Hidden Sector Dirac Dark Matter, Stueckelberg Z' Model, and the CDMS and XENON experiments

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with Kingman Cheung and Tzu-Chiang Yuan

Introduction

The Direct Detection

The Models
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Summary

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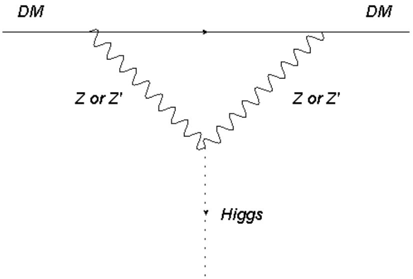
- There is a new class of models for dark matter (DM) candidates, motivated by hidden-sector models. It could be a fermion or boson inside the hidden sector.
- Here we focus on the possibility of hidden milli-charged Dirac fermion, χ as the DM candidate. And the interaction between the DM and the Standard Model (SM) particles is via Z-Z' mixing and Stueckelberg-type mixing.

Introduction

- Furthermore, we find out the effective coupling $g_{h\chi\chi}$ between the DM and Higgs boson through triangular loop of Z, Z' bosons and this gives the contribution to spin-independent cross section which may be observed in direct detection experiment such as CDMS and XENON experiments.



The Direct Detection

Suppose the effective interactions between the DM and the quarks are given by

$$\mathcal{L}_{\text{eff}} = \sum_q \{\alpha_q^S \,\overline{\chi}\chi\, \bar{q}q + \alpha_q^V \,\overline{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q\} \quad , \tag{1}$$

where α_q^S and α_q^V are the scalar and vector couplings specified respectively. Then the spin-independent cross section between the DM and the nucleon is

$$\sigma_{\chi N}^{\text{SI}} = \frac{\mu_{\chi N}^2}{\pi} \left(\left| G_s^N \right|^2 + \frac{|b_N|^2}{256} \right) , \tag{2}$$

where $\mu_{\chi N}$ is the reduce mass and G_s^N and b_N stand for the scalar and vector contributions respectively.

The Direct Detection

The vector contribution b_N contains the whole nucleus (A, Z) is $b_N \equiv \alpha_u^V(A+Z) + \alpha_d^V(2A-Z)$. By taking the average between proton and neutron, we can obtain the expression for a single nucleon.

$$b_N = \frac{3}{2}\left(\alpha_u^V + \alpha_d^V\right) \quad . \tag{3}$$

In the case of Higgs boson exchange dominance, we can write

$$\alpha_q^S = -\frac{g_{h\chi\chi} g_{hqq}}{m_h^2} \tag{4}$$

By the default values of the parameters suggested by DarkSUSY(0406204), we can further write down the cross section as (0912.4599)

$$\sigma_{\chi N}^{\mathrm{SI}} \approx \frac{g^2 m_N^4}{4\pi m_W^2} \frac{1}{m_h^4} g_{h\chi\chi}^2 (0.3766)^2 \, . \tag{5}$$

The Direct Detection

Using the XENON100 limit of $\sigma_{\chi N}^{\mathrm{SI}} \approx 7.0 \times 10^{-45}\ \mathrm{cm}^2$ (1104.2549v1) and taking $m_h = 120$ GeV, we can obtain an upper limit on the Higgs-dark-matter coupling

$$g_{h\chi\chi}^2 \lesssim 0.007 \quad . \tag{6}$$

Stueckelberg Z' Model

The Stueckelberg extension of the SM (StSM) is obtained by adding a hidden sector associated with an extra $U(1)_C$ interaction, under which the SM particles are neutral. (0606294)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm StSM}$$

with

$$\begin{aligned} \mathcal{L}_{\rm SM} &= -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i\bar{f}\gamma^\mu D_\mu f \\ &\quad + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi) \,, \end{aligned} \tag{7}$$

$$\begin{aligned} \mathcal{L}_{\rm StSM} &= -\frac{1}{4} C_{\mu\nu} C^{\mu\nu} + \frac{1}{2} (\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu)^2 \\ &\quad + \overline{\chi} \left(i\gamma^\mu D^X_\mu - M_\chi \right) \chi \,, \end{aligned} \tag{8}$$

Stueckelberg Z' Model

The covariant derivatives $D_\mu = (\partial_\mu + ig_2 \vec{T} \cdot \vec{W}_\mu + ig_Y \frac{Y}{2} B_\mu)$ and $D^X_\mu = (\partial_\mu + ig_X Q^\chi_X C_\mu)$.
After the electroweak symmetry breaking, $v \simeq 246$ GeV, the mass term for $V \equiv (C_\mu, B_\mu, W^3_\mu)^T$ is given by

$$-\frac{1}{2} V^{\mathrm{T}} M^2_{\mathrm{Stu}} V \equiv V^{\mathrm{T}} \begin{pmatrix} M_1^2 & M_1 M_2 & 0 \\ M_1 M_2 & M_2^2 + \frac{1}{4} g_Y^2 v^2 & -\frac{1}{4} g_2 g_Y v^2 \\ 0 & -\frac{1}{4} g_2 g_Y v^2 & \frac{1}{4} g_2^2 v^2 \end{pmatrix} V \,. \tag{9}$$

Since the determinant of M^2_{Stu} is zero, there is at least one zero eigenvalue to be identified as the photon mass.

