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Characteristic slepton signal in anomaly mediated SUSY breaking models via gauge boson fusion at the LHC

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Abstract

We point out that slepton pairs produced via gauge boson fusion in anomaly mediated supersymmetry breaking (AMSB) model have very characteristic and almost clean signal at the Large Hadron Collider. In this article, we discuss how one lepton associated with missing energy and produced in between two high-p_T and high-mass forward jets can explore quite heavy sleptons in this scenario.

Vector boson fusion (VBF) at hadronic machines such as the Large Hadron Collider (LHC) at CERN is a useful channel for studying the Higgs boson. Characteristic features of this mechanism are two very energetic quark-jets, produced in the forward direction in opposite hemispheres of the detector and carrying a large invariant mass. The absence of colour exchange between the forward jets ensures suppression of hadronic activities in the central region [1]. The VBF mechanism was originally proposed to produce a background-free signal for a heavy Higgs [2]. The usefulness of the VBF channel in uncovering an intermediate mass Higgs has also been subsequently demonstrated [3].

The importance of this channel has been realized as well in searching signals of supersymmetry (SUSY) especially in some pathological cases [4]. Following the same spirit, in this article we will see how sleptons up to large masses can be explored via their production by VBF and subsequent decays in the AMSB type of a model. As sleptons are only weakly interacting, production cross-sections are rather low. For a minimal gravity mediated SUSY breaking (mSUGRA) scenario, mass reach for the charged sleptons (mainly decaying to a charged lepton and the lightest neutralino, thus producing opposite-sign di-lepton with missing energy) at the LHC is quite low ($\sim$ 300 GeV) [5]. Due to the large production cross-sections the strongly interacting squarks and gluinos would

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be natural to investigate for the discovery of the SUSY particles [6] at the high energy hadron colliders. As for sleptons, couplings of the first two generations [3] to W, Z and photons are almost model independent. They are determined by the gauge quantum numbers of these particles. Thus the slepton production cross-section mainly depends on one unknown parameter, the slepton mass.

The phenomenology of a particular SUSY model is largely determined by the mechanism of SUSY breaking. In the following, we will see that in the AMSB scenario, production of sleptons and their subsequent decays can yield an almost background free signal which is very characteristic and unique to this model. A nice feature of our signal is that it does not depend on the input parameters of the model in a delicate way.

Before delving into the details of signal and background, let us discuss briefly the essence of the AMSB spectra relevant to our analysis. A detailed description of the model and the spectra can be found in many articles [7, 8, 9]. Masses of the gauginos (M_i) and the scalars (M_s) can be written as the following:

$$M_i = b_i \, \frac{g_i^2}{16\pi^2} \, m_{3/2}; \quad M_s^2 = c_s \, \frac{m_{3/2}^2}{(16\pi^2)^2} \; + \; m_0^2. \tag{1}$$

Here b_i's are coefficients occurring in the β-functions of the appropriate gauge couplings and c_s's are combinations of β-functions and anomalous dimensions of gauge and Yukawa couplings, see *e.g.* [8, 9]. For sleptons, c_s's are negative quantities and m_0 is a scalar mass parameter introduced to prevent sleptons from becoming tachyonic. The parameter m_0 is the most model dependent part of the AMSB spectrum, since there are a number of ways to remove the tachyonic masses from the spectrum, see *e.g.* [10], leading to different additions to the scalar masses. We use the simplest choice, where the same mass parameter m_0 is added to all the scalar masses (mAMSB model). The gravitino mass $m_{3/2}$ is the only other mass parameter apart from m_0 in this model.

Since the gaugino masses are proportional to the beta-functions of the corresponding gauge couplings, both the lightest neutralino (which is the LSP) and the lighter chargino turn out to be dominated by the wino, with their masses separated by a few hundreds of MeV [8]. The second lightest neutralino, on the other hand, is about three times heavier than the LSP and it is bino-dominated. This kind of a spectrum implies that the dominant ($\sim$ 95 % or more, over the whole parameter space) decay mode for the lighter chargino is $\chi_1^\pm \longrightarrow \pi^\pm \chi_1^0$ [11] . The pions in such cases are too soft to be detected, making the chargino practically invisible. The small mass difference of χ_1^0 and $\chi_1^\pm$ is essential for the signal to be discussed here. This feature is not present in mSUGRA or gauge mediated symmetry breaking (GMSB) models, and this is why our signal is so unique[4].

