Signals of supersymmetry with inaccessible first two families at the Large Hadron Collider

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\textbf{Abstract}

We investigate the signals of supersymmetry (SUSY) in a scenario where only the third family squarks and sleptons can be produced at the Large Hadron Collider (LHC), in addition to the gluino, charginos and neutralinos. The final states in such cases are marked by a multiplicity of top and/or bottom quarks. We study in particular, the case when the stop, sbottom and gluino masses are near the TeV scale due to which, the final state t’s and b’s are very energetic. We point out the difficulty in b-tagging and identifying energetic tops and suggest several event selection criteria which allow the signals to remain significantly above the standard model background. We show that such scenarios with gluino mass up to 2 TeV can be successfully probed at the LHC. Information on $\tan \beta$ can also be obtained by looking at associated Higgs production in the cascades of accompanying neutralinos. We also show that a combined analysis of event rates in the different channels and the effective mass distribution allows one to differentiate this scenario from the one where all three sfermion families are accessible.

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1 Introduction

The investigation on whether nature is supersymmetric is an important part of activities related to the Large Hadron Collider (LHC). By and large, if supersymmetry (SUSY) [1, 2, 3], broken within the TeV scale, has to offer a cold dark matter candidate, experiments at the LHC should see signals with large missing transverse energy ($E_T$), carried away by the lightest SUSY particle (LSP). The lightest neutralino turns out to be the LSP [4, 5] in most models. Hard leptons and/or jets of various multiplicity constitute the accompanying ‘visible’ signals when one has a neutralino LSP. It is from these, then, that one is left to guess the detailed character of the SUSY spectrum, and whether the low-energy spectrum is resulting from some organising principle at high scale[6].

A scenario often suggested is that the first two families of squarks and sleptons are far too heavy (∼ 5 - 10 TeV or more) to have any impact on TeV-scale phenomenology, while the third family is within or around a TeV in mass. While this still suffices in controlling the quadratically divergent contributions to the Higgs mass, the troublesome issue of flavour-changing neutral currents [7] is avoided through decoupling of the first two families [8, 9]. This kind of a SUSY spectrum therefore deserves special attention in the context of the LHC. The present work suggests some improved criteria from which one not only obtains background-free signals of such a scenario, but also can distinguish it from one where all three families of sfermions are within the reach of the LHC.

Several theoretical schemes to achieve the suggested scenario have been proposed in the literature. It is possible, for example, to have a hidden sector of such composition that the third family couples to it differentially, leading to smaller soft SUSY breaking terms compared to those of the first two [10]. In particular, such possibilities can be envisioned in string-inspired models with flavour-dependent interactions with modular fields [11]. The existence of a horizontal symmetry, with the third, and first two families being respectively singlets and doublets under it, can also cause a mass splitting [12]. In SO(10) SUSY Grand Unified Scenarios (GUT), too, suitable D-terms for the fields belonging to 5 and 10 of SU(5) may lead to a mass hierarchy of the suggested type, with appropriate adjustment of parameters [13, 14]. A similar mass separation can also arise out of the D-terms of some additional (anomalous) U(1) gauge symmetry [15, 16]. Finally, appropriate regions in the parameter space of minimal supergravity (mSUGRA), with a universal scalar soft breaking mass term well above a TeV, can lead to lower values of only the third family sfermions due to the role of Yukawa couplings in the process of running down to the electroweak scale [17, 18].

As we have already stated, our purpose is to take a close look at the LHC signals of a scenario where only the third family sfermions are within an accessible range. With this in view, we have chosen a few benchmark points in the parameter space, where masses of the first two families evolves down from a relatively high mass parameter at high scale. In contrast, masses for the third family and the two Higgs doublets originate in a relatively lower high-scale parameter, thus creating a hierarchy of the type sought after. The absolute as well as relative values of the stop and sbottom masses are decided by other parameters of the theory including tan $\beta$, the ratio of the vacuum expectation values (vev) of the two Higgs doublets, which is turn controls the mixing between the left-and right-chiral states.

Many useful studies on the collider phenomenology of similar scenarios have taken place earlier as well as in the very recent past. These include studies in both non-SUSY [25, 26] and SUSY scenarios [19, 20, 21, 27]. However, with the LHC within close range, many aspects of the detection of new signals are being realised with increasing degree of sensitivity [22, 23]. The present study is aimed to supplement and extend the
existing ones, keeping some such realisations in mind, and to demonstrate the viability of some additional final states and event selection criteria. To be specific, some aspects, on which we have improved on earlier works, are as follows:

- The signals suggested in earlier works often depend on the identification of multiple b’s in the final state. When the mass range of accessible superparticles are about a TeV or well above that, a large fraction of the b’s arising from their cascades are quite energetic. The efficiency of b-tagging, on the other hand, is optimum for the transverse momentum ($p_T$) range of 50 - 100 GeV\cite{22}. Although the performance of b-detection devices have scope for improvement beyond this, we felt that it is profitable to suggest signals with only those b’s whose $p_T$ lie in the optimal range.

