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 \[4\].

| 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        | (7\(n_1 + 3n_4\))/2 | 5\(n_1\) |
| \(d^c\)    | 3           | 1           | 1/3         | (7\(n_1 + 3n_4\))/2 | 2\(n_1 + 3n_4\) |
| \(L = (\nu,e)\) | 1           | 2           | -1/2        | \(n_4\)         | \(n_4\)         |
| \(e^c\)    | 1           | 1           | 1           | (9\(n_1 + n_4\))/2 | 3\(n_1 + 2n_4\) |
| \(N^c\)    | 1           | 1           | 0           | (9\(n_1 + n_4\))/2 | 6\(n_1 - n_4\) |
| \(\phi_1\) | 1           | 2           | -1/2        | -3\(3n_1 + n_4\)/2 | -3\(n_1 + n_4\) |
| \(\phi_2\) | 1           | 2           | 1/2         | -3\(3n_1 + n_4\)/2 | -6\(n_1\)      |
| \(S_1\)    | 1           | 1           | 0           | -3\(n_1 + n_4\)  | -(3\(n_1 + n_4\)) |
| \(S_2\)    | 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         | -4\(n_1 - 2n_4\) | -6\(n_1\)      |
| \(D\)      | 3           | 1           | -1/3        | -4\(n_1 - 2n_4\) | -6\(n_1\)      |
| \(U^c\)    | 3           | 1           | -2/3        | -5\(n_1 - n_4\)  | -3\(n_1 + n_4\) |
| \(D^c\)    | 3           | 1           | 1/3         | -5\(n_1 - n_4\)  | -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 $\phi_1, \phi_2, D, D^c$. The following terms of the superpotential are
always allowed:

$$Qu^c\phi_2, \quad Qd^c\phi_1, \quad Le^c\phi_1, \quad LN^c\phi_2, \quad S_3\phi_1\phi_2, \quad (1)$$

$$S_3UU^c, \quad S_3DD^c, \quad S_1S_2S_3. \quad (2)$$

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

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{diagram.png}
\caption{One-loop production of $S_3$ by gluon fusion.}
\end{figure}

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 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:

$$u^cN^cU, \quad u^ce^cD, \quad d^cN^cD, \quad QLD^c, \quad N^cN^cS_1.$$ (3)

This is the case studied in Ref. [1] 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 $\nu$ gets a small Majorana seesaw mass in the usual way.

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

$$u^ce^cD, \quad d^cN^cD, \quad QLD^c, \quad LS_1\phi_2, \quad N^cS_2S_3.$$ (4)
Now $D^c$ is a leptoquark, but $U$ is stable because the $U^cD^cD^c$ term is not possible as an $SU(3)$ singlet. Neutrino masses are forced to be Dirac.

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

$$u^cN^cU.$$ (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:

$$u^cd^cD^c, \quad d^cU^c, \quad QQD, \quad N^cS_2.$$ (6)

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

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

where $m_D$ comes from $\nu N^c\langle \phi_2^0 \rangle$, $m_S$ from $S_1S_2\langle S_3 \rangle$, and $M$ from $N^cS_2$. This is thus a Dirac seesaw with $m_\nu \simeq m_Dm_S/M$.

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

$$u^cd^cD^c, \quad QQD.$$ (8)

Now $D^c$ is a diquark, but $U$ is stable because the $UDD$ term is not possible as an $SU(3)$ singlet. Further, $N^c$ and $S_1$ transform in the same way under $U(1)_X$, so that a linear combination pairs up with $\nu$ to form Dirac neutrinos.
In (B) for $n_1 = -3n_4$, the only allowed new interaction is
\[ d^c d^c U^c. \] (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 $n_4 = -13n_1$ and in (B) for $n_4 = -(4/3)n_1$, the $d^c D^c U^c$ term is allowed. This means that only one of the exotic $U, D$ states is stable.

## 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 \cite{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. In most other models, either $U$ or $D$ or both are stable. Neutrino masses are Dirac in most cases with 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 \cite{6} would help distinguish among possible models of this gauge $U(1)$ framework.

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