

Two Portals to Darkness: A Dark Matter Model with Scalar and Vector Mediators

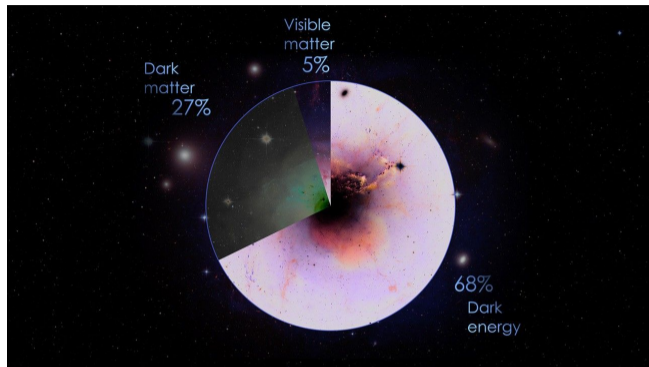
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Dark Matter

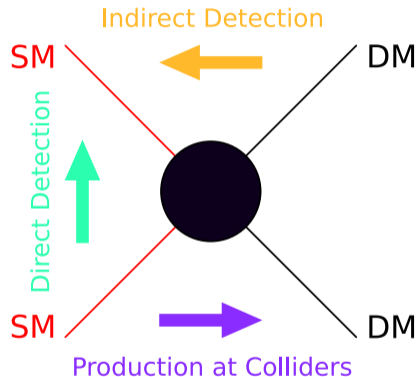
The Universe is made up of three components: normal or visible matter (5%), dark matter (DM) (27%), and dark energy (68%).



- ▶ DM, much like ordinary matter, possesses mass and extends through space. However, it neither emits, absorbs, nor reflects electromagnetic radiation in any appreciable way detectable by current instrumentation.
- ▶ Despite compelling cosmological and astrophysical evidence indicating that DM constitutes approximately 27% of the total energy density of the Universe, its fundamental nature remains unknown. A range of theoretical frameworks postulate that DM may be composed of novel, weakly interacting particles that lie beyond the Standard Model (SM).

Dark Matter Portals

- ▶ **Portals:** Mediator fields enabling interactions between the dark sector and SM particles.
- ▶ **Purpose:** Allow DM production and scattering via suppressed, indirect couplings.
- ▶ **Motivation:**
 - ▶ The SM is incomplete: describes only visible matter and known interactions.
 - ▶ Minimal extensions introduce few new fields with well-motivated couplings.
 - ▶ DM does not couple electromagnetically; requires feeble interactions with SM.
 - ▶ DM longevity ensured by fundamental (not accidental) symmetries.
- ▶ **Outcome:** Minimal, predictive, and gauge-invariant framework consistent with DM relic abundance.



Dark Matter Model that Naturally Features Both the Scalar and Vector Portals

Table: Fundamental gauge quantum numbers of the fields in the model.

Field	Components	$SU(2)_L$	$U(1)_Y$	$U(1)_V$	Sector
Lepton doublet	(ν_L, e_L)	2	-1	0	SM
Right-handed lepton	e_R	1	-2	0	SM
Quark doublet	(u_L, d_L)	2	+1/3	0	SM
Right-handed up quark	u_R	1	+4/3	0	SM
Right-handed down quark	d_R	1	-2/3	0	SM
Higgs doublet	(H^+, H^0)	2	+1	0	SM
Dark fermion	χ_L	1	0	+1/2	Dark
	χ_R	1	0	-1/2	Dark
Dark scalar	S	1	0	+1	Dark

