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Constraints on additional Z' gauge bosons from a precise measurement of the Z mass

M. C. Gonzalez-Garcia and J. W. F. Valle
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
and Departament de Física Teòrica, Universitat de València, 46100 Burjassot, València, Spain
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We analyze the constraints on the mass and mixing of a superstring-inspired E_6 Z' neutral gauge boson that follow from the recent precise Z mass measurements and show that they depend very sensitively on the assumed value of the W mass and also, to a lesser extent, on the top-quark mass.

Despite the impressive success of the standard SU(3)$\otimes$SU(2)$\otimes$U(1) model in describing the interactions of quarks and leptons, there are good reasons for believing that it is not the complete theory and there are many motivations to seek for extensions. Many of these extensions predict the existence of additional neutral gauge bosons at low energy. Here we note that the recent measurements of the Z-boson mass by the Mark II and Collider Detector at Fermilab (CDF) Collaborations[1,2] offer a valuable test on the gauge structure of the electroweak interaction.

The standard model predicts a definite correlation between the gauge-boson masses and the electroweak mixing angle. Mixing with an extra Z' gauge boson affects this correlation and on this basis we can constrain these possibilities.

Here we focus on the simplest case where the gauge sector contains an additional U(1) symmetry at low energies. Of special interest are the models where the new U(1) hypercharge quantum numbers are derived from an underlying E_6 symmetry at a sufficiently high energy scale. This typically occurs in superstring models based on Calabi-Yau compactification.[3] Another motivation for choosing this class of models is that they predict to lowest-order approximation that the ρ parameter measuring the ratio between the strength of charged to neutral currents is 1, as in the standard model. Here we analyze the impact of the new Z mass determination on the possible existence of such an additional neutral gauge boson.

Being a rank-six group, E_6 contains, in general, two neutral gauge bosons beyond those of the standard model. These couple to two new hypercharges which may be taken to be those corresponding to the U(1) symmetries in E_6/SO(10) or SO(10)/SU(5), denoted ψ and χ, respectively. These hypercharges are given in Table I.

We will assume that only one combination of the χ and ψ symmetries survives at low energies. This still leaves a continuum of possible models with an extra U(1) specified by the hypercharge[4]

$$Y(\beta)=\cos\beta\, Y_\chi+\sin\beta\, Y_\psi\,. \tag{1}$$

Which particular combination is realized at low energies depends on the assumed pattern of symmetry breaking starting from the original E_6. If E_6 is broken all the way in one step via a non-Abelian flux factor then $\cos\beta=\sqrt{3/8}$ and $\sin\beta=-\sqrt{5/8}$ leading to the η model considered in Ref. 5.

If, on the other hand, the assumed manifold discrete symmetry is Abelian, there are several rank-six choices for the resulting intermediate gauge symmetry G.[6,7] Here we focus on the simplest of these possibilities where $G=\mathrm{SU(3)}\otimes\mathrm{SU(2)}_L\otimes\mathrm{U(1)}^3$. One of the U(1)'s in G [the one in E_6/SO(10)] can then break due to a large vacuum expectation value $\langle n\rangle$ along a suitably D-flat direction[8] leading to the χ model described in Ref. 9. It is defined by the $\mathrm{U(1)}_\chi$ hypercharge of Table I, i.e., $\cos\beta=1$ and $\sin\beta=0$. In this model it is in principle possible to suppress proton decay and flavor-changing neutral currents by the large intermediate symmetry scale $\langle n\rangle$.

Arbitrary values of the angle β are possible outcomes of a primordial E_6 symmetry but are not realized in the context of the restricted class of E_6 models that arise in string theories.[10]

We will now study the constraints on the mass and mixing angle of the Z_χ and Z_η that arise from the new experimental Z mass measurements. For this we need to specify the symmetry breaking. In the present models this should occur around the TeV energy region. The electrically neutral scalars responsible for symmetry breaking are restricted, since (a) there are only doublets and singlets un-

TABLE I. Quantum numbers of the particles in the **27** of E_6 with respect to the gauge group $\mathrm{SU(3)}\otimes\mathrm{SU(2)}_L\otimes\mathrm{U(1)}_Y\otimes\mathrm{U(1)}_\chi\otimes\mathrm{U(1)}_\psi$. For proper normalization the hypercharges Y (standard), Y_χ, and Y_ψ should be scaled by factors $\sqrt{3/5}$, $1/\sqrt{40}$, and $1/\sqrt{24}$, respectively.

