RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 36, NUMBER 3 1 AUGUST 1987

Use of Z lepton asymmetry to determine mixing between Z boson and Z' boson of E_6 superstring theory

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(Received 23 March 1987)

We compare recent measurements of lepton asymmetries in Z decays at the CERN $p\bar{p}$ collider with expectations based on mixing of the Z boson with the Z' boson in superstring-inspired E_6 electroweak models. These measurements may favor Z-Z' mixing. We compare the results with what may be learned at e^+e^- colliders.

The standard electroweak gauge model[1] is consistent with all low-energy neutral-current data[2] and with the observed properties of the W and Z bosons.[3,4] However, there are many theoretical reasons for believing that the standard model is only the low-energy limit of a more complete theory. Recently, $E_8 \times E_8'$ superstring theories[5] have gained favor as a possible grand unified theory including gravity. They have an effective E_6 theory in four dimensions and have at least one additional Z boson at electroweak energies. Limits on the parameters of such models from existing low-energy data, from the gauge-boson masses, and from the negative results of direct Z searches in $p\bar{p}$ collisions have been determined.[6-10] One indication of new physics beyond the standard model would be a Z boson which deviates from standard expectations. Numerous articles[8,11] have considered what may be learned from precise studies on the Z resonance. In this Rapid Communication, we point out that currently available lepton-asymmetry measurements at the CERN $p\bar{p}$ collider provide information about possible mixing of the Z with the Z' boson of E_6 electroweak models derived from superstrings. The presence of mixing improves agreement of the data with predictions.

To study the extra neutral gauge bosons in E_6 models based on superstring theory, we consider the breakdown[12]

$$E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi .$$

The lightest extra Z boson will be a linear combination of the generators of the two additional U(1)'s: $Z' = Z_\psi \cos\alpha + Z_\chi \sin\alpha$. If E_6 is broken to a rank-6 group then the mixing angle α is, in general, unconstrained, although if the electroweak breaking occurs via Higgs bosons in the **27** representation of E_6 it must lie in the range defined by $-\sqrt{15}/4 \le \cos\alpha \le 0$.[8] If E_6 is broken to a rank-5 group then α is uniquely specified:[9,12] $\cos\alpha = \sqrt{5/8}$. The latter case has received the most attention in the literature and we will focus on it in our discussions.

The general mass matrix in a model with two Z bosons can be written in the (Z,Z') basis as

$$M^2 = \begin{bmatrix} M_Z{}^2 & \delta M^2 \\ \delta M^2 & M_{Z'}{}^2 \end{bmatrix} . \tag{1}$$

In models where there are only doublet and singlet Higgs bosons contributing to the electroweak symmetry breaking (such as the superstring-inspired E_6 models) the parameter M_Z is just the standard-model mass determined from low-energy neutral-current data; for $x_W = 0.229 \pm 0.005$ (Ref. 2), $M_Z = 92.1 \pm 0.7$ after radiative corrections.[13] The remaining two parameters δM^2 and $M_{Z'}{}^2$ are best determined from measurements at energies near the gauge-boson masses. It is convenient to use as parameters the physical masses M_{Z_1} and M_{Z_2}, and the angle θ which describes the mixing between Z and Z':

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} Z \\ Z' \end{bmatrix} . \tag{2}$$

These physical parameters are related by

$$\tan^2\theta = (M_Z{}^2 - M_{Z_1}{}^2)/(M_{Z_2}{}^2 - M_Z{}^2) . \tag{3}$$

Combining Eqs. (1)-(3) yields

$$\delta M^2 = -(M_Z{}^2 - M_{Z_1}{}^2)\cot\theta = -(M_{Z_2}{}^2 - M_Z^2)\tan\theta . \tag{4}$$

Thus the sign of δM^2 determines the sign of θ since $M_{Z_2} > M_Z$. In the limit of small mixing

$$M_{Z_1}{}^2 \approx M_Z{}^2 - (\delta M^2)^2/(M_{Z'}{}^2 - M_Z{}^2) ,$$
$$M_{Z_2}{}^2 \approx M_{Z'}{}^2 + (\delta M^2)^2/(M_{Z'}{}^2 - M_Z{}^2) . \tag{5}$$

In any particular model, the Z-boson mass matrix depends on the Higgs-boson vacuum expectation values (VEV's). For the rank-5 E_6 model the off-diagonal element is given by

$$\delta M^2 = \sqrt{x_W} \frac{(4v_1{}^2 - v_2{}^2)}{3(v_1{}^2 + v_2{}^2)} M_Z{}^2 , \tag{6}$$

where v_1 and v_2 are VEV's for the two Higgs doublets in the theory. In certain no-scale superstring models[9] in which the scale of electroweak symmetry breaking is determined dynamically, the ratio v_2/v_1 is always less than unity, and values near 0.5 are indicated. Therefore in the no-scale scenario θ is negative.

