Dark matter and radiative neutrino mass with dark SU(2) gauge symmetry

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(arXiv:2106.10451)

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1. Introduction

Existence and nature of DM is mystery in physics

DM as new particle is one of the attractive scenario

- ✧**No electric charge, no color, Non-baryonic**
- ✧**Weakly interacting**
- ✧**Stable in cosmological scale**

A DM model with hidden gauge symmetry is interesting

- **DM stability from hidden gauge symmetry**
- **Dark gauge symmetry provide DM or Z' or dark photon**
- **Vector DM + Z' mediator from non-Abelian case**

Natural resonant annihilation is realized for vector DM

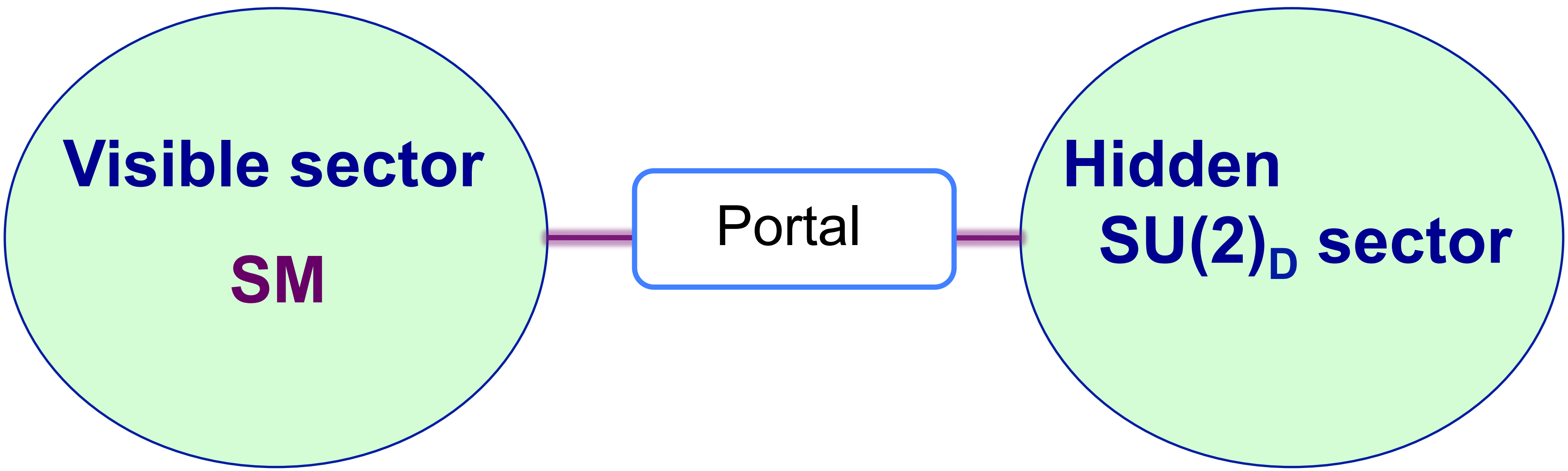
$2m_X = m_{Z'}$: when $SU(2)_H$ is broken by quintet scalar VEV

$SU(2)_H \times U(1)_{B-L}$ model C. W. Chiang, T. N, J. Tandean, (JHEP 01, 2014)

Structure of our scenario

❖Singlet under $SU(2)_D$

❖Singlet under G_{SM}



Two sector can interact via scalar mixing and/or gauge boson mixing

⇨ We consider kinetic mixing associated with $SU(2)_D$ and $U(1)_Y$

❖ In previous work we consider mass mixing in $U(1)_{B\text{-}L}$ and $SU(2)_D$

1. Introduction

For $SU(2)_D$ no generate kinetic mixing at tree level

⇨ We introduce fields charged under $SU(2)_D$ and $U(1)_Y$ to generate KM at loop level

Such new fields can be also used to generate neutrino mass

⇨ **Radiative neutrino mass**

Our scenario explain DM and neutrino mass under non-Abelian hidden gauge symmetry

2. Model

A model

❖ New field contents:

Fields	L'	N	χ	φ	Φ
$SU(2)_D$	**2**	**2**	**2**	**3**	**5**
$SU(2)_L$	**2**	**1**	**1**	**1**	**1**
$U(1)_Y$	$-\frac{1}{2}$	0	0	0	0

***New Gauge fields**

$$SU(2)_D : (X_\mu^1, X_\mu^2, X_\mu^3)$$

***Scalar fields**

Quintet: $\Phi = (\phi_2, \phi_1, \phi_0, \phi_{-1}, \phi_{-2})^T$ Triplet: $\varphi = \varphi^a \dfrac{\sigma^a}{2}$ Doublet: $\chi = \left(\chi_1, \chi_2\right)^T$

