THE Z' SEARCHES

Revised March 2002 by K.S. Babu (Oklahoma State University) and C. Kolda (Notre Dame University).

New massive and electrically neutral gauge bosons are a common feature of physics beyond the Standard Model. They are present in most extensions of the Standard Model gauge group, including models in which the Standard Model is embedded into a unifying group. They can also arise in certain classes of theories with extra dimensions. Whatever the source, such a gauge boson is called a Z'. While current theories suggest that there may be a multitude of such states at or just below the Planck scale, there exist many models in which the Z' sits at or near the weak scale. Models with extra neutral gauge bosons often contain charged gauge bosons as well; these are discussed in the review of W' physics.

The Lagrangian describing a single Z' and its interactions with the fields of the Standard Model is [1,2,3]:

$$\mathcal{L}_{Z'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\sin\chi}{2}F'_{\mu\nu}F^{\mu\nu} + M^2_{Z'}Z'_\mu Z'^\mu + \delta M^2\, Z'_\mu Z^\mu - \frac{e}{2c_W s_W}\sum_i \overline{\psi}_i\gamma^\mu(f^i_V - f^i_A\gamma^5)\psi_i Z'_\mu \tag{1}$$

where c_W, s_W are the cosine and sine of the weak angle, $F_{\mu\nu}, F'_{\mu\nu}$ are the field strength tensors for the hypercharge and the Z' gauge bosons respectively, ψ_i are the matter fields with Z' vector and axial charges f^i_V and f^i_A, and Z_μ is the electroweak Z-boson. (The overall Z' coupling strength has been normalized to that of the usual Z.) The mass terms are assumed to come from spontaneous symmetry breaking via scalar expectation values; the δM^2 term is generated by Higgs bosons that are charged under both the Standard Model and the extra gauge symmetry, and can have either sign. The above Lagrangian is general to all abelian and non-abelian extensions; however, for the non-abelian case, $F'_{\mu\nu}$ is not gauge invariant and so the kinetic mixing parameter $\chi = 0$. Most analyses take $\chi = 0$, even for the abelian case, and so we do likewise here; see Ref. 3 for a discussion of observables with $\chi \neq 0$.

Strictly speaking, the Z' defined in the Lagrangian above is not a mass eigenstate since it can mix with the usual Z boson. The mixing angle is given by

$$\xi \simeq \frac{\delta M^2}{M_Z^2 - M_{Z'}^2} \ . \tag{2}$$

This mixing can alter a large number of the Z-pole observables, including the T-parameter which receives a contribution

$$\alpha T_{\rm new} = \xi^2 \left(\frac{M_{Z'}^2}{M_Z^2} - 1 \right) \tag{3}$$

to leading order in small ξ. (For $\chi \neq 0$, both S and T receive additional contributions [4,3].) However, the oblique parameters do not encode all the effects generated by $Z-Z'$ mixing; the mixing also alters the couplings of the Z itself, shifting its vector and axial couplings to $T_3^i - 2Q^i s_W^2 + \xi f_V^i$ and $T_3^i + \xi f_A^i$ respectively.

If the Z' charges are generation-dependent, tree-level flavor-changing neutral currents will generically arise. There exist severe constraints in the first two generations coming from precision measurements such as the $K_L - K_S$ mass splitting and $B(\mu \to 3e)$; constraints on a Z' which couples differently only to the third generation are somewhat weaker. If the Z' interactions commute with the Standard Model gauge group, then per generation, there are only five independent $Z'\bar{\psi}\psi$ couplings; one can choose them to be $f_V^u, f_A^u, f_V^d, f_V^e, f_A^e$. All other couplings can be determined in terms of these, *e.g.*, $f_V^\nu = (f_V^e + f_A^e)/2$.

Experimental Constraints: There are four primary sets of constraints on the existence of a Z' which will be considered here: precision measurements of neutral current processes at low energies, Z-pole constraints on $Z-Z'$ mixing, indirect constraints from precision electroweak measurements off the Z-pole, and direct search constraints from production at very high energies. In principle, one should expect other new states to appear at the same scale as the Z', including its symmetry-breaking sector and any additional fermions necessary for anomaly cancellation. Because these states are highly model-dependent, searches for these states, or for Z' decays into them, are not included in the Listings.