Dark Matter Model that Naturally Features Both the Scalar and Vector Portals

A beyond the SM (BSM) scenario featuring a spontaneously broken $SU(2)_L \times U(1)_Y \times U(1)_V$ gauge symmetry, a complex scalar singlet field, and a fermionic DM candidate can be compactly formulated through a Lagrangian that includes the corresponding kinetic, gauge, Yukawa, and scalar terms:

$$\mathcal{L}_{\text{kinetic}} = i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R + i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{\chi}_L \not{D} \chi_L + i\bar{\chi}_R \not{D} \chi_R, \quad (1)$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} - \frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} V^{\mu\nu}, \quad (2)$$

$$\mathcal{L}_{\text{Yukawa}} = -y_d \bar{Q}_L H d_R - y_u \bar{Q}_L \tilde{H} u_R - y_e \bar{L}_L H e_R - y_\chi \bar{\chi}_L S \chi_R + \text{h.c.} \quad (3)$$

$$\mathcal{L}_{\text{Higgs,S}} = (D_\mu H)^\dagger (D^\mu H) + (D_\mu S)^\dagger (D^\mu S) - V(H, S), \quad (4)$$

$$V(H, S) = -\mu_H^2 H^\dagger H - \mu_S^2 |S|^2 + \lambda_H (H^\dagger H)^2 + \lambda_S |S|^4 + \lambda_{HS} (H^\dagger H) |S|^2. \quad (5)$$

$$D_\mu H = \left(\partial_\mu - ig_2 \frac{\sigma^i}{2} W_\mu^i - ig_1 \frac{Y_H}{2} B_\mu \right) H, \quad D_\mu S = (\partial_\mu - ig_V Y_S V_\mu) S, \quad (6)$$

$$D_\mu f_L = \left(\partial_\mu - ig_2 \frac{\sigma^i}{2} W_\mu^i - ig_1 \frac{Y_{f_L}}{2} B_\mu \right) f_L, \quad D_\mu f_R = \left(\partial_\mu - ig_1 \frac{Y_{f_R}}{2} B_\mu \right) f_R, \quad (7)$$

$$D_\mu \chi_L = (\partial_\mu - ig_V Y_{\chi_L} V_\mu) \chi_L, \quad D_\mu \chi_R = (\partial_\mu - ig_V Y_{\chi_R} V_\mu) \chi_R. \quad (8)$$

Scalar Sector

After spontaneous symmetry breaking ($\mu_H^2 > 0$, $\mu_S^2 > 0$ and $4\lambda_H\lambda_S > \lambda_{HS}^2$) the scalar fields acquire nonzero vacuum expectation values:

$$H = \begin{pmatrix} 0 \\ v + \phi_1 \\ \sqrt{2} \end{pmatrix}, \quad S = \frac{u + \phi_2}{\sqrt{2}}, \quad (9)$$

$$v^2 = \frac{4\lambda_S\mu_H^2 - 2\lambda_{HS}\mu_S^2}{4\lambda_H\lambda_S - \lambda_{HS}^2}, \quad u^2 = \frac{4\lambda_H\mu_S^2 - 2\lambda_{HS}\mu_H^2}{4\lambda_H\lambda_S - \lambda_{HS}^2}. \quad (10)$$

The masses of the mixed scalar fields are determined by the fundamental parameters of the model and the scalar mixing angle θ as follows:

$$m_{h_1, h_2}^2 = \lambda_H v^2 + \lambda_S u^2 \mp \frac{\lambda_S u^2 - \lambda_H v^2}{\cos 2\theta}, \quad (11)$$

$$\tan 2\theta = \frac{\lambda_{HS} u v}{\lambda_S u^2 - \lambda_H v^2}. \quad (12)$$

The field transformations between the interaction basis (ϕ_1, ϕ_2) and the physical mass eigenstates (h_1, h_2) are given by

$$\phi_1 = \cos \theta h_1 + \sin \theta h_2, \quad \phi_2 = -\sin \theta h_1 + \cos \theta h_2. \quad (13)$$

In what follows, we identify the field h_1 with the observed Higgs boson, discovered at the LHC in 2012, with the mass $m_{h_1} = 125$ GeV and the vacuum expectation value $v = 246$ GeV.

Free parameters in the scalar sector \rightarrow the mass of the scalar singlet m_{h_2} , the portal coupling λ_{HS} and $\sin \theta$.

