

Long-lived charged sleptons at the ILC/CLIC

Jan Heisig

II. Institute for Theoretical Physics, University of Hamburg, Germany

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Supersymmetric scenarios with a very weakly interacting lightest superpartner (LSP)—like the gravitino or axino—naturally give rise to a long-lived next-to-LSP (NLSP). If the NLSP is a charged slepton it leaves a very distinct signature in a collider experiment. At the ILC/CLIC it will be possible to capture a significant fraction of the produced charged sleptons and observe their decays. These decays potentially reveal the nature of the LSP and thus provide a unique possibility to measure the properties of a very weakly interacting LSP which otherwise is most likely hidden from any other observation, like direct or indirect dark matter searches. We review the proposals that have been made to measure the LSP properties at the ILC/CLIC and compare its potential to the capability of the LHC.

1 Introduction

In supersymmetric extensions of the standard model (SM) with conserved R -parity the lightest superpartner (LSP) is stable and thus provides a natural dark matter (DM) candidate. The lightest neutralino—being part of the minimal supersymmetric standard model (MSSM)—is the most widely studied candidate. However, in extensions of the MSSM other cosmologically viable DM candidates appear such as the gravitino or the axino.

The spin-3/2 gravitino \tilde{G} arises in the spectrum of supergravity, i.e., once supersymmetry (SUSY) is promoted from a global to a local symmetry. It is a well motivated DM candidate and can even be regarded as favored since it alleviates the cosmological gravitino problem [1] allowing for a higher reheating temperature as required for thermal leptogenesis [2]. The gravitino acquires a mass through the super Higgs mechanism once SUSY is broken. Its mass depends strongly on the SUSY breaking scheme and can range from the eV scale to scales beyond the TeV scale. Requiring a reheating temperature of $\mathcal{O}(10^9 \text{ GeV})$, masses of around and above $\mathcal{O}(10 \text{ GeV})$ are favored in order not to over-close the universe by the thermally produced gravitino abundance. The very weak coupling of the gravitino causes the next-to-LSP (NLSP) to be long-lived. Thus, in the early universe after the NLSP freeze-out, late NLSP decays taking place during or after big bang nucleosynthesis (BBN) can affect the primordial abundance of light elements. This imposes strong constraints on the couplings and lifetime of the NLSP. Accordingly, a neutralino NLSP is strongly disfavored by BBN constraints from energy injection [3, 4, 5, 6]. The lighter stau $\tilde{\tau}_1$ is therefore often considered as a natural NLSP candidate.¹ The most severe bound on the stau NLSP lifetime arises from ${}^6\text{Li}/\text{H}$ constraints requiring $\tau_{\tilde{\tau}_1} \lesssim 5 \times 10^3 \text{ s}$ [8, 9] for a typical stau yield after freeze out. The most conservative bound arises from ${}^3\text{He}/\text{D}$ constraint. It excludes lifetimes $\tau_{\tilde{\tau}_1} \gtrsim 10^6 \text{ s}$ [10]. Conclusively, lifetimes ranging from seconds to a month may be considered as interesting.

The resulting signatures of staus at colliders are charged, muon-like tracks usually leaving the detector—the decay length is large compared to the size of a detector. The tracks of staus can be discriminated against the muon background via high ionization loss and anomalous time-of-flight. The LHC provides a good environment for discovering long-lived staus. Searches for heavy stable charged particles are being performed at ATLAS [11] and CMS [12].

Ionization loss is the main source of energy loss for heavy charged particles when penetrating the detector material. The energy loss increases with decreasing velocity β . Staus that are produced with sufficiently

¹The basic ideas given in this article are expected to hold with modifications for other charged NLSP candidates or even for very different lepton scenarios. Some of the ideas discussed in this article have initially been brought up in the context of 4th generation lepton searches [7].

small β may lose their kinetic energy completely and stop inside the detector. According to its lifetime, the stau will decay leaving a characteristic signature in the detector which is uncorrelated with the bunch crossing. If it is possible to measure the lifetime, the recoil energy and even the angular distribution of the emitted SM particles in the decay, it is possible to determine the coupling, mass and even the spin of the LSP. This is a unique possibility to test a (stable) gravitino DM scenario which is hopeless to test in direct and indirect DM searches.

