Discovery limits of new extra gauge bosons at the CERN LHC

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We study the Drell-Yan production and corresponding decay signatures at the CERN Large Hadron Collider (LHC) of extra Z bosons from a superstring-inspired E_6 model characterized by an extra inert $\mathrm{SU}(2)_I$ group at electroweak energies, and from the $\mathrm{Sp}(6)_L \otimes \mathrm{U}(1)_Y$ model. We discuss how to distinguish the models by examining the extra Z-boson couplings to fermions through its leptonic decay modes and muon-pair forward-backward asymmetries.

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In spite of the remarkable experimental successes of the standard model (SM) [1] of electroweak interactions, it is commonly believed that the SM is just the low-energy limit of a more fundamental theory having new physics capable of addressing the many questions that the SM leaves unanswered. Most of these theories predict a host of new particles, including extra gauge bosons, additional fermions, etc. However, to date, there is no experimental evidence from the Fermilab Tevatron for the existence of any of these particles. It is thus necessary to consider higher collision energies to probe higher particle masses. Following the Collider Detector at Fermilab (CDF), the Large Hadron Collider (LHC) at CERN will be the next major research facility in high-energy physics. It will collide hadrons at energies an order of magnitude higher than the Tevatron. Indeed, if an extra gauge boson is discovered at the LHC we will want to learn about its gauge couplings and the model from which it originates. The cleanest way to identify an extra gauge boson in hadronic collisions is through its leptonic decays. In this work we are interested in examining expected leptonic distributions produced at the LHC by extra gauge bosons occurring in extended gauge models. In particular, we consider the $\mathrm{Sp}(6)_L \otimes \mathrm{U}(1)_Y$ model [4–7], which predicts a set of horizontal gauge bosons, and a superstring-inspired E_6 model, characterized by an extra inert $\mathrm{SU}(2)_I$ group at electroweak energies [8–10].

The standard model of electroweak interactions is in excellent agreement with existing data on low-energy neutral- and charged-current processes and on the mass of the W and Z bosons [2]. Moreover, the precision experiments from the CERN e^+e^- collider have spectacularly confirmed the model [3]. However, the family repetition of quarks and leptons strongly suggests that the electroweak group needs to be extended. Instead of an $\mathrm{SU}(2)_L$ interaction which connects the doublets in one generation, it seems natural to have a larger flavor group that can interchange fermions in different generations. The six left-handed quarks (leptons) form three doublets under the $\mathrm{SU}(2)_L$ flavor group. It is desirable to include them in a single six-dimensional representation **6** of a simple flavor gauge group. It was shown [4] that there is a unique extension of $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ into the anomaly free $\mathrm{Sp}(6)_L \otimes \mathrm{U}(1)_Y$. Under $\mathrm{Sp}(6)_L$, the left-handed quarks and leptons transform like **6** while the right-handed ones are all singlets. Sp(6) can be naturally broken into $[\mathrm{SU}(2)]^3 = \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{SU}(2)_3$, where $\mathrm{SU}(2)_i$ operates on the ith generation exclusively. Thus, the standard $\mathrm{SU}(2)_L$ is to be identified with the diagonal SU(2) subgroup of $[\mathrm{SU}(2)]^3$. In terms of the $\mathrm{SU}(2)_i$ gauge boson $\vec{\mathbf{A}}_i$, the $\mathrm{SU}(2)_L$ gauge bosons are given by $\vec{\mathbf{A}} = (1/\sqrt{3})(\vec{\mathbf{A}}_1 + \vec{\mathbf{A}}_2 + \vec{\mathbf{A}}_3)$. Of the other orthogonal combinations of $\vec{\mathbf{A}}_i$, $\vec{\mathbf{A}}' = (1/\sqrt{6})(\vec{\mathbf{A}}_1 + \vec{\mathbf{A}}_2 - 2\vec{\mathbf{A}}_3)$, which exhibits universality only among the first two generations, can have a mass scale in the TeV range [5]. The additional gauge bosons $\vec{\mathbf{A}}'$, denoted by Z' and $W'^{\pm}$, suggest new physics [6] beyond the standard model.

