Production, decays, and forward-backward asymmetries of extra gauge bosons in E_6

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(Received 4 August 1986)

We consider the Drell-Yan production of an extra Z boson from the E_6 electroweak gauge group in $p\bar{p}$ and pp colliders. If there is only one extra Z at electroweak energies, it may be a mixture of the two extra U(1) groups in E_6. We discuss how to determine this mixing by examining the extra-Z-boson couplings to fermions through its decay modes and $\mu^+\mu^-$ forward-backward asymmetries. We also discuss different mass scales of the exotic fermions present in the **27** representations of E_6.

Recent work on superstring theories[1] has indicated that the $E_8 \times E_8'$ superstring theory in 10 dimensions may yield, after compactification, a four-dimensional E_6 gauge group of the strong and electroweak interactions coupling to $N=1$ supergravity. Since E_6 has rank 6, the possibility exists for one or two extra Z bosons. Many authors have discussed the properties of extra Z bosons when E_6 is broken to a rank-5 group,[1,2] or special cases when E_6 is broken to a rank-6 group.[3,4] Constraints from low-energy neutral-current experiments and production at the Fermilab Tevatron in the general case of one light extra Z boson have also been examined.[5] In this Brief Report, we extend the previous analyses to include the production and detection of the extra Z boson in a pp collider at $\sqrt{s}=40$ TeV, and discuss how to distinguish the particular E_6-breaking scheme by studying the couplings of the extra Z to fermions using $\mu^+\mu^-$ forward-backward asymmetries and fermion-antifermion branching ratios.

To analyze the effects of an extra neutral gauge boson in E_6, consider the breakdown[5,6] $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$. If there is one light extra Z boson it will be a linear combination of the two extra U(1)'s: $Q(\alpha)=Q_\psi \cos\alpha + Q_\chi \sin\alpha$. The Z boson associated with this generator will be called $Z(\alpha)$. If E_6 is broken to a rank-6 group the mixing angle α (denoted by θ in Ref. 5) is unconstrained. However, if E_6 is broken to a rank-5 group, α is uniquely determined and has the value $\alpha \equiv \arctan(\sqrt{3/5})$ (we call this special case the Z'). In addition to the cases $\alpha=0$ (Z_ψ) and $\alpha=\pi/2$ (Z_χ) there is the special value $\alpha=\arctan(-\sqrt{5/3})$ (Z_I) corresponding to an extra SU(2) group at electroweak energies.[5,6]

In an E_6 theory, each generation of fermions belongs to a **27** representation. The decomposition of the **27** into SO(10) and SU(5) multiplets and the extra U(1) charge ($\tilde{Q}$) are given in Table I; note that $\tilde{Q}$ depends on the mixing angle α. In addition to the usual fermions $\overset{(-)}{u}$, $\overset{(-)}{d}$, $e^\pm$, and ν_e there is a charge $-\frac{1}{3}$ quark isosinglet h, charged leptons $E^\pm$, and neutral leptons ν_E, N_E, N_e, and n.

The neutral-current Lagrangian for the E_6 models with one extra Z at low energies is

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

where

$$J^\mu_{EM} \text{ and } J^\mu_Z (\equiv J^\mu_3 - x_W Q^\mu)$$

are the usual electromagnetic and Z-boson currents and

$$J^\mu_{Z(\alpha)} = \tfrac{1}{2} \sum_f \bar{f} \gamma^\mu (1-\gamma_5) \tilde{Q} f .$$

Note that the couplings of a left-handed charge-conjugate state give right-handed couplings of opposite sign. The coupling constants are

$$g' = g_Z \sqrt{x_W} = e/\sqrt{1-x_W} ,$$

where $x_W = \sin^2\theta_W$. In general, Z and $Z(\alpha)$ may mix, but fits to low-energy neutral-current data for the rank-5

TABLE I. Decomposition of **27**, and fermion quantum numbers. The $\tilde{Q}$ charges a_i are given as an amplitude times a factor which varies with α over the range -1 to $+1$.

