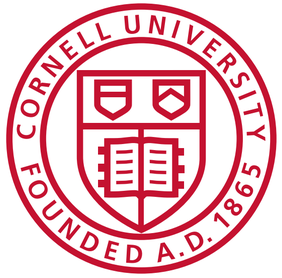
Searching for Inelastic Dark Matter with CMS

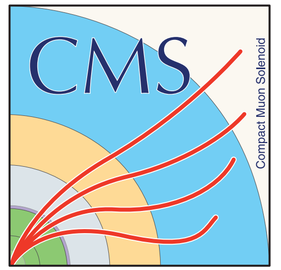
Sam Bright-Thonney[1]

on behalf of the CMS Collaboration

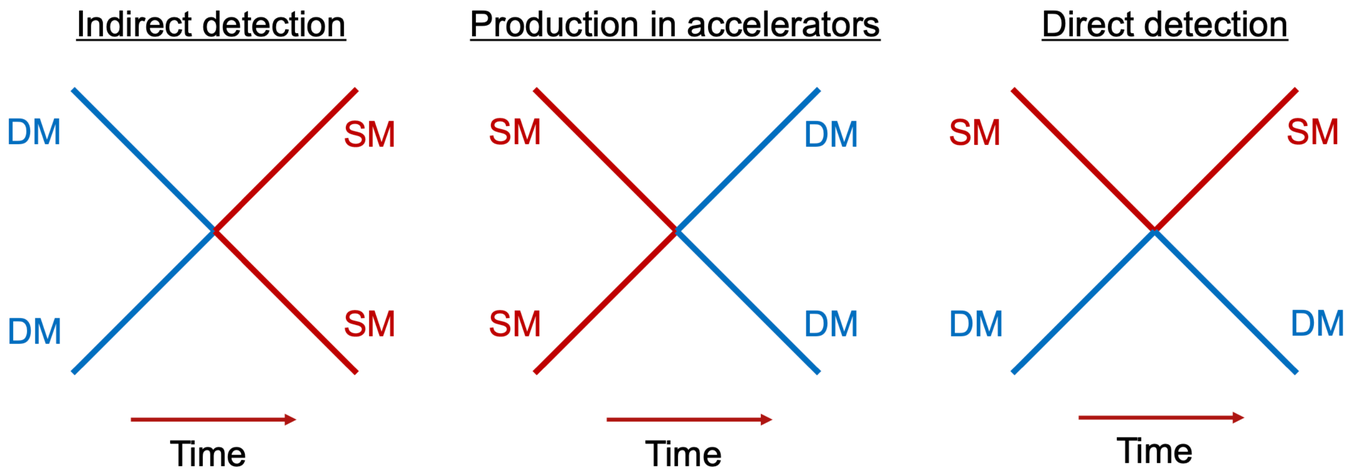
[1] Cornell University

Phenomenology 2023 Symposium





How to look for dark matter



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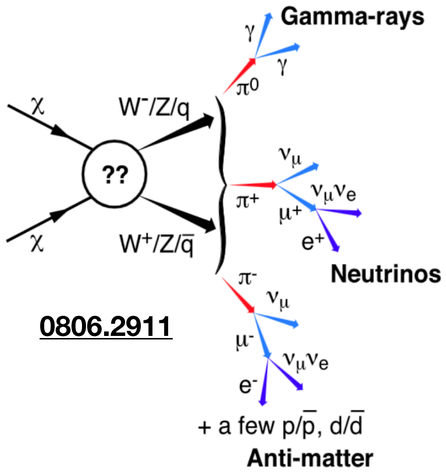
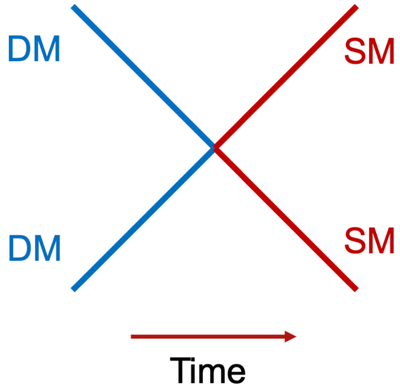
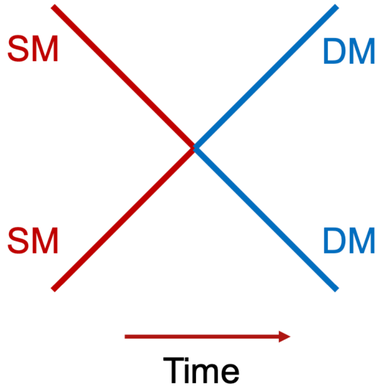


0806.2911

Indirect detection



Production in accelerators



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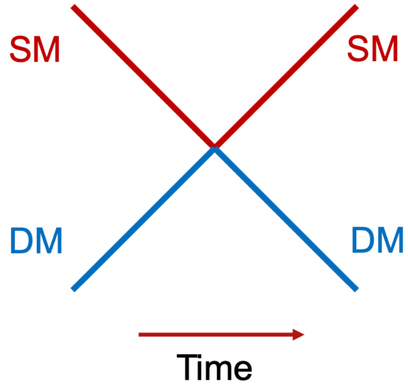

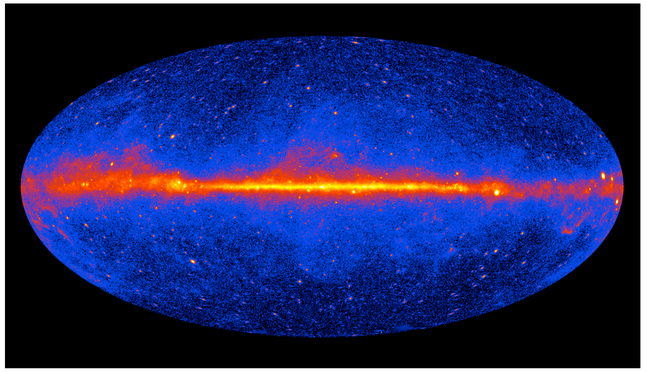

Fermi-LAT

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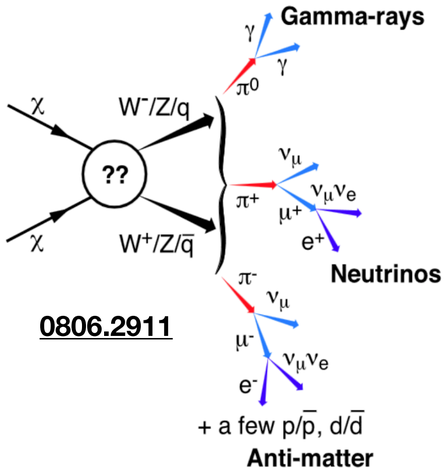

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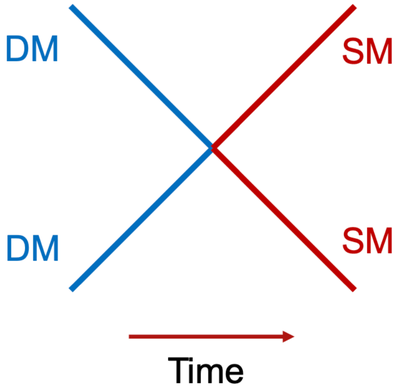

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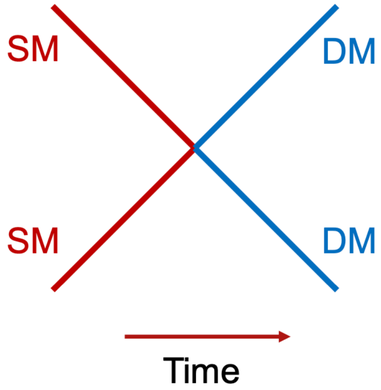

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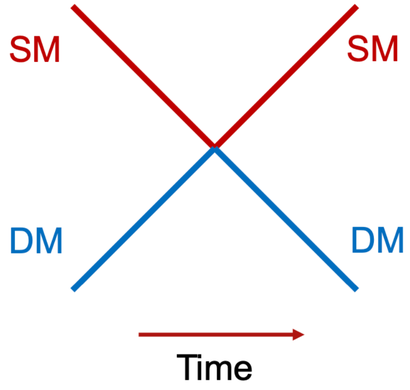
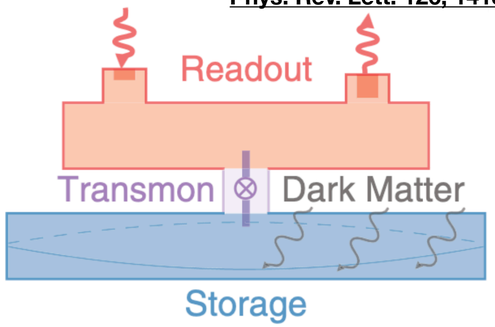
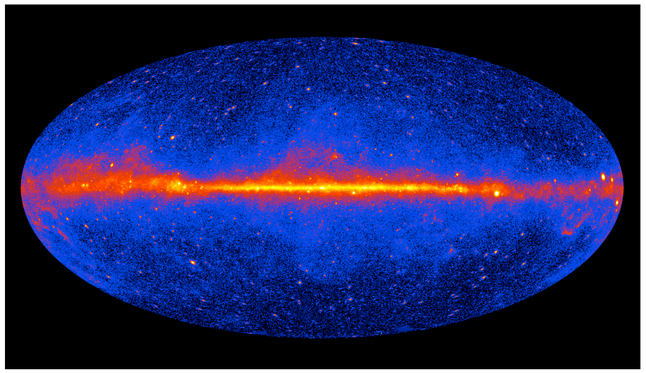


Phys. Rev. Lett. 126, 141302





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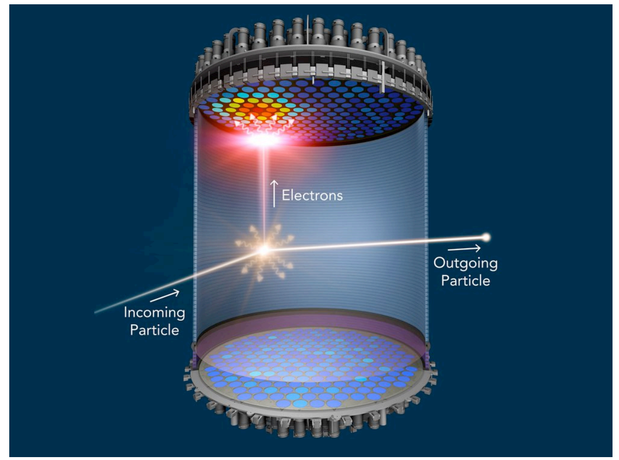

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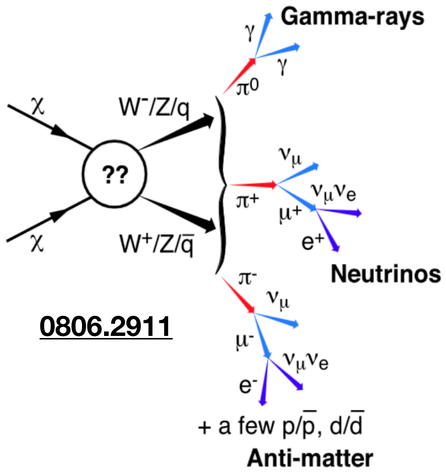

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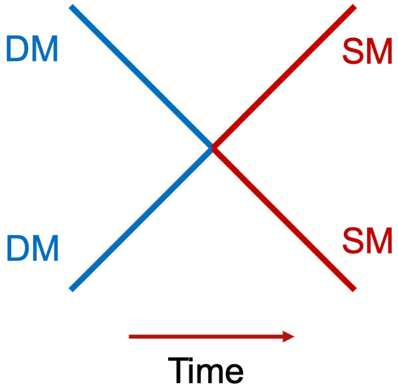

