The Degenerate Wino-like Chargino-Neutralino Scenario at a Linear Collider[1]

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Abstract. For some choices of soft SUSY–breaking parameters, the LSP is a stable neutralino $\widetilde{\chi}_1^0$, the NLSP is a chargino $\widetilde{\chi}_1^\pm$ almost degenerate in mass with the LSP ($\Delta m_{\tilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} \sim m_\pi$–few GeV), and all other sparticles are relatively heavy. We discuss the potential of the NLC for studying such models.

One interesting limiting case of SUSY boundary conditions is loop-induced gaugino masses proportional to the respective renormalization group beta functions, as in Anomaly-Mediated SUSY breaking and the simplest moduli-dominated SUSY breaking models. In such models, the mass difference $\Delta m_{\tilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ is most typically very small. The phenomenology of $\widetilde{\chi}_1^\pm$ production and decay has been studied extensively in [1,2], and also in [3,4]. For $\Delta m_{\tilde{\chi}_1} < m_\pi$, as achievable in some models even after radiative corrections, the $\widetilde{\chi}_1^\pm$ may exit the detector, leading to an easily detected long-lived heavily-ionizing track (LHIT), or decay to a soft, but visible, e or μ track in the vertex detector and inner part of the tracker yielding a disappearing isolated track (DIT). For $\Delta m_{\tilde{\chi}_1}$ above, but close to m_π, the $\widetilde{\chi}_1^\pm$ decay to a soft $\pi^\pm$ may still have sufficient path length (including sufficient β) to leave a distinctive track in the vertex detector while also having low enough β (we require $\beta < 0.8$) to be highly-ionizing. We term this a "STUB" track; the decay π need not be visible. For somewhat larger $\Delta m_{\tilde{\chi}_1}$, the STUB is not visible, but the soft $\pi^\pm$ will be detected and may have a high impact parameter (HIP). For still larger $\Delta m_{\tilde{\chi}_1}$, the $\pi^\pm$ will simply be soft, but readily detected. Once $\Delta m_{\tilde{\chi}_1} \gtrsim 2 - 3$ GeV, the $\widetilde{\chi}_1^\pm$ decay products have significant energy. The most typical range for $\Delta m_{\tilde{\chi}_1}$ in the models studied is $\Delta m_{\tilde{\chi}_1} \in [200 \text{ MeV}, 2 \text{ GeV}]$.

Assuming that only the $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$ are light, SUSY production will be primarily in the final states $\widetilde{\chi}_1^+\widetilde{\chi}_1^-$, $\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$, and (when not phase space limited) $W^\mp\widetilde{\chi}_1^0\widetilde{\chi}_1^\pm$. The possibilities for SUSY detection depend largely upon which aspects (if any) of a $\widetilde{\chi}_1^\pm$ in the final state are visible, which in turn depends almost entirely on $\Delta m_{\tilde{\chi}_1}$.

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- $\Delta m_{\tilde\chi_1} < m_\pi$: the $\widetilde\chi_1^\pm$ yields a 'stable particle' LHIT and/or DIT track and is easily detected: $\widetilde\chi_1^+\widetilde\chi_1^-$ production will be easily seen.
- $m_\pi < \Delta m_{\tilde\chi_1} < 1$ GeV: the $\widetilde\chi_1^\pm \to \widetilde\chi_1^0\pi^\pm$ decay yields a soft π track, possibly in association with a STUB ($\Delta m_{\tilde\chi_1} < 180$ MeV) or HIP ($\Delta m_{\tilde\chi_1} < 1$ GeV) signature. Direct $\widetilde\chi_1^+\widetilde\chi_1^-$ production then yields a $\not{E}+\pi\pi$ final state, where the $\not{E}$ is associated with the $\widetilde\chi_1^0$'s. However, since the π's are very soft, backgrounds to this final state from $\gamma\gamma$-induced interactions are very large. One must tag $\widetilde\chi_1^+\widetilde\chi_1^-$ production using $e^+e^- \to \gamma\widetilde\chi_1^+\widetilde\chi_1^-$, leading to a $\gamma+\not{E}+\pi\pi$ final state, or employ the more kinematically limited $W^\mp\widetilde\chi_1^0\widetilde\chi_1^\pm \to \ell^\mp+\not{E}+\pi$ final state.
- 1 GeV $< \Delta m_{\tilde\chi_1} < 2$ GeV: the $\widetilde\chi_1^\pm$ decays with roughly equal probability to $\widetilde\chi_1^0\pi^\pm$, $\widetilde\chi_1^0\pi^\pm\pi^0$ and $\widetilde\chi_1^0\ell^\pm\nu$ ($\ell = e,\mu$). The pion(s) or charged lepton will be rather soft and a γ tag will probably still be necessary to eliminate backgrounds.
- $\Delta m_{\tilde\chi_1} > 2-3$ GeV: the $\widetilde\chi_1^\pm$ decays either to $\widetilde\chi_1^0$+multipion modes at the low end which start to resolve into jets at the higher end or to $\widetilde\chi_1^0\ell^\pm\nu$. The visible decay products are sufficiently energetic that $\gamma\gamma$ induced backgrounds can be rejected (using a combination of event topology and $\not{E}$) to the extent necessary for mSUGRA-like mode detection of direct $e^+e^- \to \widetilde\chi_1^+\widetilde\chi_1^-$ production.

