Non-universal gaugino and scalar masses, hadronically quiet trileptons and the Large Hadron Collider

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\textbf{Abstract}

We investigate the parameter space of the minimal supersymmetric Standard Model (MSSM) where the gluino and squark masses are much above 1 TeV but the remaining part of the sparticle spectrum is accessible to the Large Hadron Collider at CERN. After pointing out that such a scenario may constitute an important benchmark of gaugino/scalar non-universality, we find that hadronically quiet trileptons are rather useful signals for it. Regions of the parameter space, where the signal is likely to be appreciable, are identified through a detailed scan. The advantage of hadronically quiet trileptons over other types of signals is demonstrated.

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1 Introduction

The search for physics beyond the Standard Model (SM) of elementary particles enters into an exciting phase as the Large Hadron Collider (LHC) at CERN takes off. A leading candidate among new physics options is supersymmetry (SUSY) that can survive down to the TeV scale [1, 2, 3, 4]. Hence, the search for SUSY in the context of the LHC has become one of the major areas of recent studies in particle physics [5, 6].

The minimal SUSY Standard Model (MSSM), comprising all the SM particles and their superpartners, has a large number ($\simeq 100$) of free parameters. Some organizing principle is therefore sought to simplify the picture, the popular paradigm being an approach where all of the low-scale parameters evolve out of a select few at a high scale, possibly related to a Grand Unified Theory (GUT) [7]. A frequently studied possibility in this context is a scenario based on supergravity (SUGRA) where SUSY breaking gaugino and scalar masses, get mutually related in a model dependent manner at low energy [1, 3, 8, 9]. However, such relationship is contingent upon additional features such as the absence of physics at intermediate scales.

The predicted signals of SUSY at the LHC depend largely on the production of strongly interacting superparticles, namely, the squarks and gluinos, via the annihilation of quarks, antiquarks and gluons. Their subsequent decays culminate into the lightest SUSY particle (LSP)– the lightest neutralino in most scenarios– which is stable and a dark matter candidate when R-parity is conserved. The resulting signals of SUSY consist in a large amount of missing transverse energy ($E_T$), together with hard central jets and leptons of various multiplicities [10, 11]. Of course, hadronically quiet events, such as trileptons arising from the direct production of charginos and neutralinos have also been studied as useful supporting signals which can help in probing the non-strongly interacting sector of the theory [12]. Still, the final states arising from squark/gluino cascades have overwhelming importance in general, for the sheer level of copiousness that they associate.

How about a situation where the squarks and gluinos are so heavy (say, $\gtrsim 5$ TeV) that their production rate is too low to support the cascades? In such a case, most of the signals that depend on strongly interacting superparticles will not be easy to see at the LHC. Keeping such a situation in mind, it is important in one’s preparation for the LHC to check how the ‘hadronically quiet events’ fare. One needs to know exactly over which ranges in the parameter space of SUSY, for example, the hadronically quiet trilepton events can act as the harbinger of new physics, not as a supplementary search channel but as the main one. The present work is aimed at answering such a question, by making an elaborate
survey of the SUSY parameter space, especially in terms of $M_1$ and $M_2$, the U(1) and SU(2) gaugino masses which dictate the rate of the hadronically trilepton rates. In other words, although hadronically quiet trileptons in the context of the LHC have been already studied, here we wish to make the study specifically focused on cases where squarks and gluinos tend to decouple.

Hadronically quiet trileptons occur mostly from the production $pp \rightarrow \chi^0_2 \chi^{\pm}_1$, where $\chi^0_2$ is the second lightest neutralino and $\chi^{\pm}_1$ is the lighter chargino. The hadronically quiet trilepton events have the best chance when the squarks are very heavy compared to the sleptons and decays of charginos and neutralinos to on-shell sleptons and leptons are allowed. From this point of view, the decoupled nature of squarks favours the trilepton final states. On the other hand, they have less of a chance when the decay modes $\chi^0_2 \rightarrow \chi^0_1 h^0$ or $\chi^0_2 \rightarrow \chi^0_1 Z$ have substantial branching ratios.

