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Limits on the mass of a superstring Z' from the CERN $p\bar{p}$ Collider

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Abstract

We illustrate how recent CERN $p\bar{p}$ collider data can be used to bound the mass of a possible Z' in superstring-inspired models. We take into account the fact that the Z' couplings to quarks and leptons are smaller than those of the conventional Z , and the possibility that the Z' may be able to decay into exotic particles, thereby suppressing the $Z' \rightarrow l^+l^-$ branching ratio. In the minimal rank-5 model we find $m_{Z'} > 167$ GeV if the Z' can only decay into conventional quarks and leptons and $m_{Z'} > 118$ GeV for the least favourable spectrum of 3 E_6 27 generations of particles and sparticles which is allowed by other experiments. When combined with a global analysis of neutral current data, the latter conservative limit can be increased to $m_{Z'} > 156$ GeV. We derive analogous limits for two other superstring-inspired models. We show how these limits can be improved using future FNAL Tevatron and SLC data.

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Although superstring theory [1] is undoubtedly the Theory of Everything (T. O. E.), it is not known how to subject this assertion to experimental test. The road from any fundamental formulation to the laboratory is long and tortuous with many forks where it is not clear which turning to take [2]. Probably none of the phenomenological options currently known is correct. However, by analyzing them one may develop strategies which will be useful for exploring the correct string-inspired model. One of the first phenomenological options to be favoured was compactification of the 10-dimensional $E_8 \times E'_8$ heterotic string [3] on some Calabi-Yau manifold [4]. Such compactifications give 4-dimensional gauge groups [5] of rank $r \geq 5$, and offer a unique minimal gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_E$, for which the $U(1)_E$ hypercharges Y_E of all particles are specified. All the known Calabi-Yau manifolds which could give this gauge group have phenomenological problems [6] and there is no reason to believe that a realistic model [7] based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_E$ can be found. Nevertheless, its predictions for an additional Z' gauge boson and associated neutral currents are sufficiently precise to be confronted clearly with experiment. Alternatively, one could obtain a low-energy Z' starting from a 4-dimensional gauge group of rank $r = 6$, broken down to a rank-5 group by very large v.e.v.'s of some standard model singlets in $(\underline{27} + \overline{\underline{27}})$ representations of E_6 . These constructions also face possible phenomenological drawbacks [8], but we shall consider here, for completeness, two representative examples [9,10].

Experimental probes of these models include measurements of neutral currents [11,12] and searches for the Z' boson at present and future colliders [13,14]. The former have been used to give indirect lower limits on the mass of the Z' , and yield [12] in the minimal model $m_{Z'} > 129$ GeV at the 90% c.l. if one makes no supplementary hypotheses about the v.e.v.'s of the Higgs fields which break $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_E$ down to $SU(3)_C \times U(1)_{em}$. Plausible hypotheses about the v.e.v.'s provide a dramatic improvement in this lower limit, which depends very sensitively on the confidence level required. Analogous results have also been obtained for other superstring-inspired Z' bosons. Searches for the Z' give more direct lower limits on its mass, but their interpretations depend upon hypotheses on the available Z' decay modes. The observable branching ratio for $Z' \rightarrow l^+ l^-$ ($l = e, \mu, \tau$) is largest if the Z' can only decay into con-

ventional quarks and leptons – the “minimal” hypothesis. A conservative lower bound on the Z' mass is obtained if the $p\bar{p}$ cross-section times branching ratio $\sigma(Z')BR(Z' \rightarrow l^+l^-)$ is minimized by allowing the particles and sparticles in 3 complete generations composed of $2\overline{1}$ representations of E_6 to have the least favourable spectrum permitted by other experiments in e^+e^- annihilation and at the CERN $p\bar{p}$ collider. The latter “maximal” hypothesis is in principle constrained by experimental upper limits on the decay width of the conventional Z , but in practice these are not at present important limits on exotic decays of the Z or of the Z' . Moreover, as we shall see, due to the different couplings of the Z and Z' , even extremely accurate measurements of the Z width are not as important as the improved limits on exotic particles expected in the same time scale.

