Inelastic Thermal DM @ Accelerators

Gordan Krnjaic
Fermilab

w/ Eder Izaguirre & Brian Shuve

1508.03050 **PRD D93 (2016) no.6, 063523**

Dark Sectors Workshop **SLAC, April 29, 2016**

How to make iDM?

Start with familiar model: A' + Dirac fermion $\psi = (\eta, \xi^\dagger)$

$$A'_\mu \bar{\psi}\gamma^\mu \psi = A'_\mu(\eta^\dagger \bar{\sigma}^\mu \eta - \xi^\dagger \bar{\sigma}^\mu \xi)$$

$$m_D \bar{\psi}\psi = m_D \eta\xi + h.c.$$

How to make iDM?

Start with familiar model: A' + Dirac fermion $\psi = (\eta, \xi^\dagger)$

$$A'_\mu \bar{\psi}\gamma^\mu \psi = A'_\mu(\eta^\dagger \bar{\sigma}^\mu \eta - \xi^\dagger \bar{\sigma}^\mu \xi)$$

$$m_D \bar{\psi}\psi = m_D \eta\xi + h.c.$$

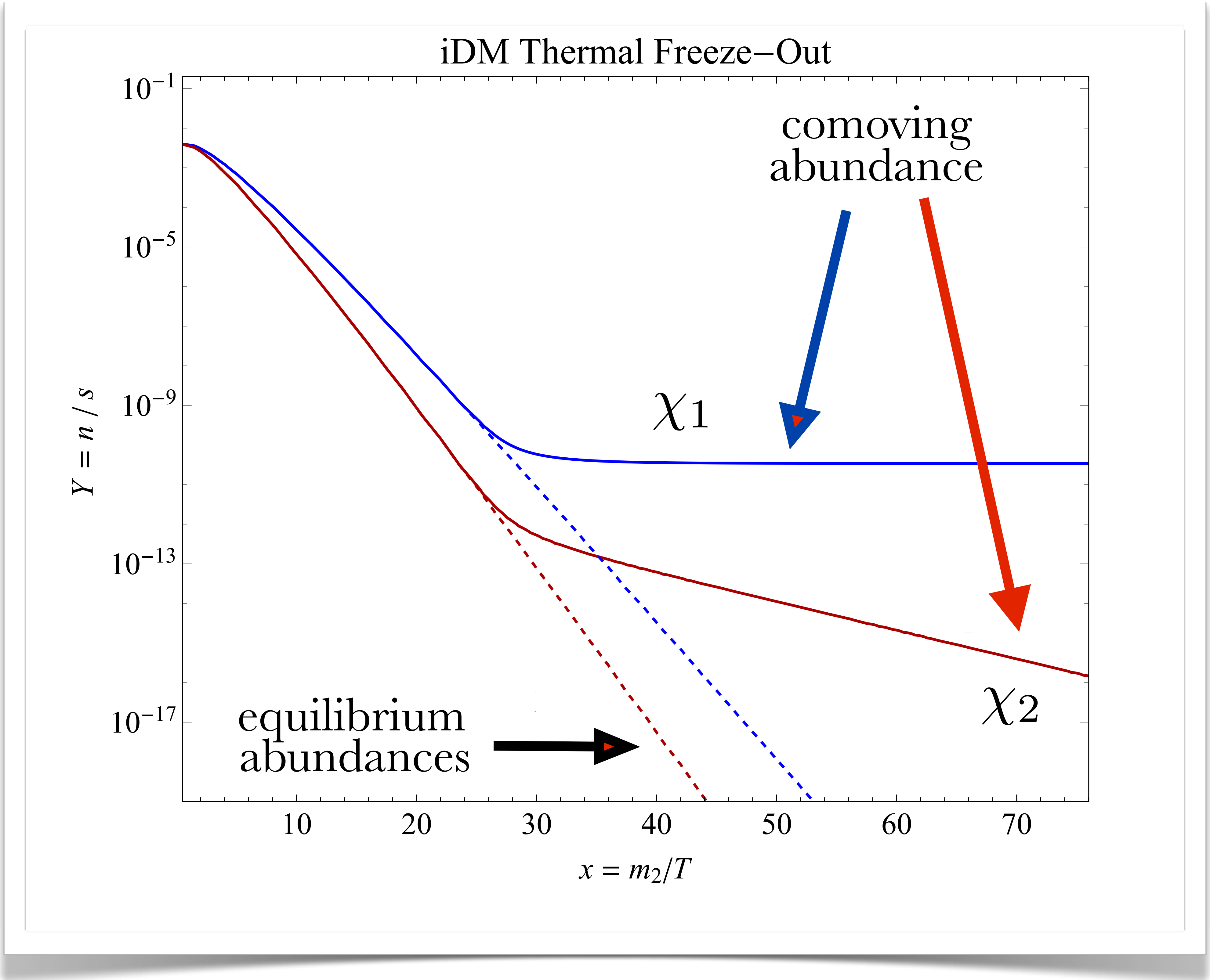
Dark Higgs can induce Majorana masses in IR

$$y H_D \eta\eta + y' H_D^\dagger \xi\xi \to m_\eta \eta\eta + m_\xi \xi\xi$$

Diagonalize to mass basis $\chi_{1,2} = \xi \pm \eta \ , \ m_{1,2} = m_D \mp \Delta$

