Inelastic Dark Matter at the LHC Lifetime Frontier

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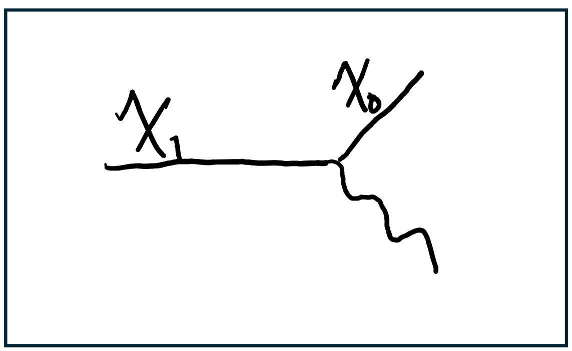
Roadmap of DM models for Run 3

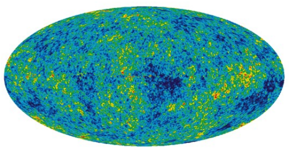
Izaguirre et al.1508.03050,

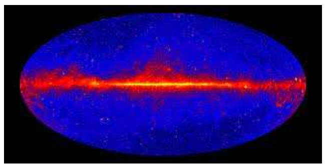
Berlin et al.1810.01879,

Dienes et al. 2301.05252

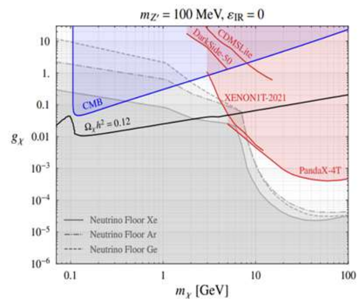


Thermal DM being attacked on all fronts



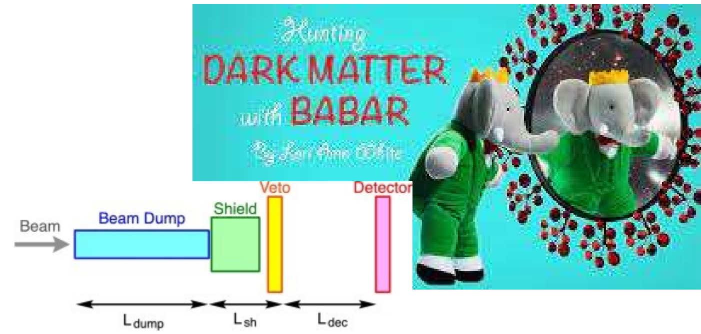


CMB distortions and γ-ray telescopes probe late annihilations

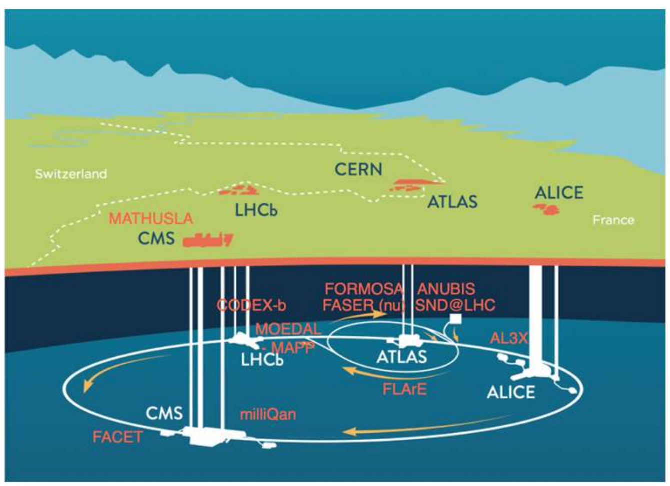


Hapitas et. Al 2021

Nuclear and electronic recoils in direct detection



Beam dumps and B-factories probing $\lesssim 10$ GeV DM

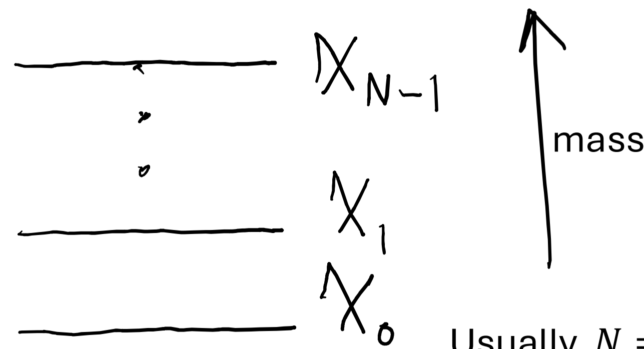


Inelastic Dark Matter has many realizations which naturally evade the indirect + direct detection constraints

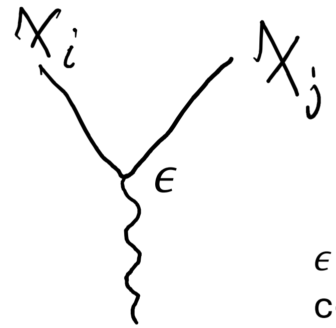
I'll discuss two models of iDM, the host of experiments at the LHC can complement lower energy accelerator experiments to probe thermal target

What is inelastic dark matter?

- Originally introduced to explain by the DAMA DD anomaly Smith, Weiner 2001
- Generally, iDM involves a mass splitting between $\mathrm{N} > 1$ dark states
- Models vary, interactions typically restricted to be off-diagonal
- Production of heavy state can lead to collider scale decay lengths $\mathrm{d} = \frac{\mathrm{E}}{\mathrm{m}} c\tau$ that we can look for
- χ_0 is a stable ground state and is the DM



Usually, $N = 2$

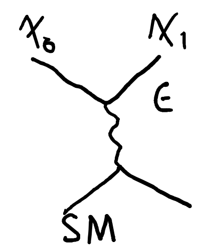


$i \neq j$

ϵ = small portal coupling to SM

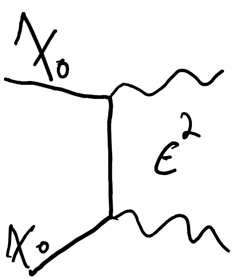
Dynamical Dark Matter (Dienes,Thomas)

Why do we care about iDM?

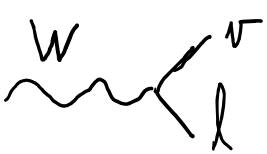


- Direct Detection bounds are quite strong
  - iDM gives a kinematic suppression for
    $m_0 v_{\rm DM}^2 < (m_1 - m_0) = \Delta\, m_0$

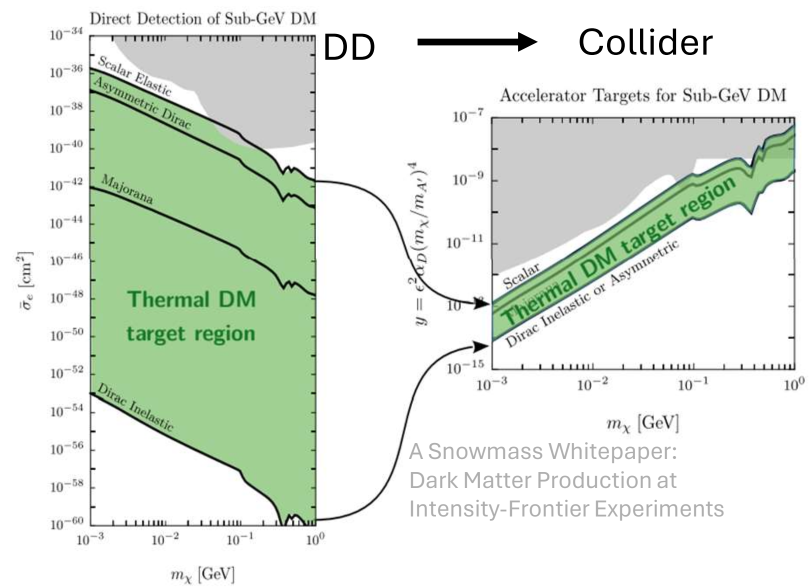
$$10^{-6} < \Delta$$



- For collider scale lifetimes χ_1 is depleted by recombination, suppressing CMB distortions and indirect detection rates (ID today suppressed by small $v_{\rm DM}$)