***New fermion** Bi-doublet: $L' = \begin{pmatrix} n_1' & n_2' \\ e_1' & e_2' \end{pmatrix}$ Doublet: $N = \left(n_1, n_2\right)^T$

❖ Scalar VEV and symmetry breaking

$$< \Phi >= (v_\Phi / \sqrt{2}, 0, 0, 0, 0) \qquad < \varphi >= \frac{1}{2\sqrt{2}} \begin{pmatrix} v_\varphi & 0 \\ 0 & -v_\varphi \end{pmatrix}$$

$SU(2)_D \to Z_4$

Z_4 charge [1,-1,±i] → eigenvalue of $\sigma^3/2$ [even, odd, (2n+1)/2]

❖ Z_4 charged particles are our DM candidate

Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{New}} =& -\frac{1}{4}\tilde{X}^{\alpha\mu\nu}\tilde{X}^{\alpha}_{\mu\nu} + \mathrm{Tr}[\bar{L}'(D_\mu\gamma^\mu - M_{L'})L'] + \bar{N}(\partial^\mu\gamma_\mu - M_N)N \\
&+ (D^\mu\chi)^\dagger(D_\mu\chi) + \frac{1}{2}\mathrm{Tr}[(D^\mu\varphi)^\dagger(D_\mu\varphi)] + \frac{1}{2}(D^\mu\Phi)^\dagger(D_\mu\Phi) \\
&+ f_{ia}\bar{L}^i_L L'^a_R(i\sigma_2)\chi + f'_{ia}\bar{L}^i_L L'^a_R\chi^* + g^{ab}_R\bar{L}'^a_R N^b_L\tilde{H} + g^{ab}_L\bar{L}'^a_L N^b_R\tilde{H} \\
&+ y^{ab}_{N_L}\overline{N^{ac}_L}(i\sigma_2)\varphi N^b_L + y^{ab}_{N_R}\overline{N^{ac}_R}(i\sigma_2)\varphi N^b_L + y^{ab}_D\bar{N}^a_L\varphi N^b_R + y_{ab}\bar{L}'^a\varphi L'^b \\
V =& -M_H^2 H^\dagger H + M_\chi^2\chi^\dagger\chi + \frac{1}{2}M_\varphi^2\mathrm{Tr}[\varphi\varphi] - M_\Phi^2\Phi^\dagger\Phi + \lambda_\chi(\chi^\dagger\chi)^2 + \lambda_\varphi\mathrm{Tr}[\varphi\varphi]^2 + \lambda_\Phi(\Phi^\dagger\Phi)^2 \\
&+ \lambda_H(H^\dagger H)^2 + \mu_1(\Phi^\dagger\hat{\varphi}\Phi) + \mu_2(\chi(i\sigma_2)\varphi\chi + h.c.) + \lambda_{\varphi\Phi}\mathrm{Tr}[\varphi\varphi](\Phi^\dagger\Phi) \\
&+ \lambda_{\varphi H}\mathrm{Tr}[\varphi\varphi](H^\dagger H) + \lambda_{\Phi H}(\Phi^\dagger\Phi)(H^\dagger H) + \lambda_{\chi H}(\chi^\dagger\chi)(H^\dagger H) + \lambda_{\chi\varphi}(\chi^\dagger\chi)\mathrm{Tr}[\varphi\varphi] \\
&+ \lambda_{\chi\Phi}(\chi^\dagger\chi)(\Phi^\dagger\Phi) + \tilde{\lambda}_{\varphi\Phi}\Phi^\dagger\hat{\varphi}\hat{\varphi}\Phi,
\end{aligned}
$$

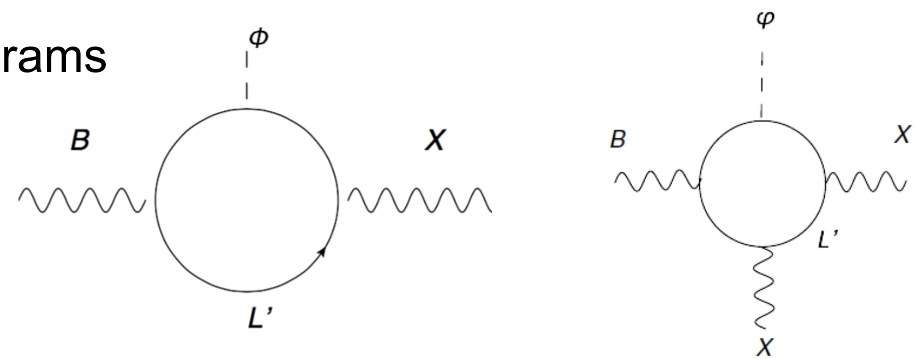
Hidden Gauge Sector with SM $U(1)_Y$

To connect $SU(2)_H$ and $U(1)_Y$ we consider one-loop effective interaction

It can be generated introducing field charged under $SU(2)_H$ and $U(1)_Y$

$SU(2)_H$ doublet fermion L' with $U(1)_Y$ charge -1/2

1-loop diagrams



Effective Lagrangian: $$\mathcal{L}_{KM} = \sum_a \frac{g_X g_B y_{aa} v_\varphi}{12\sqrt{2}\pi^2 M_{L'}} \tilde{B}_{\mu\nu} \tilde{X}^{3\mu\nu} \equiv -\frac{1}{2} \sin\chi \tilde{B}_{\mu\nu} \tilde{X}^{3\mu\nu}$$