$$\mathcal{L} \supset A'_\mu \chi_1^\dagger \bar{\sigma}^\mu \chi_2 + h.c.$$

(Slightly) Different Cosmological History

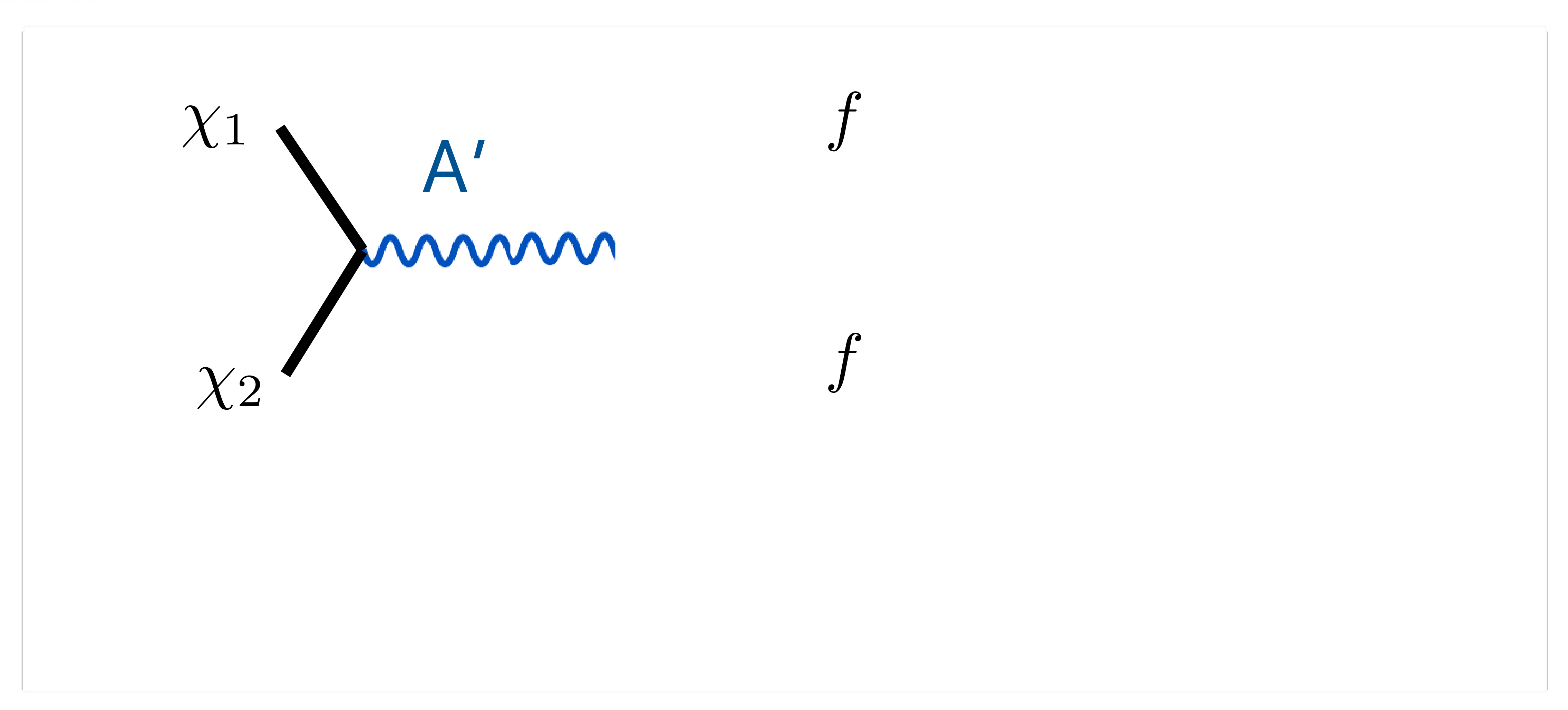


$$\alpha_D = 0.1 \ , \ m_1 = 10 \text{ GeV} \ , \ m_1/m_{A'} = 1/3$$

Recall Philip Schuster's Plenary

Thermal Origin Target

For invisibly decaying A' $m_{A'} > m_1 + m_2$



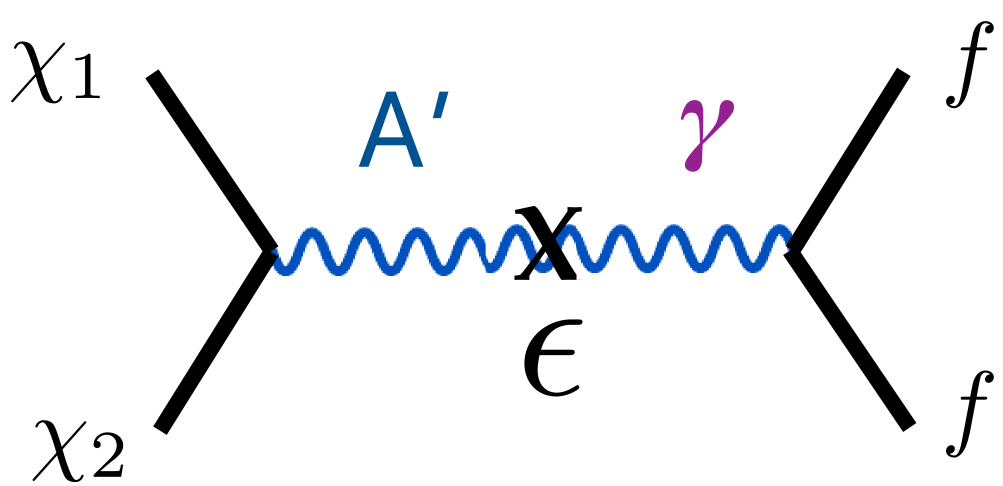
χ_1 χ_2 f f

Friday, April 29, 16

Recall Philip Schuster's Plenary

Thermal Origin Target

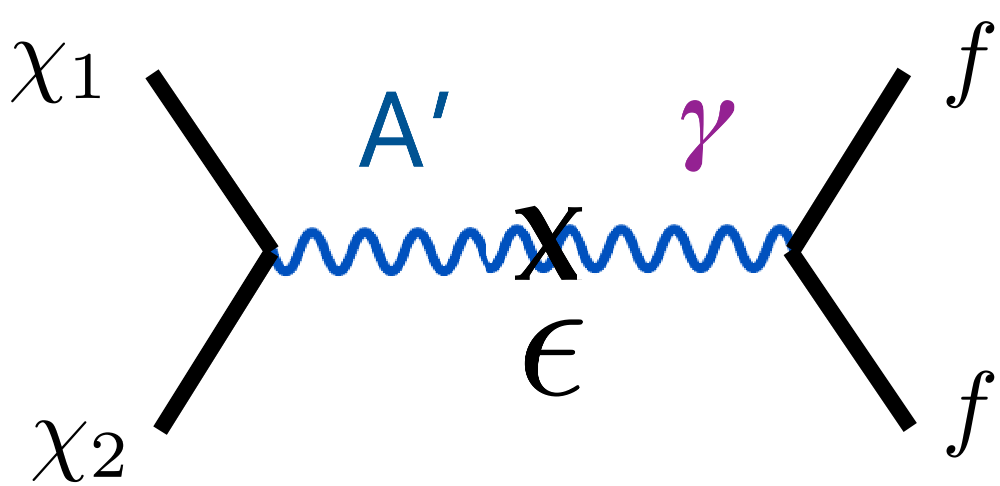
For invisibly decaying A' $\quad m_{A'} > m_1 + m_2$