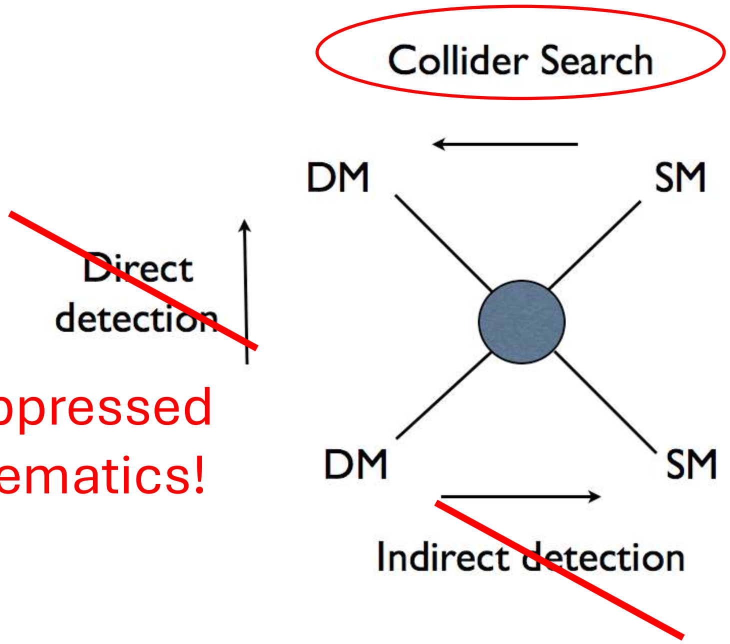


- iDM is a general model that shows up in many theories. Inelastic interactions certainly seen in the SM



In a relativistic environment, like the LHC or early universe, mass splittings and small DM velocities are not longer an issue → relic target more accessible!

How can we find it?



Suppressed kinematics!

No χ_1 left!

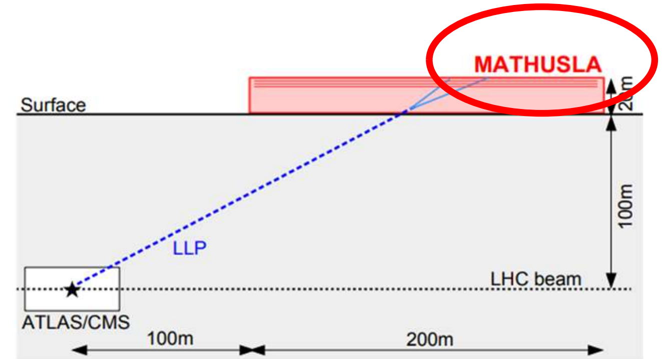
Colliders are a good bet

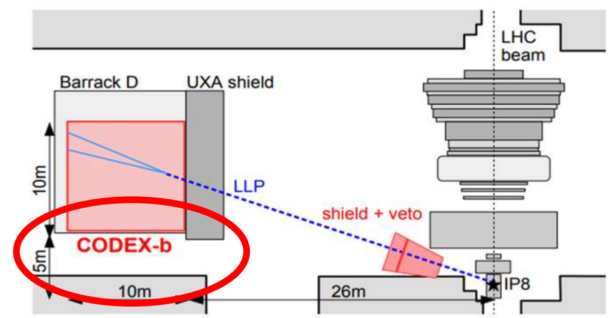
Where can iDM be discovered at the LHC?

*Exceptions, see e.g. upscattered DM (Menon et al. 2009, Krnjaic,McDermott 2019, Bell et. Al 2021)

Some existing/proposed LLP Experiments at the LHC

- Main experiments: ATLAS, CMS, LHCb
  - Displaced muon jets, timing
- Faser
  - On beam axis, 500m from IP
- Forward Physics Facility
  - Upgrade to FASER, includes a suite of expt's.
- Mathusla
  - Large decay volume on the surface for long lifetimes
- Codex-B (see Louis Henry's talk)
  - Shielded and close to LHCb
- Anubis
  - Service shafts above ATLAS / CMS
- …





Sensitivity by each to iDM largely determined by model dependent decay length + dominant production mechanism $d = \frac{E}{m} c\tau$

ANUBIS

Some models of iDM

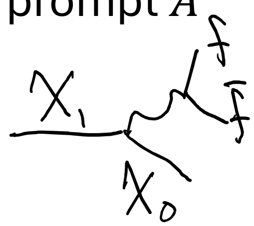
<u>Dark photon</u> broken $\mathbf{U(1)_D}$ – 5 parameters

$$\mathcal{L} = g_D\, \overline{\chi_1}\, \gamma^\mu\, \chi_0\, A'_\mu + \epsilon f \bar{f}\, A'$$

- E.g. from Majorana mass terms lead to mass splitting

- For $m_{A'} > m_{0,1}$ and $m_1 - m_0 \geq m_f$ prompt A' decay + displaced χ_1 decay

$$A' \to \chi_0 \chi_1 \to \chi_0\, \chi_0\, f \bar{f}$$



- χ_1 lab decay length

$$\bar{d}_{\chi_1} \approx 1\text{m} \times \frac{E_1}{m_1} \times \left(\frac{\alpha_D}{0.1}\right)^{-1} \left(\frac{\epsilon}{0.1}\right)^{-2} \left(\frac{m_{A'}}{3m_0}\right)^4 \left(\frac{0.05}{\Delta}\right)^5 \left(\frac{m_0}{10\text{ GeV}}\right)$$

- Many paths to LLP
  - Small couplings: $\epsilon \ll 1$
  - Phase Space: $\Delta \ll 1$
  - Scale Suppression: $m_1 \ll m_{A'}$

Izaguirre et al 2015
Berlin et al 2018

I'll be thinking of $m_{A'} > m_{0,1}$

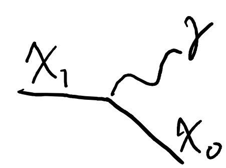
(Magnetic) Inelastic <u>Dipole</u> DM – 3 parameters

$$\mathcal{L} = \frac{1}{\Lambda}\, \overline{\chi_1} \sigma^{\mu\nu} \chi_0 F_{\mu\nu}$$

- Simple, can come from heavier particles at heavy scale Λ

- Long lived for small Δ with monophoton signal (also a suppressed $f\bar{f}$ 3-body)

$$\chi_1 \to \chi_0 \gamma$$



- χ_1 lab decay length

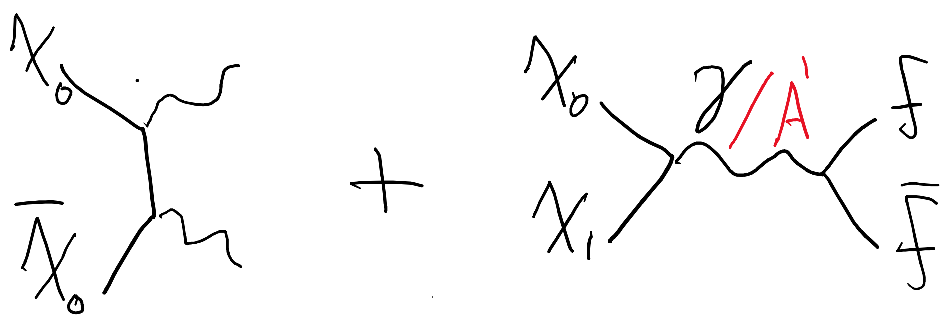
$$\bar{d}_{\chi_1} \approx 1\text{m} \left(\frac{1\text{ GeV}}{m_0}\right)^3 \left(\frac{0.01}{\Delta}\right)^3 \left(\frac{\Lambda}{15\text{ TeV}}\right)^2 \left(\frac{E_{\chi_1}}{\text{TeV}}\right)$$

