Determination of g_R/g_L in Left-Right Symmetric Models at Hadron Colliders

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Recently proposed rare decays $Z' \to f_1 \bar{f}_2 V$ (with $V=W$ or Z and $f_{1,2}$ ordinary fermions) and the forward-backward asymmetry are found to be sensitive diagnostic tests for the gauge coupling ratio g_R/g_L in left-right symmetric models ($SU_{2L} \times SU_{2R} \times U_{1(B-L)}$). At projected luminosities of the CERN Large Hadron Collider and the Superconducting Super Collider, g_R/g_L can be determined statistically to $\sim 1\%$ for $M_{Z'} \simeq 1$ TeV. The absence of related decays $W'^{\pm} \to f_1 \bar{f}_2 W^{\pm}$ would be a clean signature that W' couples to right-handed currents. Once g_R/g_L is determined, the ratio $M_{Z'}/M_{W'}$ and the decays $Z' \to W^+ W^-$ ($W'^{\pm} \to W^{\pm} Z$) provide probes for the symmetry breaking sector.

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Left-right symmetric models [1] encompass a class of theories with the extended gauge structure $SU_{2L} \times SU_{2R} \times U_{1(B-L)}$, and g_L, g_R, g_{B-L} as the respective gauge couplings. They are the simplest extended gauge groups which introduce charged current interactions for the right-handed fermions. In a class of such models parity is a Lagrangian symmetry, which is spontaneously broken at a lower scale. In addition, the left-right gauge symmetry is a part of grand unified gauge groups such as SO(10) and E_6 and of a class of heterotic superstring vacua.

The left-right symmetry is spontaneously broken to the standard electroweak gauge group $SU_{2L} \times U_{1Y}$ at a high scale with a constraint on the hypercharge $Y = T_{3R} + Y_{B-L}/2$. At this stage three gauge bosons, $W'^{\pm}$ and Z', acquire a mass. For the models with $g_L = g_R$ and equal magnitude of the left-handed and the right-handed quark-mixing matrix elements, the bound on the mass of the heavy charged W' is $M_{W'} > 1.4$ TeV, based on the K_S-K_L mass difference [2], and the W-W' mixing angle is $|\theta_+| < 0.003$, from universality [3]. For general left-right symmetric models these bounds are much weaker [4]: $g_L M_{W'}/g_R > 300$ GeV and $g_R|\theta_+|/g_L < 0.013$. Analyses of the Z pole, weak neutral current, and collider data put lower bounds [5-8] on the Z' mass in the range of 400–1000 GeV and on the Z-Z' mixing angle $|\theta_N| < 0.008$.

After the discovery of the Z' and/or $W'^{\pm}$ by their leptonic decays ($Z' \to l^+ l^-$, $W' \to l\nu$, where ν is a "right-handed" neutrino, which could be heavy or light), the next goal would be to determine the symmetry-breaking structure and the g_R/g_L ratio. The first candidate for such a test is the $M_{Z'}/M_{W'}$ mass ratio, which can be written as [9]

$$\frac{M_{Z'}^2}{M_{W'}^2} = \frac{\kappa^2 \cot^2\theta_W}{\kappa^2 \cot^2\theta_W - 1} \frac{1}{\rho_R}, \tag{1}$$

where $\kappa \equiv g_R/g_L$, $\sin\theta_W = e/g_L$, and

$$\rho_R = \frac{\sum_i (t_{iR}^2 + t_{iR} - t_{3iR}^2)|\langle\phi_i\rangle|^2}{\sum_i 2t_{3iR}^2 |\langle\phi_i\rangle|^2},$$

with t_{iR} and t_{3iR} being SU_{2R} quantum numbers of the Higgs fields ϕ_i. The parameter ρ_R efficiently parametrizes the Higgs sector and has a limited range for a large class of models.

The parameter κ is often assumed to be unity. However, $\kappa \neq 1$ in models [10] with D parity broken at a large scale ($> 10^9$ GeV); for a typical class of such models $\kappa < 1$. Note also that the constraint

$$\frac{1}{e^2} = \frac{1}{g_L^2}\left(1 + \frac{1}{\kappa^2}\right) + \frac{1}{g_{B-L}^2} \tag{2}$$

and $e^2/g_L^2 = \sin^2\theta_W \sim 0.23$ imply that κ must satisfy $\kappa^2 \cot^2\theta_W - 1 \geq 0$, and thus $\kappa \geq 0.55$ for the theory to be consistent with experiment.

