A self-consistent $U(1)$-extended model of fermionic dark matter with scalar and gauge portals: associated production with third-generation fermions at electron–positron colliders

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Motivation

- Dark matter accounts for approximately 27% of the total matter–energy content of the Universe.
- No conclusive non-gravitational evidence for dark matter interactions has been observed so far.
- Portal scenarios provide minimal and experimentally testable interactions between the visible and dark sectors.
- A self-consistent chiral $U(1)$ extension naturally realizes both scalar and vector portals within a unified framework.
- Future e^+e^- colliders provide sensitivity to feeble portal interactions.

Standard Model

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Scalar Portal

Vector Portal

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Dark Sector

Gauge Structure and Field Content

$$SU(2)_L \times U(1)_Y \times U(1)_X$$

$$V(\Phi_1, \Phi_2) \supset \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \quad \Longrightarrow \quad \text{Scalar Portal (Higgs mixing)} \tag{1}$$

$$\mathcal{L} \supset \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} \quad \Longrightarrow \quad \text{Vector Portal (kinetic mixing)} \tag{2}$$

$$\mathcal{L} \supset i\bar{\omega}_L \not{D} \omega_L + i\bar{\omega}_R \not{D} \omega_R - y\bar{\omega}_L \Phi_2 \omega_R + \ldots \quad \Longrightarrow \quad \text{Dark Sector (Dirac particles)} \tag{3}$$

Simultaneous requirements of:

- gauge invariance,
- anomaly cancellation,
- absence of Majorana masses,
- Yukawa-generated fermion masses

strongly constrain the structure of the dark sector.

Field	Spin	$U(1)_X$
Φ_2	0	q_2
ω_L	1/2	q_L
ω_R	1/2	q_R

After spontaneous symmetry breaking $\Longrightarrow$ residual $\mathbb{Z}_N$ symmetry

Why an Even Number of Chiral Fermions?

Gauge invariance of Yukawa interactions:

$$q_{iL} - q_{iR} = s_i q_2, \quad s_i = \begin{cases} +1, & \bar{\omega}_{iL}\Phi_2\omega_{iR}, \\ -1, & \bar{\omega}_{iL}\Phi_2^\dagger\omega_{iR}. \end{cases} \tag{4}$$

Cancellation of the gravitational anomaly:

$$\sum_i q_{iL} - \sum_i q_{iR} = 0 \quad \Longrightarrow \quad q_2 \sum_i s_i = 0 \quad \Longrightarrow \quad N_+ = N_-, \quad N = 2N_+. \tag{5}$$

Result

Anomaly cancellation with a charged scalar requires an even number of chiral fermion pairs.

Minimal dark sector contains two component of chiral dark matter.

Minimal Charge Assignment

Gauge invariance of Yukawa terms $\bar{\omega}_{1L}\Phi_2\omega_{1R}$, $\bar{\omega}_{2L}\Phi_2^\dagger\omega_{2R}$ with $q_2 = 2$:

$$(q_{1L}, q_{1R}), \quad (q_{2L}, q_{2R}) \quad \rightarrow \quad (q, q-2), \quad (x, x+2). \tag{6}$$

Cubic anomaly cancellation:

$$q^3 + x^3 - (q-2)^3 - (x+2)^3 = 0 \quad \rightarrow \quad \text{two branches appear:} \quad x = -q, \quad x = q-2. \tag{7}$$

The first branch allows Majorana mass terms and is excluded.

The remaining anomaly-free solution:

$$(q, q-2), \quad (q-2, q) \quad \text{with minimal integer realization:} \quad (5,3), \quad (3,5). \tag{8}$$

Allowed interactions:

$$\bar{\omega}_{1L}\Phi_2\omega_{1R}, \quad \bar{\omega}_{2L}\Phi_2^\dagger\omega_{2R}, \quad \bar{\omega}_{1L}\omega_{2R}, \quad \bar{\omega}_{2L}\omega_{1R}. \tag{9}$$

Forbidden interactions:

$$\bar{\omega}_{iL}\omega_{iR}, \quad \bar{\omega}_{1L}\Phi_2^{(\dagger)}\omega_{2R}, \quad \bar{\omega}_{2L}\Phi_2^{(\dagger)}\omega_{1R}, \quad \omega_{iL}^T C\omega_{jL}, \quad \omega_{iR}^T C\omega_{jR}, \tag{10}$$

Dark Fermion Mixing

Yukawa and mixed mass terms:

$$\mathcal{L} \supset -y_1 \bar{\omega}_{1L} \Phi_2 \omega_{1R} - y_2 \bar{\omega}_{2L} \Phi_2^\dagger \omega_{2R} - \mu_{12} \bar{\omega}_{1L} \omega_{2R} - \mu_{21} \bar{\omega}_{2L} \omega_{1R}. \tag{12}$$

