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Gauge $U(1)$ dark symmetry and radiative light fermion masses

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ABSTRACT

A gauge $U(1)$ family symmetry is proposed, spanning the quarks and leptons as well as particles of the dark sector. The breaking of $U(1)$ to Z_2 divides the two sectors and generates one-loop radiative masses for the first two families of quarks and leptons, as well as all three neutrinos. We study the phenomenological implications of this new connection between family symmetry and dark matter. In particular, a scalar or pseudoscalar particle associated with this $U(1)$ breaking may be identified with the 750 GeV diphoton resonance recently observed at the Large Hadron Collider (LHC).

1. Introduction

In any extension of the standard model (SM) of particle interactions to include dark matter, a symmetry is usually assumed, which distinguishes quarks and leptons from dark matter. For example, the simplest choice is Z_2 under which particles of the dark sector are odd and those of the visible sector are even. Suppose Z_2 is promoted to a gauge $U(1)$ symmetry, then the usual assumption is that it will not affect ordinary matter. These models all have a dark vector boson which couples only to particles of the dark sector.

In this paper, it is proposed instead that a gauge $U(1)$ extension of the SM spans both ordinary and dark matter. It is in fact also a horizontal family symmetry. It has a number of interesting consequences, including the radiative mass generation of the first two families of quarks and leptons as well as all three neutrinos, and a natural explanation of the 750 GeV diphoton resonance recently observed [1,2] at the Large Hadron Collider (LHC).

2. New gauge $U(1)_D$ symmetry

The framework that radiative fermion masses and dark matter are related has been considered previously [3]. Here it is further proposed that families are distinguished by the connecting dark symmetry. In Table 1 we show how they transform under $U(1)_D$ as well as the other particles of the dark sector. The choice of $U(1)_D$ is motivated by the well-known L_e–L_μ gauge symmetry [4] where anomaly cancellation occurs between the first two lepton families. Here it corresponds to the difference of $B-L-2Y$ between the first two quark and lepton families. This $U(1)_D$ symmetry is broken spontaneously by the vacuum expectation value $\langle\sigma_{1,2}\rangle = u_{1,2}$ to an exactly conserved Z_2 which divides the two sectors.

Table 1
Particle content of proposed model of gauge $U(1)$ dark symmetry.

Particles	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_D$	Z_2
$Q = (u, d)$	3	2	1/6	0, 0, 0	+
u^c	3*	1	−2/3	1, −1, 0	+
d^c	3*	1	1/3	−1, 1, 0	+
$L = (\nu, e)$	1	2	−1/2	0, 0, 0	+
e^c	1	1	1	−1, 1, 0	+
$\Phi = (\phi^+, \phi^0)$	1	2	1/2	0	+
σ_1	1	1	0	1	+
σ_2	1	1	0	2	+
N, N^c	1	1	0	1/2, −1/2	−
S, S^c	1	1	0	−3/2, 3/2	−
(η^0, η^-)	1	2	−1/2	1/2	−
χ^0	1	1	0	1/2	−
χ^-	1	1	−1	−1/2	−
$(\xi^{2/3}, \xi^{-1/3})$	3	2	1/6	1/2	−
$\zeta^{2/3}$	3	1	2/3	−1/2	−
$\zeta^{-1/3}$	3	1	−1/3	−1/2	−

The gauge $U(1)_D$ symmetry is almost absent of axial-vector anomalies for each family. The $[SU(3)]^2U(1)_D$ anomaly is zero from the cancellation between u^c and d^c. The $[SU(2)]^2U(1)_D$ anomaly is zero because Q and L do not transform under $U(1)_D$.

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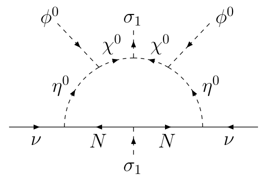

Fig. 1. One-loop neutrino mass from trilinear couplings.

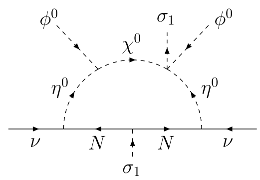

Fig. 2. One-loop neutrino mass from trilinear and quadrilinear couplings.

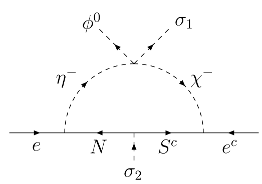

Fig. 3. One-loop electron mass.

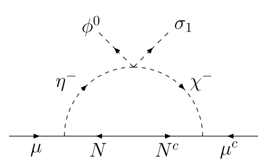

Fig. 4. One-loop muon mass.

