Decays of $W$ Bosons to Charginos and Neutralinos

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ABSTRACT

The region of the supersymmetry parameter space, in which charginos decay predominantly into sneutrinos and leptons: $\chi_1^+ \rightarrow \tilde{\nu} + l^+$, is not excluded experimentally for small mass differences between charginos and sneutrinos. The decay sneutrinos are invisible in R-parity conserving theories since they are either the lightest supersymmetric particles or they decay primarily into the channel $\tilde{\nu} \rightarrow \nu + \chi_1^0$. If the energy of the decay leptons is so small that they escape detection, chargino events $e^+e^- \rightarrow \chi_1^+\chi_1^-$ in $e^+e^-$ collisions remain invisible, eroding the excluded chargino mass range at LEP. This region of the supersymmetry parameter space can partly be covered by searching for single $W$ events in $e^+e^- \rightarrow W^+W^-$, with one $W$ boson decaying to leptons or quark jets, but the second $W$ boson decaying to (undetected) charginos and neutralinos.
1. The $e^+e^-$ collider LEP is an ideal instrument to search for charginos and neutralinos in supersymmetric theories. These particles are mixtures of gauginos and higgsinos, the supersymmetric partners of gauge bosons and Higgs bosons [1]. They can be produced pairwise in $e^+e^-$ collisions:

$$e^+e^- \rightarrow \chi^+_i\chi^0_j \quad \text{for} \quad i,j = 1,2$$  
$$e^+e^- \rightarrow \chi^0_i\chi^0_j \quad \text{for} \quad i,j = 1,\ldots,4$$ 

If the sneutrinos $\tilde{\nu}_{eL}$ are heavy, charginos can be probed up to the kinematical limit; if they are light, the upper bound on the chargino mass is reduced dramatically for gaugino-like charginos by the destructive interference between the s-channel $\gamma, Z$ and the t-channel $\tilde{\nu}_{eL}$ exchange diagrams in the production amplitude.

However, within low-energy supersymmetry there is a small spot in the SUSY parameter space in which the experimental search technique [2] for the lightest chargino in the production process $e^+e^- \rightarrow \chi^+_1\chi^+_1$ fails. If one of the sneutrino masses is just below the $\chi^+_1$ mass, $m(\tilde{\nu}_{eL}) < \sim m(\chi^+_1)$, the dominant decay mode is the 2-body decay $\chi^+_1 \rightarrow \tilde{\nu}_{eL}l^+$, since the associated left-chiral slepton $\tilde{l}_L$ is too heavy for the other 2-body decay channel $\chi^+_1 \rightarrow \tilde{l}_L\nu_l$ to be open. If the mass gap is narrow, the decay lepton $l^+$ is emitted with very low energy in the $\chi^+_1$ rest frame. The decay sneutrino is invisible since it is either the lightest supersymmetric particle or it decays primarily to the associated neutrino and the lightest neutralino $\chi^0_1$. As a result, chargino events in $e^+e^-$ collisions are invisible because the energy of the decay leptons is so small that they escape detection. In such a case, called ”blind spot” in Ref. [2], charginos can be as light as 45 GeV, the ultimate limit obtained in the search for this particle at LEP1 [3].

Several methods can be used to eliminate this spot. Constraints from future high-precision $(g - 2)_\mu$ measurements have been exploited in Ref. [4]; this method is successful for large $\tan \beta$.

However, the LEP experiments themselves can probe this exceptional part of the supersymmetry parameter space in several ways. (i) If the energy is sufficiently above the chargino mass, the boost of the decay lepton becomes so large that the particle can be tracked in the final state. (ii) The region $m(\tilde{\nu}_{eL}) < m(\chi^+_1)$ in the parameter space can be excluded if the associated left-chiral slepton with a mass $m^2(\tilde{l}_L) = m^2(\tilde{\nu}_{eL}) + \cos^2 \theta_W |\cos 2\beta| M_Z^2$ is not observed. (iii) The annihilation event may be tagged by observing single photons in $e^+e^- \rightarrow \gamma + \chi^+_1\chi^+_1$, with the two charginos not detected. The upper limit of the $\gamma$ spectrum, $E_\gamma \leq [s - 4m^2(\chi^+_1)]/2\sqrt{s}$, is characteristic for the production of the massive chargino pairs. The cross section for this photonic reaction however is very small and the background due to radiative $Z$ return is large. (iv) Finally, the production of $WW$ pairs can be used to explore this parameter region. If one of the two $W$ bosons decays undetected into a chargino
plus neutralino pair,
\[ e^+e^- \rightarrow W^+W^- \rightarrow \chi^0\chi^0 \]  

"single W" final states, \( e^+e^- \rightarrow W + (\text{no other visible particle}) \), are generated by this mode. In essence, the SM decays of the \( W \) boson in one hemisphere are used to track down invisible decays of the second \( W \) in the opposite hemisphere. This method is best suited for two real \( W \) bosons with \( m(W^+) > m(\chi^+_1) + m(\chi^0_1) \); if this condition is not fulfilled any more, the decay \( W \) boson is virtual and the rate is reduced significantly. We find that if such nonstandard invisible \( W \) boson decays occur at the level of a few percent, they should be detectable at LEP energies. Thus, the non-observation of "single W" events could therefore be used to close the blind spot in supersymmetry parameter space.

