## $Z'$-BOSON SEARCHES

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The $Z'$ boson is a hypothetical massive, electrically-neutral and color-singlet particle of spin 1. This particle is predicted in many extensions of the standard model, and has been the object of extensive phenomenological studies [1].

***$Z'$ couplings to quarks and leptons.*** The couplings of a $Z'$ boson to the first-generation fermions are given by

$$Z'_\mu \left( g_u^L\, \overline{u}_L \gamma^\mu u_L + g_d^L\, \overline{d}_L \gamma^\mu d_L + g_u^R\, \overline{u}_R \gamma^\mu u_R + g_d^R\, \overline{d}_R \gamma^\mu d_R \right.$$
$$\left. + \, g_\nu^L\, \overline{\nu}_L \gamma^\mu \nu_L + g_e^L\, \overline{e}_L \gamma^\mu e_L + g_e^R\, \overline{e}_R \gamma^\mu e_R \right) \quad , \qquad (1)$$

where $u, d, \nu$ and $e$ are the quark and lepton fields in the mass eigenstate basis, and the coefficients $g_u^L$, $g_d^L$, $g_u^R$, $g_d^R$, $g_\nu^L$, $g_e^L$, $g_e^R$ are real dimensionless parameters. If the $Z'$ couplings to quarks and leptons are generation-independent, then these seven parameters describe the couplings of the $Z'$ to all standard-model fermions. More generally, however, the $Z'$ couplings to fermions are generation-dependent, in which case Eq. (1) may be written with some generation indices $i$, $j = 1$, 2, 3 labelling the quark and lepton fields, and with the seven coefficients promoted to $3 \times 3$ Hermitian matrices.

These parameters describing the $Z'$ interactions with quarks and leptons are subject to some theoretical constraints. Quantum field theories that include a heavy spin-1 particle are well behaved at high energies only if that particle is a gauge boson associated with a spontaneously broken gauge symmetry. Quantum effects preserve the gauge symmetry only if the couplings of the gauge boson to fermions satisfy a certain set of equations called anomaly cancellation conditions. Furthermore, the charges of quarks and leptons under the new gauge symmetry are constrained by the requirement that the quarks and leptons get masses from gauge-invariant interactions with Higgs doublets or whatever else breaks the electroweak symmetry.

The relation between the couplings displayed in Eq. (1) and the gauge charges $z_{f_i}^L$ and $z_{f_i}^R$ of the fermions $f = u, d, \nu, e$

involves the unitary $3 \times 3$ matrices $V_f^L$ and $V_f^R$ that transform the gauge eigenstate fermions $f_{Li}$ and $f_{Ri}$, respectively, into the mass eigenstate ones. In addition, the $Z'$ couplings are modified if the new gauge boson $\tilde{Z}'_\mu$ (in the gauge eigenstate basis) has a kinetic mixing $(-\chi/2)B^{\mu\nu}\tilde{Z}'_{\mu\nu}$ with the hypercharge gauge boson $B^\mu$, or a mass mixing $\delta M^2 \tilde{Z}^\mu \tilde{Z}'_\mu$ with the linear combination $(\tilde{Z}_\mu)$ of neutral bosons which has same couplings as the $Z^0$ in the standard model [2]. Both the kinetic and mass mixings shift the mass and couplings of the $Z$ boson, such that the electroweak measurements impose upper limits on $\chi$ and $\delta M^2/(M_{Z'}^2 - M_Z^2)$ of the order of $10^{-3}$ [3]. Keeping only linear terms in these two small quantities, the couplings of the mass-eigenstate $Z'$ boson are given by

$$
\begin{aligned}
g_f^L &= g_z V_f^L z_f^L \left(V_f^L\right)^\dagger + \frac{e}{c_W}\left(\frac{s_W \chi M_{Z'}^2 + \delta M^2}{2 s_W \left(M_{Z'}^2 - M_Z^2\right)}\sigma_f^3 - \epsilon\, Q_f\right) \ , \\
g_f^R &= g_z V_f^R z_f^R \left(V_f^R\right)^\dagger - \frac{e}{c_W}\epsilon\, Q_f \ , \qquad (2)
\end{aligned}
$$

where $g_z$ is the new gauge coupling, $Q_f$ is the electric charge of $f$, $e$ is the electromagnetic gauge coupling, $s_W$ and $c_W$ are the sine and cosine of the weak mixing angle, $\sigma_f^3 = +1$ for $f = u, \nu$ and $\sigma_f^3 = -1$ for $f = d, e$, and

$$
\epsilon = \frac{\chi\left(M_{Z'}^2 - c_W^2 M_Z^2\right) + s_W \delta M^2}{M_{Z'}^2 - M_Z^2} \ . \qquad (3)
$$

