SUPERSYMMETRIC *W* BOSON DECAYS AS A MEANS TO SEARCH FOR CHARGINOS AND NEUTRALINOS*

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If the sneutrino mass is below the chargino mass, the dominant decay mode of the lightest chargino is via a two-body decay channel $\chi_1^\pm \to \tilde{\nu} + l^\pm$. Sneutrinos are invisible in R-parity conserving supersymmetric models and, if the mass gap $m(\chi_1^\pm) - m(\tilde{\nu})$ is sufficiently small, the soft decay lepton may escape detection leading to invisible chargino decays. This "blind spot" of the supersymmetry parameter space would jeopardize the chargino search at LEP2. We point out that such a scenario can be tested by searching for single W events in $e^+e^- \to W^+W^-$, with one W boson decaying to visible leptons or quark jets, and the second W boson decaying to invisible charginos and neutralinos.

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1. Introduction

The e^+e^- collisions at LEP2 energies have greatly improved the lower mass bounds established at LEP1 on masses of supersymmetric particles [1], in particular on the lightest chargino mass. These particles can be produced in pairs in the annihilation process $e^+e^- \to \chi_1^+\chi_1^-$ via the s-channel γ, Z and the t-channel sneutrino $\tilde{\nu}_{eL}$ exchanges. The chargino mass bound depends crucially on the sneutrino mass. If sneutrinos $\tilde{\nu}_{eL}$ are heavy, the production cross section is large and the charginos can be probed up to the kinematical limit; only for small mass gap between chargino and the lightest neutralino, chargino becomes invisible because the decay fermions (quarks or charged leptons) in the decay process $\chi^\pm \to \chi_1^0 f\bar{f}'$ are soft and escape detection. For

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$m(\tilde{\nu}_{eL}) \lesssim 200$ GeV, the destructive interference of s- and t-channel exchanges reduces the production cross section, lowering the sensitivity. However, if one of the sneutrinos is lighter than the chargino by a few GeV, the sensitivity is lost. In this case, called a "blind spot" in Ref. [2], the dominant two-body decay mode of the chargino $\chi_1^\pm \to \tilde{\nu}_{lL} l^\pm$ is invisible because (a) the decay lepton $l^\pm$ is soft and escapes detection, and (b) sneutrino is either the lightest supersymmetric particle or it decays to the lightest neutralino and corresponding neutrino. Note that the other two-body decay process, $\chi_1^\pm \to \nu_{lL} \tilde{l}^\pm$, due to the SU(2) mass relation[1]

$$m^2(\tilde{l}_L) = m^2(\tilde{\nu}_{lL}) - m_Z^2 \cos^2\theta_W \cos 2\beta \tag{1}$$

is closed kinematically because for the sneutrino almost degenerate in mass with the chargino, $m(\tilde{l}_L) > m(\chi_1^\pm)$ for the preferred values of $\tan\beta > 1$.

The "blind spot" is particularly annoying because the charginos could be as light as 45 GeV, the ultimate limit established at LEP1 [3]. There are several methods to eliminate this particular region of the parameter space by exploiting: *(i)* constraints from future high-precision measurements of $(g-2)_\mu$ [4]; this method works at large $\tan\beta \gtrsim 20$, *(ii)* the non-observation of the corresponding left-chiral slepton with the mass given by Eq. (1), *(iii)* single photons in $e^+e^- \to \gamma\chi_1^+\chi_1^-$ with charginos undetected; however the production cross section is small and the background large.

I would like to report on a recent work, done in collaboration with Zerwas [5], in which we point out that the blind spot can be explored experimentally by searching for single visible W's in the WW pair production process $e^+e^- \to W^+W^-$. If charginos are as light as 45 GeV, W bosons can decay invisibly via charginos and neutralinos, $W^\pm \to \chi^\pm\chi^0$. From the measurements of the total W boson decay width, nonstandard W decays are possible with a branching ratio of $\lesssim 7\%$ [6]. In WW pair production processes in e^+e^- collisions such invisible supersymmetric W boson decays in one hemisphere can be tagged by the observation of the standard decay modes to leptons or quark jets of the other W boson in the opposite hemisphere[2]. We show that for the invisible W decay modes at the level of a few percent, such processes should be detectable at LEP2 energies. Their non-observation will allow us to close the region $m(\chi_1^\pm) \gtrsim m(\tilde{\nu})$ of the parameter space.

