## $Z'$-BOSON SEARCHES

Revised November 2013 by G. Brooijmans (Columbia University), M.-C. Chen (UC Irvine), and B.A. Dobrescu (Fermilab).

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

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

$$Z'_\mu \left( g^L_u \, \overline{u}_L \gamma^\mu u_L + g^L_d \, \overline{d}_L \gamma^\mu d_L + g^R_u \, \overline{u}_R \gamma^\mu u_R + g^R_d \, \overline{d}_R \gamma^\mu d_R \right.$$
$$\left. + \, g^L_\nu \, \overline{\nu}_L \gamma^\mu \nu_L + g^L_e \, \overline{e}_L \gamma^\mu e_L + g^R_e \, \overline{e}_R \gamma^\mu e_R \right) \quad , \qquad (1)$$

where $u, d, \nu$ and $e$ are the quark and lepton fields in the mass eigenstate basis, and the coefficients $g^L_u$, $g^L_d$, $g^R_u$, $g^R_d$, $g^L_\nu$, $g^L_e$, $g^R_e$ are real dimensionless parameters. If the $Z'$ couplings to quarks and leptons are generation-independent, then these seven parameters describe the couplings of the $Z'$ boson to all SM fermions. More generally, however, the $Z'$ couplings to fermions are generation-dependent, in which case Eq. (1) may be written with generation indices $i$, $j = 1, 2, 3$ labeling the quark and lepton fields, and with the seven coefficients promoted to $3 \times 3$ Hermitian matrices (*e.g.*, $g^L_{eij} \, \overline{e}^i_L \gamma^\mu e^j_L$, where $e^2_L$ is the left-handed muon, etc.).

These parameters describing the $Z'$ boson 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 anomaly cancellation conditions. Furthermore, the fermion charges under the new gauge symmetry are constrained by the requirement that the quarks and leptons get masses from gauge-invariant interactions with Higgs fields.

The relation between the couplings displayed in Eq. (1) and the gauge charges $z^L_{fi}$ and $z^R_{fi}$ 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 $f_L^i$ and $f_R^i$, respectively, into the mass eigenstates. In addition, the $Z'$ couplings are modified if the new gauge boson in the gauge eigenstate basis ($\tilde{Z}'_\mu$) has a kinetic mixing $(-\chi/2)B^{\mu\nu}\tilde{Z}'_{\mu\nu}$ with the hypercharge gauge boson $B^\mu$ (due to a dimension-4 or 6 operator, depending on whether the new gauge symmetry is Abelian or not), or a mass mixing $\delta M^2 \tilde{Z}^\mu \tilde{Z}'_\mu$ with the linear combination ($\tilde{Z}_\mu$) of neutral bosons that couples as the SM $Z$ boson [2]. Since both the kinetic and mass mixings shift the mass and couplings of the $Z$ boson, 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

$$g^L_{f\,ij} = g_z V^L_{f ii'}\, z^L_{f\,i'} \left(V^L_f\right)^\dagger_{i'j} + \frac{e}{c_W}\left(\frac{s_W \chi M_{Z'}^2 + \delta M^2}{2 s_W \left(M_{Z'}^2 - M_Z^2\right)}\sigma_f^3 - \epsilon\, Q_f\right) \quad ,$$

$$g^R_{f\,ij} = g_z V^R_{f ii'}\, z^R_{f i'} \left(V^R_f\right)^\dagger_{i'j} - \frac{e}{c_W}\,\epsilon\, Q_f \quad , \tag{2}$$

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

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

While an interaction of a $Z'$ boson with a pair of $W$ bosons is also allowed, its coupling is typically smaller than the $\tilde{Z}^\mu \tilde{Z}'_\mu$ mixing.

***U*(1) *gauge groups.*** A simple origin of a $Z'$ boson 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 SM $SU(2)_W$ gauge symmetry. Given that the $U(1)'$ interaction is not asymptotically 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

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

charges) with rational numbers is highly nontrivial, and in general new fermions charged under $U(1)'$ are necessary.

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 SM 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 SM gauge group) per generation. For $x \neq 1$, it is necessary to include some fermions that are vector-like (*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 the two Higgs doublets. Vector-like 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. Other generation-independent sets of $U(1)'$ charges are given in [6].

In the absence of new fermions charged under the SM 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. An example is $B - xL_e - yL_\mu + (y - 3)L_\tau$, with $x, y$ free parameters. This allows all fermion masses to be generated by Yukawa couplings to a single Higgs doublet, without inducing tree-level flavor-changing neutral current (FCNC) processes. There are also lepton-flavor dependent charges that allow neutrino masses to arise only from operators of high dimensionality [7].

