

Right sneutrinos and signals of a stable stop at the CERN Large Hadron ColliderDebajyoti Choudhury,^{1,*} Sudhir Kumar Gupta,^{2,+} and Biswarup Mukhopadhyaya^{2,‡}¹*Department of Physics and Astrophysics, University of Delhi, Delhi-100 007, India*²*Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad-211 019, India*

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We investigate charged tracks signals of a supersymmetric scenario, where the lighter stop is the next-to-lightest supersymmetric particle. It is found that such a next-to-lightest supersymmetric particle is stable on the scale of the detector at the CERN LHC if one has a right-chiral sneutrino as the lightest supersymmetric particle. After identifying some benchmark points in the parameter space of a supergravity scenario with nonuniversal scalar masses, we study a few specific classes of signals, namely, stop pair production and gluino pair production followed by each decaying into a stop and a top. It is shown that proper kinematic cuts remove the backgrounds in each case, and an integrated luminosity of even 1 fb^{-1} is likely to yield copious events of the first kind, while a larger luminosity may be required for the other type. One can also aspire to reconstruct the gluino mass, using the “visible” stable next-to-lightest supersymmetric particle tracks.

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I. INTRODUCTION

Among the various new physics possibilities at the TeV scale, supersymmetry (SUSY) [1] occupies a slightly preferred position. From a bottom-up point of view, one reason behind this is the dual role of SUSY in stabilizing the electroweak scale and, in its minimal version, in offering a cold dark matter candidate in the form of the lightest supersymmetric particle (LSP). From the top-down standpoint, too, SUSY broken at the TeV scale fits in rather well in scenarios such as supergravity (SUGRA), which, presumably, have a close connection to physics at the Planck scale. Therefore, despite some persistent concerns such as the possible enhancement of flavor-changing neutral currents (FCNC), one feels the urge to fit in any proposed SUSY scenario into a scheme where the SUSY-breaking parameters evolve down from values inherited at a high scale. Although the simplest model to achieve this is the minimal SUGRA picture, scenarios with nonuniversal masses at high scales are also often viable.

Indeed, one has to go beyond the minimal version (of the standard model as well as its SUSY extension) if one has to explain the accumulating evidence in favor of neutrino masses and mixing [2]. The simplest way to do this is to postulate a right-handed neutrino in each generation. In a SUSY version, this entails right-chiral sneutrinos [3]. While the minimal SUSY standard model (MSSM) favors the lightest neutralino as the LSP, right-sneutrino LSPs are equally viable if the particle content is extended in the manner suggested above. This is particularly true if the neutrinos have only Dirac masses [4], for the existence of

$\Delta L = 2$ terms in the Lagrangian nominally leading to large (keeping in view the seesaw mechanism) Majorana masses would simultaneously elevate the right-sneutrino masses to high values.¹ A right-sneutrino LSP evades the limits from direct dark matter search due to its near-sterile character. Its viability as a cold dark matter candidate [4] has also been demonstrated, although there are debates about the possible nonthermal nature [5] of such dark matter.

If neutrinos have only Dirac masses, then the interactions of an LSP dominated by right sneutrinos would be proportional to the neutrino Yukawa couplings y_ν , which are of order 10^{-12} or less. This is because (a) if it is a scalar trilinear interaction, then it is proportional to y_ν , and (b) if it is a gauge interaction, then it is proportional to the overlap of the LSP with a left sneutrino, which, by virtue of the left-right mixing terms in sfermion mass matrices, is again proportional to the neutrino mass. Thus, the decay of the next-to-lightest supersymmetric particle (NLSP) to the LSP takes place over lengths much larger than the scale of collider detectors, and SUSY signals are drastically different from those of MSSM where missing transverse momentum is the key distinguishing feature [6]. Two of us have shown, in an earlier work, how, in such cases, a stau NLSP can provide signals that can be distinguished from the standard model (SM) background [7]. In this work, we

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¹A possible exception to this rule may be provided by situations wherein the right-handed neutrino mass matrix has a vanishing determinant, occasioned, for example, by texture zeroes. While such scenarios may arise naturally in models with an extended symmetry texture and may lead to very interesting phenomenology, we refrain from discussing those here.

discuss the signals characteristic of a quasistable stop NLSP.

Needless to say, right sneutrinos make a big difference to the signal if the NLSP is a charged particle, which would leave tracks in the inner tracker as well as the muon chamber. Apart from the stau (or, in special cases, sleptons of the first two families), a possible NLSP is either a chargino or a lighter squark of the third family. Theoretically though, it is difficult to render a chargino the lightest of the SM's supersymmetric partners; in other words, the coexistence of a chargino NLSP with a right-sneutrino LSP is very difficult to accommodate, even if we assume a nonuniversal gaugino mass. A stop NLSP with a right-sneutrino LSP, on the other hand, can lead to very interesting signals at the CERN LHC. Cases where such a stop decays within the detector have been studied in an earlier work [8,9]. We think that it is equally interesting to consider the situation where the stop NLSP decays into the right-sneutrino LSP through the sneutrino Yukawa coupling and, thus, escapes the muon chamber after leaving a track there. We show that, just like the case with a stau NLSP, kinematical separation of such signals from the SM backgrounds [10] is clearly possible, making such SUSY scenarios eminently distinct. Moreover, it is also possible to distinguish a stop-NLSP scenario from one with a stau NLSP, simply from a comparison of stop pair production and stau pair production (in the alternate scenario). Furthermore, the study of stops as intermediates in gluino cascade decays provides additional discriminants.

Unlike the case of a stau NLSP, a stop NLSP is difficult to obtain in a SUGRA setting with universal scalar masses at the high scale. On the other hand, such a spectrum can arise naturally when the scalar masses display some non-universality at high scales—in fact, even when only the third family displays this behavior. As nonuniversality in the third family sector is relatively easy to accommodate *vis-à-vis* flavor data, we adopt such a scenario to illustrate the viability of such a situation.

It should be emphasized that, though we are illustrating the particle spectrum under scrutiny in the context of a nonuniversal SUGRA, our real stress is on the novel phenomenology which completely changes SUSY search strategies. We all know that the most simpleminded SUGRA picture (as well as many of its variants) is beset with a number of puzzles, including issues related to FCNC. Of course, a generalization of SUGRA can avoid most of such problems [11]. In general, however, one is not sure that during SUSY searches at colliders one should adhere too much to specific scenarios based on high-scale assumptions. Our ignorance of, say, possible phenomena at intermediate scales further accentuates the need of skepticism. In view of this, one feels that a consistent SUSY scenario that leads to novel, unconventional experimental consequences is worthy of investigation, irrespective of its high-scale connection. Something that can be tested at the

early stage of the LHC is especially interesting in this regard.

In the next section, we locate a few points in the parameter space where a stop NLSP can coexist with a right-sneutrino LSP, on introduction of nonuniversal scalar masses. The characteristic signals at the LHC discussed here are (1a) $pp \rightarrow 2$ stop tracks, (1b) $pp \rightarrow$ a single stop track accompanied by missing transverse energy and (2) $pp \rightarrow 1$ or 2 stop tracks accompanied by multijets, missing transverse energy and possibly some leptons. We show that not only are these signals separable from SM backgrounds but they are also distinct from the signals of a stau (or slepton) LSP. The discussions related to these signals, together with the possibility of reconstructing gluino masses in this scenario, are the contents of Sec. III. There we also comment on the special consequences of the quasistable NLSP being colored (and capable of hadronizing). We summarize and conclude in Sec. IV.

