Dark Matter with Hidden U(1) Gauge Interaction and Kinetic Mixing

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Based on Juebin Lao, Chengfeng Cai, Zhao-Huan Yu, Yu-Pan Zeng, and Hong-Hao Zhang, 2003.02516, PRD

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**Motivation**

Hidden U(1) gauge theory

Dirac fermionic DM

Complex scalar DM

Conclusions

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**Portals for Dark Matter Interactions**

🔥 **Thermal production mechanism**

Dark matter (DM) is conventionally assumed to be thermally produced in the early Universe.

_some mediators (“portals”) are typically required to induce adequate DM interactions with standard model (SM) particles.

💡 Inspired by the SU(3)_C × SU(2)_L × U(1)_Y gauge interactions in the SM, it is natural to imagine dark matter participating a new kind of gauge interaction.

🌟 The simplest attempt is to introduce an additional U(1)_X gauge symmetry, whose gauge boson mediates the interactions between DM and SM particles.

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Hidden $U(1)_X$ Gauge Interaction

🌟 Assume all SM fields do not carry any $U(1)_X$ charges

👉 Minimize the impact on the interactions of SM particles

[Feldman, Liu, Nath, hep-ph/0702123, PRD; Pospelov, Ritz, Voloshin, 0711.4866, PLB; Mambrini, 1006.3318, JCAP; Chun, Park, Scopel, 1011.3300, JHEP; Liu, Wang, Yu, 1704.00730, JHEP; ...]

🌙 Such a $U(1)_X$ gauge interaction belongs to a hidden sector

✏️ Assume dark matter carries $U(1)_X$ charge

🌟 Mass of the $U(1)_X$ gauge boson can be generated by

ɒ either the Brout-Englert-Higgs mechanism 👉 an extra Higgs boson

[Higgs, Phys. Lett. 12 (1964) 132; Englert & Brout, PRL 13, 508 (1964)]

ɒ or the Stueckelberg mechanism 👉 no extra Higgs boson


☀️ Gauge invariance allows a renormalizable kinetic mixing term between the $U(1)_X$ and $U(1)_Y$ field strengths [Holdom, PLB 259, 329 (1991)]

👉 A portal connecting DM and SM particles
**Kinetic Mixing**

For the $U(1)_Y$ and $U(1)_X$ gauge fields $\hat{B}_\mu$ and $\hat{Z}'_\mu$, the gauge invariant kinetic terms in the Lagrangian reads

$$
\mathcal{L}_K = -\frac{1}{4} \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} - \frac{1}{4} \hat{Z}'_{\mu\nu} \hat{Z}'_{\mu\nu} - \frac{s_\epsilon}{2} \hat{B}^{\mu\nu} \hat{Z}'_{\mu\nu} = -\frac{1}{4} \left( \hat{B}^{\mu\nu}, \hat{Z}'_{\mu\nu} \right) \begin{pmatrix} 1 & s_\epsilon \\ s_\epsilon & 1 \end{pmatrix} \begin{pmatrix} \hat{B}_{\mu\nu} \\ \hat{Z}'_{\mu\nu} \end{pmatrix}
$$

Field strengths $\hat{B}_{\mu\nu} \equiv \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu$ and $\hat{Z}'_{\mu\nu} \equiv \partial_\mu \hat{Z}'_\nu - \partial_\nu \hat{Z}'_\mu$

The **kinetic mixing** term is parametrized by $s_\epsilon \in (-1, 1)$, beyond which the canonical kinetic terms have **wrong signs**

Introduce $\epsilon \in (-\pi/2, \pi/2)$ to express $s_\epsilon = \sin \epsilon$

$\mathcal{L}_K$ can be made canonical via a $GL(2, \mathbb{R})$ transformation

$$
\begin{pmatrix} \hat{B}_\mu \\ \hat{Z}'_\mu \end{pmatrix} = V_K \begin{pmatrix} B_\mu \\ \tilde{Z}'_\mu \end{pmatrix}, \quad V_K \equiv \begin{pmatrix} 1 & -t_\epsilon \\ 0 & 1/c_\epsilon \end{pmatrix}, \quad t_\epsilon \equiv \tan \epsilon, \quad c_\epsilon \equiv \cos \epsilon
$$

$$
V_K^T \begin{pmatrix} 1 & s_\epsilon \\ s_\epsilon & 1 \end{pmatrix} V_K = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \therefore \quad \mathcal{L}_K = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} \tilde{Z}'_{\mu\nu} \tilde{Z}'_{\mu\nu}
$$
We assume that the $U(1)_X$ gauge symmetry is **spontaneously broken** by a hidden Higgs field $\hat{S}$ with $U(1)_X$ charge $q_S = 1$.