The $[U(1)_Y]^2U(1)_D$ and $U(1)_Y[U(1)_D]^2$ anomalies are canceled among u^c, d^c, and e^c, i.e.

$$3\left(-\frac{2}{3}\right)^2(1)+3\left(\frac{1}{3}\right)^2(-1)+(1)^2(-1)=0, \tag{1}$$

$$3\left(-\frac{2}{3}\right)(1)^2+3\left(\frac{1}{3}\right)(-1)^2+(1)(-1)^2=0. \tag{2}$$

The $[U(1)_D]^3$ anomaly is not zero for either the first or second family, but is canceled between the two.

3. Radiative masses for neutrinos and the first and second families

At tree level, only t, b, τ acquire masses from $\langle\phi^0\rangle = v$ as in the SM. The first two families are massless because of the $U(1)_D$ symmetry. Neutrinos acquire one-loop masses through the scotogenic mechanism [5] as shown in Figs. 1 and 2. With one copy of (N, N^c), only one neutrino becomes massive. To have three massive scotogenic neutrinos, three copies of (N, N^c) are needed. The one-loop electron and muon masses are shown in Figs. 3 and 4. Note that at least two copies of (N, N^c) are needed for two charged-lepton masses. The mass matrix spanning (N, N^c, S, S^c) is of the form

$$\mathcal{M}_{N,S}=\begin{pmatrix} f_1u_1 & m_N & f_3u_1 & f_5u_2 \\ m_N & f_2u_1 & f_6u_2 & f_4u_1 \\ f_3u_1 & f_6u_2 & 0 & m_S \\ f_5u_2 & f_4u_1 & m_S & 0 \end{pmatrix}. \tag{3}$$

Note that the $f_{1,2,3,4}u_1$ terms break lepton number by two units, whereas the $f_{5,6}u_2$ terms do not.

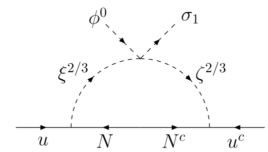

Fig. 5. One-loop u quark mass.

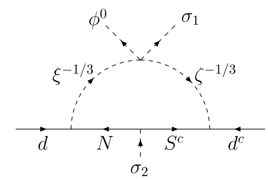

Fig. 6. One-loop d quark mass.

Lepton number $L = 1$ may be assigned to e, μ, τ, N, S and $L = -1$ to $e^c, \mu^c, \tau^c, N^c, S^c$. It is broken down to lepton parity $(-1)^L$ only by neutrino masses. The analogous one-loop u and d quark masses are shown in Figs. 5 and 6. Because the second family has opposite $U(1)_D$ charge assignments relative to the first, the c and s quarks reverse the roles of u and d. Two copies of (S, S^c) are needed to obtain the most general quark mass matrices for both the u and d sectors.

To evaluate the one-loop diagrams of Figs. 1 to 6, we note first that each is a sum of simple diagrams with one internal fermion line and one internal scalar line. Each contribution is infinite, but the sum is finite. There are 10 neutral Majorana fermion fields, spanning 3 copies of N, N^c and 2 copies of S, S^c. We denote their mass eigenstates as ψ_k with mass M_k. There are 4 real scalar fields, spanning $\sqrt{2}Re(\eta^0)$, $\sqrt{2}Im(\eta^0)$, $\sqrt{2}Re(\chi^0)$, $\sqrt{2}Im(\chi^0)$. We denote their mass eigenstates as ρ_l^0 with mass m_l. In Figs. 1 and 2, let the $\nu_i\psi_k\bar{\eta}^0$ coupling be h^ν_{ik}, then the radiative neutrino mass matrix is given by [5]

$$(\mathcal{M}_\nu)_{ij}=\sum_k \frac{h^\nu_{ik}h^\nu_{jk}M_k}{16\pi^2}\sum_l[(y_l^R)^2F(x_{lk})-(y_l^I)^2F(x_{lk})], \tag{4}$$

where $\sqrt{2}Re(\eta^0)=\sum_l y_l^R\rho_l^0$, $\sqrt{2}Im(\eta^0)=\sum_l y_l^I\rho_l^0$, with $\sum_l(y_l^R)^2=\sum_l(y_l^I)^2=1$, $x_{lk}=m_l^2/M_k^2$, and the function F is given by

$$F(x)=\frac{x\ln x}{x-1}. \tag{5}$$

There are two charged scalar fields, spanning $\eta^\pm, \chi^\pm$. We denote their mass eigenstates as ρ_r^+ with mass m_r. In Fig. 3, let the $e_L\psi_k\eta^+$ and the $e_L^c\psi_k\chi^-$ couplings be h_k^e and $h_k^{e^c}$, then

$$m_e=\sum_k \frac{h_k^e h_k^{e^c}M_k}{16\pi^2}\sum_r y_r^\eta y_r^\chi F(x_{rk}), \tag{6}$$

where $\eta^+=\sum_r y_r^\eta\rho_r^+$, $\chi^+=\sum_r y_r^\chi\rho_r^+$, with $\sum_r(y_r^\eta)^2=\sum_r(y_r^\chi)^2=1$ and $\sum_r y_r^\eta y_r^\chi=0$. A similar expression is obtained for m_μ, as well as the light quark masses.