II. RIGHT-SNEUTRINO LSP WITH A STOP NLSP

A. The scenario and some benchmark points

With R parity unbroken, the MSSM superpotential can be written as [4]

$$W_{\text{MSSM}} = y_1 L H_d E^c + y_d Q H_d D^c + y_u Q H_u U^c + \mu H_d H_u, \quad (1)$$

where H_d and H_u , respectively, are the Higgs doublets that give mass to the down-type and up-type quarks. In the presence of the additional neutrino superfields N , the superpotential can be extended by the term

$$y_\nu L H_u N, \quad (2)$$

where y_ν is given by $m_\nu = y_\nu \langle H_u \rangle = y_\nu v \sin\beta$ with v (≈ 246 GeV) being the electroweak symmetry-breaking scale and $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$. With the neutrino masses being at most a few eV, we require $y_\nu \sin\beta \approx 10^{-13} - 10^{-12}$.

The general form of the sfermion mass matrix, neglecting interfamily mixing, can be written as

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_{\tilde{f}_{LL}}^2 & m_{\tilde{f}_{LR}}^2 \\ m_{\tilde{f}_{LR}}^2 & m_{\tilde{f}_{RR}}^2 \end{pmatrix}, \quad (3)$$

where the diagonal elements are given by

$$\begin{aligned} m_{\tilde{f}_{LL}}^2 &= m_{\tilde{f}_L}^2 + m_Z^2 (T_{3L}^f - Q_f \sin^2 \theta_W) \cos 2\beta + m_f^2 \\ m_{\tilde{f}_{RR}}^2 &= m_{\tilde{f}_R}^2 + Q_f m_Z^2 \sin^2 \theta_W \cos 2\beta + m_f^2, \end{aligned} \quad (4)$$

whereas the off-diagonal terms are

$$\begin{aligned} \tilde{u}: m_{\tilde{f}_{LR}}^2 &= -m_f (A^f + \mu \cot\beta) = m_{\tilde{f}_{RL}}^2 \\ \tilde{d}: m_{\tilde{f}_{LR}}^2 &= -m_f (A^f + \mu \tan\beta) = m_{\tilde{f}_{RL}}^2. \end{aligned} \quad (5)$$

In a universal SUGRA scenario, all the low-energy masses and couplings can be expressed in terms of five free parameters defined at the grand unified theory scale, viz. the universal scalar mass m_0 , the universal gaugino mass $m_{1/2}$, the universal trilinear soft SUSY-breaking parameter A_0 , the ratio of the vacuum expectation values of two Higgses $\tan\beta$, and the sign of the Higgsino mass parameter μ , namely, $\text{sgn}(\mu)$. The relevant parameters at the electroweak scale are then determined, via renormalization group evolution, from those operative at the high scale of SUSY breaking in the hidden sector. Of the resultant corrections to the (low-energy) squark and slepton masses, the largest contributions accrue from the gauginos. The third family masses also receive substantial corrections on account of the Yukawa interactions and the mixing of left- and right-chiral states.

A right-sneutrino LSP can be achieved in a part of the parameter space mostly favoring $m_0 < m_{1/2}$. With the one loop level renormalization group evolution for $m_{\tilde{\nu}_R}$ given by

$$\frac{dm_{\tilde{\nu}_R}^2}{dt} = \frac{2}{16\pi^2} y_\nu^2 A_\nu^2, \quad (6)$$

the smallness of the Yukawa interaction ($y_\nu \leq 10^{-12}$), occasioned by our assumption of a conserved lepton number, serves to freeze the right-sneutrino mass at the high-scale value itself. The lighter sneutrino mass eigenstate is given by

$$\tilde{\nu}_1 = -\tilde{\nu}_L \sin\theta + \tilde{\nu}_R \cos\theta \simeq \tilde{\nu}_R, \quad (7)$$

where the left-right mixing between the sneutrinos is given by

$$\tan 2\theta = \frac{2y_\nu v \sin\beta |\mu \cot\beta - A_\nu|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2}. \quad (8)$$

Obviously, the state $\tilde{\nu}_1$ can become the LSP for a sufficiently small value of m_0 , and all the other particles in the spectrum couple to it with a strength proportional to y_ν . This is so on account of the $\tilde{\nu}_R$ being a gauge singlet with the consequence that its only interaction is via the Yukawa coupling. In other words, any gauge coupling to $\tilde{\nu}_1$ depends on the left-chiral component in it, which in turn again depends on y_ν (excepting for the pathological case where the two mass eigenstates are degenerate to the level of 1 in 10^{12}). Therefore, the NLSP, irrespective of its identity, will decay into the $\tilde{\nu}_1$ in an excruciatingly slow manner, making the former appear stable in accelerator experiments.

Since our interest here is in a stop NLSP, we next identify points in the SUGRA parameter space where this is possible. In this, the corresponding parameters should be allowed by the generic limits from the direct search experiments (such as the CERN LEP as well as the Fermilab Tevatron collider), and, in particular, should conform to the

specific bound on the mass of a quasistable stop. Furthermore, they should also be consistent with other low-energy constraints such as FCNC and with radiative breaking of the electroweak symmetry to yield an acceptable vacuum.

The Tevatron Run IIB data for stop search, with 1 fb^{-1} integrated luminosity, suggests that the lighter stop is constrained by $m_{\tilde{t}_1} > 220 \text{ GeV}$ [12]. In addition, in a recent simulation for stable stop search at the Tevatron, as part of the charged matter stable particles analysis, it has been claimed that the lighter stop should be above 250 GeV at 95% confidence level [13]. For our simulations, we have adopted a lower limit of 240 GeV for a quasistable stop.

To see if such a scenario can be realized within a universal SUGRA setting, we performed a detailed study of the parameter space using ISAJET 7.75 [14]. The simultaneous requirements of a stop NLSP and a right-sneutrino LSP yield only negative results. This is because, in order to get a stop NLSP, one requires a large left-right mixing which is driven by A_t and $\cot\beta$. This is essentially to counter the large gluino contribution (in the renormalization group evolution) from the top-gluino loop which is proportional to the gluino mass. The latter has to be large enough so that the mass of the lightest neutralino² exceeds that of the lighter stop \tilde{t}_1 . However, a large value of A_t to generate an effect of the above kind requires A_0 to be such as to render some slepton (stau) tachyonic, or at any rate relegate it to the level of the LSP. Based on these considerations, a stop NLSP is found very difficult to achieve in a universal SUGRA scenario.

The spectrum of the type looked for, on the other hand, can still be motivated in the SUGRA setting if some nonuniversality of scalar masses at high scale is allowed. The type of nonuniversality sought in our context is one where the third family sfermion masses are different. Representative scenarios which can motivate such spectra are those with additional U(1) symmetries (possibly anomalous) with flavor-dependent D terms [15], leading to arbitrary high-scale soft masses for the stop, sbottom, stau and tau-sneutrino states. However, rather than restricting ourselves to a particular model, we perform a phenomenological analysis, and scan the parameter space without any bias, to see if a stop NLSP can coexist with a (tau) sneutrino LSP. Table I contains four benchmark points answering to such a description, on which our collider predictions are based. The scan over the parameter space, using ISAJET 7.75, also takes into account constraints such as those from LEP, $b \rightarrow s\gamma$ as well as the prospect of charge- and color-breaking vacuum and a vacuum unbounded from below. The magnitude of the Higgsino mass parameter μ has been fixed from electroweak

²Note that this constraint would be relaxed if one were to admit nonuniversal gaugino masses at the high scale, thereby enlarging the parameter scale manifolds.