T.N. and H. Okada arXiv:2104.09494

Hidden Gauge Sector with SM $U(1)_Y$

$$L = -\frac{1}{4}X^{a\mu\nu}X^{a}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\sin\chi X^{3\mu\nu}B_{\mu\nu}$$

$$+D^{\mu}\Phi D_{\mu}\Phi + Tr[D^{\mu}\varphi D_{\mu}\varphi]$$

Diagonalizing kinetic terms

$$B_{\mu} \to B_{\mu} - \tan\chi X^{3}_{\mu}$$
$$X^{3}_{\mu} \to \frac{1}{\cos\chi}X^{3}_{\mu}$$

For tiny χ $\Longrightarrow$

$$B_{\mu} \to B_{\mu} - \chi X^{3}_{\mu}$$
$$X^{3}_{\mu} \to X^{3}_{\mu}$$

Gauge boson mass term after symmetry breaking $X^{\pm}_{\mu} = \left(X^{1}_{\mu} \mp X^{2}_{\mu}\right)/\sqrt{2}$

$$L_M = \frac{1}{2}m^2_{Z_{SM}}\tilde{Z}_{\mu}\tilde{Z} + m^2_{Z_{SM}}\chi\sin\theta_W\tilde{Z}_{\mu}X^{3\mu} + \frac{1}{2}m^2_{X^3}X^{3}_{\mu}X^{3\mu} + m^2_{X^{\pm}}X^{+}_{\mu}X^{-\mu},$$

$$m^2_{Z_{SM}} = \frac{v^2}{4}(g^2+g^2_B), \quad m^2_{X^3} = 4g^2_X v^2_{\Phi}, \quad m^2_{X^{\pm}} = g^2_X v^2_{\Phi}\left(1+\frac{v^2_{\varphi}}{v^2_{\Phi}}\right),$$

Hidden gauge boson masses and interactions

- Z,Z' masses and Z-Z' mixing:

$$m^2_{Z,Z'} = \frac{1}{2}(m^2_{X^3} + m^2_{Z_{SM}}) \mp \frac{1}{2}\sqrt{(m^2_{X^3} - m^2_{Z_{SM}})^2 + 4\chi^2 \sin^2\theta_W m^4_{Z_{SM}}},$$

$$\tan 2\theta_{ZZ'} = \frac{2\sin\theta_W \chi m^2_{Z_{SM}}}{m^2_{Z_{SM}} - m^2_{X^3}},$$

- DM mass: $m^2_{X^\pm} = g^2_X v^2_\Phi \left(1 + \frac{v^2_\varphi}{v^2_\Phi}\right)$ $\Rightarrow$ $m_{Z'} \simeq 2m_{X^\pm}(1+R_M)^{-\frac{1}{2}}$

$$R_M \equiv v^2_\varphi / v^2_\Phi$$

- Relevant DM interactions:

$$\mathcal{L} \supset i g_X C_{ZZ'} \Big[(\partial_\mu X^+_\nu - \partial_\nu X^+_\mu) X^{-\mu} Z'^\nu - (\partial_\mu X^-_\nu - \partial_\nu X^-_\mu) X^{+\mu} Z'^\nu + \frac{1}{2}(\partial_\mu Z'_\nu - \partial_\nu Z'_\mu)(X^{+\mu}X^{-\nu} - X^{-\mu}X^{+\nu}) \Big],$$

$$\left[CZZ'(SZZ') = \cos\theta_{ZZ'} (\sin\theta_{ZZ'}) \right]$$

$$\mathcal{L}_{Z'ff} = \frac{g}{\cos\theta_W} Z'_\mu \bar{f}\gamma^\mu \left[-S_{ZZ'}(T_3 - Q\sin^2\theta_W) + C_{ZZ'}\chi Y \sin\theta_W \right] f$$

