Phenomenological Mass Limits on Extra Z of E_6 Superstrings

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

N. G. Deshpande
Institute of Theoretical Science, University of Oregon, Eugene, Oregon 97403

and

K. Whisnant
Physics Department, Florida State University, Tallahassee, Florida 32306
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We fit low-energy and $p\bar{p}$ collider data with a model based on a SU(2) ⊗ U(1) ⊗ U(1) electroweak group, where the additional U(1) arises from E_6 as required by symmetry breaking in some superstring models. We find that the extra Z must have a mass greater than 143 GeV if its decays to exotic fermions are kinematically suppressed. The production and decays of this boson are discussed.

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Recent work on superstring theories has led to the interesting possibility that the $E_8 \otimes E_8'$ heterotic string theory in ten dimensions yields, after compactification, a four-dimensional E_6 gauge group coupled to $N=1$ supergravity.[1-4] Furthermore, the breaking at large scales is done by expectation values of order parameters which are in the adjoint representation. The low-energy gauge group that emerges must be larger than the standard SU(3) ⊗ SU(2) ⊗ U(1), and should contain at least one extra U(1) gauge factor. If the low-energy model contains only one additional U(1), the couplings of the extra Z boson to quarks and leptons are uniquely determined,[5] in the absence of Z-Z' mixing. We study the phenomenological implications of this extra Z boson and deduce limits on its mass from a fit to low-energy neutral-current data and the measured W and Z masses. We believe that this is the most comprehensive study fitting all the available data simultaneously.[6] We also obtain constraints on the mass of the extra Z from the nonobservation of high-mass e^+e^- pairs in $p\bar{p}$ collider experiments.

We can write the neutral-current part of the Lagrangean as

$$\mathscr{L}_{\rm NC} = eA_\mu J^\mu_{\rm em} + g_Z Z_\mu J^\mu_Z + g' Z'_\mu J^\mu_{Z'}, \qquad (1)$$

where $J^\mu_{\rm em}$ and J^μ_Z $(=J^\mu_3 - x_{\rm W} Q_\mu)$ are the usual electromagnetic and Z-boson currents and $J^\mu_{Z'} = 2\bar{f}_L \gamma^\mu \tilde{Q} f_L + 2\bar{f}_R \gamma^\mu \tilde{Q} f_R$. The fermion fields belong to a **27** representation of E_6, and their decomposition into SO(10), SU(5), and SU(3) multiplets as well as the fermion quantum numbers Q (charge), I_{3L} (weak isospin), and $\tilde{Q}$ [extra U(1) charge] are given in Table I. The coupling constant g' with our normalization of $\tilde{Q}$ charges takes the value

$$g' = e/(1-x_{\rm W})^{1/2}, \qquad (2)$$

and g_Z is given as usual by

$$g_Z = e/x_{\rm W}^{1/2}(1-x_{\rm W})^{1/2}, \qquad (3)$$

TABLE I. Decomposition of the **27** representation and fermion quantum numbers.

SO(10)	SU(5)	Left-handed state	SU(3)	Q	I_{3L}	$\tilde{Q}$
16	**5***	d^c	**3***	$\frac{1}{3}$	0	$-\frac{1}{6}$
		e^-	**1**	-1	$-\frac{1}{2}$	$-\frac{1}{6}$
		ν_e	**1**	0	$\frac{1}{2}$	$-\frac{1}{6}$
	10	e^{-c}	**1**	1	0	$\frac{1}{3}$
		d	**3**	$-\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{3}$
		u	**3**	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$
		u^c	**3***	$-\frac{2}{3}$	0	$\frac{1}{3}$
	1	N^c	**1**	0	0	$\frac{5}{6}$
10	**5***	h^c	**3***	$\frac{1}{3}$	0	$-\frac{1}{6}$
		E^-	**1**	-1	$-\frac{1}{2}$	$-\frac{1}{6}$
		ν_E	**1**	0	$\frac{1}{2}$	$-\frac{1}{6}$
	5	h	**3**	$-\frac{1}{3}$	0	$-\frac{2}{3}$
		E^{-c}	**1**	1	$\frac{1}{2}$	$-\frac{2}{3}$
		N_E^c	**1**	0	$-\frac{1}{2}$	$-\frac{2}{3}$
1	**1**	n	**1**	0	0	$\frac{5}{6}$