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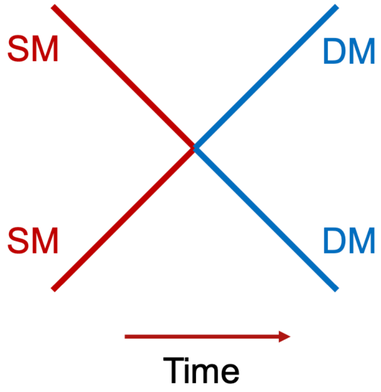

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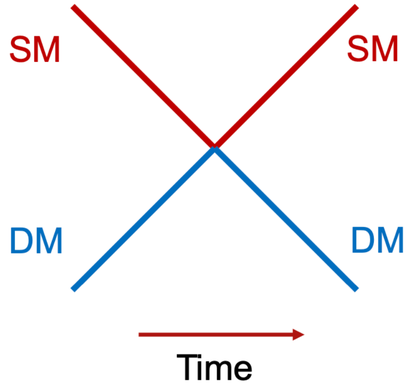

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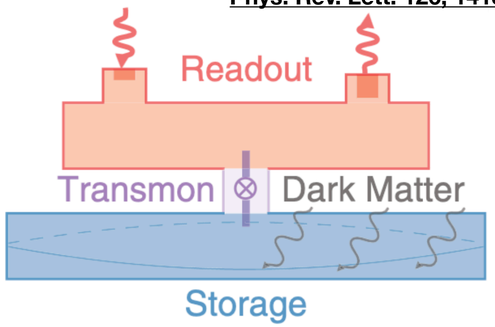

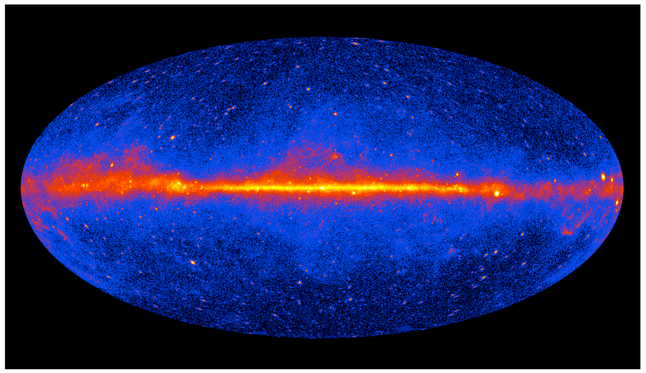

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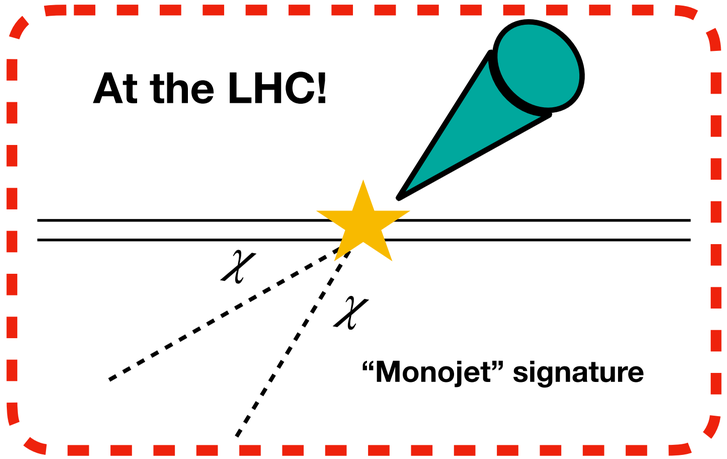

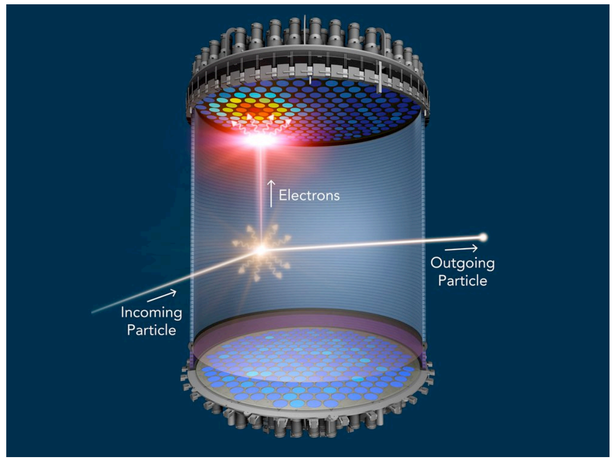

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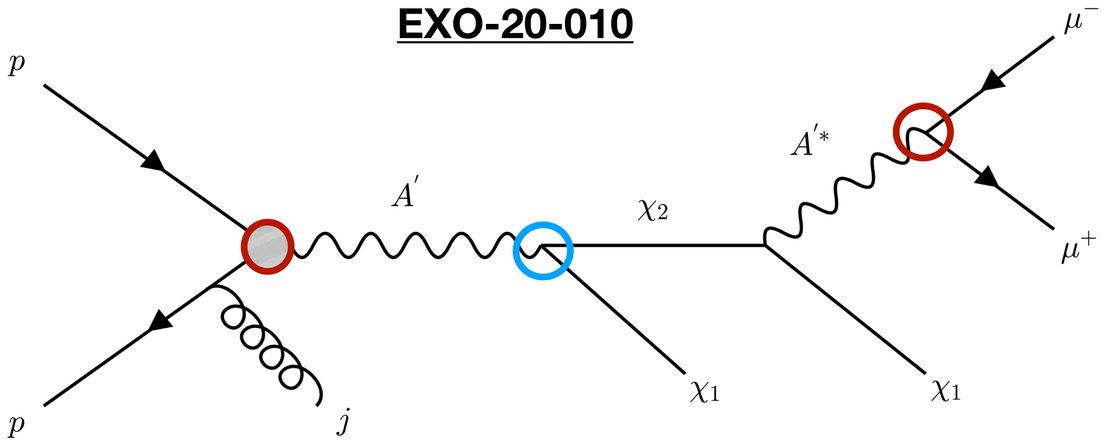
Inelastic Dark Matter

EXO-20-010



$$\overline{\psi}\gamma_\mu\psi \simeq i(\overline{\chi}_1\overline{\sigma}_\mu\chi_2 - \overline{\chi}_2\overline{\sigma}_\mu\chi_1) + \frac{\delta}{2m}(\overline{\chi}_2\overline{\sigma}_\mu\chi_2 - \overline{\chi}_1\overline{\sigma}_\mu\chi_1)$$

- **Inelastic dark matter** (iDM) model posits a dark sector with a fermion χ with a gauged $U(1)_D$ and a **dark photon** A'
  - Split DM spectrum induced by symmetry breaking + small Majorana mass term
  - Coupling to A' is predominantly **inelastic** (off-diagonal)
- **Kinetic mixing** between γ/Z and A' introduces SM portal — strength determined by parameter ϵ

Inelastic Dark Matter

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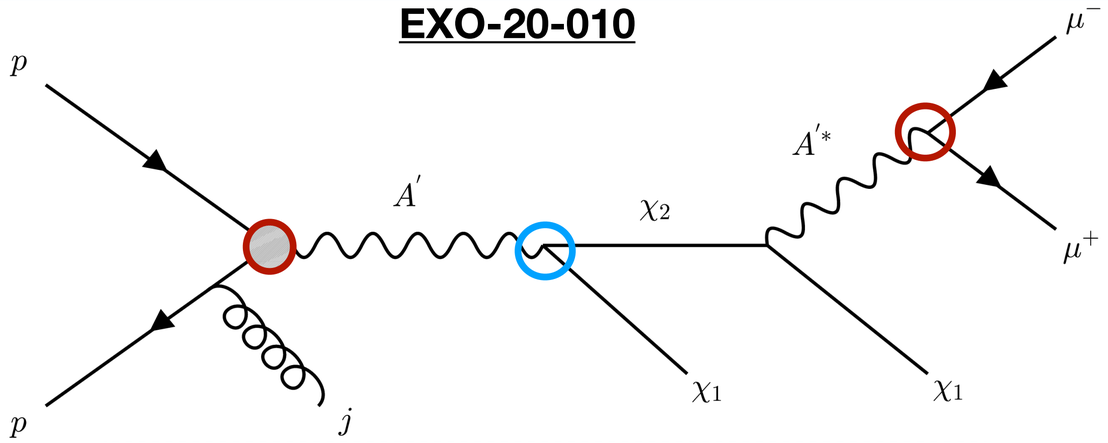

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Key Parameters

- m_1 (DM mass)
  - $\Delta \equiv m_2 - m_1 = xm_1$
- $c\tau$ (χ_2 lifetime)

} **Varied in CMS search**

- α_D (dark $U(1)$ coupling)

} **Fixed @ 0.1 or α_{EM}**

- $m_{A'} = 3m_1$
- ϵ (kinetic mixing parameter)

} **Fixed, or determined by other parameters**

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  - Split DM spectrum induced by symmetry breaking + small Majorana mass term
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$$y \equiv \epsilon^2\alpha_D\left(\frac{m_1}{m_{A'}}\right)^4 \propto \langle\sigma v\rangle$$

Determines relic density (consistency with cosmological observations)

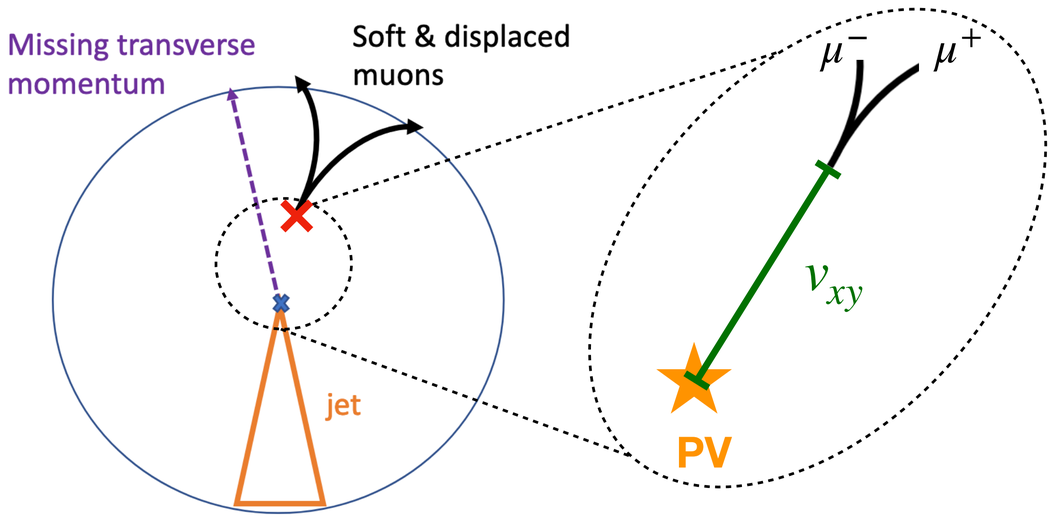
$$\Gamma_{\chi_2} \propto \frac{\epsilon^2\alpha_D\Delta^5}{m_{A'}^4}$$

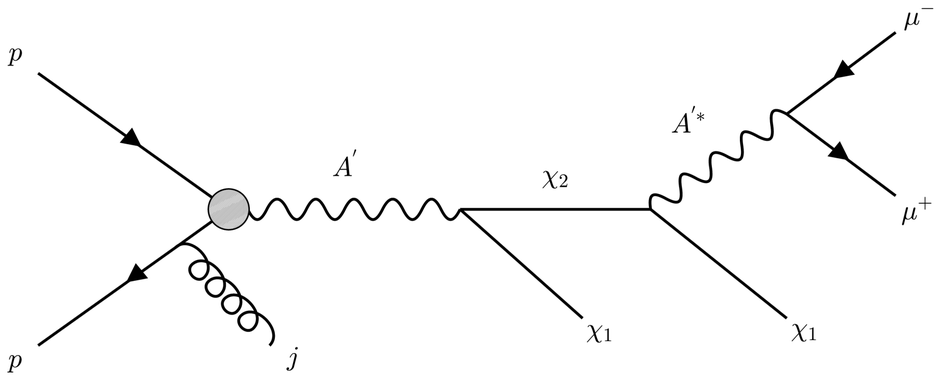
Small mass splitting Δ and kinetic mixing can **give χ_2 a macroscopic lifetime**

iDM Signature in CMS

CMS Signature **EXO-20-010**

- Dark photon A' produced, recoiling against ISR jet
- $A' \longrightarrow \chi_1 + \chi_2 (\rightarrow \chi_1 + \ell^+\ell^-)$
  - Macroscopic χ_2 lifetime creates a **displaced dilepton vertex**
  - Presence of χ_1 in the final state leaves **significant MET**
  - Boost from recoil + small DM mass splitting leads to **soft, collimated leptons aligned with MET**
- Displacement + MET $\Longrightarrow$ **low background!**