In this paper we first use the presently available CERN $p\bar{p}$ collider data to establish in the rank-5 model the lower limits $m_{Z'} > 167$ GeV and 118 GeV respectively under the minimal and maximal decay hypotheses outlined above. The conservative analysis under the latter hypothesis is then combined with the conservative analysis of neutral current data (i.e. without hypotheses on the Higgs v.e.v.'s) to give a global limit $m_{Z'} > 156$ GeV at the 90% confidence level. Analogous results are also presented for two other superstring Z' models. Next we show how data from the FNAL Tevatron collider could be used to improve these lower limits on $m_{Z'}$. Finally, we show how measurements at the SLC could be used to constrain further the spectrum of exotic particles and thereby improve the collider limits on $m_{Z'}$.

The UA1 collaboration has analyzed [15] both e^+e^- and $\mu^+\mu^-$ pairs in data sets taken at $\sqrt{s} = 546$ and 630 GeV. The e^+e^- pairs all have well measured invariant masses, and none fall outside the Z peak. One of the $\mu^+\mu^-$ pairs has a very poorly measured invariant mass and is excluded from the analysis. The data on the different l^+l^- pairs at different $\sqrt{s}$ have been combined (assuming $e-\mu$ universality) to give an effective upper limit $\sigma(Z')BR(Z' \rightarrow e^+e^-) < 3.3$ pb at the 90% confidence level for $\sqrt{s} = 630$ GeV. This limit is almost independent of $m_{Z'}$ in the range of interest, since the detection efficiency does not vary rapidly over this range. The UA2 collaboration has analyzed [16] e^+e^- data at $\sqrt{s} = 546$ and 630 GeV. All events are well measured and none fall outside the Z peak. UA2 quotes its limits on a new Z' as a bound on $\lambda_q^2 B_c$ as a function of $m_{Z'}$, where $\lambda_q^2 \equiv$

$\sum_q g_{q\bar{q}Z'}^2 w_q / \sum_q g_{q\bar{q}Z}^2$ with the weights w_q determined by the different quark-antiquark luminosities at $m_{q\bar{q}} = m_{Z'}$, and $B_e \equiv BR(Z' \rightarrow e^+e^-)/BR(Z' \rightarrow e^+e^-)_{st}$, where the latter is evaluated for standard model couplings, a mass $m_{Z'}$ and a width $\Gamma_{Z'} = \Gamma_Z m_{Z'}/m_Z$. The UA2 limit on a Z' can be re-expressed as $\sigma(Z')BR(Z' \rightarrow e^+e^-) < 4.0$ pb at the 90% confidence level for $\sqrt{s} = 630$ GeV. Again, this limit can be regarded for our purposes as independent of $m_{Z'}$ in the range of interest. Using Poisson statistics, we combine the UA1 and UA2 limits to obtain

$$\sigma(Z')BR(Z' \rightarrow e^+e^-) < 1.8 \text{ pb}, \quad (1)$$

at the 90% confidence level and for $\sqrt{s} = 630$ GeV, which we now compare with theoretical estimates.

The calculation of the production cross-section times branching ratio $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ involves several ingredients. The first is the set of Z' couplings to the matter fields contained in the fundamental $\underline{27}$ representation of E_6 , which are given in Table 1 in the limit of zero $Z - Z'$ mixing and for a restricted class of models in which the gauge coupling constant of the extra low-energy $U(1)$ is equal to that of $U(1)_Y$ (a more general discussion of the Z and Z' couplings can be found in Ref.[14]). In this case different models are described by a single parameter θ_2 ($s_2 \equiv \sin \theta_2, c_2 \equiv \cos \theta_2$), which in practice can assume only three values: $(s_2, c_2) = (0, 1)$ corresponds to the minimal rank-5 model [7], also called model A in Ref.[14]; $(s_2, c_2) = (\sqrt{5/8}, \sqrt{3/8})$ and $(s_2, c_2) = (-\sqrt{5/8}, \sqrt{3/8})$ correspond to models B [9] and C [10] of Ref.[14], characterized by large v.e.v.'s of some singlet Higgs fields and differing only in the fermion assignments inside the fundamental $\underline{27}$ representation of E_6 . Notice that the Z' couplings to ordinary quarks and leptons are in general smaller than those of the Standard Model Z : this means that our lower limits¹ on $m_{Z'}$ will be weaker than those obtained assuming Standard Model couplings for the Z' .

