Extracting GMSB Parameters at a Linear Collider [1]

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Abstract

Assuming gauge-mediated supersymmetry (SUSY) breaking (GMSB), we simulate precision measurements of fundamental parameters at a 500 GeV e^+e^- linear collider (LC) in the scenario where a neutralino is the next-to-lightest supersymmetric particle (NLSP). Information on the SUSY breaking and the messenger sectors of the theory is extracted from realistic fits to the measured mass spectrum of the Minimal SUSY Model (MSSM) particles and the NLSP lifetime.

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Supersymmetry must be broken if it is to describe nature, and GMSB [1] is one attractive way to realize this, also providing natural suppression of the SUSY contributions to flavour-changing neutral currents at low energies. In GMSB models, the gravitino $\tilde{G}$ is the LSP with mass given by $m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P'} \simeq 2.37 \left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^2$ eV, where $\sqrt{F}$ is the fundamental SUSY breaking scale. The GMSB phenomenology is characterised by decays of the NLSP to its Standard Model partner and the $\tilde{G}$ with a non-negligible or even macroscopic lifetime. In the simplest GMSB realizations, depending on the parameters $M_{\rm mess}$, $N_{\rm mess}$, Λ, $\tan\beta$, sign(μ) defining the model, the NLSP can be either the lightest neutralino $\tilde{N}_1$ or the light stau $\tilde{\tau}_1$. For this study [2], we generated several thousand GMSB models following the standard phenomenological approach [3] and focused on the neutralino NLSP scenario, for which we selected several representative points for simulation. Our aim was to explore the potential of a LC in extracting the fundamental model parameters.

Firstly, we investigated the sensitivity in determining the GMSB parameters at the messenger and electroweak scales from the knowledge of the sparticle masses that could be obtained from threshold-scanning techniques. We used a sample model with

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Parameter	Fitted value
$M_{\rm mess}$	(161 ± 2) TeV
Λ	(76.01 ± 0.08) TeV
$N_{\rm mess}$	0.9994 ± 0.0009
$\tan\beta$	3.50 ± 0.03

Table 1: *Results of fits to the parameters of the GMSB model described in the text, starting from a possible set of light sparticle masses measurements from threshold scans. A 200 fb^{-1} run at the LC is assumed.*

$M_{\rm mess} = 161$ TeV; $N_{\rm mess} = 1$; $\Lambda = 76$ TeV; $\tan\beta = 3.5$; $\mu > 0$, producing a rather light sparticle spectrum, and assumed a total of 200 fb^{-1} collected between 200 and 500 GeV c.o.m. energies at a LC. By just considering the shape of the total cross sections for several kinematically allowed SUSY production processes as functions of $\sqrt{s}$ close to the thresholds, we inferred the following approximate precisions for the sparticle masses:

$$
\begin{array}{lll}
\Delta(m_{\tilde{N}_1}) \sim 0.2 \text{ GeV}; & \Delta(m_{\tilde{N}_2}) \sim 0.8 \text{ GeV}; & \Delta(m_{\tilde{C}_1}) \sim 0.1 \text{ GeV}; \\
\Delta(m_{\tilde{e}_L}) \sim 0.2 \text{ GeV}; & \Delta(m_{\tilde{e}_R}) \sim 0.2 \text{ GeV}; & \Delta(m_{\mu_R}) \sim 0.8 \text{ GeV}; \\
\Delta(m_{\tilde{\tau}_1}) \sim 0.8 \text{ GeV}; & \Delta(m_{\tilde{\tau}_2}) \sim 2.0 \text{ GeV}; & \Delta(m_{h^0}) \sim 0.1 \text{ GeV}.
\end{array}
\tag{1}
$$

By performing a fit to minimise a χ^2 based on these errors, with the true (model-dependent) values as the central ones in the fit, we obtained an estimate of the precisions on the underlying parameters, as shown in Tab. 1. We checked that these precisions are typical for the class of models we considered.

Then, we considered $\tilde{N}_1$ lifetime measurements in the whole allowed $c\tau_{\tilde{N}_1}$ range, performing event simulation in detail for our set of representative GMSB models. Indeed, since the $\tilde{N}_1$ lifetime is related to $\sqrt{F}$ by

$$
c\tau_{\tilde{N}_1} = \frac{16\pi}{\mathcal{B}} \frac{\sqrt{F}^4}{m^5_{\tilde{N}_1}} \simeq \frac{1}{100\mathcal{B}} \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4 \left(\frac{m_{\tilde{N}_1}}{100 \text{ GeV}}\right)^{-5},
\tag{2}
$$

the GMSB framework provides an opportunity to extract information on the SUSY breaking sector of the theory from collider experiments that is not available, e.g., in supergravity-inspired models.