Another well motivated DM candidate is the axino \tilde{a} which appears once the MSSM is extended by the Peccei-Quinn mechanism, in order to solve the strong CP problem. The phenomenology at a collider is virtually identical. The decay of the stau into the axino can give insights into the Peccei-Quinn sector.

We will consider both scenarios here. In section 2 we will describe the decays of the NLSP into the gravitino or axino LSP and explain how to distinguish these cases. In section 3 we will describe the implications from the LHC and its sensitivity to these scenarios. In section 4 we will review some of the experimental ideas that have been brought up in order to realize the investigation of NLSP decays.

2 NLSP decays

In the considered scenarios the dominant decay mode of the staus is the 2-body decay $\tilde{\tau} \rightarrow \tilde{G}\tau$ or $\tilde{\tau} \rightarrow \tilde{a}\tau$. For the gravitino LSP the corresponding decay width reads

$$\Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}_1}^5}{48\pi m_{\tilde{G}}^2 M_{\text{Pl}}^2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2}\right)^4, \quad (1)$$

where M_{Pl} is the (reduced) Planck mass. The decay rate is completely determined by the masses $m_{\tilde{\tau}_1}$ and $m_{\tilde{G}}$. It is independent of any other SUSY parameter or SM coupling.

For the axino LSP the 2-body decay is loop-induced and contains further SUSY parameters in particular it depends on the stau mixing angle. For a pure right-handed stau the width has been computed in the KSVZ axino model [13],

$$\Gamma(\tilde{\tau}_1 \rightarrow \tilde{a}\tau) \simeq \frac{9\alpha^4 C_{\text{aYY}}^2}{512\pi^5 \cos^8 \theta_W} \frac{m_{\tilde{B}}^2}{f_a^2} \frac{(m_{\tilde{\tau}_1}^2 - m_{\tilde{a}}^2)^2}{m_{\tilde{\tau}_1}^3} \xi^2 \log^2 \left(\frac{f_a}{m_{\tilde{\tau}_1}}\right), \quad (2)$$

where α is the fine structure constant, θ_W is the weak mixing angle, f_a is the Peccei-Quinn scale, $m_{\tilde{B}}$ is the (pure) bino mass and C_{aYY} and ξ are $\mathcal{O}(1)$ factors expressing the Peccei-Quinn model dependence and loop cut-off uncertainties, respectively.

The typical decay length of the staus is large compared to their traveling range in the detector material. Hence, staus always decay at rest, i.e., we know the center-of-mass frame. Accordingly, if the mass of the stau is known, the LSP mass can be determined from the recoil energy of the τ produced in the 2-body decay, E_τ ,

$$m_{\text{LSP}} = \sqrt{m_{\tilde{\tau}_1}^2 + m_\tau^2 - 2m_{\tilde{\tau}_1} E_\tau}. \quad (3)$$

As pointed out in [14, 15], we can probe the hypothesis of a gravitino LSP by computing the Planck mass from (1) once $m_{\tilde{\tau}_1}$, m_{LSP} and lifetime $\tau_{\tilde{\tau}_1} = \Gamma_{\tilde{\tau}_1}^{-1}$ are known. An agreement with the Planck mass measured in macroscopic experiments would provide a strong evidence for supergravity and the existence of the gravitino. Since the gravitino mass is directly related to the scale of spontaneous SUSY breaking,

$$\langle F \rangle = \sqrt{3} M_{\text{Pl}} m_{\tilde{G}}, \quad (4)$$

these measurements would provide us with insights in the SUSY breaking sector that are otherwise beyond the reach of any experiment in the near future. For the axino LSP case, from (2) we may be able to estimate the Peccei-Quinn scale and confront it with limits from astrophysical axion studies and axion searches in the laboratory.

