Detection of long-lived staus and gravitinos at the ILC

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A study is presented illustrating the excellent potential of future International Linear Collider (ILC) experiments to detect metastable staus $\tilde{\tau}$, measure precisely their mass and lifetime, and to determine the mass of the gravitino $\tilde{G}$ from the decay $\tilde{\tau} \to \tau\tilde{G}$, thus providing direct access to the gravitational coupling, respectively Planck scale.

1 Introduction

Supersymmetry (SUSY) provides an attractive scenario to account for the amount of dark matter in the universe. If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable and an ideal dark matter candidate. A very interesting option is the spin 3/2 gravitino $\tilde{G}$. The mass of the gravitino is set by the SUSY breaking scale F via $m_{3/2} = m_{\tilde{G}} = F/\sqrt{3}\,M_P$, with $M_P \simeq 2.4 \cdot 10^{18}$ GeV the reduced Planck scale. In general $m_{3/2}$ is a free parameter and may extend over a wide range of $\mathcal{O}(\mathrm{eV} - \mathrm{TeV})$ for gauge, gaugino and supergravity mediated symmetry breaking.

A gravitino LSP may be produced in decays of SUSY particles. If the next-to-lightest supersymmetric particle (NLSP) is the scalar tau $\tilde{\tau}$, the dominant process is $\tilde{\tau} \to \tau\tilde{G}$. Since the coupling is gravitational, the lifetime may be very long, ranging from seconds to years. The decay-width $\Gamma_{\tilde{\tau}}$, respectively lifetime $\tau = \Gamma_{\tilde{\tau}}^{-1}$, of the $\tilde{\tau}$ NLSP

$$\Gamma_{\tilde{\tau}\to\tau\tilde{G}} = \frac{1}{48\pi M_P^2} \frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right]^4 \qquad (1)$$

depends only on the masses $m_{\tilde{\tau}}$ and $m_{\tilde{G}}$ as well as on the Planck scale M_P – no further SUSY parameters are required.

The cosmological production of gravitino dark matter proceeds essentially via thermal production and/or late decays of the NLSP. The big bang nucleosynthesis puts constraints on the $\tilde{\tau}$ lifetime [1], typically $\tau \lesssim 10^7$ s for $m_{\tilde{G}} \sim 100$ GeV. Bound states of $\mathcal{N}\tilde{\tau}^-$ may alter the production of light elements considerably, but possible consequences are controversial [2].

Experiments at the ILC offer a unique possibility to detect long-lived staus and to study the properties of gravitinos, which cannot be observed in astrophysical experiments. A variety of spectra and SUSY breaking scenarios have been investigated experimentally in detail [3]; here just two models, mSUGRA and GMSB scenarios, are presented.

2 $\tilde{\tau}$ detection & measurement principles

A typical ILC detector [4] is shown in Fig. 1. The main characteristics, relevant to the present study, are: a TPC with excellent tracking and dE/dx resolution to identify slow, heavy particles by ionisation; a highly segmented hadronic calorimeter (HCAL) with energy resolutions $\delta E_h/E = 0.5/\sqrt{E/\mathrm{GeV}}$ for hadrons and $\delta E_{em}/E = 0.2/\sqrt{E/\mathrm{GeV}}$ for electrons/photons; an instrumented iron yoke to allow for muon detection and coarse calorimetric measurements of hadrons. The amount of material available to absorb a heavy $\tilde{\tau}$ in the HCAL or yoke corresponds to an acceptance for scaled momenta of $p/m = \beta\gamma \lesssim 0.4 - 0.5$.

