Heavy Long-Lived Dark Vector via a Gluonic Portal

Effective Field Theory Framework & Phenomenology

Based on arXiv:2512.03153
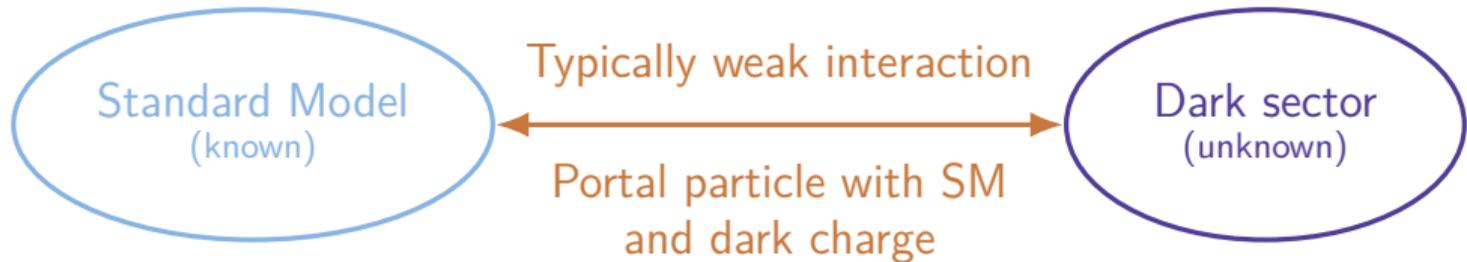
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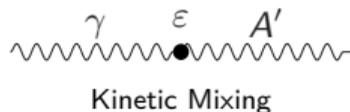
IAS Program on Fundamental Physics @HKUST

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General Picture: Portals to the Dark Sector

- A **new sizeably SM-charged particle** is necessarily heavy;
  Direct production, RG running etc.

- **But some dark particle can be light.**

Most Studied: The (Unbroken) Abelian Portal

$$\gamma \quad \varepsilon \quad A'$$

Kinetic Mixing

Theoretical Framework

- **Operator:** $\frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$

- **Induced Coupling:** Diagonalization to the **physical mass basis** $(A^\mu \mapsto A^\mu - \varepsilon A'^\mu)$ induces coupling to SM EM current:
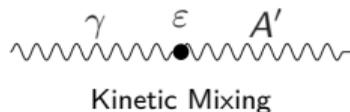
$$\mathcal{L} \supset \varepsilon e \, J^\mu_{\mathrm{EM}} A'_\mu$$

- **Decay** $(m_{A'} > 2m_e)$:
  $A' \to \ell^+\ell^-, \, q\bar{q} \quad (\Gamma \propto \varepsilon^2 \alpha m_{A'})$

Experimental Status

- **Collider & Beam Dump:**
  Prompt resonance (e^+e^-) & LLP searches.
  Q. Gao et al., JHEP **06**, 070 (2025);
  NA62 Collab., arXiv:1703.08501 [hep-ex];
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- **Astrophysics & Cosmology:**
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  A. Fradette et al., Phys. Rev. D **90**, 035022 (2014);
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$\Downarrow$ **The Less Studied: Non-Abelian Portal**

Heavy color-charged, EW-neutral mediator:

Motivation: A Gluonic Portal for a Massive Vector Z'
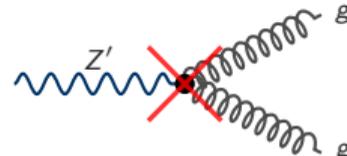
- **UV Origin:** Heavy mediators are **charged only under** $SU(3)_C$ and $U(1)_D$, and **are not involved to** dark gauge breaking.

- **EFT Setup:**
  - **Gauge Invariance:** The unbroken $SU(3)_C$ requires the operator to contain at least two gluons.
  - **Discrete Symmetries:** We impose $\mathcal{C}$ and $\mathcal{P}$ conservation (i.e. mediators are vector-like fermions or scalars with real couplings).

