Hidden Gauge Symmetries: A New Possibility at the Colliders

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We consider a new physics possibility at the colliders: the observation of TeV scale massive vector bosons in the non-adjoint representations under the Standard Model (SM) gauge symmetry. To have a unitary and renormalizable theory, we propose a class of models with gauge symmetry $\prod_i G_i \times SU(3)_C \times SU(2)_L \times U(1)_Y$, where the SM fermions and Higgs fields are singlets under the hidden gauge symmetry $\prod_i G_i$, and such massive vector bosons appear after the gauge symmetry is spontaneously broken down to the SM gauge symmetry. We discuss the model with $SU(5)$ hidden gauge symmetry in detail, and comment on the generic phenomenological implications.

PACS numbers: 14.65.Ha, 12.60.-i

[OSU-HEP-04-09, FERMILAB-PUB-04-146-T]
i.e., \( \mathcal{G} \equiv G \times SU(3)_C \times SU(2)_L \times U(1)_Y \), because the discussions for the general models are quite similar. There are many choices for \( G \), for example, \( G = SU(2), SU(3), SU(4), G_2, F_4, Sp(4), Sp(6), SU(5), SO(10), E_6 \), etc. After the gauge symmetry \( \mathcal{G} \) is spontaneously broken down to the SM gauge symmetry, the possible non-adjoint representations of the massive gauge bosons under the SM gauge symmetry \( SU(3)_C \times SU(2)_L \times U(1)_Y \) in these models are

\[
(1, 1, Q_1) + (1, 1, -Q_1), (1, 2, Q_2) + (1, 2, -Q_2),
(3, 1, Q_3) + (3, 1, -Q_3), (3, 1, 0) + (3, 1, 0),
(6, 2, Q_4) + (6, 2, -Q_4), (6, 1, Q_5) + (\bar{6}, 1, -Q_5),
(3, 3, Q_6) + (3, 3, -Q_6), (3, 2, Q_7) + (3, 2, -Q_7),
(1, 3, Q_8) + (1, 3, -Q_8),
\]

where \( Q_i \neq 0 \). In our models, there generically exist the massive gauge bosons which belong to the adjoint representations under the SM gauge symmetry. Because we are not interested in the adjoint massive gauge bosons that have been studied previously \( \boxed{\text{adjoint massive gauge bosons}} \), we emphasize that we do not consider them in this paper.

To be concrete, we shall give the formalism realizing our idea for a simple model with \( G = SU(5) \).

**Formalism** - We consider a model with \( \mathcal{G} \equiv SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge symmetry where \( SU(5) \) is a hidden gauge symmetry. We denote the gauge fields for \( SU(5) \) and \( SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge symmetry as \( A_\mu \) and \( \tilde{A}_\mu \), respectively, and the gauge couplings for \( SU(5) \), \( SU(3)_C \), \( SU(2)_L \) and \( U(1)_Y \) are \( g_5, g_3, g_2 \) and \( g_Y \), respectively. The Lie algebra indices for the generators of \( SU(3) \), \( SU(2) \) and \( U(1) \) are denoted by \( a, a^\prime \) and \( 1 \), respectively, and the Lie algebra indices for the generators of \( SU(5)/SU(3) \times SU(2) \times U(1) \) are denoted by \( \hat{a} \). After the \( SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge symmetry is broken down to the SM gauge symmetry \( SU(3)_C \times SU(2)_L \times U(1)_Y \), we denote the massless gauge fields for the SM gauge symmetry as \( A_\mu^{\prime \prime} \), and the massive gauge fields as \( B^{\prime \prime}_\mu \) and \( \tilde{A}^{\prime \prime}_\mu \). The gauge couplings for the SM gauge symmetry \( SU(3)_C \), \( SU(2)_L \) and \( U(1)_Y \) are \( g_3, g_2 \) and \( g_Y \), respectively.

