Z′ Physics at the LHC

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The existing limits on Z′ gauge bosons and prospects for discovery and diagnostic studies at the LHC are briefly reviewed.

1. Introduction

Additional Z′ gauge bosons occur frequently in extensions of the standard model (SM) or its minimal supersymmetric extension (MSSM), usually emerging as an unbroken “remnant” of a larger gauge symmetry. Examples include superstring constructions, grand unified theories, extended electroweak groups, or alternatives to the minimal Higgs mechanism for electroweak breaking. Kaluza-Klein excitations of the SM gauge bosons also occur in models involving large and/or warped extra dimensions provided the gauge bosons are free to propagate in the bulk, with \( M \sim R^{-1} \sim 2 \text{ TeV} \times (10^{-17} \text{ cm}/R) \) in the large dimension case. The new Z′s may occur at any mass scale, but here we concentrate on the TeV scale relevant to the LHC, which is especially motivated by supersymmetric U(1)′ models (in which both the electroweak and U(1)′ breaking scales are usually set by the soft supersymmetry breaking parameters) and by alternative models of electroweak symmetry breaking. We first briefly review the formalism and the existing constraints from precision electroweak (weak neutral current, Z-pole, LEP 2, and FCNC) measurements and from direct searches at the Tevatron, and then comment on the prospects for a Z′ discovery, diagnostics of its couplings, and related issues such as the associated extended Higgs and neutralino sectors at the LHC. Much more extensive discussions of specific models and other implications, along with a more complete set of references, are given in several reviews.[1,2,3] Other recent developments, especially the possibility of a Z′ as a “portal” to a quasi-hidden sector, such as may be associated with dark matter or supersymmetry breaking, were reviewed in [4,5].

2. Formalism

The interactions of the photon (A), Z (i.e., \( Z^0 \)) and other flavor-diagonal neutral gauge bosons with fermions is

\[
-\mathcal{L}_{NC} = e J_{em}^\mu A_\mu + g_1 J_{1\mu}^\mu Z_{1\mu}^0 + \sum_{\alpha=2}^{n+1} g_\alpha J_{\alpha\mu}^\mu Z_{\alpha\mu}^0,
\]

where \( g_\alpha \) are the gauge couplings (with \( g_1 = g/\cos \theta_W \)), and the currents are

\[
J_{\alpha\mu}^i = \sum_i \bar{f}_i \gamma^\mu \left[ \epsilon_{\alpha L}^i(f) P_L + \epsilon_{\alpha R}^i(f) P_R \right] f_i.
\]

\( \epsilon_{\alpha L,R}^i(f) \) are the U(1)α charges of the left- and right-handed components of fermion \( f_i \), and the theory is chiral for \( \epsilon_{\alpha L}^i(f) \neq \epsilon_{\alpha R}^i(f) \). We also define the vector and axial couplings

\[
g_{V,A}^\alpha(i) = \epsilon_{\alpha L}^i(f) \pm \epsilon_{\alpha R}^i(f).
\]

It is often convenient to instead specify the charges \( Q_\alpha \) for the left-chiral fermion \( f_L \) and and left-chiral antifermion \( f_L^c \),

\[
Q_\alpha f = \epsilon_{\alpha L}^i(f) \quad \text{and} \quad Q_\alpha f^c = -\epsilon_{\alpha R}^i(f).
\]

For example, the SM charges for the \( u_L \) and \( u_L^c \) are \( Q_{1u} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \) and \( Q_{1u^c} = +\frac{1}{3} \sin^2 \theta_W \).
One can similarly define the $U(1)_a$ charge of the scalar field $\phi$ as $Q_a\phi$.