Dimension-4 $Z'G$ – Forbidden

Violates $SU(3)_C$
(Singlet $\neq$ Octet)

Dimension-6 $Z'GG$ / $Z'G\tilde{G}$ – Forbidden

Forbidden by C-symmetry
($C_{Z'} = -$, $C_{GG/G\tilde{G}} = +$)

Heavy color-charged, EW-neutral mediator:

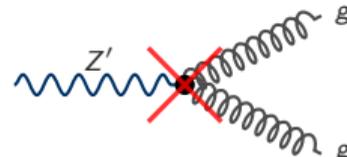**Motivation: A Gluonic Portal for a Massive Vector Z'**

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⇓ **The leading interaction: Dimension-8**

Operators: $Z'Z'GG$ and $Z'GGG$ and Long-livedness

1. $Z'Z'GG$

$\Rightarrow$ Pair production ($gg \to Z'Z'$) & scattering ($gZ' \to gZ'$)

$$\mathcal{O}_1 = \frac{X_1}{\Lambda^4} Z'_{\alpha\beta} Z'^{\alpha\beta} \, \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}],$$

$$\mathcal{O}_2 = \frac{X_2}{\Lambda^4} Z'_{\mu\beta} Z'^{\alpha\nu} \, \mathrm{Tr}\left[G_{\alpha\nu} G^{\mu\beta}\right],$$

$$\mathcal{O}_3 = \frac{X_3}{\Lambda^4} Z'_{\nu\beta} Z'^{\alpha\nu} \, \mathrm{Tr}\left[G_{\alpha\mu} G^{\mu\beta}\right],$$

$$\mathcal{O}_4 = \frac{X_4}{\Lambda^4} Z'_{\mu\beta} Z'_{\nu\alpha} \, \mathrm{Tr}\left[G^{\alpha\mu} G^{\beta\nu}\right].$$

2. $Z'GGG$

$\Rightarrow$ Decay ($Z' \to 3g$) & absorption ($Z'g \to 2g$)

$$\mathcal{O}_5 = \frac{Y_1}{\Lambda^4} Z'_{\nu\alpha} \, \mathrm{Tr}\left[G^{\alpha\beta} G_{\beta\mu} G^{\mu\nu}\right],$$

$$\mathcal{O}_6 = \frac{Y_2}{\Lambda^4} Z'_{\alpha\beta} \, \mathrm{Tr}\left[G^{\alpha\beta} G_{\mu\nu} G^{\mu\nu}\right].$$

Focus on $m_{Z'} > 1$ GeV: dominant decay channel $Z' \to 3g$

$$\Gamma(Z' \to 3g) = \frac{m_{Z'}^9}{41472 \, \pi^3 \, \Lambda^8} \left(2Y_1^2 + 7Y_1 Y_2 + 8Y_2^2\right)$$

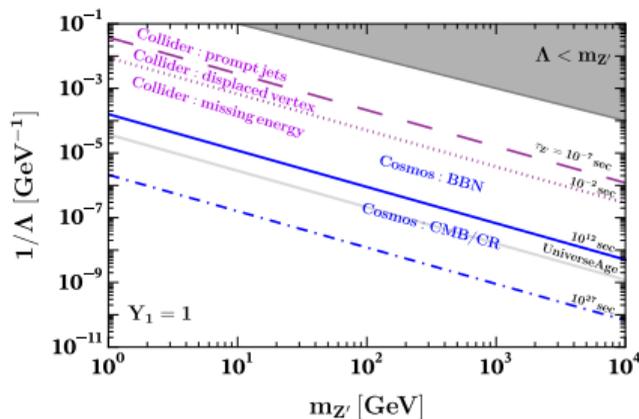Strongly suppressed by Λ^{-8}

Figure: Dependence of the Z' proper lifetime on model parameters and the corresponding experimental signatures (purple: collider; blue: cosmology).