- The signals often involve three or four top quarks in the final state. Some of these tops can be considerably boosted. Since very energetic jets acquire invariant masses amounting to 15 - 20% of their energy through spreading, it is not unlikely that these top quarks be faked by some energetic central jets in a machine like the LHC. Besides, as has been pointed out in recent studies \cite{19, 20, 21, 24, 25, 26, 27}, top detection in this scenario has a rather low efficiency. Therefore, we wish to suggest signals where the likely presence of several tops can be exploited, but the tops by themselves need not be identified.

- With both of the above points in mind, we have suggested signatures of SUSY with mass spectra of the aforementioned type, by looking for various combinations of b’s and leptons in the final state. Specific event selection criteria, especially those pertaining to the leptons, have been proposed to eliminate backgrounds and enhance the discovery reach. We have also gone beyond earlier studies by suggesting that final states with the lightest neutral Higgs, produced in association, can make the events stand out as a reflection of the nature of the neutralino spectrum.

- It is also of interest to find out if the proposed signals enable one to distinguish a SUSY spectrum where only the third family is accessible, from one where first two are also within the production threshold. We suggest an effort in this direction by comparing the event rates in various signal channels and also looking at kinematic distributions such as the scalar sum of the $p_T$'s of all particles.

It may useful to specifically mention the points on which we have gone beyond the earlier works cited in \cite{19, 20, 21, 27}. In \cite{27} and \cite{20} for example, b-tagging has been highlighted as the main criterion (with an emphasis on $\geq 3$ b-jets in \cite{27}). We have, on the other hand, taken the position that b’s may not be efficiently tagged when they are very hard, and recommended that we depend on them only when their $p_T$ lies in the range 50 – 100 GeV. We suggest the use of leptons, with specific kinematic characteristics, to make good for ‘lost’ b’s. We have also underscored the reasons why tops, being often very energetic, be better not reconstructed.

We outline our parameter choice for the benchmark points in section 2, where the justification of our approach is also given by showing the kinematic properties of tops and b’s corresponding to these points. Studies on different signals as well as the strategies adopted for suppressing backgrounds are reported in section 3. Section 4 contains a discussion on how one can hope to distinguish such a scenario from one where all sfermion families are produced at the LHC. We summarise our study and conclude in section 5.
2 Choice of benchmark points: motivation for the chosen signals

The minimal supersymmetric extension of the standard model has more than a hundred parameters. These parameters can be related by the supersymmetry breaking scheme. Since our study is essentially phenomenological, we economise on the parameters by considering an mSUGRA-like scheme, with the difference that high-scale squark and sfermion masses are not same for all generations.

We take \((m_{0}^{(1,2)}, m_{0}^{(3)}, m_{\tilde{\chi}}, \text{sign}(\mu), A^{(1,2)}, A^{(3)}, \tan\beta)\) viz. scalar masses for the first two generations of sfermions, scalar mass for the third generation of sfermions, unified gaugino mass, sign of the Higgsino parameter \(\mu\), the unified trilinear coupling for first two generations, the trilinear coupling for the third generation and \(\tan\beta\), where \(\beta\) is the angle between the VEVs of the two Higgs doublets to be the free parameters. The first two families of squarks and sleptons are degenerate and have rather high masses (\(\sim 5\) TeV) whereas the third generation has masses in the range of \(1\) to 1.5 TeV. As a consequence, the first two generations of sfermions decouple and we have enhanced production of tops and bottoms in the final states.

The benchmark points chosen by us in the above setting are based on the following considerations:

- Being able to probe situations where the tops and bottoms coming out of SUSY cascades are energetic enough, so that their identification efficiency can be suspect.
- The stops and sbottoms being within the reach of the LHC, going to values as high as possible, while there are appreciable numbers of events with an integrated luminosity of 300 fb\(^{-1}\).
- A scan over the gluino mass almost up to the search limit at the LHC, for medium as well as high values of the third family squark masses.
- A fair sampling of values of \(\tan\beta\), the chosen values being 5, 10 and 40.

With this in mind, high scale value of \(m_{0}^{(1,2)}\) is set to 5 TeV for the first two families, while the high-scale mass for the third family \((m_{0}^{(3)})\) is set so as to obtain third generation squark masses of the order of 1 TeV. The trilinear couplings \(A_{i}\) are all set to zero and we choose \(\mu > 0\). We mostly focus an \(\tan\beta = 10\) but also look at \(\tan\beta = 5, 40\) to see if any major differences are indicated. The Higgs mass parameters \(M_{H_u}\) and \(M_{H_d}\) are set to the value of the third family \(m_{0}\) at the high scale.

The particle spectrum has been generated using SuSpect 2.34 using high scale inputs in the pMSSM (phenomenological MSSM) option. The squark and gluino masses for the various benchmark points are given in Table 1. The masses for charginos and neutralinos are given in Table 2. The points itemised above, together with a glance at Tables 1 and 2, should convince the reader that the choice of our benchmark points are broadly representative of the scenario investigated here. It is obvious that in all these cases tops and bottoms will populate the final state, but will be often carry very high energies.