For a single extra $Z'$, the $Z - Z'$ mass matrix after symmetry breaking is

$$M^2_{Z-Z'} = \begin{pmatrix} M^2_\phi & \Delta^2 \\ \Delta^2 & M^2_{Z'} \end{pmatrix}.$$  \hspace{1cm} (5)

If, for example, the symmetry breaking is due to an $SU(2)$-singlet $S$ and two doublets $\phi_u = \begin{pmatrix} \phi_u^0 \\ \phi_u^+ \end{pmatrix}$, $\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^+ \end{pmatrix}$, then

$$M^2_{Z'0} = \frac{1}{4}g_1^2(\nu_u^2 + |\nu_d|^2)$$

$$\Delta^2 = \frac{1}{2}g_1g_2(Q_u|\nu_u|^2 - Q_d|\nu_d|^2)$$ \hspace{1cm} (6)

$$M^2_{Z'} = g_2^2(Q_u^2|\nu_u|^2 + Q_d^2|\nu_d|^2 + Q_d^2|s|^2),$$

where $\nu_u,d \equiv \sqrt{2}(\phi_{u,d}^0)$, $s = \sqrt{2}(S)$

$$\nu^2 = |\nu_u|^2 + |\nu_d|^2 \sim (246 \text{ GeV})^2.$$ \hspace{1cm} (7)

The physical mass eigenvalues are $M^2_{Z,Z'}$, the physical gauge particles are $Z_{1,2}$, and the mixing angle $\theta_{ZZ'}$ is given by $\tan^2 \theta_{ZZ'} = (M^2_{Z'0} - M^2_{Z'1})/(M^2_{Z'} - M^2_{Z'0})$. In the important special case $M_{Z'} \gg (M_{Z'0},|\Delta|)$ one finds

$$M^2_1 \sim M^2_{Z'0} - \frac{\Delta^4}{M^2_{Z'}} \ll M^2_{Z'}, \quad M^2_2 \sim M^2_{Z'};$$

$$\theta_{ZZ'} \sim -\frac{\Delta^2}{M^2_{Z'}} \sim C g_2^2 g_1^2 M^2_1 M^2_{Z'},$$

$$C = 2 \frac{|Q_u|\nu_u^2 + Q_d|\nu_d|^2}{|\nu_u|^2 + |\nu_d|^2}.$$

A $U(1)'$ can yield a natural solution to the supersymmetric $\mu$ problem [6] (unless the charges are obtained from $B - L$ and $Y$, by forbidding an elementary $\mu$ term but allowing the superpotential term $W \sim \lambda_S SH_uH_d$, where $S$ is a SM singlet charged under the $U(1)'$, one obtains an effective $\mu$ parameter $\mu_{eff} = \lambda_S(S)$, which is usually of the same scale as the soft supersymmetry breaking parameters $\{M_{1,2}\}$. This mechanism is similar to the NMSSM (e.g., [10,11]), but is automatically free of induced tadpole and domain wall problems.

We have so far implicitly assumed canonical kinetic energy terms for the $U(1)$ gauge bosons. However, $U(1)$ gauge invariance allows a more general kinetic mixing [12].

$$L_{kin} = -\frac{1}{4}F_1^{\mu
u}F_1^{\nu\mu} - \frac{1}{4}F_2^{\mu
u}F_2^{\nu\mu} - \frac{\sin \chi}{2} F_1^{\mu
u}F_2^{\nu\mu}$$ \hspace{1cm} (9)

for $U(1)_1 \times U(1)_2$. Such terms are usually absent initially, but a (usually small) $\chi$ may be induced by loops, e.g., from nondegenerate heavy particles, in running couplings if heavy particles decouple, or at the string level. The kinetic terms may be put in canonical form by the non-unitary transformation

$$\begin{pmatrix} Z_{1\mu}^0 \\ Z_{2\mu}^0 \end{pmatrix} = \begin{pmatrix} 1 & -\tan \chi \\ 0 & 1/\cos \chi \end{pmatrix} \begin{pmatrix} \bar{Z}_1^0 \\ \bar{Z}_2^0 \end{pmatrix},$$ \hspace{1cm} (10)

where the $\bar{Z}_i^0$ may still undergo ordinary mass mixing, as in [5]. The kinetic mixing has a negligible effect on masses for $|M^2_{Z_i}| \ll |M^2_{Z'}|$ and $|\chi| \ll 1$, but the current coupling to the heavier boson is shifted.

$$L \rightarrow g_1 J_1^\mu \bar{Z}_1 + (g_2 J_2^\mu - g_1\chi \lambda_1^\mu) \bar{Z}_2.$$ \hspace{1cm} (11)

The $Z'$ mass and mixing may also be generated by the Stückelberg mechanism [13,14,15,16].