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LHC Signatures: DV, MET & Other Constraints

Dominant Production Channels:
Processes $pp \to Z'Z'(+j)$ via $\mathcal{O}_{1-4}$ and $pp \to Z'j$ via $\mathcal{O}_{5,6}$.

Focus: $L > 3$ m (Low Background)

■ Displaced Vertex (3 m $< L <$ 14 m)
Decays within the **Muon System**.

- $Z'Z' \to$ 2 DVs or 1 DV + $\not{E}_T$.
- $Z'j \to$ 1 DV + jet.

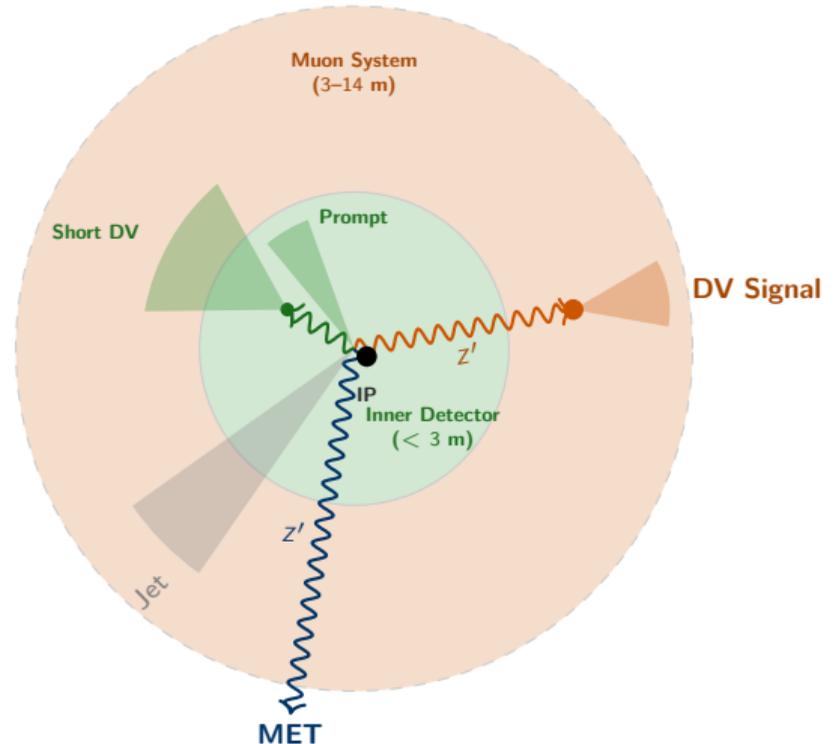**■ Missing Energy** ($L > 14$ m)
Decays outside the detector volume.

- Monojet: one jet + large $\not{E}_T$.

Simulation & Constraints
We simulate the signal with **MadGraph5** and impose
$\sigma_{\text{sig}} < \sigma_{\text{limit}}^{\text{ATLAS}}$ using ATLAS observed upper limits [Phys. Rev. D 103 (2021) 112006; Phys. Rev. D 106 (2022) 032005; arXiv:2503.20445].

Other Constraints

- **3-jet Resonance:** Weak bound ($\Lambda \sim 1$ TeV); EFT validity issues [PRD 99 012010].
- **RG Running:** Implies $\Lambda \gtrsim \mathcal{O}(100$ GeV) [NPB 936 106].

Cosmology: Late Energy Injection & Overclosure Bound

$$\dot{n}_{Z'} + 3Hn_{Z'} = - \underbrace{\langle \Gamma_{Z'} \rangle \left(n_{Z'} - n_{Z'}^{\rm eq} \right)}_{\text{Decay}} - \underbrace{\left[\langle \sigma v \rangle_{Z'g \to gg}\, n_g^{\rm eq} \left(n_{Z'} - n_{Z'}^{\rm eq} \right) + \langle \sigma v \rangle_{Z'Z' \to gg} \left(n_{Z'}^2 - (n_{Z'}^{\rm eq})^2 \right) \right]}_{\text{Production}}$$

