Discovering Supersymmetry at the Tevatron in W-ino Lightest Supersymmetric Particle Scenarios

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In supersymmetric models, W-inos, partners of the SU(2) gauge bosons, may be the lightest supersymmetric particles. For generic parameters, charged and neutral W-inos are highly degenerate. Charged W-inos travel macroscopic distances, but can decay to neutral W-inos and extremely soft leptons or pions before reaching the muon chambers, thereby circumventing conventional trigger requirements. However, these charginos are detectable, and can be triggered on when produced in association with jets. In addition, we propose a new trigger for events with a high p_T track and low hadronic activity. For Tevatron Run II with luminosity 2 fb^{-1}, the proposed searches can discover W-inos with masses up to 300 GeV and explore a substantial portion of the parameter space in sequestered sector models.

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The discovery of supersymmetry (SUSY) is greatly anticipated at high energy colliders. If SUSY is to retain its motivation of stabilizing the electroweak scale against large radiative corrections, at least some supersymmetric particles must have masses of order of the electroweak scale. In the most widely studied models, the lightest supersymmetric particle (LSP) is assumed to be stable and to be the partner of the $U(1)_Y$ gauge boson. The SUSY signals are then characterized by missing transverse energy ($\not{E}_T$) and are unlikely to escape detection when the Large Hadron Collider (LHC) at CERN begins operation near the year 2005 with center of mass energy $\sqrt{s} = 14$ TeV.

Recently, however, it was realized that many other SUSY signatures are possible and are even more striking than the classic $\not{E}_T$ signature. These imply that the discovery of SUSY need not wait for the LHC [1–3]. In this Letter, we study scenarios in which the LSP, while still the lightest neutralino, is not the $U(1)_Y$ gaugino, but the neutral SU(2) gaugino, the W-ino $\tilde{W}^0$. This simple modification leads to drastic differences in phenomenology. These were argued to make detection difficult, based on conventional triggers, in [3,4], but were argued to provide a novel identifiable signal in Ref. [5]. In this paper, we elaborate on this observation. As in more conventional scenarios, the neutral LSP interacts very weakly and escapes detection. The new element is that the next-to-lightest superpartner, the charged W-ino $\tilde{W}^{\pm}$, is generically extremely degenerate with the LSP and decays after centimeters or meters to an LSP and an extremely soft lepton or pion. Such charged W-inos are therefore missed by conventional triggers and avoid detection in traditional searches. However, if care is taken to preserve such events at the trigger level, we will see that large and spectacular signals may appear at the upcoming run of the Fermilab Tevatron with $\sqrt{s} = 2$ TeV.

At tree level, the masses of the charginos and neutralinos depend on the $U(1)_Y$ gaugino mass M_1, the SU(2) gaugino mass M_2, the Higgsino mass μ, and $\tan\beta$, the ratio of Higgs vacuum expectation values. Without loss of generality, we choose M_2 real and positive. Phases in the parameters M_1 and μ are then physical. We will consider the case $M_2 < |M_1|, |\mu|$, so that the lightest charginos and neutralinos, $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$, are W-ino-like with masses $\sim M_2$. We assume that all other superparticles are (much) heavier than the W-inos. With this assumption we may neglect corrections to charged W-ino decay from virtual supersymmetric particles.

We will consider two W-ino LSP scenarios. In the first, we consider the well-motivated sequestered sector models [5], in which there is an anomaly-mediated spectrum of gauginos and a consistent scenario involving light scalars. In these models, the gaugino mass parameters are given by [4,5] $M_i = -b_i g_i^2 M_{\rm SUSY}$, where $M_{\rm SUSY}$ determines the overall SUSY-breaking scale, $i = 1, 2, 3$ identifies the gauge group, g_i are gauge coupling constants, and b_i are the 1-loop β-function coefficients of the (full supersymmetric) theory. Substituting the weak scale values of g_i, we find $M_1{:}M_2{:}M_3 = 3.3{:}1{:}-10$. Sequestered sector models predict a large hierarchy between W-ino and squark masses. Naturalness bounds therefore suggest $M_2 \lesssim 200-300$ GeV [6], and we will see that a large portion of the parameter space in these scenarios may be explored at the Tevatron.