Sensitivity of LEP2 detectors to these various signatures was sufficient to exclude $m_{\widetilde\chi_1^\pm} < \sqrt{s}/2$ in the 'stable' and 'standard' regions of $\Delta m_{\tilde\chi_1}$ and $m_{\widetilde\chi_1^\pm} < 80$ GeV (assuming the $\widetilde\nu_e$ is heavy) in the $m_\pi \le \Delta m_{\tilde\chi_1} \le 2$ GeV region [5,6]. In particular, the backgrounds to the 'stable' and γ-tag+$\not{E}$+soft-π signals are very small. In our analysis, we argue that they can continue to be neglected relative to our signal rates at the LC after simple cuts. For the γ-tag+soft-π signal, we require $p_T^\gamma > 10$ GeV, $10^\circ \le \theta_\gamma \le 170^\circ$; instrumentation down to 1° is necessary to detect and reject $e^\pm$'s from 2-photon reactions. Another primary cut will be $M_{\chi\chi} > 2m_{\widetilde\chi_1^\pm}$, where $M_{\chi\chi}^2 = (p_{e^+}+p_{e^-}-p_\gamma)^2$, when searching for $\widetilde\chi_1^\pm$'s of a certain mass. Most of $M_{\chi\chi}$ will be invisible, being carried by the $\widetilde\chi_1^0\widetilde\chi_1^0$ pair. The $\pi^+\pi^-$ in the final state will be very soft and central.

Detector design is critical to observing the soft pion signatures. If the $\vec{B}$ field is too strong, soft pions will curl up before they can be detected/tracked. Then, the only signal $\gamma\widetilde\chi_1^+\widetilde\chi_1^-$ production yields $\gamma+\not{M}$, which has a large $\gamma\nu\bar\nu$ background, and the discovery reach will be more limited (see Fig. 1). The $\ell^\mp+\not{M}$ final state from $W^\mp\widetilde\chi_1^0\widetilde\chi_1^\pm$ production will provide an alternative signal with similar reach in $m_{\widetilde\chi_1^\pm}$; the only SM background is single $W\to\ell\nu$ production with the ℓ lost down the beam pipe.

Focusing on the most natural case of small $\Delta m_{\tilde\chi_1} \gtrsim 200$ MeV and $m_{\widetilde\chi_1^+} < 200$ GeV, and assuming adequate instrumentation to observe soft pions, background free event rates will be large for $\gamma\widetilde\chi_1^+\widetilde\chi_1^-$ production and one can perform precision studies. We find that $m_{\widetilde\chi_1^+}$ can be determined to 1 GeV and $\Delta m_{\tilde\chi_1}$ to 1 MeV using the $[E_\pi, M_{\chi\chi}]$ event distribution. Further, cross sections and angular asymmetries can be used to determine M_2 and $|\mu|$ to roughly $\pm 8(8)\%$ and

