Detection of W-boson supersymmetric decay modes

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It has been suggested that in a wide class of models based on $N=1$ supergravity the W boson can decay into a W gaugino and photino. Experimentally it will be very difficult to distinguish this decay mode from that to a fourth-generation heavy lepton with mass approximately equal to the W-gaugino mass. The angular decay spectra is, though, strongly dependent on the polarization state of the W. We therefore investigate the angular decay spectra of W's decaying to both W gauginos and heavy leptons for highly polarized W's produced in association with a hard photon or gluon jet, and we find a potentially observable signal for supersymmetric decays.

I. INTRODUCTION

The discovery that there must be gauge fermions lighter than the W and the Z in certain classes of supersymmetric theories[1] has led inexorably to more detailed studies of W-gaugino ($\widetilde{W}$) production through W decay. To enhance the possibility that the decay is kinematically allowed, a light, supersymmetric, decay partner is needed: the photino ($\widetilde{\gamma}$) is a likely candidate.

In a recent paper, Dicus, Nandi, Repko, and Tata[2] examined the electron decay spectra of a W gaugino, itself the decay product of a W which is produced by $p\bar{p}$ annihilation, $p\bar{p}\rightarrow X(W\rightarrow\widetilde{W}\widetilde{\gamma})$. They treated the W boson produced in this reaction as essentially unpolarized and with an isotropic distribution and concluded that a supersymmetric decay from such a W could not be easily distinguished from the decay to an unknown heavy lepton of the same mass as the W gaugino. Including the effects of the polarization of the W does not circumvent the problem. However, a highly polarized W with a manifestly nonisotropic distribution would allow us to disentangle the two different decay modes. Such a W is produced in the reaction $p\bar{p}\rightarrow W\gamma X$ (Refs. 3 and 4). By studying the decay distributions of a W produced with a photon, we will be able to include the polarization and angular distribution information necessary to distinguish supersymmetric from leptonic decays.

Another candidate reaction is the production of a W with a hard gluon jet: $p\bar{p}\rightarrow \text{jet}\,WX$ ($W\rightarrow\widetilde{W}\widetilde{\gamma}$). The advantage of this process is that it has very high rates compared to $W\gamma$ production and clean polarization states[3] for the W which will give clear decay signals.

The disadvantage is that the gluon is detected only as a jet of hadrons, and so, there are experimental difficulties in separating out unambiguous events. The gluon jet must be separated from the rest of the hadronic debris and we must ensure that it came from the same hard process as formed the W. Also, so that the process will be calculable perturbatively in QCD (Ref. 5), the gluon jet must be hard and produced away from the beam axis; this will require large angular and energy cuts on the gluon. These cuts are in accord with experimental requirements: the gluon jet cannot be detected as such if it is too low in energy or too close to the beam axis. Once cuts are imposed, the rates for Wg production are substantially decreased but still much higher than those for $W\gamma$.

In both cases, production of a W through $W\gamma$ or Wg, the angular distribution for the W decaying into a heavy lepton and its neutrino is different from that of a W decaying into a W gaugino and photino. The production of $W\gamma$ pairs and the leptonic decay of the W have already been considered by us;[4] here we shall concentrate on the supersymmetric and heavy-leptonic decay modes of the W: $W\rightarrow\widetilde{W}\widetilde{\gamma}$ or $W\rightarrow L\nu_L$. The branching ratio for the decay $W\rightarrow\widetilde{W}\widetilde{\gamma}$ has been found by Nath, Chamseddine, and Arnowitt (Ref. 1) to be large, of the order of 40–50 % of the leptonic rate. The production cross section for $W\gamma$ pairs in $p\bar{p}$ collisions[4] is such that the process is potentially observable at the CERN collider, particularly with an upgrade in energy and/or luminosity, and should certainly be seen at the Fermilab 2-TeV collider.

To include an unknown heavy-lepton decay product in the W's repertoire, we assume a new left-handed lepton SU(2) doublet with standard $V-A$ couplings.[6] The lepton is denoted by L with mass m_L; the corresponding neutrino (ν_L) is assumed massless. For the supersymmetric W decay, we use the $W\widetilde{W}\widetilde{\gamma}$ vertex as parametrized by Chamseddine, Nath, and Arnowitt[7] for supergravity theories. The W gaugino ($\widetilde{W}$) is a linear combination of two SU(2) Majorana gauginos and the Higgs fermion. We consider only the case where the photino ($\widetilde{\gamma}$) is massless at the tree level but obtains a small mass ($\widetilde{m}_\gamma$), in the range of 1–10 GeV, through gauge interactions.[8] We assume that it (or its decay products) remains undetected. The light-W-gaugino mass is taken to be 30 GeV.