An exhaustive investigation of the SUSY parameter space in this light has to go beyond universality of gauginos and scalars at high scale. We outline some ways of theoretically motivating non-universality in the next section. However, we wish to re-iterate that, in the absence of any concrete knowledge of high scale physics as well as whether a ‘grand desert’ exists, it is really important in the context of collider studies to go beyond specific theoretical schemes. We rather propose to establish a new benchmark of non-universal SUSY breaking masses, distinguished by the suppression of final states arising from strong production. The remaining part of the paper is an exercise in this direction and therefore in our collider studies we treat the strong versus electroweak gaugino and scalar masses essentially as phenomenological inputs.

In section 2 we first outline some standard GUT-based schemes of achieving non-universal SUSY breaking masses. Then it is shown that the situation with heavy squarks and gluinos may require one to go beyond such schemes, and establish our benchmark based on this consideration. A detailed discussion of the hadronically quiet trilpton signal, and the main backgrounds, is presented in section 3. In section 4 we present numerical predictions for leptonic final states of various multiplicity, with accompanying hard jets. We conclude in section 5.

2 Non-universality and hadronically quiet signals

The kind of spectrum that we use for our study can be motivated from the non-universality of gaugino and scalar masses at high scale.
As is well known, universality of gaugino masses at high scale is not a necessity even in GUT-based scenarios. A number of nonuniversal ratios among $M_{1,2,3}$ can arise, say, in $SU(5)$ and $SO(10)$ scenarios, with general gauge kinetic functions

$$f_{\alpha\beta}(\Phi^j) = f_0(\Phi^S)\delta_{\alpha\beta} + \sum_N \xi_N(\Phi^S)\frac{\Phi_N^{\alpha\beta}}{M} + \mathcal{O}(\frac{\Phi^N}{M})^2$$

(1)

where $f_0$ and $\xi^N$ are functions of chiral singlet superfields, and $M$ is the reduced Planck mass $= M_{Pl}/\sqrt{8\pi}$. Here $\Phi^S$ and $\Phi^N$ are Higgs multiplets that are, respectively, singlets and non-singlets under the GUT group. Different non-singlet representations leading to the breaking of the GUT group, arising from symmetric products of the adjoint representations, lead to different ratios among the high-scale values of the three gaugino masses [13, 14, 15]. However, in neither of the cases pertaining to the two GUT groups mentioned above can one have $M_3 \gg M_{1,2}$ at the electroweak scale (see Table 2). One cannot achieve the above hierarchy by breaking the GUT group via linear combinations of various non-singlet representations unless there is strong cancellation among various contributing multiplets.

Nonetheless, as has been already mentioned, a hierarchy of the gluino and electroweak gaugino masses can arise from hitherto unknown effects, such as the presence of intermediate scale(s) as well as the evolution between the Planck and the GUT scales.

| $m_\tilde{\ell}$ in GeV | $(M_1, M_2)$ in GeV | OSD | SSD | $3\ell + \text{jets}$ | $\geq 3 \text{jets}$ | $3\ell$ |
|--------------------------|---------------------|-----|-----|-----------------------|-----------------|------|
| 200                      | (150,300)           | 1.25| 0.04| 0.11                  | 2.82            | 5.99 |
| 300                      | (232,350)           | 0.55| 0.07| 0.10                  | 1.79            | 2.39 |
| 400                      | (179,200)           | 0.24| 0.07| 0.01                  | 3.37            | 0.11 |

Table 1: Different final state rates (fb) with cuts at the LHC with $M_3 = m_{\tilde{g}} = 5$ TeV, $m_{\tilde{q}} = 5$ TeV, $\mu = 1$ TeV, $m_A = 500$ GeV, $A = 0$, $\tan \beta = 10$, where $\mu$, $A$ and $\tan \beta$ are respectively the Higgsino mass parameter, the trilinear soft SUSY breaking parameter and the ratio of the vacuum expectation values of the two Higgs doublets. All the parameters are at the electroweak scale with appropriate mixing in the third family. $\ell$ stands for electrons and muons. CTEQ5L PDFset used with $\mu_F = \mu_R = \sqrt{s}$.