TABLE I. Proposed benchmark points (BPs) for a stop NLSP in a nonuniversal right-chiral sneutrino LSP SUGRA scenario. Nonuniversality in third generation sfermion masses has been assumed. Top mass is assumed to be 171.4 GeV. Values of all the mass parameters are in GeV units. Other SUSY parameters are $\tan\beta = 20$ and $\text{sgn}(\mu) = +$. Note that $m_{\tilde{\nu}_{\tau_1}}$ can be fixed at any value below $m_{\tilde{\tau}_1}$.

	Parameter	BP1	BP2	BP3	BP4
Input (GeV)	$m_0, m_{1/2}, A_0$	184, 600, -2400	370, 650, -2600	540, 700, -2500	325, 800, -3000
	$m_{\tilde{t}_L}, m_{\tilde{t}_R}$	600, 301	700, 400	1000, 200	1000, 260, 750
	$m_{\tilde{b}_R} = m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$	500	750	750	750
Output	$ \mu $	1363	1459	1479	1750
	$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	461	585	743	659
	$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	244	415	528	336
	$m_{\tilde{\nu}_{eL}}, m_{\tilde{\nu}_{\mu L}}$	450	576	735	648
	$m_{\tilde{\nu}_{\tau_2}}$	581	765	1071	865
	$m_{\tilde{\nu}_{eR}}, m_{\tilde{\nu}_{\mu R}}$	184	370	540	325
	$m_{\tilde{\tau}_1}$	316	555	871	544
	$m_{\tilde{\tau}_2}$	595	775	1077	873
	$m_{\chi_1^0}$	253	276	299	342
	$m_{\chi_2^0}$	485	528	571	652
	$m_{\chi_3^0}$	1359	1455	1478	1756
	$m_{\chi_4^0}$	1361	1457	1481	1748
	$m_{\chi_1^\pm}$	488	532	574	657
	$m_{\chi_2^\pm}$	1363	1459	1483	1750
	$m_{\tilde{g}}$	1367	1477	1594	1790
	$m_{\tilde{u}_L}, m_{\tilde{c}_L}$	1260	1391	1530	1653
	$m_{\tilde{u}_R}, m_{\tilde{c}_R}$	1222	1350	1502	1612
	$m_{\tilde{d}_L}, m_{\tilde{s}_L}$	1263	1394	1532	1655
	$m_{\tilde{d}_R}, m_{\tilde{s}_R}$	1207	1337	1470	1580
	$m_{\tilde{t}_1}$	240	273	296	330
	$m_{\tilde{t}_2}$	1109	1203	1443	1544
	$m_{\tilde{b}_1}$	1075	1174	1423	1534
	$m_{\tilde{b}_2}$	1209	1284	1476	1615
	m_{h^0}	116	117	121	120
	m_{H^0}	1305	1429	1507	1706
	m_{A^0}	1297	1421	1498	1695
	m_{H^\pm}	1308	1432	1510	1708

symmetry-breaking conditions, and the sign of μ (to which our results are not sensitive) has been taken as positive. The value of the right-sneutrino mass does not affect the collider phenomenology in any way unless it is heavier than the stop NLSP. We have thus kept it as a free parameter, which can assume *any value compatible with dark matter requirements*.

It should be mentioned here that a stop NLSP can also be achieved with universal squark and slepton masses but different high-scale A parameters for the squark and slepton sectors. With $A_l \ll A_q$, dangers such as tachyonic state modes can then be averted. Also, even though we have ensured that processes such as $b \rightarrow s\gamma$ are within control with our parameter choice, a satisfactory suppression of FCNC (including contributions to $B^0 - \bar{B}^0$ mixing) over a range of parameters will require some model-dependent alignment mechanism for the quark and squark mass ma-

trices. Such a mechanism can keep the “super-Cabibbo-Kobayashi-Maskawa” angles suitably small.

The proliferation of parameters in this scenario, which is not surprising in a phenomenological study, makes it less illuminating than in a universal SUGRA to seek a pattern in the underlying high-scale physics. Nonetheless, we notice the following general features in the choices that give rise to the spectrum under study:

- (i) A large $|A_0|$ is required to generate a large left-right mixing in the stop sector, so that a sufficiently large $m_{1/2}$ (required to push up the lightest neutralino mass) can still be compatible with a stop NLSP.
- (ii) For a fixed (high-scale) $m_{\tilde{t}_R}$, the allowed parameter space becomes narrower as we increase $\tan\beta$. To push up the down-sector sfermion masses above the NLSP mass, we require large values of m_0 , while the need to place neutralinos above the NLSP implies a

large $m_{1/2}$. A $\tan\beta$ in the range 5–35 seems to be relatively more favorable for this purpose.

B. Stop lifetime and stop hadrons

The major decay modes available to the \tilde{t}_1 NLSP are $\tilde{t}_1 \rightarrow b\tilde{\nu}_1\tau^+$ (via $\tilde{\chi}_i^\pm$) and $\tilde{t}_1 \rightarrow t\tilde{\nu}_1\nu$ (via $\tilde{\chi}_i^0$). The corresponding Feynman diagrams are presented in Fig. 1. The dependence of the decay rates on the neutrino Yukawa couplings has already been discussed. In Fig. 2, we present the decay lifetime for a wide range of LSP (NLSP) masses for a fixed NLSP (LSP) mass. The lifetime rises with an increase in LSP mass whereas it understandably decreases when the NLSP mass increases. The order of magnitude of the \tilde{t}_1 lifetime shows rather unambiguously that, over a wide choice of $\tilde{\nu}_1$ masses, the stop NLSP will decay way outside the detector. A similar pattern in the lifetime plots of a stop NLSP with a gravitino LSP has been reported earlier [9]. It is also to be noted that though the NLSP is long-lived, its lifetime is always smaller than the age of the Universe, with the present study safe from the viewpoint of charged dark matter. And, as long as the lifetime is not too large ($\lesssim 10^8$ s), one is safe from other cosmological bounds such as those from big bang nucleosynthesis [16].

Even the minimal of lifetimes as in Fig. 2 imply that the stop hadronizes before decaying. While the exact nature of fragmentation characteristics would need to be worked out in detail, it is a very good approximation to consider that half of the stops thus produced would result in singly charged stop hadrons (say, $\tilde{t}_1\bar{d}$) while the other half would result in neutrals ($\tilde{t}_1\bar{u}$).³ Although other hadrons, including doubly charged ones (such as \tilde{t}_1uu), or excited states such as $\tilde{t}_1\bar{d}g$ are possible as well, fragmentation into them is suppressed and deviations from the two-way splitting (with a 1:1 ratio) are expected to be modified only to a very small extent. Furthermore, the very small mass difference between such hadrons implies that each of them would be quasistable on the scale of the detector.

It has been argued [18] though that the heavier of these quasistable hadrons may decay strongly into the lighter ones (and, in principle, cascade down) as long as they are kinematically allowed to do so. For example, if the charged hadron mass is larger than that of the corresponding neutral hadron by an amount exceeding the pion mass, such strong decays would cause the charged track(s) to disappear. On the other hand, if neutral stop hadrons are similarly heavier, then the charge tracks are produced and sustained, and the two tracks signal rates are enhanced over what they have been found here. While a definitive statement can be made only on computing the spectrum of such stop hadrons, our experience with ordinary heavy-light quark bound systems suggests that the mass difference between

³This can also happen in models with a stop LSP and a very small R -parity violation, if one gives up on SUSY dark matter. For related work, see, for example, Ref. [17].