Vector Sector

Three fields B_μ , W_μ^3 , and V_μ experience mixing both in the kinetic and mass sectors. A well-chosen linear transformation allows us to simultaneously bring the kinetic terms to a canonical form and diagonalize the mass matrix. As a result, we obtain one massless and two massive vector fields:

$$m_A^2 = 0, \quad m_Z^2 = (\cos \beta - \tan \alpha \sin \beta \sin \theta_W)^2 m_{Z0}^2 + \frac{\sin^2 \beta}{\cos^2 \alpha} m_{Z'0}^2, \quad (14)$$

$$m_{Z'}^2 = (\sin \beta + \tan \alpha \cos \beta \sin \theta_W)^2 m_{Z0}^2 + \frac{\cos^2 \beta}{\cos^2 \alpha} m_{Z'0}^2, \quad (15)$$

where

$$\tan 2\beta = \frac{\sin 2\alpha \sin \theta_W}{(m_{Z'0}/m_{Z0})^2 - 1 + \sin^2 \alpha (1 + \sin^2 \theta_W)}, \quad \sin \alpha = \varepsilon / \cos \theta_W, \quad (16)$$

$$m_{Z0}^2 = \frac{g_2^2 + g_1^2}{4} v^2, \quad m_{Z'0}^2 = g_V^2 u^2. \quad (17)$$

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

$$B_\mu = \cos \theta_W A_\mu - (\cos \beta \sin \theta_W - \sin \beta \tan \alpha) Z_\mu - (\sin \beta \sin \theta_W + \tan \alpha \cos \beta) Z'_\mu, \quad (18)$$

$$W_\mu^3 = \sin \theta_W A_\mu + \cos \beta \cos \theta_W Z_\mu + \sin \beta \cos \theta_W Z'_\mu, \quad (19)$$

$$V_\mu = -\frac{\sin \beta}{\cos \alpha} Z_\mu + \frac{\cos \beta}{\cos \alpha} Z'_\mu; \quad (20)$$

Free parameters in the vector sector \longrightarrow the mass of the vector boson $m_{Z'}$, the kinetic mixing parameter ε , and the gauge coupling g_V associated with the additional $U(1)_V$ symmetry.

The relevant terms from the Lagrangian (3) describing Yukawa interactions in terms of physical fields can be written as

$$\begin{aligned}
 \mathcal{L}_{\text{Yukawa}} = & - m_e \bar{e}e - m_u \bar{u}u - m_d \bar{d}d \\
 & - \cos \theta \frac{m_e}{v} h_1 \bar{e}e - \cos \theta \frac{m_u}{v} h_1 \bar{u}u - \cos \theta \frac{m_d}{v} h_1 \bar{d}d \\
 & - \sin \theta \frac{m_e}{v} h_2 \bar{e}e - \sin \theta \frac{m_u}{v} h_2 \bar{u}u - \sin \theta \frac{m_d}{v} h_2 \bar{d}d \\
 & - m_\chi \bar{\chi}\chi + \sin \theta \frac{m_\chi}{u} h_1 \bar{\chi}\chi - \cos \theta \frac{m_\chi}{u} h_2 \bar{\chi}\chi.
 \end{aligned} \tag{21}$$

After spontaneous symmetry breaking, fermion masses arise from their interactions with scalar fields. For small values of the mixing parameter $\sin \theta \ll 1$, the couplings of the Higgs boson h_1 to massive leptons and quarks remain nearly identical to those in the SM, up to $\mathcal{O}(\sin^2 \theta)$ corrections.

The couplings of the scalar singlet h_2 to SM fermions are proportional to their masses, but suppressed by the small mixing angle $\sin \theta$. The last two terms describe the interactions of the Higgs boson and the new scalar mediator with the DM fermions.