SO(10)	SU(5)	Left-handed state	$\tilde{Q}$
16	10	e^{-c}, d, u, u^c	$a_1 = \frac{1}{3}(\sqrt{5/8}\cos\alpha + \sqrt{3/8}\sin\alpha)$
	5*	d^c, e^-, ν_e	$a_2 = \frac{2}{3}(\sqrt{5/32}\cos\alpha - \sqrt{27/32}\sin\alpha)$
	1	N_e^c	$a_3 = \frac{\sqrt{10}}{3}\left[\frac{1}{4}\cos\alpha + \frac{\sqrt{15}}{4}\sin\alpha\right]$
10	5*	h^c, E^-, ν_E	$a_4 = \frac{2}{3}(-\sqrt{5/8}\cos\alpha + \sqrt{3/8}\sin\alpha)$
	5	h, E^{-c}, N_E^c	$a_5 = \frac{2}{3}(-\sqrt{5/8}\cos\alpha - \sqrt{3/8}\sin\alpha)$
1	1	n	$a_6 = \frac{\sqrt{10}}{3}\cos\alpha$

value of α ($\tan\alpha=\sqrt{3/5}$) show that this mixing is very small.[2] Hence we shall ignore Z-$Z(\alpha)$ mixing in our analysis.

The partial width for the decay of $Z(\alpha)$ into a fermion-antifermion pair in the limit $m_f \ll M_{Z(\alpha)}$ is

$$\Gamma(Z(\alpha)\to f\bar{f})=\alpha_{\rm EM}M_{Z(\alpha)}[6(1-x_W)]^{-1}(g_L{}^2+g_R{}^2)c_f \ ,$$

where g_L and g_R are the left- and right-handed couplings which can be read off from Table I, and c_f is 1 for leptons and 3 for quarks. We take the fine-structure constant to be $\alpha_{\rm EM}{}^{-1}(M_W)=128.5$. If n_G generations of exotic fermions contribute fully (i.e., with no phase space suppression) in $Z(\alpha)$ decays then the total width is

$$\Gamma(Z(\alpha))=\alpha_{\rm EM}M_{Z(\alpha)}[2(1-x_W)]^{-1} \times[10a_1{}^2+5a_2{}^2+n_G(5-10a_1{}^2-5a_2{}^2)/3] \ . \quad (1)$$

If $n_G=3$ the width is independent of the mixing α: $\Gamma(Z(\alpha))=0.025M_{Z(\alpha)}$. Figure 1(a) shows the $Z(\alpha)$ width versus $\cos\alpha$ when the $Z(\alpha)$ decays to all exotic fermions are inaccessible. Figures 1(b) and 1(d) show $Z(\alpha)$ branching ratios versus $\cos\alpha$ in the two extreme cases $n_G=0$ and $n_G=3$. The e^+e^- branching fraction varies from 3.3% to 6.7% (0.7% to 3.0%) for $n_G=0$ (3). Exotic-fermion branching fractions for $n_G=3$ are given in Fig. 1(c).

The differential cross section for the reaction $q\bar{q}\to\mu^+\mu^-$ (or e^+e^-) in a model with two Z bosons in the limit of negligible fermion masses can be written

$$\frac{d\sigma^{q\bar{q}}}{d\cos\theta^*}=\frac{\pi\alpha_{\rm EM}{}^2[S_q(1+\cos^2\theta^*)+A_q 2\cos\theta^*]}{2m^2} \ , \quad (2)$$

where θ^* is the angle of the outgoing μ^- with respect to the quark q in the $q\bar{q}$ center of mass, m is the lepton-pair mass and

$$S_q,A_q=\sum_{j,k}(g_j/e)^2(g_k/e)^2m^4[(m^2-M_j{}^2)(m^2-M_k{}^2)+M_jM_k\Gamma_j\Gamma_k]D_j{}^{-1}D_k{}^{-1} \times[g_L^j(\mu)g_L^k(\mu)\pm g_R^j(\mu)g_R^k(\mu)][g_L^j(q)g_L^k(q)\pm g_R^j(q)g_R^k(q)]/4 \ , \quad (3)$$

where g_j,M_j,Γ_j are the gauge-boson coupling strengths, masses, and widths, respectively, and the Breit-Wigner denominators are $D_j=(m^2-M_j{}^2)^2+M_j{}^2\Gamma_j{}^2$. For the photon ($j,k=0$), $g_0=e$, $M_0=\Gamma_0=0$ and the photon couplings to a fermion f are $g_L^0(f)=g_R^0(f)=Q_f$. The hadronic cross section for $A+B\to\mu^+\mu^-X$ is easily found by folding Eq. (2) with the quark distribution functions. In our calculations we use the structure functions of Ref. 7, except where noted otherwise, and sum over u, d, and s quark contributions. We also include an m^2-dependent K factor as discussed in Ref. 8.

