Quiver Approach to Massive Gauge Bosons Beyond the Standard Model

Paul Howard Frampton

Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255.

Abstract

We address the question of the possible existence of massive gauge bosons beyond the $W^\pm$ and $Z^0$ of the standard model. Our intuitive and aesthetic approach is based on quiver theory. Examples thereof arise, for example, from compactification of the type IIB superstring on $AdS_5 \times S_5/Z_n$ orbifolds. We explore the quiver theory framework more generally than string theory. The practical question is what gauge bosons to look for at the upgraded LHC, in terms of color and electric charge, and of their couplings to quarks and leptons. Axigluons and bileptons are favored.
1 Introduction

With the discovery \cite{1,2} of the BEH scalar particle, all the particles in the standard model (SM) have been found. The practical question therefore is which particles, especially massive gauge bosons, are waiting to be discovered in pp-collisions at a center of mass energy $\sqrt{s} = 14$ TeV?

Of the twelve known gauge bosons associated with the group $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ the eight gluons of unbroken color $G_{QCD} = SU(3)_C$ are massless, as is the electromagnetic photon of unbroken $U(1)_{em}$ which survives the symmetry breaking of the electroweak group $G_{EW} = SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$. The remaining three known gauge bosons are massive with mass arising from the BEH mechanism \cite{3,4} so that \cite{5} the $W^{\pm}$ has mass $M_W = 80.385 \pm 0.015$ GeV and $Z^0$ has mass $M_Z = 91.1876 \pm 0.0021$ GeV.

In the present article, we shall assume that at energy scales accessible to the LHC the gauge group is a semi-simple group or more specifically a quasi-simple group $G_{\text{quiver}} \ni G_{SM}$ with $G_{\text{quiver}} = SU(N)^n$. To accommodate $G_{QCD}$, it is suggested to identify $N = 3$, whereupon $G_{\text{quiver}} = SU(3)^n$. We are, to some extent, divorcing quiver theory from string theory by omitting a non-simple factor $U(1)^n$ which is present when the Type IIB superstring is compactified on the orbifold $AdS_5 \times S^5/Z_n$ \cite{6}. For the case $n = 1$ the $U(1)$ can be rotated away since none of the matter fields carry a charge under it. For all $n \geq 2$, however, the $U(1)$’s are present and cause at least two difficulties: firstly, there are uncanceled triangle anomalies; secondly, the associated renormalization group (RG) beta functions are positive definite thus precluding ultra violet (UV) conformality.

UV conformality is an underlying motivation but can, at best, hold good only within some conformality ”window” covering a finite energy range because at the Planck energy gravitation enters and necessarily breaks conformal invariance since Newton’s constant is dimensionful. There is a significant no-go theorem \cite{7} for non-SUSY $\mathcal{N} = 0$ quiver theory showing that within certain strong assumptions there exist double-trace operators whose couplings are non-conformal. Nevertheless, this theorem makes both a one-loop approximation and a leading-order $1/N$ approximation so that conformality remains an open question when one allows cancelation between different loop orders and/or (probably ”and”) different orders in $1/N$.

We shall focus primarily on the $\mathcal{N} = 0$ non-SUSY quiver theories because the experiments (LHC) show no indication of weak-scale supersymmetry. $\mathcal{N} = 2$ theories are generally non-chiral and phenomenologically disfavored, while $\mathcal{N} = 1$ theories can be chiral and more readily possess UV conformality.

We shall omit all gravitational effects. The spacetime dimension will be anchored at four normal bosonic flat dimensions. Our analysis is deliberately ultraconservative although we are using quiver ideas which stem in part from speculative directions.
We shall study separately the color sector which is simple and straightforward, restricted to only two possibilities (QCD and chiral color) then the much richer electroweak sector.

2 Color and electroweak sectors

We consider two possibilities for the color part of the quiver. Firstly, we may take simply $G_{\text{color}} = G_{\text{QCD}}$ in which case the remainder of the gauge group is $SU(3)^{(n-1)}$. In this case, there are no additional gauge bosons beyond the massless eight gluons. Alternatively, we may assign two quiver nodes to color in the style of chiral color. In this case, there are eight additional massive gauge bosons which are a color octet of axigluons. The remainder of the quiver gauge group is $SU(3)^{(n-2)}$. The axigluons are the only examples of massive gauge bosons with color that we shall encounter. Axigluons have no electric charge. The current lower limit on the axigluon mass from LHC data is at least 3 TeV \cite{8}.