In the scalar sector, while certain SUSY-GUT effects like $SO(10)$ $D$-terms can lead to non-universality of mass parameters at high scale [16, 17, 18, 19], it is generally difficult to accommodate squarks much heavier than sleptons in such a framework. One cannot however
rule out, for example, additional $U(1)$ symmetries under which the squarks and sleptons have widely disparate charges, and which breaks to make the squarks much heavier than sleptons via $D$-terms. In addition, if a large hierarchy exists in the gaugino sector, making the $SU(3)$ gaugino mass much higher than those of the $SU(2)$ and $U(1)$ gauginos at high scale, then even a universal scalar mass scenario can make the squarks much heavier at the electroweak scale, through the large gluino contribution in the process of running.

In the rest of our study we take the low-energy spectrum as a phenomenological input, and look at regions where large squark and gluino masses prevent strong processes from contributing significantly to SUSY signals at the LHC. We wish to see SUSY signals when, in the above situation, the sleptons and electroweak gauginos are well within the reach of the machine.

We show in Table 1 three sample points in situations of the above type. These points are consistent with the cold dark matter relic density indicated by the WMAP results $(0.91 < \Omega_{CDM} h^2 < 0.128$ within $3\sigma$ limit) [20]. The relic density for these points have been computed using the SLHA output of the low-energy SUSY spectra from Suspect v2.3 [21] and feeding it to the code micrOMEGAs v2.0 [22]. Corresponding to these points, rates are presented for opposite-sign dileptons (OSD), same-sign dileptons (SSD) and trilepton final states ($3\ell + jets$) each associated with hard central jets, as also for the inclusive jets ($\geq 3$ jets). Lastly, the hadronically quiet trilepton ($3\ell$) rate is presented, each case being characterized by missing $E_T$. Acceptance cuts as specified in our earlier works [15, 19] have been used in computing these rates. It can be seen that all these rates are suppressed in this region of the parameter space. Compared to them, the rate for hadronically quiet trileptons arising from purely electroweak processes turns out to be higher, though they are still somewhat small in the absolute sense. The points chosen in Table 1 are samples, where the statistical significance of the signals over backgrounds is not as much the issue as the relative strengths of the hadronically quiet trileptons vis-a-vis other signals. We show after a detailed scan of the parameter space that the hadronically quiet trilepton signal, largely the result of $\chi_1^\pm \chi_2^0$ production, is still significant over a noticeable region of the parameter space.

It is in general seen that the signals are appreciable, and simultaneously the WMAP bound can be satisfied with relative ease, if the slepton mass is on the low side ($\lesssim 300$ GeV). For $m_{\tilde{\ell}} = 200$ GeV, the WMAP-allowed region spans over $M_1$ in the range between 103 GeV and $\simeq 175$ GeV, while $M_2$ varies in the range 120 - 300 GeV. For larger slepton masses, the allowed band shifts to larger values of $M_1$ (approximately 170 - 235 GeV for a
slepton mass of 300 GeV) for the same $M_2$. The allowed band includes regions of lower $M_1$ and $M_2$ for lower values of $\mu$ where, however, the hadronically quiet signals become more intractable, as the enhanced Higgsino components in $\chi_1^\pm$ and $\chi_2^0$ reduce their couplings to leptons of the first two families.