We explore regions of the parameter space where squarks are lighter than the gluino and of the order of \(\sim 1\) TeV. Cases where the gluino is considerably lighter than all squarks are left out for the following reasons. First, such a situation is typical of a focus point scenario, which has been already investigated [27]. Secondly, the gluino in such cases will have three-body decays only, and the tops and bottoms produced in the process will not be excessively hard, so that the conventional search strategies should work well. Thirdly, with a relatively light and therefore copiously produced gluino, there can be like-sign dilepton events in abundance, thus making the scenario conspicuous.
### Table 1: Third generation squark and gluino masses in GeV for the benchmark points considered.

| Point | $\tan\beta$ | $m_{\tilde{t}}$ | $m_{\tilde{q}}^{(3)}$ | $m_{\tilde{g}}$ | $m_{\tilde{g}_1(\tilde{t}_2)}$ | $m_{\tilde{b}_1(\tilde{b}_2)}$ |
|-------|-------------|----------------|----------------|----------------|----------------|----------------|
| 1A    | 10          | 800            | 800           | 1918           | 1124 (1403)   | 1376 (1502)   |
| 1B    | 10          | 600            | 1000          | 1496           | 856 (1130)    | 1100(1283)    |
| 1C    | 10          | 400            | 1200          | 1063           | 623 (916)     | 892 (1153)    |
| 2A    | 5           | 600            | 1000          | 1496           | 842 (1130)    | 1100(1290)    |
| 2B    | 5           | 400            | 1200          | 1063           | 603 (916)     | 890(1160)     |
| 3A    | 40          | 600            | 1000          | 1493           | 856 (1065)    | 1024(1157)    |
| 3B    | 40          | 400            | 1200          | 1058           | 619 (819)     | 783(982)      |

### Table 2: Chargino and Neutralino masses in GeV for all the benchmark points.

| Point | $m_{\chi^+_1}$ | $m_{\chi^+_2}$ | $m_{\chi^-_1}$ | $m_{\chi^-_2}$ | $m_{\chi^0_1}$ | $m_{\chi^0_2}$ |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1A    | 660            | 881            | 348            | 660            | 864            | 881            |
| 1B    | 484            | 648            | 258            | 484            | 622            | 649            |
| 1C    | 288            | 409            | 167            | 290            | 356            | 410            |
| 2A    | 487            | 707            | 258            | 488            | 686            | 701            |
| 2B    | 313            | 492            | 168            | 315            | 465            | 492            |
| 3A    | 482            | 619            | 259            | 482            | 590            | 619            |
| 3B    | 261            | 384            | 166            | 265            | 302            | 383            |

A b-tagging efficiency of 50% with a rejection of QCD jets at more than 99% is well established for b-hadrons with the transverse momentum ($p_T$) between 50 to 80 GeV. But in our case, it can be seen that the $p_T$ of b-hadrons very often exceeds this. It is not clear how the efficiency goes down as $p_T$ increases above 100 GeV. The $p_T$-distribution of b’s in four-b events can be seen in Figures 1 and 2.

Top quarks can be identified by a combination of a b-jet and a $W$ which give an invariant mass within a window of the top mass. The candidate $W$s are obtained from jet-pairs having invariant mass in the range $M_W \pm 15$ GeV. Besides the aforementioned b-tagging difficulty, this top reconstruction is complicated by two other factors in our situation.

First, at very high boosts, the jets from decay of the top can be highly collimated. However, very high energy QCD jets can also develop an invariant mass up to 15 - 20% of the jet energy, and thus, a top depositing a large energy in the hadron calorimeter can be faked by a similarly energetic jet whose ‘effective’ invariant mass may be of the same order as the top mass. In such cases, one has to resort to special techniques, such as specific kinematics, energetic leptons contained in jets, and using jet-substructure. Such techniques have been studied recently by various groups [28, 29].

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3 While there are many events in our chosen regions with both three-and four top quarks in the final state, 3b final states are only possible via squark-gluino production, and that too driven by the b-quark distribution in the proton. Thus the number of 3b events is relatively small.
Secondly, we have Higgs production through the cascade \( \chi_0^2 \rightarrow h\chi_1^0 \). The \( \chi_0^2 \) is produced in about 50% of the events we generate, and low tan\( \beta \) its decay into a Higgs has a large branching ratio. The Higgs then decays into a pair of b's. The mass of the Higgs in all our benchmark points lies at \( \lesssim 120 \) GeV. In cases where both the b-jets are not identified, the W-peak from invariant mass of jet-pairs, which is important in retracing the top via the W, is largely washed out by that of the Higgs and due to the large combinatorial background arising from a large jet multiplicity. Thus our benchmark points highlight one additional difficulty in identifying the final states via the top. To ameliorate these difficulties, we do not emphasise the reconstruction of the top. We also supplement b-tagging by identifying hard leptons from the decay of energetic top quarks. We find that looking for leptons of various multiplicity can compensate for the potentially low tagging efficiencies for very high energy b's.