- Other variations w/ same signal different dynamics:
  - Electric Dipole: $\sigma^{\mu\nu} \to \sigma^{\mu\nu}\gamma^5$
  - Charge Radius: $\sigma^{\mu\nu}F_{\mu\nu} \to \gamma^\mu \delta^\nu F_{\mu\nu}$
  - Anapole: : $\sigma^{\mu\nu}F_{\mu\nu} \to \gamma^\mu \delta^\nu F_{\mu\nu}\, \gamma^5$

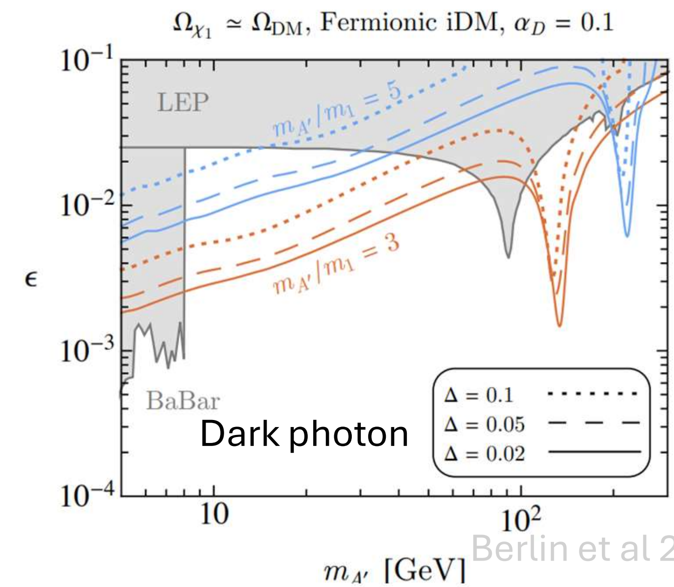
Izaguirre et al 2015
Dienes et al. 2023
Jodlowski 2023

The relic target

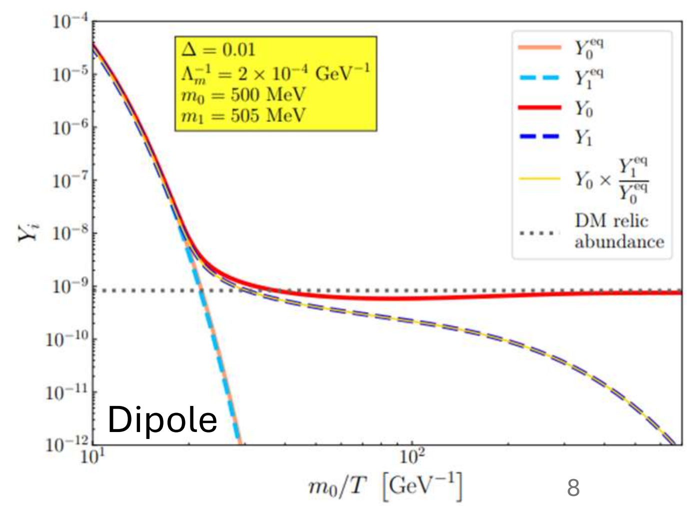
- Both models have unprobed parameter space that reproduce Ω_{DM} through (co-)annihilation freezeout



- Large $\Delta \rightarrow$ mainly annihilation, require larger couplings, heavy χ decouples
- Small $\Delta \rightarrow$mainly co-annihilation, smaller couplings. Approaches elastic limit