While the sample points shown in Table 1 are fully consistent with the WMAP constraints, and serve to illustrate the efficacy of the hadronically quiet trilepton channel, we feel that a scan over a large region of the parameter space should be made in an analysis pertaining to the LHC. In this spirit, we have calculated the signal rates in the entire region over the $M_1 - M_2$ space allowed by terrestrial experiments, with various values of the slepton mass, assuming that the squark and gluino masses are 5 TeV (where they contribute little to the cascades). Apart from the values of $M_1$, $M_2$ and the slepton mass, all the other SUSY parameters are fixed at values used in Table 1 for most of our analysis. Variation with squark/gluino mass and $\tan \beta$ are shown only at the end of the next section, to demonstrate how they affect the predictions.

We indicate in Table 2 some sample high scale parameters that generate a representative SUSY spectrum in our benchmark scenario, running two loop renormalisation group equation (RGE) with radiative corrections to all squark and gaugino masses in Suspect v2.3. It has been obtained by using the pMSSM option of the code. It is demonstrated that non-universality in the gaugino sector can be responsible for the kind of spectrum phenomenologically adopted by us. It should be noted that the non-universality of $M_3$ with $M_{1,2}$ required here, can be produced within the ambit of familiar SUSY-GUT, but with a strong cancellation between different contributing non-singlet representations, as mentioned earlier.

| GUT-Scale input | $M_1$ | $M_2$ | $M_3$ | $m_{\tilde{\ell}}$ | $m_{\tilde{\nu}}$ | $\text{sgn}(\mu)$ |
|-----------------|-------|-------|-------|-------------------|-------------------|-----------------|
|                 | 300   | 300   | 2400  | 300               | 300               | +ve             |
| Low-Scale Output | $M_1$ | $M_2$ | $m_{\tilde{g}}$ | $m_{\tilde{\ell}}$ | $m_{\tilde{\nu}}$ | $\mu$ |
|                 | 113.8 | 194.0 | 4961.4 | 300               | 4200              | 2630 |

Table 2: Spectrum (in GeV) generated with Suspect v2.3 by having high scale gaugino mass non-universality. $\tan \beta = 10$, $A_0 = 0$. Radiative electroweak symmetry breaking is ensured. High scale Higgs mass parameters $m_{H_u}^2$ and $m_{H_d}^2$ are kept degenerate with universal scalar masses ($m_{\tilde{\ell}} = m_{\tilde{\nu}}$) at the same scale.


3 Signal and backgrounds: hadronically quiet trileptons

We have used the event generator Pythia v6.4.16 [23] for the generation of low-energy SUSY spectra. The consistency of parameter combinations under investigation have been checked with the programme Suspect v2.3, where all the low-energy constraints from $b \rightarrow s\gamma$, muon anomalous magnetic moment etc. are taken into account [24]. The Higgsino mass parameter $\mu$ is used as a free parameter in the numerical study.

Pythia v6.4.16 has also been used for the simulation of $pp$ collision with the centre-of-mass energy of 14 TeV, with hadronization effects turned on. We have used CTEQ5L [25] parton distribution functions, the QCD renormalization and factorization scales ($\mu_R, \mu_F$) being both set at the subprocess centre-of-mass energy $\sqrt{s}$. As we shall show later, the overall conclusions are rather insensitive to the choice of scales.

All possible SUSY processes and decay chains consistent with conserved $R$-parity have been kept open. We have switched on initial and final state radiations (ISR and FSR respectively) with the functions built within Pythia v6.4.16, but otherwise confined ourselves to the lowest order matrix elements for the signal. The effect of multiple interactions has been neglected.

Jets are formed in Pythia using PYCELL jet formation criteria with $|\eta_{\text{jet}}| \leq 5$ in the calorimeter, $N_{\eta_{\text{bin}}} = 100$ and $N_{\phi_{\text{bin}}} = 64$. For a partonic jet to be considered as a jet initiator, $E_T > 2$ GeV is required, while a cluster of partonic jets is branded as a hadron-jet when $\sum_{\text{parton}} E_T^{\text{jet}}$ is more than 20 GeV. The maximum $\Delta R$ from the initiator jet is taken to be 0.4. We have cross-checked the hard scattering cross-sections of various production processes with CalcHEP [26]. All the final states with jets at the parton level have been checked against the results available in [27]. The calculation of hadronically quiet trilepton rates have been checked against other standard works, in the appropriate limits [12].