Now let us focus ourselves on the sleptons. Unlike the gauginos, slepton masses are dependent on m_0 as well as on $m_{3/2}$. These two parameters have opposite effects on the slepton mass which is evident from eq. (1). Let us also note that the first two generations of the sleptons have almost equal masses due to the small contributions from the corresponding lepton masses. In addition, the

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[3] Throughout this paper, we will restrict ourselves to the first two generations of the sleptons.

[4] We note that by taking non-universal boundary conditions one can tune a model to look like an AMSB model at any particular point of the parameter space. We do not aim to separate between those models and AMSB.

left-handed and right-handed charged sleptons as well as the sneutrinos have masses close to each other in the mAMSB model [8]. Except for the stau, the slepton masses are not very sensitive to $\tan\beta$.

Depending on the mass parameters m_0 and $m_{3/2}$, the sleptons can be heavier or lighter than the second lightest neutralino. The mass ordering determines the decay patterns of these scalars. The possible decay channels of $\tilde{l}_L$ and $\tilde{\nu}$ are

$$\tilde{l}_L \to \nu_l \chi_1^- \text{ or } l^- \chi_i^0, \quad \tilde{\nu}_l \to l^- \chi_1^+ \text{ or } \nu_l \chi_i^0,$$

where $i = 1, 2$. (We denote first two generations of sleptons and leptons by $\tilde{l}$ and l.) Let us first discuss the case when the sleptons are lighter than the χ_2^0. The decay branching ratio to the final state comprising $\chi_1^\pm$ has higher (almost the double) branching ratio than the final state comprising the LSP. On the other hand $\tilde{l}_R$ can decay to $l^- \; \tau^\pm \; \tilde{\tau}^\mp$ or to $l^- \chi_1^0$ (this two body decay can take place because of a tiny bino-component in χ_1^0). The relative strength of these decays depends on $\tan\beta$. When kinematically allowed, sleptons can decay to χ_2^0. Since χ_2^0 is thrice as heavy as χ_1^0 or $\chi_1^\pm$, this new decay mode of $\tilde{l}_L$ and $\tilde{\nu}_l$ has a very small branching ratio[5]. On the other hand, $\tilde{l}_R \to l^- \chi_2^0$ could be dominant when kinematically allowed. It is interesting to observe that the decay branching ratios of $\tilde{l}_L$ and $\tilde{\nu}_l$ do not change much over the parameter space in AMSB. This is an outcome of the characteristic spectrum of the model. $\tilde{l}_L$ and $\tilde{\nu}_l$ when decaying to the lighter chargino have a branching ratio about 66 % while rest of the time they are decaying to the lightest neutralino.

The signals of the AMSB scenario at a future e^+e^- linear collider were studied in the refs. [9, 12]. However, we find it important to look for the signature of the AMSB scenario at the LHC which is planned to start operation in next five years. Studies to probe anomaly mediation scenarios at the LHC, using decay cascades for strongly interacting squarks and gluinos, have been done in [13, 14]. In the present work we will concentrate only on slepton production and decay and see how our proposed signal carries the unique stamp of this kind of a model.

We are now in a position to discuss the signal of the sleptons we are interested in. Since the lighter chargino is invisible in our considerations, $\tilde{l}_L$ decaying to $\chi_1^\pm$ produces no charged lepton and $\tilde{\nu}$ produces only one lepton. Thus from the decays of pair produced $\tilde{l}_L \; \bar{\tilde{l}}_L$, $\tilde{\nu}_l \bar{\tilde{\nu}}_l$ or $\tilde{l}_L \bar{\tilde{\nu}}_L$ one frequently has the *one lepton and missing energy* final state (with effective branching ratios of 43%, 43% and 54% respectively), unlike in the other SUSY breaking models. In contrast, pair production of $\tilde{l}_R$s always produces pair of leptons while decaying. We calculate the cross-sections for the processes $pp \to \tilde{\nu}_l \bar{\tilde{l}}_L, \tilde{\nu}_l \bar{\tilde{\nu}}_l, \tilde{l}_L \bar{\tilde{l}}_L$ associated with two forward jets, and consequent decays of the sleptons to produce one lepton final state. Therefore, the signal we will be looking for is two high-p_T jets produced in the forward region of the detector along with an energetic lepton ($e^\pm$ or $\mu^\pm$) produced in the rapidity region between two jets. One lepton final state can also arise from