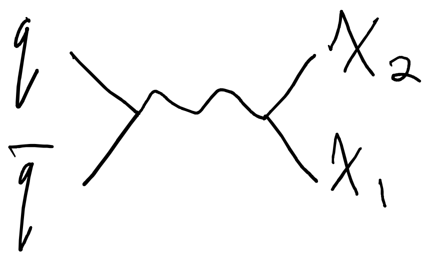


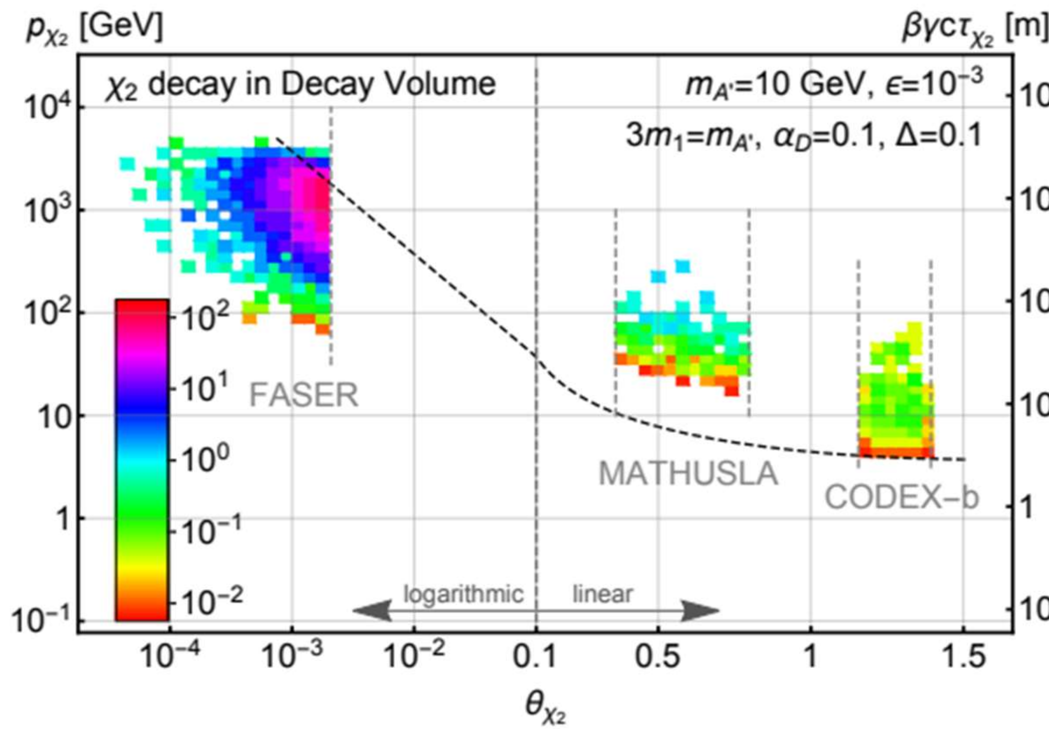
Berlin et al 2018



Production at an accelerator

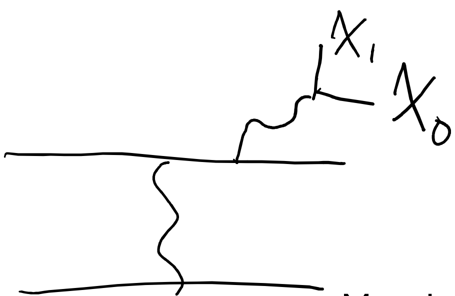
- Drell-Yan





Production at an accelerator

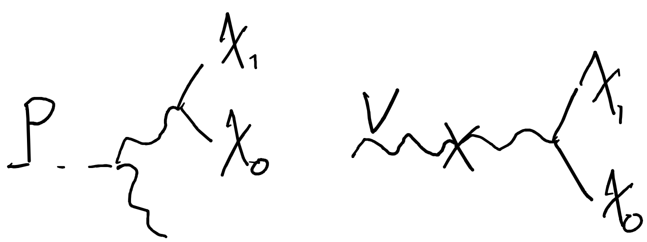
Dark-Brem

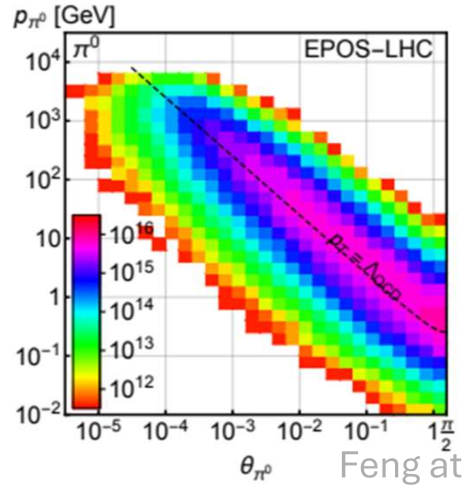


Mostly forward production

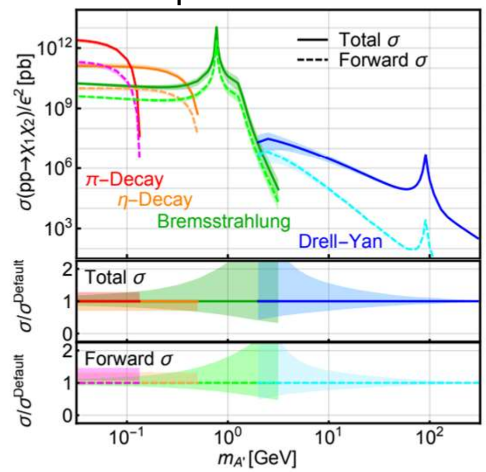
$m_{\text{meson}} > m_1 + m_2$

Meson Decay

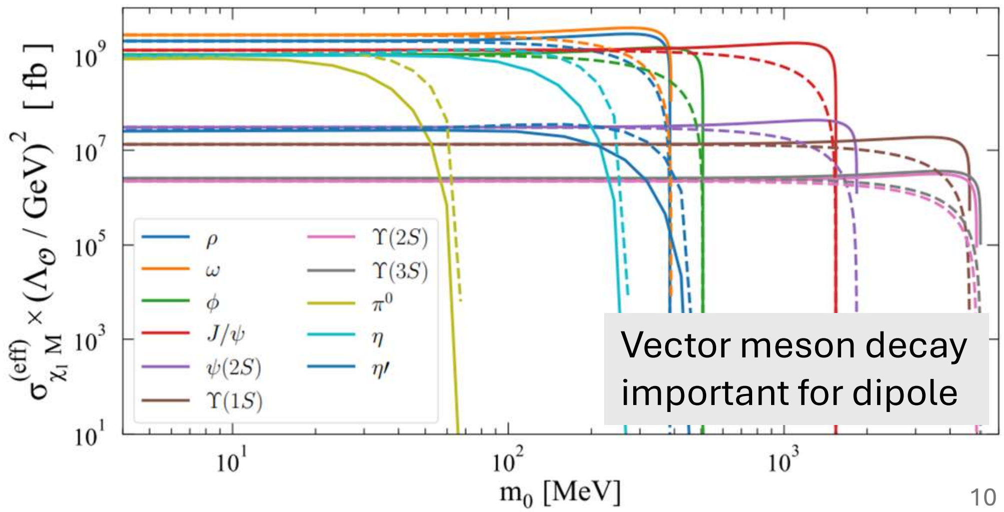




Dark photon



Feng at. al 2018

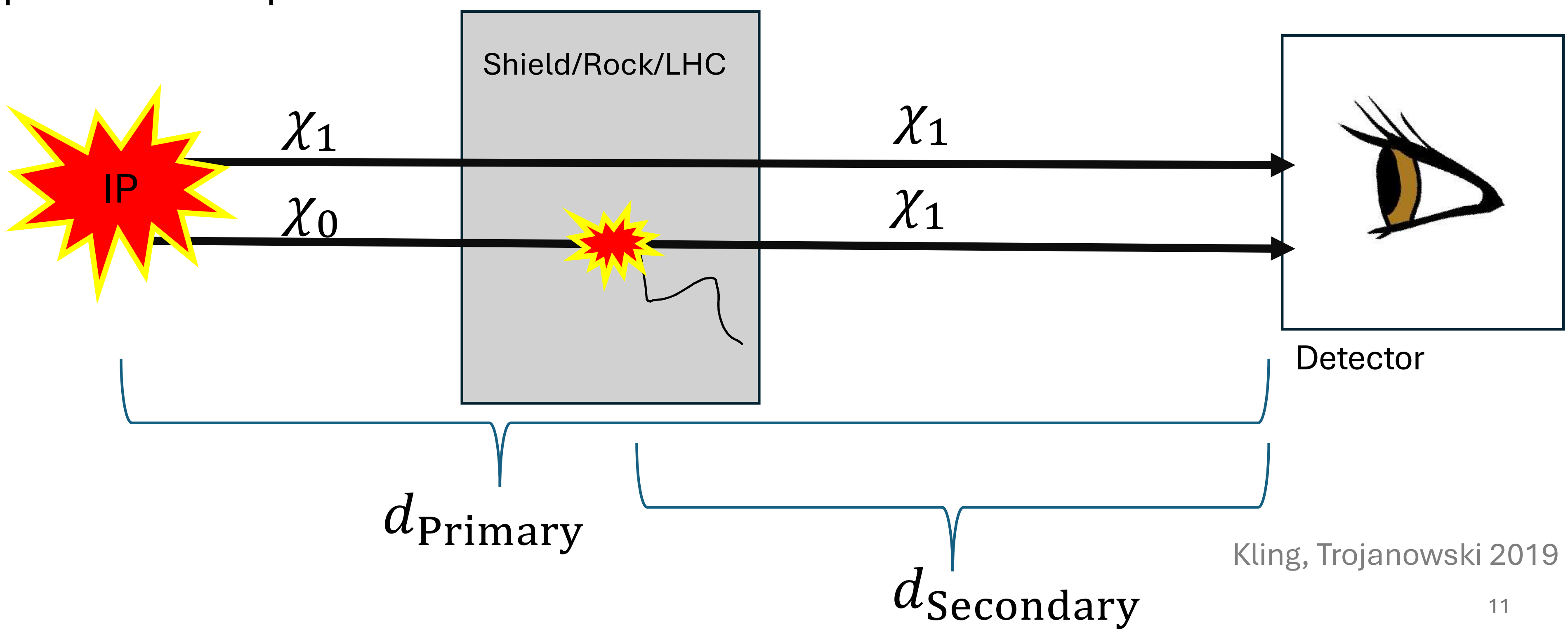


Dipole

Production at an accelerator: Secondary Production

Can probe shorter decay lengths with the same experiment! Sensitive to larger coupling

- Large couplings → shorter decay lengths + larger upscattering probability → secondary production important