More generally, the W-ino LSP scenario may be realized for a large region of SUSY parameter space if the assumption of gaugino mass unification is relaxed [3,7]. We will therefore also consider an alternative set of parameters with $M_1 = -1.5 M_2$. As will be seen, this choice lead to significant differences from the anomaly-mediated case, and so serves as an illustrative alternative. Since these parameters are not motivated by any model, the W-ino mass M_2 is less constrained in this case.

The SUSY signal depends strongly on $\Delta M \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$. It is enlightening to first consider the tree-level chargino and neutralino masses in a perturbation series in $1/\mu$ for large $|\mu|$. The lightest chargino and neutralino are degenerate at zeroth order, with $m_{\tilde{\chi}_1^\pm}^{(0)} = m_{\tilde{\chi}_1^0}^{(0)} = M_2$. At the next order in $1/\mu$, they receive corrections from mixing with the Higgsinos. However, both masses are corrected by $m_{\tilde{\chi}_1^\pm}^{(1)} = m_{\tilde{\chi}_1^0}^{(1)} = m_W^2 \sin 2\beta/\mu$, so the degeneracy remains. It is only at the next order, where the neutralino mass receives contributions from $U(1)_Y$ gaugino mixing which have no counterpart in the chargino sector, that the degeneracy is broken:

$$\Delta M_{\rm tree} \approx m_{\tilde{\chi}_1^\pm}^{(2)} - m_{\tilde{\chi}_1^0}^{(2)} = \frac{m_W^4 \tan^2\theta_W}{(M_1 - M_2)\mu^2} \sin^2 2\beta\,. \quad (1)$$

Note that, for large $\tan\beta$, even this contribution is suppressed. In fact, for $\tan\beta \to \infty$, $\Delta M_{\rm tree} \propto 1/\mu^4$. (A $1/\mu^3$ contribution vanishes because, in this limit, an exact Peccei-Quinn symmetry relates $\mu \leftrightarrow -\mu$.) For all of these reasons, the mass splitting is highly suppressed, even for moderate values of $|\mu|$.

Given the large suppression of $\Delta M_{\rm tree}$, 1-loop contributions may be important. The leading contribution to the mass splitting from loop effects is from custodial SU(2) breaking in the gauge boson sector. (Loop contributions from sleptons and squarks are insignificant for heavy top and bottom squarks [7].) The loop contribution is positive, and, in the pure W-ino limit, it has the simple form [7], letting $r_i = m_i/M_2$, $c_W = \cos\theta_W$, $s_W = \sin\theta_W$,

$$\Delta M_{\rm loop} = \frac{\alpha_2 M_2}{4\pi}\left[f(r_W) - c_W^2 f(r_Z) - s_W^2 f(r_\gamma)\right], \quad (2)$$

where $f(a) = \int_0^1 dx\,(2 + 2x)\log[x^2 + (1 - x)a^2]$.

In Fig. 1a, we plot the total mass splitting ΔM for the anomaly-mediated value of M_1/M_2 and a moderate value of $\tan\beta$, where the tree-level mass matrices have been corrected by 1-loop gauge boson contributions including chargino and neutralino mixing [8] and have been diagonalized numerically. We show the region (for $\mu < 0$) of parameter space which is consistent with naturalness constraints [6]. Typical mass splittings are of order 150 MeV to 1 GeV. In Fig. 1b we do the same for a model with $M_1 = -1.5M_2$, in which ΔM may be even smaller. Note that the near degeneracy of the W-ino-like chargino and neutralino is generic. Generally, this degeneracy is not of great phenomenological importance, as the W-ino-like chargino and neutralino both decay quickly to other particles. However, when one of them is the LSP, the other must decay into it, and the near degeneracy results in macroscopic decay lengths with important implications.

For mass splitting in the range of a few hundred MeV, the dominant chargino decays are the three-body decays $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0(e^+\nu_e, \mu^+\nu_\mu)$ and the two-body decay $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\pi^+$. For $\Delta M \lesssim m_{\pi^\pm} \simeq 140$ MeV, the decay rate is dominated by the electron mode, with $\Gamma(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+\nu) \approx \frac{G_F^2}{(2\pi)^3}\frac{16}{15}(\Delta M)^5$, corresponding to a decay length of $c\tau|_{e\,\rm mode} = 34\ {\rm m} \times (100\ {\rm MeV}/\Delta M)^5$ [5].