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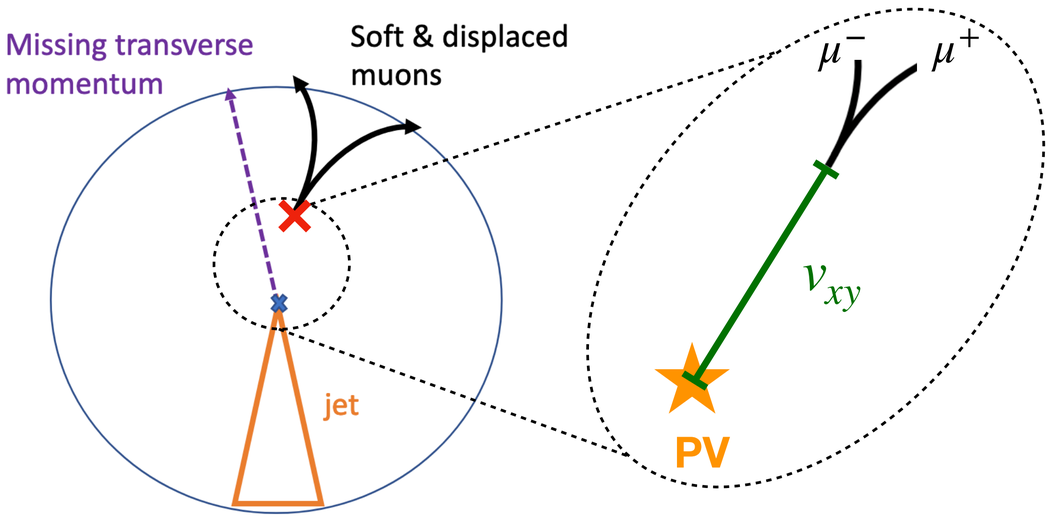
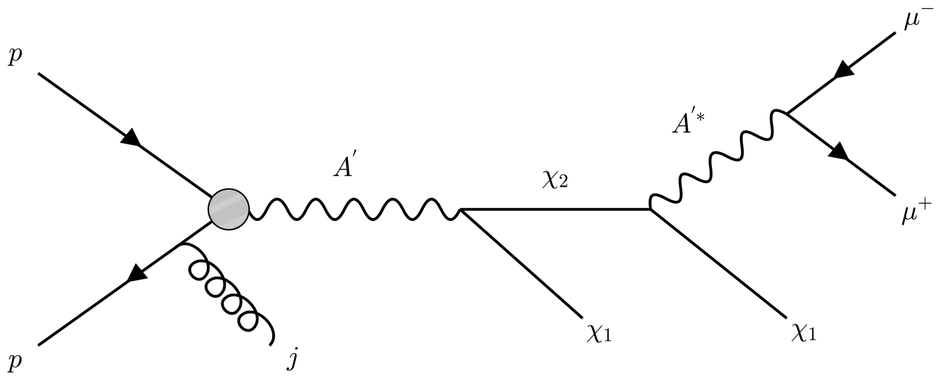
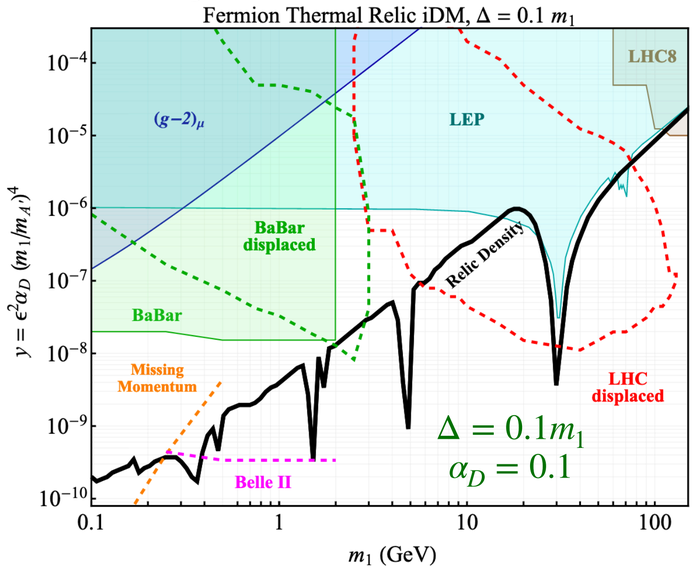




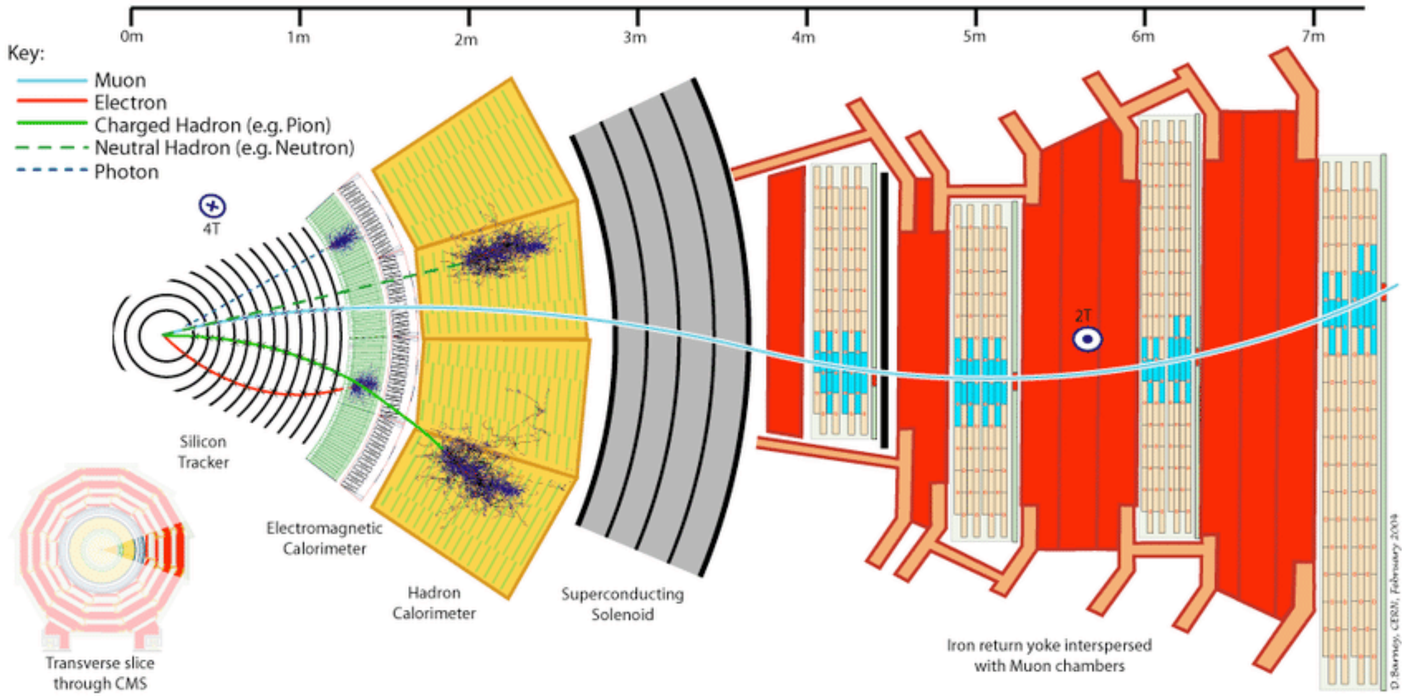
Parameter Space

- $m_1 \sim 1 - 100$ GeV
- $\Delta = 0.1m_1, 0.4m_1$
- $c\tau_{\chi_2} = 1, 10, 100, 1000$ mm
- $\alpha_D = 0.1, \alpha_{EM}$

Phys. Rev. D 93, 063523



Displaced Muon Reconstruction



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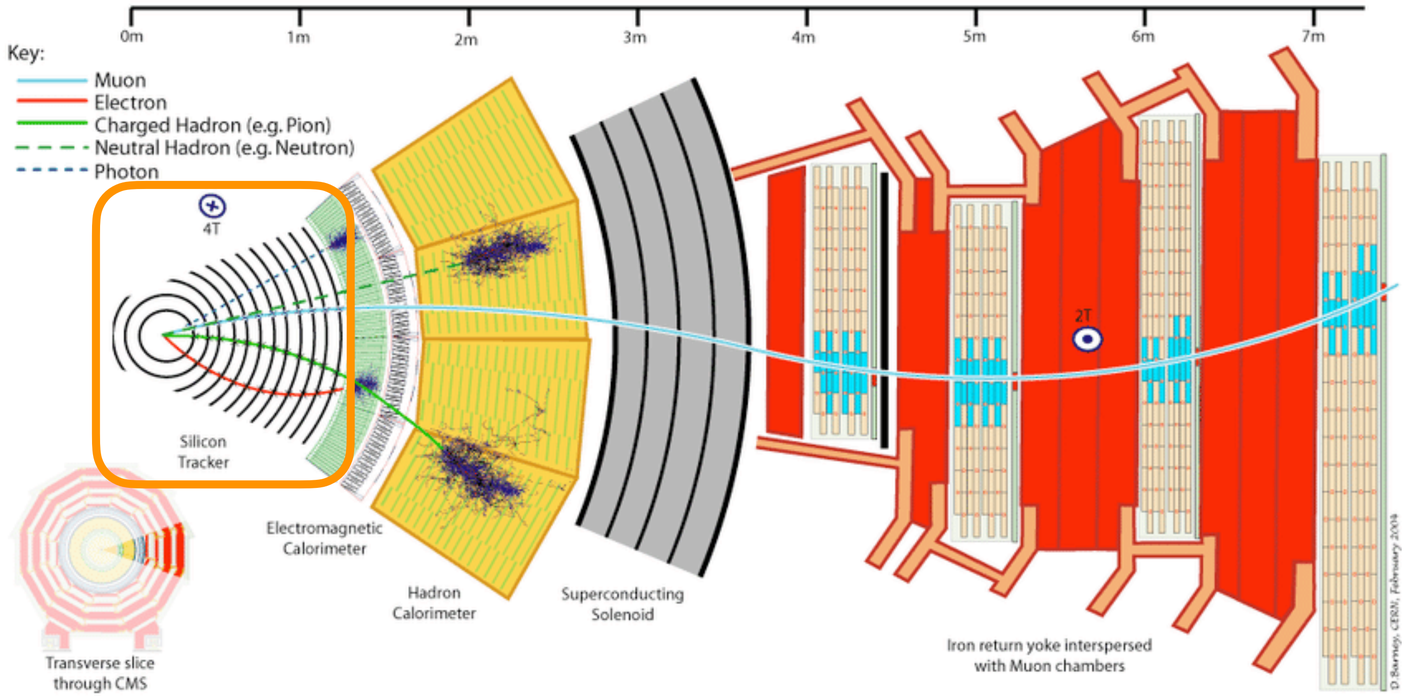

- Charged particle reconstruction is nominally limited to the **tracker** ($v_{xy} \lesssim 60\,\mathrm{cm}$)
  - ~1m radius severely limits sensitivity to particles produced with large v_{xy}

