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ScienceDirect
Nuclear and Particle Physics Proceedings 273–275 (2016) 2421–2423
www.elsevier.com/locate/nppp

Precision Measurements of Supersymmetry at the International Linear Collider

J. List, on behalf of the ILC Physics and Detector Study

DESY, Notkestr. 85, 22607 Hamburg, Germany

Abstract

While the 7 and 8 TeV results from the LHC exclude highly constrained SUSY models with a light sparticle spectrum, less constrained models are still viable. Certain such models promise both discovery of coloured sparticles during the 14 TeV run of the LHC, and a rich spectrum of non-coloured states, accessible at the ILC. The LHC might or might not give a hint of the existence of these electro-weak states, but only at the ILC can measurements with sufficient precision be done to elucidate the details of the model. This contribution reports on studies of such models at the ILC based on simulation of the current detector proposals.

Keywords: Linear Collider, Supersymmetry, Sleptons, Neutrinos, NMSSM, Dark Matter, Threshold Scan

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1. Introduction

The first SUSY channel to manifest itself at the ILC depends on the SUSY scenario and on the inital center-of-mass energy of the machine. An example for a scenario consistent with all current constraints, which predicts an extremely rich spectrum in the kinematic reach of the ILC are the STC series [1]. The large number of different thresholds and the effect of different beam polarisation choices is illustrated in Fig. 1(left). If the ILC starts out as a Higgs factory at $\sqrt{s} = 250\,\mathrm{GeV}$, $e^+e^- \rightarrow \tilde{\tau}_1\tilde{\tau}_1$ (brown) and $\tilde{\chi}^0_1\tilde{\chi}^0_1\gamma$ (blue) would be the first observable channels in this scenario.

2. Early Discovery

As soon as the center-of-mass energy is raised past the pair production threshold for right-handed selectrons (in STC4 when $\sqrt{s} > 270\,\mathrm{GeV}$), the e^+e^-+missing 4-momentum signature would see the striking signal shown in Fig. 1(right) within a few days. With an integrated luminosity of $500\,\mathrm{fb}^{-1}$, the $\tilde{e}_R$ and LSP masses can be measured with precisions of $\delta M_{\tilde{e}_R} = 230\,\mathrm{MeV}$ and $\delta M_{\tilde{\chi}^0_1} = 170\,\mathrm{MeV}$, respectively.

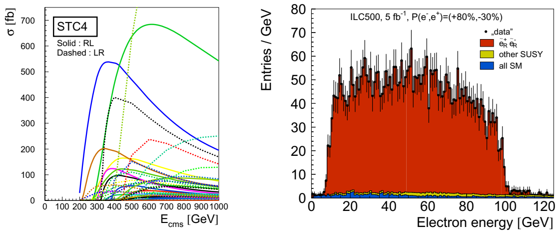

Figure 1: Left: Cross-sections of various SUSY processes in STC4 vs $\sqrt{s}$. Solid lines: $P(e^-, e^+) = (+80\%, -30\%)$, dashed lines $P(e^-, e^+) = (-80\%, +30\%)$. From [2]. Right: Energy spectrum of electron candidates in events with e^+e^- and missing 4-momentum for $5\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$ and beam polarisations of $P(e^-, e^+) = (+80\%, -30\%)$ [3].

3. Kinematic Edges vs Threshold Scan

The cross-section for $\tilde{\mu}_R$ pair production is much lower than for $\tilde{e}_R$'s due to the absence of a t-channel. Still the $\tilde{\mu}_R$ mass can be determined from the kinematic endpoints of the decay muon energy spectrum shown in Fig. 2(left). With $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$ and $P(e^-, e^+) = (+80\%, -30\%)$, precisions of $\delta M_{\tilde{\mu}_R} = 500\,\mathrm{MeV}$ and $\delta M_{\tilde{\chi}^0_1} = 380\,\mathrm{MeV}$ can be achieved by this technique. These numbers can be improved by collecting more data, or by exploiting the tunable center-

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.412

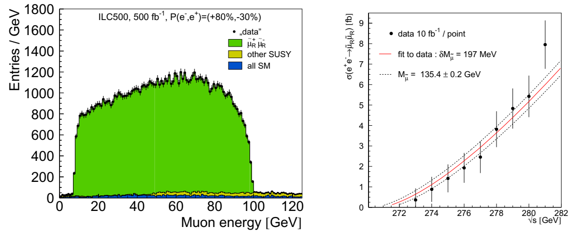

Figure 2: Left: Energy spectrum of muon candidates in events with $\mu^+\mu^-$ and missing 4-momentum for 500 fb^{-1} at $\sqrt{s}$ = 500 GeV and beam polarisations of $P(e^-, e^+) = (+80\%, -30\%)$ [3]. Right: Simulated measurements of the $\tilde{\mu}_R$ pair production cross-section near threshold with 10 fb^{-1} per point and beam polarisations of $P(e^-, e^+) = (+80\%, -30\%)$ [3].

of-mass energy of the ILC for a scan of the production threshold near 270 GeV (Fig. 2(right)). Collecting 90 fb^{-1} of data, again with $P(e^-, e^+) = (+80\%, -30\%)$, is sufficient to achieve a precision of 200 MeV for the $\tilde{\mu}_R$ and LSP masses.

