Supersymmetric contributions to the decay of an extra Z boson

Tony Gherghetta,* Thomas A. Kaeding,† and Gordon L. Kane‡
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120

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We analyze in detail the supersymmetric contributions to the decay of an extra Z boson in effective rank 5 models, including the important effect of D terms on sfermion masses. The inclusion of supersymmetric decay channels will reduce the Z' branching ratio to standard model particles, resulting in lower Z' mass limits than those often quoted. In particular, the supersymmetric parameter space motivated by the recent Fermilab $ee\gamma\gamma$ event and other suggestive evidence results in a branching fraction $B(Z'\to e^+e^-)\simeq 2-4$ %. The expected cross sections and branching ratios could give a few events in the present data and we speculate on the connection to the three e^+e^- events observed at Fermilab with large dielectron invariant mass.
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Low energy supersymmetry provides the most successful solution to the naturalness problems which plague the standard model (SM). This has led to an extensive study of the experimental consequences of low energy supersymmetry in the literature and the next generation of colliders will explore a substantial fraction of the supersymmetric parameter space. If superstring theory is assumed to be the underlying fundamental theory at the Planck scale, then not only is it responsible for low energy supersymmetry, but the possibility exists that the SM gauge group may be larger at the TeV scale.

The simplest possible extension of the SM gauge group suggested by a gauge group of larger rank involves the introduction of one extra U(1) factor. This produces an extra neutral gauge boson, Z', in the particle spectrum. The low energy phenomenology of Z' bosons has been extensively discussed in the literature (see [1] and references therein). Recently, particularly strong motivation for having the Z' mass below a TeV has been emphasized by Cvetič and Langacker [2]. However, most analyses of Z' physics do not discuss supersymmetric contributions in detail. In this work we will examine the supersymmetric decay channels of the Z' boson, including decays to neutralinos, charginos and supersymmetric Higgs bosons which are normally neglected. Our analysis will also include D-term corrections to the scalar masses which can have appreciable effects and are also not normally included.

In the breakdown of extended gauge groups such as E_6 there can be at most 2 additional gauge bosons in the low energy spectrum. However, for simplicity we will consider an effective rank 5 low energy theory with only one additional gauge boson associated with an extra U(1) and parametrized by $Z'(\theta)=Z_\psi\cos\theta-Z_\chi\sin\theta$, where θ is a mixing angle and (i) Z_ψ occurs when $E_6\to SO(10)\times U(1)_\psi$, (ii) Z_χ occurs when $SO(10)\to SU(5)\times U(1)_\chi$. The orthogonal combination to $Z'(\theta)$ is assumed to have a mass at the intermediate or Planck scale. When E_6 breaks directly to a rank 5 group $[\mathrm{SM}\times U(1)_\eta]$ as in superstring inspired models via Wilson line breaking, the extra Z boson is denoted $Z_\eta\equiv\sqrt{5/8}\,Z_\psi-\sqrt{3/8}\,Z_\chi$. We will also consider the model with $\theta=\eta-\pi/2$ which will be referred to as Z_I. This model occurs when E_6 breaks down to $SU(6)\times SU(2)_I$ and is orthogonal to the η model.

The matter superfields will be assumed to reside in the fundamental **27** of E_6, which consists of the left handed fields $\mathbf{27}=(Q,u^c,e^c,L,d^c,\nu^c,H,D^c,H^c,D,S^c)_L$. The U(1) charge assignments can be found in [1] and the general $U(1)'$ charge of a field Φ will be denoted $Q'(\Phi)\equiv Q_\psi(\Phi)\cos\theta-Q_\chi(\Phi)\sin\theta$.