Interactions of Matter Fields with Gauge Bosons

Lepton interactions:

$$\begin{aligned}
 \mathcal{L}_{\text{leptons}} = & i\bar{e}\gamma^\mu\partial_\mu e + i\bar{\nu}_L\gamma^\mu\partial_\mu\nu_L - eA_\mu\bar{e}\gamma^\mu e \\
 & + Z_\mu\bar{e}\left(\frac{g_L^e}{2}\gamma^\mu(1-\gamma_5) + \frac{g_R^e}{2}\gamma^\mu(1+\gamma_5)\right)e + Z'_\mu\bar{e}\left(\frac{\tilde{g}_L^e}{2}\gamma^\mu(1-\gamma_5) + \frac{\tilde{g}_R^e}{2}\gamma^\mu(1+\gamma_5)\right)e \\
 & + Z_\mu\bar{\nu}_L\frac{g_L^\nu}{2}\gamma^\mu(1-\gamma_5)\nu_L + Z'_\mu\bar{\nu}_L\frac{\tilde{g}_L^\nu}{2}\gamma^\mu(1-\gamma_5)\nu_L \\
 & + \frac{e}{2\sqrt{2}\sin\theta_W}W_\mu^+\bar{\nu}_L\gamma^\mu(1-\gamma_5)e + \frac{e}{2\sqrt{2}\sin\theta_W}W_\mu^-\bar{e}\gamma^\mu(1-\gamma_5)\nu_L.
 \end{aligned} \tag{22}$$

Quark interactions:

$$\begin{aligned}
 \mathcal{L}_{\text{quarks}} = & i\bar{u}\gamma^\mu\partial_\mu u + i\bar{d}\gamma^\mu\partial_\mu d + \frac{2}{3}eA_\mu\bar{u}\gamma^\mu u - \frac{1}{3}eA_\mu\bar{d}\gamma^\mu d \\
 & + Z_\mu\bar{u}\left(\frac{g_L^u}{2}\gamma^\mu(1-\gamma_5) + \frac{g_R^u}{2}\gamma^\mu(1+\gamma_5)\right)u + Z_\mu\bar{d}\left(\frac{g_L^d}{2}\gamma^\mu(1-\gamma_5) + \frac{g_R^d}{2}\gamma^\mu(1+\gamma_5)\right)d \\
 & + Z'_\mu\bar{u}\left(\frac{\tilde{g}_L^u}{2}\gamma^\mu(1-\gamma_5) + \frac{\tilde{g}_R^u}{2}\gamma^\mu(1+\gamma_5)\right)u + Z'_\mu\bar{d}\left(\frac{\tilde{g}_L^d}{2}\gamma^\mu(1-\gamma_5) + \frac{\tilde{g}_R^d}{2}\gamma^\mu(1+\gamma_5)\right)d \\
 & + \frac{e}{2\sqrt{2}\sin\theta_W}W_\mu^+\bar{u}\gamma^\mu(1-\gamma_5)d + \frac{e}{2\sqrt{2}\sin\theta_W}W_\mu^-\bar{d}\gamma^\mu(1-\gamma_5)u.
 \end{aligned} \tag{23}$$

Interactions of Matter Fields with Gauge Bosons

The left- and right-handed couplings for leptons:

$$g_L^e = -e \frac{\cos \beta (1 - 2 \sin^2 \theta_W) + \tan \alpha \sin \beta \sin \theta_W}{\sin 2\theta_W}, \quad g_R^e = e \frac{2 \cos \beta \sin^2 \theta_W - 2 \tan \alpha \sin \beta \sin \theta_W}{\sin 2\theta_W}, \quad (24)$$

$$g_L^\nu = e \frac{\cos \beta - \tan \alpha \sin \beta \sin \theta_W}{\sin 2\theta_W}, \quad (25)$$

$$\tilde{g}_L^e = -e \frac{\sin \beta (1 - 2 \sin^2 \theta_W) - \tan \alpha \cos \beta \sin \theta_W}{\sin 2\theta_W}, \quad \tilde{g}_R^e = e \frac{2 \sin \beta \sin^2 \theta_W + 2 \tan \alpha \cos \beta \sin \theta_W}{\sin 2\theta_W}, \quad (26)$$

$$\tilde{g}_L^\nu = e \frac{\sin \beta + \tan \alpha \cos \beta \sin \theta_W}{\sin 2\theta_W}. \quad (27)$$

