THE Z' SEARCHES

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If the Standard Model is enhanced by additional gauge symmetries or embedded into a larger gauge group, there will arise new heavy gauge bosons, some of which generically are electrically neutral. Such a gauge boson is called a Z'. Consider the most general renormalizable Lagrangian describing the complete set of interactions of the neutral gauge bosons among themselves and with fermions, which is that of the Standard Model plus the following new pieces [1,2,3]:

$$\begin{aligned}\mathcal{L}_{Z'} = &-\frac{1}{4}\widehat{F}'_{\mu\nu}\widehat{F}'^{\mu\nu} - \frac{\sin\chi}{2}\widehat{F}'_{\mu\nu}\widehat{F}^{\mu\nu} + \frac{1}{2}\widehat{M}^2_{Z'}\widehat{Z}'_\mu\widehat{Z}'^\mu \\ &+ \delta\widehat{M}^2\,\widehat{Z}'_\mu\widehat{Z}^\mu - \frac{\widehat{g}'}{2}\sum_i \overline{\psi}_i\gamma^\mu(f^i_V - f^i_A\gamma^5)\psi_i\widehat{Z}'_\mu \qquad (1)\end{aligned}$$

where $\widehat{F}_{\mu\nu}, \widehat{F}'_{\mu\nu}$ are the field strength tensors for the hypercharge $\widehat{B}_\mu$ gauge boson and the Z' respectively before any diagonalizations are performed, ψ_i are the matter fields with Z' vector and axial charges f^i_V and f^i_A, and $\widehat{Z}_\mu$ is the electroweak Z boson in this basis. (See the Review on "Electroweak Model and Constraints on New Physics" for the Standard Model pieces of the Lagrangian.) The mass terms are assumed to come from spontaneous symmetry breaking via scalar expectation values. The above Lagrangian is general to all abelian and non-abelian extensions, except that $\chi = 0$ for the non-abelian case since then $\widehat{F}'_{\mu\nu}$ is not gauge invariant. Most analyses take $\chi = 0$ even for the abelian case.

Going to the physical eigenbasis requires diagonalizing both the gauge kinetic and mass terms, with mass eigenstates denoted Z_1 and Z_2, where we choose Z_1 to be the observed Z boson. The interaction Lagrangian for Z_1 has the form, to leading order in the mixing angle ξ ($s_W \equiv \sin\theta_W$, etc.):

$$\begin{aligned}\mathcal{L}_{Z_1} = &-\frac{e}{2s_W c_W}\left(1+\frac{\alpha T}{2}\right)\overline{\psi}_i\gamma^\mu\left\{\left(g^i_V + \xi\tilde{f}^i_V\right)\right. \\ &\left.-\left(g^i_A + \xi\tilde{f}^i_A\right)\gamma^5\right\}\psi_i Z_{1\mu} \qquad (2)\end{aligned}$$

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where

$$\xi \simeq \frac{-\cos\chi(\delta\widehat{M}^2 + \widehat{M}_Z^2 s_W \sin\chi)}{\widehat{M}_{Z'}^2 - \widehat{M}_Z^2 \cos^2\chi + \widehat{M}_Z^2 s_W^2 \sin^2\chi + 2\,\delta\widehat{M}^2\, s_W \sin\chi} \quad . \tag{3}$$

We have made the identifications $g_A^i = T_3^i$, $g_V^i = T_3^i - 2Q^i s_*^2$, $\tilde{f}_{V,A}^i = (\widehat{g}' s_W c_W / e \cos\chi) f_{V,A}^i$, and s_W^2 is identified to be the $s_{M_Z}^2$ defined in the "Electroweak Model and Constraints on New Physics" review. Note that the value of the weak angle that appears in the vector coupling is shifted by the S and T oblique parameters:

$$s_*^2 = s_W^2 + \frac{1}{s_W^2 - c_W^2}\left(\frac{1}{4}\alpha S - c_W^2 s_W^2 \alpha T\right) \quad . \tag{4}$$