3. Existing Limits

$Z'$s with electroweak coupling are mainly constrained by precision electroweak data, direct searches at the Tevatron, and searches for flavor changing neutral currents (FCNC). Low energy weak neutral current processes, which are still very important, would be affected by $Z_2$ exchange and by $Z - Z'$ mixing [17,18,19,20,21,22]. The effective four-Fermi WNC interaction becomes

$$L_{eff} = \frac{4G_F}{\sqrt{2}} (\rho_{eff} J_1^2 + 2wJ_1J_2 + yJ_2^2),$$ \hspace{1cm} (12)

where

$$\rho_{eff} = \rho_1 \cos^2 \theta_{ZZ'} + \rho_2 \sin^2 \theta_{ZZ'},$$

$$w = \frac{g_2}{g_1} \cos \theta_{ZZ'} \sin \theta_{ZZ'} (\rho_1 - \rho_2)$$ \hspace{1cm} (13)

$$y = \left(\frac{g_2}{g_1}\right)^2 (\rho_1 \sin^2 \theta_{ZZ'} + \rho_2 \cos^2 \theta_{ZZ'}).$$
with
\[ \rho_\alpha \equiv M_W^2 / (M_\alpha^2 \cos^2 \theta_W). \] (14)

The Z-pole experiments at LEP and SLC \[22\] are extremely sensitive to \(Z - Z'\) mixing, which shifts \(M_1\) downward from the SM expectation and also affects the \(Z_1\) vector and axial vertices, which become
\[ V_i = \cos \theta_{ZZ'} g_1^V (i) + \frac{g_2}{g_1} \sin \theta_{ZZ'} g_2^V (i) \]
\[ A_i = \cos \theta_{ZZ'} g_1^A (i) + \frac{g_2}{g_1} \sin \theta_{ZZ'} g_2^A (i). \] (15)

However, the Z-pole experiments have little sensitivity to \(Z_2\) exchange. At LEP2 \[24\] virtual \(Z_2\) exchange leads to a four-fermi operator, analogous to the \(\rho_2\) part of \(\mathcal{L}_{\text{eff}}\) in \[12\], which interferes with the \(\gamma\) and \(Z\).

The CDF \[25,26\] and DØ \[27\] collaborations at the Tevatron have searched for Drell-Yan resonances, especially \(\bar{p}p \to e^+e^-, \mu^+\mu^- \) \[28\], as illustrated in Figure 1. In the narrow width approximation, the tree-level rapidity distribution for \(AB \to Z_\alpha\) is
\[ \frac{d\sigma_{Z_\alpha}}{dy} = \frac{4\pi^2 x_1 x_2}{3M_\alpha^3} \sum f_{\alpha}(x_1) f_{\bar{\alpha}}(x_2) \]
\[ + f_{\alpha}(x_1) f_{\bar{\alpha}}(x_2) \Gamma(Z_\alpha \to q\bar{q}), \] (16)
where the \(f\)'s are the parton distribution functions, the partial widths are
\[ \Gamma(Z_\alpha \to f_1 \bar{f}_1) = \frac{g_2^2 C_{fi} M_\alpha}{24\pi} (\epsilon_\alpha^2 (i)^2 + \epsilon_{\bar{\alpha}}^2 (i)^2), \] (17)
\(x_{1,2} = (M_\alpha/\sqrt{s}) e^{\pm y}\), and \(C_{fi}\) is the color factor. More detailed estimates for the Tevatron and LHC are given in \[22,29,30,31,32,33,34,35,36,37\], including discussions of parton distribution functions, higher order QCD and electroweak effects, fermion mass corrections, decays into bosons or Majorana fermions, width effects, resolutions, and backgrounds.

Other search channels relevant to hadron colliders include \(Z' \to e^+e^-\) \[38\]; \(\tau^+\tau^-\) \[39\]; \(jj\), where \(j = \text{jet}\) \[29,30\]; \(bb\); and \(t\bar{t}\) \[40,41,42,43\]. Another important probe is the forward-backward asymmetry for \(pp(\bar{p}p) \to \ell^+\ell^-\) (as a function of rapidity, \(y\), for \(pp\) due to \(\gamma, Z, Z'\) interference below the \(Z'\) peak \[44,45,46,47\].

