A light in the dark sector with a Stueckelberg extension of the Standard Model

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Abstract. In this work we present a double extension to the Standard Model (SM). One of the extensions is introduced, via minimal coupling, generating a massive Z' boson. This enlarged SM is coupled to a dark matter sector through the Stueckelberg mechanism by a A' boson. However, the A' boson does not interact directly with the SM fermions. In our study, we found that the A' is a massless photon-like particle in dark sector. We obtain a new coupling between the usual photon and the dark fermions. Constraints are made on its values.

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THE MODEL

The model is a double extension of the Standard Model (SM). One of them is via minimal coupling and the second one is via Stueckelberg mechanism, where we introduce a pseudo-scalar field that decouple from the real fields and it don't interfere in the results. The model lagrangian density that represents this gauge group is written in a general form as a sum of

$$\mathscr{L} = \mathscr{L}_{\text{eSM}} + \mathscr{L}_{\text{St}}, \tag{1}$$

where the enlarged Standard Model (eSM) part is defined by

$$\begin{aligned} \mathscr{L}_{\text{eSM}} &= -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} \\ &\quad -D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi^\dagger\Phi) + i\bar{\psi}\gamma^\mu D_\mu\psi, \end{aligned} \tag{2}$$

which represents a modified SM, obtained by introducing a new $U(1)$ boson field C_μ and the field tensor $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$. This field is coupled to the other SM bosons in the covariant derivative [1]

$$D_\mu = \partial_\mu + ig_2\frac{\tau^a}{2}W^a_\mu + ig_Y\frac{Y}{2}B_\mu + ig_c\frac{1}{2}C_\mu\,, \tag{3}$$

where Φ is the usual Higgs field. The Stueckelberg dark sector lagrangian is written as [2]

$$\mathscr{L}_{\text{St}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1C_\mu + M_2X_\mu)^2 + \mathscr{L}_\chi, \tag{4}$$

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where the new $U(1)$ vector boson in the dark sector is X_μ with its field tensor $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$. The second term in (4) is the Stueckelberg coupling term between the two boson fields C_μ and X_μ via an axial pseudo-scalar σ field. The σ field is unphysical and decouples from all fields after gauge fixing. The last term $\mathscr{L}_\chi$ is a general fermion term of the dark sector. This type of model was first proposed by [3], but with just one dark field, and was applied as well in [4]. Using this full Lagrangian (1) and taking into account just the terms that contribute to the bosons masses, we obtain

$$\mathscr{L}' = \ldots - \frac{1}{2} V^{\mu\,T} M^2 V_\mu \,, \tag{5}$$

where $V^{\mu\,T} = \left(X^\mu, C^\mu, B^\mu, W^{3\mu}\right)$ and the mass matrix is

$$M^2 = \begin{pmatrix} M_2^2 & M_1 M_2 & 0 & 0 \\ M_1 M_2 & M_1^2 + \frac{g_c^2 v^2}{4} & \frac{1}{4} g_c g_Y v^2 & -\frac{1}{4} g_2 g_c v^2 \\ 0 & \frac{1}{4} g_c g_Y v^2 & \frac{g_Y^2 v^2}{4} & -\frac{1}{4} g_2 g_Y v^2 \\ 0 & -\frac{1}{4} g_2 g_c v^2 & -\frac{1}{4} g_2 g_Y v^2 & \frac{g_2^2 v^2}{4} \end{pmatrix} . \tag{6}$$

TRANSFORMATION MATRIX

Based on the matrix (6) we obtain an orthogonal matrix O, such that $O^T M^2 O = M^2_{diag}$ and $O^T O = I$. This matrix is of the form

$$O = \begin{pmatrix} c_\eta s_\phi & c_\phi c_\psi + s_\eta s_\phi s_\psi s_\theta & c_\phi s_\psi - c_\psi s_\eta s_\phi s_\theta & -c_\theta s_\eta s_\phi \\ -c_\eta c_\phi & c_\psi s_\phi - c_\phi s_\eta s_\psi s_\theta & s_\phi s_\psi + c_\phi c_\psi s_\eta s_\theta & c_\phi c_\theta s_\eta \\ s_\eta & -c_\eta s_\psi s_\theta & c_\eta c_\psi s_\theta & c_\eta c_\theta \\ 0 & c_\theta s_\psi & -c_\psi c_\theta & s_\theta \end{pmatrix} , \tag{7}$$

where $c_\theta = \cos\theta$, $s_\theta = \sin\theta$ and the angles are $\delta = \tan\phi = \frac{M_1}{M_2}$, $\tan\eta = \frac{g_C}{g_y}\cos\phi$, $\tan\theta = \frac{g_Y}{g_2}\sec\eta$ and $\tan\psi = \frac{M_W^2 \sin\eta \tan\phi \sin\theta}{M_W^2 - M_{Z'}^2 \cos^2\theta}$.