We are looking at very high masses for squarks and gluinos and consequently rather low production cross sections. Thus, it will require a large integrated luminosity at the LHC to achieve the required statistical significance. By that time, we assume that the lightest neutral SUSY Higgs has already been identified. An additional handle for our benchmark points is thus provided by the possibility of looking for final states with leptons/b-quarks, together with not only large missing energy but also a Higgs in the final state, identified by a mass peak.

Thus our chosen benchmark points elicit a number of features of the signals of SUSY with only the third family of sfermions accessible. We use these in our study of the suggested signals in the next section.

### 3 Signals and Backgrounds

We are concerned primarily with observing final states with a large number of top and bottom quarks. Signal events have been generated using Pythia v6.409 by allowing the squark-squark, gluino-gluino and squark-gluino production channels. We have used CTEQ5L parton distribution functions. The factorisation and renormalisation scales have been set to \( \mu_R = \mu_F = \sqrt{p_T^2 + (P_1^2 + P_2^2 + m_3^2 + m_4^2)/2} \) where \( P_1, P_2 \) are the virtualities of the incoming particles, \( p_T \) is the transverse momentum of the scattering process and \( m_3, m_4 \) are the masses of the outgoing particles in the initial hard scattering process.

We concentrate on three and four-top events in particular. The \( \tilde{g} \) can decay into \( \tilde{t}_i \) or \( \tilde{b}_{i,2} \). Whenever it is kinematically allowed, the squarks can then decay via \( \tilde{t}_{1,2} \rightarrow t\chi_i^0 \) (with \( i = 1 - 4 \)), \( \tilde{t}_{1,2} \rightarrow b\chi_{1,2}^\pm \), \( \tilde{b}_{1,2} \rightarrow b\chi_1^0 \) and, \( \tilde{b}_{1,2} \rightarrow t\chi_1^+ \). Thus, \( \tilde{g}\tilde{g} \) production can give four-top final states via \( \tilde{g}\tilde{g} \rightarrow \tilde{t}_{1,2}\tilde{t}_{1,2} \) and each \( \tilde{t}_{1,2} \rightarrow t\chi_i^0 \). Three-top final states can be obtained when \( \tilde{g}\tilde{g} \rightarrow \tilde{t}_{1,2}\tilde{b}_{1,2} \) with \( \tilde{b}_{1,2} \rightarrow t\chi_{1,2}^\pm \). Figures 1 and 2 give the energy distribution of the top quarks for benchmark points 1A (highest squark/gluino masses) and 1C (lowest squark/gluino masses). The transverse momentum \( (p_T) \) distribution of the b-quarks is shown in Figure 3.

As has been mentioned in the previous section, we have examined final states with various combinations of b's and leptons. We comment first on certain generic features of signal identification, before the numerical results for each signal are presented. These features also help us in evolving the event selection criteria for this scenario.

- **Identification of leptons** \((e, \mu)\): We are interested in identifying leptons coming from top decay. Since the parent W of the lepton is on-shell, we expect that the lepton to be well isolated from the nearest jet. We first identify leptons with the following cuts:
Figure 1: Energy($E$) distribution of tops for four- and three-t events for benchmark point 1A.

Figure 2: Same as in Figure 1, for benchmark point 1C.

1. $p_T^l > 10$ GeV (trigger)
2. Separation from each jet $\Delta R_{lj} > 0.4$

Lepton momenta are smeared according to the prescription $\sigma(E) = a\sqrt{E} + bE$ where $\sigma(E)$ is the resolution, with $a = 0.055(0.02)$ and $b = 0.005(0.037)$ for electrons (muons) and energy measured in GeV.

We subsequently apply further cuts for each channel to restrict to leptons coming from tops.

- **Jets:** Jets are formed using the routine PYCELL built into PYTHIA. The jet energy is smeared using $\sigma(E) = \sqrt{E}$. The parton-level processes that lead to the final states of interest to us have usually a large jet multiplicity. Using PYTHIA, the multiplicity peaks at 6 when both initial and final state radiation are taken into account. With this in view, we have always demanded a minimum of four jets in the final state.
**b-Tagging:** In the absence of any clear guideline on the tagging efficiency for very high-$p_T$ b-hadrons, we take a conservative approach and restrict our b-tagging capabilities to hadrons with $p_T$ between 50 and 100 GeV. A jet is assumed b-tagged with an efficiency of 0.50 if:

1. A b-hadron lies within a cone of $\Delta R < 0.5$ of the jet-axis
2. The b-hadron has a $50 \text{ GeV} \leq p_T \leq 100 \text{ GeV}$.

