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Constraints on Extended Neutral Gauge Structures

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Abstract

Indirect precision data are used to constrain the masses of possible extra Z' bosons and their mixings with the ordinary Z. We study a variety of Z' bosons as they appear in E_6 and left-right unification models, the sequential Z boson, and the example of an additional $U(1)$ in a concrete model from heterotic string theory. In all cases the mixings are severely constrained ($\sin\theta < 0.01$). The lower mass limits are generally of the order of several hundred GeV and competitive with collider bounds. The exception is the Z_ψ boson, whose vector couplings vanish and whose limits are weaker. The results change little when the ρ parameter is allowed, which corresponds to a completely arbitrary Higgs sector. On the other hand, in specific models with minimal Higgs structures the limits are generally pushed into the TeV region.

The possibility of additional neutral gauge bosons, Z's, is among the best motivated types of physics beyond the Standard Model (SM). They are predicted by most unifying theories, such as Grand Unified Theories (GUTs), left-right unification, superstring theories and their strong coupling generalizations. In many cases their masses remain unpredicted and may or may not be of the electroweak scale. In the context of superstring models, however, which are much more constrained than purely field theoretical models, they are often predicted to arise at the electroweak scale, as we will discuss below. In this paper we consider six different types of Z' bosons:

1. The Z_χ boson is defined by $SO(10) \to SU(5) \times U(1)_\chi$. This boson is also the unique solution to the conditions of (i) family universality, (ii) no extra matter other than the right-handed neutrino, (iii) absence of gauge and mixed gauge/gravitational anomalies, and (iv) orthogonality to the hypercharge generator. In the context of a minimal $SO(10)$ GUT, conditions (i) and (ii) are satisfied by assumption, while (iii) and (iv) are automatic. Relaxing condition (iv) allows other solutions (including the Z_{LR} below) which differ from the Z_χ by a shift proportional to the third component of the right-handed isospin generator.

2. The Z_ψ boson is defined by $E_6 \to SO(10) \times U(1)_\psi$. It possesses only axial-vector couplings to the ordinary fermions. As a consequence it is the least constrained of our examples.

3. The Z_η boson is the linear combination $\sqrt{3/8}\,Z_\chi - \sqrt{5/8}\,Z_\psi$. It occurs in Calabi-Yau compactifications [1] of the heterotic string [2] if E_6 breaks directly to a rank 5 subgroup [3] via the Hosotani mechanism [4].

4. The Z_{LR} boson occurs in left-right models with gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \subset SO(10)$ and is defined through the current $J_{LR} = \sqrt{3/5}\,[\alpha J_{3R} - 1/(2\alpha) J_{B-L}]$. J_{3R} couples to the third component of $SU(2)_R$, B and L coincide with baryon and lepton number for the ordinary fermions, $\alpha = \sqrt{g_R^2/g_L^2 \cot^2\theta_W - 1}$, where $g_{L,R}$ are the $SU(2)_{L,R}$ gauge couplings, and θ_W is the weak mixing angle.

5. The *sequential* Z_{SM} boson is defined to have the same couplings to fermions as the SM Z boson. Such a boson is not expected in the context of gauge theories unless it has different couplings to exotic fermions than the ordinary Z. However, it serves as a useful reference case when comparing constraints from various sources. It could also play the role of an excited state of the ordinary Z in models with extra dimensions at the weak scale.

6. Finally we consider a superstring motivated Z_{string} boson appearing in a specific model [5] based on the free fermionic string construction with real fermions. This model has been investigated in considerable detail [6] with the goal of understanding some of the characteristics of (weakly coupled) string theories, and of contrasting them with the more conventional ideas such as GUTs. While this specific model itself is not realistic (for example it fails to produce an acceptable fermion mass spectrum) the predicted Z_{string} it contains is not ruled out. Its coupling strength is predicted and so are its fermion couplings. It is particularly interesting in that its couplings are family non-universal. While this may induce problems with too large flavor changing neutral currents through a violation of the GIM mechanism [7], we will not address this issue here. Another important observation is that such a Z_{string} can be naturally at the electroweak scale[8]. The basic reasons are strong restrictions on the superpotential, and that in a given model the sectors of supersymmetry (SUSY) breaking, and its mediation are usually not arbitrary. In string models one also expects bilinear terms in the Higgs superpotential to vanish at tree level (otherwise they should be of the order of the Planck scale) and to be generated in the process of radiative symmetry breaking. This is linked to the top quark Yukawa coupling driven symmetry breaking and typically involves extra Higgs singlets which are predicted in many string models.