To study the helicity structure of the $Z(\alpha)$ couplings, as exhibited by the coefficients S_q and A_q in Eq. (2), one may look at the forward-backward asymmetry as a function of y:

$$A^{FB}(y)=\frac{d\sigma^F/dy-d\sigma^B/dy}{d\sigma^F/dy+d\sigma^B/dy}=\frac{3}{4}\frac{g_R(\mu)^2-g_L(\mu)^2}{g_R(\mu)^2+g_L(\mu)^2}\frac{\sum_q[g_R(q)^2-g_L(q)^2]G_q^-}{\sum_q[g_R(q)^2+g_L(q)^2]G_q^+} \ . \quad (4)$$

Forward (backward) is defined in the $Z(\alpha)$ rest frame as $\theta^*<\pi/2$ ($\theta^*>\pi/2$) and $G_q^\pm(y,m^2,\sqrt{s})=f_{q/A}(x_A)f_{\bar{q}/B}(x_B)$

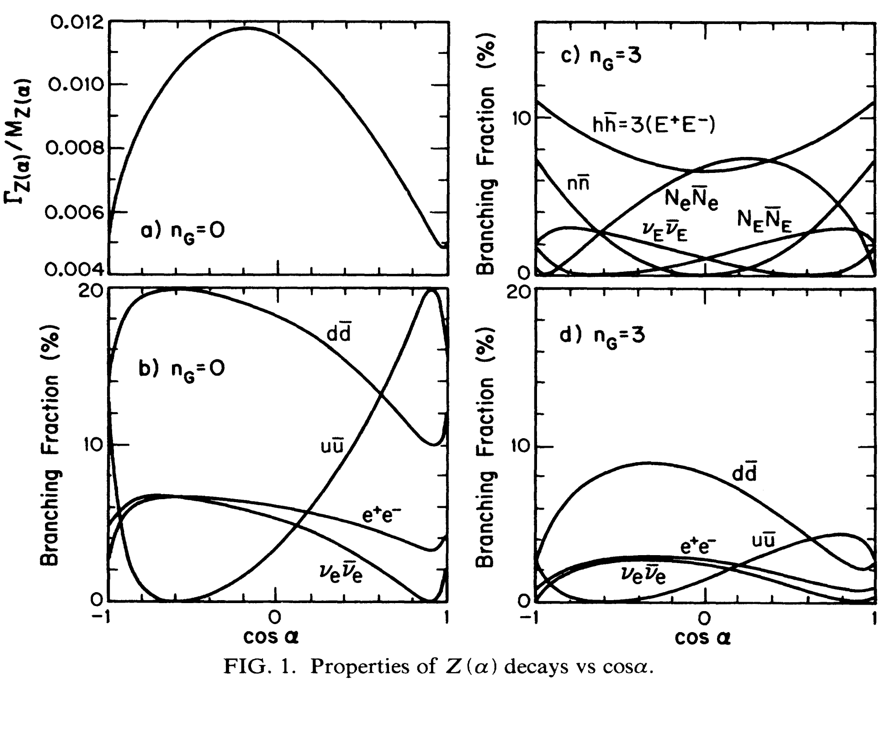

FIG. 1. Properties of $Z(\alpha)$ decays vs $\cos\alpha$.