**Missing transverse energy ($E_T$) and the effective mass ($M_{eff}$):** Since we are considering R-parity conserving supersymmetry, the lightest supersymmetric particle (LSP) is stable. In our case, the first neutralino is the LSP and since it is uncharged, it escapes detection. This gives a very large missing-$E_T$ which gives us the first handle for discriminating supersymmetric events. Also, since the masses of the supersymmetric particles are very high for the scenarios investigated here, the effective mass of the event, defined by $M_{eff} = \sum_{\text{jets}} |p_{Tj}| + \sum_{\text{leptons}} |p_{Tl}| + E_T$ also takes a very high value compared to what is expected of standard model processes. The $E_T$ and $M_{eff}$ distributions for two benchmark points are shown in Figure 4, along with the corresponding distribution for standard model backgrounds.

The calculation of $E_T$ has to take into account not only the ‘visible’ $p_T$ due to jets, leptons and photons that satisfy the requisite triggers but also objects with $p_T > 0.5 \text{ GeV}$ and $|\eta| < 5$ which are not identified as leptons or do not fall within any jet cone. The contribution from this extra part is summed up as the ‘soft-$p_T$’ component. This is smeared according to the prescription $\sigma(p_T) = \alpha \sqrt{p_T}$ with $\alpha = 0.55$. The total visible transverse momentum is given by $p_T^{vis} = \sum_{\text{jets}} p_{Tj}^\prime + \sum_{\text{lepton}} p_{Tl}^\prime + p_{Tsoft}$. Missing $E_T$ is then the magnitude $|p_T^{vis}|$.

In gluino decay, the production of the $\tilde{\chi}^0_2$ occurs in about 50% of all events. For the benchmark points with $\tan \beta = 5, 10$, the difference between masses of the second and the first neutralino is more than the mass of the lightest neutral Higgs ($m_{h^0}$). The most common decay channel $\tilde{\chi}^0_2 \rightarrow h\tilde{\chi}_1^0$ yields a neutral Higgs in the final state which then decays into a pair of b-quarks. This is because there are two two-body decays of the $\tilde{\chi}^0_2$, namely, $\tilde{\chi}^0_2 \rightarrow h\tilde{\chi}_1^0$, $\tilde{\chi}^0_2 \rightarrow Z\tilde{\chi}_1^0$ and the three body decay $\tilde{\chi}^0_2 \rightarrow \tau\bar{\tau}\tilde{\chi}_1^0$. Of these, the third one is kinematically...
Figure 4: Missing transverse energy ($E_T$) and effective mass $M_{\text{eff}}$ distribution for benchmark points 1A, 1C and the dominant standard model background ($t\bar{t}$).

disallowed due to large $m_{\tilde{\tau}}$. The decay into a $Z$ is suppressed by the product of Higgsino components of both $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. The decay into a Higgs requires the Higgsino component of any one neutralino and it therefore wins when kinematics are favourable. For the case with $\tan \beta = 40$, the mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ is smaller than $m_{h^0}$. As a result, $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ is the dominant decay. The identification of Higgs can therefore give us information on the value of $\tan \beta$.

Based on the above observations, we now list the basic cuts that have to be satisfied by all events:

1. $E_T \geq 300$ GeV
2. $m_{\text{eff}} = (\sum |p_T^\tau| + E_T) \geq 1000$ GeV
3. Jet multiplicity $n_{\text{jet}} \geq 4$
4. $p_T(j_1) > 100$ GeV
5. $p_T(j_2) > 80$ GeV
6. $p_T(j_3) > 40$ GeV

The inclusive cross sections for ‘all events’ satisfying the basic cuts for our benchmark points are summarised in Table 3.

| Point | 1A | 1B | 1C | 2A | 2B | 3A | 3B |
|-------|----|----|----|----|----|----|----|
| $\sigma_{\text{nocuts}}$ | 4.51 | 32.47 | 308.00 | 37.07 | 352.01 | 34.62.0 | 337.51 |
| $\sigma_{\text{basic}}$ | 3.89 | 15.09 | 83.87 | 17.21 | 98.31 | 16.62 | 93.767 |

Table 3: Total $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production cross sections for all the benchmark points before and after basic cuts.
We now discuss signals in various channels. The cuts or extra identification criteria applied henceforward will be over and above the basic cuts enumerated above.

### 3.1 Channels: $1b + 2l$, $1b + 2l_{(SSD)}$ and $2l_{(SSD)}$

As mentioned earlier, the tops produced from the decay of heavy squarks and gluinos are highly energetic. Even in three-top (four-top) events which would give three (four) b-quarks, it is not always possible to tag all of them. However, we expect that leptons arising out of the decay of the tops to be very energetic. Therefore, we look at two energetic leptons with and without additional b-tags.

The backgrounds are calculated including the processes $t\bar{t}+jets$, $Wb\bar{b}+jets$, $Wt\bar{t}+jets$, $Zt\bar{t}+jets$, $Zb\bar{b}+jets$, $4t$, $4b$ and $2t2b$ generated with the help of ALPGEN [31]. Most of the background comes from the $t\bar{t}$ channel. The $p_T$ distributions for leptons for benchmark points 1A and 1C along with $t\bar{t}$ are given in Figure 6. We therefore apply the following cuts to select leptons over those from standard model backgrounds.

