Fermi National Accelerator Laboratory

FERMILAB-PUB-87/118-T
OSU Research Note 193
July, 1987

Weak Neutralino Decays of an Extra Z boson

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Abstract

We calculate the decay widths of an extra Z boson (Z_2) into a pair of weak neutralinos in a superstring inspired $SU(2) \times U(1) \times U'(1)$ gauge theories. If kinematically allowed, the branching ratio can be as large as about sixteen percent. Subsequent decays of these neutralino pairs give rise to multilepton events (four charged leptons with high p_T) which will be an interesting signal for supersymmetry.

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The standard $SU(2) \times U(1)$ gauge theory of the weak and electromagnetic interactions [1–3] is in excellent agreement with the observed properties of the W and the Z bosons, and with all the existing neutral current experiments. However, the possibility that the symmetry group is larger, such as having an extra $U(1)$ at the 100 GeV or higher energy scale, is not excluded by the available data. The possibility of the existence of such an extra $U(1)$ is indicated by the recent developments in the superstring theories. The mass scale, at which this extra $U(1)$ is broken, is not given by the theory. We shall assume that this extra $U(1)$ remains unbroken all the way down to the weak scale, and thus there is an extra gauge boson, Z_2, with mass of the order of the weak scale. Recently, a number of groups[4–13] have worked out the phenomenological consequences of such an extra gauge boson on the neutral current experiments, the W and Z masses, and its searches in collider experiments. The typical bound on the Z_2 mass is that it can be as low as around 150 GeV. The decays of Z_2 to the usual quarks and leptons have been widely discussed. In recent works, it was shown that the decays $Z_2 \rightarrow Z_1 H$[14–18,24], $Z_2 \rightarrow W^+W^-$[19–24] have substantial branching ratios (typically a few percent), and thus are very important processes for observing the Higgs boson, and the W boson pairs respectively. In this work, we consider another important decay mode, $Z_2 \rightarrow \tilde{Z}_i \tilde{Z}_j$, $\tilde{Z}_i$ being a weak neutralino. This decay mode is a supersymmetric counterpart of the $Z_2 \rightarrow Z_1 H$ mode, and thus expected to be a substantial branching fraction. The subsequent decays of these neutralino pairs will give rise to four charged leptons with large p_T in the final state (along with the missing photinos). This will be an interesting signal for supersymmetry. In the following, we shall diagonalize the 6x6 neutralino mass matrix, and calculate the coupling constants for the interactions of the gauge boson Z_2 with the weak neutralinos. We then calculate the decay widths, and discuss the four charged leptons signal from the subsequent decays of these neutralinos.

We start with the gauge group $SU(2) \times U(1) \times U'(1)$. The gauge fields (couplings) are $A_{\mu i}(g), B_\mu(g'/2)$ and $C_\mu(g'')$ respectively. For the Higgs scalars, we take two doublets, $H, \bar{H}$ and one singlet, N with the hyperchanges 1, -1, 0 respectively with respect to the usual $U(1)$, and $Y, \bar{Y}, Y_N$ respectively with respect to the extra $U'(1)$. We assume the vacuum expectation values of the Higgs fields to be

$$< H >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ V \end{pmatrix}, < \bar{H} >= \frac{1}{\sqrt{2}} \begin{pmatrix} \bar{V} \\ 0 \end{pmatrix}, < N >= \frac{1}{\sqrt{2}} X \qquad (1)$$

In general, the neutral gauginos $(\tilde{A}_3, \tilde{B}, \tilde{C})$ will mix with the neutral Higgsunos $(\tilde{H}_0, \tilde{\bar{H}}_0, \tilde{N})$, and the weak neutralino mass matrix will be 6x6. Though our considerations are valid for any extra $U(1)$, for the calculation of the coupling constants and the branching ratios, we shall use the extra $U(1)$ that arises in the superstring E_6 theories. In E_6 models, of current interest because of superstrings, there are two extra gauge bosons, called Z_ψ and Z_χ. Z_ψ arise when E_6 breaks down to an $S0(10)$ x $U(1)$ and Z_χ arises when $S0(10)$ breaks down to $SU(5)$ x $U(1)$. The lowest lying "extra Z" is in general, an arbitrary mixture of Z_ψ and Z_χ.

