Chapter 4

Neutralino mass reconstruction

4.1 Introduction

Measurement of mass of the superparticle, if SUSY at all exists at the TeV scale, will be a crucial objective of physicists at the LHC. In general, mass measurement at the LHC is one of the most challenging task when large $E_T$ is the only signature of SUSY. However, as we have mentioned earlier when the NLSP is a charged particle and stable at the length scale of the detector, it is possible to reconstruct the masses of the superparticles by studying the details kinematics of the final state.

We have considered the mass reconstruction of the neutralinos [1] in the scenario where $\tilde{\nu}_R$ is the LSP and $\tilde{\tau}$ is the NLSP. Measurement of neutralino masses can give some hints about the gaugino mass ratio at the low scale, which in turn may points towards some high-scale relation between the gaugino masses.

Neutralinos are produced in SUSY cascade via the cascade decay of squarks and gluinos. The neutralino further decays into a $\tilde{\tau}\tilde{\tau}$ pair. It is to be noted that, although we have worked under an mSUGRA framework for economy of param-
eters, the cascades that lead to our desired final state are quite generic in SUSY models.

\[ \tilde{q} \tilde{\chi}^0 \tilde{\tau}^\pm \]

\[ \tilde{q} \tilde{\chi}^0 \tilde{\tau}^\pm \]

Figure 4.1: Schematic diagram of a typical SUSY cascade for reconstruction of the neutralinos.

We use the technique of tau reconstruction for this purpose. Often on-shell intermediate states are helpful here (and in the subsequent two chapters as well) in reconstructing various masses. Also, we depend neither on ionisation energy-loss nor on time delay for extracting the mass of the stable stau, but rather obtain it using an algorithm that depends on event-by-event information on two taus and two stable tracks in the final state.

In section 4.2, we discuss the choice of benchmark points used for demonstrating our claims, in the context of a supergravity scenario. The signal looked for, the corresponding standard model backgrounds and the event selection criteria chosen by us are discussed in section 4.3. Section 4.4 contains discussions on the various steps in reconstructing neutralinos. The regions in the $m_0 - m_{1/2}$ plane in a SUGRA scenario, where neutralino reconstruction is possible in our method, are also pointed out in this section. We summarise and conclude in section 4.5.

### 4.2 Choice of benchmark points

We try to identify regions of the parameter space, where neutralinos decaying into a tau and a stau can be reconstructed, through the reconstruction of the tau and the detection of the stau in the muon chamber. The rates for electroweak production of neutralinos are generally rather low for this process. Therefore, the
procedure works better when neutralinos are produced from the cascade decays of squarks and gluinos. This is in spite of the additional number of jets in such processes, which may fake the tau in certain cases and complicate the analysis of the signals. We are thus limited to those regions of the parameter space, where the gluino and squark production rates are appreciable, and therefore the value of $m_{1/2}$ is not too high.

With all the above considerations in mind, we concentrate on the lighter stau ($\tilde{\tau}_1$) to be the NLSP with lifetime large enough to penetrate collider detectors like the muons themselves. Using the spectrum generator of ISAJET 7.78 [2], we find that a large mSUGRA parameter space can realise this scenario of a right-sneutrino LSP and stau NLSP, provided that $m_0 < m_{1/2}$ and one has $\tan\beta$ in the range $\gtrsim 25$, 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 4.1 we identify a few benchmark points, all within a SUGRA scenario with universal scalar and gaugino masses, characterised by long-lived staus at the LHC.

In the next section we use these benchmark points to discuss the signatures of the stau NLSP at the LHC and look for the final states in which it is possible to reconstruct the neutralinos.

### 4.3 Signal and backgrounds

The signal which we have studied as a signature of stau NLSP and motivated by the possible reconstruction of the neutralinos from the final state, is given by

- $2\tau_j + 2\tilde{\tau}(\text{charged } - \text{track}) + E_T + X$

where $\tau_j$ denotes a jet out of a one-prong decay of the tau, $E_T$ stands for missing transverse energy and all accompanying hard jets arising from cascades are included in $X$. The $E_T$, of course, consists of two neutrinos out of tau decays in the final state.