where $x_W = \sin^2\theta_W$. The assumption in (2) is that the evolution of the two U(1) factors from the grand-unification scale to M_W is the same up to normalization constants. This assumes that the masses of all fermions in the **27** representation (and their superpartners) are approximately degenerate. The fields Z_μ and Z'_μ are, in general, not mass eigenstates. In superstring theories the Higgs bosons that are responsible for the breaking of the low-energy group are also in the **27** representation, which has only $SU(2)_L$ doublets and singlet fields. If v_1 and v_2 are the vacuum expectation values of the two doublets required in supersymmetric theories and χ that of the singlet, the mass matrix is

$$M^2 = M_Z^2 \begin{pmatrix} 1 & \sqrt{x_W}\dfrac{(4v_1^2 - v_2^2)}{3(v_1^2+v_2^2)} \\ \sqrt{x_W}\dfrac{(4v_1^2 - v_2^2)}{3(v_1^2+v_2^2)} & x_W\dfrac{16v_1^2+v_2^2+25\chi^2}{9(v_1^2+v_2^2)} \end{pmatrix}, \quad (4)$$

where $M_Z^2 = M_W^2/(1-x_W)$. The low-energy theory is then described by the effective Lagrangean (of the same form as in the work of Barger, Ma, and Whisnant[7,8])

$$\mathscr{L}_{\rm eff}^{\rm NC} = (4G_F/\sqrt{2})[(\rho_1 J_Z)^2 + (\rho_2 J_Z + \eta J_{Z'})^2], \quad (5)$$

where ρ_i and η are dependent on the mass matrix and the coupling constants. For our case, with use of Eqs. (2)–(4),

$$\rho_1 = 1, \quad (6a)$$

$$\frac{\rho_2}{\eta} = \frac{v_2^2 - 4v_1^2}{3(v_1^2+v_2^2)}, \quad (6b)$$

$$\frac{\rho_2^2+1}{\eta^2} = \frac{16v_1^2+v_2^2+25\chi^2}{9(v_1^2+v_2^2)}. \quad (6c)$$

Determination of x_W, ρ_2, and η from experiment then yields limits on M_{Z_1} and M_{Z_2}, which are the eigenvalues of the mass matrix. The low-energy parameters in neutrino-quark and neutrino-electron scattering and the parameters involved in atomic parity nonconservation and asymmetry in electron-deuteron scattering for our Lagrangean are listed in Table II, where we use the same notation as Kim *et al.*[9] For $e^+e^- \to \mu^+\mu^-$ we use the exact form for the cross section with Z-resonance contributions and the Z-Z' mixing angle given by $\tan 2\theta = -2\rho_2\eta/(1+\rho_2^2-\rho_2\eta)$.

TABLE II. Parameters of the effective Lagrangean.

$\alpha = 1 + \rho_2^2 - \frac{1}{3}\rho_2\eta, \quad \beta = \rho_2\eta - \frac{1}{3}\eta^2$
$\gamma = 1 + \rho_2^2 + \frac{4}{3}\rho_2\eta, \quad \delta = \rho_2\eta + \frac{4}{3}\eta^2$
$\epsilon_L^u = (\frac{1}{2} - \frac{2}{3}x_W)\alpha + \frac{1}{3}\beta$
$\epsilon_R^u = (-\frac{2}{3}x_W)\alpha - \frac{1}{3}\beta$
$\epsilon_L^d = (-\frac{1}{2} + \frac{1}{3}x_W)\alpha + \frac{1}{3}\beta$
$\epsilon_R^d = (\frac{1}{3}x_W)\alpha + \frac{1}{6}\beta$
$g_V^e = (-\frac{1}{2} + 2x_W)\alpha - \frac{1}{2}\beta$
$g_A^e = -\frac{1}{2}\alpha + \frac{1}{6}\beta$
$C_1^u = (-\frac{1}{2} + \frac{4}{3}x_W)\alpha$
$C_1^d = (\frac{1}{2} - \frac{2}{3}x_W)\alpha - \frac{1}{2}\beta$
$C_2^u = (-\frac{1}{2} + 2x_W)\gamma - \frac{1}{2}\delta$
$C_2^d = (\frac{1}{2} - 2x_W)\alpha + \frac{1}{2}\beta$

