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

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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.

有些 mediator（"portals"）are typically required to induce adequate DM interactions with standard model (SM) particles.

💡 Inspired by the SU(3)$_C \times$ SU(2)$_L \times$ 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

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

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

🌟 or the Stueckelberg mechanism 👉 no extra Higgs boson

[Stueckelberg, Helv. Phys. Acta 11 (1938) 225; Chodos & Cooper, PRD 3, 2461 (1971)]

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

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

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

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

$$V_K^T \begin{pmatrix} 1 & s_\epsilon \\ s_\epsilon & 1 \end{pmatrix} V_K = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_K = -\frac{1}{4} B^{\mu \nu} B_{\mu \nu} - \frac{1}{4} \tilde{Z}'^{\mu \nu} \tilde{Z}'_{\mu \nu}$$
Spontaneous Breaking of the $U(1)_X$ Gauge Symmetry

🌟 We assume that the $U(1)_X$ gauge symmetry is **spontaneously broken** by a hidden Higgs field $\hat{S}$ with $U(1)_X$ charge $q_S = 1$

📍 $SU(2)_L \times U(1)_Y \times U(1)_X$ gauge invariant Lagrangian

$$\mathcal{L}_H = (D^\mu \hat{H})^\dagger (D_\mu \hat{H}) + (D^\mu \hat{S})^\dagger (D_\mu \hat{S}) + \mu^2 |\hat{H}|^2 + \mu_S^2 |\hat{S}|^2 - \frac{1}{2} \lambda_H |\hat{H}|^4 - \frac{1}{2} \lambda_S |\hat{S}|^4 - \lambda_{HS} |\hat{H}|^2 |\hat{S}|^2$$

📍 $\hat{H}$ is the **SM Higgs doublet** with $D_\mu \hat{H} = (\partial_\mu - i \hat{g} W^a_\mu \sigma^a / 2 - i \hat{g}' \hat{B}_\mu / 2) \hat{H}$

📍 $\hat{S}$ satisfies $D_\mu \hat{S} = (\partial_\mu - i g_X \hat{Z}'_\mu) \hat{S}$, 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

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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 \((H, S)\):

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

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

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

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 \(\nu_s\):

\[
M_1^2 = \begin{pmatrix}
\hat{g}'^2 \nu^2 / 4 & -\hat{g} \hat{g}' \nu^2 / 4 \\
-\hat{g} \hat{g}' \nu^2 / 4 & \hat{g}^2 \nu^2 / 4 \\
\hat{g}_X^2 \nu_s^2 & \hat{g}^2 \nu^2 / 4
\end{pmatrix}, \quad W^\pm \text{ boson mass } m_W = \frac{1}{2} \hat{g} \nu
\]

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: \(\hat{m}_Z^2 \equiv (\hat{g}^2 + \hat{g}'^2) \nu^2 / 4\), \(\hat{m}_{Z'}^2 \equiv \hat{g}_X^2 \nu_s^2\)

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

Rotation angle \(\xi\) is given by

\[
\tan 2\xi = \frac{s_2 \epsilon \hat{s}_W \nu^2 (\hat{g}^2 + \hat{g}'^2)}{c_\epsilon^2 \nu^2 (\hat{g}^2 + \hat{g}'^2)(1 - \hat{s}_W^2 t_\epsilon^2) - 4 \hat{g}_X^2 \nu_s^2}
\]
Neutral Gauge Boson Mixing

Transform the **gauge basis** \((\hat{B}_\mu, W^3_\mu, \hat{Z}'_\mu)\) to the **mass basis** \((A_\mu, Z_\mu, Z'_\mu)\)

\[
\begin{pmatrix}
\hat{B}_\mu \\
W^3_\mu \\
\hat{Z}'_\mu
\end{pmatrix} = V(\epsilon) R_3(\hat{\theta}_W) R_1(\xi) 
\begin{pmatrix}
A_\mu \\
Z_\mu \\
Z'_\mu
\end{pmatrix}
\]

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

[Babu, Kolda, March-Russell, hep-ph/9710441, PRD]
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

\[ \mathcal{L}_{cc} = \frac{1}{\sqrt{2}} (W_\mu^+ J_{\mu}^{+, \mu} + \text{H.c.}) \]

where \( J_{\mu}^{+, \mu} = \hat{g} (\bar{u}_i \gamma^\mu V_{ij} d_j + \bar{\nu}_i \gamma^\mu \ell_j) \).