Since $M_Z{}^2$ is fixed by low-energy data, M_{Z_2} is determined once M_{Z_1} is measured and θ is deduced from a study of the Z_1 couplings. Since the couplings depend on the angle α of the E_6 model and on θ, the prediction for M_{Z_2} is thereby model dependent. Measurements of M_{Z_1} exist from $p\bar{p}$ collider data,[3,4] and recently data have become available from the $p\bar{p}$ collider on lepton asymmetries in Z decays which can be compared with Z-Z' mixing predictions.

Before mixing, the neutral-current Lagrangian is

$$L_{\rm NC} = g_Z J_Z Z + g' J_{Q'} Z' , \qquad (7)$$

where $J_Z = J_{3L} - x_W J_{\rm EM}$ is the usual Z-boson current and $J^{\mu}_{Q'} = \frac{1}{2}\sum_f \bar{f}\gamma^{\mu}(1-\gamma_5)Q' f$. The coupling constants are $g' = g_Z\sqrt{x_W} = e/\sqrt{1-x_W}$, where $x_W = \sin^2\theta_W$. The Q' charges[8] of the left-handed fermion states for two-Z models based on E_6 are $Q' = (\sqrt{5/8}\cos\alpha + \sqrt{3/8}\sin\alpha)/3$ for e^{-c}, d, u, u^c and $Q' = 2(\sqrt{5/32}\cos\alpha - \sqrt{27/32}\sin\alpha)/3$ for $d^c, e^-\nu_e$; for the rank-5 scenario, $\cos\alpha = \sqrt{5/8}$. The fermion couplings to the Z_1 are easily found from Eq. (7) by applying the rotation of Eq. (2).

In $p\bar{p} \to Z_1 X$, $Z_1 \to e^+e^-$ one can measure the angular distribution of the e^- in the electron-pair center of mass, given by

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^* + 2\cos\theta^* \frac{4}{3} A_{FB}\right) , \qquad (8)$$

where θ^* is the angle of the outgoing e^- with respect to the p beam, and

$$A_{FB} = \frac{3}{4}\frac{[g_R(e)^2 - g_L(e)^2]}{[g_R(e)^2 + g_L(e)^2]}\left\{\frac{\sum_q [g_R(q)^2 - g_L(q)^2] H_q^-}{\sum_q [g_R(q)^2 + g_L(q)^2] H_q^+}\right\} \qquad (9)$$

is the integrated forward-backward asymmetry.[14] In Eq. (7), $g_L(f)$ and $g_R(f)$ are the couplings of the Z_1 to left- and right-handed fermions, respectively, and

$$H_q^{\pm}(M_{Z_1}{}^2, \sqrt{s}) = \int_{-\ln\sqrt{s}/M_{Z_1}}^{\ln\sqrt{s}/M_{Z_1}} [f_{q/p}(x_+) f_{\bar{q}/\bar{p}}(x_-) \pm f_{\bar{q}/p}(x_+) f_{q/\bar{p}}(x_-)]\, dy , \qquad (10)$$

where $f_{q/A}(x_A)$ is the distribution of q in hadron A and $x_{\pm} = \exp(\pm y) M_{Z_1}/\sqrt{s}$.

In Fig. 1(a) we show the differential cross section versus the electron angle θ^* for three values of the Z-boson mixing angle θ in the rank-5 E_6 model. In Fig. 1(b) we show A_{FB} vs θ for the rank-5 case and two scenarios[8] for rank-6 breaking ($\cos\alpha = -\sqrt{15}/4$ and $\cos\alpha = 0$) which correspond to having one of the two SU(2)-singlet VEV's in the **27** of E_6 be much larger than the other. Changing x_W by ± 0.005 shifts the A_{FB} curves by ∓ 0.03. These predictions use the parton distributions of Ref. 15.