$$Z(\alpha) = Z_\psi \cos\alpha + Z_\chi \sin\alpha \qquad (2)$$

where α is a mixing angle which specifies a model. The coupling constant, g'' of this extra $U(1)$ group, corresponding to any $Z(\alpha)$ is

$$g'' = \sqrt{\frac{5}{3}} g' = \sqrt{\frac{5}{3}} \frac{e}{\cos\theta_W} \qquad (3)$$

The extra Z boson, Z_η that appears in the superstring E_6 corresponds to $\alpha = 37.8°$. For this case, the value of the hypercharges of the Higgs fields are

$$Y = \frac{-4}{2\sqrt{15}},\ \bar{Y} = \frac{-1}{2\sqrt{15}},\ Y_N = \frac{5}{2\sqrt{15}} \qquad (4)$$

We also choose that the Higgs superfields belong to the same 27-plet of E_6 to which the heaviest quarks and lepton generation belongs. $H, \bar{H}$ belong to the 10-plets of $S0(10)$, with the conventional Higgs quantum numbers, while N is the $S0(10)$ singlet. We also assume that Higgs fields belonging to the lighter generations have no VEV's and hence do not contribute to the neutralino mass matrix. Then, the

6x6 neutralino mass matrix, in the basis $(\tilde{B}, \tilde{A}_3, \tilde{C}, \tilde{H}_0, \tilde{\bar{H}}_0, \tilde{N})$ is

$$\begin{pmatrix} m_1 & 0 & 0 & \frac{g'V}{2} & \frac{-g'\bar{V}}{2} & 0 \\ 0 & m_2 & 0 & \frac{-gV}{2} & \frac{g\bar{V}}{2} & 0 \\ 0 & 0 & m' & -\sqrt{\frac{4}{15}}g''V & \frac{-g''\bar{V}}{\sqrt{60}} & \sqrt{\frac{5}{12}}g''X \\ \frac{g'V}{2} & \frac{-gV}{2} & -\sqrt{\frac{4}{15}}g''V & 0 & \beta\frac{X}{\sqrt{2}} & \beta\frac{\bar{V}}{\sqrt{2}} \\ -\frac{g'\bar{V}}{2} & \frac{g\bar{V}}{2} & -\frac{g''\bar{V}}{\sqrt{60}} & \frac{\beta X}{\sqrt{2}} & 0 & \beta\frac{V}{\sqrt{2}} \\ 0 & 0 & \sqrt{\frac{5}{12}}g''X & \beta\frac{\bar{V}}{\sqrt{2}} & \beta\frac{V}{\sqrt{2}} & 0 \end{pmatrix} \tag{5}$$

In (6), the mass terms with the gauge coupling constants (g, g', g'') arises from the usual supersymmetric interaction terms between the gauginos $(\tilde{A}, \tilde{B}, \tilde{C})$, the Higgsinos $(\tilde{H}, \tilde{\bar{H}}, \tilde{N})$ and the Higgs bosons $(H, \bar{H}, N)$. The mass terms with β comes from the trilinear interaction $\beta H\bar{H}N$. m_1, m_2 and m' are the tree level soft gaugino masses. Our mass matrix (6) agrees with that of ref. 5 with the appropriate replacement $(V, \bar{V}, X) \rightarrow \frac{1}{\sqrt{2}}(V, \bar{V}, X), g_1 \rightarrow \sqrt{\frac{5}{3}}g', g_E \rightarrow g''$.

The mass matrix (5) has six dimensional parameters, $m_1, m_2, m', V, \bar{V}, X$, and has to be diagonalized numerically. However, since the supersymmetry is softly broken at the W-scale, we expect m_1, m_2, m' to be of order $\sim m_W$, and hence $(m_1, m_2, m', V, \bar{V}) \ll X$. We shall set $m_1 = m_2 = m' = V = \bar{V} = 0$ in (5) and diagonalize it exactly. This will be a reasonable approximation for the case of $M_{Z2} \gg m_W$, and will give us the dominant $Z_2\tilde{Z}_i\tilde{Z}_j$ couplings. In this limit, the mass eigenvalues are

$$\lambda_{1,2} = 0, \lambda_{3,4} = \pm\beta X, \lambda_{5,6} = \pm\sqrt{\frac{5}{12}}g''X \tag{6}$$

We point out that $\lambda_{1,2} = 0$ is a result of our approximation, and will be of order V without that.