All of these existing limits are listed for a variety of models in Table 1 and the allowed regions in mass and mixing are displayed in Figure 2 for two examples in the often studied \(Z_3\) models \[44,45,46,47\] based on the \(E_6\) decomposition \(E_6 \to SO(10) \times U(1)_V \to SU(5) \times U(1)_\chi \times U(1)_\psi\).

There are also significant constraints on \(Z_3\)'s with fermion mixing, and from \(\mu\) decays and interferences, are usually sufficiently stringent to exclude such effects for the first two families for a TeV \(Z'\) with electroweak couplings \[49\]. However, the third family could be nonuniversal, and \(Z'\)-mediated effects could account for possible anomalies in the \(B\) system \[50,51,52,53,54,55,56,57\].

There has recently been considerable discussion of a possible light \(Z'\) in the MeV-GeV range (referred to as a \(U\)-boson \[58,59\]) which only couples to ordinary matter through kinetic mixing with the photon. Such a particle, which is motivated by dark matter considerations \[60\], could have implications for or is constrained by, e.g., \(g_\gamma - 2, e^+e^- \to U\gamma \to e^+e^-\gamma\), the HyperCP events,
Figure 2. Experimental constraints on the mass and mixing angle for the $Z'$, from [17]. The solid lines show the regions allowed by precision electroweak data at 95% C.L. assuming Higgs doublets and singlets, while the dashed regions allow arbitrary Higgs. The labeled curves assume specific ratios of Higgs doublet VEVs.

4. The LHC

4.1. discovery

The LHC should ultimately have a discovery reach for $Z'$s with electroweak-strength couplings to $u,d,e,$ and $\mu$ up to $M_{Z'} \sim 4 - 5$ TeV [29,30,32-37]. This is based on decays into $\ell^+\ell^-$ where $\ell = e$ or $\mu$, and assumes $\sqrt{s} = 14$ TeV and $\mathcal{L}_f = \int dt = 100$ fb$^{-1}$. The reach for a number of models is shown for various energies and integrated luminosities in Figure 3. A recent detailed study emphasized the $Z'$ discovery potential in early LHC running at lower energy and luminosity for couplings to $B - L$ and $Y$ [73].

The cross section for $pp \to f\bar f$ (or $\bar pp \to f\bar f$) for a specific final fermion $f$ is just

$$\sigma_f \equiv \sigma_{Z'}B_f = N_f/\mathcal{L}_f,$$

where $B_f = \Gamma_f/\Gamma_{Z'}$ is the branching ratio into $f\bar f$, $\sigma_{Z'} = \int \frac{d\sigma_{Z'}}{dy}dy$, and $N_f$ is the number of produced $f\bar f$ pairs for integrated luminosity $\mathcal{L}_f$. For given couplings to the SM particles, $\sigma_{Z'}$ and therefore the discovery reach depend on the total width $\Gamma_{Z'}$. For example, in the $E_6$ models $\Gamma_{Z'}/M_{Z'}$ can vary from $\sim 0.01 - 0.05$ depending on whether the important open channels include light (compared to $M_{Z'}$) superpartners and exotics in addition to the SM fermions [32]. The consequences for the discovery reaches at the Tevatron and LHC are illustrated in Figure 4 where it is seen, e.g., that the LHC reach can...
Table 1 95% C.L. limits on $M_{Z'}$ and central values and 95% C.L. upper and lower limits on $\sin \theta_{ZZ'}$ for a variety of models. The results are updated from [17], where the models are defined.

| $Z'$          | $M_{Z'}$ [GeV] | $\sin \theta_{ZZ'}$ | $\sin \theta_{\text{min}}^{ZZ'}$ | $\sin \theta_{\text{max}}^{ZZ'}$ | $\chi^2_{\text{min}}$ |
|---------------|----------------|----------------------|----------------------------------|----------------------------------|----------------------|
| electroweak   | 1.141          | 892                  | 800                              | 673                              | -0.0004              |
| Z$_W$        | 147            | 878                  | 763                              | 481                              | -0.0005              |
| Z$_n$        | 427            | 982                  | 810                              | 434                              | -0.0015              |
| Z$_I$        | 1,204          | 789                  | 692                              | 0.0003                           | 0.0012               |
| Z$_S$        | 1,257          | 821                  | 719                              | -0.0003                          | 0.0005               |
| Z$_N$        | 623            | 861                  | 744                              | -0.0004                          | 0.0009               |
| Z$_R$        | 442            |                      | 0.0003                           | 0.0015                           | 0.0007               |
| $Z_{LR}$     | 998            | 630                  | 804                              | -0.0004                          | 0.0013               |
| $Z_{E6}$     | (803)          | (740)                |                                  | -0.0015                          | 0.0081               |
| $Z_{SM}$     | 1,403          | 1,030                | 950                              | 1,787                            | -0.0008                          |
| $Z_{\text{string}}$ | 1,362         |                      |                                  | 0.0002                           | 0.0009               |
| SM           | $\infty$       |                      |                                  | 0.0002                           | 48.5                 |

