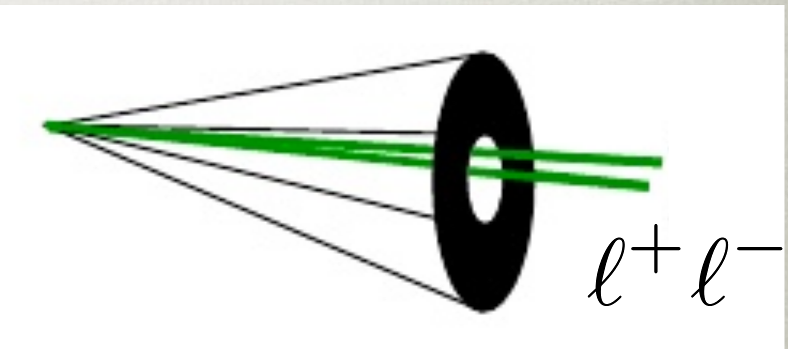
Izaguirre, Krnjaic, BS 2015; also Strassler, Zurek 2006; Baumgart *et al.* 2009; Bai, Tait 2012; Schwaller *et al.* 2015; Cohen *et al.* 2015; Primulando *et al.* 2015; Autran *et al.* 2015; Bai *et al.* 2015; Buschmann *et al.* 2015

Discovering a Dark Sector

Generic Signatures:

- Missing momentum

- Light DM is **boosted** when produced at high-energy collider



- Get **long lifetimes** due to low mass, mixing angle suppression

$$c\tau(\pi^\pm) \sim 10 \text{ m} \qquad c\tau(D^\pm) \sim 0.1 \text{ mm}$$

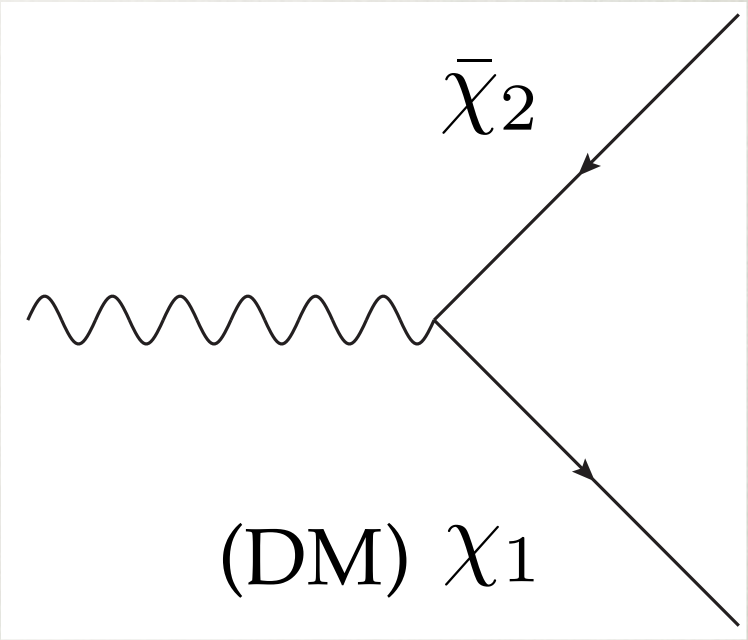
$$c\tau(K^0_\mathrm{S}) \sim 1 \text{ cm} \qquad c\tau(B^\pm) \sim 0.1 \text{ mm}$$

c.f. hidden valleys (Strassler, Zurek 2006)

Multicomponent Dark Matter

- Consider two representative scenarios:

1. <u>Inelastic Dark Matter:</u>
    - not currently covered
    - can represent many dark sectors/HVs



Izaguirre, Krnjaic, BS arXiv:1508.03050 (PRD)

2. <u>New Electroweak State:</u>
    - generic extension of SM but hard to find

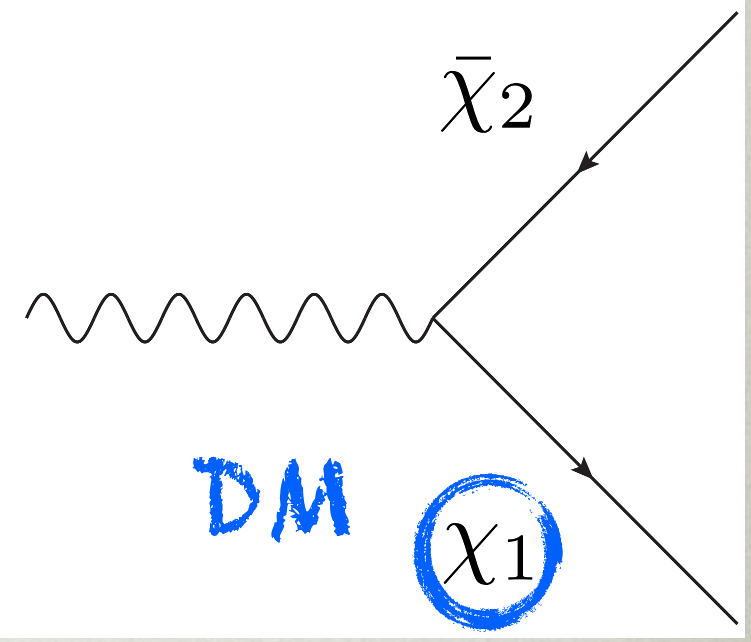
$$\chi = \begin{pmatrix} \psi^+ \\ \psi^0 \\ \psi^- \end{pmatrix}$$

Ismail, Izaguirre, BS arXiv:1605.00658 (PRD)

1) Inelastic Dark Matter

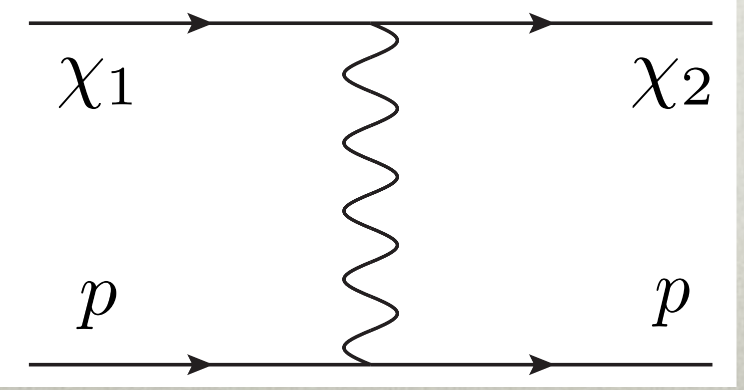
- In **Inelastic Dark Matter** (iDM) scenarios, interactions always involve two **different** dark particles

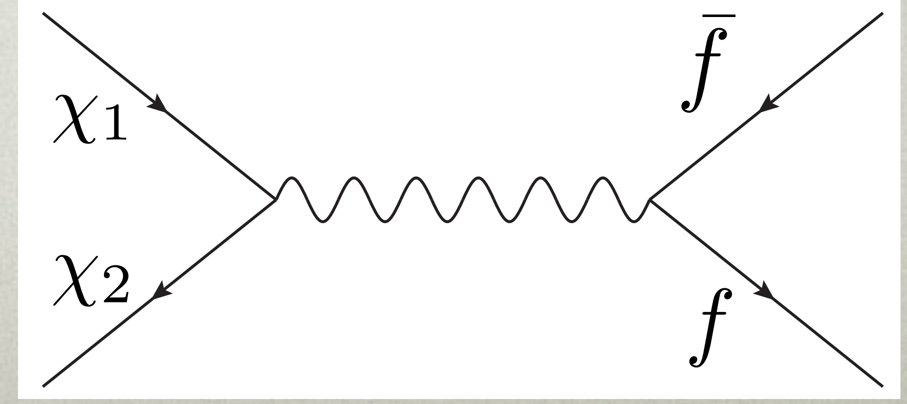
Tucker-Smith, Weiner, hep-ph/0101138



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

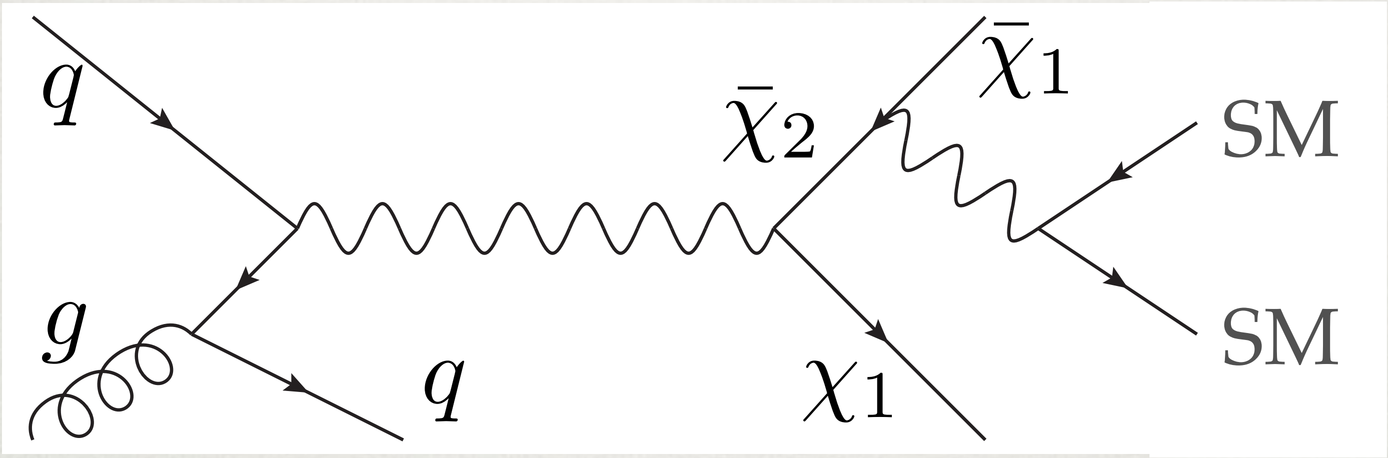
- Greatly suppressed direct & indirect DM signals!





Inelastic Dark Matter

- Colliders can easily produce both $(\Delta \lesssim \text{TeV})$



Bai, Tait, 2011; Izaguirre, Krnjaic, BS, 2015

- Similarities with compressed spectra

e.g., Giudice *et al.*, 1004.4902; Han *et al.*, 1401.1235, …

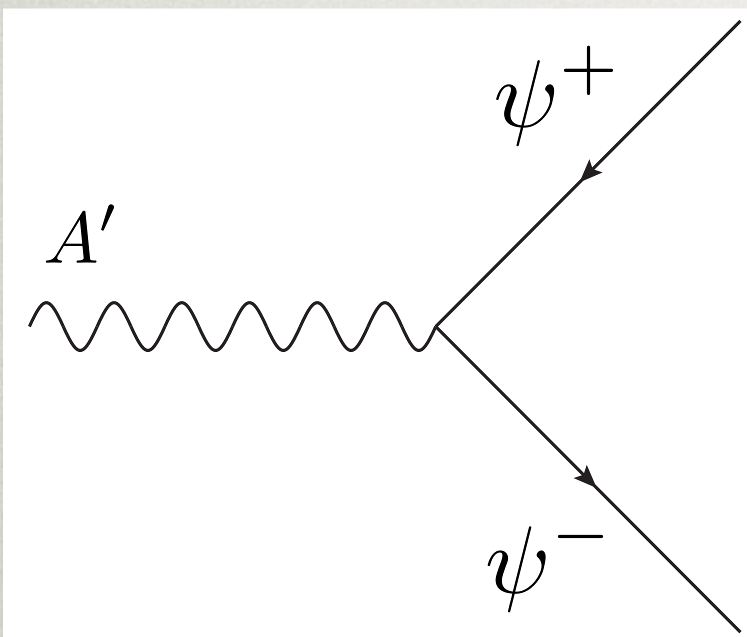
- If mass splitting large, can directly tag decay of heavier DM

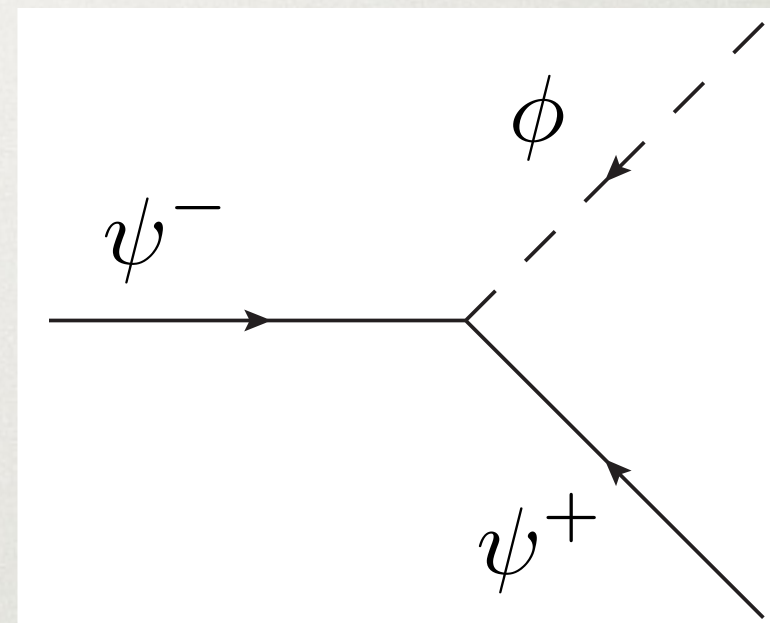
Weiner, Yavin, 1206.2910; Primulando *et al.*, 1503.04204

An Inelastic Benchmark

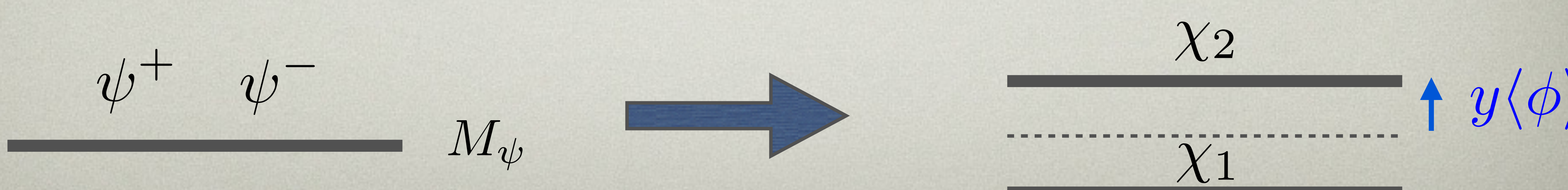
Tucker-Smith, Weiner, hep-ph/0101138; Izaguirre, Krnjaic, BS, 1508.03050