Low-energy Constraints: After the gauge symmetry of the Z' and the electroweak symmetry are both broken, the Z of the Standard Model can mix with the Z', with mixing angle ξ defined above. As already discussed, this $Z-Z'$ mixing implies a shift in the usual oblique parameters. Current bounds on T (and S) translate into stringent constraints on the mixing angle, ξ, requiring $\xi \ll 1$; similar constraints on ξ arise from the LEP Z-pole data. Thus, we will only consider the small-ξ limit henceforth.

Whether or not the new gauge interactions are parity violating, stringent constraints can arise from atomic parity violation (APV) and polarized electron-nucleon scattering experiments [5]. At low energies, the effective neutral current Lagrangian is conventionally written:

$$\mathcal{L}_{\rm NC} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left\{ C_{1q}(\bar{e}\gamma_\mu\gamma^5 e)(\bar{q}\gamma^\mu q) + C_{2q}(\bar{e}\gamma_\mu e)(\bar{q}\gamma^\mu\gamma^5 q) \right\} . \tag{4}$$

APV experiments are sensitive only to C_{1u} and C_{1d} through the "weak charge" $Q_W = -2\left[C_{1u}(2Z+N) + C_{1d}(Z+2N)\right]$, where

$$C_{1q} = 2(1+\alpha T)(g_A^e + \xi f_A^e)(g_V^q + \xi f_V^q) + 2r(f_A^e f_V^q) \tag{5}$$

with $r = M_Z^2/M_{Z'}^2$. (Terms $\mathcal{O}(r\xi)$ are dropped.) The r-dependent terms arise from Z' exchange and can interfere constructively or destructively with the Z contribution. In the limit $\xi = r = 0$, this reduces to the Standard Model expression. Polarized electron scattering is sensitive to both the C_{1q} and C_{2q} couplings, again as discussed in the Standard Model review. The C_{2q} can be derived from the expression for C_{1q} with the complete interchange $V \leftrightarrow A$.

Stringent limits also arise from neutrino-hadron scattering. One usually expresses experimental results in terms of the effective 4-fermion operators $(\bar{\nu}\gamma_\mu\nu)(\bar{q}_{L,R}\gamma^\mu q_{L,R})$ with coefficients

$(2\sqrt{2}G_F)\epsilon_{L,R}(q)$. (Again, see the Standard Model review.) In the presence of the Z and Z', the $\epsilon_{L,R}(q)$ are given by:

$$\epsilon_{L,R}(q) = \frac{1+\alpha T}{2}\left\{(g_V^q \pm g_A^q)[1+\xi(f_V^\nu \pm f_A^\nu)] + \xi(f_V^q \pm f_A^q)\right\} + \frac{r}{2}(f_V^q \pm f_A^q)(f_V^\nu \pm f_A^\nu)\ . \tag{6}$$

Again, the r-dependent terms arise from Z'-exchange.

Z-pole Constraints: Electroweak measurements made at LEP and SLC while sitting on the Z-resonance are generally sensitive to Z' physics only through the mixing with the Z, unless the Z and Z' are very nearly degenerate. Constraints on the allowed mixing angle and Z' couplings arise by fitting all data simultaneously to the *ansatz* of $Z-Z'$ mixing. A number of such fits are included in the Listings. If the listed analysis uses data only from the Z resonance, it is marked with a comment "Z parameters" while it is commented as "Electroweak" if low-energy data is also included in the fits. Both types of fits place simultaneous limits on the Z' mass and on ξ.

High-energy Indirect Constraints: At $\sqrt{s} < M_{Z'}$, but off the Z-pole, strong constraints on new Z' physics arise by comparing measurements of asymmetries and leptonic and hadronic cross-sections with their Standard Model predictions. These processes are sensitive not only to $Z-Z'$ mixing, but also to direct Z' exchange primarily through $\gamma-Z'$ and $Z-Z'$ interference; therefore, information on the Z' couplings and mass can be extracted that is not accessible via $Z-Z'$ mixing alone.

Far below the Z' mass scale, experiments at a given $\sqrt{s}$ are only sensitive to the scaled Z' couplings $\sqrt{s}f^i_{V,A}/M_{Z'}$. However, the Z' mass and overall magnitude of the couplings can be separately extracted if measurements are made at more than one energy. As $\sqrt{s}$ approaches $M_{Z'}$ the Z' exchange can no longer be approximated by a contact interaction and the mass and couplings can be simultaneously extracted.

