Discovering Supersymmetric Particles in W-Boson Decay and e^+e^- Annihilation

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The reported discovery of the W boson may provide the opportunity either to discover the supersymmetric partners of the neutrino and the electron or to set greatly improved limits on their masses. Also discussed is a search for scalar neutrinos in e^+e^- annihilation (off and on the Z^0).

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One of the reasons for the proliferation of supersymmetric models[1] has been the lack of experimental restraints. Future progress in this field would be aided greatly by the discovery of even a single supersymmetric partner of a presently known particle. Even an improvement of the experimental limits on the masses of such particles would be helpful. At this state a purely phenomenological study, as model independent as possible, is indicated.[2]

It is clear that processes involving supersymmetric particles are quite rare, and we therefore believe that one should look for events with very distinctive signatures. We have found that the decays of the scalar neutrino ν_s and the scalar electron e_s (or scalar muon) can lead to such signatures. Furthermore, measurements of ν_s decays are interesting since there are no real limits on the masses of the scalar neutrinos. The processes that we consider are the supersymmetric analogs of $W\to e\bar{\nu}$ (in $p\bar{p}$ scattering) and $e^+e^-\to\nu\bar{\nu}$, i.e., $W\to e_s\bar{\nu}_s$ and $e^+e^-\to\nu_s\bar{\nu}_s$. We find that these processes either could lead to the discovery of the ν_s or e_s, or could at least set greatly improved limits for their masses.

For some but not all of our results we make use of our previous work[3] where we showed that for certain sets of parameters a significant fraction (see Fig. 1) of the ν_s will decay into charged modes such as $\nu_s\to e^-u\bar{d}\tilde{g}$, $\nu_s\to\nu u\bar{u}\tilde{g}$ (where $\tilde{g}$ denotes the supersymmetric partner of the gluon), or if kinematically allowed $\nu_s\to e_s u\bar{d}$. Otherwise the main decay mode is usually expected[4] to be $\nu_s\to\nu\tilde{\gamma}$ (where $\tilde{\gamma}$ denotes the supersymmetric partner of the photon). We assume that the $\tilde{\gamma}$ behaves like a neutrino experimentally so that the two-body ν_s decays are invisible.

Let us consider first the process $p\bar{p}\to W+$anything with $W\to e_s\nu_s$. At the CERN SPS collider several events with $W\to e\nu$ have been observed by two experiments,[5] and we therefore feel that it is reasonable to assume that many more W bosons will be produced in the near future. Of these, a significant fraction may decay into $e_s\nu_s$ (see Fig. 2) depending on their masses:

$$r\equiv\frac{\Gamma(W^+\to e_s{}^+\nu_s)}{\Gamma(W^+\to e^+\nu)}=\frac{1}{2}\left[\left(1-\frac{M_{\nu_s}{}^2}{M_W{}^2}-\frac{M_{e_s}{}^2}{M_W{}^2}\right)^2-4\,\frac{M_{\nu_s}{}^2M_{e_s}{}^2}{M_W{}^4}\right]^{3/2}. \tag{1}$$

The identification of these events requires their separation from $e\nu$ events and from other backgrounds (such as the semileptonic decays of a pair of heavy quarks). To aid in this identification, we have calculated a variety of distributions of νe and $\nu_s e_s$ processes under the assumption that ν_s decays invisibly. We used Monte Carlo techniques to simulate W bosons with appropriate longitudinal and transverse momentum distributions,[6] and to have the W bosons decay into either $e\nu$ or $e_s\nu_s$ (the e_s then decayed into $e\tilde{\gamma}$). Using the standard model of electroweak interactions, we have applied the appropriate angular distributions for the $e\nu$ and for $e_s\nu_s$. The transverse momentum ($p_e{}^\perp$) spectra for the final electrons is shown in Fig. 3. By assuming that the process is $W\to e\nu$, one can calculate the $p_\nu{}^\perp$ spectra for the final neutrino ($\vec{p}_\nu{}^\perp=-\vec{p}_{\rm had}{}^\perp-\vec{p}_e{}^\perp$); the distributions look very similar to those in Fig. 3. For $e^\mp\nu$ the $\cos\theta$ distribution (θ being the angle between electron and proton beams) still shows the forward-backward asymmetry although the $(1\pm\cos\theta)^2$ dependence of $u\bar{d}\to e\nu$ is somewhat mod-