- Higgsed dark QED





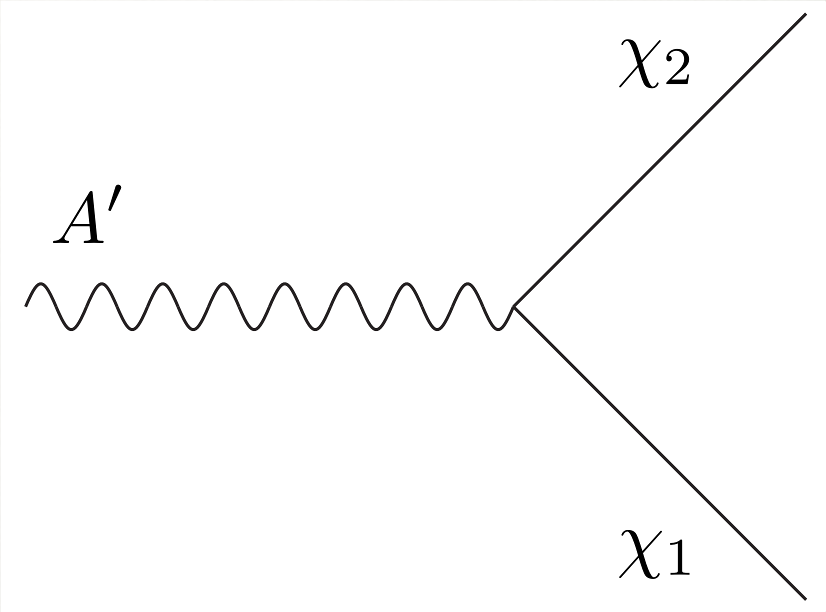
$$\mathcal{L} \supset ig'\bar{\psi}\gamma^\mu\psi A'_\mu - M_\psi\bar{\psi}\psi + y\phi\bar{\psi}^c\psi$$



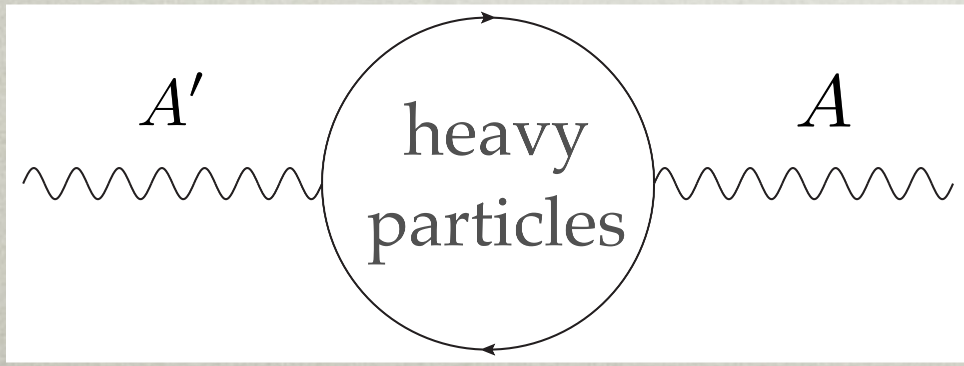
An Inelastic Benchmark

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

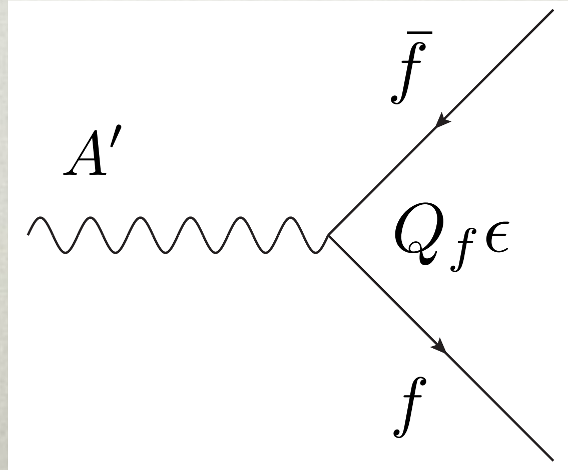
$$\mathcal{L} \supset ig' \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu$$



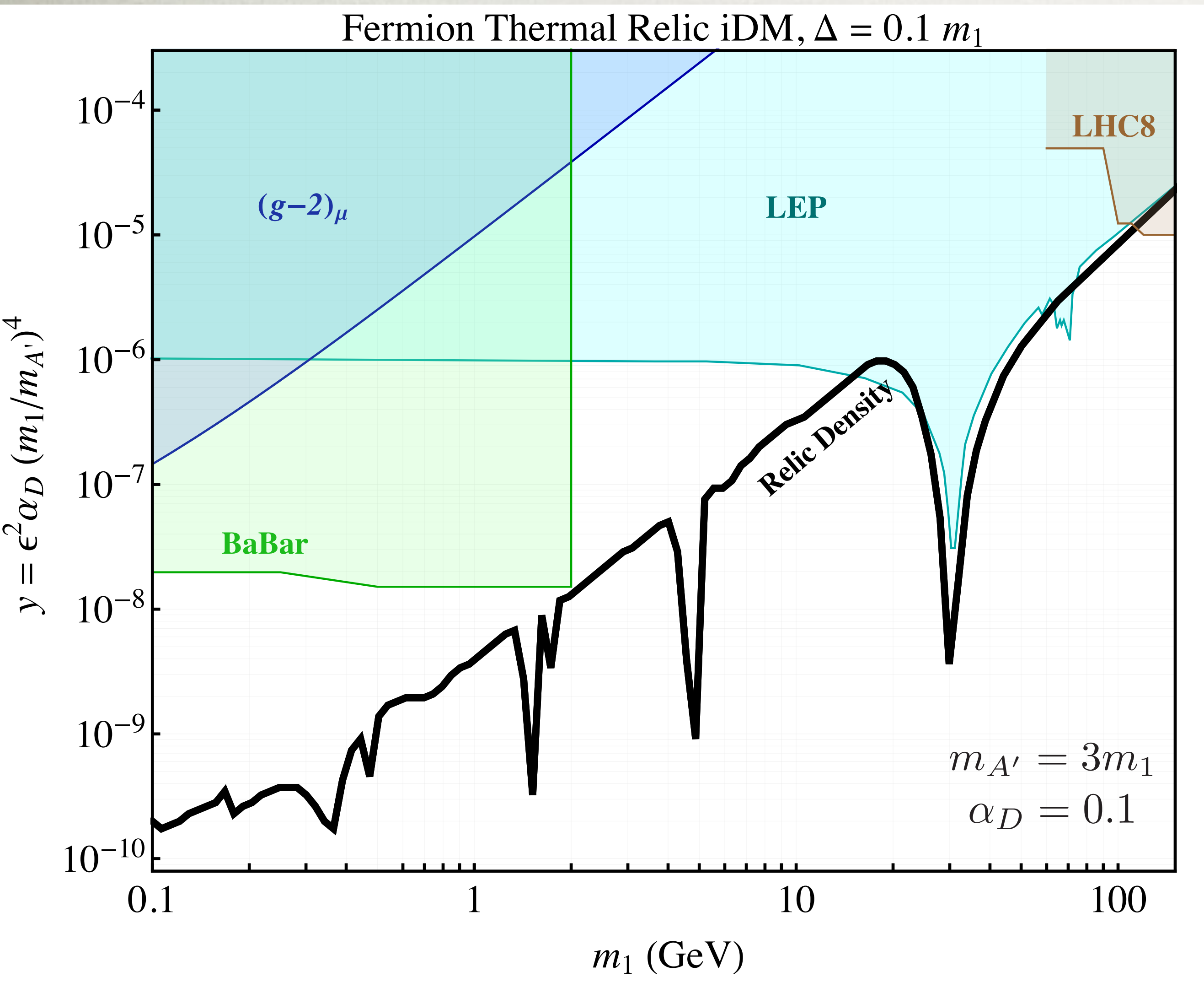
- Only remaining thing to be specified is A' coupling to SM

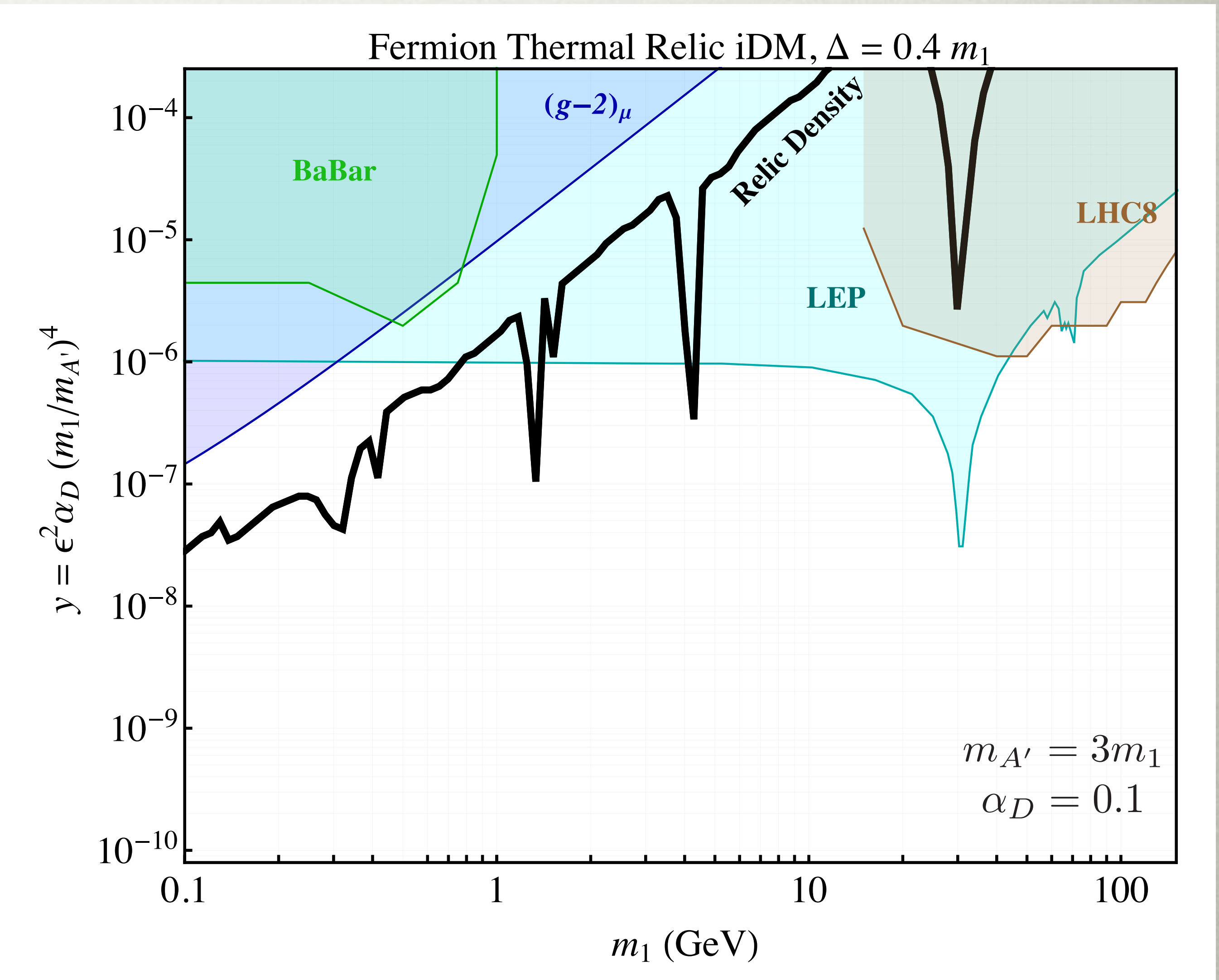


$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

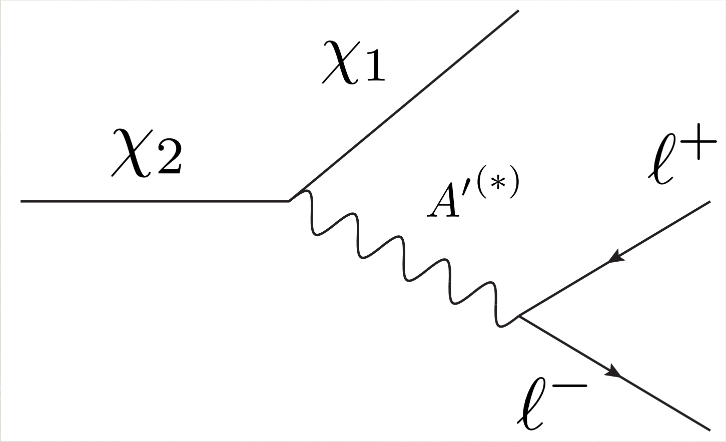


An Inelastic Benchmark





Improving the Searches

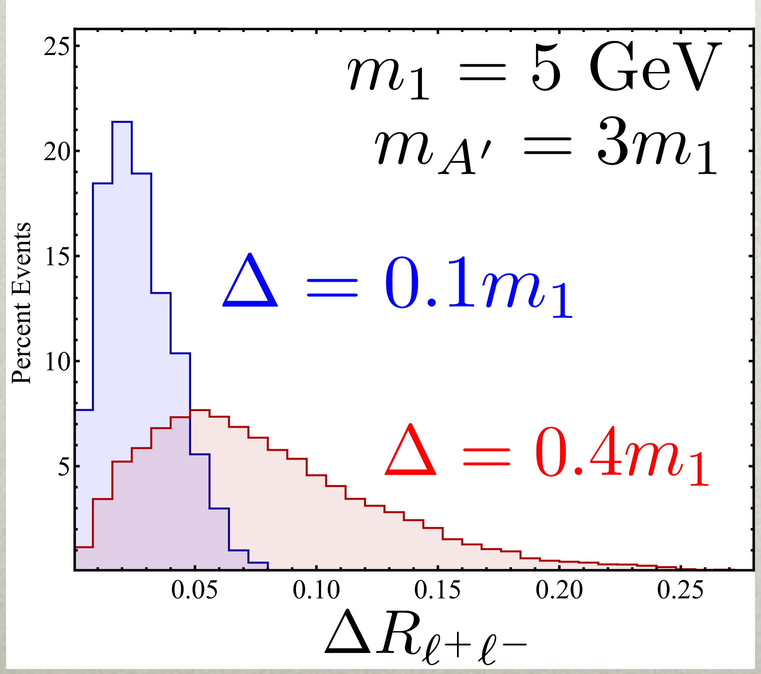


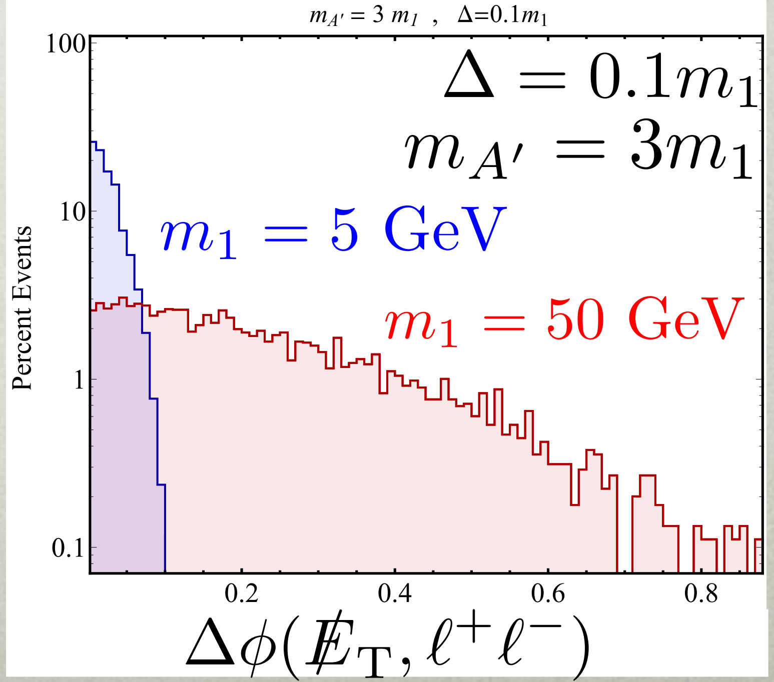
$$\Gamma_{\chi_2} \sim \frac{\alpha \alpha_{\mathrm{D}} \epsilon^2 \Delta^5}{M_{A'}^4}$$

- Get displaced decay!