The stau detection and measurement principle consists of several steps: identify a $\tilde{\tau}$ and determine its mass from kinematics; follow the track until it is trapped inside the detector; observe the stopping point until a decay $\tilde{\tau} \to \tau \tilde{G}$ is triggered by a large energy release uncorrelated to beam collisions; record the decay time to determine the $\tilde{\tau}$ lifetime; finally, measure the τ recoil energy to get the gravitino mass

$$E_\tau \quad = \quad \frac{m_{\tilde{\tau}}}{2} \left(1 - \frac{m_{\tilde{G}}^2 - m_\tau^2}{m_{\tilde{\tau}}^2} \right) \ . \qquad (2)$$

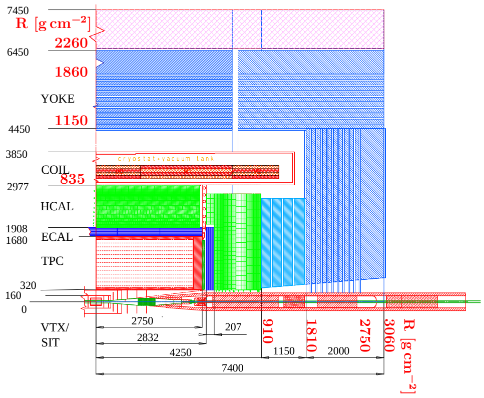

Figure 1: Quadrant of a typical ILC detector [4], length units in mm; amount of material indicated by R [g cm^{-2}]

The ILC provides a very favourable environment. The energy can be adjusted to optimise the number of observable staus. The e^+e^- beams collide in bunch trains of 1 ms duration repeated every 200 ms; the detector is inactive most of the time and ideally suited to measure long-lived particles. However, it is envisaged to operate the HCAL in a pulsed mode, switching on only during collisions. Clearly this concept has to be revised.

3 Experimental analyses – case studies

The analysis is based on a complete event simulation including QED radiation, beamstrahlung and detector resolutions. The experimental signature is very clean and distinct from Standard Model background. There are no missing particles (except $\nu' s$ from decays), the observed particle momenta are balanced, $|\sum_i \vec{p_i}| \simeq 0$, but don't sum up to the cms energy $\sum_i p_i < \sqrt{s}$. These features allow the sparticle masses and decay chains to be reconstructed from the event kinematics. Each SUSY event contains two $\tilde{\tau}' s$, easily identified by ionisation in the TPC, and their passage through the detector can be accurately followed. Stopping $\tilde{\tau}' s$ can be located within a volume of a few cm^3.

The production of low momentum $\tilde{\tau}' s$ with a suitable $\beta\gamma$ factor to be trapped in the detector proceeds either directly or via cascade decays from light sleptons or neutralinos. These processes — $\tilde{\tau}_1\tilde{\tau}_1$, $\tilde{e}_R\tilde{e}_R$, $\tilde{\mu}_R\tilde{\mu}_R$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0$ — rise only slowly above kinematic threshold with cross sections $\sigma \propto \beta^3$, thus providing relatively low rates. More efficient, if kinematically accessible, is associated selectron production $e^+e^- \to \tilde{e}_R\tilde{e}_L$, increasing as $\sigma \propto \beta$ near threshold. The event signatures are multi-lepton topologies: $2\tilde{\tau}_1$ from pair production, $2\tilde{\tau}_1 2\tau$ from neutralino production and $2\tilde{\tau}_1 2\tau 2\ell$ from selectron and smuon production.

3.1 mSUGRA scenario GDM ϵ

In *supergravity mediated symmetry breaking* (SUGRA) the gravitino mass $m_{3/2}$ is a free parameter of the same order as the other sparticle masses. In minimal versions with $\tilde{\tau}$ NLSP the common scalar mass m_0 has to be small and much lower than the common gaugino mass $M_{1/2}$. The mSUGRA scenario GDM ϵ [5] implies unified scalar and gravitino masses $m_0 = m_{3/2} = 20\,\text{GeV}$, $M_{1/2} = 440\,\text{GeV}$, $A_0 = 25\,\text{GeV}$, $\tan\beta = 15$ and sign $\mu = +$. The corresponding sparticle spectrum is compiled in Table 1.

