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Precision GMSB at a Linear Collider ^{*}

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Abstract

We simulate precision measurements of gauge-mediated supersymmetry breaking (GMSB) parameters at a 500 GeV e^+e^- linear collider in the scenario where a neutralino is the next-to-lightest supersymmetric particle. Information on the supersymmetry breaking and the messenger sectors of the theory is extracted from the measured sparticle mass spectrum and neutralino lifetime.

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PRECISION GMSB AT A LINEAR COLLIDER ^a

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We simulate precision measurements of gauge-mediated supersymmetry (SUSY) breaking (GMSB) 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 the measured sparticle mass spectrum and neutralino lifetime.

GMSB ¹ is an attractive possibility for physics beyond the standard model (SM) and provides 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 SM partner and the \tilde{G} with a non-negligible or even macroscopic lifetime. In the simplest GMSB realizations, depending on the parameters M_{mess} , N_{mess} , Λ , $\tan\beta$, $\text{sign}(\mu)$ 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 determining the GMSB parameters. Firstly, for a sample model with light sparticles, we considered a measurement of the spectrum via threshold scanning and found that N_{mess} and Λ (M_{mess} and $\tan\beta$) can be determined to 0.1 (1)% after a 200 fb⁻¹ run with c.o.m. energy between 200 and 500 GeV. Then, we investigated \tilde{N}_1 lifetime measurements in the whole allowed $c\tau_{\tilde{N}_1}$ range, performing detailed event simulation for a set of representative GMSB models. Indeed, since the \tilde{N}_1 lifetime is related to \sqrt{F} by

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

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.

For the models we considered, the neutralino lifetime ranges from microns to tens of metres. While the lower bound on $c\tau_{\tilde{N}_1}$ 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. This circumstance is summarised in Fig. 1.

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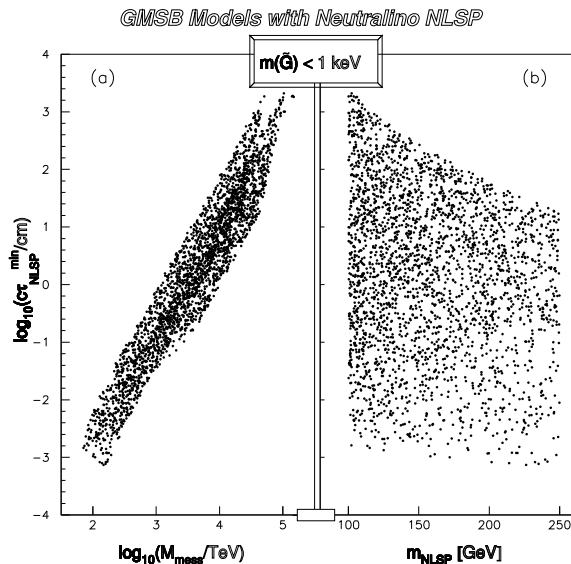


Figure 1: Scatter plot of the neutralino NLSP lifetime as a function of the messenger scale M_{mess} (a) and $m_{\tilde{N}_1}$ (b). For each set of GMSB model input parameters, we plot the lower limit on $c\tau_{\tilde{N}_1}$, corresponding to $\sqrt{F} \simeq \sqrt{F_{\text{mess}}} = \sqrt{\Lambda M_{\text{mess}}}$.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

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. (1), whose variation is quite limited in GMSB models (cfr. Fig. 2a).

For our simulations, and in particular for short $c\tau_{\tilde{N}_1}$ measurements, it was fundamental to take the $\tilde{N}_1 \rightarrow \tilde{G}f\bar{f}$ decays into account, in addition to the dominant one $\tilde{N}_1 \rightarrow \gamma\tilde{G}$. We performed a complete analysis of these channels and found that in most cases of interest for our study the total width is given approximately by

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

where the expressions for the widths of the 2-body \tilde{N}_1 decays are well-known⁵. In Fig. 2b, the branching ratio (BR) of the $\tilde{N}_1 \rightarrow \gamma\tilde{G}$ decay is compared to those of $\tilde{N}_1 \rightarrow Z\tilde{G}$ and $\tilde{N}_1 \rightarrow h^0\tilde{G}$ (in the on-shell approximation) and those of the main $\tilde{N}_1 \rightarrow f\bar{f}\tilde{G}$ channels (including virtual-photon exchange contributions only).