A second ingredient of the calculation is the choice of parton distribution functions. Both UA1 and UA2 find that their W and Z production data [17,18] are fitted well by the Duke and Owens model 1 distributions [19], which we also use here for the computation of $\sigma(Z')$.

¹Our predictions for $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ cannot be significantly altered by $Z - Z'$ mixing in the range allowed by analyses of neutral current data [12].

Then one has to estimate $BR(Z' \rightarrow e^+e^-)$, which depends on the competing decay modes available to the Z' . In Calabi-Yau compactifications like those assumed here, there should be 3 generations which each contain $2\bar{7}$ E_6 representations of particles and sparticles. There could also be additional light survivors from conjugate $2\bar{7} + 2\bar{7}$ pairs of E_6 representations, but we will not include them here. The minimal hypothesis would be that all exotic particles beyond the conventional 3 generations of quarks and leptons are too heavy to be produced in Z' decay, in which case

$$BR(Z' \rightarrow e^+e^-) = \frac{\Gamma(Z' \rightarrow e^+e^-)}{\sum_f \Gamma(Z' \rightarrow f\bar{f}) + \Gamma(Z' \rightarrow t\bar{t})}, \quad (2)$$

where the sum in the denominator runs over $f = u, d, s, c, b, \nu_e, e, \nu_\mu, \mu, \nu_\tau, \tau$ and, in the models under consideration and in the limit of zero $Z - Z'$ mixing,

$$\Gamma(Z' \rightarrow t\bar{t}) = \begin{cases} \frac{m_{Z'}}{12\pi} (1 - 4\eta_{top})^{3/2} C_f (a_{Z'}^u)^2 & \text{for } m_{top} \leq \frac{m_{Z'}}{2} \\ 0 & \text{for } m_{top} > \frac{m_{Z'}}{2} \end{cases}, \quad (3)$$

where $C_f \simeq 3$ is the colour factor, $\eta_{top} = (m_{top}/m_{Z'})^2$ is a kinematical suppression factor and $a_{Z'}^u$ is given in Table 1 (using the fact that $v_{Z'}^u = 0$ for the models under consideration). If there are no light exotic particles, we are entitled to make use of the UA1 limit [18] $m_{top} \geq 44$ GeV. A more conservative assumption is to allow all the as yet unseen particles and sparticles in the chiral $2\bar{7}$ supermultiplets to be as light as permitted by other experimental limits, and to consider the mass spectrum which gives the lowest possible lower limit on $m_{Z'}$ based on eq.(1). To simplify the analysis, we assume that all squarks have the same mass $m_{\tilde{q}}$. This means that, on the basis of UA1 data [20]

$$m_{\tilde{q}} \geq 45 \text{ GeV}. \quad (4)$$

On the other hand, on the basis of e^+e^- data [21] we can assume

$$m_{\pm} \geq 22.7 \text{ GeV} \quad (5)$$

for all other charged particles², whether of spin 0 or $\frac{1}{2}$ and including the D-

²This is the limit coming from experiments at PETRA. Data from TRISTAN can slightly improve this limit, but they are still preliminary and we do not use them here.

particles³ and the top quark. However, there are no direct mass constraints on unknown neutral particles such as ν^c , $\tilde{\nu}$, $\tilde{\nu}^c$, N , $\tilde{N}$, H^0 , $\tilde{H}^0$, $\bar{H}^0$, $\tilde{\bar{H}}^0$, so we allow them to have zero mass⁴. The Z and W could also decay into these undetected exotica and upper limits on the total widths Γ_Z and Γ_W could in principle become inconsistent with assigning such light masses to all these particles⁵. For any given spectrum of exotic particles to be acceptable, we check that it is consistent with the present experimental upper bounds [17,22]:

$$\Gamma(Z \rightarrow \text{all}) < 5.2 \text{ GeV}, \quad \Gamma(W \rightarrow \text{all}) < 5.4 \text{ GeV}, \quad (\text{UA1, 90\%c.l.}); \quad (6)$$

$$\Gamma(Z \rightarrow \text{all}) < 5.6 \text{ GeV}, \quad \Gamma(W \rightarrow \text{all}) < 7.0 \text{ GeV}, \quad (\text{UA2, 90\%c.l.}). \quad (7)$$