Z' studies done before LEP relied heavily on this approach; see, for example, Ref. 6. LEP has also done similar work using data collected above the Z-peak; see, for example, Ref. 7. For indirect Z' searches at future facilities, see, for example, Refs. 8,9. At a hadron collider the possibility of measuring leptonic forward-backward asymmetries has been suggested [10] and used [11] in searches for a Z' below its threshold.

Direct Search Constraints: Finally, high-energy experiments have searched for on-shell Z' production and decay. Searches can be classified by the initial state off of which the Z' is produced, and the final state into which the Z' decays; exotic decays of a Z' are not included in the listings. Experiments to date have been sensitive to Z' production via their coupling to quarks ($p\bar{p}$ colliders), to electrons (e^+e^-), or to both (ep).

For a heavy Z' ($M_{Z'} \gg M_Z$), the best limits come from $p\bar{p}$ machines via Drell-Yan production and subsequent decay to charged leptons. For $M_{Z'} > 600\,\text{GeV}$, CDF [12] quotes limits on $\sigma(p\bar{p} \to Z'X) \cdot B(Z' \to \ell^+\ell^-) < 0.04\,\text{pb}$ at 95% C.L. for $\ell = e+\mu$ combined; DØ [13] quotes $\sigma \cdot B < 0.06\,\text{pb}$ for $\ell = e$ and $M_{Z'} > 500\,\text{GeV}$. For smaller masses, the bounds can be found in the original literature. For studies of the search capabilities of future facilities, see, for example, Ref. 8.

If the Z' has suppressed, or no, couplings to leptons (*i.e.*, it is leptophobic), then experimental sensitivities are much weaker. Searches for a Z' via hadronic decays at CDF [14] are unable to rule out a Z' with quark couplings identical to those of the Z in any mass region. UA2 [15] does find $\sigma \cdot B(Z' \to jj) < 11.7\,\text{pb}$ at 90% C.L. for $M_{Z'} > 200\,\text{GeV}$, with more complicated bounds in the range $130\,\text{GeV} < M_{Z'} < 200\,\text{GeV}$.

For a light Z' ($M_{Z'} < M_Z$), direct searches in e^+e^- colliders have ruled out any Z', unless it has extremely weak couplings to leptons. For a combined analysis of the various pre-LEP experiments see Ref. 6.

Canonical Models: One of the prime motivations for an additional Z' has come from string theory, in which certain compactifications lead naturally to an E_6 gauge group, or one of its subgroups. E_6 contains two U(1) factors beyond the Standard Model, a basis for which is formed by the two groups $\mathrm{U}(1)_\chi$ and $\mathrm{U}(1)_\psi$, defined via the decompositions $E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ and $\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi$; one special case often encountered is $\mathrm{U}(1)_\eta$, where $Q_\eta = \sqrt{\frac{3}{8}} Q_\chi - \sqrt{\frac{5}{8}} Q_\psi$. The charges of the SM fermions under these U(1)'s can be found in Table 1, and a discussion of their experimental signatures can be found in Ref. 16. A separate listing appears for each of the canonical models, with direct and indirect constraints combined.

Table 1: Charges of Standard Model fermions in canonical Z' models.

	Y	T_{3R}	$B-L$	$\sqrt{24}Q_\chi$	$\sqrt{\frac{72}{5}}Q_\psi$	Q_η
ν_L, e_L	$-\frac{1}{2}$	0	-1	$+3$	$+1$	$+\frac{1}{6}$
ν_R	0	$+\frac{1}{2}$	-1	$+5$	-1	$+\frac{5}{6}$
e_R	-1	$-\frac{1}{2}$	-1	$+1$	-1	$+\frac{1}{3}$
u_L, d_L	$+\frac{1}{6}$	0	$+\frac{1}{3}$	-1	$+1$	$-\frac{1}{3}$
u_R	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	$+1$	-1	$+\frac{1}{3}$
d_R	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	-3	-1	$-\frac{1}{6}$

It is also common to express experimental bounds in terms of a toy Z', usually denoted Z'_{SM}. This Z'_{SM}, of arbitrary mass, couples to the SM fermions identically to the usual Z. Almost all analyses of Z' physics have worked with one of these canonical models and have assumed zero kinetic mixing at the weak scale.