multiplet	$100\,Q'$
$\begin{pmatrix} t \\ b \end{pmatrix}_L$	-71
t_R	$+133$
b_R	-136
$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L$	$+68$
u_R, c_R	-6
d_R, s_R	$+3$
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$+74$
τ_R	-130
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	-65
μ_R	$+9$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	-204
e_R	$+9$

In all cases, there is a relation between the mixing angle θ between the ordinary Z and the extra Z' from the diagonalization of the neutral vector boson mass matrix,

$$\tan^2\theta = \frac{M_0^2 - M_Z^2}{{M_{Z'}}^2 - M_0^2} = \frac{1-\rho_0/\rho_1}{\rho_0/\rho_2 - 1}, \tag{1}$$

where M_Z and $M_{Z'}$ are the physical boson masses, and M_0 is the mass of the ordinary Z in the absence of mixing. The second equality in relation (1) uses the neutral and charged boson mass interdependence which reads at tree level,

$$M_\alpha = \frac{M_W}{\sqrt{\rho_\alpha}\cos\theta_W}. \tag{2}$$

As in the case of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ model,

$$\rho_0 = \frac{\sum_i (t_i^2 - t_{3i}^2 + t_i)|\langle\phi_i\rangle|^2}{\sum_i 2t_{3i}^2|\langle\phi_i\rangle|^2}, \tag{3}$$

where t_i (t_{3i}) is (the third component of) the weak isospin of the Higgs field ϕ_i. $\rho_0 = 1$ if only $SU(2)$ Higgs doublets and singlets are present, in which case M_0 would be known independently. Nondegenerate $SU(2)$ multiplets of extra fermions and scalars affect the W and Z self-energies at the loop level, and therefore contribute to the T parameter [9]. They can arise, for example, in E_6 models, and in their presence ρ_0 should be replaced by $\rho_0/(1-\alpha(M_Z)T)$.

If the Higgs $U(1)'$ quantum numbers are known, as well, there will be an extra constraint,

$$\theta = C\frac{g_2}{g_1}\frac{M_Z^2}{M_{Z'}^2}, \tag{4}$$

where $g_{1,2}$ are the $U(1)$ and $U(1)'$ gauge couplings with

$$g_2 = \sqrt{\frac{5}{3}}\sin\theta_W\sqrt{\lambda}\,g_1. \tag{5}$$

$\lambda = 1$ if the GUT group breaks directly to $SU(3)\times SU(2)\times U(1)\times U(1)'$, while in general λ is still of $\mathcal{O}(1)$. We will quote our results assuming $\lambda = 1$, but our limits also apply to $\sqrt{\lambda}\sin\theta$ and $\frac{M_{Z'}}{\sqrt{\lambda}}$ for other values of λ (we always assume $M_{Z'} \gg M_Z$). Similar to ρ_0,

$$C = -\frac{\sum_i t_{3i}Q_i'|\langle\phi_i\rangle|^2}{\sum_i t_{3i}^2|\langle\phi_i\rangle|^2} \tag{6}$$

is another function of vacuum expectation values (VEVs), where Q_i' are the $U(1)'$ charges. For minimal cases, the functions C are given explicitly in Table III of reference [10]. Similarly, for the fermion couplings of the various Z's we refer to Table II of the same work.

There is the possibility of an extra gauge invariant term, mixing the field strength tensors of the hypercharge and the new gauge bosons. We do not consider such a term here, since it is expected to be small in typical models[1]. The phenomenology of gauge kinetic mixing has been

[1] It was shown in Ref. [12] that a relatively large kinetic mixing term can be generated at the loop level when Higgs doublets from a **78** representation of E_6 are employed. However, restriction to Higgs doublets from **27** and $\overline{\mathbf{27}}$ representations yields much smaller effects [13].