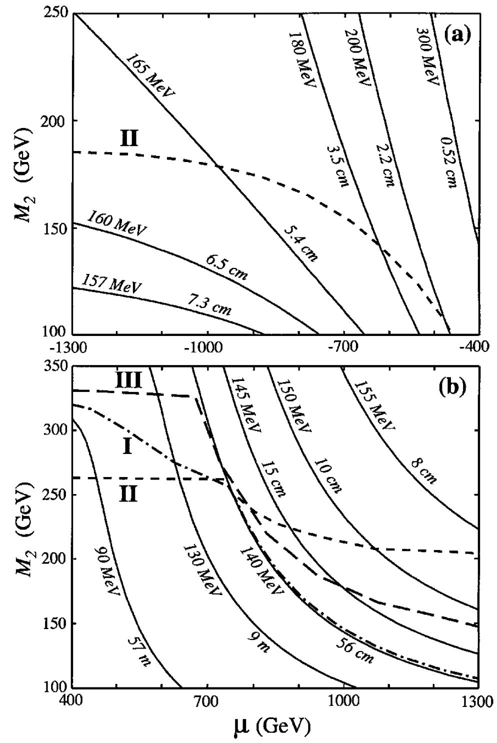

FIG. 1. The mass splitting $\Delta M \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and decay lengths $c\tau$ in the (μ, M_2) plane. (a) The anomaly-mediated relation $M_1 \approx 3.3M_2$ is assumed, and $\tan\beta = 10$. Similar results are obtained for $\mu > 0$. The discovery region for trigger II is shown (see text). (b) The same for a more general W-ino LSP model, with $\tan\beta = 3$ and $M_1 = -1.5M_2$, along with the discovery reach for triggers I–III (see text).

However, once the pion mode becomes available, it quickly dominates [3,9], and $c\tau$ becomes of order 10 cm or less. In Fig. 1, the contours are also labeled with decay lengths $c\tau$, where all final states are included. We find macroscopic decay lengths on the order of centimeters to meters in much of the parameter space.

Amazingly, the W-ino LSP scenario guarantees a mass splitting such that the chargino could decay in any of the detector components. This is an automatic consequence of the W-ino LSP scenario. With conventional triggering, such W-inos generally evade detection. For some range of parameters, the splitting is such that W-inos decay before the muon chambers (although for long lifetimes those that do reach the muon chamber will be important). Furthermore, the decay products are soft, and will generally neither meet the calorimeter trigger threshold nor provide an observable kink. For short-lived tracks with sufficiently hard decay products and for long-lived tracks, the current bound from LEP II [10] is about 90 GeV; otherwise it is 45–63 GeV.

Of course, if chargino events are accepted, the signal of a high p_T track that disappears, leaving only a low momentum charged lepton or pion, is spectacular, and could hardly escape off-line analysis. The essential difficulty then is the acceptance of chargino events into the data sample. In the following, we propose a number of solutions to this difficulty and consider the prospects for probing the W-ino LSP scenario at the Fermilab detectors CDF II (Collider Detector at Fermilab) and D0 (DZero) in the next Tevatron run.

We discuss several possible triggers. (I) For sufficiently long-lived W-inos, one can apply the usual search for heavy particles that trigger in the muon chambers. (II) For shorter-lived charginos which do not reach the muon chamber, events in which a high p_T jet accompanies the W-inos can be used by triggering on the jet and the associated missing E_T. Distinguishing these events from background in the off-line analysis will require identifying the W-ino track itself. Finally, as a supplement to these two triggers, we propose to search for W-inos too short-lived to reach the muon chamber by using the fact that they leave stiff tracks in the tracking chamber in events that are hadronically quiet. This can be done by (III) triggering on events with a single stiff track and no localized energy (in the form of jets) in the calorimeter. The addition of this trigger will extend the Tevatron reach for the light W-ino search and furthermore should considerably enhance statistics. We will also discuss a more conservative but less powerful variation of this trigger (III′) that requires two stiff tracks with balancing p_T. If ΔM is significantly above m_π, as for sequestered sector models, only trigger II is useful, but in more general W-ino LSP models, all three triggers can be important.