Lagrangian $\mathcal{L}_H$ is given by:

$$\mathcal{L}_H = (D^\mu \hat{H})^\dagger (D_\mu \hat{H}) + (D^\mu \hat{S})^\dagger (D_\mu \hat{S}) + \mu^2 |\hat{H}|^2 + \mu_S^2 |\hat{S}|^2$$

$$-\frac{1}{2} \lambda_H |\hat{H}|^4 - \frac{1}{2} \lambda_S |\hat{S}|^4 - \lambda_{HS} |\hat{H}|^2 |\hat{S}|^2$$

$\hat{H}$ is the **SM Higgs doublet** with $D_\mu \hat{H} = (\partial_\mu - i\hat{g} W_\mu^a \sigma^a / 2 - i\hat{g}' B_\mu / 2) \hat{H}$.

$\hat{S}$ satisfies $D_\mu \hat{S} = (\partial_\mu - i g_X Z'_\mu) \hat{S}$, where $g_X$ is the $U(1)_X$ gauge coupling.

If $\mu^2 > 0$, $\mu_S^2 > 0$, $\lambda_H > 0$, $\lambda_S > 0$, and $|\lambda_{HS}| < \sqrt{\lambda_H \lambda_S}$,

$\hat{H}$ and $\hat{S}$ acquire **nonzero** vacuum expectation values (VEVs) $v$ and $v_S$.

**Spontaneous breaking** of the $SU(2)_L \times U(1)_Y \times U(1)_X$ gauge symmetry.
Higgs Boson Mixing and Masses

In the unitary gauge, the Higgs field can be expressed as

$$\hat{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \hat{S} = \frac{1}{\sqrt{2}} (v_S + S)$$

Mass-squared matrix for **Higgs bosons** \((H, S)\):

$$M_0^2 = \begin{pmatrix} \lambda_H v^2 & \lambda_{HS} v v_S \\ \lambda_{HS} v v_S & \lambda_S v_S^2 \end{pmatrix}$$

Diagonalization by a rotation with an angle \(\eta \in [-\pi/4, \pi/4]\)

$$\begin{pmatrix} H \\ S \end{pmatrix} = \begin{pmatrix} c_\eta & -s_\eta \\ s_\eta & c_\eta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}, \quad \tan 2\eta = \frac{2\lambda_{HS} v v_S}{\lambda_H v^2 - \lambda_S v_S^2}$$

Masses squared for the **mass eigenstates** \((h, s)\)

$$m_h^2 = \frac{1}{2} \left[ \lambda_H v^2 + \lambda_S v_S^2 + (\lambda_H v^2 - \lambda_S v_S^2)/c_{2\eta} \right]$$

$$m_s^2 = \frac{1}{2} \left[ \lambda_H v^2 + \lambda_S v_S^2 + (\lambda_S v_S^2 - \lambda_H v^2)/c_{2\eta} \right]$$

\(h\) should be the **125 GeV SM-like Higgs boson**
Gauge Boson Masses

Mass-squared matrix for \((\hat{B}_\mu, W^3_\mu, \hat{Z}'_\mu)\) generated by the Higgs VEVs \(\nu\) and \(\nu_s\)

\[
M_1^2 = \begin{pmatrix}
\hat{g}'^2 \nu^2 / 4 & -\hat{g} \hat{g}' \nu^2 / 4 \\
-\hat{g} \hat{g}' \nu^2 / 4 & \hat{g}^2 \nu^2 / 4 \\
\end{pmatrix}
\]

\(W^\pm\) boson mass \(m_W = \frac{1}{2} \hat{g} \nu\)

Taking into account the kinetic mixing \(s_\epsilon\) and the diagonalization of the mass-squared matrix, the photon \(\gamma\) remain massless, while the masses of the \(Z\) boson and a new massive neutral vector boson \(Z'\) are given by

\[
m_Z^2 = \hat{m}_Z^2 (1 + \hat{s}_W t_\epsilon t_\xi), \quad m_{Z'}^2 = \frac{\hat{m}_{Z'}^2}{c_\epsilon^2 (1 + \hat{s}_W t_\epsilon t_\xi)}
\]

