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Long-lived staus at future colliders

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Summary. — We review the prospects to produce and identify long-lived staus at a future e^+e^- or e^-e^- collider and discuss some interesting studies which could be performed. We also review the possibility of stopping and collecting long-lived staus.

PACS 12.60.Jv – Supersymmetric models.
PACS 14.80.Ly – Supersymmetric partners of known particles.
PACS 13.66.Hk – Production of non-standard model particles in e^-e^+ interactions.

1. – Introduction

Supersymmetric (SUSY) models predict the existence of many new particles with a hitherto unknown mass spectrum. In the most studied supersymmetric scenario, the Lightest Supersymmetric Particle (LSP) is the lightest neutralino. Being the neutralino a weakly interacting massive particle (WIMP), thermal scatterings in the early Universe could have generated a relic population of neutralinos with the correct abundance to account for the dark matter of the Universe. Nevertheless, this is not the only SUSY scenario: the LSP could also be a superweakly interacting massive particle (superWIMP), such as the gravitino, the axino or a hidden $U(1)$ gaugino. The gravitino is the superpartner of the graviton in supergravity scenarios and has interactions with ordinary matter suppressed by a plausibly large SUSY breaking scale. On the other hand, the axino is the superpartner of the axion in scenarios implementing the Peccei-Quinn solution to the strong CP problem and has interactions suppressed by the Peccei-Quinn scale. Lastly, the hidden $U(1)$ gaugino is the superpartner of a hidden $U(1)$ gauge boson which communicates to the observable sector via kinetic mixing with the $U(1)$ of hypercharge, and has interactions suppressed by the small kinetic mixing parameter. As in the case of neutralino LSP, in these three scenarios a population of superWIMP LSPs could have been produced in the early Universe in sufficiently large amounts to account for the cold dark matter of the Universe [1-3].

Scenarios with superWIMP LSP share one common feature: if R-parity is conserved, the next-to-LSP (NLSP) is very long-lived, since it can only decay into Standard Model particles and the superWIMP LSP via a highly suppressed interaction. In scenarios with superWIMP LSP and neutralino NLSP the collider signatures are essentially identical to the extensively studied case with WIMP LSP, since the long-lived neutralino NLSP just escapes the detector. However, in a large class of scenarios with superWIMP LSP, the NLSP is a (mostly right-handed) stau. In these scenarios the long-lived staus produce long charged tracks as they propagate through the detector, yielding collider signatures which are qualitatively different from the extensively discussed WIMP LSP scenario.

In sect. **2** we will review the production of long-lived staus at a future e^+e^- or e^-e^- linear collider and the prospects to identify the staus, as well as some of the physics studies which could be performed in this class of scenarios. In sect. **3** we will discuss the possibility of stopping and collecting long-lived staus and lastly, in sect. **4** we will present some conclusions.

2. – Production and detection of long-lived staus at the Linear Collider

Staus could be copiously produced at a future e^-e^- or e^+e^- linear collider. In the e^-e^- mode, selectrons are produced by t-channel neutralino exchange and eventually decay into leptons and staus: $\tilde{e}_R^- \to e^-\,\tau^\pm\tilde{\tau}_1^\mp$, $\tilde{e}_L^- \to e^-\,\tau^\pm\tilde{\tau}_1^\mp$, $\tilde{e}_L^- \to \nu_e\,\bar{\nu}_\tau\tilde{\tau}_1^-$. For typical SUSY parameters the production cross-section is $\mathcal{O}(100)$ fb for $\sqrt{s} = 500\,\mathrm{GeV}$ [4]. In the e^+e^- mode, selectrons could be produced via the t-channel neutralino exchange and via s-channel Z-boson exchange. In this case, the cross-section is again $\mathcal{O}(100)$ fb, although smaller than in the e^-e^- mode due to the destructive interference of these two diagrams [4]. Moreover, there could be direct production of staus in the s-channel, with a cross-section $\mathcal{O}(10)$ fb.