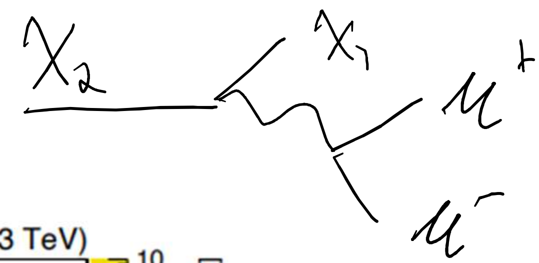


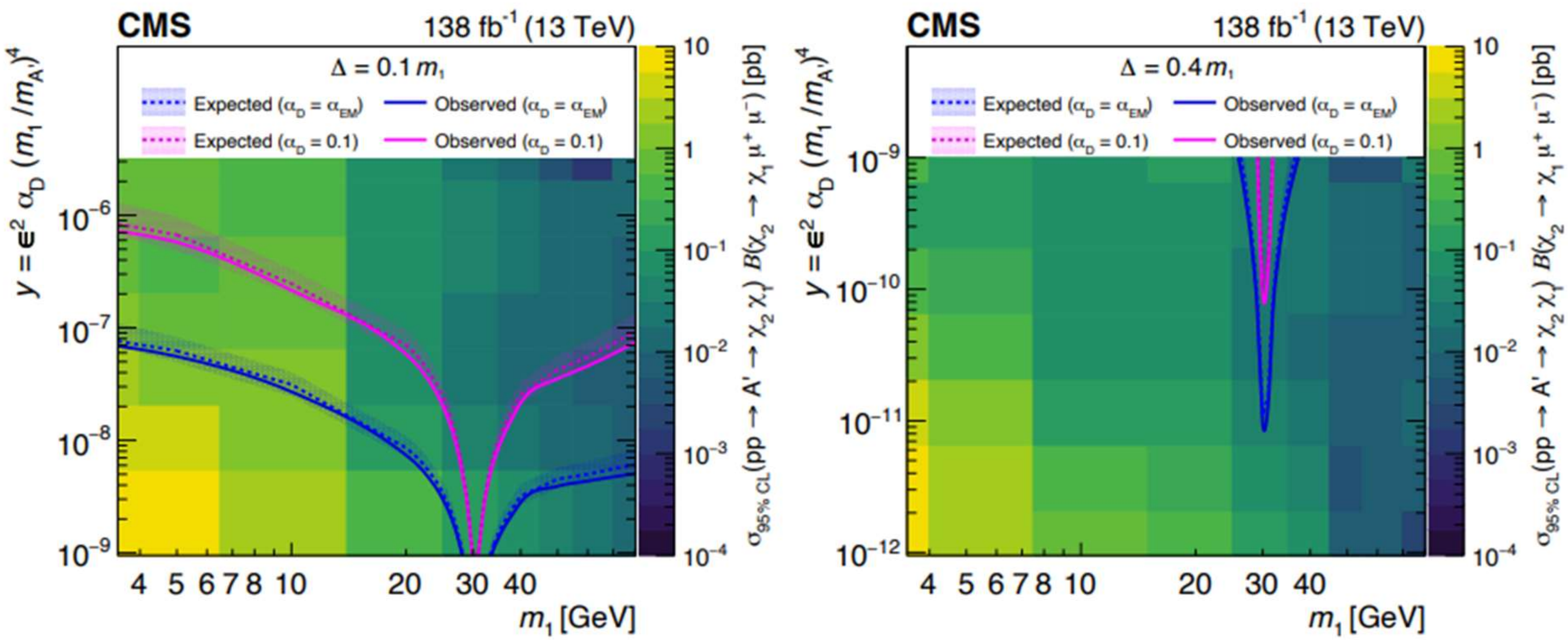
Kling, Trojanowski 2019

What is the sensitivity to iDM at the LHC?

CMS did the first dedicated collider search for iDM

- Displaced Muon Jet (CMS 2305.11649)

