Lepton Flavours at the Early LHC Experiments as the Footprints of the Dark Matter Producing Mechanisms

Nabanita Bhattacharyya\(^{(a)}\)\(^1\), Amitava Datta\(^{(a)}\)\(^2\) and Sujoy Poddar\(^{(a)}\)\(^3\)

\(^{(a)}\) Indian Institute of Science Education and Research, Kolkata, HC-VII, Sector III, Salt Lake City, Kolkata 700 106, India.

Abstract

The mSUGRA parameter space corresponding to light sleptons well within the reach of LHC and relatively light squarks and gluinos (mass \(\leq 1\) TeV) has three regions consistent with the WMAP data on dark matter relic density and direct mass bounds from LEP 2. Each region can lead to distinct leptonic signatures from squark-gluino events during the early LHC experiments (integrated luminosity \(\sim 10\) fb\(^{-1}\) or even smaller). In the much studied stau-LSP coannihilation region with a vanishing common trilinear coupling \((A_0)\) at the GUT scale a large fraction of the final states contain electrons and / or muons and \(e - \mu - \tau\) universality holds to a good approximation. In the not so well studied scenarios with non-vanishing \(A_0\) both LSP pair annihilation and stau-LSP coannihilation could contribute significantly to the dark matter relic density for even smaller squark-gluino masses. Our simulations indicate that the corresponding signatures are final states rich in \(\tau\)-leptons while final states with electrons and muons are suppressed leading to a violation of lepton universality. These features may be observed to a lesser extent even in the modified parameter space (with non-zero \(A_0\)) where the coannihilation process dominates. We also show that the generic \(m\)-leptons + \(n\)-jets+ \(E_T\) signatures without flavour tagging can also discriminate among the three scenarios. However, the signals become more informative if the \(\tau\) and \(b\)-jet tagging facilities at the LHC experiments are utilized.

PACS no:04.65.+e,13.85.-t,14.80.Ly

\(^1\)nabanita@iiserkol.ac.in
\(^2\)adatta@iiserkol.ac.in
\(^3\)sujoy_phy@iiserkol.ac.in


1 Introduction

Models with supersymmetry (SUSY) [1] are interesting for a variety of theoretical and phenomenological reasons. A specially attractive feature of the minimal supersymmetric standard model (MSSM) with R-parity conservation is the presence of the stable, weakly interacting lightest neutralino (\(\tilde{\chi}_1^0\)) [2] which is assumed to the lightest supersymmetric particle (LSP). This turns out to be a very good candidate for the observed dark matter (DM) in the universe [3, 4, 5].

Various SUSY models have been proposed and constrained by the data on DM relic density [6]-[14]. The recent revival of interest in this field is due to the very restrictive data from the Wilkinson Microwave Anisotropy Probe (WMAP) observation [15]. Combining the WMAP data with the results from the SDSS (Sloan Digital Sky Survey) one obtains the conservative 3 \(\sigma\) limits

\[
0.09 < \Omega_{DM} h^2 < 0.13
\]

where \(\Omega_{DM} h^2\) is the DM relic density in units of the critical density, \(h = 0.71 \pm 0.026\) is the Hubble constant in units of 100 Km s\(^{-1}\) Mpc\(^{-1}\). In this paper we shall assume that \(\Omega_{DM} \equiv \Omega_{\tilde{\chi}_1^0}\). We should note here that the upper bound on \(\Omega_{\tilde{\chi}_1^0}\) in Eq.(1) must hold in any model with SUSY. In contrast the lower bound evaporates if the possibility of non-SUSY origin of DM is left open.

In the thermally generated DM scenario the present value of \(\Omega_{\tilde{\chi}_1^0} h^2\) can be computed by solving the Boltzmann equation for \(n_{\tilde{\chi}_1^0}\), the number density of the LSP in a Friedmann-Robertson-Walker universe. The most important particle physics input in this calculation is the thermally averaged quantity \(<\sigma_{eff} v>\), where \(v\) is the relative velocity between two neutralinos annihilating each other and \(\sigma_{eff}\) is the annihilation cross-section for all possible final states involving SM particles only. In addition to the negation of a LSP pair, coannihilation of the LSP [6]-[9],[10] with supersymmetric particles (sparticles) approximately degenerate with the LSP may also be important. The smaller the annihilation/coannihilation cross-section the larger becomes the LSP relic density. In addition to the parameters of the standard model the annihilation cross-section \(\sigma_{eff}\) depends on the masses and the couplings of the sparticles and on the magnitudes of the bino (\(\tilde{B}\)), wino (\(\tilde{W}\)) and Higgsino (\(\tilde{H}_0^0, \tilde{H}_2^0\)) components of the LSP. Discovery of SUSY at the LHC followed by the measurement of the above parameters can, therefore, verify the hypothesis of supersymmetric DM as well as identify the underlying DM relic density producing mechanism [16]. This, however, is likely
to take some time.

SUSY models with relatively small squark, gluino masses are of considerable contemporary interest since such strongly interacting sparticles with large production cross-sections are expected to show up in the early stages of the LHC experiments. In this case there are a few important relic density producing mechanisms like the LSP pair annihilation, LSP - lighter stau ($\tilde{\tau}_1$) and LSP-lighter-stop ($\tilde{t}_1$) coannihilation [13], [6]-[9], [10]. Each mechanism is active in one or more regions of the SUSY parameter space. It is worthwhile to check whether the sparticle spectra corresponding to each region yield distinct signatures at the early LHC experiments so that some idea of the DM producing mechanism, though qualitative, can be obtained.

In this paper we shall restrict ourselves to the popular minimal supergravity (mSUGRA)model [17] with moderate values of the parameter $\tan \beta$ (to be defined in the next section). Our attention will be focussed on the regions of the parameter space consistent with the WMAP data and within the reach of the early runs. This region necessarily corresponds to light sleptons well within the reach of LHC but unlikely to be discovered directly by the early experiments (see section 3 for the details). Moreover the slepton signature alone carries very little information about the underlying DM relic density producing mechanism.

In mSUGRA the above scenario also involves relatively light squarks and gluinos. The lighter chargino ($\tilde{\chi}^{\pm}_1$) and the second lightest neutralino ($\tilde{\chi}^0_2$) are copiously present in the squark-gluino decay cascades. In the light slepton scenario these inos almost exclusively decay leptonically via two body decay modes. The lepton flavour content of the final states thus obtained from squark-gluino events at the early stages of the LHC run may reflect the underlying relic density producing mechanisms [18] (see section 2 for a brief review). Thus at least the footprints of these mechanisms may be viewed long before reconstruction of the sparticle masses and other relevant parameters establish the model rigorously.

In the next section we shall review the important DM relic density producing mechanisms in different regions of the mSUGRA parameter space with sparticle spectrum as described above and qualitatively review the characteristics of the squark-gluino signatures from each region. In section 3 we shall go beyond [18] and present the results of our simulations revealing new aspects of the signals. This will justify the qualitative discussions of the previous section. The summary along with future outlooks will be the content of the last section.
2 The Early LHC signatures: a qualitative discussion

The simplest gravity mediated SUSY breaking model - the minimal supergravity (mSUGRA) [17] model- has only five free parameters. These are $m_{1/2}$ (the common gaugino mass), $m_0$ (the common scalar mass) and the common trilinear coupling parameter $A_0$, all given at the gauge coupling unification scale ($M_G \sim 2 \times 10^{16}$ GeV), the ratio of Higgs vacuum expectation values at the electroweak scale namely $\tan \beta$ and the sign of $\mu$, the higgsino mixing parameter. The magnitude of $\mu$ is determined by the radiative electroweak symmetry breaking (REWSB) condition [19]. The low energy sparticle spectra and couplings at the electroweak scale are generated by renormalization group evolutions (RGE) of the soft breaking masses and coupling parameters [20]. In this paper we shall restrict ourselves to a moderate value of $\tan \beta$ namely 10 and positive $\mu$. Representative values of the remaining parameters will be used to highlight different DM relic density producing mechanisms and the corresponding collider signals. Since the entire sparticle spectra and the couplings can be computed in terms of the five parameters only, the calculation of the LSP annihilation or coannihilation cross-sections and, consequently, the DM relic density are rather precise in this framework [6, 13, 21].