After being produced, the staus propagate through the detector leaving a charged track in the tracking chamber with little calorimeter activity. The signature could be easily confused with a muon track except for: i) The larger mass, which allows to distinguish a stau from a muon by using appropriate kinematical cuts. ii) The lower speed, which could be measured with a good Time-of-Flight (ToF) device. iii) The energy loss, which occurs mostly by ionization (in contrast to muons which lose energy mostly by radiation) and which could be measured by a good Time Projection Chamber (TPC). In a future linear collider, the combination of the three techniques to discriminate staus from muons will allow an efficiency in the identification of staus larger than $\sim 80\%$ for stau masses in the range 100–300 GeV [5].

The very good prospects to produce and identify long-lived staus at a future linear collider opens the door to many interesting physics studies. One of them is sparticle mass measurements. Let us assume, for definiteness, a SUSY mass spectrum as in the ϵ benchmark point defined in [6], where the LSP is the gravitino while the NLSP is a (mostly right-handed) stau. Concretely, the masses of the lightest SUSY particles are: $m_{3/2} = 20\,\mathrm{GeV}$, $m_{\tilde{\tau}_1} = 157.6\,\mathrm{GeV}$, $m_{\tilde{\chi}_1} = 179.6\,\mathrm{GeV}$, $m_{\tilde{e}_R} = 175.1\,\mathrm{GeV}$, etc. With this mass spectrum, the lifetime of the lightest stau is 2.5×10^6 s. A detailed simulation of the TESLA detector [7] in a future e^+e^- linear collider with $\sqrt{s} = 500\,\mathrm{GeV}$ and an integrated luminosity $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ shows that the mean value stau momentum can be determined with high accuracy $\langle p_{\tilde{\tau}_1}\rangle = 192.4 \pm 0.2\,\mathrm{GeV}$, leading to a very precise stau mass measurement $m_{\tilde{\tau}_1} = 157.6 \pm 0.2\,\mathrm{GeV}$ [8].

Another interesting study in scenarios with long-lived staus is the search for lepton flavour violation [9]. In the e^-e^- collider, if lepton flavour is conserved only the process

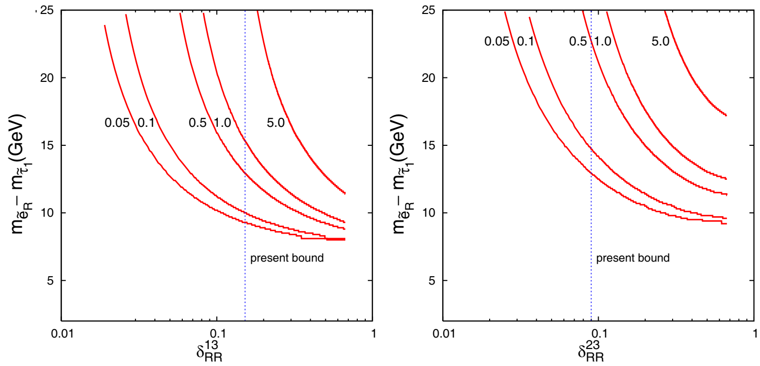

Fig. 1. – Contours of constant cross-section for the lepton flavour violating processes $e^-e^- \to \tilde{e}^-_R\tilde{\tau}^-_1 \to (e^-\tau^\pm\tilde{\tau}^\mp_1)\tilde{\tau}^-_1$ (left panel) and $e^-e^- \to \tilde{e}^-_R\tilde{e}^-_R \to (e^-\mu^\pm\tilde{\tau}^\mp_1)(e^-\tau^\pm\tilde{\tau}^\mp_1)$ (right-panel) in fb with $\sqrt{s} = 500\,\text{GeV}$. Both e^- beams are unpolarized. We also show the present experimental upper bound on δ^{13}_{RR} and δ^{23}_{RR} stemming from the non-observation of flavour violating tau decays. The remaining parameters are chosen as in the ϵ benchmark point (see text for details).