Scalar doublet mass eigenstates

Mass matrix

$$\begin{pmatrix} \chi_1^* \\ \tilde{\chi}_2^* \end{pmatrix}^T \begin{pmatrix} \tilde{M}_\chi^2 & -\sqrt{2}\mu_2 v_\varphi \\ -\sqrt{2}\mu_2 v_\varphi & \tilde{M}_\chi^2 \end{pmatrix} \begin{pmatrix} \chi_1 \\ \tilde{\chi}_2 \end{pmatrix}$$

$$\left(\begin{array}{c} \tilde{\chi}_2 \equiv \chi_2^* \\ M_\chi^2 + \frac{1}{2}\lambda_{\chi H} v^2 + \frac{1}{2}\lambda_{\chi\varphi} v_\varphi^2 + \frac{1}{2}\lambda_{\chi\Phi} v_\Phi^2 \end{array} \right)$$

Mass eigenstates

$$\begin{pmatrix} \chi_1 \\ \tilde{\chi}_2 \end{pmatrix}^T = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$m_{1,2}^2 = \tilde{M}_\chi^2 \pm \sqrt{2}\mu_2 v_\varphi$$

Hidden neutral fermion masses

Mass terms after SSB

$$\begin{aligned} L_{M_N} =& M_N^{ab}(\overline{n_1^a}n_1^b + \overline{n_2^a}n_2^b) + M_{nn}^{ab}(\overline{n_{2L}^{ca}}n_{1L}^b + \overline{n_{1L}^{ca}}n_{2L}^b) + \tilde{M}_{nn}^{ab}(\overline{n_{2R}^{ca}}n_{1R}^b + \overline{n_{1R}^{ca}}n_{2R}^b) \\ &+ M_{D_n}^{ab}(\overline{n_{1L}^a}n_{1R}^b - \overline{n_{2L}^a}n_{2R}^b) + M_{nn'}^{ab}(\overline{n_{1R}'^a}n_{1L}^b + \overline{n_{2R}'^a}n_{2L}^b) + \tilde{M}_{nn'}^{ab}(\overline{n_{1L}'^a}n_{1R}^b + \overline{n_{2L}'^a}n_{2R}^b) \\ &+ M_{L'}^{ab}(\overline{n_1'^a}n_1'^b + \overline{n_2'^a}n_2'^b), \end{aligned} \tag{31}$$

Mass terms are diagonalized by matrix V_R

⇨ Mass eigenstates: $\psi_R = V_N^T \Psi_R$

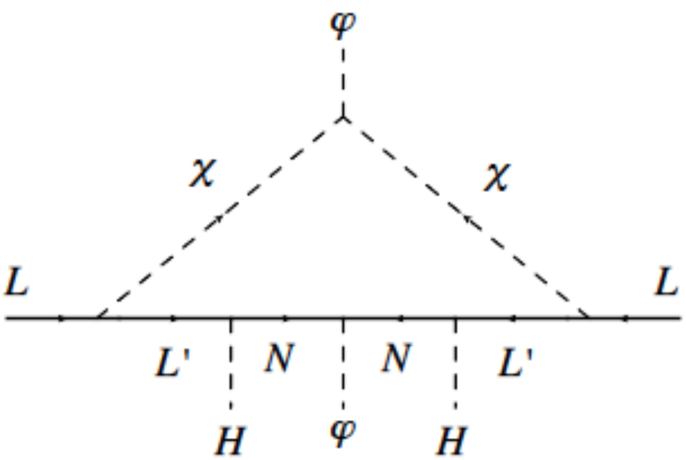
⇩

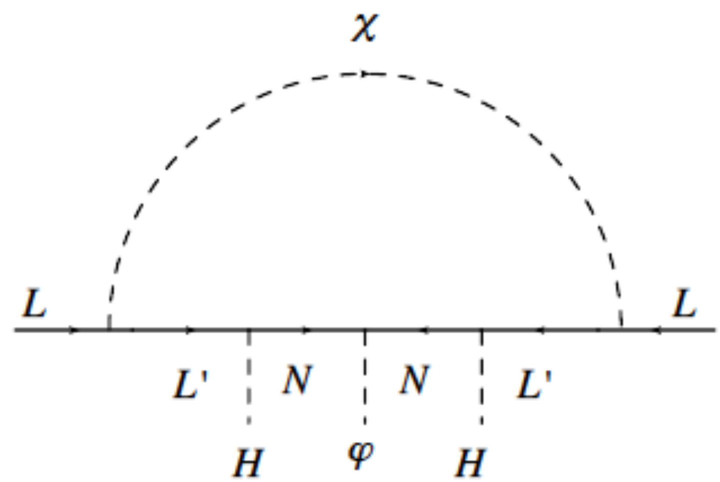
$$(n'_{1R}, n'_{2R}, n'^c_{1L}, n'^c_{2L}, n_{1R}, n_{2R}, n^c_{1L}, n^c_{2L})^T$$

