

Right-Chiral Sneutrino LSP in mSUGRA: Event characteristics of NLSP at the LHC

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Abstract. We study a supersymmetric scenario where the lighter tau-sneutrino is the lightest supersymmetric particle, while the lighter stau-state is the next lightest. Such a scenario can be motivated within the framework of minimal supergravity, with just the addition of a right-chiral neutrino superfield. Such a spectrum leads to rather unusual signals of supersymmetry, showing stable tracks of the stau in the muon chambers. We study the event characteristics of the long-lived staus at the LHC and demonstrate that the stau tracks can be distinguished from the muonic ones through proper kinematic cuts which also enable one to remove all standard model backgrounds.

PACS. 12.60.Jv Supersymmetric unified models – 04.65.+e Supergravity

1 Introduction

Supersymmetry (SUSY) is still the most sought-after new physics option around the TeV scale. Apart from stabilizing the electroweak symmetry breaking sector and providing a rather tantalizing hint of Grand Unification, SUSY (in the R-parity conserving version) also provides a cold dark matter candidate in the form of the stable lightest supersymmetric particle (LSP). The most common practice is to assume that the lightest neutralino is the LSP, and the ‘standard’ signals such as (jets + E_T), (dileptons + E_T) etc. are widely studied under this assumption. However one must also know (a) how tractable are SUSY signals with other types of LSP? And (b) is it possible to have quasi-stable but cosmologically allowed charged particles in a SUSY scenario, with distinct collider signatures?

The shortest step beyond the standard electroweak model, which provides an explanation of neutrino mass, consists in hypothesizing a right-handed neutrino for each fermion family [1]. At the same time depending on SUSY for the stabilization of the electroweak scale, three additional members are added to the assortment of R-odd (super)particles, namely, the right-chiral sneutrinos. The non-interactive nature of the dominantly right-chiral state ($\tilde{\nu}_1$) relative to the left-chiral one makes it possible for the former to be a dark matter candidate [2]. We study a SUSY spectrum with such a sneutrino as the LSP. For the next-to-lightest SUSY particle (NLSP) one can have a slepton NLSP (especially the stau, with its opportunity to have a rather light mass eigenstate with large $\tan\beta$, $\tan\beta$ being the ratio of the vacuum expectation

values of the two Higgs doublets), out of the many possibilities. Interestingly, for a $\tilde{\nu}_1$ LSP, any NLSP will decay into it only through an interaction strength proportional to the neutrino mass. This is because Yukawa interactions will invariably involve this mass, while gauge interaction will depend on the admixture of the $SU(2)_L$ doublet component in $\tilde{\nu}_1$ proportional to the neutrino Yukawa coupling. Thus the decay of the NLSP to the LSP is too suppressed over most of the viable parameter space to take place within the detector and the NLSP appears to be stable, as far as collider detectors are concerned. We emphasize the following in this work: (a) The stau can become an NLSP, and the corresponding right sneutrino, the LSP, in rather natural regions of the SUGRA parameter space, provided that right sneutrino mass is allowed to evolve from the common scalar mass at high scale. (b) The stau NLSP is likely to leave charged tracks on reaching the muon detector.

We wish to point out that the very kinematic properties of the tracks in the muon chamber set the long-lived staus apart from the muons in a conspicuous fashion [3], and the characteristic signal events of such a scenario can be separated from the standard model (SM) backgrounds in a rather straightforward manner.

2 Right sneutrino LSP in supergravity

The simplest extension to the SM spectrum to give Dirac masses to neutrinos, by adding right-handed neutrino for each generation would imply that the neutrino Yukawa couplings are quite small ($\sim 10^{-13}$). The superpotential of the minimal SUSY standard model (MSSM) is extended by just one term which, for a

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particular family, is of the form

$$W_\nu^R = y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c \quad (1)$$

where y_ν is the Yukawa coupling, \hat{L} is the left-handed lepton superfield and \hat{H}_u is the Higgs superfield responsible for giving mass to the $T_3 = +1/2$ fermions. The above term in the superpotential obviously implies the inclusion of right-handed sneutrinos in the particle spectrum which will have all their interactions proportional to the corresponding neutrino masses. So the dominantly right-handed eigenstate of the tau-sneutrino might become a possible candidate for the LSP in the framework of minimal supergravity (mSUGRA) model of SUSY, consistent with all experimental bounds [4] and also within the acceptable limits of dark matter density in the universe [5,6]. The decay rate of the stau-NLSP is extremely suppressed because of the smallness of the Yukawa coupling and plays a crucial role in our understanding of the spectrum and its consequent features.