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 $Z'$ boson (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 $Z'$ boson exchange [8]. 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 [9]. 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 SM.

The anomaly cancellation conditions for $U(1)'$ could be relaxed only if there is an axion with 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 $M_{Z'}$ [10].

***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 $SU(3)_W \times U(1)$ [11]. If the larger group is spontaneously broken down to $SU(2)_W \times U(1)_Y \times U(1)'$ at a scale $v_\star \gg M_{Z'}/g_z$, then the above discussion applies up to corrections of order $M_{Z'}^2/(g_z v_\star)^2$. For $v_\star \sim M_{Z'}/g_z$, additional gauge bosons have masses comparable to $M_{Z'}$, including at least a $W'$ boson [11]. If the larger gauge group breaks together with the electroweak symmetry directly to the electromagnetic $U(1)_{\rm em}$, then the left-handed fermion charges are no longer correlated ($z_u^L \neq z_d^L$, $z_\nu^L \neq z_e^L$) and a $Z'W^+W^-$ coupling is induced.

If the electroweak gauge bosons propagate in extra dimensions, then their Kaluza-Klein (KK) 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 KK particles depend strongly on the extra-dimensional theory [12]. 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 KK bosons, while allowing couplings to pairs of fermions involving a SM and a heavy vector-like 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 SM fields propagate along the extra dimension.

$Z'$ bosons may also be composite particles. For example, in confining gauge theories [13], the $\rho$-like bound state is a spin-1 boson that may be interpreted as arising from a spontaneously broken gauge symmetry [14].

***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 colliders, and would decay to pairs of fermions. The decay width into a pair of electrons is given by

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

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

***LEP-II limits.*** The $Z'$ contribution to the cross sections for $e^+e^- \rightarrow f\bar{f}$ 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 SM 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

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

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) is 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 [15]. Thus, one may derive bounds on $(M_{Z'}/g_z)|z_e^L z_f^L|^{-1/2}$ and the analogous combinations of $LR$, $RL$ and $RR$ charges, which are typically on the order of a few TeV. LEP-II limits were derived [4] on the four sets of charges shown in Table 1.

Somewhat stronger bounds can be set on $M_{Z'}/g_z$ for specific sets of $Z'$ couplings if the effects of several operators from Eq. (5) are combined. Dedicated analyses by the LEP collaborations have set limits on $Z'$ bosons for particular values of the gauge coupling (see section 3.5.2 of [15]).

***Searches at hadron colliders.*** $Z'$ bosons with couplings to quarks (see Eq. (1)) may be produced at hadron colliders in the $s$-channel, and would show up as resonances in the invariant mass distribution of the decay products. The cross section for producing a $Z'$ boson at the LHC which then decays to some $f\bar{f}$ final state takes the form

$$\sigma\left(pp \to Z'X \to f\bar{f}X\right) \simeq \frac{\pi}{48\,s} \sum_q c_q^f \, w_q\big(s, M_{Z'}^2\big) \qquad (6)$$

for flavor-diagonal couplings to quarks. Here we have neglected the interference with the SM contribution to $f\bar{f}$ production, which is a good approximation for a narrow $Z'$ resonance (deviations from the narrow width approximation are discussed in [16]). The coefficients

$$c_q^f = \left[\left(g_q^L\right)^2 + \left(g_q^R\right)^2\right] B(Z' \to f\bar{f}) \qquad (7)$$

contain all the dependence on the $Z'$ couplings, while the functions $w_q$ include all the information about parton distributions and QCD corrections [4,6]. This factorization holds exactly to NLO, and the deviations from it induced at NNLO are very small. Note that the $w_u$ and $w_d$ functions are substantially larger than the $w_q$ functions for the other quarks. Eq. (6) also applies to the Tevatron, except for changing the $pp$ initial state to $p\bar{p}$, which implies that the $w_q(s, M_{Z'}^2)$ functions are replaced by some other functions $\bar{w}_q((1.96\,\text{TeV})^2, M_{Z'}^2)$.