be reduced by $\sim 1$ TeV if there are many open channels.

There are a number of other potential two-fermion discovery channels, such as $\tau^+\tau^-$ and $t\bar{t}$, as mentioned in Section 3, while multibody channels will be touched on in Section 4.2. In principle, the LHC reach in the Drell-Yan dilepton channels can be extended by using virtual $Z'$ interference effects (cf., the observation of $Z$-propagator effects below the $Z$-pole at TRISTAN [75]), though this is difficult in practice [76].

4.2. Diagnostics

The spin of a resonance in the $\ell^+\ell^-$ channel would distinguish a $Z'$ or other vector from, e.g., a spin-0 Higgs resonance or a spin-2 Kaluza-Klein graviton excitation. The spin can be determined by the angular distribution in the resonance rest frame, which for the spin-1 interactions in [1] is

$$\frac{d\sigma_{Z'}}{d\cos \theta^*} \propto \frac{3}{8} \left(1 + \cos^2 \theta^* \right) + A_{FB} \cos \theta^*,$$

(19)

where $\theta^*$ is the angle between the incident quark and the $\ell$. (Magnetic or electric dipole interactions lead to a different distribution [77].) One does not know which hadron is the source of the $q$ and which the $\bar{q}$ on an event by event basis, but the ambiguity washes out in the determination of the $1 + \cos^2 \theta^*$ distribution [44,46]. See [78] for

Figure 3. LHC discovery reach, based on 5 dilepton events, for typical $Z'$ models as a function of energy and integrated luminosity, from [37].
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Figure 4. Discovery reach of the Tevatron and LHC (at 14 TeV) for $E_6$ models, assuming decays (a) into SM particles only (SM) and (b) allowing unsuppressed decays into exotics and sparticles (ALL), based on 10 dilepton events. The charges are $Q = Q_X \cos \theta + Q_\psi \sin \theta$, where $Q_X$ and $Q_\psi$ are associated with $SO(10)$ and $E_6$, respectively. From [32].

A recent detailed study. The $Z'$ spin can also be probed in $t\bar{t}$ decays [79].

Useful diagnostic probes of the chiral couplings to the quarks, leptons, and other particles, which would help discriminate between $Z'$ models, should be possible for masses up to $\sim 2 - 2.5$ TeV at the LHC, assuming typical couplings. (The gauge coupling $g_2$ can be fixed to the value $g_2 = \sqrt{5/3} g \tan \theta_W \sim 0.46$ suggested by some grand unified theories, or alternatively can be taken as a free parameter if the charges are normalized by some other convention.)

For $pp \to Z' \to \ell^+ \ell^-$ ($\ell = e, \mu$), one would be able to measure the mass $M_{Z'}$, the leptonic cross section $\sigma_{\ell Z'} = \sigma_{Z'} B_\ell$, and possibly the width $\Gamma_{Z'}$ (if it is not too small compared to the detector resolutions). The expected dilepton lineshape is illustrated in Figure 5. By itself, $\sigma_{\ell Z'}$ is not a useful diagnostic for the $Z'$ couplings to quarks and leptons: while $\sigma_{Z'}$ can be calculated to within a few percent for given $Z'$ couplings, $B_\ell$ depends strongly on the contribution of exotics and superpartners to $\Gamma_{Z'}$ [32]. However, $\sigma_{\ell Z'}$ would be a useful indirect probe for the existence of the exotics or superpartners. The absolute magnitude of the quark and lepton couplings is probed by the product $\sigma_{\ell Z'} \Gamma_{Z'} = \sigma_{Z'} \Gamma_\ell$.