In general, breaking the $U(1)'$ gauge symmetry with Higgs field vacuum expectation values (VEVs) contributes to sfermion masses via $U(1)'$ D terms in the scalar potential [3]. Depending on the number of Higgs fields which are used to spontaneously break the gauge symmetry, the contribution to the scalar mass squared term has the form

$$\Delta\tilde{m}_a^2=g'^2Q'_a\sum_i Q'_i\langle\phi_i\rangle^2, \tag{1}$$

where the sum is over all Higgs fields which obtain VEVs. In the pure rank 5 or η model the $U(1)'$ symmetry is broken using only one SM $U(1)'$ singlet. However, in the effective rank 5 models which are parametrized by the angle θ, there are also orthogonal D terms which come from breaking the extra $U(1)''$ at an intermediate or Planck scale. Since these orthogonal D terms can raise the sparticle mass spectrum to energy scales much greater than a TeV, we will assume that their contribution is negligible. This can be achieved by using a mirrorlike pair of $U(1)''$ charged SM singlets with charges of opposite sign to ensure D'' flatness. This amounts to assuming degeneracy of the mirrorlike Higgs soft masses at some high energy scale. Thus in the effective rank 5 models the D-term contribution to the scalar masses [assuming again that $U(1)'$ is broken by one SM singlet] becomes

$$\Delta\tilde{m}_a^2=\frac{g'^2}{2}(Q'_1v_1^2+Q'_2v_2^2+Q'_3v_3^2)Q'(a), \tag{2}$$

where the neutral scalar components of H,H^c and S^c have VEVs $\langle\phi_i^0\rangle=v_i/\sqrt{2}$ where $i=1,2,3$ respectively.

*Email address: tgher@umich.edu
†Email address: kaeding@feynman.physics.lsa.umich.edu
‡Email address: gkane@umich.edu

While we can treat the VEVs v_i as phenomenological parameters it is also interesting to examine the consequences for effective rank 5 models if we assume that a radiative mechanism is responsible for breaking the U(1)$'$ gauge symmetry. This is similar to the analysis done by Cvetič and Langacker [2] where it was shown that it is possible to achieve an $M_{Z'}/M_Z$ hierarchy for general string models, without excessive fine-tuning provided $M_{Z'} \lesssim 1$ TeV (see also [4]). We will consider the case of grand unification with effective rank 5 models parametrized by $Z'(\theta)$. If the radiative breaking of U(1)$'$ is due to one SM singlet and the superpotential contains a term $W=\lambda\Phi_1\Phi_2\Phi_3$, then at low energies we will assume that the scalar potential for the neutral Higgs bosons has the form

$$\begin{aligned} V=&m_1^2|\phi_1^0|^2-m_2^2|\phi_2^0|^2-m_3^2|\phi_3^0|^2+(\lambda A_\lambda \phi_1^0\phi_2^0\phi_3^0+\text{H.c.})\\ &+\lambda^2(|\phi_1^0|^2|\phi_2^0|^2+|\phi_1^0|^2|\phi_3^0|^2+|\phi_2^0|^2|\phi_3^0|^2)\\ &+\tfrac{1}{8}g_W^2(|\phi_1^0|^2-|\phi_2^0|^2)^2+\tfrac{1}{2}g'^2(Q_1'|\phi_1^0|^2+Q_2'|\phi_2^0|^2\\ &+Q_3'|\phi_3^0|^2)^2 \end{aligned} \tag{3}$$

where m_1, m_2, m_3 are the soft supersymmetric Higgs boson masses and A_λ is a soft trilinear parameter. Given that $v_2 = v_1\tan\beta$, the minimum of the potential (3) occurs at

$$v_1^2 \simeq \frac{8}{g_W^2(1-\tan^2\beta)^2}\left[-m_1^2+m_2^2\tan^2\beta-\frac{(Q_1'+Q_2'\tan^2\beta)}{Q_3'}m_3^2\right] \tag{4}$$

$$v_3^2 \simeq \frac{2m_3^2}{g'^2Q_3'^2}-\frac{(Q_1'+Q_2'\tan^2\beta)}{Q_3'}v_1^2, \tag{5}$$

where we have neglected the corrections from the potential terms involving λ. The matrix elements of the Z-Z' mass mixing matrix become

$$M_Z^2 \simeq 2\frac{(1+\tan^2\beta)}{(1-\tan^2\beta)^2}\left[-m_1^2+m_2^2\tan^2\beta-\frac{(Q_1'+Q_2'\tan^2\beta)}{Q_3'}m_3^2\right] \tag{6}$$