4. Tree-level flavor-changing neutral couplings

Since different $U(1)_D$ charges are assigned to (u^c, c^c, t^c) as well as (d^c, s^c, b^c), there are unavoidable flavor-changing neutral currents. In the gauge sector, it does not affect the SM Z couplings because there is no tree-level Z–Z_D mixing, but the Z_D couplings themselves are in general flavor-changing after diagonalization of the quark mass matrices. Even though Z_D is heavy, these effects are potentially dangerous as they may induce K^0–$\bar{K}^0$ mixing, etc. They can be minimized by the following assumptions. Let the two 3×3 quark mass matrices linking (u,c,t) to (u^c,c^c,t^c) and (d,s,b) to (d^c,s^c,b^c) be of the form

$$\mathcal{M}_u = U_L^{(u)}\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}, \quad \mathcal{M}_d = U_L^{(d)}\begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}, \tag{7}$$

where $U_{CKM} = (U_L^{(u)})^\dagger U_L^{(d)}$ is the quark charged-current mixing matrix. Since Z_D does not couple to left-handed quarks, and its couplings to right-handed quarks have been chosen to be diagonal in their mass eigenstates, flavor-changing neutral currents are absent in this sector. Of course, they will appear in the scalar sector, and further phenomenological constraints on its parameters will apply.

However, since there is only one Higgs doublet Φ which is responsible for all of electroweak symmetry breaking, all quark masses must come from $\langle\phi^0\rangle = v$. Hence the physical Higgs boson $h = \sqrt{2}(Re\phi^0 - v)$ couples to all diagonal terms of the quark mass matrices according to $m_q(1+\epsilon)/v\sqrt{2}$. In the case of tree-level Higgs couplings for the t and b quarks, $\epsilon = 0$. For the first two families, ϵ is not zero because of their radiative masses [6,7]. If ϵ is negligible, the unitary matrices of Eq. (7) also diagonalize the Higgs coupling matrices, resulting thus in the absence of flavor-changing neutral interactions. The residual off-diagonal entries come from nonzero ϵ but are also suppressed by small quark masses. Since the value of ϵ in each case depends on the scalar quark masses and their interactions [6,7], a full analysis is not simple and will be left to a future study.

5. Z_D gauge boson

As $\sigma_{1,2}$ acquire vacuum expectation values $u_{1,2}$ respectively, the Z_D gauge boson obtains a mass given by

$$m^2_{Z_D} = 2g_D^2(u_1^2 + 4u_2^2). \tag{8}$$

Since $\sigma_{1,2}$ do not transform under the SM, and Φ does not under $U(1)_D$, there is no mixing between Z_D and Z. Using Table 1 and assuming that all new particles are lighter than Z_D, the branching fraction of Z_D to $e^-e^+ + \mu^-\mu^+$ is estimated to be 0.07. The $c_{u,d}$ coefficients used in the experimental search [8,9] of Z_D are then

$$c_u = c_d = g_D^2\ (0.07). \tag{9}$$

For $g_D = 0.3$, a lower bound of about 3.1 TeV on m_{Z_D} is obtained from LHC data based on the 7 and 8 TeV runs. For our subsequent discussion, let $u_1 = 1$ TeV, $u_2 = 4$ TeV, then $m_{Z_D} = 3.4$ TeV. Note that Z_D does not couple to the third family, so if $\bar{t}t$, $\bar{b}b$, or $\tau^+\tau^-$ final states are observed, this model is ruled out.