1. Constraints on Abundance

Upper limits on $\Omega_{Z'}$ are derived from energy injection constraints and the overclosure bound:

- **BBN** (10^{-2}–10^{12} s): hadronic injection ($Z' \to 3g$) alters n/p and dissociates light nuclei (D, ^{4}He, ^{7}Li). [Kawasaki et al., PRD 71 (2005); Angel et al., 2501.09120]

- **CMB** (10^{11}–10^{24} s): EM energy injection ($Z' \to ggg \to \pi^0 \to \gamma\gamma$) modifies recombination history and hence the CMB anisotropy power spectra. [Acharya & Khatri, JCAP 12 (2019)]

- **Late Universe** ($\tau_{Z'} \gtrsim \tau_U$): effectively stable DM.
  - Overclosure Bound: require $\Omega_{Z'} \leq \Omega_{\rm DM}$. [Planck Collaboration 2018]
  - Cosmic Rays: constrain injected hadronic power. [Paopiamsap et al., PRD 109 (2024)]

2. Numerical Evolution Setup

- **Initial Condition:** $n_{Z'}(T_{\rm RH}) = 0$ (**UV-dominated freeze-in**).
- **Evolution:** $T_{\rm RH} \to T_{\rm end} \simeq m_{Z'}/100$.
- **Validity:** $\Lambda_{\rm EFT} > T_{\rm RH}$; Sensitive if $\tau_{Z'} \gtrsim 10^{-2}$ s.

Abundance of $\Omega_{Z'}$ at T = $m_{Z'}/100$, $T_{\rm RH} = 10^5$ GeV
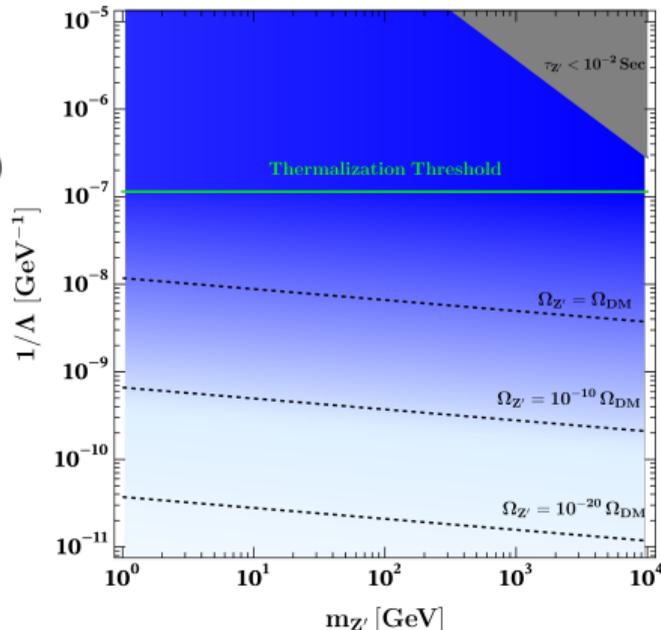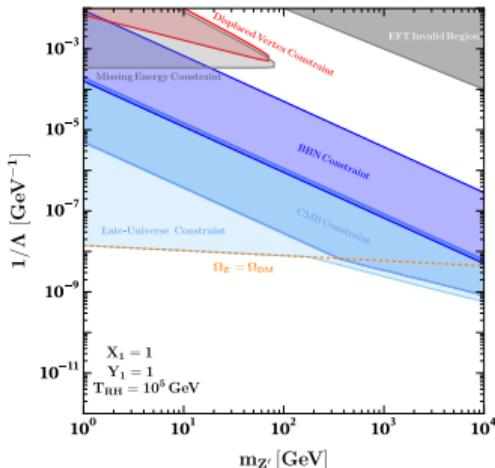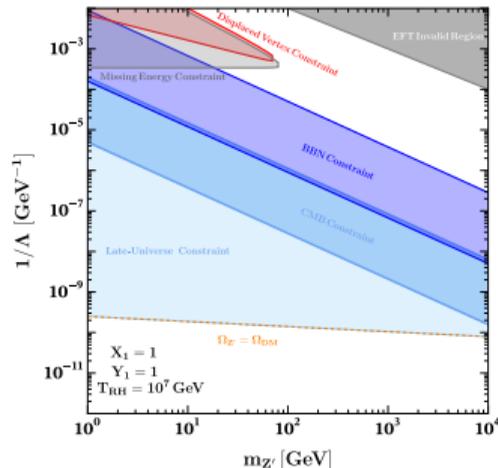