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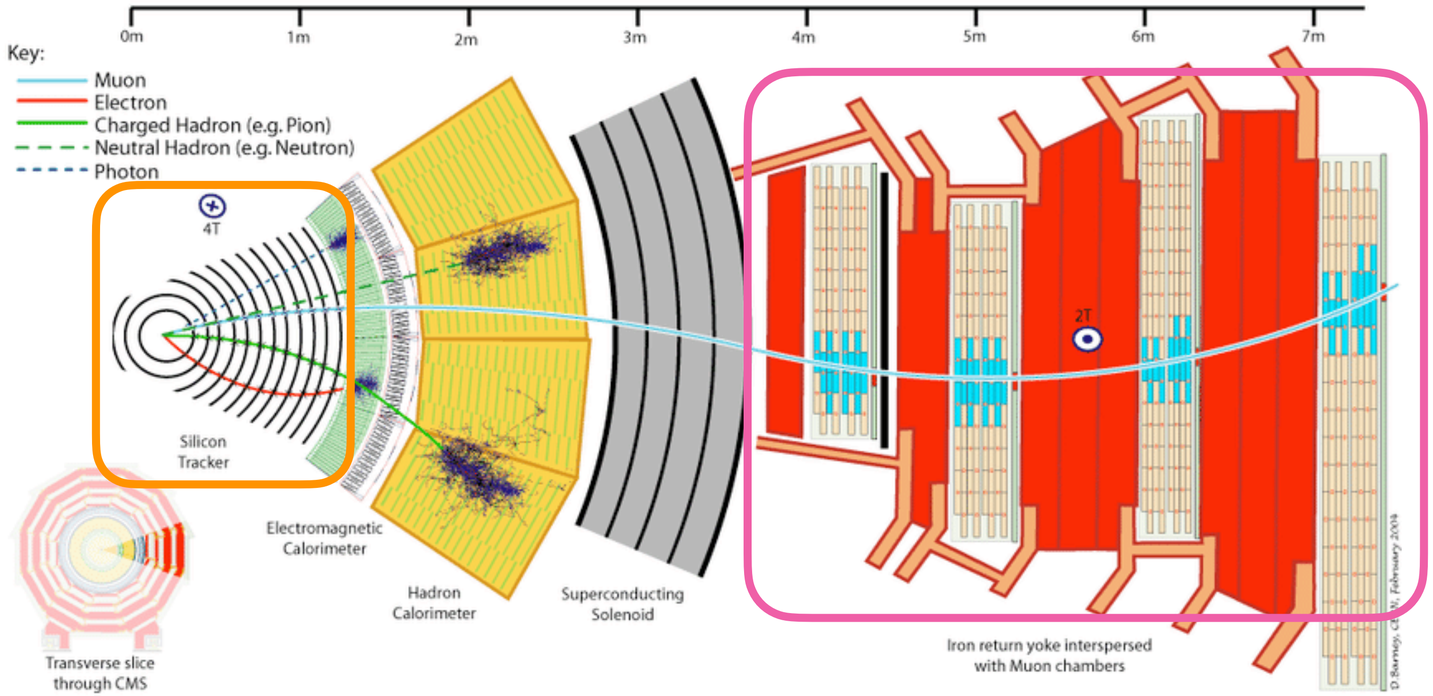

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  - ~1m radius severely limits sensitivity to particles produced with large v_{xy}
- Muons in particular benefit from the **muon chambers** at large radius
  - Dedicated algorithm reconstructs **displaced standalone (dSA) muons**
  - Independent of PF reconstruction, relies solely on muon chamber hits
  - Worse track and momentum resolution, but significantly extends reach

EXO-20-010

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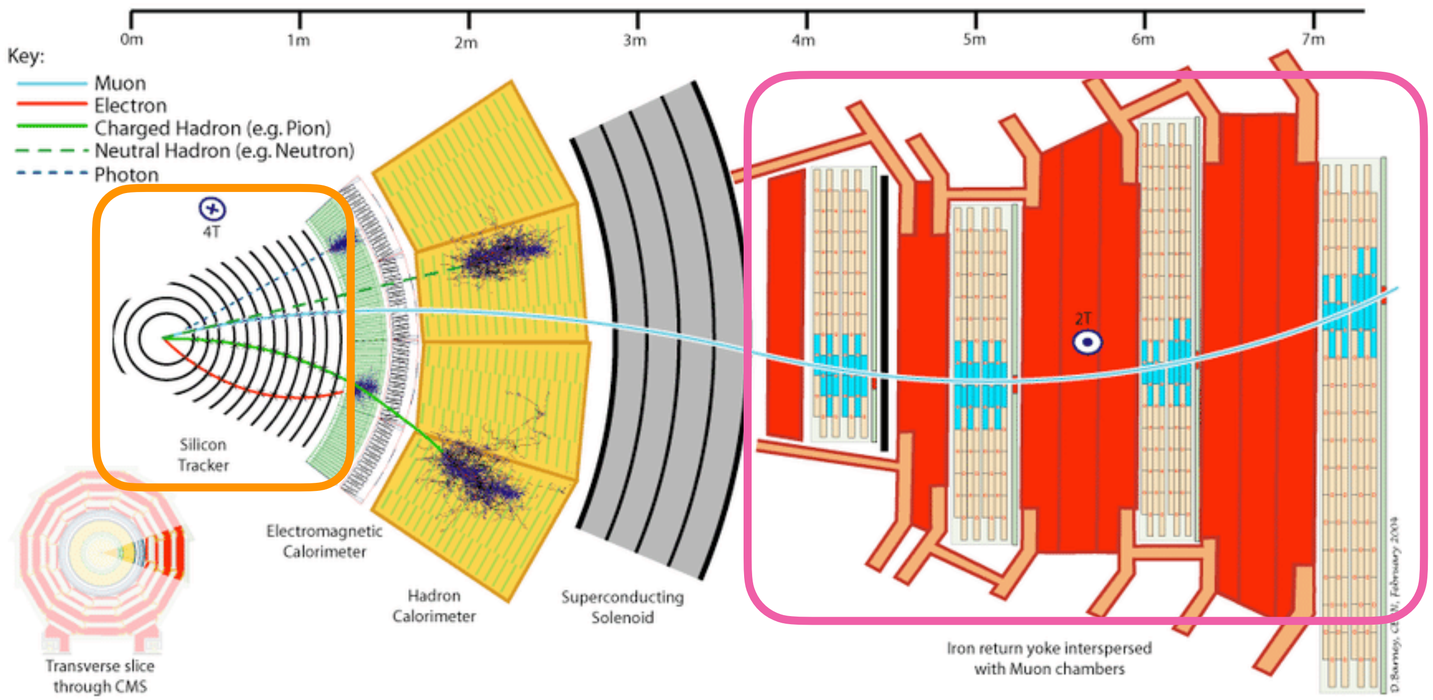

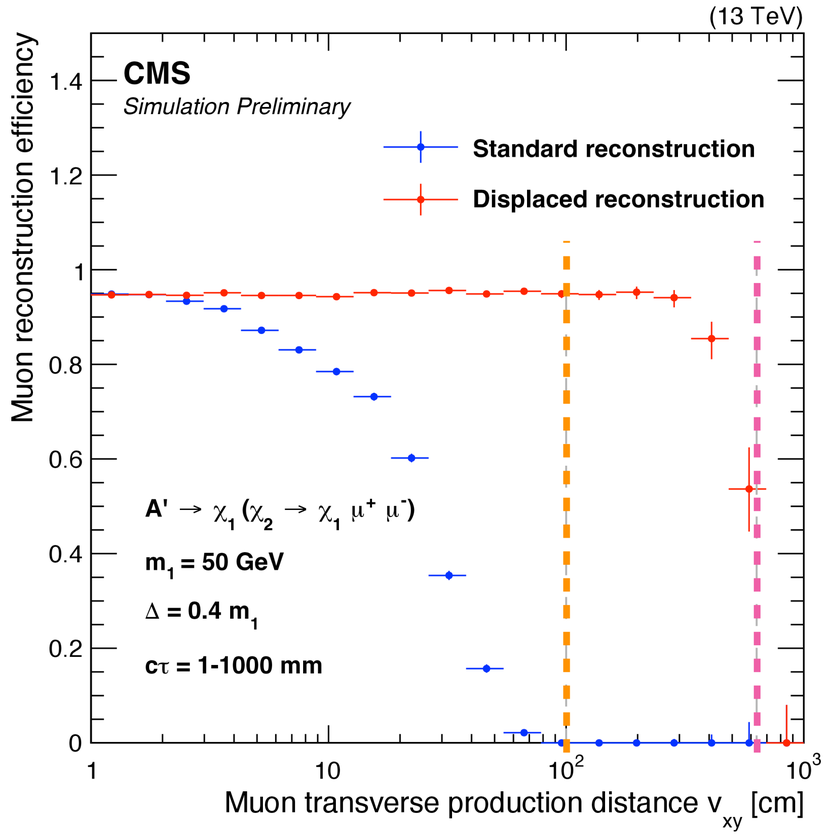

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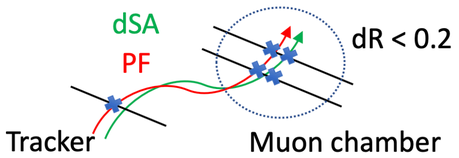
Displaced Muon Selection & Vertexing

- Particle Flow (tracker) muons are preferred when available
  - dSA muons used by default, but replaced with tracker muons when matched within $\Delta R < 0.2$
  - Events categorized into 0-, 1-, and 2-match categories
  - SM backgrounds particularly suppressed in the 0-match category



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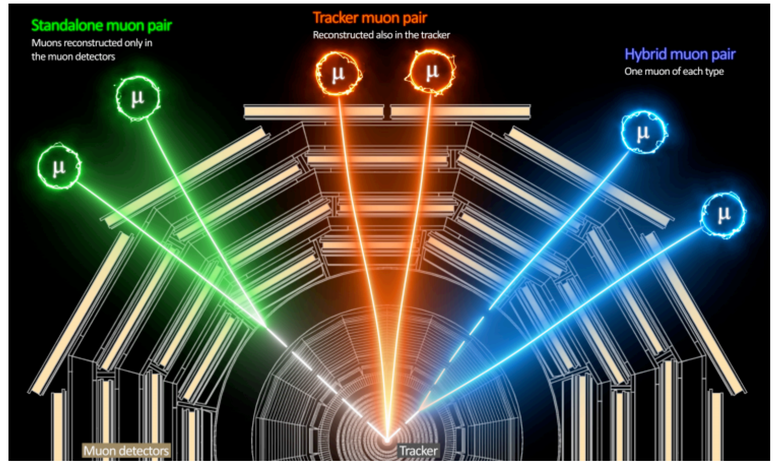

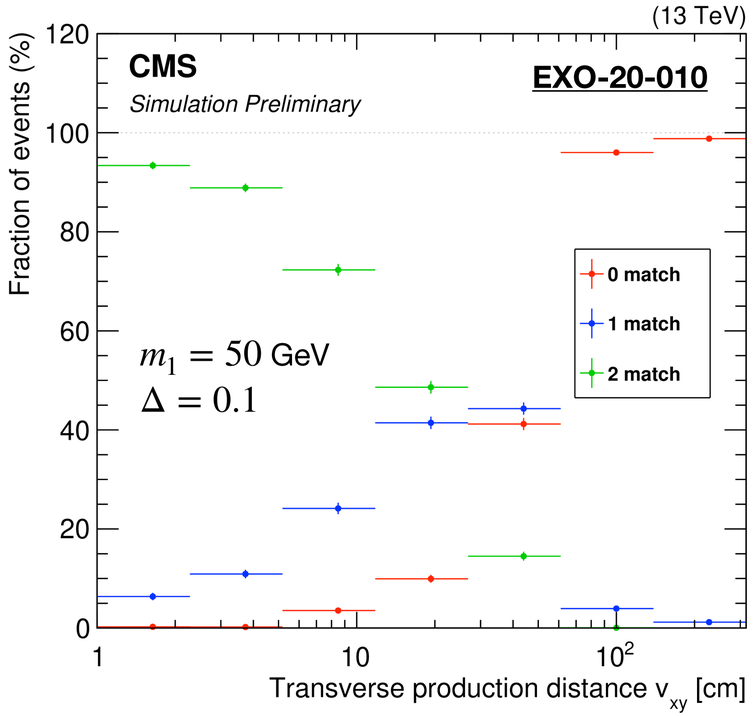

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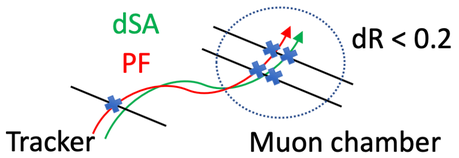