***$U(1)$ gauge groups.*** A simple origin of a $Z'$ is a new $U(1)'$ gauge symmetry. In that case, the matricial equalities $z_u^L = z_d^L$ and $z_\nu^L = z_e^L$ are required by the $SU(2)_W$ gauge symmetry. Given that the $U(1)'$ interaction is not asympotically free, the theory may be well-behaved at high energies (for example, by embedding $U(1)'$ in a non-Abelian gauge group) only if the $Z'$ couplings are commensurate numbers, *i.e.*, any ratio of couplings is a rational number. Satisfying the anomaly cancellation conditions (which include an equation cubic in charges) with rational numbers is highly nontrivial, and in general new fermions charged under $U(1)'$ are necessary. Even then, one should make sure that some anomaly-free set of fermions exists

**Table 1:** Examples of generation-independent $U(1)'$ charges for quarks and leptons. The parameter $x$ is an arbitrary rational number. Anomaly cancellation requires certain new fermions [4].

| fermion | $U(1)_{B-xL}$ | $U(1)_{10+x\bar{5}}$ | $U(1)_{d-xu}$ | $U(1)_{q+xu}$ |
|---|---|---|---|---|
| $(u_L, d_L)$ | $1/3$ | $1/3$ | $0$ | $1/3$ |
| $u_R$ | $1/3$ | $-1/3$ | $-x/3$ | $x/3$ |
| $d_R$ | $1/3$ | $-x/3$ | $1/3$ | $(2-x)/3$ |
| $(\nu_L, e_L)$ | $-x$ | $x/3$ | $(-1+x)/3$ | $-1$ |
| $e_R$ | $-x$ | $-1/3$ | $x/3$ | $-(2+x)/3$ |

before assuming specific couplings of the $Z'$ to quarks and leptons.

Consider first the case where the couplings are generation-independent (the $V_f$ matrices then disappear from Eq. (2)), so that there are five commensurate couplings: $g_q^L$, $g_u^R$, $g_d^R$, $g_l^L$, $g_e^R$. Four sets of charges are displayed in Table 1, each of them spanned by one free parameter, $x$ [4]. The first set, labelled $B - xL$, has charges proportional to the baryon number minus $x$ times the lepton number. These charges allow all standard model Yukawa couplings to a Higgs doublet which is neutral under $U(1)_{B-xL}$, so that there is no tree-level $\tilde{Z} - \tilde{Z}'$ mixing. For $x = 1$ one recovers the $U(1)_{B-L}$ group, which is non-anomalous in the presence of one "right-handed neutrino" (a chiral fermion that is a singlet under the standard model gauge group) per generation. For $x \neq 1$, it is necessary to include some fermions that are vectorlike (*i.e.*, their mass terms are gauge invariant) with respect to the electroweak gauge group and chiral with respect to $U(1)_{B-xL}$. In the particular cases $x = 0$ or $x \gg 1$ the $Z'$ is leptophobic or quark-phobic, respectively.

The second set, $U(1)_{10+x\bar{5}}$, has charges that commute with the representations of the $SU(5)$ grand unified group. Here $x$ is related to the mixing angle between the two $U(1)$ bosons encountered in the $E_6 \to SU(5) \times U(1) \times U(1)$ symmetry breaking patterns of grand unified theories [1,5]. This set leads to $\tilde{Z} - \tilde{Z}'$ mass mixing at tree level, such that for a $Z'$ mass close to the electroweak scale, the measurements at the $Z$-pole require some fine tuning between the charges and VEVs of two Higgs doublets. Vectorlike fermions charged under the electroweak gauge group and also carrying color are required (except for $x = -3$) to make this set anomaly free. The particular cases $x = -3, 1, -1/2$ are usually labelled $U(1)_\chi$, $U(1)_\psi$, and $U(1)_\eta$, respectively. Under the third set, $U(1)_{d-xu}$, the weak-doublet quarks are neutral, and the ratio of $u_R$ and $d_R$ charges is $-x$. For $x = 1$ this is the "right-handed" group $U(1)_R$. For $x = 0$, the charges are those of the $E_6$-inspired $U(1)_I$ group, which requires new quarks and leptons.