Typical neutralino lifetimes for our models range from microns to tens of metres. While the lower bound on $c\tau_{\tilde{\rm N}_1}$ comes from requiring perturbativity up to the grand unification scale [3], the upper bound is only valid if the $\tilde{G}$ mass is restricted to be lighter than about 1 keV, as suggested by some cosmological arguments [4] (cfr. Fig. 1).

For given $\tilde{N}_1$ mass and lifetime, the residual theoretical uncertainty on determining $\sqrt{F}$ is due to the factor of order unity $\mathcal{B}$ in Eq. (2), whose variation is quite limited in GMSB models (cfr. Fig. 2a).

In addition to the dominant $\tilde{N}_1 \to \gamma\tilde{G}$ decay, it was fundamental to our analysis to take the $\tilde{N}_1 \to \tilde{G} f\bar{f}$ decays into account, in order to use the tracking detectors for measurements of shorter neutralino lifetimes. We performed a complete study of these channels and found that in most cases of interest for our study the total width is given

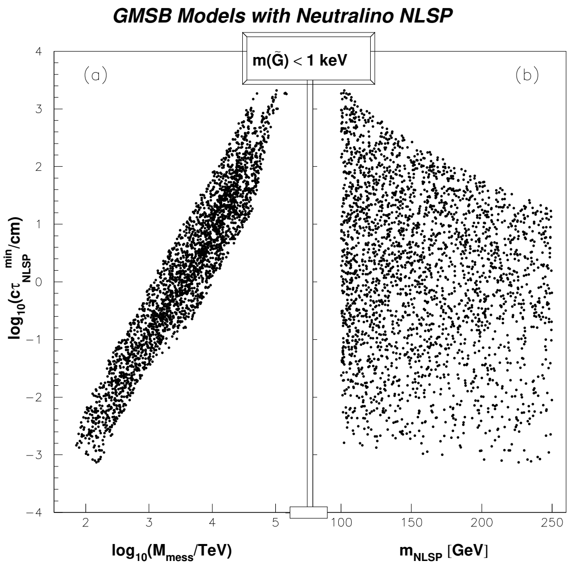

Figure 1: *Scatter plot of the neutralino NLSP lifetime as a function of the messenger scale* $M_{\rm mess}$ *(a) and* $m_{\tilde{N}_1}$ *(b). For each set of GMSB model input parameters, we plot the lower limit on* $c\tau_{\tilde{N}_1}$, *corresponding to* $\sqrt{F} \simeq \sqrt{F}_{\rm mess} = \sqrt{\Lambda M_{\rm mess}}$. *We use only models that fulfil the limit* $m_{\tilde{G}} \lesssim 1$ keV $\Rightarrow \sqrt{F}_{\rm mess} \lesssim \sqrt{F} \lesssim 2000$ *TeV suggested by simple cosmology.*

approximately by

$$\Gamma(\tilde{N}_1 \to f\bar{f}\tilde{G}) \simeq \Gamma(\tilde{N}_1 \to \gamma\tilde{G})\frac{\alpha_{\rm em}}{3\pi}N_f^c Q_f^2\left[2\ln\frac{m_{\tilde{N}_1}}{m_f} - \frac{15}{4}\right] + \Gamma(\tilde{N}_1 \to Z\tilde{G})B(Z \to f\bar{f})\ , \tag{3}$$

where the expressions for the widths of the 2-body $\tilde{N}_1$ decays are well-known [5]. In Fig. 2b, the branching ratio (BR) of the $\tilde{N}_1 \to \gamma\tilde{G}$ decay is compared to those of $\tilde{N}_1 \to Z\tilde{G}$ and $\tilde{N}_1 \to h^0\tilde{G}$ (in the on-shell approximation) and those of the main $\tilde{N}_1 \to f\bar{f}\tilde{G}$ channels (including virtual-photon exchange contributions only).