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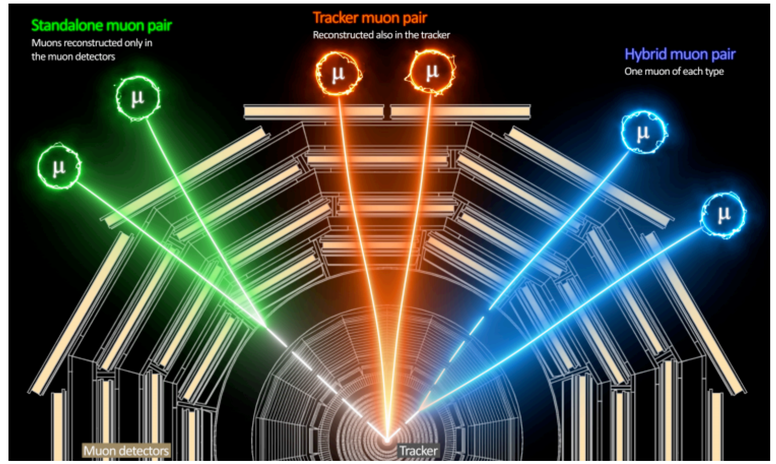
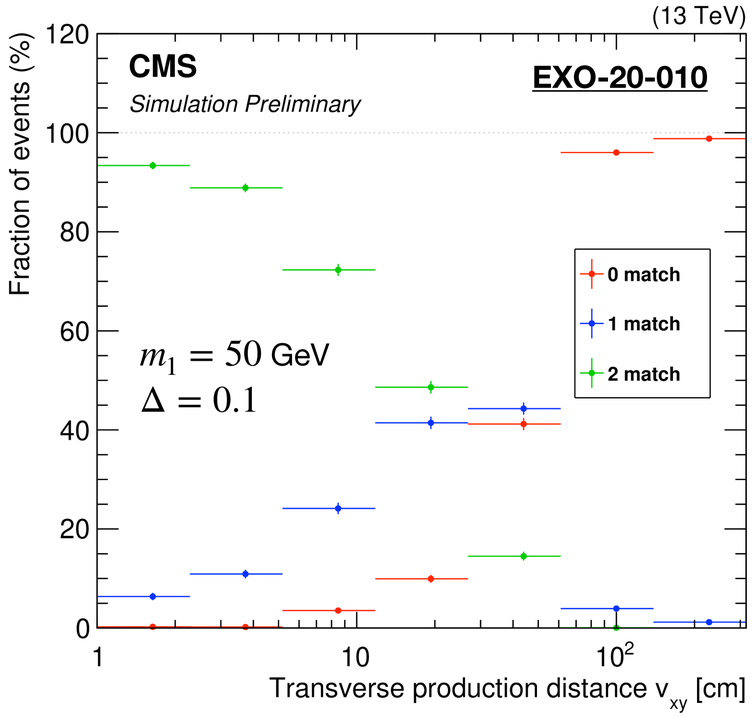
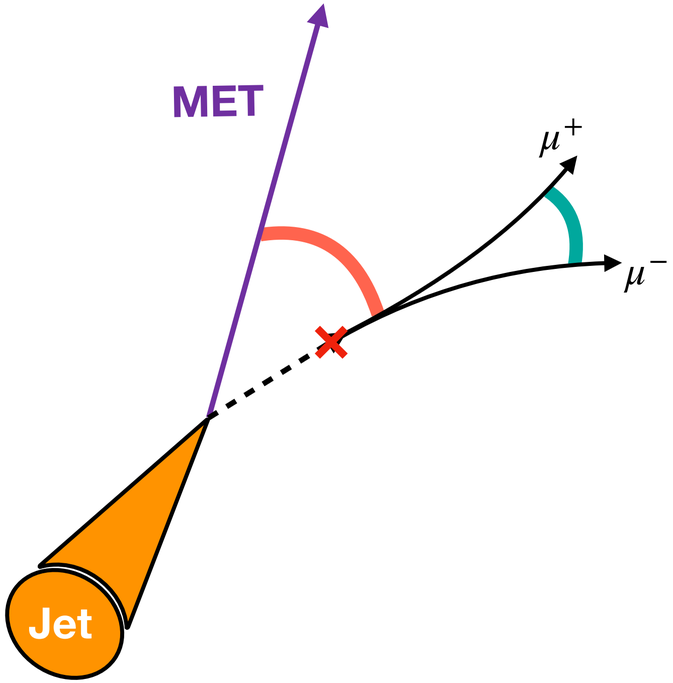






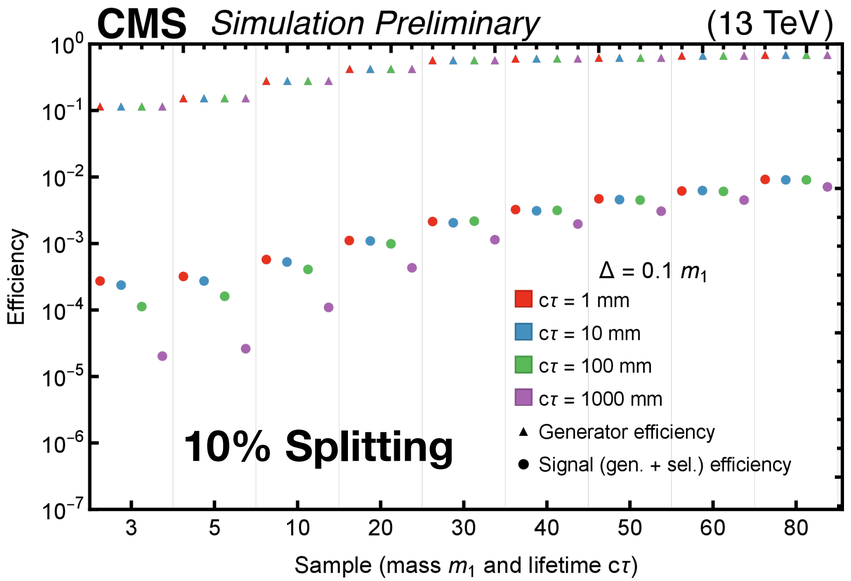
Muon Selection

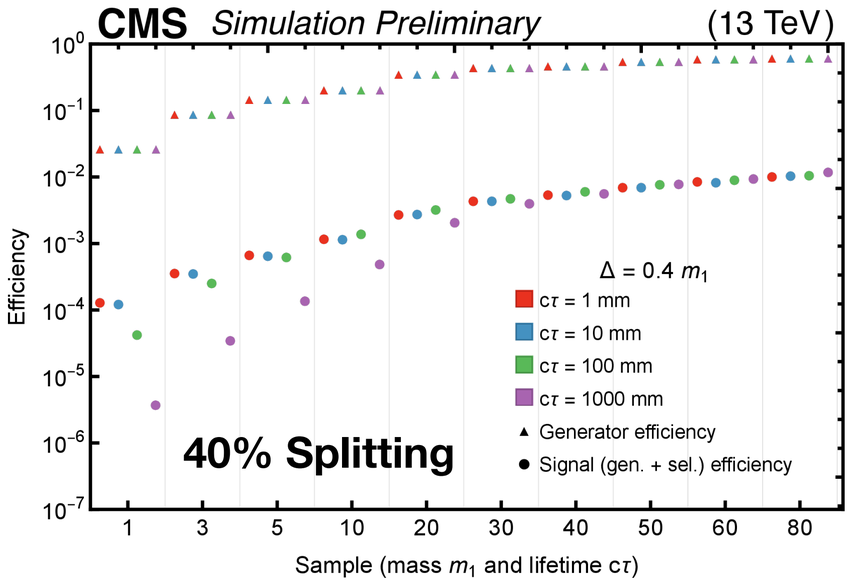
- ID & kinematic cuts
- $\Delta R_{\mu\mu} < 0.9$
- $|\Delta\phi(p_T^{\mu\mu}, p_T^{\text{miss}})| < 0.5$

Collimation requirements are unique to iDM signal!

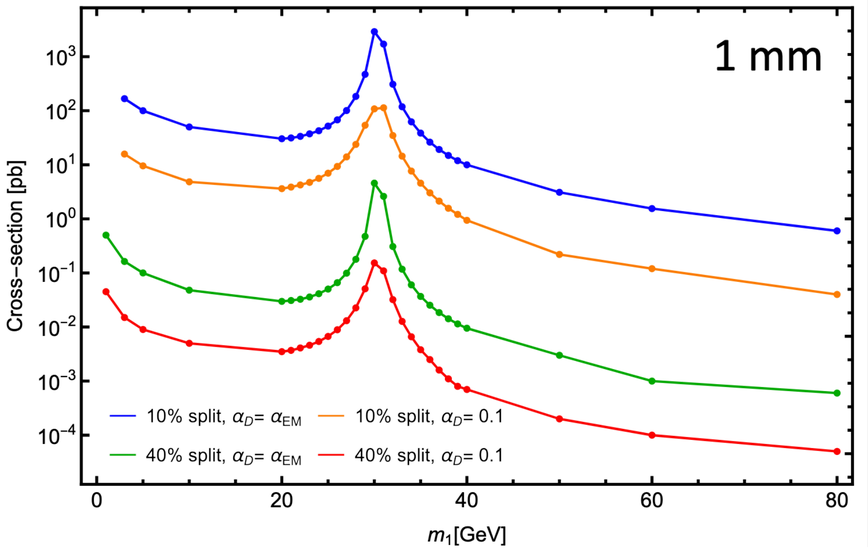
Event Selection & Signal Efficiency

EXO-20-010



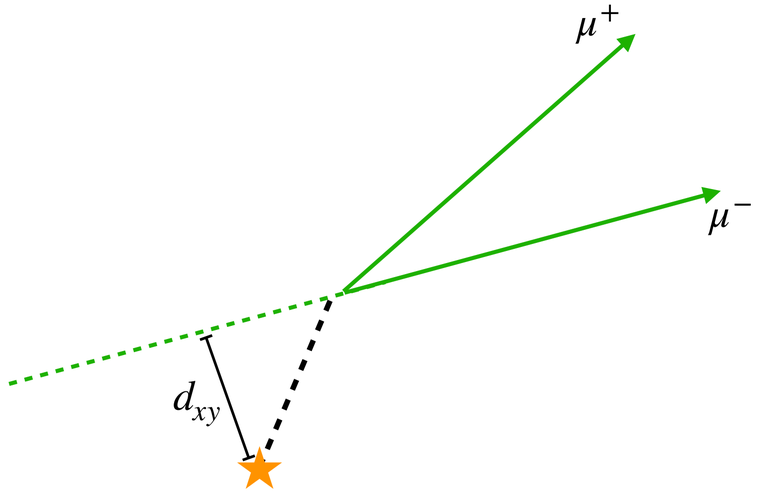


- Full event selection designed to suppress major backgrounds (QCD, EW, Top):
  - MET Trigger + strict offline cut (200 GeV)
  - 0 < nJets < 3, no b-tagged jets, jets well-separated from MET
- Signal selection efficiencies are generally quite low (sub-1%)
  - Driven by muon displacement and soft p_T spectrum ($\lesssim 20$ GeV)
  - High production cross section makes up for low selection efficiency