$$\begin{aligned}\Delta M^2 \simeq -4\frac{g'}{g_W}\frac{(Q_1'-Q_2'\tan^2\beta)}{(1-\tan^2\beta)^2}\Bigg[&-m_1^2+m_2^2\tan^2\beta\\ &-\frac{(Q_1'+Q_2'\tan^2\beta)}{Q_3'}m_3^2\Bigg]\end{aligned} \tag{7}$$

$$\begin{aligned} M_{Z'}^2 \simeq 2m_3^2+8\frac{g'^2}{g_W^2}\frac{1}{(1-\tan^2\beta)^2}\Bigg[&Q_1'^2\left(1-\frac{Q_3'}{Q_1'}\right)\\ &+Q_2'^2\left(1-\frac{Q_3'}{Q_2'}\right)\tan^2\beta\Bigg]\Bigg[-m_1^2+m_2^2\tan^2\beta\\ &-\frac{(Q_1'+Q_2'\tan^2\beta)}{Q_3'}m_3^2\Bigg]. \end{aligned} \tag{8}$$

If $\tan\beta=0$ and $m_1^2<0$, then the above expressions agree with those in [2]. In order to achieve a reasonable hierarchy between M_Z and $M_{Z'}$ for negligible Z-Z' mixing ϕ we must have $v_1^2 \ll m_3^2$. If minima exist for $m_1^2<0$ in Eq. (3), then this can only occur when the charge combination $Q_1'+Q_2'\tan^2\beta$ has the same relative sign as Q_3'. If $\tan\beta \gtrsim 1$, this will happen when $-\pi/2 \leqslant \theta \lesssim -\pi/3$. For example, an exact numerical determination of the minimum at $\theta=-1.161$ for the parameters $\tan\beta=1.5, m_1=m_2=100$ GeV, $m_3=500$ GeV, $A_\lambda=1$ TeV and $\lambda=0.02$ yields an acceptable Z-Z' hierarchy with $M_{Z'}\simeq 700$ GeV and $\phi=-0.0057$. At values of $\theta \gtrsim -\pi/3$ an extreme fine-tuning of the soft breaking parameters is needed for a radiative mechanism to work. However, if $m_1^2>0$ in the potential (3), then we do not necessarily need the charge combination $Q_1'+Q_2'\tan^2\beta$ to have the same relative sign as Q_3'. In this case no fine-tuning of the soft parameters is needed as v_1^2 can be made small by cancellation of the positive terms against $-m_1^2$ for all values of θ. Particular scenarios for achieving these various symmetry breaking potentials at low energies requires a complete renormalization group analysis.

The decay modes of the Z' include decays to fermions, sfermions and Higgs bosons. The expressions for these modes appear in [1], but need to be generalized for arbitrary $Z'(\theta)$ and nontrivial phase space factors. Because of space limitations here, the complete expressions appear in [5].

In the gaugino sector there will be two extra neutralinos in addition to the four found in the minimal supersymmetric standard model (MSSM). The expression for the Z' decay width into neutralinos in this more general context can be found in [6]. However, since the Z' boson and the singlet

TABLE I. Branching fractions of all possible Z' decay channels in a supersymmetric framework for various Z' models.

Z' decay channel	Z_I	Z_ψ	Z_η
e^+e^-	0.0391	0.0280	0.0171
$\mu^+\mu^-$	0.0391	0.0280	0.0171
$\tau^+\tau^-$	0.0391	0.0280	0.0171
$\overline{\nu_e}\,\nu_e$	0.0782	0.0280	0.0890
$\overline{\nu_\mu}\,\nu_\mu$	0.0782	0.0280	0.0890
$\overline{\nu_\tau}\,\nu_\tau$	0.0782	0.0280	0.0890
$\overline{u}\,u$	0.0000	0.0839	0.0820
$\overline{c}\,c$	0.0000	0.0839	0.0820
$\overline{t}\,t$	0.0000	0.0553	0.0540
$\overline{d}\,d$	0.1174	0.0839	0.0513
$\overline{s}\,s$	0.1174	0.0839	0.0513
$\overline{b}\,b$	0.1174	0.0839	0.0513
$\Sigma\tilde{u}_i^*\tilde{u}_j$	0.0000	0.0000	0.0000
$\Sigma\tilde{d}_i^*\tilde{d}_j$	0.1746	0.0000	0.0000
$\Sigma\tilde{e}_i^*\tilde{e}_j$	0.0000	0.0000	0.0000
$\Sigma\tilde{\nu}_i^*\tilde{\nu}_i$	0.0000	0.0000	0.1280
H^+H^-	0.0048	0.0021	0.0003
$\Sigma P_0H_i^0$	0.0110	0.0038	0.0010
$W^\pm H^\mp$	0.0018	0.0102	0.0039
ΣZH_i^0	0.0075	0.0500	0.0206
W^+W^-	0.0028	0.0062	0.0155
$\Sigma\tilde{C}_i\tilde{C}_j$	0.0182	0.0759	0.0329
$\Sigma\tilde{N}_i\tilde{N}_j$	0.0753	0.2090	0.1077