While the minimum $E_T$ or trigger for jet formation is 20 GeV, hadronically quiet trilepton events (with $\ell = e, \mu$) have been defined following our earlier work [19]. With this definition, the absence of any accompanying central jet ($|\eta_{\text{jet}}| \leq 2.5$) with $E_T^{\text{jet}} \geq 100$ GeV qualifies the event as hadronically quiet. This avoids unnecessary vetoing of trilepton events along with jets originating from ISR/FSR, underlying events and pile-up effects. Strong cascades with events leading to relatively soft jets also add to the signal.

The background to the proposed signal can come from a number of processes including $WZ/Z^*/\gamma^*$, $t\bar{t}$ as well as heavy flavours. The $WZ^*/W\gamma^*$ and heavy flavour (mostly $b$)
channels are brought under control with a large missing-$E_T$ cut [28]. Furthermore, we have demanded the three leptons to be isolated, according to the criteria listed below. In addition, at least one pair of opposite charged leptons (electrons/muons) have to be of the same flavour. This finally leaves us with $t\bar{t}$ and $WZ$ production. Of the latter channel, whatever survives the missing-$E_T$ cut is suppressed by imposing an invariant mass cut on opposite-sign, same flavour dileptons. Thus it is the $t\bar{t}$ channel that really constitutes the irreducible background, mostly due to the overwhelmingly large rate of top-quark pair production at the LHC.

We have generated all dominant SM events in Pythia for the same final states, using the same renormalization/factorization scale, parton distributions and cuts. The $WZ$ and $t\bar{t}$ channels are dominant among the backgrounds. While the former is effectively suppressed through an invariant mass cut on the same flavour, opposite-sign lepton pairs, the $t\bar{t}$ background is of an irreducible nature, since, with the huge production cross-section at the LHC, jets that do not satisfy either the trigger or our imposed cuts can masquerade as hadronically quiet events. An enhancement of statistical significance of the signal over such backgrounds is attempted with the help of the missing $E_T$ cut. As we shall see in the numerical results, a higher degree of significance is expected when the mass differences between the $\chi^0_1$ and each of the $\chi^0_2$ and the $\chi^\pm_1$ are on the higher side, thus allowing a harder $p_T$ spectrum for the leptons. The other backgrounds, namely, the ones from virtual $Z$/photons, are found to be under control after imposing the cuts, which are as follows [29]:

- Missing transverse energy $E_{T} \geq 100$ GeV
- $p_{T}^\ell \geq 20$ GeV and $|\eta_\ell| \leq 2.5$
- Lepton isolation, such that lepton-lepton separation $\Delta R_{\ell\ell} \geq 0.2$, lepton-jet separation $\Delta R_{\ell j} \geq 0.4$. The $E_T$ deposit due to jet activity around a lepton $E_T$ within a cone of $\Delta R \leq 0.2$ of the lepton axis should be $< 10$ GeV
- No jet with $E_T^{\text{jet}} \geq 100$ GeV and $|\eta_\text{jet}| \leq 2.5$ (Vetoing central hard jets)
- Invariant mass of any same flavour, opposite sign lepton pair with $|m_Z - M_{\ell^+\ell^-}| \geq 10$ GeV

where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is the so-called isolation parameter which is the separation in the pseudo-rapidity and the azimuthal angle plane.
Cuts
\[ \bar{t} t \rightarrow 3 \ell \quad \sigma_{WZ \rightarrow 3 \ell} \quad \sigma_{3\ell(\text{total})} \]

| Cuts                          | \( \sigma_{t \bar{t} \rightarrow 3\ell} \) | \( \sigma_{WZ \rightarrow 3\ell} \) | \( \sigma_{3\ell(\text{total})} \) |
|-------------------------------|--------------------------------|--------------------------------|----------------------------------|
| \( p_T, \eta \) cut \,(on \, \ell, \, jets) | 2.428                     | 0.130                          | 2.557                           |
| +lepton isolation             | 0.473                     | 0.031                          | 0.504                           |
| +\( E_T \) cut                | 0.267                     | 0.010                          | 0.277                           |
| +invariant mass cut           | 0.129                     | 0.008                          | 0.137                           |