In a previous study [7], characteristic signals in hadronic collisions, resulting from the neutral member Z', were analyzed and compared with those from the neutral gauge bosons Z_{LR}, occurring in left-right symmetric models, and Z_χ, Z_ψ, and Z_η, occurring in superstring-inspired E_6 electroweak models. In this work we extend the previous analyses to include a neutral gauge boson, Z_I, occurring in a superstring-inspired E_6 model (model I), and corresponds to an extra inert $\mathrm{SU}(2)_I$ group at electroweak energies [8]. The breaking of E_6 leads to effective strong-electroweak groups of rank 5 and rank 6 at low energies. Of the rank-6 models, we are interested here in the decomposition $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_I \otimes \mathrm{U}(1)'$. This rank-6 low-energy group can be reduced further into an effective rank-5 model through the reduction $\mathrm{SU}(2)_I \otimes \mathrm{U}(1)' \to \mathrm{SU}(2)_I$. The $\mathrm{SU}(2)_I$ in this model does not contribute to electromagnetic charge; it is thus "inert." When $\mathrm{SU}(2)_I$ is broken, its gauge bosons Z_I and $W_I^{\pm}$ become massive. Notice that the $\pm$ signs refer to the $\mathrm{SU}(2)_I$ charge. All the $\mathrm{SU}(2)_I$ gauge bosons are electromagnetically neutral. The members of the **27**-plet representation of E_6 form doublets and singlets under $\mathrm{SU}(2)_I$. The left-handed doublets are $\binom{\bar{h}}{\bar{d}}\binom{E^-}{\bar{e}^-}\binom{\nu_E}{\bar{\nu}_e}\binom{\bar{N}_e}{n}$, where h, E^-, ν_E, N_e, and n are exotic fermions [9]. All other particles are singlets under $\mathrm{SU}(2)_I$. Of the ordinary fermions, Z_I couples only to left-handed leptons and right-handed d-type quarks. On the other hand, the W_I's can participate in the production of exotic particles and rare processes, especially flavor changing neutral currents [10].

With one additional neutral gauge boson, the neutral-current Lagrangian is modified so as to contain an additional term:

$$-\mathcal{L}_{\mathrm{NC}} = eJ^\mu_{\mathrm{e.m.}} A_\mu + g_1 J_1^\mu Z^0_{1\mu} + g_2 J_2^\mu Z^0_{2\mu}, \tag{1}$$

where Z_1^0 is the $SU(2)_L \otimes U(1)_Y$ boson and Z_2^0 is the additional boson in the weak eigenstate basis. The g_i are the gauge couplings with $g_1 = g/\cos\vartheta_W$, where $g = e/\sin\vartheta_W$. For the $Sp(6)_L \otimes U(1)_Y$ model, $g_2 = \sqrt{(1-x)/2}g_1 = g/\sqrt{2}$, $x = \sin^2\vartheta_W$. For model I, $g_2 = g$. The neutral currents J_i, $i = 1,2$, are given by

$$J_i^\mu = \frac{1}{2}\sum_f \bar{\psi}_f \gamma^\mu [g_V^{(i)}(f) + g_A^{(i)}(f)\gamma_5]\psi_f. \tag{2}$$

Here $g_{V,A}^{(i)}(f)$ are the vector and axial-vector couplings of fermion f to Z_i^0, respectively. They are related to the chiral couplings $\varepsilon_{L,R}^{(i)}(f)$ by

$$g_{V,A}^{(i)}(f) = \varepsilon_L^{(i)}(f) \pm \varepsilon_R^{(i)}(f). \tag{3}$$

After symmetry breaking the weak eigenstate bosons Z_i^0 are related to the mass eigenstate bosons Z_i by

$$\begin{aligned} Z_1 &= Z_1^0 \cos\varphi + Z_2^0 \sin\varphi, \\ Z_2 &= -Z_1^0 \sin\varphi + Z_2^0 \cos\varphi, \end{aligned} \tag{4}$$

where φ denotes the mixing angle between Z_1^0 and Z_2^0. The neutral-current Lagrangian now reads

$$-\mathcal{L}_{\rm NC} = g_1 \sum_{i=1}^{2}\left[\sum_f \bar{\psi}_f \gamma_\mu [V^{(i)}(f) + A^{(i)}(f)\gamma_5]\psi_f\right] Z_i^\mu, \tag{5}$$

where

$$V^{(1)}(f), A^{(1)}(f) = \frac{1}{2}\left[g_{V,A}^{(1)}(f)\cos\varphi + \frac{g_2}{g_1} g_{V,A}^{(2)}(f)\sin\varphi\right], \tag{6}$$

$$V^{(2)}(f), A^{(2)}(f) = \frac{1}{2}\left[-g_{V,A}^{(1)}(f)\sin\varphi + \frac{g_2}{g_1} g_{V,A}^{(2)}(f)\cos\varphi\right]. \tag{7}$$

In our analysis, we make the simplifying assumption that Z_1^0-Z_2^0 mixing can be ignored, as it is constrained to be tiny for the models considered in this work [11,12].