The left- and right-handed couplings for up- and down-type quarks:

$$g_L^u = e \frac{\cos \beta (3 - 4 \sin^2 \theta_W) + \tan \alpha \sin \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad g_R^u = -e \frac{4 \cos \beta \sin^2 \theta_W - 4 \tan \alpha \sin \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad (28)$$

$$g_L^d = -e \frac{\cos \beta (1 + 2 \cos^2 \theta_W) - \tan \alpha \sin \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad g_R^d = e \frac{2 \cos \beta \sin^2 \theta_W - 2 \tan \alpha \sin \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad (29)$$

$$\tilde{g}_L^u = e \frac{\sin \beta (3 - 4 \sin^2 \theta_W) - \tan \alpha \cos \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad \tilde{g}_R^u = -e \frac{4 \sin \beta \sin^2 \theta_W + 4 \tan \alpha \cos \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad (30)$$

$$\tilde{g}_L^d = -e \frac{\sin \beta (1 + 2 \cos^2 \theta_W) + \tan \alpha \cos \beta \sin \theta_W}{3 \sin 2\theta_W}, \quad \tilde{g}_R^d = e \frac{2 \sin \beta \sin^2 \theta_W + 2 \tan \alpha \cos \beta \sin \theta_W}{3 \sin 2\theta_W}. \quad (31)$$

Dark Matter Interactions

$$\begin{aligned} \mathcal{L}_{\text{dark matter}} = & i\bar{\chi}\gamma^\mu\partial_\mu\chi - g_V\frac{\sin\beta}{\cos\alpha}Z_\mu\bar{\chi}\gamma^\mu\left(\frac{Y_{\chi L}+Y_{\chi R}}{2}-\frac{Y_{\chi L}-Y_{\chi R}}{2}\gamma_5\right)\chi \\ & + g_V\frac{\cos\beta}{\cos\alpha}Z'_\mu\bar{\chi}\gamma^\mu\left(\frac{Y_{\chi L}+Y_{\chi R}}{2}-\frac{Y_{\chi L}-Y_{\chi R}}{2}\gamma_5\right)\chi = \end{aligned} \quad (32)$$

Dark charge $e_V = g_V/2 \rightarrow$

$$i\bar{\chi}\gamma^\mu\partial_\mu\chi + e_V\frac{\sin\beta}{\cos\alpha}Z_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - e_V\frac{\cos\beta}{\cos\alpha}Z'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi, \quad (33)$$

$$\tan 2\beta = \frac{\sin 2\alpha \sin \theta_W}{(m_{Z'0}/m_{Z0})^2 - 1 + \sin^2 \alpha (1 + \sin^2 \theta_W)}, \quad \sin \alpha = \epsilon / \cos \theta_W, \quad (34)$$

$$m_{Z0}^2 = \frac{g_2^2 + g_1^2}{4}v^2, \quad m_{Z'0}^2 = g_V^2 u^2. \quad (35)$$

The Interaction Lagrangian terms beyond the SM

$$\Delta\mathcal{L}_{\text{Scalar,SM}} = -\sin\theta \frac{m_e}{v} h_2 \bar{e}e - \sin\theta \frac{m_u}{v} h_2 \bar{u}u - \sin\theta \frac{m_d}{v} h_2 \bar{d}d; \quad (36)$$

$$\Delta\mathcal{L}_{\text{Scalar,DM}} = -2e_V \sin\theta \frac{m_\chi}{m_{Z'}} h_1 \bar{\chi}\chi - 2e_V \frac{m_\chi}{m_{Z'}} h_2 \bar{\chi}\chi. \quad (37)$$