$e^-e^- \to \tilde{e}^-\tilde{e}^-$ can take place, with the selectrons eventually decaying into staus and leptons. For instance,

$$e^-e^- \to \tilde{e}^-_R\tilde{e}^-_R \to (e^-\tau^\pm\tilde{\tau}^\mp_1)(e^-\tau^\pm\tilde{\tau}^\mp_1). \tag{1}$$

Thus, in the final state there are two long-lived staus and four charged leptons. On the other hand, if lepton flavour is violated in the $\tilde{e}_R - \tilde{\tau}_R$ sector, direct production of one stau could also occur,

$$e^-e^- \to \tilde{e}^-\tilde{\tau}^-_1 \to (e^-\tau^\pm\tilde{\tau}^\mp_1)\tilde{\tau}^-_1 \quad \text{if} \quad \delta^{13}_{RR} \neq 0, \tag{2}$$

yielding in the final state two staus and two leptons. The difference in the number of particles in the final state could be used to search for lepton flavour violation in the slepton sector. This procedure would be straightforward if all the leptons in the final state could be detected. However, the production of a left-handed selectron and its subsequent decay into invisible neutrinos, $e^-e^- \to \tilde{e}^-\tilde{e}^- \to (e^-\tau^\pm\tilde{\tau}^\mp_1)(\nu_e\bar{\nu}_\tau\tilde{\tau}^-_1)$, yields a very similar signature in the detector. Noting that in the signal event all the particles can in principle be detected, most of this background could be eliminated by imposing $\not{p}_T < 5\,\text{GeV}$.

To illustrate the discovery potential of lepton flavour violation in scenarios with long-lived staus at a future linear collider we show in fig. 1 contour plots of constant cross-section for a variant of the ϵ benchmark point of [6], leaving the mass of the long-lived stau as a free parameter between 144 GeV and 167 GeV. After imposing standard cuts we find that a future e^-e^- linear collider with $\sqrt{s} = 500\,\text{GeV}$ and an integrated luminosity $\mathcal{L} = 500\,\text{fb}^{-1}$ could be sensitive to lepton flavour violation in the $\tilde{e}_R - \tilde{\tau}_R$ sector down to the level $\delta^{13}_{RR} \sim 0.02$ when the SUSY spectrum is as in the ϵ benchmark point. The sensitivity improves when the mass splitting increases, whereas for smaller mass splittings the outgoing charged leptons are too soft and the cross-section is significantly reduced. This sensitivity is better, for the same benchmark point, than the present sensitivity of experiments searching for the rare decay $\tau \to e\gamma$, $\delta^{13}_{RR} \leq 0.15$ (corresponding to BR($\tau \to e\gamma$) $\leq 1.2 \times 10^{-7}$ [10]) and comparable to the projected sensitivity of the projected super B factory, $\delta^{13}_{RR} \sim 0.01$ (corresponding to BR($\tau \to e\gamma$) $\sim 10^{-9}$ [11]).

The search for lepton flavour violation in the $\tilde{e}_R - \tilde{\mu}_R$ or the $\tilde{\mu}_R - \tilde{\tau}_R$ sectors follows from the flavour identification of the particles in the final state. If lepton flavour is violated in the $\tilde{e}_R - \tilde{\mu}_R$ or $\tilde{\mu}_R - \tilde{\tau}_R$ sectors, the following processes could be observed:

$$e^- e^- \to \tilde{e}^-_R \tilde{e}^-_R \to \left(\mu^- \tau^\pm \tilde{\tau}^\mp_1\right)\left(e^- \tau^\pm \tilde{\tau}^\mp_1\right) \quad \text{if} \quad \delta^{12}_{RR} \neq 0, \tag{3}$$

$$e^- e^- \to \tilde{e}^-_R \tilde{e}^-_R \to \left(e^- \mu^\pm \tilde{\tau}^\mp_1\right)\left(e^- \tau^\pm \tilde{\tau}^\mp_1\right) \quad \text{if} \quad \delta^{23}_{RR} \neq 0, \tag{4}$$