mSUGRA scenario GDM ϵ

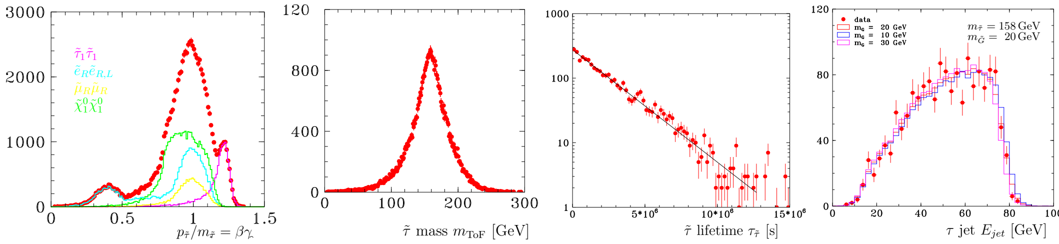

Figure 2: GDM ϵ scenario, assuming $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$: (a) $\tilde\tau$ production spectra of scaled momentum $p/m = \beta\gamma$ with contributions from various processes; (b) $\tilde\tau$ mass $m_{\rm ToF}$ spectrum; (c) $\tilde\tau$ lifetime distribution; (d) τ jet energy spectrum of the decay $\tilde\tau_1 \to \tau\tilde G$ compared with simulations of $m_{\tilde G} = 20\,\mathrm{GeV}$, $10\,\mathrm{GeV}$ and $30\,\mathrm{GeV}$

	m [GeV]	$\mathcal{B}$		m [GeV]	$\mathcal{B}$
$\tilde\tau_1$	157.6	$\tau\tilde G$	$\tilde\mu_R$	175.1	$\mu\tau\tilde\tau$
$\tilde e_R$	175.1	$e\tau\tilde\tau$	$\tilde e_L$	303.0	$e\tilde\chi^0_1$
$\tilde\chi^0_1$	179.4	$\tau\tilde\tau$	$\tilde G$	20	

Table 1: Sparticle masses and decay modes of the mSUGRA scenario GDM ϵ accessible at $\sqrt{s} = 500\,\mathrm{GeV}$

The experimental assumptions for the case study are the canonical ILC energy $\sqrt{s} = 500\,\mathrm{GeV}$ and an integrated luminosity $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ (< 1 year of data taking). The inclusive $\tilde\tau$ production cross section is $\sigma(\tilde\tau_1\tilde\tau_1 X) = 300\,\mathrm{fb}$.

The prolific *stau production* rate is characterised by the scaled momentum distribution $p/m = \beta\gamma$, shown in Fig. 2 a for the various reactions. The majority of particles come from diagonal slepton and neutralino pairs and leave the detector (peak around $\beta\gamma \simeq 1$). One observes, however, a second peak at low $\beta\gamma \lesssim 0.5$ from $\tilde e_R\tilde e_L$ decays, which will be stopped in the detector. The number of trapped $\tilde\tau's$ are $N_{\tilde\tau}^{\rm hcal} = 4100$ and $N_{\tilde\tau}^{\rm yoke} = 1850$ in the hadron calorimeter and yoke, respectively.

The *stau mass* measurement is based on the kinematics of $e^+e^- \to \tilde\tau_1\tilde\tau_1$, see magenta curve in Fig. 2 a, to be identified as a pair of collinear, non-interacting particles with momenta $p_{\tilde\tau} < \sqrt{s}/2 = E_{\tilde\tau}$. A determination of the mean momentum $\langle p_{\tilde\tau}\rangle = 192.4 \pm 0.2$ GeV leads to a precise $\tilde\tau$ mass of $m_{\tilde\tau} = 157.6 \pm 0.2$ GeV.

Alternatively one may select all identified $\tilde\tau's$ and perform a time-of-flight measurement using the calorimeter, having a resolution of $\delta t = 1\,\mathrm{ns}$. The reconstructed mass distribution $m_{\rm ToF} = \sqrt{(1/\beta^2 - 1)\,p^2}$, displayed in Fig. 2 b, provides an accuracy $\delta m_{\rm ToF} = 0.15$ GeV, similar to that of the momentum measurement.

The *stau lifetime* measurement is based on the decays of $\tilde\tau's$ which have been stopped in the detector. Requiring an isolated energetic cluster or muon above a certain threshold originating somewhere inside the sensitive fiducial volume of the calorimeter or yoke, results in the decay time distribution shown in Fig. 2 c. A fit to the spectrum gives a $\tilde\tau$ lifetime of $\tau = (2.6 \pm 0.05)\cdot 10^6\,\mathrm{s}$, corresponding to roughly one month.