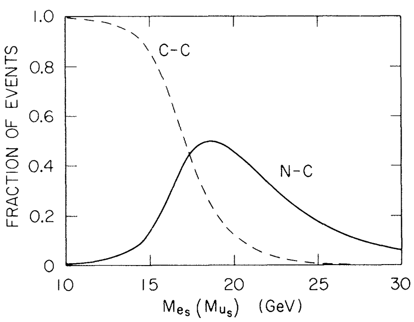

FIG. 1. Fraction of $e^+e^- \to \nu_s\bar{\nu}_s$ events where one of the scalar neutrinos decays into charged particles and the other one decays into invisible neutrals (solid line); and fraction of events where both scalar neutrinos decay into charged particles (dashed line). We have assumed that $M_{u_s} \approx M_{e_s}$, $M_\omega = M_W$, and $M_{\tilde{\gamma}} \approx M_{\tilde{g}} \approx 0$. We choose $M_{\nu_s} = 20$ GeV; however, the curve is nearly independent of the mass scale as long as M_{ν_s}, $M_{e_s} < M_W$. The increase of the dashed line for small M_{e_s} (M_{u_s}) corresponds to the production of on-shell scalar electrons (scalar u quarks) which then decay into charged modes.

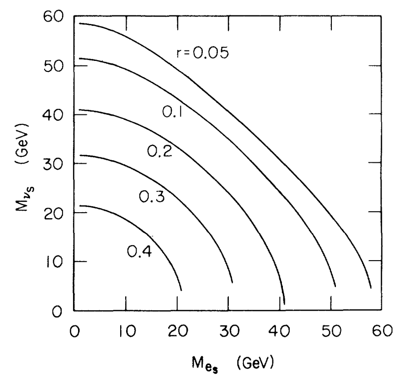

FIG. 2. Curves of constant r are shown. $r \equiv \Gamma(W \to e_s\nu_s)/\Gamma(W \to e\nu)$ is a function of M_{ν_s} and M_{e_s} [cf. Eq. (1)]. There is a large range of mass parameters for which the decay of the W into scalar leptons would have a significant branching ratio. Since there is virtually no limit on M_{ν_s} and the limit on M_{e_s} is only 17 GeV, even a value of $r = 0.4$ is not yet excluded.

ified since the W is not produced at rest. For $e_s\nu_s$ events the momentum of the parent W changes the center-of-mass $\sin^2\theta$ distribution of the $e_s^{\pm}$ into a relatively flat distribution for the $e^{\pm}$ which actually dips at $\cos\theta \approx 0$. Another useful distribution is related to the calculated longitudinal momentum $p_\nu^{\parallel}$ of the neutrino under the assumption $W \to e\nu$. Even if W indeed decays into $e\nu$ there is an often unresolvable ambiguity in the determination of $p_\nu^{\parallel}$. The two solutions are

$$p_\nu^{\parallel} = \frac{M_W^2 + 2\vec{p}_\nu^{\,\perp}\cdot\vec{p}_e^{\,\perp}}{2p_e^{\perp 2}}\left\{p_e^{\parallel} \pm p_e\left[1 - \frac{4p_\nu^{\perp 2}p_e^{\perp 2}}{(M_W^2 + 2\vec{p}_\nu^{\,\perp}\cdot\vec{p}_e^{\,\perp})^2}\right]^{1/2}\right\}. \qquad (2)$$

We choose a variable p_m which is uniquely defined as that solution to Eq. (2) with the smaller absolute value. The sign of this solution is kept. For $e_s\nu_s$ events p_m does not have a simple kinematical interpretation.

