

# Signals of neutralinos and charginos from gauge boson fusion at the CERN Large Hadron Collider

Anindya Datta <sup>1</sup>, Partha Konar <sup>2</sup> and Biswarup Mukhopadhyaya <sup>3</sup>  
*Harish-Chandra Research Institute,*  
*Chhatnag Road, Jhusi, Allahabad - 211 019, India,*

## Abstract

We point out that interesting signals of the non-strongly interacting sector of the supersymmetric standard model arise from the production of charginos and neutralinos via vector boson fusion (VBF) at the Large Hadron Collider (LHC). In particular, if R-parity is violated, the hadronically quiet signals of charginos and neutralinos through direct production get considerably suppressed. We show that in such cases, the VBF channel can be useful in identifying this sector through clean and background-free final states.

## 1 Introduction

It is well-established that vector boson fusion (VBF) at a high-energy, high luminosity hadron collider provides a useful channel for the identification and detailed study of the Higgs boson [1]. This technique is applicable to both a standard Higgs and one occurring in the supersymmetric (SUSY) extension of the standard model [2]. The feasibility of tagging the two forward jets from which the gauge bosons originate, with no hadronic activity in the rapidity interval between them, gives added incentive to this search strategy at the Large Hadron Collider (LHC) at CERN. In this paper, we want to emphasize that it may be worthwhile to use the VBF channel to also look for signatures of the chargino-neutralino sector of the supersymmetric standard model, at least in certain scenarios.

Let us briefly recall the generally accepted strategy for identifying modes of direct production and decay for charginos and neutralinos at hadron colliders. These modes are important for an understanding of the superparticle spectrum, especially in the non-strongly interacting sector of

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<sup>1</sup>E-mail: anindya@mri.ernet.in

<sup>2</sup>E-mail: konar@mri.ernet.in

<sup>3</sup>E-mail: biswarup@mri.ernet.in

the theory. The most conspicuous signal is expected from direct production of a  $\chi_1^\pm \chi_2^0$  pair (i.e. the lighter chargino together with the second lightest neutralino). In the minimal SUSY standard model (MSSM) [3] with conserved R-parity (defined as  $R = (-)^{(3B+L+2S)}$ ), the  $\chi_2^0$  and  $\chi_1^\pm$  have substantial branching ratios for leptonic decays in the channels  $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$  and  $\chi_1^\pm \rightarrow \chi_1^0 l^\pm \nu_l$  ( $\bar{\nu}_l$ ) respectively. Thus one has the so-called ‘hadronically quiet’ *trilepton* +  $\cancel{E}_T$  signal. Such a signal can easily be made free from standard model backgrounds, and it bears an unambiguous stamp of the non-strongly interacting sector of the MSSM. Detailed estimates of such signals, including QCD corrections, exist in the literature [4]. In addition, it has also been argued that dilepton signals, of both like and unlike signs, ensue when one of the three leptons mentioned above escapes undetected, thereby giving additional types of easily distinguishable events [5].

However, the leptonic decay channels might be relatively suppressed in certain cases. For example, as we shall see afterwards,  $\chi_2^0$  and  $\chi_1^\pm$  may decay directly into leptons and jets in an R-parity violating scenario [6]. Since R-parity is not necessitated by any inherent symmetry of the theory, it is perfectly natural to envision such a situation. Under such circumstances, while the trilepton signals suffer from a suppression, the final states obtained from R-violating decays of charginos and neutralinos may be difficult to disentangle from signals of the strongly interacting sector, namely, gluinos and squarks. It is for such situations that we point out the usefulness of the VBF channel in isolating charginos and neutralinos through clearly identifiable and background-free events.

In section 2, we discuss neutralino and chargino decays in an R-parity violating model, and demonstrate that in certain cases the MSSM decays can be suppressed. The signals for these cases in the VBF channels, together with the event selection criteria, are discussed in section 3. We wind up with some concluding remarks in section 4.

