Discovering Supersymmetry at the Tevatron in Wino LSP Scenarios

Jonathan L. Feng,\textsuperscript{a} Takeo Moroi,\textsuperscript{a} Lisa Randall,\textsuperscript{b,c} Matthew Strassler,\textsuperscript{a} and Shufang Su\textsuperscript{c}

\textsuperscript{a}School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540 USA
\textsuperscript{b}Joseph Henry Laboratories, Princeton University, Princeton, NJ 08543 USA
\textsuperscript{c}Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

Abstract

In supersymmetric models, Winos, partners of the SU(2) gauge bosons, may be the lightest supersymmetric particles (LSPs). For generic parameters, charged and neutral Winos are highly degenerate. Charged Winos travel macroscopic distances, but can decay to neutral Winos and extremely soft leptons or pions before reaching the muon chambers, thereby circumventing conventional trigger requirements based on energetic decay products or muon chamber hits. 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 Winos with masses up to 300 GeV and explore a substantial portion of the parameter space in sequestered sector models [1].
The discovery of supersymmetry (SUSY) is much 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 the electroweak scale. In the most widely studied models, the lightest supersymmetric particle (LSP) is assumed to be stable and the partner of the U(1)$_Y$ gauge boson. SUSY signals are then characterized by missing transverse energy ($E_T$) and are unlikely to escape detection when the Large Hadron Collider (LHC) at CERN begins operation around 2005 with center of mass energy $\sqrt{s} = 14$ TeV.

Recently, however, it has been realized that many other SUSY signatures are possible. While these signatures vary widely, a number of them are in fact even more striking than the classic $E_T$ signature and give new life to the hope that the discovery of SUSY need not wait for the LHC [2–4]. 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 Wino $\tilde{W}^0$. We will see that this simple modification leads to drastic differences in phenomenology. These were argued to make detection difficult, based on conventional triggers, in [4,5], but were argued to provide a novel identifiable signal in Ref. [1]. 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 Wino $\tilde{W}^\pm$, 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 Winos 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 $\mu$, 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 $\mu$ are then physical. We will consider the case $M_2 < \{|M_1|, |\mu|\}$, so that the lightest charginos and neutralinos, $\tilde{\chi}^\pm$ and $\tilde{\chi}^0_1$, are Wino-like with masses $\sim M_2$. We assume that all other superparticles are (much) heavier than the Winos. With this assumption we may neglect corrections to charged Wino decay from virtual supersymmetric particles.

We will consider two Wino LSP scenarios. In the first, we consider the well-motivated sequestered sector models [1], 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 [1][3]

$$M_i = -b_i g_i^2 M_{\text{SUSY}},$$

where $M_{\text{SUSY}}$ 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 $\beta$-function coefficients of the (full supersymmetric) theory. Substituting the weak scale values of $g_i$, we find $M_1 : M_2 : M_3 = 3.3 : 1 : -10$. It should be borne in mind that sequestered sector models predict a large hierarchy between Wino and squark masses. Naturalness bounds therefore suggest $M_2 \lesssim 200 - 300$ GeV, and we will see that a large portion of the parameter space in these scenarios may be explored at the Tevatron.

More generally, the Wino LSP scenario may be realized for a large region of SUSY
parameter space if the assumption of gaugino mass unification is relaxed \( [4, 5] \). We will therefore also consider an alternative set of parameters with \( M_1 = -1.5 M_2 \). As will be seen, this choice leads 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 Wino mass \( M_2 \) is less constrained in this case.

The SUSY signal depends strongly on \( \Delta M \equiv m_{\tilde{\chi}^+_i} - m_{\tilde{\chi}^0_i} \). At tree level, the chargino mass matrix is

\[
\begin{pmatrix}
M_2 & \sqrt{2} m_W s_\beta \\
\sqrt{2} m_W c_\beta & \mu
\end{pmatrix}
\]

in the basis \((-i \tilde{W}^\pm, \tilde{H}^\pm)\), and the neutralino mass matrix is

\[
\begin{pmatrix}
M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\
0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\
-m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\
m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0
\end{pmatrix}
\]

in the basis \((-i \tilde{B}, -i \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)\). Here \( s_W \equiv \sin \theta_W, c_W \equiv \cos \theta_W, s_\beta \equiv \sin \beta, \) and \( c_\beta \equiv \cos \beta \).