In the absence of new fermions charged under the standard model group, the most general generation-independent charge assignment is $U(1)_{q+xu}$, which is a linear combination of hypercharge and $B - L$. Many other anomaly-free solutions exist if generation-dependent charges are allowed. Table 2 shows such solutions that depend on two free parameters, $x$ and $y$, with generation dependence only in the lepton sector, which includes one right-handed neutrino per generation. The charged-lepton masses may be generated by Yukawa couplings to a single Higgs doublet. These are forced to be flavor diagonal by the generation-dependent $U(1)'$ charges, so that there are

**Table 2:** Lepton-flavor dependent charges under various $U(1)$ gauge groups. No new fermions other than right-handed neutrinos are required.

| fermion | $B - xL_e - yL_\mu$ | 2+1 leptocratic |
|---|---|---|
| $q_{1_L}, q_{2_L}, q_{3_L}$ | 1/3 | 1/3 |
| $u_R, c_R, t_R$ | 1/3 | $x/3$ |
| $d_R, s_R, b_R$ | 1/3 | $(2-x)/3$ |
| $(\nu_L^e, e_L)$ | $-x$ | $-1-2y$ |
| $(\nu_L^\mu, \mu_L)$ | $-y$ | $-1+y$ |
| $(\nu_L^\tau, \tau_L)$ | $x+y-3$ | $-1+y$ |
| $e_R$ | $-x$ | $-(2+x)/3-2y$ |
| $\mu_R$ | $-y$ | $-(2+x)/3+y$ |
| $\tau_R$ | $x+y-3$ | $-(2+x)/3+y$ |

no tree-level flavor-changing neutral current (FCNC) processes involving electrically-charged leptons. For the "leptocratic" set, neutrino masses are induced by operators of high dimensionality that may explain their smallness [6].

If the $SU(2)_W$-doublet quarks have generation-dependent $U(1)'$ charges, then the mass eigenstate quarks have flavor off-diagonal couplings to the $Z'$ (see Eq. (1), and note that $V_u^L \left(V_d^L\right)^\dagger$ is the CKM matrix). These are severely constrained by measurements of FCNC processes, which in this case are mediated at tree-level by $Z'$ exchange [7]. The constraints are relaxed if the first and second generation charges are the same, although they are increasingly tightened by the measurements of $B$ meson properties. If only the $SU(2)_W$-singlet quarks have generation-dependent $U(1)'$ charges, there is more freedom in adjusting the flavor off-diagonal couplings because the $V_{u,d}^R$ matrices are not observable in the standard model.

The anomaly cancellation conditions for $U(1)'$ could be relaxed only if at scales above $\sim 4\pi M_{Z'}/g_z$ there is an axion which has certain dimension-5 couplings to the gauge bosons. However, such a scenario violates unitarity unless the quantum field theory description breaks down at a scale near $M_{Z'}$.

***Other models.*** $Z'$ bosons may also arise from larger gauge groups. These may be orthogonal to the electroweak group, as in $SU(2)_W \times U(1)_Y \times SU(2)'$, or may embed the electroweak group, as in $SU(3)_W \times U(1)$. If the larger group is spontaneously broken down to $SU(2)_W \times U(1)_Y \times U(1)'$ at a scale $v'$ larger than the electroweak scale $v$, then the above discussion applies up to corrections of order $(v/v')^2$. In some cases, though, the larger gauge group may break together with the electroweak symmetry directly to the electromagnetic $U(1)_{\rm em}$. Consequently, the left-handed fermion charges are no longer correlated, *i.e.*, $z_u^L \neq z_d^L$ and $z_\nu^L \neq z_e^L$. Furthermore, additional gauge bosons are present at the electroweak scale, including at least a $W'$ boson [8], and the $Z'$ couples to a pair of $W$ bosons.

If the electroweak gauge bosons propagate in extra dimensions, then their Kaluza-Klein excitations include a series of $Z'$ boson pairs. Each of these pairs can be associated with a different $SU(2) \times U(1)$ gauge group in four dimensions. The properties of the Kaluza-Klein particles depend strongly on the extra-dimensional theory [9]. For example, in universal extra dimensions there is a parity that forces all couplings of Eq. (1) to vanish in the case of the lightest Kaluza-Klein bosons, while allowing couplings to pairs of fermions involving a standard model one and a heavy vectorlike fermion. There are also 4-dimensional gauge theories (*e.g.*, little Higgs with $T$ parity) with $Z'$ bosons exhibiting similar properties. By contrast, in a warped extra dimension, the couplings of Eq. (1) may be sizable even when standard model fields propagate along the extra dimension.