Upon inclusion of right-chiral neutrino superfield into the SUGRA fold, the superparticle spectrum mimics the mSUGRA spectrum in all details except for the identity of the LSP. The mass terms for sneutrinos (neglecting inter-family mixing) are given by

$$-\mathcal{L}_{soft} \sim M_{\tilde{\nu}_R}^2 |\tilde{\nu}_R|^2 + (y_\nu A_\nu H_u \tilde{L} \tilde{\nu}_R^c + h.c.) \quad (2)$$

where A_ν is the term driving left-right mixing in the scalar mass matrix, and is obtained by running of the trilinear soft SUSY breaking term A . One expects minimal left-right mixing of sneutrinos as the Yukawa couplings are all extremely small. The mass-squared matrix for the sneutrino thus looks like

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & y_\nu v (A_\nu \sin \beta - \mu \cos \beta) \\ y_\nu v (A_\nu \sin \beta - \mu \cos \beta) & M_{\tilde{\nu}_R}^2 \end{pmatrix}$$

where $M_{\tilde{L}}$ is the soft scalar mass for the left-handed sleptons whereas the $M_{\tilde{\nu}_R}$ is that for the right-handed sneutrino. In general, $M_{\tilde{L}} \neq M_{\tilde{\nu}_R}$ because of their different evolution patterns as well as the D-term contribution for the former. While the evolution of all parameters of minimal SUSY remain practically unaffected in this scenario, the right-chiral sneutrino mass parameter evolves [2] at the one-loop level as:

$$\frac{dM_{\tilde{\nu}_R}^2}{dt} = \frac{2}{16\pi^2} y_\nu^2 A_\nu^2 \quad (3)$$

The extremely small Yukawa couplings cause $M_{\tilde{\nu}_R}$ to remain nearly frozen at the value m_0 , whereas the other sfermion masses are jacked up at the electroweak scale. Thus, for a wide range of values of the gaugino mass, one naturally has sneutrino LSP's, which, for every family, is dominated by the right-chiral state:

$$\tilde{\nu}_1 = -\tilde{\nu}_L \sin \theta + \tilde{\nu}_R \cos \theta \quad (4)$$

The mixing angle is clearly suppressed due to the smallness of y_ν . However, of the three charged slepton families, the amount of left-right mixing is always the

largest in the third (being, of course, more pronounced for large $\tan \beta$), and the lighter stau ($\tilde{\tau}_1$) often turns out to be the NLSP in such a scenario. Thus the mSUGRA parameter set ($m_0, m_{1/2}, A, \text{sign}(\mu)$ and $\tan \beta$) in an R-parity conserving scenario can eminently lead to a spectrum where the right-sneutrinos will be either stable or metastable but very long-lived and gives a SUSY spectrum with a $\tilde{\tau}$ NLSP. Using the spectrum gener-

Input	BP-1	BP-2
mSUGRA	$m_0 = 100 \text{ GeV}$, $m_{1/2} = 600 \text{ GeV}$ $\tan \beta = 30$	$m_0 = 110 \text{ GeV}$, $m_{1/2} = 700 \text{ GeV}$ $\tan \beta = 10$
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	420	486
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	251	289
$m_{\tilde{\nu}_{eL}}, m_{\tilde{\nu}_{\mu L}}$	412	479
$m_{\tilde{\nu}_{\tau L}}$	403	478
$m_{\tilde{\nu}_{iR}}$	100	110
$m_{\tilde{\tau}_1}$	187	281
$m_{\tilde{\tau}_2}$	422	486
$m_{\chi_1^0}$	243	285
$m_{\chi_2^0}$	469	551
$m_{\chi_1^\pm}$	470	552
$m_{\tilde{g}}$	1366	1574
$m_{\tilde{t}_1}$	984	1137
$m_{\tilde{t}_2}$	1176	1365
m_{h^0}	118	118