2. In this letter we investigate the decay of the \( W \) bosons to charginos and neutralinos:
\[ W^+ \rightarrow \chi^+_i \chi^0_j \quad [i = 1, 2; j = 1, ..., 4] \]  

In practice, we can restrict ourselves to the lightest chargino to allow for maximum phase space, though the generalization to the other pairings is straightforward. In some areas of the parameter space the heavier neutralinos \( \chi^0_j \) may still be light enough and their coupling large enough to allow for \( W \) decays into these states too. In the numerical analysis all kinematically possible decay modes to charginos and neutralinos will be taken into account.

The analysis is set up within the frame of the minimal low-energy supersymmetric theory. Even though no reference is made to underlying unified theories, we assume the relation \( M_1 = \frac{5}{3} M_2 \tan^2 \theta_W \) for gaugino mass parameters just for sake of simplicity; this assumption can easily be lifted. Within this frame, the chargino/neutralino sector is characterized by three parameters: the mixing angle \( \beta \), the wino mass \( M_2 \) and the higgsino mass parameter \( \mu \).

Extending the calculations of Refs.[5] to the case of general mixing in the chargino and neutralino sectors, the partial widths for the decay processes (4) are given by the expressions

\[ \Gamma(W^+ \rightarrow \chi^+_i \chi^0_j) = \frac{G_F m_W^3 \lambda_{ij}^{1/2}}{6\sqrt{2}\pi} \times \left\{ \left[ 2 - \kappa^2_i - \kappa^2_j - (\kappa^2_i - \kappa^2_j)^2 \right] (Q^2_{Li} + Q^2_{Ri}) + 12\kappa_i\kappa_j Q_{Li} Q_{Ri} \right\} \]  

where, with \( m_{i,j} \) being the chargino/neutralino masses, \( \kappa_i = m_i/m_W \) and \( \lambda_{ij} = (1 - \kappa^2_i - \kappa^2_j)^2 - 4\kappa^2_i\kappa^2_j \), the usual 2-body phase space coefficient. The couplings of
the $W$ boson to charginos and neutralinos are written in the usual form as

\begin{align}
Q_{Li j} &= Z_{j2} V_{i1} - \frac{1}{\sqrt{2}} Z_{j4} V_{i2} \\
Q_{Ri j} &= Z_{j2} U_{i1} + \frac{1}{\sqrt{2}} Z_{j3} U_{i2}
\end{align}

(6) (7)

where $U$, $V$ are the mixing matrices in the chargino sector, and $Z$ in neutralino sector [6].

Since the $W$ bosons are generated predominantly in a state of transverse polarization, the decay to the $\chi^{\pm}\chi^0$ pair is not isotropic. However, the impact of the $W$ polarization on the angular distribution is small due to the large masses of the decay particles. We have quantitatively checked this point by analyzing the angular distribution of polarized $W$ decays. The spin axis is chosen as the reference axis for the polar angle $\theta$ of the chargino/neutralino axis. In this frame the angular distribution for the decay $W^\pm(S_z = \pm 1, 0) \to \chi_i^\pm \chi_j^0$ is given by

\begin{align}
\frac{d\Gamma^+}{d\cos \theta} &\sim [1 - \kappa_i^2 - \kappa_j^2 - \frac{1}{2} \lambda_{ij} \sin^2 \theta] [Q^2_{Lij} + Q^2_{Rij}] + 4 \kappa_i \kappa_j Q_{Lij} Q_{Rij} \\
\frac{d\Gamma^0}{d\cos \theta} &\sim [1 - \kappa_i^2 - \kappa_j^2 - \lambda_{ij} \cos^2 \theta] [Q^2_{Lij} + Q^2_{Rij}] + 4 \kappa_i \kappa_j Q_{Lij} Q_{Rij}
\end{align}

(8) (9)

Since the $W\chi\chi$ coupling is $C$ and $\mathcal{P}$ symmetric, no forward–backward asymmetry is generated.

The range of the parameters $M_\chi$ and $\mu$, which determine masses and couplings of charginos and neutralinos, is restricted by the $Z$ decays at LEP1 [3]. The impact on the $\chi^0_1$ mass from the Tristan analysis [7] of the selectron production for $m(\tilde{e}) > 65$ GeV is small. From the LEP runs above the $Z$, the parameters are restricted by the non-observation of $\chi^0_1\chi^0_1$ signals [8]. Note however that these bounds have not been derived for the special condition $m(\tilde{\nu}_L) \lesssim m(\chi^+)$ which the present analysis is based upon. They should therefore be taken only as a general guideline.