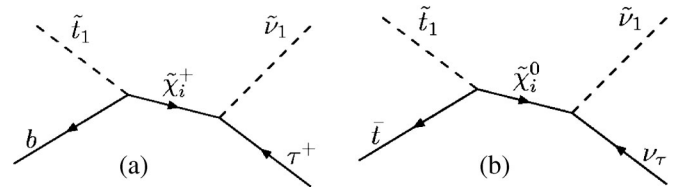


FIG. 1. Stop decay channels.

these two states (which, presumably are the lightest of the stop hadrons) would be well below m_π , thus preventing a strong decay. The weak decay lifetime, on the other hand, is much too long for it to be relevant to collider studies. While this argument would not hold for the decays of, say, $\tilde{t}\bar{s}$ or $\tilde{t}\bar{u}g$, the lower fragmentation into these states renders such worries irrelevant at the current level of sophistication.

Of more significance is the possibility that the stop hadrons may deposit some energy in the calorimeters through either quasielastic or inelastic collisions [15]. Various claims [18,19] and counterclaims have been made in the literature in this regard. In addition to the possibility of energy deposits by the stop track in the hadron calorimeter, it is also possible that the interaction with the calorimeter material will convert charged stop hadrons into neutral ones or vice versa [20]. In this process, one may observe a charged track in the inner tracking chamber, but no track in the muon detector. Alternatively, a neutral quasistable hadron with no record in the inner tracker may get converted into a charged one and display a track in the muon chamber, thus yielding signals of a very novel type. A quantitative prediction of signals based on the above observations will require (a) an elaborate detector simulation, buttressed with data from initial run of the LHC, and (b) a reliable model of hadronization of (quasi)stable supersymmetric particles. What we may conclude with a reasonable degree of confidence is that the stop hadron would deposit a small amount of its energy in the hadronic calorimeter (differing from a quasistable stau in this regard). Furthermore, the fraction deposited is generally small enough for it to pierce through to the muon chamber. Thus, in spite of some quantitative uncertainties on this issue, one can still predict a definite excess of signal over background, based on rather simple assumptions. And, given the lack of an unambiguous estimation of the conversion between stop hadrons in matter, we deliberately choose to discount the novel signatures arising therefrom, limiting ourselves to the more conservative signals constructed solely with quasistable stop hadrons that leave no trace when they are neutral and only a track when charged.

III. SIGNATURES OF STOP NLSP AT THE LHC

In the previous section, we observed that the stop NLSP will typically decay outside the detector. Thus, its collider signatures will be in the form of charged tracks that show

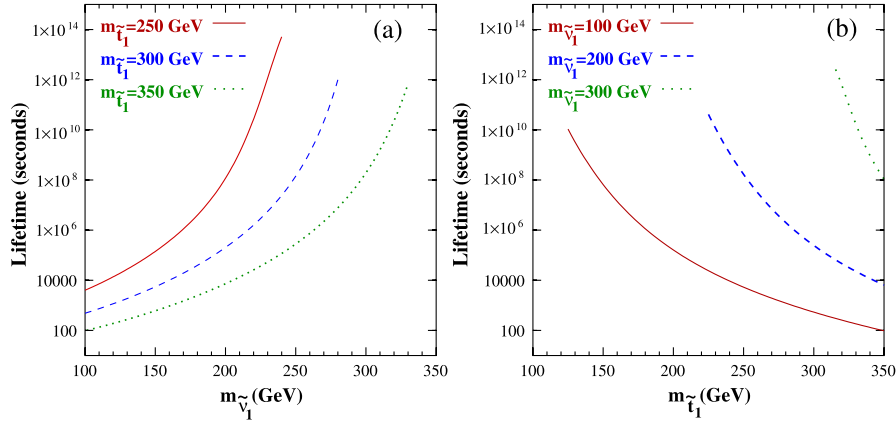


FIG. 2 (color online). Rest frame lifetime of the stop NLSP for (a) fixed NLSP mass and (b) fixed LSP mass.

up in both the inner tracker and the muon chamber. In general, the high velocities (note that stop production has a very large P -wave contribution) of these stable stops will make their identification from time delays rather difficult. Although one can think in terms of the thickness of the tracks and the small amount of energy deposit in the hadron calorimeter, it is desirable to identify, instead, kinematic characteristics that distinguish them. This is of paramount importance since the most distinctive feature of SUSY in the minimal form, namely, \cancel{E}_T , may be absent in a large fraction of the events in this scenario, yet the signals thereof may be striking for it is the tracks in the muon chambers that carry its imprints and truly characterize the scenario.

The most copious signal is the pair production of stable stops. This yields a very large number of events of the type of Drell-Yan muon pair production. However, as already mentioned, a stable stop will hadronize; we tentatively assume that its probability of forming a charged or neutral hadron is 50% each (see Sec. II B). Accordingly, one has events with either one or two charged tracks events and these are discussed in Sec. III A.

With the stop being considerably lighter than any of the other strongly interacting sparticles, a gluino decays substantially into a top and a stop. This leads to additional signals consisting of stable stop tracks and a pair of top quarks produced in association (see Table II). Such signals

have the advantage of distinguishing stop tracks from those of stable staus. They can also, in principle, enable one to reconstruct the gluino mass. We discuss these signals in Secs. III B and III C respectively.

A. Double- and single-stop tracks

The main partonic processes responsible for this final state are $gg \rightarrow \tilde{t}_1 \tilde{t}_1^*$ and $q\bar{q} \rightarrow \tilde{t}_1 \tilde{t}_1^*$. We use a CALCHEP-PYTHIA [21,22] interface for our analysis, with CTEQ6L parton densities [23]. For the renormalization scale μ_R and factorization scale μ_F , we use

$$\mu_R = 2m_{\tilde{t}_1} = \mu_F \tag{9}$$

throughout the analysis. To obtain the next-to-leading order results, we multiply with the appropriate K factor for the \tilde{t}_1 pair production as computed in Refs. [24,25]. The results presented correspond to an integrated luminosity of 1 fb^{-1} at the LHC.

In order to get two charged tracks, each produced stop must hadronize to a charged hadron, thus reducing the rate by a factor of 4. For the two-track events, we use the following *basic cuts* at the outset:

- (i) Each \tilde{t}_1 track should carry $p_T > 25 \text{ GeV}$.
- (ii) Both \tilde{t}_1 's should satisfy $|\eta| \leq 2.7$ to ensure that they lie within the coverage of the muon detector.

TABLE II. A list of various signals with two and one charged track(s).

