Detection of long-lived staus and gravitinos at the ILC

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Abstract. A study is presented illustrating the excellent potential of future International Linear Collider (ILC) experiments to detect metastable staus, measure precisely their mass and lifetime, and to determine the mass of the gravitino \(\tilde{G}\) from the decay \(\tilde{\tau} \rightarrow \tau \tilde{G}\), 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 \(M_P \simeq 2.4 \times 10^{18}\) GeV the reduced Planck scale. In general \(m_{3/2}\) is a free parameter and may extend over a wide range of \(\mathcal{O} (\text{eV} - \text{TeV})\) for gaugino, 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 \(\tilde{\tau}\) overproduction \(\tilde{\tau} \rightarrow \tau \tilde{G}\) may alter \(\delta E_{\text{kin}}/E = 0.5/\sqrt{E/\text{GeV}}\) for hadrons and \(\delta E_{\text{em}}/E = 0.2/\sqrt{E/\text{GeV}}\) 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 \(p/m = \beta \gamma \lesssim 0.4 - 0.5\).

2 \(\tilde{\tau}\) detection & measurement principles

A typical ILC detector [5] is displayed 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 \(\delta E_{\text{kin}}/E = 0.5/\sqrt{E/\text{GeV}}\) for hadrons and \(\delta E_{\text{em}}/E = 0.2/\sqrt{E/\text{GeV}}\) for electrons/photons; an instrumented iron yoke to allow for muon detection and coarse calorimetric measurements of hadrons.

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 \([1]\), e.g. from the energy release in hadronic decays one expects \(\tau \lesssim 10^7\) s for \(m_{\tilde{G}} \sim 100\) GeV. Bound states of \(N\tilde{\tau}\) may alter the production of light elements considerably, although possible consequences are controversial. To avoid \(^{6}\text{Li}\) overproduction the \(\tilde{\tau}\) lifetime should be restricted to \(\tau \lesssim 5 \times 10^3\) s \([2]\), while the author of \([3]\) argues that the prior synthesised elements may be destroyed again at longer lifetimes.

Experiments at the ILC offer a unique possibility to detect long-lived staus and to study the properties of gravitinos, which otherwise cannot be observed in astrophysical experiments. A variety of spectra and Susy breaking scenarios have been investigated experimentally in detail \([4]\); here just two models, mSUGRA and GMSB scenarios, are presented.
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 \( \tau \) recoil energy to get the gravitino mass

\[
E_\tau = \frac{m_\tau}{2} \left( 1 - \frac{m_\tau^2 - m_\tilde{\tau}^2}{m_\tilde{\tau}^2} \right). \tag{2}
\]

The ILC provides a very favourable environment. The centre of mass 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; thus, the detector is most of the time inactive and in principle 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 to reach a reasonable duty cycle.

### 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 which can be efficiently rejected. There are no missing particles (except \( \nu \)'s from decays), the observed particle momenta are balanced, \[ \sum_i p_i = \text{const} \], but their moduli 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 \( (dE/dx \sim \beta^{-2}) \), and their passage through the detector can be accurately followed. The location of stopping \( \tilde{\tau} \)’s can be determined 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. All these processes — \( \tilde{\tau} \tilde{\tau}, \tilde{\epsilon}_R\tilde{\epsilon}_L, \tilde{\mu}_R\tilde{\mu}_R \) and \( \chi_1^0 \chi_1^0 \) — 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, \( 2\tilde{\tau}_1 \tilde{\tau}_2 \) from neutralino production and \( 2\tilde{\tau}_1 \tilde{\tau}_2 \tilde{\epsilon}_L \) from selectron and smuon production.

#### 3.1 mSUGRA scenario GDM \( \epsilon \)

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 the \( \tilde{\tau} \) NLSP the common scalar mass \( m_0 \) has to be small and much lower than the common gaugino mass \( M_{1/2} \). In the mSUGRA scenario GDM \( \epsilon \) [6] a tighter definition is used with 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 \( \text{sign} \mu = + \). The corresponding sparticle spectrum is compiled in Table 1.

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

The prolific \textit{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 \( \beta\gamma \approx 1 \)). One observes, however, a second peak at low \( \beta\gamma \leq 0.5 \) from cascade decays of \( \tilde{\epsilon}_R\tilde{\epsilon}_L \) production, which will be stopped in the detector. The number of \( \tilde{\tau} \)’s trapped are \( N_{\tilde{\tau}}^\text{heal} = 4100 \) and \( N_{\tilde{\tau}}^\text{yoke} = 1850 \) in the hadron calorimeter and yoke, respectively. The choice of energy turns out to be optimal. Similar rates can be obtained at 380 GeV, just above the slepton/neutralino thresholds. Selecting \( \tilde{\tau}_1\tilde{\tau}_1 \) pairs to absorb \( \tilde{\tau} \)’s is much less efficient, \textit{e.g.} \( N_{\tilde{\tau}}^\text{heal} = 1600 \) at \( \sqrt{s} = 340 \text{ GeV} \) for the same integrated luminosity.