Trigger I is useful for detecting the processes

$$q\bar{q} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^- \qquad (3)$$

when the W-ino tracks have lengths of order of meters or more. Of course, for the muon chamber trigger to be useful we must distinguish W-inos from muons. Fortunately, W-inos tend to have low velocities and associated high ionization energy loss rates dE/dx in the vertex detector and tracking chambers. We will require the W-ino tracks to have $\beta\gamma < 0.85$, which corresponds to dE/dx approximately double minimally ionizing [2]. In Fig. 2, we present the combined cross section for processes (3), using the following technique. Let L be the minimum radial distance a charged track must travel in order to be detected by a given trigger (here, the distance to the muon chambers). We require that each event have a charged track of length L or greater, with pseudorapidity $|\eta| < 1.2$. The cross section for such events depends on ΔM through the combination $c\tau/L$. We present curves for several values of $c\tau/L$, with and without the cut on $\beta\gamma$. The figure shows that a cut on $\beta\gamma$ retains a large signal, allowing W-inos to be discovered in searches for massive long-lived charged particles [1,2]. The relative sensitivity of this search depends, of course, on the chargino decay length $c\tau$. For example, from Fig. 2, we find that for muon chambers with $L \approx 4.5$ m, assuming 2 fb^{-1} integrated luminosity and demanding five events for discovery, the mass reach for W-inos with $c\tau \geq 6$ m is at least 260 GeV. Additional information from time of flight may also be useful for distinguishing W-inos from muons.

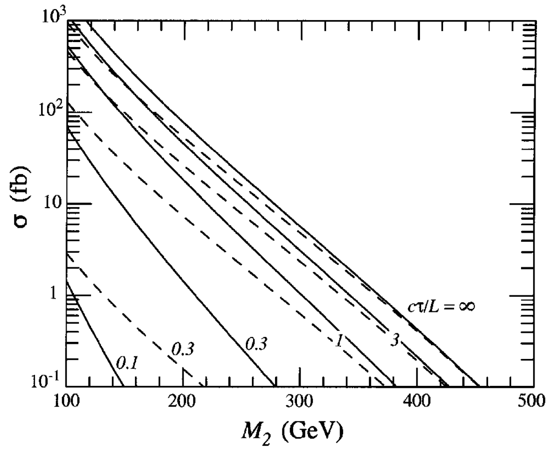

FIG. 2. Cross sections (solid lines) at $\sqrt{s} = 2$ TeV for W-ino pair production with at least one charged track traveling a radial length L with $|\eta| < 1.2$. The dependence on decay length $c\tau$ is shown. For the dashed lines, the charged track is also required to have $\beta\gamma < 0.85$. See discussion of triggers I and III in text.

Next we consider trigger II, sensitive to the production of W-inos plus a jet. Such topologies may be produced through the parton level processes

$$q\bar{q} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 g, \tilde{\chi}_1^+\tilde{\chi}_1^- g; \quad qg \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 q, \tilde{\chi}_1^+\tilde{\chi}_1^- q\,. \qquad (4)$$

When the jet is hard, these events are characterized by large $\not{E}_T$ resulting from a single high p_T jet, and one or two charginos that decay in the detector. In our analysis, we require an event with $\not{E}_T > 30$ GeV, and a jet with $p_T > 30$ GeV and $|\eta| < 1.2$.

For the signal to be distinguishable in the off-line analysis from backgrounds, such as monojets resulting from $q\bar{q} \to gZ \to g\nu\bar{\nu}$, the charginos, or their decay products, must be visible. The most obvious possibility is that the charginos leave tracks in detector components before decaying. We assume the off-line analysis will require at least one isolated high p_T track, with $|\eta| < 2$, that travels a radial distance greater than some minimum detection length L. These tracks will not deposit much energy in the calorimeters or (if short) hit the muon chambers, and should therefore leave a spectacular, background-free signal. (Note that in events with long tracks that also hit the muon chambers, a cut on $\beta\gamma$ will distinguish charginos from muons, as discussed below.)

In Fig. 3, we plot cross sections, combining the four relevant processes of (4) for various values of $c\tau/L$. The cross sections are clearly strongly dependent on the length L. For both CDF II and D0, a chargino traveling a radial length $L = 10$ cm or greater should be easily identified, as such charginos will travel through essentially all layers of the silicon vertex detector. With the same discovery criterion as above, we find a discovery reach of $M_2 \approx 140$, 210, and 240 GeV for decay lengths $c\tau = 3$, 10, and 30 cm, respectively.