Table 1. Proposed benchmark points for study of stau-NLSP scenario in the SUGRA fold with right-sneutrino LSP. We choose $A = 100 \text{ GeV}$ and $\text{sgn}(\mu) = +$ for both benchmark points.

ator of the package ISAJET 7.69 [7], we find that a large mSUGRA parameter space can realize this scenario of a right-sneutrino LSP and stau NLSP, provided that $m_0 < m_{1/2}$ and one has $\tan \beta$ of the order of 10 and above, the latter condition being responsible for a larger left-right off-diagonal term in the stau mass matrix (and thus one smaller eigenvalue). In Table 1 we present two benchmark points, Benchmark Point 1 (BP-1) and Benchmark Point 2 (BP-2) for our study of such long-lived staus at the LHC.

3 Signatures of stau-NLSP at LHC

In this section we discuss the signatures of the long-lived stau-NLSP at the LHC and concentrate on two different final states, viz.

- $2\tilde{\tau}_1 + 2(\text{or more}) \text{ jets}$ ($p_T > 100 \text{ GeV}$)
- $2\tilde{\tau}_1 + \text{dimuon} + 2(\text{or more}) \text{ jets}$ ($p_T > 100 \text{ GeV}$)

Keeping the above signals in mind, we focus on the two benchmark points listed in Table 1 and study their signatures at the LHC, for an integrated luminosity of 30 fb^{-1} .

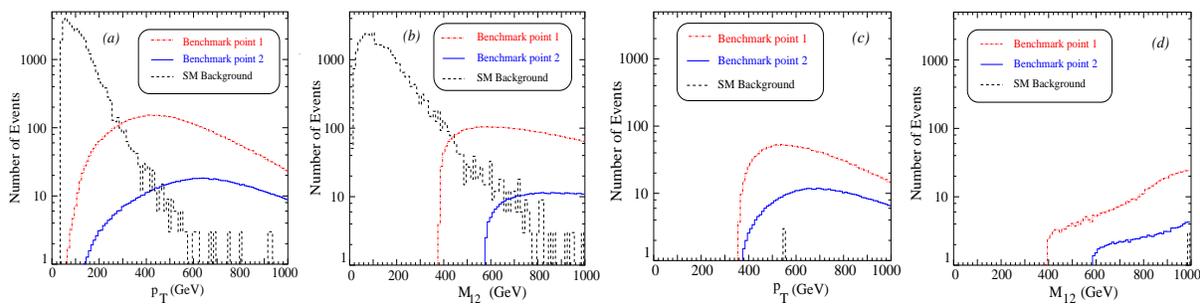


Fig. 1. Kinematic distributions for the signal $2\tilde{\tau}_1 + (\geq 2)$ hard jets. In (a) the transverse momentum distributions for the harder $\tilde{\tau}_1$ is shown and (b) shows the invariant mass distribution for the $\tilde{\tau}_1$ pair. (c) and (d) show the same distributions after imposing the stronger cuts.

The $\tilde{\tau}_1$ -NLSP is long-lived and stable in the context of collider studies. So it will almost always decay outside the detector, leaving characteristic signals like charged tracks, with large transverse momenta. In fact this would be quite a contrast to the traditionally thought of SUSY signals with *large missing transverse energy* and the stable stau will behave just like a muon. However, in the absence of spin identification, these staus will behave more like very heavy muon-like particles with $\beta (= v/c) < 1$ and such heavy charged particles will have high specific ionisation due to their slow motion within the detector. In this work we take a qualitatively different approach, which would be based more on an analysis pertaining to studying the kinematics of processes producing such particles at the LHC.