We have simulated pp collisions with a centre-of-mass energy $E_{CM} = 14TeV$. The prediction of events assumes an integrated luminosity of 300 $fb^{-1}$. The signal and various backgrounds are calculated using PYTHIA (version-6.4.16) [3]. Numerical values of various parameters, used in our calculation, are as follows [4]:

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\[ M_Z = 91.2 \text{ GeV} \quad M_W = 80.4 \text{ GeV} \quad M_t = 171.4 \text{ GeV} \quad M_H = 120 \text{ GeV} \]
\[ \alpha^{-1}_\text{em}(M_Z) = 127.9 \quad \alpha_s(M_Z) = 0.118 \]

We have worked with the CTEQ5L parton distribution function [5]. The factorisation and renormalisation scales are set at \( \mu_F = \mu_R = m_{\text{final}} \), average mass of the final state particles produced in the initial hard scattering. In order to make our estimate conservative, the signal rates have not been multiplied by any K-factor [6], while the main background, namely, that from \( t\bar{t} \) production, has been multiplied by a K-factor of 1.8 [7]. The effects of initial state radiation (ISR) and final state radiation (FSR) have been considered in our study.

### 4.3.1 Signal subprocesses:

We have studied all SUSY subprocesses leading to the desired final states. Neutralinos are mostly produced in cascade decays of strongly interacting sparticles. The dominant contributions thus come from

- **gluino pair production**: \( pp \to \tilde{g} \tilde{g} \)
- **squark pair production**: \( pp \to \tilde{q}_i \tilde{q}_j, \tilde{q}_i \tilde{q}^*_i \)
- **associated squark-gluino production**: \( pp \to \tilde{q} \tilde{g} \)

In addition, electroweak pair-production of neutralinos can also contribute to the signal we are looking for. The rates are, however, much smaller [see Table 4.2]. Moreover, the relatively small masses of the lightest and the second lightest neutralinos (as compared to the squarks and the gluino) cause the signal from such subprocesses to be drastically reduced by the cut employed by us on the scalar sum of all visible \( p_T \)'s. For example, for benchmark point 1 (BP1), one has less than 5% of the total contribution from electroweak processes.

The production of squarks and gluinos have potentially large cross sections at the LHC. For all our benchmark points listed in Table 4.1, the gluino is heavier than the squarks. Thus its dominant decay is into a squark and a quark. \( \chi_1^0 \) being mostly \( \tilde{B} \) dominated the main contribution to \( \chi_1^0 \) production comes from the decay of right handed squarks \( (\tilde{q}_R) \) and its decay branching ratio into the \( \tau^-\tau^+ \) pair is almost 100% when it is just above the lighter stau in the spectrum. On the other hand, the \( \chi_2^0 \) is mostly \( \tilde{W}_3 \)-dominated, and therefore the main source of its production is cascade decay of left-chiral squarks \( (\tilde{q}_L) \). Such a \( \chi_2^0 \) can also decay...
into a $\tilde{\tau}$-$\tau$ pair.

If one can obtain complete information on the four-momentum of the $\tilde{\tau}$ and the $\tau$, then it is possible to reconstruct both $\chi^0_1$ and $\chi^0_2$ using the final state mentioned above. The other two heavier neutralinos ($\chi^0_3$ and $\chi^0_4$), due to their low production rate and small decay branching ratios into the $\tilde{\tau}$-$\tau$ pair, are relatively difficult to reconstruct.

4.3.2 Background subprocesses:

The standard model background to $2\tau_j + 2\tilde{\tau} + E_T$ comes mainly from the following subprocesses:

- **$t\bar{t}$ production, $t\bar{t} \rightarrow bWbW$:**
  Where two of the resulting jets can be faked as a tau-jet, and muons can come from the W’s. One can also have a situation in which any (or both) of the b-quark decays semileptonically ($b \rightarrow c\mu\nu_{\mu}$) and any (or both) of the W decays to a $\tau - \nu_{\tau}$ pair. Though the efficiency of a non-tau jet being identified as a narrow tau-like jet is small (as will be discussed in a later section), and it is very unlikely to have isolated muons from semileptonic decays of the b, the overwhelmingly large number of $t\bar{t}$ events produced at the LHC makes this subprocess quite a serious source of backgrounds.

- **$Z^0$-pair production, $ZZ \rightarrow 2\tau + 2\mu$:**
  This subprocess also gives an additional contribution to the background, when one Z decays into a $\tau\tau$ pair and the other one into a pair of muons.

- **Associated ZH-production, $ZH \rightarrow 2\tau + 2\mu$:**
  This subprocess, though have a small cross-section, can contribute to the background through the decay of $H \rightarrow \tau\tau$ and $Z \rightarrow \mu\mu$, which can fake our signal as well.