After spontaneous symmetry breaking:

$$M = \begin{pmatrix} m_1 & \mu_{12} \\ \mu_{21} & m_2 \end{pmatrix}. \tag{13}$$

Biunitary diagonalization:

$$U_L^\dagger M U_R = \mathrm{diag}(M_1, M_2). \tag{14}$$

Field transformations:

$$\begin{pmatrix} \omega_{1L} \\ \omega_{2L} \end{pmatrix} = \begin{pmatrix} c_L & s_L e^{i\delta_L} \\ -s_L e^{-i\delta_L} & c_L \end{pmatrix} \begin{pmatrix} \chi_{1L} \\ \chi_{2L} \end{pmatrix}, \quad \tan 2\theta_L = \frac{2|m_1 \mu_{21}^* + \mu_{12} m_2^*|}{|m_2|^2 + |\mu_{21}|^2 - |\mu_{12}|^2 - |m_1|^2}; \tag{15}$$

$$\begin{pmatrix} \omega_{1R} \\ \omega_{2R} \end{pmatrix} = \begin{pmatrix} c_R & s_R e^{i\delta_R} \\ -s_R e^{-i\delta_R} & c_R \end{pmatrix} \begin{pmatrix} \chi_{1R} \\ \chi_{2R} \end{pmatrix}, \quad \tan 2\theta_R = \frac{2|m_1^* \mu_{12} + \mu_{21}^* m_2|}{|m_2|^2 + |\mu_{12}|^2 - |\mu_{21}|^2 - |m_1|^2}. \tag{16}$$

Result

The mixed Dirac mass terms generate mixing between the original chiral states.

Scalar Interactions in the Mass Basis

After the rotation to the mass basis

$$\mathcal{L} \supset -\phi_2 \bar{\chi}_L U_L^\dagger Y U_R \chi_R + \text{h.c.} \tag{17}$$

The scalar interaction matrix becomes non-diagonal:

$$U_L^\dagger Y U_R = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}, \tag{18}$$

$$C_{11} = \frac{1}{\sqrt{2}}\left(c_L c_R y_1 + s_L s_R y_2 e^{i(\delta_L - \delta_R)}\right), \quad C_{12} = \frac{1}{\sqrt{2}}\left(c_L s_R y_1 e^{i\delta_R} - s_L c_R y_2 e^{i\delta_L}\right), \tag{19}$$

$$C_{21} = \frac{1}{\sqrt{2}}\left(s_L c_R y_1 e^{-i\delta_L} - c_L s_R y_2 e^{-i\delta_R}\right), \quad C_{22} = \frac{1}{\sqrt{2}}\left(s_L s_R y_1 e^{-i(\delta_L - \delta_R)} + c_L c_R y_2\right). \tag{20}$$

Resulting interactions:

$$\begin{aligned} \mathcal{L} \supset & -\phi_2 \bar{\chi}_1 (\mathrm{Re}\, C_{11} + i\, \mathrm{Im}\, C_{11} \gamma_5) \chi_1, -\phi_2 \bar{\chi}_2 (\mathrm{Re}\, C_{22} + i\, \mathrm{Im}\, C_{22} \gamma_5) \chi_2 \\ & -\phi_2 \bar{\chi}_1 \left[\frac{C_{12} + C_{21}^*}{2} + \frac{C_{12} - C_{21}^*}{2} \gamma_5\right] \chi_2 - \phi_2 \bar{\chi}_2 \left[\frac{C_{21} + C_{12}^*}{2} + \frac{C_{21} - C_{12}^*}{2} \gamma_5\right] \chi_1 . \end{aligned} \tag{21}$$

Physical consequence

Mixing induces off-diagonal scalar interactions: $\chi_2 \leftrightarrow \chi_1 + \phi_2$.

Gauge Interactions in the Mass Basis

Gauge interactions before diagonalization:

$$g_X X_\mu \bar{\omega}_{L,R} \gamma^\mu Q_{L,R} \omega_{L,R}. \tag{22}$$

After the field rotations the charge matrices become non-diagonal:

$$U_L^\dagger Q_L U_L, \qquad U_R^\dagger Q_R U_R. \tag{23}$$

$$\mathcal{L}_X^{\rm diag} = g_X X_\mu \left[\bar{\chi}_1 \gamma^\mu \left(g_{11}^V - g_{11}^A \gamma_5\right)\chi_1 + \bar{\chi}_2 \gamma^\mu \left(g_{22}^V - g_{22}^A \gamma_5\right)\chi_2\right], \tag{24}$$