The final cuts on the leptons are:

1. $p_T(l_1) \geq 80$ GeV
2. $p_T(l_2) \geq 30$ GeV

![Figure 5: Magnitudes of $p_T$ for the two hardest leptons for points 1A, 1C and standard model $t\bar{t}$ production.](image)

To suppress the $t\bar{t}$ background even further, we demand that the leptons be of the same sign. We also look at the inclusive same-sign dilepton channel (without any b-tags). The signals and backgrounds for such dilepton events, with and without a tagged b-jet, are seen in Table 4. We have calculated the number of events, for both signals and backgrounds, corresponding to an integrated luminosity of 300 fb$^{-1}$. The advantage of the di-lepton final states over, say, the $2b$ channel (with or without one lepton) is quite appreciable.

### 3.2 Channels: $2b + l$ and $3b$

The first consequence of having only third family squarks accessible is that all SUSY processes involving the production of strongly interacting superparticles lead to a multiplicity of b’s in the final state. As we
Table 4: Signals and backgrounds for different channels for an integrated luminosity of 300 fb$^{-1}$.

have mentioned already, most of these have too high $p_T$ to be reliably tagged. However, there will still be sufficient number of events with two or three b-tags. There one has to compromise on lepton identification, so as to gain in branching ratios. On the whole, this reflects a tug-of-war between the loss in rate due to branching ratios and that due to our demand that only b’s in a specific $p_T$-range be identified. Thus for identifying events with high squark and gluino masses, where the cross section is already very low, we recommend looking at only single-lepton events when more than one b’s are tagged.

For two b-tagged events, we find a very large background from $t\bar{t}$ processes. We suppress this by demanding the presence of a high-$p_T$, isolated lepton, satisfying $p_T(l_1) \geq 80$ GeV. The requirement of leptons has to be given up for 3b events, for otherwise the overall rates will be far too small.

The primary backgrounds for $2b+l$ channel are same as $1b+l$, viz. $t\bar{t}+jets, Wb\bar{b}+jets, Wt\bar{t}+jets, Zt\bar{t}+jets, Zb\bar{b}+jets, 4t, 4b$ and $2t2b$. Again, we have used ALPGEN to compute the background rates.

Since the 3b cannot result from tree-level standard model processes (excepting those suppressed by weak mixing), the backgrounds are only due to $4t, 2t2b$ and 4b. However, the 4b processes do not have a source of high $E_T$, so the highest contribution comes from $2t2b$ production processes.

The results are presented in Table 4.

### 3.3 Inclusion of the Higgs

In this study, we wish to emphasise situations where the gluino mass is $\gtrsim 1$ TeV. This roughly corresponds the region of the parameter space with $m_{1/2} \gtrsim 400$ GeV. As can be seen from Figure 7, decay $\tilde{\chi}^0_2 \rightarrow b\tilde{\chi}^0_1$ has a branching ratio greater than 90% over most of the region of parameter space for $\tan \beta = 5$. $\tilde{\chi}^0_2 \rightarrow Z\tilde{\chi}^0_1$ is suppressed in these regions, and the lightest neutral Higgs occurs in a significant number of events in this scenario. For $\tan \beta = 40$, this region is much reduced and the decay into a Higgs is appreciable only in the region $m_{1/2} > 700$ GeV where the gluino mass is close to the upper limit of accessibility. The dominant decay then is $\tilde{\chi}^0_2 \rightarrow Z\tilde{\chi}^0_1$. Thus the production of the Higgs can give information whether $\tan \beta$ is high or low.

We are discussing a situation where the lightest neutral Higgs has already been discovered and it’s mass is known. Ideally, one would like to identify the Higgs by picking a b-jet pair with it’s invariant mass near the mass of the Higgs. However, in most events, both b’s from the Higgs cannot be identified (as seen from
Figure 6: Regions in parameter space corresponding to the branching fraction $BF(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) > 0.9$ for $\tan\beta = 5$ and 40.

Figure 7). And demanding only one b-tagged jet instead of two leads to a combinatorial background much higher than actual number of signal events. To be able to reduce this, we compare the $p_T$ distribution of jets from Higgs decay and the opening angle between the jets for true Higgs events and the combinatorial background. The distributions are shown in Figure 7.

We then claim to have identified a Higgs through a jet pair if:

1. $|M_{j_1j_2} - M_h| < 15.0$ GeV where $M_{j_1j_2}$ is the invariant mass of the jet pair.
2. The second (less energetic) jet has $p_T < 80$ GeV.
3. At least one of the two jets is b-tagged.

4. The opening angle between the jets is less than $\pi/2$.

These cuts reduce the combinatorial background to about half that of the signal. Identifying the Higgs means at least one b-tag. Therefore, we study the channels $2l + h$, $2l_{(SSD)} + h$, $1b + l + h$ and $2b + h$ with exactly the same hard-lepton cuts. The signals and backgrounds for all Higgs channels are summarised in Table 5. The combinatorial background is mentioned in the parenthesis accompanying each number of signal events.