Stueckelberg Z' Model

A similarity transformation O can bring the mass matrix $M^2_{\rm Stu}$ into a diagonal form

$$\begin{pmatrix} C_\mu \\ B_\mu \\ W^3_\mu \end{pmatrix} = O \begin{pmatrix} Z'_\mu \\ Z_\mu \\ A_\mu \end{pmatrix} \quad , \qquad O^{\rm T} M^2_{\rm Stu}\, O = {\rm Diag}\left[M^2_{Z'},\, M^2_Z,\, 0\right] \ . \tag{10}$$

The orthogonal matrix O is parameterized as in (0701107)

The couplings

The couplings between the neutral gauge bosons and the Higgs are given by

$$\begin{aligned}\mathcal{L}_{\mathrm{Higgs}-Z-Z'} &= \frac{1}{8}\left(H^2+2vH\right) \\ &\Big[\left(g_2 O_{32}-g_Y O_{22}\right)^2 Z_\mu Z^\mu + \left(g_2 O_{31}-g_Y O_{21}\right)^2 Z'_\mu Z'^\mu \\ &+ 2\left(g_2 O_{31}-g_Y O_{21}\right)\left(g_2 O_{32}-g_Y O_{22}\right) Z_\mu Z'^\mu\Big] \;. \qquad (11)\end{aligned}$$

The neutral current interactions are given by

$$\begin{aligned}-\mathcal{L}_{\mathrm{int}}^{NC} &= \bar{f}\,\gamma^\mu \Big[\left(\epsilon_{Z'}^{f_L} P_L + \epsilon_{Z'}^{f_R} P_R\right) Z'_\mu + \left(\epsilon_{Z}^{f_L} P_L + \epsilon_{Z}^{f_R} P_R\right) Z_\mu \\ &+ eQ_{\mathrm{em}} A_\mu\Big] f + \overline{\chi}\gamma^\mu \left[\epsilon_{Z'}^{\chi} Z'_\mu + \epsilon_{Z}^{\chi} Z_\mu + \epsilon_{\gamma}^{\chi} A_\mu\right] \chi \qquad (12)\end{aligned}$$

The couplings

Therefore, the couplings among the Higgs boson, Z and Z' are

$$\begin{aligned} C_{Z'Z'} &= \left(g_2 O_{31} - g_Y O_{21}\right)^2 O_{11}^2 \quad , \qquad (13)\\ C_{ZZ} &= \left(g_2 O_{32} - g_Y O_{22}\right)^2 O_{12}^2 \quad , \qquad (14)\\ C_{Z'Z} &= C_{ZZ'} = \sqrt{C_{Z'Z'} C_{ZZ}} \quad , \\ &= \left(g_2 O_{31} - g_Y O_{21}\right)\left(g_2 O_{32} - g_Y O_{22}\right) O_{11} O_{12} \quad . \qquad (15) \end{aligned}$$

With all these couplings and inputs we can compute the effective coupling $g_{h\chi\chi}$ and thus the spin-independent cross section $\sigma_{\chi N}^{\mathrm{SI}}$.

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- However, this milli-charged DM will loss its kinetic energy via the long range Coulomb force before it reaches the detector.
- We estimate the stopping distance by

$$\begin{aligned} L &\approx \frac{m_A^2 m_\chi v_\chi^4}{8\pi\rho\,(\tilde{\epsilon}_\gamma^\chi \alpha Z)^2 \log\left(E_R^{\max}/E_R^{\min}\right)} \\ &\approx 0.27 \left(\frac{10^{-3}}{\tilde{\epsilon}_\gamma^\chi}\right)^2 \left(\frac{m_A}{32\,\mathrm{GeV}}\right)^2 \left(\frac{16}{Z}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right) \\ &\quad \left(\frac{5\,\mathrm{g/cm^3}}{\rho}\right) \left(\frac{v_\chi}{300\,\mathrm{km/s}}\right)^4 \ [\mathrm{m}] \end{aligned} \tag{16}$$

The Tree-Level mixing

We also discuss the t-pole contributions from the Z and Z' diagrams.