II. CALCULATIONS

The decay density matrix for a W decaying into a W gaugino and photino is given by

$$M_{ab}=2e^2\eta^*_\alpha(a)\eta_\beta(b)D^{\alpha\beta}\,, \quad (1)$$

where η is the polarization vector of the W, a and b index the polarization states, and

$$D^{\alpha\beta}=(s^2+c^2)(q^\alpha p^\beta+q^\beta p^\alpha-g^{\alpha\beta}q\cdot p)+2sc\tilde{m}_\gamma \tilde{m}_W g^{\alpha\beta}-i(s^2-c^2)\epsilon^{\mu\alpha\nu\beta}q_\mu p_\nu \ . \tag{2}$$

The photino momentum is q and p is the W-gaugino momentum. The decay is parametrized (in the notation of Ref. 7) in terms of $s=\sin(\beta_+ +\beta_-)$ and $c=\cos(\beta_+ -\beta_-)$. We repeat their formulas for convenience

$$\tan 2\beta_\pm=\frac{\mu\mp\tilde{m}_2}{2v_\pm}\ ,\qquad \sqrt{2}v_\pm=M_W(\cos\alpha\pm\sin\alpha)\ , \tag{3}$$

and the loop SU(2) gaugino mass is

$$\tilde{m}_2=\frac{3\tilde{m}_\gamma}{8\sin^2\theta_W}\ . \tag{4}$$

The parameters μ and α are model dependent and may be adjusted to accommodate various symmetry-breaking mechanisms in terms of the coupling constants of the theory. For a supergravity grand unified model with SU(2)×U(1) breaking at the tree level[9] (TB), they find $\alpha\simeq 45°$ and $\mu\simeq m_{3/2}\simeq 100$ GeV. Models which are dynamically broken by renormalization-group (RG) loop corrections[10] have $\alpha\simeq 15°$ and $\mu\simeq \alpha m_{3/2}$.

We choose a gravitino mass of $m_{3/2}=\sqrt{2}M_W$ GeV and a photino mass of $\tilde{m}_\gamma=2$ GeV. For RG models we choose $\alpha=17°$ and $\mu=37$ GeV and we use $\alpha=45°$ and $\mu=162$ GeV for TB models; these correspond to a W-gaugino mass of 30 GeV.

The invariant decay distribution of the quark subprocess is given by

$$E\frac{dN}{d^3p}[q\bar{q}'\to\gamma(W\to\tilde{W}\tilde{\gamma})]=\frac{1}{\Gamma(W\to\tilde{W}\tilde{\gamma})}\int d\Omega_W \mathrm{Tr}\left[\rho(q\bar{q}'\to W\gamma)\frac{EdR(W\to\tilde{W}\tilde{\gamma})}{d^3p}\right]\ , \tag{5}$$

where E is the W-gaugino energy, Ω_W is the solid angle of the W, and ρ is the differential polarization density matrix of the W (Ref. 11), normalized such that

$$\mathrm{Tr}\rho=\frac{d\sigma(q\bar{q}'\to W\gamma)}{d\Omega_W}\ . \tag{6}$$

Γ is the total rate of W decay for the process being considered and dR/d^3p is the differential decay matrix in the quark c.m. frame:[11,12]

$$E\frac{dR_{ab}}{d^3p}=\frac{1}{4E_W(2\pi)^2}\delta((p_W-p)^2-\tilde{m}_\gamma{}^2)M_{ab}\Bigg|_{q^0>0}\ . \tag{7}$$

E_W is the energy of W, and M_{ab} is given in Eq. (1). The decay distribution in the proton-antiproton c.m. frame is obtained by integrating over the fractional momenta of the quark and antiquark, x_A and x_B, with an appropriate momentum distribution function, and summing over quark pairs. Another integration is carried out over the W-gaugino momentum to give the angular decay distribution:

$$\frac{dN(p\bar{p}\to X\gamma(W\to\tilde{W}\tilde{\gamma}))}{d\cos\alpha}=\frac{2\pi}{3}\sum_{\text{quarks}}\int_0^{|\mathbf{p}_L|_{\max}}\frac{|\mathbf{p}_L|^2 d|\mathbf{p}_L|}{E_L}\int_{\text{threshold}}^1 dx_A dx_B F_{q\bar{q}'}^{p\bar{p}}(x_A,x_B,S)\times\frac{E\,dN(q\bar{q}'\to\gamma(W\to\tilde{W}\tilde{\gamma}))}{d^3p}\ . \tag{8}$$

E_L and p_L are the W-gaugino energy and momentum in the $p\bar{p}$ c.m. frame, α is the angle between the W gaugino and the proton, and the function F is the product of the momentum distributions:

$$F_{q\bar{q}}^{p\bar{p}}(x_A,x_B,S)=f_q^p(x_A,Q^2)f_{\bar{q}'}^{\bar{p}}(x_B,Q^2)+f_{\bar{q}'}^p(x_A,Q^2)f_q^{\bar{p}}(x_B,Q^2)\ . \tag{9}$$

The variables S and Q^2 are defined by

$$S=(p_p+p_{\bar{p}})^2\ ,\qquad Q^2=x_Ax_BS\ . \tag{10}$$

For simplicity we use scaling structure functions.[13]

The angular decay distribution for the W decaying into a heavy lepton and its massless neutrino is obtained in the same way, only now the decay density matrix is calculated using standard SU(2)×U(1) couplings. We choose a mass $m_L=30$ GeV for comparison with the $W\to\tilde{W}\tilde{\gamma}$ decays. Events with the photon produced within 5° of the beam axis were discarded to account for the physical characteristics of the collider detector, and an energy cut of $E_\gamma>10$ GeV was imposed on the photon.

The resultant decay distributions for a $p\bar{p}$ c.m. energy of $\sqrt{S}=540$ GeV are presented in Fig. 1. For definiteness, we have looked at the decay of a positively charged W. The curves are labeled according to the W decay products and, in the case of the supersymmetric decay, according to which model parameters were used.

The W^+ produced in $p\bar{p}\to W^+\gamma X$ is left-handed in the forward direction (where "forward" is the direction of the proton) and right-handed in the backward direction,[3,4]

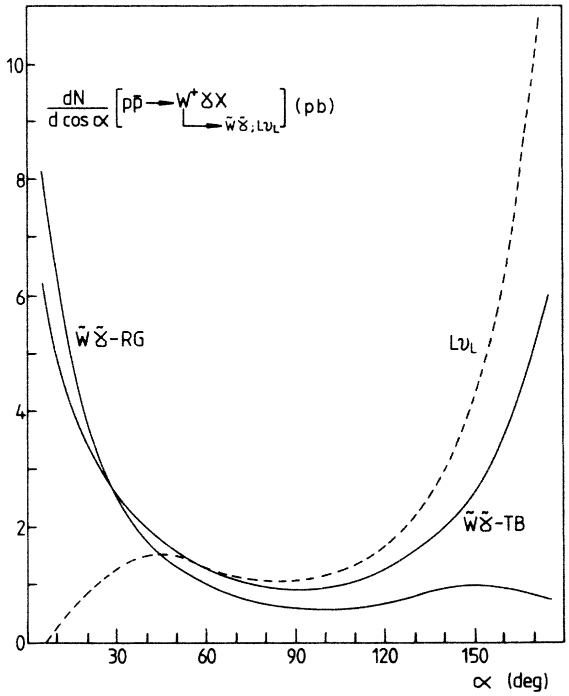

FIG. 1. Charged-decay-fermion angular distribution for various W decay products in the $p\bar{p}$ c.m. frame at an energy of $\sqrt{S}=540$ GeV for a W produced with a hard photon. The photon is produced at an angle $\theta_\gamma > 5°$ from the beam axis and an energy $E_\gamma > 10$ GeV. The mass of the W is 80 GeV and $1\ pb = 10^{-36}\ \text{cm}^2$.