Table 3: Cross-sections (pb) for leading sources of SM background after successive application of different cuts, \( m_t = 171.4 \) GeV. CTEQ5L PDFset used with \( \mu_F = \mu_R = \sqrt{s} \). \( \sigma_{t \bar{t} \rightarrow 3\ell} \) is presented after multiplying by appropriate \( K \)-factor (2.04).

The cross-sections for the backgrounds from the dominant sources, subjected to the cuts that are used in the signal-analysis, are presented in Table 3. The effectiveness of cuts at successive levels have been shown.

The numbers of signal and background events have been calculated for an integrated luminosity of 100 fb\(^{-1}\). The significance is obtained in the Gaussian limit, using \( \sigma = S/\sqrt{B} \) where \( S \) and \( B \) denote the number of signal and the background events respectively.

In Figure 1 we plot the significance of hadronically quiet trileptons in the \( M_1 - M_2 \) plane, for three different slepton masses which are all kept to be degenerate at 200 GeV, 300 GeV and 400 GeV. Of course, the lighter stau is somewhat lighter than the other sleptons, and we truncate the value of \( M_1 \) accordingly in each plot, so as to disallow a scenario with stau as the lightest SUSY particle (LSP). In each case, the gluino and squark masses are kept at 5 TeV, with \( \mu = 1 \) TeV and \( \tan \beta = 10 \). While regions with less than 2\( \sigma \) have not been marked, regions marked in red correspond to significance more than 5, blue, to significance in the 3-5\( \sigma \) range and black, to the 2-3\( \sigma \) range, while in black-and-white print light grey, grey and black implies above significance respectively.

For a slepton mass of 200 GeV (the top left plot), there is a large region of parameter space for \( M_1 \) between 50 GeV and 125 GeV and \( M_2 \) between 240 GeV and 300 GeV with significance more than 5\( \sigma \). There also exists a small region at the bottom left portion of the graph for \( M_1 \) between 50 GeV and 90 GeV and for low \( M_2 \) (between 100 GeV and 140 GeV) which has significance more than 5\( \sigma \). The regions of significance between 3-5\( \sigma \) and 2-3\( \sigma \) lie around the region of \( \sigma \geq 5 \). The statistical significance in various regions can be explained by remembering that the rate of \( \chi_1^\pm \chi_2^0 \) production is large for smaller chargino and neutralino masses, thus giving higher overall rates. At the same time, there is a complementary trend of a larger number of events surviving the hardness cut once one has larger \( M_2 \), thus creating a rather large region in the parameter space with higher significance of the signal. In addition,
Figure 1: Significance contours for hadronically quiet trilepton events, for an integrated luminosity of 100 fb$^{-1}$ in $M_1 - M_2$ plane. Colour Code: Black: $2 \leq \sigma < 3$, Blue: $3 \leq \sigma < 5$, Red: $\sigma \geq 5$ (in black-and-white print: Black: $2 \leq \sigma < 3$, Grey: $3 \leq \sigma < 5$, Light Grey: $\sigma \geq 5$). Top left: Slepton mass = 200 GeV, Top right: Slepton mass = 300 GeV, Bottom: Slepton mass = 400 GeV. CTEQ5L PDF set used with $\mu_F = \mu_R = \sqrt{s}$. 
there is a dynamical effect [30], namely, the destructive interference between the $Z$-and slepton-mediated diagrams in $\chi_2^0$ decays, when on-shell sleptons are not produced. The observed pattern of significance contours is a consequence of such effects as well.