- The leptons are typically soft, so trigger on monojet + missing pT

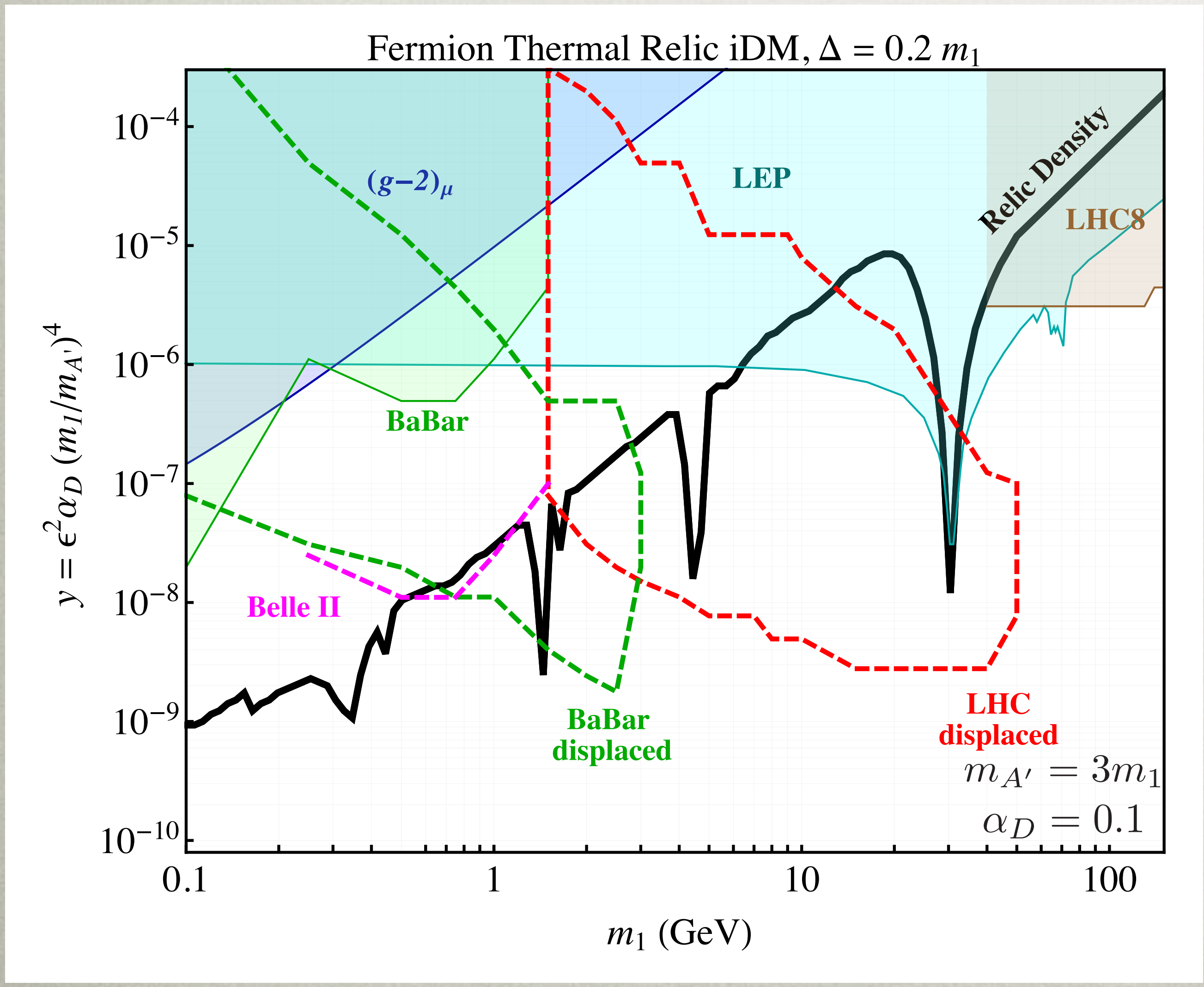
- The DM produced through on-shell A', so typically **boosted**

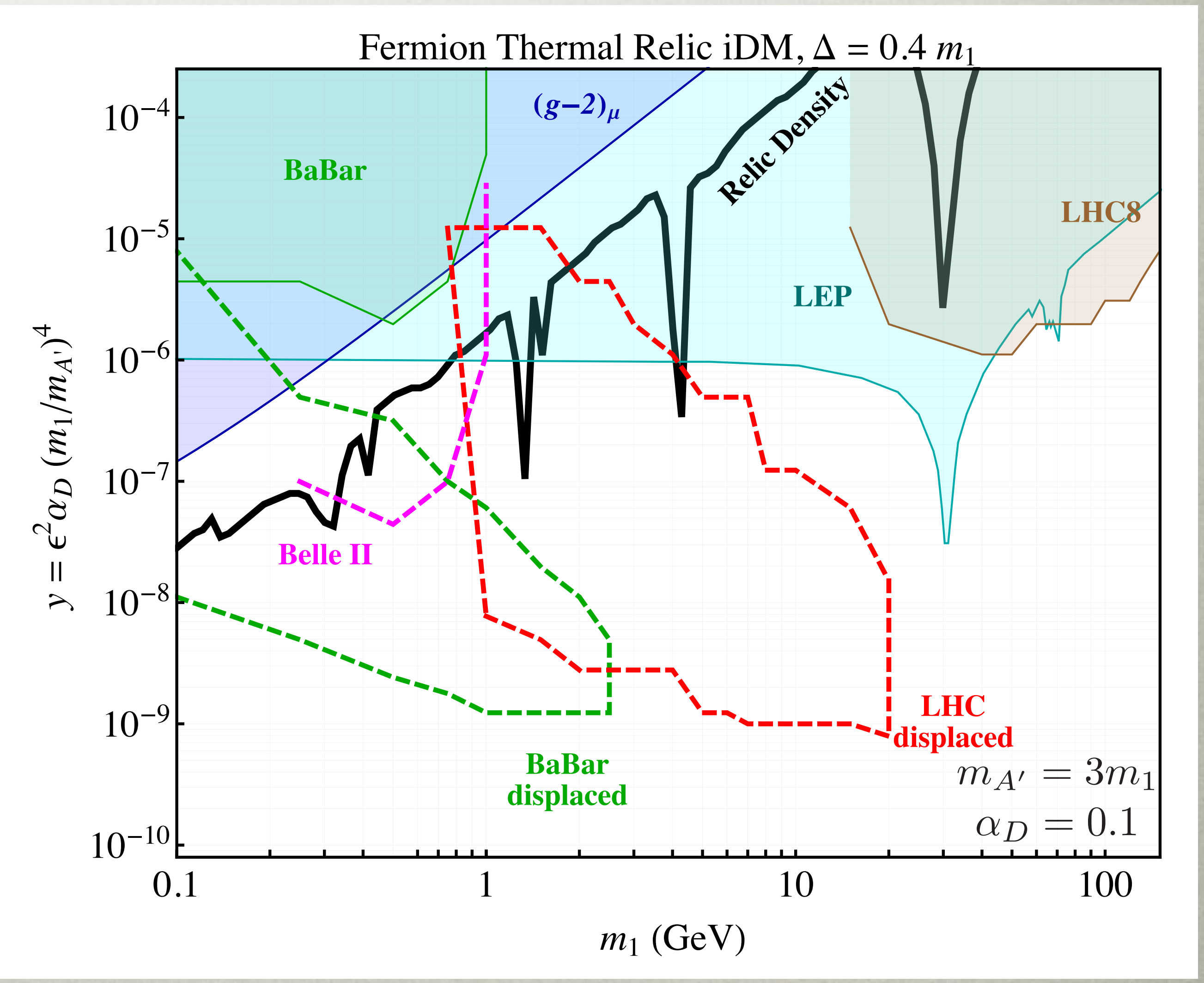




LHC Results

- Signature: monojet + missing pT, displaced boosted lepton pair
- Searches likely bkd-free, plot sensitivity to 10 signal events
- Show reach of LHC and low-energy colliders (BaBar, Belle II)





2) New Electroweak Multiplet

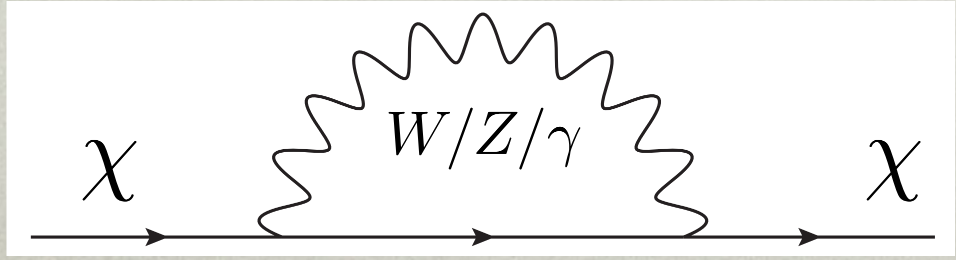
- One of the simplest dark matter scenarios ("minimal DM")

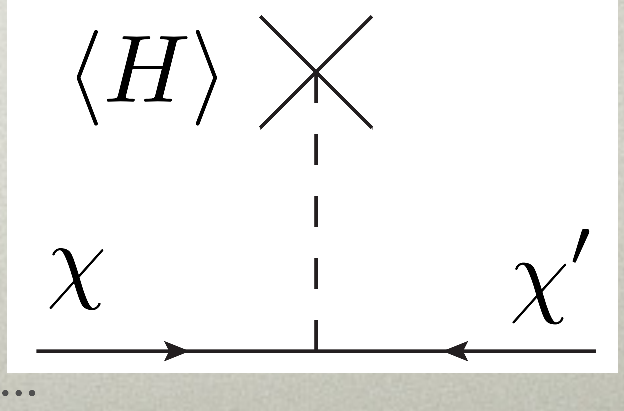
Cirelli, Fornengo, Strumia, hep-ph/0512090

- Expected in **natural** weak-scale theories (SUSY)
    - *e.g.* Higgsino doublet

$$(\chi^+, \chi^0)$$

- Electroweak symmetry ensures states are **nearly degenerate**

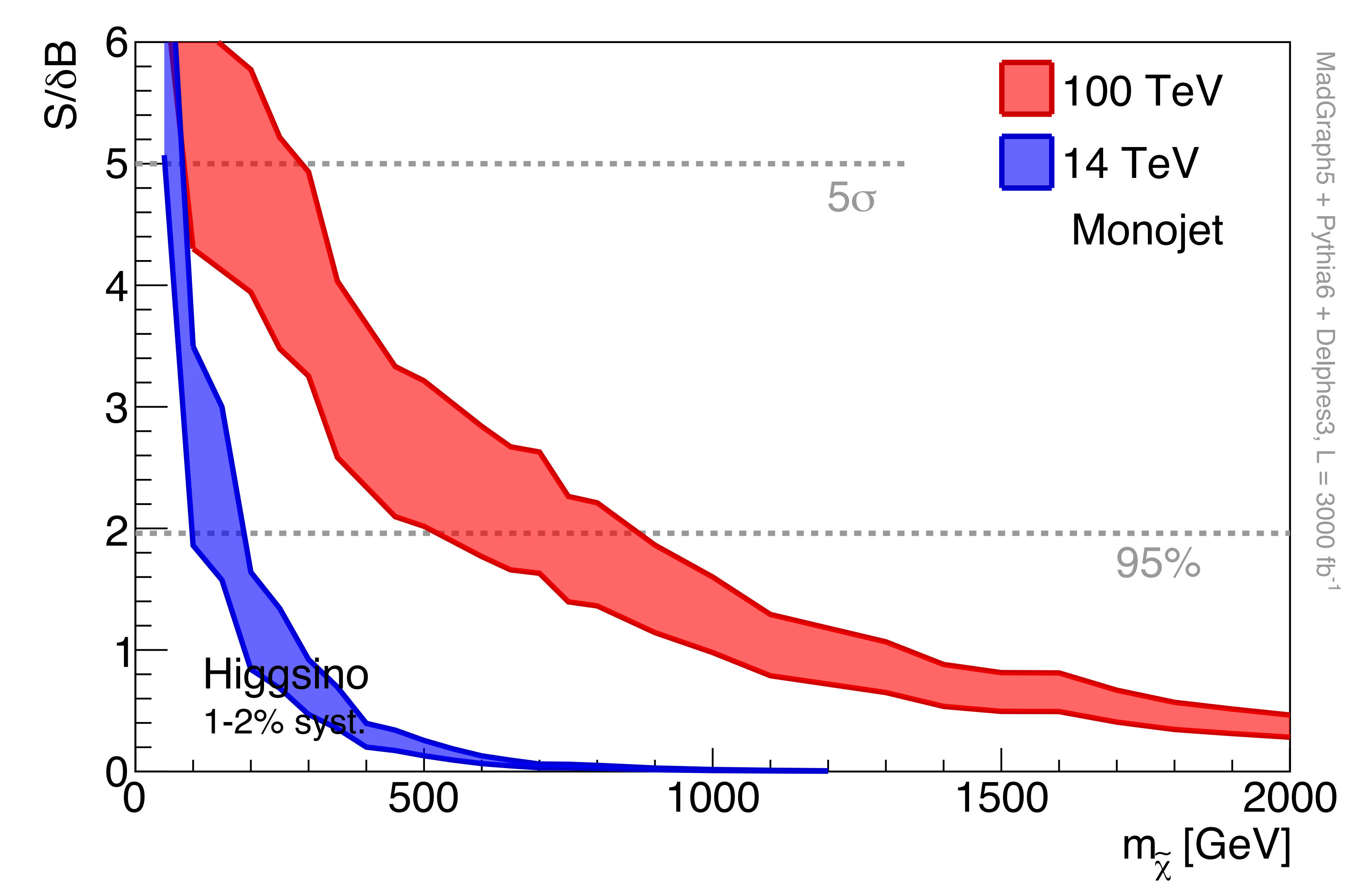




Stoker *et al.*, 1989; Chen *et al.*, 1995; Thomas, Wells, hep-ph/9804359, ...

Higgsino Doublet

- With minimal splittings, dominant decay mode is $\chi^{\pm} \to \pi^{\pm}\chi^{0}$ (crossed out)
- "Charged" particle is invisible!