The remainder of the quiver gauge group is $SU(3)^m$ where $m = (n - 1)$ (for QCD) or $m = (n - 2)$ (for chiral color). We shall normalize the Gell-Mann $SU(3)$ matrices by $\text{Tr}(\lambda_a \lambda_b) = \frac{1}{2} \delta_{ab}$, so that for the diagonal generators $\lambda_3, \lambda_8$ to be used in the electric charge $Q$ we shall always mean

$$
\lambda_3 = \left( \frac{1}{2} \right) \begin{pmatrix}
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & 0
\end{pmatrix}
$$

$$
\lambda_8 = \left( \frac{1}{2\sqrt{3}} \right) \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -2
\end{pmatrix}
$$

For the $m$ $SU(3)$ factors we shall label the generators by $\lambda_i^{(i)}$ with $1 \leq i \leq m$. We may without loss of generality embed naturally the $SU(2)_L$ of $G_{SM}$ in the first $SU(3)$ so that $(T_3)_L \equiv \lambda_3^{(1)}$. We may then rewrite the weak hypercharge $Y$ as

$$
Q = (T_3)_L + \frac{1}{2} Y \\
= \lambda_3^{(1)} + \sum_{i=2}^{m} C_3^{i} \lambda_3^{(i)} + \sum_{i=1}^{m} C_8^{i} \lambda_8^{(i)}
$$

To proceed, we shall borrow the quiver rules \cite{6, 9, 10} which we carry over from the orbifolding of the Type IIB superstring on $AdS_5 \times S_5 / Z_n$. We must specify four integers which show the embedding of $Z_n$ in the $SU(4)$ which acts on the $\mathcal{N} = 4$ supersymmetries. We write
\[ 4 = A_\mu = (A_1, A_2, A_3, A_4) \] (4)

where \( \Sigma_{\mu=1}^{\mu=4} A_\mu = 0 \) (mod n). To have a non-SUSY \( \mathcal{N} = 0 \) quiver gauge theory all of the \( A_\mu \) must be non-vanishing (mod n).

From this 4 of \( SU(4) \) we construct the real 6 = 3 + 3* with

\[ 3 = a_i = (a_1, a_2, a_3) \] (5)

where

\[ \begin{align*}
a_1 &= A_2 + A_3 \\
a_2 &= A_3 + A_1 \\
a_3 &= A_1 + A_2
\end{align*} \] (6)

With these definitions, the chiral fermions are in the representation \( \mathcal{R}_F \):

\[ \mathcal{R}_F = \Sigma_{j=1}^{j=n} \Sigma_{\mu=1}^{\mu=4} (3_j, \bar{3}_j + A_\mu) \] (7)

while the complex scalars are in the related representation \( \mathcal{R}_S \)

\[ \mathcal{R}_S = \Sigma_{j=1}^{j=n} \Sigma_{i=1}^{i=3} (3_j, \bar{3}_j \pm a_i) \] (8)

The chiral fermions (oriented) and complex scalars (non-oriented) are conveniently displayed on a quiver diagram with n nodes. The representations \( \mathcal{R}_F \) and \( \mathcal{R}_S \) are related so that the Yukawa couplings correspond to triangles with two sides being oriented chiral fermions and the third side being a non-oriented complex scalar.

The gauge bosons which are in \( SU(3) \) octets at each node. In particular, we study the electric charges \( Q \) according to Eq.(3) and the couplings to chiral fermions which enter and leave the node according to their representation \( \mathcal{R}_F \) given in Eq.(7).

If the electric charges of the particles in the defining 3 are \( Q = (q_1, q_2, q_3) \) then the corresponding charges of the eight gauge bosons are \( \pm(q_1 - q_2), \pm(q_2 - q_3), \pm(q_3 - q_1) \), together with two neutrals. For example, taking into account only the contribution to \( Q \) from the first \( m = 1 \) \( SU(3) \) factor and assigning \( C_8^t = \sqrt{3} \) one finds for the first 3 that \( Q = (+1, 0, -1) \) and the gauge boson electric charges are ++, +, +, 0, 0, −, −, −. This is the simplest possibility which will continue for all subsequent \( SU(3) \) s, \( i = 2, 3, \ldots \) as long as \( C_3^t = 1 \) and \( C_8^t = \sqrt{3} \).