Using CompHEP 3.3.18⁶ together with a home-made lagrangian including the relevant gravitino interaction vertices in a suitable approximation, we also studied the kinematical distributions of the $\tilde{N}_1 \rightarrow f\bar{f}\tilde{G}$ channels and implemented the numerical results in our GMSB event generator.

For this purpose, we used SUSYGEN 2.2/03⁷, modified to include the 3-body neutralino decays as discussed above. 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

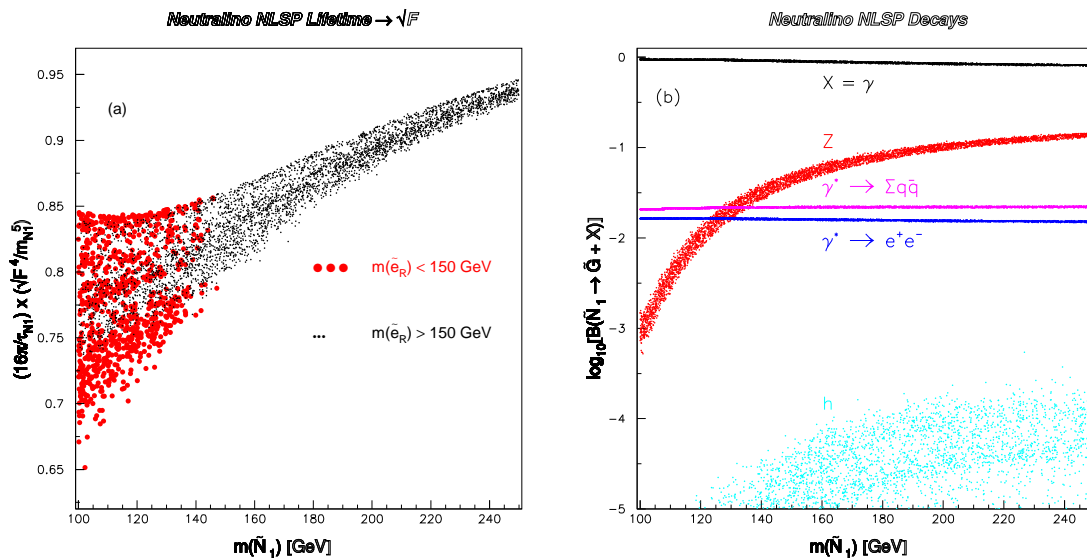


Figure 2: (a) Scatter plot showing the relation between the neutralino NLSP lifetime and the fundamental scale of SUSY breaking \sqrt{F} , i.e. the factor \mathcal{B} in Eq.(1), as a function of the neutralino mass in GMSB models of interest for the LC ($100 \lesssim m_{\tilde{N}_1} \lesssim 250$ GeV). 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 $\tilde{N}_1 \rightarrow \gamma\tilde{G}$, $\tilde{N}_1 \rightarrow Z\tilde{G}$ (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 $\tilde{N}_1 \rightarrow h^0\tilde{G}$ decay in the on-shell approximation, whose BR is always negligible.

process open is NLSP pair production $e^+e^- \rightarrow \tilde{N}_1\tilde{N}_1$, 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 cuts 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 3.21⁸ simulation of the detector as described in the ECFA/DESY CDR⁹. 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 resolution of $50/\sqrt{E}$ mrad and timing resolution of $2/\sqrt{E}$ ns. The dimensions of the whole calorimeter (electromagnetic and hadronic) were $172 \text{ cm} < r < 210 \text{ cm}$ and $280 \text{ cm} < |z| < 330 \text{ cm}$.