Mass eigenvalues : M_x

Neutrino mass generation

Relevant one-loop diagrams





$$(M_\nu)_{ij} = \frac{M_x}{(4\pi)^2}(f^+_{ia} f^-_{jb} m_1^2 - f^-_{ia} f^+_{jb} m_2^2)(V_N)_{ax}(V_N)_{3+b,x} \int_0^1 [dX]_3 \frac{1}{xM_x^2 + ym_1^2 + zm_2^2}$$

$$\simeq 10^{-10}\mathrm{GeV}\frac{M_x}{\mathrm{TeV}} \frac{\left(f^+_{ia} f^-_{jb} \frac{m_1^2}{m_2^2} - f^-_{ia} f^+_{jb}\right)(V_N)_{ax}(V_N)_{3+b,x}}{10^{-11}} \int_0^1 [dX]_3 \frac{m_{\rho_2}^2}{xM_x^2 + ym_1^2 + zm_2^2}$$

$$\left[\; f^+_{ia} = (f + f')_{ia} \text{ and } f^-_{ia} = (f - f')_{ia} \;\right]$$

We can easily fit neutrino data using d.o.f of Yukawa couplings

3. DM phenomenology

DM candidates

Z_4 charged neutral particles are DM candidate

⇨ **Due to the nature of remnant Z_4 we have multicomponent DM**

We consider following candidates

Dark gauge boson: $X^\pm$

$SU(2)_D$ doublet Scalar: χ (lighter component)

Mass relation and DM candidate

1. $m_{X^\pm} + m_1 < m_2 \;\; \to X^\pm$ and ρ_1 are DM,
2. $m_1 + m_2 < m_{X^\pm} \;\; \to \rho_1$ and ρ_2 are DM,

Consider two cases

3. $m_2 - m_1 < m_{X^\pm} < m_1 + m_2 \;\; \to \rho_1, \rho_2$ and $X^\pm$ are DM.