The mass matrices may be diagonalized exactly, but it is enlightening to consider a perturbation series in \( 1/\mu \) for large \( |\mu| \). The lightest chargino and neutralino are degenerate at zeroth order with \( m_{\tilde{\chi}^+_1}^{(0)} = m_{\tilde{\chi}^0_1}^{(0)} = M_2 \). At the next order in \( 1/\mu \), they receive corrections from mixing with the Higgsinos. However, both masses are corrected by \( m_{\tilde{\chi}^+_1}^{(1)} = m_{\tilde{\chi}^0_1}^{(1)} = -m^2_W \sin \beta/\mu \), 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:

\[
\Delta M_{\text{tree}} \approx m_{\tilde{\chi}^+_1}^{(2)} - m_{\tilde{\chi}^0_1}^{(2)} = \frac{m_W^4 \tan^2 \theta_W}{(M_1 - M_2) \mu^2} \sin^2 2\beta.
\]

Note that for large \( \tan \beta \), even this contribution is suppressed. In fact, for \( \tan \beta \to \infty \), \( \Delta M_{\text{tree}} \propto 1/\mu^4 \). (A \( 1/\mu^3 \) contribution vanishes because, in this limit, the bilinear Higgs scalar coupling \( B \) vanishes, and so 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 \( \Delta M_{\text{tree}} \), 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 \([4]\).) The loop contribution is positive, and, in the pure Wino limit, it has the simple form \([6]\), letting \( r_i = m_i/M_2 \),

\[
\Delta M_{1-\text{loop}} = \frac{\alpha_2 M_2}{4\pi} \left[ f(r_W) - c_W^2 f(r_Z) - s_W^2 f(r_\gamma) \right],
\]

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

In Fig. \([4]\), we plot the total mass splitting \( \Delta M \) 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
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 $(\mu, M_2)$ 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 Wino LSP model, with $\tan \beta = 3$ and $M_1 = -1.5M_2$, along with the discovery reach for triggers I – III. (See text.)

1-loop gauge boson contributions including chargino and neutralino mixing [7] and have been diagonalized numerically. We show the region (for $\mu < 0$) of parameter space which is consistent with naturalness constraints [8]. Typical mass splittings are of order 150 MeV to 1 GeV. In Fig. b we do the same for a model with $M_1 = -1.5M_2$, in which $\Delta M$ may be even smaller. Note that the near-degeneracy of the Wino-like chargino and neutralino is generic. Generally, this degeneracy is not of great phenomenological importance, as the Wino-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 splittings 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 $\Delta M \lesssim m_{\pi^\pm} \approx 140$ MeV, the decay rate is dominated by the electron mode, with $\Gamma(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu) \approx \frac{G_F^2}{2\pi} \frac{16}{13} (\Delta M)^5$, corresponding to a decay length of $c\tau|_{\text{e mode}} = 34$ meters $\times (100 \text{ MeV}/\Delta M)^5$. However, once the pion mode becomes available, it quickly domi-
nates $[4,9]$, and $c\tau$ becomes of order 10 cm or less. In Fig. 1, the contours are labeled also 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 Wino 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 Wino LSP scenario. With conventional triggering, such Winos generally evade detection. For some range of parameters, the splitting is such that Winos 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 Wino LSP scenario at the Fermilab detectors CDF II (Collider Detector at Fermilab) and DØ (DZero) in the next Tevatron run.

We discuss several possible triggers. (I) For sufficiently long-lived Winos, 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 Winos 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 Wino track itself. Finally, as a supplement to these two triggers, we propose to search for Winos 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 Wino search and furthermore should considerably enhance statistics. A more conservative but less powerful approach (III’) would be to trigger instead on events containing two stiff tracks with balancing $p_T$. If $\Delta M$ is significantly above $m_\pi$, as for sequestered sector models, only trigger II is useful, but in more general Wino LSP models all three triggers can be important.