Once κ is determined from experiments discussed below, the ratio in Eq. (1) yields information about the Higgs sector of the theory. For example, for the Higgs sector with $\phi \sim (2,2,0)$, $\Delta_L = (3,1,2)$, $\Delta_R = (1,3,2)$, and $\langle\Delta_R\rangle \gg \langle\phi\rangle \gg \langle\Delta_L\rangle$ (see the first model in Table I), one obtains $\rho_R = \frac{1}{2}$ and thus for $\kappa = 1$ (0.7), $M_{Z'}/M_{W'} = 1.7$ (2.3). Other mutually exclusive values for the mass ratio can be obtained for other Higgs sectors (see Table I).

Other probes of the symmetry breaking structure are the decays [11,12] $Z' \to W^+ W^-$ and $W'^{\pm} \to W^{\pm} Z$, which are diagnostic tests for the Z-Z' mixing angle θ_N and the W-W' mixing angles θ_+, respectively. Although such decays are suppressed by $\theta_{N,+}^2$ ($\propto M_{Z,W}^4/M_{Z',W'}^4$), the longitudinal components of gauge bosons give an enhancement $\propto M_{Z',W'}^4/M_{Z,W}^4$, thus yielding sizable decay rates:

$$\Gamma_{Z'WW} = \frac{\alpha\theta_N^2}{48\tan^2\theta_W} M_{Z'} \left(\frac{M_{Z'}}{M_W}\right)^4, \tag{3}$$

$$\Gamma_{W'ZW} = \frac{\alpha|\theta_+|^2}{48\sin^2\theta_W} M_{W'} \left(\frac{M_{W'}}{M_W}\right)^4, \tag{4}$$

where

$$\theta_N = \frac{-\sin\theta_W(1 + \kappa^2\cot^2\theta_W \sigma_3)}{(\kappa^2\cot^2\theta_W - 1)^{1/2}(M_Z^2/M_{Z'}^2)}$$

and $|\theta_+| = \kappa|\sigma_+|(M_W^2/M_{W'}^2)$. Parameters

$$\sigma_3 \equiv \frac{\sum_i t_{i3L} t_{i3R} |\langle\phi_i\rangle|^2}{\sum_i t_{i3L}^2 |\langle\phi_i\rangle|^2}$$

and

$$\sigma_+ = \frac{\sum_i \langle\phi_i|T_{-L}T_{+R}|\phi_i\rangle}{\sum_i (t_{iL}^2 + t_{iL} - t_{3iL}^2)|\langle\phi_i\rangle|^2}$$

again efficiently parametrize a Higgs sector and have a limited range for a large class of theories. (See Table I for the value of $\sigma_{3,+}$ parameters for three typical Higgs sectors.) Here $t_{i3(L,R)}$ are the $SU_{2(L,R)}$ quantum numbers of the Higgs field ϕ_i, $T_{\pm(L,R)}$ are the raising and lowering operators of $SU_{2(L,R)}$, and $\alpha = e^2/4\pi$. Once κ is determined, the mixing angles $\theta_{N,+}$ can then yield information on the Higgs sector. For example, for the first model in Table I, one has $\sigma_3 \simeq -1$ and $0 \le |\sigma_+| \le 1$. Thus, for $\kappa = 1$ (0.7), $C_N \equiv \theta_N/(M_Z^2/M_{Z'}^2) \simeq 0.73$ (0.38) and $C_+ \equiv |\theta_+|/(M_W^2/M_{W'}^2) \le 1$ (0.7). Note that $\sigma_3 \simeq -1$ has a fixed value for the first and the third models of Table I and therefore C_N is fixed for these two models for a given κ. For the second model $0 \ge \sigma_3 \ge -1$, and thus for $\kappa = 1$ (0.7), one has $-0.31 \le C_N \le 0.73$ $(-0.60 \le C_N \le 0.38)$. On the other hand, $0 \le |\sigma_+| \le 1$, and thus $0 \le |C_+| \le \kappa$ for all three models.