Recall Philip Schuster's Plenary

Thermal Origin Target

For invisibly decaying A' $\quad m_{A'} > m_1 + m_2$

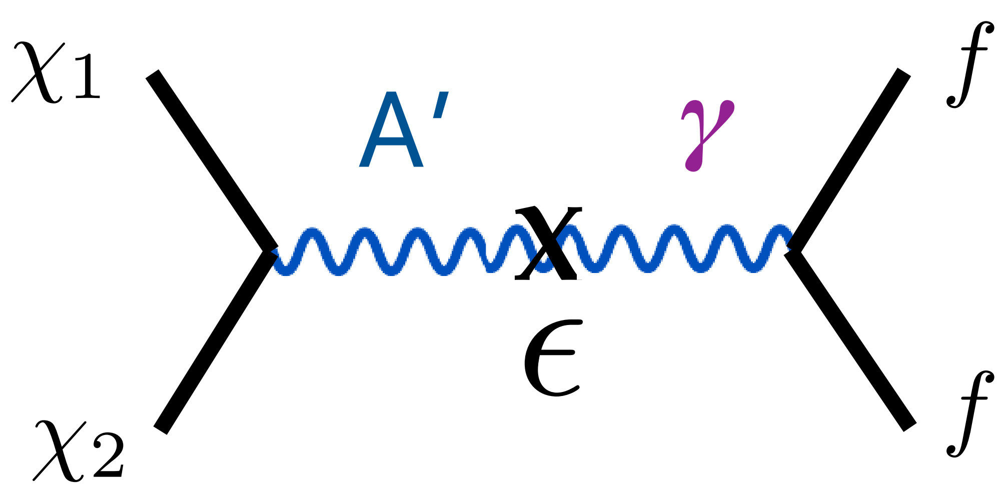


$$\times m_\chi^2 \times \frac{1}{m_\chi^2}$$

Recall Philip Schuster's Plenary

Thermal Origin Target

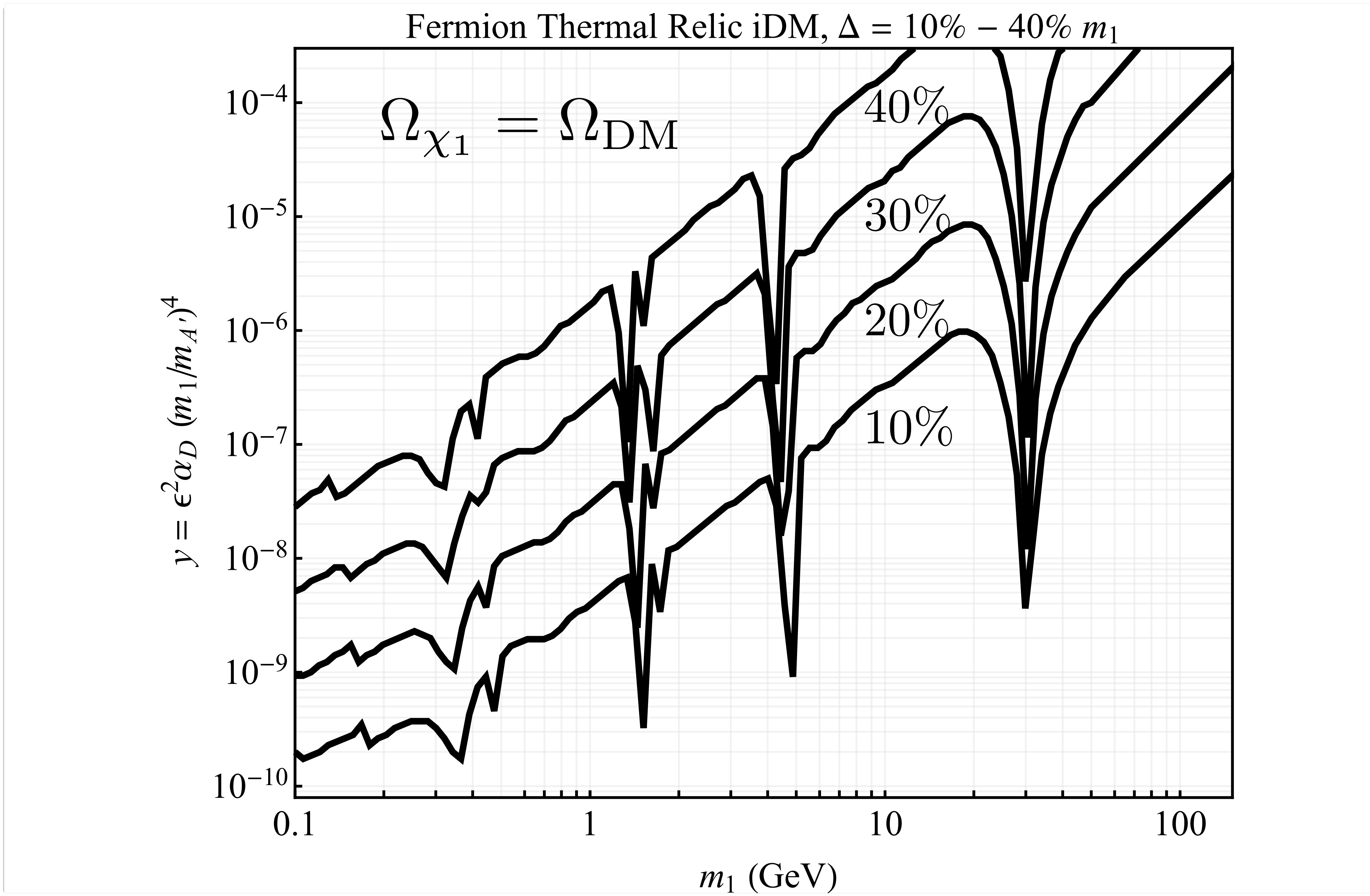
For invisibly decaying A' $\qquad m_{A'} > m_1 + m_2$



$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4} \times m_\chi^2 \times \frac{1}{m_\chi^2}$$