The \textit{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 \( p_\tau < \sqrt{s}/2 = E_\tau \). A determination of the mean momentum \( \langle p_\tau \rangle = 192.4 \pm 0.2 \text{ GeV} \) leads to a precise \( \tilde{\tau} \) mass of

\[ m_\tau = 157.6 \pm 0.2 \text{ GeV}. \]

Alternatively one may use the much larger sample of all identified \( \tilde{\tau} \)’s, also those leaving the detector, and perform a the time-of-flight measurement using the calorimeter. The time resolution is \( \delta t = 1 \text{ ns} \), the track lengths are \( \sim 2 - 4 \text{ m} \). The reconstructed mass distribution \( m_{\tilde{\tau}_\tau\tilde{\tau}} \) displayed in Fig. 2 b, provides an accuracy \( \delta m_{\tilde{\tau}_\tau\tilde{\tau}} = 0.15 \text{ GeV} \), similar to that of the momentum measurement.

The \textit{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

\[ \tau = (2.6 \pm 0.05) \times 10^{-6} \text{ s}, \]

\[ \begin{array}{cccc}
\text{Table 1. Sparticle masses and decay modes of mSUGRA scenario GDM } \epsilon \text{ accessible at } \sqrt{s} = 500 \text{ GeV} \\

| m [GeV] | \B | m [GeV] | \B |
|---------|---|---------|---|
| \tilde{\tau}_1 | 157.6 | \tau \tilde{G} | 175.1 | \mu \tau \tilde{G} |
| \tilde{\epsilon}_R | 175.1 | e\tau \tilde{\tau} | 303.0 | e\chi_1^0 |
| \tilde{\chi}_1^0 | 179.4 | \tau \tilde{\tau} | 20 |
\end{array} \]
corresponding to roughly one month. For the actual conditions the lifetime scales as $\tau \sim m_\tilde{G}^2$ (also valid for very low masses) and rises significantly faster for $m_\tilde{G} > 0.25 m_\tilde{\tau}$, reaching $10^8$ s for a 75 GeV gravitino.

**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. Technically, there may be a limitation to measure lifetimes below 1 ms which corresponds to the sensitive time of beam collisions.

A direct gravitino mass measurement can be performed by exploiting the $\tau$ recoil of the decay $\tilde{\tau} \rightarrow \tau \tilde{G}$, see (2). The upper endpoints of the energy spectrum which coincide with the primary $\tau$ energy $E_\tau = 77.5$ GeV, are directly related to the masses involved. The leptonic 3-body decays $\tau \rightarrow \ell \nu \nu$ and $\tau \rightarrow \pi \pi \pi \nu$ are not very useful due to the soft spectrum peaking at low values. Well defined upper edges are provided by the hadronic decays to heavier final states $\tau \rightarrow \rho \omega$ and $\tau \rightarrow \pi \pi \pi \nu$. The energy distribution of both decay modes, defined as `\tau jets`, is shown in Fig. 2 d. In order to illustrate the sensitivity to the gravitino mass, simulations assuming the nominal value of $m_\tilde{G} = 20$ GeV and shifted by $\pm 10$ GeV are shown as well. A fit to the $\tau$ jet energy spectrum, yields a gravitino mass

$$m_\tilde{G} = 20 \pm 4 \text{ GeV}$$

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 $m_\tilde{\tau}$, $\tau$ and $m_\tilde{G}$ in (1) one finds for the supergravity Planck scale

$$M_P = (2.4 \pm 0.5) \cdot 10^{18} \text{ GeV},$$

where the error is dominated by the precision on the gravitino mass.

The gravitino mass can be deduced more precisely from the $\tau$ 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 $m_\tilde{G} = 20 \pm 0.2 \text{ GeV}$, where the error is dominated by the lifetime measurement. This mass value can be used to get access to the supersymmetry breaking scale $F = \sqrt{3} M_P m_{3/2} = (8.3 \pm 0.1) \cdot 10^{19} \text{ GeV}^2$, which is an important parameter to unravel the nature of the supersymmetry breaking mechanism.

The expected accuracies on the $\tilde{\tau}$ and $\tilde{G}$ observables and derived quantities of the GDM $\epsilon$ scenario are summarised in Table 2.

**Table 2.** Expected accuracies on $\tilde{\tau}$ and $\tilde{G}$ properties of observables and derived quantities; GDM $\epsilon$ scenario, based on $L = 100 \text{ fb}^{-1}$ at $\sqrt{s} = 500$ GeV

| observables | derived quantities |
|-------------|-------------------|
| $m_\tilde{\tau}$ | 157.6 $\pm$ 0.2 GeV |
| $\tau_\tilde{\tau}$ | $(2.6 \pm 0.05) \times 10^6 \text{ s}$ |
| $m_\tilde{G}$ | $20 \pm 0.2$ GeV |
| $M_P$ | $(2.4 \pm 0.5) \times 10^{18}$ GeV |

It is a unique feature of gravitino LSP scenarios that the Planck scale can be directly measured in microscopic particle experiments by studying the properties of the NLSP and its decay. A further interesting test to reveal the nature of the gravitino as the supersymmetric partner of the graviton would be to determine the spin, which is possible by studying correlations in the radiative decays $\tilde{\tau} \rightarrow \tau G$ [7].