Direct contributions from the VEVs: \(\hat{m}_Z^2 \equiv (\hat{g}^2 + \hat{g}'^2) \nu^2 / 4, \quad \hat{m}_{Z'}^2 \equiv g_X^2 \nu_S^2\)

Weak mixing angle \(\hat{\theta}_W\) satisfies \(\hat{s}_W \equiv \sin \hat{\theta}_W = \frac{\hat{g}'}{\sqrt{\hat{g}^2 + \hat{g}'^2}}, \quad \hat{c}_W \equiv \cos \hat{\theta}_W\)

Rotation angle \(\xi\) is given by \(\tan 2\xi = \frac{s_{2\epsilon} \hat{s}_W \nu^2 (\hat{g}^2 + \hat{g}'^2)}{c_\epsilon^2 \nu^2 (\hat{g}^2 + \hat{g}'^2)(1 - \hat{s}_W t_\epsilon^2) - 4g_X^2 \nu_S^2}\)
Neutral Gauge Boson Mixing

Transform the gauge basis $(\hat{B}_\mu, W_3^\mu, \hat{Z}_\mu')$ to the mass basis $(A_\mu, Z_\mu, Z'_\mu)$

$$
\begin{pmatrix}
\hat{B}_\mu \\
W_3^\mu \\
\hat{Z}_\mu'
\end{pmatrix} = V(\varepsilon) R_3(\hat{\theta}_W) R_1(\xi)
\begin{pmatrix}
A_\mu \\
Z_\mu \\
Z'_\mu
\end{pmatrix}
$$

$$
V(\varepsilon) = \begin{pmatrix} 1 & -t_\varepsilon \\ 1 & 1 \\ 0 & 1/c_\varepsilon \end{pmatrix}, \quad R_3(\hat{\theta}_W) = \begin{pmatrix} \hat{c}_W & -\hat{s}_W \\ \hat{s}_W & \hat{c}_W \\ 0 & 1 \end{pmatrix}, \quad R_1(\xi) = \begin{pmatrix} 1 & c_\xi & -s_\xi \\ s_\xi & c_\xi \end{pmatrix}
$$

**Electroweak (EW) Current Interactions**

At tree level, the **charge current interactions** of SM fermions are not affected by the kinetic mixing, remaining a form of

\[
\mathcal{L}_{CC} = \frac{1}{\sqrt{2}} (W_\mu^+ J_W^{+, \mu} + \text{H.c.}), \quad J_W^{+, \mu} = \hat{g} (\bar{u}_i L \gamma^\mu V_{ij} d_j L + \bar{\nu}_i L \gamma^\mu \ell_j L)
\]

- \(\nu\) is still directly related to the Fermi constant \(G_F = \frac{\hat{g}^2}{4\sqrt{2} m_W^2} = \frac{1}{\sqrt{2} v^2}\)

**Neutral current interactions** become

\[
\mathcal{L}_{NC} = j_\mu^{\text{EM}} A_\mu + j_\mu^{\text{Z}} Z_\mu + j_\mu^{\text{Z}'} Z'_\mu
\]

- **Electromagnetic current** \(j_\mu^{\text{EM}} = \sum_f Q_f e \bar{f} \gamma^\mu f\) with \(e = \frac{\hat{g} \hat{g}'}{\sqrt{\hat{g}^2 + \hat{g}'^2}}\)

- **Z current** \(j_\mu^Z = \frac{ec_\xi}{2 \hat{s}_W \hat{c}_W} \sum_f \bar{f} \gamma^\mu (T^3_f - 2Q_f s^2_* - T^3_f \gamma_5)f + s_\xi \frac{c_\xi}{c_\epsilon} j_\mu^{\text{DM}}\)

- **Z' current** \(j_\mu^{Z'} = \frac{e(\hat{s}_W t_\epsilon c_\xi - s_\xi)}{2 \hat{s}_W \hat{c}_W} \sum_f \bar{f} \gamma^\mu (T^3_f - 2Q_f s^2_* - T^3_f \gamma_5)f - \hat{c}_W t_\epsilon c_\xi j_\mu^{\text{EM}} + \frac{c_\xi}{c_\epsilon} j_\mu^{\text{DM}}\)

- **Dark matter U(1)_X current** \(j_\mu^{\text{DM}} \propto g_X, \quad s^2_* \equiv s^2_W + c^2_W \frac{\hat{s}_W t_\epsilon t_\xi}{1 + \hat{s}_W t_\epsilon t_\xi} (\text{or DM mass})\)
Independent Parameters

In the **SM**, the weak mixing angle obeys $s^2_W c^2_W = \frac{\pi \alpha}{\sqrt{2} G_F m^2_Z}$ at tree level.