In this approximation, the current eigenstates $(\tilde{B}, \tilde{A}_3, \tilde{C}, \tilde{H}_0, \tilde{\bar{H}}_0, \tilde{N})$ in terms of the mass eigenstates $(\tilde{\gamma}, \tilde{Z}_i, i = 1-5)$ are

$$\begin{pmatrix} \tilde{B} \\ \tilde{A}_3 \\ \tilde{C} \\ \tilde{H}_0 \\ \tilde{\tilde{H}}_0 \\ \tilde{N} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 & 0 & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \tilde{\gamma} \\ \tilde{Z}_1 \\ \tilde{Z}_2 \\ \tilde{Z}_3 \\ \tilde{Z}_4 \\ \tilde{Z}_5 \end{pmatrix} \tag{7}$$

where θ is an arbitrary angle in this approximation.

Now, we are ready to calculate the interactions between the Majorana weak neutralinos and the neutral gauge bosons. The relevant interaction terms in terms of the current eigenstates are

$$\begin{aligned} L &= \bar{\tilde{H}}\, \gamma^\mu \gamma_5 \left[g\left(-\frac{1}{2}\right) A_{3\mu} + \frac{g'}{2} B_\mu + g'' Y C_\mu \right] \tilde{H} \\ &+ \bar{\tilde{\tilde{H}}}\, \gamma^\mu \gamma_5 \left[g\left(\frac{1}{2}\right) A_{3\mu} - \frac{g'}{2} B_\mu + g'' \bar{Y} C_\mu \right] \tilde{\tilde{H}} \\ &+ \bar{\tilde{N}}\, \gamma_\mu \gamma_5 \left[g'' Y_N C_\mu \right] \tilde{N} \,. \end{aligned} \tag{8}$$

Using $g'B - gA_3 = \sqrt{g^2 + g'^2}\, Z$, and ignoring the small Z–C mixing (so that $Z = Z_1, C = Z_2,\ \ Z_1, Z_2$ being the mass eigenstates), we obtain

$$\begin{aligned} L &= \bar{\tilde{H}}\, \gamma^\mu \gamma_5 \left[\frac{1}{2}\sqrt{g^2 + g'^2}\, Z_{1\mu} + g'' Y Z_{2\mu} \right] \tilde{H} \\ &+ \bar{\tilde{\tilde{H}}}\, \gamma^\mu \gamma_5 \left[-\frac{1}{2}\sqrt{g^2 + g'^2}\, Z_{1\mu} + g'' \bar{Y} Z_{2\mu} \right] \tilde{\tilde{H}} \\ &+ \bar{\tilde{N}}\, \gamma^\mu \gamma_5 \left[g'' Y_N Z_{2\mu} \right] \tilde{N} \end{aligned} \tag{9}$$

The interactions between the mass eigenstates neutralinos $(\tilde{\gamma}_i, \tilde{Z}_i, i = 1-5)$ and the gauge boson Z_2 are obtained by substituting $\tilde{H}, \tilde{\tilde{H}}$ and $\tilde{N}$ in terms of $\tilde{\gamma}_i, \tilde{Z}_i$ from eq. (7). Writing these as

$$L = \sum_{i,j} g_{Z_2 \tilde{Z}_i \tilde{Z}_j} \quad \bar{\tilde{Z}}_i \gamma^\mu \gamma_5 \tilde{Z}_j Z_{2\mu}, \tag{10}$$

we find that only non–zero couplings are

$$g_{Z_2 \tilde{Z}_2 \tilde{Z}_2} = g_{Z_2 \tilde{Z}_3 \tilde{Z}_3} = \frac{1}{2} g'' \left(Y + \bar{Y} \right). \tag{11}$$

We point out that the vanishing of all the other couplings is the result of our approximation ($m_1 = m_2 = m' = V = \bar{V} = 0$). Without it, those couplings will be of $0(r)$ or $0(r^2)$ where $r = V/X$. We emphasize that the couplings given by (11) are as big as the usual gauge couplings. They are not suppressed by the small ratio, r.