We find that we can separate $e_s\nu_s$ events from $e\nu$ events by making cuts in these four variables. We can then identify the presence of $e_s\nu_s$ events from the resulting distributions. For example, by eliminating all events with $p_e^{\perp}$ or $p_\nu^{\perp} > 35$ GeV, or $\cos\theta > 0.65$, or $-40 < p_m < 20$ GeV we find that 90% of $e\nu$ events but less than half of $e_s\nu_s$ events are eliminated. This will be discussed in greater detail in a future paper.[7]

We do not wish to minimize the problem of backgrounds (including standard physics backgrounds such as from dual semileptonic heavy-quark decays where the leptons carry almost all the energy). It is important for experimentalists to measure backgrounds, determine efficiencies, etc., in order to find out how well they can separate the signal from the noise. Some backgrounds may be eliminated by requiring the absence of accompanying hadronic jets. One clearly must have a minimum $p_e^{\perp}$ cut. We chose $p_e^{\perp} > 12$ GeV but a higher cut is possible. The number of events from the background of $W \to \nu\tau$ with $\tau \to \nu\nu e$ is precisely calculable given the $W \to \nu e$ rate. They also have a softer $p_e^{\perp}$ spectrum and have the forward-backward asymmetry of $W \to \nu e$ events.

In order to find particles or set limits in the region $M_{\nu_s} \approx M_{e_s} \approx 30$ GeV or $M_{e_s} \approx 40$ GeV, $M_{\nu_s} \approx 10$ GeV (i.e., $r > 0.2$ in Fig. 1), one will need an integrated luminosity adequate to produce at least 200 to 300 $W \to e\nu$ events (and 40 to 60 $e_s\nu_s$ events).

If the ν_s has a substantial charged-decay mode, then one may in addition look for events with a high-energy electron plus a hadron jet plus missing $E^{\perp}$ (from the $\tilde{\gamma}$). The hadron jet should have a very high invariant mass which should help to separate these events from heavy-quark (b or c) production.

Let us now consider $e^+e^- \to \nu_s\bar{\nu}_s$ which occurs via s channel Z^0 and t-channel ω exchange (where we define $\omega^{\pm}$ to be the appropriate mixtures of

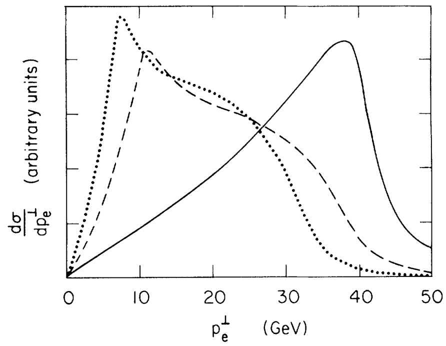

FIG. 3. The shape of the transverse momentum $p_e^{\perp}$ distribution of the electron resulting from the decay of a W produced in $p\bar{p}$ collisions. The curves are normalized to equal area. The solid curve refers to $W \to e\nu$. The Jacobian peak is clearly visible. The two other curves show the $p_e^{\perp}$ distribution for $W \to e_s \nu_s$ where $e_s \to e\tilde{\gamma}$. The dashed curve corresponds to $M_{e_s} = 40$ GeV and $M_{\nu_s} = 10$ GeV. The dotted curve corresponds to $M_{e_s} = M_{\nu_s} = 30$ GeV.

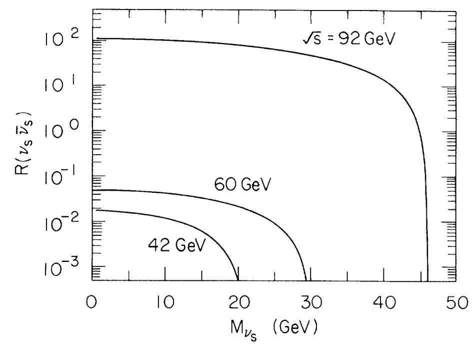

FIG. 4. The ratio $R \equiv \sigma(\nu_s \bar{\nu}_s)/\sigma^{\text{em}}(\mu^+\mu^-)$ as a function of the mass of the scalar neutrino. We have assumed that $M_\omega = M_W$. In some models, with one ω lighter than the W, the values of R could be significantly enhanced (below the Z^0 resonance). Note that this cross section will be difficult to detect unless (at least) one of the ν_s decays via charged modes.