$Z'$ bosons may also be composite particles. For example, in technicolor theories, the techni-$\rho$ is a spin-1 boson that may be interpreted as arising from a spontaneously broken gauge symmetry [10].

***Resonances versus cascade decays.*** In the presence of the couplings shown in Eq. (1), the $Z'$ boson may be produced in the $s$-channel at hadron or lepton colliders, and would decay to pairs of fermions. The decay width into a pair of electrons is given by

$$\Gamma\left(Z' \to e^+e^-\right) \approx \left[\left(g_e^L\right)^2 + \left(g_e^R\right)^2\right] \frac{M_{Z'}}{24\pi} \ , \tag{4}$$

where small corrections from electroweak loops are not included. The decay width into $q\bar{q}$ is similar, except for an additional color factor of 3, QCD radiative corrections, and fermion mass corrections. Thus, one may compute the $Z'$ branching fractions in terms of the couplings of Eq. (1). However, other decay channels, such as $WW$ or a pair of new particles, could have large widths and need to be added to the total decay width.

As mentioned above, there are interesting theories in which the $Z'$ couplings are controlled by a discrete symmetry which does not allow its decay into a pair of standard model particles. Typically, such theories involve several new particles, which may be produced only in pairs and undergo cascade decays through $Z'$'s, leading to signals involving some missing transverse energy. Given that the cascade decays depend on the properties of new particles other than $Z'$, this case is not discussed further here.

***LEP-II limits.*** The $Z'$ contribution to the cross sections for $e^+e^- \to f\bar{f}$ proceeds through an $s$-channel $Z'$ exchange (when $f = e$, there are also $t$- and $u$-channel exchanges). For $M_{Z'} < \sqrt{s}$, the $Z'$ appears as an $f\bar{f}$ resonance in the radiative return process where photon emission tunes the effective center-of-mass energy to $M_{Z'}$. The agreement between the LEP-II measurements and the standard model predictions implies that either the $Z'$ couplings are smaller than or of order $10^{-2}$, or else $M_{Z'}$ is above 209 GeV, the maximum energy of LEP-II. In the latter case, the $Z'$ effects may be approximated up to corrections of order $s/M_{Z'}^2$ by the contact interactions

$$\frac{g_z^2}{M_{Z'}^2 - s} \left[\bar{e}\gamma_\mu \left(z_e^L P_L + z_e^R P_R\right) e\right] \left[\bar{f}\gamma^\mu \left(z_f^L P_L + z_f^R P_R\right) f\right] \quad , \quad (5)$$

where $P_{L,R}$ are chirality projection operators, and the relation between $Z'$ couplings and charges (see Eq. (2) in the limit where the mass and kinetic mixings are neglected) was used assuming generation-independent charges. The four LEP collaborations have set limits on the coefficients of such operators for all possible chiral structures and for various combinations of fermions [11]. Thus, one may derive bounds on $(M_{Z'}/g_z)|z_e^L z_f^L|^{-1/2}$ and the analoguous combinations of $LR$, $RL$ and $RR$ charges, which are typically on the order of a few TeV. Fig. 1 shows the LEP-II limits derived in [4] on the four sets of charges shown in Table 1.

Somewhat stronger bounds could be set on $M_{Z'}/g_z$ for specific sets of $Z'$ couplings if the combined effects of several operators from Eq. (5) are taken into account. Even better limits on $Z'$ bosons having various couplings could be set by dedicated analyses by the LEP collaborations. Such analyses have so far been performed only for fixed values of the gauge coupling (see section 3.5.2 of [11]) .

***Tevatron searches.*** At hadron colliders, $Z'$ bosons with couplings to quarks (see Eq. (1)) may be produced in the $s$ channel, and would show up as resonances in the invariant mass distribution of the decay products. Searches for $Z'$ bosons in the Run II at the Tevatron have been performed by the CDF and DØ

Collaborations in $e^+e^-$ [12,13], $\mu^+\mu^-$ [14], $e\mu$ [15], $\tau^+\tau^-$ [16] and $t\bar{t}$ [17] final states. In addition to the invariant mass distribution for each of these pairs, the angular distribution can be used to set limits on (or measure, after discovery) several combinations of $Z'$ parameters.