The additional backgrounds from $t\bar{t}W$, $t\bar{t}Z$ and Z+jets can be suppressed by the same cuts as those described below. Also a higher non-tau-jet rejection factor and Z invariant mass cut can reduce the $t\bar{t}Z$ and Z+jets backgrounds considerably.
4.3.3 Event selection criteria:

In selecting the candidate events selected for neutralino reconstruction, we choose the two highest-$p_T$ isolated charged tracks showing up in the muon chamber, both with $p_T > 100$ GeV, as stable staus (see the detailed discussion later in this section.). The isolation criteria for the tracks are shown in Table 4.3. In addition to the $p_T$ cut, the scalar sum of all jets and lepton in each event is required to be greater than 1 TeV. It is clear from Figures 4.2 and 4.3 that the standard model backgrounds are effectively eliminated through the above criteria. In addition, we require two τ-jets with $p_T > 50$ GeV, and $E_T > 40$ GeV for each event. The justification for both of these cuts is provided when we discuss τ-tagging and reconstruction.

The isolation and 3-momentum reconstruction of the charged track at the muon chamber is done following the same criteria and procedure as those for muons.

![Figure 4.2](image1.png)

Figure 4.2: $p_T$ distribution (normalised to unity) of the muon like track for the signal and the background, for all benchmark points. The vertical lines indicate the effects of a $p_T$ cut at 100 GeV.

In order to obtain the invariant mass of a tau-stau pair, one needs to extract information on the mass of the stable charged particle (the stau in our context). While standard techniques such as time delay measurement or the degree of ionisation produced has been suggested in a number of earlier works [8], we extract mass information from an event-by-event analysis which is reported in the next.
section. The efficiency for the reconstruction of staus has been taken to be the same as that of muons with $p_T > 10$ GeV in the pseudorapidity range $|\eta| < 2.5$, and is set at 90% following [9].

**τ-jet tagging and τ-reconstruction:**

τ-jet identification and τ-reconstruction are necessary for both background reduction and mass reconstruction of the neutralinos. We have concentrated on hadronic decays of the τ in the one-prong channel. These are jet-like clusters in the calorimeter containing a relatively small number of charged and neutral hadrons. A τ decays hadronically about 65% of the time, producing a τ-jet. The momentum of such a jet in the plane transverse to the parent τ is small compared to the τ-energy, so long as the $p_T$ of the τ-jet is large compared to the tau mass. In this limit, hadronic τ decays produce narrow jets collinear with the parent τ. The neutrinos that carry missing $E_T$ also have the same direction in this limit. This gives one a handle in reconstructing the τ’s, if one selects events where no other invisible particle is likely to be produced.

Given the masses of the SUSY particles in our benchmark scenarios, the τ’s produced out of neutralino decay are hard enough, so that one can simulate τ-decays in the collinear approximation described above. A detailed discussion

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1We have not considered the leptonic decay of τ, as it is difficult to identify lepton coming from τ decay to that coming from cascade decay of other objects like heavy quarks or W’s
on the procedure followed for complete reconstruction of a pair of $\tau$’s is found in [10]. We have selected hadronic jets with $E_T > 50$ GeV as candidate products of $\tau$-decay. A rather conservative non-tau jet rejection factor of 20 has been assumed, while the identification efficiency of a true tau-jet has been assumed to be 50% following [11, 12].

To describe the procedure in brief, one can fully reconstruct the $\tau$ by knowing $x_{\tau_i}$ ($i = 1, 2$), the fractions of the parent $\tau$-energy carried by each product jet. Here $i = 1, 2$ represent the two branches of cascades that lead to the two $\tau$’s. The two unknowns can be solved from the two components of the missing transverse momentum ($\vec{p}_T$) of a particular event.

If $p_{\mu i}, p_{\mu hi}$ are, respectively the components of four-momentum of the parent $\tau$ and the collinear jet produced from it ($i = 1, 2$), then

$$p_{\mu hi} = x_{\tau hi} p_{\mu i} \quad (\mu = 0, 1, .., 4)$$

(as $E_\tau \approx |\vec{p}_\tau|$, in the limit $m_\tau \to 0$)

and one can write

$$\vec{p}_T = (\frac{1}{x_{\tau h1}} - 1) \vec{p}_{h1} + (\frac{1}{x_{\tau h2}} - 1) \vec{p}_{h2}$$