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[1] We consider a low-energy supersymmetry with no reference to grand unified scenarios.

[2] This is similar to the model-independent Higgs boson search in the Bjorken process $e^+e^- \to ZH$ by tagging only Z bosons in the final state.

2. Invisible supersymmetric W decays

With LEP1 limits on the supersymmetry parameter space, the decay of the W bosons to charginos and neutralinos are kinematically open:

$$W^{\pm} \to \chi_i^{\pm} \chi_j^0 \qquad [i = 1,2;\, j = 1, ..., 4]\,. \tag{2}$$

In practice, it is enough to restrict the analysis to the lightest chargino in order to allow for maximum phase space. In some areas of the parameter space the heavier neutralinos χ_j^0 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 supersymmetric W decays have been extensively discussed in the literature [7]. Extending to the case of general mixing in the chargino and neutralino sectors, the partial widths for the decay processes (2) are given by the expression

$$\begin{aligned} \Gamma(W^{\pm} \to \chi_i^{\pm} \chi_j^0) &= \frac{G_F m_W^3 \lambda_{ij}^{1/2}}{6\sqrt{2}\pi} \\ &\times \left\{ \left[2 - \kappa_i^2 - \kappa_j^2 - (\kappa_i^2 - \kappa_j^2)^2 \right] (Q_{Lij}^2 + Q_{Rij}^2) + 12\kappa_i\kappa_j Q_{Lij} Q_{Rij} \right\}, \end{aligned} \tag{3}$$

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

$$Q_{Lij} = Z_{j2}V_{i1} - \frac{1}{\sqrt{2}} Z_{j4} V_{i2} \tag{4}$$

$$Q_{Rij} = Z_{j2}U_{i1} + \frac{1}{\sqrt{2}} Z_{j3} U_{i2}\,, \tag{5}$$

where U, V are the mixing matrices in the chargino sector, and Z in neutralino sector [8]. The mass matrix of charginos depends on the mixing angle β and the wino mass M_2; the neutralino mass depends in addition on the bino mass M_1 and the higgsino mass parameter μ. For the sake of simplicity, in the numerical analysis below we will adopt the unification mass relation $M_1 = \frac{5}{3} M_2 \tan^2 \theta_W$.

The range of the parameters $[M_2, \mu]$ for fixed $\tan\beta$ is restricted by the measurements at LEP1 [3], the non-observation of neutrino pair production $\chi_1^0\chi_i^0$ (i=2, 3, 4) above LEP1 [1] and limits on the total W decay width measured at Tevatron [6]. The impact of the AMY limit on $m(\tilde{e}) \gtrsim 65$ GeV [9] is small. The envelope of these constraints, built up by $m(\chi_1^+) = 45$ GeV,

$m(\chi_1^0) = 12$ GeV and $m(\chi_2^0) = 45$ GeV, is shown in Fig. 1 for $\tan\beta = 1.5$; the area between and below the dashed lines is excluded. Note however, that these limits should only be considered as a guide line because they have not been derived for the special case $m(\chi_1^\pm) \gtrsim m(\tilde{\nu})$ which is the subject of the present analysis. For large $\tan\beta$, the mass limits on charginos and neutralinos forbid on-shell supersymmetric W decays.