	$\mathrm{SU(3)}\otimes\mathrm{SU(2)}\otimes\mathrm{U(1)}_Y\otimes\mathrm{U(1)}_\chi\otimes\mathrm{U(1)}_\psi$
Q	$(3,2,1/6,-1,1)$
u^c	$(\bar{3},1,-2/3,-1,1)$
e^c	$(1,1,1,-1,1)$
d^c	$(\bar{3},1,1/3,3,1)$
l	$(1,2,-1/2,3,1)$
H_d	$(1,2,-1/2,-2,-2)$
g^c	$(\bar{3},1,1/3,-2,-2)$
H_u	$(1,2,1/2,2,-2)$
g	$(3,1,-1/3,2,-2)$
ν^c	$(1,1,0,-5,1)$
n	$(1,1,0,0,4)$

der $SU(2)_L$ and (b) they lie in the **27** of E_6. The singlets have the quantum numbers of n and ν^c, given in Table I, and may acquire relatively large vacuum expectation values (VEV's) (in the TeV region), i.e., $\langle\nu\rangle^c\neq 0$ (Ref. 11) and/or $\langle n\rangle\neq 0$, in order to break the new U(1). The doublets have the quantum numbers of H_u, H_d, and l, and their VEV's are responsible for electroweak breaking. It is straightforward then to work out from Table I the neutral-vector-boson mass matrix in these models. In order to properly identify the massless photon field and the correct electric charge we must require $\tan\theta_W = g'/g$, where $g' = \sqrt{3/5}\, g_1$ gives the relation between the standard hypercharge gauge coupling constant at low energy and the constant g_1 corresponding to the properly normalized E_6 generator. Here g is the $SU(2)_L$ gauge coupling. The resulting 2×2 mass matrix has the form

$$\begin{bmatrix} m_{Z^0}^2 & \mu^2 \\ \mu^2 & M^2 \end{bmatrix}, \tag{2}$$

where $m_{Z^0}^2$ would be the Z mass in the absence of mixing with the extra Z',

$$m_{Z^0}^2 = \frac{m_W^2}{\cos^2\theta_W} \tag{3}$$

and

$$\cos^2\theta_W = 1 - A^2/m_W^2 , \tag{4}$$

where the parameter

$$A^2 = \frac{\pi\alpha}{\sqrt{2}G_F} \simeq (37.281\,\mathrm{GeV})^2 \tag{5}$$

is well determined from Thomson scattering (α) and μ decay (G_F). The mixing parameter μ^2 is given by

$$\mu^2 = m_{Z^0}^2 \sin\theta_W \left[\frac{\sqrt{10}}{3}(1-2\xi)\sin\beta - \sqrt{2/3}\cos\beta \right] \tag{6}$$

and depends on the chosen model through the angle β and also through the dynamical parameter ξ:[14]

$$\xi = \frac{\langle H_d\rangle^2}{\langle H_u\rangle^2 + \langle H_d\rangle^2} . \tag{7}$$

Similarly M^2 is another model-dependent parameter related to the symmetry-breaking scale of the extra U(1).

So far we have neglected radiative corrections. These are of two types. The dominant source of corrections is the running of α from $\alpha(q^2=0)$ up its short-distance value relevant to us. Another potentially large contribution may arise, e.g., from a heavy top quark. The net effect of these corrections is to rescale the parameter A^2 in Eq. (5), so that Eq. (4) should be replaced by

$$\sin^2\theta_W = \frac{A^2}{m_W^2(1-\Delta r)} . \tag{8}$$

In the figures we display the constraints on the Z' mass and mixing obtained from Eq. (2) corresponding to a representative top mass of 90 GeV and a Higgs-boson mass of 100 GeV, using the value $\Delta r = 0.0606$ taken from Ref. 15. For the mass of the Z we use the central value and error given by the Mark II Collaboration,[1] i.e., $m_Z = 91.17 \pm 0.18$ GeV.