$$\sigma^{\rm SI}_{\chi N} = \frac{\mu^2_{\chi N}|b_N|^2}{256\pi} \; , \tag{17}$$

where $b_N = \frac{3}{2}(\alpha^V_u + \alpha^V_d)$ and

$$\alpha^V_f = \frac{\epsilon^{\chi}_Z}{2m^2_Z}\left(\epsilon^{f_L}_Z + \epsilon^{f_R}_Z\right) + \frac{\epsilon^{\chi}_{Z'}}{2m^2_{Z'}}\left(\epsilon^{f_L}_{Z'} + \epsilon^{f_R}_{Z'}\right) \; , \tag{18}$$

We find out in the case of $m_{Z'} = 1$ Tev and $tan\phi = 0.01$, the spin-independent cross section:

$$\sigma^{\rm SI}_{\chi N} \approx 0.44 \times 10^{-45} \; [{\rm cm}^2] \; . \tag{19}$$

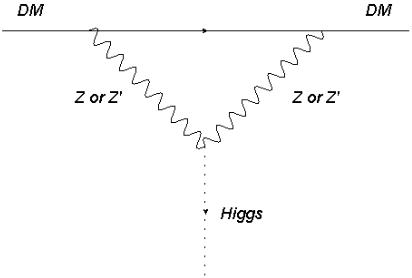
However, the long range Coulomb force interaction between the milli-charged dark matter and the nuclei may be too severe for the DM to reach the underground detector.

The Effective Couplings in Stueckelberg Z' Model

The effective coupling between the SM Higgs and the hidden milli-charged dark matter χ can be induced at one-loop level.

$$\overline{\chi}(p') \left[F(q^2) + i\gamma_5 G(q^2)\right] \chi(p)\, H \tag{20}$$

with $F(q^2)$ and $G(q^2)$ being the scalar and pseudoscalar form factors, and $q = p - p'$.



The Effective Couplings in Stueckelberg Z' Model

For on-shell χ in the initial and final states, we find that $G(q^2) = 0$ and

$$F(q^2) = -\frac{\left(g_X Q_X^\chi\right)^2}{8\pi^2}\frac{m_W m_\chi}{g_2} \sum_{(i,j)=\{(Z',Z'),(Z,Z),(Z',Z),(Z,Z')\}} C_{ij}\int_0^1 dx \int_0^x dy \frac{(1+y)}{\Delta_{ij}(x,y)}$$

where $g_X Q_X^\chi$ is the gauge coupling of the DM to the vector gauge boson in the hidden sector. And $C_{Z_i Z_j}$ are those couplings of HZZ' from Stuchelberg model.

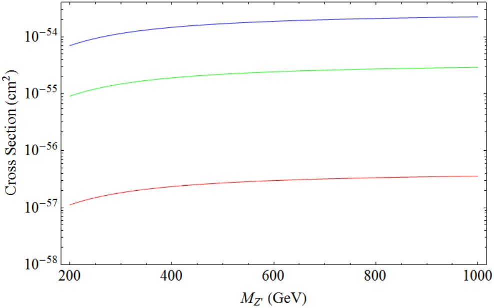
The effective Higgs-dark-matter coupling $g_{h\chi\chi}$ relevant for spin-independent cross section is then given by

$$g_{h\chi\chi} = F(q^2 = 0) \tag{21}$$

The Effective Couplings in Stueckelberg Z' Model

When tan$\phi=\frac{M_2}{M_1}$ and $M_{Z'}$ are fixed, all parameters of the Stueckelberg Z' model are fixed as well.($g_X Q_X^{\chi} = g_2$, $m_{\chi} = 100$ GeV and $m_h = 120$ GeV)

The cross section with different tanϕ.(Red:0.01, Green:0.03, and Blue:0.05)



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- We study the effective couplings which contributes to the σ_{SI} for the DM direct detection.
- The scalar contribution to the σ_{SI} from Z-Z' mixing model are well below the current CDMS II and XENON100 experiment data.
- The future XENON100 data will help us to probe the parameter space more effectively.

Thanks for your attention.