The WMAP allowed regions of the mSUGRA parameter space can be classified into several regions depending on the dominant LSP annihilation/coannihilation mechanisms. The details can be found in [3, 4, 5, 21]. In the following we list the mechanisms which will be relevant for the discussions in this paper focussing on relatively light sleptons, squarks and gluinos.

One such region corresponds to small $m_0$ but somewhat larger $m_{1/2}$ (numerical examples will be given later). This choice leads to sleptons lighter than the charginos and the heavier neutralinos. Moreover, the mass difference between the lighter stau ($\tilde{\tau}_1$) and the LSP turns out to be at most 30 GeV or so. Consequently $\tilde{\tau}_1$-LSP coannihilation [6] often abbreviated as $\tilde{\tau}$-coannihilation occurs quite efficiently sufficient for producing the DM in the universe. The importance of this region, which we shall refer to as the conventional $\tilde{\tau}$- coannihilation zone, in the context of the WMAP data has recently been emphasized by several groups [21].

Most of the above analyses, however, were based on the choice $A_0 = 0$ without any compelling theoretical or empirical reason. One consequence of this ad hoc choice is that in order to satisfy the LEP bound on the lightest Higgs boson mass: $m_h > 114.4$ GeV [22] one requires relatively large $m_{1/2}$. Typically for $m_0 \sim 100$ GeV one requires $m_{1/2} \sim 500$
GeV to satisfy the $m_h$ bound and the WMAP constraints. As a result the squarks and gluinos become approximately degenerate, the latter being slightly heavier. The masses of these superpartners turn out to be $\mathcal{O}(1 \text{ TeV})$ or larger. Nevertheless the total squark-gluino production cross section is sufficient to produce observable signatures at the LHC (See, e.g., [23]) throughout the $\tilde{\tau}$-coannihilation region. The lighter top squark mass is smaller than the other squarks due to the usual renormalization group effects driven by its large Yukawa coupling. However, due to the choice $A_0 = 0$ its mass is not further suppressed by mixing effects in the mass matrix. Therefore its mass is also of the order of one TeV. Such heavy $\tilde{t}_1$ does not participate in $\tilde{t}_1$ - LSP coannihilation. Moreover the production of $\tilde{t}_1$ pairs do not affect the total squark-gluino production significantly. The features discussed in the last two paragraphs lead to distinct collider signatures as we shall illustrate below with numerical examples.

The other region of interest is the bulk annihilation region or the bulk region [4, 5, 13] where $m_0$ and $m_{1/2}$ are such that many of the sparticles are significantly lighter than those in the conventional $\tilde{\tau}$-coannihilation region. The LSP turns out to be bino dominated and, consequently, couples favourably to right sleptons, which in fact are the lightest sfermions in this region of the parameter space. As a result an LSP pair efficiently annihilates into SM fermions via the exchange of light sfermions in the $t$-channel. This cross-section depends on the mass of the LSP ($m_{\tilde{\chi}_0^0}$), the masses of the exchanged sfermions and the LSP-sfermion couplings [4, 5, 13]. This region characterized by relatively light sparticles is especially interesting since SUSY signals with large events rates may be expected at the early LHC runs.

Strong lower bounds on sparticle masses [24], particularly on the slepton masses from LEP 2 disfavor a part of the bulk annihilation zone. We, however, wish to emphasize that the direct bounds on the slepton masses alone can not eliminate the entire bulk region. Nevertheless a more severe restriction practically rules out the $(m_0 - m_{1/2})$ plane containing the bulk region for $A_0 = 0$. This arises from the LEP 2 bound on lightest Higgs boson mass ($m_h$) [22] since $m_h$ and slepton masses are correlated in mSUGRA. Thus it has often been claimed in the recent literature that the mSUGRA parameter space with low values of both $m_0$ and $m_{1/2}$ and, consequently, the entire bulk region is strongly disfavoured [21].

It was emphasized in [18] that the above conclusions are artifacts of the ad hoc choice $A_0 = 0$. On the other hand it is well known that for given $m_0$ and $m_{1/2}$ moderate to
large negative\textsuperscript{4} values of $A_0$ lead to larger $m_h$ \textsuperscript{5}. Hence in this case the bound on $m_h$ can be satisfied even for relatively small $m_0$ and $m_{1/2}$. This revives the region where LSP pair annihilation is the dominant DM producing mechanism. This can be seen, e.g., from Fig.1 of [18] (see the blue(deep shaded)region; several other figures of the above reference corresponding to different choices of mSUGRA parameters also exhibit similar features). Moreover the low $m_0 - m_{1/2}$ regions of the mSUGRA parameter space are characterized by relatively light squarks and gluinos. This along with the inevitable presence of light sleptons in this region of the parameter space leads to distinct signals from squark-gluino events.

There is also a region where $\tilde{\tau}$-coannihilation is still the most important mechanism for creating the observed DM in the universe( see the pink (the light shaded) regions of Fig. 1 [18] and other similar figures). Remarkably, even this region corresponds to much smaller $m_{1/2}$ compared to what one would obtain for the $A_0 =0$ case (i.e., for the conventional $\tilde{\tau}$-coannihilation region).

Furthermore large negative values of $A_0$ leads to a relatively light top squark. In fact for a small but non-negligible region of the parameter space, the LSP - $\tilde{t}_1$ coannihilation [10] along with bulk annihilation may significantly contribute to the observed DM density with the $\tilde{t}_1$ well within the kinematic reach of the Tevatron (see the red region of Fig. 1 [18] and other figures).

In [18] some features of the sparticle spectrum and signals at the Tevatron and the LHC corresponding to the WMAP allowed regions of the parameter space opened up by non-zero $A_0$ were studied. The results were compared and contrasted with the expectations from the well publicized conventional $\tilde{\tau}_1$-coannihilation scenario with $A_0 = 0$ by introducing three benchmark scenarios A, B and C ( Table 1 of [18], which has also been reproduced here as Table 1 for a ready reference). In scenario A with a relatively large $A_0$ both bulk annihilation and $\tilde{\tau}$-coannihilation are responsible for producing the observed DM relic density although the former dominates. On the other hand in scenario B with somewhat larger $m_{1/2}$ the latter dominates but the contribution of the bulk annihilation is non-negligible. Finally in scenario C with $A_0 = 0$ the conventional $\tilde{\tau}$- coannihilation is the only significant DM producing mechanism. The scenario C corresponds to the smallest $m_{1/2}$ which is consistent with the

\textsuperscript{4}We follow the standard sign convention of Ref. [26] for the signs of $\mu$ and $A_0$.

\textsuperscript{5}For $A_0 > 0$, one requires $m_0$ and $m_{1/2}$ typically larger than the corresponding values for $A_0=0$. This does not lead to any novel collider signal.
Higgs mass bound and the WMAP data.

In the following the main features of the signal in the three scenarios [18] are summarized. The tables referred to in the rest of this section belongs to the original work unless stated otherwise explicitly.

The sparticle spectra in the three scenarios can be found in Table 2 and the total squark-gluino cross-section in Table 6. These lowest order cross-sections have been computed by CalcHEP (version 2.3.7) [27].

The signals at the LHC are governed by the cascade decays of the above sparticles. In all three cases the gluinos are heavier than all squarks. As a result the gluinos decay into quark-squark pairs (see Table 3). The squarks belonging to the third generation are relatively light due to the usual renormalization group effects in the mSUGRA model. Their masses are further suppressed by mixing effects in the mass matrix due to the non-vanishing $A_0$ parameter scenarios A and B. As a result these squarks are more frequently present in gluino decay products in these scenarios compared to C.

The squarks belonging to the first two generations in general decay into the corresponding lighter quarks and an appropriate electroweak gaugino (Table 3). The lighter top squark similarly decays into appropriate quark-gaugino pairs. The bottom squarks of both type may decay, in addition to above channels, into a lighter top squark and a W boson in some scenarios (Table 4) with non-negligible branching ratios (BRs). Nevertheless, the decay of each third generation squark inevitably contains a b quark. This is the origin of the large fraction of final states with b-partons as noted in [18]. In scenario C the fraction of third generation squarks in gluino decay is relatively small and the above effect is suppressed to some extent.

The decay properties of the lighter chargino ($\tilde{\chi}_1^\pm$) and the second lightest neutralino ($\tilde{\chi}_2^0$) which, in addition to the LSP, are often present in squark-gluino decays determine the lepton content of the final states to a large extent. As a direct consequence of the presence of the light sleptons, these two unstable gauginos decay almost exclusively into leptonic channels via two body modes in all three scenarios.