This yields two conditions for $x_{\tau hi}$. Solving them, one obtains the $\tau$ four-momenta as $p_{\mu hi}/x_{\tau hi}$, from the knowledge of the energy and momenta of the resulting jets. In practice, as will be discussed below, the recorded missing momentum, $\vec{p}_{T \text{rec}}$, is different from the true one, namely, $\vec{p}_{T \text{true}}$. This error can lead to unphysical solutions for the reconstructed $\tau$-momenta in some cases. Such a situation often arises when the two taus are produced back-to-back. This in turn means that the $\tau$-neutrino’s are also produced back-to-back in the collinear approximation. This reduces the magnitude of $\vec{p}_T$, when errors due to mismeasurements can lead to unphysical solutions. This is sometimes avoided by leaving out back-to-back orientation of the two $\tau$-jet candidates, with some tolerance. In our analysis, a minimum value for $E_T$ ($\approx 40$ GeV) and positivity of $x_{\tau hi}$’s have been imposed as necessary conditions, in order to minimise the number of unphysical solutions. Besides, $p_T > 50$ GeV for each $\tau$-jets ensures the validity of the collinear approximation in $\tau$-decays. The $\tau$-identification efficiency and the jet rejection factor are also better optimized with this $p_T$-cut [11, 12].
Of course, with a jet rejection factor of 1/20, one cannot rule out the possibility of QCD jets masquerading as τ’s, in view of the huge number of QCD events at the LHC. Such fakes constitute irreducible backgrounds to the τ-reconstruction procedure. However, as we shall see in the numerical results presented in the next section, triggering on the rather strikingly spectacular properties of the quasi-stable stau-pair enables one to filter out the genuine events in the majority of cases.

**Reconstruction of \( \vec{p}_T \):**

It is evident from the above observations that the reconstruction of \( \vec{p}_T \) is very crucial for our study. The reconstructed \( \vec{p}_T \) differs considerably from true \( \vec{p}_T \), due to several reasons. The true \( \vec{p}_T^{true} \) is related to the experimentally reconstructed \( \vec{p}_T^{rec} \) by the following relation

\[
\vec{p}_T^{rec} = \vec{p}_T^{true} + \vec{p}_T^{Forw} + \vec{p}_T^{< 0.5}
\]

where \( \vec{p}_T^{Forw} \) corresponds to the total transverse momentum carried by the particles escaping detection in the range \(|\eta| > 5\) and \(\vec{p}_T^{< 0.5}\) corresponds to the total transverse momentum carried by the particles in the range \(|\eta| < 5\) with \(p_T < 0.5\) GeV\(^2\), which contributes to the true \( \vec{p}_T \). In addition to this, mismeasurement of the transverse momenta for jets, leptons etc. alters the true \( \vec{p}_T \) by a sizable amount. This is due to the finite resolution of detectors, and is handled in theoretical predictions by smearing the energy/momentum of a particle through a Gaussian function.

In our study, we have tried to reconstruct \( \vec{p}_T \), taking into account all the above issues. The missing transverse momentum in any event is defined as

\[
\vec{p}_T = -\Sigma \vec{p}_{T}^{visible}
\]

where the \( \Sigma \vec{p}_{T}^{visible} \) consists of isolated leptons/photons/jets and also those objects which do not belong to any of these components but are detected at the detector, constituting the so called ‘soft part’ or the ‘unclustered component’ of the visible momentum. We describe below the various components of the visible \( \vec{p}_T \), and their respective resolution functions.

**Resolution effects:**

Among the finite resolution effects of the detector, taken into account in our analysis, most important are the finite resolutions of the electromagnetic and

\(^2\)The threshold is 0.5 GeV for CMS and 1 GeV for ATLAS.
hadron calorimeters, and the muon track resolution. Since the kind of final state we are dealing with does not require any isolated electrons/photons, we have not considered electron or photon resolution. The electrons/photons which are not isolated but have $E_T \geq 10$ GeV and $|\eta| < 5$ have been considered as jets and their resolution has been parametrised according to that of jets. Jets have been defined within a cone of $\Delta R = 0.4$ and $E_T \geq 20$ GeV using the PYCELL fixed cone jet formation algorithm in PYTHIA. Since the staus are long-lived and leave charged tracks in the muon chamber, their smearing criteria have been taken to be the same as those of isolated muons. Though one can describe the resolution of the track of staus and muons by different resolution functions (as $m_{\tilde{\tau}} >> m_{\mu}$), one does not envision any significant deviation in the prediction of events via such difference. Therefore, in the absence of any clear guidelines, we have treated them on equal footing, as far as the Gaussian smearing function is concerned. The tracks which show up in the muon chamber, but are not isolated, having $E_T > 10$ GeV and $|\eta| < 2.5$, have been considered as jets and smeared accordingly.