For the SM, $g_V^{(1)}(f) = (T_{3L} - 2xQ)_f$ and $g_A^{(1)}(f) = (T_{3L})_f$. Here $(T_{3L})_f$ and Q_f are the third component of weak isospin and electric charge of fermion f, respectively. For the $Sp(6)_L \otimes U(1)_Y$ model $g_V^{(2)}(f) = g_A^{(2)}(f) = (T_{3L})_f$ for the first two generations and $g_V^{(2)}(f) = g_A^{(2)}(f) = -2(T_{3L})_f$ for the third one. Thus, the fermion couplings in the $Sp(6)_L \otimes U(1)_Y$ model are purely left handed. For model I, the couplings of fermions, including exotics, are given in [13].

Several articles have dealt with phenomenological effects resulting from the presence of theoretically motivated, additional neutral gauge bosons [14]. However, up until now, there is no experimental evidence from the Fermilab Tevatron for the existence of any additional neutral gauge bosons [15]. It is now commonly believed that, if an additional neutral gauge boson exists, it should be observed through the Drell-Yan process at high-energy pp colliders, if its mass is in the few TeV range or less. Consider the Drell-Yan process for colliding hadrons A and B: $A + B \to l\bar{l}X$. Let θ^* be the angle between l and q in the quark-antiquark center of mass frame for the subprocess $q\bar{q} \to l\bar{l}$. The forward-backward asymmetries A_{FB} are defined by

$$A_{FB}(y) = \frac{F - B}{F + B}, \tag{8}$$

where

$$F \pm B = \left[\int_0^1 \pm \int_{-1}^0\right] d(\cos\theta^*) \frac{d^2\sigma}{dy\, d(\cos\theta^*)}, \tag{9}$$

here $d^2\sigma/dy\, d(\cos\theta^*)$ is the differential cross section per unit rapidity [7]. We then find

$$A_{FB}(y) = \frac{3}{4}\frac{\varepsilon_R(l)^2 - \varepsilon_L(l)^2}{\varepsilon_R(l)^2 + \varepsilon_L(l)^2} \times \frac{\sum_q [\varepsilon_R(q)^2 - \varepsilon_L(q)^2] G_q^-}{\sum_q [\varepsilon_R(q)^2 + \varepsilon_L(q)^2] G_q^+}, \tag{10}$$

where

$$G_q^{\pm} = f_{q/A}(x_A) f_{\bar{q}/B}(x_B) \pm f_{\bar{q}/A}(x_A) f_{q/B}(x_B). \tag{11}$$

Here $f_{q/A}(x_A)$ is the parton distribution of quark q in hadron A. The forward-backward asymmetry $A_{FB}(y)$ is even (odd) in y for $p\bar{p}$ (pp) machines. The integrated forward-backward asymmetry is defined by

$$A^{FB} = \frac{\left[\int_0^{y_m} \pm \int_{-y_m}^0\right] dy(F - B)}{\left[\int_0^{y_m} + \int_{-y_m}^0\right] dy(F + B)} \tag{12}$$

with the + (−) sign relevant for $p\bar{p}$ (pp) collisions and $y_m = \ln(\sqrt{s}/M)$, where $\sqrt{s}$ is the total c.m. energy and M is the gauge boson mass.