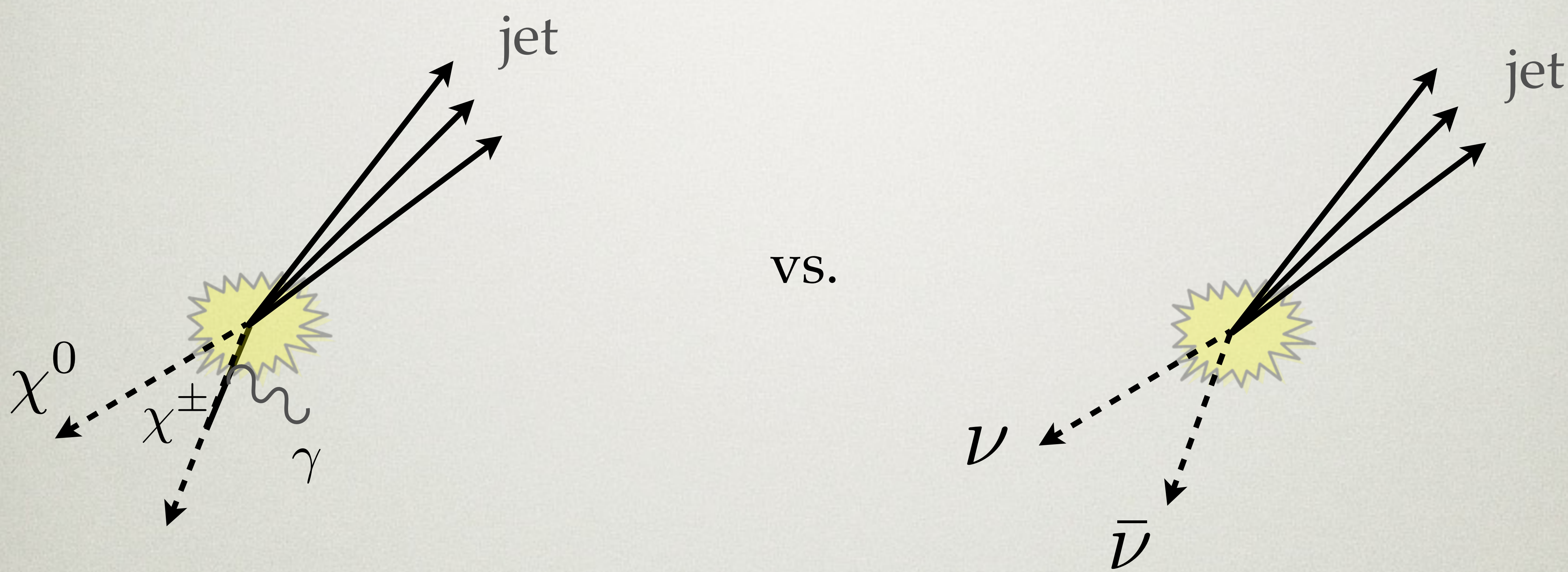


Low, Wang, 1404.0682

Higgsino Doublet

Ismail, Izaguirre, BS, 1605.00658

- Use fact that "invisible" particles are actually **charged**



- Can get **soft photon** correlated with MET direction
    - Collinear enhancement when DM is highly boosted

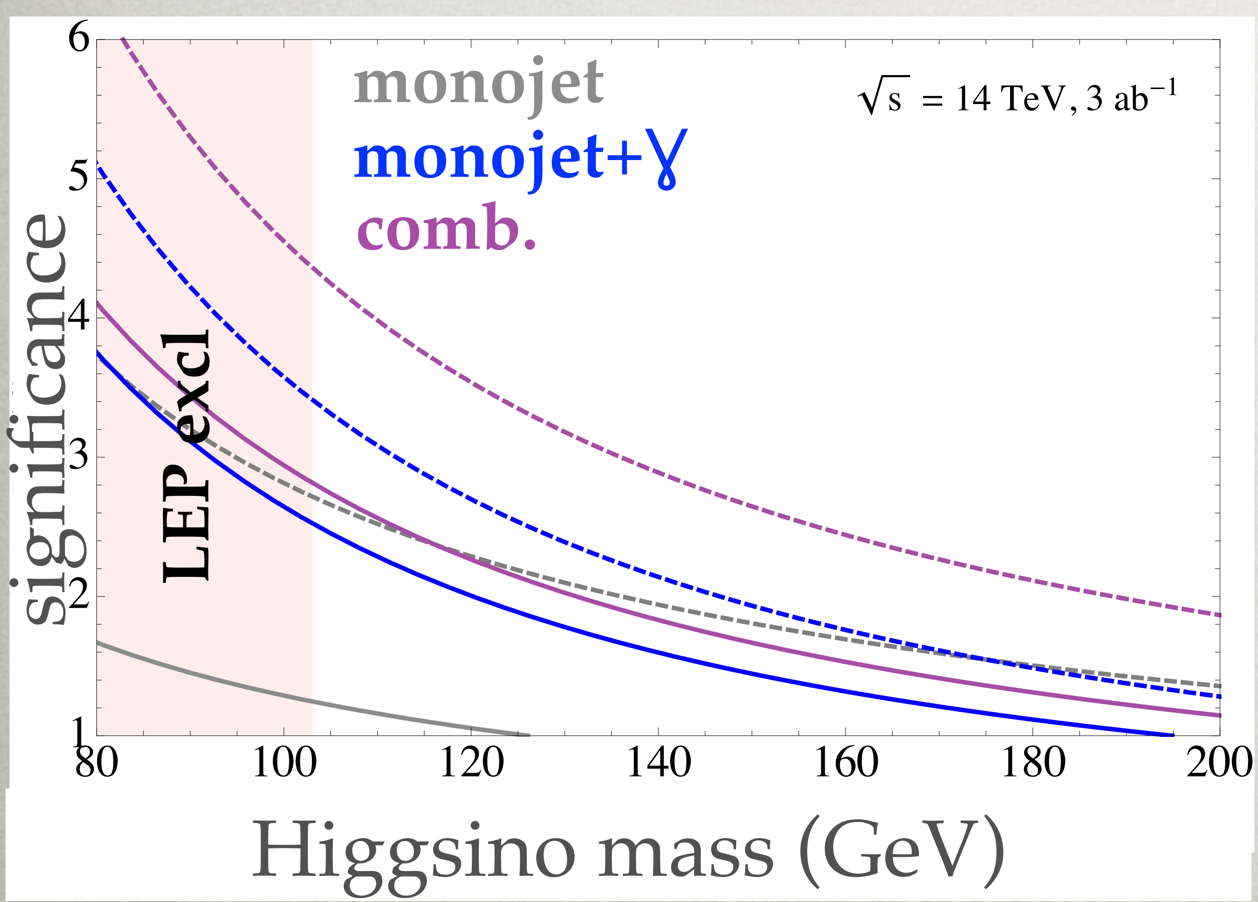
- Take hit in signal rate to improve S/B

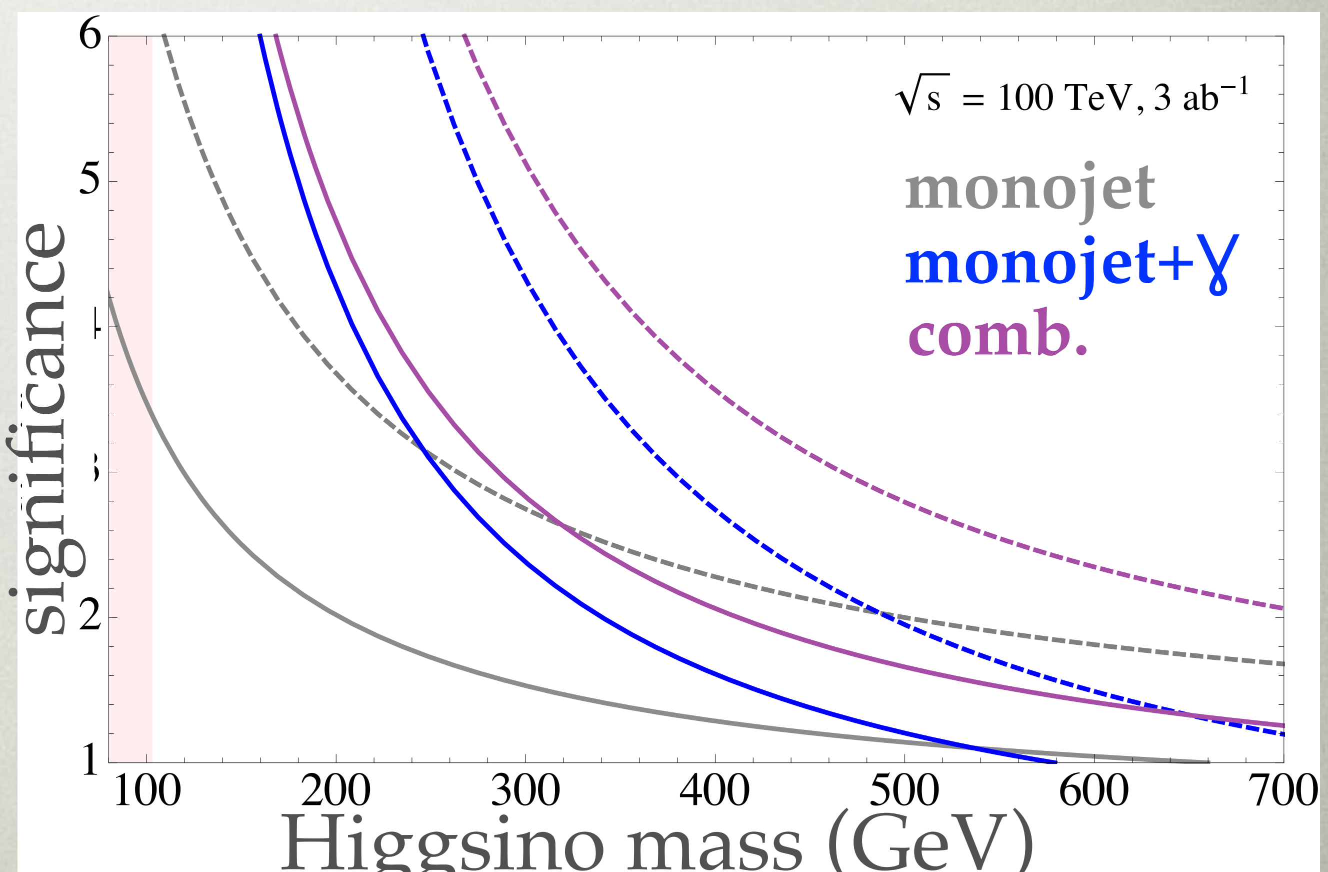
Higgsino Doublet Results

- Optimize over other kinematic cuts (MET, jet p_T, etc.)

HL-LHC **100 TeV, 3/ab**

solid = 5% syst.
dotted = 2% syst.





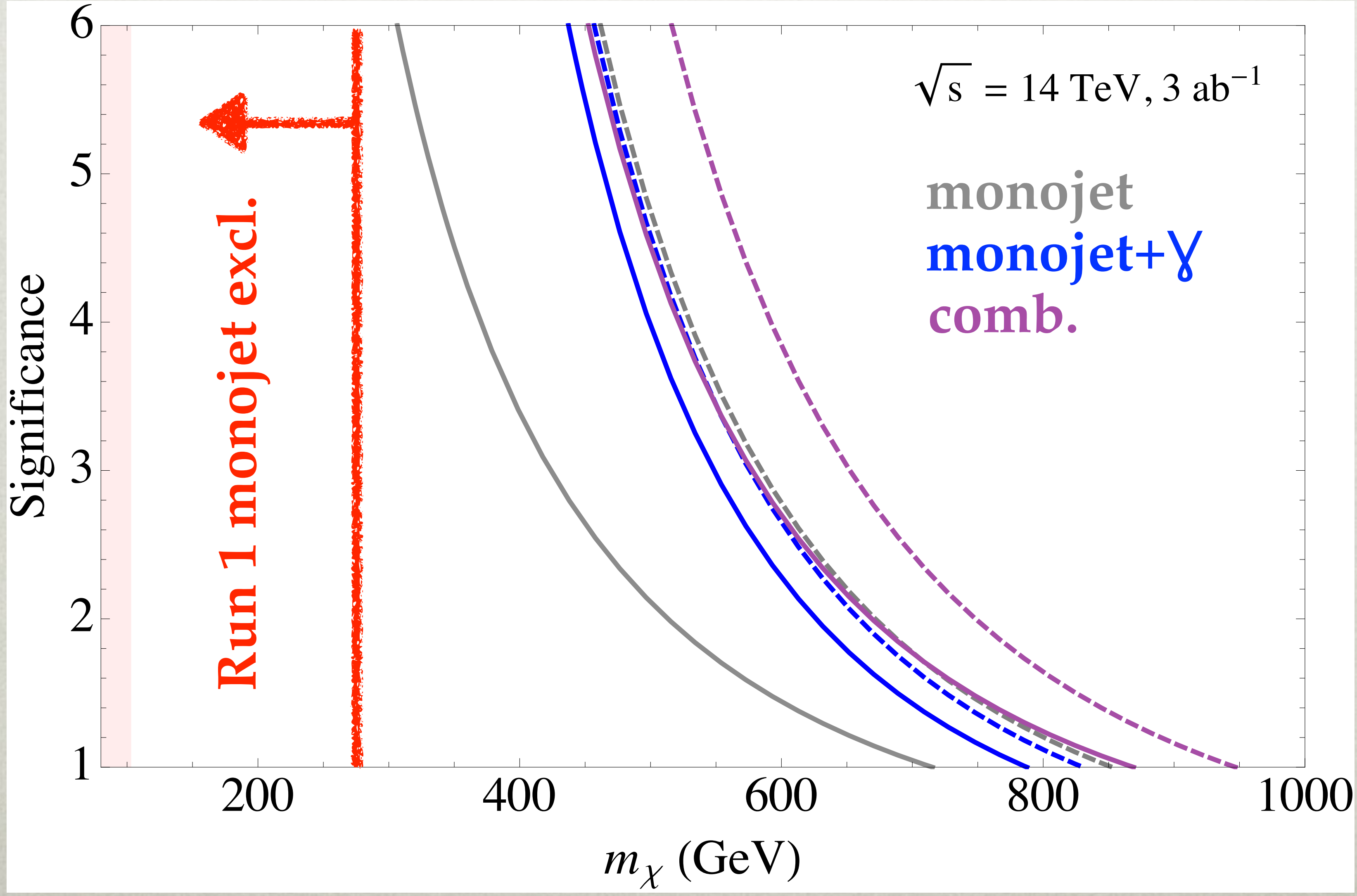
Ismail, Izaguirre, BS, 1605.00658

Quintuplet Results

- Can also consider other states, like a quintuplet with $Y = 0$
- With 20/fb, competitive with current bound (~400 GeV in comb.)

HL-LHC

solid = 5% syst.
dotted = 2% syst.



