1815: Search for SUSY Particles at Future $e^+ e^-$ Colliders

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Abstract. Experimental aspects of searches and studies of SUSY particles, scalar leptons, charginos and the stop quark, at future e^+e^- colliders are discussed.

1 Introduction

The minimal supersymmetric extension of the Standard Model assigns to each particle a SUSY partner differing by spin 1/2. In GUT scenarios the particle spectrum is completely specified by five parameters (m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign\,\mu$). Generally the lightest supersymmetric particle is the neutralino χ^0_1.

A high energy e^+e^- linear collider is an ideal place to discover SUSY particles [1, 2] up to the kinematic limit already with moderate luminosities of $\mathcal{L} \sim 10$ fb^{-1}. Here, experimental aspects to study their properties with high precision will be discussed [3]. The requirements on the detector performance are modest: good particle identification over a large solid angle $|\cos\theta| < 0.98$, a momentum resolution of $\delta p_\perp / p_\perp = 1.5 \cdot 10^{-4}\, p_\perp$ [GeV] and a calorimetric resolution of $\delta E_h / E_h = 0.50/\sqrt{E_h\ [\mathrm{GeV}]} \oplus 0.04$. It is important that for precision mass measurements the beamstrahlung effects of the $e+e-$ collider have to be kept small.

2 Scalar Leptons

Mass Determination of $m_{\tilde\mu_R}$ and $m_{\chi^0_1}$ Scalar leptons $\tilde\ell^\pm$ are pair-produced via s channel γ/Z exchange and t channel $\tilde\nu_e$ exchange ($\tilde e$). The production of scalar muons $\tilde\mu_R$ has been studied at $\sqrt{s} = 800$ GeV [3]

$$
\begin{aligned}
e^+ e^- &\to \tilde\mu^+_R\, \tilde\mu^-_R\ , \\
\tilde\mu_R &\to \mu\, \chi^0_1 \qquad\qquad \mathcal{BR} \ = \ 99.5\,\%\ ,
\end{aligned}
$$

assuming masses of $m_{\tilde\mu_R} = 275.1$ GeV and $m_{\chi^0_1} = 88.1$ GeV. The neutralino χ^0_1 escapes detection, thus the experimental signature is an acoplanar $\mu^+\mu^-$ pair plus missing energy. The cross section is $\mathcal{O}(20\ \mathrm{fb})$ and simple selection criteria give an efficiency of $\epsilon \simeq 0.5$. The most severe background comes from $e^+e^- \to W\,W$ with $W \to \mu\,\nu$. This background can be reduced by an order of magnitude by running with right-handed polarised electrons of $P_{e^-_R} = 90\,\%$. Simultaneously, the signal can be enhanced by a factor of two.

The masses of the scalar muon $\tilde{\mu}_R$ and the neutralino χ_1^0 can be accessed through the energy spectrum of the final state leptons. The scalar muon decays isotropically and the two-body kinematics results in a flat muon energy distribution with endpoint energies

$$\frac{m_{\tilde{\mu}_R}}{2}\left(1-\frac{m^2_{\chi^0_1}}{m^2_{\tilde{\mu}_R}}\right)\gamma\,(1-\beta)\ \leq E_\mu \leq\ \frac{m_{\tilde{\mu}_R}}{2}\left(1-\frac{m^2_{\chi^0_1}}{m^2_{\tilde{\mu}_R}}\right)\gamma\,(1+\beta)\ .$$

The lepton energy spectra for unpolarised and right-handed polarised electrons are shown in figure 2. The sharp rise at E_μ^{min} is most sensitive to