A sub-dominant but nevertheless very important decay mode of the stau is the 3-body decay $\tilde{\tau} \rightarrow \tilde{G}\tau\gamma$ or $\tilde{\tau} \rightarrow \tilde{a}\tau\gamma$ which has been studied in [14, 13]. As pointed out in these references, from the 3-body decay

branching ratio as well as from the distribution of the angle between the τ and the photon, the spin of the LSP can be determined. More precisely, it has been shown that it is possible to distinguish between the spin-3/2 gravitino and a spin-1/2 axino. The observation of a spin-3/2 LSP would be an important confirmation of supergravity. In particular, for small gravitino masses $m_{\tilde{G}} \lesssim 0.1 m_{\tilde{\tau}_1}$ the determination of $m_{\tilde{G}}$ requires a very precise measurement of the tau recoil energy at below the percent level. Thus, (3) may only provide an upper limit on the gravitino mass in these cases. In such a situation a much better determination of $m_{\tilde{G}}$ can be achieved via (1) from the measurement of the stau lifetime once we are convinced that the LSP is indeed a gravitino by the measurement of its spin.

3 Implications from the LHC

Before the stau will be observed at the ILC/CLIC we expect its discovery at the LHC.² Therefore, in this section we will briefly review the LHC potential.

Long-lived staus leave a prominent signature in the detectors of the LHC. Combining ionization loss and time-of-flight measurements provide very clean signal regions and, at the same time, high efficiencies. Consequently, the discovery of long-lived staus typically can be claimed on the basis of a very few events and thus is expected to be established in a rather short time period without providing any hints in advance.

The direct production of staus provides a robust lower limit on the stau mass [16]. Null searches for this channel at the 7 TeV, 5 fb^{-1} LHC run [12] can be interpreted in the most conservative limit to exclude stau masses below 216 GeV [17]. Although the LHC provides a very good environment to discover heavy stable charged particles, it is typically difficult to capture a sufficiently large number of staus in the detector in order to be able to study its decays systematically. As shown in [18] especially widely spread spectra (spectra with large mass gaps between the colored sparticles and the stau) provide way too little stopped staus for the desired measurements (see figure 1). For such spectra even a scenario with $m_{\tilde{\tau}_1}$ just above the above quoted limit provides less than 100 events of staus that are stopped inside a LHC detector for the 14 TeV, 300 fb^{-1} LHC run. Proposals to study stopped staus at the LHC are discussed in [19, 20, 21, 22, 23, 24].

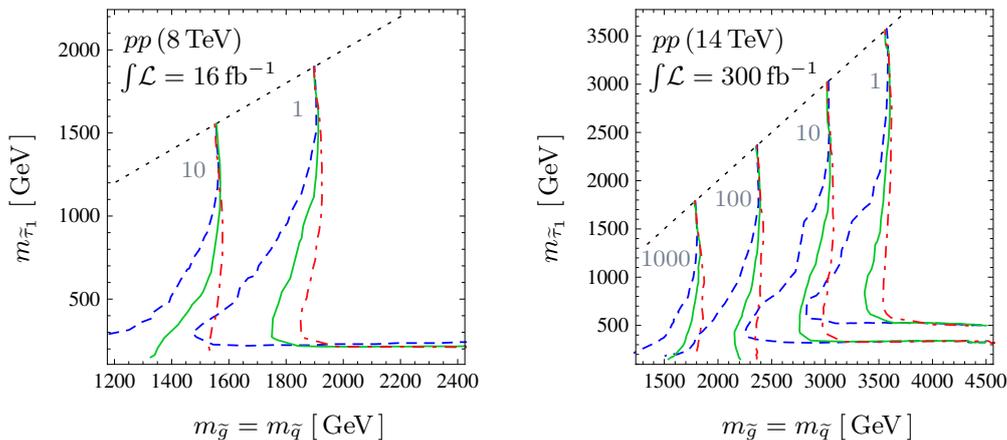


Figure 1: Expected number of events that contain staus that are stopped inside an LHC detector. The results are expressed in a simplified model framework considering direct stau production as well as the production via the decay of strongly produced sparticles. A common squark and gluino mass, $m_{\tilde{q}} = m_{\tilde{g}}$, has been chosen. The three different line styles refer to three different mass patterns of intermediate sparticles in the decay chain. Taken from [18].

²In the long-lived stau scenario there are very little regions in parameter space that are not accessible with the long-term 14 TeV LHC run but with a mid-term 3 TeV CLIC run.

