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Compendium of Models from a Gauge U(1) Framework

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Abstract

A gauge $U(1)$ framework was established in 2002 to extend the supersymmetric standard model. It has many possible realizations. Whereas all have the necessary and sufficient ingredients to explain the possible 750 GeV diphoton excess, observed recently by the ATLAS Collaboration at the Large Hadron Collider (LHC), they differ in other essential aspects. A compendium of such models is discussed.

1 Introduction

The recent announcement [1] by the ATLAS Collaboration at the Large Hadron Collider (LHC) of a diphoton excess around 750 GeV has excited the high-energy phenomenology community in recent weeks. In a short note [2], I have pointed out that a gauge $U(1)$ framework I established in 2002 [3] has exactly all the necessary and sufficient particles and interactions for explaining this observation. There are actually many explicit realizations of this proposal. All contain the ingredients to accommodate the diphoton excess, but they differ in other essential aspects, such as neutrino mass, leptoquark, or diquark interactions, etc. This paper discusses each in turn. One specific version was already studied in 2010 [4].

Table 1: Particle content of gauge $U(1)$ framework.

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X : (A)$	$U(1)_X : (B)$
$Q = (u, d)$	3	2	1/6	n_1	n_1
u^c	3^*	1	$-2/3$	$(7n_1 + 3n_4)/2$	$5n_1$
d^c	3^*	1	1/3	$(7n_1 + 3n_4)/2$	$2n_1 + 3n_4$
$L = (\nu, e)$	1	2	$-1/2$	n_4	n_4
e^c	1	1	1	$(9n_1 + n_4)/2$	$3n_1 + 2n_4$
N^c	1	1	0	$(9n_1 + n_4)/2$	$6n_1 - n_4$
ϕ_1	1	2	$-1/2$	$-3(3n_1 + n_4)/2$	$-3(n_1 + n_4)$
ϕ_2	1	2	1/2	$-3(3n_1 + n_4)/2$	$-6n_1$
S_1	1	1	0	$-(3n_1 + n_4)$	$-(3n_1 + n_4)$
S_2	1	1	0	$-2(3n_1 + n_4)$	$-2(3n_1 + n_4)$
S_3	1	1	0	$3(3n_1 + n_4)$	$3(3n_1 + n_4)$
U	3	1	2/3	$-4n_1 - 2n_4$	$-6n_1$
D	3	1	$-1/3$	$-4n_1 - 2n_4$	$-6n_1$
U^c	3^*	1	$-2/3$	$-5n_1 - n_4$	$-3(n_1 + n_4)$
D^c	3^*	1	1/3	$-5n_1 - n_4$	$-3(n_1 + n_4)$

The particle content of this gauge $U(1)_X$ extension of the supersymmetric standard model is fixed. Whereas certain interactions are mandatory, others are not. As explained in Ref. [3], different models come from choosing one of two classes of solutions: (A) or (B). For each, there is also the ratio of two charges which may vary. Hence there are many possible models within this framework. Each will have all the mandatory interactions required to explain the 750 GeV observation, but will have different predictions regarding other phenomena.

2 Generic Solutions of Classes (A) and (B)

Consider the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ with the particle content of Ref. [3] as shown in Table 1. There are three copies of $Q, u^c, d^c, L, e^c, N^c, S_1, S_2$; two copies of U, U^c, S_3; and one copy of ϕ_1, ϕ_2, D, D^c. The following terms of the superpotential are always allowed:

$$Qu^c\phi_2, \quad Qd^c\phi_1, \quad Le^c\phi_1, \quad LN^c\phi_2, \quad S_3\phi_1\phi_2, \tag{1}$$

$$S_3UU^c, \quad S_3DD^c, \quad S_1S_2S_3. \tag{2}$$

The charges n_1 and n_4 are arbitrary, except that $3n_1 + n_4 \neq 0$ is required to forbid the $\mu\phi_1\phi_2$ term of the minimal supersymmetric standard model (MSSM). Hence S_3 always has the interactions which allow it to be produced by gluon fusion in one loop as shown in Fig. 1, and then decays in one loop to two photons as shown in Fig. 2. It may also decay into S_1S_2

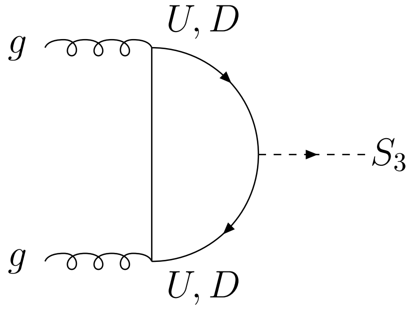

Figure 1: One-loop production of S_3 by gluon fusion.

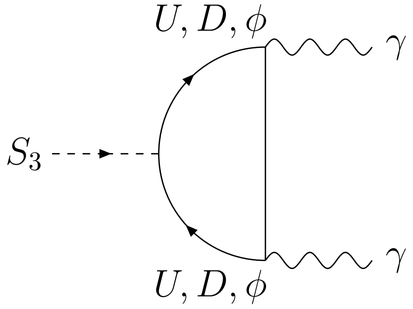

Figure 2: One-loop decay of S_3 to two photons.

final states directly and increase its total width. These are then the essential ingredients which could explain the 750 GeV observation.

In choosing n_1 and n_4, if the resulting model has only those interactions of Eqs. (1) and (2), then the U, D particles are stable. They may form bound states with the known quarks and become exotic stable matter. In the following, only cases with additional interactions are considered.