Now we turn to our results. The relevant quantity that we will first consider here is σB: the gauge boson production cross section times the branching fraction into dileptons. We calculated σB for Z' and Z_I at $\sqrt{s} = 14$ TeV (LHC), assuming that $\varphi = 0$. In calculating cross sections, we use the Martin-Roberts-Stirling-Thorne 2001 (MRST 2001) set of parton distribution functions [16]. For comparison, we also consider a gauge boson Z with couplings identical to those of the standard Z, but with mass being a free parameter. We assume that Z_I is much heavier than any of the fermions. The product σB is presented in Fig. 1 as a function of the gauge boson mass M for $M \geqslant 0.5$ TeV. Experimental direct-search bounds on the Z' and Z_I masses have indeed put a lower limit on M, $M \geqslant 0.5$ TeV [17]. Figure 1 shows that the $\mu^+\mu^-$ production rate for Z' and Z_I bosons is lower than the cor-

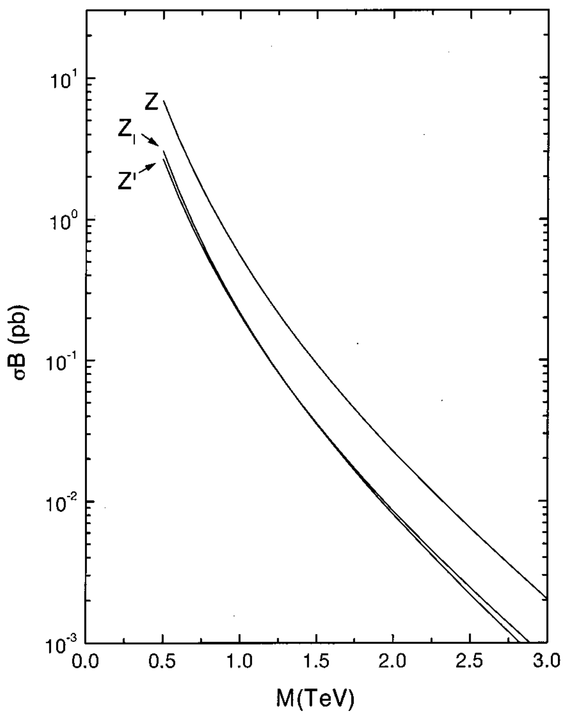

FIG. 1. Gauge boson production cross section times branching fraction into $\mu^+\mu^-$ pair (σB), for Z', Z_I, and Z, in pp collisions at $\sqrt{s}=14$ TeV as a function of the gauge boson mass M. Z here represents a gauge boson with the couplings of the standard Z, but with mass being a free parameter.

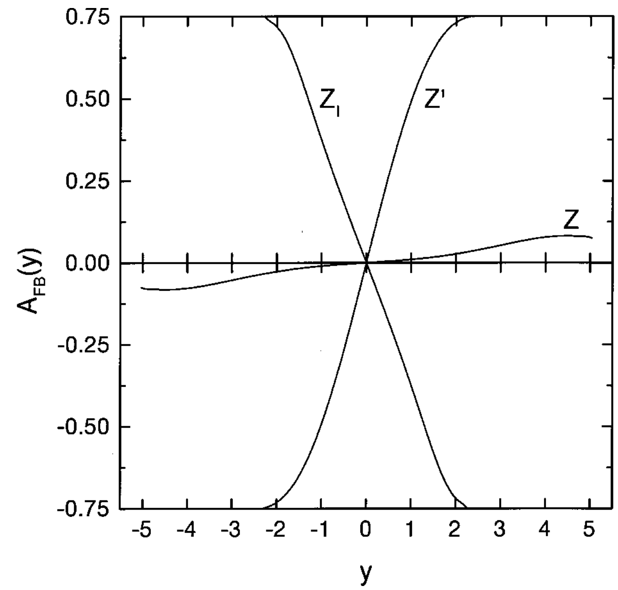

FIG. 2. Forward-backward asymmetries $A_{FB}(y)$ for $pp\to Z_2+\cdots\to\mu^+\mu^-$ at $\sqrt{s}=14$ TeV, with $M=1$ TeV. Also shown is $A_{FB}(y)$ for the standard model gauge boson Z.