4 Prospects at the ILC/CLIC

The challenge in the study of stau decays is to trap as many staus as possible in a well defined volume that is sensitive to the observables of the produced SM particles in the decay. An e^+e^- -collider provides an appropriate environment for this task. On the one hand the direct production of staus provides a velocity distribution that can be tuned through the center-of-mass energy in order to maximize the number of stopped staus in a given volume. On the other hand it provides a well defined angular distribution. Together with the option of adding extra stopping material in appropriate regions [23] it provides an ideal framework to obtain a large number of observed stau decays.

The stau may be produced directly or in a decay chain following the production of other sparticles. The cross sections for different production processes have different velocity dependencies near threshold. For slepton production via s -channel γ/Z the cross section increases as β^3 . For polarized e^+e^- beams the production cross section for selectron pairs via t -channel $\tilde{\chi}^0$ exchange ($e_L^+e_L^- \rightarrow \tilde{e}_R^+\tilde{e}_L^-$ or $e_R^+e_R^- \rightarrow \tilde{e}_L^+\tilde{e}_R^-$) increases linear in β and thus provides an enhanced number of selectrons close to threshold [25, 26].³ Hence, if the spectrum features a selectron which is close in mass to the stau, one could greatly benefit from the use of polarized electron beams to increase the number of produced selectrons near threshold and therefore increase the number of stopped staus. For small mass gaps between the selectron and the stau this advantage overcompensates the boost that staus achieve from the decay of the selectron (which would lead to higher stau velocities).

Once a stau pair is produced it will be identified via highly ionizing tracks. Their passage through the detector can be accurately followed. If the stau stops inside the detector the location of the stopped stau is expected to be determinable within a volume of a few cm^3 [29]. The location and time of the stopped stau may be recorded. In general the stau will decay out-of-time with the beam collisions. Hence, the decay can then be triggered by an isolated, out-of-time hadronic or electromagnetic cluster in the hadronic calorimeter (HCAL), a hadronic shower in the iron yoke or by a muon originating in the HCAL or yoke above an appropriate energy threshold ($E > 10 \text{ GeV}$) [29]. Background from cosmic rays may be rejected by a veto against vertices in the outermost detector layers. Background from atmospheric neutrinos is expected to be sufficiently rejected by the required energy threshold and furthermore by the requirement of a matching of the recorded stopping positions [23]. A precise measurement of the stau mass which is required in order to estimate the gravitino mass can be obtained from the reconstruction of the complete event kinematics.

The potential to measure $m_{\tilde{\tau}_1}$, $m_{\tilde{G}}$ and $\tau_{\tilde{\tau}_1}$ at the ILC/CLIC equipped with a general purpose detector [30, 31] has been studied for several benchmark points in [29, 32]. Both studies contain the mSUGRA points GDM ζ ($m_{\tilde{\tau}_1} = 346 \text{ GeV}$, $m_{\tilde{G}} = 100 \text{ GeV}$) and GDM η ($m_{\tilde{\tau}_1} = 327 \text{ GeV}$, $m_{\tilde{G}} = 20 \text{ GeV}$) [24]. Provided a fixed center-of-mass energy of 800 GeV and a luminosity of 1000 fb^{-1} , $m_{\tilde{\tau}_1}$ and $\tau_{\tilde{\tau}_1}$ have been found to be measurable at the level of one per mille and a few per cent, respectively, for both scenarios. The gravitino mass $m_{\tilde{G}}$ has been found to be measurable at a ten per cent level for GDM ζ and with an uncertainty comparable to its actual value for GDM η [29]. These numbers have been obtained with unpolarized beams. Polarization is expected to enhance the number of stopped staus by a factor of almost three [29] and thus improve these results. The optimization of the beam energy for given stau masses and production processes has been discussed in [32].

Further optimizations can be achieved by placing additional active stopper material [23] around the general purpose detector. Another approach is the installation of water tanks [22] that accumulate stopped staus. The water can then be transported to a quiet environment in order to study the decays. It has also been proposed to collect staus in a storage ring [14]. This could most easily be done if staus were produced preferably in the forward region, i.e., via selectron pair production (see figure 11 in [32]).