To generate GMSB events, we modified `SUSYGEN 2.2/03` [6], to take the 3-body neutralino decays into account as follows. We implemented in `CompHEP 3.3.18` [7] a home-made lagrangian including the relevant gravitino interaction vertices in a suitable approximation. Then, we studied the kinematical distributions of the $\tilde{N}_1 \to f\bar{f}\tilde{G}$ channels and passed the results to the event generator numerically. For each sample GMSB model, we considered in most cases a LC run at a c.o.m. energy such that the only SUSY production process open is NLSP pair production $e^+e^- \to \tilde{N}_1\tilde{N}_1$, followed by $\tilde{N}_1$ decays through all possible channels. For more challenging models where the light SUSY thresholds are close to each other, we simulated also events from R-slepton pair production and used some selection to isolate the $\tilde{N}_1\tilde{N}_1$ events, for which the $\tilde{N}_1$ production energy is fixed by the beam energy (we also took into account initial-state radiation as well as beamstrahlung effects), allowing a cleaner $c\tau_{\tilde{N}_1}$ measurement.

The primary vertex of the events was first smeared according to the assumed beamspot size of 5 nm in y, 500 nm in x and 400 μm in z and then the events were passed through a full `GEANT 3.21` [8] simulation of the detector as described in the ECFA/DESY CDR [9]. The tracking detector components essential to our analysis included a 5-layer vertex detector with a point precision of 3.5 μm in $r\phi$ and z, a TPC possessing 118 padrows with point resolution of 160 μm in $r\phi$ and 0.1 cm in z. In addition, we assumed an electromagnetic calorimeter with energy resolution given by $(10.3/\sqrt{E} + 0.6)\%$, angular pointing

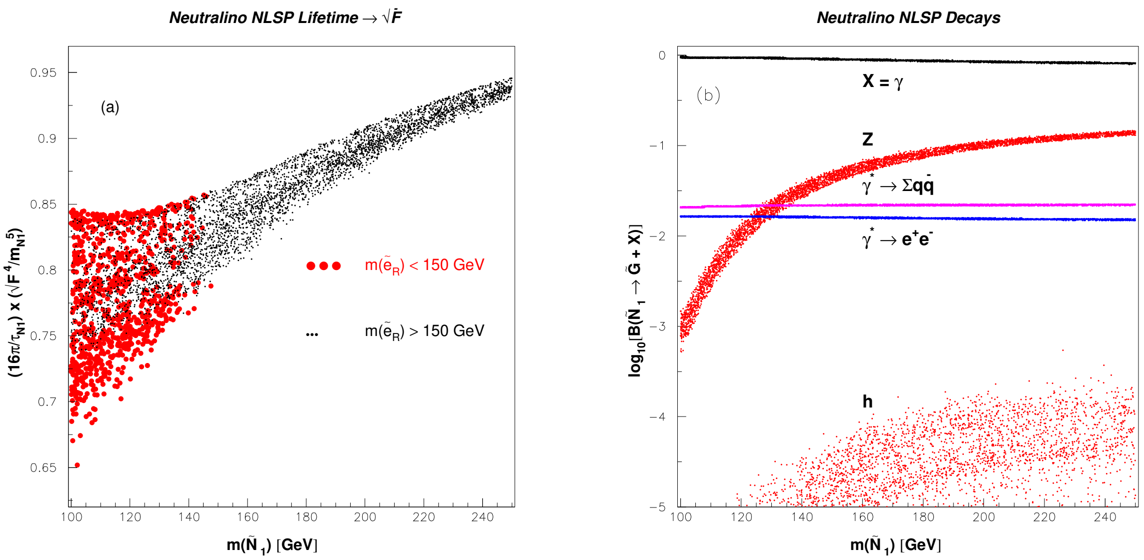

Figure 2: *(a) Scatter plot showing the relation between the neutralino NLSP lifetime and the fundamental scale of SUSY breaking $\sqrt{F}$, i.e. the factor $\mathcal{B}$ in Eq.(2), as a function of the neutralino mass in GMSB models of interest for the LC (100 $\lesssim m_{\tilde{N}_1} \lesssim$ 250 GeV). Big grey dots in represent models with a light R-selectron (102–150 GeV), small black dots are for the heavier selectron case (150–430 GeV). (b) Scatter plot for the BR's of various $\tilde{N}_1$ decay channels as a function of the $\tilde{N}_1$ mass. Dots in different grey scale (colours) refer to the decays $\tilde{N}_1 \to \gamma\tilde{G}$, $\tilde{N}_1 \to Z\tilde{G}$ (including off-shell effects), and to hadrons or e^+e^- plus gravitino via virtual photon, as labelled. For reference, we also report results for the 2-body $\tilde{N}_1 \to h^0\tilde{G}$ decay in the on-shell approximation, whose BR is always negligible.*

resolution of $50/\sqrt{E}$ mrad and timing resolution of $2/\sqrt{E}$ ns. The dimensions of the whole calorimeter (electromagnetic and hadronic) were 172 cm $< r <$ 210 cm and 280 cm $< |z| <$ 330 cm.