We fit simultaneously all the low-energy data to determine x_W, ρ_2, and η. We impose the restriction $-\frac{4}{3} < \rho_2/\eta < \frac{1}{3}$ coming from Eq. (6b). There are 53 data points used in the analysis. Data from the following categories are taken from Ref. 6: νN (eighteen data points), νe (seven data points), and A_{ed} (eleven data points). We have also included low-energy data from atomic parity nonconservation (one data point from Bouchiat *et al.*[10]) and $e^+e^- \to \mu^+\mu^-$ (twelve data points from the compilation of Barbiellini and Santoni[11]). The measured W mass gives a constraint on x_W through the radiatively corrected[12] relation $M_W = (38.65\ {\rm GeV})/\sqrt{x_W}$. The measured Z mass gives a constraint on the lowest mass eigenstate, M_{Z_1}. The Z mass eigenstates are related to the Lagrangean parameters by

$$M_{Z_{1,2}}^2 = \tfrac{1}{2}M_Z^2\left(1 + x_W(1+\rho_2^2)/\eta^2 \pm \{[1 - x_W(1+\rho_2^2)/\eta^2]^2 + 4x_W\rho_2^2/\eta^4\}^{1/2}\right). \quad (7)$$

The following W and Z mass-data values[13] are used in the fit:

$$M_W = 83.1 \pm 3.2\ {\rm GeV}, \quad M_{Z_1} = 93.0 \pm 3.4\ {\rm GeV};$$

$$M_W = 81.2 \pm 1.7\ {\rm GeV}, \quad M_{Z_1} = 92.5 \pm 2.0\ {\rm GeV}$$

(UA1 Collaboration and UA2 Collaboration values, respectively).

The analysis gives the following best-fit values ($\chi^2/{\rm d.o.f.} = 31/50$):

$$x_W = 0.222^{+0.017}_{-0.013}, \quad \rho_2 = 0.08^{+0.07}_{-0.24}, \quad \eta = 0.26^{+0.22}_{-0.26}, \quad (8)$$

where an average radiative correction to the low-energy x_W of -0.013 is included. The one- and two-standard-deviation limits on M_{Z_2} are

$$M_{Z_2} > 1.13 M_Z = 105 \text{ GeV} \quad (1\sigma),$$
$$> 1.02 M_Z = 95 \text{ GeV} \quad (2\sigma). \tag{9}$$

The mixing angle between Z and Z' is $\theta = -0.02 \pm 0.06$ rad.

The fact that e^+e^- pairs from the Z_2 have not yet been detected at the CERN $p\bar{p}$ collider also puts a limit on the Z_2 mass. An extra Z with standard-model couplings is excluded[13] below 200 GeV. The application of this constraint depends on both the Z_2/Z_1 production and the branching fraction ratios. Adjusted for the different couplings of the Z_2 to the u and d quarks, the Z_2/Z_1 cross-section ratio in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV is approximately

$$\sigma_{Z_2}/\sigma_{Z_1} = 0.28 \exp[-0.033(M_2 - M_1)]. \tag{10}$$

The partial widths for $Z_2 \to f\bar{f}$ decays are

$$\Gamma(Z_2 \to f\bar{f}) = (x_W M_2/M_1)(1.412 \text{ GeV}) c_f (1 - 4m_f^2/M_2^2)^{1/2} \{g_V^2 (1 + 2m_f^4/M_2^2) + g_A^2 (1 - 4m_f^2/M_2^2)\}, \tag{11}$$

where $c_f = 1$ for leptons and $c_f = 3.12$ for quarks; the g_V and g_A couplings can be deduced from the $J^\mu_{Z'} = \bar{f}\gamma^\mu (g_V - g_A \gamma_5) f$ and Table I. The major difference from the corresponding expression for the Z_1 partial width (aside from different g_V and g_A) is the factor $x_W M_2/M_1$. Typical partial widths are given in Table III, for the case in which decays to the exotic fermions are not phase-space suppressed (i.e., $m_f < 30$ GeV); supersymmetric particles are assumed to be heavy. Results for W partial widths are also given in Table III.

The ratio of the e^+e^- branching fractions is

$$\frac{B(Z_2 \to e^+e^-)}{B(Z_1 \to e^+e^-)} \simeq 0.45 \ (1.3), \tag{12}$$

for no (complete) phase-space suppression of Z_1 and Z_2 decays into three generations of exotic fermions.