$y \equiv$ Dimensionless parameter controlling cross-section

Thermal Relic Targets

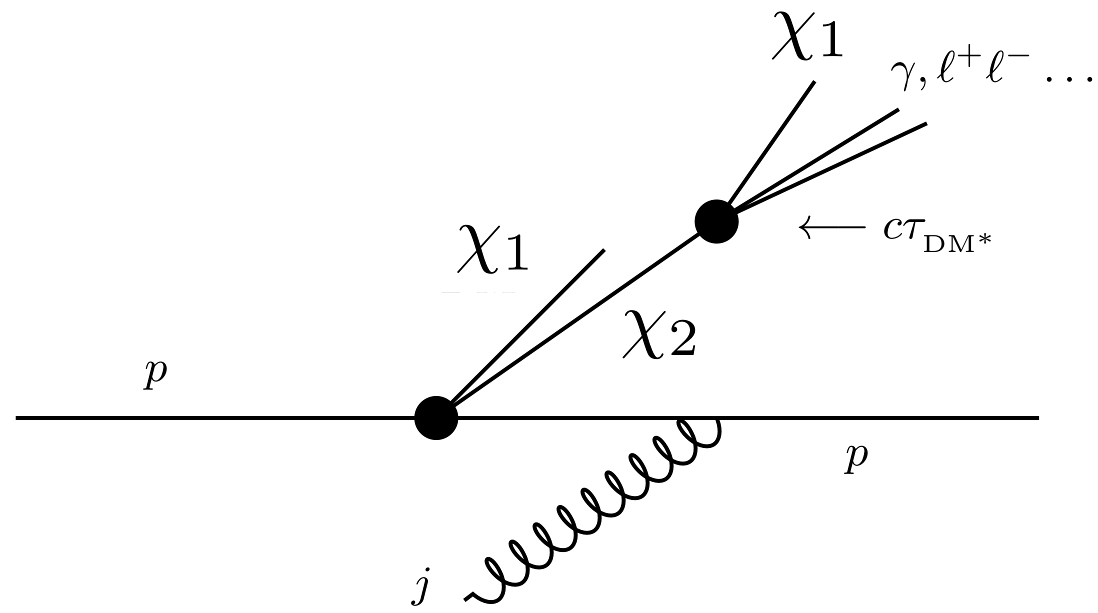


For given splitting, required "y" fixed by DM mass

Signal Topology

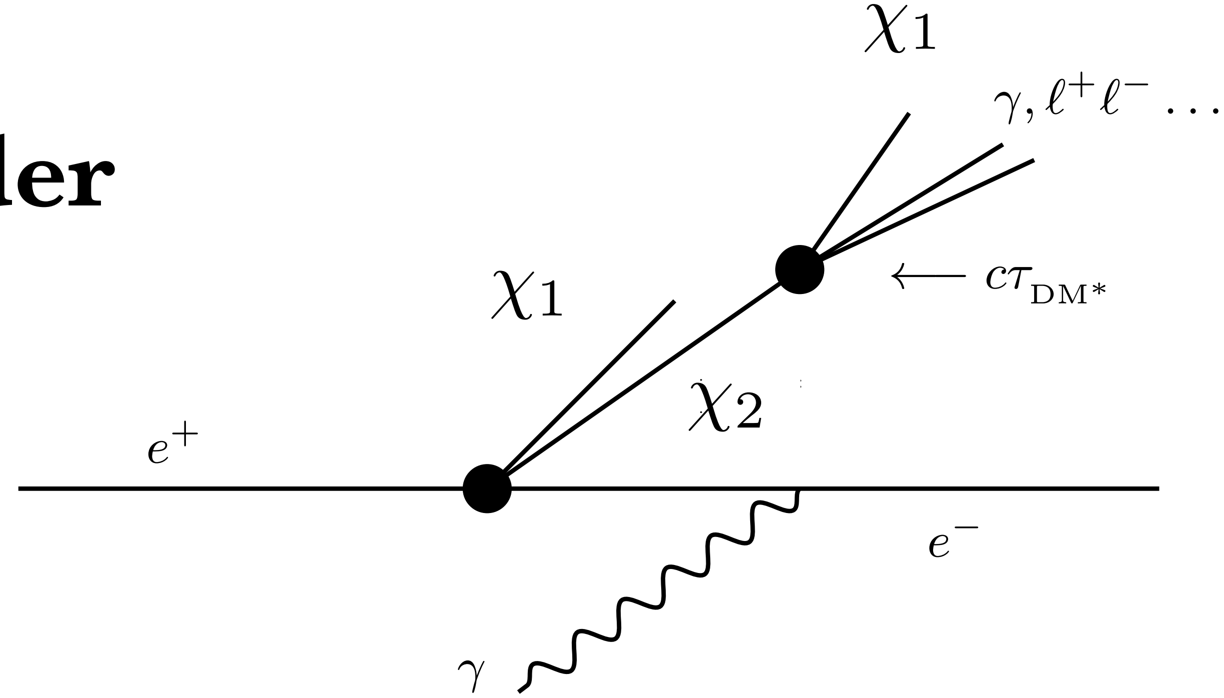
Hadron Collider

$J + \not{E}_T + \ell^+\ell^-$

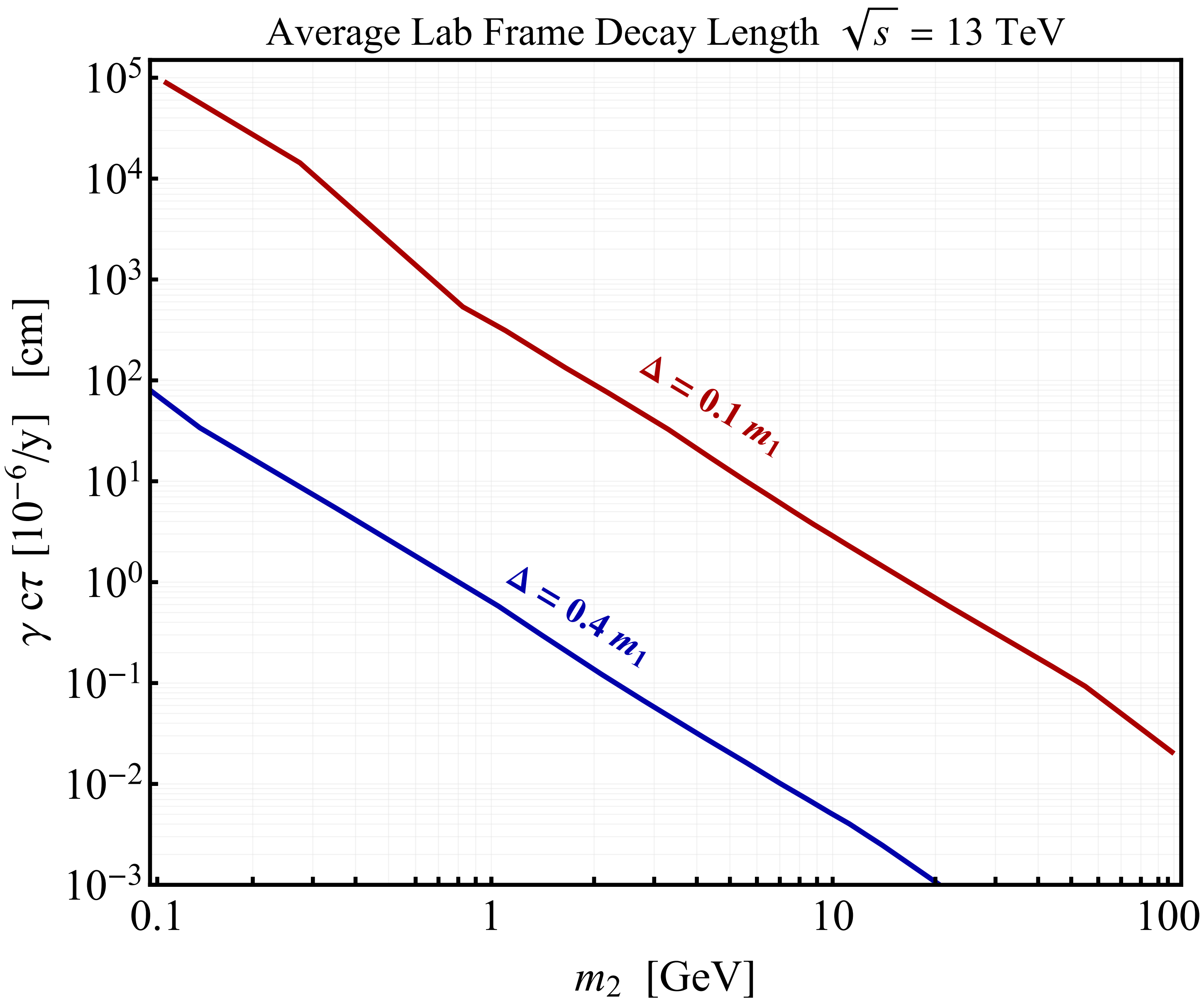


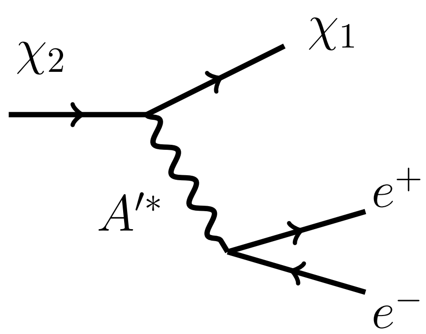
Lepton Collider

$\gamma + \not{E} + \ell^+\ell^-$



Signal Feature: Displaced Vertex

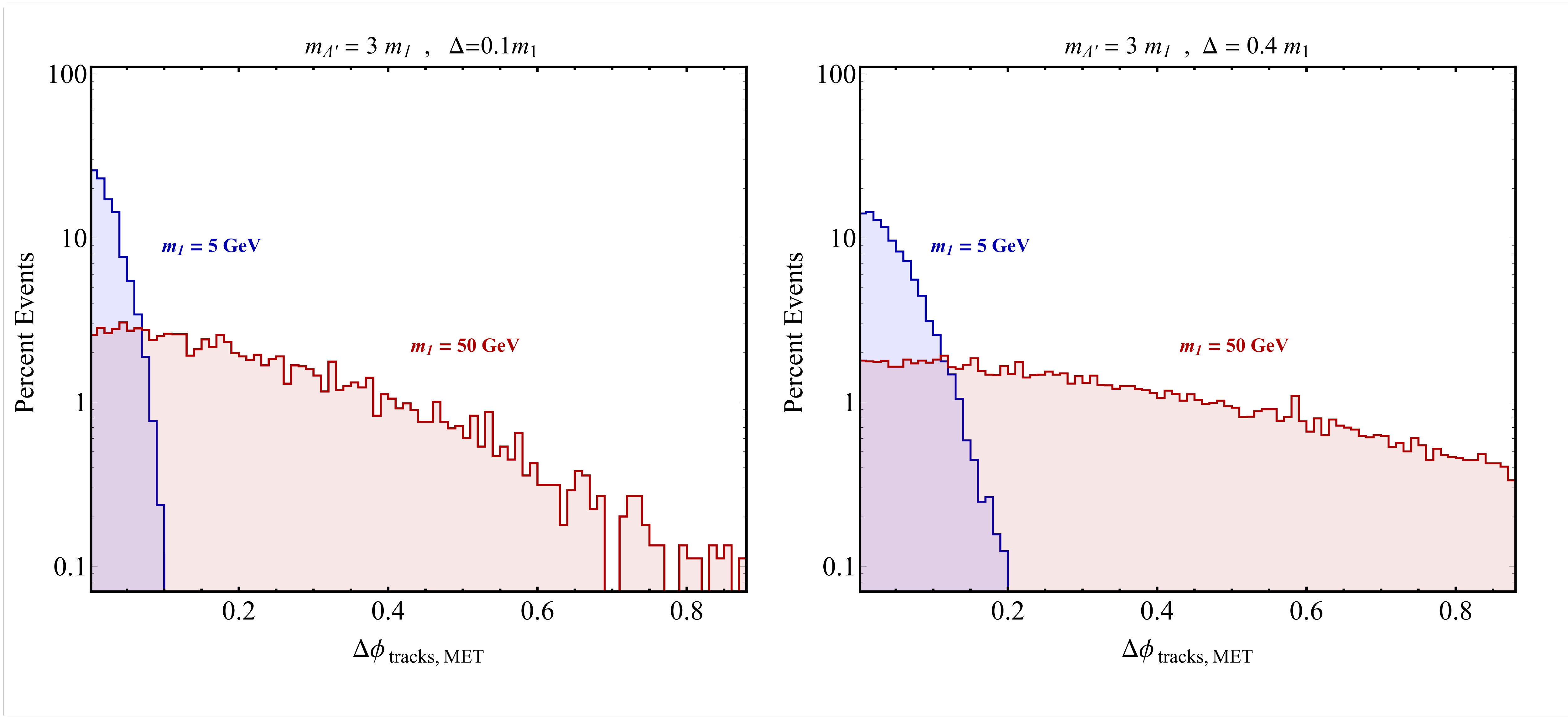




$$\Gamma_{\chi_2} = \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15\pi m_{A'}^4}$$