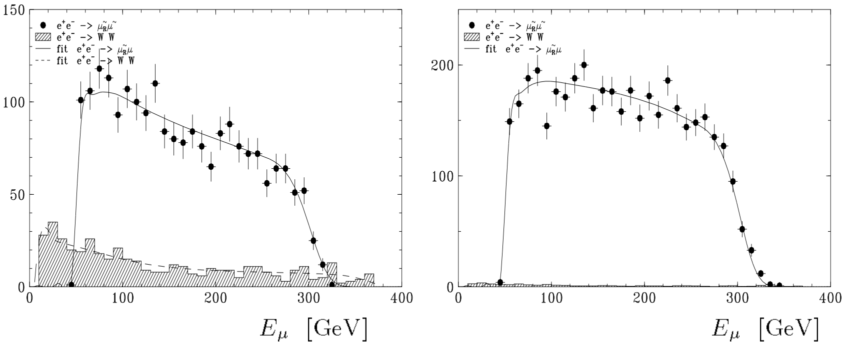

Fig. 1. Left: Energy spectrum of the final state $\mu^\pm$ for the reaction $e^+\,e^- \to \tilde{\mu}_R\,\tilde{\mu}_R$ (• and —) and the background $e^+\,e^- \to W\,W$ (histogram), assuming $\mathcal{L} = 125$ fb^{-1} at $\sqrt{s} = 800$ GeV. **Right:** Same for $e^+\,e^-_R \to \tilde{\mu}_R\,\tilde{\mu}_R$, polarisation $P_{e^-_R} = 90\,\%$

$m_{\tilde{\mu}_R}$, while E_μ^{max} is more sensitive to $m_{\chi_1^0}$. A two-parameter mass fit yields $m_{\tilde{\mu}_R} = 274.1\ ^{+1.7}_{-1.9}$ GeV and $m_{\chi_1^0} = 87.2\ ^{+2.1}_{-2.4}$ GeV for unpolarised beams, respectively $m_{\tilde{\mu}_R} = 275.3\ ^{+0.9}_{-0.7}$ GeV and $m_{\chi_1^0} = 88.2\ ^{+1.8}_{-1.6}$ GeV for right-handed polarised electrons.

Threshold Scan A more precise $\tilde{\mu}_R$ mass determination can be obtained by a scan around the production threshold. The signature are two almost monoenergetic leptons, not spoiled by cascade decays. A fit to the excitation curve, shown in figure 2, gives $m_{\tilde{\mu}_R} = 275.1\ ^{+0.35}_{-0.30}$ GeV. At the same time a cross section measurement, $\sigma \propto \beta^3$, allows to determine the spin 0 of the scalar muon.

3 Charginos

Mass determination of $m_{\chi_1^\pm}$ *and* $m_{\chi_1^0}$ Chargino production $\chi^\pm$ occurs via vector bosons γ, Z in the s channel and via $\tilde{\nu}_e$ exchange in the t channel. A study of the lightest chargino production $\chi_1^\pm$ and its decay into $W^*\,\chi_1^0$ at $\sqrt{s} = 500$ GeV has been performed [3]

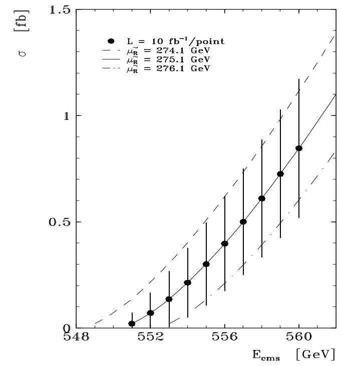

Fig. 2. Cross section for $e^+ e^-_R \to \tilde{\mu}_R \tilde{\mu}_R$ around the kinematic threshold, assuming $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ per measurement (•). The curves indicate scalar muon masses of $m_{\tilde{\mu}_R} = 275.1 \pm 1.0$ GeV

$$
\begin{aligned}
e^+ e^- &\to \chi_1^+ \chi_1^- \ , \\
\chi_1^\pm &\to \ell^\pm \nu \chi_1^0 \qquad \mathcal{BR} = 34.5 \ , \quad \ell = e,\ \mu,\ \tau \ , \\
&\to q \bar{q}' \chi_1^0 \qquad \mathcal{BR} = 65.5\,\% \ ,
\end{aligned}
$$

assuming masses of $m_{\chi_1^\pm} = 168.2$ GeV, $m_{\chi_1^0} = 88.1$ GeV and $m_{\tilde{\nu}_e} = 304$ GeV. The experimental signature is an isolated lepton e or μ and two hadronic jets plus missing energy. The cross section receives large t channel contributions, the χ_1^- being preferentially emitted into the forward direction. This behaviour is quite different from the dominant $e^+e^- \to W W$ background. The event rates are comfortably high ($\sigma_{\chi_1^+\chi_1^-} = 245$ fb, $\epsilon \simeq 0.12$ mainly due to decay branching ratios) and the background amounts to $\sim 10\,\%$.