Quantity	Group(s)	Value	Standard Model	pull
M_Z [GeV]	LEP	91.1867 ± 0.0021	91.1865 ± 0.0021	0.1
Γ_Z [GeV]	LEP	2.4939 ± 0.0024	2.4957 ± 0.0017	-0.8
$\Gamma(\mathrm{had})$ [GeV]	LEP	1.7423 ± 0.0023	1.7424 ± 0.0016	—
$\Gamma(\mathrm{inv})$ [MeV]	LEP	500.1 ± 1.9	501.6 ± 0.2	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.90 ± 0.10	83.98 ± 0.03	—
σ_{had} [nb]	LEP	41.491 ± 0.058	41.473 ± 0.015	0.3
R_e	LEP	20.783 ± 0.052	20.748 ± 0.019	0.7
R_μ	LEP	20.789 ± 0.034	20.749 ± 0.019	1.2
R_τ	LEP	20.764 ± 0.045	20.794 ± 0.019	-0.7
$A_{FB}(e)$	LEP	0.0153 ± 0.0025	0.0161 ± 0.0003	-0.3
$A_{FB}(\mu)$	LEP	0.0164 ± 0.0013		0.2
$A_{FB}(\tau)$	LEP	0.0183 ± 0.0017		1.3
R_b	LEP + SLD	0.21656 ± 0.00074	0.2158 ± 0.0002	1.0
R_c	LEP + SLD	0.1735 ± 0.0044	0.1723 ± 0.0001	0.3
$R_{s,d}/R_{(d+u+s)}$	OPAL	0.371 ± 0.023	0.3592 ± 0.0001	0.5
$A_{FB}(b)$	LEP	0.0990 ± 0.0021	0.1028 ± 0.0010	-1.8
$A_{FB}(c)$	LEP	0.0709 ± 0.0044	0.0734 ± 0.0008	-0.6
$A_{FB}(s)$	DELPHI + OPAL	0.101 ± 0.015	0.1029 ± 0.0010	-0.1
A_b	SLD	0.867 ± 0.035	0.9347 ± 0.0001	-1.9
A_c	SLD	0.647 ± 0.040	0.6676 ± 0.0006	-0.5
A_s	SLD	0.82 ± 0.12	0.9356 ± 0.0001	-1.0
A_{LR} (hadrons)	SLD	0.1510 ± 0.0025	0.1466 ± 0.0015	1.8
A_{LR} (leptons)	SLD	0.1504 ± 0.0072		0.5
A_μ	SLD	0.120 ± 0.019		-1.4
A_τ	SLD	0.142 ± 0.019		-0.2
$A_e(Q_{LR})$	SLD	0.162 ± 0.043		0.4
$A_\tau(\mathcal{P}_\tau)$	LEP	0.1431 ± 0.0045		-0.8
$A_e(\mathcal{P}_\tau)$	LEP	0.1479 ± 0.0051		0.3
$\bar{s}_\ell^2(Q_{FB})$	LEP	0.2321 ± 0.0010	0.2316 ± 0.0002	0.5

Table 1: Z pole precision observables from LEP [14,15] and the SLC [16–18]. Shown are the experimental results, the SM predictions, and the pulls. The SM errors are from the uncertainties in M_Z, $\ln M_H$, m_t, $\alpha(M_Z)$, and α_s. They have been treated as Gaussian and their correlations have been taken into account. The first set of measurements is from the Z line shape and leptonic forward-backward asymmetries, $A_{FB}(\ell) = 3/4 A_e A_\ell$. The hadronic, invisible, and leptonic decay widths are not independent of the total width, the hadronic peak cross section, and the $R_\ell = \Gamma(\mathrm{had})/\Gamma(\ell^+\ell^-)$, and are shown for illustration only. The second set represents the quark sector, where $R_q = \Gamma(q\bar{q})/\Gamma(\mathrm{had})$, and $A_q = 4/3 A_{LR}^{FB}(q)$ is a function of the effective weak mixing angle of quark q. The third set is a variety of polarization and forward-backward asymmetries sensitive to the leptonic weak mixing angle, where analogous definitions apply. For details see reference [19].

reviewed in reference [21]; constraints on leptophobic Z' bosons can be found in reference [22]; reference [23] are detailed reviews on extra neutral gauge bosons at colliders; and for related topics in neutral current physics see reference [24].