with different charged leptons compared to the lepton flavour conserving process eq. (1). A linear collider with $\sqrt{s} = 500\,\text{GeV}$ and an integrated luminosity $\mathcal{L} = 500\,\text{fb}^{-1}$ could discover, for the ϵ benchmark point, lepton flavour violation down to the level $\delta^{12}_{RR} \sim 0.04$, $\delta^{23}_{RR} \sim 0.03$. For this benchmark point, the sensitivity to lepton flavour violation in the $\tilde{\mu}_R - \tilde{\tau}_R$ sector is slightly better than the present sensitivity from the rare decay $\tau \to \mu\gamma$, $\delta^{23}_{RR} \leq 0.09$, corresponding to BR($\tau \to \mu\gamma$) $\leq 4.5 \times 10^{-8}$ [12]. However, for the $\tilde{e}_R - \tilde{\mu}_R$ sector the sensitivity is much worse than from the decay $\mu \to e\gamma$, $\delta^{12}_{RR} \leq 6 \times 10^{-4}$, corresponding to BR($\mu \to e\gamma$) $\leq 1.2 \times 10^{-11}$ [13]. The prospects for detecting lepton flavour violation at the e^+e^- linear collider are slightly worst due to the smaller selectron production cross-section.

3. – Trapping of long-lived staus

Long-lived staus lose energy as they propagate in the hadronic calorimeter and the iron yoke of the detector. Thus, if they are produced with low enough velocity, they could be trapped in the detector or its surroundings. Concretely, for a linear collider with $\sqrt{s} = 500\,\text{GeV}$ and $\mathcal{L} = 100\,\text{fb}^{-1}$ it could be possible to trap, for the ϵ benchmark point, around 4100 staus in the hadronic calorimeter and around 1850 staus in the iron yoke [8], allowing several interesting measurements. The number of staus trapped could be further enhanced surrounding the detectors by water [14] or by iron [15], allowing to capture $\mathcal{O}(10^3$–$10^5)$ staus. If the stopper material simultaneously serves as an active real-time detector, the decay products and their distributions could be studied in further detail [15].

One interesting possibility is the determination of the Planck mass in a Particle Physics experiment [16]. In a SUGRA model the stau lifetime reads

$$t^{-1}_{\tilde{\tau}} = \Gamma_{\tilde{\tau} \to \tau \psi_{3/2}} = \frac{1}{48\pi M_P^2} \frac{m^5_{\tilde{\tau}}}{m^2_{3/2}} \left(1 - \frac{m^2_{3/2}}{m^2_{\tilde{\tau}}}\right)^4, \tag{5}$$

where $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. Therefore,

$$M_P = \sqrt{\frac{t_{\tilde{\tau}} m_{\tilde{\tau}}}{48\pi} \frac{m^2_{\tilde{\tau}}}{m_{3/2}}} \left(1 - \frac{m^2_{3/2}}{m^2_{\tilde{\tau}}}\right)^2. \tag{6}$$

Thus, the measurement of the stau mass, the stau lifetime and the gravitino mass in principle allows the determination of Planck mass. More concretely, for SUSY parameters as in the ϵ benchmark point, in a e^+e^- collider with $\sqrt{s} = 500\,\text{GeV}$ and $\mathcal{L} = 100\,\text{fb}^{-1}$, the stau mass can be measured at the per mil level, $m_{\tilde{\tau}} = 157.6 \pm 0.2\,\text{GeV}$, the stau lifetime at the percent level, $t_{\tilde{\tau}} = (2.6 \pm 0.05) \times 10^6$ s and the gravitino mass at the 10% level, from the τ recoil energy in the stau decay $\tilde{\tau} \to \tau\psi_{3/2}$, $m_{3/2} = 20 \pm 4$ GeV. These three measurements lead to a fairly accurate *microscopic* determination of the Planck mass $M_P = (2.4 \pm 0.4) \times 10^{18}$ GeV. It has been noted, though, that such long-lived staus jeopardize the successful predictions of the standard Big Bang nucleosynthesis scenario [17]. Consistency with primordial nucleosynthesis typically requires a stau lifetime shorter than 5×10^3 s, which translates into a gravitino mass smaller than 0.8 GeV for $m_{\tilde{\tau}} = 150$ GeV. If this is the case, the gravitino mass is too small to be measured through the τ recoil energy. Interestingly, the scale of SUSY breaking $F = \sqrt{3} m_{3/2} M_P$ could still be determined from $F = \left(\frac{t_{\tilde{\tau}} m_{\tilde{\tau}}^5}{16\pi}\right)^{1/2}$ which only requires the measurement of the stau mass and the stau lifetime.