The $Z'$ decay into $e^+e^-$ is interesting due to relatively good mass resolution and large acceptance. Fig. 1 shows the limits on the sets of $U(1)$ charges from Table 1 obtained by

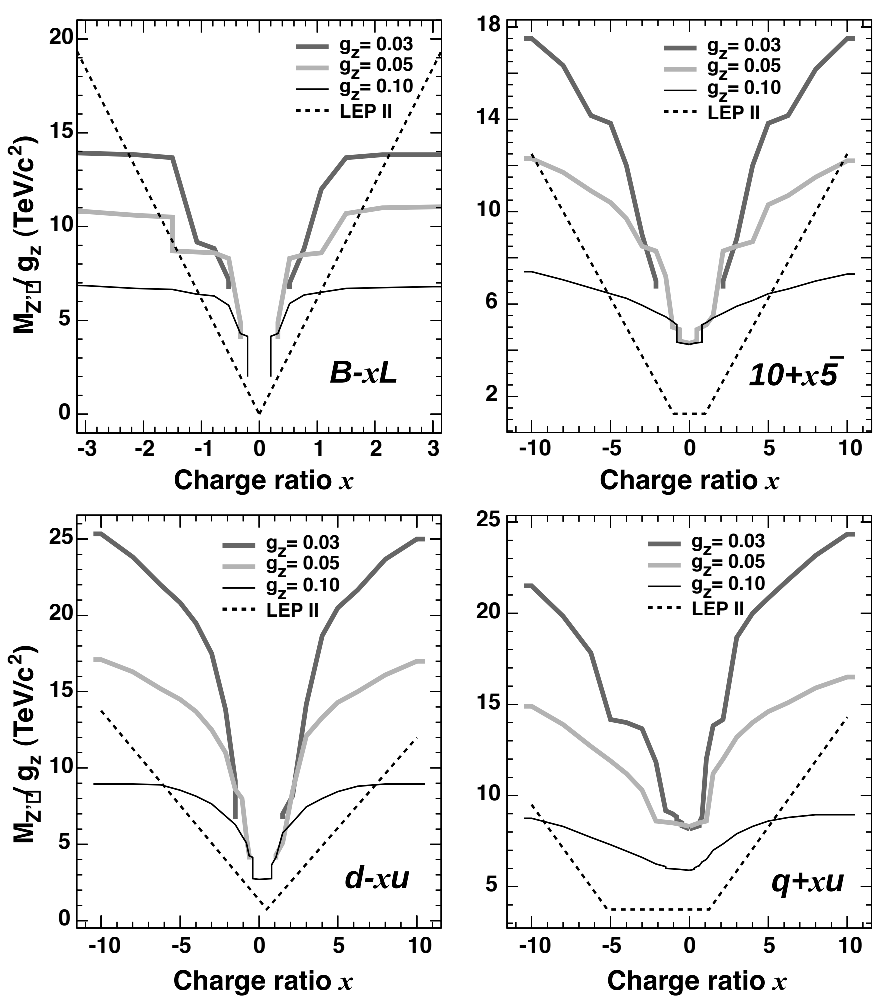


**Figure 1:** Exclusion limits on the sets of $U(1)$ charges shown in Table 1, from CDF (for different values of the gauge coupling $g_z$) and the LEP-II experiments [13]. The CDF analysis combined the invariant mass and angular distributions of the $e^+e^-$ final state.

CDF with 450 pb$^{-1}$ in the $e^+e^-$ final state [14]. The $Z'$ decay into $\mu^+\mu^-$, $e\mu$ and $\tau^+\tau^-$, along with $t\bar{t}$ which suffers from larger backgrounds, are also important as they probe various combinations of couplings. Furthermore, these channels are sensitive to $Z'$ bosons with suppressed couplings to the electrons (see Table 2), which are not constrained by the LEP searches.