To break the \( SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge symmetry down to the SM gauge symmetry, we introduce four bifundamental Higgs fields \( U_1, U_2, U_3 \) and \( U_4 \) with the following quantum numbers:

| Fields | \( SU(5) \) | \( SU(3)_C \times SU(2)_L \times U(1)_Y \) |
|--------|---------------|-----------------------------------|
| \( U_1 \) | 5 | \((3, 1, 1/3)\) |
| \( U_2 \) | 5 | \((3, 1, -1/3)\) |
| \( U_3 \) | 5 | \((1, 2, -1/2)\) |
| \( U_4 \) | 5 | \((1, 2, 1/2)\) |

In order to break the \( SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge symmetry down to the SM gauge symmetry, we only need two Higgs fields, one from the \( U_1 \) and \( U_2 \), and the other one from the \( U_3 \) and \( U_4 \). The reason, for choosing four Higgs fields \( U_1, U_2, U_3 \) and \( U_4 \), is that we can generalize this non-supersymmetric model to the supersymmetric model without adding the new particle contents except the superpartners of the particles.

To give the vacuum expectation values (VEVs) to the bifundamental Higgs fields \( U_i \), we consider the following potential

\[
V = \sum_{i=1}^{4} \left[ \lambda_i \left( |U_i|^2 - \tilde{v}_i^2 \right)^2 \right] + \lambda_{12} |U_1 U_2 - \tilde{v}_{12}^2|^2 + \lambda_{34} |U_3 U_4 - \tilde{v}_{34}^2|^2 + \left[ \tilde{m}_3^2 |U_1|^2 + \tilde{m}_3^2 |U_2|^2 + \tilde{m}_3^2 |U_3|^2 + \tilde{m}_3^2 |U_4|^2 \right] + \lambda_{1234} U_1 U_2 U_3 U_4 + \frac{y_{13}}{M_{13}} U_1 U_1 U_3 U_3 + \frac{y_{24}}{M_{24}} U_2 U_3 U_4 U_4 + \text{H.C.},
\]

where \( M_{13} \) and \( M_{24} \) need not be at the GUT scale or Planck scale, and can be the mass scales of the heavy fields because the non-renormalizable operators can be obtained from the renormalizable operators by integrating out the heavy fields. In addition, there is no global symmetry in above potential except the gauge symmetry \( SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y \), so, there is no Goldstone boson.

We choose the following VEVs for the fields \( U_i \)

\[
< U_1 > = v_1 \left( \begin{array}{c} I_{3 \times 3} \\ 0_{2 \times 3} \end{array} \right), \quad < U_2 > = v_2 \left( \begin{array}{c} I_{3 \times 3} \\ 0_{2 \times 3} \end{array} \right),
\]

\[
< U_3 > = v_3 \left( \begin{array}{c} 0_{3 \times 2} \\ I_{2 \times 2} \end{array} \right), \quad < U_4 > = v_4 \left( \begin{array}{c} 0_{3 \times 2} \\ I_{2 \times 2} \end{array} \right),
\]

where \( I_{i \times j} \) is the \( i \times j \) identity matrix, and \( 0_{i \times j} \) is the \( i \times j \) matrix where all the entries are zero. We assume that \( v_i (i = 1, 2, 3, 4) \) are in the TeV range so that the massive gauge bosons have TeV scale masses.

From the kinetic terms for the fields \( U_i \), we obtain the mass terms for the gauge fields

\[
\sum_{i=1}^{4} (D_\mu U_i)^\dagger D^\mu U_i = \frac{1}{2} \left( v_1^2 + v_2^2 \right) \left( g_5 \tilde{A}^{a_3}_{\mu} - g_3 \tilde{A}_{\mu}^{a_3} \right)^2 + \frac{1}{2} \left( v_3^2 + v_4^2 \right) \left( g_5 \tilde{A}_{\mu}^{a_2} - g_2 \tilde{A}_{\mu}^{a_2} \right)^2 + \left( \frac{v_1^2}{3} + \frac{v_2^2}{3} + \frac{v_3^2}{2} + \frac{v_4^2}{2} \right) \left( g_5 \tilde{A}_{\mu}^{a_1} - g_Y \tilde{A}_{\mu}^{a_1} \right)^2 + \frac{1}{2} \left( g_5 \tilde{A}_{\mu}^{a_1} - g_Y \tilde{A}_{\mu}^{a_1} \right)^2 \left( X_\mu X_\mu + Y_\mu Y_\mu \right),
\]