Non-Minimal Couplings

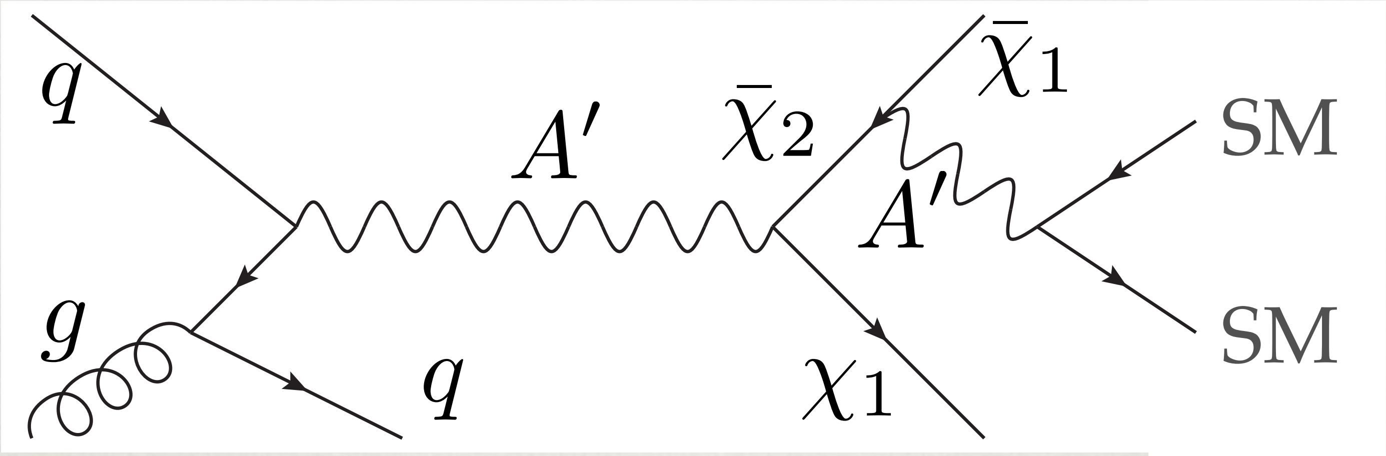
BS, I. Yavin, arXiv:1403.2727

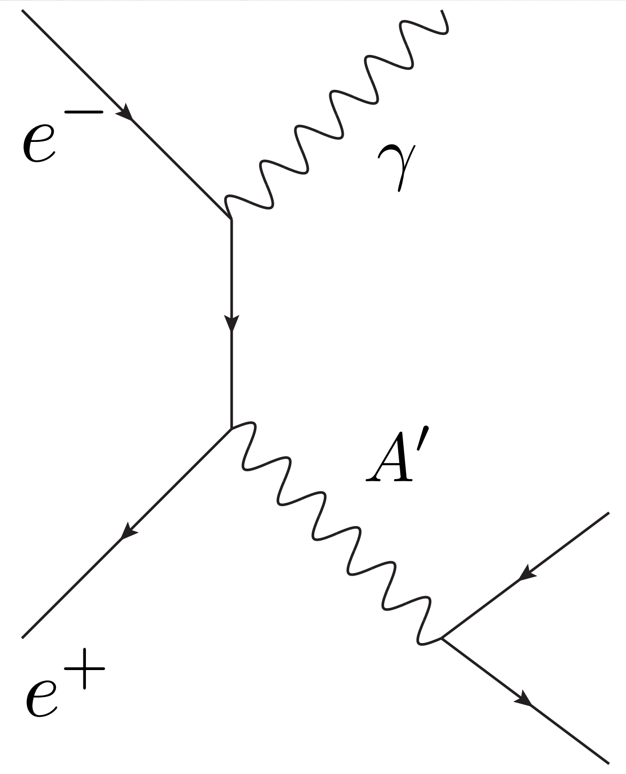
BaBar, arXiv:1606.03501

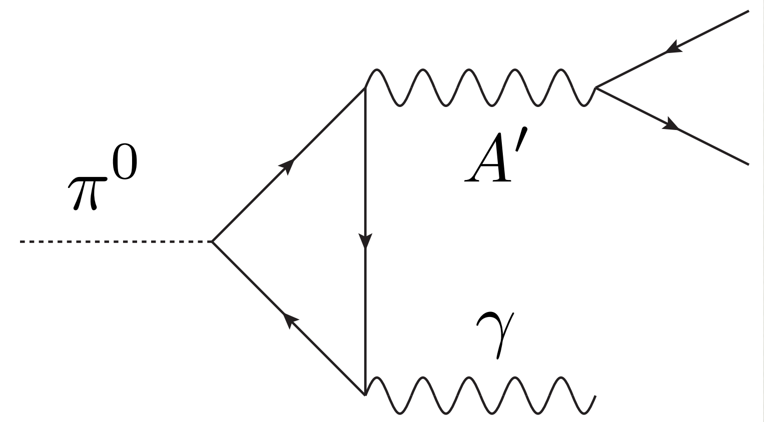
BaBar [in progress]

Non-Minimal Couplings

- In the previous examples, we assumed the dark sector particles could be produced via coupling to light-flavour particles





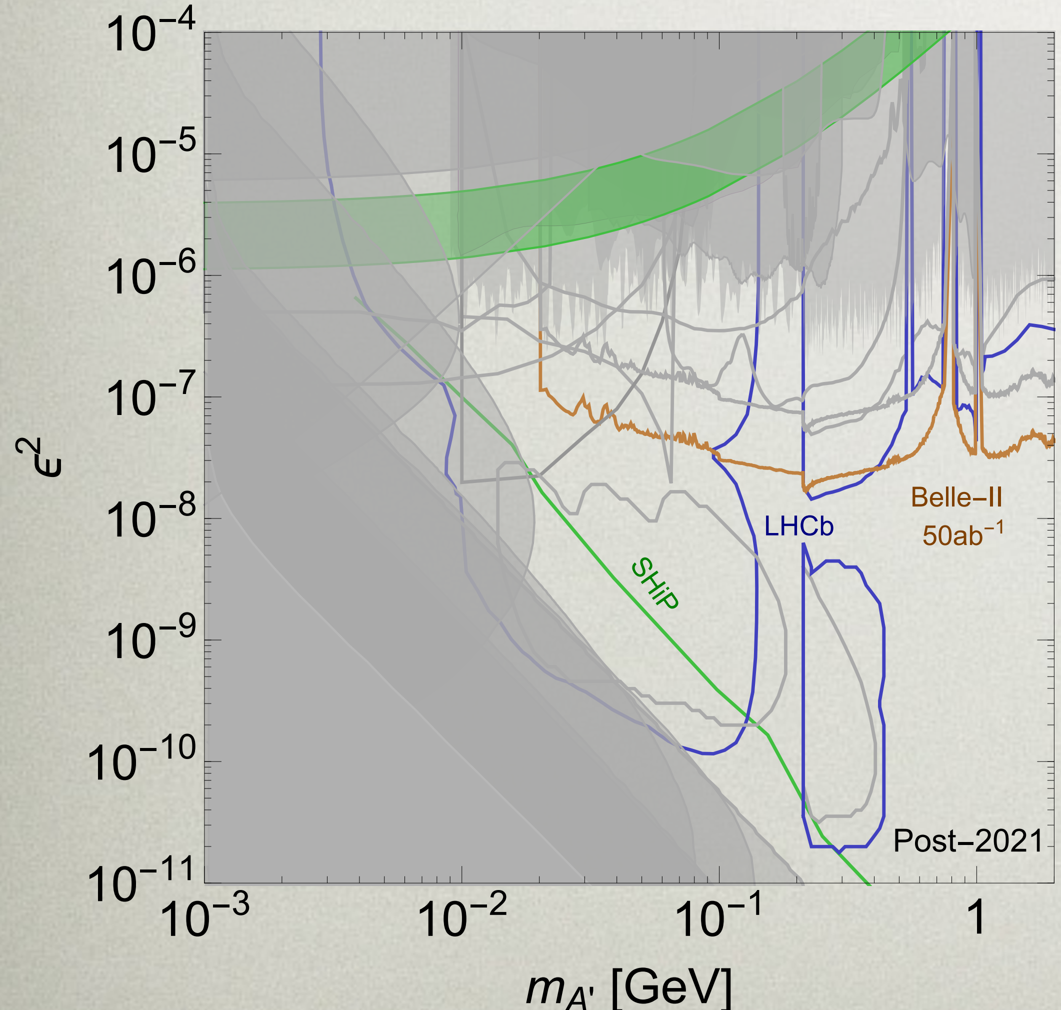


Non-Minimal Couplings

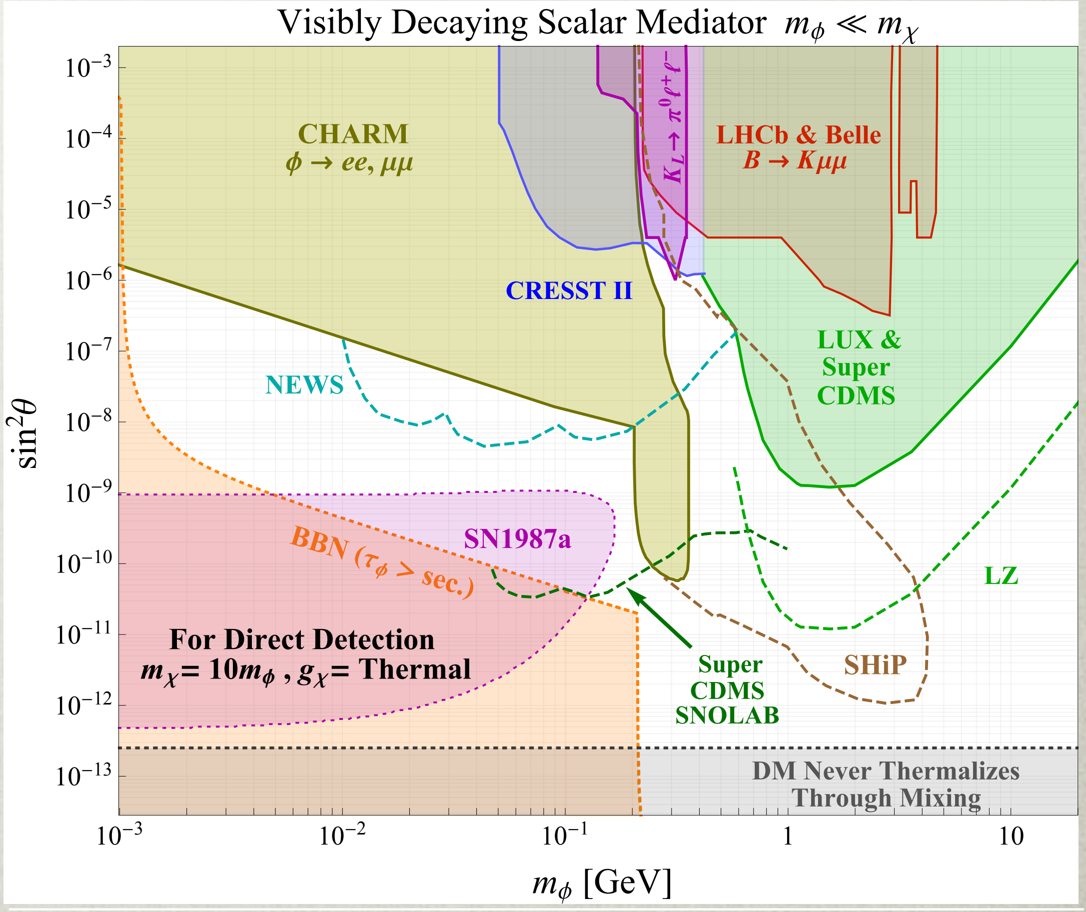
- These constraints are generally pretty powerful…

photon-like coupling

Higgs-like coupling



Dark Sectors 2016 Whitepaper

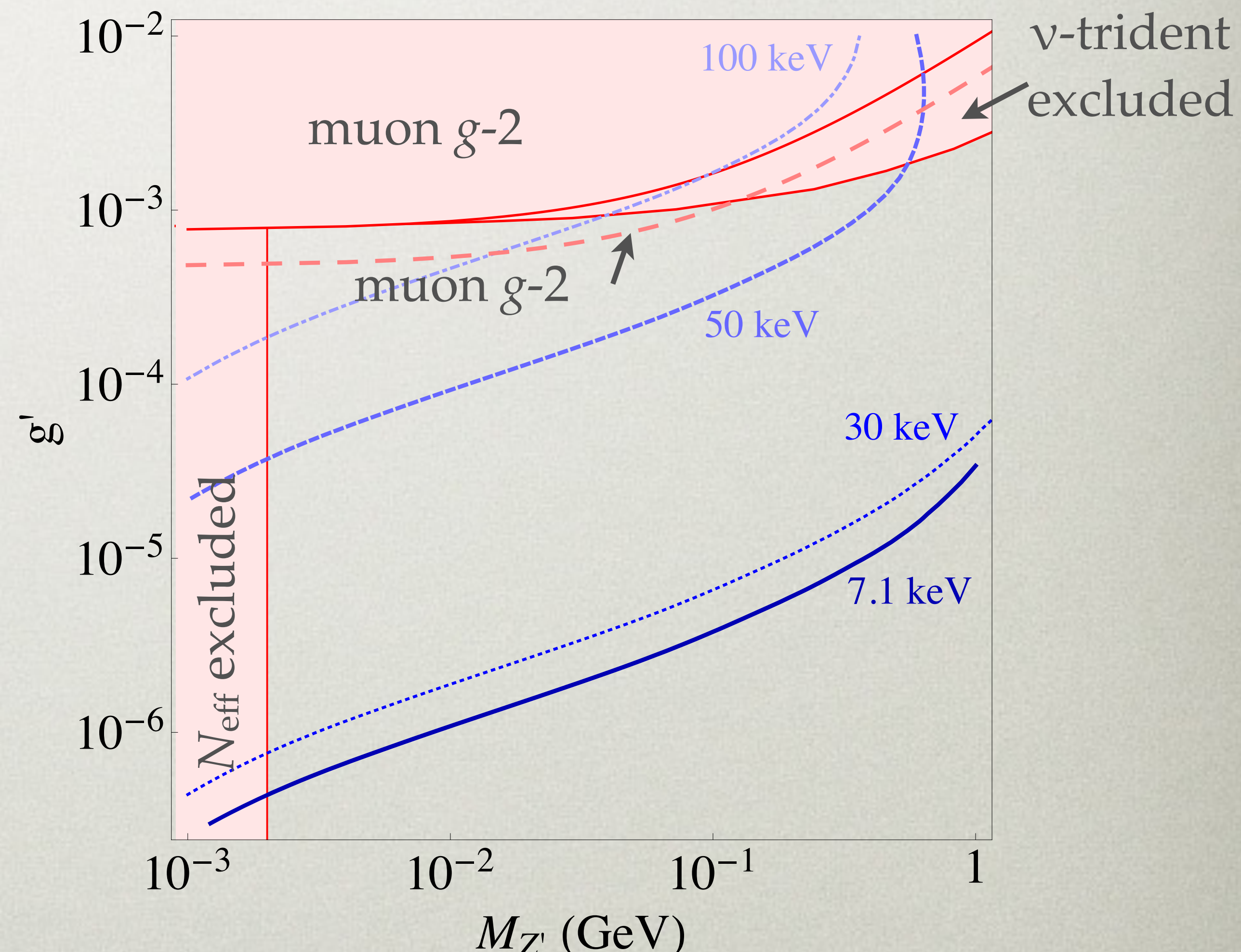


(Batell et al, arXiv:1606.04934)

Non-Minimal Couplings

- If couplings to electrons & quarks suppressed, however, bounds are *substantially* weaker

BS, I. Yavin, arXiv:1403.2727



- Gauged lepton number currents (such as L_μ-L_τ)

- "Leptophilic" Higgs with mass-proportional coupling

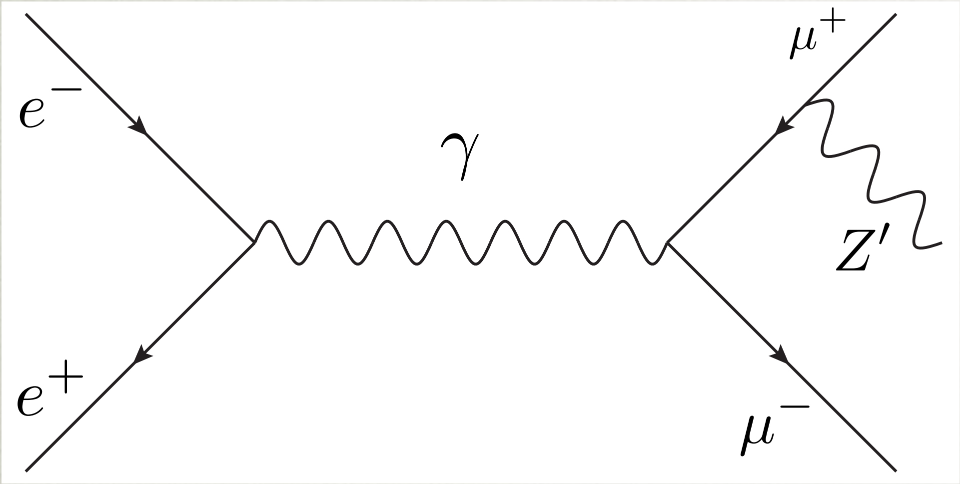
(Batell et al, *arXiv:1606.04934)*

- Could explain various "muon anomalies" (*g*-2, proton radius, …)