We find that for points with gluino mass $> \sim 1.5$ TeV, the event rates are not significant enough to make a distinction between the region favouring Higgs production and the region where it is suppressed. However, for points 1C, 2B and 3B, we can see a clear distinction in the number of Higgs events. In particular, the $1b + l + h$ and $2b + h$ channels have the added advantage of having a low combinatorial background. These channels show a significant excess even after taking the combinatorial background into consideration. The leptonic channels have a large combinatorial background which make them unreliable for making definite statements about Higgs production with the identification criteria stated above. Thus, one can use this information to infer whether the situation corresponds to low or high $\tan\beta$.

![Table 5](image)

Table 5: Signals and backgrounds for different channels with Higgs identification for an integrated luminosity of 300 fb$^{-1}$. The irreducible combinatorial background for each channel is given the parentheses.

4 Distinction from scenarios where the first two sfermion families are also accessible

While signals have been suggested above for discovering SUSY with only the third family light, it is also instructive to ask whether such a scenario can be distinguished from the more frequently discussed case where all three families are within the reach of the LHC. We take up such a discussion in this section, showing that this can be done by (a) considering the ‘effective mass’ distribution of events, and (b) taking event ratios for different channels. For illustration, we choose the benchmark point 1C from our previous analysis and
choose two points generated in the mSUGRA scenario (i.e. all sfermion masses now arise from the same $m_0$) as representatives of the case when all three sfermion families are accessible.

The first point (S1) is generated so as to have low-scale stop and gluino masses as close to 1C as possible. As one can see from Figure 8, this corresponds to a nearly identical $M_{\text{eff}}$ distribution. The second point (S2) was generated to give the similar number of events at 300 $fb^{-1}$ in several channels. Since in our previous analysis, we have found SSD to be a clean channel, it has been used here for illustration. The low-scale masses for third-generation squarks and gluinos for the two mSUGRA points corresponding to the point 1C are given, along with the high-scale values of $(m_0, m_\tilde{g})$, in Table 6. The values of $\tan\beta$ and $\text{sign}(\mu)$ are chosen to be 10 and positive respectively. The trilinear soft breaking parameter $A$ is set to zero at high scale.

| Point | $\tan\beta$ | $m_{1/2}$ | $m_0$ $(m_0^{(3)})$ | $m_{\tilde{g}}$ | $m_{\tilde{t}_1(\tilde{u}_2)}$ | $m_{\tilde{b}_1(\tilde{d}_2)}$ |
|-------|--------------|-----------|-------------------|----------------|-----------------|------------------|
| 1C    | 10           | 400       | 1200              | 1063           | 623 (916)       | 892 (1153)       |
| S1    | 10           | 400       | 100               | 998            | 697 (895)       | 847 (879)        |
| S2    | 10           | 570       | 1200              | 1362           | 1163 (1468)     | 1453 (1616)      |

Table 6: Third generation squark and gluino masses in GeV for two mSUGRA points and point 1C.

We calculate the event rates for the same channels $(1b+2l, 1b+2l(\text{SSD}), 2l(\text{SSD}), 2b+3l)$ as before. The basic cuts as well as any extra cuts applied are same as in section 3. The event rates are given in Table 7.

| Point | $\sigma_{\text{basic}}(fb)$ | $1b+2l$ | $1b+2l(\text{SSD})$ | $2l(\text{SSD})$ | $2b+l$ | $3b$ |
|-------|---------------------------|--------|-------------------|-----------------|--------|-----|
| 1C    | 83.87                     | 478    | 221               | 626             | 147    | 175 |
| S1    | 1160                      | 1619   | 298               | 3239            | 255    | 213 |
| S2    | 74.63                     | 446    | 195               | 622             | 117    | 123 |
| Background | 10              | 4       | 4                 | 1514            | 5      |

Table 7: Number of events at 300 $fb^{-1}$ for the mSUGRA points S1 and S2. We have repeated the numbers for point 1C and background for comparison.

In R-parity conserving SUSY, only even number of superparticles can be produced. Therefore, the peak of the $M_{\text{eff}}$ distribution corresponds roughly to twice the mass of the lightest superparticle pair-produced through hard scattering. This gives us an indication of the mass scale of SUSY particles. It should be noted that, in mSUGRA-based models, too, the third family sfermions are usually the lightest (though the first two are not necessarily decoupled.) Thus the masses of the gluino and/or the third family squarks will be indicated by the peak of the $M_{\text{eff}}$ distribution. The $M_{\text{eff}}$ distributions for points 1C, S1 and S2 are shown in Figure 8.

Based on the information from the $M_{\text{eff}}$ distribution and the event rates, we can draw the following inferences:

1. (a) The points 1C and S1 have a very similar spectrum for third generation squarks and gluino masses.