where \( g_5^Y \equiv \sqrt{3} g_5 / \sqrt{5} \), and we define the complex fields \( (X_\mu, Y_\mu) \) and \( (\overline{X}_\mu, \overline{Y}_\mu) \) with quantum numbers \( (3, 2, \)
and \( -5/6 \) (and \( 3, 2, 5/6 \), respectively from the gauge fields \( \tilde{A}_\mu^a \), similar to that in the usual SU(5) model \([11]\).

From the original gauge fields \( \tilde{A}_\mu^a \) and \( \tilde{A}_\mu^i \) and from Eq. (5), we obtain the massless gauge bosons \( A_\mu^a \) and the TeV scale massive gauge bosons \( B_\mu^a \) \((i = 3, 2, 1)\) which are in the adjoint representations of the SM gauge symmetry

\[
\left( \begin{array}{c} A_\mu^a \\ B_\mu^a \\ \end{array} \right) = \left( \begin{array}{cc} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{array} \right) \left( \begin{array}{c} \tilde{A}_\mu^a \\ \tilde{A}_\mu^i \end{array} \right),
\]

where \( i = 3, 2, 1 \), and

\[
\sin \theta_j = \frac{g_5}{\sqrt{g_5^2 + (g_5')^2}}, \quad \sin \theta_2 = \frac{g_5'}{\sqrt{(g_5')^2 + (g_5')^2}},
\]

where \( j = 3, 2 \). We also have the massive gauge bosons \((X_\mu, Y_\mu)\) and \((\bar{X}_\mu, \bar{Y}_\mu)\) which are not in the adjoint representations of the SM gauge symmetry. So, the \( SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y \) gauge symmetry is broken down to the diagonal SM gauge symmetry \( SU(3)'_C \times SU(2)'_L \times U(1)'_Y \), and the theory is unitary and renormalizable. The SM gauge couplings \( g_j \) \((j = 3, 2)\) and \( g_Y \) are given by

\[
\frac{1}{g_j^2} = \frac{1}{g_3^2} + \frac{1}{g_2^2} + \frac{1}{g_Y^2}.
\]

If the theory is perturbative, the upper and low bounds on the gauge couplings \( g_3, g_2' \) and \( g_3' \) are

\[
g_3 < g_5 < \sqrt{4\pi}, \quad g_3 < g_3' < \sqrt{4\pi},
\]

\[
g_2 < g_2' < \sqrt{g_3^2 - g_2^2},
\]

\[
g_Y < g_Y' < \sqrt{3g_3g_Y^2 - 5g_Y^2}.
\]

Note that the gauge coupling \( g_5 \) for SU(5) is naturally large at the TeV scale because the beta function of SU(5) is negative, i.e., SU(5) is asymptotically free.

**Phenomenological Implications** - The interactions among the gauge bosons of \( SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y \) can be obtained from the kinetic terms of the gauge fields. For instance, the interactions between the SM gauge bosons \( A_\mu^a \) and the massive gauge bosons \( B_\mu^a \) are given by

\[
-\mathcal{L}_{\text{gauge}} = \frac{1}{2} g_j \left[ A_3^2 + 3A_2B^2 + 2\cot 2\theta B^3 \right] + \frac{1}{4} g_j^2 \left[ A_4^2 + 6A_2^2B^2 + 4(2\cot 2\theta)AB^3 + (\tan^2 \theta + \cot^2 \theta - 1)B^4 \right],
\]

where \( j = 2, 3 \). The \( A_3 \) and \( A_4 \) represent schematically the usual three and four point gauge interactions, respectively

\[
A_3 \equiv \sum_{abc} (\partial_\mu A_{\nu a} - \partial_\nu A_{\mu a}) A_{\mu b}^a A_{\nu c}^a A_{\nu}^c,
\]

\[
A_4 \equiv \sum_{abc} \sum_{i=1}^5 (\partial_\mu A_{\nu a} - \partial_\nu A_{\mu a}) A_{\mu b}^a A_{\nu c}^a A_{\nu d}^f A_{\nu}^e.
\]

And we choose the similar convention for the other terms. Note that a single heavy boson \( B_5^a \) does not couple to two or three gluons, and hence can only be pair produced via the gluon-gluon fusions, or s-channel gluon exchanges, or t-channel \( B_5^a \) exchanges at the hadronic colliders such as the LHC.