The probability for a single neutralino produced with energy $E_{\tilde{N}_1}$ to decay before travelling a distance λ is given by $P(\lambda) = 1 - \exp(-\lambda/L)$, where $L = c\tau_{\tilde{N}_1}(\beta\gamma)_{\tilde{N}_1}$ is the $\tilde{N}_1$ "average" decay length and $(\beta\gamma)_{\tilde{N}_1} = (E^2_{\tilde{N}_1}/m^2_{\tilde{N}_1} - 1)^{1/2}$.

For L less than a few cm, we used tracking for measuring the vertex of $\tilde{N}_1 \to \tilde{G}f\bar{f}$ decays. When L is very short, less than a few hundred μm, the beamspot size becomes important and a 3D procedure is not appropriate. Instead, the reconstructed vertex was projected onto the xy plane, where the beamspot size is very small, and we used the resulting distributions to measure the $\tilde{N}_1$ lifetime. We studied several GMSB models with $c\tau_{\tilde{N}_1}$ in the allowed range and found that the intrinsic resolution of the method was approximately 10 μm. An example of the reconstructed 2D decay length distribution for a challenging model where the neutralino lifetime can be very short [2] is shown in Fig. 3 for statistics corresponding to 200 fb^{-1} (r is the xy component of λ).

For 500 μm $\lesssim L \lesssim$ 15 cm, we used 3D vertexing to determine the decay length distribution and hence the lifetime of the $\tilde{N}_1$. Vertices arising from $\tilde{N}_1 \to \gamma\tilde{G}$ and photon conversions in detector material were essentially eliminated using cuts on the invariant mass of the daughter pairs together with geometrical projection cuts involving the mass of the $\tilde{N}_1$ and the topology of the daughter tracks. Methods of measuring the $\tilde{N}_1$ mass using the endpoints of photon energies or threshold techniques, together with details of the projection cuts have been described [2]. Using 200 fb^{-1} of data, we concluded that a

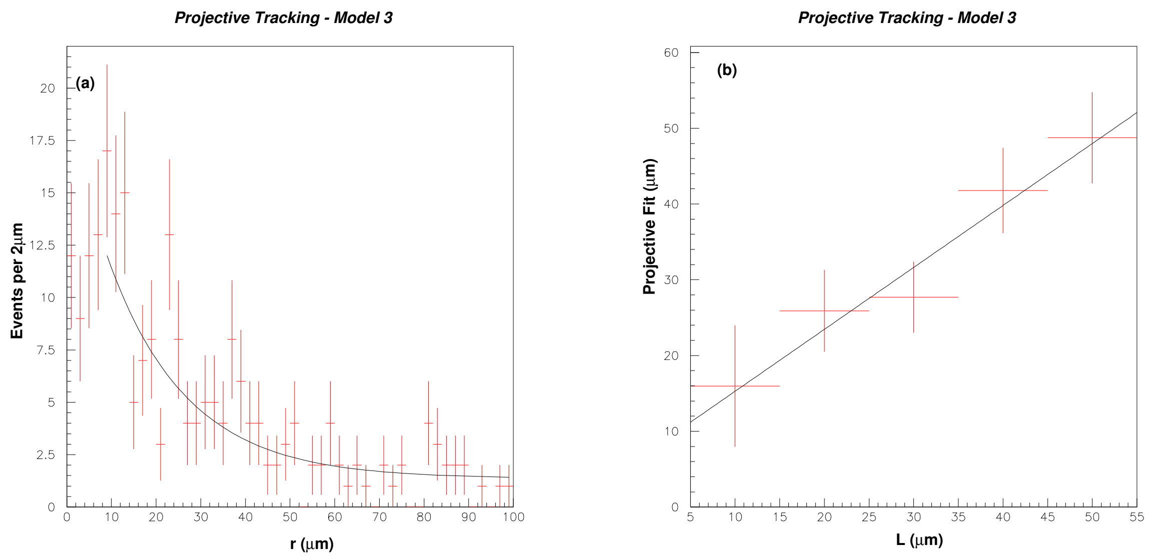

Figure 3: *(a) Reconstructed projective radial distances, r, of the $\tilde{N}_1 \to f\bar{f}\tilde{G}$ decay vertex, for a LC run on a short-lifetime model with $L = 10\ \mu m$ together with a fit to an exponential plus constant. (b) Shows the results of the corresponding fits for a range of L values.*

$c\tau_{\tilde{N}_1}$ measurement with statistical error of $\sim 4\%$ could be made using this method.