Use this relation to define a **“physical”** weak mixing angle $\theta_W$ via the best measured parameters $\alpha$, $G_F$, and $m_Z$ [Burgess et al., hep-ph/9312291, PRD]

Similar relation in the hidden $U(1)_X$ gauge theory: $\hat{s}_W^2 \hat{c}_W^2 = \frac{\pi \alpha}{\sqrt{2} G_F \hat{m}_Z^2}$

\[
\hat{s}_W \hat{c}_W \hat{m}_Z = s_W c_W m_Z
\]

\[
s^2_W c^2_W = \frac{\hat{s}_W^2 \hat{c}_W^2}{1 + \hat{s}_W t_\epsilon t_\xi}
\]

The angle $\xi$ satisfies $t_\xi = \frac{2 \hat{s}_W t_\epsilon}{1 - r} \left[ 1 + \sqrt{1 - r \left( \frac{2 \hat{s}_W t_\epsilon}{1 - r} \right)^2} \right]^{-1}$ with $r \equiv \frac{m^2_{Z'}}{m^2_Z}$

Utilizing these relations, we obtain $\hat{s}_W$ and $t_\xi$ as functions of $s_\epsilon$ and $m_{Z'}$.

**Independent parameters** can be chosen as $\{g_X, m_{Z'}, m_s, s_\epsilon, s_\eta\}$

EW gauge couplings $\hat{g} = \frac{e}{\hat{s}_W}$ and $\hat{g}' = \frac{e}{\hat{c}_W}$ with $e = \sqrt{4\pi \alpha}$
Electroweak Oblique Parameters

**Kinetic mixing** $s_\epsilon$ modifies **EW oblique parameters** $S$ and $T$ at **tree level**

In the effective Lagrangian formulation, $Z f f$ neutral current interactions can be expressed as [Burgess et al., hep-ph/9312291, PRD]

$$\mathcal{L}_{Z f f} = \frac{e}{2s_W c_W} \left(1 + \frac{\alpha T}{2}\right) Z_\mu \sum_f \bar{f} \gamma^\mu (T_f^3 - 2 Q_f s_\epsilon^2 - T_f^3 \gamma_5) f$$

$$s_\epsilon^2 = s_W^2 + \frac{1}{c_W^2 - s_W^2} \left(\frac{\alpha S}{4} - s_W^2 c_W^2 \alpha T\right)$$

Applying it to the Hidden $U(1)_X$ gauge theory, we find $\alpha T = 2 c_\xi \sqrt{1 + \hat{s}_W t_\epsilon t_\xi} - 2$

$$\alpha S = 4(c_W^2 - s_W^2) \left(\hat{s}_W^2 - s_W^2 + \frac{\hat{c}_W^2 \hat{s}_W t_\epsilon t_\xi}{1 + \hat{s}_W t_\epsilon t_\xi}\right)$$

$$+ 4s_W^2 c_W^2 \alpha T$$

For $\epsilon \ll 1$, we have

$$S \simeq \frac{4s_W^2 c_W^2 \epsilon^2}{\alpha(1 - r)} \left(1 - \frac{s_W^2}{1 - r}\right), \quad T \simeq -\frac{r s_W^2 \epsilon^2}{\alpha(1 - r)^2}$$
Upper Limits from EW Oblique Parameters

**Current measurement:** $S = 0.06 \pm 0.09, \quad T = 0.10 \pm 0.07, \quad \rho_{ST} = 0.91$

[Gfitter Group, 1407.3792, EPJC]

**Projected CEPC precision:** $\sigma_S = 0.010, \quad \sigma_T = 0.011, \quad \rho_{ST} = 0.62$

[CEPC Study Group, 1811.10545]