Higgs S^c supermultiplets are electromagnetically neutral, they do not contribute any extra particles to the chargino spectrum. The Z' can of course couple to the charged Higgsinos which leads to the chargino Lagrangian

$$\mathcal{L}=\frac{1}{2}g'\sum_{i,j=1}^{2}\overline{\widetilde{C}_i}\gamma^\mu(v_{ij}+a_{ij}\gamma_5)\widetilde{C}_j Z'_\mu \tag{9}$$

where $\widetilde{C}_i$ are the chargino mass eigenstates and

$$v_{11}=Q'_1\sin^2\phi_- - Q'_2\sin^2\phi_+ , \tag{10}$$

$$a_{11}=Q'_1\sin^2\phi_- + Q'_2\sin^2\phi_+ , \tag{11}$$

$$v_{12}=v_{21}=Q'_1\sin\phi_-\cos\phi_- - \delta Q'_2\sin\phi_+\cos\phi_+ , \tag{12}$$

$$a_{12}=a_{21}=Q'_1\sin\phi_-\cos\phi_- + \delta Q'_2\sin\phi_+\cos\phi_+ , \tag{13}$$

$$v_{22}=Q'_1\cos^2\phi_- - Q'_2\cos^2\phi_+ , \tag{14}$$

$$a_{22}=Q'_1\cos^2\phi_- + Q'_2\cos^2\phi_+ . \tag{15}$$

In Eqs. (10)–(15), $\phi_\pm$ are the angles of the unitary transformation matrices used to diagonalize the chargino mass matrix [7] and $\delta=n_1n_2$, where $n_1=\mathrm{sgn}(m_{\widetilde{C}_1^\pm})$ and $n_2=\mathrm{sgn}(m_{\widetilde{C}_2^\pm})$. The Z' decay rate into chargino pairs is calculated from the Lagrangian (9) to be

$$\Gamma(Z'\to\widetilde{C}_i\widetilde{C}_j)=\frac{g'^2}{48\pi}M_{Z'}\left[(v_{ij}^2+a_{ij}^2)\left(1-\frac{(m_i^2+m_j^2)}{2M_{Z'}^2}-\frac{(m_i^2-m_j^2)^2}{2M_{Z'}^4}\right)+3(v_{ij}^2-a_{ij}^2)\frac{m_im_j}{M_{Z'}^2}\right]\times\sqrt{\left(1-\frac{(m_i+m_j)^2}{M_{Z'}^2}\right)\left(1-\frac{(m_i-m_j)^2}{M_{Z'}^2}\right)}. \tag{16}$$

At the $p\bar{p}$ Tevatron collider the Z' production mechanism is due to the Drell-Yan process. Direct limits on $p\bar{p}\to Z'\to e^+e^-$ at the Tevatron can place a lower bound on the Z' mass depending on the value of the branching ratio $B(Z'\to e^+e^-)$ [8]. In order to estimate the e^+e^- branching ratio in a supersymmetric framework, all possible decay channels (such as decays to sparticles) need to be included. While there are many unknown parameters in the supersymmetric standard model it is possible to constrain parameters by requiring consistency with other indirect studies of supersymmetric parameter space. For example, in the recent supersymmetric interpretation of the $ee\gamma\gamma$ event, the supersymmetric parameters $\mu,\tan\beta,M_1$ and M_2 are constrained [9]. The parameter ranges of these variables will in turn constrain the neutralino and chargino mass spectrum.