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[5] This branching ratio cannot be bigger than 1- 2 % over the parameter space. So in spite of this new decay mode, decay branching ratios to χ_1^0 and $\chi_1^\pm$ remain practically unchanged.

the pair production of $\chi_1^0\chi_2^0$ and subsequent decay of χ_2^0. However, this contribution is negligible compared to the ones we have discussed before [6].

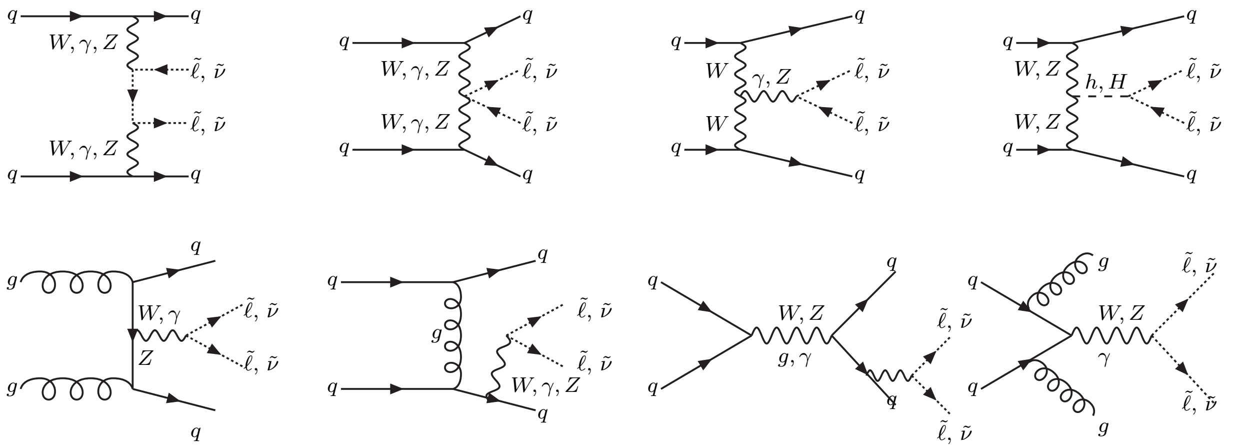

Figure 1: *Generic parton level diagrams leading to slepton pair production with two jets at hadronic colliders. The diagrams in the first row dominantly contribute to our considered signal. Diagrams in the second row have a small contribution to our signal due to kinematic cuts.*

The relevant generic Feynman diagrams are depicted in fig. 1. In the first row we have presented those diagrams which are really due to vector boson fusion. These diagrams contribute to the cross-section dominantly. The diagrams in the second row contribute to the slepton pair production along with two jets, but we have explicitly checked that they do not contribute to the total cross-section significantly as they do not survive the kinematic cuts. It is also important to note that for the first two diagrams in the second row, colored particles are exchanged along two final partons. For these processes, there are gluon emissions in the central rapidity region. As we demand for our signal that the central region between two forward jets be hadronically quiet, we expect that these diagrams would not pass the central jet veto. However, since we are limited to the LO diagrams, simulation of jet emission in the central region and use of central jet veto is beyond our calculation. We have evaluated numerically the amplitudes using the computer code HELAS [15] and then used a Monte Carlo routine to integrate over the phase-space. In our numerical calculations we have used the CTEQ4L set of parton parametrisation in [16].