## 2 An R-parity violating scenario: chargino and neutralino decays, and what happens to the direct signals

In general, R-parity violation in a SUSY model implies that the MSSM superpotential, written in terms of the quark, lepton and Higgs superfields, gets augmented by the following terms [7]:

$$W_{\mathcal{R}} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^c + \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c + \epsilon_i \hat{L}_i \hat{H}_2 \quad (1)$$

The non-observation of proton decay leads to the further assumption that only L (through the  $\lambda$ ,  $\lambda'$  or  $\epsilon$ -type couplings) or B (through the  $\lambda''$ -type couplings) can be violated at a time. We demonstrate our main point in a simplified scenario where only *one*  $\lambda'$ -type coupling is present. We shall comment on the other types of L-violating couplings in the last section.

In presence of a  $\lambda'$ -type term in the superpotential, the following additional decay modes become available to neutralinos and charginos:

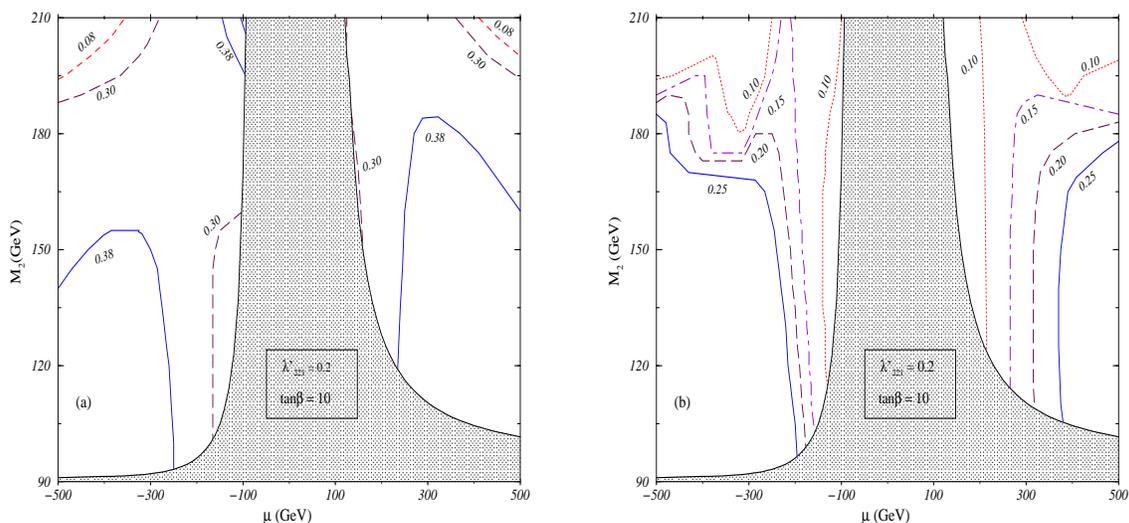


Figure 1: Contours of constant branching ratios for the decays (a)  $\chi_2^0 \rightarrow l^\pm q \bar{q}'$  and (b)  $\chi^\pm \rightarrow l^\pm q \bar{q}$  in  $M_2 - \mu$  plane, with  $\lambda'_{221} = 0.2$  and  $\tan \beta = 10$ . We have assumed  $m_{\bar{q}} = 300$  GeV,  $m_{\bar{l}} = 200$  GeV. The shaded region is disallowed from LEP data.

$$\chi^0 \longrightarrow l^\pm q \bar{q}' \quad (2)$$

$$\chi^\pm \longrightarrow l^\pm q \bar{q} \quad (3)$$

the branching ratios depending on the strength of the R-violating interaction. In addition, of course, final states with neutrinos replacing leptons are also possible.

Our numerical estimates are done by assuming  $\lambda'_{221}$  to be the only non-zero L-violating coupling. Throughout this study, we have fixed slepton and squark masses at 200 and 300 GeV respectively. For such a squark mass, the maximum allowed value for  $\lambda'_{221}$  is 0.54 [8]. We use values well within this limit to compute the branching ratios for the decays mentioned in (2) and (3). Gaugino mass unification at a high energy scale has been assumed, so that all masses and mixing angles in the chargino-neutralino sector are fixed when we specify the SU(2) gaugino mass  $M_2$ , the Higgsino mass parameter  $\mu$ , and  $\tan \beta$ , the ratio of the vacuum expectation values (vev) of the two Higgs doublets. We have *not* restricted ourselves by any further assumption about high scale physics (such as a supergravity framework), and thus the squark and slepton masses (and also  $\mu$ ) have been treated essentially as free parameters.