• $2\tilde{\tau}_1 + \text{hard jets}$

The signals mentioned here arise mostly from the direct decay of gluinos and squarks, produced via strong interaction at the LHC, into the lightest neutralino, with the latter decaying into a tau and a lighter stau, and the tau decaying hadronically in turn. Cascades through other neutralinos and charginos supplement the rates to a moderate extent. We have used PYTHIA 6.409 [8] for our event generation and interfaced it with ISASUGRA, contained in ISAJET 7.69, to generate the mSUGRA spectrum with a right-sneutrino LSP with its corresponding renormalization group equation RGE (eqn. 3) also included.

The parton densities have been evaluated at $Q = 2m_{\tilde{\tau}_1}$ using CTEQ5L [9], and the renormalization scale and factorization scale are $\mu_F = Q = \mu_R$. The effects of both initial state radiation (ISR) and final state radiation (FSR) along with the effects of hadronization and multiple interaction with the help of PYTHIA

hadronization schemes are included. To define jets we use the simple-minded jet cone algorithm implemented in PYTHIA through the subroutine PYCELL. To select our final states, we demand the following requirements (called basic cuts) on our sample events:

- Each $\tilde{\tau}_1$ should have $p_T > 30$ GeV and at least two jets with $p_T > 100$ GeV (hard jets).
- Both the $\tilde{\tau}_1$'s should satisfy $|\eta| \leq 2.5$, to ensure that they lie within the coverage of the muon detector.
- $\Delta R_{\tilde{\tau}_1 \tilde{\tau}_1} \geq 0.2$, to ensure that the $\tilde{\tau}_1$'s are well resolved in space.
- In addition we have rejected events having photons with $|\eta_\gamma| \leq 2.5$ and $p_{T_\gamma} \geq 25$ GeV.

As the charged tracks pass through the muon chamber, it is probable that the muonic events will fake our signal. Therefore, events with two or more hard jets and two central muons will *prima facie* constitute our standard model background. The leading contribution to such final states satisfying our basic cuts comes from top-pair production and its subsequent decay into dimuons, with similar topology as that of the signal. The sub-leading contributions consist in weak boson pair production. For performing the background analysis we again used the same criteria as stated above for the signal, with all kinematic features of the long-lived charged tracks attributed to the muons.

An important point to note is that the background is almost completely reducible with the imposition of stronger event selection criteria, as we shall see below. In Figure 1, we present distributions of a few observables where we could distinguish the signal from backgrounds. These are the transverse momentum (p_T) of the harder charged track (and the harder muon in the case of backgrounds) and the invariant mass (M_{12}) of the two charged tracks (or dimuons). In addition, the radii of curvatures of the stau tracks will also lie in a clearly distinguishable range, as seen from the p_T -distributions. On examining the p_T -distributions, we find it most convenient to eliminate the background by imposing a stronger p_T cut on *both the charged tracks* of 350 GeV. This makes the signal stand out clearly for both the benchmark points, as can be seen from Table 2 and also Figure 1(c) and 1(d). These constitute the real ‘signal distributions’, and can be used to

Cuts	SM	BP-1	BP-2
Basic	39617	8337	1278
Basic + $p_T > 350$ GeV	5	2587	737

Table 2. The expected number of events for the signal and background with the different cuts imposed on the selection of events.

extract information, for example, about the mass of the stau-NLSP and other SUSY parameters.

The signals in the scenario under investigation here will be more severely affected when a missing- p_T cut is imposed. To take a specific example, the signal rate at BP-1 becomes about 48% of its original value when the requirement of a minimum missing- p_T of 100 GeV is imposed. In contrast, at a nearby point in the parameter space ($m_0 = 200$ GeV, $m_{1/2} = 600$ GeV, $A = 100$ GeV, $\tan\beta = 30$, $\text{sgn}(\mu) = +ve$), the same missing- p_T cut allows about 97% survival of the $\text{jets} + \text{dimuons} + \cancel{p}_T$ signal. Thus the response to missing- p_T cuts turns out to be an effective tool of differentiation between our signal and that coming from MSSM (with neutralino LSP), at least when R-parity is conserved.