### 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 [8] is described by the conventional parameters $A = 40 \text{ TeV}$, $M_m = 80 \text{ TeV}$, $N_m = 3$, tan $\beta = 15$ and sign $\mu = +$. The sparticles are relatively light: $m_{\tilde{\chi}^0_1} = 123.4 \text{ GeV}$, $m_{\tilde{\chi}^+_1} = 130.9 \text{ GeV}$, $m_{\tilde{\ell}_L} = 262.8 \text{ GeV}$, $m_{\tilde{\chi}^0_1} = 163.7 \text{ GeV}$. The gravitino mass is set arbitrarily to $m_\tilde{G} = 0.1 \text{ GeV}$.

The SPS 7 model is investigated assuming $\sqrt{s} = 410 \text{ GeV}$ and $L = 100 \text{ fb}^{-1}$, with a large inclusive $\tilde{\tau}$ cross section of $\sigma(\tilde{\tau} \tilde{\tau} X) = 420 \text{ fb}$. As seen in the $\beta\gamma$ distribution of Fig. 3 a, most $\beta\gamma$ leave the detector. There is, however, a large signal at $\beta\gamma \approx 0.4$ from $\tilde{e}_R \tilde{e}_L$ production, contributing to samples of $N_{\text{hcal}}^{\text{eal}} = 10000$. 

![Graph](image.png)

**Fig. 2.** GDM $\epsilon$ scenario, assuming $L = 100 \text{ fb}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$: (a) $\tilde{\tau}$ production spectra of scaled momentum $p/m = \beta\gamma$ with contributions from various processes; (b) $\tilde{\tau}$ mass $m_\text{ToP}$ spectrum; (c) $\tilde{\tau}$ lifetime distribution; (d) $\tilde{\tau}$ jet energy spectrum of the decay $\tilde{\tau}_1 \rightarrow \tau \tilde{G}$, compared with simulations of $m_\tilde{G} = 20 \text{ GeV}$, 10 GeV and 30 GeV.
assumptions, respectively. More accurate gravitino mass of the upper edge of the observable τ measurement of very large τ the sensitivity to low gravitino masses decreases rapidly, which requires E/τ to be known with a precision well below. Notice that E/τ is the upper edge of the observable τ jet energy. A direct measurement of very large τ − G mass splittings becomes experimentally extremely difficult, getting gradually impossible for ratios m_G/m_{10} ≲ 0.1.

The nature of the LSP remains undetermined without knowing the gravitino mass. Further information can be gained from a study of radiative three-body decays τ → τγG. The differential decay rates and γ − τ correlations for a light spin 3/2 gravitino G to be compared with a spin 1/2 neutralino \( \tilde{\chi} \) [7] and a spin 1/2 axino \( \tilde{\alpha} \) [9] have been calculated and found to be quite different in particular phase space regions of back-to-back topologies. Experimentally the analysis of radiative τ decays is quite ambitious: the branching ratios are suppressed by two orders of magnitude and single γ’s have to be disentangled from the bulk of photons and hadrons in τ decays. The excellent performance of the proposed high granularity, ‘pictorial’ calorimeter [5] together with the large data samples expected at the ILC should make it possible to discriminate between a light gravitino, a neutralino and an axino LSP.

The analysis of \( \tilde{\tau}_1 \tilde{\tau}_1 \) pair production yields a mass of \( m_{\tilde{\tau}_1} = 124.3 \pm 0.1 \) GeV. From a fit to the decay time distribution, shown in Fig. 3b, one obtains a lifetime of \( \tau = 209.3 \pm 2.4 \) s. These values can be used to derive a very accurate gravitino mass of \( m_G = 100 \pm 1 \) MeV assuming a gravitational coupling. To illustrate the sensitivity to low gravitino masses as expected in many GMSB models: a gravitino mass of 0.5 MeV corresponds a τ lifetime of 5 ms, which should be easily measurable.

The τ jet recoil energy spectrum is displayed in Fig. 3c. 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 serve to set an upper limit of \( m_G < 9 \) GeV (at 95% CL).

This limitation can be understood from (2). The sensitivity to low gravitino masses decreases rapidly, e.g. for \( m_G = 0.1 m_\tau \) the energy deviates from \( m_\tau/2 \) by one percent, which requires \( E_\tau \) to be known with a precision well below. Notice that \( E_\tau \) is the maximum, the upper edge of the observable τ jet energy. A direct measurement of very large τ − G mass splittings becomes experimentally extremely difficult, getting gradually impossible for ratios \( m_G/m_\tau \lesssim 0.1 \).

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