Figure: Relic abundance. Green line = thermalization threshold; below = freeze-in; above = ultra-relativistic freeze-out.

Constraints on LLP Gluonic Z' ($X_1 = Y_1 = 1$)

(a) Low $T_{\mathrm{RH}} = 10^5 \, \mathrm{GeV}$

(b) High $T_{\mathrm{RH}} = 10^7 \, \mathrm{GeV}$

Constraints: **Red**: Displaced Vertex (DV)   Gray: Missing Energy (MET)   **Blue**: Cosmology Bounds

Dominant DM Component: $\Omega_{Z'} = \Omega_{\mathrm{DM}}$

(Orange dashed line: Above $\Rightarrow$ Overabundant; Below $\Rightarrow$ Subdominant)

- Low Reheating ($T_{\mathrm{RH}} = 10^5$ GeV): **Viable only for $m_{Z'} \lesssim 200$ GeV.** Heavier $Z' \rightarrow$ shorter $\tau_{Z'} \rightarrow$ excluded by CMB/Cosmic Rays.

- High Reheating ($T_{\mathrm{RH}} = 10^7$ GeV): **Viable over the full mass range in our study.** Freeze-in scaling $\Omega_{Z'} \propto m_{Z'} \, T_{\mathrm{RH}}^7 / \Lambda^8$ implies higher T_{RH} allows larger Λ (weaker coupling), naturally yielding a longer $\tau_{Z'}$ to evade bounds.

Why impose a $\mathbb{Z}_2$?   Stable Gluonic Z' DM & Production
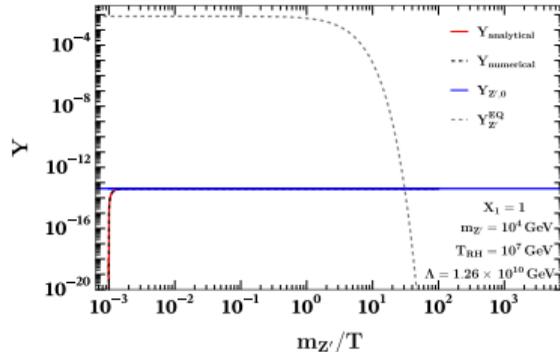
Motivation for $\mathbb{Z}_2$ Symmetry

Without extra symmetry, cosmological stability ($\tau_{Z'} \gtrsim 10^{17}$ s) forces *extremely* weak couplings, limiting detection prospects. Imposing a residual $\mathbb{Z}_2$ forbids decay operators $\mathcal{O}_{5,6}$, ensuring Z' stability (e.g. doublets of opposite dark charges).[T. Hambye & M.H.G. Tytgat, 0907.1007; J.L. Diaz-Cruz & E. Ma, 1007.2631, ...]

The DM Relic Abundance Requirement: $\Omega_{Z'} h^2 \simeq 0.12$

1. Freeze-in (FI)

- Initial: $n_{Z'}(T_{\mathrm{RH}}) \simeq 0$.
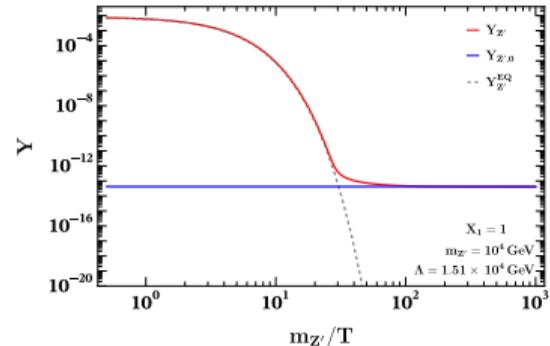- Production: $gg \to Z'Z'$ (UV-dominated).