In Table 2 of this paper, which is an enlarged version of Table 5 of [18], we present the relevant branching ratios of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. In scenario A the wino dominated lighter chargino, is not kinematically allowed to decay into L-type charged sleptons. Its two body decay into a lepton-sneutrino pair, though kinematically allowed, is phase space suppressed. It therefore
decays into R-type sleptons through its subdominant Higgsino component with a large BR. This results in a very large fraction of final states containing the $\tilde{\tau}_1$, which eventually decays into a $\tau$-LSP pair. Only a tiny fraction of the final states contains electrons and muons. Unlike the SM the hallmark of this scenario is, therefore, lepton non-universality in the final states. For similar reasons the $\tilde{\chi}^0_2$ decays primarily into $\tau$-LSP pair while a much smaller fraction decays into neutrino-sneutrino pairs, contributing further to the $\tau$ dominance of the final states. The sneutrinos in turn decay into the invisible neutrino-LSP channel in all three scenarios and act as additional carriers of missing energy.

The scenario B has all the above features albeit to a lesser extent. The $\tau$ dominance in both $\tilde{\chi}_1^\pm$ and $\tilde{\chi}^0_2$ decays exists but is reduced significantly compared to the predictions of scenario A. The fraction of invisible decays of $\tilde{\chi}^0_3$ into $\nu - \bar{\nu}$ pair increases. This common feature of A and B can be easily illustrated by a parton level calculation (see Table 7). In a realistic LHC experiment with good $\tau$ tagging capabilities the observability of this $\tau$ excess has been demonstrated by simulation (see Table 8) using Pythia.

In Table 2 our focus was on the three benchmark scenarios. In order to illustrate that the lepton flavour content of the final state is indeed correlated with the DM producing mechanism we have selected several representative points ($S_1 - S_7$) from the figures in [18]. The dominant DM producing mechanism and the figure no. in [18] are given in parentheses. For all points $\tan \beta = 10; \mu > 0$. The other parameters are as given below.

$S_1 : m_0 = 100; m_{1/2} = 250; A_0 = -700$ (Bulk ; Fig. 4)
$S_2 : m_0 = 125; m_{1/2} = 400; A_0 = -700$ (Coannihilation ; Fig. 4)
$S_3 : m_0 = 120; m_{1/2} = 400; A_0 = -800$ (Coannihilation ; Fig. 1(a))
$S_4 : m_0 = 120; m_{1/2} = 265; A_0 = -900$ (Bulk ; Fig. 1(a))
$S_5 : m_0 = 120; m_{1/2} = 300; A_0 = -1000$ (Bulk ; Fig. 1(a))
$S_6 : m_0 = 170; m_{1/2} = 500; A_0 = -1200$ (Coannihilation ; Fig. 1(c))
$S_7 : m_0 = 170; m_{1/2} = 500; A_0 = -1400$ (Coannihilation ; Fig. 1(c))

The relevant BRs of lighter chargino and second lightest neutralino decays are presented in Table 3. It is readily seen that if the bulk annihilation ($\tilde{\tau}$-coannihilation) is the dominant mechanism, the decays follow the patterns of scenario A (B) (compare with Table 2).

In scenario C the $\tilde{\chi}^\pm_1$ decays into left slepton- neutrino pairs or sneutrino-lepton pairs
belonging to the first two generations with equal BR of sizable magnitudes. The fraction of final states involving $\tau$s is only marginally larger and lepton universality holds to a very good approximation. In fact due to limited $\tau$ detection efficiency, the fraction of observed final states involving $e$ and/or $\mu$ will be apparently larger in stark contrast to the predictions of scenarios A and B. The decays of $\tilde{\chi}^0_2$ contributes further to the restoration of lepton universality. The $\tilde{\chi}^0_2$ now dominantly decays into the invisible final state consisting of a neutrino and a sneutrino with 51.6% BR. Thus it largely acts as a carrier of missing energy in addition to the LSP and the sneutrino. Although we have presented numerical results for scenario C only we have verified that the above features hold qualitatively for the entire $\tau$-coannihilation strip.

Scenarios with the electroweak gauginos decaying into purely leptonic two body channels and sneutrinos and $\tilde{\chi}^0_2$ acting as additional carriers of missing energy have already been discussed in details in the context of MSSM. The characteristic signatures from final states containing excess of electrons and/or muons and more than one invisible particles at the Tevatron [28] and at $e^+ - e^-$ colliders like LEP or the NLC [29, 30] were simulated at the parton level. An ISAJET based analysis in the context of the Tevatron Run I was also done [31]. The scope of accommodating such scenarios in the mSUGRA models and several of its variants was also discussed [32].

However, the connection of this scenario with a WMAP allowed region of the mSUGRA parameter space has not been highlighted in the existing literature. Nor were the LHC signatures of this scenario studied with due emphasis. It is interesting to note that this virtual LSP('VLSP') or effective LSP('ELSP') scenario\textsuperscript{6} is realized in the well studied conventional $\tau$-coannihilation region of the mSUGRA parameter space. In the next section we shall simulate the LHC signatures of this scenario in great details.

In this paper we complement and extend the analysis in [18] in several ways. First of all we have simulated the popular $m$-leptons $+ n$-jets $+ \not{E}_T$ signature for $n \geq 2$ and several choices of $m$, which stands for the number of electrons and muons. No flavour tagging is required at this stage. It is gratifying to note that the scenarios can be distinguished reasonably well via these signatures inspite of the uncertainties in the cross-sections due to the choice of QCD scales. The relative enhancement of the final states with $e$ and/or $\mu$\textsuperscript{8}.

\textsuperscript{6}The invisibly decaying $\tilde{\nu}$'s and $\tilde{\chi}^0_2$ acting as additional carriers of missing energy may be called VLSP or ELSP in the context of collider physics.
compared to $m = 0$ final states, a distinct characteristic of the VLSP scenario, has been illustrated in the next section with several examples in scenario C.

Next we consider events of the type $1\tau + X$, $1\mu + X$ and $1e + X$, where $X$ includes all possible states with two or more jets but no stable lepton or tagged $\tau$ (the difference in the definition of $X$ compared to that in [18] should be noted). In this work we also consider final states with 2 leptons of the same flavour in all possible charge combinations + $X$. We have used the $\tau$-tagging efficiencies provided by the CMS collaboration [33] in our Pythia based simulations. As discussed in the earlier paragraphs an excess of events with $\tau$ have been demonstrated in scenario A and to a lesser extent in scenario B. Finally we examine the $b$-jet content of the final states beyond the parton level using Pythia.

In [18] the $t\bar{t}$ events were assumed to be the dominant source of backgrounds. In this paper we have extended the background analysis by considering several other processes. In particular we have found that for some signals the QCD background is more important than the $t\bar{t}$ background. The details will be presented in the next section.

3 The Signals at the LHC

| mSUGRA parameters | A   | B   | C   |
|--------------------|-----|-----|-----|
| $m_0$              | 120.0 | 120.0 | 120.0 |
| $m_{1/2}$          | 300.0 | 350.0 | 500.0 |
| $A_0$              | -930.0 | -930.0 | 0.0   |
| $\tan \beta$      | 10.0  | 10.0  | 10.0  |
| $sign(\mu)$       | 1.0   | 1.0   | 1.0   |

Table 1: Three bench mark scenarios introduced in [18].

In this section we begin with the generic SUSY signals of the type $m - l + n - j + E_T$, where $l = e$ or $\mu$ and $j$ is any jet. At first we do not employ any flavour tagging. Our aim is to study the feasibility of discriminating among the three models under consideration using these generic signals. Next we shall employ flavour tagging and demonstrate that it further
Table 2: The BRs of the dominant decay modes of the lighter chargino and the second lightest neutralino. All sneutrinos decay into the invisible channel $\nu + \tilde{\chi}_1^0$ in the three cases understudy. Here $l$ stands both for $e$ and $\mu$.

enhances our discriminatory power.

The production and decay of all squark-gluino pairs are generated by Pythia (version 6.409) [34]. Initial and final state radiation, decay, hadronization, fragmentation and jet formation are implemented following the standard procedures in Pythia. We have used the toy calorimeter simulation (PYCELL) provided in Pythia with the following criteria:

- The calorimeter coverage is $|\eta| < 4.5$. The segmentation is given by $\Delta \eta \times \Delta \phi = 0.09 \times 0.09$ which resembles a generic LHC detector.