Interactions among DM and Z' boson

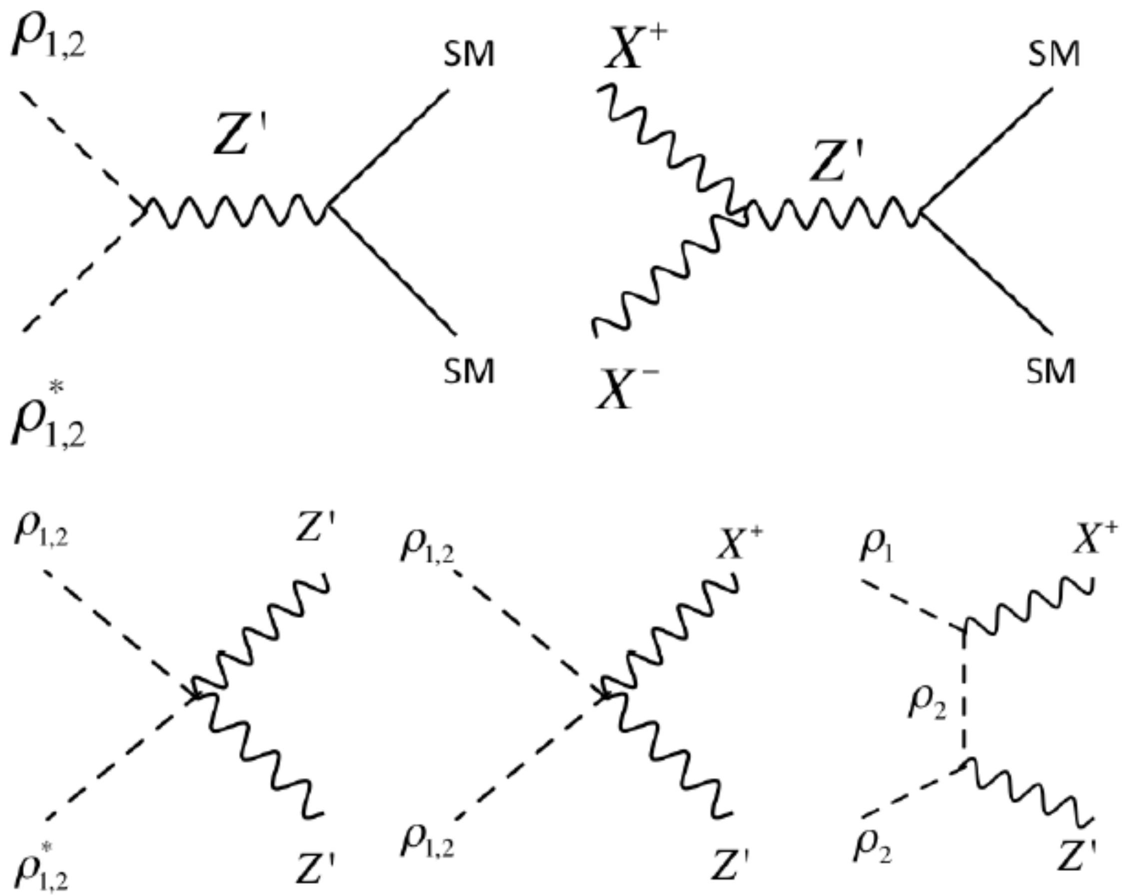
❖ **Vector DM**

$$\mathcal{L} \supset i g_X C_{ZZ'} \Big[(\partial_\mu X^+_\nu - \partial_\nu X^+_\mu) X^{-\mu} Z'^\nu - (\partial_\mu X^-_\nu - \partial_\nu X^-_\mu) X^{+\mu} Z'^\nu + \frac{1}{2} (\partial_\mu Z'_\nu - \partial_\nu Z'_\mu)(X^{+\mu} X^{-\nu} - X^{-\mu} X^{+\nu}) \Big],$$

❖ **Scalar DM**

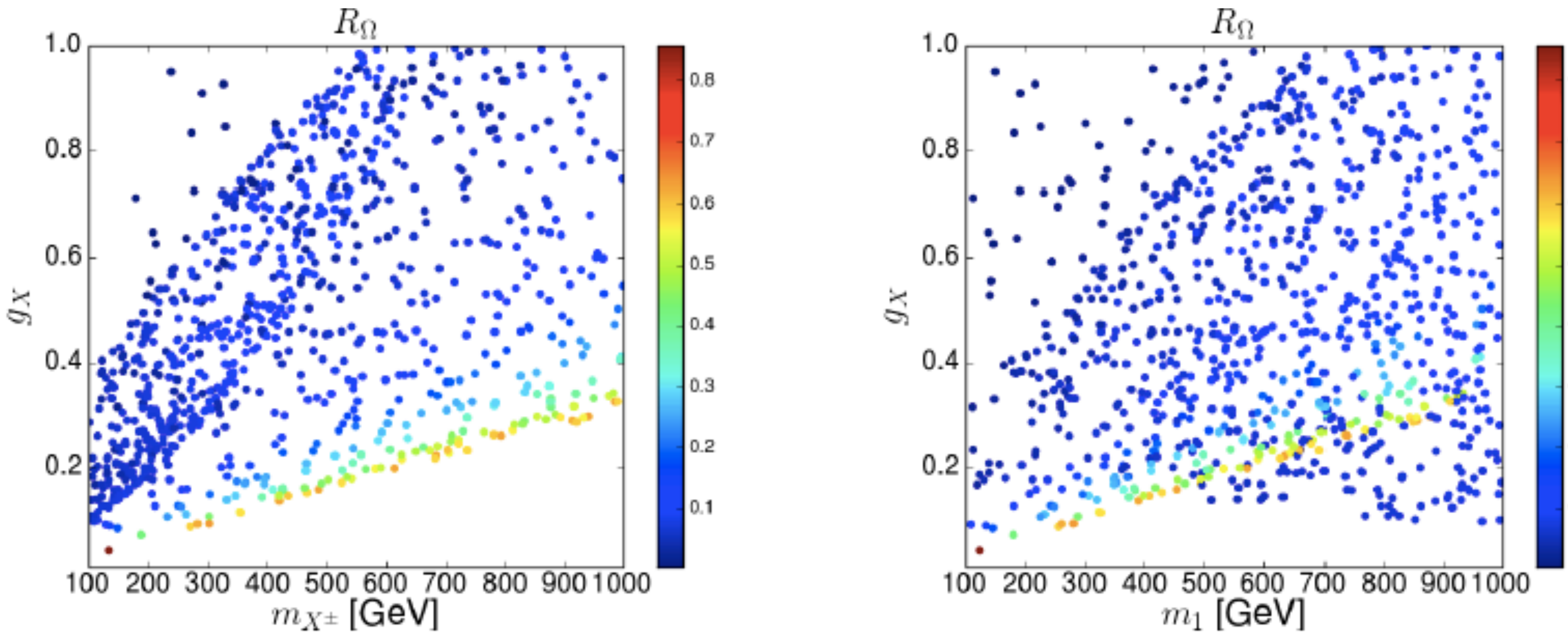
$$\begin{aligned}
\mathcal{L} \supset\ & i \frac{g_X C_{ZZ'}}{2} Z'_\mu (\rho_1^* \partial^\mu \rho_1 - \rho_1 \partial^\mu \rho_1^* + \rho_2^* \partial^\mu \rho_2 - \rho_2 \partial^\mu \rho_2^*) \\
& + i \frac{g_X}{\sqrt{2}} X^+_\mu (\rho_1^* \partial^\mu \rho_2^* - \rho_2^* \partial^\mu \rho_1^*) - i \frac{g_X}{\sqrt{2}} X^-_\mu (\rho_1 \partial^\mu \rho_2 - \rho_2 \partial^\mu \rho_1) \\
& + \frac{g_X^2}{4} C_{ZZ'}^2 Z'_\mu Z'^\mu (\rho_1^* \rho_1 + \rho_2^* \rho_2) - \frac{g_X^2}{2} (X^+_\mu Z'^\mu \rho_1^* \rho_2^* + X^-_\mu Z'^\mu \rho_1 \rho_2).
\end{aligned}$$