the charged gauge and Higgs fermions as determined by the mass matrix). If ν_s has only invisible decays, one must rely on neutrino-counting techniques.[8] If the charged-decay modes are significant, then there are some very distinctive signatures in e^+e^- physics. These occur when one ν_s decays invisibly while the other ν_s decays into modes such as $e^- u\bar{d}\tilde{g}$ or $\nu u\bar{u}\tilde{g}$. The rate of $\nu_s \bar{\nu}_s$ production is dependent on M_{ν_s} and beam energy as shown in Fig. 4 (where $M_\omega = M_W$ was assumed). If the ω is significantly lighter[9] than the W, then these rates may be significantly enhanced.[10] At the PETRA storage ring (DESY) for a luminosity of 1.3×10^{31} sec^{-1} cm^{-2} at $\sqrt{s} = 42$ GeV, if $M_{\nu_s} = 18$ GeV and if we count $\nu_s^e \bar{\nu}_s^e$, $\nu_s^\mu \bar{\nu}_s^\mu$, and $\nu_s^\tau \bar{\nu}_s^\tau$ events, then a year's running (with 50% uptime) may yield 14 events with one neutral and one charged decay. At TRISTAN (Japanese National Laboratory for High Energy Physics, KEK) ($\sqrt{s} = 60$ GeV) a year's running may yield 450 such events; whereas at SLC (SLAC) and LEP (CERN), running on the Z^0 resonance may yield many more events or could set much higher limits on the masses. As a result of the large production cross section of $\nu_s \bar{\nu}_s$ at the Z^0, one is much more sensitive to rare decay modes of the ν_s which can lead to very dramatic signatures. For example, in $Z^0 \to \nu_s \bar{\nu}_s$ with $\nu_s \to \nu\mu^+ e^- \tilde{\gamma}$ (and $\bar{\nu}_s \to$ unobserved neutrals), one will observe $\mu^+ e^-$ and considerable missing energy.

The angular distribution of $\nu_s \bar{\nu}_s$ events (neglecting electron mass) is

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2 s}{32X^2}\left(1 - \frac{4M^2}{s}\right)^{3/2} \sin^2\theta \left\{ \frac{1}{(M_\omega{}^2 - t)^2} + \left(\frac{(4X-1)^2+1}{8(1-X)^2}\right)\left(\frac{1}{(M_Z{}^2 - s)^2 + \Gamma^2 M_Z{}^2}\right) + \left(\frac{2X-1}{1-X}\right)\left(\frac{1}{M_\omega{}^2 - t}\right)\left(\frac{M_Z - s}{(M_Z - s)^2 + \Gamma^2 M_Z{}^2}\right)\right\}, \tag{3}$$

where $X \equiv \sin^2\theta_W$, $M \equiv M_{\nu_s}$, and $t = M^2 - \frac{1}{2}s + \frac{1}{2}s(1 - 4M^2/s)^{1/2}\cos\theta$. The threshold behavior and the overall $\sin^2\theta$ dependence reflect the p-wave nature of this process and result from the spin of ν_s and its chiral couplings.

This angular dependence is very helpful in separating these events from the primary backgrounds. One background is beam-gas events which can be totally separated. Another is two-photon events in which one electron is missed down the beam pipe and the other electron comes out at a large angle but goes through a "hole" in the detector. Our discussions with experimentalists leave us confident that our events can be isolated from all backgrounds even if the numbers are small.