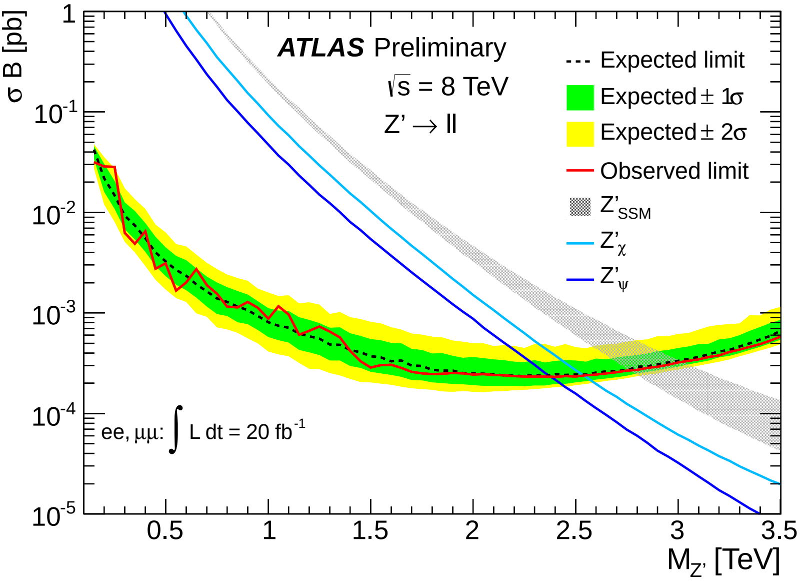


**Figure 1:** Upper limit on $\sigma\left(pp \to Z'X \to \ell^+\ell^-X\right)$ with $\ell = e$ or $\mu$ as a function of $M_{Z'}$ [17], assuming equal couplings for electrons and muons. The lines labelled by $Z'_\psi$ and $Z'_\chi$ are theoretical predictions for the $U(1)_{10+x\bar{5}}$ models in Table 1 with $x = -3$ and $x = +1$, respectively, for $g_z$ fixed by an $E_6$ unification condition. The $Z'_{\rm SSM}$ line corresponds to $Z'$ couplings equal to those of the $Z$ boson.

It is common to present results of $Z'$ searches as limits on the cross section versus $M_{Z'}$ (see for example Fig. 1). An alternative is to plot exclusion curves for fixed $M_{Z'}$ values in the $c_u^f - c_d^f$ planes, allowing a simple derivation of the mass limit within any $Z'$ model. LHC limits in the $c_u^\ell - c_d^\ell$ plane ($\ell = e$ or $\mu$) for different $M_{Z'}$ are shown in Fig. 2 (for Tevatron limits, see [18,6]).

The discovery of a dilepton resonance at the LHC would determine the $Z'$ mass and width. A measurement of the total cross section would define a band in the $c_u^\ell - c_d^\ell$ plane. Angular distributions can be used to measure several combinations of $Z'$ parameters (an example of how angular distributions improve the Tevatron sensitivity is given in [19]). Even though the original quark direction in a $pp$ collider is unknown, the leptonic forward-backward asymmetry $A^{\ell}_{\mathrm{FB}}$ can be extracted from the kinematics of the dilepton system, and is sensitive to parity-violating couplings. A fit to the $Z'$ rapidity distribution can distinguish between the couplings to up and down quarks. These measurements, combined with off-peak observables, have the potential to differentiate among various $Z'$ models [20]. For example, the couplings of a $Z'$ boson with mass below 1.5 TeV can be well determined with 100 fb$^{-1}$ of data at $\sqrt{s} = 14$ TeV. With this amount of data, the spin of the $Z'$ boson may be determined for $M_{Z'} \leq 3$ TeV [21], and the expected sensitivity extends to $M_{Z'} \sim 4-5$ TeV for many models [22].