The total cross section is typically the most sensitive observable to a $Z'$. For a narrow $s$-channel resonance, the interference of $Z'$ with the $Z$ or photon may be neglected, and the total cross section in the dilepton channel takes the form

$$\sigma\left(p\bar{p} \to Z'X \to \ell^+\ell^-X\right) = \frac{\pi}{48\,s}\sum_q c_q\, w_q\big(s, M_{Z'}^2\big) \qquad (6)$$

for flavor-diagonal couplings to quarks. The coefficients

$$c_q = \left[\left(g_q^L\right)^2 + \left(g_q^R\right)^2\right]\, B(Z' \to \ell^+\ell^-) \qquad (7)$$

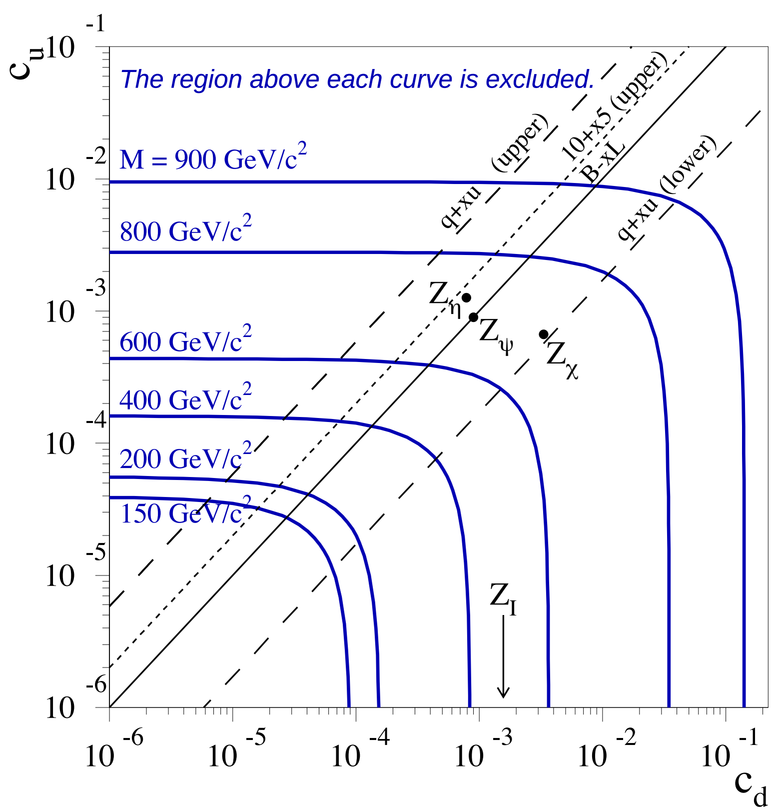


**Figure 2:** Exclusion region in the $c_u - c_d$ plane (see Eq. (7)) from [14] for given $M_{Z'}$.

contain all the dependence on the couplings of quarks and leptons to the $Z'$, while the functions $w_q$ include all the information about parton distributions and QCD corrections [4]. This factorization holds exactly to NLO, and the deviations from it induced at NNLO are very small. Note that only the $w_u$ and $w_d$ functions are likely to be sizable.

The results are often presented as an exclusion limit in the $\sigma\left(p\bar{p} \to Z'X \to \ell^+\ell^- X\right)$ versus $M_{Z'}$ plane (the current limit for the $e^+e^-$ channel, based on 1.3 fb$^{-1}$ of data, is 20 fb for $M_Z' \approx 300$ GeV, decreasing to 6 fb for $M_Z' > 600$ GeV [12]) . An alternative is to plot exclusion curves for fixed $M_{Z'}$ values in the $c_u - c_d$ plane. Fig. 2 shows the 95% limits set by CDF with 200 pb$^{-1}$ by combining the $e^+e^-$ and $\mu^+\mu^-$ final states, assuming generation-independent $M_{Z'}$ couplings. The diagonal lines indicate the regions allowed for the sets of $U(1)$ charges shown in Table 1. The $B - xL$ set implies $c_u = c_d$, for $10 + x\,\bar{5}$ all values $c_u \leq 2\,c_d$ are allowed, while the $q+xu$ set is restricted between the two dashed lines. The points marked $Z_\chi$, $Z_\psi$, $Z_\eta$ and $Z_I$ correspond to the $E_6$-inspired $U(1)'$ couplings with the gauge coupling $g_z$ fixed by some unification condition [1,5].