Another important set of experiments are those that would provide a diagnostic study of the gauge coupling ratio $\kappa = g_R/g_L$. One possibility would be the measurement of σB. However, while the production cross section σ could be calculated for a given set of $V' \equiv (W'^{\pm}, Z')$ couplings to within a few percent, the theoretical branching ratio, $B \equiv \Gamma(V' \to f\bar{f})/\Gamma(V' \to \sum f_i \bar{f}_i)$ is model dependent because it depends on whether exotic fermions contribute to the V' width, which could easily change σB by a factor of 2. Thus, σB is not a reliable way to measure κ. However, once κ is known, σB would be a useful indirect probe for the existence of exotic fermions.

In this Letter we describe two important probes for studying the gauge coupling ratio κ. Both rely on the fact that the heavy Z' coupling depends on κ, and both are independent of absolute production rates or branching ratios. The first test consists of the recently proposed [13] rare decays $Z' \to f_1 \bar{f}_2 V$, with $V = W$ or Z and $f_{1,2}$ the ordinary fermions. For $V = Z$ the combination $g_1^2 g_2^2 (\hat{g}_{L1}^2 \hat{g}_{L2}^2 + \hat{g}_{R1}^2 \hat{g}_{R2}^2)$ is measured, while for $V = W$ such decays project out $\hat{g}_{L2}$ couplings. Here, g_1 and g_2 are the gauge coupling constants of the V and Z', respectively, while $\hat{g}_{(L,R)1}$ and $\hat{g}_{(L,R)2}$ correspond to the (left,right) charges of the V and Z', respectively. Although such decays are suppressed by a factor $\alpha/2\pi$ compared to $Z' \to f\bar{f}$, they have a logarithmic enhancement proportional to $\ln^2(M_{Z'}^2/M_V^2)$, due to collinear and infrared singularities of QED [14]. The second probe for gauge couplings is the forward-backward asymmetry A_{FB} for the process $pp \to Z' \to e^+e^-$ or $\mu^+\mu^-$.

In the left-right symmetric model the neutral current gauge interaction term can be written as

$$-L_{NC} = eJ_{em}^{\mu} A_\mu + g_1 J_1^{\mu} Z_{1\mu} + g_2 J_2^{\mu} Z_{2\mu} . \qquad (5)$$

Here $g_1 = g_L/\cos\theta_W$ and $g_2 = g_1 (5\sin^2\theta_W/3)^{1/2}$. The photon A, the $SU_2 \times U_{1Y}$ boson Z_1, and the additional Z_2 gauge boson in the weak eigenstate basis are related to the neutral gauge bosons W_{3L}, W_{3R}, and B in the $SU_{2L} \times SU_{2R} \times U_{1(B-L)}$ basis by

$$A = e(W_{3L}/g_L + W_{3R}/g_R + B/g_{B-L}) ,$$

$$Z_1 = e[W_{3L}/g_Y - (g_Y/g_L)(W_{3R}/g_R + B/g_{B-1})] ,$$

and

$$Z_2 = g_Y(W_{3R}/g_{B-L} - B/g_R) .$$

Here, $1/g_Y^2 \equiv 1/g_R^2 + 1/g_{B-L}^2$. The currents are defined as

$$J_j^{\mu} = \tfrac{1}{2} \sum_i \bar{\psi}_i \gamma^{\mu} [\hat{g}_{V_j}^i - \hat{g}_{A_j}^i \gamma_5] \psi_i , \quad j = 1,2 , \qquad (6)$$

where the sum runs over fermions and the $\hat{g}^i_{(V,A)_j}$ correspond to the vector and axial-vector couplings of Z_j to the ith flavor. The corresponding chiral couplings are $\hat{g}^i_{(L,R)j} = \frac{1}{2}(\hat{g}^i_{V_j} \pm \hat{g}^i_{A_j})$. With the above definition of the gauge bosons one can show [15] that $J_2^{\mu} = \sqrt{3/5}[\beta J_{3R}^{\mu} - (1/2\beta) J_{B-L}^{\mu}]$, where $\beta = (\kappa^2 \cot^2\theta_W - 1)^{1/2}$, and thus $\hat{g}^i_{(L,R)2}$ can be readily obtained from the $SU_{2L} \times SU_{2R}$