Signal	Source	Nomenclature
2 charged tracks	distop pair production	1a
1 charged track + \cancel{E}_T	distop pair production	1b
2 charged tracks + 2 leptons + 2 jets + \cancel{E}_T	gluino pair production	2a
2 charged tracks + 1 leptons + 4 jets + \cancel{E}_T	gluino pair production	2b
2 charged tracks + 0 leptons + 6 jets + \cancel{E}_T	gluino pair production	2c
1 charged track + 2 leptons + 2 jets + \cancel{E}_T	gluino pair production	3a
1 charged track + 1 lepton + 4 jets + \cancel{E}_T	gluino pair production	3b
1 charged track + 0 leptons + 6 jets + \cancel{E}_T	gluino pair production	3c

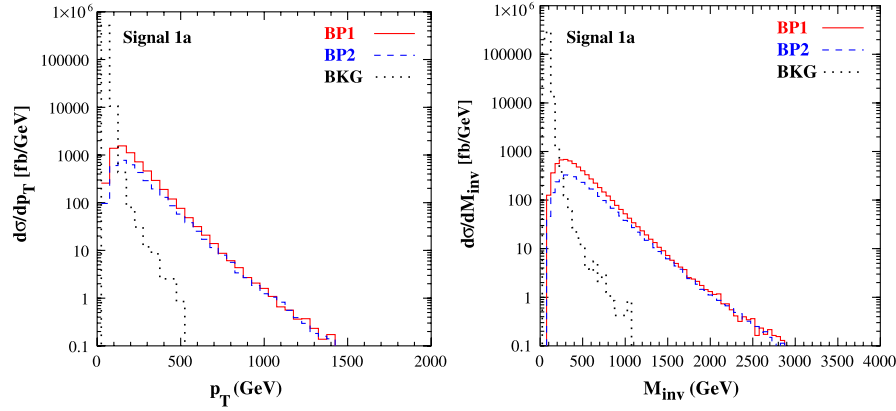


FIG. 3 (color online). p_T (of the harder track) and track pair invariant mass distributions with basic cuts for signal 1a. Red (solid line) and blue (dashed line) histograms are for the signals BP1 and BP2 and black (dotted line) histogram is for the standard model background in both the plots.

TABLE III. The number of events—after various cuts—expected at the LHC for signals 1a and 1b and for each of the benchmark points. The integrated luminosity is assumed to be 1 fb^{-1} . Also shown is the number of background events. Symbols have their usual meaning.

Signal	Cuts	BP1	BP2	BP3	BP4	BKG
1a	Basic	6290	3390	2270	1320	6.60×10^3
1a	Basic + $p_T(\tilde{t}) \geq 200 \text{ GeV}$	1970	1290	970	645	104
1a	Basic + $p_T(\tilde{t}) \geq 520 \text{ GeV}$	119	99	87	71	0
1a	Basic + $p_T(\tilde{t}) \geq 200 \text{ GeV} + m_{\tilde{t}\tilde{t}} \geq 1100 \text{ GeV}$	161	131	114	92	0
1b	Basic	14000	7510	5030	2910	5.75×10^4
1b	Basic + $p_T(\text{track}) \geq 200 \text{ GeV}$	4060	2660	1990	1320	500
1b	Basic + $p_T(\text{track}) \geq 200 \text{ GeV} + \cancel{E}_T \geq 400 \text{ GeV}$	671	528	432	325	0

(iii) $\Delta R_{\tilde{t}_1\tilde{t}_1} \geq 0.2$ to ensure that the \tilde{t}_1 's are well resolved in space.

The most important background [10] to this signal comes from muon pairs produced in the Drell-Yan channel. The other source for the background is WW pair production. We have also considered processes like WZ and ZZ , giving rise to two detectable tracks in the muon chamber. There are still other sources such as triple gauge boson production, but the requirement of the invariant mass being sufficiently above m_Z will, in general, asphyxiate such events.

Assuming that the stop tracks are likely to be buried within the copious backgrounds, we look for kinematic characteristics that can cause our predicted signal to stand out. With this in view, we show, in Fig. 3, the p_T distributions of the signal and the background. Also shown are the invariant mass distributions of the pair of tracks, where the particles have been assumed to be massless (so as to maximize the probability of faking by Drell-Yan final states). Two out of the four benchmark points have been chosen in each case, from which the general features are obvious.

It is clear from Fig. 3 that most of the background muons are concentrated in the region of relatively low p_T . Therefore, an additional p_T cut of 200 GeV has been

imposed, which suppresses the background significantly. In addition, a further cut on invariant mass on the pair of charged tracks, namely, $m_{\tilde{t}_1\tilde{t}_1} > 1100 \text{ GeV}$, completely removes the dimuon background. Note that the stop mass is unknown here, and the invariant mass is calculated from the track momentum, assuming that it is a massless particle. As the results demonstrate, this provides an effective event selection criteria for the signal. Thus a clean signature of the quasistable stop pair is obtained with an integrated luminosity $\int \mathcal{L} dt = 1 \text{ fb}^{-1}$ at the LHC,⁴ as can be seen from Table III. As the same table shows, it is more efficient to use the combination of the $(p_T + m_{\tilde{t}_1\tilde{t}_1})$ cuts than just a higher p_T cut of 520 GeV, which is the softest one with which the background is completely gone.

The single-track events, on the contrary, are associated with missing E_T , assuming that the energy deposited by such superheavy neutral hadrons in the hadron calorimeter is negligible.⁵ The p_T distribution of the track is the same as in Fig. 3. Interestingly, a very similar distribution is

⁴In fact, if the detectors are well understood, even a luminosity of 100 pb^{-1} would be enough.

⁵Similar conclusions are drawn about the R hadrons formed by long-lived gluinos in theories such as split supersymmetry.

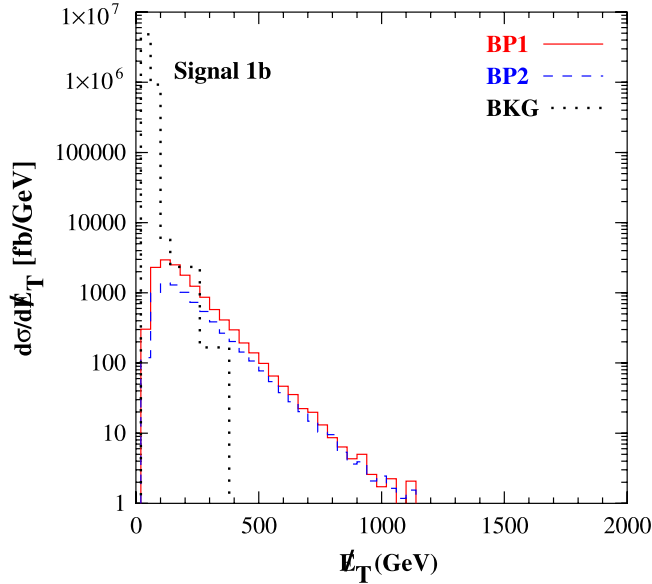


FIG. 4 (color online). \cancel{E}_T distributions with basic cuts for signal 1b. Red (solid line) and blue (dashed line) histograms are for signals BP1 and BP2 and black (dotted line) histogram is for the standard model background.

expected for \cancel{E}_T in this case (Fig. 4), allowing deviations due to p_T measurement only.

Elimination of SM backgrounds (mostly from single W production) can be done by a procedure similar to the previous case. In this case, one can apply a \cancel{E}_T cut. The results are shown in Table III. One can see that there are more signal events with zero background now. The reasons are (a) factor 2 enhancement for the one charged track and one neutral track, (b) the absence of any isolation requirements and (c) the \cancel{E}_T cut replacing the invariant mass cut for two charged tracks.

One may, however, like to ensure that these tracks are traced out by a colored particle such as a stop and not, for example, a pair of stable staus. With this in view, we have also considered the production of stop tracks in cascades originating in gluino pair production at the LHC, whose very nature distinguishes the tracks as those of squarks and not sleptons.