The measurement of the $W$ width and the $W$ decay branching ratios at the Tevatron [9] provide additional restrictions on possible supersymmetric decay modes of the $W$ boson; we demand that $\Gamma(W \to \chi\chi) < 140$ MeV be fulfilled for the $\chi$ masses discussed in this note. The envelope of the constraints listed above is shown by the broken lines in Fig.1 for the representative value $\tan \beta = 1.5$. The zone excluded is the area below and in between these lines. For large $\tan \beta$, the $\chi^+_1$ and $\chi^0_1$ mass constraints forbid on-shell $W$ decays to charginos and neutralinos.

The main result of this letter is summarized in Fig.1. The solid contour lines represent $W$ decay branching ratios of 7, 5, 3 and 1% into chargino and neutralino final states within the area allowed by the mass constraints for $\tan \beta = 1.5$. The
only channels which enter the total width in the $W$ branching ratios, are the usual channels of the Standard Model and the new $\chi^\pm \chi^0$ decay channels. The numbers quoted above for the branching ratios correspond to partial widths of approximately 140 MeV down to 20 MeV. An additional narrow strip is excluded for positive $\mu$ by the boundary condition $\text{BR}(W \to \chi \chi) < 7\%$. For better illustration, the contour lines are shown in Fig.2 only in the window $100 < \mu < 300$ GeV and $60 < M_2 < 140$ GeV. The contour lines continue in narrow strips to larger $\mu$ and $M_2$ values. For negative $\mu$, $W$ decays to charginos and neutralinos can occur in the strip $\mu < -20$ GeV adjacent to the LEP1 limit.

The same contour lines for the $W$ branching ratios of 7, 5, 3 and 1% are shown in Fig.3 as a function of $m(\chi^+_1), m(\chi^0_1)$, separately for positive and negative $\mu$. Only solutions with $m(\chi^0_2) > 45$ GeV are displayed. The regions corresponding to higgsino-like (large $M_2$) or gaugino-like (large $|\mu|$) light charginos and neutralinos, are marked explicitly. For positive $\mu$ the contour lines extend up to $m(\chi^+_1) \sim 54$ GeV, for negative $\mu$ up to $m(\chi^+_1) \sim 65$ GeV. In the case of negative $\mu$, there are two branches of the contour lines for 1 and 3%, in analogy to Fig.1. Some contour lines terminate inside the figure because either the $m(\chi^0_2) = 45$ GeV limit is reached or one of the $M_2$ or $|\mu|$ parameters is larger than 400 GeV.

3. From the contour lines given in Figs.1/3, it is manifest that $W \to \chi \chi$ branching ratios up to order 7% are still in the allowed zones of the $[m(\chi^+_1), m(\chi^0_1)]$ plane. To estimate the feasibility of observing the invisible supersymmetric $W \to \chi \chi$ decays in $e^+e^- \to W^+W^-$ production processes, we consider, as an illustrative example, events collected at the LEP 172 GeV run. Assuming 7% branching ratio for the supersymmetric $W$ decay modes, one expects both $W$ bosons to decay to standard model particles in 86.5% of the cases, both $W$ bosons decaying to charginos and neutralinos in 0.5% of the cases, and finally the signal events defined as one $W$ boson decaying to standard particles and the other to chargino and neutralino to occur in 13% of the cases. The total $WW$ cross section at this energy is $\sim 13$ pb, which then leads to the signal cross section of the order 1.7 pb. With the combined integrated luminosity $L \sim 4 \times 11$ pb$^{-1} = 44$ pb$^{-1}$ of the four LEP experiments at $\sqrt{s} = 172$ GeV, a total of about 570 $WW$ events have been produced, i.e. 1140 $W$ bosons out of which 80 $W$ bosons are potential candidates for chargino/neutralino decays if $\text{BR}(W \to \chi \chi) = 7\%$. Therefore 74 signal events with mixed standard and supersymmetric $W$ decays can be expected.

According to the underlying assumptions, the signature of these events would be a single $W$ boson, $e^+e^- \to W^+$ (no other visible particle), with the isolated $W$ boson carrying the beam energy. The $W$ boson may be tagged in the 2-jet decay mode or, with reduced branching ratios, in the leptonic $e\nu_e$ and $\mu\nu_\mu$ decay modes. Using selection cuts for single $W$ production consistent with on-shell $WW$ kinematics, we
estimate that in the leptonic tagging mode ($W \rightarrow e\nu/\mu\nu$) an efficiency at least as large as in the search for acoplanar lepton pairs, i.e. better than 70%, and in the 2-jet tagging mode ($W \rightarrow q\bar{q}'$) an efficiency comparable to that of the search for $WW \rightarrow \tau\nu q\bar{q}'$, i.e. better than 30% can be achieved. Combining the cross sections with the experimental efficiencies etc., it would give rise to $\sim 10$ signal events in the leptonic, and $\sim 15$ signal events in the hadronic tagging mode for the LEP172 run. If the $\text{BR}(W \rightarrow \chi\chi)$ is smaller than 7%, the expected number of events is reduced accordingly.