$$\Omega_{Z'} h^2 \propto m_{Z'} \frac{T_{\mathrm{RH}}^7}{\Lambda^8}$$

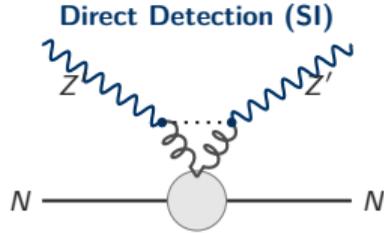

2. Freeze-out (FO)

- Initial: Thermal Equilibrium ($n_{Z'}^{\mathrm{eq}}$).
- Annihilation: $Z'Z' \to gg$ (via $\mathcal{O}_{1-4}$).

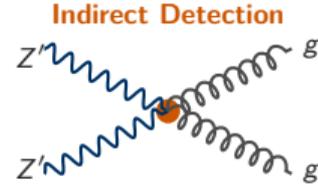$$\Omega_{Z'} h^2 \sim \frac{0.1 \ \mathrm{pb}}{\langle \sigma v \rangle_{Z'Z' \to gg}}$$

DM Detection Prospects: Direct & Indirect

Direct Detection (SI)

Mechanism: Elastic $Z'N \to Z'N$ scattering yields **nuclear recoils**.

Status: Null results from **LZ**, **PandaX-4T**, and **DarkSide** set upper limits on $\sigma_{Z'n}^{\mathrm{SI}}$. [LZ Collab., arXiv:2410.17036; PandaX Collab., PRL 130 (2023); DarkSide-20k Collab., Commun. Phys. 7 (2024)]

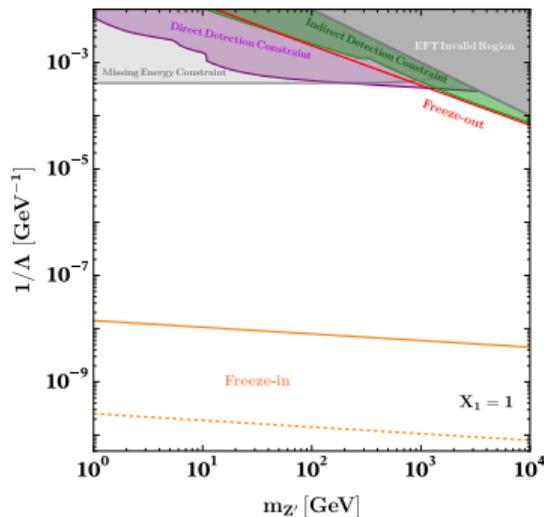$$\sigma_{Z'n}^{\mathrm{SI}} \propto \frac{m_{Z'}^4}{\Lambda^8} \left(\frac{m_G}{m_n + m_{Z'}} \right)^2 .$$

Indirect Detection

Mechanism: $Z'Z' \to gg$ yields **continuum** photons via hadronization and $\pi^0 \to \gamma\gamma$. It may induce excess γ-rays, $\bar{p}$, and high-energy neutrinos beyond standard astrophysical backgrounds.

Status: **H.E.S.S.** and **Fermi-LAT** data bound $\langle \sigma v \rangle$ for hadronic final states. [Paopiamsap et al., PRD 109 (2024); H.E.S.S. Collab., PRL 129 (2022)]

$$\langle \sigma v_{\mathrm{M\varnothing 1}} \rangle_{Z'Z' \to gg} = \frac{32\sqrt{2}\, m_{Z'}^6}{3\pi\, \Lambda^8} .$$

Constraints on Stable Gluonic Z' DM ($X_1 = 1$)

Parameter Space Constraints ($m_{Z'}$, $1/\Lambda$)

- **Excluded Regions:** Collider (E_T^{miss}), Direct Det., Indirect Det.
- **Freeze-out (Red Line):** Viable for $m_{Z'} \gtrsim 1$ TeV .
- **Freeze-in (Orange):** Viable over the full mass range in our study ($T_{\mathrm{RH}} = 10^5/10^7$ GeV shown).