To show the efficacy of our chosen VBF channel for large slepton masses, we will first present the cross-sections for the slepton pair production at the LHC energies in fig. 2. For the purpose of comparison, we will also present the cross-section of slepton pair via Drell-Yan (DY) production. From the figure it is evident that for large slepton masses the VBF cross-section is larger than the DY cross-section, which falls off quite fast with slepton mass. The advantage of using the VBF method for slepton production at LHC becomes even more obvious - at least at the preliminary

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[6] The cross section for $pp \to \chi_1^0\chi_2^0 \to$ one lepton final state remains below 10^{-2} fb for the allowed parameter range.

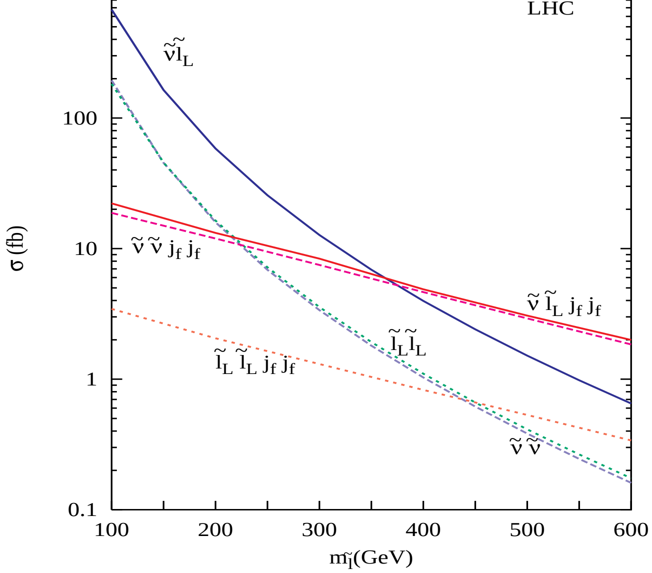

Figure 2: *Cross-sections of slepton pair production from VBF and DY channels. Kinematic cuts defined in the text have been used to calculate the VBF cross-sections.*

stage - when we note that in calculating the VBF cross-sections we have used the kinematic cuts defined in the following part of the text, while there are no kinematic cuts applied in calculation of the DY cross-section.

The proposed signal is not background free. Similar events can be faked by the production of a real or virtual W along with two forward jets, followed by the leptonic decay of the W. Such final states can arise in the SM from real emission corrections to single W-production process ($\mathcal{O}(\alpha_s^2\alpha_W^2)$) as well as from the electroweak W production along with two jets ($\mathcal{O}(\alpha_W^4)$). We have calculated the full tree-level contribution to the process $pp \to j_f j_f(W, W^* \to)l\nu$ using the package MADGRAPH [17]. Transverse mass distribution of the above background has a sharp edge for the leptons coming from the decay of a real W. On the other hand, $l\nu$ coming from a W^*, can smear the sharp edge of this transverse-mass distribution. The finite detector resolution is another source for smearing. To take into account the detector effects we have (gaussian) smeared the jet and lepton energies using [18]:

$$\Delta E_j/E_j = 0.6/\sqrt{E_j} + 0.03, \qquad \Delta E_l/E_l = 0.15/\sqrt{E_j} + 0.01$$

for the signal and all background processes. Finally, we calculate the missing p_T by imposing the conservation of momentum along transverse direction.

The other source of one lepton background is WZ production along with 2 forward jets, followed by the leptonic decay of W and invisible decay of Z to a pair of neutrinos. We have also estimated this background.

We plot the normalised transverse mass distribution of signal (coming from $\tilde{l}\tilde{\nu}$ production and decay. For this plot we have used $m_{\tilde{l}} = m_{\tilde{\nu}} = 163$ GeV and $m_{\chi_1^0} = m_{\chi_1^+} = 90$ GeV. The kinematics of all three processes contributing to the signal are very similar, since all the sleptons as well as the lightest neutralino and chargino are almost degenerate in mass in AMSB model. Thus we present only the $\tilde{l}\tilde{\nu}$ case.) and backgrounds in figure 3 for illustration. The sharp decrease of W/W^*