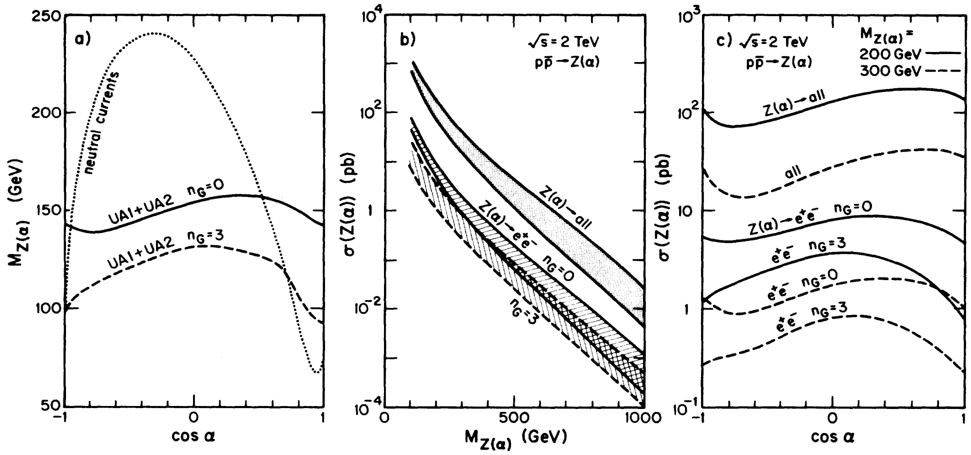

FIG. 2. (a) Lower bounds on mass of extra Z boson vs $\cos\alpha$ deduced from UA1 and UA2 searches for $Z \rightarrow e^+e^-$ at $\sqrt{s}=630$ GeV. The solid (dashed) curves assumes $n_G=0$ (3). The dotted curve denotes the lower bound on $M_{Z(\alpha)}$ from neutral-current data. Predictions for $Z(\alpha)$ production at the 2-TeV Fermilab $p\bar{p}$ collider: (b) σ of $Z(\alpha)$ and $\sigma B(Z(\alpha)\rightarrow e^+e^-)$ vs $M_{Z(\alpha)}$, for the two extreme cases $n_G=0$ and 3 exotic fermions. The shaded regions correspond to the range allowed by varying α. (c) σ and σB for $M_{Z(\alpha)}=200$ and 300 GeV shown vs $\cos\alpha$.

$\pm f_{\bar{q}/A}(x_A) f_{q/b}(x_B)$, where $f_{q/A}(x_A)$ is the distribution of q in hadron A. Exact double zeros in A^{FB} occur when

$$a_1 = \pm a_2 \ (\cos\alpha = \sqrt{3/8}, \pm 1)$$

because for those α values

$$g_R(\mu)^2 - g_L(\mu)^2 = g_R(d)^2 - g_L(d)^2 \rightarrow 0$$

and the u quark, which always has an axial-vector coupling to $Z(\alpha)$, does not contribute to the numerator in Eq. (4). $A^{FB}(y)$ is even (odd) for y for $p\bar{p}$ (pp) machines. For $p\bar{p}$ reactions, and A^{FB} integrated over y can be obtained from Eq. (4). For pp reactions the appropriate quantity is

$$A^{FB} = \frac{\left[\int_0^{\ln\sqrt{s}/m} dy - \int_{-\ln\sqrt{s}/m}^{0} dy \right] (d\sigma^F/dy - d\sigma^B/dy)}{\left[\int_0^{\ln\sqrt{s}/m} dy + \int_{-\ln\sqrt{s}/m}^{0} dy \right] (d\sigma^F/dy + d\sigma^B/dy)} \,. \tag{5}$$