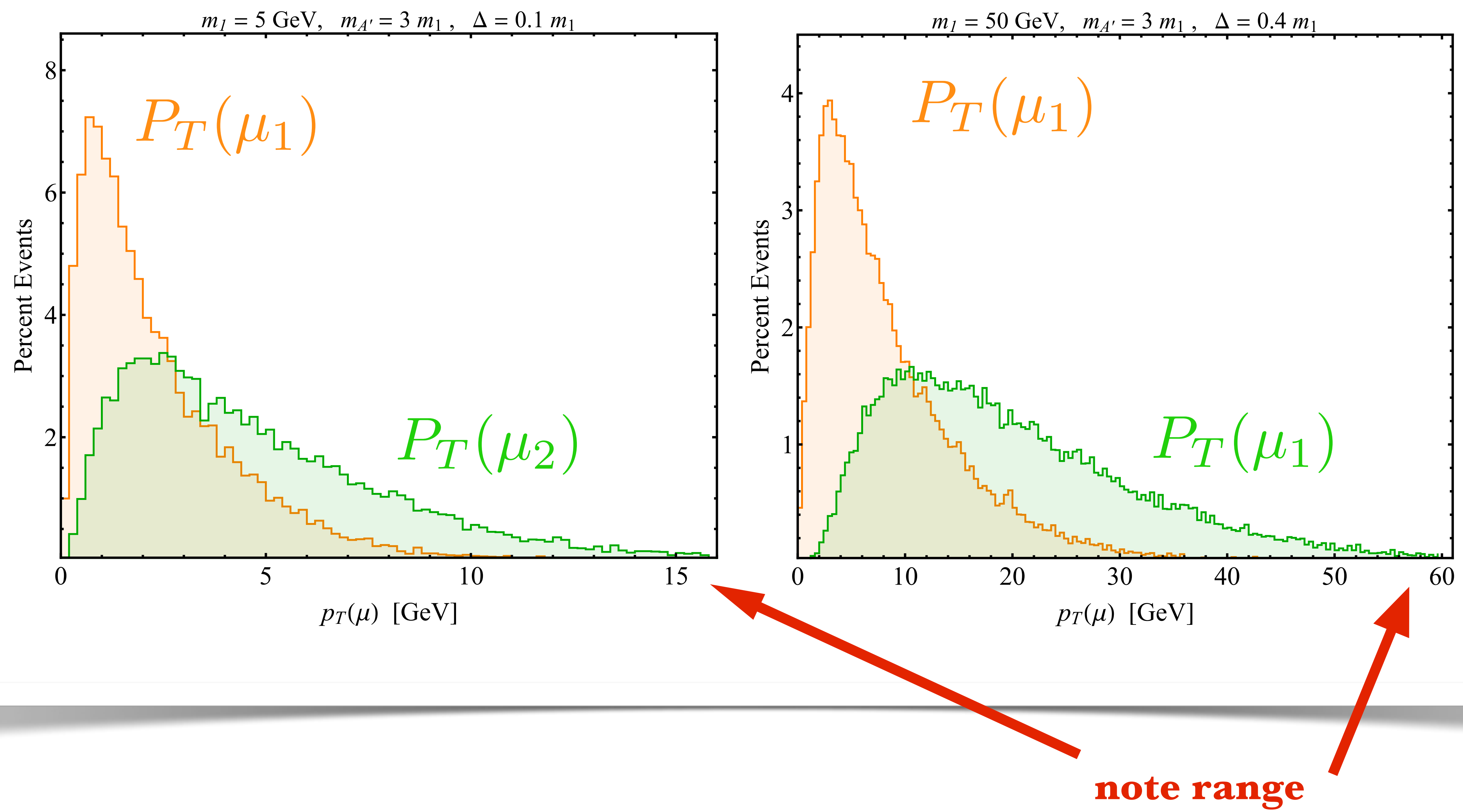
LHC 13 TeV $\quad \alpha_D = 0.1\ ,\ m_1/m_{A'} = 1/3$

Signal Feature: MET/Lepton Correlated



LHC 13 TeV $\alpha_D = 0.1\ ,\ m_1/m_{A'} = 1/3$

Signal Feature(Bug): Soft Leptons



LHC 13 TeV $\alpha_D = 0.1\ ,\ m_1/m_{A'} = 1/3$

LHC 13 Signal Region

- Trigger on monojet + $\not{E}_T > 120$ GeV
- Leading jet $P_T(j) > 120$ GeV
- Leading jet & $\not{E}_T$ back-to-back
- Displaced muon jet ~ 1mm - 30cm
- Muon $P_T(\mu) > 5$ GeV
- Muons not isolated $|\Delta\phi(\not{E}_T, \mu J)| < 0.4.$

LHC Backgrounds

Dileptons from photon conversion in detector

Dileptons from displaced QCD

Pile Up

Jets + $\tau\tau$

Verdict: small, reducible (see backup slides)

BaBar/Belle Search

$$e^+e^- \to \gamma A' \to \gamma \chi_1 \chi_2 \to \gamma \not{E} + \ell^+\ell^-$$

Signal Region

- Trigger on lepton p > 100 MeV
- Transverse impact param. ~ 1mm - 30cm

Potential BGs low:

Hadronic resonances (can reconstruct)

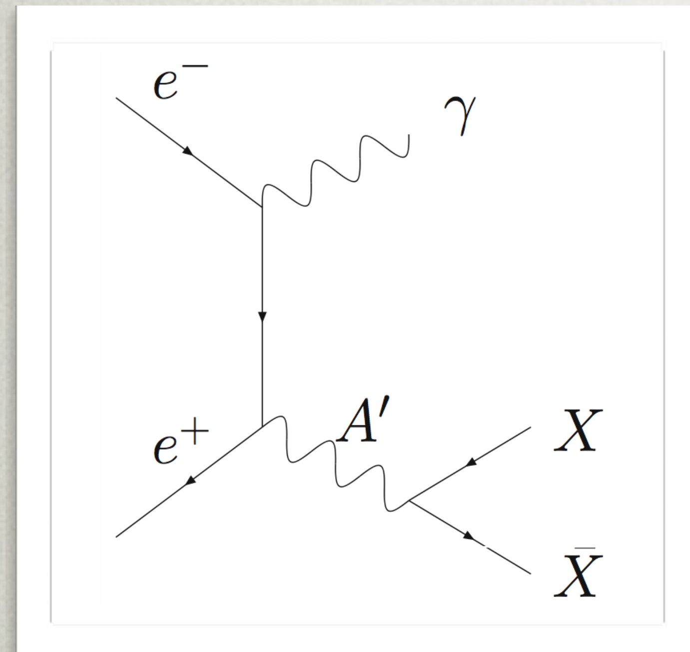
Conversion from $e^+e^- \to \gamma\pi^+\pi^-$ $e^+e^- \to \gamma\gamma$

reducible w/ missing mass and displacement

Recall from Philip's Primer

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

For direct DM production (on-shell mediator):



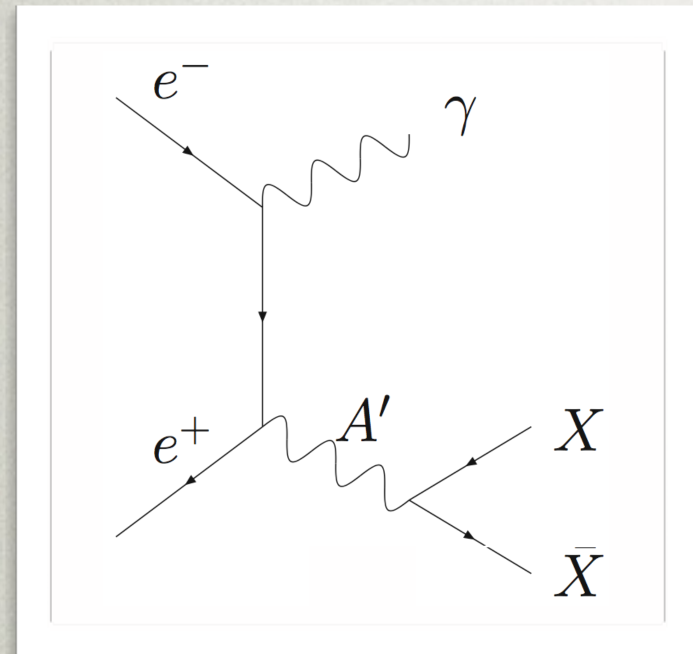
$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

$$\sim y \times \underbrace{\frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4}$$

Recall from Philip's Primer

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

For direct DM production (on-shell mediator):



$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

$$\sim y \times \underbrace{\frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4}$$