6. Scalar sector

There are three scalars with integral charges under $U(1)_D$, i.e. Φ and $\sigma_{1,2}$. Whereas $\langle\phi^0\rangle = v$ breaks the electroweak $SU(2)_L \times U(1)_Y$ gauge symmetry as in the SM, $\langle\sigma_{1,2}\rangle = u_{1,2}$ break $U(1)_D$ to Z_2, with all those particles with half-integral $U(1)_D$ charges becoming odd under this exactly conserved dark Z_2 parity. The relevant scalar potential is given by

$$\begin{aligned} V = {} & \mu_0^2\Phi^\dagger\Phi + m_1^2\sigma_1^*\sigma_1 + m_2^2\sigma_2^*\sigma_2 + m_{12}\sigma_1^2\sigma_2^* + m_{12}(\sigma_1^*)^2\sigma_2 \\ & + \frac{1}{2}\lambda_0(\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_1(\sigma_1^*\sigma_1)^2 + \frac{1}{2}\lambda_2(\sigma_2^*\sigma_2)^2 \\ & + \lambda_3(\sigma_1^*\sigma_1)(\sigma_2^*\sigma_2) + \lambda_4(\Phi^\dagger\Phi)(\sigma_1^*\sigma_1) \\ & + \lambda_5(\Phi^\dagger\Phi)(\sigma_2^*\sigma_2), \end{aligned} \tag{10}$$

where m_{12} has been rendered real by absorbing the relative phase between $\sigma_{1,2}$. The conditions for v and $u_{1,2}$ are

$$0 = \mu_0^2 + \lambda_0 v^2 + \lambda_4 u_1^2 + \lambda_5 u_2^2, \tag{11}$$

$$0 = m_1^2 + \lambda_1 u_1^2 + \lambda_3 u_2^2 + \lambda_4 v^2 + 2m_{12}u_2, \tag{12}$$

$$0 = m_2^2 + \lambda_2 u_2^2 + \lambda_3 u_1^2 + \lambda_5 v^2 + m_{12}u_1^2/u_2. \tag{13}$$

As in the SM, $\phi^\pm$ and $\sqrt{2}Im(\phi^0)$ become longitudinal components of $W^\pm$ and Z, and $\sqrt{2}Re(\phi^0) = h$ is the one physical Higgs boson associated with electroweak symmetry breaking. Let $\sigma_1 = (\sigma_{1R} + i\sigma_{1I})/\sqrt{2}$ and $\sigma_2 = (\sigma_{2R} + i\sigma_{2I})/\sqrt{2}$, then the mass-squared matrix spanning $h, \sigma_{1R,2R}$ is

$$\mathcal{M}_R^2 = \begin{pmatrix} 2\lambda_0 v^2 & 2\lambda_4 v u_1 & 2\lambda_5 v u_2 \\ 2\lambda_4 v u_1 & 2\lambda_1 u_1^2 & 2\lambda_3 u_1 u_2 + 2m_{12}u_1 \\ 2\lambda_5 v u_2 & 2\lambda_3 u_1 u_2 + 2m_{12}u_1 & 2\lambda_2 u_2^2 - m_{12}u_1^2/u_2 \end{pmatrix}, \tag{14}$$

and that spanning $\sigma_{1I,2I}$ is

$$\mathcal{M}_I^2 = \begin{pmatrix} -4m_{12}u_2 & 2m_{12}u_1 \\ 2m_{12}u_1 & -m_{12}u_1^2/u_2 \end{pmatrix}. \tag{15}$$

The linear combination $(u_1\sigma_{1I} + 2u_2\sigma_{2I})/\sqrt{u_1^2 + 4u_2^2}$ has zero mass and becomes the longitudinal component of the massive Z_D gauge boson. The orthogonal component is a pseudoscalar, call it A, with a mass given by $m_A^2 = -m_{12}(u_1^2 + 4u_2^2)/u_2$. In Eq. (14), σ_{1R} and σ_{2R} mix in general. For simplicity, let $m_{12} = -\lambda_3 u_2$, then for $v^2 << u^2_{1,2}$, we obtain

$$m^2_{\sigma_{1R}} = 2\lambda_1 u_1^2, \quad m^2_{\sigma_{2R}} = 2\lambda_2 u_2^2 + \lambda_3 u_1^2, \quad m_A^2 = \lambda_3(u_1^2 + 4u_2^2), \tag{16}$$

$$m_h^2 = 2\left[\lambda_0 - \frac{\lambda_4^2}{\lambda_1} - \frac{2\lambda_5^2 u_2^2}{2\lambda_2 u_2^2 + \lambda_3 u_1^2}\right] v^2. \tag{17}$$

7. Relevance to the diphoton excess

Any one of the three particles $\sigma_{1R}, \sigma_{2R}, A$ may be identified with the 750 GeV diphoton excess. For illustration, let us consider σ_{1R}. The production cross section through gluon fusion is given by

$$\hat{\sigma}(gg \to \sigma_{1R}) = \frac{\pi^2}{8m_{\sigma_{1R}}}\Gamma(\sigma_{1R} \to gg)\delta(\hat{s} - m^2_{\sigma_{1R}}). \tag{18}$$