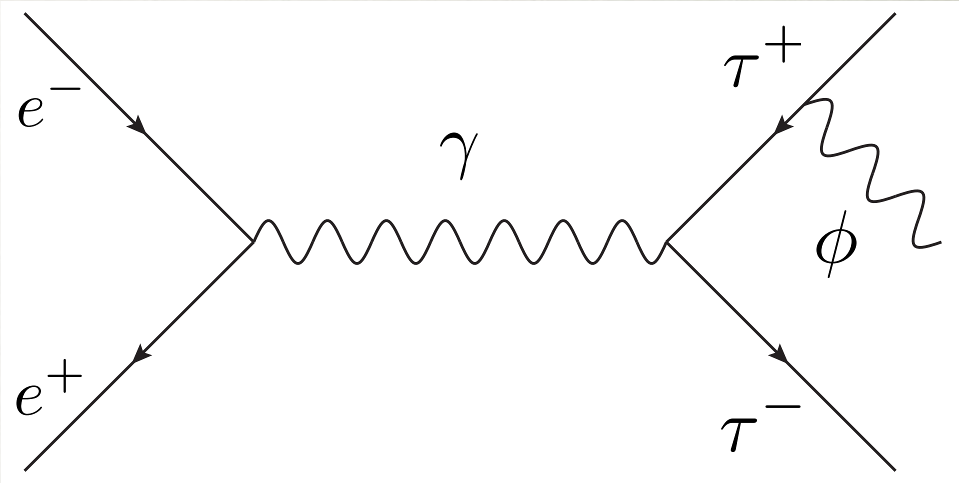
Non-Minimal Couplings

- Must rely on **final-state radiation** of dark sector particle

L_μ-L_τ



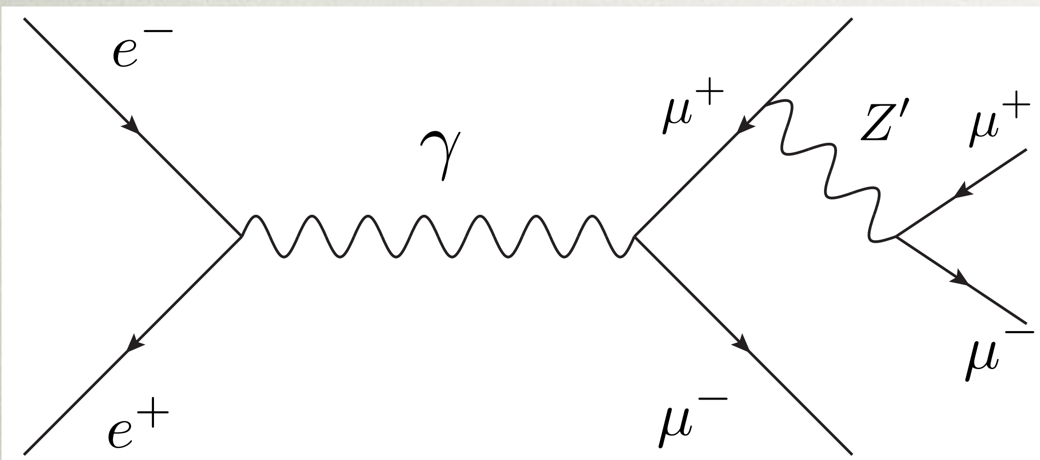
leptophilic scalar

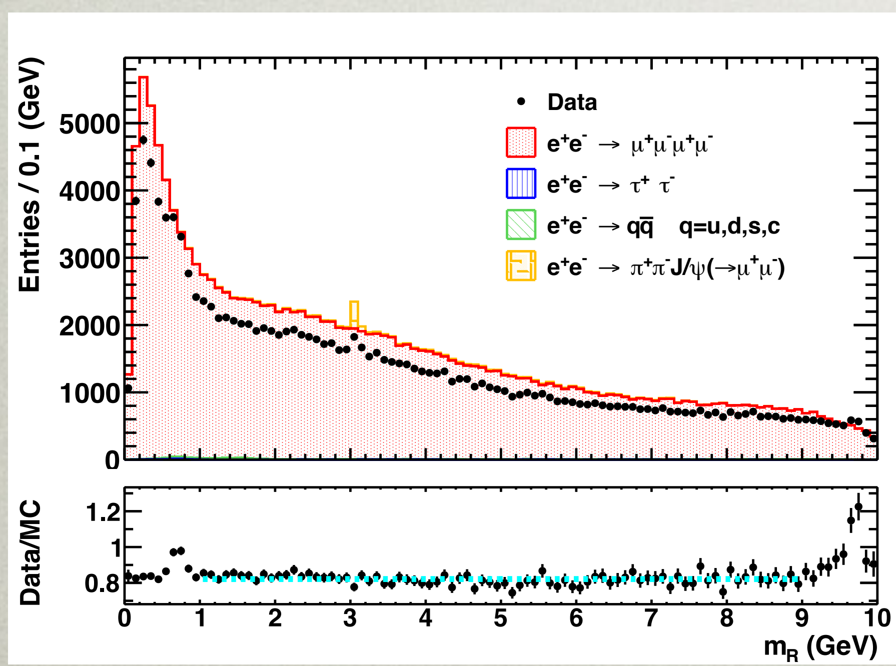


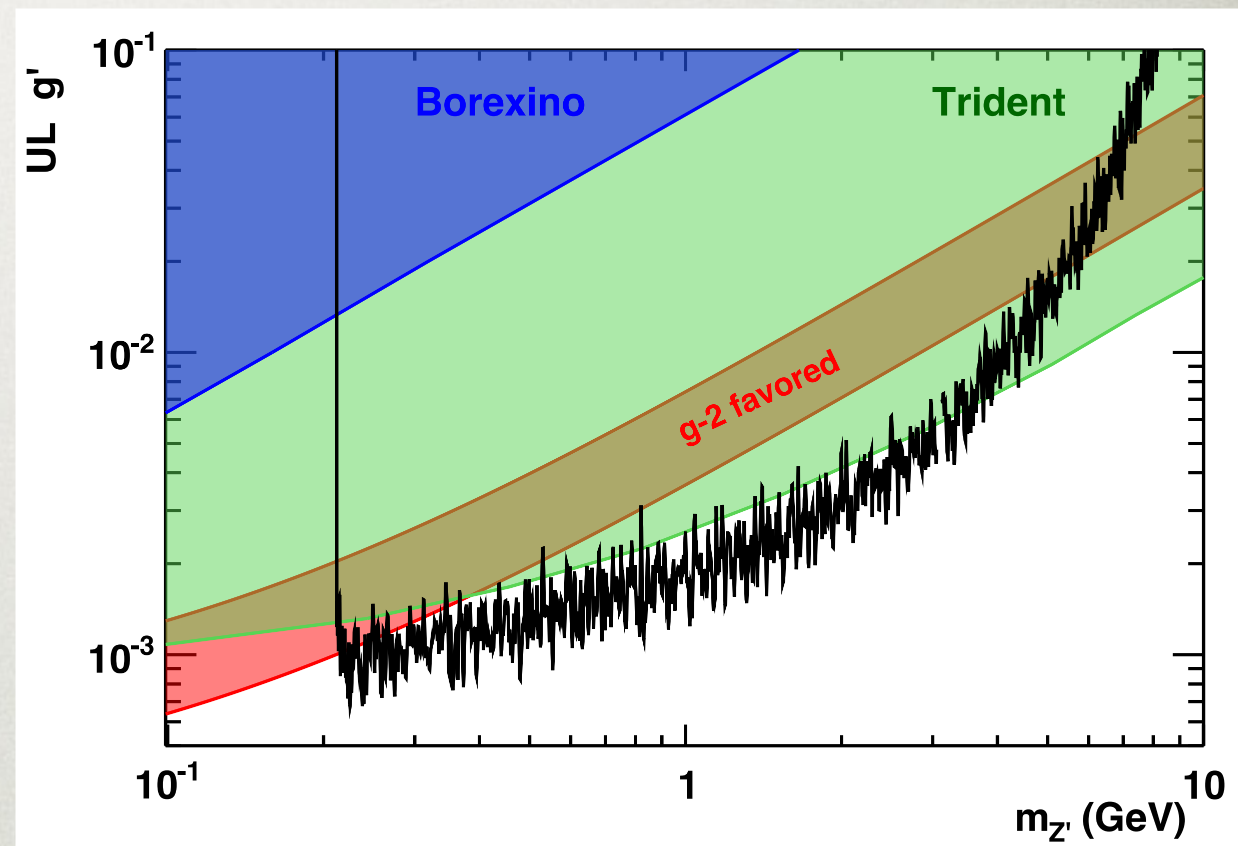
- Dedicated search for dark force in association with 2 leptons
- Can decay **visibly** (to muons or electrons) or to DM (invisible)
- Low-energy, high-intensity colliders like BaBar or Belle are ideal