We are now in a position to calculate the branching ratios for the process $Z_2 \rightarrow \tilde{Z}_i \tilde{Z}_j$ using eqs. (10)–(11). The decay widths are

$$\begin{aligned} \Gamma\left(Z_a \rightarrow \tilde{Z}_i \tilde{Z}_j\right) &= \frac{g^2_{Z_2 \tilde{Z}_i \tilde{Z}_j} M_a}{12\pi} \\ &* \left[1 - \frac{1}{2}\left(\frac{m_i^2 + m_j^2}{M_a^2}\right) - \frac{1}{2}\frac{(m_i^2 - m_j^2)^2}{M_a^4} - 3\frac{m_i m_j}{M_a^2} \right] \\ &* \sqrt{\lambda\left(1, m_i^2/M_a^2, m_j^2/M_a^2\right)} \end{aligned} \tag{12}$$

where

$$\lambda\left(1, b, C\right) = 1 + b^2 + c^2 - 2b - 2c - 2bc \tag{13}$$

Using eqs. (3), (4) and (11), in the limit of $M_2 \gg m_2 (m_2 = m_3$ being the masses of $\tilde{Z}_2, \tilde{Z}_3)$, we obtain from eq. (12),

$$\Gamma\left(Z_2 \rightarrow \tilde{Z}_2 \tilde{Z}_2\right) = \Gamma\left(Z_2 \rightarrow \tilde{Z}_3 \tilde{Z}_3\right) = \frac{25\alpha_{em}}{432 \cos^2\theta_W} M_2 \simeq 0.6\text{x}10^{-3} M_2 \tag{14}$$

The decay width of Z_2 for decays to 3 familes of the usual quarks and leptons (allowing decays to only 15 ordinary fermions) is given by (for the case of the superstring $E_6, \alpha = 37.8°$)

$$\Gamma\left(Z_2 \rightarrow \sum f\bar{f}\right) = \frac{5\alpha_{em}}{8\cos^2\theta_W} M_2 \simeq 6.3\text{x}10^{-3} M_2 \tag{15}$$

From eqs. (14) and (15), we see that the total branching ratio to weak neutralino decays can be as large as 16%.

We mention that in order that the decays $Z_2 \to \tilde{Z}_2\tilde{Z}_2$, $\tilde{Z}_3\tilde{Z}_3$ to be kinematically allowed, we must have

$$\beta X < \frac{1}{2}M_2 \tag{16}$$

The mass M_2 of the Z_2 boson in our approximation is

$$M_2 \simeq \frac{1}{2}g''Y_N X \tag{17}$$

Using eqs. (3), (4), (16) and (17), the necessary condition on the trilinear coupling parameter, β becomes

$$\beta < \frac{5}{24}\ \frac{e}{\cos\theta_W} \simeq 0.24e \tag{18}$$

We consider (18) to be a rather weak condition on the parameter β.

We now consider briefly the multilepton signal arising from the decays

$$Z_2 \to \tilde{Z}_i\tilde{Z}_i \to \left(\ell_1^+\ell_1^-\tilde{\gamma}\right) + \left(\ell_2^+\ell_2^-\tilde{\gamma}\right) \tag{19}$$

where $\ell = e$ or μ. In electron–positron collider (such as LEP), we can sit at the Z_2 resonance. The total cross–section at the Z_2 resonance is

$$\sigma_{Z_2} \equiv \sigma\left(e^+e^- \to Z_2 \to \mathrm{all}\right) = \frac{4\pi\alpha_{em}\left(\alpha_2^2+\beta_2^2\right)}{M_2\Gamma_2} \tag{20}$$

where Γ_2 is the total width of Z_2, and $e\alpha_2(e\beta_2)$ are the vector (axial vector) couplings of the electron to Z_2. For the case of the superstring E_6,

$$\alpha_2 = \frac{-1}{4\cos\theta_W}, \quad \beta_2 = \frac{-1}{12\cos\theta_W} \tag{21}$$

Using (21) and the value of Γ_2 from (14) and (15), we obtain,

$$\sigma_{Z_2} \simeq 10^4 pb \ \text{ for } \ M_2 = 200\ \mathrm{GeV} \tag{22}$$

The branching ratio, B_1 for $\tilde{Z}_i \to \ell^+\ell^-\tilde{\gamma}$ is $\sim 0.11\mathrm{x}2 \simeq 0.22$, counting both e and μ. As shown before, the branching ratio, B_2 for $Z_2 \to \tilde{Z}_1\tilde{Z}_1 + \tilde{Z}_2\tilde{Z}_2$ is $\simeq 0.16$. Thus, the branching ratio,

$$B\left(Z_2 \to \tilde{Z}_1\tilde{Z}_1 + \tilde{Z}_2\tilde{Z}_2 \to \ell_1^+\ell_1^+\tilde{\gamma} + \ell_2^+\ell_2^-\tilde{\gamma}\right) = B_1^2 B_2 \simeq 7.7\mathrm{x}10^{-3} \tag{23}$$