For the LHC at 13 TeV, the diphoton cross section is roughly [10]

$$\sigma(gg \to \sigma_{1R} \to \gamma\gamma) \simeq (100\ \text{pb}) \times (\lambda_g\ \text{TeV})^2 \times B(\sigma_{1R} \to \gamma\gamma), \tag{19}$$

where λ_g is the effective coupling of σ_{1R} to two gluons, normalized by

$$\Gamma(\sigma_{1R} \to gg) = \frac{\lambda_g^2}{8\pi}m^3_{\sigma_{1R}}, \tag{20}$$

and the corresponding λ_γ comes from

$$\Gamma(\sigma_{1R} \to \gamma\gamma) = \frac{\lambda_\gamma^2}{64\pi}m^3_{\sigma_{1R}}. \tag{21}$$

If σ_{1R} decays only to two gluons and two photons, and assuming $\lambda_\gamma^2/8 << \lambda_g^2$, then

$$\sigma(gg \to \sigma_{1R} \to \gamma\gamma) \simeq (100\ \text{pb}) \times (\lambda_\gamma\ \text{TeV})^2/8, \tag{22}$$

which is supposed to be about 6.2 fb from the recent data [1,2]. This means that $\lambda_\gamma \simeq 2.2 \times 10^{-2}$ (TeV)$^{-1}$, and $\Gamma(\sigma_{1R} \to \gamma\gamma) \simeq$ 1 MeV.

Now σ_{1R} couples to the new scalars $\xi^{2/3}, \xi^{-1/3}, \zeta^{2/3}, \zeta^{-1/3}, \eta^-, \chi^-$ through $\sqrt{2}u_1$ multiplied by the individual quartic scalar couplings. For simplicity, let all these couplings be the same, say λ_σ, and all the masses be the same, say m_0, then [11]

$$\lambda_\gamma = \frac{\alpha u_1 \lambda_\sigma}{\sqrt{2}\pi m^2_{\sigma_{1R}}}\left[6\left(\frac{2}{3}\right)^2 + 6\left(-\frac{1}{3}\right)^2 + 2(-1)^2\right] f\left(\frac{m_0^2}{m^2_{\sigma_{1R}}}\right), \tag{23}$$

where the function f is given by

$$f(x) = 8x\left[\arctan\left(\frac{1}{\sqrt{4x-1}}\right)\right]^2 - 2. \tag{24}$$

Let $m_0 = 700$ GeV, then $x = 0.87$ and $f = 1.23$. Hence for $u_1 =$ 1 TeV and $\lambda_\sigma = 1.1$, the required $\lambda_\gamma \simeq 0.022$ (TeV)$^{-1}$ is obtained. For this λ_σ, we find $\lambda_g = 0.128$, hence $\Gamma(\sigma_{1R} \to gg) \simeq 0.27$ GeV, which is below the energy resolution of ATLAS and CMS. This narrow width is not favored by the ATLAS data, but cannot be ruled out at this time.

8. Dark matter

The lightest neutral particle with odd Z_2 is a good dark-matter candidate. In this model, it could be the lightest scalar particle in the sector consisting of $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ and $\chi^0 = (\chi_R + i\chi_I)/\sqrt{2}$. There are two sectors, the mass-squared matrix spanning η_R, χ_R is given by

$$\mathcal{M}_R^2 = \begin{pmatrix} m_\eta^2 & A \\ A & m_\chi^2 + C \end{pmatrix}, \tag{25}$$

and that spanning η_I, χ_I is

$$\mathcal{M}_I^2 = \begin{pmatrix} m_\eta^2 & B \\ B & m_\chi^2 - C \end{pmatrix}, \tag{26}$$

where A, B come from the $\phi^0\eta^0(\chi^0)^*$ and $\phi^0\eta^0\chi^0(\sigma_1)^*$ couplings and C from the $\chi^0\chi^0(\sigma_1)^*$ coupling. The phenomenology of the lightest particle in this group is similar to that of the so-called inert Higgs doublet model [5,12,13]. For details, see for example recent updates [14–16].

9. Conclusion

A new idea linking family symmetry to dark symmetry is proposed using a gauge $U(1)_D$ symmetry, which breaks to exactly conserved Z_2. The first and second families of quarks and leptons transform under this $U(1)_D$ so that their masses are forbidden at tree level. They interact with the dark sector in such a way that they acquire one-loop finite masses, together with all three neutrinos. The extra Z_D gauge boson may have a mass of order a few TeV, and one particle associated with the breaking of $U(1)_D$ may be identified with the 750 GeV diphoton excess recently observed at the LHC.

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