DM annihilation processes



- ➢ Z’ mediated annihilation into SM particles
- ➢ Semi-(co)annihilation processes of scalar DM

Parameter region realizing observed relic density



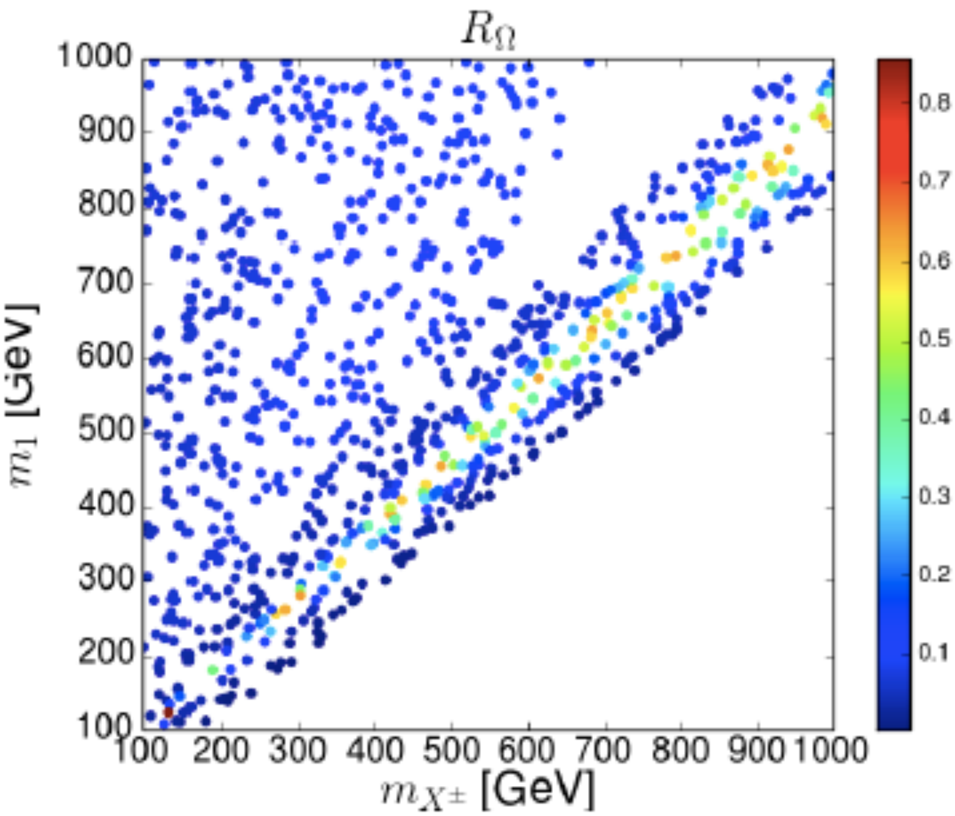
$\chi = 5\times10^{-4}$

$v_\varphi^2/v_\Phi^2 = 0.1$

$$0.11 < \Omega h^2 = (\Omega_{X^\pm} + \Omega_{\rho_1})h^2 < 0.13 \qquad R_\Omega \equiv \Omega_{X^\pm}/\Omega_{\rho_1}$$

- O(0.01)-O(1) gauge coupling for 100 GeV – 1000 GeV DM mass
- Relic density of vector DM tends to be small → due to resonanse effect

Parameter region realizing observed relic density



- $m_{X\pm} \sim m_1$ region → resonant annihilation dominate
- $m_1 > m_{X\pm}$ region → scalar DM annihilate into dark gauge bosons

Summary and discussion

Construction of model with dark SU(2) model

- ✧Remnant Z_4 symmetry as a subgroup of SU(2)
- ✧Multi DM components: vector + scalar DM
- ✧DM interaction with SM through kinetic mixing
- ✧Neutrino mass generation at one-loop level

Application to DM phenomenology

- ✧Relic density of DM
- ✧Wide parameter range to explain relic density

Appendix

Z_4 symmetry as a remnant of $SU(2)_H$

Suppose SU(2) quintet and triplet scalars Φ,Φ' get VEVs

where components with eigenvalue of T_3 is 0 and 2

$$\exp\left[iT_3\pi\right]\left|Vacuum\right\rangle = \left|Vacuum\right\rangle$$ **Remaining discrete symmetry**