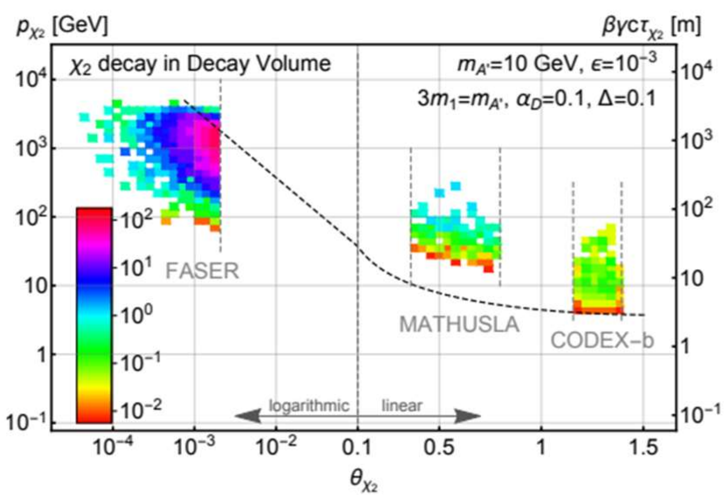


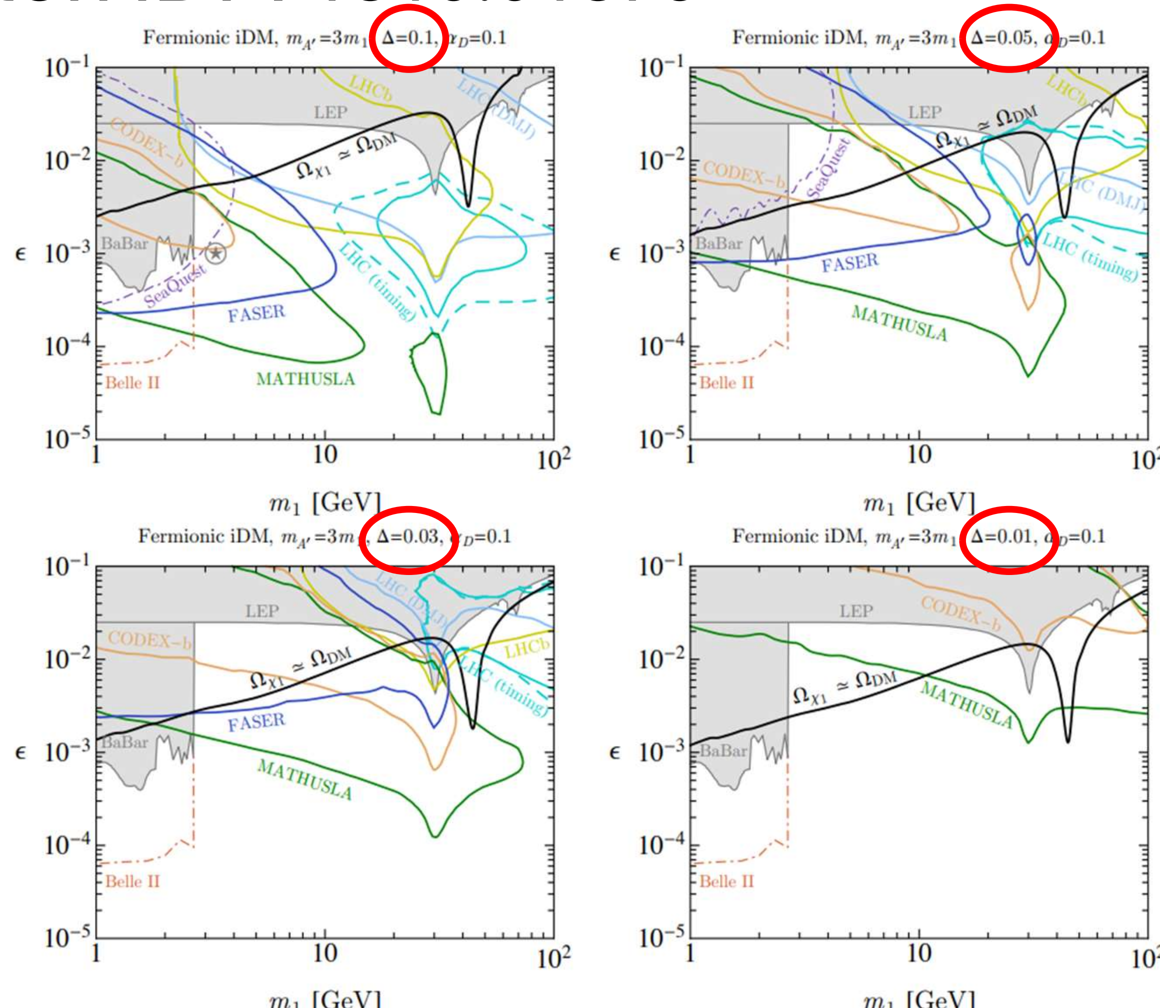


Projections – Dark Photon iDM 1810.01879

Decreasing Δ from top-left $\tau \sim \Delta^{-5}$

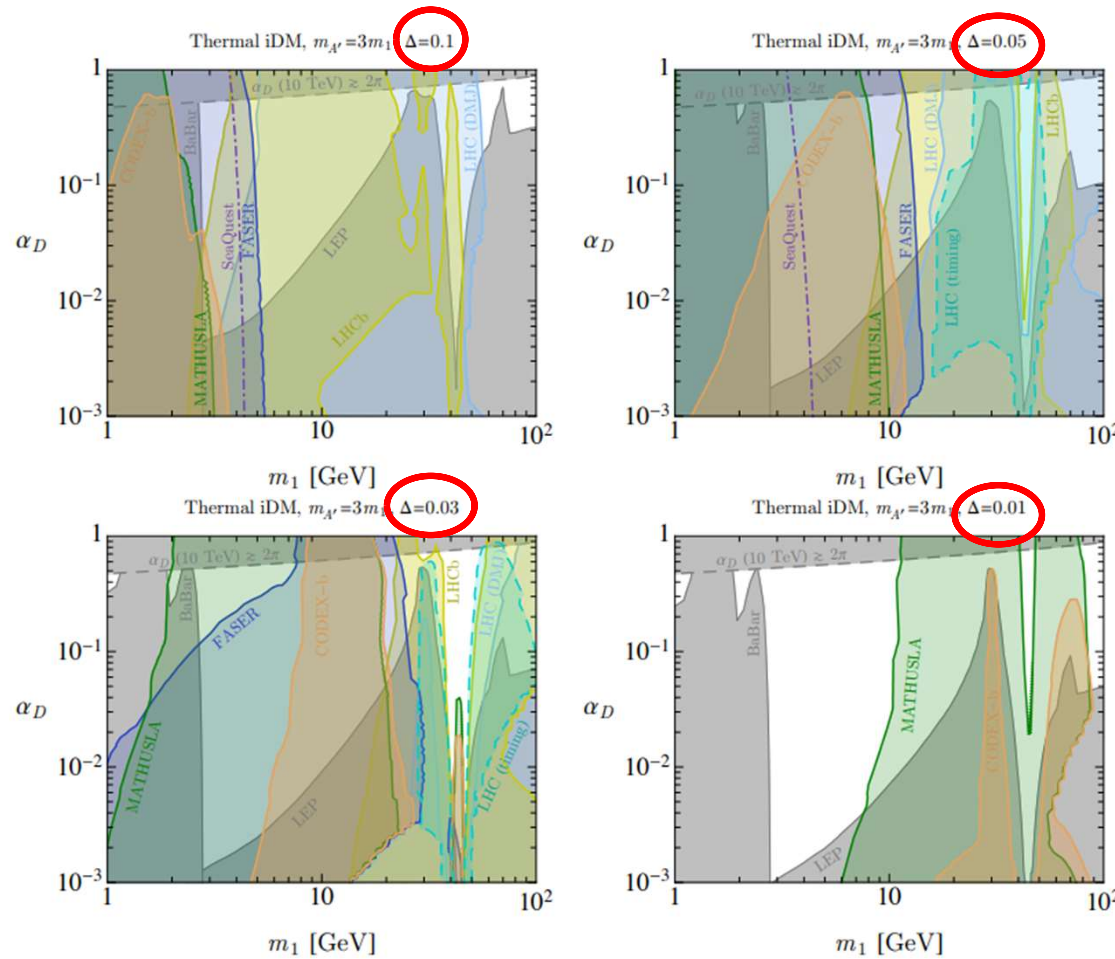
- Relic line saturates for $\Delta \approx 0.03$
- Faser, Codex-B, Mathusla, LHCb all have sensitivity to relic target
- All expt's too close for $\Delta < 0.01$
  - still far away from DD!





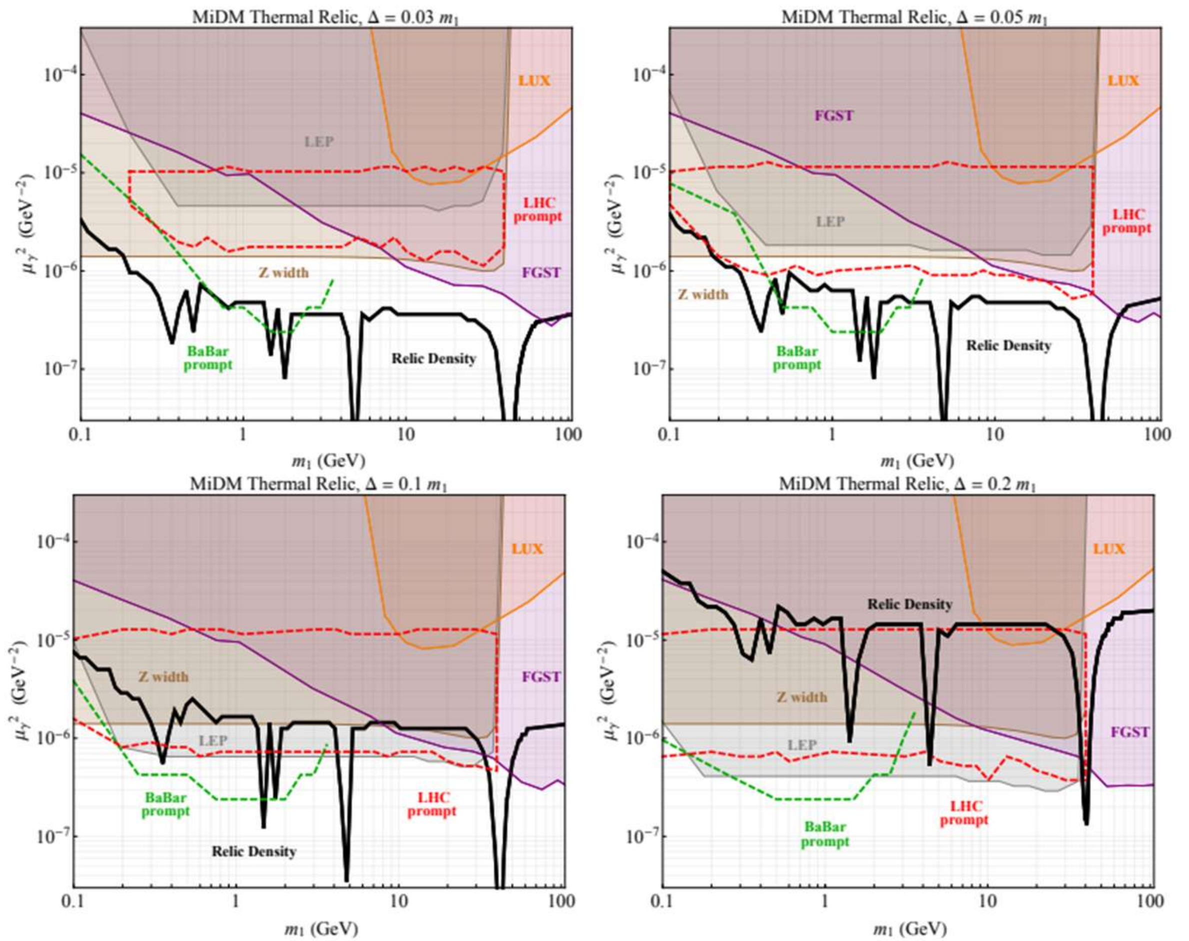
Projections – Dark Photon iDM Thermal Relic Space

- Every point has ϵ scaled to match Ω_{DM}
  - $\frac{m_{A'}}{m_{\mathrm{DM}}} = 3$ fixed
- Many experiments with different $c\tau$ sensitivities needed to cover cosmologically viable parameter space!
- Other experiments, B-factories (Belle, Babar), Seaquest, LSND, E137, BDX, LDMX, MiniBoone have/will provide complimentary coverage

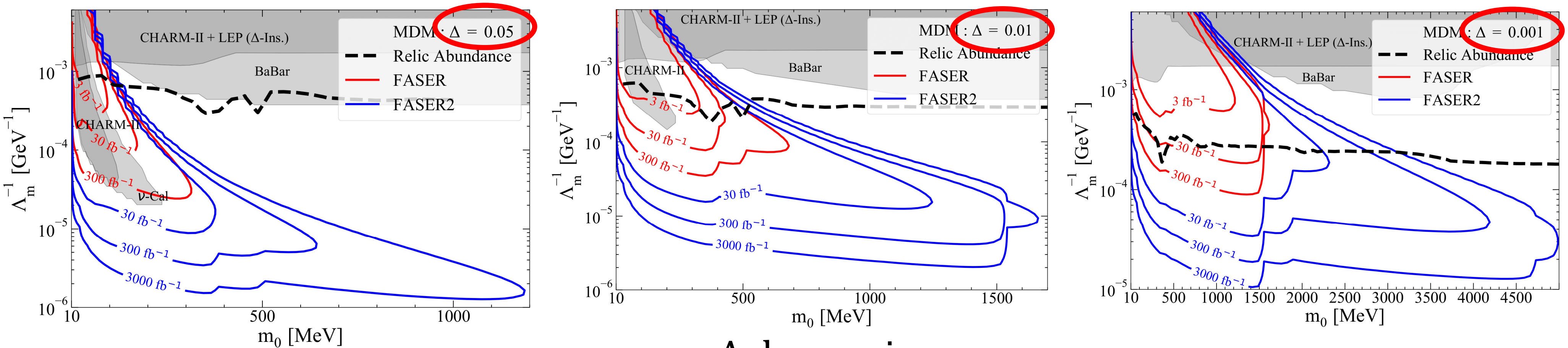


Projections – Dipole iDM at BaBar and LHC 1508.03050

- LHC
  - $pp \to j\chi_0\chi_1 \to j\chi_0\chi_0\gamma$
  - Jet + photon + missing energy
- BaBar
  - 1photon + missing energy
  - 2photons + missing energy
- Lose sensitivity for $\Delta \lesssim 5\%$
  - Too long lived