3 Leptoquark Models

In (A) for $n_1 = 0$, the following interactions become allowed:

$$u^c N^c U, \quad u^c e^c D, \quad d^c N^c D, \quad QLD^c, \quad N^c N^c S_1. \tag{3}$$

This is the case studied in Ref. [4] and used in Ref. [2] for illustration. Now U^c, D^c should be considered as leptoquark superfields, which may also be relevant [5] in understanding other possible LHC flavor anomalies. For $\langle S_1 \rangle \neq 0$, N^c acquires a large Majorana mass, hence ν gets a small Majorana seesaw mass in the usual way.

In (B) for $n_4 = -n_1$, the following interactions become allowed:

$$u^c e^c D, \quad d^c N^c D, \quad QLD^c, \quad U^c D^c D^c, \quad LS_1\phi_2, \quad N^c S_2 S_3. \tag{4}$$

Now D^c is a leptoquark, but U is a dileptoquark because it could decay into 2 leptons and 2 quarks. Neutrino masses are forced to be Dirac.

In (B) for $n_4 = 5n_1$, the only allowed new interaction is

$$u^c N^c U. \tag{5}$$

Hence U is a leptoquark, but D is a stable heavy quark. Neutrino masses must again be Dirac.

4 Diquark Models

In (A) for $n_4 = -n_1$, the following interactions become allowed:

$$u^c d^c D^c, \quad d^c d^c U^c, \quad QQD, \quad N^c S_2. \tag{6}$$

Now both U^c, D^c are diquarks, and neutrinos obtain seesaw Dirac masses as follows. In the space spanned by (ν, S_1, N^c, S_2), the 12×12 neutrino mass matrix is of the form

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & 0 & m_D & 0 \\ 0 & 0 & 0 & m_S \\ m_D & 0 & 0 & M \\ 0 & m_S & M & 0 \end{pmatrix}, \tag{7}$$

where m_D comes from $\nu N^c \langle \phi_2^0 \rangle$, m_S from $S_1 S_2 \langle S_3 \rangle$, and M from $N^c S_2$. This is thus a Dirac seesaw with $m_\nu \simeq m_D m_S / M$.

In (B) for $n_1 = 0$, the following interactions become allowed:

$$u^c d^c D^c, \quad QQD, \quad UDD. \tag{8}$$

Now D^c is a diquark, but U is a tetraquark because it could decay into 4 quarks. Further, N^c and S_1 transform in the same way under $U(1)_X$, so that a linear combination pairs up with ν to form Dirac neutrinos.

In (B) for $n_1 = -3n_4$, the only allowed new interaction is

$$d^c d^c U^c. \tag{9}$$

Hence U is a diquark, but D is a stable heavy quark. Neutrino masses must again be Dirac.

5 Heavy Quark Models

The U^c, D^c singlets may transform in the same way as u^c, d^c under $U(1)_X$. In that case, they will mix and the heavy ones will decay to the lighter ones. Another possibility is that $u^c U$ or $d^c D$ is an allowed mass term under $U(1)_X$, in which case there is again mixing.

In (A) for $n_4 = -(17/5)n_1$, U^c, D^c and u^c, d^c transform in the same way under $U(1)_X$. In (B) for $n_4 = -(8/3)n_1$, U^c and u^c transform in the same way, but D remains stable. In (B) for $n_4 = -(5/6)n_1$, D^c and d^c transform in the same way, but U remains stable. In (B) for $n_4 = (4/3)n_1$, $d^c D$ is a mass term, but U is also stable. In all cases, neutrino masses are Dirac.

In (A) for $n_4 = -2n_1$, the UDD term is allowed, but there is no term connecting U or D with the usual quarks. In (A) for $n_4 = -5n_1$, the $U^c D^c D^c$ term is allowed, but again there is no term linking them with the usual quarks.

6 Majorana Neutrino Mass Models

To allow Majorana neutrino masses, the term $S_i N^c N^c$ should be present. For $S_1 N^c N^c$, it implies $n_1 = 0$ in (A) and $n_4 = 3n_1$ in (B). For $S_2 N^c N^c$ which automatically allows $S_1 N^c$, it implies $n_4 = 3n_1$ in (A) and $n_4 = (3/2)n_1$ in (B). For $S_3 N^c N^c$, it implies $n_4 = -(9/2)n_1$ in (A) and $n_4 = -21n_1$ in (B). In all cases except the first, i.e. $n_1 = 0$ in (A) which leads to Eq. (3), the exotic U, D quarks are stable and there is no other interaction involving them.

The $N^c N^c$ term by itself is allowed if $n_4 = -9n_1$ in (A) or $n_4 = 6n_1$ in (B). There is however no other allowed term beyond Eqs. (1) and (2). The exotic U, D quarks are stable in these cases.

7 Conclusion

The two most plausible models are those described by Eqs. (3) and (6). The former [4] has U^c, D^c as leptoquarks, and neutrino masses are Majorana from a TeV scale seesaw mechanism. The latter has U^c, D^c as diquarks, and neutrino masses are Dirac from a high scale seesaw mechanism. However, the models described by Eqs. (4) and (8) have unusual predictions which should also be searched for at the LHC. The former predicts D^c as a leptoquark, but U as a dileptoquark. The latter predicts D^c as a diquark, but U as a tetraquark. However, neutrino masses are Dirac in these cases and there is no understanding of why they are so small.

Since the $U(1)_X$ charge assignments of quarks and leptons are all different in these various models, the key is in the observation of the associated Z_X gauge boson. If the LHC finds a Z' gauge boson, its decay branching fractions [6] would help distinguish among possible models of this gauge $U(1)$ framework.

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