Then for any particle with odd T_3 value

$$\exp\left[iT_3\pi\right]X = \exp\left[i(2n+1)\pi\right]X = -X$$

Then for any particle with (2n+1)/2 T_3 value

$$\exp\left[iT_3\pi\right]X = \exp\left[i(2n+1)\pi/2\right]X = \pm iX$$ (±:depending on n)

⇨ Z_4 symmetry

The lightest Z_4 odd particle in dark sector is DM

Scalar VEV and hidden gauge boson masses

When a component of scalar $SU(2)_H$ multiplet (characterized by l,m) gets VEV

$$\frac{g_X^2}{4}\left[(C^+_{\ell,m})^2+(C^-_{\ell,m})^2\right]v_\Phi^2 X^+_\mu X^{-\mu}+\frac{g_X^2}{2}m^2 v_\Phi^2 X^3_\mu X^{3\mu}$$

$$\equiv m^2_{X^\pm}X^+_\mu X^{-\mu}+\frac{1}{2}m^2_{X^3}X^3_\mu X^{3\mu}.$$

$$X^\pm_\mu \equiv (X^1_\mu \mp i X^2_\mu)/\sqrt{2}$$

$$C^+_{\ell,m}\equiv\sqrt{(\ell-m)(\ell+m+1)}\text{ and }C^-_{\ell,m}\equiv\sqrt{(\ell+m)(\ell-m+1)}.$$

Mass relation

$$\frac{m^2_{X^3}}{m^2_{X^\pm}}=\frac{4m^2}{(C^+_{\ell,m})^2+(C^-_{\ell,m})^2}=\frac{4m^2}{(\ell-m)(\ell+m+1)+(\ell+m)(\ell-m+1)}.$$

Z-Z' mixing

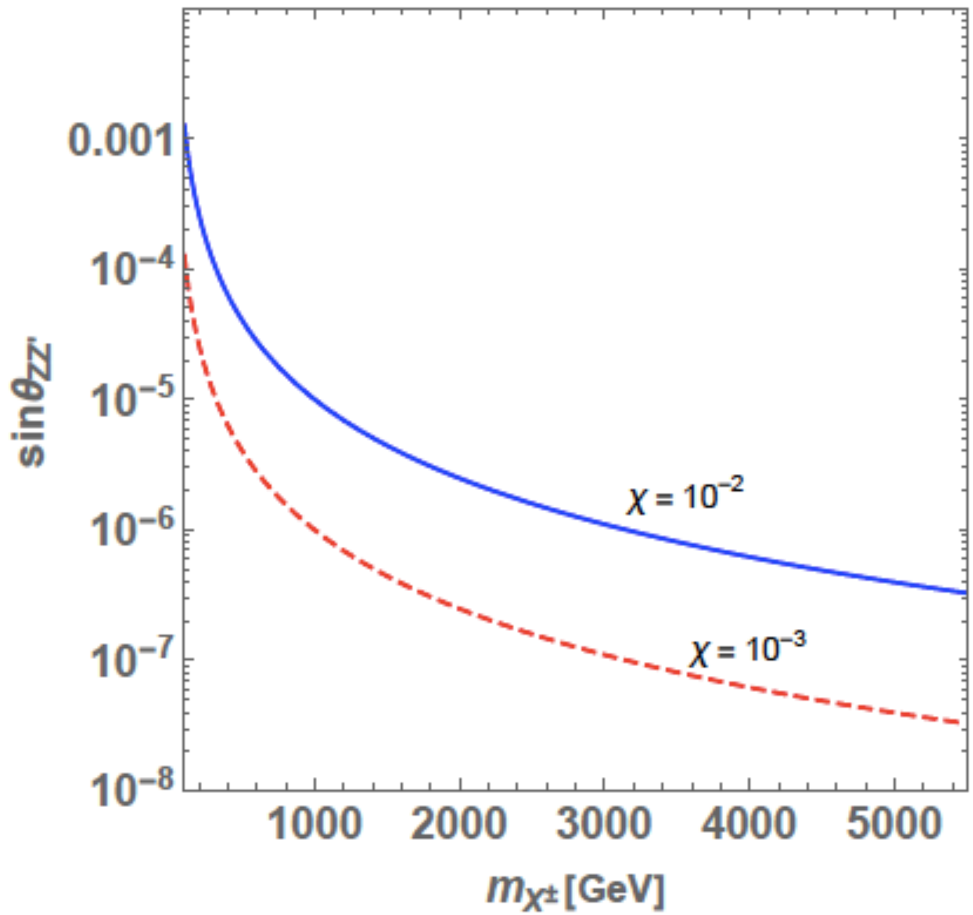


FIG. 1: $\sin\theta_{ZZ'}$ as a function of $m_{\chi^\pm}$ for $\chi = 10^{-2}$ and 10^{-3} where we fix $2v_\varphi^2/v_\Phi^2 = 0.01$.