B. Charged tracks from gluino production

In order to establish that these tracks are really due to stops (and not staus), we have studied signals 2 (with a single charged track) and 3 (with two charged tracks) listed in Table II. Such signals can arise from gluino (\tilde{g}) pair production, where both of the gluinos decay into a (lighter) stop and a top, i.e. $\tilde{g} \rightarrow \tilde{t}_1 t$. The different final state topologies arise due to leptonic or hadronic decays of the W . For example, in the cases of signals 2a and 3a both the W 's decay leptonically, for 2b and 3b one W decays leptonically whereas the other decays hadronically and, finally, in the cases of 2c and 3c both the W 's decay hadronically.

Thus from each top we will get either one b jet, one lepton and missing energy (due to neutrinos) or one b jet and two other jets from the hadronic decay of a W . The decay products of the two top quarks produced in association with the stops establish the bona fide of the stop tracks. Although they are not considered here, characteristic final states can be similarly chosen to identify a sbottom NLSP.

It should be remembered, however, that the gluino-induced signals are not as abundant as in the previous case. The main reason for this is that we have assumed gaugino universality in our study. With such an assumption, when the lightest neutralino is required to be heavier than the lighter stop [whose mass in turn has to be at least about 250 GeV from the Collider Detector at Fermilab (CDF) limits], the corresponding gluino mass is rather high, leading to detectable but relatively small cross sections.⁶ The rates are further suppressed by branching ratios for specific decays (with one or two leptons in final state) and the acceptance cuts. Thus, in spite of the rather spectacular nature of the proposed signal, one has to struggle against statistics in general, and higher luminosity is required. With this in view, we have made all predictions for this class of signals with an integrated luminosity of 300 fb^{-1} .

The results of our analysis are presented in Tables IV and V. The major sources for the backgrounds are trigauge bosons productions and $t\bar{t}l^+l'^-$ (in the case of two charged tracks), $t\bar{t}l\nu$ (in the case of one charged track).

We work with the same basic cuts for these signals as mentioned in the previous subsection. In order that we are not inhibited by efficiency factors, we give up b tagging, which is not a serious disadvantage, in view of the multiplicity of leptons (or muonlike tracks) in the final state. In addition, we impose the following cuts:

- (i) Each *jet* should have $p_{Tj} > 50 \text{ GeV}$ and $|\eta_j| \leq 2.7$.
- (ii) $\Delta R_{\tilde{t}_1 j} \geq 0.4$.
- (iii) $\Delta R_{lj} \geq 0.4$.
- (iv) Events must have missing energy $E_T > 30 \text{ GeV}$.

Figures 5 and 6 contain plots of the transverse momentum of the \tilde{t}_1 and the scalar sum of the transverse momenta of all visible particles for signals 2a–c (each with two charged tracks). Similarly, missing energy distributions for signals (3a–c) with one charged track are shown in Fig. 7. The corresponding plots for the background are also shown.

It is found that a cut on the scalar sum of transverse momenta of visible particles, namely, $\Sigma p_T > 800, 1200$ and 1500 GeV , removes the background completely in the cases of signals 2a, 2b and 2c, respectively. The corresponding requirement in the case of each of signals 3a–c is a missing energy cut of $\cancel{E}_T > 600 \text{ GeV}$. The efficiency of these cuts for all the four benchmark points is demon-

⁶As mentioned earlier, nonuniversal gaugino masses could improve the situation dramatically.

TABLE IV. The number of events after various cuts for signals 2a–c at the LHC. The integrated luminosity is assumed to be 300 fb^{-1} . Symbols have their usual meaning. The b -tagging efficiency is not folded in.

Signal	Cuts	BP1	BP2	BP3	BP4	BKG
2a	Basic	11	7	4	2	33
2a	Basic + $\Sigma p_T \geq 800 \text{ GeV}$	11	7	4	2	0
2b	Basic	20	12	6	4	48
2b	Basic + $\Sigma p_T \geq 1200 \text{ GeV}$	20	12	6	4	0
2c	Basic	35	25	14	9	98
2c	Basic + $\Sigma p_T \geq 1500 \text{ GeV}$	34	25	14	9	0

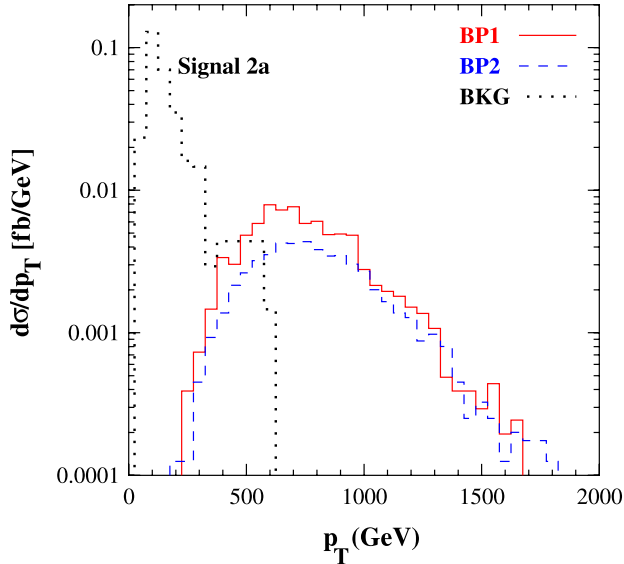


FIG. 5 (color online). p_T (of the harder track) distributions with basic cuts for signal 2a. Red (solid line) and blue (dashed line) histograms are for BP1 and BP2 and black (dotted line) histogram is for the standard model background. Symbols have their usual meaning.

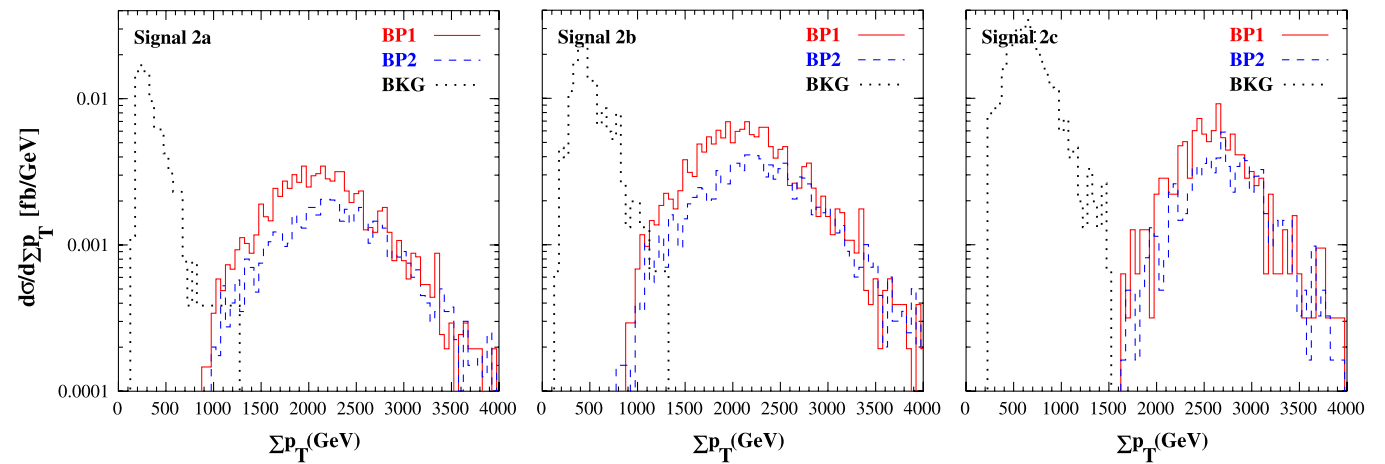


FIG. 6 (color online). Scalar summed p_T distributions with basic cuts for signals 2a–c. Red (solid line) and blue (dashed line) histograms are for BP1 and BP2 and black (dotted line) histogram is for the standard model background in all the plots. Symbols have their usual meaning.

strated in Table IV for signals 2a–c and in Table V for signals 3a–c. It should be noted that the low event rate due to branching fraction suppression implies that such signals require $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$. Clearly, b tagging will destroy the detectability of BP4, but not for the other benchmark points in the case of signals 2a–c and 3a.