The feasibility of studying 3-body decays and distinguishing gravitinos from axinos has been discussed in [13]. The distribution of stau decay events in the two variables θ , the opening angle between the photon and the tau, and $x_\gamma \equiv 2E_\gamma/m_{\tilde{\tau}_1}$ is shown in figure 2. For the gravitino the events are peaked only in the region of soft and collinear photon emission whereas for the axino a second peak shows up characterized by a back-to-back tau-photon emission and large photon energies. For a total number of 10^4 analyzed stau decays in the scenario considered in [13] it has been found that 110 ± 10 (stat.) and 165 ± 13 (stat.) 3-body decays will be observed in the gravitino and axino LSP scenario, respectively, 1% and 28% of which are expected

³In [27, 28] the possibility of an e^-e^- -collider to obtain a $\propto\beta$ -behavior near threshold has been discussed.

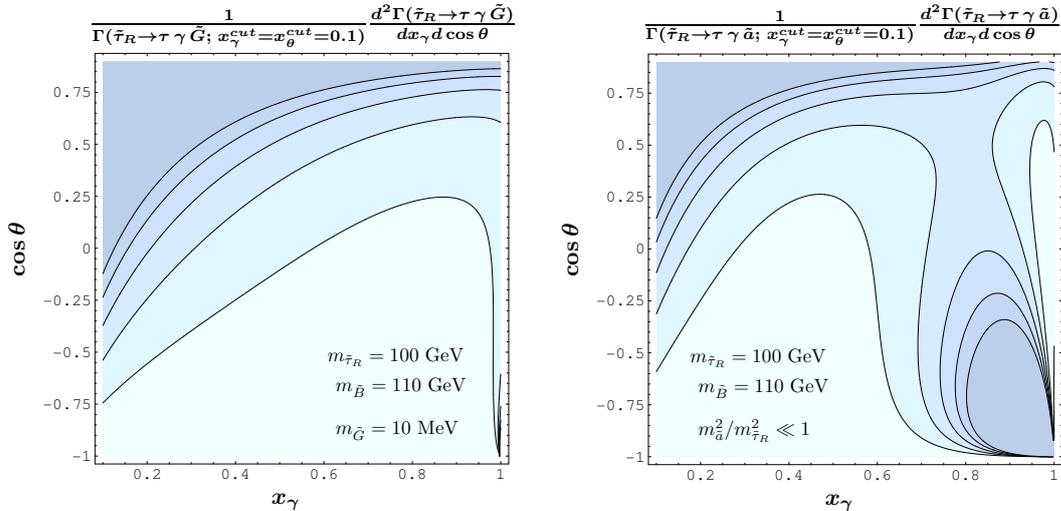


Figure 2: The normalized differential distributions of the visible decay products in the decays $\tilde{\tau} \rightarrow \tau\gamma\tilde{G}$ for the gravitino LSP scenario (left) and $\tilde{\tau} \rightarrow \tau\gamma\tilde{a}$ for the axino LSP scenario (right) for $m_{\tilde{\tau}_R} = 100$ GeV, $m_{\tilde{B}} = 110$ GeV, $m_{\tilde{a}}^2/m_{\tilde{\tau}_1}^2 \ll 1$, and $m_{\tilde{G}} = 10$ MeV. The contour lines represent the values 0.2, 0.4, 0.6, 0.8, and 1.0, where the darker shading implies a higher number of events. Taken from [13].

to be selected by imposing appropriate cuts in the x_γ - $\cos\theta$ -plane. These numbers illustrate that $\mathcal{O}(10^4)$ of analyzed stau decays could be sufficient for a significant distinction of those scenarios.

5 Conclusions

Supersymmetric scenarios with a very weakly interacting LSP are well motivated from cosmology. The very weak coupling naturally gives rise to a long-lived NLSP which is considered to be the lighter stau here. These particles usually pass the detector and can be directly detected. If these particles will be discovered at the LHC, the ILC/CLIC provides the unique environment to study the decays of the stau in detail. Reconstructed 2-body decays will allow for a measurement of the scale of supersymmetry breaking $\langle F \rangle$ (in the case of a gravitino LSP) or the Peccei-Quinn scale (in the case of an axino LSP). From 3-body decays it is even possible to measure the spin of the LSP. For a gravitino LSP this leads to the attractive possibility to test the supergravity paradigm. Additionally, the measurement of the life-time from 2-body decays provides direct access to the gravitational coupling. Hence, two independent unequivocal predictions of supergravity can be probed.