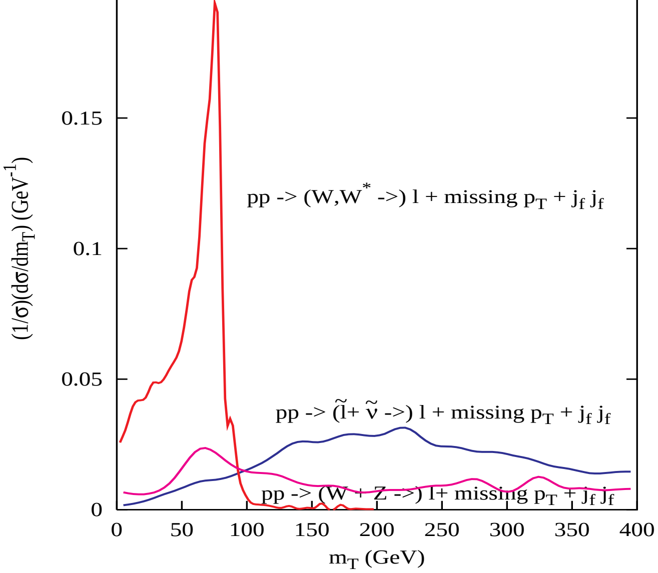

Figure 3: *Normalised transverse mass distribution of signal and backgrounds. The small structures in the plots are due to Monte Carlo fluctuations.*

background around W-mass, clearly points to the fact that dominant part of this background comes from a real W production, while the tail of this distribution beyond W-mass is due to the contribution from off-shell W, in addition to the detector resolution effects, which we have taken into account as well. The other background from WZ production has similar kind of transverse mass distribution to that of the signal. For heavier charged-sleptons/sneutrinos the maximum (which is not very sharp) of the signal distribution is shifted more towards right. From the distributions it is evident that once we demand that the transverse mass constructed from the lepton and the missing p_T vector is greater than 100 GeV, a large part of W, W^* background can be removed. In this process we loose part of the signal and WZ background. We will soon see that the remaining number of signal events is enough to be statistically significant over the remaining background.

We have used the following set of cuts to minimize the background:

- Two forward jets in opposite hemispheres, with $E_T > 40\ GeV$ and $2.0 \leq |\eta_j| \leq 5.0$.
- $\Delta\eta_{jj} > 4$.
- $M_{inv}(jj) > 650\ GeV$.
- $\not{E}_T > 100\ GeV$.
- $p_T^l > 15\ GeV$.
- $|\eta_l| < 2$.
- $m_T(l\not{p}_T) > 100\ GeV$.

Use of the above set of cuts reduces the one lepton background down to 16 fb (14 fb from WZ and 2 fb from W/W^* production). We have also estimated backgrounds coming from W^+W^-+ 2 forward jets $\rightarrow \nu\nu l^+l^-+$ 2 forward jets and $(\gamma^*, Z \rightarrow)l^+l^-+$ 2 forward jets production, with one lepton going down the beam pipe. After the cuts these backgrounds are less than 10^{-5} fb.

To calculate the signal significance over the background, it is very important to know the normalisation of the latter accurately. Unfortunately, the normalisation for the WZ production

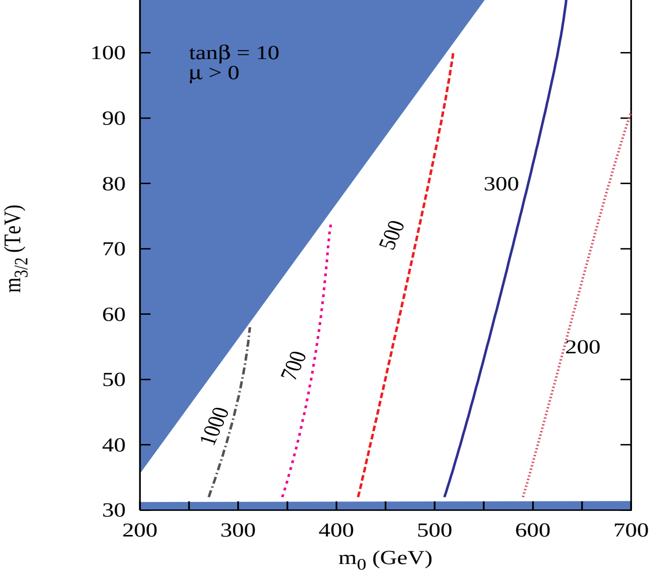

Figure 4: *Lines of constant number of events in* $m_0 - m_{3/2}$ *plane for* $\tan\beta = 10$ *and* $\mu > 0$. *The shaded regions are constrained from theoretical and experimental considerations. On the upper x-axis the* $\tilde{l}_L$ *masses are given for* $m_{3/2}$ *= 30 TeV. We have assumed 100fb*$^{-1}$ *for integrated luminosity.*

associated with two forward jets is not known. One of the reasons is that we require that there is no jet activity in the central part of the detector, and to parametrise this kind of veto is beyond the perturbative QCD calculations. These issues have been discussed in detail in ref. [19]. Thus the exact normalisation has to be calculated from the LHC data itself. We just want to comment that this is possible in principle by estimating $pp \to Z(\to e^+e^-)W(\to \mu\nu_\mu)+$ *2 forward jets* events. From this three lepton final state we can get cross-section for one lepton final state by scaling with the appropriate branching ratios. Since the background cross-section is only of the leading order it depends strongly on the choice of the scale of α_s and also on the factorization scale of the parton distribution functions. We have chosen the scale to be at min $(p_T^{j_1}, p_T^{j_2})$ when estimating the background. On the other hand for the signal the factorization scale for parton distribution functions has been chosen to be at the sum of the slepton masses we are producing.

We present the numbers of 1-lepton + $\not{E}_T$+ 2 forward-jets events in Fig. 4. We choose to present the contours of constant number of events in $m_0 - m_{3/2}$ plane for $\tan\beta = 10$ and $\mu > 0$. Results are not very sensitive to the sign of μ. As mentioned earlier, the interactions necessary to calculate the slepton pair production in VBF do not depend on any unknown SUSY parameters. As we are interested only in the first two generations of the sleptons, mixing of the left- and right-sleptons is not very important. One also needs the couplings of CP-even neutral Higgses to a pair of sleptons (which are somewhat model dependent) but we checked that those diagrams contribute little to the total cross-section. Thus, slepton pair production cross-section along with two forward jets depends mainly on the slepton masses. Increasing m_0 will decrease the cross-section, while increasing $m_{3/2}$ tends to increase the cross-section by decreasing the slepton masses. Let us now come to the decay of the sleptons. It has already been pointed out that changing the input parameters has little impact on the slepton branching ratios unless we are close to the kinematic limits. On the other hand, the decay kinematics depends somewhat on the parameters. As we increase $m_{3/2}$, the masses of χ_1^0 and $\chi_1^\pm$ increase and affect the two body decay kinematics. The resulting contours, for the number of events, closely resemble the contours of constant slepton masses. The $\tilde{e}_L$ masses for $m_{3/2} = 30$ TeV are also shown in the plot on the upper x-axis to indicate how the production cross-section falls with slepton mass. We want to point out that, from the Figure 4, it is evident that for large slepton masses the cross-section falls off quite slowly. This is in contrast with the Drell-Yan production of sleptons [20]. One can easily check from the plot that production cross-section $(\tilde{\nu}_l \tilde{\bar{l}}_L + \tilde{\nu}_l \tilde{\bar{\nu}}_l + \tilde{l}_L \tilde{\bar{l}}_L)$ is at the fb level for 500 GeV slepton masses after the suppression from branching ratios and kinematic cuts, while in the Drell-Yan case [20] the raw cross-section is of the order of 1 fb for a slepton mass of 500 GeV. This clarifies why we stick to the VBF channel for producing the slepton pairs. Indeed, for low mass sleptons, cross-section from direct production [20] is always an order of magnitude higher. However, the direct production cross-section falls quite fast with slepton mass. For slepton masses greater than 450 GeV, the VBF cross-section is larger than the direct one.

With 100 fb^{-1} integrated luminosity, 16 fb of the SM background implies that one needs to have around 200 signal events for a 5σ discovery and around 120 events for a 3σ discovery. It is evident from the figure 4, that one can probe slepton masses up to 600 GeV which is quite remarkable. If we assume a 5% uncertainty in our estimated background (as we do not know the background normalisation accurately) and add this error with our estimated number of background events in quadrature [19], the above 5σ mass limit goes down close to 450 GeV (in this case one needs nearly 450 events for the 5σ discovery).

One could have one lepton signal in mSUGRA (and GMSB [7]) model as well. The dominant contribution comes from the production of $\tilde{l}_L(\rightarrow l\chi_1^0)\tilde{\nu}(\rightarrow \nu\chi_1^0)$ and $\chi_1^\pm(\rightarrow l\nu\chi_1^0)\ \chi_2^0(\rightarrow \nu\nu\chi_1^0)$ associated with two forward jets. The cross-section can be as large as 6 fb for the former one for light sleptons, while the latter one can be of the order of 0.1 fb. The sum is comparable with the one lepton cross section in the AMSB scenario. Thus one might assume that our proposed signal cannot be used as some benchmark for this scenario. However, neutralinos and charginos in mSUGRA or GMSB, have a very distinct and clean $3l + \not{E}_T$ signature coming from $pp \rightarrow \chi_1^\pm(\rightarrow l\nu\chi_1^0)\ \chi_2^0(\rightarrow l\bar{l}\chi_1^0)$ [22]. (This cross-section can be as high as 100 fb in regions of parameter space.) This is practically absent in the AMSB scenario. We have explicitly checked that in AMSB, the cross section of $3l + \not{E}_T$ final state from chargino neutralino and slepton production and decay is always below 10^{-2} fb level. The absence of this clean tri-lepton final state but appearance of 1 lepton + 2 forward jet signature clearly points to the 'AMSB' kind of SUSY breaking.

Moreover it is important to note that in the AMSB-like scenarios, lighter chargino has a comparatively long life time (unlike in mSUGRA and GMSB), and it may leave an ionized track in the detector before its decay. This issue has been discussed and exploited to dig out the signals of AMSB [14, 21]. In our analysis we have assumed that the chargino is almost invisible, but

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[7] We note that in the simplest GMSB model, over most of the parameter space χ_1^0 decays dominantly to a photon and a gravitino. This provides an additional method to discriminate between GMSB and AMSB.

detailed simulation in the context of AMSB search at LHC reveals [14] that identifying this kind of a macroscopic ionizing tracks is possible with high efficiency with off-line analysis of the data. In that case, our signal will indeed be free of any 'physics-background' and the mass reach will certainly improve beyond 600 GeV.

The shaded region parallel to the x-axis in the plot is ruled out from the direct chargino search at LEP [23]. Region shaded in the upper left corner of the figure is excluded from the consideration that in this region the lighter stau is the lightest supersymmetric particle which may not be desirable from cosmological considerations. There are also other constraints coming from the considerations of radiative decay of B-mesons and muon $(g-2)$ [24], and also from analyzing the nature of the vacuum due to the scalar sector of AMSB model [25]. We have not shown or considered them, but the effect of the constraints on the parameter space can be readily read from the given references. However, direct search experiments should not be biased by other experimental results, which may, furthermore, be model dependent. We want to stress that our proposed signal is unique and can provide a smoking gun signature of this kind of SUSY breaking at a hadronic collider like LHC over a large area of parameter space.

Furthermore, we emphasize that the signal we propose is characteristic of not only the minimal AMSB scenario but also to the other variants of this model, or any model with AMSB-like mass spectrum. The one lepton signature is an outcome of the invisibility of the chargino decay and mass spectrum of the model. Decay pattern of the $\chi_1^\pm$, along with its composition (also the composition of χ_1^0) are general features of the considered alternative AMSB models. In several variants of the AMSB type models, for the first two generations of sleptons $\tilde{l}_L, \tilde{\nu}_l$ masses are not only close to each other, but they are heavier than the $\chi_1^\pm$ or χ_1^0. This ensures the previously discussed decay pattern and decay branching ratios for these particles.

To summarise, pair production of sleptons associated with two forward jets, and their decay to one lepton final state can be used at the LHC to look for a signal of anomaly mediated SUSY breaking model. We have analyzed the signal and background and have shown that up to large slepton masses one can have a very distinct signature of this model coming from the slepton pair production and decay. Our proposed signal not only characterizes the minimal model but also the other variants of AMSB.

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