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Supersymmetric decay widths of weak bosons

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The partial widths of W and Z decays to supersymmetric particles are evaluated in the simplest $N=1$ supergravity model. The total widths can be 50% greater than the standard-model predictions. Measurements of the widths at the $\bar{p}p$ collider can thereby be used either to place improved lower limits on gaugino, scalar-quark, and scalar-lepton masses or to provide indirect evidence for supersymmetry.

The decays of weak bosons offer the most promising means of searching in the near future for supersymmetric (SUSY) particles at the CERN $\bar{p}p$ collider. In recognition of this possibility, a number of recent papers[1-7] have addressed particular SUSY decay modes of $W^{\pm}$ and Z and their experimental signatures. In this paper we undertake to evaluate the contributions of all expected SUSY gaugino and s-fermion (scalar-quark and scalar-lepton) modes to the total widths of the weak bosons, versus the masses of the SUSY decay products. We find that SUSY contributions can increase the weak-boson widths by 50% (Ref. 8), with SUSY masses above present limits. Accordingly, measurements of the total widths in CERN $\bar{p}p$ collider experiments can be used either to improve the existing lower limits on gaugino or s-fermion masses or to provide indirect evidence for supersymmetry. If the measured widths turn out to be between 1 and 1.5 times the standard-model values, they could be used to estimate the SUSY mass gap.

Our present considerations are based on the $N=1$ supergravity grand unified model of Refs. 1 and 2, with $SU(2)\times U(1)$ breaking at tree level,[1,2,4,9] though the results can be readily extended to other models. The SUSY partners of the W^i and B^0 bosons are Majorana fermions $\tilde{W}^i$ and $\tilde{B}^0$. The model has two left-handed Higgs doublets $H_1=(H_1^+,H_1^0)_L$ and $H_2=(H_2^0,H_2^-)_L$, with equal vacuum expectation values $\langle 0|H_{1,2}^0|0\rangle\equiv v$, and a Higgs singlet U_L. The corresponding Higgs fermions are denoted by $\tilde{H}$ and $\tilde{U}$. We introduce a Majorana basis for these states,

$$\begin{aligned}\mathscr{D}^+ &= -i(\tilde{H}_{1L}^+ - \tilde{H}_{2L}^{-c}) \ ,\\ \mathscr{D}_i^0 &= -i(\tilde{H}_{iL}^0 - \tilde{H}_{iL}^{0c}) \ ,\\ \mathscr{U} &= -i(\tilde{U}_L - \tilde{U}_L^c) \ ,\end{aligned} \tag{1}$$

where c denotes a charge-conjugate state $\tilde{H}_i^c = C(\bar{\tilde{H}}_i)^T$ and $i=1,2$. The Lagrangian terms which contribute to the mass matrix are

$$\mathscr{L} = [-i\sqrt{2}\bar{\tilde{H}}(g_2T_j\tilde{W}^j + g_1Y\tilde{B})H - 2\epsilon\bar{\tilde{H}}_1(i\tau_2)\tilde{H}_2^c + \lambda H_1^0(\bar{\tilde{U}}^c\tilde{H}_2^0) + \lambda H_2^0(\bar{\tilde{U}}^c\tilde{H}_1^0)] + \text{H.c.} \ , \tag{2}$$

where $g_2=e/\sin\theta_W$ and $g_1=e/\cos\theta_W$. In terms of the $\tilde{\gamma},\tilde{Z}$ (SUSY partners of γ,Z) and the Higgs-fermion combinations

$$\mathscr{A}=(\mathscr{D}_2-\mathscr{D}_1)/\sqrt{2}, \quad \mathscr{S}=(\mathscr{D}_1+\mathscr{D}_2)/\sqrt{2} \ , \tag{3}$$

the mass terms take the form

$$-\mathscr{L} = (\overline{\mathscr{D}^+,\tilde{W}^+})\begin{pmatrix}-2\epsilon & M_W\\ M_W & 0\end{pmatrix}\begin{pmatrix}\mathscr{D}^+\\ \tilde{W}^+\end{pmatrix} + (\overline{\mathscr{A},\tilde{Z}})\frac{1}{2}\begin{pmatrix}-2\epsilon & M_Z\\ M_Z & 0\end{pmatrix}\begin{pmatrix}\mathscr{A}\\ \tilde{Z}\end{pmatrix} + (\overline{\mathscr{S},\mathscr{U}})\frac{1}{2}\begin{pmatrix}2\epsilon & \rho\\ \rho & 0\end{pmatrix}\begin{pmatrix}\mathscr{S}\\ \mathscr{U}\end{pmatrix} \ , \tag{4}$$

where $\rho\equiv\sqrt{2}\lambda v$. The eigenstates, masses, and mixing angles are then

$$\begin{aligned}\omega_1^+ &= \mathscr{D}^+\cos\alpha + \tilde{W}^+\sin\alpha, \quad M_{1,2}=(M_W{}^2+\epsilon^2)^{1/2}\mp\epsilon \ ,\\ \omega_2^+ &= \gamma^5(-\mathscr{D}^+\sin\alpha + \tilde{W}^+\cos\alpha), \quad \tan\alpha = M_W/M_1 \ ,\end{aligned} \tag{5a}$$