Heavy mediators ($m_{Z'} > m_Z$):

$$\begin{aligned} \Delta\mathcal{L}_{\text{Vector,SM}} = & Z'_\mu \bar{e}\gamma^\mu [(1 - \gamma_5) + 2(1 + \gamma_5)] e + x Z'_\mu \bar{\nu}_L \gamma^\mu (1 - \gamma_5) \nu_L \\ & - \frac{x}{3} Z'_\mu \bar{u}\gamma^\mu [(1 - \gamma_5) + 4(1 + \gamma_5)] u \\ & - \frac{x}{3} Z'_\mu \bar{d}\gamma^\mu [(1 - \gamma_5) - 2(1 + \gamma_5)] d, \quad x = \varepsilon e / 4 \cos^2 \theta_W; \end{aligned} \quad (38)$$

(39)

$$\Delta\mathcal{L}_{\text{Vector,DM}} = e_V Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi + \varepsilon e_V \tan \theta_W Z_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi; \quad (40)$$

Light mediators ($m_{Z'} < m_Z$), $Z' \rightarrow A'$:

$$\Delta\mathcal{L}_{\text{Vector,SM}} = -\varepsilon e A'_\mu \bar{e}\gamma^\mu e + \frac{2}{3} \varepsilon e A'_\mu \bar{u}\gamma^\mu u - \frac{1}{3} \varepsilon e A'_\mu \bar{d}\gamma^\mu d, \quad (41)$$

$$\Delta\mathcal{L}_{\text{Vector,DM}} = -e_V A'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - \varepsilon e_V \tan \theta_W Z_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi, \quad (42)$$

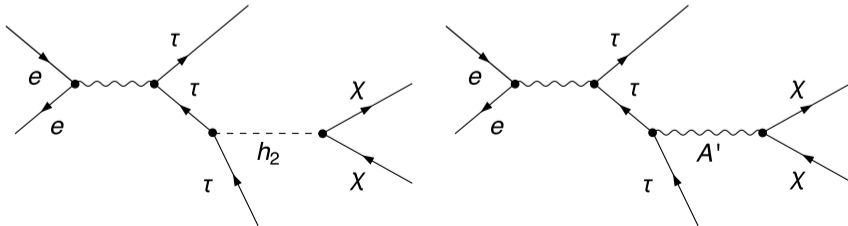
Free parameters: m_{h_2} , $m_{Z'}$, m_χ , $\sin\theta$, ε , e_V .

Associated Light Dark Matter Production in e^+e^- Collisions

Since the Yukawa interactions are proportional to the fermion masses, processes involving third-generation fermions — particularly the associated DM production with tau leptons — deserve special attention. The vector portal, realized through dark photon exchange, provides an additional contribution, enabling alternative production channels involving both visible and hidden sector particles.

The proposed e^+e^- collider STCF [1], designed to operate with high luminosity above $0.5 \times 10^{35}, \text{cm}^{-2}, \text{s}^{-1}$ at center-of-mass energies in the range $\sqrt{s} = 2-7 \text{ GeV}$, is primarily aimed at precision measurements of tau lepton properties and related phenomena. Nevertheless, its key features — energy range, low background levels, excellent resolution, and high event reconstruction efficiency — make it a promising platform for probing physics beyond the SM, including searches for light DM and associated light portal mediators.

We consider the process of associated DM production with a $\tau^+\tau^-$ pair in e^+e^- collisions at $\sqrt{s} = 7 \text{ GeV}$. In the framework of the self-consistent model, this production may be mediated either by the vector or scalar portal, as shown by the representative Feynman diagrams:



Associated Light Dark Matter Production in e^+e^- Collisions

We focus on the most natural case where the scalar and vector mediators have equal masses, $m_{h_2} = m_{A'} = m_{\text{med}}$, and take $\sin \theta = 10^{-4}$, which lies in a phenomenologically viable region of parameter space.

$e_V = \sqrt{4\pi\alpha_V}$, corresponding to assuming that $\alpha_V = 0.1$, $m_{\text{med}} = 3m_\chi$.