We will return to this issue later when we investigate how SLC limits on Γ_Z and on $m_{\pm}$ could be used to improve the present lower limit on $m_{Z'}$. With the conservative mass assignments (4-5) and still neglecting $Z - Z'$ mixing one must use the general formula

$$BR(Z' \rightarrow e^+e^-) = \frac{\Gamma(Z' \rightarrow e^+e^-)}{\sum_f \Gamma(Z' \rightarrow f\bar{f}) + \sum_f \Gamma(Z' \rightarrow \tilde{f}_{L,R} \tilde{\bar{f}}_{L,R})}, \quad (8)$$

where now f runs over all the states in 3 $\underline{27}$ representations of E_6 and

$$\Gamma(Z' \rightarrow f\bar{f}) = \frac{m_{Z'}}{12\pi} (1 - 4\eta_f)^{1/2} C_f \left\{ (v_{Z'}^f)^2 + (a_{Z'}^f)^2 + 2 \left[(v_{Z'}^f)^2 - 2(a_{Z'}^f)^2 \right] \eta_f \right\}, \quad (9)$$

$$\Gamma(Z' \rightarrow \tilde{f}_{L,R} \tilde{\bar{f}}_{L,R}) = \frac{m_{Z'}}{12\pi} (1 - 4\eta_f)^{3/2} \frac{1}{4} C_f (v_{Z'}^f \mp a_{Z'}^f)^2, \quad (10)$$

where we have assumed for simplicity that spin-0 fields belonging to the same chiral supermultiplet are degenerate in mass, $\eta_{f(\bar{f})} \equiv (m_{f(\bar{f})}/m_{Z'})^2$ and

³The D -particles can have either leptoquark or anti-diquark couplings. The UA1 lower limit of 33 GeV on the mass of a leptoquark decaying into μq and/or νq cannot be used directly to bound m_{D_0} , because there are possible competing decay modes $D_0 \rightarrow e q$, τq or $\bar{q}\bar{q}$.

⁴Note that, as shown in Table 1, the ν^c and N fields have large couplings to the Z' and do not couple to the Z , so that they can make important contributions to $\Gamma_{Z'}$ without affecting Γ_Z .

⁵One could in principle devise more stringent lower limits on exotic particle masses using a model for their spectrum, but the conclusions so obtained would be very model-dependent.

the relevant couplings can be read off Table 1. Again, these expressions are for $\eta < .25$, and become zero for $\eta \geq .25$.

Finally, to get the observed value of $\sigma(Z)BR(Z \rightarrow l^+l^-)$ one needs a K-factor. The experimental data from $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV are [17,18]:

$$\sigma(Z)BR(Z \rightarrow l^+l^-) = \begin{cases} 74 \pm 14 \pm 11 & \text{pb} & (\text{UA1}, e^+e^-) \\ 67 \pm 17 \pm 11 & \text{pb} & (\text{UA1}, \mu^+\mu^-) \\ 73 \pm 14 \pm 7 & \text{pb} & (\text{UA2}, e^+e^-) \end{cases} \quad (11)$$

Adding statistical and systematical errors in quadrature and averaging the three determinations we obtain

$$\sigma(Z)BR(Z \rightarrow l^+l^-) = 72 \pm 10 \text{ pb}. \quad (12)$$

In order to be very conservative, for each model and particle spectrum we have computed the value of K by normalizing the theoretical expression for $\sigma(Z)BR(Z \rightarrow l^+l^-)$, obtained with the Duke and Owens I distribution functions, to the one-sigma lower limit of eq.(12). After checking that K is within the range allowed by higher-order QCD corrections [23], we have assumed the same value when calculating $\sigma(Z')BR(Z' \rightarrow e^+e^-)$.

It is interesting to note that the smallest value of $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ is not obtained, as one could naively expect, by assigning to any exotic particle the lightest mass compatible with the present experimental limits. In fact, exotic particles lighter than $m_Z/2$ correspond also to new decay channels for the ordinary Z , thus requiring higher values of the K-factor to match the Z production data. The conservative limits we quote in this paper correspond to the spectrum of exotic particles allowed by the other constraints, that minimizes $\sigma(Z')BR(Z' \rightarrow e^+e^-)$.