Trigger I is useful for detecting the processes

$$q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-$$  \hspace{1cm} (6)$$

when the Winos tracks have lengths of order meters or more. Of course, for the muon chamber trigger to be useful we must distinguish Wino tracks from those produced by muons. Fortunately, Winos 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 Wino tracks to have $\beta\gamma < 0.85$, which corresponds to $dE/dx$ approximately double minimally-ionizing [3]. 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
FIG. 2. Cross sections (solid) at $\sqrt{s} = 2$ TeV for Wino 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 contours, the charged track is also required to have $\beta\gamma < 0.85$. See associated discussion of triggers I, III.

$|\eta| < 1.2$. The cross section for such events depends on $\Delta M$ 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 Winos to be discovered in searches for massive long-lived charged particles \[3,4\]. 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 $2 \text{ fb}^{-1}$ integrated luminosity and demanding 5 events for discovery, the mass reach for Winos with $c\tau \geq 6$ m is at least 260 GeV. Additional information from time-of-flight may also be useful for distinguishing Winos from muons.

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

$$q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^- g \quad \text{and} \quad gg \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 q, \tilde{\chi}_1^+ \tilde{\chi}_1^- q. \quad (7)$$

When the jet is hard, these events are characterized by large $E_T$ 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 $E_T > 30$ 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 $q\bar{q} \rightarrow gZ \rightarrow g\nu\bar{\nu}$, 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 (7) for various values of $c\tau/L$. The cross sections are clearly strongly dependent on the length $L$. For both CDF II and DØ, 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 $M_2 \approx 140, 210, \text{ and } 240 \text{ GeV}$ for decay lengths $c\tau = 3, 10, \text{ and } 30 \text{ cm}$, respectively.

Winos with $c\tau < 10 \text{ cm}$ decay predominantly through the pion mode. If these pions can be identified, they could conceivably extend the reach of this search for $\Delta M > m_\pi$. However, this requires careful study outside the scope of this paper.

If the chargino track lengths are $O(10 \text{ cm})$ or longer, trigger III could be applied to processes (6). The rate 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 (DØ) detector, tracking information is available at the trigger level if $L \gtrsim 1 \text{ m} (50 \text{ cm})$. 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 $c\tau = 6 \text{ m}$, both detectors have a mass reach of roughly 320 GeV. Furthermore, as can be seen from Fig. 4, for $c\tau \sim 6 \text{ m}$ 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 (6), and requires that both chargino tracks travel through a substantial portion of the tracking chamber. Though fewer signal events pass this trigger, the ratio of signal to trigger background may be better than for trigger III. The utility of trigger III’ is less than that of trigger III, but is comparable to that of trigger I for $\Delta M < m_\pi$. If, contrary to our assumptions, the sleptons are not much heavier than $M_2$, then the chargino lifetime would be smaller, and the power of trigger I reduced, making trigger III’ potentially more important.

In our discussion of the discovery region for $\Delta M < m_\pi$, we have neglected the fact that some fraction of the events passing triggers II, III, and III’ will contain Wino 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,

![Cross sections at $\sqrt{s} = 2 \text{ TeV}$ for associated production of a Wino pair and a jet with $p_T > 30 \text{ GeV}$ and $|\eta| < 1.2$. At least one charged Wino is required to travel a radial length $L$ with $|\eta| < 2$. The dependence on decay length $c\tau$ is shown. See associated discussion of trigger II.](image-url)
reducing the discovery reach by at most 5–10 GeV.

In order to summarize the discovery reach, we show in Fig. 1 the 5 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 Wino LSP model in which the discovery reach is markedly enhanced using triggers I and III. In particular, triggers I and III, which require small $\Delta M$ so that chargino tracks are sufficiently long, are useful at large Wino masses where Wino 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 $\text{sign}(\mu)$; these particular cases are for illustration only.

If candidate events are discovered, a number of important checks can be made on the Wino 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 [2,3], 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 Wino mass discovery reaches estimated above increase by up to 100 GeV. It is exciting that Wino LSP searches will explore a large fraction of the parameter space of the sequestered sector scenario [1] even before the LHC, giving the Tevatron the possibility of finding the first evidence for extra space-time dimensions.

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