Recall that $\rho = 1 + \alpha T$ defines the usual ρ parameter. In the presence of Z–Z' mixing, the oblique parameters receive contributions [4]:

$$\begin{aligned}
\alpha S &= 4\xi c_W^2 s_W \tan\chi \\
\alpha T &= \xi^2\left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 1\right) + 2\xi s_W \tan\chi \\
\alpha U &= 0
\end{aligned} \tag{5}$$

to leading order in small ξ. These contributions are in addition to those coming from top quark and Higgs boson loops in the Standard Model. (This is in contrast to the "Electroweak Model and Constraints on New Physics" Review in which oblique parameters are defined to be zero for reference values of m_t and M_H.) Note that nonzero Z–Z' contributions to S arise only in the presence of kinetic mixing.

The corresponding $Z_2\overline{\psi}\psi$ interaction Lagrangian is:

$$\mathcal{L}_{Z_2} = -\frac{e}{2s_W c_W}\overline{\psi}_i\gamma^\mu\left\{\left(h_V^i - g_V^i\xi\right) - \left(h_A^i - g_A^i\xi\right)\gamma^5\right\}\psi_i Z_{2\mu} \tag{6}$$

with the following definitions:

$$\begin{aligned}
h_V^i &= \tilde{f}_V^i + \widetilde{s}(T_3^i - 2Q^i)\tan\chi \\
h_A^i &= \tilde{f}_A^i + \widetilde{s}T_3^i\tan\chi \\
\widetilde{s} &= s_W + \frac{s_W^3}{c_W^2 - s_W^2}\left(\frac{1}{4c_W^2}\alpha S - \frac{1}{2}\alpha T\right)
\end{aligned} \tag{7}$$

where the last equation defines a weak angle appropriate for the Z_2 interactions.

If the Z' charges are generation-dependent, there exist severe constraints in the first two generations coming from precision measurements such as the K_L–K_S mass splitting and $B(\mu \to 3e)$ owing to the lack of GIM suppression in the Z' interactions; however, constraints on a Z' which couples differently only to the third generation are somewhat weaker. (It will be assumed in the Z-pole constraint section that the Z' couples identically to all three generations of matter; all other results are general.) If the new Z' interactions commute with the Standard Model gauge group, then per generation, there are only five independent $Z'\overline{\psi}\psi$ couplings; we can choose them to be $\tilde{f}_V^u$, $\tilde{f}_A^u$, $\tilde{f}_V^d$, $\tilde{f}_V^e$, and $\tilde{f}_A^e$. All other couplings can be determined in terms of these, *e.g.*, $\tilde{f}_V^\nu = (\tilde{f}_V^e + \tilde{f}_A^e)/2$.

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 $Z_\eta = \sqrt{\frac{3}{8}}Z_\chi - \sqrt{\frac{5}{8}}Z_\psi$. The charges of the SM fermions under these U(1)'s, and a discussion of their experimental signals, can be found in Ref. 5.

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.

Experimental constraints: There are three 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, and direct search constraints from production at very high energies. In principle, one usually expects 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. However, because these states are highly model-dependent, we will not include searches for them, or Z' decays to them, in the bounds that follow.

Low-energy constraints: After the breaking of the new gauge group and the usual electroweak breaking, 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 [S, T, U defined in Eq. (5)]. Current bounds on S and T 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 [6]. At low energies, the effective neutral-current Lagrangian is conventionally written:

$$\mathcal{L}_{\rm NC} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left\{ C_{1q} (\overline{e}\gamma_\mu \gamma^5 e)(\overline{q}\gamma^\mu q) + C_{2q} (\overline{e}\gamma_\mu e)(\overline{q}\gamma^\mu \gamma^5 q) \right\} \quad . \tag{8}$$