• Dimuon and $2\tilde{\tau}$ and (≥ 2) jets:

With the stringent demand on the hardness of the jets, this is a very clean signal, albeit less copious than the previous one (BP-1=689 events, BP-2=103 events, SM=83 events). Such final states will require cascade decays of gluinos and squarks involving the charginos and heavier neutralinos. The same ‘basic cuts’ are imposed here, too, which are found to be sufficient in drastically reducing the SM backgrounds in the form of four muons together with two or more jets with $p_T > 100$ GeV (SM=29 events). In Figure 2

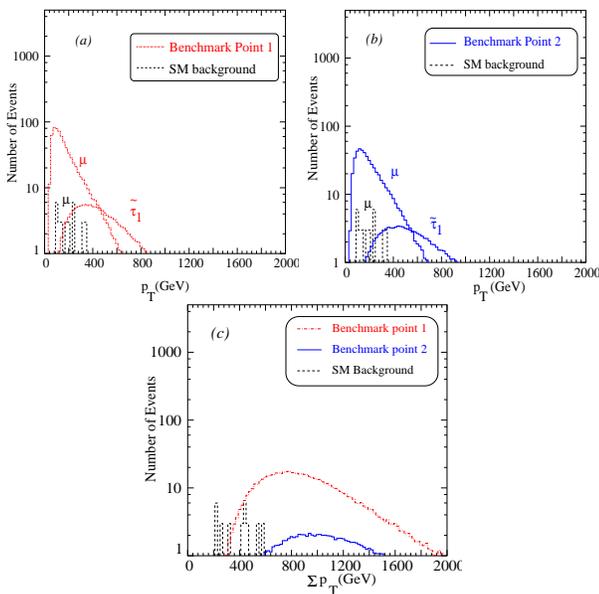


Fig. 2. Kinematic distributions for the signal $2\tilde{\tau}_1 + \text{dimuon} + (\geq 2)$ hard jets with basic cuts. In (a) and (b) the transverse momentum distributions for the harder $\tilde{\tau}_1$ and harder muon of the signal is shown and (c) shows the scalar sum of p_T 's of (dimuon + $2\tilde{\tau}_1$) of the signal. We follow the same notation as in Figure 1.

we plot the corresponding distributions for the above final states. Furthermore, the plot of the scalar sum of the individual transverse momenta of the charged tracks in the muon chamber, in Figure 2(c), indicates that a cut of 600 GeV on this sum washes out the

backgrounds completely leaving 553 events for BP-1 and 89 events for BP-2. The advantage of applying this cut is that there is no loss of signal events in the case of a relatively heavy NLSP. In Figure 2(a) and (b), the p_T -distributions of the (harder) muon and the corresponding stau-track are seen to have a substantial overlap. Therefore, a distinction between them based on the thickness of the tracks as well as the information provided by measurement of the ‘time-of-flight’ can be useful here.

4 Summary and conclusions

We have studied a SUSY scenario with a stau-NLSP and an overwhelmingly right-chiral sneutrino as the LSP, where the sneutrino is at least partially responsible for the cold dark matter of the universe. A mass spectrum corresponding to such a scenario can be motivated in a SUGRA framework, including right-chiral sneutrinos whose masses remain practically frozen at the universal scalar mass at the SUSY breaking scale. We find that the superparticle cascades culminating into the production of stau-pairs give rise to very distinct signals of such a scenario. Although the charged tracks of the quasi-stable staus tend to fake muonic signals in the muon chamber, our analysis reveals considerable difference in their kinematic characters. Such difference can be used in a straightforward way to distinguish between the long-lived staus and the muons, and also to eliminate all standard model backgrounds. Since the mass spectrum under consideration here is as probable as one with a neutralino LSP in mSUGRA, further study of all possible ways of uncovering its signature at the LHC should be of paramount importance.

This talk was based on the work done in Ref [3].

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