Figure 2: Variation of rates (pb) with cuts for hadronically quiet trilepton events with degenerate squark-gluino mass. Other relevant parameters are at the following values: $m_{\tilde{\ell}} = 200$ GeV, $M_1 = 100$ GeV and $M_2 = 300$ GeV, $\mu = 1$ TeV, and $\tan \beta = 10$. CTEQ5L PDFset used with $\mu_F = \mu_R = \sqrt{s}$.

For higher slepton masses, namely, $m_{\tilde{\ell}}= 300$ or 400 GeV, the region of the parameter space depicting $\sigma \geq 5$ for $m_{\tilde{\ell}}= 200$ GeV shrinks. Only the small region at the bottom left corner of the graph shows $\sigma \geq 5$, although it also shrinks to a considerable extent compared to the case of $m_{\tilde{\ell}}= 200$ GeV.

However, for the case of $m_{\tilde{\ell}}= 300$ GeV, although the 3-5$\sigma$ region is absent in the upper segment, the region of 2-3$\sigma$ extends upto $M_1 = 180$ GeV, and for $M_2$ slightly on the higher side (340 GeV to 400 GeV). This is because, with the degenerate slepton masses going up, the allowed region with neutralino LSP is larger, and at the same time the leptons in the final state tend to be harder. The regions with $\sigma \geq 5$ correspond to regions with very low $M_2$ (110 GeV to 160 GeV) for a slepton mass of 400 GeV. The erstwhile regions of high significance for larger values of $M_2$ are gone for heavier sleptons. In such cases, as has been mentioned earlier, the $\chi_1^0h$ and $\chi_1^0Z$ channels tend to dominate in the decays of $\chi_2^0$, thus
reducing the significance of the trilepton signals.

We have also checked the dependence of our predictions on the QCD renormalization/factorization scales by setting, for instance, both the scales at the average mass of the final state particles in the hard scattering. While this affects both signal and background rates, the significance contours remain very similar to the corresponding case with the scale set at the subprocess centre-of-mass energy. This shows the robustness of the expected significance levels.

![Figure 3: Variation of rates (pb) with cuts for hadronically quiet trilepton events with tan β. Other relevant parameters are at the following values: $m_{\tilde{g}} = m_{\tilde{q}} = 5$ TeV, $m_{\tilde{\ell}} = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 300$ GeV, and $\mu = 1$ TeV. CTEQ5L PDF set used with $\mu_F = \mu_R = \sqrt{s}$.](image)

We also plot in Figure 2 the variation in rates for hadronically quiet trilepton ($3\ell$) events with $m_{\tilde{g}} = m_{\tilde{q}}$ varying from 1 to 7 TeV for $m_{\tilde{\ell}} = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 300$ GeV, $\mu = 1$ TeV with tan $\beta = 10$. The rate for hadronically quiet trileptons increases gradually with the coloured sparticle mass going up, due to the interference between the $s$-and squark-mediated $t$-channel diagrams. The effect dwindles as the squark and gluino mass reaches 3 TeV, and a plateau is clear from about 5 TeV onwards.

We also show the variation with tan $\beta$ from 3 to 20 in Fig 3 in the same region of parameter space with $m_{\tilde{g}} = m_{\tilde{q}} = 5$ TeV where the cross-section decreases sharply. Beyond 20 one ends up with a stau LSP, which turns into tachyonic stau state as tan $\beta$ grows larger. The signal
Figure 4: Scattered plot of the significance of single-lepton events (on the left side) and dilepton events (on the right side) for an integrated luminosity of 100 fb$^{-1}$ in $M_1 - M_2$ plane. 