In the case that the LSP is the axino, a similar argument allows to determine experimentally the Peccei-Quinn scale from the measurement of the stau lifetime, the stau mass and the bino mass [18]. Lastly, if the LSP is a hidden $U(1)$ gaugino, the measurement of the stau lifetime and the stau mass allows the determination of the kinetic mixing parameter [3]. Furthermore, the search for the three-body decay $\tilde{\tau} \to \tau + \gamma + \not{p}_T$ may allow the determination of the spin of the invisible particle from the analysis of the angular and energy distributions of photons [16, 18].

Trapping staus also opens the possibility of searching for lepton flavour violation [19]. If lepton flavour is conserved, the stau can only decay into a tau and missing energy (gravitinos, axinos or hidden gauginos). However, if lepton flavour is violated in Nature, the stau could also decay into an electron or a muon. Thus, the observation of electrons and muons springing from a point of the detector and moving in a non-radial direction will constitute a strong indication for lepton flavour violation. More concretely, if 3×10^3 (3×10^4) staus could be collected, it could be possible to probe mixing angles in the $\tilde{e}_R - \tilde{\tau}_R$ sector down to the level $\sim 3 \times 10^{-2}$ (9×10^{-3}) [19], which is better than the present sensitivity of experiments searching for $\tau \to e\gamma$.

4. – R-parity violation

In most analyses of the Minimal Supersymmetric Standard Model it is implicitly assumed that R-parity is conserved. However, the general MSSM (without imposing R-parity conservation) is viable as long as the R-parity breaking parameters are small enough to satisfy all the experimental constraints. If R-parity is not imposed, the neutralino LSP typically decays too fast to constitute a good dark matter candidate. Nevertheless, it is interesting that even when R-parity is not imposed, superWIMP LPSs, such as the gravitino, the axino or the hidden $U(1)$ gaugino, can be long-lived enough to constitute the dark matter or the Universe, due to the double suppression of the decay rate by the small coupling with the ordinary matter and by the small R-parity violation [20].

This class of scenarios is very interesting from the cosmological point of view. Indeed, a scenario with gravitinos as dark matter particles and a small amount of R-parity violation is a simple and viable SUSY scenario that incorporates SUSY dark matter, primordial nucleosynthesis and baryogenesis through thermal leptogenesis [21]. In this scenario, the gravitino eventually decays into Standard Model particles, opening the exciting possibility of the indirect detection of dark matter gravitinos through an excess in the cosmic ray fluxes of gamma-rays or electrons/positrons [21, 22].

In scenarios where R-parity is not conserved, the stau NLSP usually does not decay into a charged lepton and a superWIMP (gravitino, axino or hidden $U(1)$ gaugino) but into Standard Model particles. The main decay channel is $\tilde{\tau}_1 \to \tau\nu_\mu,\ \mu\nu_\tau$ through the R-parity violating coupling in the superpotential $\lambda_{ijk} L_i L_j e^c_k$. The decay length is

$$c\tau^{\text{lep}}_{\tilde{\tau}} \sim 30\,\text{cm} \left(\frac{m_{\tilde{\tau}}}{200\,\text{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}, \tag{7}$$

which has been normalized to $\lambda_{323} = 10^{-8}$, which yields a gravitino lifetime of the order of 10^{26} s, as required by the decaying dark matter interpretation [23] of the positron excess observed by the PAMELA Collaboration [24]. If this scenario is realized in Nature, future colliders will observe a very peculiar signature consisting of a long heavily ionizing charged track followed by a muon track or a tau jet with identical probabilities [21].

5. – Conclusions

We have reviewed some supersymmetric scenarios where long-lived staus naturally arise and we have discussed the prospects to produce long-lived staus at a future linear collider. We have also discussed the prospects to discriminate long-lived staus from muons in the detector and some interesting measurements which can be performed in such scenarios, namely the determination of the stau mass, the search for lepton flavour violation and the determination of the small coupling between the stau, the tau and the LSP.

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