All the particles (electron, photon, muon, and stau) with $0.5 < E_T < 10$ GeV and $|\eta| < 5$ (for muon or muon-like tracks, $|\eta| < 2.5$), or hadrons with $0.5 < E_T < 20$ GeV and $|\eta| < 5$, which constitute ‘hits’ in the detector, are considered as soft or unclustered components. Their resolution functions have been considered separately. We present below the different parametrisation of the different component of the final state, assuming the smearing to be Gaussian in nature.

- **Jet energy resolution**:

\[
\sigma(E)/E = a/\sqrt{E} \oplus b \oplus c/E
\]  

(4.2)

where

\[
\begin{align*}
a &= 0.7 \text{ [GeV}^{1/2}\text{]}, & b &= 0.08 & c &= 0.009 \text{ [GeV]} & \text{for } |\eta| < 1.5 \\
&= 1 & = 0.1 & = 0.009 & 1.5 < |\eta| < 5
\end{align*}
\]

- **Muon/Stau $p_T$ resolution**:

\[
\sigma(p_T)/p_T = a \quad \text{if } p_T < \xi
\]

(4.3)

\[
= a + b \log(p_T/\xi) \quad \text{if } p_T > \xi
\]

(4.4)
where
\[ a = 0.008, \quad b = 0.037 \quad \text{and} \quad \xi = 100 \, \text{[GeV]} \quad \text{for} \quad |\eta| < 1.5 \]
\[ = 0.02 \quad = 0.05 \quad \xi = 100 \quad 1.5 < |\eta| < 2.5 \]

- **Soft component resolution:**

\[ \sigma(E_T) = \alpha \sqrt{\sum E_{T}^{(\text{soft})}} \]  
(4.5)

with \( \alpha \approx 0.55 \). One should keep in mind that the x and y component of \( E_{T}^{\text{soft}} \) need to be smeared independently.

It is of great importance to ensure that the stable \( \tilde{\tau} \) leaving a track in the muon chamber is not faked by an actual muon arising from a standard model process. As has been mentioned in section 4.3.3, we have found certain kinematic prescriptions to be effective as well as reliable in this respect. In order to see this clearly, we present the \( p_T \)-distributions of the harder muon and the \( \tilde{\tau} \)-track in Figure 4.2. The \( \tilde{\tau}-p_T \) clearly shows a harder distribution, owing to the fact that the stau takes away the lion’s share of the \( p_T \) possessed by the parent neutralino. Another useful discriminator is the scalar sum of transverse momenta of all detected particles (jets, leptons and unclustered components). The distribution in \( \Sigma |\vec{p}_T| \), defined in the above manner, displays a marked distinction for the signal events, as shown in Figure 4.3. The cuts chosen in Table 4.3 have been guided by both of the above considerations. They have been applied for all the benchmark points, as also for the background calculation.

### 4.4 Numerical results and neutralino reconstruction:

#### 4.4.1 The reconstruction strategy

Having obtained the \( \tau \) four-momenta, the neutralinos can be reconstructed, once we obtain the energy of the \( \tilde{\tau} \)'s whose three-momenta are already known from the curvature of the tracks in the muon chamber. For this, one needs to know the \( \tilde{\tau} \)-mass. In addition, the requirements are, of course, sufficient statistics, minimisation of errors due to QCD jets faking the \( \tau \)'s, and the suppression of combinatorial backgrounds. For the first of these, we have presented our numerical results uniformly for an integrated luminosity of 300 \( fb^{-1} \), although some of our benchmark points requires much less luminosity for effective reconstruction. We have already remarked on the possibility of reducing the faking of \( \tau \)'s. As we shall
show below, a systematic procedure can also be adopted for minimising combinatorial backgrounds to the reconstruction of neutralinos. The primary step in this is to combine each such \( \tau \) with one of the two hardest tracks in the muon chamber, which satisfy the cuts listed in Table 4.3. A particular \( \tau \) is combined with a heavy track of opposite charge. However, since neutralinos are Majorana fermions, producing pairs of \( \tau^+ \bar{\tau}^- \) and \( \tau^- \bar{\tau}^+ \) with equal probability, this is not enough to avoid the combinatorial backgrounds. Therefore, out of the two \( \tau \)'s and two heavy tracks, we select those pairs which give the closer spaced invariant masses, with \(|M_{\tau\tau}^{\text{pair1}} - M_{\tau\tau}^{\text{pair2}}| < 50 \text{ GeV}\). The number of signal and background events, after the successive application of cuts are listed in Table 4.4.