The promotion from \( SU(2)_L \) to \( SU(3)_L \) will generally, although not always, lead to double electric charges for the new massive gauge bosons, so this is what we can fasten upon in our attempt to make the most likely predictions for additional particles.
3 More than three massive gauge bosons

The discovery of the $W^\pm$ and $Z^0$ massive gauge bosons in 1983 provided a watershed which confirmed the correctness of the SM. Furthermore, the masses $M_W = 80.385 \pm 0.015$ GeV and $M_Z = 91.1876 \pm 0.0021$ GeV were consistent with the theory of spontaneous symmetry breaking via the BEH mechanism.

One oft speculated additional massive gauge boson is a $Z^0$ arising from an extra $U(1)$ gauge group. But this makes the gauge group less simple. Aesthetically and intuitively $G_{SM} = SU(3) \times SU(2) \times U(1)$ has the unsatisfying feature of not being even semi-simple. UV conformality strongly disfavors any $U(1)$ gauge factor, in favor of a gauge group with only non-abelian factors. Even more attractive is a quasi-simple gauge group like $SU(3)$ which with a discrete symmetry needs only one coupling constant. Of course, quasi-simple quivers may also contain $Z^0$-type gauge bosons, but we are more interested in massive gauge bosons with nontrivial color and electric charge under the unbroken vacuum gauge symmetry $G_{VACUUM} \equiv G_{QCD} \times G_{em} \equiv SU(3)_C \times U(1)_{em}$.

To examine the fermion couplings of the doubly electric charged $Y^{\pm\pm}$ gauge bosons, consider the case with electroweak gauge group $SU(3)_L \times U(1)_X$ and

$$Q = \lambda^{(1)}_3 + \sqrt{3} \lambda^{(1)}_8 + X$$

(9)

The leptons are in $X = 0$ antitriplet of $SU(3)_L$ as

$$\begin{pmatrix}
  e^+ \\
  \nu_e \\
  e^-
\end{pmatrix}
= \begin{pmatrix}
  \mu^+ \\
  \nu_\mu \\
  \mu^-
\end{pmatrix}
= \begin{pmatrix}
  \tau^+ \\
  \nu_\tau \\
  \tau^-
\end{pmatrix}$$

(10)

In the quark sector, $Y^{\pm\pm}$ must couple to exotic quarks with electric charges $-4/3$ or $+5/3$ so the best signature must be purely bileptonic like $Y^{\pm\pm} \to \mu^\pm \mu^\pm$.

Such a quiver theory may be UV conformally invariant, meaning that when gravity is included there will be a conformality window as discussed earlier. Such a theory is free of triangle anomalies and renormalizable, just like the SM. Using only the criteria of quiver theory, we expect the simplest extensions of $G_{SM} = SU(3) \times SU(2) \times U(1)$ to be $SU(3)^3$ with QCD or $SU(3)^4$ with chiral color.

In conclusion, assuming that the gauge group $G_{SM}$ fills out to $SU(N)^n$ where probably $N = 3$ and $n = 3, 4, ...$ then the most likely additional massive gauge bosons which transform nontrivially under $G_{VACUUM}$ are either (i) color-octet axigluons and/ or (ii) doubly electrically charged bileptons $Y^{\pm\pm}$ which could be observed at the upgraded LHC as resonant states respectively in (i) dijets and (ii) like-sign lepton pairs. Present lower limits on their masses are respectively (i) 3 TeV [8] and (ii) 850 GeV [11] so higher masses await investigation and LHC data are eagerly awaited.
Acknowledgement

This work was supported in part by U.S. Department of Energy Grant DE-FG02-06ER41418.

References

[1] G. Aad, et al. (ATLAS Collabortion), Phys. Lett. B716, 1 (2012). arXiv:1207.7214[hep-ex]

[2] S. Chatrchyan, et al. (CMS Collabortion), Phys. Lett. B716, 30 (2012). arXiv:1207.7235[hep-ex]

[3] F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964).

[4] P.W. Higgs, ibid 13, 508 (1964).

[5] J. Beringer, et al. (Particle Data Group), Phys Rev. D86, 010001 (2012).

[6] P.H. Frampton and T.W. Kephart, Phys. Reports, 454, 203 (2008). arXiv:0706.4259[hep-th]

[7] A. Dymarsky, I.R. Klebanov, and R. Roiban, JHEP 0511:038 (2005). arXiv:hep-th/0509132

[8] B. Diaz and A.R. Zerwekh. arXiv:1308.0166[hep-ph].

[9] P.H. Frampton, Phys. Rev. D60, 041901 (1999). hep-th/9812117

[10] P.H. Frampton and C. Vafa. hep-th/9903226

[11] L. Willmann, et al. Phys. Rev. Lett. 82, 49 (1999). arXiv:hep-ex/9807011