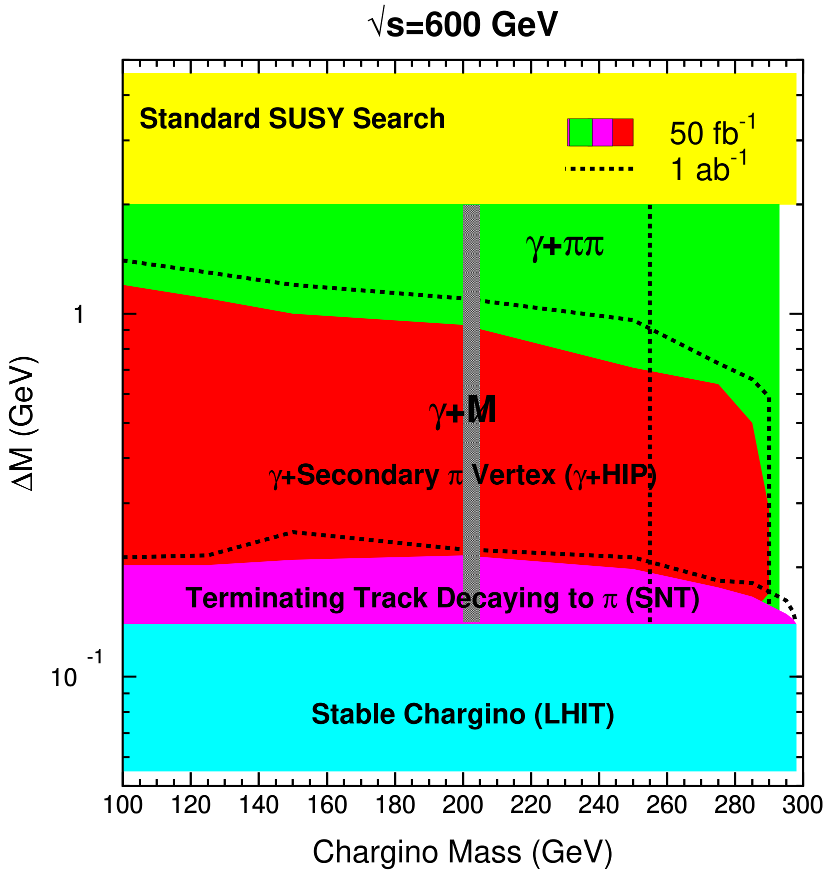

FIGURE 1. Regions in $\Delta m_{\tilde{\chi}_1}$, $m_{\tilde{\chi}_1^\pm}$ parameter space for which different discovery modes are viable. The SNT, γ+HIP and $\gamma+\pi\pi$ modes are presumed to be background free; we assume that 10 events will be adequate for discovery. For the SNT, γ+HIP and $\gamma+\not{M}$ signals, discovery reach is given for $L = 50$ fb^{-1} and also for $L = 1$ ab^{-1}. The vertical band for $L = 50$ fb^{-1} and line for $L = 1$ ab^{-1} show the reach of the $\gamma+\not{M}$ detection mode, which is relevant only if the soft π's are not detectable, as might be the case for some range of $\Delta m_{\tilde{\chi}_1} \gtrsim 200$ MeV.

$\pm 16(40)\%$, respectively, at $\mu \sim 400(600)$ GeV. However, the sign of μ and $\tan\beta$ typically cannot be determined. Finally, the impact parameter distribution for the pions can provide valuable additional information on model parameters.

Since the reach of LEP is limited to $m_{\tilde{\chi}_1^\pm} < 100$ GeV and the future of a Next Linear Collider is unclear, it may be that only hadron colliders will provide an opportunity for SUSY detection over the next decade. Briefly, the Tevatron and LHC will have reach in $m_{\tilde{\chi}_1^\pm}$ for LHIT and DIT 'stable'-chargino signals similar to the LC [2,7]. For larger $\Delta m_{\tilde{\chi}_1}$, the most useful signal is jets + $\not{E}_T$. In the AMSB scenario, $\tilde{g}\tilde{g}$ production at the LHC will be sufficiently abundant to probe up to $M_{\tilde{g}} \sim 1.7$ TeV (1.45 TeV) for $L = 300$ fb^{-1} ($L = 30$ fb^{-1}), assuming that squarks and sleptons are too heavy to provide useful signals. Using the relation $M_{\tilde{g}} \sim 7 m_{\tilde{\chi}_1^\pm}$, the LHC reach of $M_{\widetilde{g}} \sim 1.7$ TeV is equivalent to $m_{\widetilde{\chi}_1^\pm} \sim 250$ GeV, the effective reach of a $\sqrt{s} = 500$ GeV LC. Assuming that the soft pions or leptons from chargino decay are unobservable at the LHC, there will be no unambiguous evidence of the presence of a chargino. Thus, *both* the LC and LHC are needed to see direct evidence of *both* charginos and gluinos in the model-preferred $\Delta m_{\tilde{\chi}_1} \in [200~\mathrm{MeV}, 2~\mathrm{GeV}]$ interval.

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