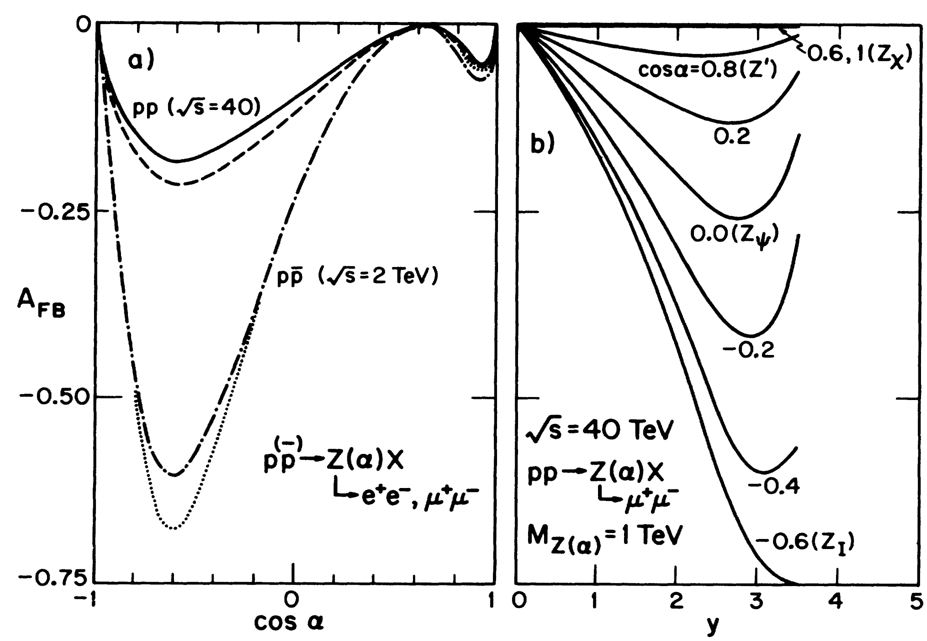

FIG. 3. Forward-backward asymmetries for the reactions $p\overset{(-)}{p} \rightarrow Z(\alpha)X$, $Z(\alpha)\rightarrow e^+e^-$ or $\mu^+\mu^-$: (a) asymmetry integrated over y vs $\cos\alpha$ for $p\bar{p}$ at $\sqrt{s}=2$ TeV, $M_{Z(\alpha)}=200$ (dotted-dashed curve) and 300 GeV (dotted curve), and pp at $\sqrt{s}=40$ TeV, $M_{Z(\alpha)}=0.5$ (solid curve) and 1 TeV (dashed curve); (b) asymmetry vs y for representative $\cos\alpha$ for pp at $\sqrt{s}=40$ TeV, $M_{Z(\alpha)}=1$ TeV.

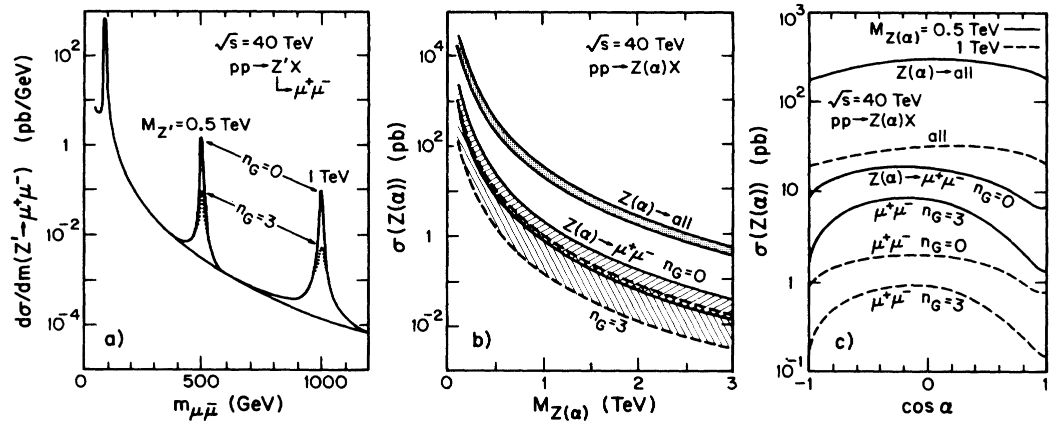

FIG. 4. Predictions for Z' ($\cos\alpha=\sqrt{5/8}$) production in a pp collider at $\sqrt{s}=40$ TeV: (a) $d\sigma/dm(pp\to e^+e^-X)$ vs dilepton invariant mass for $M_{Z'}=0.5$ and 1 TeV; the solid (dotted) curves correspond to $n_G=0(3)$; (b) σ and $\sigma B(Z(\alpha)\to e^+e^-)$ for producing $Z(\alpha)$ vs $M_{Z(\alpha)}$; the shaded regions correspond to the range allowed by varying α; (c) σ and $\sigma B(Z(\alpha)\to e^+e^-)$ for $M_{Z(\alpha)}=0.5$ and 1 TeV vs $\cos\alpha$.

$p\bar{p}$ colliders. We calculate the production cross section of $Z(\alpha)$ at $\sqrt{s}=630$ GeV for the CERN $p\bar{p}$ collider using the structure functions of Ref. 9. Figure 2(a) shows the lower limit on $M_{Z(\alpha)}$ versus $\cos\alpha$ deduced from the combined UA1-UA2 upper limit[10] of $\sigma B\leq 3$ pb on an extra Z boson in its e^+e^- decay channel, for the cases $n_G=0$ and $n_G=3$. Also shown is the lower bound on $M_{Z(\alpha)}$ deduced from fits to neutral-current data.[5] All limits are at the 90% confidence level.