The main backgrounds for the leptonic and 2-jet tagging modes of the supersymmetric invisible $W$ decays are $WW$ events where one boson decays leptonically, single $W$ final states $W e\nu$, and $q\bar{q}\gamma$ events. In these cases either the lepton or the photon may escape undetected along the beam pipe giving rise to a fake ”single $W$” signal event. The cross sections for these background processes have been obtained with the CompHEP program [10] without taking into account hadronization of quarks and detector effects. Of course, hadronization of quark jets and smearing due to the experimental resolution have to be taken into account when an exact analysis of the signal and background is performed. However, this needs be done in the experimental analysis, which is beyond the scope of this paper.

The background from the $WW$ events is small since only in a small fraction of the $WW \rightarrow Wl\nu_l$ events the lepton is emitted at a small angle with the beam pipe. The cross section of 0.03 pb is expected for events with the lepton in a cone of an half-opening angle $5^\circ$ around the beam pipe [and 0.02 pb for $WW \rightarrow Wq\bar{q}'$ events due to the ”invisible” SM hadronic decay modes]. The single $W$-boson production is more difficult to suppress. An important subprocess in this channel is the photoproduction process $\gamma e \rightarrow W\nu_e$ with the Weizsäcker-Williams photon radiated off the second lepton in the $e^+e^-$ initial state. This leads to a background cross section of 0.11 pb and 0.32 pb in the leptonic and 2-jet tagging modes, respectively. Exploiting the special kinematics of the on-shell $WW$ signal process [i.e. the energy $E_i$ of the $W$ decay products is restricted to the range $26 \text{ GeV} \leq E_i \leq 62 \text{ GeV}$ at $\sqrt{s} = 172$ GeV], the above cross sections can be reduced by 20%. The $q\bar{q}\gamma$ final states, with the photon escaping along the beam pipe, are primarily induced by the radiative return to the $Z \rightarrow q\bar{q}'$, for which a cross section of 120 pb is predicted [11]. Even though the cross section is large, it can be suppressed very efficiently by requiring a cut on the invariant mass of the two jets, $70 \text{ GeV} \leq M_{q\bar{q}'} \leq 90 \text{ GeV}$ and the above cut on jet energies, reducing the value down to 5 pb. A further cut on the vector sum of the jet momenta with the beam pipe will reduce this background to a sufficiently low level.

4. In summary: the special kinematics of on-shell $WW$ production with 2-body $W$ decay, i.e. the invariant mass and the energy conditions, provide powerful
constraints. They can be used to select efficiently the signal events and to suppress the background processes. From the above estimates of the signal and background, both the leptonic and the 2-jet tagging modes seem to be promising channels for the search for supersymmetric $W$ boson decays at the level of a few percent. Therefore the analysis of $W$ production in $e^+e^-$ collisions can be used to exclude part of the area in the supersymmetry parameter space in which chargino and sneutrino masses are nearly degenerate – or to realize this exceptional case experimentally. The blind spot left in the analysis of chargino pair production in $e^+e^-$ annihilation can thus partly be closed by exploiting $WW$ production data.

Acknowledgments : We would like to thank W. de Boer for useful comments. Special thanks go to D. Zerwas for numerous discussions on the material presented in this note. The work of JK is partially supported by the KBN grant 2 P03B 180 09.
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Figure Captions

1. Contour lines for $\tan \beta = 1.5$ in the $[\mu, M_2]$ plane along which the branching ratios $\text{BR}(W \rightarrow \chi \chi)$ of $W$ decays to charginos and neutralinos are 7,5,3 and 1% (full curves). Also shown are the contour lines for the mass bounds $m(\chi^0_1) = 12$ GeV, $m(\chi^0_2) = 45$ GeV and $m(\chi^+_1) = 45$ GeV (dashed curves).

2. Blow-up of the positive $\mu$ area in the previous figure for the sake of clarity.

3. Contour lines for $\tan \beta = 1.5$, $\mu > 0$ [upper plot] and $\mu < 0$ [lower plot] in the $[m_{\chi^+_1}, m_{\chi^0_1}]$ plane along which the branching ratios $\text{BR}(W \rightarrow \chi \chi)$ of $W$ decays to charginos and neutralinos are 7,5,3 and 1%.
Figure 1:
Figure 2:
Figure 3: