Tracking down the elusive charginos/neutralinos through τ leptons at the Large Hadron Collider

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An unconstrained minimal supersymmetric standard model with the superpartners of the strongly interacting particles very heavy (close to the kinematic reach of the LHC or even beyond it) and a relatively light electroweak sector is considered. Using the event generator PYTHIA it is shown that the 1τ-jet (tagged) $+ 2l$ and 2τ-jets (tagged) $+ 1l$ signals with a reasonably hard $\not{E}_T$ spectrum either by themselves or in combination with the conventional $3l$ signal, which is known to be of rather modest size with a soft $\not{E}_T$ spectrum, may appreciably extend the reach of chargino-neutralino search at the LHC with 10 fb^{-1} of integrated luminosity. This is especially so if the lighter chargino and the second lightest neutralino decays via two body leptonic modes with large branching ratios. The theoretical motivation of this scenario, yielding large values of the fine-tuning parameters but consistent with various indirect constraints including the dark matter relic density, is briefly discussed. It is shown that in the minimal supergravity model with an universal scalar mass at the grand unified theory scale, the signals involving τ-jets are not viable. Theoretically well-motivated variations of these boundary conditions are, however, adequate for reviving these signals.

I. INTRODUCTION

Supersymmetry (SUSY) [1] is one of the most well-motivated extensions of the standard model (SM) of particle physics. Moreover, it is widely expected on general theoretical arguments like the naturalness of the Higgs boson mass [2,3] that the masses of the superpartners of the SM particles, collectively called the sparticles, should be $\mathcal{O}(1 \text{ TeV})$. Therefore, the discovery of SUSY at the LHC, the first accelerator designed for probing TeV scale physics, is eagerly awaited.

Unfortunately, the SUSY breaking mechanism and, consequently, the mass spectrum of the sparticles at the energies of experimental interest is still unknown. Thus one cannot *a priori* exclude the possibility that a subset of the sparticles may very well be too heavy and escape detection at the LHC. Whether the relatively light sparticles are adequate to produce observable signatures at the LHC is then one of the main concerns of the SUSY search strategists at the LHC.

Very heavy sparticles, however, tend to violate the naturalness criterion [2,3]. There are attempts to quantify the degree of naturalness violation by defining a set of fine-tuning parameters [4]. Large magnitudes of these parameters increase the degree of violation. Thus models with heavy sparticles have been seriously considered only if the magnitudes of the fine-tuning parameters turn out to be small. A case in point is focus point supersymmetry [5]. In this particular parameter space of the minimal supergravity (mSUGRA) [6] model, the scalar superpartners turn out to

be very heavy. Nevertheless the naturalness parameters have acceptably small magnitudes. Moreover, the signatures of the gluinos ($\tilde{g}$), which could be relatively light, are easily observable at the LHC [7] if the gluino mass ($m_{\tilde{g}}$) is $\lesssim 2 \text{ TeV}$.

However, it has recently been emphasized that SUSY has many other attractive features apart from the solution of the naturalness problem. The simplest versions of the supersymmetric grand unified theories (SUSYGUTs) allow the unification of the strong, electromagnetic, and weak forces [8]. Moreover, the stable, neutral, and weakly interacting lightest superpartner (LSP) in a R-parity conserving theory is an ideal candidate for explaining the observed dark matter relic density in the universe [9,10]. Thus, models have been constructed [11] with very heavy scalars (squarks and sleptons), which can explain the coupling constant unification at the grand unified theory (GUT) scale (M_G) and the relic density data [10]. As expected, such models predict large values of the fine-tuning parameters [11]. The additional virtues of these models with very heavy scalars are highly suppressed flavour changing neutral current (FCNC) induced processes and *CP* violating phenomenon [11]. The LHC signatures of these ''unnatural'' split SUSY models, which mainly arises from gluino production and decays have been analyzed in great detail [12]. It should be borne in mind that it is hard to precisely quantify the acceptable magnitudes of the fine-tuning parameters. Moreover, the fact that one has to live with fine-tuned parameters (e.g., a tiny cosmological constant) in many other cases, provides further motivation for these unnatural models.

In order to settle the all important issue of existence or nonexistence of SUSY experimentally without any theo-

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retical bias, one would like to develop a search strategy at the LHC, which could probe the unexplored parameter space just beyond the regions excluded by the searches at the Large Electron Positron collider (LEP) [13] and the Tevatron collider [14–16] and could continue these probes up to the kinematic reach of LHC. The best limits on the masses of the sparticles belonging to the electroweak sector comes from the LEP experiments [13]. Typically these mass limits are ≈ 100 GeV which is approximately the kinematic reach of LEP experiments.[1] The best limits on the strongly interacting squark-gluino sector come from the searches at the $p\bar{p}$ collider Tevatron. These limits are, however, more model dependent. The CDF and D0 collaborations have been looking for the sparticles since the dawn of the Tevatron experiments nearly 20 years ago [16]. Assuming that there are five flavors of squarks of L and R type and each has approximately the same mass as the gluino ($m_{\tilde{q}} \approx m_{\tilde{g}} = \tilde{m}$), the CDF collaboration obtained the limit $\tilde{m} > 392$ GeV. For heavier squarks $m_{\tilde{q}} = 600$ GeV, the gluino mass limit is $m_{\tilde{g}} > 280$ GeV [14]. The D0 collaboration has obtained similar limits [15].

The above limits imply that in a subspace of the parameter space yet to be probed experimentally, the masses of the sparticles belonging to the electroweak sector could be well within the reach of the LHC (≥ 100 GeV), while the strongly interacting sparticles could be rather heavy (close to the kinematic reach of the LHC or even beyond it). In this paper we focus attention on this parameter space. From the point of view of LHC search strategies this scenario is challenging since signals from the strongly interacting sparticles most easily accessible at hadron colliders are absent. Henceforth in this paper we shall refer to this scenario as the light electroweak gaugino-slepton scenario (LEWGSS).

Of course this sparticle spectrum is not realized in conventional models of SUSY breaking like the much advertised mSUGRA model [6]. In the latter model there are only five free parameters [1] namely a common scalar mass (m_0), a common gaugino mass ($m_{1/2}$), $\tan\beta$, A_0 and sign of μ. Here $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs bosons in the model, A_0 is the trilinear soft breaking term and μ is the Higgsino mass parameter; the magnitude of μ is fixed by the radiative electroweak symmetry breaking condition [18]. As a result it leads to a highly correlated sparticle mass spectrum which is rather restrictive. However, this is certainly allowed in more general frameworks and should receive due attention since the mechanism of SUSY breaking is still unknown. Later on we shall discuss some possible theoretical frameworks leading to such sparticle spectra and the

impact of the indirect constraints (e.g., the constraints imposed by the observed DM relic density [10]) on this parameter space.

That the SUSY signals in this case may not be easily accessible even at the LHC can be anticipated from the simulations by the CMS [see [19] Fig. 13.32 (left)] and the ATLAS [20] collaborations in the mSUGRA model. From the scalar sector only the dilepton $+\not{E}_T$ signature from slepton pair production may be observable for slepton mass ($m_{\tilde{l}_L}$) $\lesssim 300$ GeV for an integrated luminosity ($\mathcal{L}$) of 60 fb^{-1} [21]. However, the existence of this signal alone can hardly establish SUSY.

The only other viable signal within the framework of the minimal supergravity (mSUGRA) model from the electroweak sector alone is the hadronically quiet trilepton ($3l$, $l = e$ or μ) events [22] from the production of the lighter chargino ($\tilde{\chi}_1^{\pm}$) and the second lightest neutralino ($\tilde{\chi}_2^0$) pairs. But the chargino-neutralino mass reach attainable is rather modest. Observable signals correspond to $m_{\tilde{\chi}_1^{\pm}} < 107$ GeV for $\mathcal{L}$ of 10 fb^{-1} [19] if the slepton mass ($m_{\tilde{l}}$) is much larger ($m_{\tilde{l}_R} > 500$ GeV) than the lighter chargino and the second lightest neutralino. In this case, the produced gauginos decay via three body modes with branching ratio (BR)s very similar to that of the W and Z bosons. As a result the produced chargino/neutralino pairs decay into e, μ, and τ channels with nearly equal BRs irrespective of the specific magnitude of $m_{\tilde{l}}$. These leptonic BRs are relatively small since the hadronic decays of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ dominate.

However, in a large region of the parameter space of interest sleptons could be lighter than the $\tilde{\chi}_1^{\pm}$ and the heavier neutralinos. In this case the $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_2^0$) decays into two body final states involving slepton-neutrino and sneutrino -lepton (slepton-lepton and sneutrino-neutrino) pairs of all flavours. Because of the absence of the hadronic channels the combined BRs of these leptonic modes are nearly 100% and consequently in a limited region of the parameter space the $\tilde{\chi}_1^{\pm}$ mass reach can be marginally improved compared to the one presented in the last paragraph ($m_{\tilde{\chi}_1^{\pm}} < 136$ GeV for $m_{\tilde{l}_R} \approx 100$ GeV and $\mathcal{L} = 10$ fb^{-1}) [19].

In either case the mass reach is not much larger than the current LEP lower bounds. We also emphasize that almost the entire parameter space probed in [19] accessible to the clean trilepton signal is forbidden by the lower limit on the lightest Higgs boson mass (m_h): $m_h > 114.7$ GeV due to the special correlations among the sparticle masses in mSUGRA. The only exception is the region with $m_0 \gtrsim 1400$ GeV.

The absence of viable signals from the electroweak sector is not a serious hindrance in the mSUGRA model, since a large region of this parameter space can, in any case, be scanned via the squark-gluino events. However, in a more general framework like the LEWGSS, with the squarks and the gluinos beyond the kinematical reach of the LHC, the electroweak sector could be the only source

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[1]If sneutrinos decay invisibly, the best lower limit on their mass ($\approx M_Z/2$) from the invisible width of Z measured at LEP turns out to be much weaker. A proposal for improving this limit can be found in [17].

of information on SUSY. Thus, one would like to optimize the search strategy for this sector.

It should be emphasized that in the parameter space where the leptonic two body decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ dominate, the lighter stau mass eigenstate ($\tilde{\tau}_1$) is often significantly lighter than the other sleptons due to mixing in the $\tilde{\tau}$ mass matrix [1]. Thus, the chargino-neutralino pairs may preferentially decay into final states involving one or more τ-jets and the $3l$ signal could be degraded or even depleted for all practical purposes. We refer to this parameter space as the ``τ-corridor.''

It may be noted that scenarios with light $\tilde{\tau}$ mostly in the context of the mSUGRA model have been considered in the literature [23]. These studies, however, concentrated on the impact of the light $\tilde{\tau}$ scenario on the signals from squark-gluino events. The direct signals from a relatively light electroweak sector did not receive the due attention.

In this paper we propose that signals with $1l + 2\tau$-jets, $2l + 1\tau$-jet in the final state be also included in the search strategy especially if the strongly interacting sparticles are very heavy. These signals will be the main discovery channel in the τ corridor and, as shown in a subsequent section, may extend the chargino mass reach significantly. Moreover, these final states in conjunction with the conventional $3l$ signal, will cover a significantly larger parameter space even outside the corridor, where two body decays of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ still dominate and extend the chargino mass reach appreciably.

It is well-known that the chargino-neutralino signals—like all other SUSY signals—is accompanied by large missing transverse energy ($\not{E}_T$). Unfortunately, the $\not{E}_T$ spectrum accompanying the $3l$ signal turns out to be rather soft. In fact it has been already observed in [19] that cuts on $\not{E}_T$ do not improve the signal-background ratio since the signal is also considerably depleted by this cut.

However, the final states with τ-jets have additional neutrinos and the $\not{E}_T$ spectrum is much harder as we shall show. Thus, a suitable cut on this variable may discriminate against the SM backgrounds more effectively and compensate for the reduction in the signal size due to limited τ-jet detection efficiency. It has been noted that there are hitherto neglected backgrounds (mainly from heavy flavor production) to the $3l$ signal which reduces its visibility [24]. In principle these backgrounds may affect the signals involving τ-jets as well. It is reassuring to note that these new backgrounds also involve rather soft $\not{E}_T$ spectrum [24] and may be drastically reduced by a strong cut which does not affect the signal very much (see Sec. II for the details).

In order to illustrate the proposed signals and the expected improvements in the chargino mass reach, we simulate $\tilde{\chi}_1^\pm$-$\tilde{\chi}_2^0$ production followed by their decays using the event generator PYTHIA (version 6.409) [25] in Sec. II. In the same section we also comment qualitatively on the compatibility of the LEWGSS in some specific SUSY breaking models. We also comment on the compatibility

of this model with indirect constraints like the one from the dark matter relic density.

In the next section we revisit the mSUGRA model with low m_0 and $m_{1/2}$ where two-body decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ dominate. This region is ruled out by the lower bound on the lighter Higgs scalar mass from LEP only if the trilinear SUSY breaking coupling A_0 is chosen to be zero. However, for nonzero trilinear coupling this parameter space is compatible with both the Higgs mass bound and the WMAP data on dark matter relic density [26]. More importantly this parameter space leads to novel signals with τ-rich final states [26,27] at the LHC. We shall, therefore, analyze the prospect of the signals with τ-jets proposed in this paper and revisit the conventional $3l$ signal. We shall summarize the results and future outlooks in Sec. IV.

II. THE SIGNALS WITH AND WITHOUT τ-JETS

In this section we focus our attention on signals involving one or more τ-jets arising from $\tilde{\chi}_1^\pm$-$\tilde{\chi}_2^0$ pair production at the LHC in the LEWGSS. Throughout this paper all masses and parameters which have dimension of mass are expressed in GeV unless otherwise stated explicitly.

We have generated the sparticle spectrum using SUSPECT (version 2.3) [28] with the following choice of the weak scale parameters: a common mass for the L and R type weak eigenstates of sleptons of all three generations ($m_{\tilde{l}_L} = m_{\tilde{l}_R} = m_{\tilde{l}}$). We shall comment on this slepton spectrum which is somewhat different from the one in the mSUGRA model. For simplicity we have also assumed $M_1 \approx 0.5 M_2$, which is the typical expectation in a model with a unified gaugino mass in the electroweak sector at a high scale (the GUT scale, say) [1]. However, this is not a crucial assumption for the viability of the proposed signals as long as the LSP is significantly lighter than the sleptons. We have also assumed the $\tilde{g}$ and L and R squarks belonging to all three generations to be very heavy: $m_{\tilde{g}} = m_{\tilde{q}} = 3.0$ TeV. So far as the trilepton signal goes it hardly matters even if the strongly interacting sparticles are assumed to be even heavier.

We further assume that $\tan\beta = 10$, $A_0 = 0$, $m_A = 1000$, where m_A is the mass of the pseudoscalar Higgs boson. The last choice, which leads to a decoupled Higgs sector with only one light neutral standard model like Higgs scalar, is also not very crucial for the signals from the electroweak gauginos.

The size of the signals of interest crucially depend on the mixing in the $\tilde{\tau}$ sector driven by the parameter $X_\tau = m_\tau(A_\tau - \mu\tan\beta)$. Earlier several authors have addressed squark-gluino production in mSUGRA by considering large $\tan\beta$ [23] only. We have varied the parameter μ to investigate the effect of this mixing. We have represented the large (small) $\tilde{\tau}$ mixing scenario by $\mu = 1000(500)$. Since the dependence of the chargino-neutralino sector on μ and $\tan\beta$ are very different, both approaches seem to be worth investigating unless additional theoretical assump-

TABLE I. The BRs of the dominant decay modes of the $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ for $\mu = 500$ at two representative points inside and outside the τ corridor.

$(m_{\tilde{l}_l}, m_{\tilde{\chi}_2^0})$	(160, 274)	(270, 274)
Decay modes		
$\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_l l^+$	37.8	38.6
$\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_\tau \tau^+$	18.9	19.4
$\tilde{\chi}_1^+ \rightarrow \tilde{l}_l \nu_l$	27.8	1.6
$\tilde{\chi}_1^+ \rightarrow \tilde{\tau}_1^+ \nu_\tau$	10.7	20.1
$\tilde{\chi}_1^+ \rightarrow \tilde{\tau}_2^+ \nu_\tau$	4.2	$\cdots$
$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W$	$\cdots$	21.5
$\tilde{\chi}_2^0 \rightarrow \tilde{l}_l l$	30.6	2.8
$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$	11.6	22.5
$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_2 \tau$	4.8	$\cdots$
$\tilde{\chi}_2^0 \rightarrow \tilde{\nu} \nu$	52.5	57.2
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$	$\cdots$	17.0
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$	$\cdots$	$\cdots$

tions like the common scalar mass m_0 in mSUGRA fixes μ completely from EW symmetry breaking [18].

Over the entire parameter space scanned by us $m_{\tilde{\tau}_1} \lesssim m_{\tilde{e}_{L,R}}, m_{\tilde{\mu}_{L,R}}$ due to mixing effects in the $\tilde{\tau}$ mass matrix. The mass difference of course increases for larger mixing.

In Table I we present the BRs of the lighter chargino (see the upper half) and the second lightest neutralino (see the lower half) decays in two representative scenarios. In the first case (see the second column) the common slepton mass is much smaller than the chargino mass. Consequently BRs of the two body chargino and neutralino decays in different leptonic channels are approximately the same in spite of the fact that the $\tilde{\tau}_1$ lighter than the other sleptons.

Through the second scenario we illustrate the 'τ corridor' defined in the introduction. Here the $m_{\tilde{l}}$ is close to the chargino mass, yet the $\tilde{\tau}_1$ is considerably lighter due to mixing. The resulting BRs are presented in the third column of Table I. These suggest that the $3l$ signal will be heavily suppressed compared to case 1, but the final states with $1\tau + 2l$ and $2\tau + 1l$ may produce observable signals.

We have simulated all events with gaugino pair production by PYTHIA (version 6409) [25]. Initial and final state radiation, decay, hadronization, fragmentation, and jet formation are implemented following the standard procedures in PYTHIA. The backgrounds have also been simulated by PYTHIA.

We next discuss different signals and the kinematical cuts for improving their size relative to the background.

For events with τ-jets, the parent τs are selected with $P_T \geq 20$ and $|\eta| < 2.4$. The τ-jets are then divided into several E_T bins from 30 to 200. A τ-jet in any bin is then treated as tagged or untagged according to the efficiency (ϵ_τ) given in [29] for that bin. Isolated leptons ($l = e, \mu$) are selected if $P_T^e \geq 17$ and $P_T^\mu \geq 10$ and $|\eta^l| < 2.4$. For lepton-jet isolation we require $\Delta R(l, j) > 0.5$, where $\Delta R = $

$\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The detection efficiencies of e and μ are assumed to be 100% for simplicity. An invariant mass cut on the opposite sign dilepton pair $80 < M_{inv}^{ll} < 100$ is employed for the $1\tau + 2l$ signal to remove the backgrounds from the Z-bosons. We have further rejected all events with tagged b-jets to reduce the $t\bar{t}$ background. This reduces the $t\bar{t}$ background from 0.064 pb to 0.012 pb. In contrast the signal, e.g., with $\mu = 500$, $m_{\tilde{\chi}_1^\pm} = 253.7$, and $m_{\tilde{l}} = 150$ reduces from 0.0042 pb to 0.0041 pb. On the other hand, the usual veto against light flavour jets other than the tagged τ-jets is not used as it does not improve the $S/\sqrt{B}$ ratio, where $S(B)$ is the total number of signal (background) events.

In order to examine whether the events with τ-jets, if combined with the clean $3l$ events, improve the chargino mass reach at the LHC, we have also simulated the later events using Pythia. However, since the purpose of this generator level work is to suggest a new possibility for chargino-neutralino search and not to present a complete analysis, we do not make a full background analysis. We simply follow the analysis of CMS collaboration for the $3l$ signal and use the total background estimated by them (0.059 53 pb) (see [19], Sec. 13.14). The cuts imposed on the $3l$ the signal are summarized below. (i) Events with 3 *leptons* with $P_T^l > 10$, $|\eta^l| < 2.4$ are selected. (ii) Events with jets having transverse energy $E_T > 30$ and $|\eta| < 2.4$ are vetoed. (iii) Events involving two same flavor opposite sign (SFOS) isolated leptons (e or μ) in $|\eta| < 2.4$ with $P_T^e > 10$, $P_T^\mu > 17$ and the dilepton invariant mass below the Z peak $M_{ll} < 75$ are retained. The third lepton in the event is required to have $P_T^{\mu,e} > 10$ in $|\eta| < 2.4$. We note in passing that vetoing events with tagged b-jets, as suggested above, would further suppress the background while leaving the signal practically unaffected.

The $\not{E}_T$ spectrum of the $3l$, $1\tau + 2l$ and $2\tau + 1l$ events, can be seen in Fig. 1 (left). All distributions are obtained after applying all but the $\not{E}_T$ cut. The plots in Fig. 1 correspond to $\mu = 500$, $m_{\tilde{\chi}_1^\pm} = 253$ and $m_{\tilde{l}} = 170$ other parameters are given at the beginning of this section. It is clear from the $\not{E}_T$ plot that the events containing one or more τ-jets have significantly harder $\not{E}_T$ distribution than the $3l$ events. In fact it has already been noted in [19] and, more recently, in [24] that the rather soft $\not{E}_T$ distribution of the $3l$ signal does not permit an improvement of its significance by a strong $\not{E}_T$ cut. For $2\tau + 1l$ and $1\tau + 2l$ events we apply a cut $\not{E}_T > 100$ for background rejection. We also present the P_T distribution of $2\tau + 1l$ events in Fig. 1 (right) for the same spectrum, from where it is clear that the signal will involve high P_T τ-jets which are taggable with high efficiencies according to the simulation by the CMS collaboration [29].

We have analyzed the following backgrounds for the τ-jet signals: WW, WZ, ZZ, $t\bar{t}$, QCD, $Zb\bar{b}$, $Z +$ jets, $W\gamma^*/Z^*$. It may be recalled that the importance of the last process and its interference with WZ amplitude has

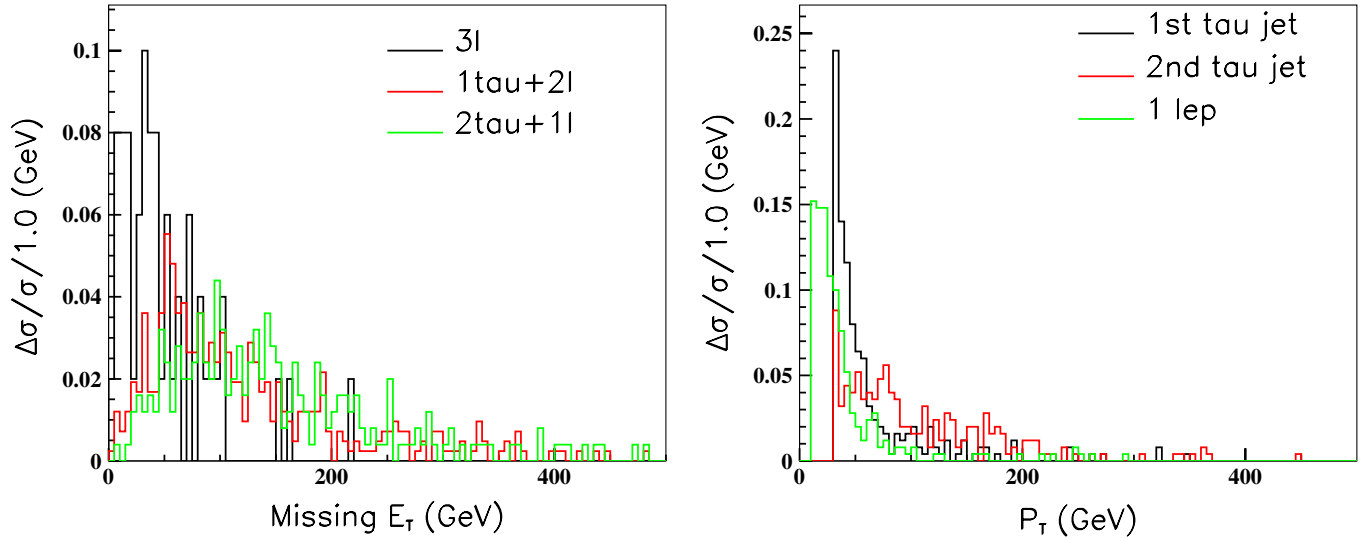FIG. 1 (color online).   The normalized distribution of missing transverse energy ($\not{E}_T$) (left) after applying all cuts except the one on $\not{E}_T$ and the ordered transverse momentum (P_T) distribution of the two τ-jets and the lepton for $2\tau + 1l$ events (right) after selection cuts on the lepton and the τ-jets. The details of the parameter space is given in the text.

often been emphasized in the past [24,30] although several analyses neglected it. We have generated these events using CALCHEP [31] and interfaced them with PYTHIA. We find that the strong $\not{E}_T$ cut efficiently removes these backgrounds. The backgrounds involving heavy flavour (e.g., $Zb\bar{b}$ events) are also potentially dangerous for the $3l$ signal [24]. They are unimportant for the signals involving τ-jets for two reasons. First, the probability of τ-emission from heavy flavour decay is significantly smaller than that for e/μ emission. In addition the $\not{E}_T$ spectra of these backgrounds are also rather soft [24].

For the $2\tau + 1l$ events the largest surviving background after all cuts comes from $W\gamma^*/Z^*$ (0.000 502 pb). For $1\tau + 2l$ signals, $t\bar{t}$ events play this role with a size of 0.012 pb, $W\gamma^*/Z^*$ contributes 0.000 314 pb. We summarize the observability of various signals in Fig. 2 (Fig. 3) for the large mixing (small mixing) case. Throughout the white region to the left of the blue dotted line corresponding to $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$, $\tilde{\tau}_1$ is the LSP and it is theoretically disallowed. The red line corresponds to $m_{\tilde{\chi}_1^\pm} = m_{\tilde{l}}$. No observable signal can be seen in the remaining white regions in the figures.

The blue crosses in both the figures indicate the parameter space where 5σ signal via the combined $1\tau + 2l$ and $2\tau + 1l$ events can be achieved with $\mathcal{L} = 10$ fb^{-1}. Clearly a significantly larger parameter space can be covered compared to the pure $3l$ signal. In the large mixing case one can even probe some parameter space where the common slepton mass is larger than the $m_{\tilde{\chi}_1^\pm}$. The best chargino mass reach is estimated to be $m_{\tilde{\chi}_1^\pm} \leq 350(330)$ for $m_{\tilde{l}} \leq 250(290)$ in the large mixing (small mixing) case. The red circles indicate the regions where 3σ signal is achievable through these channels. For higher luminosity the reach can certainly be extended. For example, with $m_{\tilde{\chi}_1^\pm} =$

500(425), $m_{\tilde{l}} = 300$, a 5σ signal at 300 fb^{-1} can be attained in the large mixing (small mixing) scenario.

It may be interesting to compare the LHC mass reach with the current limits obtained from $3l$ events at the Tevatron. The CDF collaboration, for example, analyzed the small τ-mixing scenario in mSUGRA with $\tan\beta = 3$ [32]. Analysing 2 fb^{-1} of data they obtain lower limits of 145 (127) on $m_{\tilde{\chi}_1^\pm}$ if two body (three body) decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ dominate.

Even in the regions where the clean $3l$ channel alone gives a satisfactory signal, the inclusion of the $2\tau + 1l$ and $1\tau + 2l$ events may improve the overall statistical significance. This could be especially important in view of the
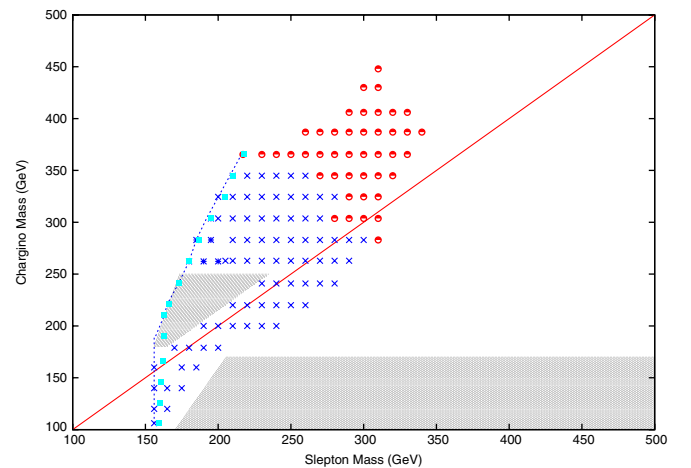

FIG. 2 (color online).   Regions of $m_{\tilde{\chi}_1^\pm}$-$m_{\tilde{l}}$ plane which could be probed by (i) $2\tau + 1l$ (ii) $1\tau + 2l$, and (iii) $3l$ signals for $\mu = 1000$ (large $\tilde{\tau}$ mixing scenario), $A_0 = 0$ and $\tan\beta = 10$ (see text for details).
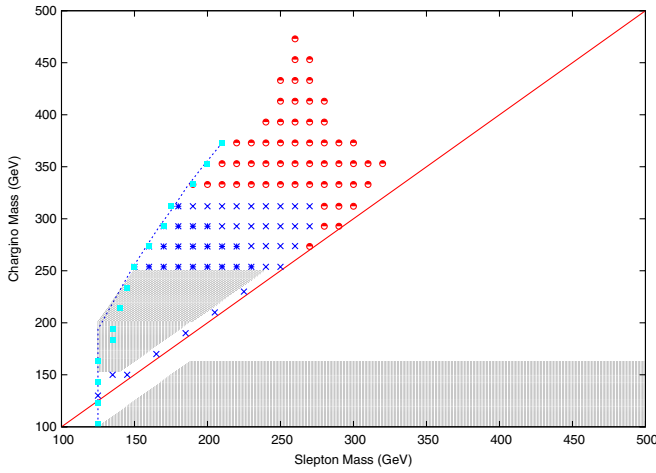
FIG. 3 (color online).   Regions of $m_{\tilde{\chi}_1^\pm}$-$m_{\tilde{l}}$ plane which could be probed by (i) $2\tau + 1l$ (ii) $1\tau + 2l$, and (iii) $3l$ signals for $\mu = 500$ (small $\tilde{\tau}$ mixing scenario), $A_0 = 0$ and $\tan\beta = 10$ (see text for details).

observation that several new backgrounds neglected in the earlier analyses may reduce the currently estimated statistical significance of the $3l$ signal [24].

The grey shaded regions in Figs. 2 and 3 corresponds to $S/\sqrt{(B)} \geq 5$ for the clean $3l$ signal alone. Since our parametrization is somewhat different from the mSUGRA scenario our signal size differs from the CMS analysis. For example, for very heavy squarks the $\tilde{\chi}_1^\pm$-$\tilde{\chi}_2^0$ pair production cross section increases by 15–20% compared to the cross sections in mSUGRA for comparable chargino-neutralino masses. However qualitatively our conclusion is quite similar to [19]. Moreover, we have explicitly checked that for the mSUGRA point LM9 our efficiencies agrees with that given in Table 13.15 of [19]. We have, however, not included the trigger efficiency ($\approx 80\%$) in our analysis, nor have we taken detector effects into account. The $m_{\tilde{\chi}_1^\pm}$ reach is seen to be 250 for $m_{\tilde{l}_{L,R}} < m_{\tilde{\chi}_1^\pm}$ (i.e., if the 2 body leptonic decays of the electroweak gauginos are the dominant channels).

If the channels involving τ-jets are combined with the $3l$ we obtain 5σ signal in a sizable region outside the τ-corridor for both small and large τ-mixing (see the regions demarcated by blue stars in Figs. 2 and 3).

For larger $m_{\tilde{l}}$ the decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ mediated by W and Z respectively dominate. This reduces the leptonic BRs and, consequently, the $\tilde{\chi}_1^\pm$ mass reach is smaller ($m_{\tilde{\chi}_1^\pm} < 170$ (see the grey shaded areas in Figs. 2 and 3 for large $m_{\tilde{l}}$). It should, however, be stressed that all grey shaded regions are consistent with the lower bound on the Higgs mass from LEP. This is due to the large radiative correction to the Higgs sector by the heavy squarks.

The chargino mass reach in this region cannot be further improved by combining the $1\tau + 2l$ and $2\tau + l$ events with the clean trilepton signal. This is because here both the

signals are rather weak due to small BRs as well as suppression resulting from τ detection efficiencies.

Throughout this analysis we have used leading order cross sections for the signals as well as the backgrounds using CALCHEP. If next to leading order (NLO) corrections are included the signal cross section is expected to increase by 1.25 to 1.35 [33]. As noted above $t\bar{t}$ events are the dominant background for the $1\tau + 2l$ signals. The NLO cross section for $t\bar{t}$ production is 800 pb [34] which is about a factor of 2 larger than the leading order cross section used in this paper. The significance $S/\sqrt{B}$ estimated for this signal in this paper, therefore, will remain almost unchanged. The relevant backgrounds for the other signals ($3l$ and $2\tau + 1l$) come from pure electroweak processes ($W\gamma^*/Z^*$ etc.). One can therefore conservatively conclude that the total background is not likely to be enhanced by a factor larger than 2. The significance of various signals estimated by us are therefore conservative vis-a-vis the uncertainties in the production cross sections.

Close to the line $m_{\tilde{\tau}_1} \approx m_{\tilde{\chi}_1^0}$ in Fig. 2 and 3 the dark matter (DM) relic density computed by the program MICROMEGAS (version 2.0) [35] turns out to be consistent with the WMAP data [10]: $0.09 < \Omega_{CDM}h^2 < 0.13$ where, $\Omega_{CDM}h^2$ is the DM relic density in units of critical density, h is the Hubble constant. (see the blue squares). Both bulk annihilation and $\tilde{\tau}$—coannihilation contributes dominantly to the relic density. In the large τ-mixing scenario (Fig. 2) observable signals may be obtained in regions consistent with the WMAP data through (i) the clean $3l$ events alone, (ii) events of type (i) augmented by the events containing τ-jets, or (iii) purely τ-jet type events. If τ mixing is small signal (iii) is somewhat disfavored. The sparticle spectrum at a representative point is presented in Table II. At this point an observable signal is obtained by combining the $3l$ events with the events involving the τ-jets.

We have checked that if A, $\tan\beta$, and μ are varied, keeping X_τ fixed, the area of the region consistent with WMAP data increases. The above variations do not affect the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay characteristics drastically. Since the size of the signal basically depends on masses of the $\tilde{\chi}_1^\pm$ and the $\tilde{\chi}_2^0$ and their BRs, the mass reach remains more or less the same.

TABLE II.   The Mass spectrum in order of ascending masses for a representative point $M_1 = 125$, $M_2 = 250$, $M_{\tilde{q},\tilde{g}} = 3000$, $m_{\tilde{l}} = 150$, $\mu = 500$, $A = 0$, $\tan\beta = 10$, and Omega(Ω) = 0.0903.

$\tilde{\chi}_1^0$	123.6	$\tilde{\tau}_1$	125.4	$\tilde{\nu}_{l_L}$	136.0
$\tilde{\nu}_{\tau_L}$	136.0	$\tilde{l}_R$	156.3	$\tilde{l}_l$	156.8
$\tilde{\tau}_2$	182.4	$\tilde{\chi}_1^\pm$	253.6	$\tilde{\chi}_2^0$	253.8
$\tilde{\chi}_3^0$	518.9	$\tilde{\chi}_4^0$	531.7	$\tilde{\chi}_2^\pm$	531.9
$\tilde{b}_1$	2888.7	$\tilde{q}_L$	2890.0	$\tilde{q}_R$	2890.0
$\tilde{b}_2$	2893.0	$\tilde{t}_1$	2923.3	$\tilde{g}$	2942.9
$\tilde{t}_2$	2956.5				

It should, however, be noted that a large part of the parameter space corresponding to the corridor is disfavored by the WMAP data. Moreover in this region the predictions exceed the observed relic density. If signals corresponding to this region are observed, then SUSY cannot be the origin of the observed dark matter relic density. But this region may still be of interest as far as the LHC signals are concerned. For example, a tiny R-parity violating coupling—induced, for example, by higher dimensional operators—would make the neutralino stable at LHC experiments but unstable cosmologically. Thus the issue of dark matter could be completely decoupled from collider signals.

Large supersymmetric contributions to FCNC processes (the SUSY flavour problem) or CP violating processes (the SUSY CP problem) are potentially dangerous and may lead to strong indirect constraints on model parameters. The SUSY flavor problem in the squark sector can be evaded or, at the very least, can be much softened by the large squark-gluino masses. We remind the reader that the signal discussed in the paper are insensitive to $m_{\tilde{q},\tilde{g}}$ once these parameters are beyond the kinematic reach of the LHC. The same is true for the SUSY CP problem in the squark sector. However, some tuning of the SUSY CP phases and other parameters may be needed for accommodating the bounds on the electric dipole moment (EDM) of the electron. The $g-2$ of the muon may receive a large SUSY contribution as we have checked with SUSPECT. For the point shown above this contribution: 2.86×10^{-9} is, however, acceptable. According to recent estimates $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = +302(88) \times 10^{-11}$, where a_μ is the anomalous magnetic moment of the muon [36].

The only Achilles' heel of the proposed scenario could be the high value of the naturalness parameter as we have checked with SUSPECT. However, as already noted in the introduction, the main interest is to see the predictions of a model which retains all virtues of SUSY except for the naturalness.

The scenario understudy may arise naturally in gravity mediated SUSY breaking provided the gaugino mass universality at the GUT scale is given up. Gaugino masses at the high scale are generated by a chiral superfield. If this superfield is singlet under the GUT group then an universal gaugino mass ($M_1 = M_2 = M_3 = m_{1/2}$) emerge at M_G. GUT nonsinglet superfields in general leads to nonuniversal gaugino masses at M_G [37]. If $M_3 \gg M_1$, M_2 at M_G, then the squarks and the gluinos will be naturally heavy at M_G, while the sparticles belonging to the electroweak sector may have smaller masses if the common scalar mass m_0 and $m_{1/2} = M_1 = M_2$ at the GUT scale are small. The clean $3l$ signal in several scenarios with nonuniversal gaugino masses has recently been studied in [38].

However, the desired scenario cannot be accommodated in SUSYGUTs based on SU(5) or SO(10) if a single chiral superfield, nonsinglet under the GUT group, generates the

gaugino masses [37]. If on the other hand a combination of several chiral superfields, transforming differently under the GUT group, contributes to this nonuniversality then the desired pattern may emerge in principle. The key point is that the chiral superfields belonging to different GUT representations contribute to the gaugino masses with different magnitudes and signs. Thus the mass pattern may emerge if a suitable linear combination of these chiral superfields come into play.

With $M_3 = 1200$, $M_1 = M_2 = 300$ at the GUT scale, we obtain the spectrum in Table III with features similar to the spectrum used in the LEWGSS. We also obtain $\Omega = 0.10$ with the dominant contribution coming from bulk annihilation (63%) while 33% comes from coannihilation. Observable signals with τ-jets in the final state are predicted. Coupling constant unification at M_G ($\sim 10^{16}$) also occur naturally.

However, in this scenario with fixed boundary conditions at the GUT scale, μ at the weak scale is determined by the EW symmetry breaking condition. The large μ obtained in this case tend to make the naturalness parameters [4], computed by SUSPECT, rather large. If the squark and gluino masses are lowered to 2 TeV and /or m_{H_u} and m_{H_d} at M_{GUT} are increased relative to m_0 the magnitudes of these above parameters tend to reduce.

Intuitively another natural framework for the LEWGSS scenario seems to be the gauge mediated symmetry breaking (GMSB) [39]. Here the strongly interacting sparticles with masses proportional to α_s^2, where α_s is the strong coupling constant, tend to be heavy. In contrast the sparticles in the electroweak sector with masses determined by the corresponding couplings, are naturally light. However, one may have to go beyond the conventional GMSB scenario with the gravitino as the LSP and $\tilde{\chi}_1^0$ as the NLSP (next LSP). In this scenario the $\tilde{\chi}_1^0$ decays into gravitino + photon leading to entirely different collider signals. In more general GMSB frameworks the sequestered gauge mediated models it may be possible to accommodate the neutralino LSP as the dark matter candidate [40]. On the other hand models with a $\tilde{\tau}$ NLSP looks promising and may lead to models similar to the one considered here. We leave the other details as challenges for the model builders.

TABLE III. The Mass spectrum in order of ascending masses for a representative GUT boundary condition $M_1 = M_2 = 300$, $M_3 = 1200$, $m_{\tilde{l}} = 150$, $m_0 = 160$, $A_0 = 0$, $\tan\beta = 10$, and Omega(Ω) = 0.10.

$\tilde{\chi}_1^0$	117.2	$\tilde{\tau}_1$	132.1	$\tilde{l}_R$	193.6
$\tilde{\nu}_{\tau_L}$	221.6	$\tilde{\nu}_{l_L}$	222.5	$\tilde{\chi}_1^\pm$	225.3
$\tilde{\chi}_2^0$	225.3	$\tilde{l}_l$	235.7	$\tilde{\tau}_2$	272.7
$\tilde{\chi}_3^0$	1433.5	$\tilde{\chi}_4^0$	1435.4	$\tilde{\chi}_2^\pm$	1436.1
$\tilde{t}_1$	1913.1	$\tilde{b}_1$	2101.9	$\tilde{t}_2$	2125.9
$\tilde{b}_2$	2240.9	$\tilde{q}_L$	2245.1	$\tilde{q}_R$	2248.6
$\tilde{g}$	2594.7				

III. THE ELECTROWEAK GAUGINO SIGNALS IN MSUGRA REVISITED

As noted earlier almost the entire parameter space corresponding to observable $3l$ signal in mSUGRA is disfavored by the lower bound on m_h from LEP data (see [19] Fig. 13.32), if the trilinear coupling A_0 is chosen to be zero. For nonvanishing A_0 even small values of m_0 and $m_{1/2}$ are allowed by the above bound [26]. It is therefore worthwhile to check the size of the $3l$ and the τ-jet induced signals in the modified picture. However, these signals are not the discovery channels since in any case larger signals can be obtained from the squark-gluino events.

The three benchmark mSUGRA scenarios A, B and C [26] have common $m_0 = 120$, $\tan\beta = 10$, and $\mu > 0$. The values of $(m_{1/2}, A_0)$ are $(300.0, -930.0)$, $(350.0, -930.0)$, and $(500.0, 0.0)$ for A, B, and C, respectively. The sparticle spectrum and the BRs can be seen from Tables 2 and 5 of [26]. SUSY events in scenarios A and B will contain more τ than e or μ showing a strong departure from "lepton universality" [26,27]. However, in scenario C lepton universality is restored.

The dominant DM relic density producing mechanisms in the above scenarios are given in Fig. 1(a) of [26]. Scenario A is characterized by both LSP pair annihilation [41] and LSP-$\tilde{\tau}_1$ coannihilation [42]. In scenario B, $\tilde{\tau}_1$ coannihilation dominates among the relic density producing processes although LSP pair annihilation plays a significant role. In scenario C with $A_0 = 0$ $\tilde{\tau}_1$ coannihilation is the only DM producing mechanism.

Using the cuts introduced in the last section we compute the $2\tau + 1l$, $1\tau + 2l$, and $3l$ in the three scenarios. In scenarios A, B the detection efficiencies of the τ-jets will be rather low due to low $\tilde{\tau}$ mass. On the other hand, the $3l$ signals will be degraded due to small BRs. In scenario C the observable signal in any channel cannot be found due to small production cross section of the $\tilde{\chi}_1^{\pm}$-$\tilde{\chi}_2^0$ pair. The results are summarized in Table IV. We have also investigated other parameter spaces consistent with the relic density data. We find that none of the three signals is at the observable level. Hence an important feature of WMAP allowed mSUGRA parameter space for low m_0 and $m_{1/2}$ is that signal from direct EW gaugino production is strongly disfavored even if A_0 is nonzero.

We next investigate the parameter space not allowed by the DM data but consistent with the m_h bound from LEP

TABLE IV. Cross section times efficiency (in pb) of the three signals after all cuts mentioned in the text.

	A	B	C
σ (pb)	0.747	0.403	0.106
$2\tau + 1l$	0.000 149	0.000 100	0.000 120
$1\tau + 2l$	0.000 172	0.000 165	0.000 670
$3l$	0.000 179	0.000 117	0.001 181

(see Fig. 4 of [26]). The choice of parameter is $A_0 = -700$, $\tan\beta = 10$, and $\mu > 0$. We find that there is a small region where W, Z mediated three body decays of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ dominate and observable $3l$ signal is possible. Some representative parameter spaces are: (i) $m_{1/2} = 200$, $210 < m_0 < 300$, (ii) $m_{1/2} = 220$, $230 < m_0 < 280$, (iii) $m_{1/2} = 230$, $240 < m_0 < 250$.

It is worthwhile to compare the LEWGSS in Sec. II with mSUGRA and identify the features of the sparticle spectrum responsible for the degradation of chargino-neutralino signals in mSUGRA with low m_0 and $m_{1/2}$. We can identify the following points. The heavy squarks in the more general scenario yield a larger $\tilde{\chi}_1^{\pm}$-$\tilde{\chi}_2^0$ production cross section compared to mSUGRA for the same $m_{\tilde{\chi}_1^{\pm}}$. In mSUGRA with a common scalar mass m_0 at M_G, $\tilde{\tau}_R$ turns out to be the lightest charged slepton at the weak scale due to renormalization group evolution from M_G to M_{weak}. Consequently the decay products of the lighter mass eigenstate $\tilde{\tau}_1$, which is dominantly $\tilde{\tau}_R$, are rather soft. As a result the number of taggable τ-jets above a certain P_T threshold, in the final state is small compared to the LEWGSS with a common slepton mass ($m_{\tilde{\tau}_L} \approx m_{\tilde{\tau}_R}$) at the weak scale. It is to be noted that in principle the mSUGRA condition $m_{\tilde{l}_R} = m_{\tilde{l}_L} = m_0$ may hold at a higher mass scale higher than M_G (say, at the Planck scale M_P). The evolution between M_P and M_W may induce a relatively large $m_{\tilde{l}_R}$ at M_W. Thus the spectrum of sleptons at the weak scale may contain a heavier right slepton relative to mSUGRA. In fact in a SU(5) SUSYGUT the bulk of the R-type slepton mass at the weak scale may come from the M_P-M_G evolution [43]. Thus viable signals involving τ-jets may also arise within the framework of gravity mediated SUSY breaking with a physically well-motivated variation in the boundary conditions at the high scale. The R-type slepton mass may also be enhanced by the D-terms which arise naturally if the rank of the GUT group is reduced after the break down of the GUT symmetry [44]. For collider signatures in supergravity models with universal boundary conditions modified by the $SO(10)$ D-terms see [45].

IV. CONCLUSIONS

We consider an unconstrained MSSM with very heavy strongly interacting sparticles (close to the kinematic reach of the LHC or even beyond it) and relatively light electroweak gauginos and sleptons. In this scenario, referred to as the LEWGSS, the slepton pair production via a Drell-Yan like mechanism and the clean $3l$ signal via $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ pair production are the main SUSY search channels at the LHC. From the existing simulations (see, e.g., Fig. 13.32 of [19,21]) it is, however, expected that these signals are of modest size.

In a significant region of the parameter space under consideration the sleptons can be lighter than $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$.

In this case the final states from the decays of these gauginos naturally contain more τ leptons than electrons and muons (see Secs. I and II). As a consequence the 1τ-jet (tagged) $+ 2l$ and 2τ-jets (tagged) $+ 1l$ signals from $\tilde{\chi}_1^{\pm}$ or $\tilde{\chi}_2^0$ production, either by themselves or in conjunction with the usual clean $3l$ signal, may appreciably extend the reach of chargino-neutralino search at the LHC. For the signals involving τ-jets, it is easier to suppress the SM background because of the harder $\not{E}_T$ spectrum of the signal (see Fig. 1). We also veto events with tagged b-jets for rejecting the $t\bar{t}$ background. The results are summarized in Figs. 2 and 3. These results are insensitive to the precise values of the squark and the gluino masses as long as they are near or beyond the kinematic reach ($\gtrsim 2.5$ TeV) of the LHC. It also follows that if sleptons are much heavier than the $\tilde{\chi}_1^{\pm}$ or $\tilde{\chi}_2^0$ then the signals involving the τ-jets are not viable and mass reach via the $3l$ signal alone remain modest as usual.

In this scenario the SUSY induced FCNC processes or CP violating processes in the squark sector will be naturally small. Coupling constant unification at M_G occurs as usual. The WMAP data on dark matter relic density is satisfied over a small but nontrivial region of the parameter space. The only Achille's heel of the model is the large values of the fine-tuning parameters. However, in many other fields one has to live with unnatural values of parameters and one may accept the model under consideration in this spirit which is similar to the philosophy of split SUSY.

The theoretical motivations for the above scenario are briefly discussed in Sec. II. Gravity mediated SUSY breaking with nonuniversal gaugino masses at M_G with the hierarchy $M_3 \gg M_2 \approx M_1$ may generate the mass hierarchy between the strong sector and electroweak sector considered in this paper. Scenarios similar to the GMSB model where the soft breaking masses of the sparticles are proportional to the corresponding gauge coupling is another possibility.

It is shown in Sec. III that in the minimal supergravity model (mSUGRA), however, the signals involving the τ-jets are not observable due to the special correlations among the sparticle masses in mSUGRA. In particular the mass relation $m_{\tilde{\tau}_L} > m_{\tilde{\tau}_R}$ at the weak scale in mSUGRA makes the decay products of the lighter physical state $\tilde{\tau}_1$, which is dominantly $\tilde{\tau}_R$, rather soft. Consequently, the number of taggable τ-jets in the final state is small compared to the LEWGSS considered in Sec. II with $m_{\tilde{\tau}_L} \approx m_{\tilde{\tau}_R}$ at the weak scale. As discussed in Sec. III the relatively heavy $\tilde{\tau}_R$'s at the weak scale can be realized in gravity mediated SUSY breaking with theoretically well-motivated boundary conditions at M_G. Signals involving τ-jets may, therefore, improve the chargino-neutralino mass reach in these modified scenarios.

ACKNOWLEDGMENTS

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