Stueckelberg Z' Model

A similarity transformation O can bring the mass matrix $M^2_{\rm Stu}$ into a diagonal form

$$\left(\begin{array}{c} C_\mu \\ B_\mu \\ W^3_\mu \end{array}\right) = O \left(\begin{array}{c} Z'_\mu \\ Z_\mu \\ A_\mu \end{array}\right) , \qquad O^{\rm T} M^2_{\rm Stu}\, O = {\rm Diag}\left[M^2_{Z'},\, M^2_Z,\, 0\right] . \tag{22}$$

The $m^2_{Z'}$ and m^2_Z are given by

$$\begin{aligned} m^2_{Z',Z} &= \frac{1}{2}\Big[M_1^2 + M_2^2 + \frac{1}{4}(g_Y^2 + g_2^2)v^2 \\ &\pm((M_1^2 + M_2^2 + \frac{1}{4}g_Y^2 v^2 + \frac{1}{4}g_2^2 v^2)^2 \\ &-(M_1^2(g_Y^2 + g_2^2)v^2 + g_2^2 M_2^2 v^2))^{1/2}\Big] \end{aligned} \tag{23}$$

Stueckelberg Z' Model

The orthogonal matrix O is parameterized as (0701107)

$$O = \begin{pmatrix} c_\psi c_\phi - s_\theta s_\phi s_\psi & s_\psi c_\phi + s_\theta s_\phi c_\psi & -c_\theta s_\phi \\ c_\psi s_\phi + s_\theta c_\phi s_\psi & s_\psi s_\phi - s_\theta c_\phi c_\psi & c_\theta c_\phi \\ -c_\theta s_\psi & c_\theta c_\psi & s_\theta \end{pmatrix} \tag{24}$$

where the angels are defined as

$$\tan\phi = \frac{M_2}{M_1},\ \tan\theta = \frac{g_Y \cos\phi}{g_2},$$
$$\tan\psi = \frac{\tan\theta\ \tan\phi\, m_W^2}{\cos\theta[m_{Z'}^2 - m_W^2(1+\tan^2\theta)]} \tag{25}$$

The couplings

The couplings between the neutral gauge bosons and the Higgs are given by

$$\begin{aligned}\mathcal{L}_{\mathrm{Higgs}-Z-Z'} &= \frac{1}{8}\left(H^2+2vH\right) \\ &\quad \Big[\left(g_2 O_{32}-g_Y O_{22}\right)^2 Z_\mu Z^\mu + \left(g_2 O_{31}-g_Y O_{21}\right)^2 Z'_\mu Z'^\mu \\ &+ 2\left(g_2 O_{31}-g_Y O_{21}\right)\left(g_2 O_{32}-g_Y O_{22}\right) Z_\mu Z'^\mu\Big] . \qquad (26)\end{aligned}$$

The couplings

The neutral current interactions are given by

$$-\mathcal{L}_{\rm int}^{NC} = \bar{f}\,\gamma^{\mu}\left[\left(\epsilon_{Z'}^{f_L}P_L+\epsilon_{Z'}^{f_R}P_R\right)\,Z'_{\mu}+\left(\epsilon_{Z}^{f_L}P_L+\epsilon_{Z}^{f_R}P_R\right)\,Z_{\mu}\right.$$
$$\left.+eQ_{\rm em}A_{\mu}\right]f+\overline{\chi}\gamma^{\mu}\left[\epsilon_{Z'}^{\chi}Z'_{\mu}+\epsilon_{Z}^{\chi}Z_{\mu}+\epsilon_{\gamma}^{\chi}A_{\mu}\right]\,\chi \quad (27)$$

The couplings

$$
\begin{aligned}
\epsilon_Z^{f_L} &= \frac{g_2}{\cos\theta}\cos\psi\left[\left(1-\epsilon\sin\theta\tan\psi\right)T_f^3-\sin^2\theta\left(1-\epsilon\csc\theta\tan\psi\right)Q_f\right] \\
\epsilon_Z^{f_R} &= -\frac{g_2}{\cos\theta}\cos\psi\sin^2\theta\left(1-\epsilon\csc\theta\tan\psi\right)Q_f \ , \\
\epsilon_{Z'}^{f_L} &= -\frac{g_2}{\cos\theta}\cos\psi\left[\left(\tan\psi+\epsilon\sin\theta\right)T_f^3-\sin^2\theta\left(\epsilon\csc\theta+\tan\psi\right)Q_f\right] \ , \\
\epsilon_{Z'}^{f_R} &= \frac{g_2}{\cos\theta}\cos\psi\sin^2\theta\left(\epsilon\csc\theta+\tan\psi\right)Q_f \ , \\
\epsilon_{V_i}^{\chi} &= g_X Q_X^{\chi} O_{1i} \ , \qquad (28
\end{aligned}
$$

and $\epsilon\equiv\tan\phi$.

Higgs Decay Channel

If kinematically allowed, the SM Higgs can decay into the invisible $\overline{\chi}\chi$ mode and its width is given by

$$\Gamma\left(h \longrightarrow \overline{\chi}\chi\right) = \frac{m_h}{8\pi}\left|F\left(m_h^2\right)\right|^2 \left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{\frac{3}{2}} \quad . \tag{29}$$

However, this decay channel is very tiny and will not affect on Higgs decay significantly.