APV experiments are sensitive only to C_{1u} and C_{1d} (see the "Electroweak Model and Constraints on New Physics" Review for the nuclear weak charge, Q_W, in terms of the C_{1q}) where in the presence of the Z and Z':

$$C_{1q} = 2(1+\alpha T)(g_A^e + \xi \tilde{f}_A^e)(g_V^q + \xi \tilde{f}_V^q) + 2r(h_A^e - \xi g_A^e)(h_V^q - \xi g_V^q) \tag{9}$$

where $r = (M_{Z_1}/M_{Z_2})^2$. The r-dependent terms arise from Z_2 exchange and can interfere constructively or destructively with the Z_1 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 "Electroweak Model and Constraints on New Physics" 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 $(\overline{\nu}\gamma_\mu\nu)(\overline{q}_{L,R}\gamma^\mu q_{L,R})$ with coefficients $(2\sqrt{2}G_F)\epsilon_{L,R}(q)$. (Again, see the "Electroweak Model and Constraints on New Physics" Review.) In the presence of the Z and Z', the $\epsilon_{L,R}(q)$ are given by:

$$\begin{aligned}\epsilon_{L,R}(q) =& \frac{1+\alpha T}{2}\Big\{(g_V^q \pm g_A^q)[1+\xi(\tilde{f}_V^\nu \pm \tilde{f}_A^\nu)] + \xi(\tilde{f}_V^q \pm \tilde{f}_A^q)\Big\} \\ &+ \frac{r}{2}\left\{(h_V^q \pm h_A^q)(h_V^\nu \pm h_A^\nu) - \xi(g_V^q \pm g_A^q)(h_V^\nu \pm h_A^\nu)\right. \\ &\left. - \xi(h_V^q \pm h_A^q)\right\} \quad . \end{aligned} \tag{10}$$

Again, the r-dependent terms arise from Z_2-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, a possibility we ignore. Constraints on the allowed mixing angle and Z couplings arise by fitting all data simultaneously to the *ansatz* of Z–Z' mixing. For any observable, $\mathcal{O}$, the shift in that observable, $\Delta\mathcal{O}$, can be expressed (following the procedure of Ref. 7) as:

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = \mathcal{A}_{\mathcal{O}}^S\,\alpha S + \mathcal{A}_{\mathcal{O}}^T\,\alpha T + \xi\sum_i \mathcal{B}_{\mathcal{O}}^{(i)}\tilde{f}^i \tag{11}$$

where i runs over the 5 independent $Z'\overline{\psi}\psi$ couplings listed earlier (assuming a Z' couplings commute with the generation and gauge symmetries of the Standard Model; this is the only place where we enforce such a restriction). The coefficients $\mathcal{A}_{\mathcal{O}}^{S,T}$ and $\mathcal{B}_{\mathcal{O}}^{(i)}$, which are functions only of the Standard Model parameters, are given in Table 1. The first 5 observables are directly measured at LEP and SLC, while $\overline{A}_e$, $\overline{A}_b$ and $\overline{A}_c$ are measured via the asymmetries $\overline{A}_{FB}^{(0,f)} = \frac{3}{4}\overline{A}_e\overline{A}_f$ and $A_{LR}^0 = \overline{A}_e$ as defined in the "Electroweak Model and Constraints on New Physics" Review. As an example, the shift in $\overline{A}_e$ due to Z' physics is given by

$$\frac{\Delta\overline{A}_e}{\overline{A}_e} = -24.9\,\alpha S + 17.7\,\alpha T - 26.7\,\xi\,\tilde{f}_V^e + 2.0\,\xi\,\tilde{f}_A^e \quad . \tag{12}$$

Table 1: Expansion coefficients for shifts in Z-pole observables normalized to the Standard Model value of the observable [7,3].