The most useful diagnostics involve the relative strengths of $Z'$ couplings to ordinary quarks and leptons. The forward-backward asymmetry as a function of the $Z'$ rapidity, $A_{FB}(y) [14,15,16]$, avoids the $q\bar{q}$ ambiguity in Eq. [19]. For $AB \to Z' \to f\bar{f}$, define $\theta_{CM}$ as the angle of fermion $f$ with respect to the direction of hadron $A$ in the $Z'$ rest frame, and let $F$ ($B$) be the cross section for fixed rapidity $y$ with $\cos \theta_{CM} > 0$ ($< 0$). Then, $A_{FB}(y) = (F - B) / (F + B)$, with

$$F \pm B \sim \left[ \frac{4/3}{1} \right] \times \sum_i \left( f_{q_i}^A(x_1) f_{\bar{q}_i}^B(x_2) \pm f_{q_i}^B(x_1) f_{\bar{q}_i}^A(x_2) \right) \left( \epsilon_L(f)^2 \pm \epsilon_R(f)^2 \right).$$

Clearly, $A_{FB}(y)$ vanishes for $pp$ at $y = 0$, but can be nonzero at large $y$ where there is more likely a valence $q$ from the first proton and sea $\bar{q}$ from the other. The leptonic forward-backward asymmetry is sensitive to a combination of quark and lepton chiral couplings and is a powerful discrimi-
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Figure 5. Dilepton mass spectrum at the LHC for typical models with $M_{Z'} = 1.5$ TeV, $\sqrt{s} = 14$ TeV, and an integrated luminosity of 100 fb$^{-1}$, from [80].

An invariant definition of the asymmetry based on the pseudorapidities of the leptons is another possibility [81].

The ratio of cross sections for $Z' \rightarrow \ell^+\ell^-$ in different rapidity bins [81] gives information on the relative $u$ and $d$ couplings (Figure 6). Possible observables in other two-fermion final state channels include the polarization of produced $\gamma$'s [82]; the $pp \rightarrow Z' \rightarrow jj$ cross section [83,90]; and branching ratios, forward-backward asymmetries, and spin correlations for $b\bar{b}$ and $t\bar{t}$ [79,84,85,86]. There are no current plans for polarization at the LHC, but polarization asymmetries at a future or upgraded hadron collider would provide another useful diagnostic [87]. Family nonuniversal but flavor conserving effects are discussed in [88,90].

In four-fermion final state channels the rare decays $Z' \rightarrow Vf\bar{f}_2$, where $V = W$ or $Z$ is radiated from the $Z'$ decay products, have a double logarithmic enhancement. In particular, $Z' \rightarrow Wl\nu_l$ (with $W \rightarrow$ hadrons and an $l\nu_l$ transverse mass > 90 GeV to separate from SM background) may be observable and projects out the left-chiral lepton couplings [90,91,92]. Similarly, the associated productions $pp \rightarrow Z'V$ with $V = (Z, W)$ [93] and $V = \gamma$ [94] could yield information on the quark chiral couplings. The processes $pp \rightarrow Z'Z$ or $Z'\gamma$ with the $Z'$ decaying invisibly into neutrinos or hidden sector particles may also be observable and could serve as a discovery mode if the $Z'$ does not couple to charged leptons [95,96].

The importance of the width for invisible $Z'$ decays for constraining certain extra-dimensional models has been emphasized in [97].

Decays into two bosons, such as $Z' \rightarrow W^+W^-, Zh$, or $W^\pm H^\mp$, can usually occur only by $Z-Z'$ mixing or with amplitudes related to the mixing. However, this suppression may be compensated for the longitudinal modes of the $W$ or $Z$ by the large polarization vectors, with components scaling as $M_{Z'}/M_W$ [28,95,96,100,101,102,103,104]. For example, $\Gamma(Z' \rightarrow W^+W^-) \sim \theta_{ZZ'}^2$, which appears to be hopelessly small to observe. However, the enhancement factor is $\sim (M_{Z'}/M_W)^4$. Thus, from Eq. 8 these factors compensate, leaving a possibly observable rate that in principle could give information on the Higgs charges. In the limit of $M_{Z'} \gg M_Z$ one has

$$\Gamma(Z' \rightarrow W^+W^-) = \frac{g_2^2\theta_{ZZ'}^2 M_{Z'}}{192\pi} \left(\frac{M_{Z'}}{M_Z}\right)^4$$