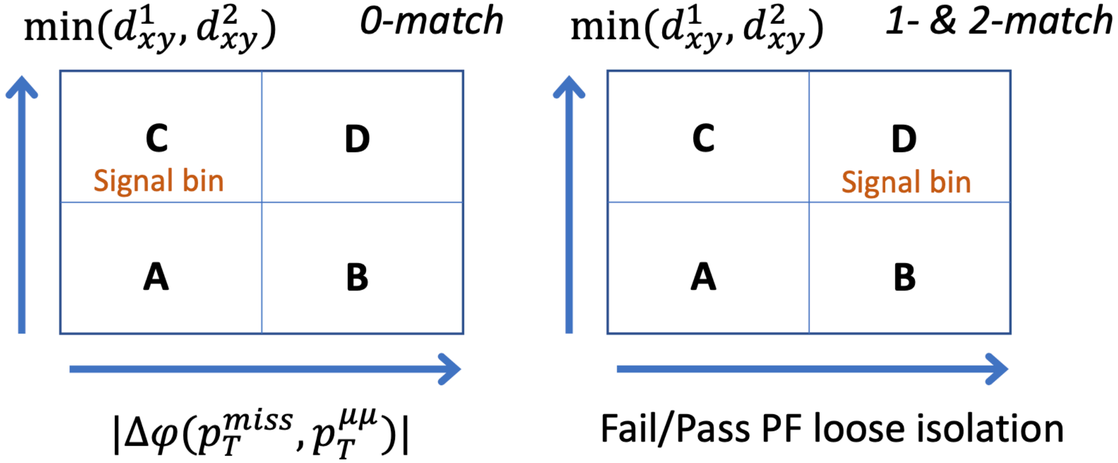
Background Estimation

- After baseline selection, two handles remain to isolate signal:
  1. **Displacement** — Search becomes nearly completely background-free with increasing vertex displacement (v_{xy})
  2. **Isolation** — iDM signal recoils against a jet; should be very little activity around the muons themselves



- Isolate signal and perform data-driven background estimation using the **ABCD method**
  - All categories use $\min(d_{xy,1}, d_{xy,2})$ — proxy for vertex displacement
  - Where PF muons available (1- and 2-match) , use PF isolation of $\min(d_{xy})$ muon
  - Use $\Delta\phi(p_T^{\mu\mu}, p_T^{\text{miss}})$ in the 0-match category

$$N_D^{pred} = \frac{N_B^{obs} \times N_C^{obs}}{N_A^{obs}}$$



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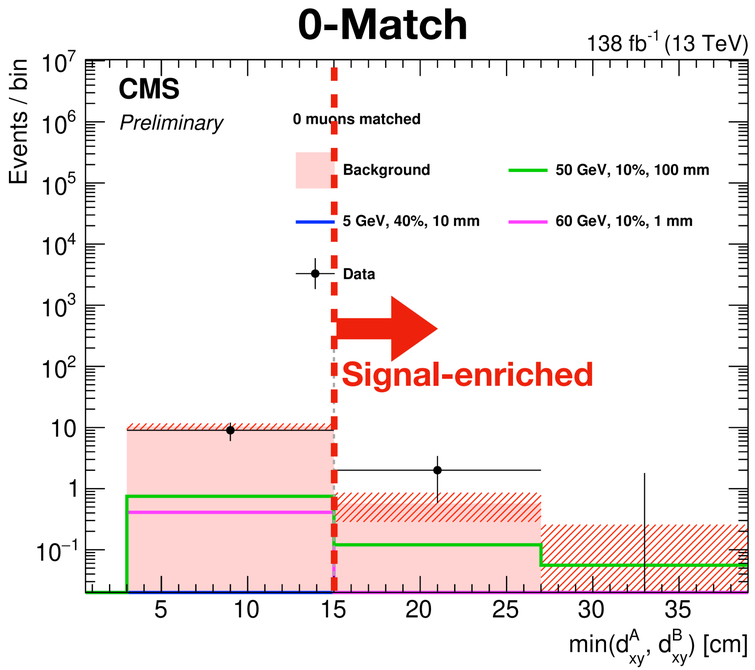
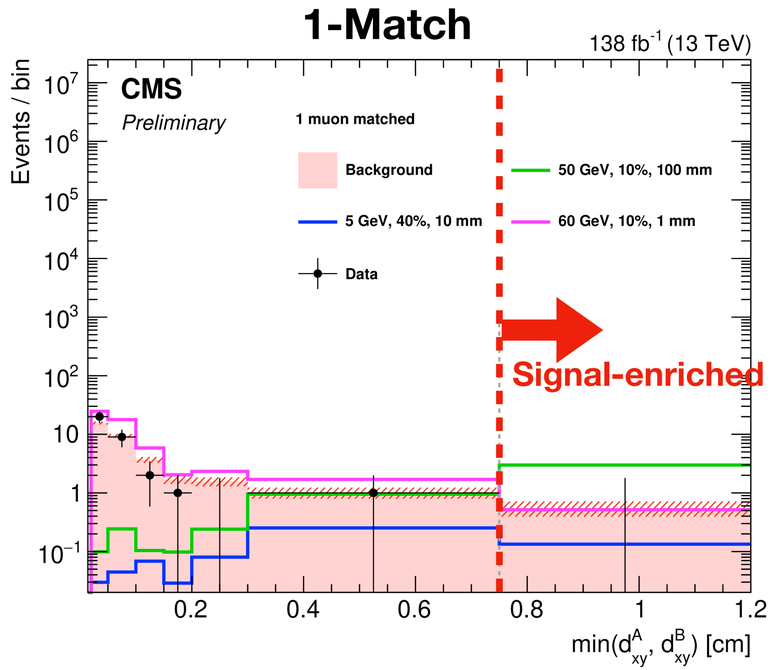
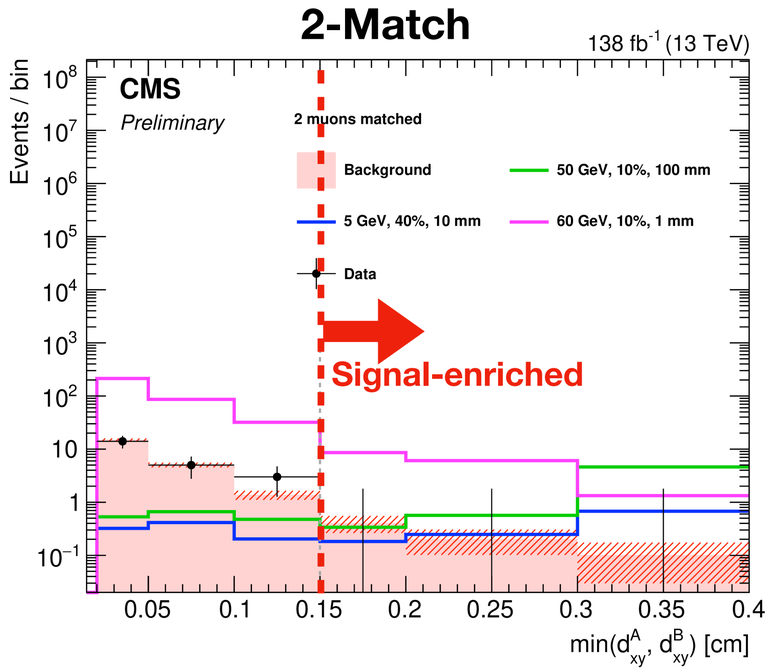
Unblinded Results



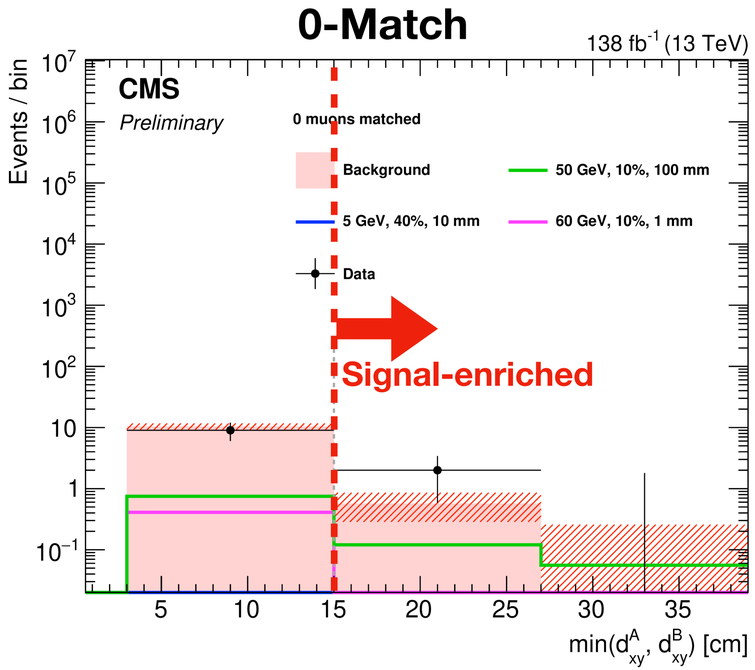


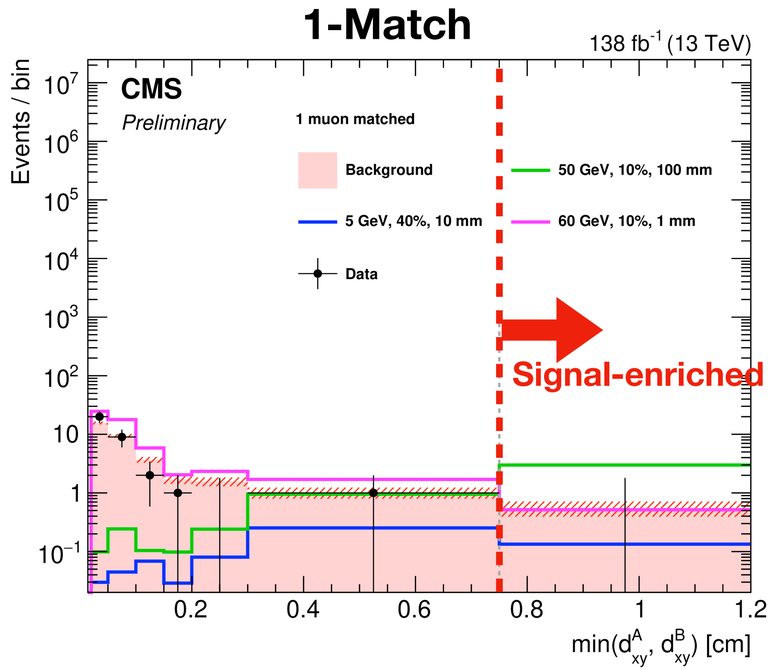


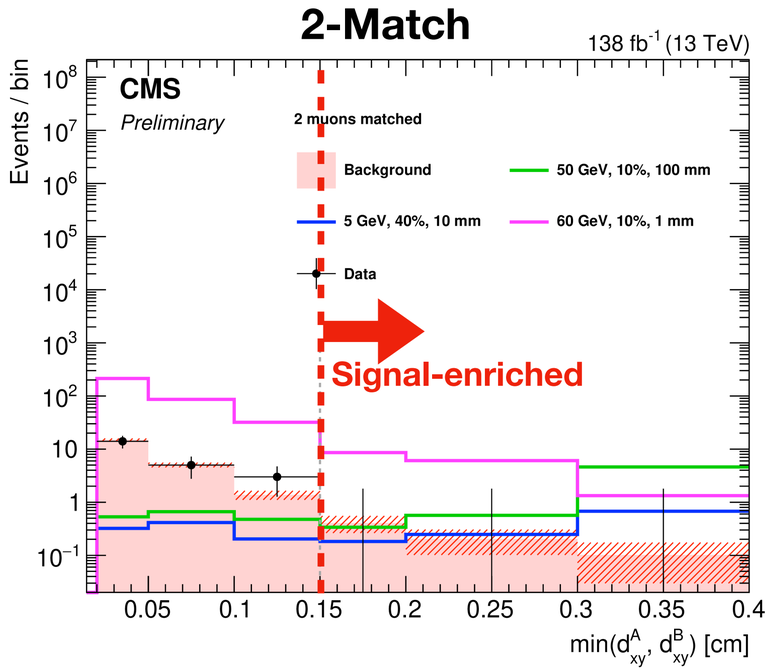
Bin	0-match			1-match			2-match		
	$\Delta\phi_{\mu\mu}^{MET}$	min-d_{xy} [cm]	Events	$I_{\mathrm{PF}}^{\mathrm{rel}}$	min-d_{xy} [cm]	Events	$I_{\mathrm{PF}}^{\mathrm{rel}}$	min-d_{xy} [cm]	Events
Obs. A	0–0.1	3–15	68	> 0.25	0.02–0.75	716	> 0.25	0.02–0.15	424
Obs. B	0.1–0.5	3–15	9	< 0.25	0.02–0.75	33	< 0.25	0.02–0.15	22
Obs. C	0–0.1	> 15	9	> 0.25	> 0.75	12	> 0.25	> 0.15	10
Pred. D	0.1–0.5	> 15	1.2 ± 0.6	< 0.25	> 0.75	0.5 ± 0.3	< 0.25	> 0.15	0.5 ± 0.3
Obs. D			2			0			0