The $p\bar{p}$ total cross section and lepton pair signal are shown in Fig. 2(b) versus $M_{Z(\alpha)}$ at $\sqrt{s}=2$ TeV. The shaded bands correspond to variations with the mixing angle α. This dependence on α is shown in Fig. 2(c) for specific values of the $Z(\alpha)$ mass. In Fig. 3(a) the integrated forward-backward asymmetry computed using Eq. (4) is shown. With an annual luminosity $\int\mathscr{L}=1$ pb^{-1} one expects from 1 to 20 events in each dilepton channel for $M_{Z(\alpha)}=300$ GeV. Assuming 100 events are needed to achieve a ± 0.1 uncertainty in A^{FB}, an integrated luminosity $\int\mathscr{L}=10$ pb^{-1} is required to probe the asymmetry for $Z(\alpha)$ masses below 200 GeV.

pp colliders. A high-luminosity pp collider will be an excellent source for producing the $Z(\alpha)$ boson. We calculate $d\sigma/dm$ for $pp\to Z(\alpha)X$, $Z(\alpha)\to\mu^+\mu^-$ at $\sqrt{s}=40$ TeV as a function of dilepton mass m; the results are shown in Fig. 4(a) for $M_{Z(\alpha)}=0.5$ and 1 TeV. The $Z(\alpha)$ peaks are shown for the two extreme cases $n_G=0$ and $n_G=3$. The total $Z(\alpha)$ production cross sections and cross sections times leptonic branching ratio as a function of $Z(\alpha)$ mass are given in Fig. 4(b); the α dependence is shown in Fig. 4(c) for $M_{Z(\alpha)}=0.5$ and 1 TeV. The forward-backward asymmetry defined in Eq. (4) is shown in Fig. 3(b) versus y for various values of $\cos\alpha$, for $M_{Z(\alpha)}=1$ TeV; the integrated asymmetry of Eq. (5) is given in Fig. 3(a) as a function of $\cos\alpha$.

For masses below 4 TeV the $Z(\alpha)$ boson of E_6 theories should be easily detectable through its leptonic decays in a pp machine at $\sqrt{s}=40$ TeV with integrated luminosity $\int\mathscr{L}=10^4$ pb^{-1}, irrespective of the mixing angle α or the exotic-fermion masses. If the exotic-fermion decay channels of the $Z(\alpha)$ are kinematically inaccessible then even higher $Z(\alpha)$ masses may be probed. The $Z(\alpha)$ mass and production cross section will provide some information on α. For no phase-space suppression of exotic fermions in $Z(\alpha)$ decays, accurate measurements of forward-backward asymmetries in $pp\to Z(\alpha)X$, $Z(\alpha)\to\mu^+\mu^-$, and $Z(\alpha)$ branching ratios will further constrain α for $Z(\alpha)$ masses below 1 TeV; if the exotic-fermion decays are kinematically suppressed, a good determination of α may be possible if $M_{Z(\alpha)}\lesssim 1.5$ TeV.

This research was supported by the U.S. Department of Energy.

[1]M. B. Green and J. H. Schwarz, Phys. Lett. **149B**, 117 (1984); **151B**, 21 (1985); P. Candelas, G. Horowitz, A. Strominger, and E. Witten, Nucl. Phys. **B258**, 46 (1985); E. Witten, *ibid.* **B258**, 75 (1985); M. Dine *et al.*, *ibid.* **B259**, 549 (1985); P. Binetruy *et al.*, *ibid.* **B273**, 501 (1986); J. Ellis *et al.*, *ibid.* **B276**, 14 (1986); J. L. Rosner, Comments Nucl. Part. Phys. **15**, 195 (1986); and Report No. EFI 86-19 (unpublished).

[2]V. Barger *et al.*, Phys. Rev. Lett. **56**, 30 (1986); Phys. Rev. D **33**, 1912 (1986).

[3]S. M. Barr, Phys. Rev. Lett. **55**, 2778 (1985).

[4]L. S. Durkin and P. Langacker, Phys. Lett. **166B**, 436 (1986).

[5]D. London and J. L. Rosner, Phys. Rev. D **34**, 1530 (1986).

[6]P. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. D **30**, 1470 (1984).

[7]E. Eichten, I. Hinchcliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

[8]V. Barger, in *Proceedings of the Oregon Meeting,* Annual Meeting of the Division of Particles and Fields of the APS, Eugene, 1985, edited by R. Hwa (World Scientific, Singapore, 1986), p. 95.

[9]D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).

[10]S. Geer, in Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, California, 1986, edited by S. Loken (World Scientific, Singapore, to be published).