C. Gluino mass reconstruction

Since the quasistable stop is visible in this scenario, a variant of the signal discussed in the previous subsection can be used for the direct reconstruction of the gluino mass. Note that this is very difficult to achieve in the minimal SUGRA scenarios on account of the fact that each supersymmetric production event results in a pair of (invisible) LSPs being produced.

The dominant decay mode involves both tops going hadronically, resulting in as many as six jets along with stop track(s) and/or missing transverse energy. Although it is possible, in principle, to use such a final state for this purpose, it is normally beset with problems and the attendant loss in accuracy. In our study, therefore, we shall omit this channel altogether and concentrate on subdominant modes even at the cost of signal strength. In other words, we only consider the case where, of the two top quarks produced from a gluino pair, one decays hadronically and the other leptonically.

1. Two stop tracks

If both stops hadronize into charged tracks, the signal becomes

$$pp \longrightarrow 2 \text{ stop tracks} + 1 \text{ lepton} + 2b + 2 \text{ jets} + \cancel{E}_T.$$

The successful removal of backgrounds due to $t\bar{t}l\nu_l$, and also the suppression of a rather sizable combinatorial background, prompt us to advocate b tagging in this case.

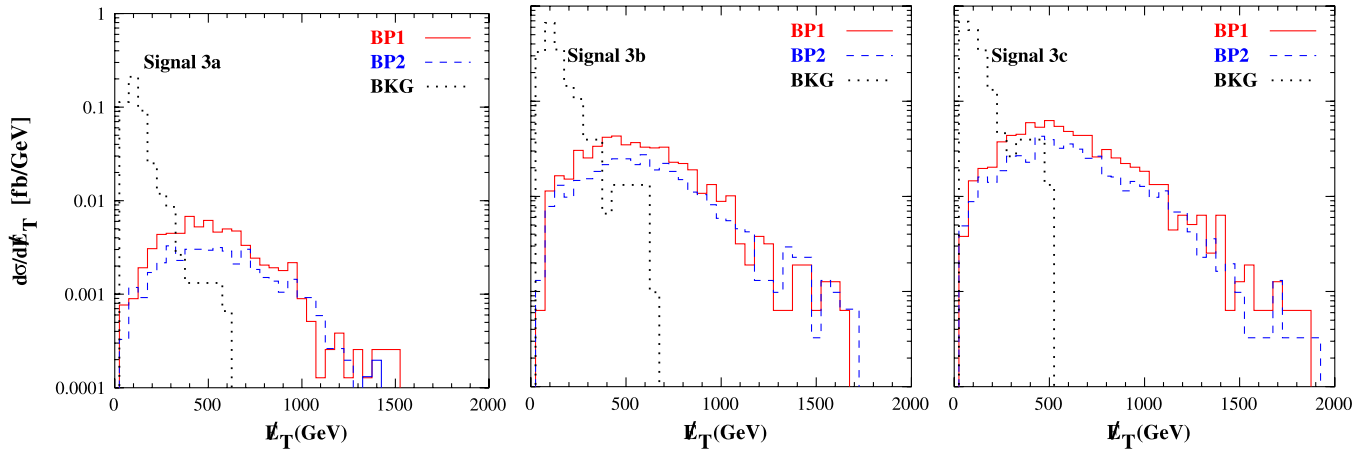


FIG. 7 (color online). \cancel{E}_T distributions with basic cuts for signals 3a–c. Red (solid line) and blue (dashed line) histograms are for BP1 and BP2 and black (dotted line) histogram is for the standard model background in all the plots. Symbols have their usual meaning.

To be able to reconstruct the gluino mass, we need to assume that the entire missing transverse energy in such events accrues from a single invisible particle in the final state, namely, the neutrino. Using energy and momentum balance in the transverse plane, and the fact that the neutrino arises from a W (of known mass), one can then reconstruct the longitudinal component of the neutrino momentum (and, thus, of the W) up to a twofold ambiguity. The second W is completely reconstructed through hadronic decays. This, then, allows us to reconstruct both the tops without any ambiguity (on insisting that the two tops thus reconstructed should have the same mass up to measurement and resolution uncertainties).

Next, we face a further combinatorial ambiguity, namely, that arising from the correct identification of the top-stop pairings. Note, though, that the charge of each stop track is measurable and that a $\tilde{t}(\tilde{t}^*)$ would, in general, be associated with a positively (negatively) charged track. Thus, if the lepton were positively (negatively) charged, the corresponding top (antitop) should be paired with a negatively (positively) charged track. However, since the gluino is a Majorana fermion, both stop tracks can be of the same charge in 50% of the cases. This uncertainty as well as a twofold ambiguity due to the neutrino can be removed

TABLE V. The number of events after various cuts for signals 3a–c at the LHC. The integrated luminosity is assumed to be 300 fb^{-1} . Symbols have their usual meaning.

Signal	Cuts	BP1	BP2	BP3	BP4	BKG
3a	Basic	21	13	7	4	140
3a	Basic + $\cancel{E}_T \geq 600 \text{ GeV}$	8	6	4	2	0
3b	Basic	155	102	55	32	519
3b	Basic + $\cancel{E}_T \geq 600 \text{ GeV}$	62	42	28	18	0
3c	Basic	236	148	79	49	558
3c	Basic + $\cancel{E}_T \geq 600 \text{ GeV}$	94	64	45	31	0

by demanding that the two gluino masses, thus reconstructed, should not differ by more than 50 GeV. In this manner, one can throw out the wrong combinations and reconstruct the gluino peak.

We may now use the same basic cuts as those suggested in the previous subsection. To make the reconstruction as clean as possible, we require $\sum p_T > 1200 \text{ GeV}$. Table V shows that the backgrounds can still be eliminated by this method, although the number of events is less than in the previous case, due to b tagging (with an assumed efficiency of 60% [26]).

The results of this procedure for two of our four benchmark points are presented in Fig. 8, which show that the gluino mass can be reconstructed with about 10% uncertainty. The event rates corresponding to the two remaining benchmark points are even lower (as seen in Table IV).

On the whole, though the method described above works in principle (and, barring the 6-jet final state, is perhaps the best option) for the said channel, it suffers from the problem of poor statistics. To enhance the number of events, we now explore the other channel, namely, where one of the two stops from gluino decay is invisible, and investigate its usefulness in gluino mass reconstruction.

2. One stop track

With one stop going to a charged supersymmetric hadron and the other into a similar neutral hadron, the number of events in this channel would be at least twice as many as in Sec. III B. The signal now is

$$pp \longrightarrow 1 \text{ stop track} + 1 \text{ lepton} + 2b + 2 \text{ jets} + \cancel{E}_T,$$

where the missing transverse energy now has two irreducible sources, namely, the neutral s hadron and the neutrino from the top decay. Once again, b tagging is needed.