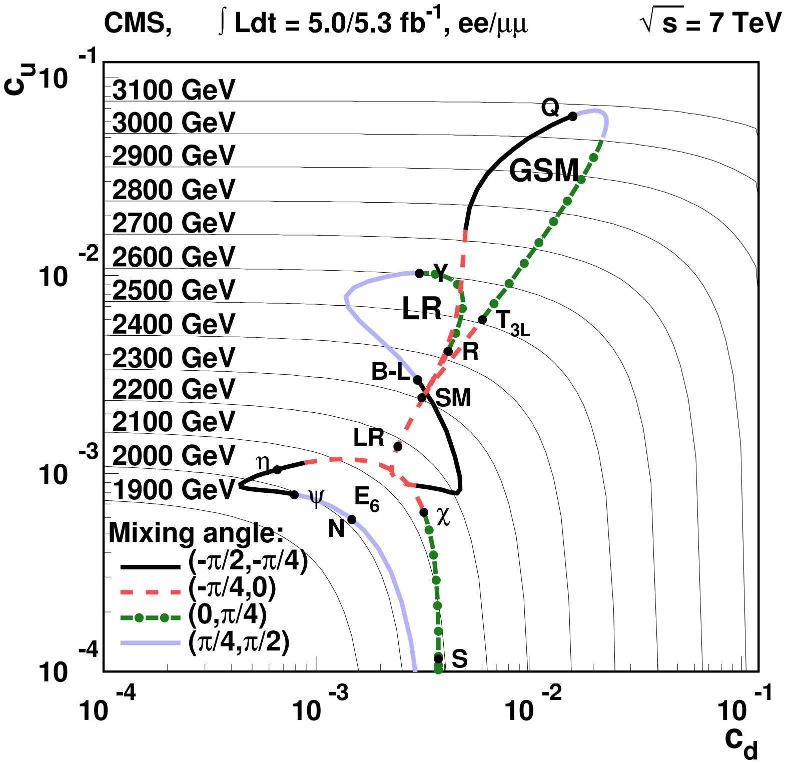


**Figure 2:** CMS results from [23]. Limits in the $c_u^{\ell} - c_d^{\ell}$ plane ($\ell = e$ or $\mu$) are shown as thin lines for certain $M_{Z'}$ values. For specific sets of charges (described in [6]), parametrized by a mixing angle, the mass limit is given by the intersection of the thick and thin lines.

The $Z'$ decays into $e^+e^-$ and $\mu^+\mu^-$ are useful due to relatively good mass resolution and large acceptance. The $Z'$ decays into $e\mu$ and $\tau^+\tau^-$, along with $t\bar{t}$, $b\bar{b}$ and $jj$ which suffer from larger backgrounds, are also important as they probe various combinations of $Z'$ couplings to fermions. The ATLAS and CMS Collaborations have performed $Z'$ searches at the LHC in all these fermionic final states: $e^+e^-$ and $\mu^+\mu^-$ [17,24], $e^\pm\mu^\mp$ [25], $\tau^+\tau^-$ [26], $t\bar{t}$ [27], $b\bar{b}$ [28] and $jj$ [29].

The $pp \to Z'X \to W^+W^-X$ process may also be explored at the LHC. The $Z'$ boson may be produced in this process through its couplings to either quarks [30] or $W$ bosons [31].

At the Tevatron, the CDF and DØ Collaborations have searched for $Z'$ bosons in the $e^+e^-$ [32], $\mu^+\mu^-$ [33], $e^\pm\mu^\mp$ [34], $\tau^+\tau^-$ [35], $t\bar{t}$ [36], $jj$ [37] and $WW$ [38] final states. Although these limits have been often superseded by the LHC results, the Tevatron limits on certain $Z'$ couplings (most notably, those arising from $jj$ resonance searches [39]) remain the most stringent ones for low $M_Z'$.

***Low-energy constraints.*** $Z'$ boson properties are also constrained by a variety of low-energy experiments [40]. 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] . In some models, the lower limits on $M_{Z'}$ set by low energy data are above 1 TeV.

Although the LHC 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 $Z'$ coupled to $B - yL_\mu + (y-3)L_\tau$ has implications for the muon $g-2$, neutrino oscillations or $\tau$ decays, and would be hard to see in processes involving first-generation fermions. Moreover, the combination of LHC searches and low-energy measurements could allow a precise determination of the $Z'$ parameters [41].