In Table I we list the branching fraction of all possible Z' decay channels in various $Z(\theta)$ models for the following choice of supersymmetric parameters:

$$\tan\beta=1.5,\quad \mu=-50\ \mathrm{GeV}$$

$$M_1=80\ \mathrm{GeV},\quad M_2=100\ \mathrm{GeV},\quad M'=300\ \mathrm{GeV}$$

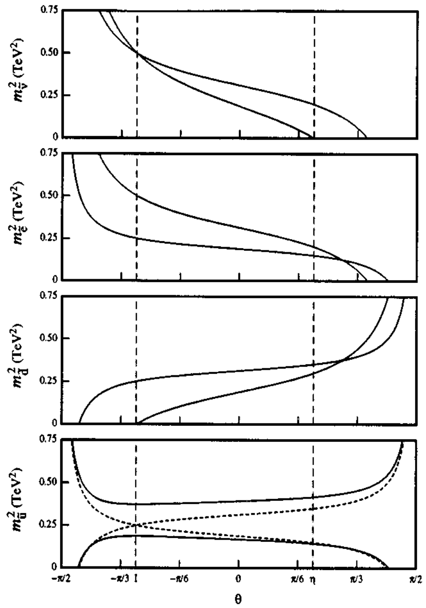

FIG. 1. The squark and slepton masses squared as a function of the Z' mixing parameter θ. Mixing is only important for the top squarks and the solid line in the up squark plot represents $\tilde{t}_{1,2}$.

$$\widetilde{m}=500\ \mathrm{GeV},\quad A=500\ \mathrm{GeV}$$

where we have assumed common scalar mass $\widetilde{m}$ and A terms. In addition we also fix the Z' mass to be $M_{Z'}\simeq 700$ GeV, which sets the scale for all the kinematically allowed decays.

In Fig. 1 we show the squark and slepton masses including the D-term contributions. The general effect of the D-term contributions is to make the squarks and sleptons heavy since the scale of the D terms is set by $M_{Z'}$ (or v_3). However, in Fig. 1 there are special values of the mixing parameter θ where the D-term contributions cancel and the squark and slepton masses become light. These are the only points that could be consistent with squarks and sleptons that would have appeared already at Fermilab [10]. Such sensitivities are very encouraging from the point of view of extracting information about new physics from limited data. Beyond these values the squared masses become negative and this signals the onset of charge and color breaking minima. It may be possible that radiative corrections can stabilize the vacuum but an analysis of these corrections is beyond the scope of this paper. When the Z' mixing parameter θ approaches $\pm\pi/2$ the squark and slepton masses become unacceptably large. This is because the D-term contribution to the scalar masses from v_3 [Eq. (2)] is $\Delta\widetilde{m}_a^2\propto M_{Z'}^2/Q'_3$ and when $Q'_3\to 0$ we have $\Delta\widetilde{m}_a^2\to\pm\infty$. Thus, in effective rank 5 models with a U(1)$'$ symmetry breaking potential of the form (3) one can exclude χ-like models (or regions near $\theta\simeq\pm\pi/2$) because the squark and slepton masses become large and negative, leading to charge and color breaking minima (where we have neglected radiative corrections).

As far as determining a lower Z' mass bound from collider experiments, the main consequence of accurately including all supersymmetric decay channels is that the branching fraction into leptons and quarks is reduced. This