- A cone algorithm with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.5$ has been used for jet finding.

- $E_{T,\text{min}} = 30\text{GeV}$ and jets are ordered in $E_T$. 

| Decay modes (Gauginos) | A   | B   | C    |
|-------------------------|-----|-----|------|
| $\tilde{\chi}_2^0 \rightarrow l_L l^+$ | 0.0 | 2.2 | 23.1 |
| $\tilde{\chi}_2^0 \rightarrow l_R l^+$ | 0.9 | 0.6 | 0.8  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^+ \tau^-$ | 78.6 | 46.0 | 8.4  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_2^+ \tau^-$ | 0.0 | 0.7 | 10.2 |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$ | 0.3 | 0.2 | 0.4  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ | 0.0 | 1.9 | 5.2  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\nu} l$ | 5.2 | 24.0 | 33.8 |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\nu} \tau$ | 15.0 | 24.0 | 17.8 |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^+$ | 2.6 | 2.6 | 5.1  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\nu} l^+$ | 5.4 | 25.0 | 36.0 |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\nu} \tau$ | 16.0 | 25.0 | 19.2 |
| $\tilde{\chi}_1^+ \rightarrow l_L l$ | 0.0 | 2.0 | 22.0 |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\tau}_1^+ \nu$ | 76.0 | 44.0 | 7.8  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\tau}_2^+ \nu$ | 0.0 | 0.7 | 9.6  |
The stable leptons are selected according to the criterion:

- Leptons ($l = e, \mu$) are selected with $P_T \geq 30$ GeV and $|\eta| < 2.5$. For lepton-jet isolation we require $\Delta R(l, j) > 0.5$. The detection efficiency of the leptons are assumed to be 100%.

The following cuts are implemented for background rejection:

- Leptons ($l = e, \mu$) with $P_T \leq 60$ GeV are rejected to ensure the rejection of leptons coming from $\tau$ decay. (CUT 1)

- We reject events without at least two jets having $P_T > 150$ GeV (CUT 2)

- Events with missing energy ($E_T$) $< 200$ GeV are rejected. (CUT 3)

### Table 3: Same as Table 2 in the scenarios $S_1 - S_7$ (see text).

| Decay modes (Gauginos) | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ |
|------------------------|-------|-------|-------|-------|-------|-------|-------|
| $\tilde{\chi}_2^0 \rightarrow \tilde{l}_L^+ l^-$ | 0.0   | 10.2  | 12.5  | 0.0   | 0.0   | 15.5  | 15.0  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^+ l^-$ | 1.6   | 0.7   | 0.5   | 0.9   | 0.7   | 0.2   | 0.2   |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^- \tau^-$ | 85.8  | 26.6  | 24.2  | 95.4  | 76.9  | 19.7  | 20.2  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_2^+ \tau^-$ | 0.0   | 4.3   | 5.4   | 0.0   | 0.0   | 9.8   | 10.6  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$  | 0.0   | 0.2   | 0.2   | 0.2   | 0.2   | 0.1   | 0.1   |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$  | 0.0   | 3.3   | 2.3   | 0.0   | 0.0   | 2.0   | 1.4   |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\nu}_l \nu_l$ | 2.8   | 31.8  | 31.3  | 0.0   | 5.5   | 28.8  | 27.3  |
| $\tilde{\chi}_2^0 \rightarrow \tilde{\nu}_\tau \nu_\tau$ | 9.7   | 22.2  | 22.7  | 3.5   | 16.7  | 23.8  | 25.0  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^+$ | 1.3   | 3.6   | 2.5   | 1.9   | 2.2   | 2.0   | 1.5   |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_l l^+$ | 3.0   | 33.4  | 33.4  | 0.0   | 5.7   | 29.6  | 28.0  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_\tau \tau^+$ | 11.0  | 23.4  | 23.9  | 3.6   | 17.7  | 24.5  | 25.7  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{l}_L^+ \nu_l$ | 0.0   | 10.1  | 11.8  | 0.0   | 0.0   | 15.1  | 14.6  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{l}_R^+ \nu_l$ | 84.7  | 25.4  | 23.1  | 94.5  | 74.3  | 19.2  | 19.8  |
| $\tilde{\chi}_1^+ \rightarrow \tilde{\tau}_1^+ \nu_\tau$ | 0.0   | 4.0   | 5.2   | 0.0   | 0.0   | 9.5   | 10.3  |
Events with $M_{eff} < 1000$ are rejected, where $M_{eff} = |E_T| + \Sigma_i|P^l_T| + \Sigma_i|P^3_i| \ (l = e, \mu ).$ (CUT 4)

Only events with jets having $S_T > 2.0$, where $S_T$ is a standard function of the eigenvalues of the transverse sphericity tensor, are accepted. (CUT 5)

| QCD scale | $0.5\sqrt{\hat{s}}$ | $\sqrt{\hat{s}}$ | $2.0\sqrt{\hat{s}}$ |
|-----------|---------------------|-------------------|---------------------|
| A         | 19.41               | 15.58             | 12.10               |
| B         | 6.79                | 5.74              | 4.26                |
| C         | 0.84                | 0.74              | 0.51                |

Table 4: Variation of total cross-section in pb of squark-gluino events with the QCD scale in A, B and C.

| Q | $0.5\sqrt{\hat{s}}$ | $\sqrt{\hat{s}}$ | $2.0\sqrt{\hat{s}}$ |
|---|---------------------|-------------------|---------------------|
| A | 0l                  | 2.54              | 2.03                | 1.59                |
|   | 1l                  | 0.25              | 0.20                | 0.15                |
| B | 0l                  | 1.45              | 1.21                | 0.90                |
|   | 1l                  | 0.21              | 0.17                | 0.13                |
| C | 0l                  | 0.24              | 0.21                | 0.15                |
|   | 1l                  | 0.11              | 0.09                | 0.06                |

Table 5: The cross-sections (including efficiency) in pb of events with $m = 0$ and 1 (see text).

Cut 1 will be employed in the second part of our analysis when the relative abundance of final states with $e, \mu$ and $\tau$ will be studied. For establishing $m - l + n - j + E_T$ signals Cut 2 - Cut 4 are adequate.

Table 4 illustrates that, as expected, the variation of the total cross-section of squark-gluino events with the choice of the QCD scale is rather large in each model. In spite of this
large variation it is clear that each scenario is characterized by a typical size of the cross-section. This cross-section is the largest in scenario A because squark and gluino masses are the smallest in this case (see [18]). In particular the contribution of the lighter top squark enhances the cross-section significantly. The last feature is a direct consequence of large negative $A_0$ in scenario A. The corresponding masses are significantly larger in the other two scenarios resulting in smaller cross-sections.

It is, however, impossible to conclusively identify a particular DM scenario by the size of the cross-section alone since a similar cross-section may arise from a different combination of mSUGRA parameters which may or may not be allowed by the relic density constraint. Moreover, the signal corresponding to a larger raw cross-section may eventually be suppressed due to the effects of the kinematical cuts, small BRs of the underlying decays etc. Several examples of this will be presented in the following paragraphs.

The total cross-section at best provides a hint for the underlying SUSY model and LSP annihilation mechanism but no definite conclusion can be drawn. In the following we shall show that a multi-channel analysis using signals with different choices of $m$ (the number of leptons in the final state) may very efficiently discriminate among different scenarios.

First we assume that the SM backgrounds will be determined either from data or from theory with next to leading order accuracy and can be subtracted from the event sample without introducing large errors. The leading order signal cross-sections in pb (including the BRs and the efficiency of the cuts $C_2$-$C_5$ listed above) for $m = 0$ and 1 are presented in Table 5. It is readily seen that the variation of the cross-sections due to the QCD scale, the difference in BRs (see section 2 and [17] for further details) and the efficiency of the kinematical cuts in different scenarios may conspire in such a way that the cross-sections for $m = 0$ ($\sigma_0$) may look rather similar in different scenarios (see, e.g., $\sigma_0$ in model A at $Q = 2.0\sqrt{s}$ and in model B at $Q = 0.5\sqrt{s}$) at least for relatively low integrated luminosities ($\mathcal{L}$). Similarly the predictions for $m = 1$($\sigma_1$) may appear to be quite similar in different scenarios. However, it can be easily checked that in each scenario the ratio $R = \sigma_0 / \sigma_1$ is scale independent to a very good approximation. The value of $R$ for $\mathcal{L}$ of 10 fb$^{-1}$ in A, B and C are 10.3, 7.0 and 2.3 respectively. Introducing a statistical uncertainty $\sqrt{N}$ for $N$ counts and using the standard method for estimating the uncertainty we find $R_A = 10.3 \pm 0.24$, $R_B = 7.0 \pm 0.18$ and $R_C = 2.3 \pm 0.9$. Thus it is fair to conclude that different scenarios can be readily distinguished from each other. Ratios involving cross-sections with other choices
of $m$ exhibit similar scale independence.