TABLE I. The Higgs multiplets [beside the Higgs field $\phi \sim (2,2,0)$], the hierarchy of their vacuum expectation values (VEV's), the values for the ρ_R parameter and $\sigma_{3,+}$ parameters, and the values for $M_{Z'}/M_{W'}$ (for $\kappa = 1, 0.7$). The two diagonal vacuum expectation values of the Higgs field ϕ are denoted k and k'.

Higgs sector	VEV's	ρ_R	σ_3	σ_+	$M_{Z'}/M_{W'}$
$\Delta_L \sim (3,1,2)$, $\Delta_R \sim (1,3,2)$	$\langle\Delta_R\rangle \gg \langle\phi\rangle \gg \langle\Delta_L\rangle$	$\frac{1}{2}$	-1	$\frac{2k^*k'}{\|k\|^2+\|k'\|^2}$	1.7,2.3
$\delta_L \sim (2,1,1)$, $\delta_R \sim (1,2,1)$	$\langle\delta_R\rangle \gg \{\langle\phi\rangle, \langle\delta_L\rangle\}$	1	$\frac{-\|k\|^2-\|k'\|^2}{\|k\|^2+\|k'\|^2+\|\langle\delta_L\rangle\|^2}$	$\frac{2k^*k'}{\|k\|^2+\|k'\|^2+\|\langle\delta_L\rangle\|^2}$	1.2,1.6
$\chi_L \sim (3,1,0)$, $\chi_R \sim (1,3,0)$	$\langle\chi_R\rangle \gg \langle\phi\rangle \gg \langle\chi_L\rangle$	∞	-1	$\frac{2k^*k'}{\|k\|^2+\|k'\|^2}$	0,0

$\times U_{1(B-L)}$ quantum numbers of the ith fermion.

Because of existing limits one can safely neglect Z_1-Z_2 mixing, and thus the weak eigenstates Z_1 and Z_2 can be identified with the mass eigenstates Z and Z', respectively. The decay rate for the process $Z' \to f\bar{f}Z$ can be written for $\mu = M_Z^2/M_{Z'}^2 \ll 1$ as [13]

$$\Gamma_{ffZ} = \frac{M_{Z'} C_{ffZ}}{192\pi^3} \{(\ln\mu)^2 + 3\ln\mu + 5 - \tfrac{1}{3}\pi^2 + O(\mu)\}\,, \quad (7)$$

which clearly indicates the collinear and infrared singularity. Here $C_{ffZ} = g_1^2 g_2^2 (\hat{g}_{L1}^{f2} \hat{g}_{L2}^{f2} + \hat{g}_{R1}^{f2} \hat{g}_{R2}^{f2})$. The decay rate for $Z' \to f_1 \bar{f}_2 W$ has the same form as Eq. (7) with the corresponding changes in the gauge couplings (i.e., $\hat{g}_{L1} = \cos\theta_W/\sqrt{2}$, $\hat{g}_{R1} = 0$), and M_Z replaced by M_W. Decay rates $W' \to f_1 \bar{f}_2 V$ with $V = Z$ or W can be studied in an analogous manner.

Rare decays $Z' \to f_1 \bar{f}_2 V$ should be compared with the basic process $Z' \to f\bar{f}$. In particular, the ratio of branching ratios $r_{12V} = B(Z' \to f_1 \bar{f}_2 V)/B(Z' \to l\bar{l})$ can be determined cleanly. The l in the denominator refers to the sum over leptons e and μ.

We first evaluate $\sigma B(Z' \to e^+e^-)$ for the CERN Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC) for different values of $M_{Z'}$ and κ. We assume the branching ratios B from decays into 16-plets. This is just an example for estimating statistical errors; the actual values for r's are independent of the exotic decay modes. The number of events for $Z' \to e^+e^-$ (or $\mu^+\mu^-$) for a one-year run (10^7 s) at the expected LHC luminosity $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1} is 2.8×10^4, 170, and 4 for $\kappa = 1$ and $M_{Z'} = 1$, 3, and 5 TeV, respectively. The corresponding numbers for the SSC with $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1} are 1.1×10^4, 220, and 22. For the projected luminosities and $M_{Z'} = 1$ TeV, LHC is better by a factor of 2, while the SSC is better for higher values of $M_{Z'}$.