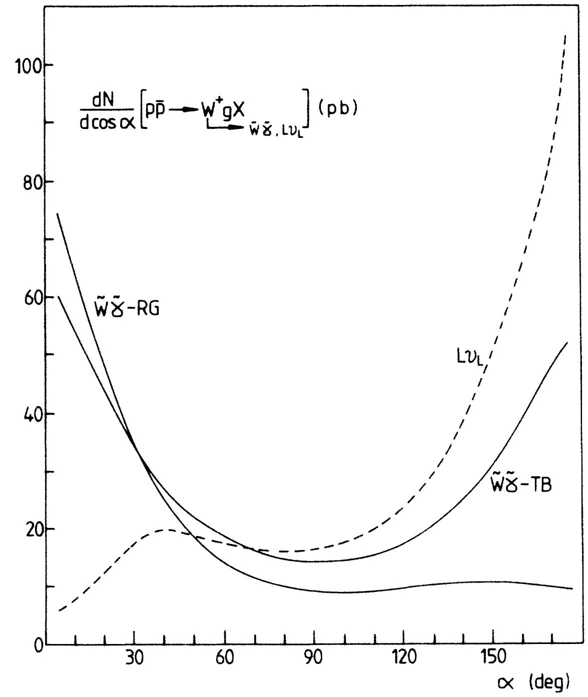

FIG. 2. Same as Fig. 1 but for a W produced with a hard gluon jet, with the gluon angle $\theta_g > 20°$ and energy $E_g > 30$ GeV.

and thus, emits the left-handed neutrino in the forward direction and its heavy partner (L) in the backward direction. This is clearly evidenced by the $L\nu_L$ angular decay distribution. The supersymmetric decay product distributions, on the other hand, do not show this backward peaking. The TB-model curve is virtually symmetric about $\alpha=90°$ with a dip in the center and peaks in both the forward and backward directions. The RG-model curve peaks in the forward direction and is suppressed in the backward direction. Both supersymmetric angular decay distributions are clearly different from the leptonic-decay distribution. The physical origin of this difference lies in the fact that the $W\tilde{W}\tilde{\gamma}$ vertex[7] is not a purely left-handed coupling in either the TB or RG models, whereas the $WL\nu_L$ coupling is left-handed.

The mass of the photino was chosen to be 2 GeV throughout this calculation; however, varying the photino mass, in the range 1–10 GeV, had very little effect. The curves are sensitive to the mass of the W gaugino, and we have presented only the most interesting case (i.e., a fairly light W gaugino) here. For higher W-gaugino masses, not only is the branching ratio for $W \rightarrow \tilde{W}\tilde{\gamma}$ smaller,[7] but the curves become peaked in both the forward and backward directions and it becomes difficult to distinguish heavy-leptonic from supersymmetric decay distributions.

The angular decay distributions of a W produced with a hard gluon jet are calculated in much the same manner as for $W\gamma$, with the assumption that the dominant parton-level process is $q\bar{q}' \rightarrow Wg$. We are only interested here in the effect on the W decay distribution of the W being produced in association with a hard gluon and not in the subsequent details of the gluon jet evolution.

In the interest of minimizing the difficulties which beset experimental detection of the jet at low energies and small angles, we will choose a somewhat conservative approach and present decay distributions for a gluon energy cut of $E_g > 30$ GeV and an angular cutoff of 20°. For lower-energy cuts, we can expect an enhancement of the decay distribution without a substantial change in shape.

The results are presented in Fig. 2 for leptonic and two supersymmetric decay modes. Once again, we have presented results at $\sqrt{S}=540$ GeV for a W-gaugino mass of 30 GeV. The cross section is enhanced by a factor of 10 over the $W\gamma$ case, but the overall shape of the curves remains the same: the heavy-leptonic angular decay distribution of the W is peaked in the backward direction whereas the supersymmetric TB-model distribution is peaked forward and backward, and the RG-model curve is suppressed in the backward and enhanced in the forward direction. As before, the curves are fairly insensitive to variations in the photino mass, but become nearly indistinguishable as the W-gaugino mass is taken to large values ($\simeq 70$ GeV).

III. CONCLUSIONS

The inclusion of a photon or gluon in the production of a W at $p\bar{p}$ colliders ensures a highly polarized W with a nonisotropic distribution.[3] We have presented angular decay distributions for such a W decaying into either a fourth-generation lepton pair or into $\tilde{W}\tilde{\gamma}$ pairs. The angular decay distributions were found to differ substantially for the different decay products and may provide a test of the W-gaugino properties if it is found. The decay distributions presented here justify further study of these reactions including the subsequent decay of the heavy lepton or the W gaugino. It will be expected that the observable decay particles of the W gaugino or heavy lepton would mirror in their angular distribution that of their parent particle. These processes may then offer a useful way of discriminating between fourth-generation leptons and the supersymmetric partners of the W.

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