$$\begin{aligned}z_1 &= \mathscr{A}\cos\beta + \tilde{Z}\sin\beta, \quad \mu_{1,2}=(M_Z{}^2+\epsilon^2)^{1/2}\mp\epsilon \ ,\\ z_2 &= \gamma^5(-\mathscr{A}\sin\beta + \tilde{Z}\cos\beta), \quad \tan\beta = M_Z/\mu_1 \ ,\end{aligned} \tag{5b}$$

$$\begin{aligned}h_1 &= \gamma^5(\mathscr{S}\cos\delta + \mathscr{U}\sin\delta), \quad m_{1,2}=(\rho^2+\epsilon^2)^{1/2}\mp\epsilon \ ,\\ h_2 &= (-\mathscr{S}\sin\delta + \mathscr{U}\cos\delta), \quad \tan\delta = -\rho/m_1 \ .\end{aligned} \tag{5c}$$

We consider $\epsilon>0$ so that M_1, μ_1, and m_1 are the light-mass eigenvalues. The γ_5 factors result from chiral rotations to make the masses of the ω_2^+, z_2, and h_1 states positive. The gauge interactions of the SUSY fermions,

$$\begin{aligned}\mathscr{L} = {} & [-eW_\mu^+(\bar{\tilde{W}}^+\gamma^\mu\tilde{\gamma}) - e\cot\theta_W W_\mu^+(\bar{\tilde{W}}^+\gamma^\mu\tilde{Z}) + e(\sqrt{2}\sin\theta_W)^{-1}W_\mu^+(\bar{\tilde{H}}_1^+\gamma^\mu\tilde{H}_{1L}^0 - \bar{\tilde{H}}_2^{-c}\gamma^\mu\tilde{H}_{2L}^{0c}) + \text{H.c.}]\\ & + e\cot\theta_W Z_\mu(\bar{\tilde{W}}^+\gamma^\mu\tilde{W}^+) + e(\sin2\theta_W)^{-1}Z_\mu[(1-2\sin^2\theta_W)(\bar{\tilde{H}}_1^+\gamma^\mu\tilde{H}_{1L}^+ + \bar{\tilde{H}}_2^{-c}\gamma^\mu\tilde{H}_{2L}^{-c}) - (\bar{\tilde{H}}_1^0\gamma^\mu\tilde{H}_{1L}^0 + \bar{\tilde{H}}_2^{0c}\gamma^\mu\tilde{H}_{2L}^{0c})] \ ,\end{aligned} \tag{6}$$

can be expressed in terms of the eigenstates of Eq. (5). The couplings for the physical modes are given in Table I, based on

TABLE I. The couplings for the general transition of the gauge boson to the gaugino states.

$X \to b\bar{a}$	g_V	g_A
$W^+ \to \omega_1^+\tilde{\gamma}$	$-\sin\alpha$	0
$\omega_1^+ z_1$	$-\sin\alpha\sin\beta\cot\theta_W - \cos\alpha\cos\beta/(2\sin\theta_W)$	0
$\omega_1^+ h_1$	$-\cos\alpha\cos\delta/(2\sin\theta_W)$	0
$Z \to \omega_1^+\omega_1^-$	$2(\cos^2\theta_W - \frac{1}{2}\cos^2\alpha)/(\sin 2\theta_W)$	0
$z_1 h_1$	$-\cos\beta\cos\delta/(\sin 2\theta_W)$	0

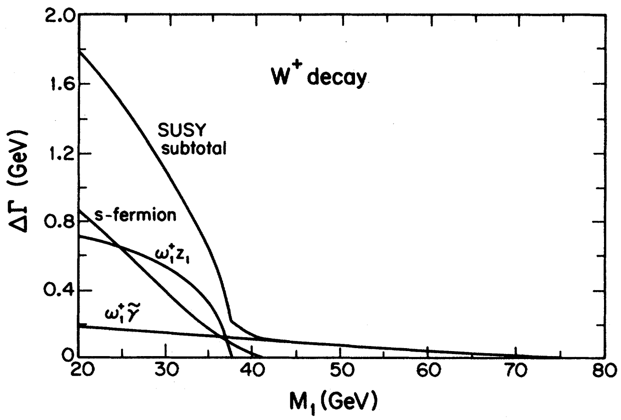

FIG. 1. SUSY gaugino and s-fermion contributions to the W^+-boson decay width vs the mass of ω_1^+; see Eq. (5). The partial width for $W^+ \to \omega_1^+ h_1$ is negligible on this scale.

the Lagrangian form

$$\mathscr{L} = eX_\mu(g_V\bar{b}\gamma^\mu a + g_A\bar{b}\gamma^\mu\gamma^5 a) \tag{7}$$

for the general transition $X \to b\bar{a}$ to gaugino final states. The decay rates are determined by

$$\Gamma(X \to b\bar{a}) = \tfrac{1}{3}M_X\alpha\lambda^{1/2}(1,x_a,x_b)\{(g_V{}^2+g_A{}^2)[1-\tfrac{1}{2}x_a-\tfrac{1}{2}x_b-\tfrac{1}{2}(x_a-x_b)^2]+3(g_V{}^2-g_A{}^2)(x_a x_b)^{1/2}\}\ , \tag{8}$$

where $x_a = m_a{}^2/M_X{}^2$, $x_b = m_b{}^2/M_X{}^2$,

$$\lambda(1,x_a,x_b) = 1 + x_a{}^2 + x_b{}^2 - 2x_a - 2x_b - 2x_a x_b\ ,$$

and $\alpha = \frac{1}{128}$.