The relatively large value of $R$ in scenario A is partly due to the $\tau$ dominance of the final states in this scenario as discussed in the last section. Since the $\tau$ decays into hadrons with a large BR, the numerator of $R$ is naturally enhanced. The denominator of $R$ on the other hand is small because, as explained in the last section, the number of final states involving $e$ and $\mu$ are suppressed.

The above properties also hold in scenario B to a lesser extent yielding a value of $R$ smaller than that in A but significantly larger than the one in C. In C, as in any other VLSP scenario, the denominator of $R$ is rather large for reasons already discussed and a smaller $R$ is obtained.

In order to provide some estimate of the dominant backgrounds we present in Table 6 the signal and the important standard model backgrounds for several values of $m$ in the leading order for $Q = \sqrt{s}$. This will be followed by the usual analysis of the significance $(S/\sqrt{B})$, where $S(B)$ is the total number of signal (background) events. Although we have listed only the backgrounds from $t\bar{t}$, QCD (including all quark-anti-quark and gluon events in Pythia in the lowest order) we have also simulated $WW, ZZ, WZ$ and Drell-Yan backgrounds and have found them to be indeed negligible. For later use we have simulated the background from $W + jets$ events.

The $W + jets$ cross-section has been computed for $\hat{p}_{T} > 50$ where $\hat{p}_{T}$ is defined in the rest frame of the parton-parton collision. The QCD cross-section has been computed in two $\hat{p}_{T}$ bins: (i) $400 \text{ GeV} < \hat{p}_{T} < 1000 \text{ GeV}$ and (ii) $1000 \text{ GeV} < \hat{p}_{T} < 2000 \text{ GeV}$. The corresponding cross-sections being $2090 \text{ pb}$ and $10 \text{ pb}$ respectively. Outside these bins the number of events are negligible.

Although the squark-gluino production cross-section is rather tiny in scenario C the signal cross-sections predicted for $m \geq 2$ is larger than the corresponding signals in A and B with much larger raw production cross-section. This again is a direct consequence of the large leptonic BRs of gaugino decays in the underlying VLSP scenario as discussed above. The significance (without systematic errors) of the signal for different $m$ and the representative $\mathcal{L}$ of $10 \text{ fb}^{-1}$ are in Table 7. The corresponding numbers for other $\mathcal{L}$ s can be estimated by simple scaling and one can easily verify that in several channels statistically significant signals can be obtained for much lower $\mathcal{L}$ s.

From Tables 6 and 7 it is clear that one way to unambiguously discriminate between A,
B on the one hand and C on the other is the count of \(0 - l\) events. This conclusion based on leading order cross-sections is likely to hold inspite of the scale uncertainty discussed above and the possibility that the systematic errors, which we have not considered in this paper, might be relatively large in the early stages of the LHC and affect the significance. The same count may discriminate between A and B although the theoretical uncertainties illustrated in Table 4 may cast some doubt on the results. The observation of the clean almost background free signal for \(m = 3\) may vindicate model C since no statistically significant signal is expected from A or B in this case. On the other hand in the VLSP scenario C an acceptable signal in this channel is expected even for \(\mathcal{L}\) significantly smaller than 10 fb\(^{-1}\).

Counting experiments alone for \(m = 1\) or \(m = 2\) may not be very useful for discriminating between A and B during the early stages of the LHC run because of the theoretical uncertainties and low statistics. As discussed above one can form several QCD scale invariant ratios of observables to distinguish between scenarios A and B. For example \(R' = \frac{\sigma_0}{\sigma_{2OS}}\), where \(\sigma_{2OS}\) is the cross-sections for \(m = 2\) involving opposite sign leptons, \(R'_A = 312.3 \pm 38.7\) and \(R'_B = 131.5 \pm 13.8\). Another example is \(R'' = \frac{\sigma_1}{\sigma_{2SS}}\), where \(\sigma_{2SS}\) is the cross-sections for \(m = 2\) same sign leptons, \(R''_A = 83.3 \pm 17.1\) and \(R''_B = 50.0 \pm 8.7\). However, more statistics will be required to make the distinction unambiguous.

One could use the next to leading order cross-section for squark-gluino production [35]. However, the uncertainty in the dominant QCD background in the canonical \(0 - l\) channel due to higher order effects is not known precisely. We have therefore restricted ourselves to leading order cross-sections for both the signal and the backgrounds. It is somewhat reassuring to note that the leading order signal cross-sections are typically multiplied by a factor of 1.4 - 1.5 in the next to leading order. Thus the significance will remain the same even if we have underestimated the background by a factor of two.

Obviously the dominance of final states involving \(\tau\) leptons in some of the models under consideration can not be directly established from the generic observables. Nor can the dominance of final states with B-hadrons in certain scenarios be tested. For this \(\tau\) and \(b\)-jet tagging facilities must be relied upon.

We, therefore, turn our attention to final states of the type \(1\tau + X\) where \(X\) includes two or more hard jets but no \(e\) or \(\mu\) or tagged \(\tau\). Tagging of \(\tau\) jets are implemented according to the following procedure.

Only hadronic \(\tau\) decays are selected. The \(\tau\)-jets with \(\eta < 3.0\) are then divided into
Table 6: The cross-sections (including efficiency) at $Q = \sqrt{s}$ for signal process with different $m$, $t\bar{t}$ and QCD events. Here $SS$ refers to $m = 2$ with leptons carrying the same charge and $OS$ refers to similar events with leptons carrying opposite charge. No entry in a particular column (-) means negligible background.

|          | SIGNAL | background |
|----------|--------|------------|
|          | A      | B          | C          | $t\bar{t}$ | QCD     |
| $\sigma$ (pb) | 15.58  | 5.74       | 0.74       | 400        | 2100    |
| $0l$     | 2.03   | 1.21       | 0.21       | 0.33       | 3.55    |
| $1l$     | 0.20   | 0.17       | 0.09       | 0.16       | $5.0 \times 10^{-3}$ |
| $SS$     | $2.4 \times 10^{-3}$ | $3.4 \times 10^{-3}$ | $6.0 \times 10^{-3}$ | $7.2 \times 10^{-4}$ | -      |
| $OS$     | $6.5 \times 10^{-3}$ | $9.2 \times 10^{-3}$ | 0.02       | 0.01       | -      |
| $3l$     | $2.6 \times 10^{-4}$ | $4.9 \times 10^{-4}$ | $3.5 \times 10^{-3}$ | $3.2 \times 10^{-4}$ | -      |

several $P_T$ bins. A $\tau$-jet in any $P_T$ bin is then treated as tagged or untagged according to the efficiency ($\epsilon_\tau$) given in [33] figure 12.9 for a particular bin. In this analysis we have applied Cuts 1-5. The corresponding efficiencies for various signals in scenario A and the dominant QCD and $t\bar{t}$ backgrounds are listed in Tables 8-10.

The computation of $1e + X$ type events are rather straight forward. Here for simplicity we have assumed the e-detection efficiency to be 100%. In our generator level analysis the result for $1\mu + X$ is expected to be the same to a good approximation and we do not present them separately. The number of events of the above two types subject to the kinematical cuts listed above are presented in the second and third rows of Table 11 along with the dominant SM backgrounds. The QCD background to $1\tau + X$ events stems from mistagging of light flavour jets as $\tau$-jets. The mistagging probability has also been taken from [33] figure 12.9.