After the Z' properties have been specified, the new contributions to the precision observables can be computed using the formalism presented in references [10,25]. The new Z' boson is treated as a small perturbation to the SM relations. The most important effect is the modification of the M_Z–M_W–$\sin^2\theta_W$ interdependence via Z–Z' mixing. Z pole observables are affected by the modification of the Z couplings to fermions, which is another manifestation of the Z' admixture. This change in couplings is also relevant for the low energy observables from neutrino scattering and atomic parity violation (APV). For these there will be additional effects from Z' exchange, and Z–Z' (γ–Z') interference. Such effects can be neglected at the Z pole, but the interference terms are relevant for the cross section measurements at LEP 2. They give interesting constraints on $M_{Z'}$ [27] practically independent of the mixing parameter θ. These constraints are complementary to the direct search limits at Fermilab [28], where additional assumptions about possible exotic decay channels have to be specified.

Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	173.8 ± 5.0	171.4 ± 4.8	0.5
M_W [GeV]	Tevatron + UA2	80.404 ± 0.087	80.362 ± 0.023	0.5
M_W [GeV]	LEP	80.37 ± 0.09		0.1
R^-	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	0.2297 ± 0.0003	-0.9
R^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5827 ± 0.0005	-0.2
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3089 ± 0.0003	0.2
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$R^{\bar\nu}$	CDHS	$0.384 \pm 0.016 \pm 0.007$	0.3859 ± 0.0003	-0.1
$R^{\bar\nu}$	CHARM	$0.403 \pm 0.014 \pm 0.007$		1.1
$R^{\bar\nu}$	CDHS 1979	$0.365 \pm 0.015 \pm 0.007$	0.3813 ± 0.0003	-1.0
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0395 ± 0.0004	—
$g_V^{\nu e}$	all	-0.041 ± 0.015		-0.1
$g_A^{\nu e}$	CHARM II	-0.503 ± 0.017	-0.5063 ± 0.0002	—
$g_A^{\nu e}$	all	-0.507 ± 0.014		-0.1
$Q_W(\mathrm{Cs})$	Boulder	$-72.41 \pm 0.25 \pm 0.80$	-73.10 ± 0.04	0.8
$Q_W(\mathrm{Tl})$	Oxford + Seattle	$-114.8 \pm 1.2 \pm 3.4$	-116.7 ± 0.1	0.5

Table 2: Non-Z pole precision observables from Fermilab [29–33], CERN [14,34], and elsewhere. The second error after the experimental value, where given, is theoretical. The SM errors are from the inputs as in Table 1. The various quantities R are cross section ratios from ν-hadron scattering, where the CHARM [35] results have been adjusted to CDHS [36] conditions, and can be directly compared. The $g_{V,A}$ are effective four-Fermi couplings from ν-e scattering [37], and Q_W denotes the weak charge appearing in APV [38–41].

In our analysis we use the data as of ICHEP 98 at Vancouver. It includes the very precise Z pole measurements from LEP and the SLC, which are close to being finalized; the W

boson and top quark mass measurements, M_W and m_t, from the Tevatron run I, and further M_W determinations from LEP 2; results from deep inelastic ν-hadron scattering at CERN and Fermilab; ν-electron scattering; and atomic parity violation. The low energy measurements in neutrino scattering and APV are very important in the presence of new physics, and in particular, for the Z' bosons discussed here. They offer complementary information about Z' exchange and interference effects, which are suppressed at the Z pole. The Z pole observables are summarized in Table 1 and the non-Z pole observables in Table 2. For more details and further references we refer to our recent reviews [19].

The theoretical evaluation uses the FORTRAN package GAPP [42] dedicated to the Global Analysis of Particle Properties. GAPP attempts to gather all available theoretical and experimental information from precision measurements in particle physics. It treats all relevant SM inputs and new physics parameters as global fit parameters. For clarity and to minimize CPU costs it avoids numerical integrations throughout. GAPP is based on the $\overline{\text{MS}}$ renormalization scheme which demonstrably avoids large expansion coefficients.