Following the procedure described above for models A,B,C and for the two hypotheses on the exotic particles spectrum, we obtain the predictions for $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ shown in Fig. 1. Comparing these with the combined UA1 and UA2 limit (1), we infer that if the Z' can only decay into conventional quarks and leptons, taking the conservative value $m_t = 45$ GeV:

$$m_{Z'} > 167 \text{ GeV} \quad (\text{model A}), \quad (13)$$

$$m_{Z'} > 170 \text{ GeV} \quad (\text{model B}), \quad (14)$$

$$m_{Z'} > 158 \text{ GeV} \quad (\text{model C}), \quad (15)$$

whereas if it can also decay into exotic particles with the least favourable spectrum allowed by the experimental limits (4-5), then

$$m_{Z'} > 118 \text{ GeV} \quad (\text{model A}), \quad (16)$$

$$m_{Z'} > 140 \text{ GeV} \quad (\text{model B}), \quad (17)$$

$$m_{Z'} > 115 \text{ GeV} \quad (\text{model C}). \quad (18)$$

These results become only slightly more stringent if we relax our conservative determination of the K-factor: using the central value of eq.(12), the limits of eqs.(13-15) and (16-18) become $m_{Z'_{(A,B,C)}} > (172, 175, 163) \text{ GeV}$ and $m_{Z'_{(A,B,C)}} > (122, 144, 119) \text{ GeV}$, respectively⁶.

It is instructive to compare the limits (13-18) with those obtained previously from global analyses of neutral current data [12]. For the minimal rank-5 model (model A), the optimistic lower limit (13) is considerably stronger than the model-independent lower limit $m_{Z'} > 129 \text{ GeV}$ (90% c.l.) found there⁷, but is quite model-dependent, and less stringent than the bound $m_{Z'} > 375 \text{ GeV}$ (90% c.l.) found there⁸ using supplementary assumptions on the Higgs v.e.v.'s. The more conservative lower limit (16) is comparable with the previous model-independent neutral current bound. Knowing the variation of χ^2 with $m_{Z'}$ in the neutral current fit [24], we are able to derive a joint lower bound on $m_{Z'}$ using all the information from the $p\bar{p}$ collider and from neutral currents under the two more conservative hypotheses:

$$m_{Z'} > 156 \text{ GeV} \quad (90\% \text{ c.l.}). \quad (19)$$

We consider (19) to be the most stringent reliable lower bound on $m_{Z'}$ which can be derived from the ensemble of present data. For models B and C, the limits obtained in the present work are still weaker than those of Ref.[12], namely $m_{Z'} > 352$ (500) GeV at 90% c.l. for model B and $m_{Z'} > 180$ (181) GeV at 90% c.l. for model C, where the numbers in parentheses use some supplementary assumptions on the Higgs v.e.v.'s.

⁶This corresponds to rescaling the 1.8 pb line of Fig.1 by a factor (62/72).

⁷Note that this lower limit is slightly improved to 134 GeV if the probabilities given by the χ^2 distribution are renormalized to incorporate the physical constraint $m_{Z'} > 0$.

⁸The reader should however keep in mind that this bound is very sensitive to the confidence level required.

What are the prospects for Z' searches using future data? The prospects for the CERN $p\bar{p}$ collider with ACOL can be read directly off the curves for $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ in Fig. 1. One can also make an analysis for the FNAL Tevatron collider using the same assumptions on the spectrum of exotic particles as those used above for the CERN $p\bar{p}$ collider. The corresponding predictions for the ratio $R \equiv \sigma(Z')BR(Z' \rightarrow e^+e^-)/\sigma(Z)BR(Z \rightarrow e^+e^-)$ are shown in Fig. 2 for the optimistic (conservative) assumptions as solid (dashed) lines. We see that if no $Z' \rightarrow e^+e^-$ candidates were seen in an event sample containing 100 (1000) $Z \rightarrow e^+e^-$, the lower limits on $m_{Z'}$ would be