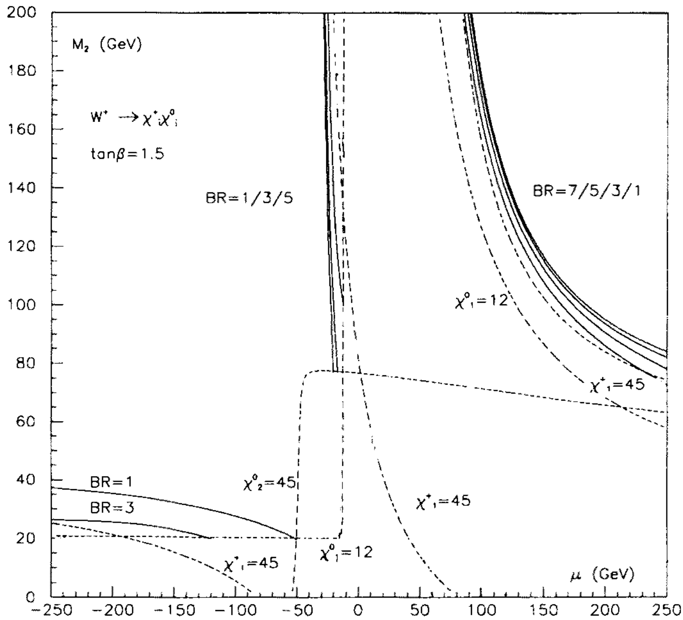

Fig. 1. Contour lines for $\tan\beta = 1.5$ in the $[\mu, M_2]$ plane along which the branching ratios BR($W \to \chi\chi$) of W decays to charginos and neutralinos are 7, 5, 3 and 1% (full curves). Also shown are the contour lines for the mass bounds $m(\chi_1^0) = 12$ GeV, $m(\chi_2^0) = 45$ GeV and $m(\chi_1^+) = 45$ GeV (dashed curves).

In Fig. 1 the solid lines are the contour lines for W decays to charginos and neutralinos with the branching ratios of 1, 3, 5 and 7%, with the total decay width given by the standard decay modes and $\chi^\pm\chi^0$ mode. The numbers quoted for the branching ratios correspond to the partial decay widths of approximately 20 MeV to 140 MeV. Such decays still can occur in narrow strips adjacent to LEP1 limits.

The same contour lines for supersymmetric W decays are plotted in Fig. 2 as a function of lightest chargino and neutralino masses. Only region

$m(\chi^{\pm}) > 45$ GeV and $m(\chi_1^0) > 12$ GeV is shown. Some lines terminate in the figure because either M_2 or $|\mu|$ is larger than 400 GeV. In the case of negative μ, the lines corresponding to 1 and 3% have two branches, in analogy to Fig. 1. The cases corresponding to higgsino-like (large M_2) and gaugino-like (large $|\mu|$) light charginos and neutralinos are shown in the figure. For positive μ the contour lines extend to $m(\chi_1^{\pm}) \sim 54$ GeV, for negative μ up to $m(\chi_1^{\pm}) \sim 65$ GeV.

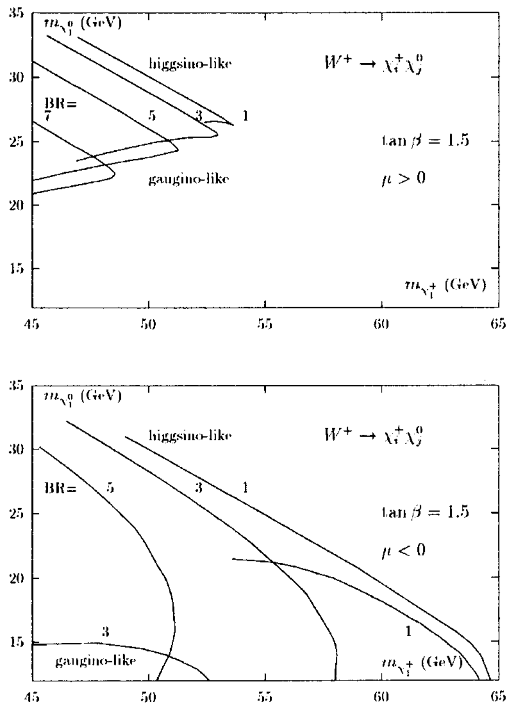

Fig. 2. Contour lines for $\tan\beta = 1.5$, $\mu > 0$ [upper plot] and $\mu < 0$ [lower plot] in the $[m_{\chi_1^+}, m_{\chi_1^0}]$ plane along which the branching ratios BR($W \to \chi\chi$) of W decays to charginos and neutralinos are 7, 5, 3 and 1%.