		Z_χ	Z_ψ	Z_η	Z_{LR}	Z_{SM}	Z_{string}	SM
ρ_0 free		551(591)	151(162)	379(433)	570(609)	822(924)	582(618)	
	$\sin\theta$	-0.0006	$+0.0004$	-0.0010	$+0.0002$	-0.0015	-0.0002	
	$\sin\theta_{\text{min}}$	-0.0022	-0.0015	-0.0058	-0.0010	-0.0040	-0.0011	
	$\sin\theta_{\text{max}}$	$+0.0020$	$+0.0021$	$+0.0019$	$+0.0022$	$+0.0008$	$+0.0008$	
	ρ_0	0.9993	0.9974	0.9979	0.9995	0.9982	0.9996	0.9996
	ρ_0^{min}	0.9931	0.9923	0.9931	0.9917	0.9933	0.9986	0.9985
	ρ_0^{max}	1.0010	1.0017	1.0017	1.0013	1.0018	1.0011	1.0017
	χ^2_{min}	27.62	27.52	27.34	27.71	26.83	27.34	28.37
$\rho_0 = 1$		545(582)	146(155)	365(408)	564(602)	809(894)	578(612)	
	$\sin\theta$	-0.0003	$+0.0005$	-0.0026	$+0.0003$	-0.0019	-0.0002	
	$\sin\theta_{\text{min}}$	-0.0020	-0.0013	-0.0062	-0.0009	-0.0041	-0.0011	
	$\sin\theta_{\text{max}}$	$+0.0015$	$+0.0024$	$+0.0011$	$+0.0017$	$+0.0003$	$+0.0007$	
	χ^2_{min}	28.43	28.09	28.17	28.22	27.43	27.82	28.79

Table 3: Mass limits [in GeV] on extra Z' bosons and constraints on Z–Z' mixing for two classes of Higgs sectors. The upper part of the Table allows ρ_0 as a free fit parameter and corresponds to a completely arbitrary Higgs sector. The lower part assumes $\rho_0 = 1$, but is arbitrary otherwise. The first (second) numbers correspond to the 95 (90)% CL lower mass limits. Below this we show the central values and the 95% lower and upper limits on $\sin\theta$. Also shown are the central values and 95% limits for ρ_0 as a fit parameter. Finally we indicate the minimal χ^2 for each model. The last column is included for comparison with the standard case of only one Z boson. All results assume $M_Z \leq M_H \leq 1$ TeV.

In Tables 3 and 4 and Figure 1 we present our main results. We list lower limits on Z' boson masses for a variety of cases. Note, that the new physics, i.e., the Z's and the extra Higgs bosons, decouple and that the SM ($M_{Z'} = \infty$, $\theta = 0$) is well within the allowed regions of Figure 1. As a consequence a rigorous Bayesian integration over the $M_{Z'}$ probability distribution diverges[2]. Therefore, we approximate the 95 (90)% CL limits by requiring $\Delta\chi^2 = 3.84$ (2.71), which is motivated by a reference univariate normal distribution. Similarly, we define the 90% allowed region in the $(M_{Z'}, \sin\theta)$-plane by $\Delta\chi^2 < 4.61$, here referring to a bivariate Gaussian.

The first set of fits in Table 3 is for the most general case of completely arbitrary Higgs sector, while the second set is for $\rho_0 = 1$. Below the mass limits we show the best fit values and 95% lower and upper limits on the mixing parameter $\sin\theta$. Results on ρ_0 and the χ^2 minimum are also shown. For comparison we have included the $SU(2) \times U(1)$ case in the last column.

We note that the Z_{LR} boson is equivalent to the Z_χ boson with a non-vanishing kinetic mixing term,

$$-\frac{\sin\chi}{2} B^{\mu\nu} Z'_{\mu\nu}.$$

It can be absorbed by a shift of the gauge couplings proportional to the third component of the right-handed isospin generator and a rescaling of the coupling ratio λ. In models with given Higgs structure the parameter $C \to C - \sqrt{\frac{3}{5\lambda_g}} \sin\chi$ is shifted, as well, while ρ_0 is unaffected. The limits on masses and mixings of the Z_χ and Z_{LR} bosons, shown in Tables 3 and 4 (with $\lambda = 1$), are indeed quite similar.

Our mass limits on extra Z' bosons are somewhat stronger than those from a recent analysis [43] of Z's in supersymmetric E_6 models [44]. The differences are due to a slightly different and more recent data set in our analysis, different implementations of radiative corrections, different statistical methods[3], and our alternative evaluation of the photonic vacuum polarization effects [45] with advantages for global fits. Moreover, reference [43] assumes the SUSY inspired range for the Higgs mass, $M_H < 150$ GeV [46].