The masses of the chargino $m_{\chi_1^\pm}$ and the neutralino $m_{\chi_1^0}$ can be accessed through a study of the continuous energy spectrum of the di-jet system, shown in figure 3. A two-parameter fit to the spectrum yields a statistical accuracy of $m_{\chi_1^\pm} = 167.6 \pm 1.1$ GeV and $m_{\chi_1^0} = 88.2 \pm 0.6$ GeV.

Threshold Energy Scan An alternative method to determine the chargino mass with high precision is to measure the $\chi_1^+ \chi_1^-$ production cross section at the kinematic threshold, shown in figure 3. The chargino mass resolution, $m_{\chi_1^\pm} = 168.2 \pm 0.10$ GeV, can be improved by an order of magnitude with a moderate integrated luminosity. A measurement of the excitation curve, $\sigma \propto \beta\,(3 - \beta^2)/2$, allows to determine the spin 1/2 of the chargino $\chi_1^\pm$.

Polarised Beams Polarisation does not improve the signal to bacckground ratio of chargino production. However, polarised beams offer the possibility to disentangle the s and $\tilde{\nu}_e$ t channel diagrams and to determine the gaugino and higgsino components of the chargino: $\chi_1^\pm = \alpha\,\tilde{W}^\pm + \beta\,\tilde{H}^\pm$. At high energy γ and Z decouple to B^0/W^3 and the wino couples only to left-handed electrons, while the higgsino couples to both left-handed and right-handed electrons (s channel). Thus, precise measurements of σ_L and σ_R allow to determine the chargino mixing parameters. With a luminosity of $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ one expects statistical accuracies of $\delta\sigma_L \simeq 4.5\,\%$ and $\delta\sigma_R \simeq 15\,\%$.

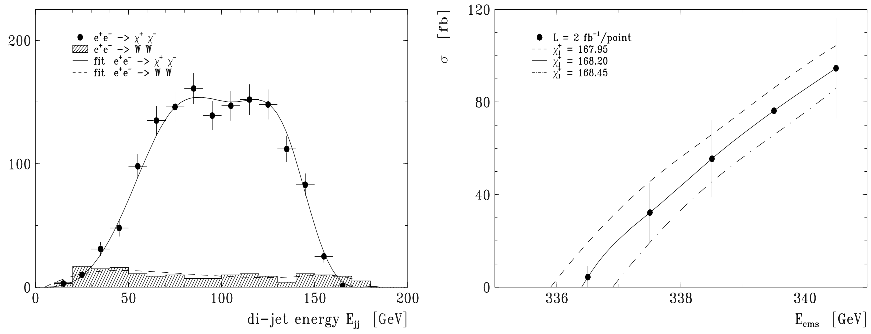

Fig. 3. Left: Di-jet energy spectrum E_{jj} of the reaction $e^+e^- \to \chi_1^+\chi_1^-$ ($\bullet$ and —) and the background reaction $e^+e^- \to WW$ (histogram and $--$), assuming $\mathcal{L} = 50\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 500$ GeV. **Right:** Cross section for $e^+e^- \to \chi_1^+\chi_1^-$ around the kinematic threshold assuming $\mathcal{L} = 2\ \mathrm{fb}^{-1}$ per measurement ($\bullet$). The curves indicate chargino masses of $m_{\chi_1^\pm} = 168.2 \pm 0.25$ GeV