(21)

The decay $Z' \rightarrow ZZ$ has recently been considered [105]. The Landau-Yang theorem [100] can be evaded by anomaly-induced or $CP$-violating operators involving a longitudinal $Z$. The LHC reach of spin-1 resonances associated with electroweak symmetry breaking and the associated $Z' \rightarrow W^+W^-$ or $W' \rightarrow ZW$ decays have been studied in [107], and more complicated decays such as $Z' \rightarrow ggg$ or $gg\gamma$ in [108].

An alternative source of triple gauge vertices involves anomalous $U(1)'$ symmetries, which often occur in string constructions. The anomalies must be cancelled by a generalized Green-Schwarz mechanism. The $Z'$ associated with the $U(1)'$ acquires a string-scale mass by what is essentially the Stuckelberg mechanism, and effective trilinear vertices may be generated between the $Z'$ and the SM gauge bosons [109,110]. If there are large extra dimensions the string scale and therefore the
$Z'$ mass may be very low, e.g., at the TeV scale, with anomalous decays into $ZZ$, $WW$, and $Z\gamma$, e.g., $[111,112,113]$. Some $Z'$ models lead to distinctive multi-lepton decay modes at a possibly observable rate that are almost entirely free of SM backgrounds. For example, a $Z'$ could decay into $\ell\bar{\ell}\ell\bar{\ell}$ via intermediate sneutrinos in an $R$-parity violating supersymmetric model $[114]$, or $Z' \rightarrow 3\ell\bar{\ell}$ by an intermediate $ZH \rightarrow 3Z$ in some models with extended Higgs structures $[115]$. The latter could occur even in leptophobic models (i.e., with no direct coupling to leptons). A light (GeV scale) $Z'$, suggested by some recent dark matter models, would be highly boosted at the LHC, leading to narrow “lepton jets” from $Z' \rightarrow \ell^+\ell^-$ and possible displaced vertices, e.g., $[72,73,4]$. 

Global studies of the possible LHC diagnostic possibilities for determining ratios of chiral charges in a model independent way and discriminating models are given in $[30,34,37,46,81,116,117]$. The complementarity of LHC and ILC observations is especially emphasized in $[116,118,119,29]$. 

5. Other LHC Implications

There are several other implications of a $Z'$ for the LHC. For example, TeV scale $U(1)'$ models generally involve an extended Higgs sector, requiring at least a SM singlet $S$ to break the $U(1)'$ symmetry. New $F$ and $D$-term contributions can relax the theoretical upper limit of $\sim 130$ GeV on the lightest Higgs scalar in the MSSM up to $\sim 150$ GeV, and smaller values of $\tan\beta$, e.g. $\sim 1$, become possible. Conversely, doublet-singlet mixing can allow a Higgs lighter than the direct SM and MSSM limits. Such mixing as well as the extended neutralino sector can lead to non-standard collider signatures, e.g., $[101,120,121]$. $U(1)'$ models also have extended neutralino sectors $[122,123]$, involving at least the $Z'$ gaugino and the $S$ singlino, allowing non-standard couplings (e.g., light singlino-dominated), extended cascades, and modified possibilities for cold dark matter, $g_\nu - 2$, etc. Most $U(1)'$ models (with the exception of those involving $B - L$ and $Y$) require new exotic fermions to cancel anomalies. These are usually non-chiral with respect to the SM (to avoid precision electroweak constraints) but chiral under the $U(1)'$. A typical example is a pair of $SU(2)$-singlet colored quarks $D_{L,R}$ with charge $-1/3$. Such exotics may decay by mixing, although that is often forbidden by $R$-parity. They may also decay by diquark or leptoquark couplings, or they be quasi-stable, decaying by higher-dimensional operators $[124,125,126]$. 

A heavy $Z'$ may decay efficiently into particles, exotics, etc., constituting a “SUSY factory” $[32,114,127,128,129]$. For other theoretical, experimental, and cosmological/astrophysical $Z'$ implications see $[114]$. 

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