**Significance Code:** Triangular points: $1 \leq \sigma < 1.5$, Star marked points: $\sigma \geq 1.5$. Top row: Slepton mass = 200 GeV, Bottom row: Slepton mass = 400 GeV, Left Column: Single-lepton events, Right Column: Dilepton events. **CTEQ5L** PDF set used with $\mu_F = \mu_R = \sqrt{s}$. 
rate goes down for higher \( \tan \beta \). This is because the lighter stau eigenstate becomes gradually lighter with respect to the other sleptons, and the decays of the lighter chargino and the second lightest neutralino take place more into the tau-channels. Again, smaller values of \( \mu \) will affect the signal adversely, since the lighter chargino/neutralino eigenstates then have enhanced Higgsino components. This either tends to open their decays into a Higgs, or causes them to decay into final states involving \( \tau \)'s.

We have discussed above the viability of the hadronically quiet trilepton signals at the LHC in terms of statistical significance in specific situations. It should be noted that we have left out the effects of systematic errors here. When the signal is a few percent of the background, one may have problems due to systematic shift in the background, especially if the background is large [31]. How well the signals can fare under such circumstances depends on whether the systematics affect the signal and the background strengths in a similar way or not. In addition, the ultimate success of probes in such a final state will depend on the accurate estimate of backgrounds, possibly in the light of initial data available at the LHC. Since this is an open issue, which is serious in much wider context, we would just like to keep the reader aware of the need to be cautious on this matter.

4 Other signals

It may be worthwhile to check whether our benchmark scenario has accessibility by other types of signals. Table 1 shows the advantage of the hadronically quiet trilepton signal. However, a scan over the parameters is required to establish a general conclusion on the scenario where the coloured superparticles are too massive to have any significant contribution to final states at the LHC. With this in view, we have studied signals with \( n\ell + \geq 2 \text{ hard jets} + \not{E_T} \) across the \( M_1 - M_2 \) plane, with the slepton mass set at 200 and 400 GeV respectively. The various panels in Figure 4 contain the results of this scan. Each of the hard jets is required to have \( E_T \geq 100 \text{ GeV} \) and \( |\eta| \leq 2.5 \), the cuts on leptons and \( \not{E_T} \) being the same as in the case of hadronically quiet trileptons.

The figure shows that the single-and dilepton signals both fail to achieve significance higher than \( 2\sigma \) in the entire region of relevance, with an integrated luminosity of 100 \( fb^{-1} \). For the trilepton channel with associated hard jets, it is even less than 1 and have not been presented pictorially. Thus in general the other channels are always of less advantage than hadronically quiet trileptons, as was suggested at the beginning of the paper. The reason behind this is the low event rate from gluino/squark production when both of them are very
heavy. Thus we are essentially dependent on electroweak processes, where the demand of at least two hard central jets has a negative effect. Without such jets, on the other hand, one has rather large backgrounds which could be handled in the case of hadronically quiet trileptons with the help of an invariant mass cut.

We have also checked the effect of reducing the $p_T$ cut on the hard jets to 75 and 50 GeV in succession. It is found that the significance increases at best by about a factor of two in the favourable situations. However, the uncertainty in backgrounds increases considerably in such cases.

5 Conclusions

In summary, SUSY scenarios with non-universality in both gaugino and scalar masses, can envision regions in the parameter space where the usual signals from the cascade decays of strongly interacting superparticles involving hard multi-jets drop below the threshold of observability. We demonstrate that hadronically quiet trileptons can be of significant help in these cases. As a numerical study presented here indicates, other signals such as single-or dileptons, for which additional hard jets are required for background supression, are decidedly less advantageous for such a scenario. Most favourable in this respect are regions with slepton masses not too far above 200 GeV, and either both $M_1$ and $M_2$ in the 100 - 200 GeV range, with relatively large production rates, or with a large separation between them so as to enable the decay- leptons to be harder. These two effects yield a substantial region in the parameter space with $5\sigma$ or better statistics, while a still larger region with $3$-$5\sigma$ effects can be identified for an integrated luminosity of 100 fb$^{-1}$. With higher accumulated luminosity, of course, the reach of the signal increases. The effects can be expected to be experimentally favourable for $\tan \beta \lesssim 15 - 20$, and with gaugino-dominated low-lying neutralino and chargino states.

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