Similarly, the gauge bosons \( X_\mu \) and \( Y_\mu \) will couple to the SM gauge bosons via the gauge kinetic terms for the SU(5) gauge bosons. So, they can be pair produced from the fusions of the SM gauge bosons, or s-channel SM gauge boson exchanges, or t-channel \( X_\mu \) and \( Y_\mu \) exchanges in the colliders, for instance, the gluon fusions for the hadronic colliders.

The interactions between the gauge bosons and the SM fermions can be obtained from the kinetic terms of the SM fermions. For example, let us consider the quark doublet \( Q_i \) with quantum number \((1, 3, 2, 1/6)\) under the gauge symmetry \( SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y \). The Lagrangian for \( Q_i \) is

\[
-\mathcal{L} = \bar{Q}_i \gamma^\mu D_\mu Q_i + \text{(Higgs and other terms)}
\]

where

\[
D_\mu \equiv \partial_\mu - ig_3 T^{a3} A_{\mu}^a - ig_2 T^{a2} A_{\mu}^a - ig_2 T^{a2} \tilde{A}_{\mu}^a - \frac{1}{6} g_Y A_5^a
\]

The model proposed here has two kinds of the new vector bosons with masses at TeV scale: one kind of gauge bosons belongs to the adjoint representations of the SM gauge symmetry, while the other kind of gauge bosons \((X_\mu, Y_\mu)\) and \((\bar{X}_\mu, \bar{Y}_\mu)\) has quantum numbers \((3, 2, -5/6)\) and \((3, 2, 5/6)\) under the SM gauge symmetry. Both kinds of massive gauge bosons have many phenomenological implications which can be tested at the upcoming LHC. In the following, we list some of these phenomenological implications:
(i) The massive QCD type gauge bosons $B_{\mu}^{a3}$ belonging to the $(8, 1, 0)$ representation of the SM gauge symmetry will couple to the gluons, and will be dominantly pair produced via the gluon-gluon fusions, or $s$-chanel gluon exchanges, or $t$-chanel $B_{\mu}^{a3}$ exchanges at the LHC. They will decay dominantly to $q\bar{q}$ pairs. Thus, the 4 jet high $p_T$ signal will be significantly enhanced compared to that in the SM due to these heavy gluon productions.

(ii) The heavy electroweak type gauge bosons, with quantum numbers $(1, 3, 0)$ and $(1, 1, 0)$ under the SM gauge symmetry, will be singly produced at the LHC via $q\bar{q}$ annihilations, as well as will be pair produced via the $WW$ and $ZZ$ fusions. The decays of the heavy photon and $Z$ boson to the lepton pair $l^+l^-$ will give very clean signals.

(iii) The signals of these gauge bosons $B_{\mu}^{ai}$ ($i = 3, 2, 1$) are very different from those in the topcolor and topflavor models, as our gauge bosons couple to all three families of the SM fermions universally.

(iv) These TeV scale gauge bosons will produce the off-shell effects in the future ILC, and will also contribute to $g_\mu - 2$.

(v) The gauge bosons in the non-adjoint representations of the SM gauge symmetry (such as $X_\mu$ and $Y_\mu$ type particles in this simple model) can also be pair produced via the gluon fusions, or $s$-chanel gluon exchanges, or $t$-chanel massive gauge bosons (for example, $X_\mu$ and $Y_\mu$) exchanges at the LHC. Because their couplings to the SM fermions are highly suppressed and they can not decay to the bifundamental Higgs fields $U_i$ due to the kinematics reason, they will be meta-stable and behave like the stable heavy quarks and anti-quarks. If produced at the LHC, they can be detected by their ionizations as they pass through the detector.