$$m_{Z'} > 212 \text{ (386) GeV} \quad (\text{model A}), \quad (20)$$

$$m_{Z'} > 235 \text{ (403) GeV} \quad (\text{model B}), \quad (21)$$

$$m_{Z'} > 206 \text{ (368) GeV} \quad (\text{model C}) \quad (22)$$

under the optimistic assumption (2), with $m_t = 45$ GeV, and

$$m_{Z'} > 130 \text{ (250) GeV} \quad (\text{model A}), \quad (23)$$

$$m_{Z'} > 176 \text{ (316) GeV} \quad (\text{model B}), \quad (24)$$

$$m_{Z'} > 131 \text{ (243) GeV} \quad (\text{model C}) \quad (25)$$

under the more conservative assumption (8).

The conservative lower limits (16-18) on $m_{Z'}$ could also be improved by better lower limits on exotic particle masses. In the near future, the best prospects for significant improvements seem to be from SLC (for $m_{\pm}$) and the CERN $p\bar{p}$ collider with ACOL or the Tevatron collider (for $m_{\tilde{q},t}$). The latter are difficult to quantify, so we concentrate on the prospective SLC limits. We expect that in the near future the SLC should be able to establish lower limits $m_{\pm} > 45$ GeV on all exotic charged particles, and should place an upper limit on deviations of Γ_Z from the Standard Model prediction. Calculations of $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ using these prospective improved lower limits on $m_{\pm}$ are shown as the dotted lines in Figs. 1 and 2. We see that this would enable the conservative CERN $p\bar{p}$ collider limits (16-18) to be improved to $m_{Z'_{(A,B,C)}} > (122, 141, 121)$ GeV even without the accumulation of more data. We find that with improved limits on $m_{\pm}$, after minimizing $\sigma(Z')BR(Z' \rightarrow e^+e^-)$, the value predicted for Γ_Z is within 100

MeV of its value with no exotic decay channels. Moreover, determination of Γ_Z to arbitrary accuracy provides negligible improvement to the limits on $m_{Z'}$.

Summarizing, in this paper we have analyzed how the present CERN $p\bar{p}$ collider searches for an additional neutral gauge boson can be used to constrain the mass of the Z' in three prototype superstring-inspired models. In the minimal rank-5 model we find that the present data, analyzed under conservative assumptions, give a lower limit on $m_{Z'}$ which is very competitive with that found previously from a global analysis of neutral current data. These two analyses can be combined to give an overall lower limit $m_{Z'} > 156$ GeV at the 90% confidence level. For models B and C the indirect bounds coming from neutral currents are still much stronger than the direct collider bounds derived here. ACO, the FNAL Tevatron collider and the SLC offer prospects for improving all these bounds.

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$v_Z^u = \frac{e}{s_W c_W} \left(\frac{1}{4} - \frac{2}{3} s_W^2 \right)$	$a_Z^u = \frac{e}{s_W c_W} \left(-\frac{1}{4} \right)$
$v_{Z'}^u = 0$	$a_{Z'}^u = \frac{e}{s_W c_W} \left(\frac{1}{3} s_W c_2 \right)$
$v_Z^d = \frac{e}{s_W c_W} \left(-\frac{1}{4} + \frac{1}{3} s_W^2 \right)$	$a_Z^d = \frac{e}{s_W c_W} \left(\frac{1}{4} \right)$
$v_{Z'}^d = \frac{e}{s_W c_W} \left[-\frac{1}{4} s_W \left(c_2 + \sqrt{\frac{5}{3}} s_2 \right) \right]$	$a_{Z'}^d = \frac{e}{s_W c_W} \left[-\frac{1}{4} s_W \left(-\frac{1}{3} c_2 + \sqrt{\frac{5}{3}} s_2 \right) \right]$
$v_\alpha^e = -2v_\alpha^u - v_\alpha^d$	$a_\alpha^e = a_\alpha^d \quad (\alpha = Z, Z')$
$v_\alpha^\nu = -v_\alpha^d - \frac{1}{2} v_\alpha^u - \frac{1}{2} a_\alpha^u$	$a_\alpha^\nu = -v_\alpha^\nu \quad (\alpha = Z, Z')$
$v_\alpha^D = -v_\alpha^u - v_\alpha^d$	$a_\alpha^D = -a_\alpha^u - a_\alpha^d \quad (\alpha = Z, Z')$
$v_\alpha^{H^\pm} = v_\alpha^d - v_\alpha^u$	$a_\alpha^{H^\pm} = -a_\alpha^u - a_\alpha^d \quad (\alpha = Z, Z')$
$v_\alpha^{\overline{H}^0} = a_\alpha^d$	$a_\alpha^{\overline{H}^0} = -v_\alpha^{\overline{H}^0} \quad (\alpha = Z, Z')$
$v_\alpha^{H^0} = a_\alpha^u$	$a_\alpha^{H^0} = -v_\alpha^{H^0} \quad (\alpha = Z, Z')$
$v_\alpha^{\nu^c} = v_\alpha^d + \frac{1}{2} v_\alpha^u - \frac{1}{2} a_\alpha^u$	$a_\alpha^{\nu^c} = -v_\alpha^{\nu^c} \quad (\alpha = Z, Z')$
$v_\alpha^N = -a_\alpha^u - a_\alpha^d$	$a_\alpha^N = -v_\alpha^N \quad (\alpha = Z, Z')$