The recent data from the UA1 collaboration[3] are also shown in Fig. 1. The data seem to favor positive mixing angles and place the limit $\theta > -3°$ at 90% C.L. and $\theta > -10°$ at 95% C.L. in the rank-5 model. From Eqs. (1) and (7) one can construct an effective Lagrangian and use low-energy neutral-current data to place limits on the parameters; for rank-5 E_6 superstring models, these data allow Z-boson mixing in the range $-4° < \theta < 20°$ at 90% C.L.[7,8,16] The solutions with large positive θ allowed by low-energy analyses are in better agreement with the UA1 lepton-asymmetry data than the standard model Z with

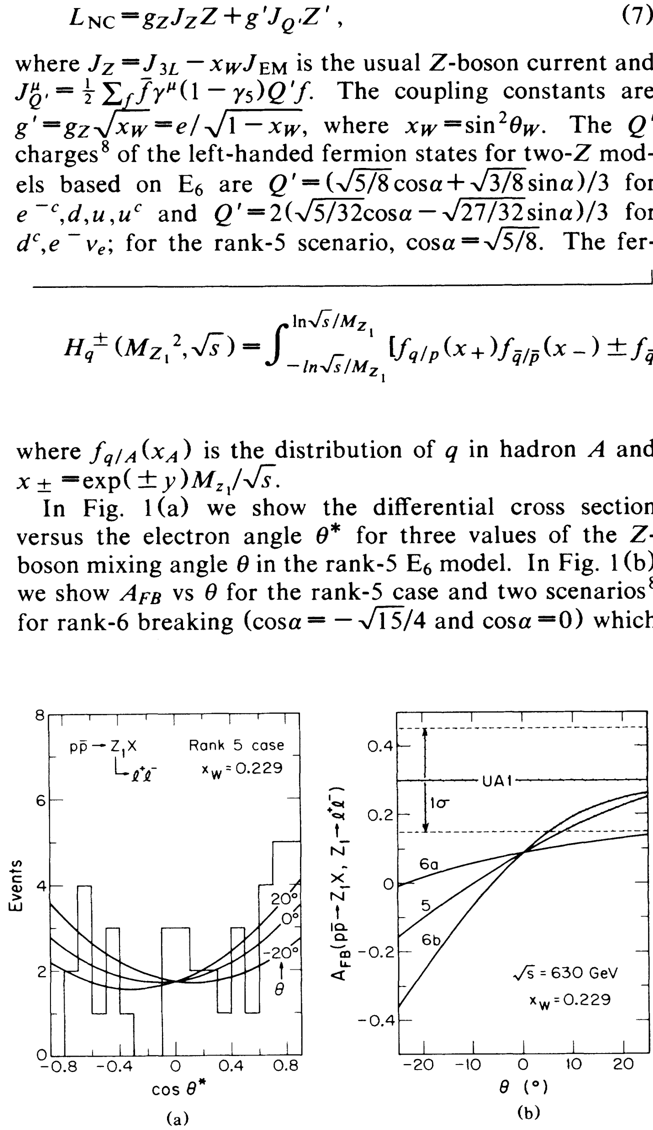

FIG. 1. (a) Predicted number of events (normalized to the observed cross section) vs electron center-of-mass angle θ^* for lepton pairs from Z decays in $p\bar{p} \to l^+l^-X$ at $\sqrt{s} = 630$ GeV for three values of the Z-boson mixing angle θ in rank-5 E_6 models, and (b) integrated forward-backward asymmetry for the same reaction vs the Z-boson mixing angle θ for the rank-5 case ($\cos\alpha = \sqrt{5/8}$) and two rank-6 scenarios labeled $6a$ ($\cos\alpha = -\sqrt{15}/4$) and $6b$ ($\cos\alpha = 0$). UA1 data from Ref. 3 are shown. The 90% allowed regions from low-energy neutral-current data are $-4° < \theta < 20°$ in the rank-5 model, $-4° < \theta < 6°$ for model $6a$, and $-3° < \theta < 3°$ for model $6b$.

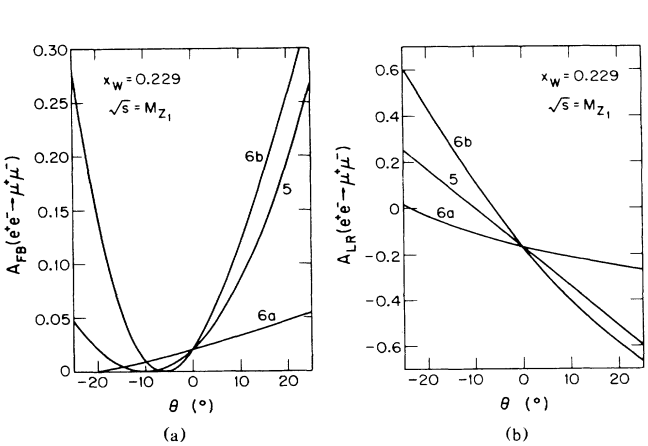

FIG. 2. (a) Integrated forward-backward asymmetry and (b) polarization asymmetry for $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = M_{Z_1}$ vs the Z-boson mixing angle θ for the three E_6 scenarios considered in Fig. 1(b).

no mixing.