4. Cascade decays: SUSY is a peak!

A particularly interesting channel for slepton reconstruction is $e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2$ followed by $\tilde{\chi}^0_2 \rightarrow \tilde{\mu}_R\mu$ or $\tilde{e}_R e$, even if the branching ratio is at the level of a few percent like in our example point. These cascade decays can be fully kinematically constrained at the ILC, and promise to yield even lower uncertainties on the $\tilde{\mu}_R$ and $\tilde{e}_R$ masses than the threshold scans, of the order of 25 MeV. This is estimated based on an earlier study [4] in a scenario with branching ratios about twice as large for the considered decay mode, where a precision of 10 MeV was found. The corresponding distribution of the reconstructed $\tilde{\mu}_R$ mass is shown in Fig. 3(left) including all SM and SUSY backgrounds. Even the decays to $\tilde{\tau}_1\tau$, which are more challenging due to the undetected neutrinos, can be reconstructed as shown in Fig. 3(right) and yield results comparable to a threshold scan.

5. The Cosmic Connection: $\tilde{\tau}$ Mass and Cross-section

Especially in $\tilde{\tau}$-coannihilation scenarios like the STC series, a precise determination of the $\tilde{\tau}$ sector is essential in order to test whether the $\tilde{\chi}^0_1$ is indeed the dominant Dark Matter constituent. With the ILC at $\sqrt{s}$ = 500 GeV, the $\tilde{\tau}_1$ mass can be determined to 200 MeV (Fig. 4(left)), and the $\tilde{\tau}_2$ mass to 5 GeV from the endpoint of the τ-jet energy spectrum. The production cross-sections for both these modes can be determined at the level of 4% [5]. By using all available collider observables to constrain the relevant SUSY parameters, one can predict the relic density based on the assumption that the $\tilde{\chi}^0_1$ is the only contribution to Dark Matter. This was studied by the Fittino group in a similar model, in particular the $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$ properties were identical to STC4. Figure 4(right) shows the result of determining $\Omega_{DM}h^2$ from a fit with 18 free SUSY parameters from LHC data alone and from both LHC and ILC data.

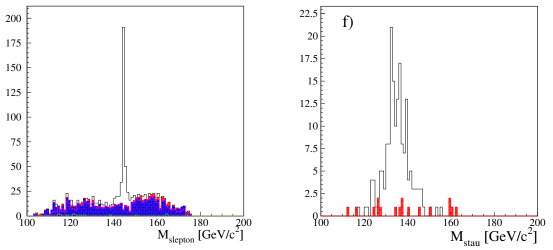

Figure 3: In cascade decays, the mass of sleptons can be directly reconstructed due to the knowledge of the inital state. Left: $\tilde{\mu}_R$ mass Right: $\tilde{\tau}_1$ mass. Both from [4].

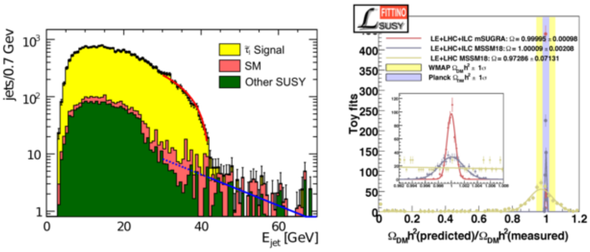

Figure 4: Left: Energy spectrum of τ candidates in events with $\tau^+\tau^-$ and missing 4-momentum for 500 fb^{-1} at $\sqrt{s}$ = 500 GeV and beam polarisations of $P(e^-, e^+) = (+80\%, -30\%)$. From [5]. Right: $\Omega_{DM}h^2$ from SUSY parameter fits based on LHC and ILC data. From [6].

6. The ILC at Full Speed: τ polarisation, $\tilde{\tau}$ mixing and $\tilde{\chi}^0_1$ nature

The polarisation of τ-leptons originating from the $\tilde{\tau}_1$ decay, which gives access to the $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$ mixing - gauginos conserve chirality, higgsinos flip it - can be measured with an accuracy better than 10%, eg. from $\tau \rightarrow \pi^{\pm}\nu_\tau$ decays or from decays to ρ-mesons ($\tau \rightarrow \rho^{\pm}\nu\tau \rightarrow \pi^{\pm}\pi^0\nu_\tau$). In the latter case, the observable $R = E_\pi/E_{\mathrm{jet}}$ can be used to measure the τ-polarisation to ±5% by a fit of templates for the τ's being of negative, of opposite, or positive helicity (Fig. 5) to the data (Fig. 6 (left)). The $\tilde{\tau}$ mixing itself can be extracted in several ways: Comparing the cross-section at different beam polarisations, determining the cross-section for $\tilde{\tau}_1\tilde{\tau}_2$ production, or from comparing the masses of the (un-mixed) $\tilde{e}$'s and $\tilde{\mu}$'s to $M_{\tilde{\tau}_1}$ and $M_{\tilde{\tau}_2}$ [5].