The reconstruction of the hadronically decaying top proceeds as in the previous subsection. For obvious rea-

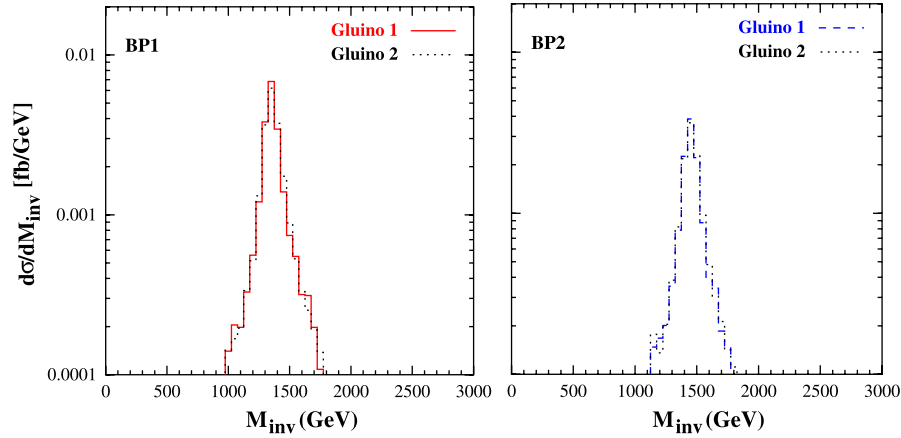


FIG. 8 (color online). Reconstructed invariant mass peaks for two gluinos for BP1 and BP2 in the signal $pp \rightarrow 2$ charged track + 1 lepton + $2b + 2$ jets + \cancel{E}_T .

sons, the reconstruction of the leptonically decaying W , and hence the parent (second) top, cannot be done now. The key step, then, is to decide whether the reconstructed top came from the same gluino as the visible stop track. In the absence of such a decision algorithm, the naive procedure would be to forcibly associate the two and consider the resultant invariant mass. The “correct” cases (where the $b + 2$ jets system yields the top mass), then, would be expected to lead to a concentration of events near the true mass (modulo resolution effects), while the wrong identifications would lead to a scattered distribution. The resultant is displayed in Fig. 9.

Were gluinos not Majorana particles [27], the situation could have been easily improved by the charge identification method suggested above. Note that the sign of the charge of the visible stop track is easily measurable and corresponds almost uniquely to the charge of the stop. Similarly, the sign of the lepton uniquely determines the sign of the top decaying leptonically. Thus, for the stop track to have arisen from the same parent Dirac gluino as

the reconstructed top, the sign of its charge would have to be the same as that of the lepton. Unfortunately, though, the Majorana nature of the gluino precludes such an association, and the opposite charge combination (for stop and lepton) is as likely to occur as the same-sign one.

We may now attempt to combine the significance of both methods to get the final resolution on the gluino mass. It should be noted that the stop track has been assigned zero mass in the reconstruction algorithm, in spite of which the peaks are recovered quite accurately, modulo the statistics in each case.

IV. SUMMARY AND CONCLUSION

We have investigated the signals of a stop NLSP in a scenario where the LSP is a right sneutrino, with the stop decay into the LSP taking place outside the detector. After convincing ourselves that such a scenario can arise in SUGRA with nonuniversality in third family sfermion masses, we have identified a few benchmark points, allowed by all the electroweak and dark matter constraints,

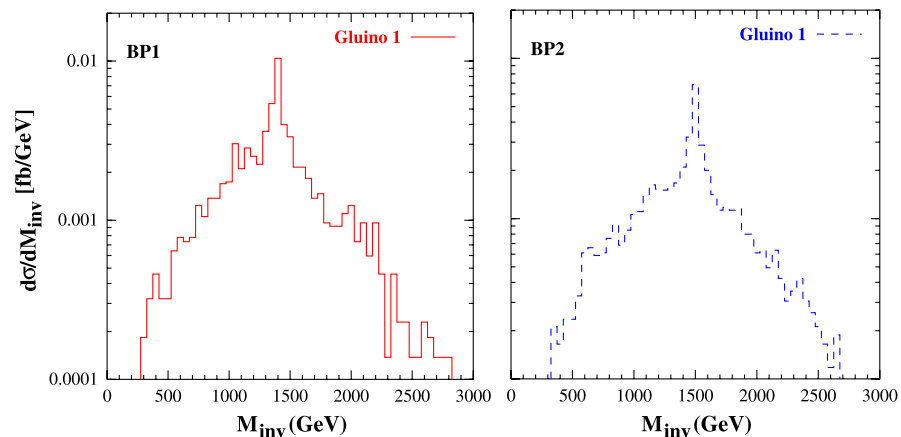


FIG. 9 (color online). Reconstructed invariant mass for one gluino for BP1 and BP2 in the signal $pp \rightarrow 1$ charged track + 1 lepton + $2b + 2$ jets + \cancel{E}_T .

where the long-lived stop NLSP can be visible in the form of charged tracks in the muon chamber. We have analyzed different signatures of such tracks at the LHC, suggesting acceptance cuts with which one can remove standard model backgrounds effectively. Final states with *two charged tracks* (where a pair of stops both hadronize into charged hadrons) and those with *one visible track* have been studied in this spirit. It is found that one can have enough signal events with no background, with an integrated luminosity of 1 fb^{-1} or even less, so that such a new physics signal cannot be missed.

In fact, even for the initial run of the LHC at 10 TeV, there is hope for having the first hints of such a scenario if it exists. For BP1, for example, our estimate predicts about 5 events for signal 1a, and for BP2, 4 events, with $\sqrt{s} = 10 \text{ TeV}$, an integrated luminosity of 100 pb^{-1} and the same cuts as reported earlier. For signal 1b, about twice as many events in each case can be expected. Since a reduction in the center-of-mass energy means the tracks are slightly softer, the background is absent in these cases even with the same cuts. Thus signals 1a and 1b are predicted at the discovery level for the 10 TeV run, if $\int \mathcal{L} dt = 100 \text{ pb}^{-1}$ is attained.

Moreover, the stop track can be distinguished from a slepton or stau track (or that of a long-lived squark of the first two families) through gluino decay into a top and a stop, and stable tracks produced in association with a pair of top quarks. However, for the region of parameter space that is phenomenologically consistent, the event rate is smaller than that in the previous case, and one may require an integrated luminosity of 300 fb^{-1} . It is also possible to use the long-lived stops to reconstruct the gluino mass, so long as it is within about 1.5 TeV.

It should also be borne in mind that the rather poor statistics expected in the channel used for gluino recon-

struction are due to the fact that we are adhering to a scenario with gaugino mass unification. The unification conditions require the gluino to be rather heavy, and therefore the production rates correspondingly suppressed, since the lightest neutralino (to whose mass the gluino is related by the unification condition) is to be higher than the lighter stop. However, such a restriction does not apply to a situation where either gaugino universality is absent or the grand unification group is broken by some nontrivial representation [28]. A relatively lighter gluino in any of these “nonuniversal” cases is bound to push up the event rates for gluino pair production considerably, and one has much better hopes of their reconstruction if a sneutrino LSP scenario prevails. In fact, this is one reason why we have discussed our suggested reconstruction techniques so elaborately.

Further study related to spin measurement of such a stop NLSP can be worthwhile, thus providing clues on whether the tracks can be faked by some long-lived fermion. However, such a study is beyond the scope of the present work.

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