We studied the following leptonic ratios:

$$r_{llZ} \equiv B(Z' \to l^+l^-Z)/B(Z' \to l^+l^-)\,,$$

$$r_{l\nu W} \equiv B(Z' \to l^{\mp}\nu_l W^{\pm})/B(Z' \to l^+l^-)\,,$$

$$r_{\nu\nu Z} \equiv B(Z' \to \nu_l \bar{\nu}_l Z)/B(Z' \to l^+l^-)\,,$$

where l refers to the summation over e and μ and ν_l in $r_{\nu\nu Z}$ refers to the summation over ν_e, ν_μ, and ν_τ. The above ratios can be measured by either leptonic or hadronic W or Z decays. Ratios where $f_{1,2}$ are hadrons, i.e., $r_{\text{had}\,Z}$ and $r_{\text{had}\,W}$, are defined analogously. We do not include the t quark in the definition of $r_{\text{had}\,(W,Z)}$.

The detection of leptonic and semileptonic decays for r's has been discussed in Ref. [13] for a class of extended gauge structures, including the left-right symmetric model with $\kappa = 1$. Here we would like to explore r's as a function of κ. In Fig. 1 the r's are plotted as a function of κ along with typical error bars. It turns out that the r's are sensitive functions of κ for $0.8 < \kappa < 1.1$ (with the exception of r_{llZ} which is insensitive due to $\hat{g}_{L1}^2 \sim \hat{g}_{R1}^2$ for $l = e, \mu$). In particular, $r_{l\nu W}$ and $r_{\nu\nu Z}$ would yield in-

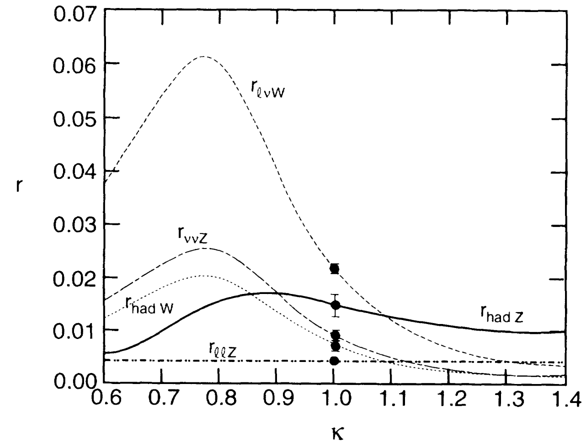

FIG. 1. Ratios r as a function of $\kappa = g_R/g_L$. The error bars are for the LHC with $M_{Z'} = 1$ TeV. For r_{llZ}, $r_{l\nu W}$, and $r_{\nu\nu Z}$, the error bars include both leptonic and hadronic decays of W and Z, while the error bars for $r_{\text{had}\,W}$ and $r_{\text{had}\,Z}$ include only leptonic decays.

dependent determinations of κ, each with a statistical precision of $< 1\%$ for $M_{Z'} = 1$ TeV. Also, the comparison of r's [13] for a general E_6 gauge boson with the range of r's in the left-right symmetric models indicates that r's can provide a useful tool to distinguish between the two types of models.

Backgrounds associated with the above ratios have been discussed in Ref. [13] for the left-right symmetric model with $\kappa = 1$ and a class of E_6 models. The same arguments apply to the case with $\kappa \neq 1$. Purely leptonic decays $Z' \to Zl^+l^-$ with $Z \to l^+l^-$ are clean events with good statistics. On the other hand, $Z' \to Z\nu_l\bar{\nu}_l$ has a serious background [13] $pp \to ZZ$, with $Z \to \nu_l\bar{\nu}_l$. The most promising signal is for $Z' \to W^{\pm}e^{\mp}\nu_e$ with $W \to$ hadrons. The background from $pp \to W^+W^-$ can be cleanly eliminated at a loss of only $\sim 4\%$ of the signal by requiring the transverse mass $m_{Tl\nu_l}$ of the $l\nu_l$ system to be larger than 90 GeV. These events also have a comparable rate with $Z' \to W^+W^-$ events, which probe the symmetry breaking scheme. The latter can again be eliminated by an $m_{T\nu_l}$ cut.