## References


1. For reviews, see P. Langacker, Rev. Mod. Phys. **81**, 1199 (2009); A. Leike, Phys. Rept. **317**, 143 (1999); J. Hewett and T. Rizzo, Phys. Rept. **183**, 193 (1989).
2. K.S. Babu *et al.*, Phys. Rev. **D57**, 6788 (1998); B. Holdom, Phys. Lett. **B259**, 329 (1991).
3. J. Erler *et al.*, JHEP **0908**, 017 (2009).
4. M.S. Carena *et al.*, Phys. Rev. D**70**, 093009 (2004).
5. See, *e.g.*, F. Del Aguila *et al.*, Phys. Rev. D**52**, 37 (1995).
6. E. Accomando *et al.*, Phys. Rev. **D83**, 075012 (2011).
7. M.-C. Chen *et al.*, Phys. Rev. D**75**, 055009 (2007).
8. P. Langacker and M. Plumacher, Phys. Rev. D**62**, 013006 (2000); R.S. Chivukula and E.H. Simmons, Phys. Rev. D**66**, 015006 (2002).
9. A. J. Buras, F. De Fazio, and J. Girrbach, JHEP **1302**, 116 (2013).
10. L.E. Ibanez and G.G. Ross, Phys. Lett. B**332**, 100 (1994).
11. See the Section on "$W'$ searches" in this *Review*.
12. J. Parsons and A. Pomarol, "Extra dimensions" in this *Review*.
13. R.S. Chivukula *et al.*, "Dynamical electroweak symmetry breaking" in this *Review*.
14. M. Bando *et al.*, Phys. Rept. **164**, 217 (1988).
15. J. Alcaraz *et al.* [ALEPH, DELPHI, L3, OPAL Collabs., LEP Electroweak Working Group], `hep-ex/0612034`.
16. E. Accomando *et al.*, JHEP **1310**, 153 (2013).
17. ATLAS Collab., note ATLAS-CONF-2013-017, Mar. 2013.
18. A. Abulencia *et al.* [CDF Collab.], Phys. Rev. Lett. **95**, 252001 (2005).
19. A. Abulencia *et al.* [CDF Collab.], Phys. Rev. Lett. **96**, 211801 (2006).
20. F. Petriello and S. Quackenbush, Phys. Rev. D**77**, 115004 (2008).
21. P. Osland *et al*, Phys. Rev. D**79**, 115021 (2009).
22. G.L. Bayatian *et al.* [CMS Collab.], J. Phys. G**34**, 995 (2007).
23. S. Chatrchyan *et al.* [CMS Collab.], Phys. Lett. B**714**, 158 (2012).

24. CMS Collab., note PAS-EXO-12-061, Feb. 2013.

25. G. Aad *et al.* [ATLAS Collab.], Eur. Phys. J. C**71**, 1809 (2011).

26. S. Chatrchyan *et al.* [CMS Collab.], Phys. Lett. B**716**, 82 (2012);
G. Aad *et al.* [ATLAS Collab.], Phys. Lett. B**719**, 242 (2013); note ATLAS-CONF-2013-066, July 2013.

27. G. Aad *et al.* [ATLAS Collab.], JHEP **1301**, 116 (2013); note ATLAS-CONF-2013-052, May 2013;
S. Chatrchyan *et al.* [CMS Collab.], `arXiv:1309.2030`.

28. CMS Collab., note PAS-EXO-12-023, Apr. 2013.

29. S. Chatrchyan *et al.* [CMS Collab.], `arXiv:1302.4794`; JHEP 1301, 013 (2013); note PAS-EXO-12-059, Feb. 2013; note PAS-EXO-11-094, July 2012.

30. A. Alves *et al.*, Phys. Rev. D**80**, 073011 (2009).

31. H. J. He *et al.*, Phys. Rev. D**78**, 031701 (2008).

32. V. M. Abazov *et al.* [D0 Collab.], Phys. Lett. B**695**, 88 (2011); T. Aaltonen *et al.* [CDF Collab.], Phys. Rev. Lett. **102**, 031801 (2009).

33. T. Aaltonen *et al.* [CDF Collab.], Phys. Rev. Lett. **106**, 121801 (2011).

34. A. Abulencia *et al.* [CDF Collab.], Phys. Rev. Lett. **96**, 211802 (2006); V. M. Abazov *et al.* [D0 Collab.], Phys. Rev. Lett. **105**, 191802 (2010).

35. D. Acosta *et al.* [CDF Collab.], Phys. Rev. Lett. **95**, 131801 (2005).

36. T. Aaltonen *et al.* [CDF Collab.], Phys. Rev. D**84**, 072004 (2011); V. M. Abazov *et al.* [D0 Collab.], Phys. Rev. D**85**, 051101 (2012).

37. T. Aaltonen *et al.* [CDF Collab.], Phys. Rev. D**79**, 112002 (2009).

38. T. Aaltonen *et al.* [CDF Collab.], Phys. Rev. Lett. **104**, 241801 (2010).

39. B.A. Dobrescu and F. Yu, Phys. Rev. D**88**, 035021 (2013).

40. See, *e.g.*, V.D. Barger *et al.*, Phys. Rev. D**57**, 391 (1998); J. Erler and M.J. Ramsey-Musolf, Prog. Part. Nucl. Phys. **54**, 351 (2005).

41. Y. Li *et al.*, Phys. Rev. D**80**, 055018 (2009).