***LHC discovery potential.*** $Z'$ bosons may be discovered at the LHC through their decays into $e^+e^-$, $\mu^+\mu^-$ and other fermion pairs. The factorization given in Eq. (6) is also applicable to the LHC, with different $w_q$ functions, which now depend on the PDF's for the two incoming protons. Assuming that the couplings to fermions are of order 0.1 or larger, the ATLAS and CMS experiments will probe $Z'$ masses up to 5 TeV with 100 fb$^{-1}$ of data [18]. A 1% accuracy in the total cross sections at the LHC may be obtained by measuring the ratio of the $Z'$ and $Z$ productions. Even though the original quark direction in a $pp$ collider is unknown, the leptonic forward-backward asymmetry $A^\ell_{\rm FB}$ can be extracted from the kinematics of the dilepton system. These measurements, combined with a fit to the $Z'$ rapidity distribution and other observables have the potential to distinguish the $Z'$ couplings to fermions arising from different models. The ATLAS and CMS experiments may also be sensitive to the effects of the $Z'$ interference with the $Z$ and photon contributions to the dilepton signal.

***Low-energy constraints.*** $Z'$ properties are also constrained by a variety of low-energy experiments [19]. Polarized electron-nucleon scattering and atomic parity violation are sensitive to electron-quark contact interactions, which get contributions from $Z'$ exchange that can be expressed in terms of the couplings introduced in Eq. (1) and $M'_Z$. Further corrections to the electron-quark contact interactions are induced in the presence of $\tilde{Z} - \tilde{Z}'$ mixing because of the shifts in the $Z$ couplings to quarks and leptons [2]. Deep-inelastic neutrino-nucleon scattering is similarly affected by $Z'$ bosons. Other low-energy observables are discussed in [3].

Although the LEP and Tevatron data are most constraining for many $Z'$ models, one should be careful in assessing the relative reach of various experiments given the freedom in $Z'$ couplings. For example, a $Z'$ associated with the $U(1)_{B-xL_e-yL_\mu}$ model (see Table 2) for $x = 0$ and $y \gg 1$ couples only to leptons of the second and third generations, with implications for the muon $g - 2$, neutrino oscillations or $\tau$ decays, and would be hard to see in processes involving first-generation fermions.

**References**

1. For reviews, see J. Hewett and T. Rizzo, Phys. Rept. **183**, 193 (1989); A. Leike, Phys. Rept. **317**, 143 (1999).
2. K.S. Babu, C. Kolda, and J. March-Russell, Phys. Rev. **D57**, 6788 (1998); B. Holdom, Phys. Lett. **B259**, 329 (1991).
3. J. Erler and P. Langacker, "Electroweak model and constraints on new physics" in this *Review*.
4. M.S. Carena *et al.*, Phys. Rev. D **70**, 093009 (2004).
5. See, *e.g.*, F. Del Aguila, M. Cvetic, and P. Langacker, Phys. Rev. D **52**, 37 (1995).
6. M.-C. Chen, A. de Gouvêa, and B.A. Dobrescu, Phys. Rev. D **75**, 055009 (2007).
7. P. Langacker and M. Plumacher, Phys. Rev. D **62**, 013006 (2000); R.S. Chivukula and E.H. Simmons, Phys. Rev. D **66**, 015006 (2002).
8. See the Section on "$W'$ searches" in this *Review*.
9. G.F. Giudice and J.D. Wells, "Extra dimensions" in this *Review*.

10. M. Bando, T. Kugo, and K. Yamawaki, Phys. Rept. **164**, 217 (1988).
11. J. Alcaraz *et al.* [ALEPH, DELPHI, L3, OPAL Collaborations, LEP Electroweak Working Group], `hep-ex/0612034`.
12. T. Aaltonen *et al.* [CDF Collaboration], `hep-ex/0707.2524`; DØ Collaboration, note 4375-Conf (2004).
13. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **96**, 211801 (2006).
14. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **95**, 252001 (2005);
    DØ Collaboration, note 4577-Conf (2004).
15. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **96**, 211802 (2006).
16. D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **95**, 131801 (2005).
17. T. Aaltonen *et al.* [CDF Collaboration], `hep-ex/0709.0705`;
    CDF Collaboration, note 8675 (2007);
    DØ Collaboration, notes 5443-Conf and 5393-Conf (2007).
18. See, *e.g.*, M. Dittmar, A.S. Nicollerat, and A. Djouadi, Phys. Lett. B **583**, 111 (2004).
19. See, *e.g.*, V.D. Barger *et al.*, Phys. Rev. D **57**, 391 (1998).