Summary & Outlook

1. Theoretical Framework: A Gluonic Portal for a Massive Vector Z'

We study a **massive dark vector** Z' coupled to gluons via a portal induced by a heavy color-charged, EW-neutral mediator.

- **Symmetry:** $SU(3)_C$ gauge invariance and C/P-symmetry forbid dim-4/6 operators.
- **Leading EFT:** dim-8 operators $\propto \Lambda^{-4}$.
- **Implication:** strong suppression $\Rightarrow$ naturally **long-lived** Z' (LLP).

2. Phenomenology Summary

Scenario	Key Experimental Signatures	DM Production / Viability
A. Unstable (LLP, $Z' \to 3g$)	• **LHC:** DV and MET • **Cosmology:** energy injection and overclosure bound	**Requires Freeze-in Production** • Viable window: $m_{Z'} \lesssim 200$ GeV
B. Stable (DM, Z_2-protected)	• **DM relic abundance:** $\Omega_{Z'} h^2 \simeq 0.12$ • **Direct:** Nuclear Recoils (LZ, PandaX) • **Indirect:** γ-ray excess (H.E.S.S.)	**Both Mechanisms Possible** • **Freeze-in:** Viable for all masses • **Freeze-out:** Viable for $m_{Z'} > 1$ TeV

3. Future Outlook: UV Completion

- **UV Model Building:** We construct explicit UV completions with $SU(3)_C \times U(1)_D$-charged mediators, and study the phenomenology when the mediator is not exceedingly heavy.

Thank You

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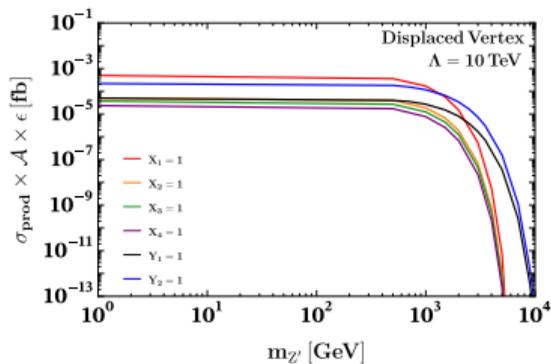
arXiv:2512.03153

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DV & MET Stimulation

DV • $Z'Z'$: 2 DVs or 1 DV + $\not{E}_T$ • $Z'j$: 1 DV + jet

Selection Criteria:

- Acceptance $\mathcal{A}$: $|\eta_D| < 2.4$.
- Detection efficiency $\epsilon = 1$.

MET Monojet: one jet + large $\not{E}_T$

Selection Criteria:

- Large MET: $E_T^{\mathrm{miss}} > 1200$ GeV.
- Acceptance $\mathcal{A}$: $|\eta_j| < 2.4$.
- Detection efficiency $\epsilon = 1$.

Signal Cross Section & Decay Probability Factors

$$\sigma_{\mathrm{sig}} = \underbrace{[\sigma_{\mathrm{prod}} \times \mathcal{A} \times \epsilon]_{\mathrm{Plots}}}_{\text{shown in figures}} \times \underbrace{\mathcal{P}_{\mathrm{decay}}[L_1, L_2]}_{\substack{\text{decay probability into the target region} \\ \text{(DV window / outside-detector)}}} < \sigma_{\mathrm{limit}}^{\mathrm{Exp}}.$$

DV (Muon): $L \in [3, 14]$ m; $\sigma_{\mathrm{sig}} \lesssim 0.1$ pb   **MET (Outside):** $L > 14$ m; $\sigma_{\mathrm{sig}} < 0.3$ fb

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