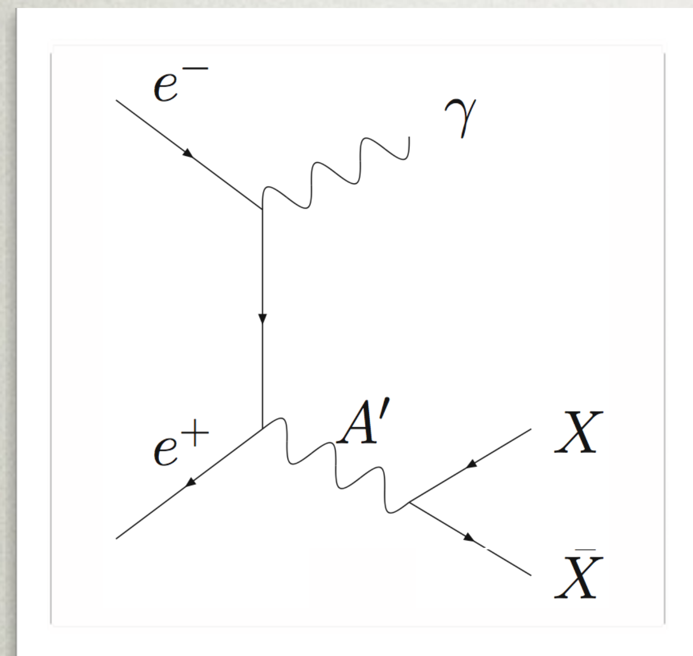
In this scenario $\begin{bmatrix} \alpha_D \leq 0.1 - 1 \\ m_{A'} \geq (2-3) m_\chi \end{bmatrix} \Rightarrow$ combination >100

Friday, April 29, 16

Recall from Philip's Primer

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

For direct DM production (on-shell mediator):



$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

$$\sim y \times \underbrace{\frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4}$$

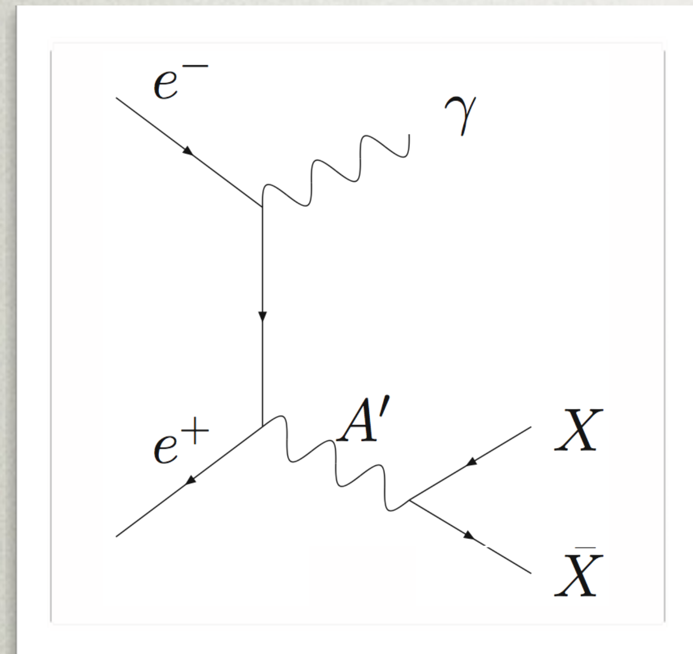
In this scenario $\begin{bmatrix} \alpha_D \leq 0.1 - 1 \\ m_{A'} \geq (2-3) m_\chi \end{bmatrix} \Rightarrow$ combination >100

Saturate inequalities to show worst-case sensitivity

Recall from Philip's Primer

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

For direct DM production (on-shell mediator):



$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

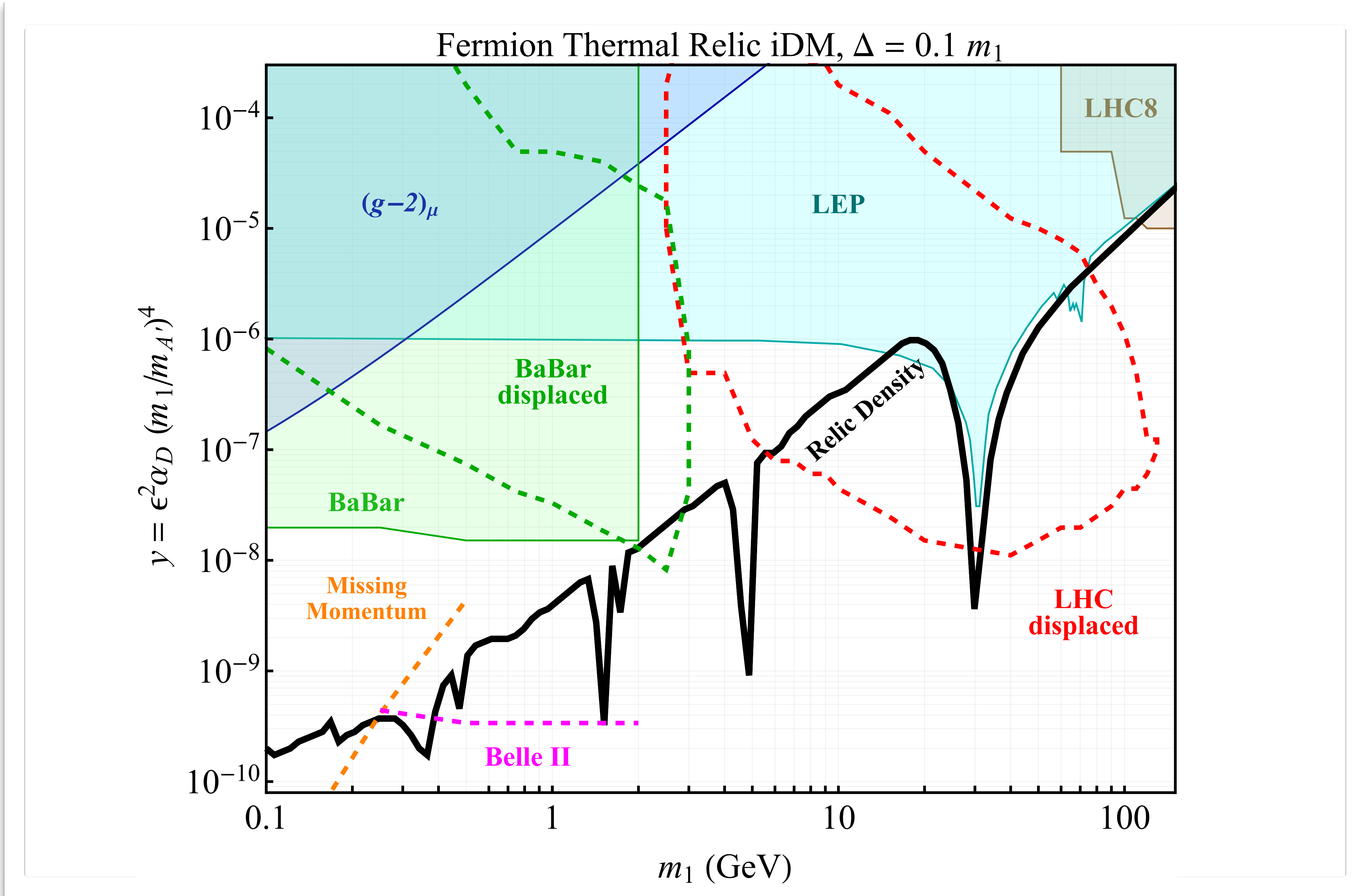
$$\sim y \times \frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4$$

In this scenario $\begin{bmatrix} \alpha_D \leq 0.1 - 1 \\ m_{A'} \geq (2-3) m_\chi \end{bmatrix} \Rightarrow$ combination >100