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

Neutral current interactions become

\[ \mathcal{L}_{nc} = j_{EM}^\mu A_\mu + j_{Z}^\mu Z_\mu + j_{Z^0}^\mu Z^0_\mu \]

Electromagnetic current

\[ j_{EM}^\mu = \sum_f Q_f e \bar{f} \gamma^\mu f \quad \text{with} \quad e = \frac{\hat{g} \hat{g}'}{\sqrt{\hat{g}^2 + \hat{g}'^2}} \]

Z current

\[ j_{Z}^\mu = \frac{ec_\xi (1 + \hat{s}_W t_\epsilon t_\xi)}{2\hat{s}_W \hat{c}_W} \sum_f \bar{f} \gamma^\mu (T_3^f - 2Q_f s^2 s_\ast - T_3^f \gamma_5) f + \frac{s_\xi}{c_\epsilon} j_{DM}^\mu \]

Z' current

\[ j_{Z'}^\mu = \frac{e(\hat{s}_W t_\epsilon c_\xi - s_\xi)}{2\hat{s}_W \hat{c}_W} \sum_f \bar{f} \gamma^\mu (T_3^f - 2Q_f s^2 s_\ast - T_3^f \gamma_5) f - \hat{c}_W t_\epsilon c_\xi j_{EM}^\mu + \frac{c_\xi}{c_\epsilon} j_{DM}^\mu \]

Dark matter \( U(1)_X \) current

\[ j_{DM}^\mu \propto g_X, \quad s_\ast^2 \equiv \frac{\hat{s}_W^2 + \hat{c}_W^2}{1 + \hat{s}_W t_\epsilon t_\xi} \frac{\hat{s}_W t_\epsilon t_\xi}{1 + \hat{s}_W t_\epsilon t_\xi} \]
Independent Parameters

In the SM, the weak mixing angle obeys \( s_W^2 c_W^2 = \frac{\pi \alpha}{\sqrt{2} G_F m_Z^2} \) 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 \( \text{U}(1)_X \) gauge theory:

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

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

The angle \( \xi \) satisfies \( t_\xi = \frac{2\hat{s}_W t_\varepsilon}{1 - r} \left[ 1 + \sqrt{1 - r \left( \frac{2\hat{s}_W t_\varepsilon}{1 - r} \right)^2} \right]^{-1} \) with \( r \equiv \frac{m_{Z'}^2}{m_Z^2} \).

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

**Independent parameters** can be chosen as \( \{g_X, m_{Z'}, m_s, s_\varepsilon, s_\eta\} \).

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**

**Spark** 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]

$$\mathcal{L}_{Z f f} = \frac{e}{2 s_W c_W} \left( 1 + \frac{\alpha T}{2} \right) Z_\mu \sum_f \bar{f} \gamma^\mu (T_f^3 - 2 Q_f s_*^2 - T_f^3 Y_5) f$$

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

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

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

For $\epsilon \ll 1$, we have $S \simeq \frac{4 s_W^2 c_W^2 \epsilon^2}{\alpha (1 - r)} \left( 1 - \frac{s_W^2}{1 - r} \right)$, $T \simeq -\frac{r s_W^2 \epsilon^2}{\alpha (1 - r)^2}$
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 $\mathcal{L}_\chi = i \bar{\chi} \gamma^\mu D_\mu \chi - m_\chi \bar{\chi} \gamma^\mu \chi$, $D_\mu \chi = (\partial_\mu - iq_\chi g_X \hat{Z}_\mu) \chi$

**DM neutral current** $j^\mu_{\text{DM}} = q_\chi g_X \bar{\chi} \gamma^\mu \chi$

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**

$$\mathcal{L}_{\chi q} = \sum_q G^V_{\chi q} \bar{\chi} \gamma^\mu \chi q q_\mu q$$

$$G^V_{\chi q} = - \frac{q_\chi g_X}{c_\xi} \left( \frac{s_\xi g^q_Z}{m^2_Z} + \frac{c_\xi g^q_{Z'}}{m^2_{Z'}} \right)$$

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

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

$$g^q_{Z'} = \frac{e(\hat{s}_W t_\epsilon c_\xi - s_\xi)}{2\hat{s}_W \hat{c}_W} (T^3_q - 2Q_q \hat{s}_W^2) - Q_q e\hat{c}_W t_\epsilon c_\xi$$
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

\[ G^V_{\chi p} = \frac{q_\chi g_X e \hat{c}_W t_\epsilon c^2_\xi (1 + t^2_\xi r)}{c_\epsilon m^2_{Z'}} \]