$$\mathcal{L}_X^{\rm off} = g_X X_\mu \left[\bar{\chi}_1 \gamma^\mu \left(g_{12}^V - g_{12}^A \gamma_5\right)\chi_2 + \bar{\chi}_2 \gamma^\mu \left(\left(g_{12}^V\right)^* - \left(g_{12}^A\right)^* \gamma_5\right)\chi_1\right], \tag{25}$$

$$g_{11}^V = q - s_L^2 - c_R^2, \quad g_{11}^A = c_R^2 - s_L^2, \tag{26}$$

$$g_{22}^V = q - c_L^2 - s_R^2, \quad g_{22}^A = s_R^2 - c_L^2. \tag{27}$$

$$g_{12}^L = 2 c_L s_L e^{i\delta_L}, \quad g_{12}^R = -2 c_R s_R e^{i\delta_R}. \tag{28}$$

$$g_{12}^V = c_L s_L e^{i\delta_L} - c_R s_R e^{i\delta_R}, \quad g_{12}^A = c_L s_L e^{i\delta_L} + c_R s_R e^{i\delta_R}. \tag{29}$$

$$g_{21}^V = \left(g_{12}^V\right)^*, \quad g_{21}^A = \left(g_{12}^A\right)^*. \tag{30}$$

Physical consequence

Mixing generates transitions: $\chi_2 \leftrightarrow \chi_1 + X$.

Scalar and Vector Portals

Scalar portal

$$(\phi_1, \phi_2) \to (h_1, h_2):$$

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \tag{31}$$

$$\tan 2\theta = \frac{\lambda_3 v_1 v_2}{\lambda_1 v_1^2 - \lambda_2 v_2^2}. \tag{32}$$

$$\Downarrow$$

$$h_2 \bar{f} f \propto s_\theta, \tag{33}$$

$$h_1 \bar{\chi}\chi \propto s_\theta. \tag{34}$$

Vector portal

$$(B_\mu, W_\mu^3, X_\mu) \to (A_\mu, Z_\mu, Z'_\mu):$$

$$\begin{pmatrix} c_W & -c_\xi s_W - s_\xi \frac{\epsilon}{\sqrt{1-\epsilon^2}} & s_\xi s_W - c_\xi \frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ s_W & c_\xi c_W & -s_\xi c_W \\ 0 & \frac{s_\xi}{\sqrt{1-\epsilon^2}} & \frac{c_\xi}{\sqrt{1-\epsilon^2}} \end{pmatrix}, \tag{35}$$

$$\tan 2\xi = \frac{2\epsilon\sqrt{1-\epsilon^2} s_W m_{Z_0}^2}{m_{Z_0}^2(1-\epsilon^2(1+s_W^2)) - m_{Z'_0}^2}. \tag{36}$$

$$\Downarrow$$

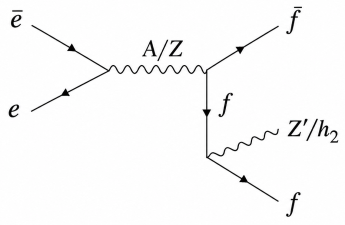
$$Z'_\mu \bar{f}\gamma^\mu (g_V - g_A\gamma_5) f \propto \epsilon, \tag{37}$$

$$Z_\mu \bar{\chi}\gamma^\mu (g_V - g_A\gamma_5)\chi \propto \epsilon. \tag{38}$$

Associated Production with Third-Generation Fermions

We consider dark matter production in electron–positron collisions:

$$e^+e^- \to f\bar{f}\,\chi_1\bar{\chi}_1, \qquad f = \tau,\ b. \qquad (39)$$



The relevant mediator decay channels are $Z' \to \chi_1\bar{\chi}_1,$, $h_2 \to \chi_1\bar{\chi}_1$.

Thus the target signatures are

$e^+e^- \to \tau^+\tau^- + \not{E}$, at STCF ($\sqrt{s} = 7$ GeV); $e^+e^- \to \bar{b}b + \not{E}$ at CEPC ($\sqrt{s} = 90$ GeV).