**Projected FCC-ee precision:** $\sigma_S = 0.0092, \quad \sigma_T = 0.0062, \quad \rho_{ST} = 0.79$

[Fan, Reece, Wang, 1411.1054, JHEP]
Dirac Fermionic Dark Matter

Assume the DM particle is a Dirac fermion $\chi$ with $U(1)_X$ charge $q_\chi$

Related Lagrangian $\mathcal{L}_\chi = i \bar{\chi} \gamma^\mu D_\mu \chi - m_\chi \bar{\chi} \chi$, $D_\mu \chi = (\partial_\mu - iq_\chi g_X \hat{Z}_\mu) \chi$

DM neutral current $j_{DM}^\mu = q_\chi g_X \bar{\chi} \gamma^\mu \chi$

Based on the kinetic mixing portal, $\chi$ particles can communicate with SM fermions through the mediation of $Z$ and $Z'$ bosons

In the zero momentum transfer limit $k^2 \rightarrow 0$, interactions between $\chi$ and quarks $q = d, u, s, c, b, t$ can be described by an effective Lagrangian

$$\mathcal{L}_{\chi q} = \sum_q G^V_{\chi q} \bar{\chi} \gamma^\mu \chi q \gamma_\mu q, \quad G^V_{\chi q} = -\frac{q_\chi g_X}{c_\xi} \left( \frac{s_\xi g_Z^q}{m_Z^2} + \frac{c_\xi g_{Z'}^q}{m_{Z'}^2} \right)$$

Vector current couplings of quarks to $Z$ and $Z'$

$$g_Z^q = \frac{ec_\xi (1 + \hat{s}_W t_\epsilon t_\xi)}{2\hat{s}_W \hat{c}_W} (T^3_q - 2Q_q \hat{s}_W^2)$$

$$g_{Z'}^q = \frac{e(\hat{s}_W t_\epsilon c_\xi - s_\xi)}{2\hat{s}_W \hat{c}_W} (T^3_q - 2Q_q \hat{s}_W^2) - Q_q e \hat{c}_W t_\epsilon c_\xi$$
DM-nucleon Interactions

**DM-nucleon effective interactions** are induced by DM-quark interactions

\[ \mathcal{L}_{\chi N} = \sum_{N=p,n} G^V_{\chi N} \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu N, \quad G^V_{\chi p} = 2G^V_{\chi u} + G^V_{\chi d}, \quad G^V_{\chi n} = G^V_{\chi u} + 2G^V_{\chi d} \]

Further calculation gives

\[ G^V_{\chi p} = \frac{q_\chi g_x e \hat{c}_W t_\epsilon c_\xi^2 (1 + t_\xi^2 r)}{c_\epsilon m^2_{Z'}} \], \quad G^V_{\chi n} = 0

For \( \epsilon \ll 1 \), \( G^V_{\chi p} \approx q_\chi g_x e c_W \epsilon \frac{m^2_{Z'}}{c_\epsilon} \)

In the \( k^2 \to 0 \) limit, the kinetic mixing factor \( \epsilon k^2 \) can only picks up the \( 1/k^2 \) pole in the massless photon propagator, while the lower diagram vanishes because \( \hat{Z} \) is massive

\( \chi q \) scattering is essentially induced by \( j^\mu_{EM} \)

\( n \) carries no net electric charge \( G^V_{\chi n} = 0 \)
Direct Detection

\[ G^V_{\chi n} = 0 \neq G^V_{\chi p} \]

Isospin violation in DM scattering off nucleons

[Feng et al., 1102.4331, PLB]

Data analyses in direct detection experiments conventionally assume isospin conservation constraints on the normalized-to-nucleon cross section \( \sigma_{\chi n}^Z \)

Now the spin-independent (SI) normalized-to-nucleon cross section becomes

\[
\sigma_{\chi n}^Z = \sigma_{\chi p} \frac{\sum_i \eta_i \mu_{\chi A_i}^2 [Z + (A_i - Z)G^V_{\chi n}/G^V_{\chi p}]^2}{\sum_i \eta_i \mu_{\chi A_i}^2 A_i^2} = \sigma_{\chi p} \frac{\sum_i \eta_i \mu_{\chi A_i}^2 Z^2}{\sum_i \eta_i \mu_{\chi A_i}^2 A_i^2}
\]

Reduced mass \( \mu_{\chi A_i} \equiv m_{\chi} m_{A_i} / (m_{\chi} + m_{A_i}) \)

\( \chi p \) scattering cross section

\[
\sigma_{\chi p} = \mu_{\chi p}^2 (G^V_{\chi p})^2 / \pi
\]