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

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

\[ G^V_{\chi n} = 0 \neq G^V_{\chi p} \] \hspace{1cm} \textbf{Isospin violation} in DM scattering off nucleons

[Feng et al., 1102.4331, PLB]

Data analyses in direct detection experiments conventionally assume \textit{isospin conservation} constraints on the \textit{normalized-to-nucleon cross section} \( \sigma^Z_N \)

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

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

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 \textbf{xenon} (\( Z = 54 \)) detection material, \( A_i = \{128, 129, 130, 131, 132, 134, 136\} \)

Fractional number abundance of \( A_i \) in nature \( \eta_i = \{1.9\%, 26\%, 4.1\%, 21\%, 27\%, 10\%, 8.9\%\} \)
**Phenomenological Constraints for $q_\chi = 1$**

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

$$f \bar{f}, \ W^+W^-, \ h_ih_j, \ Z_iZ_j, \ h_iZ_j$$

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

\[
\mathcal{L}_\phi = (D^\mu \phi)^\dagger(D_\mu \phi) - \mu_\phi^2 \phi^\dagger \phi + \lambda_{S\phi} \hat{S}^\dagger \hat{S} \phi^\dagger \phi + \lambda_{H\phi} \hat{H}^\dagger \hat{H} \phi^\dagger \phi + \lambda_{\phi} (\phi^\dagger \phi)^2
\]

**DM neutral current** \( j_{\text{DM}}^\mu = q_\phi g_X \phi^\dagger i \partial^\mu \phi \)

**Global \( U(1) \) symmetry** \( \phi \rightarrow e^{iq_\phi \theta} \phi \) should be **preserved** to protect \( j_{\text{DM}}^\mu \)

Assume the \( \phi \) does not develop a VEV \( \rightarrow \) **stable** \( \phi \) and \( \bar{\phi} \) particles

The charge choice \( q_\phi = q_S/4 \) **forbids** unwanted scalar interaction terms like \( \hat{S}^\dagger \hat{S}^\dagger \hat{S}^\dagger \phi \), \( \hat{S}^\dagger \hat{S}^\dagger \phi \), \( \hat{S}^\dagger \hat{S}^\dagger \phi \phi \), \( \hat{S}^\dagger \phi \phi \), and \( \hat{S}^\dagger \phi \phi \phi \), 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 \( m_\phi^2 = \mu_\phi^2 - \frac{1}{2} \lambda_{S\phi} v_S^2 - \frac{1}{2} \lambda_{H\phi} v^2 \)

**Kinetic mixing portal**: mediation of the \( Z \) and \( Z' \) vector bosons

**Higgs portal**: mediation of the \( h \) and \( s \) scalar bosons

\[
\mathcal{L}_{\phi hs} = (\lambda_{S\phi} s_\eta v_S + \lambda_{H\phi} c_\eta v) h \phi^\dagger \phi + (\lambda_{S\phi} c_\eta v_S - \lambda_{H\phi} s_\eta v) s \phi^\dagger \phi
\]
Effective DM Interactions

**DM-quark** effective interactions

\[ \mathcal{L}_{\phi q} = \sum_q \left[ G_{\phi q}^V (\phi^\dagger i \partial^\mu \phi) \bar{q} \gamma_\mu q + G_{\phi q}^S \phi^\dagger \phi \bar{q} q \right], \quad G_{\phi q}^V = -\frac{q_\phi g_X}{c_\varepsilon} \left( \frac{s_\xi g_Z^{q_2}}{m_Z^2} + \frac{c_\xi g_{Z'}^q}{m_{Z'}^2} \right) \]

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

**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

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

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

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

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

Normalized-to-nucleon cross section

\[
\sigma_N^Z = \frac{\sigma_{\phi p}}{2} \sum_i \eta_i \mu_{\phi A_i}^2 A_i^2 \sum_i \eta_i \mu_{\phi A_i}^2 \times \left\{ \left[ Z + (A_i - Z) f_{\phi n}/f_{\phi p} \right]^2 \right. \\
\left. + \left[ Z f_{\bar{\phi} p}/f_{\phi p} + (A_i - Z) f_{\bar{\phi} n}/f_{\phi p} \right]^2 \right\}
\]
Phenomenological Constraints

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

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

- CEPC sensitivity for invisible Higgs decays: $B_{\text{inv}} < 0.3\%$ @ 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.
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**Thanks for your attention!**