Semileptonic decay modes $Z' \to Vl_1\bar{l}_2$ with V decaying hadronically have a completely different kinematic distribution [13] from the QCD background [16,17] $pp \to V$ + jet + jet where V decays leptonically. However, the kinematics of semihadronic decays $Z' \to V$ + hadrons with $V \to \bar{l}_1 l_2$ suffer from the strong QCD background $pp \to V$ + jet + jet where V decays leptonically.

The forward-backward asymmetry [18,19] A_{FB} for $pp \to Z' \to e^+e^-$ or $\mu^+\mu^-$ serves as another diagnostic test for Z' gauge couplings. Let θ be the e^- angle with respect to the beam in the Z' rest frame and y be the Z' rapidity. Then $A_{\text{FB}}(y) = [F(y) - B(y)]/[F(y) + B(y)]$, with $F(y) \pm B(y) = [\int_0^1 \pm \int_{-1}^0] d\cos\theta\, d^2\sigma/dy\, d\cos\theta$. For pp colliders $A_{\text{FB}}(y) = -A_{\text{FB}}(-y)$. The integrated forward-backward asymmetry is then defined as

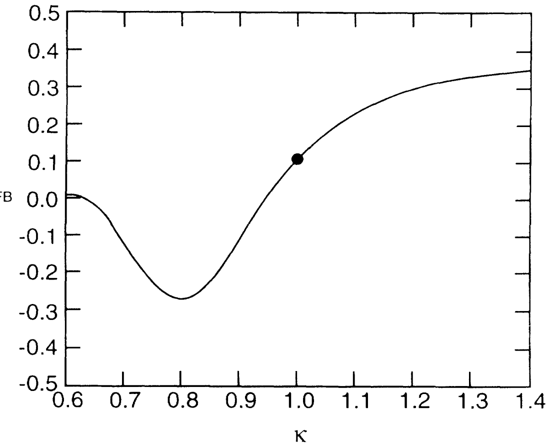

FIG. 2. A_{FB} at the LHC with $M_{Z'}=1$ TeV, plotted as a function of $\kappa = g_R/g_L$.

$$A_{\mathrm{FB}}=\frac{\left[\int_0^{y_{\max}}-\int_{y_{\min}}^0\right][F(y)-B(y)]dy}{\int_{y_{\min}}^{y_{\max}}[F(y)+B(y)]dy}. \tag{8}$$

The statistical error is $\Delta A_{\mathrm{FB}}=[(1-A_{\mathrm{FB}}^2)/N]^{1/2}$, where N is the total number of events.

In Fig. 2 A_{FB} is plotted as a function of κ as well as a typical error bar. Again A_{FB} is a sensitive function of κ in the physically interesting region $0.8<\kappa<1.1$, and it serves as an excellent complement to the rare decays. For $M_{Z'}=1$ TeV it would yield an independent determination of κ with a statistical precision better than 1%.

The forward-backward asymmetry A_{FB} for the process $pp\to W'\to e\nu$ or $\mu\nu$ yields information about the $[(\hat{g}^q_{L2})^2-(\hat{g}^q_{R2})^2]\times[(\hat{g}^l_{L2})^2-(\hat{g}^l_{R2})^2]$ combination of the W' gauge couplings, and thus it cannot distinguish between pure left-handed or pure right-handed coupling of a W'. On the other hand, the rare decay $W'\to f\bar{f}W$ (for fermions f much lighter than M_W) directly probes the $(\hat{g}^f_{L2})^2$, and thus it should be highly suppressed (by the square of the W-W' mixing angle or by $m_f^2/M_{W'}^2$) in the left-right symmetric models. The absence of such events would thus provide a good check that the coupling of W' is right handed. ($W'\to f\bar{f}W$ events can in principle be distinguished from $W'\to WZ$ events by appropriate kinematic cuts.)

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