(vi) Choosing the different groups for the hidden gauge symmetry $G$, such as $SU(2)$, $SU(3)$ and $SU(4)$, etc, we can have the massive gauge bosons with different non-adjoint representations under the SM gauge symmetry. Note that in some of these models, the massive gauge bosons and the bifundamental Higgs fields do not cause the proton decay, and thus the massive gauge bosons' couplings to the SM fermions via the bifundamental Higgs fields by the non-renormalizable operators need not to be Planck scale suppressed. So, their productions and subsequent decays might give rise to the other interesting signals at the LHC.

Although we have discussed the phenomenological implications, mostly for the LHC, our proposal has similar implications for the ongoing Tevatron Run 2, and off-shell effects in the future ILC. If our proposed massive vector bosons are light enough, the color octet ($B_{\mu}^{a3}$) can be pair produced or the electroweak massive bosons ($B_{\mu}^{a1,2}$) can be singly produced at the Tevatron Run 2, giving rise to similar signals as at the LHC. Also the metastable $X_\mu$ and $Y_\mu$ bosons can be pair produced, and can be searched by looking for their ionization tracks. We encourage the Run 2 Groups to look for these signals.

Conclusions – We have proposed the interesting new physics possibility at the colliders: the observation of TeV scale massive vector bosons belonging to the non-adjoint representations under the SM gauge symmetry. A class of the $\prod_i G_i \times SU(3)_C \times SU(2)_L \times U(1)_Y$ models realizing this possibility is presented, where such vector bosons are generated when the $\prod_i G_i \times SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry is spontaneously broken down to the SM gauge symmetry via the Higgs mechanism. These theories are thus unitary as well as renormalizable. The observation of such gauge bosons at the Tevatron Run 2, the LHC, or the future ILC will open up a new window for our understanding of physics beyond the Standard Model.

Acknowledgments – We would like to thank S. Adler and J. Lykken for helpful discussions. SN wishes to thank the members of the School of Natural Sciences, Institute for Advanced Study for their warm hospitality and support during his Summer Visit there when this work was initiated. He also wishes to thank the members of the Theory Group at Fermilab for their warm hospitality and support during his Summer Visit there when this work was completed. The research of T. Li was supported by the National Science Foundation under Grant No. PHY-0070928, and the research of S. Nandi is supported in part by the Department of Energy Grants DE-FG02-04ER46140 and DE-FG02-04ER41306.

* S. Nandi was a Summer Visitor at Fermilab.

[1] T. D. Lee and C. N. Yang, Phys. Rev. 128, 885 (1962).
[2] G. ’t Hooft, Nucl. Phys. B 33, 173 (1971); G. ’t Hooft and M. J. G. Veltman, Nucl. Phys. B 50, 318 (1972).
[3] B. W. Lee and J. Zinn-Justin, Phys. Rev. D 5, 3121 (1972); Phys. Rev. D 5, 3137 (1972); Phys. Rev. D 5, 3155 (1972); Phys. Rev. D 7, 1049 (1973).
[4] C. T. Hill, Phys. Lett. B 266, 419 (1991); Phys. Lett. B 345, 483 (1995).
[5] C. T. Hill and S. J. Parke, Phys. Rev. D 49, 4454 (1994).
[6] D. A. Dicus, B. Dutta and S. Nandi, Phys. Rev. D 51, 6085 (1995).
[7] D. J. Muller and S. Nandi, Phys. Lett. B 383, 345 (1996).
[8] E. Malkawi, T. Tait and C. P. Yuan, Phys. Lett. B 385, 304 (1996).
[9] J. Erler, P. Langacker and T. Li, Phys. Rev. D 66, 015002 (2002), and references therein.
[10] J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 566 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975).
[11] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974).
[12] H. Georgi, Particles and Fields, 1974 (APS/DPF Williamsburg), ed. C. E. Carlson (AIP, New York, 1975) p.575; H. Fritzsch and P. Minkowski, Annals Phys. 93, 193 (1975).
[13] For example, M. Cvetic, T. Li and T. Liu, Nucl. Phys. B 698, 163 (2004), and references therein.