The $1\tau + X$ signal, if unambiguously observed, will disfavour model C. The size of the signal or the ratio $N(1\tau + X)/N(1e + X)$ can distinguish between scenarios A and B inspite of theoretical and possible systematic uncertainties. If this signal is not observed then the $1e + X$ signal can establish scenario C. If we require $X$ to be free of $b$-jets then the significance marginally increases because of the reduced background from $t\bar{t}$ events. The
Table 7: The significance \( \left( \frac{S}{\sqrt{B(t\bar{t} + QCD)}} \right) \) of signals in Table 6 for \( \mathcal{L} = 10\text{fb}^{-1} \).

|   | A | B | C |
|---|---|---|---|
| 0l | 103 | 61 | 11 |
| 1l | 49 | 42 | 22 |
| SS | 9 | 13 | 22 |
| OS | 5 | 8 | 16 |
| 3l | 1 | 3 | 20 |

Table 8: The cumulative efficiency of the cuts for signal(A) given by \( \frac{N_i}{N} \), where \( N_i \) is the number of events survived after successive application of Cut 1 to Cut i and \( N \) is the total sample generated.

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| Cut 1 | Cut 2 | Cut 3 | Cut 4 | Cut 5 |
| 1\(\tau\) + X | 0.0712 | 0.0441 | 0.0334 | 0.0263 | 0.0155 |
| 1e + X | 0.0214 | 0.0084 | 0.0061 | 0.0051 | 0.0034 |
| 1\(\tau\) + 0b + X | 0.0391 | 0.0273 | 0.0201 | 0.0161 | 0.0097 |
| 1\(\tau\) + 1b + X | 0.0194 | 0.0112 | 0.0081 | 0.0062 | 0.0034 |
| 1\(\tau\) + 2b + X | 0.0113 | 0.0061 | 0.0041 | 0.0039 | 0.0022 |
| 1e + 0b + X | 0.0065 | 0.0030 | 0.0023 | 0.0019 | 0.0012 |
| 1e + 1b + X | 0.0083 | 0.0031 | 0.0022 | 0.0019 | 0.0012 |
| 1e + 2b + X | 0.0047 | 0.0019 | 0.0014 | 0.0012 | 0.0008 |
|                  | Cut 1       | Cut 2       | Cut 3       | Cut 4       | Cut 5       |
|------------------|-------------|-------------|-------------|-------------|-------------|
| $1\tau + X$     | 0.1374      | 0.0135      | 0.0006      | 0.0006      | 1.29×10^{-4}|
| $1e + X$        | 3.7×10^{-5} | 3.6×10^{-5} | 2.7×10^{-6} | 2.7×10^{-6} | 1.9×10^{-7} |
| $1\tau + 0b + X$| 0.1261      | 0.0125      | 2.7×10^{-4} | 2.4×10^{-4} | 4.6×10^{-5} |
| $1\tau + 1b + X$| 0.0087      | 0.0085      | 2.8×10^{-4} | 2.5×10^{-4} | 5.6×10^{-5} |
| $1\tau + 2b + X$| 0.0019      | 0.0019      | 8.5×10^{-5} | 7.9×10^{-5} | 2.5×10^{-5} |
| $1e + 0b + X$   | 2.2×10^{-5} | 2.1×10^{-5} | 1.3×10^{-6} | 1.3×10^{-6} | 1.9×10^{-7} |
| $1e + 1b + X$   | 1.2×10^{-5} | 1.2×10^{-5} | 1.3×10^{-6} | 1.3×10^{-6} | -           |
| $1e + 2b + X$   | 2.0×10^{-6} | 2.0×10^{-6} | -           | -           | -           |

Table 9: Same as Table 8 for QCD events.

|                  | Cut 1       | Cut 2       | Cut 3       | Cut 4       | Cut 5       |
|------------------|-------------|-------------|-------------|-------------|-------------|
| $1\tau + X$     | 0.0392      | 0.0041      | 0.0006      | 0.0005      | 0.0001      |
| $1e + X$        | 0.0481      | 0.0034      | 0.0004      | 0.0003      | 0.0001      |
| $1\tau + 0b + X$| 0.0101      | 0.0008      | 0.0002      | 0.0001      | 2.3×10^{-5} |
| $1\tau + 1b + X$| 0.0192      | 0.0023      | 0.0003      | 0.0002      | 5.6×10^{-5} |
| $1\tau + 2b + X$| 0.0097      | 0.0013      | 0.0002      | 0.0001      | 3.0×10^{-5} |
| $1e + 0b + X$   | 0.0133      | 0.0006      | 0.0001      | 6×10^{-5}   | 2.5×10^{-5} |
| $1e + 1b + X$   | 0.0244      | 0.0016      | 0.0002      | 0.0001      | 4.6×10^{-5} |
| $1e + 2b + X$   | 0.0113      | 0.0011      | 0.0001      | 9×10^{-5}   | 3.0×10^{-5} |

Table 10: Same as Table 8 for $t\bar{t}$ events.
statistical significance of various signals for the representative $\mathcal{L}$ of 10 fb$^{-1}$ are listed in Table 12.

We next illustrate that both scenarios A and B are expected to be rich in $b$-jets. A jet with $|\eta| < 2.5$ matching with a B-hadron of decay length $> 0.9\text{mm}$ has been marked tagged. The above criteria ensures that $\epsilon_b \simeq 0.5$ in $t\bar{t}$ events, where $\epsilon_b$ is the single $b$-jet tagging efficiency (i.e., the ratio of the number of tagged $b$-jets and the number of taggable $b$-jets in $t\bar{t}$ events). It is readily seen that, the fraction of $1e + X$ events with at least one tagged $b$-jet is quite large in A (0.59) and B (0.63) and somewhat smaller in C(0.31). The significance of different signals are in Table 12.

Finally we present in Table 13 events of the type $2\tau + X$ and $2e + X$ with different number of tagged $b$-jets. It is to be noted that $2\tau + X$ events ($2e + X$ events) are statistically significant in A and B (C). Moreover an observable signal in $2\tau + (\geq 1b) + X$ channel is expected only in model A.

Although all the scenarios under consideration involve light sleptons direct slepton
Table 12: The $S/\sqrt{B}(t\bar{t} + Wjets + QCD)$ ratio for the signals in Table 11 corresponding to $L = 10\text{fb}^{-1}$.

| SIGNAL          | A   | B   | C   |
|-----------------|-----|-----|-----|
| $\sigma(\text{pb})$ | 15.58 | 5.74 | 0.74 |
| $1\tau + X$     | 42.9 | 22.2 | 4.1  |
| $1e + X$        | 26.3 | 21.0 | 14.6 |
| $1\tau + 0b + X$| 46.4 | 22.7 | 4.6  |
| $1\tau + (\geq 1b) + X$ | 19.2 | 11.0 | 1.5  |
| $1e + 0b + X$   | 18.3 | 12.8 | 18.3 |
| $1e + (\geq 1b) + X$ | 17.9 | 15.6 | 5.4  |

Table 13: The cross-sections (including efficiency) of events with two detected $\tau$ and two isolated $e$. The other conventions are as in Table 11.

| SIGNAL          | A   | B   | C   | $t\bar{t}$ | QCD |
|-----------------|-----|-----|-----|-----------|-----|
| $\sigma(\text{pb})$ | 15.58 | 5.74 | 0.74 | 400       | 2100|
| $2\tau + X$     | 0.0171 | 0.0078 | 0.0019 | 0.0015   | 0.0231|
| $2e + X$        | 0.0008 | 0.0009 | 0.0031 | 0.0010   | -    |
| $2\tau + 0b + X$| 0.0105 | 0.0039 | 0.0012 | 0.0002   | 0.0084|
| $2\tau + 1b + X$| 0.0038 | 0.0019 | 0.0003 | 0.0007   | 0.0073|
| $2\tau + 2b + X$| 0.0028 | 0.0017 | 0.0003 | 0.0006   | 0.0067|
| $2e + 0b + X$   | 0.0004 | 0.0004 | 0.0021 | 0.0002   | -    |
| $2e + 1b + X$   | 0.0003 | 0.0003 | 0.0005 | 0.0006   | -    |
| $2e + 2b + X$   | 0.0001 | 0.0002 | 0.0004 | 0.0002   | -    |

searches are unlikely to yield signals at the early LHC experiments. The slepton discovery plot in the $m_0 - m_{1/2}$ plane (see [36] Fig. 13.29) shows that for $m_0 = 120$ GeV, our common choice for all three scenarios, the reach in $m_{1/2}$ for $10 \text{fb}^{-1}$ is only about 150 GeV.
Table 14: The \( S/\sqrt{B(t\bar{t} + QCD)} \) ratio of the signals in Table 13 for \( L = 10\text{fb}^{-1} \).