If the chargino track lengths are $\mathcal{O}(10$ cm) or longer, trigger III could be applied to processes (3). The rate

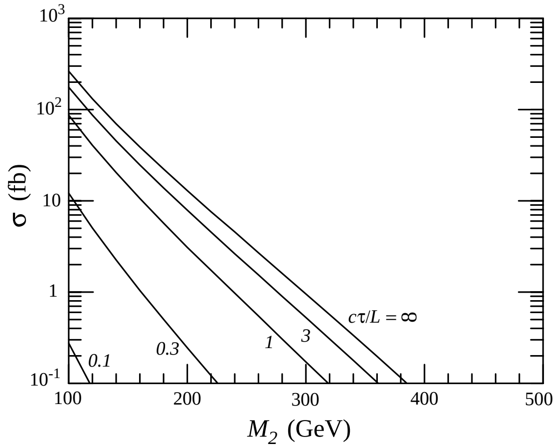

FIG. 3. Cross sections at $\sqrt{s} = 2$ TeV for associated production of a W-ino pair and a jet with $p_T > 30$ GeV and $|\eta| < 1.2$. At least one charged W-ino is required to travel a radial length L with $|\eta| < 2$. The dependence on decay length $c\tau$ is shown. See discussion of trigger II in text.

for chargino events accepted by such a trigger may be determined from the solid curves in Fig. 2 for various $c\tau$.

As in the previous case, the cross sections depend strongly on the required L. For the CDF II (D0) detector, tracking information is available at the trigger level if $L \gtrsim 1$ m (50 cm). Once such events are accepted, the lack of calorimeter activity makes them striking; physics backgrounds are negligible, and the leading backgrounds are expected to be instrumental. (Long tracks hitting the muon chamber will be discussed below.) With the same discovery criterion as above and $c\tau = 6$ m, both detectors have a mass reach of roughly 320 GeV. Furthermore, as can be seen from Fig. 2, for $c\tau \sim 6$ m the signal passing trigger III ($c\tau/L \sim 10$) is several times larger than that passing trigger I ($c\tau/L \sim 1$).

Trigger III′ accepts only the second process in (3), and requires that both chargino tracks travel through a substantial portion of the tracking chamber. Although fewer signal events pass this trigger, the ratio of signal-to-trigger background may be better than for trigger III.

In our discussion of the discovery region for $\Delta M < m_\pi$, we have neglected the fact that some events passing triggers II and III contain W-ino tracks that also pass trigger I. As before, these charginos must be distinguished from muons using a $\beta\gamma$ cut. However, most charginos are produced slowly, so the impact of the $\beta\gamma$ cut is small, reducing the discovery reach by at most 5–10 GeV.

In order to summarize the discovery reach, we show in Fig. 1 the five event discovery contours for triggers I, II, and III with $L = 4.5$ m, 10 cm, and 50 cm, respectively. In (a) we have taken M_1/M_2 as suggested by the anomaly-mediated supersymmetry breaking. Since $\Delta M > m_\pi$, only trigger II plays a role, but fortunately it can cover a large fraction of the parameter space of the sequestered sector models. In (b) we consider a more general W-ino LSP model in which the discovery reach is markedly enhanced using triggers I and III. In particular, triggers I and III, which require small ΔM so that chargino tracks are sufficiently long, are useful at large W-ino masses, where W-ino production is too rare for trigger II to find a signal. Note that the discovery reaches depend significantly on M_1/M_2, $\tan\beta$, and sgn(μ); these particular cases are for illustration only.

If the candidate events are discovered, a number of important checks can be made on the W-ino LSP interpretation. These include comparing the number of events with one and two charged tracks, and determining the fraction of events with anomalously large dE/dx as mentioned above. In addition, in order to distinguish this scenario from gauge-mediated scenarios with long-lived sleptons, where macroscopic decay lengths result not from degeneracy but from highly suppressed couplings [1,2], correlations between particle masses and cross sections may be used. Finally, as the signals discussed above are essentially background-free, the discovery potential is highly sensitive to integrated luminosity. For example, if the total luminosity is increased to 30 fb^{-1}, the various W-ino mass discovery reaches estimated above increase by up to 100 GeV. It is exciting that W-ino LSP searches will explore a large fraction of the parameter space of the sequestered sector scenario [5] even before the LHC, giving the Tevatron the possibility of finding the first evidence for extra space-time dimensions.

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