Non-Minimal Couplings

- First model-independent test of **dark muonic force** at BaBar



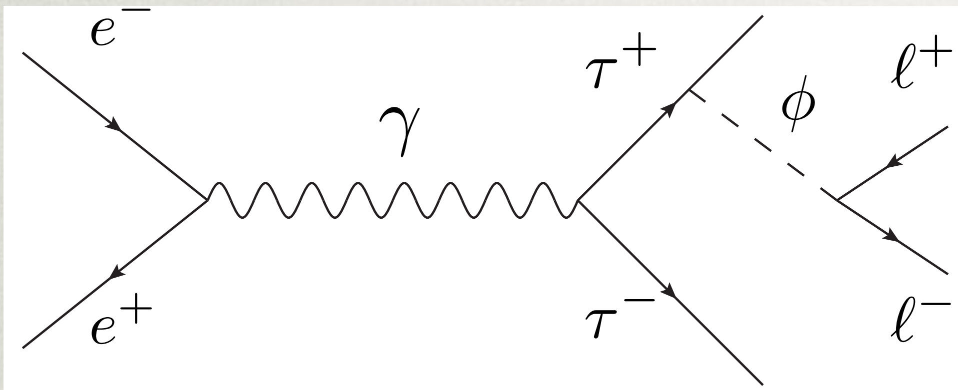


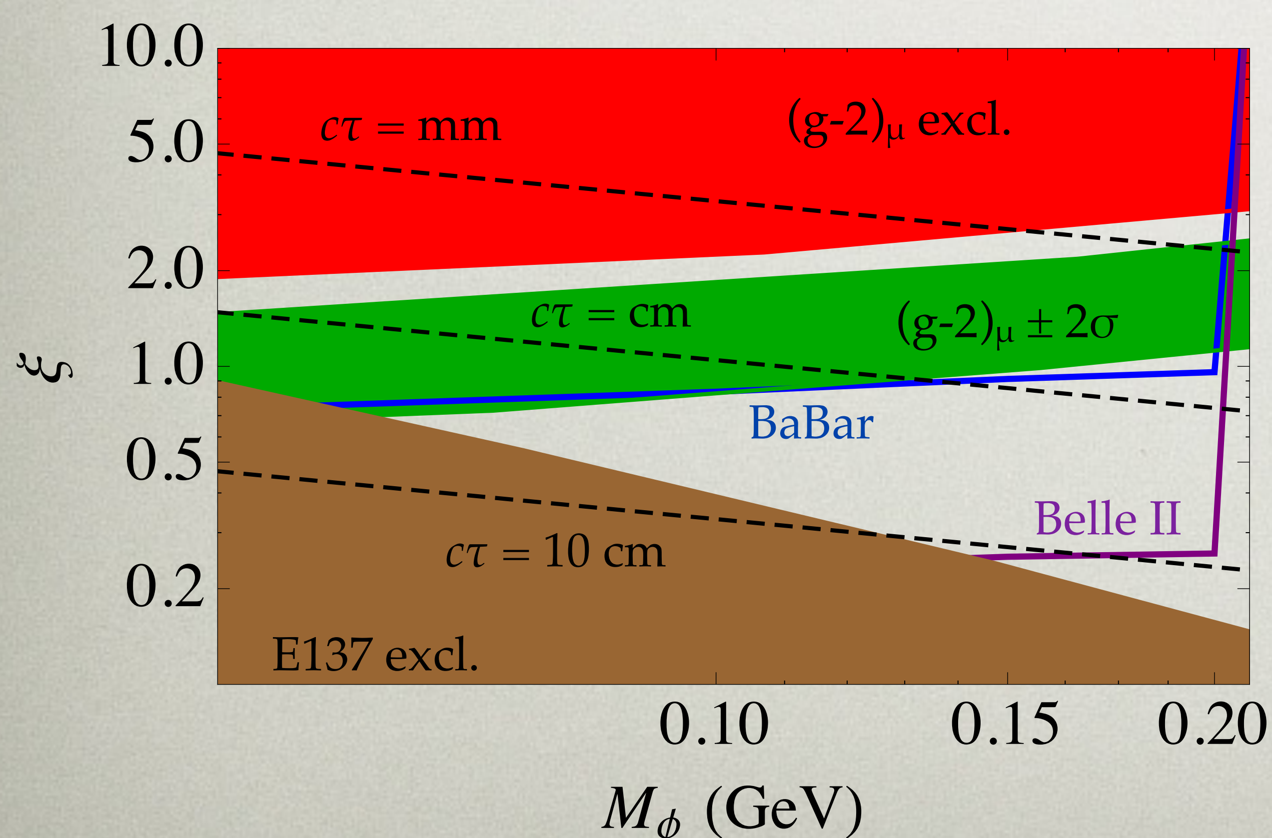


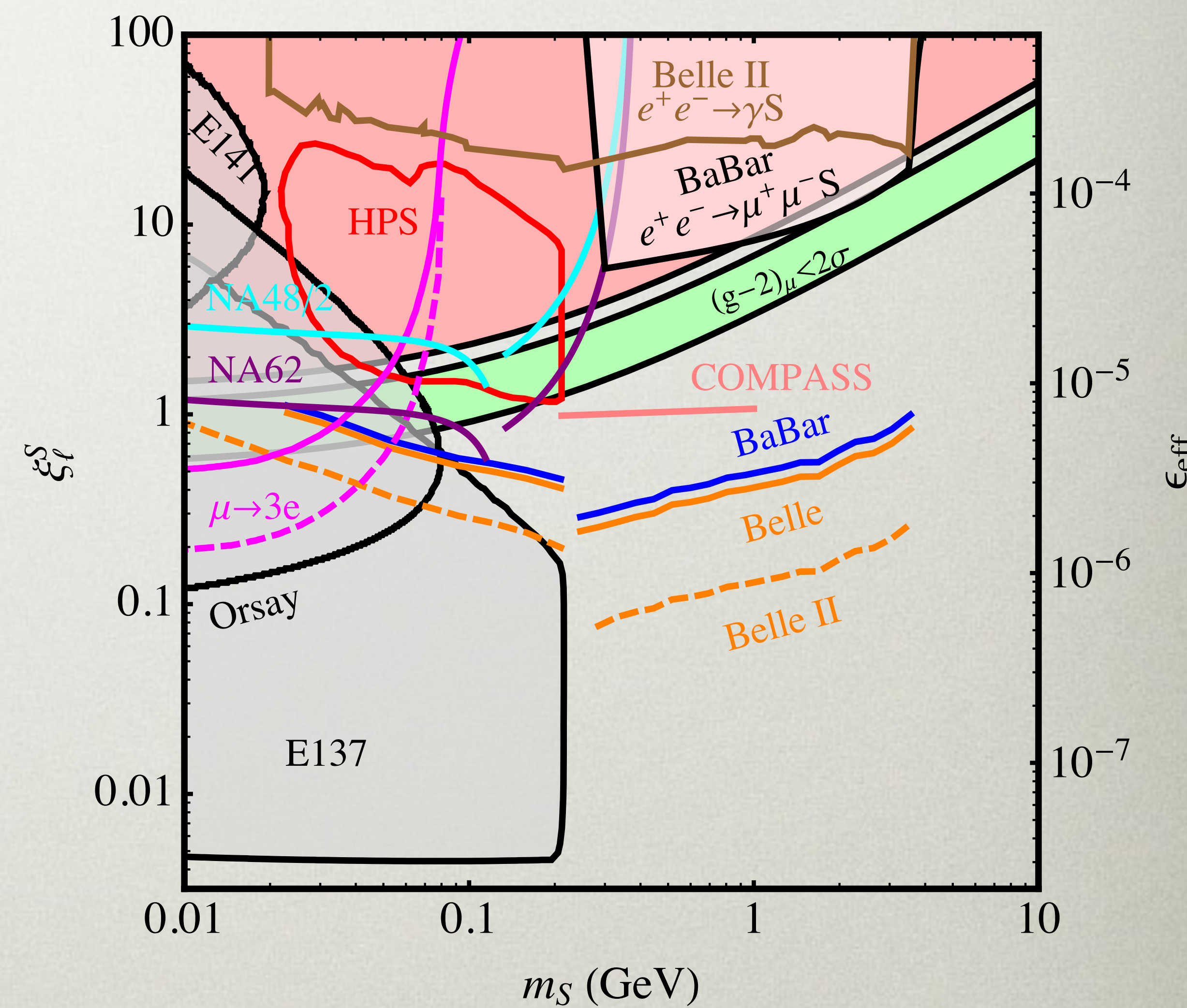
BaBar, arXiv:1606.03501

Non-Minimal Couplings

- Leptophilic scalar searches are ongoing







(*Batell* et al, *arXiv:1606.04934*)

Summary

- New physics at or below the weak scale is motivated by naturalness, dark matter, baryogenesis, and neutrino masses

- Many diverse hidden sector models and frameworks predict **similar signatures**

- In many cases backgrounds are so low that a discovery is possible even in very low-mass final states, but dedicated searches needed

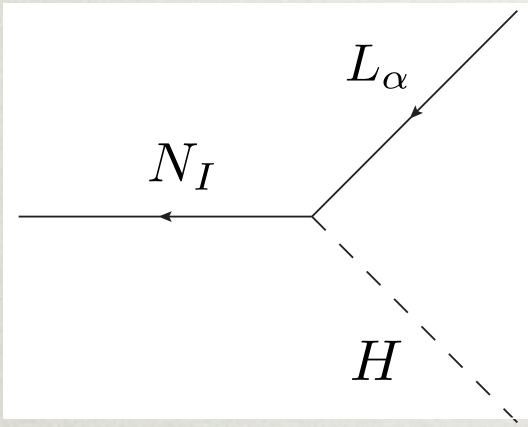
- Let's hope for discovery in both high- and low-mass new physics!

Back-up slides

Organizing Signatures

- In the limit of decoupled or absent UV states, the dominant couplings of new gauge singlet fields are via **renormalizable portals**

NEUTRINO PORTAL

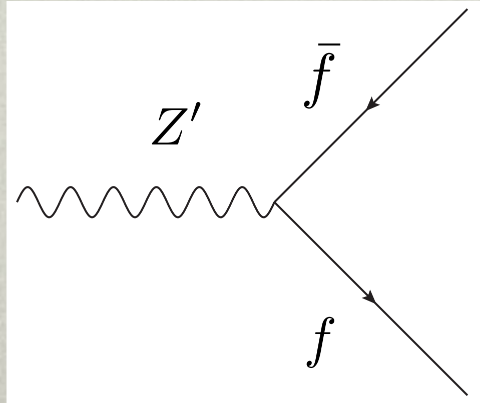


$$\mathcal{L}_\nu = F_{I\alpha}\bar{N}_I H L_\alpha$$

VECTOR PORTAL

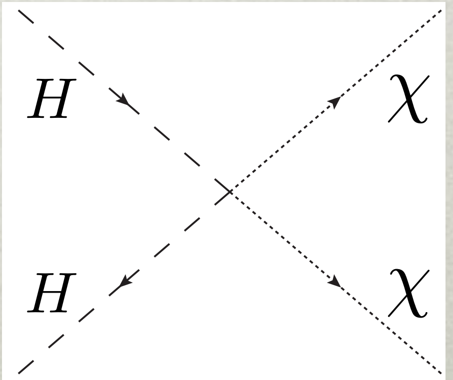
$$\mathcal{L}_{\text{vector}} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

Z′ PORTAL



$$\mathcal{L}_{Z'} = g_{Z'}\bar{f}_{\text{SM}}\gamma^\mu f_{\text{SM}} Z'_\mu$$

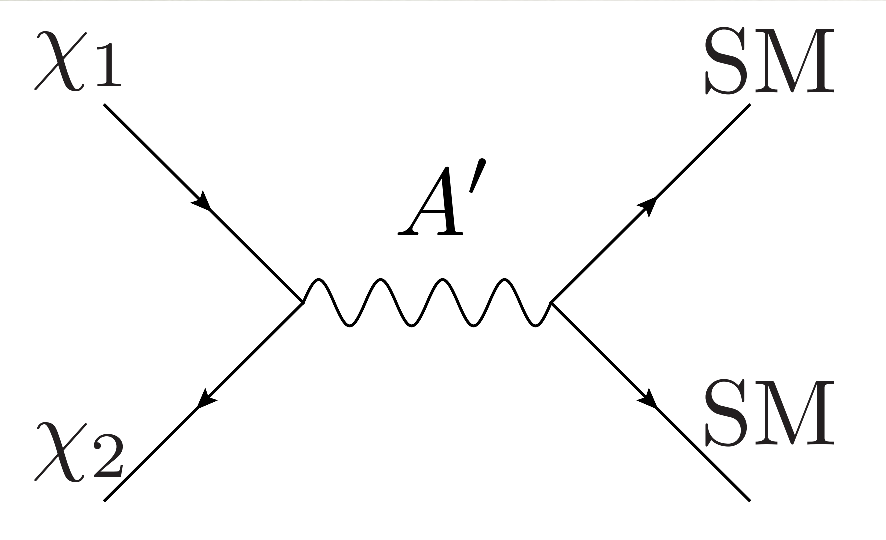
HIGGS PORTAL



$$\mathcal{L}_H = -\lambda|H|^2|\chi|^2$$

Inelastic Freeze-out

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



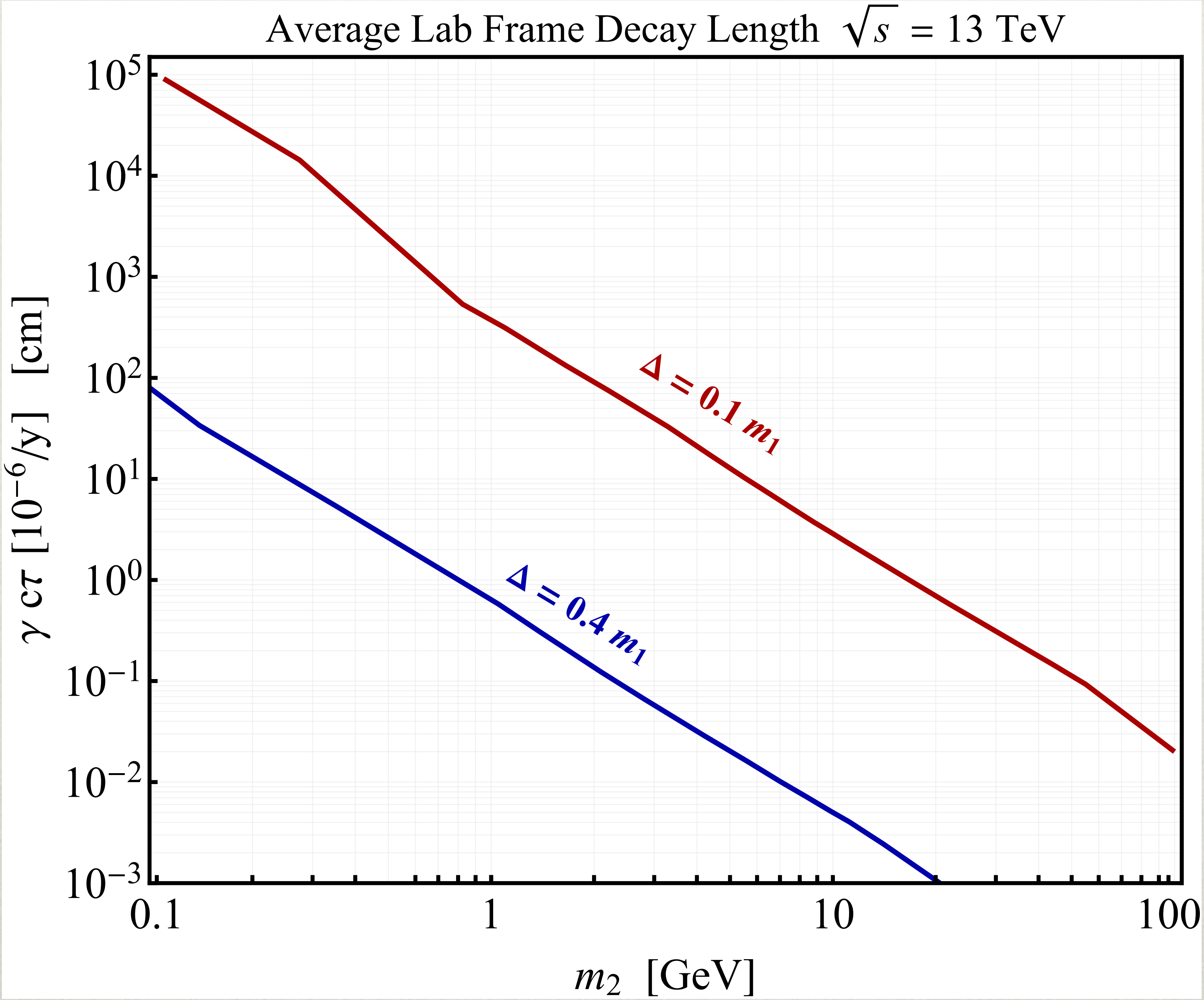
$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_D M_1^2}{M_{A'}^4} = \frac{y}{M_1^2} \qquad (M_{A'} \gg M_1)$$

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

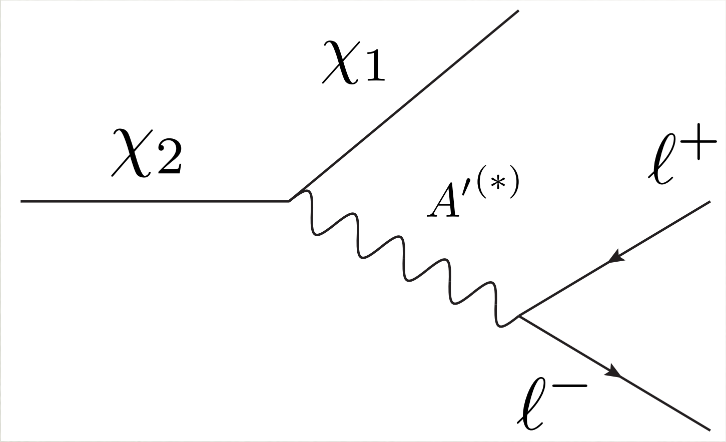
- Choose large value of α_D to avoid over-stating bounds

(Izaguirre *et al.*, 2015)

iDM Lifetimes

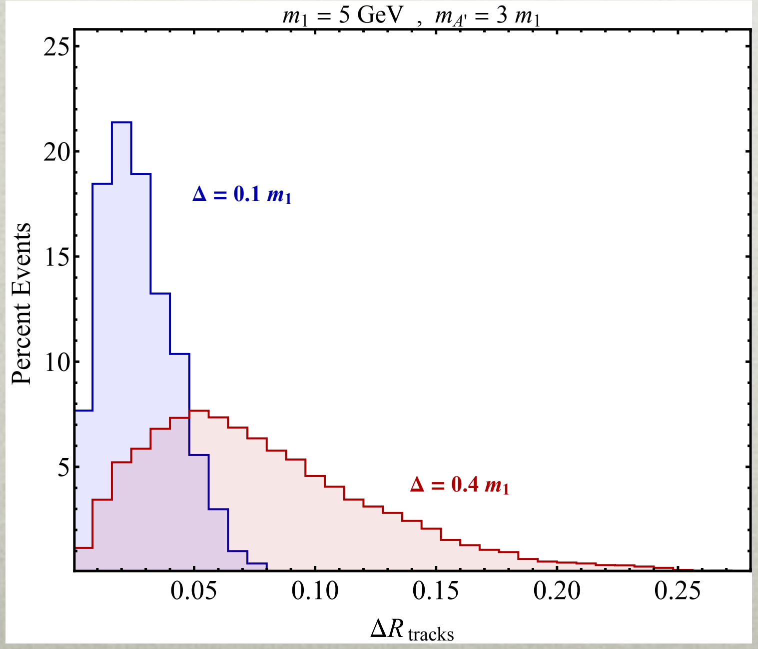


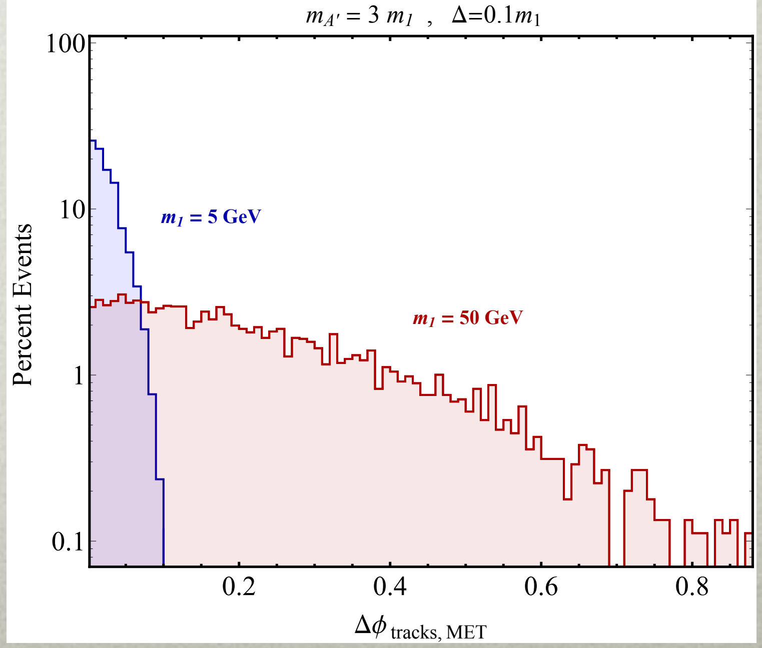
Improving the Searches



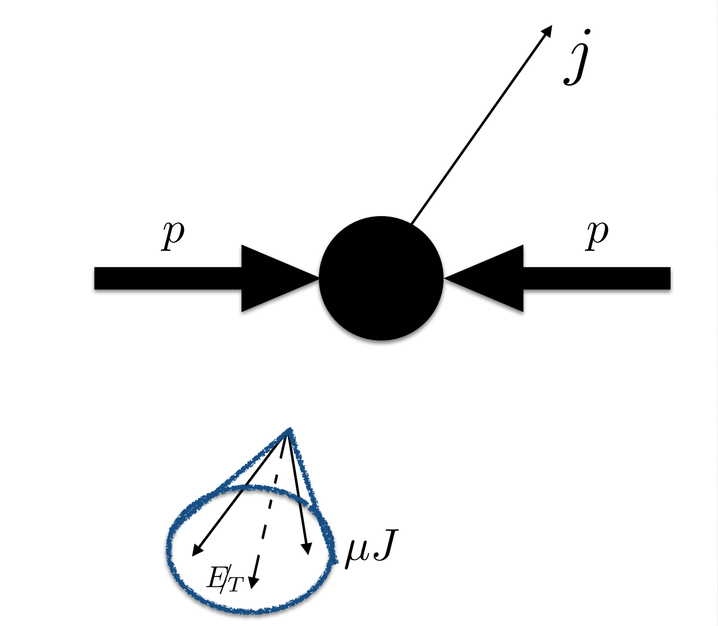
- 3-body decay is suppressed: $\Gamma_{\chi_2} \sim \frac{\alpha \alpha_D \epsilon^2 \Delta^5}{M_{A'}^4}$
- **Displaced decay** $(c\tau_{\chi_2} \gtrsim \text{mm})$ over much of parameter space