The Higgs boson invisible decays, $h_1 \rightarrow h_2 h_2$ and $h_1 \rightarrow \bar{\chi}\chi$, scale as $\lambda_{HS}^2 \sin^4 \theta$ and $\sin^2 \theta$, respectively \rightarrow well below the current experimental constraints, $\mathcal{B}(h_1 \rightarrow \text{inv}) < 0.11$ [2].

In analyzing the parameter space of the model, we also take into account the perturbative unitarity constraints from scalar-scalar scattering $h_i h_i \rightarrow h_j h_j$ [3].

The dimensionless parameter y , proportional to the thermally averaged DM annihilation cross section in the early Universe, is defined as

$$y = y_V + y_S, \quad (43)$$

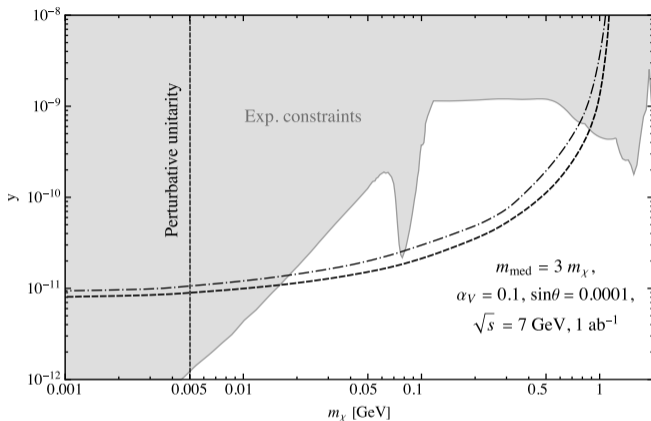
where

$$y_V = \varepsilon^2 \alpha_V \left(\frac{m_\chi}{m_{A'}} \right)^4, \quad y_S = \sin^2 \theta \alpha_S \left(\frac{m_\chi}{m_{h_2}} \right)^4, \quad (44)$$

and, for the specific case $m_{\text{med}} = m_{A'} = m_{h_2}$ and $\alpha_S = (4/9)\alpha_V$, we obtain

$$y = \left(\varepsilon^2 + \frac{4}{9} \sin^2 \theta \right) \alpha_V \left(\frac{m_\chi}{m_{\text{med}}} \right)^4. \quad (45)$$

Associated Light Dark Matter Production in e^+e^- Collisions



The dashed red line denotes the 90% C.L. sensitivity region for the process $e^+e^- \rightarrow \tau^+\tau^-(A', h_2 \rightarrow \bar{\chi}\chi)$ within the framework of the self-consistent model.

The dashed blue line corresponds to the sensitivity derived from analyzing the process $e^+e^- \rightarrow \tau^+\tau^-(A' \rightarrow \bar{\chi}\chi)$ serving as a reference scenario with DM interacting exclusively through a dark photon, evaluated under the same energy and parameter conditions [4].

The shaded exclusion regions correspond to current constraints [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

Conclusions

- ▶ The self-consistent DM model with two portal interactions developed in this work demonstrates internal theoretical consistency and offers broad potential for phenomenological applications.
- ▶ The combined presence of vector (kinetic-mixing) and scalar (Higgs) portals provides an efficient framework for describing the interactions between DM and the visible sector over a wide mass range.
- ▶ Within this model, we have formulated the full Lagrangian, obtained exact expressions for the interaction terms, and derived internally consistent parameter relations inherent to its gauge-invariant framework.
- ▶ Numerical calculations of the cross sections for the associated light DM production with a $\tau^+\tau^-$ pair in e^+e^- collisions at $\sqrt{s} = 7$ GeV, mediated by both scalar and vector portals, demonstrate that even for small scalar mixing values $\sin\theta \sim 10^{-4}$, the scalar channel contribution remains phenomenologically significant within the self-consistent framework.

Thank you for your attention!

Questions?



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