References

- [1] J. R. Ellis, D. V. Nanopoulos, and S. Sarkar, “The Cosmology of Decaying Gravitinos”, *Nucl. Phys.* **B259** (1985) 175.
- [2] M. Bolz, W. Buchmüller, and M. Plümacher, “Baryon asymmetry and dark matter”, *Phys. Lett.* **B443** (1998) 209–213, [arXiv:hep-ph/9809381](#).
- [3] J. L. Feng, S. Su, and F. Takayama, “Supergravity with a gravitino LSP”, *Phys. Rev.* **D70** (2004) 075019, [arXiv:hep-ph/0404231](#) [[hep-ph](#)].
- [4] L. Roszkowski, R. Ruiz de Austri, and K.-Y. Choi, “Gravitino dark matter in the CMSSM and implications for leptogenesis and the LHC”, *JHEP* **0508** (2005) 080, [arXiv:hep-ph/0408227](#) [[hep-ph](#)].

- [5] D. G. Cerdeno, K.-Y. Choi, K. Jedamzik, L. Roszkowski, and R. Ruiz de Austri, “Gravitino dark matter in the CMSSM with improved constraints from BBN”, *JCAP* **0606** (2006) 005, [arXiv:hep-ph/0509275](#) [[hep-ph](#)].
- [6] R. H. Cyburt, J. R. Ellis, B. D. Fields, K. A. Olive, and V. C. Spanos, “Bound-State Effects on Light-Element Abundances in Gravitino Dark Matter Scenarios”, *JCAP* **0611** (2006) 014, [arXiv:astro-ph/0608562](#) [[astro-ph](#)].
- [7] J. Goity, W. Kossler, and M. Sher, “Production, collection and utilization of very longlived heavy charged leptons”, *Phys. Rev.* **D48** (1993) 5437–5439, [arXiv:hep-ph/9305244](#) [[hep-ph](#)].
- [8] M. Pospelov, “Particle physics catalysis of thermal Big Bang Nucleosynthesis”, *Phys. Rev. Lett.* **98** (2007) 231301, [arXiv:hep-ph/0605215](#).
- [9] J. Pradler and F. D. Steffen, “Implications of catalyzed BBN in the CMSSM with gravitino dark matter”, *Phys. Lett.* **B666** (2008) 181–184, [arXiv:0710.2213](#) [[hep-ph](#)].
- [10] J. Pradler and F. D. Steffen, “CBBN in the CMSSM”, *Eur.Phys.J.* **C56** (2008) 287–291, [arXiv:0710.4548](#) [[hep-ph](#)].
- [11] ATLAS Collaboration, G. Aad *et al.*, “Search for heavy long-lived charged particles with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV”, *Phys. Lett.* **B703** (2011) 428–446, [arXiv:1106.4495](#) [[hep-ex](#)].
- [12] CMS Collaboration, S. Chatrchyan *et al.*, “Search for heavy long-lived charged particles in pp collisions at $\sqrt{s}=7$ TeV”, [arXiv:1205.0272](#) [[hep-ex](#)]. Submitted to *Physics Letters B*.
- [13] A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski, and F. D. Steffen, “Signatures of axinos and gravitinos at colliders”, *Phys. Lett.* **B617** (2005) 99–111, [arXiv:hep-ph/0501287](#).
- [14] W. Buchmüller, K. Hamaguchi, M. Ratz, and T. Yanagida, “Supergravity at colliders”, *Phys. Lett.* **B588** (2004) 90–98, [arXiv:hep-ph/0402179](#).
- [15] J. L. Feng, A. Rajaraman, and F. Takayama, “Probing gravitational interactions of elementary particles”, *Int. J. Mod. Phys.* **D13** (2004) 2355–2359, [arXiv:hep-th/0405248](#).
- [16] J. Heisig and J. Kersten, “Production of long-lived staus in the Drell-Yan process”, *Phys. Rev.* **D84** (2011) 115009, [arXiv:1106.0764](#) [[hep-ph](#)].
- [17] J. Heisig, “Long-lived staus at the LHC”, in *Proceedings of the XLVIIIth Rencontres de Moriond*. 2012. [arXiv:1207.3058](#) [[hep-ph](#)].
- [18] J. Heisig and J. Kersten, “Long-lived staus from strong production in a simplified model approach”, [arXiv:1203.1581](#) [[hep-ph](#)].
- [19] K. Hamaguchi, M. M. Nojiri, and A. de Roeck, “Prospects to study a long-lived charged next lightest supersymmetric particle at the LHC”, *JHEP* **0703** (2007) 046, [arXiv:hep-ph/0612060](#) [[hep-ph](#)].
- [20] J. Pinfold and L. Sibley, “Measuring the Lifetime of Trapped Sleptons Using the General Purpose LHC Detectors”, *Phys. Rev.* **D83** (2011) 035021, [arXiv:1006.3293](#) [[hep-ph](#)].
- [21] P. W. Graham, K. Howe, S. Rajendran, and D. Stolarski, “New Measurements with Stopped Particles at the LHC”, [arXiv:1111.4176](#) [[hep-ph](#)].
- [22] J. L. Feng and B. T. Smith, “Slepton trapping at the large hadron and international linear colliders”, *Phys. Rev.* **D71** (2005) 015004, [arXiv:hep-ph/0409278](#).
- [23] K. Hamaguchi, Y. Kuno, T. Nakaya, and M. M. Nojiri, “A Study of late decaying charged particles at future colliders”, *Phys. Rev.* **D70** (2004) 115007, [arXiv:hep-ph/0409248](#).