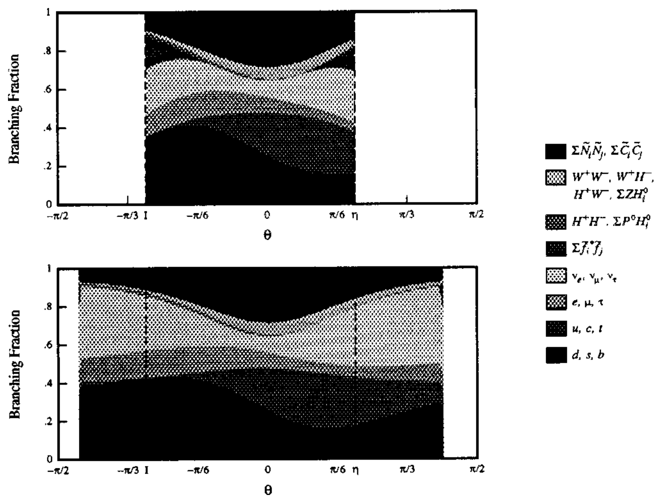

FIG. 2. The Z' decay branching fractions as a function of the mixing parameter θ for a representative set of supersymmetric parameters as defined in the text. The lower figure has $\tilde{m}=1$ TeV.

lowers the Z' mass bound from that normally quoted in the literature. The e^+e^- branching fraction from Table I is in the range 2–4 %, where typically in non-supersymmetric models one obtains 3–6 % [11]. If we use the direct limit from a recent combined analysis of Collider Detector at Fermilab (CDF) and D0 data [$\sigma\times B(Z'\rightarrow e^+e^-)\leqslant 0.28$ pb] [8], then for the branching fractions listed in Table I we obtain $M_{Z'}\gtrsim 360{,}370{,}360$ GeV for Z_I,Z_ψ and Z_η respectively.

The importance of various decay channels can be determined from how the branching fractions in Table I vary as a function of the Z' mixing parameter θ. This dependence is shown in Fig. 2 for $\tilde{m}=500$ and 1000 GeV. We have excluded the regions corresponding to negative squark and slepton masses which are near $\theta=\pm\pi/2$. As the soft mass parameter $\tilde{m}$ becomes larger the charge and color breaking regions shrink. Near the excluded regions (which correspond to Z_η and Z_I for $\tilde{m}=500$ GeV) the Z' branching fractions to squark and sleptons are maximized because their masses become light enough to be kinematically allowed. As $\theta\rightarrow 0$ the D-term corrections make the squarks and sleptons kinematically inaccessible. A significant neutralino and chargino branching fraction occurs in models which are ψ-like (or $\theta\simeq 0$). Specifically, decays to the lightest neutralino can be as large as 10% and this would contribute greatly to the Z' invisible width. As $\theta\rightarrow\pm\pi/2$ the branching fraction to neutralino and chargino pairs gets smaller while the neutrino branching fraction becomes larger. Decays to Higgs bosons become non-negligible for $\theta\lesssim 0$. One should also note that the branching fraction to leptons and quarks remains fairly constant. In particular the branching fraction to light quarks (u,c,d,s,b) is at most 0.45. Thus for light quarks $\sigma\times B(Z'\rightarrow\overline{q}q)\simeq 0.25$ pb where we have assumed $m_{Z'}\simeq 700$ GeV. This is too small to be observable in the inclusive jet cross section. Note that the branching fraction to up quarks vanishes for Z_I-type models. This is a consequence of the fact that the up-quark Z' coupling becomes zero.

It is also amusing to note that both CDF [12] and D0 [13] report events with dielectron invariant mass $\gtrsim 500$ GeV and CDF also has a second event with invariant mass $\simeq 350$ GeV. If one assumes that these high energy events are due to the decay of a Z' boson, then given our range of $B(Z'\rightarrow e^+e^-)$, this would correspond to a Z' mass $m_{Z'}\simeq 600$–700 GeV. (Note that in more general supersymmetric models there may be other dilepton sources beyond those considered here.) One would also expect these events to be backward, i.e. $\cos\theta^*<0$ where θ^* is the angle of the outgoing e^- with respect to the quark in the $q\overline{q}$ center of mass frame [11,14]. A very large asymmetry is expected for Z_I-type models. It is tantalizing that the two events reported by CDF with invariant masses of 350 GeV and 504 GeV have $\cos\theta^*$ values of -0.14 and -0.27 respectively [12]. If we require that the probability of observing two backward events be at least $1/e$, then one would need $A_{FB}\lesssim -0.2$. The measurement of A_{FB} will provide an interesting test for Z' models at future colliders.

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