A single neutralino produced with energy $E_{\tilde{N}_1}$ will decay before travelling a distance λ with a probability given by $P(\lambda) = 1 - \exp(-\lambda/L)$, where $L = c\tau_{\tilde{N}_1}(\beta\gamma)_{\tilde{N}_1}$

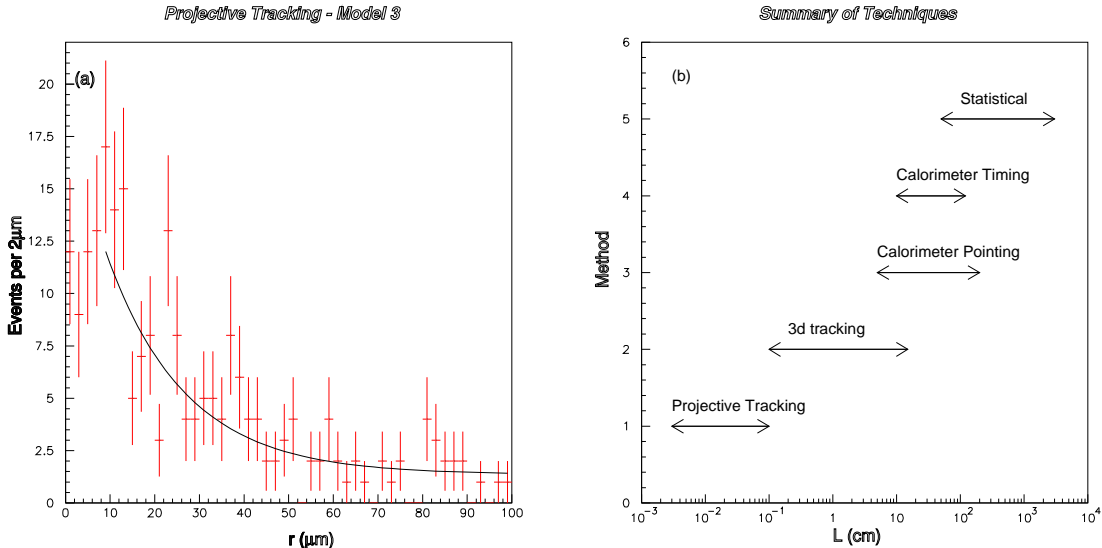


Figure 3: (a) Reconstructed projective radial distances, r , of the $\tilde{N}_1 \rightarrow f\bar{f}\tilde{G}$ decay vertex, for a LC run on a short-lifetime model with $L = 10 \mu\text{m}$ together with a fit to an exponential plus constant. (b) Summary of the techniques used here for a $c\tau_{\tilde{N}_1}$ measurement to 10% or better.

is the \tilde{N}_1 “average” decay length and $(\beta\gamma)_{\tilde{N}_1} = (E_{\tilde{N}_1}^2/m_{\tilde{N}_1}^2 - 1)^{1/2}$.

For L less than a few cm, we used tracking for measuring the vertex of $\tilde{N}_1 \rightarrow \tilde{G}f\bar{f}$ decays. For the very short case, L 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 $10 \mu\text{m}$. An example of the reconstructed 2D decay length distribution for a challenging model where the neutralino lifetime can be very short² is shown in Fig. 3a for statistics corresponding to 200 fb^{-1} (r is the xy component of λ).

For $500 \mu\text{m} \lesssim L \lesssim 15 \text{ cm}$, we used 3D vertexing to determine the decay length distribution and hence the lifetime of the \tilde{N}_1 . Vertices arising from $\tilde{N}_1 \rightarrow \gamma\tilde{G}$ 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 described². Using 200 fb^{-1} of data, we concluded that a lifetime measurement with statistical error of approximately 4% could be made using this method.

For L larger than a few cm, we used the $\tilde{N}_1 \rightarrow \gamma\tilde{G}$ channel. 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 demonstrated² 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 of less use than calorimeter pointing. However, the use of timing in assigning purely photonic events to bunch crossings and for rejecting cosmic backgrounds should not be underestimated.

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 $c\tau_{\tilde{N}_1}$, requiring the presence of at least one displaced γ . 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 SUSY events to one photon events was also discussed². The latter allows a greater length reach, but relies on model-dependent assumptions.

In Fig. 3b, 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 $\mu\text{m} \lesssim L \lesssim$ 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. (1), 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 negligible².

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 simply by 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, distributions.

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