Note: The relative precision on the $\tilde\tau$ lifetime does not depend on the gravitino mass, should it be much lighter as for larger mass splittings or in gauge mediated supersymmetry models.

A *direct gravitino mass* measurement can be performed by exploiting the τ recoil of the decay $\tilde\tau \to \tau\tilde G$, see (2). The upper endpoints of the energy spectra which coincide with

GMSB scenario SPS 7

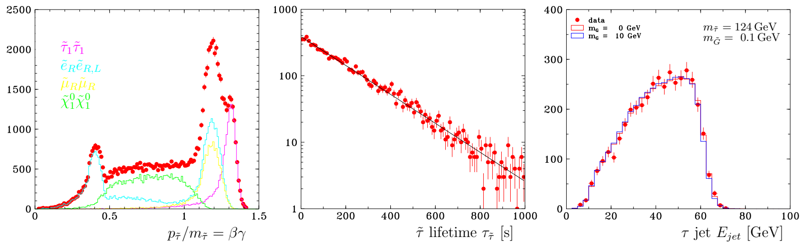

Figure 3: SPS 7 scenario, assuming $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 410\,\mathrm{GeV}$: (a) $\tilde\tau$ production spectra of scaled momentum $p/m = \beta\gamma$ with contributions from various processes; (b) $\tilde\tau$ lifetime distribution; (c) τ jet energy spectrum of the decay $\tilde\tau_1 \to \tau\tilde{G}$ compared with simulations of $m_{\tilde G} = 0\,\mathrm{GeV}$ and $10\,\mathrm{GeV}$

the primary τ energy $E_\tau = 77.5\,\mathrm{GeV}$, are directly related to the masses involved. Well defined upper edges are provided by the hadronic decays $\tau \to \rho\nu$ and $\tau \to \pi\pi\pi\nu$. The energy distribution of both decay modes, defined as 'τ jets', is shown in Fig. 2 d. In order to illustrate the sensitivity to the gravitino mass, simulations assuming the nominal value of $m_{\tilde G} = 20\,\mathrm{GeV}$ and shifted by $\pm 10\,\mathrm{GeV}$ are shown as well. A fit to the τ jet energy spectrum yields a gravitino mass $m_{\tilde G} = 20 \pm 4\,\mathrm{GeV}$.

Combining all results one can test the gravitational coupling of the stau to the gravitino and access the Planck scale, respectively Newton's constant. Inserting the expected values and accuracies on $m_{\tilde\tau}$, τ and $m_{\tilde G}$ in (1) one finds for the supergravity Planck scale $M_P = (2.4 \pm 0.5) \cdot 10^{18}$ GeV, where the error is dominated by the gravitino mass measurement. It is a unique feature of gravitino LSP scenarios that the Planck scale can be directly measured in particle experiments by investigating the properties of the NLSP and its decay.

The *gravitino mass* can be deduced more precisely from the $\tilde\tau$ mass and lifetime, if the gravitational coupling is shown to be responsible for the decay or is *assumed* and the macroscopic value of M_P is taken in the decay-width of (1). The resulting gravitino mass is $m_{\tilde G} = 20 \pm 0.2\,\mathrm{GeV}$. This value can be used to get the supersymmetry breaking scale $F = \sqrt{3}\, M_P\, m_{3/2} = (8.3 \pm 0.1) \cdot 10^{19}\,\mathrm{GeV}^2$, which is an important parameter to unravel the supersymmetry breaking mechanism.