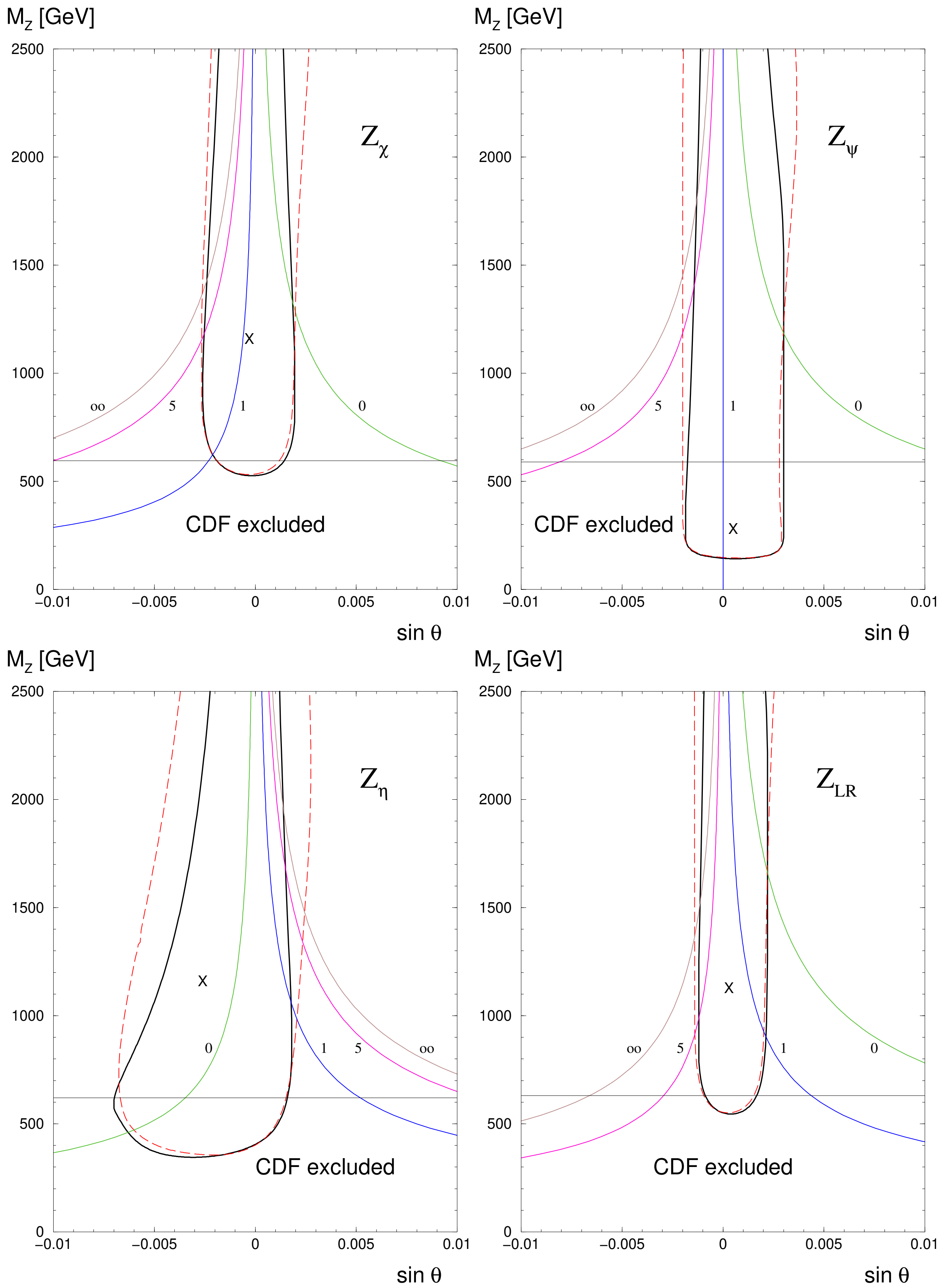
	Z_χ	Z_ψ	Z_η	Z_{LR}
$\sigma = 0$	1368(1528)	1181(1275)	470(498)	1673(1799)
$\sigma = 1$	643(688)	146(156)	1075(1235)	925(987)
$\sigma = 5$	1210(1314)	1393(1581)	1701(1948)	980(1076)
$\sigma = \infty$	1464(1601)	1810(2039)	1985(2277)	1537(1711)

Table 4: 95 (90)% CL lower mass limits on specific Z' bosons as they appear in models of unification. Assumed are minimal Higgs structures and $\rho_0 = 1$. Note that σ is defined differently for the Z_ψ and Z_η models, and the Z_χ and Z_{LR} models, respectively, as explained in the text. In particular, the versions of the Z_χ and Z_{LR} models most often considered correspond to $\sigma = 0$.