4 Scalar Top Quark

The scalar top quark $\tilde{t}_1$ may be the lightest squark. Due to large Yukawa terms its mass may evolve to lower values than for the first generations and the off-diagonal elements of the mass matrix can be large leading to strong $\tilde{t}_R - \tilde{t}_L$ mixing in the mass eigenstates

$$\begin{aligned} \tilde{t}_1 &= \cos\theta_{\tilde{t}}\,\tilde{t}_R + \sin\theta_{\tilde{t}}\,\tilde{t}_L\ , \\ \tilde{t}_2 &= -\sin\theta_{\tilde{t}}\,\tilde{t}_R + \cos\theta_{\tilde{t}}\,\tilde{t}_L\ . \end{aligned}$$

Scalar top production has been studied at $\sqrt{s} = 500$ GeV assuming a mixing angle of $|\cos\theta_{\tilde{t}}| = 0.57$, *i.e.* implying low cross sections, and the following masses and decay modes [3]

$$\begin{aligned} e^+e^- &\to \tilde{t}_1\,\tilde{t}_1 & m_{\tilde{t}_1} &= 180\ \mathrm{GeV}\ , \\ \tilde{t}_1 &\to b\,\chi_1^\pm & m_{\chi_1^\pm} &= 150\ \mathrm{GeV}\ , \\ &\to c\,\chi_1^0 & m_{\chi_1^0} &= 100\ \mathrm{GeV}\ . \end{aligned}$$

Since the final state contains many invisible particles, a direct mass reconstruction is impossible. However, the event topology can be clearly identified and polarised electron cross section measurements can be used to determine the scalar top mass and mixing angle. For a polarisation of $P_{e^-} = \pm 90\,\%$ and $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ one expects a precision of $\sigma_L(\tilde{t}_1\,\tilde{t}_1) = 48.6 \pm 6.0$ fb and $\sigma_R(\tilde{t}_1\,\tilde{t}_1) = 46.1 \pm 4.9$ fb. The results are displayed in figure 4, leading to a measurement of the scalar top mass of $m_{\tilde{t}_1} = 180 \pm 7$ GeV and a mixing angle of $|\cos\theta_{\tilde{t}}| = 0.57 \pm 0.06$.

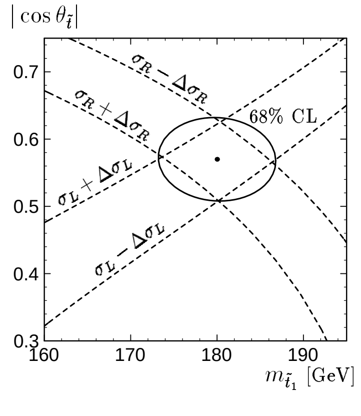

Fig. 4. Measurement of the stop mass $m_{\tilde{t}_1}$ and the mixing angle $\theta_{\tilde{t}}$ in the reactions $e^+e^-_L \to \tilde{t}_1\tilde{t}_1$ and $e^+e^-_R \to \tilde{t}_1\tilde{t}_1$ assuming $\mathcal{L} = 10$ fb^{-1} at $\sqrt{s} = 500$ GeV

5 Conclusions

The physics programme of a future e^+e^- linear collider extends the SUSY particle searches at LEP and is in many aspects complementary to LHC. The great advantage of e^+e^- colliders is the high precision of experimental analyses – masses, cross sections and couplings – covering the kinematically accessible domain in a conclusive manner. An overconstrained set of observables allows to check the basic SUSY–GUT parameters, *e.g.* the gaugino mass relations $M_i = \alpha_i/\alpha_{\rm GUT}\, m_{1/2}$ and slepton mass differences, to a high precision. At a future e^+e^- collider with an energy upgrade 500 GeV $\to$ 1 TeV $\to$ 2 TeV and highly polarised beams the complete SUSY particle spectrum may be explored.

References

[1] Proceedings *'e^+e^- Collisions at 500 GeV: The Physics Potential'*, ed. P.M. Zerwas, DESY 92-123 A+B, DESY 93-123 C and DESY 96-123 D.
[2] T. Tsukamoto *et al.*, Phys. Rev. D 51 (1995) 3153.
[3] *'Conceptual Design Report of a 500 GeV e^+e^- Linear Collider'*, DESY 1997-048 and http://www.desy.de/HEP/desy-hep.html.