For xenon \((Z = 54)\) detection material,

\( A_i = \{128, 129, 130, 131, 132, 134, 136\} \)

Fractional number abundance of \( A_i \) in nature

\( \eta_i = \{1.9\%, 26\%, 4.1\%, 21\%, 27\%, 10\%, 8.9\%\} \)

[XENON Coll., 1805.12562, PRL]
Phenomenological Constraints for $q_\chi = 1$

🔥 Possible $\chi \bar{\chi}$ annihilation channels:

$$f \bar{f} , \ W^+ W^- , \ h_i h_j , \ Z_i Z_j , \ h_i Z_j$$

with $h_i \in \{h,s\}$ and $Z_i \in \{Z,Z'\}$

🔥 Experimental constraints and sensitivity

DM relic abundance $\Omega_{DM} h^2 = 0.120 \pm 0.001$

[Planck Coll., 1807.06209, Astron. Astrophys.]

🔥 95% C.L. upper limits on DM annihilation cross section from Fermi-LAT $\gamma$-ray observations of dwarf galaxies [Fermi-LAT Coll., 1503.02641, PRL]

🔥 90% C.L. exclusion limits on $\sigma^Z_N$ from the XENON1T direct detection experiment

[XENON Coll., 1805.12562, PRL]

🔥 90% C.L. sensitivity of the future LZ direct detection experiment [Mount et al., 1703.09144]
Complex Scalar Dark Matter

Assume the DM particle is a scalar boson $\phi$ with $U(1)_X$ charge $q_\phi = 1/4$

$$\mathcal{L}_\phi = (D^\mu \phi)^\dag (D_\mu \phi) - \mu_\phi^2 \phi^\dag \phi + \lambda_S \phi^\dag \phi \phi^\dag \phi + \lambda_H \phi^\dag \phi + \lambda_\phi (\phi^\dag \phi)^2$$

$D_\mu \phi = (\partial_\mu - iq_\phi g_X \hat{Z}_\mu') \phi$ DM neutral current $j^\mu_{DM} = q_\phi g_X \phi^\dag i \partial_\mu \phi$

Global $U(1)$ symmetry $\phi \rightarrow e^{iq_\phi \theta} \phi$ should be preserved to protect $j^\mu_{DM}$

Assume the $\phi$ does not develop a VEV stable $\phi$ and $\bar{\phi}$ particles

The charge choice $q_\phi = q_S/4$ forbids unwanted scalar interaction terms like $\hat{S}^\dag \hat{S}^\dag \hat{S}^\dag \phi$, $\hat{S}^\dag \hat{S}^\dag \hat{S}^\dag \phi \phi$, $\hat{S}^\dag \hat{S}^\dag \phi \phi$, and $\hat{S}^\dag \phi \phi \phi$, which would violate the global $U(1)$ symmetry $\phi \rightarrow e^{iq_\phi \theta} \phi$ after the $U(1)_X$ spontaneous symmetry breaking

The $\phi$ mass is given by $m_\phi^2 = \mu_\phi^2 - \frac{1}{2} \lambda_S v_S^2 - \frac{1}{2} \lambda_H v^2$

Kinetic mixing portal: mediation of the $Z$ and $Z'$ vector bosons

Higgs portal: mediation of the $h$ and $s$ scalar bosons

$$\mathcal{L}_{\phi hs} = (\lambda_S s_\eta v_S + \lambda_H c_\eta v) h \phi^\dag \phi + (\lambda_S c_\eta v_S - \lambda_H s_\eta v) s \phi^\dag \phi$$
Effective DM Interactions

**DM-quark** effective interactions

\[
\mathcal{L}_{\phi q} = \sum_q \left[ G_{\phi q}^V (\phi^\dagger i \partial^\mu \phi) \bar{q} \gamma_\mu q + G_{\phi q}^S \phi^\dagger \phi \bar{q} q \right], \quad G_{\phi q}^V = -\frac{q \phi g_x}{c_\varepsilon} \left( \frac{s_\xi g_{Z}^q}{m_Z^2} + \frac{c_\xi g_{Z'}^q}{m_{Z'}^2} \right)
\]

\[
G_{\phi q}^S = \frac{m_q}{v} \left[ \frac{s_\eta}{m_s^2} \left( \lambda_{S\phi} c_\eta v_S - \lambda_{H\phi} s_\eta v \right) - \frac{c_\eta}{m_h^2} \left( \lambda_{S\phi} s_\eta v_S + \lambda_{H\phi} c_\eta v \right) \right]
\]