This finally brings us to the all-important issue of knowing the stau-mass. The \( \bar{\tau} \)-mass can be reconstructed from the information on time delay \( \Delta t \) between the inner tracker and the outer muon system and the measured three-momentum of the charged track [8]. The accuracy of this method depends on the accurate determination of \( \Delta t \), which can be limited when the particles are highly boosted. We have followed a somewhat different approach to find the actual mass of the particle associated with the charged track. We have found this method effective when both pairs of \( \tau \bar{\tau} \) come from \( \chi^0_1 \chi^0_1 \) or \( \chi^0_2 \chi^0_2 \).

**Solving for the \( \bar{\tau} \)-mass**: The actual \( \bar{\tau} \)-mass can be extracted by demanding that the invariant mass of the two correct \( \bar{\tau} \bar{\tau} \)-pairs are equal, which yields an equation involving one unknown, namely, \( m_{\bar{\tau}} \):

\[
\sqrt{m_{\bar{\tau}}^2 + |\vec{p}_{\bar{\tau}_1}|^2 E_{\tau_1} - \sqrt{m_{\bar{\tau}}^2 + |\vec{p}_{\bar{\tau}_2}|^2 E_{\tau_2}}} = \vec{p}_{\bar{\tau}_1} \cdot \vec{p}_{\tau_1} - \vec{p}_{\bar{\tau}_2} \cdot \vec{p}_{\tau_2}
\]

(4.6)

where the variables have their usual meanings and are experimentally measurable event-by-event. \( \bar{\tau}_{1,2} \) here denote the lighter \( \bar{\tau} \)s on two sides of the cascade, and not the two \( \bar{\tau} \) mass eigenstates.)

The right combination is assumed to be selected whenever the difference between \(|M_{\tau\bar{\tau}}^{\text{pair1}} - M_{\tau\bar{\tau}}^{\text{pair2}}| \) is minimum and differ by not more than 50 GeV, as mentioned earlier. It should be noted that the unambiguous identification of the right \( \tau \bar{\tau} \)-pairs which come from decays of two neutralinos \( (\chi^0_1 \chi^0_1 \text{ or } \chi^0_2 \chi^0_2) \) does not depend on the actual stau mass. Thus we can use a ‘seed value’ of the stau mass as input to the above equation, in identifying the right \( \tau \bar{\tau} \) combinations. We have used a seed value of \( m_{\tau} \approx 100 \text{ GeV} \) (motivated by the LEP limit on \( m_{\tau} \)). The SM background has already been suppressed by demanding the \( p_T \) of each charged track to be greater than 100 GeV, together with \( \Sigma |p_T| > 1 \text{ TeV} \).

Once the right pairs are chosen using the seed value of the \( \bar{\tau} \)-mass, we need
not use that value any more, and instead solve equation 4.6 which is quadratic in $m^2_{\tilde{\tau}}$. We have kept only those events in which at least one positive solution for $m^2_{\tilde{\tau}}$ exists. When both roots of the equation are positive, the higher value is always found to be beyond the reach of the maximum centre-of-mass energy available for the process. Hence we have considered the solution corresponding to the lower value of the root. The distribution of the solutions thus obtained has a peak around the actual $\tilde{\tau}$-mass. The $\tilde{\tau}$-track four-momenta are completely constructed, using this peak value as the actual mass of the $\tilde{\tau}$-NLSP (see Figure 4.4).

This sets the stage fully for the reconstruction of neutralinos, the results of which are shown in Figure 4.5. For BP1, BP2 and BP3 one can see that there is only one peak which corresponds to the $\chi^0_1$. This is because the $\chi^0_2$ production rate in cascade is relatively small for these points. For BP4 and BP5, on the other hand, we have distinct peaks for both $\chi^0_1$ and $\chi^0_2$. At BP6, however, we only have the $\chi^0_2$ peak. This is due to the small mass splitting between $\chi^0_1$ ($m_{\chi^0_1} = 129$ GeV) and $\tilde{\tau}$ ($m_{\tilde{\tau}} = 124$ GeV), which softens the tau (jet) arising from its decay, preventing it from passing the requisite hardness cuts. On the whole, it is clear from Figure 4.5 (comparing the peaks with the input values of the neutralino masses) that, in spite of adulteration by QCD jets that fake the $\tau$'s, our event selection criteria can lead to faithful reconstruction of neutralino masses.