From (22) and (23), we obtain the four charged lepton signal (for $M_2 = 200$ GeV),

$$\sigma \cdot B \simeq 77pb \tag{24}$$

For a luminosity of $L = 10^{32} cm^{-2} \sec^{-1}$, (22) and (24) will give rise to about $10^5 Z_2$ and ~ 770 four charged leptons events per day. For $M_2 = 1$ TeV, $\sigma_{Z_2} \simeq 460pb$ and $\sigma \cdot B \simeq 3.5pb$.

In hadronic colliders, such as TEVATRON ($\bar{P}P, \sqrt{S} = 2$ TeV), we obtain, for $M_2 = 200$ GeV, $\sigma_{Z_2+X} \simeq 200pb, \sigma \cdot B \simeq 1.5pb \simeq 10$ events/year.

In the SSC ($PP, \sqrt{S} = 40$ TeV), with an annual luminosity, $\int \mathcal{L}dt = 10^4 pb^{-1}$, for $M_2 = 200$ GeV,

$$\sigma_{Z_2+X} \simeq 10^4 pb, \quad \sigma \cdot B \simeq 77pb \simeq 8\text{x}10^5 \text{ events/yr.} \tag{25}$$

For $M_2 = 1$ TeV,

$$\sigma_{Z_2+X} \simeq 50pb, \quad \sigma \cdot B \simeq 0.4 \;\; pb \simeq 4\text{x}10^3 \text{ events/yr.} \tag{26}$$

while for $M_2 = 2$ TeV,

$$\sigma_{Z_2+X} \simeq 2pb, \; \sigma \cdot B \simeq 1.6\text{x}10^{-2} pb \simeq 160 \text{ events/yr.} \tag{27}$$

There will be background to the four charged lepton signals given by (24)-(27), coming from the top quark. In e^+e^- collider, this will come from the decay $Z_2 \to t\bar{t}$, and the subsequent semileptonic decays of t and $\bar{t}$.

$$t\bar{t} \to \left(\ell_1^+ + \nu_1 + \ell_2^- + \bar{\nu}_2 + c\right) + \left(\ell_2^- + \bar{\nu}_3 + \ell_4^+ + \nu_4 + \bar{c}\right) \tag{28}$$

In hadronic colliders, there will be additional background coming from the direct production of $t\bar{t}$. Because of one more decay chain being involved, we expect the final state charged leptons here to carry much less p_T on the average. So, with suitable p_T cuts, it may be possible to eliminate most of the background events.

We note, in passing, that $M_2 = 200$ GeV corresponds to, using eq. (17), $X \simeq$ 1500 GeV giving $r \equiv V/X \simeq 0.12$, whereas $M_2 = 1$ TeV corresponds to $X \simeq 8$ TeV giving $r \simeq 0.02$. So our diagonalization of the mass matrix (7) setting $r = 0$ is reasonably justified for these values of M_2.

We conclude by stating our main results. We have calculated the branching ratio for the decays of the extra neutral gauge boson, Z_2 into pairs of weak neutralinos. The branching ratio can be as large as about 16%. The subsequent decays of these neutralinos give rise to four charged leptons with high p_T. The signal is significant both at LEP and SSC and will be an interesting signature for supersymmetry. Calculations of the branching ratios for Z_1 and Z_2 decays to the photinos and the lighter neutralino ($\tilde{Z}_1$) (which involves the diagonalization of the mass matrix to order $r \equiv V/X$), and also a detailed study of the four charged lepton signal and the background in lepton and hadron colliders will be reported elsewhere[25]

ACKNOWLEDGEMENT

I am very grateful to Dick Annowitt for a very interesting discussion, at the DPF meeting in Salt Lake City, which eventually led to this work. Thanks are also due to him, and also to M. Glover, P. Nath, T.R. Rizzo and X. Tata for many useful discussions. Finally, I thank the Theoretical Physics Department of Fermilab for the warm hospitality during my visit when this work was completed. This work was supported in part by the U.S. Department of Energy, DE/FG05/85ER 40214, and also by a Dean's incentive grant from the Oklahoma State University.

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