EXO-20-010

Unblinded Results







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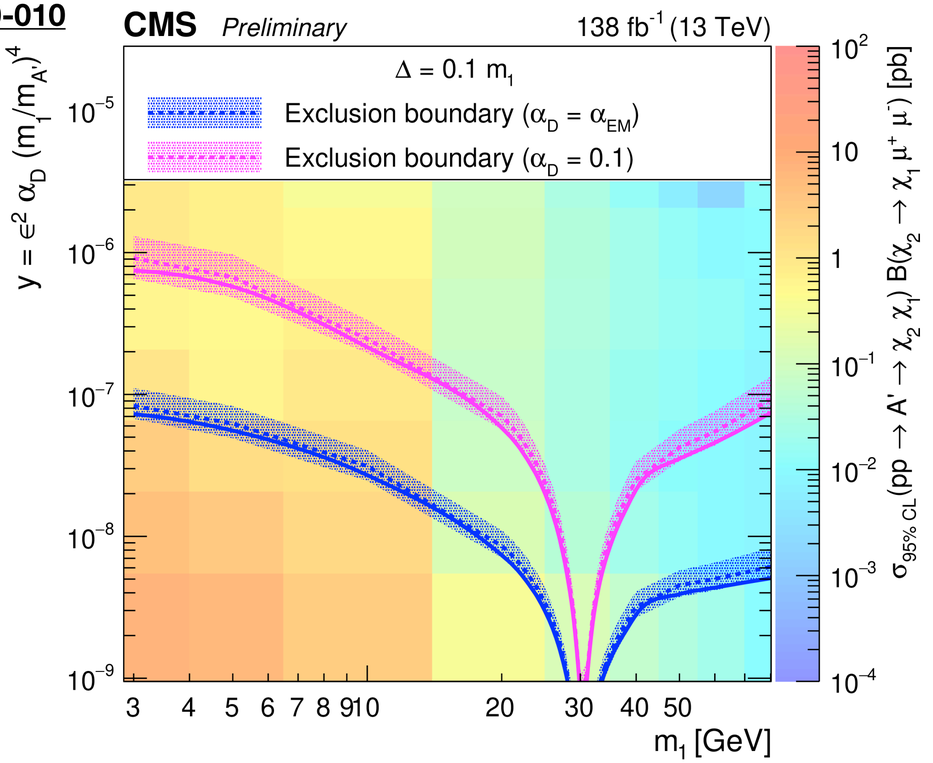
Obs. D			2			0			0

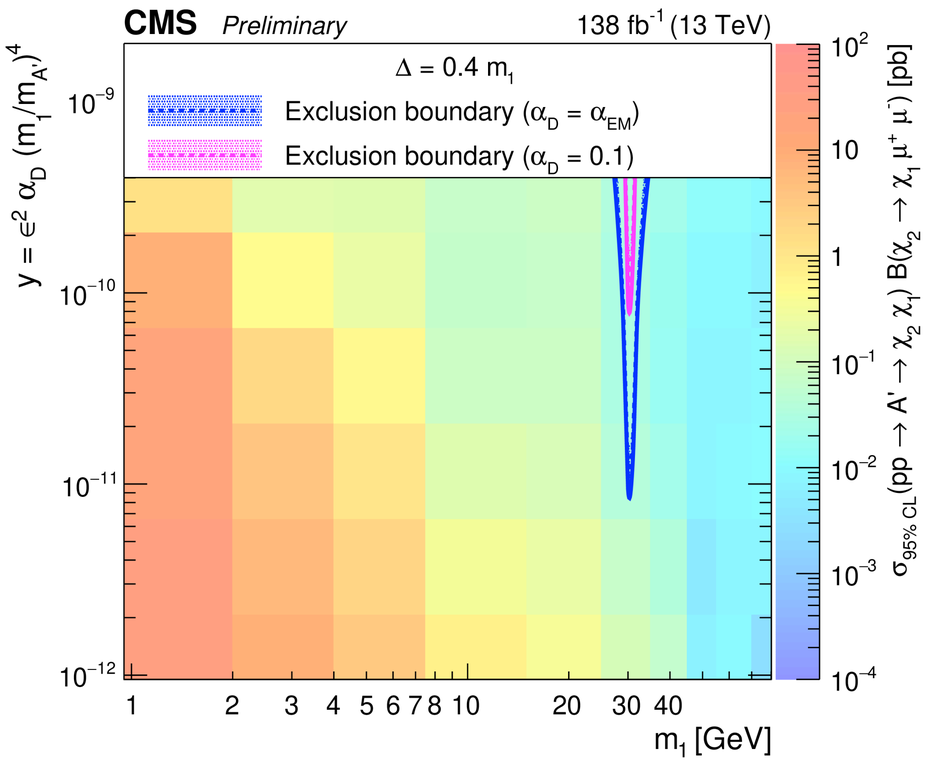
- No excess observed above SM prediction — now we can set limits!
- Good agreement between data and predicted background

EXO-20-010

Limits

EXO-20-010

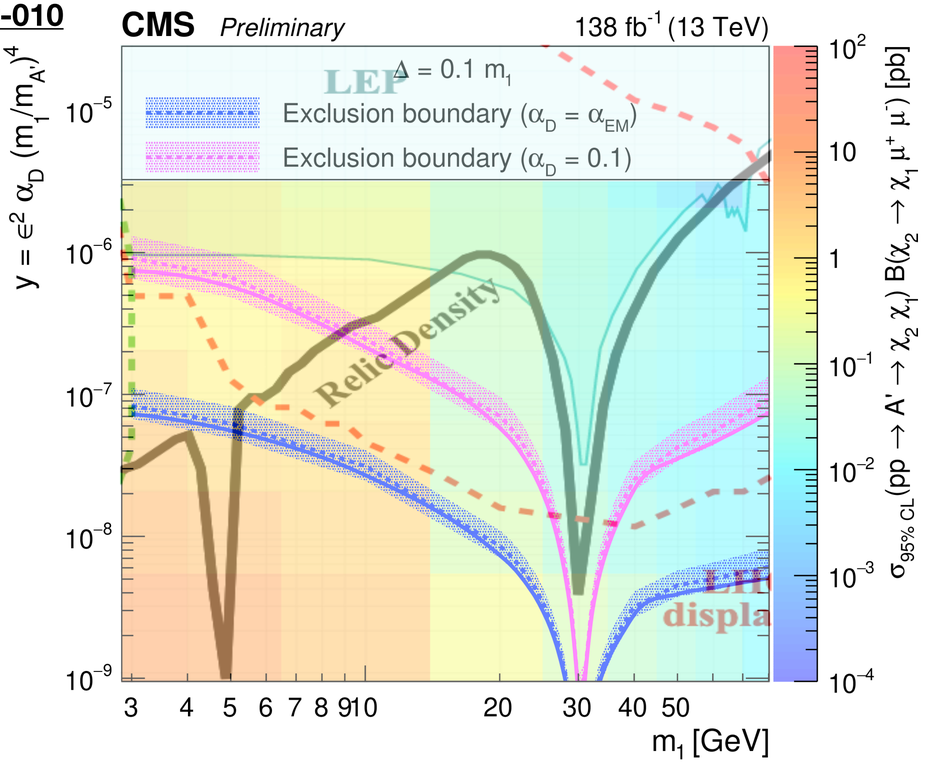




- Cross section limits are shown for a range an array of $(m_1, c\tau_{\chi_2})$ signal points with $\alpha_D = 0.1, \alpha_{EM}$ (filled boxes)
  - First ever set of limits on iDM from the LHC!
- Nice exclusion 10% splitting case — on-par with projections from pheno paper, and excludes range of relic-compatible parameter space
- Challenging to set limits for $\Delta = 0.4m_1$ case due to low signal cross section

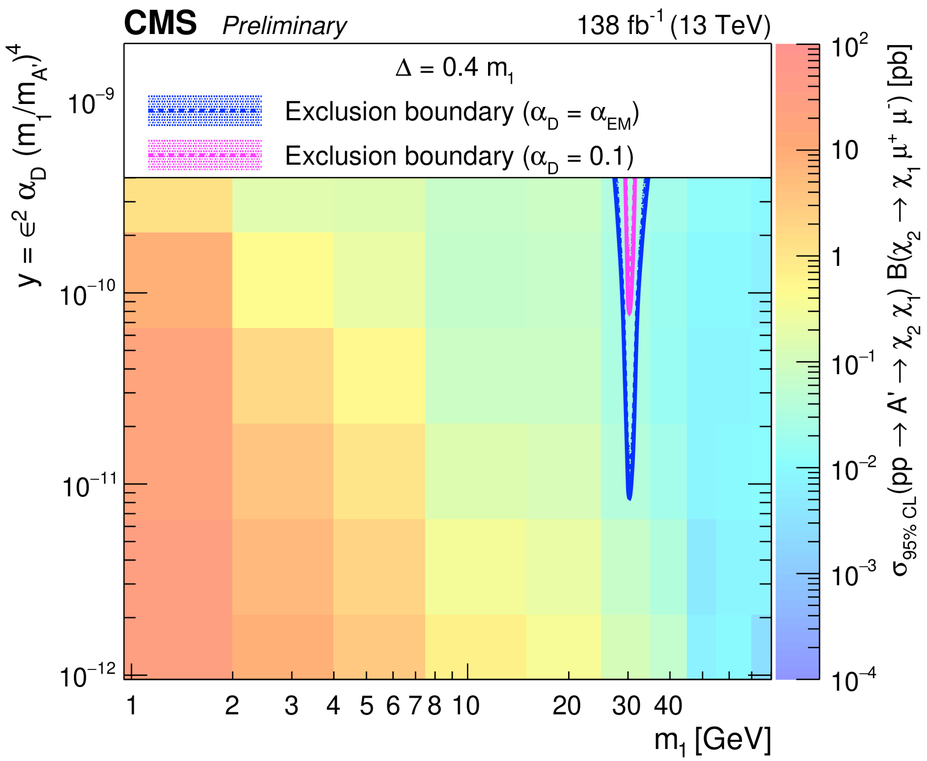
Limits

EXO-20-010



Compare **pink** to **black** & **red** curves

With $\alpha_D = 0.1$
pink = Obs. limit
black = relic density
red = LHC projection @ 300/fb