If the SUSY scalars are light, the weak bosons will also decay into scalar-lepton pairs $\bar{\tilde{l}}\,\tilde{l}$ and scalar-quark pairs $\bar{\tilde{q}}\tilde{q}$. The Lagrangian for these decays is

$$\mathscr{L} = \frac{i}{\sqrt{2}}g_2 W_\mu^+ \bar{\tilde{f}}\overleftrightarrow{\partial}^\mu\tau^+\tilde{f} + \frac{ig_2}{\cos\theta_W}Z_\mu\bar{\tilde{f}}\overleftrightarrow{\partial}^\mu(\tfrac{1}{2}\tau_3 - \sin^2\theta_W Q)\tilde{f}\ , \tag{9}$$

where $\tilde{f}$ is the partner of fermion doublet f (we assume that scalar and pseudoscalar states are degenerate). The partial widths of these decays are

$$\Gamma(W^+ \to a\bar{b}) = c\tfrac{1}{2}\Gamma_W^0\lambda^{3/2}(1,x_a,x_b)\ ,$$
$$\Gamma(Z \to a\bar{a}) = c\tfrac{1}{2}\Gamma_Z^0\lambda^{3/2}(1,y_a,y_a) \times (1 - 4|Q_a|\sin^2\theta_W + 8Q_a{}^2\sin^4\theta_W)\ , \tag{10}$$

where Γ_W^0 and Γ_Z^0 are the partial widths

$$\Gamma_W^0 = \frac{G_F M_W{}^3}{6\sqrt{2}\pi},\quad \Gamma_Z^0 = \frac{G_F M_Z{}^3}{12\sqrt{2}\pi} \tag{11}$$

for the ordinary $W \to e\nu$ and $Z \to \bar{\nu}\nu$ decays, respectively. In Eq. (10) $c=1$ for scalar-lepton and $c=3$ for scalar-quark final states; also $x_a = m_a{}^2/M_W{}^2$ and $y_a = m_a{}^2/M_Z{}^2$.

To make numerical estimates of the above contributions to the weak-boson decay widths and branching fractions, we take[10]

$$m_{\tilde{f}}{}^2 = m_S{}^2 + m_f{}^2\ , \tag{12}$$

where m_f is the mass of an ordinary quark or lepton and m_S is the SUSY mass gap. PETRA data indicate that $m_S > 17$ GeV.[11] For the SUSY-fermion decays we assume that $\rho = M_W$ in Eq. (5) and vary the mass M_1 of ω_1^+ from $\frac{1}{4}M_W$ to M_W.

The values of the calculated widths depend somewhat on the input $W^\pm$ and Z masses. For the present we use the theoretical values[12] of $M_{W^\pm} = 83$ GeV, $M_Z = 94$ GeV, and $\sin^2\theta_W = 0.215$, which are consistent with the first measurements.[13] The total widths from the standard leptons and quarks, including QCD corrections and assuming $m_t = 35$ GeV, are $\Gamma_W \simeq \Gamma_Z \simeq 2.9$ GeV.

Figure 1 shows the predicted partial widths for the various possible SUSY modes equating, for economy of parameters, the SUSY gap to the ω_1^+ mass, $m_S = M_1$. The contributions from the SUSY modes are sizable if their masses are considerably below M_W. Measurements of the widths at the $\bar{p}p$

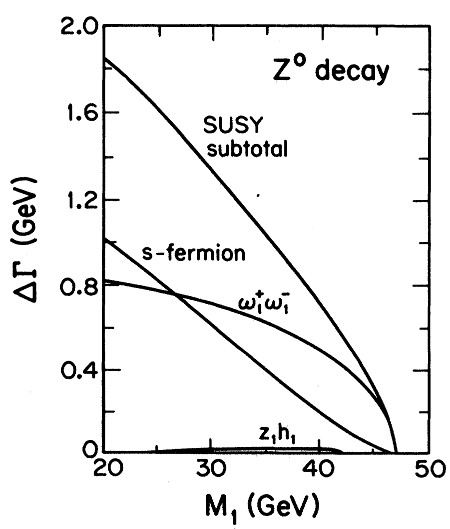

FIG. 2. SUSY contributions to the Z^0 width vs the mass of ω_1^+.

collider can lead to improved lower limits on gaugino and s-fermion masses or provide indirect evidence for supersymmetry (see Fig. 2). The SUSY increases in the total widths imply corresponding decreases in the branching fractions $B(W^+ \to e\nu)$ and $B(Z \to e^+e^-)$, since the leptonic partial widths are still given by the standard model.

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