In $e^+e^- \rightarrow \mu^+\mu^-$, the forward-backward asymmetry on the Z_1 resonance is similar to Eq. (9), except that the sum over quarks is replaced by the same expression for muons with $H^\pm \rightarrow 1$, and θ^* is interpreted as the angle of the outgoing μ^- with respect to the e^- beam. Since the muon couplings are presumed to be identical to the electron couplings, A_{FB} in e^+e^- collisions on the Z_1 resonance is always positive. In Fig. 2(a) we show predictions for the integrated A_{FB} in $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = M_{Z_1}$ versus the Z-boson mixing angle θ in the rank-5 E_6 model and the two rank-6 models. The uncertainty in this measurement at the Stanford Linear Collider (SLC) is expected[17] to be about 0.005, so that θ will be determined to an accuracy of order 1° for any given value of α.

Once electron-beam polarization is also available, one can measure the differential cross sections for a right- or left-handed polarized electron on the Z_1 resonance

$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma_{R,L}}{d\cos\theta^*} = \tfrac{3}{8}(1 \pm A_{LR}) \times (1+\cos^2\theta^* \pm 2\cos\theta^* A_{LR}) , \quad (11)$$

where A_{LR} is the integrated polarization asymmetry for purely polarized beams

$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{g_R(e)^2 - g_L(e)^2}{g_R(e)^2 + g_L(e)^2} , \quad (12)$$

and $\sigma_{\text{tot}} = (\sigma_R + \sigma_L)/2$. For partially polarized beams the terms in Eq. (11) linear in A_{LR} should be multiplied by the beam polarization P_e. Note that the equality of electron and muon couplings implies $A_{FB} = \frac{3}{4} A_{LR}{}^2$ on resonance. The experimental uncertainty in A_{LR} is controlled mostly by knowledge of the beam polarization, and is expected[17] to be around 5%. Predictions for A_{LR} are shown in Fig. 2(b); changing x_W by ± 0.005 shifts the curves for A_{LR} by ± 0.05.

Another means of testing the Z boson for deviations from the standard model will be to study its total width and branching fractions into known fermions;[8] these are shown for the rank-5 model versus θ in Fig. 3, assuming the t-quark mass is greater than $M_{Z_1}/2$. The partial widths for light fermions are given by

$$\Gamma(Z_1 \rightarrow f\bar{f}) = \alpha_{\text{EM}} M_{Z_1} [6x_W(1-x_W)]^{-1} \times [g_L(f)^2 + g_R(f)^2] c_f , \quad (13)$$

where c_f is 1 for leptons and 3 for quarks and α_{EM} is evaluated at scale M_W. The contributions of individual quark channels are particularly sensitive to the mixing angle θ. The b and c heavy flavors should be experimentally identifiable and the ratio $\Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow c\bar{c})$ will provide a valuable measure of any Z mixing.

Another consequence of large positive Z-boson mixing angles is a decrease in the total Z width of up to 400 MeV, assuming decays to exotic fermions are not important. The Z width can be accurately measured at SLC and CERN LEP I. Such a change in the Z width would affect neutrino-counting arguments based on Γ_Z or on $p\bar{p}$ collider measurements of Γ_Z/Γ_W.[18]

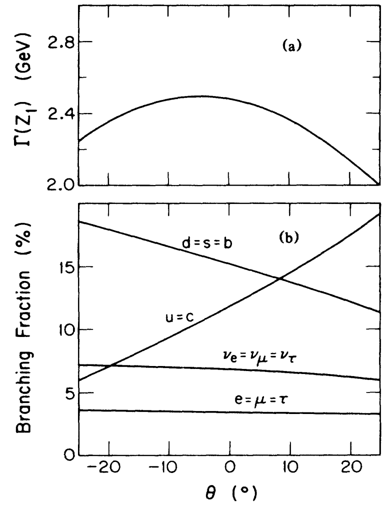

FIG. 3. (a) Total width and (b) branching fractions of the Z_1 vs the Z-boson mixing angle θ for the three E_6 scenarios considered in Fig. 1(b).

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