Table 4 lists results for specific Higgs charge assignments as they occur in "minimal" models: For the Z_ψ and Z_η bosons, we assume an $SU(2)$ Higgs singlet with a large VEV s to ensure $M_{Z'} \gg M_Z$, and in addition a pair of Higgs doublets with quantum numbers as in the $\mathbf{5} + \bar{\mathbf{5}}$ of $SU(5)$ appearing in the $\mathbf{27}$ of E_6. They receive VEVs v and $\bar{v}$, where the combination

[2] The Bayesian confidence integral in Eq. (4.13) of reference [43] is not well-defined unless a non-trivial Jacobian is implicitly included.

[3] The difference goes beyond the more common choices of Bayesian versus frequentist kind of approaches. The authors of reference [43] choose to allow three fit parameters, of which only two are independent. This is a problematic procedure when parameter estimation is desired and renders confidence intervals ambiguous.


M_Z [GeV]
2500
2000
1500
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500
0
−0.01
−0.005
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sin θ
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5
1
0
x
CDF excluded
Z_ψ
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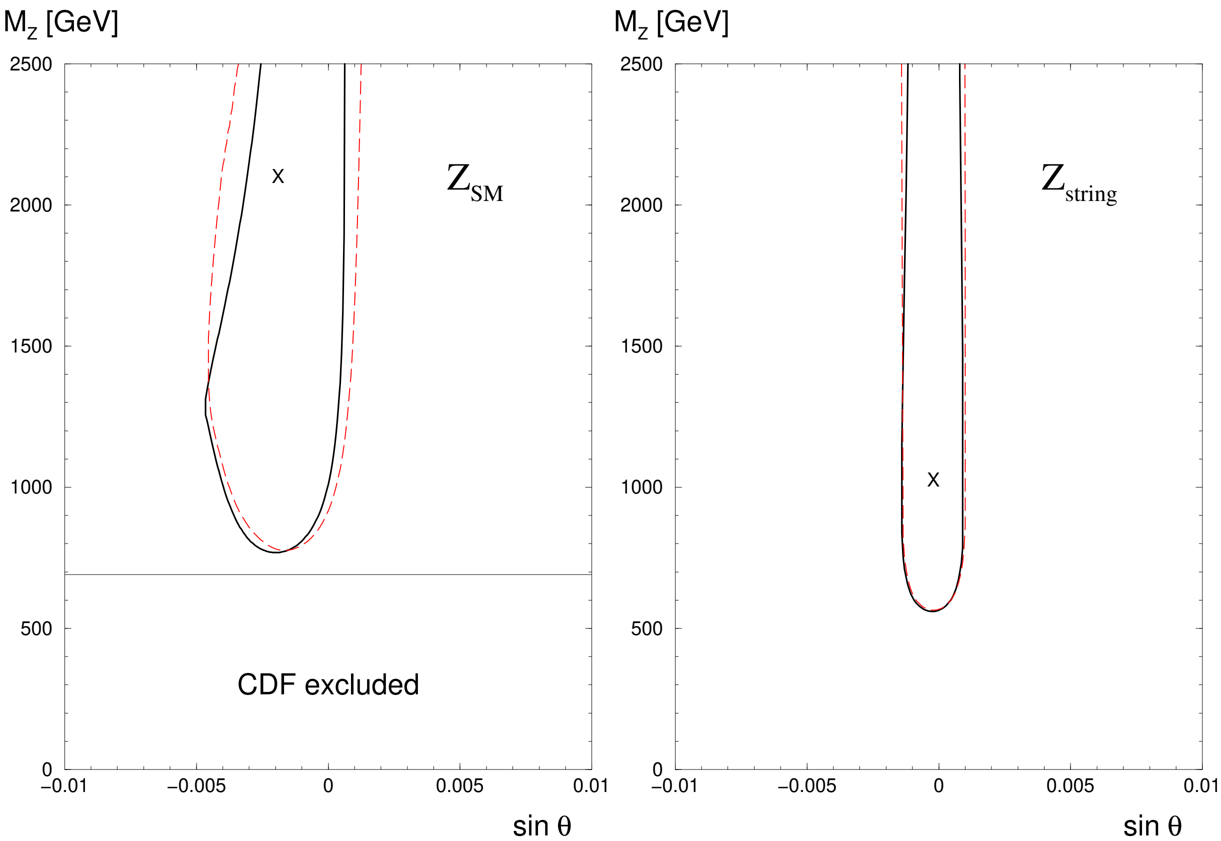