For L larger than a few cm, we used the $\tilde{N}_1 \to \gamma\tilde{G}$ channel, providing much larger statistics. The calorimeter was assumed to have pointing capability, using the shower shapes together with appropriate use of pre-shower detectors. Assuming the pointing angular resolution mentioned above, we demonstrated [2] how a decay length measurement can be made. We concluded that for lifetimes ranging from approximately 5 cm to approximately 2 m this method worked excellently, with statistical precisions ranging from a few % at the shorter end to about 6% at the upper end of the range. We also investigated the use of timing information to provide a lifetime measurement, but found it to be less useful than calorimeter pointing. However, the use of timing might be relevant to assign purely photonic events to bunch crossings and to reject cosmic backgrounds.

For very long lifetimes, we employed a statistical technique where the ratio of the number of one photon events in the detector to the number of two photon events was determined as a function of $c\tau_{\tilde{N}_1}$. This allowed a largely model-independent measurement out to $c\tau_{\tilde{N}_1} \simeq$ few 10's m. The possibility of using the ratio of the number of no-photon events to one photon events was also discussed [2]. The latter allows a greater length reach, but relies on model-dependent assumptions.

In Fig. 4, we summarise the techniques we have used as a function of L for a sample model. The criterion for indicating a method as successful is a measurement of L and the $\tilde{N}_1$ lifetime to 10% or better. It can be seen that L can be well measured for 10's of μm $\lesssim L \lesssim$ 10's of m, which is in most cases enough to cover the wide range allowed by theory and suggested by cosmology.

With reference to Eq. (2), we note that a 10% error in $c\tau_{\tilde{N}_1}$ corresponds to a 3% error in $\sqrt{F}$. This is of the same order of magnitude as the uncertainty on the factor $\mathcal{B}$, which parameterises mainly the different possible $\tilde{N}_1$ physical compositions in GMSB models (cfr. Fig. 2a). We also checked explicitly that, in comparison, the contributing error from a neutralino mass measurement using threshold-scanning techniques or end-point methods is negligible [2].

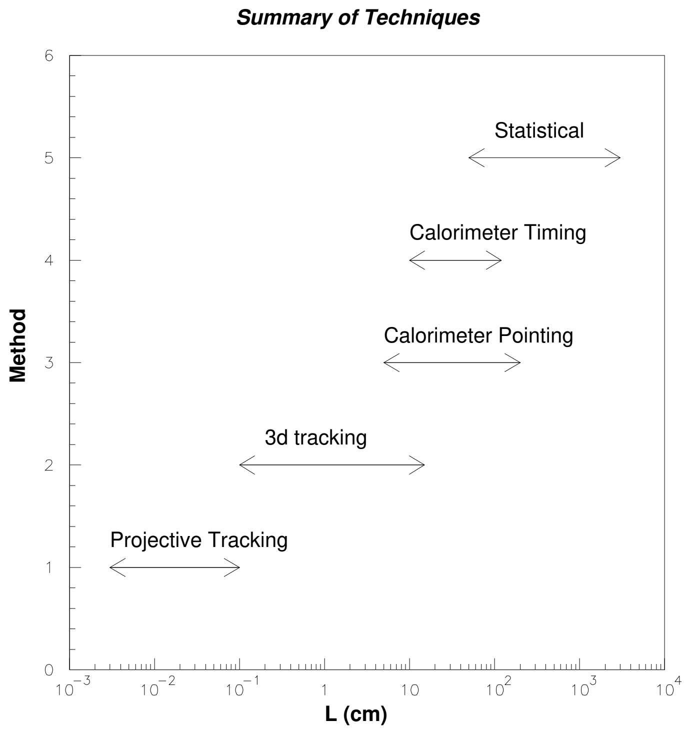

Figure 4: *Summary of the techniques used here for a $c\tau_{\tilde{N}_1}$ measurement at the level of 10% or better.*

Hence we conclude that, for the models considered and under conservative assumptions, a determination of $\sqrt{F}$ with a precision of approximately 5% is achievable at a LC by only performing $\tilde{N}_1$ lifetime and mass measurements in the context of GMSB with neutralino NLSP. Less model dependent and more precise results can be obtained by adding information on the $\tilde{N}_1$ physical composition from other observables, such as $\tilde{N}_1$ decay BR's, cross sections and distributions.

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