One may still like to know whether a neutralino reconstructed in this manner is the $\chi^0_1$ or the $\chi^0_2$, when only one peak is visible. This requires further information on the SUSY spectrum. For example, the information on the gluino mass, extracted from the effective mass (defined as $(\Sigma |\vec{p}_T| + E_T)$) distribution, may enable one to distinguish between the $\chi^0_1$ and the $\chi^0_2$, once gaugino mass unification at high scale is assumed.

**4.4.2 LHC reach in the $m_0 - m_{1/2}$ -plane:**

We have also identified the region in the $m_0 - m_{1/2}$ plane, where at least one of the two lightest neutralinos can be reconstructed. For this, we have scanned over the region of the $m_0 - m_{1/2}$ plane using the spectrum generator SuSpect (v 2.34) [13] which leads to a $\tilde{\tau}$ LSP in a usual mSUGRA scenario without the right handed sneutrino [14]. Results of this scan are shown in Figure 4.6. The coloured (shaded) areas are consistent with all the low energy constraints like $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $\Delta(g_\mu - 2)$ and the LEP limits on the low energy spectrum. The value of $\tan\beta$ has been fixed at 30, and $A_0 = 100$ has been chosen.

The regions where reconstruction is possible have been determined using the following criteria:

- In the parameter space, we have not gone into regions where the gluino mass exceeds $\approx 2$ TeV.
<table>
<thead>
<tr>
<th>Benchmark Point</th>
<th>$m_{\tilde{\chi}_0^1}$ (GeV)</th>
<th>No. of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>248</td>
<td>450</td>
</tr>
<tr>
<td>BP2</td>
<td>204</td>
<td>350</td>
</tr>
<tr>
<td>BP3</td>
<td>161</td>
<td>200</td>
</tr>
<tr>
<td>BP4</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>BP5</td>
<td>129</td>
<td>100</td>
</tr>
<tr>
<td>BP6</td>
<td>129</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 4.4: The $\tilde{\tau}$ mass peak as obtained from eventwise reconstruction as described in the text, for all the benchmark points at luminosity 300 $fb^{-1}$. 
Figure 4.5: $M_{\tau\tau}$ distribution for all the benchmark points at luminosity $300 \ f b^{-1}$. BP1, BP2 and BP3 show only the $\chi_1^0$ peak. Both the $\chi_1^0$ and $\chi_2^0$ peaks are visible for BP4 and BP5, while BP6 displays only the $\chi_2^0$ peak.
Figure 4.6: The region in the $m_0 - m_{1/2}$ plane, where it is possible to reconstruct at least one of the neutralinos at the LHC, with $\tan \beta = 30$ and $A_0 = 100$ GeV. In the blue (dark shade) region, at least 100 events are predicted in the vicinity of the peak. The additional available region where 50 events in the vicinity of the peak are assumed to suffice for reconstruction, is marked in green (light shade). The entire region above the dashed line indicates the scenario where one has a $\tilde{\nu}_R$-LSP and a $\tilde{\tau}$-NLSP.

- The number of events satisfying $|M_{\tau\tau} - M_{\text{peak}}| < 0.1M_{\text{peak}}$ at an integrated luminosity of 300 $fb^{-1}$ must be greater than a specific number in order that the peak is said to be reconstructed. One obtains the blue (dark shade) region if this number is set at 100. If the peak can be constructed from more than 50 events, the additional region, marked in green (light shade), becomes allowed.