However, for (50 - 60) \( \text{fb}^{-1} \) sleptons in scenarios A and B should be detected. In the conventional \( \tau \)-annihilation scenario larger \( L \) will be required for this discovery. The direct detection of sleptons will provide additional insight into the DM relic density production.

Several earlier analyses of DM relic density in mSUGRA or other models considered non-zero input values of \( A_0 \) [37, 38] with different emphasis. Arnowitt et al in [6] showed that the \( \tau \)-coannihilation corridor in the \( m_0-m_{1/2} \) plane is highly sensitive to \( A_0 \). For large \( A_0 \), \( \tau \)-coannihilation is effective even for \( m_0 \) as large as 1 TeV. In a more recent work [39] new benchmark points with non-zero \( A_0 \) allowed by WMAP data were introduced. These points corresponds to new mass hierarchies and, consequently, new collider signatures. However, the correlation between leptonic signatures at LHC and different DM relic density producing mechanisms was not discussed before.

In this paper we have considered the observed DM relic density constraints and direct constraints on sparticle masses from accelerators. We have not considered indirect constraints like the measured value of \( \text{BR}(B \to s\gamma) \). Many of the latter constraints arise from flavour violating processes. Strictly speaking these constraints are sensitive to the assumption that the quark and the squark mass matrices are aligned in the flavour space so that the same mixing matrix as the CKM matrix operate in the squark sector. This assumption of minimum flavour violation fails even if there are small off-diagonal elements of the squark mass matrix at the GUT scale. On the other hand such small elements does not affect processes like
neutralino annihilation and squark-gluino production and decay. For further discussions on this point we refer the reader to Djouadi et al in [21] and references there in. We, note in passing that model B and model C are allowed by the above constraint (see [18]).

4 Summary and Conclusions

We have examined the parameter space of the mSUGRA model with moderate values of the parameter $\tan \beta$. We focussed on zones of the $m_0 - m_{1/2}$ plane corresponding to light sleptons and relatively light squark and gluinos compatible with the DM relic density data and constraints from direct sparticle searches. This part of the parameter space is interesting since viable signals from squark-gluino events are expected in the early stages of the LHC experiments.

If one employs the often used but rather ad hoc assumption that the common trilinear coupling ($A_0$) vanishes at the GUT scale it is well known that there is only one such zone where $\tilde{\tau}$-coannihilation is the dominant mechanism for producing the relic density [21]. In this scenario the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ present in squark gluino decay cascades exclusively decay via two body modes into appropriate neutrino (sneutrino) - slepton (lepton) pairs and lepton-slepton, neutrino-sneutrino pairs. Lepton flavour universality holds in these decays to a very good approximation. The sneutrinos decay into invisible channels with almost 100% BR. The $\tilde{\chi}_2^0$ also decays into invisible channels with large BRs. The suppression of hadronic decays of the lighter electroweak gauginos and the presence of additional carriers of missing energy lead to spectacular collider signals as has already been noted in the context of LEP/NLC [29, 30] and Tevatron [28]. In this paper we emphasize that this VLSP or ELSP scenario is realized in the popular $\tilde{\tau}$-coannihilation region of the mSUGRA model and discuss the signatures at the LHC in detail by introducing the benchmark scenario C (see Table 1).

If the ad hoc assumption of vanishing $A_0$ is given up additional WMAP allowed parameter spaces open up [18]. It is possible that the LSP pair annihilation and $\tilde{\tau}$- coannihilation both contribute significantly to DM relic density production although the former dominates. To illustrate the collider signals in this case the bench mark scenario A (see Table 1) is introduced. It is also possible that even with non-zero $A_0$ the $\tilde{\tau}$ coannihilation is the dominant mechanism but the corresponding squark-gluino masses are much smaller compared to C (see scenario B, Table 1). In scenario A and, to a lesser extent, in scenario B both $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$
decay dominantly into final states involving $\tau$ leptons (see the discussions in section 2 and Table 2) and lepton universality is violated. Moreover, these final states from squark-gluino production should be rich in $b$-jets.

In [18] the collider signals from squark-gluino events in three scenarios were compared and contrasted by exploiting the above characteristics. The calculations were done mostly at the parton level although in order to simulate the effects of $\tau$ tagging some Pythia based analyses were also reported.

In this paper we first employ the generic $m$-leptons + $n$-jets + $E_T$ signatures to discriminate among the three scenarios (see Tables 6 and 7), where only final states with stable leptons have been considered. We demonstrate that some qualitative idea about the DM relic density producing mechanisms may be obtained even without flavour tagging. It is shown that the fraction of events with $m = 0$ is much larger than that for $m \geq 1$ in scenarios A and B. The relative weight of the leptonic events, however, is significantly larger in scenario C (see Tables 5 - 7).

Next we illustrate the $\tau$ dominance of the final states in A and B by including $\tau$ detection efficiency in our simulation (see Tables 11 - 14). Here we have extended the analysis of [18] by considering $2l + X$ states where $l$ stands for $e$ and tagged $\tau$ and $X$ corresponds to hadronic states. In particular the observation of $2\tau + X$ events may provide a very convincing test of scenario A. The number of tagged $b$-jets may further help to discriminate among different scenarios. Most of the crucial signatures discussed in this paper may be observed with $L$ of 10 fb$^{-1}$. Some of them are observable with much smaller accumulated luminosity.

Acknowledgment: AD, SP and NB acknowledge financial support from Department of Science and Technology, Government of India under the project No (SR/S2/HEP-18/2003). SP also thanks the Council of Scientific and Industrial Research (CSIR), India for a research fellowship. A large part of this work was done when the authors were in the Department of Physics, Jadavpur University, Kolkata 700 032, India.

References

[1] For reviews on Supersymmetry, see, e.g., H. P. Nilles, Phys. Rep. 110, 1 (1984); H. E. Haber and G. Kane, Phys. Rep. 117, 75 (1985); J. Wess and J. Bagger, Supersymmetry
and Supergravity, 2nd ed., (Princeton, 1991); M. Drees, P. Roy and R. M. Godbole, Theory and Phenomenology of Sparticles, (World Scientific, Singapore, 2005).

[2] H. Goldberg, Phys. Rev. Lett. 50, 1419 (1983); J. Ellis, J. Hagelin, D. Nanopoulos and M. Srednicki, Phys. Lett. B127, 233 (1983); J. Ellis, J. Hagelin, D. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. B238, 453 (1984).

[3] G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005), [arXiv:hep-ph/0404175]; W. L. Freedman and M. S. Turner, Rev. Mod. Phys. 75, 1433 (2003), [arXiv:astro-ph/0308418]; L. Roszkowski, Pramana 62, 389 (2004), [arXiv:hep-ph/0404052].

[4] A. B. Lahanas, N. E. Mavromatos and D. V. Nanopoulos, Int. J. Mod. Phys. D 12, 1529 (2003) [arXiv:hep-ph/0308251]; C. Munoz, Int. J. Mod. Phys. A 19, 3093 (2004) [arXiv:hep-ph/0309346]; Manuel Drees, Plenary talk at 11th International Symposium on Particles, Strings and Cosmology (PASCOS 2005), Gyeongju, Korea, 30 May - 4 June 2005 (published in AIP Conf.Proc., 805, 48-54 (2006).

[5] G. Jungman, M. Kamionkowski and K. Greist, Phys. Rep. 267, 195 (1996).

[6] J. R. Ellis, T. Falk and K. A. Olive, Phys. Lett. B 444, 367 (1998); J. R. Ellis, T. Falk, K. A. Olive and M. Srednicki, Astropart. Phys. 13, 181 (2000) [Erratum-ibid. 15, 413 (2001)]; A. Lahanas, D. V. Nanopoulos and V. Spanos, Phys. Rev. D 62, 023515 (2000); R. Arnowitt, B. Dutta and Y. Santoso, Nucl. Phys. B606, 59(2001); T. Nihei, L. Roszkowski and R. Ruiz de Austri, J. High Energy Phys. 0207, 024 (2002); V. A. Bednyakov, H. V. Klapdor-Kleingrothaus and V. Gronewold, Phys. Rev. D 66, 115005 (2002).