$\mathcal{O}$	$\mathcal{A}_{\mathcal{O}}^{S}$	$\mathcal{A}_{\mathcal{O}}^{T}$	$\mathcal{B}_{\mathcal{O}}^{Vu}$	$\mathcal{B}_{\mathcal{O}}^{Au}$	$\mathcal{B}_{\mathcal{O}}^{Vd}$	$\mathcal{B}_{\mathcal{O}}^{Ve}$	$\mathcal{B}_{\mathcal{O}}^{Ae}$
Γ_Z	-0.49	1.35	-0.89	-0.40	0.37	0.37	0
R_ℓ	-0.39	0.28	-1.3	-0.56	0.52	0.30	4.0
σ_h	0.046	-0.033	0.50	0.22	-0.21	-1.0	-4.0
R_b	0.085	-0.061	-1.4	-2.1	0.29	0	0
R_c	-0.16	0.12	2.7	4.1	-0.59	0	0
$\overline{A}_e$	-24.9	17.7	0	0	0	-26.7	2.0
$\overline{A}_b$	-0.32	0.23	0.71	0.71	-1.73	0	0
$\overline{A}_c$	-2.42	1.72	3.89	-1.49	0	0	0
M_W^2	-0.93	1.43	0	0	0	0	0

High-energy indirect constraints: At $\sqrt{s} < M_{Z_2}$, but off the Z_1 pole, strong constraints on new Z' physics arise from measurements of deviations of asymmetries and leptonic and hadronic cross sections from their Standard Model predictions. These processes are sensitive not only to Z–Z' mixing but also to direct Z_2 exchange primarily through γ–Z_2 and Z_1–Z_2 interference; therefore information on the Z_2 couplings and mass can be extracted that is not accessible via Z–Z' mixing alone.

Far below the Z_2 mass scale, experiment is only sensitive to the scaled Z_2 couplings $(\sqrt{s}/M_{Z_2}) \cdot h^i_{V,A}$ so the Z_2 mass and overall magnitude of the couplings cannot both be extracted. However as $\sqrt{s}$ approaches M_{Z_2} the Z_2 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, *e.g.*, Ref. 8. LEP has also done similar work using data collected above the Z peak; see, *e.g.*, Ref. 9. For indirect Z' searches at future facilities, see, *e.g.* Refs. 10 and 11.

Direct-search constraints: Finally, high-energy experiments have searched for on-shell Z' (here Z_2) 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;

we will not include here exotic decays of a Z'. Experiments to date have been sensitive to Z' production via their coupling to quarks ($p\overline{p}$ colliders), to electrons (e^+e^-) or to both (ep).

For a heavy Z' ($M_{Z_2} \gg M_{Z_1}$), the best limits come from $p\overline{p}$ machines via Drell-Yan production and subsequent decay to charged leptons. For $M_{Z_2} > 600\,\mathrm{GeV}$, CDF [12] quotes limits on $\sigma(p\overline{p} \to Z_2 X) \cdot B(Z_2 \to \ell^+\ell^-) < 0.04\,\mathrm{pb}$ at 95% C.L. for $\ell = e + \mu$ combined; DØ [13] quotes $\sigma \cdot B < 0.025\,\mathrm{pb}$ for $\ell = e$. For $M_{Z_2} < 600\,\mathrm{GeV}$, the mass dependence is complicated and one should refer to the original literature. For studies of the search capabilities of future facilities, see *e.g.* Ref. 10.

If the Z' has suppressed, or no, couplings to leptons (*i.e.*, it is leptophobic) then experimental sensitivities are much weaker. In particular, searches for a Z' via hadronic decays at DØ [14] are able to rule out a Z' with quark couplings identical to those of the Z only in the mass range $365\,\mathrm{GeV} < M_{Z_2} < 615\,\mathrm{GeV}$; CDF [15] cannot exclude even this range. Additionally, UA2 [16] finds $\sigma \cdot B(Z' \to jj) < 11.7\,\mathrm{pb}$ at 90% C.L. for $M_{Z'} > 200\,\mathrm{GeV}$ and more complicated bounds in the range $130\,\mathrm{GeV} < M_{Z'} < 200\,\mathrm{GeV}$.

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. 8.

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