3.2 GMSB scenario SPS 7

Gauge mediated symmetry breaking (GMSB) usually occurs at rather low scales and a light gravitino is naturally the LSP. Typical masses are of order eV to keV which may be extended in the GeV range. The GMSB reference scenario SPS 7 [7] is described by the conventional parameters $\Lambda = 40\,\mathrm{TeV}$, $M_m = 80\,\mathrm{TeV}$, $N_m = 3$, $\tan\beta = 15$ and $\mathrm{sign}\,\mu = +$, The sparticles are relatively light: $m_{\tilde\tau_1} = 123.4\,\mathrm{GeV}$, $m_{\tilde\ell_R} = 130.9\,\mathrm{GeV}$, $m_{\tilde\ell_L} = 262.8\,\mathrm{GeV}$, $m_{\tilde\chi^0_1} = 163.7\,\mathrm{GeV}$. The gravitino mass is set arbitrarily to $m_{\tilde G} = 0.1\,\mathrm{GeV}$.

The SPS 7 model is investigated assuming $\sqrt{s} = 410\,\mathrm{GeV}$ and $\mathcal{L} = 100\,\mathrm{fb}^{-1}$, with a large inclusive $\tilde\tau$ cross section of $\sigma(\tilde\tau_1\tilde\tau_1 X) = 420\,\mathrm{fb}$. As seen in the $\beta\gamma$ distribution of Fig. 3 a, most $\tilde\tau's$ leave the detector. There is, however, a large signal at $\beta\gamma \simeq 0.4$ from $\tilde e_R \tilde e_L$ production, contributing to $N^{\mathrm{hcal}}_{\tilde\tau} = 10000$ and $N^{\mathrm{yoke}}_{\tilde\tau} = 4900$ trapped $\tilde\tau's$ in the calorimeter and yoke.

The analysis of $\tilde\tau_1\tilde\tau_1$ pair production yields a mass of $m_{\tilde\tau_1} = 124.3 \pm 0.1\,\mathrm{GeV}$. From a fit to the decay time distribution, shown in Fig. 3 b, one obtains a lifetime of $\tau = 209.3 \pm 2.4\,\mathrm{s}$. These values can be used to derive a very accurate gravitino mass of $m_{\tilde{G}} = 100 \pm 1\,\mathrm{MeV}$ *assuming* a gravitational coupling. To illustrate of the sensitivity to low gravitino masses as expected in many GMSB models: a gravitino mass of 0.5 MeV corresponds a $\tilde{\tau}$ lifetime of 5 ms, which should be easily measurable.

The τ recoil energy spectrum is displayed in Fig. 3 c. As can be seen from the simulation curves for 0 GeV and 10 GeV gravitinos, the measurement is not sensitive to such low masses and can only set an upper limit of $m_{\tilde{G}} < 9\,\mathrm{GeV}$ (at 95% CL). The sensitivity to low gravitino masses decreases rapidly, see (2). A direct measurement of large $\tilde{\tau} - \tilde{G}$ mass splittings becomes extremely difficult, getting impossible for $m_{\tilde{G}}/m_{\tilde{\tau}} \lesssim 0.1$.

The nature of the LSP remains undetermined without knowing the gravitino mass. Further information can be gained from radiative decays $\tilde{\tau} \to \tau\gamma\tilde{G}$. The differential decay rates for a light spin 3/2 gravitino $\tilde{G}$ compared with a spin 1/2 neutralino $\tilde{\chi}$ [6] and a spin 1/2 axino $\tilde{a}$ [8] are found to exhibit detectable differences. Although experimentally ambitious – branching ratios suppressed by $\mathcal{O}(100)$, single $\gamma's$ to be disentangled from τ decays – the performance of the 'pictorial' calorimeter [4] and the large ILC data samples should allow one to discriminate between a light gravitino, a neutralino and an axino LSP.

4 Conclusions

Future ILC experiments have a rich potential to study SUSY scenarios where the gravitino $\tilde{G}$ is the LSP and a charged stau $\tilde{\tau}$ is the long-lived, metastable NLSP. Precise determinations of the $\tilde{\tau}$ mass and lifetime and of the $\tilde{G}$ mass appear feasible already with moderate integrated luminosity. (More SUSY scenarios can be found in [3].) A measurement of the gravitino mass from the τ recoil spectra of the decay $\tilde{\tau} \to \tau\tilde{G}$ gives access to the gravitational coupling, *i.e.* to the Planck scale, and provides a unique test of supergravity. Such observations will put stringent constraints on the gravitino as dark matter candidate.

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