Table 1: Vector and axial couplings of Z and Z' to the matter fields in the $\underline{27}$ of E_6 , for the class of models considered in the text and in the limit of zero mixing.

References

1. For a review and references see, for example: Superstring Theory, by M. B. Green, J. H. Schwarz and E. Witten, Cambridge University Press, 1987.
2. For recent reviews of superstring phenomenology see, for example: L. Ibáñez, preprint CERN-TH.4769/87 (1987); J. Ellis, preprint CERN-TH.4840/87 (1987).
3. D. J. Gross, J. A. Harvey, E. Martinec and R. Rohm, Phys. Rev. Lett. **54** (1985) 502; Nucl. Phys. **B256** (1985) 253; Nucl. Phys. **B267** (1986) 75.
4. P. Candelas, G. T. Horowitz, A. Strominger and E. Witten, Nucl. Phys. **B258** (1985) 46.
5. E. Witten, Nucl. Phys. **B258** (1985) 75; M. Dine, V. Kaplunovsky, M. Mangano, C. Nappi and N. Seiberg, Nucl. Phys. **B259** (1985) 549; J. Breit, B. Ovrut and G. Segre, Phys. Lett. **158B** (1985) 33; S. Cecotti, J.-P. Derendinger, S. Ferrara, L. Girardello and M. Roncadelli, Phys. Lett. **156B** (1985) 318.
6. J. Ellis, K. Enqvist, S. Kalara, D. V. Nanopoulos and K. A. Olive, preprint CERN-TH.4470/87, MAD/TH/87-17, UMN-TH-609/87 (1987).
7. J. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Nucl. Phys. **B276** (1986) 14 and Mod. Phys. Lett. **A1** (1986) 57.
8. K. Enqvist, D. V. Nanopoulos and M. Quirós, Phys. Lett. **169B** (1986) 343; B. Campbell, J. Ellis, M. K Gaillard, D. V. Nanopoulos and K. A. Olive, Phys. Lett. **180B** (1986) 77; J. Ellis, K. Enqvist, D. V. Nanopoulos and K. A. Olive, Phys. Lett. **188B** (1987) 415; B. A. Campbell, K. A. Olive and D. B. Reiss, preprint UMN-TH-608/87 (1987).
9. F. del Aguila, G. Blair, M. Daniel and G. G. Ross, Nucl. Phys. **B272** (1986) 413.