Saturate inequalities to show worst-case sensitivity

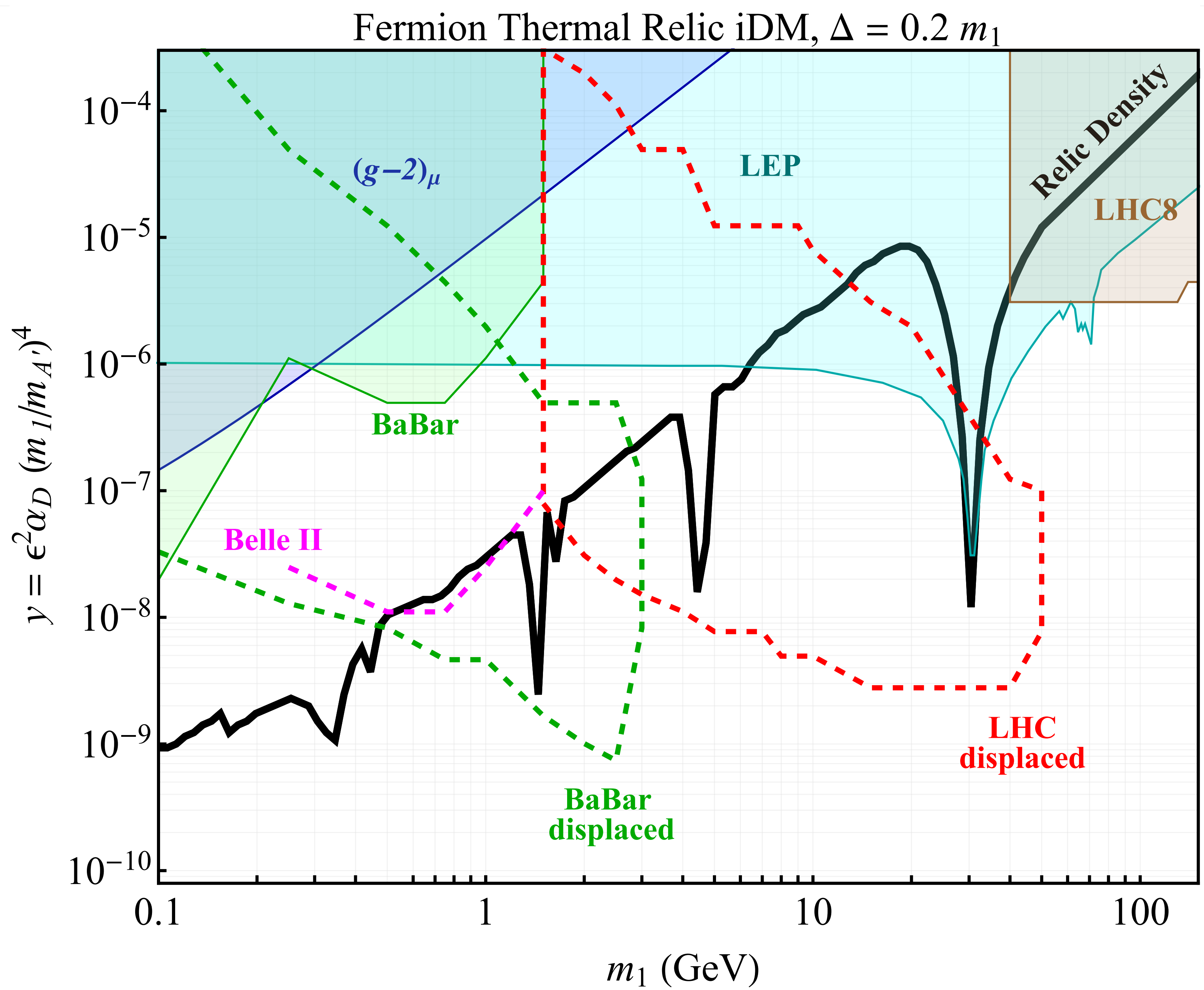
Logic applies to both LHC & LEP

10% Splitting



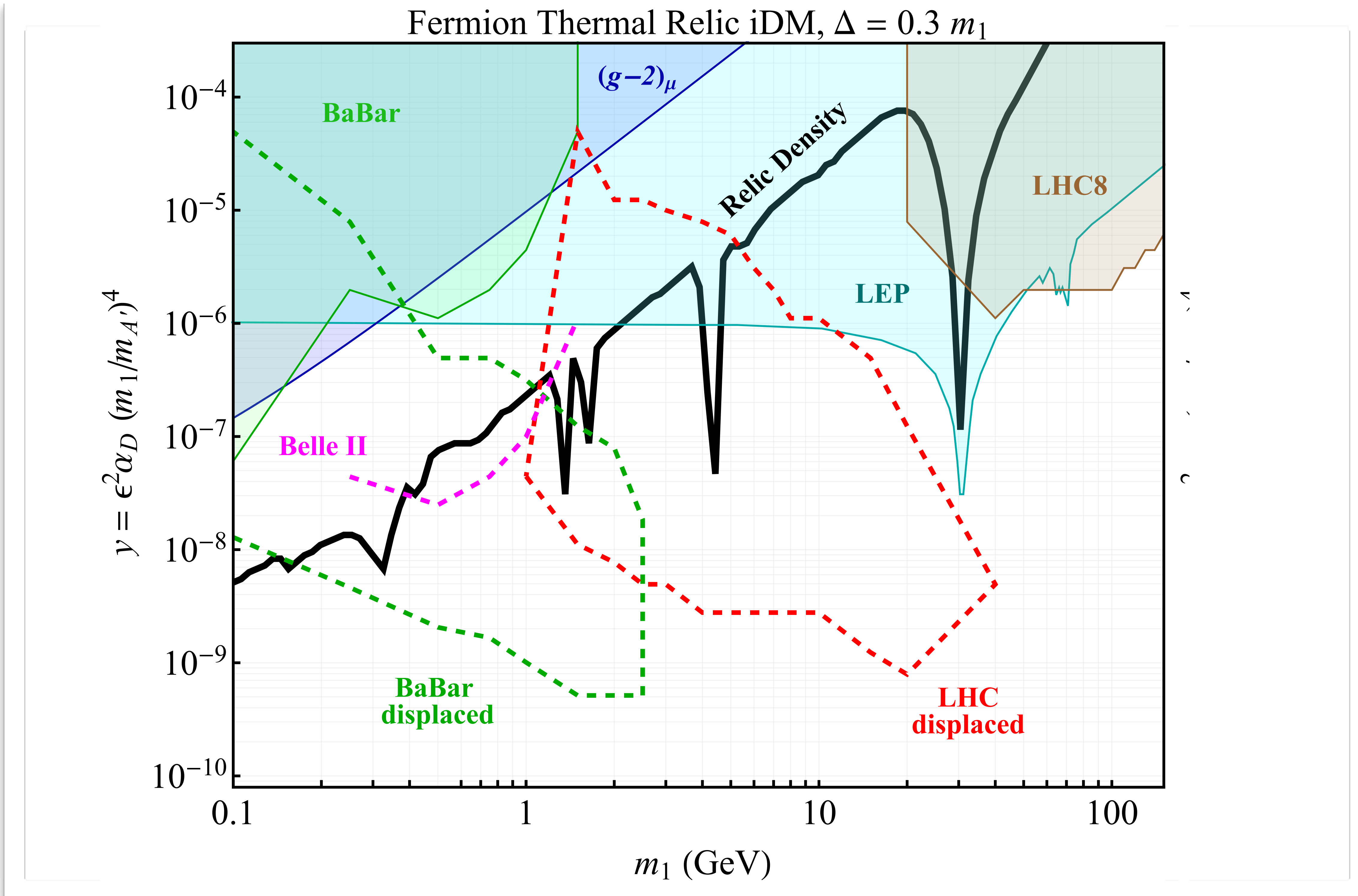
Conservative $\alpha_D = 0.1\ ,\ m_{A'}/m_1 = 3$