They are not distinguishable by looking at the $M_{\text{eff}}$ distribution alone.
(b) The cross section for squark and gluino production for S1 is very high since all the squarks are accessible. Note, in particular, that the ratio \( 3b_{1C} : 3b_{S1} = 0.82 \) is close to one whereas the ratio \( SSD_{1C} : SSD_{S1} = 0.19 \) is much smaller. The \( 3b \) final state which comes only from \( \tilde{g}\tilde{g} \) production shows comparable number of events due to similar gluino mass. The masses of \( \tilde{t}_2, \tilde{b}_1 \) and \( \tilde{b}_2 \) are smaller in S1 as compared to 1C. The b’s in their cascades are therefore likely to have lower \( p_T \) and therefore, their identification efficiency will be higher.

(c) Rates for the channels \( 1b + 2l \) and \( SSD \) are highly enhanced for the points S1. Since \( \tilde{q}\tilde{q},(q = u, d, s, c) \) is allowed, their cascades into charginos yield larger number of dileptons. This also explains why on demanding one b-tag (\( 1b + 2l(SSD) \) channel), the increase in the number of events is not so dramatic.

2. (a) The \( M_{eff} \) distribution for the two points is very different and easily distinguishable.

(b) As intended, the number of events in the \( SSD \) channel are nearly same \( 3b_{1C} : 3b_{S2} = 1.01 \) for points 1C and S2. The \( 3b \) channel however, shows more events in the case of 1C (\( SSD_{1C} : SSD_{S2} = 1.42 \). This is to be expected since the mass of the gluino is higher for S2 and therefore, the cross section of \( \tilde{g}\tilde{g} \) is lower. Also, the masses of \( \tilde{t}_{1,2} \) and \( \tilde{b}_{1,2} \) are higher resulting in higher \( p_T \) of b’s in the final state and hence lower identification efficiency.

Thus we find the the total cross sections for sparticle production are much lower for the case where only third family sfermions are accessible, making detection more challenging than the case where all three generations have masses \( \sim 1 \) TeV. However, the points in parameter space of mSUGRA which mimic the scenario are characterised either by a very different effective mass distribution or very different rates in the leptonic channels. We can conclude that this scenario can be distinguished from a universal scenario with all three generations are accessible.
5 Summary and conclusions

We have investigated the signals of SUSY at the LHC, when only the third squark family is kinematically accessible. We have emphasised the difficulties in identifying highly energetic tops and bottoms and suggested various combinations of b- and leptonic final states, including those with like-sign dileptons as viable alternatives to reconstruction of the top. Only those b’s whose $p_T$ lies in the range 50 – 100 GeV have been included so that the tagging efficiency is optimal. We have also used a large missing-$E_T$ cut of 300 GeV, and taken particular care in calculating the missing energy, including soft contributions to the visible energy. The above event selection criteria, together with the variable effective mass, become particularly useful in eliminating backgrounds. Also, the fact that such scenarios have large production of the lightest neutral Higgs on-shell (in the decay $\chi_2^0 \rightarrow \chi_1^0 h$) when $\tan \beta$ is low gives us an additional handle on identifying the order of $\tan \beta$.

There are earlier studies in similar directions, to which we have already referred. In addition, while this paper was almost complete, we came to know about another work [32] where studies in similar lines have been carried out. While we agree with their main points, we have gone beyond the parameter region used by them (with $m_{\tilde{g}} = 650$ GeV), and have explored the regions where gluinos are close to the LHC search limit, thus addressing relatively ‘difficult’ regions in the parameter space where event rates are low.

We end by re-iterating that the present work has improved upon each of the earlier ones in the following respects. (a) The difficulties in identifying high-energy tops and bottoms have been explicitly addressed (b) The squark and gluino production cross section for such scenarios is one to two orders of magnitude lower than the universal case with all three families accessible. Even with limited top and b-identification, our multichannel analysis, strengthened by the use of leptons having specified kinematic properties in the final state, can take the discovery reach at the LHC for such scenarios to close to 2 TeV in the gluino mass, for an integrated luminosity of 300 fb$^{-1}$. (c) The suggestion of using the associated Higgs production is of added advantage, as it emphasises the nature of the spectrum through the viability of the decay $\chi_2^0 \rightarrow \chi_1^0 h$ depending on the value of $\tan \beta$. (d) The prospect of distinguishing the scenario under investigation from one with all three sfermion families accessible is emphasised through a combination of kinematic studies and ratios of event rates in various channels. Thus it is hoped that not only can one discover a SUSY scenario where only the third family is accessible, but can also set the scenario apart from the ones with all scalar families accessible, when sufficient luminosity accumulates at the LHC.

Acknowledgement: We thank Bruce Mellado for a number of useful suggestions. In addition, we acknowledge helpful discussions with Priyotosh Bandyopadhyay, Subhaditya Bhattacharya, Sanjoy Biswas, Aseshkrishna Datta and V. Ravindran. This work was partially supported by funding available from the Department of Atomic Energy, Government of India for the Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute. Computational work for this study was partially carried out at the cluster computing facility of Harish-Chandra Research Institute (http://cluster.mri.ernet.in).

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