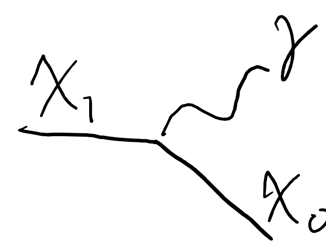
Projections – Dipole iDM at FASER 2301.05252



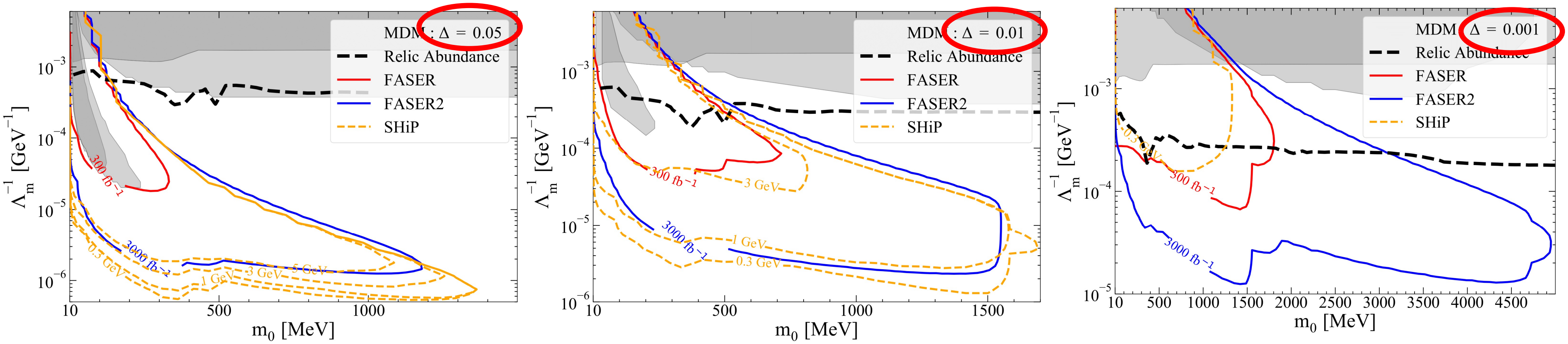
Δ decreasing →

- Decreasing Δ brings softer decay photons → passes below thresholds
- FASER has TeV χ_1, good for compressed spectra.
  - $E_\gamma \approx 10\text{ GeV} \times \frac{\Delta}{0.01}$
- Forward production benefits from mass enhancement in vector meson decay: $\text{BF} \sim \frac{m_{\text{meson}}^2}{\Lambda^2}$
- Other LHC experiments may have sensitivity to relic target
  - We also made SHiP projections

$\tau \sim \Delta^{-3}$



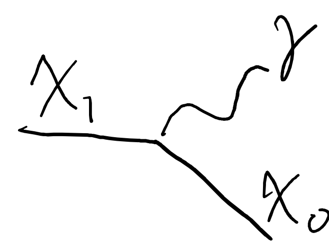
Projections – Dipole iDM at FASER 2301.05252



Δ decreasing →

- SHiP and FASER cover similar decay lengths

$\tau \sim \Delta^{-3}$



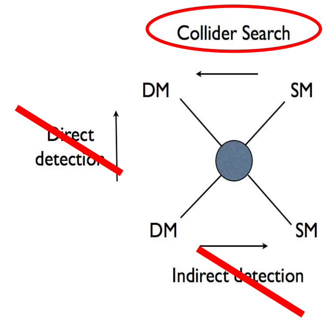
- SHiP uses intense SPS beam
  - $> 10^{20}$ POT but lower energy
  - Outperforms FASER for $\Delta > 0.01$

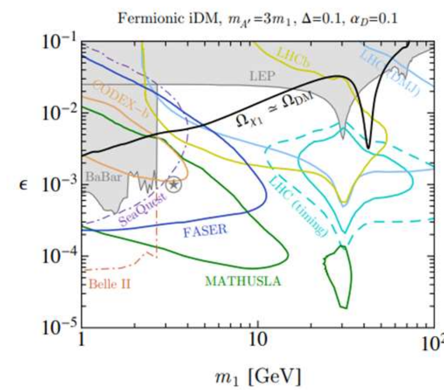
- As Δ is decreased, need to rely more on large boost to pick out decay products

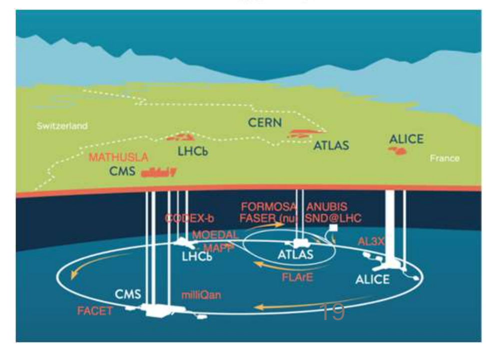
Summary

- Inelastic dark matter is a general model, naturally insensitive to experiments targeting DM via ID, DD
  - Brings an LLP, motivates displaced decay searches!
  - Many realizations with different signals, $\tau(\Delta)$, dominant production mechanisms
  - I discussed the dark photon and dipole iDM models $\bar{d} \approx 1\text{m}$
- The relic target is actively being probed by experiments today
  - Sensitivity largely dependent on Δ, relic target is not
- LHC the best place to search for $m_{\text{DM}} > O(10)\text{GeV}$
  - Complementary to lower energy beam dumps and B factories
  - Many experiments needed to cover the relic target space!

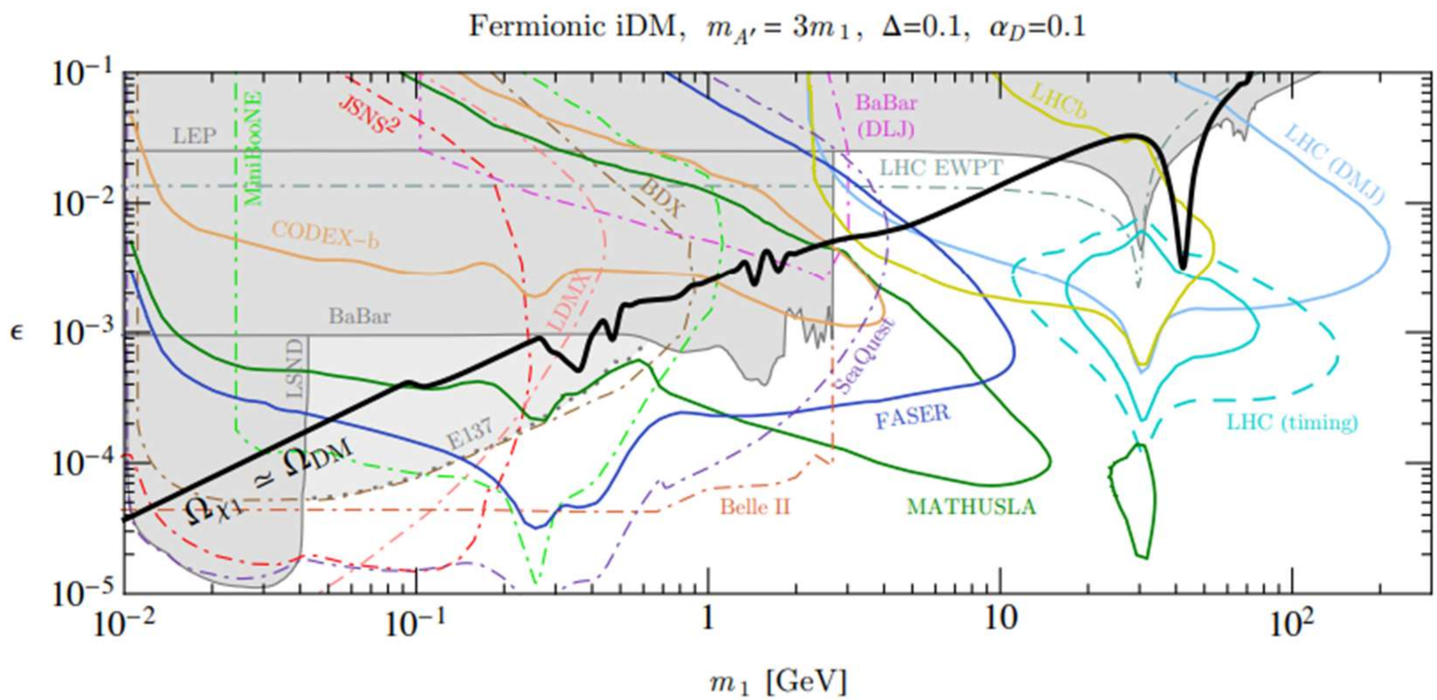
Thank You!