After diagonalizing the matrix (6) we obtain 4 mass eigenvalues. They are

$$\begin{aligned} M_{Z'}^2, M_Z^2 &= \frac{1}{8}\left[v^2\left(g_2^2 + g_c^2 + g_y^2\right) + 4M_1^2 + 4M_2^2 \pm \Delta\right] \\ M_\gamma^2 &= 0 \quad ; \quad M_{\gamma'}^2 = 0. \end{aligned} \tag{8}$$

where

$$\Delta = \sqrt{8M_1^2\left(4M_2^2 - v^2\left[g_2^2 - g_c^2 + g_y^2\right]\right) + \left(v^2\left[g_2^2 + g_c^2 + g_y^2\right] - 4M_2^2\right)^2 + 16M_1^4} \, .$$

We identify the masses with the Z and Z' bosons masses. One of the zero eigenvalues can be associated, as usual, to the photon and the other one to a new massless boson, which we shall call a *dark photon* γ'.

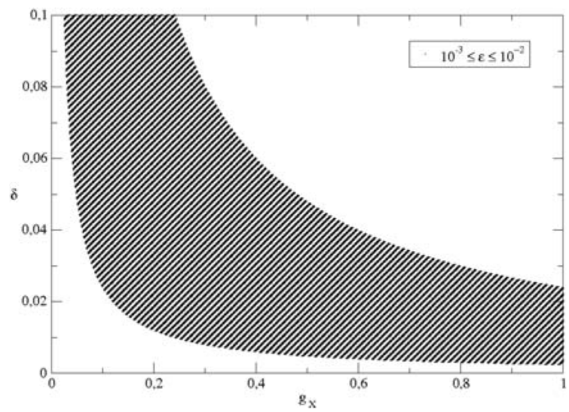

FIGURE 1. Region with the possible values for the coupling g_X with respect to parameter δ

Furthermore, the matrix O mixes the boson fields, such that $U^\mu = OV^\mu$, where $V^{T\mu} = \left(X^\mu, C^\mu, B^\mu, W^{3\mu}\right)$ and $U^{T\mu} = \left(A'^\mu, Z'^\mu, Z^\mu, A^\mu\right)$. By this mixing we redefine the coupling strength in which dark fermions couple to the standard model photon This can be written as

$$e_\chi = \varepsilon e, \tag{9}$$

where

$$\varepsilon = \frac{g_c g_X \delta}{g_c^2 + g_Y^2(1+\delta^2)} \tag{10}$$

and e is the eletric charge. In reference [5] we can see the possible values for g_c and we assume that e_χ is a fraction of the order $\approx 10^{-3}$ of the eletric charge in the same way as obtained in reference [4]. In figure 1, we present the values of g_X and δ, that generate values of $1.0 \times 10^{-3} \leq \varepsilon \leq 1.0 \times 10^{-2}$. It is important to note that the result here agree with the same paramenters values in [4].

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REFERENCES

1. P. Langacker Rev. of Mod. Phys. **81** (2009) 3.
2. E. C. G. Stueckelber, Helv. Phys. Acta **11** (1938) 225; H. Ruegg and M. Ruiz-Altaba, Int. Jour. of Mod. Phys. A **19** (2004) 3265.
3. B. Körs and P. Nath, Phys. Lett. B **586** (2004) 366; and JHEP **07** (2005) 069.
4. K. Cheung Tzu-C. Yuan, JHEP **03** (2007) 120; Y. Zhang, S. Wang and Q. Wang, JHEP **03** (2008) 047; D. Feldman, Z. Liu, P. Nath and G. Peim, Phis. Rev. D **81** (2010) 095017.
5. A.L. dos Santos, D. Hadjimichef, **arXiv**:1207.6662v1.