**DM-nucleon** effective interactions

\[
\mathcal{L}_{\phi N} = \sum_{N=p,n} \left[ G_{\phi N}^V (\phi^\dagger i \partial^\mu \phi) \bar{N} \gamma_\mu N + G_{\phi N}^S \phi^\dagger \phi \bar{N} N \right]
\]

Similar to the Dirac fermion case, we have

\[
G_{\phi p}^V = \frac{q \phi g_x e \hat{c}_W t_\varepsilon c_\xi^2 (1 + t_\xi^2 r)}{c_\varepsilon m_{Z'}^2}, \quad G_{\phi n}^V = 0
\]

Scalar-type effective couplings

\[
G_{\phi N}^S = m_N \sum_q \frac{G_{\phi q}^S f_q^N}{m_q}, \quad f_q^N \text{ are quark form factors}
\]

\[
G_{\phi p}^S \approx G_{\phi n}^S
\]
Direct Detection

- $\phi N$ and $\bar{\phi} N$ scattering cross sections

$$
\sigma_{\phi N} = \frac{\mu_{\phi N}^2 f_{\phi N}^2}{\pi}, \quad f_{\phi N} = \frac{G_{\phi N}^S}{2m_{\phi}} + G_{\phi N}^V
$$

$$
\sigma_{\bar{\phi} N} = \frac{\mu_{\phi N}^2 f_{\bar{\phi} N}^2}{\pi}, \quad f_{\bar{\phi} N} = \frac{G_{\phi N}^S}{2m_{\phi}} - G_{\phi N}^V
$$

- The difference between $f_{\phi N}$ and $f_{\bar{\phi} N}$ comes from the **arrow directions** of the $\phi/\bar{\phi}$ lines in the Feynman diagrams.

- $G_{\phi n}^V = 0$  
  $f_{\phi n} = f_{\bar{\phi} n} = G_{\phi n}^S / (2m_{\phi})$

- Normalized-to-nucleon cross section

$$
\sigma_Z^N = \frac{\sigma_{\phi p}}{2 \sum_i \eta_i \mu_{\phi A_i}^2 A_i^2 \sum_i \eta_i \mu_{\phi A_i}^2} \sum \eta_i \mu_{\phi A_i}^2 \\
\times \left\{ \left[ Z + (A_i - Z) f_{\phi n} / f_{\phi p} \right]^2 \\
+ \left[ Z f_{\bar{\phi} p} / f_{\phi p} + (A_i - Z) f_{\bar{\phi} n} / f_{\phi p} \right]^2 \right\}
$$

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Phenomenological Constraints

- Special $\phi \bar{\phi}$ annihilation regions: $h$, $s$, and $Z'$ resonances
- $ZZ$, $sZ$, and $ss$ thresholds

- LHC constraint on invisible Higgs decays: $B_{inv} < 24\%$ @ 95\% C.L.
  [CMS Coll., 1610.09218, JHEP]

- CEPC sensitivity for invisible Higgs decays: $B_{inv} < 0.3\%$ @ 95\% C.L.
  [CEPC Study Group, 1811.10545]
Conclusions

- We explore **Dirac fermionic** and **complex scalar dark matter** in a hidden **$U(1)_X$ gauge theory** with kinetic mixing.
- The $U(1)_X$ gauge symmetry is spontaneously broken due to a Higgs field.
- The **kinetic mixing** provides a **portal** to dark matter.
- An additional **Higgs portal** can be realized in the complex scalar DM case.
- Dark matter interactions with nucleons are typically **isospin violating**, and **direct detection** constraints could be **relieved**.
- We find that there are several available parameter regions predicting the **observed relic abundance** and have not been totally explored in current DM detection experiments.
We explore Dirac fermionic and complex scalar dark matter in a hidden $U(1)_X$ gauge theory with kinetic mixing.

The $U(1)_X$ gauge symmetry is spontaneously broken due to a Higgs field.

The kinetic mixing provides a portal to dark matter.

An additional Higgs portal can be realized in the complex scalar DM case.

Dark matter interactions with nucleons are typically isospin violating, and direct detection constraints could be relieved.

We find that there are several available parameter regions predicting the observed relic abundance and have not been totally explored in current DM detection experiments.

Thanks for your attention!