[7] J. Edsjo and P. Gondolo, Phys. Rev. D 56, 1879 (1997).

[8] S. Mizuta and M. Yamaguchi, Phys. Lett. B 298, 120 (1993) [arXiv:hep-ph/9208251].

[9] R. Arnowitt, B. Dutta and Y. Santoso, Nucl. Phys. B606, 59 (2001); V. A. Bednyakov, H. V. Klapdor-Kleingrothaus and V. Gronewold,

[10] C. Boehm, A. Djouadi and Manuel Drees, Phys. Rev. D 62, 035012 (2000); J. R. Ellis, K. A. Olive and Y. Santoso, Astropart. Phys. 18, 395 (2003)
[arXiv:hep-ph/0208178].

[11] J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. D 61, 075005 (2000); Phys. Rev. Lett. 84, 2322 (2000); J. L. Feng, K. T. Matchev and F. Wilczek, Phys. Lett. B 482, 388 (2000); J. L. Feng and F. Wilczek, Phys. Lett. B 631, 170 (2005) [arXiv:hep-ph/0507032].

[12] K. L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D 58, 096004 (1998); [arXiv:hep-ph/9710473]; U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. D 68, 035005 (2003) [arXiv:hep-ph/0303201].

[13] M. Drees and M. Nojiri, Phys. Rev. D 47, 376 (1993).

[14] R. Arnowitt and P. Nath, Phys. Rev. Lett. 70, 3696 (1993); H. Baer and M. Brhlik, Phys. Rev. D 53, 597 (1996), Phys. Rev. D 57, 567 (1998); H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D 63, 015007 (2001); J. R. Ellis, T. Falk, G. Ganis, K. A. Olive and M. Srednicki, Phys. Lett. B 510, 236 (2001); A. B. Lahanas and V. C. Spanos, Eur. Phys. J. C 23, 185 (2002); A. Djouadi, M. Drees and J. Kneur, Phys. Lett. B 624, 60 (2005).

[15] D. N. Spergel et al., Astrophys. J. Suppl. 170, 377 (2007), [arXiv:astro-ph/0603449].

[16] M. Battaglia, I. Hinchliffe and D. Tovey, J. Phys. G 30, R217 (2004); B. C. Allanach, G. Belanger, F. Boudjema and A. Phukov, J. High Energy Phys. 0412, 020 (2004); M. M. Nojiri, G. Polesello and D. R. Tovey, J. High Energy Phys. 0603, 063 (2006).

[17] A. H. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49, 970 (1982); R. Barbieri, S. Ferrara and C. A. Savoy, Phys. Lett. B 119, 343 (1982); L. J. Hall, J. Lykken and S. Weinberg, Phys. Rev. D 27, 2359 (1983); P. Nath, R. Arnowitt and A. H. Chamseddine, Nucl. Phys. B227, 121 (1983); N. Ohta, Prog. Theor. Phys. 70, 542 (1983).

[18] Utpal Chattopadhyay, Debottam Das, Amitava Datta and Sujoy Poddar, Phys. Rev. D 76, 055008 (2007).

[19] L. E. Ibanez and G. G. Ross, Phys. Lett. B 110, 215 (1982); K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, Prog. Theor. Phys. 68, 927 (1982) [Erratum-ibid. 70, 330 (1983)]; J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos and K. Tamvakis, Phys. Lett.
B 125, 275 (1983); L. Alvarez-Gaume, J. Polchinski and M. B. Wise, Nucl. Phys. B221, 495 (1983). [1] and P. Nath, R. Arnowitt and A.H. Chamseddine, Applied N =1 Supergravity (World Scientific, Singapore, 1984).

[20] Komatsu et al; M. E. Machacek and M. T. Vaughn, Nucl. Phys. B222, 83 (1983); Yukawa Couplings,” Nucl. Phys. B236, 221 (1984); Nucl. Phys. B249, 70 (1985).

[21] J. R. Ellis, K. A. Olive and Y. Santoso, New J. Phys. 4, 32 (2002) J. Ellis, K. Olive, Y. Santoso and V. Spanos, Phys. Lett. B 565 176 (2003); H. Baer and C. Balazs, J. Cosmology and Astroparticle Phys. 0305, 006 (2003); H.Baer, C.Balazs, A.Belyaev, J.Mizukoshi, X.Tata, Y.Wang J. High Energy Phys. 0207, 050 (2002) U. Chattapadhyay, A. Corsetti and P. Nath, Phys. Rev. D 68, 035005 (2003); A. Lahanas and D. V. Nanopoulos, Phys. Lett. B 568, 55 (2003); A. Djouadi, M. Drees and J. L. Kneur, J. High Energy Phys. 0603, 033 (2006).

[22] For the latest limits on the sparticle masses from LEP experiments: see http://lepsusy.web.cern.ch/lepsusy/

[23] G. Polesello and D.R.Tovey, J. High Energy Phys. 0405, 071 (2004). H. Baer and X. Tata arXiv:0805.1905.

[24] R. Barate et al. [LEP Working Group for Higgs boson searches], Phys. Lett. B 565, 61 (2003) [arXiv:hep-ex/0306033].

[25] For a review see,e.g., Higgs boson theory and phenomenology. Marcela Carena (Fermilab) , Howard E. Haber (UC, Santa Cruz) . FERMILAB-PUB-02-114-T, SCIPP-02-07, Aug 2002. 87pp. Published in Prog. Part. Nucl. Phys. 50, 63-152 (2003), [hep-ph/0208209 (review)].

[26] SUGRA Working Group Collaboration (S. Abel et. al.), hep-ph/0003154.

[27] See, e.g., A.Pukhov, CalCHEP—a package for evaluation of Feynman diagrams and integration over multi-particle phase space (hep-ph/9908288). For the more recent versions see: http://www.ifh.de/pukhov/calchep.html.

[28] Amitava Datta, M. Guchhait and B. Mukhopadhyaya, Mod. Phys. Lett A 10, 1011 (1995); Amitava Datta, Surojit Chakravarti and M. Guchait, Z. Phys. C 68, 325
(1995). Aseshkrishna Datta, M. Guchait and K. K. Jeong, Int. J. Mod. Phys. A 14, 2239 (1999).

[29] Amitava Datta, M. Drees and M. Guchhait, Z. Phys. C 69, 347 (1996).

[30] Amitava Datta, AseshKrishna Datta and Sreerup Raychaudhuri, Phys.Lett. B 349, 113 (1995); Eur. Phys. J. C 1, 375 (1998); Amitava Datta and AseshKrishna Datta, Phys. Lett B 578, 165 (2004); H. Dreiner, O.Kittel and U. Langenfeld, Phys. Rev. D 74, 115010 (2006)

[31] Amitava Datta, M. Guchait and N. Parua, Phys.Lett. B 395, 54 (1997).

[32] Amitava Datta, Aseshkrishna Datta and M. K. Parida, Phys.Lett. B 431, 347 (1998).

[33] CMS physics, Technical Design Report, vol-I.

[34] T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin, Comp. Phys. Comm. 135, 238 (2001); For a more recent version see, J. High Energy Phys. 0605, 026 (2006)

[35] W. Beenakker, R. Hopker, M. Spira and P. M. Zerwas, Nucl. Phys. B492, 51 (1997).

[36] CMS physics, Technical Design Report, vol-II

[37] V. A. Bednyakov, S. G. Kovalenko, H. V. Klapdor-Kleingrothaus and Y. Ramachers, Z. Phys. A 357, 339 (1997); V. A. Bednyakov, H. V. Klapdor-Kleingrothaus and S. G. Kovalenko, Phys. Rev. D 55, 503 (1997); A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D 63, 125003 (2001); J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Rev. D 69, 015005 (2004); V. A. Bednyakov and H. V. Klapdor-Kleingrothaus, Phys. Rev. D 70, 096006 (2004); L. Calibbi, Y. Mambrini and S. K. Vempati, J. High Energy Phys. 0709, 081 (2007), [arXiv:0704.3518 [hep-ph]].

[38] L.S. Stark, P. Hafliger, A. Biland and F. Pauss, J. High Energy Phys. 08, 059 (2005)

[39] D. Feldman, Z. Liu and P. Nath, Phys. Rev. Lett. 99, 251802 (2007) [arXiv:0707.1873 [hep-ph]].