Finally, it should be added that W decay and e^+e^- physics can also be used to study the production of other supersymmetric particles.[11] Sometimes the signatures of these events can be quite similar to those discussed here. Consider for example, the case which has been proposed in the literature, that one of the $\omega^{\pm}$ is light.[9,10] If the two lightest mass eigenstates $\chi_1{}^0$ and $\chi_2{}^0$ of the neutral gauge- and Higgs-fermion mass matrix are also light, the following decays become possible: $W^{\pm} \to \omega^{\pm}\chi_{1,2}{}^0$ and $e^+e^- \to \chi_{1,2}{}^0\chi_{1,2}{}^0$. In particular, if the decay $\chi_2{}^0 \to \chi_1{}^0 +$ hadronic jets occurs (where $\chi_1{}^0$ behaves like the $\tilde{\gamma}$), then $e^+e^- \to \chi_1{}^0\chi_2{}^0$ events will resemble our $e^+e^- \to \nu_s\bar{\nu}_s$ events where one ν_s decays into charged particles and the other decays invisibly. Clearly, the observation of such events would also be a signal of physics beyond the standard model and a hint for supersymmetry.

We believe that the combination of searches in W-boson decay and $e^+e^- \to \nu_s\bar{\nu}_s$ has the potential of setting greatly improved limits on supersymmetric scalar leptons and could even lead to their discovery in the next few years.

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[1]For a recent review, see B. Zumino, University of California at Berkeley Report No. UCB-PTH-83/2, 1983 (unpublished).

[2]A list of related papers on phenomenology of supersymmetry will appear in a longer version of this paper. See also a recent review by G. L. Kane, in Proceedings of the Fourth Workshop on Grand Unification, April 1983, University of Michigan Report No. UM-TH 83-11, 1983 (to be published).

[3]R. M. Barnett, H. E. Haber, and K. S. Lackner, Phys. Lett. 126B, 64 (1983), and to be published.

[4]For simplicity, we assume that $\tilde{\gamma}$ is the lightest supersymmetric particle with a mass less than (say) 5 GeV. However, in general the mass matrix consisting of the neutral gauge and Higgs fermions can be far more complicated. For example, the lightest fermion may be quite massive and/or might not contain a substantial $\tilde{\gamma}$ component. [See J. Ellis and G. G. Ross, Phys. Lett. 117B, 397 (1982); J. Ellis, L. E. Ibanez, and G. G. Ross, CERN Report No. CERN-TH-3382, 1982 (unpublished); J. M. Frere and G. L. Kane, University of Michigan Report No. UM-TH 83-2, 1983 (unpublished).] Alternatively, the ν_s could conceivably be the lightest supersymmetric particle and stable.

[5]G. Arnison *et al.*, Phys. Lett. 112B, 103 (1983); M. Banner *et al.*, Phys. Lett. 122B, 476 (1983), and CERN Report No. CERN-EP/83-23, 1983 (unpublished).

[6]See, e.g., F. Halzen, A. D. Martin, and D. M. Scott, Phys. Rev. D 25, 754 (1982).

[7]H. E. Haber, R. M. Barnett, and K. S. Lackner, to be published.

[8]See, e.g., G. Barbiellini, B. Richter, and J. L. Siegrist, Phys. Lett. 106B, 414 (1981).

[9]S. Weinberg, Phys. Rev. Lett. 50, 387 (1983); R. Arnowitt, A. H. Chamseddine, and P. Nath, Phys. Rev. Lett. 50, 232 (1983); L. Alvarez-Gaume, J. Polchinski, and M. B. Wise, Harvard University Report No. HUTP-82/A063, 1983 (unpublished); P. Fayet, Ecole Normale Superieure Report No. LPTENS-83/16, 1983 (unpublished).

[10]The rates we refer to are enhanced only if the light ω consists dominantly of gauge-fermion components. This is a model-dependent question, see Ref. 9.

[11]Frere and Kane, Ref. 4; J. Ellis, J. S. Hagelin, D. V. Nanopoulos, and M. Srednicki, Stanford Linear Accelerator Center Report No. SLAC-PUB-3099, 1983 (unpublished); L. Littenberg and F. Paige, private communication.