3. Tagging invisible *W* decays

From the Figs. 1 and 2 it is clear that $W \to \chi\chi$ branching ratios up to order 7% are still in the allowed zones of the $[m(\chi_1^+), m(\chi_1^0)]$ plane. Assuming a branching ratio of 7% for the $W \to \chi^+\chi^0$ decay modes, one expects 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. Both W bosons decaying to standard model particles are then expected in 86.5% of the cases, and both W bosons decaying to charginos and neutralinos in 0.5% of the cases. Even with limited statistics collected at the LEP2 measurements so far ($\sim$ 600 WW pairs in the 4 experiments), we can expect tens of WW signal events with mixed standard and supersymmetric W decays. Their observability depends crucially on the efficiencies for the signal and contamination from the background processes.

To estimate the feasibility of observing the invisible supersymmetric $W \to \chi\chi$ decays in $e^+e^- \to W^+W^-$ production process, we consider, as an illustrative example, events collected at the LEP 172 GeV run. The total WW cross section at this energy is $\sim$ 13 pb. With the combined integrated luminosity $\mathcal{L} \sim 4 \times 11$ 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. If BR($W \to \chi\chi$) = 7%, the signal cross section is of the order 1.7 pb, which means that 80 W bosons are potential candidates for chargino/neutralino decays. Therefore 74 signal events with mixed standard and supersymmetric W decays can be expected.

The signature of these events would be a single W boson, $e^+e^- \to W+$ (no other visible particle). They 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. An important feature of these events is the kinematic constraint that the isolated W bosons carry the beam energy. With this kinematical constraint, we expect in the leptonic tagging mode ($W \to e\nu/\mu\nu$) an efficiency at least as large as in the search for acoplanar lepton pairs, *i.e.* better than 70%. In the 2-jet tagging mode ($W \to q\bar{q}'$) an efficiency comparable to that of the search for $WW \to \tau\nu q\bar{q}'$, *i.e.* better than 30% can be achieved. This 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 BR($W \to \chi\chi$) is smaller than 7%, the expected number of events is reduced accordingly.

The irreducible background for both the leptonic and 2-jet tagging modes of the supersymmetric invisible W decays comes from the WW events where one boson decays leptonically with undetected lepton. Other important background processes include single W final states $We\nu_e$, and $q\bar{q}\gamma$ events. In these processes 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 the hadronization of quarks and detector effects. Of course, the hadronization of quark jets and the smearing due to the experimental resolution must be included when an experimentally realistic analysis of the signal and background is performed; however, this is beyond the scope of our analysis.

The background from the WW events is small since only in a small fraction of the $WW \to Wl\nu_l$ 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 a half-opening angle 5^o around the beam pipe[3]. The single W-boson production is more difficult to suppress. An important subprocess in this channel is the photoproduction process $\gamma e \to W\nu_e$ 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. The above cross sections can be further reduced at a level of 20% by exploiting the special kinematics of the on-shell WW signal process, *i.e.* that the energy E_i of the W decay products is restricted to the range 26 GeV $\leq E_i \leq$ 62 GeV at $\sqrt{s}$ = 172 GeV. 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 with subsequent $q\bar{q}'$ decays, 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 GeV $\leq M_{q\bar{q}'} \leq$ 90 GeV, and the cut on jet energies, 26 GeV $\leq E_i \leq$ 62 GeV, reducing the value down to 5 pb. A further cut on the vector sum of the jet momenta with respect to the beam axis will reduce this background to a sufficiently low level.

4. Summary

If one of the sneutrinos is just below the chargino mass, the standard experimental search techniques for charginos in $e^+e^- \to \chi_1^+\chi_1^-$ at LEP 2 fail. To probe this exceptional case we propose to search for "single W" final states in WW pair production in which one of the W bosons decays invisibly to charginos and neutralinos. The special kinematics of on-shell WW production with 2-body W decay, *i.e.* the invariant mass and the energy constraints, provide powerful tools to select efficiently the signal events and to suppress the background processes. Our estimates of signal and backgrounds show that 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 even with the limited statistics collected so far at LEP 2. With the next run at 184 GeV and larger luminosities a significant improvement in the sensitivity can be expected. 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.

[3] For $WW \to Wq\bar{q}'$ events due to the "invisible" SM hadronic decay modes with $q\bar{q}'$ escaping along the beam pipe, the cross section is of the order 0.02 pb.

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