- The leptons are typically soft, so trigger on the monojet + MET
- The DM is produced through an on-shell A', which is typically **boosted**
  - Leptons are close together (LJ) and aligned with MET





Improving the Searches



- Monojet + soft displaced lepton jet + MET
- Could be background free:
  plot sensitivity for **ten** signal events

- Require $\not{H}_{\mathrm{T}} > 120\ \mathrm{GeV}$
- Leading jet $p_{\mathrm{T}} > 120$ GeV, veto 3rd jet $p_{\mathrm{T}} > 30$ GeV
- Two displaced muon tracks, $p_{\mathrm{T}} > 5$ GeV, crossing within 1 mm of one another
- $\Delta R < 0.4$ between muons
- $|\Delta\phi| < 0.4$ between lepton jet and MET

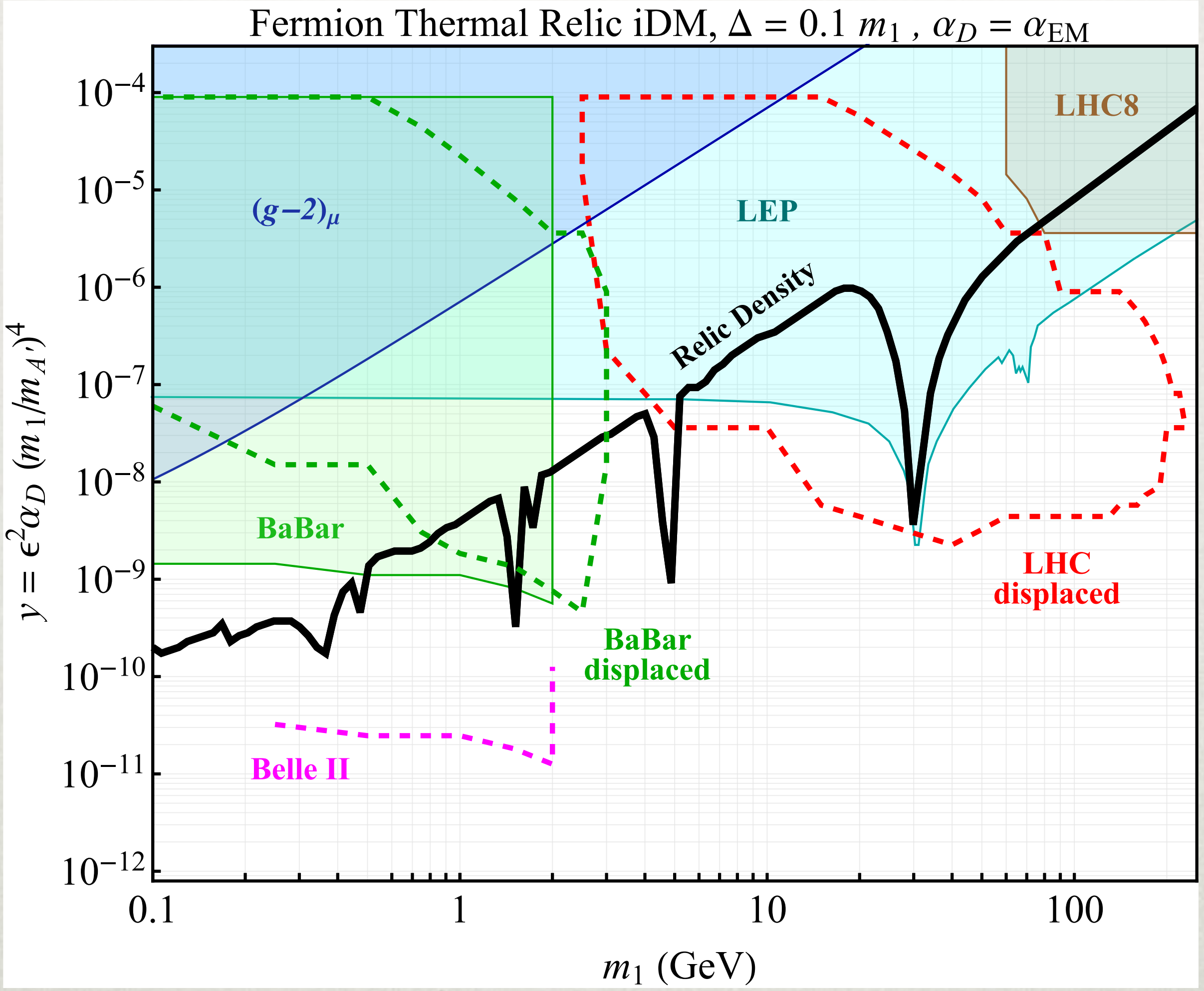
Backgrounds

- Random track crossings
  - Can't do first principles estimate
  - We look at QCD events ($p_{Tj} > 120$ GeV, no MET cut) and find the efficiency for two isolated muon tracks satisfying the signal requirements
  - We find no events, bounds QCD contribution < 100 fb
  - Adding requirement for additional invisible Z/W, kinematic requirements leads to expectation of ≲ few events

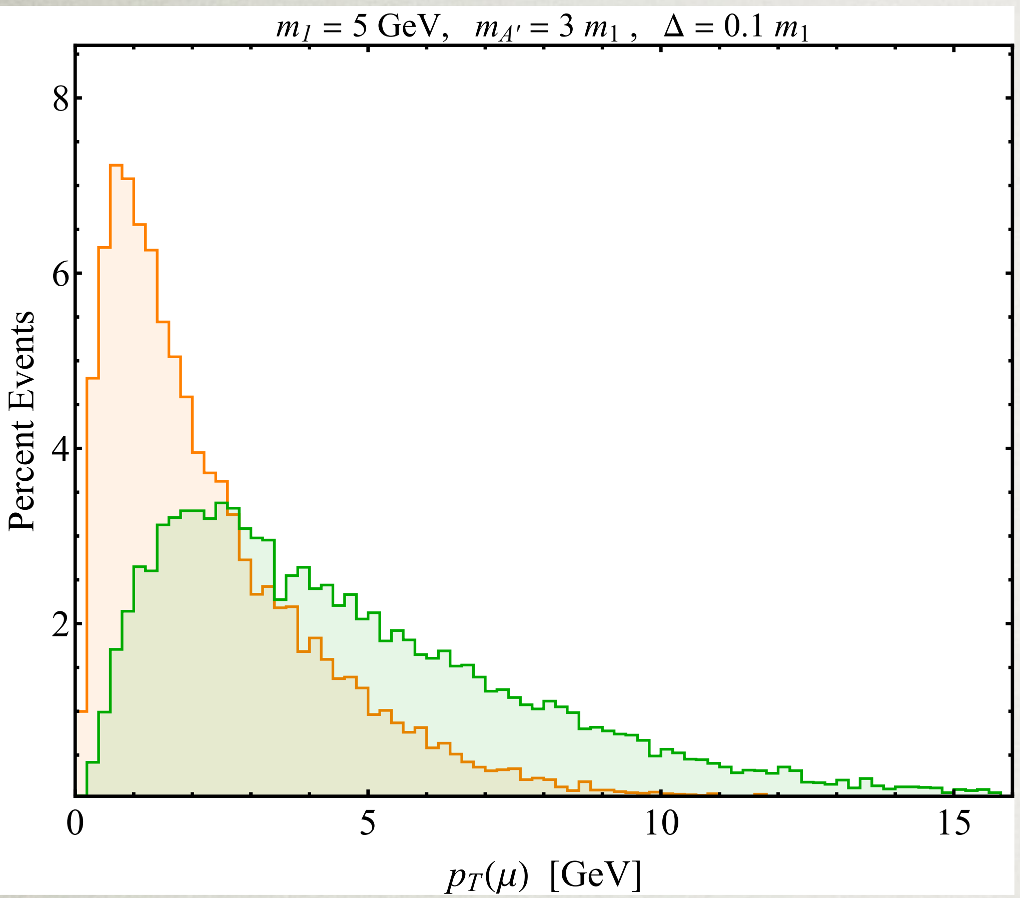
2. **Photon conversion to muons**
   - Cross section for Z + jet + gamma is ~ 100 fb after jet p_T, photon E_T cut
   - Even though the probability for conversion to leptons is $O(1)$, the ratio of e/mu is

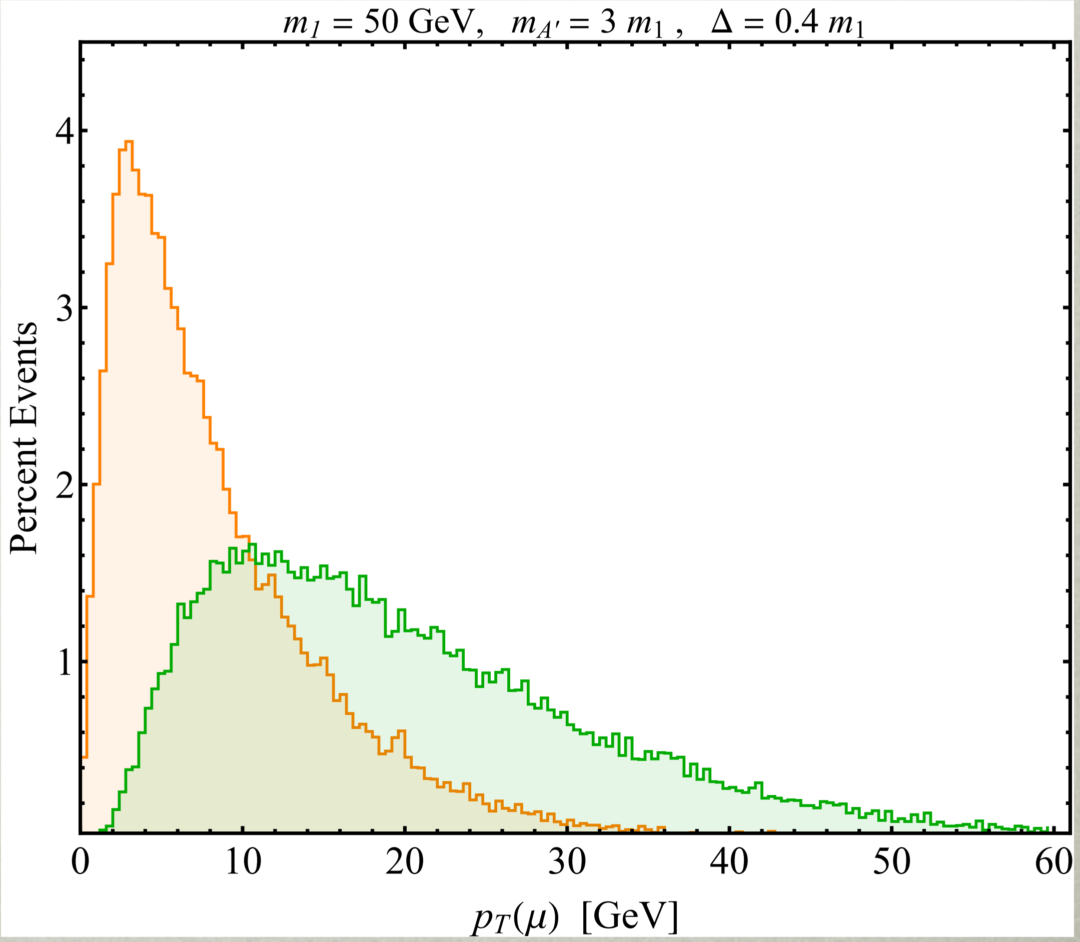
$$\frac{\sigma(\gamma \to \mu\mu)}{\sigma(\gamma \to ee)} \sim \frac{m_e^2}{m_\mu^2}$$

3. **Pile-up crossings**
   - Since LJ is collinear with χ_2, require that muons point back to same vertex as jet



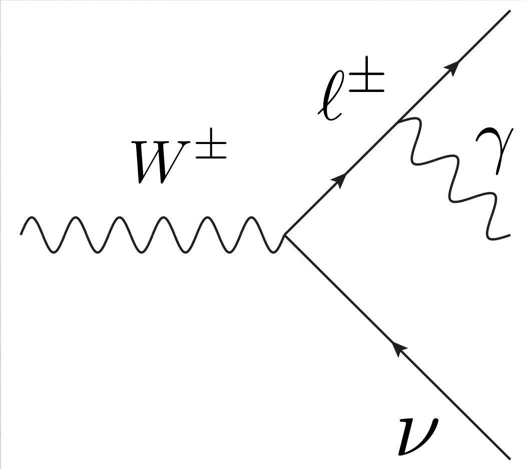
Fermion Thermal Relic iDM, Δ = 0.1 m_1 , $\alpha_D = \alpha_{EM}$
$y = \epsilon^2 \alpha_D (m_1/m_{A'})^4$
m_1 (GeV)
$(g-2)_\mu$
LEP
LHC8
Relic Density
BaBar
BaBar displaced
LHC displaced
Belle II


$m_1 = 5$ GeV, $m_{A'} = 3\, m_1$, $\Delta = 0.1\, m_1$
Percent Events
$p_T(\mu)$ [GeV]


$m_1 = 50$ GeV, $m_{A'} = 3\, m_1$, $\Delta = 0.4\, m_1$
Percent Events
$p_T(\mu)$ [GeV]

Higgsino Doublet

- Subdominant *W* background becomes important



$$M_{\rm T} = \sqrt{2E_{\rm T}^{\gamma}\not{E}_{\rm T}[1-\cos\Delta\phi(\gamma,\not{E}_{\rm T})]}$$

- Photon direction more correlated with MET for signal