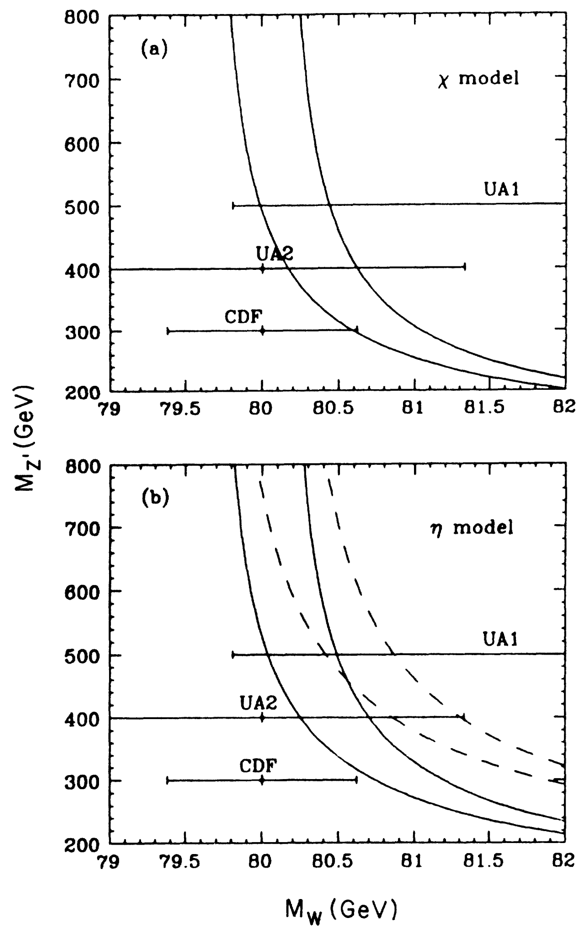

FIG. 1. The allowed region of the Z' mass plotted as a function of the W mass for a top-quark mass of 90 GeV. The upper curve corresponds to $m_Z = 91.35$ GeV while the lower one is for $m_Z = 90.99$ GeV. (a) corresponds to the χ model while (b) is for the η model. The dashed curves correspond to $\xi = 0.04$ while the solid curves are for $\xi = 0.27$. We also show the various existing W mass measurements with their errors.

In Fig. 1 we plot the dependence of the mass of Z' on the mass of W in both the χ and η models given the new Z mass measurements. In both models the bounds on the Z' mass depend on the assumed value of the W mass.

For *large W* masses (certainly consistent with UA1 data) there is a narrow band of relatively low Z' masses which is allowed by the gauge-boson mass data and in this case a nonzero mixing should exist, as seen from Fig. 2. If however, as is already indicated by preliminary CDF results,[2] the W mass turns out to be on the *low* side, then one expects to be very close to the standard model. This is exactly what the figures show: we obtain a stringent lower limit on the Z' mass and a stringent upper limit for the mixing angle as can be seen from Fig. 2. To obtain the constraints on the Z' parameters in the η model we need to assume a value for the dynamical ξ parameter, and we have chosen a reasonable range, recommended in Ref. 10 with ξ varying between $\xi = 0.04$ and $\xi = 0.27$. Uncertainties in the detailed dynamics in these models could allow