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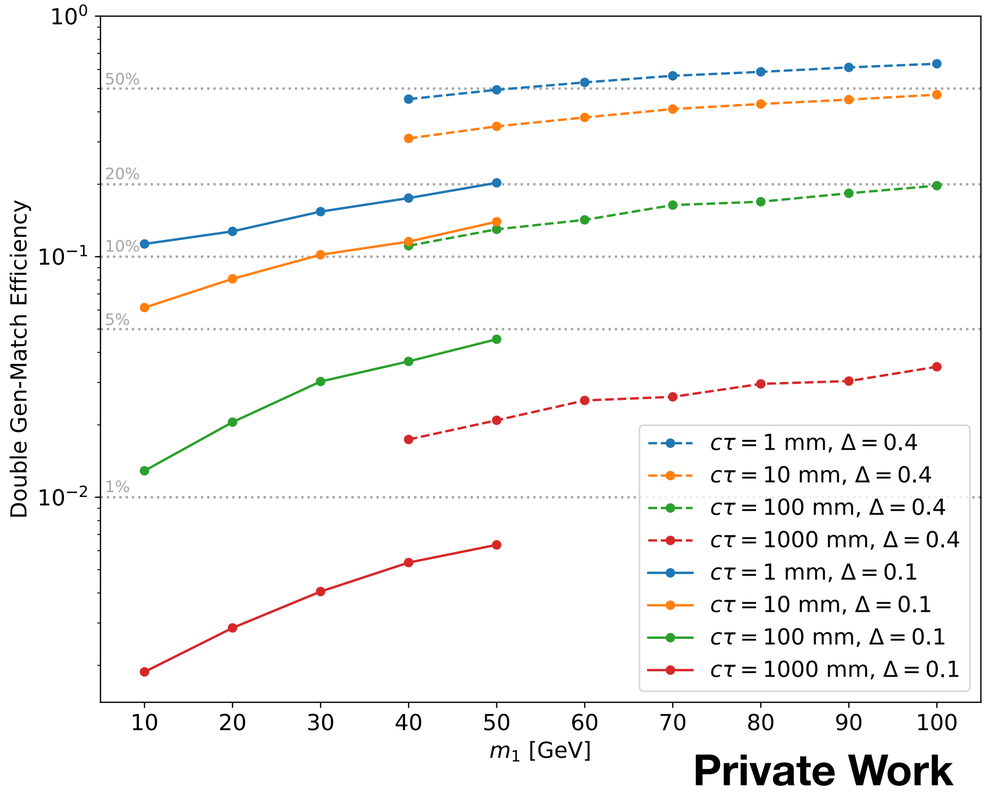
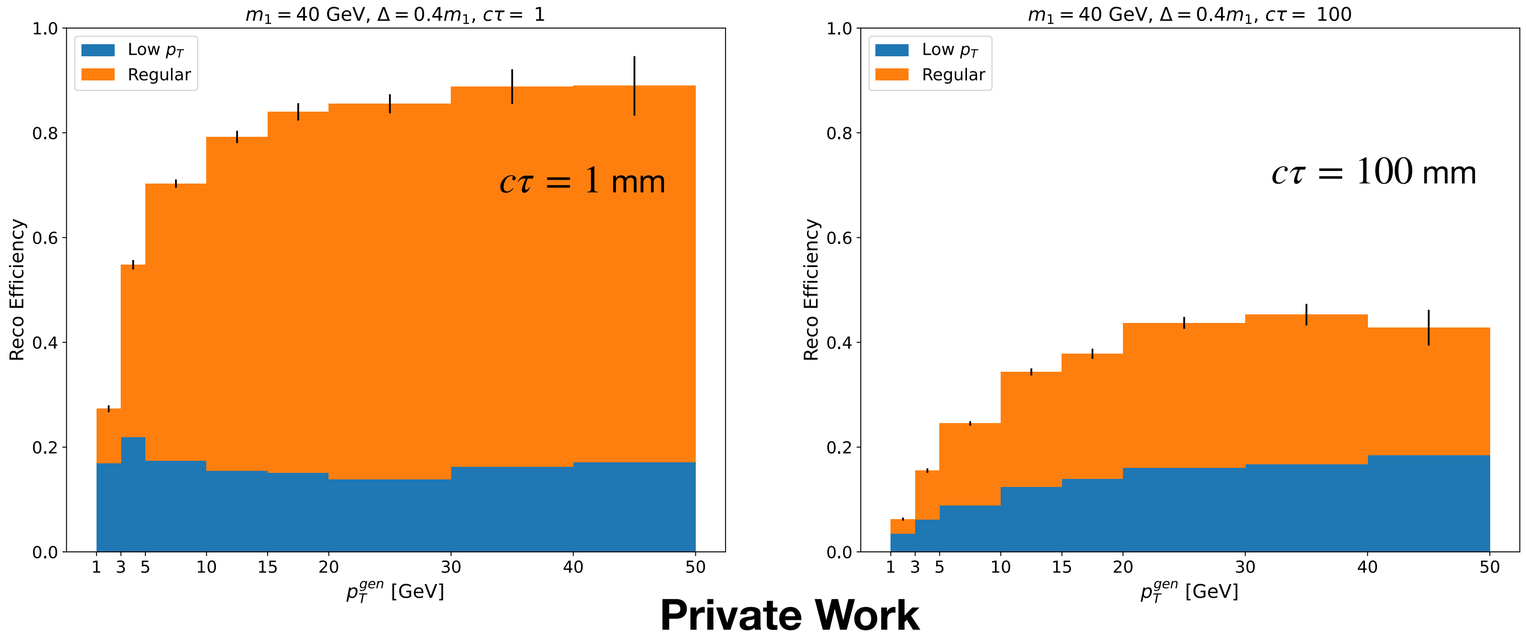
Sneak Preview: iDM with Electrons!

- **Can we do this analysis with electrons too?**
  - The short answer is **yes!**
  - Tracker limits v_{xy} reach, but new low-p_T electron reco algorithm is efficient down to $p_T \sim 1$ GeV!
  - Analysis underway!





Conclusion

- The first dedicated collider search for inelastic dark matter!
  - Exploits displaced muon reconstruction algorithm to enhance signal efficiency and probe long-lived iDM scenarios in a nearly background-free environment
  - New exclusion limits probe unexplored iDM parameter space for the 10% and 40% mass splitting scenarios

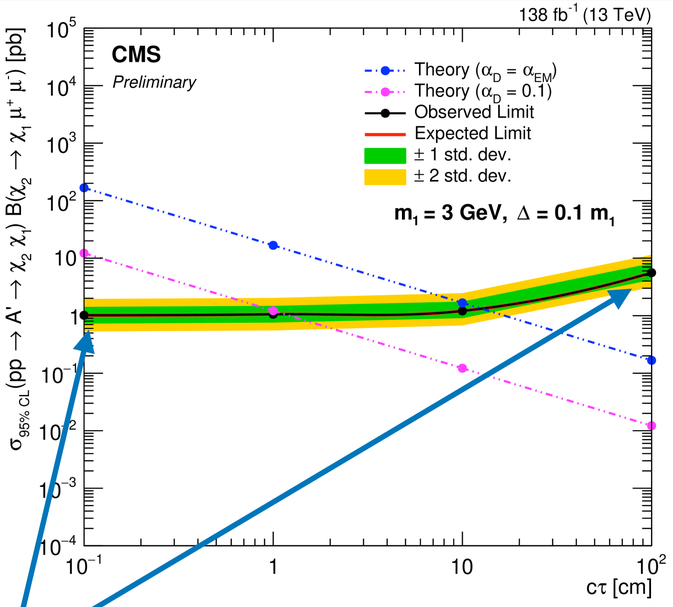
- **Next steps:**
  - Ongoing trigger development for displaced+MET signatures
  - Follow-up analysis underway using the electron channel — aided by new low p_T reconstruction

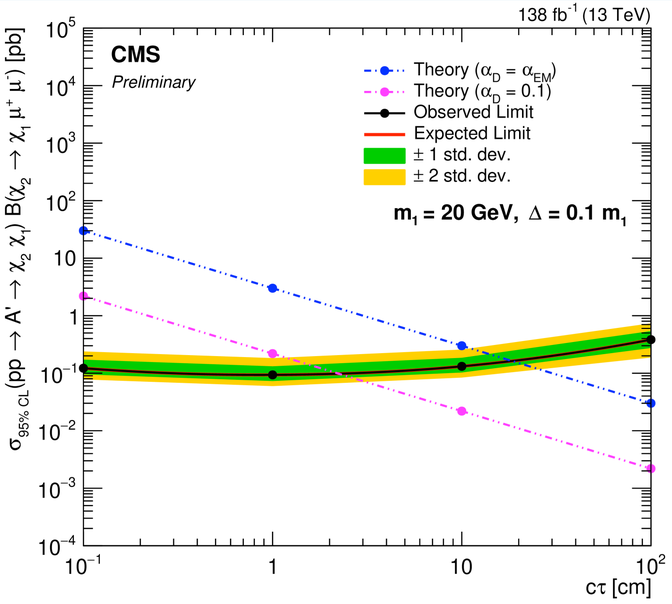
Backup

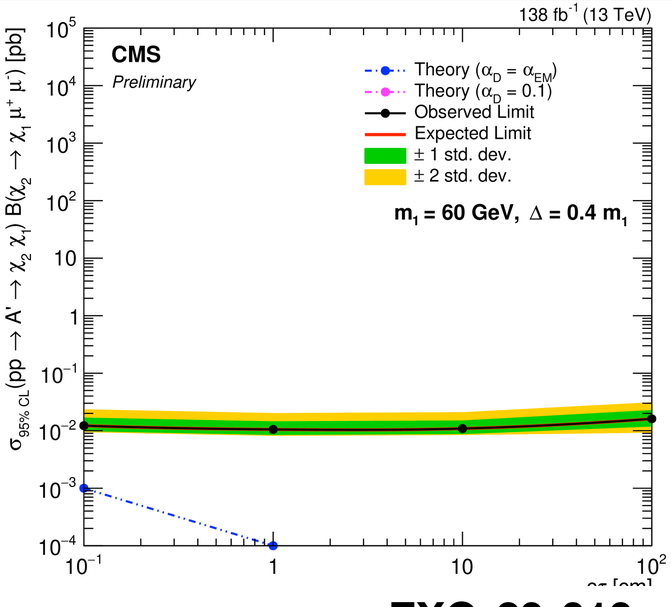
Full Event Selection

Jet and p_{T}^{miss} selection	Trigger on $p_{\mathrm{T}}^{\mathrm{miss}}$ without muons (120 GeV)
	$p_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$
	At most 2 jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$
	Leading jet $p_{\mathrm{T}} > 80\,\mathrm{GeV}$
	Leading jet $\lvert\eta\rvert < 2.4$
	$\lvert\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\text{leading jet}})\rvert > 1.5$
	$\lvert\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\text{sub-leading jet}})\rvert > 0.75$
	No jets identified with b-tagging algorithm
	Pass $p_{\mathrm{T}}^{\mathrm{miss}}$ cleaning filters
	Pass HEM veto
	$\lvert 1 - \mathrm{PFMET}/\mathrm{CaloMET}\rvert < 1$
Dimuon selection	At least two identified displaced muons
	Muons opposite charge
	Vertex $\chi^2/\mathrm{dof} < 4$ (pick lowest)
	$\Delta R(\mu\mu) < 0.9$
	3D angle $\alpha_{\mu\mu} > 2.8\,\mathrm{rad}$ (or $\cos\alpha > -0.94$)
	$\lvert\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mu\mu})\rvert < 0.5$
Signal region categorization	0 matched muons (+ $\min(d_{xy}^{A}, d_{xy}^{B}) > 3\,\mathrm{cm}$)
	1 matched muons (+ $\min(d_{xy}^{A}, d_{xy}^{B}) > 0.02\,\mathrm{cm}$)
	2 matched muons (+ $\min(d_{xy}^{A}, d_{xy}^{B}) > 0.02\,\mathrm{cm}$)

1D Limits







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For the 10% samples, larger backgrounds limit sensitivity for prompt lifetimes (1mm); reco efficiency limits at high lifetimes (1000mm)

For the 40% samples, sensitivity limited across the board by very low theory cross sections, despite kinematic advantage (more energetic muons)