Portal Interactions in the Small-Mixing Limits

$$\epsilon \ll 1, \quad s_\theta \ll 1, \quad \mu_{ij} \ll m_k, \quad \phi_{CP} = \arg(m_1 m_2 \mu_{12}^* \mu_{21}^*) = \phi_1 + \phi_2 - \phi_{12} - \phi_{21} = 0. \tag{40}$$

Scalar interaction with SM fermions:

$$\mathcal{L} \supset s_\theta \sum_{f=\ell,\,q} \frac{m_f}{v_1} m_f h_2 \bar{f} f . \tag{41}$$

Scalar interaction with dark matter:

$$\mathcal{L} \supset -\frac{g_X q_2}{m_{Z'}} (s_\theta h_1 + h_2)(M_1 \bar{\chi}_1 \chi_1 + M_2 \bar{\chi}_2 \chi_2) \tag{42}$$

$$+ \frac{g_X q_2}{2 m_{Z'}} (s_\theta h_1 + h_2) \bar{\chi}_1 \left[\mu_{12} + \mu_{21} + (\mu_{12} - \mu_{21})\gamma_5\right] \chi_2 . \tag{43}$$

In the limit,

$$m_{Z'}^2 \ll m_Z^2, \qquad \varepsilon = -\epsilon c_W, \tag{44}$$

one obtains

$$\mathcal{L} \supset -\varepsilon e Z'_\mu \bar{e}\gamma^\mu e + \frac{2}{3}\varepsilon e Z'_\mu \bar{u}\gamma^\mu u - \frac{1}{3}\varepsilon e Z'_\mu \bar{d}\gamma^\mu d. \tag{45}$$

The dominant dark-sector interaction is

$$\mathcal{L} \supset g_X Z'_\mu \bar{\chi}_1\gamma^\mu(4-\gamma_5)\chi_1 + g_X Z'_\mu \bar{\chi}_2\gamma^\mu(4+\gamma_5)\chi_2 \tag{46}$$

$$+ g_X Z'_\mu \bar{\chi}_1\gamma^\mu \left[-\frac{\mu_{21}-\mu_{12}}{m_1+m_2} - \frac{\mu_{21}+\mu_{12}}{m_2-m_1}\gamma_5\right]\chi_2. \tag{47}$$

Heavy dark-sector component

If $M_2 \gg m_{\rm med}$ collider signatures are dominated by the lightest state χ_1.

$$M_2 - M_1 \gg T_f, \qquad T_f \simeq M_1/20, \tag{48}$$

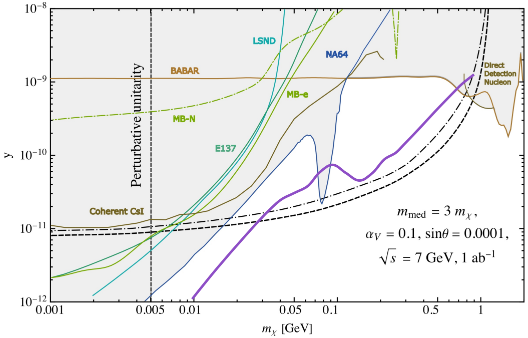
such that the heavier component is Boltzmann suppressed:

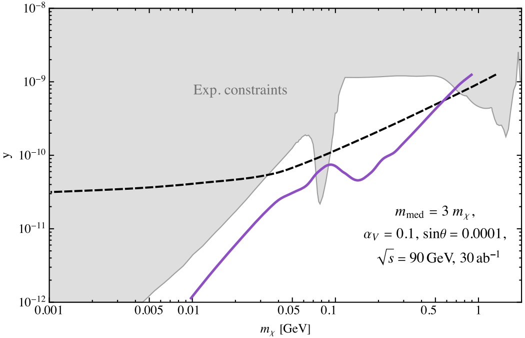
$$n_2 \propto e^{-(M_2-M_1)/T}. \tag{49}$$

If the decay rate satisfies $\Gamma_{\chi_2} \gg H(T_f)$, the state χ_2 efficiently decays into χ_1 before freeze-out. Therefore, the present-day relic density is dominated by the lightest state χ_1.

Sensitivity to Associated Dark Matter Production

$$m_{Z'} = m_{h_2} = 3m_{\chi_1}, \quad \Omega_{\rm DM} h^2 \simeq 0.12, \quad y = \left(\varepsilon^2 + \frac{4}{9}\sin^2\theta\right)\alpha_V \left(\frac{m_\chi}{m_{\rm med}}\right)^4, \qquad (50)$$





$e^+e^- \to \tau^+\tau^-\ (Z', h_2 \to \bar{\chi}\chi)$

STCF

$e^+e^- \to b\bar{b}\ (Z', h_2 \to \bar{\chi}\chi)$

CEPC

Conclusions

- A minimal anomaly-free chiral dark sector was constructed.
- Fermion masses are generated through Yukawa interactions after spontaneous symmetry breaking.
- Residual $\mathbb{Z}_2$ symmetry stabilizes the lightest dark-sector state.
- The model contains both scalar and vector portal interactions.
- The standard dark photon scenario is recovered in the light-mediator limit.
- Future e^+e^- colliders provide sensitivity to the phenomenologically relevant parameter region.

Thank you for your attention