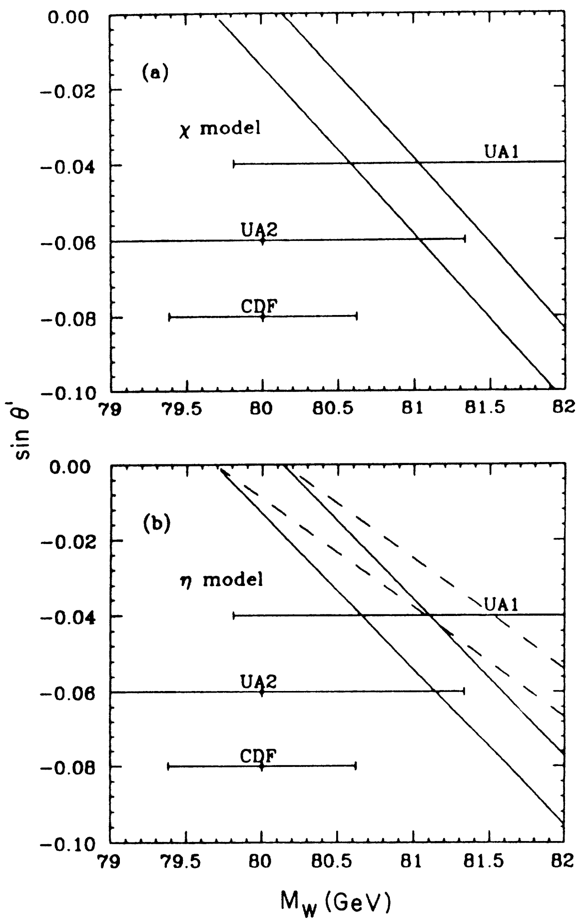

FIG. 2. Same as in Fig. 1, for the Z' mixing angle.

for a larger value of $\xi \simeq 0.5$ that would somewhat weaken our constraints for the η model.

The recent measurement repeated by CDF, $m_W = 80.0 \pm 0.6$ GeV would imply a 95% confidence lower limit on the Z' mass of about 270 GeV in either the χ or η case. For a heavier top quark and a fixed value of the W mass the constraints on the extra Z' become *more stringent.* However, they depend only to a very mild degree on the unknown Higgs-boson mass.

The limits obtained above should be complemented with others similar to those of Refs. 16 and 17 obtained by combining W,Z mass data with low-energy neutral-current data. We expect such combined constraints to leave very little room for new superstring E_6 gauge bosons. This is largely due to the restricted set of Higgs scalars present in string models. Since the sign of the Z-Z' mixing angle is determined by that of μ^2 it crucially depends on dynamics, e.g., in the case of the η model, on the allowed values of the parameter ξ. The mixing angle could only become positive (in our sign conventions) in situations where R parity is substantially broken[12] through a nonzero expectation value for the left-handed sneutrino, i.e., $\langle \tilde{l} \rangle^0 \neq 0$ but it is not clear to what extent this would be phenomenologically permissible. As a result in both the χ and η models [with no sneutrino VEV and no renormalization of the U(1) gauge couplings] the allowed mixing angle values *are precisely those for which the neutral-current constraints are the strongest.* We therefore expect that superstring E_6 gauge bosons are excluded unless the Z-Z' mixing is extremely small and the Z' mass extremely large. In fact, if one simply compares our results with those given in Refs. 16 and 17 taking the correct sign into account one obtains an improvement by a factor of 2–3 (Ref. 18) relative to what the bounds would be in a nonsuperstring E_6 model. This agrees with the results of Ref. 17 but disagrees with Ref. 19. For a careful quantitative determination of the combined constraints on the Z' mass and mixing, it would be desirable to have a detailed study of the neutral currents along the lines of Refs. 16 and 17 but incorporating the improved Z mass in a consistent way throughout the analysis.

To conclude, the increased precision expected from low-energy neutral-current measurements of $\sin^2\theta_W$ and from the W mass determination at the Fermilab Tevatron will substantially improve our understanding of the gauge structure of the electroweak interaction. Further improvement may come from more refined e^+e^- experiments, including the possible study of polarization asymmetries, such as suggested at the SLAC Linear Collider. Our work highlights the importance and complementarity of these experiments in further constraining the new-physics possibilities suggested by superstring models and presumably in discriminating between different options. Finally, the limits obtained here should serve as useful guides for planning direct searches of new Z's at hadron colliders such as the Superconducting Super Collider.

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