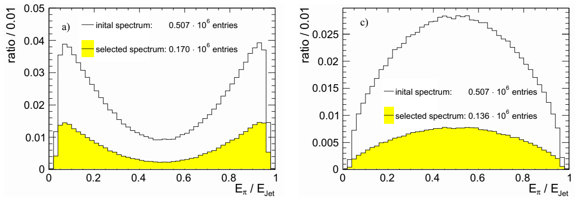

Figure 5: Determination of the τ polarisation in $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$ decays: Templates of R for the two τ's being of negative (left) and positive (right) helicity. From [5].

7. Neutrino Mass Generation

SUSY with bilinear R-parity violation can generate neutrino masses via a lowscale seesaw mechanism. In such scenarios, neutrino observables fix the bRPV couplings. Thus collider measurements of RPV decays can test this mechanism of neutrino mass generation. At the ILC, the branching ratios for $\tilde{\chi}_1^0 \rightarrow \mu W$ and $\tilde{\chi}_1^0 \rightarrow \tau W$ can be measured e.g. in LSP pair production. At tree-level, their ratio is directly proportional to $\tan^2\theta_{23}$, while loop corrections introduce dependencies on other SUSY parameters. With $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$ and $P(e^-, e^+) = (+80\%, -30\%)$, the projected precision is $\frac{\delta\sin^2\theta_{23}}{\sin^2\theta_{23}} = 4\%\,(\mathrm{stat.}) \oplus 0.85\%\,(\mathrm{syst.}) \oplus 7\%\,(\mathrm{par.})$ [7].

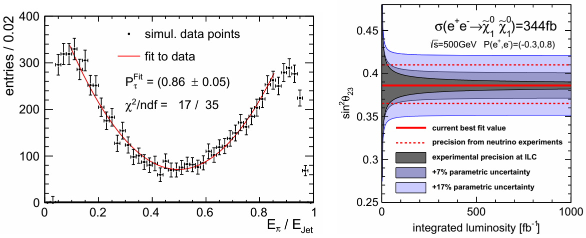

Figure 6: Left: Result of the template fit for determining the τ polarisation in $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$ decays. From [5]. Right: Neutrino mass generation in bRPV SUSY: Measurement of $\sin^2\theta_{23}$ from LSP decays at the ILC and from neutrino oscillations. From [7].

8. SUSY at $\sqrt{s}$ = 250 GeV: NMSSM Higgs Bosons

In the NMSSM, the Higgs boson discovered at the LHC does not need to be the lightest Higgs boson. Current limits on invisible decays allow for a sizable branching fraction of $h_{1,2} \rightarrow a_1 a_1$, where a_1 can be very light down to a few GeV and decays eg. to τ or μ pairs. Already at a 250 GeV ILC, these states can be discovered and their masses measured to $\delta M_{a_1} = 5\,\mathrm{MeV}$ and $\delta M_{h_{1,2}} = 200\,\mathrm{MeV}$ from $250\,\mathrm{fb}^{-1}$ of data, using kinematic reconstruction (a_1, Fig. 7(left)) and recoil techniques ($h_{1,2}$, Fig. 7(right)) [8].

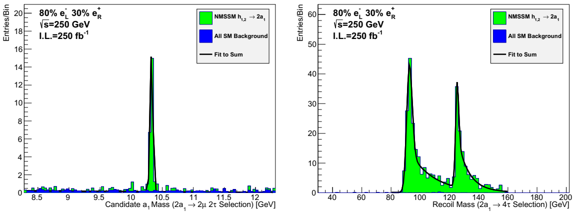

Figure 7: Reconstruction of NMSSM Higgs masses: Kinematic reconstruction of M_{a_1} from $a_1 a_1 \rightarrow \mu\mu\tau\tau$ (left) and recoil mass from $e^+e^- \rightarrow Zh_{1,2}$. From [8].

9. Conclusions

Although Supersymmetry has not yet been discovered at the LHC, there are plenty of opportunities for electroweak states, sleptons and additional Higgs bosons to be observable at the ILC. This contribution illustrated the ILC's potential for precision measurements of SUSY particles with several examples, all based on realistic detector simulations. If new particles are discovered in future runs of the LHC or at the ILC itself, the ILC will be able to measure masses, polarised crosssections and other observables at the level of a few percent or better, which enables to test the connection of the new particles to the big open questions of particle physics, such as the nature of Dark Matter or the origin of neutrino masses.

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