Extra Dimensions: A new motivation for Z' searches comes from recent work on extensions of the Standard Model into extra dimensions. (See the "Review of Extra Dimensions" for many details not included here.) In some classes of these models, the gauge bosons of the Standard Model can inhabit these new directions [17]. When compactified down to the usual (3+1) dimensions, the extra degrees of freedom that were present in the higher-dimensional theory (associated with propagation in the extra dimensions) appear as a tower of massive gauge bosons, called Kaluza-Klein (KK) states. The simplest case is the compactification of a $(4+d)$-dimensional space on a d-torus (T^d) of uniform radius R in all d directions. Then a tower of massive gauge bosons are present with masses

$$M^2_{V_{\vec{n}}} = M^2_{V_{\vec{0}}} + \frac{\vec{n}\cdot\vec{n}}{R^2}\,, \tag{7}$$

where V represents any of the gauge fields of the Standard Model and $\vec{n}$ is a d-vector whose components are semi-positive integers; the vector $\vec{n} = (0, 0, \ldots 0)$ corresponds to the "zero-mode" gauge boson, which is nothing more than the usual gauge boson of the Standard Model, with mass $M_{V_{\vec{0}}} = M_V$. Compactifications on either non-factorizable or asymmetric manifolds can significantly alter the KK mass formula, but a tower of states will nonetheless persist. All bounds cited in the Listings assume the maximally symmetric spectrum given above for simplicity.

The KK mass formula, coupled with the absence of any observational evidence for W' or Z' states below the weak scale, implies that the extra dimensions in which gauge bosons can propagate must have inverse radii greater than at least a few hundred GeV. If any extra dimensions are larger than this, gravity alone may propagate in them.

Though the gauge principle guarantees that the usual Standard Model gauge fields couple with universal strength (or gauge coupling) to all charged matter, the coupling of KK bosons to ordinary matter is highly model-dependent. In the simplest case, all Standard Model fields are localized at the same point in the d-dimensional subspace; in the parlance of the field, they all live on the same 3-brane. Then the couplings of KK bosons are identical to those of the usual gauge fields, but enhanced: $g_{KK} = \sqrt{2}\,g$. However, in many models, particularly those which naturally suppress proton decay [18], it is common to find ordinary fermions living on different, parallel branes in the extra dimensions. In such cases, different fermions experience very different coupling strengths for the KK states; the effective coupling varies fermion by fermion, and also KK mode by KK mode. In the particular case that fermions of different generations with identical quantum numbers are placed on different branes, large flavor-changing neutral currents can occur unless the mass scale of the KK states is very heavy: $R^{-1} \gtrsim 1000\,\mathrm{TeV}$ [19]. In the Listings, all bounds assume that Standard Model fermions live on a single 3-brane. (The case of the Higgs field is again complicated; see the footnotes on the individual listings.)

In some sense, searches for KK bosons are no different than searches for any other Z' or W'; in fact, bounds on the artificially defined Z'_{SM} are almost precisely bounds on the first KK mode of the Z^0, modulo the $\sqrt{2}$ enhancement in the coupling strength. To date, no experiment has examined direct production of KK Z^0 bosons, but an approximate bound of 820 GeV [20] can be inferred from the CDF bound on Z'_{SM} [12].

Indirect bounds have a very different behavior for KK gauge bosons than for canonical Z' bosons; a number of indirect bounds are given in the Listings. Indirect bounds arise from virtual boson exchange and require a summation over the entire tower of KK states. For $d > 1$, this summation diverges, a remnant of the non-renormalizability of the underlying $(4+d)$-dimensional field theory. In a fully consistent theory, such as a string theory, the summation would be regularized and finite. However, this procedure cannot be uniquely defined within the confines of our present knowledge, and so most authors choose to terminate the sum with an explicit cut-off, Λ_{KK}, set equal to the "Planck scale" of the D-dimensional theory, M_D [21]. Reasonable arguments exist that this cut-off could be very different and could vary by process, and so these bounds should be regarded merely as indicative [22].

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