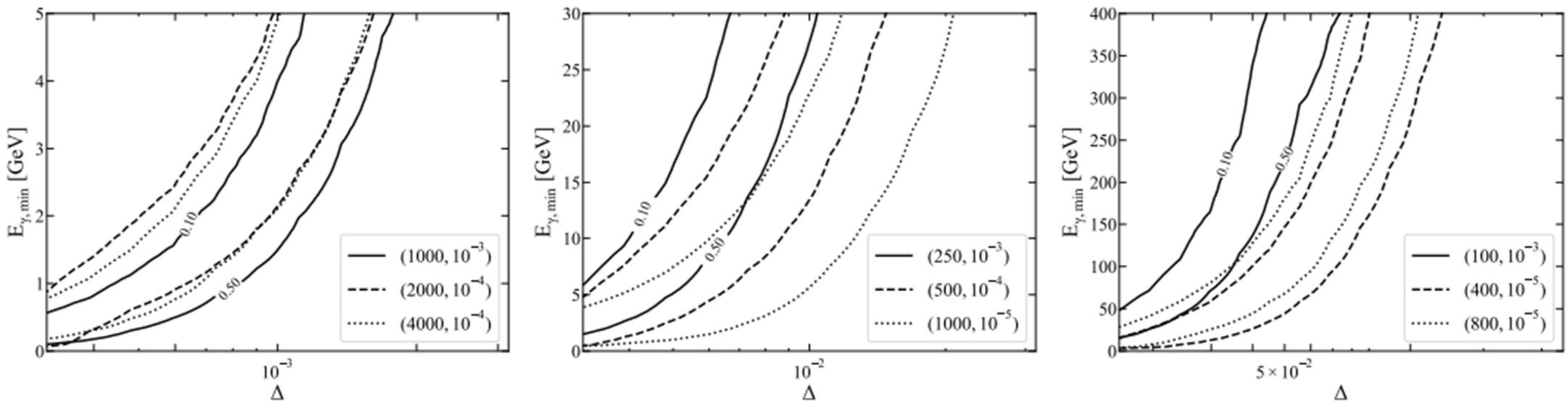


• 1810.01879

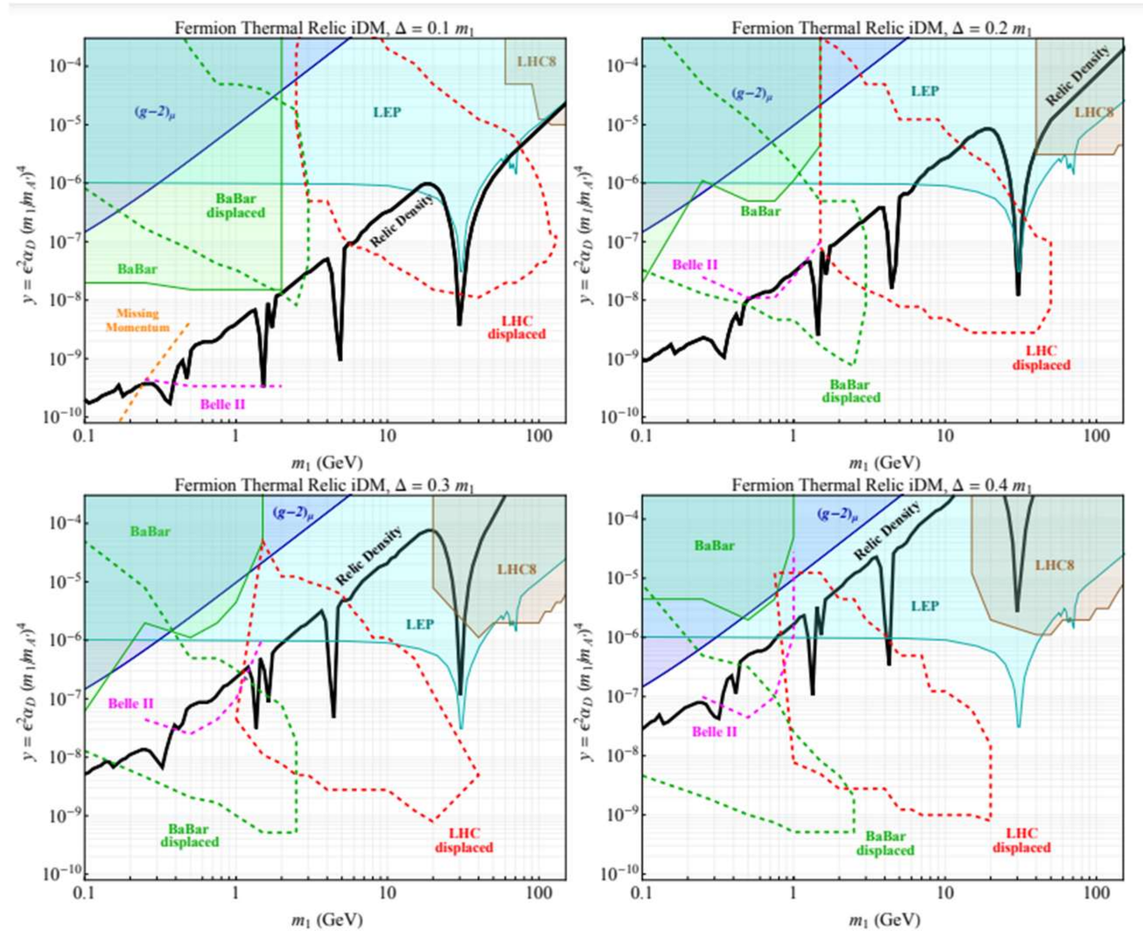


Fermionic iDM, $m_{A'} = 3m_1$, Δ=0.1, α_D=0.1
ϵ
m_1 [GeV]
LEP
MiniBooNE
JSNS^2
BaBar (DLJ)
LHCb
LHC (DMJ)
LHC EWPT
BDX
CODEX-b
LDMX
BaBar
LSND
E137
Sea Quest
FASER
LHC (timing)
$\Omega_{\chi_1} \simeq \Omega_{DM}$
Belle II
MATHUSLA

- Loss of reach with increasing energy cut
- 2301.05252



- 1508.03050



Fermion Thermal Relic iDM, Δ = 0.1 m1
Fermion Thermal Relic iDM, Δ = 0.2 m1
Fermion Thermal Relic iDM, Δ = 0.3 m1
Fermion Thermal Relic iDM, Δ = 0.4 m1
y = ε²α_D (m1/m_A')⁴
m1 (GeV)
(g−2)μ
LEP
LHC8
BaBar
BaBar displaced
Relic Density
LHC displaced
Missing Momentum
Belle II