10. L. E. Ibáñez and J. Mas, Nucl. Phys. B286 (1987) 107.
11. E. Cohen, J. Ellis, K. Enqvist and D. V. Nanopoulos, Phys. Lett. 165B (1985) 76; S. M. Barr, Phys. Rev. Lett. 55 (1985) 2778; V. Barger, N. G. Deshpande and K. Whisnant, Phys. Rev. Lett. 56 (1986) 30; L. S. Durkin and P. Langacker, Phys. Lett. 166B (1986) 436; D. London and J. Rosner, Phys. Rev. D34 (1986) 1530; F. del Aguila, G. Blair, M. Daniel and G. G. Ross, Nucl. Phys. B283 (1987) 50.
12. G. Costa, J. Ellis, G. L. Fogli, D. V. Nanopoulos and F. Zwirner, preprint CERN-TH.4675/87, MAD/TH/87-07, LBL-23271, to appear on Nuclear Physics B; see also U. Amaldi, A. Böhm, L. S. Durkin, P. Langacker, A. K. Mann, W. J. Marciano, A. Sirlin and H. H. Williams, Phys. Rev. D36 (1987) 1385.
13. P. Langacker, R. W. Robinett and J. L. Rosner, Phys. Rev. D30 (1984) 1470; V. Angelopoulos, J. Ellis, D. V. Nanopoulos and N. Tracas, Phys. Lett. 176B (1986) 203; B. Adeva, F. del Aguila, D. V. Nanopoulos, M. Quirós and F. Zwirner, in Proceedings of the 1986 Summer Study on the Physics of the Superconducting Supercollider (R. Donaldson and J. Marx eds.), p.257; V. Barger, N. G. Deshpande, J. L. Rosner and K. Whisnant, Phys. Rev. D35 (1987) 2893; F. del Aguila, M. Quirós and F. Zwirner, Nucl. Phys. B284 (1987) 530; P. J. Franzini and F. Gilman, Phys. Rev. D35 (1987) 855; M. Čvetic and B. W. Lynn, Phys. Rev. D35 (1987) 51; J. F. Gunion, L. Roszkowski and H. E. Haber, Phys. Lett. 189B (1987) 409.
14. F. del Aguila, M. Quirós and F. Zwirner, Nucl. Phys. B287 (1987) 419.
15. S. Geer (UA1 Collaboration), talk given at the International Europhysics Conference on High-Energy Physics (Uppsala, 25 June - 1 July 1987), preprint CERN-EP/87-163 (1987).
16. R. Ansari et al. (UA2 Collaboration), Phys. Lett. 195B (1987) 613.
17. C. Albajar et al. (UA1 Collaboration), preprint CERN-EP/87-149 (1987).

18. R. Ansari et al. (UA2 Collaboration), Phys. Lett. 194B (1987) 158.
19. D. W. Duke and J. F. Owens, Phys. Rev. D30 (1984) 49.
20. C. Albajar et al. (UA1 Collaboration), preprint CERN-EP/87-148 (1987).
21. M. Davier, in Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, July 1986 (S. C. Loken ed.), p.25 (1987); see also F. Takasaki, talk given at the 1987 Int. Symp. on Lepton and Photon Interactions at High Energies, Hamburg, July 1987, to appear in the Proceedings.
22. R. Ansari et al. (UA2 Collaboration), Phys. Lett. 186B (1987) 440.
23. G. Altarelli, R. K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. B246 (1984) 12; G. Altarelli, R. K. Ellis and G. Martinelli, Z. Phys. C27 (1985) 617; G. Altarelli, G. Martinelli and F. Rapuano, Z. Phys. C32 (1986) 369.
24. G. Costa, J. Ellis, G. L. Fogli, D. V. Nanopoulos and F. Zwirner, unpublished (1987).

Figure captions

Figure 1: Calculations of $\sigma(Z')BR(Z' \rightarrow e^+e^-)$ (in pb) at the CERN $p\bar{p}$ collider ($\sqrt{s} = 630$ GeV) for models A,B,C and minimal (solid line), maximal (dashed line) and SLC-maximal (dotted line) assumptions on the spectrum of exotic particles. Also shown is the combined UA1/UA2 90% c.l. upper limit.

Figure 2: Calculations of $R \equiv \sigma(Z')BR(Z' \rightarrow e^+e^-)/\sigma(Z)BR(Z \rightarrow e^+e^-)$ at the FNAL Tevatron collider ($\sqrt{s} = 1800$ GeV) under the same assumptions as for Fig.1. Also shown are the 90% c.l. upper limits corresponding to no $Z' \rightarrow l^+l^-$ candidates in a sample of 100(1000) $Z' \rightarrow l^+l^-$ events.

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Fig. 1a

Fig. 1b

Fig. 1c

Fig. 2a

Fig. 2b

Fig. 2c