responding rate for Z. Also, the Z' muon-pair production rate overlaps the corresponding rate for Z_I. However, we note that the $Z'\to\tau^+\tau^-$ production rate at LHC is higher than the corresponding rate for Z_I, allowing Z' to be distinguished [7]. The forward-backward asymmetry $A_{FB}(y)$ in the gauge boson leptonic decay is expected to provide crucial "fingerprints" of the gauge boson couplings. In Fig. 2 we present $A_{FB}(y)$ for the models considered here as a function of y, where we take $M=1$ TeV. We also consider the standard model gauge boson Z with mass $M=91.1882$ GeV. Small asymmetries are expected for Z because $\varepsilon_L^2(e)\approx\varepsilon_R^2(e)$. Maximal asymmetries are expected for Z' because of its pure left-handed couplings to fermions. Thus, for Z', with $\varepsilon_L^2(u)=\varepsilon_L^2(d)=\varepsilon_L^2(e)$, $A_{FB}(y)$ is expected to approach ±0.75 at $\pm y_m$, respectively. On the other hand, since Z_I couples only to right-handed d-type quarks and left-handed l, $A_{FB}(y)$ is expected to approach ±0.75 at $\mp y_m$, respectively. Maximal forward-backward asymmetries are therefore expected in both Z' and Z_I leptonic decays. However, the signs of the asymmetries in Z' production are opposite to those in Z_I production, for the same value of y, allowing the models to be distinguished. In Fig. 3 we present the integrated forward-backward asymmetries A^{FB} as a function of the gauge boson mass which is taken as a free parameter. Figure 3 shows that for Z' and $M\geqslant1$ TeV, A^{FB} is fairly constant with $A^{FB}\approx0.39$. For Z_I, A^{FB} decreases steadily over the considered range of M with $A^{FB}\approx-0.24$ at $M=0.5$ TeV and $A^{FB}\approx-0.35$ at $M=3.0$ TeV. When Z_{LR}, Z_χ, Z_ψ, and Z_η are included [7], we find that the integrated forward-backward asymmetry A^{FB} is highest for Z' and lowest for Z_I.

In conclusion, the $\mathrm{Sp}(6)_L\otimes U(1)_Y$ extension of the standard model gauge group suggests an extra set of horizontal gauge bosons Z', $W'^{\pm}$. A superstring-inspired E_6 model, characterized by an extra inert $\mathrm{SU}(2)_I$ group at electroweak energies suggests an extra set of neutral gauge bosons Z_I, $W_I^{\pm}$. We studied distributions of leptons at the LHC, produced by the neutral gauge bosons Z' and Z_I. We find that Z' is difficult to distinguish through its $\mu^+\mu^-$ production

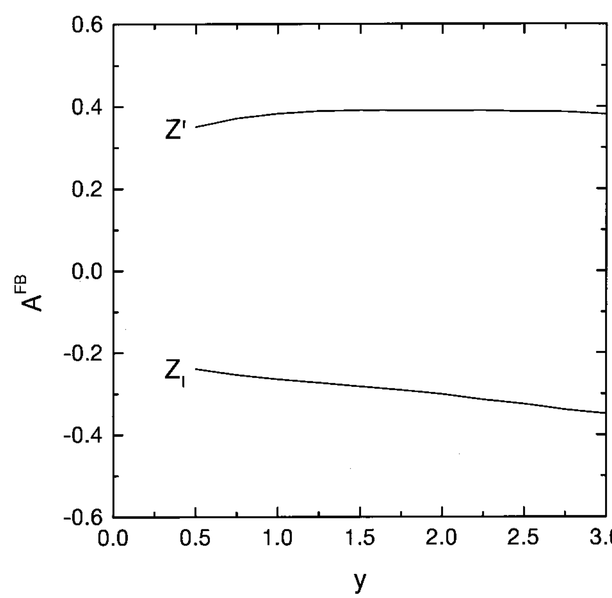

FIG. 3. Integrated forward-backward asymmetries A^{FB} for $pp\to Z_2+\cdots\to\mu^+\mu^-$, at $\sqrt{s}=14$ TeV, as a function of the gauge boson mass M.

rate because of the overlapping with Z_I. However, the forward-backward asymmetry in the gauge boson leptonic decay, $A_{FB}(y)$, is very useful for identifying gauge bosons because it is very sensitive to specific forms of the couplings. The Z' couplings to fermions are purely left handed, while Z_I couples only to left-handed leptons and right-handed d-type quarks. Because of these couplings, both Z' and Z_I are expected to exhibit maximal asymmetries. However, the signs of the asymmetries in Z' production are opposite to those in the Z_I production, yet allowing the models to be distinguished. The integrated forward-backward asymmetry A^{FB} is higher for Z', with $A^{FB}\approx 0.39$, and lower for Z_I, ranging from $A^{FB}\approx -0.24$ for $M=0.5$ TeV to $A^{FB}\approx -0.35$ for $M=3$ TeV.

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