- [24] A. De Roeck, J. R. Ellis, F. Gianotti, F. Moortgat, K. Olive, *et al.*, “Supersymmetric benchmarks with non-universal scalar masses or gravitino dark matter”, *Eur. Phys. J.* **C49** (2007) 1041–1066, [arXiv:hep-ph/0508198](#) [hep-ph].
- [25] A. Freitas, . Miller, D.J., and P. Zerwas, “Pair production of smuons and selectrons near threshold in $e^+ e^-$ and $e^- e^-$ collisions”, *Eur. Phys. J.* **C21** (2001) 361–368, [arXiv:hep-ph/0106198](#) [hep-ph].
- [26] A. Freitas, A. von Manteuffel, and P. Zerwas, “Slepton production at $e^+ e^-$ and $e^- e^-$ linear colliders”, *Eur. Phys. J.* **C34** (2004) 487–512, [arXiv:hep-ph/0310182](#) [hep-ph].
- [27] J. L. Feng, “Supersymmetry at linear colliders: The Importance of being $e^- e^-$ ”, *Int. J. Mod. Phys.* **A13** (1998) 2319–2328, [arXiv:hep-ph/9803319](#) [hep-ph].
- [28] J. L. Feng and M. E. Peskin, “Selectron studies at $e^- e^-$ and $e^+ e^-$ colliders”, *Phys. Rev.* **D64** (2001) 115002, [arXiv:hep-ph/0105100](#) [hep-ph].
- [29] H.-U. Martyn, “Detecting metastable staus and gravitinos at the ILC”, *Eur. Phys. J.* **C48** (2006) 15–24, [arXiv:hep-ph/0605257](#).
- [30] L. Linssen, A. Miyamoto, M. Stanitzki, and H. Weerts, “Physics and Detectors at CLIC: CLIC Conceptual Design Report”, [arXiv:1202.5940](#) [physics.ins-det].
- [31] ILC Collaboration, E. Brau, James *et al.*, “ILC Reference Design Report: ILC Global Design Effort and World Wide Study”, [arXiv:0712.1950](#) [physics.acc-ph].
- [32] O. Çakır, İ. T. Çakır, J. R. Ellis, and Z. Kırca, “Study of Metastable Staus at Linear Colliders”, [arXiv:hep-ph/0703121](#).