Figure 1 shows the $Z_2 \to e^+e^-$ production rate relative to $Z_1 \to e^+e^-$ for the above two extreme cases. Also shown is the CERN limit[13] which requires at 90% confidence level

$$M_{Z_2} > 107 \text{ GeV} \ (143 \text{ GeV}) \tag{13}$$

for unsuppressed (completely suppressed) decays to exotic fermions.

The Z_2 could also be produced in e^+e^- collisions. The Z_2 to Z_1 ratio of integrated total cross sections is

$$\frac{\int d\sqrt{s}\ \sigma_{Z_2}}{\int d\sqrt{s}\ \sigma_{Z_1}} = \frac{M_1}{M_2} x_W \frac{(g_V^2 + g_A^2)_2}{(g_V^2 + g_A^2)_1} \simeq 0.24 \frac{M_1}{M_2}. \tag{14}$$

In $p\bar{p}$ collisions the quantity

$$R = \frac{\sigma^{W^+ + W^-} B(W \to e\nu)}{\sigma^Z B(Z \to e^+e^-)} \tag{15}$$

has been measured. The combined UA1-UA2 measurement[13] is $1/R = 0.125 \pm 0.023$. The ratio of cross sections and partial widths can be calculated.[14] The resulting constraint on the ratio of total widths is

$$\Gamma^W/\Gamma^Z = (8.9 \pm 0.9)/R = 1.11 \pm 0.23. \tag{16}$$

If there are three generations of neutral exotic leptons (ν_E, N_E, etc.) with masses <30 GeV, but all charged exotic fermions are heavy (>50 GeV), then the

TABLE III. Partial widths for Z and W decays to exotic fermions, under the assumption of no phase-space suppression; note that the Z_2 partial widths scale with M_2/M_1. Total widths assume $m_t = 40$ GeV and three generations of exotics with no (complete) phase-space suppression.

Channel	Γ_{Z_1} (GeV)	$(M_1/M_2)\Gamma_{Z_2}$ (GeV)	Channel	Γ_W (GeV)
$h\bar{h}$	0.02	0.23	$\bar{\nu}_E E^-$	0.24
$E^- E^+$	0.11	0.07	$\bar{N}_E E^-$	0.24
$\nu_E \bar{\nu}_E$	0.18	0.004		
$N_E \bar{N}_E$	0.18	0.07		
$N\bar{N}$	0	0.11		
$n\bar{n}$	0	0.11		
Total width	4.22 (2.75)	2.27 (0.50)		4.16 (2.71)

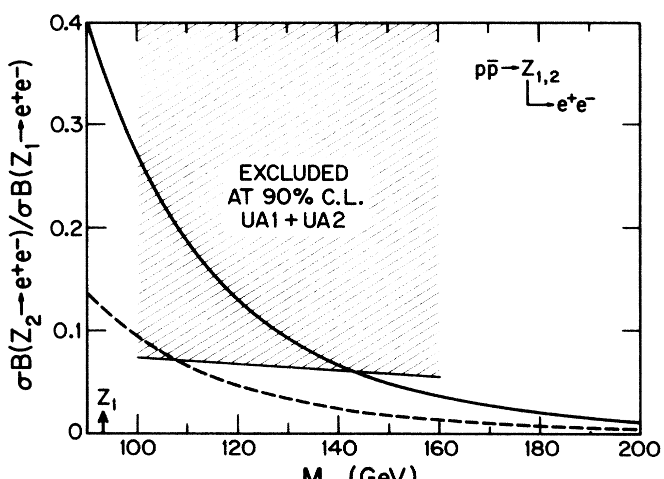

FIG. 1. The $Z_2 \to e^+e^-$ to $Z_1 \to e^+e^-$ production rates in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV vs the Z_2 mass. The solid (dashed) curve assumes complete (no) phase-space suppression of Z_1 and Z_2 decays into three generations of E_6 exotic fermions. The shaded region is excluded by the present UA1 and UA2 searches (see Ref. 13).

predicted width ratio would be $\Gamma^W/\Gamma^Z = 0.71$, which is almost 2σ below the value in Eq. (16). Alternatively, if all exotic fermions in each generation are roughly degenerate in mass and contribute to Z decays but not to W decays as a result of kinematic suppression, then $\Gamma^W/\Gamma^Z \simeq 0.80$ is predicted. On the other hand, if all exotics are heavy, then the standard-model value $\Gamma^W/\Gamma^Z = 0.98$ is realized. When all exotics are degenerate and <30 GeV, then the result is again close to the standard-model value.

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