4.5 Summary and conclusions

We have considered a SUGRA scenario, with universal scalar and gaugino masses, where a right-chiral neutrino superfield exists for each family. We have identified several benchmark points in the parameter space of such a theory, where a right-sneutrino is the LSP, and a $\tilde{\tau}$ mass eigenstate is the NLSP. The $\tilde{\tau}$, stable on the distance scale of the detectors, leaves a charged track in the muon chamber, which is the characteristic feature of SUSY signals in this scenario. We use this feature to reconstruct neutralinos in the $\tau\tilde{\tau}$ channel. For this, we use the collinear approximation to obtain the four-momentum of the $\tau$, and suggest a number of
event selection criteria to reduce backgrounds, including combinatorial ones. We also suggest that the $\tilde{\tau}$ mass may be extracted by solving the equation encapsulating the equality of invariant masses of two $\tau \tilde{\tau}$ pairs in each event. We find that at least one of the two lightest neutralinos can be thus reconstructed clearly over a rather large region in the $m_0 - m_{1/2}$ plane, following our specified criteria.
<table>
<thead>
<tr>
<th>Input</th>
<th>BP-1</th>
<th>BP-2</th>
<th>BP-3</th>
<th>BP-4</th>
<th>BP-5</th>
<th>BP-6</th>
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<tbody>
<tr>
<td>mSUGRA</td>
<td>m₀  = 100</td>
<td>m₀  = 100</td>
<td>m₀  = 100</td>
<td>m₀  = 100</td>
<td>m₀  = 100</td>
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<td></td>
<td>m₁/₂ = 600</td>
<td>m₁/₂ = 500</td>
<td>m₁/₂ = 400</td>
<td>m₁/₂ = 350</td>
<td>m₁/₂ = 325</td>
<td>m₁/₂ = 325</td>
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<tr>
<td>tan β = 30</td>
<td>tan β = 30</td>
<td>tan β = 30</td>
<td>tan β = 30</td>
<td>tan β = 30</td>
<td>tan β = 30</td>
<td>tan β = 25</td>
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<tr>
<td>m₁/e, m₁/µ</td>
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<td>355</td>
<td>292</td>
<td>262</td>
<td>247</td>
<td>247</td>
</tr>
<tr>
<td>m₁/µ, m₁/µ</td>
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<td>214</td>
<td>183</td>
<td>169</td>
<td>162</td>
<td>162</td>
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<tr>
<td>m₁/ν, m₁/ν</td>
<td>408</td>
<td>343</td>
<td>279</td>
<td>247</td>
<td>232</td>
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<tr>
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<tr>
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<tr>
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<td>301</td>
<td>273</td>
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<td>255</td>
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<tr>
<td>m₁/χ₁0²</td>
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<td>204</td>
<td>161</td>
<td>140</td>
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<tr>
<td>m₁/χ₁0²</td>
<td>469</td>
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<td>261</td>
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<td>m₁/χ₁0²</td>
<td>470</td>
<td>387</td>
<td>303</td>
<td>262</td>
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<tr>
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<tr>
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<tr>
<td>m₁/χ₁0²</td>
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<td>114</td>
<td>112</td>
<td>111</td>
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Table 4.1: Proposed benchmark points (BP) for the study of the stau-NLSP scenario in the SUGRA with right-sneutrino LSP. The value of m₀ and m₁/₂ are given in GeV. We have also set A₀ = 100 GeV and sgn(µ) = + for benchmark points under study.
Table 4.2: The number of $2\tau_j + \tilde{\tau}$ (charged-track) + $E_T + X$ events, satisfying our basic cuts, for $\int L dt = 300 \text{ GeV}$, from various channel.

<table>
<thead>
<tr>
<th>Subprocesses</th>
<th>BP-1</th>
<th>BP-2</th>
<th>BP-3</th>
<th>BP-4</th>
<th>BP-5</th>
<th>BP-6</th>
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<tr>
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<td>4143</td>
<td>11726</td>
<td>20889</td>
<td>28864</td>
<td>15439</td>
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<tr>
<td>$\tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$</td>
<td>1616</td>
<td>3897</td>
<td>11061</td>
<td>19765</td>
<td>27785</td>
<td>14426</td>
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Table 4.3: Cuts applied for event selection, background elimination and neutralino reconstruction.
<table>
<thead>
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<th>Cuts</th>
<th>Signal</th>
<th>Background</th>
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</thead>
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<tr>
<td></td>
<td>BP1</td>
<td>BP2</td>
</tr>
<tr>
<td>Basic Cuts</td>
<td>1765</td>
<td>4143</td>
</tr>
<tr>
<td>+P_T Cut</td>
<td>1588</td>
<td>3631</td>
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<tr>
<td>+Σ</td>
<td>P_T</td>
<td>Cut</td>
</tr>
<tr>
<td>+</td>
<td>M_T^{pair1} - M_T^{pair2}</td>
<td>Cut</td>
</tr>
</tbody>
</table>

Table 4.4: Number of signal and background events for $2\tau_j + 2\bar{\tau}$ (charged-track) + $E_T + X$ final state with an integrated luminosity of 300 fb$^{-1}$, considering all SUSY processes. The standard model Higgs mass is taken to be 120 GeV in background calculation.
Bibliography