Figure 1: 90% CL contours for various Z' models. The solid contour lines use the constraint $\rho_0 = 1$ (the cross denotes the best fit location for the $\rho_0 = 1$ case), while the long-dashed lines are for arbitrary Higgs sectors. Also shown are the additional constraints in minimal Higgs scenarios for several VEV ratios as discussed in the text. The lower direct production limits from CDF [28] are also shown. They assume that all exotic decay channels are closed, and have to be relaxed by about 100 to 150 GeV when all exotic decays (including channels involving superparticles) are kinematically allowed [28].

$v^2 + \bar{v}^2$ is fixed by the measured value of the Fermi constant. Thus, these models are described by an extra parameter $\sigma = |\bar{v}/v|^2$ which is analogous to $\tan^2\beta$ in supersymmetric extensions of the standard model.

The Z_χ model does not depend on the ratio $|\bar{v}/v|$ so that $C = 2/\sqrt{10}$ is predicted. If we add another Higgs doublet with quantum numbers like the SM leptons and VEV x, we have the extra parameter $\sigma = |x|^2/(v^2 + \bar{v}^2)$, and then $C \in 1/\sqrt{10}\,[-3, 2]$. However, in those models of SUSY in which this Higgs doublet is identified with the superpartner of a SM lepton doublet, one has to require $x = \sigma = 0$ to avoid severe problems with charged-current universality.

The Higgs content of the Z_χ model can be lifted to an appropriate Higgs structure for a Z_{LR} model (LR 1), transforming under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ as $(\mathbf{2}, \bar{\mathbf{2}}, 0) + (\mathbf{2}, \mathbf{1}, 1/2) + (\mathbf{1}, \mathbf{2}, 1/2)$. The same definitions and remarks apply, except that here $C \in \sqrt{3/5}\,[-1/\alpha, \alpha]$. Another possibility (LR 2) is a Higgs sector transforming as $(\mathbf{2}, \bar{\mathbf{2}}, 0) + (\mathbf{3}, \mathbf{1}, 1) + (\mathbf{1}, \mathbf{3}, 1)$ which results in $C = \sqrt{3/5}\,\alpha$. There are no $SU(2)$ triplets in a **27** of E_6, but one might find them in string models without an intermediate GUT group, if they are realized at higher Kac-Moody levels ($k > 1$). In the context of SUSY the Higgs fields carrying $B - L$ charge have to be supplemented by extra fields with opposite charge to cancel anomalies and (in the case of LR 1) to generate fermion masses.

There is no analog of a minimal Higgs sector for the sequential Z_{SM}. In the $Z_{\rm string}$ model $\rho_0 = 1$ is predicted, and even the Z' mass and the Z–Z' mixing can be calculated in principle. Universal high scale boundary conditions yield too large a value for θ and are excluded [13]. Non-universal boundary conditions on the soft SUSY breaking terms can yield acceptable mixing. In any case, the concrete realization of the soft terms depends strongly on the SUSY breaking and mediation mechanisms. We parametrize our lack of understanding by allowing an arbitrary Higgs sector (except for $\rho_0 = 1$).

In conclusion, indirect constraints from high precision observables on and off the Z pole continue to play an important role for searches for new physics, and in particular for extra gauge bosons. The obtained mass limits are competitive with current direct searches at colliders with the highest attainable energies. Moreover, no assumptions about the absence of exotic decay channels are necessary[4]. The indirect constraints are even much stronger in specific models with known Higgs structure, where lower limits are typically in the 1 to 2 TeV range. Finally, Z–Z' mixing effects are severely constrained to the sub per cent level in all cases.

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