20% Splitting



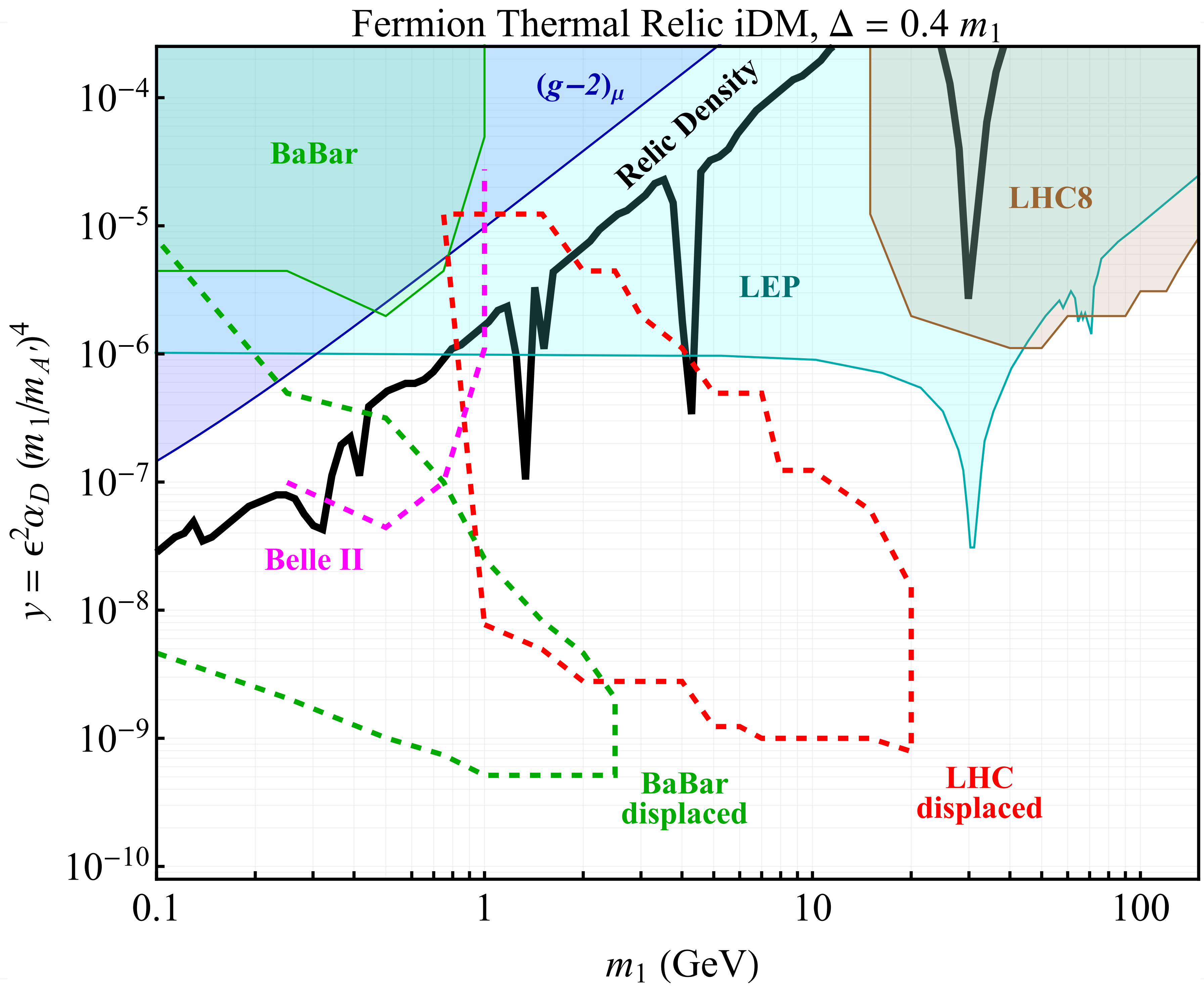
Conservative $\alpha_D = 0.1 \ , \ m_{A'}/m_1 = 3$

30% Splitting



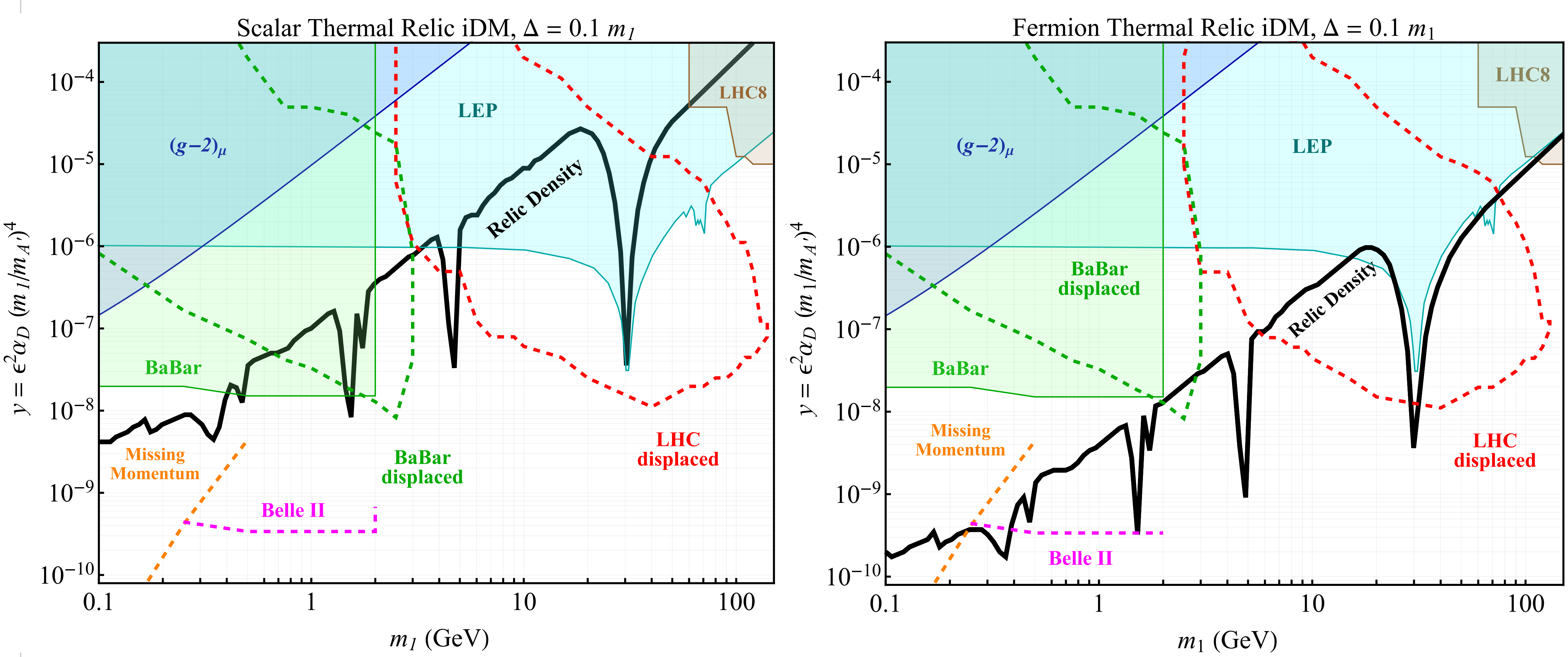
Conservative $\alpha_D = 0.1\ ,\ m_{A'}/m_1 = 3$

40% Splitting



Conservative $\alpha_D = 0.1$, $m_{A'}/m_1 = 3$

Scalar vs. Fermion



$$\alpha_D = 0.1\ ,\ m_{A'}/m_1 = 3 \qquad \sigma v_{\text{scalar}} \sim \sigma v_{\text{fermion}} v^2$$

Concluding Remarks

Inelastic DM: simple, **viable**, & **needs colliders**

- **Clear, bounded parameter space**: conservatively test thermal iDM for O(1) splittings, comparable masses, small kinetic mixing
- **Cosmology @ Colliders** (jet/photon+MET +displaced dimuons) can close nearly all remaining thermal territory w/ LHC run 2 and BaBar
- **Future Challenge:** Exploit direct and/or resonant production mode (no jet/photon) LHCb Triggerless readout?...

LHC Backgrounds

Leptons from photon conversion in detector

$$pp \to j\gamma Z \to j\gamma(Z \to \nu\nu) \ , \ \sigma \approx 100 \text{ fb}$$

Reduction Strategy

- Veto (leptons point to detector region)
- Veto (strict lepton isolation)
- Veto (dilepton invariant mass near ~ 0)
- Demand muons, reduce conversion prob.

  $(m_e/m_\mu)^2 \approx 10^{-5}$

Verdict: Very Small

LHC Backgrounds

dileptons from displaced QCD

Difficult to calculate, but (theorist) estimate w/

- QCD event w/ hard jet + 2 muons
- Muon displacement 1cm - 30 cm
- Point of closest approach < 1 mm

Total prob. $\sim 10^{-7} \implies \quad \sigma_{\mathrm{QCD,BG}} < 100 \text{ fb}$

All this is before demanding large MET

Verdict: Probably Very Small

Similar argument for j + W/Z BG

LHC Backgrounds

Pile Up

High Impact-parameter muons from other vertex

- Signal muons highly collimated from decay of boosted particle
- Dimuon momentum points back to primary vertex
- Same primary vertex as leading jet

Verdict: Probably Very Small, Very Reducible

LHC Backgrounds

Jets + $\tau\tau$

Boosted taus decay to yield displaced muons

- Total cross section ~ 10 fb
- Add muon decay penalty ~ 0.1 fb
- Also need both to decay within $\sim \mu$m
- Dimuon distribution will be different (single parent)

Verdict: Very Small, Very Reducible