Some branching ratio contours for such decays for  $\chi_2^0$  and  $\chi_1^+$  in the  $\mu - M_2$  parameter space are shown in figures 1(a) and 1(b), for  $\lambda'_{221} = 0.2$  and  $\tan \beta = 10$ . The regions constrained by LEP data [9] are also shown in the same figures. We supplement these by figures 2(a) and 2(b), which show the variation of the same branching ratios with  $\lambda'_{221}$  and  $\tan \beta$ . The dip in the curves from  $\tan \beta \simeq 30$  onwards is due to the lowering of the lighter stau mass to such a level that the tau-stau

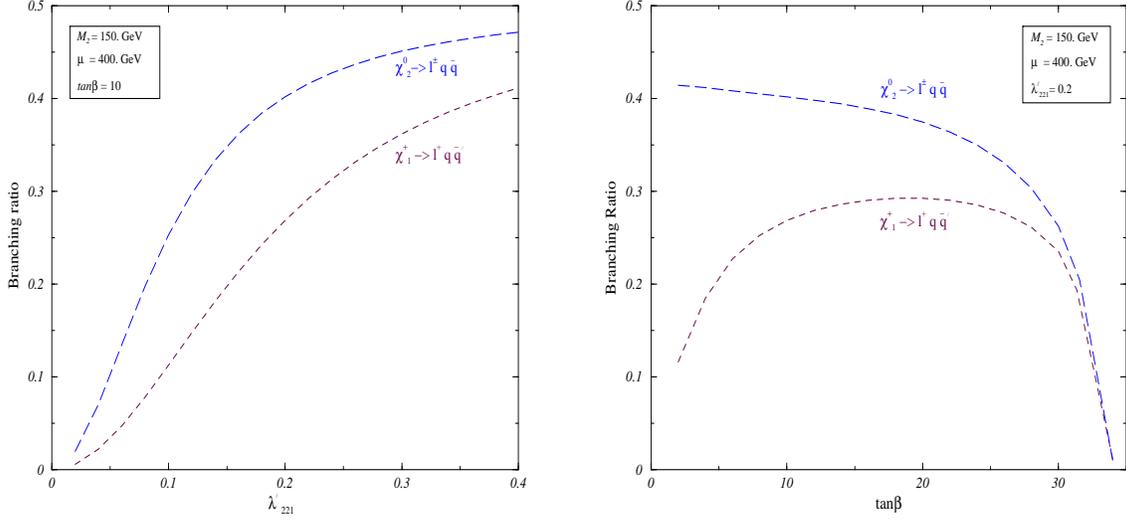


Figure 2: Variation of the branching ratios for the R-parity violating decays of  $\chi_2^0$  and  $\chi_1^\pm$  with (a) the coupling  $\lambda'_{221}$  and (b)  $\tan\beta$ .

(neutrino-stau) decay channel opens up for the  $\chi_2^0$  ( $\chi_1^\pm$ ). Similarly, for low  $\tan\beta$ , the couplings (which are functions of the chargino and neutralino mixing elements) driving the MSSM chargino decays undergo a rise. This in turn explains the relative insignificance of the R-parity violating widths. The numerical results presented here use  $\tan\beta = 10$ , which corresponds to the plateau in figure 2b.

In addition to what is shown in equation (3), the chargino will also have an R-violating decay mode into a neutrino, driven by the same coupling. As for the neutralino, its Majorana character implies the existence of four R-violating decay modes altogether. Taking all of these into account, the contours shown in the figures imply considerable suppression of the MSSM decay channels for  $\chi_2^0$  and  $\chi_1^\pm$  over a substantial region of the allowed parameter space. On the whole, for  $\mu = 400 \text{ GeV}$ ,  $M_2 = 150 \text{ GeV}$  and  $\tan\beta = 10$ , the combined trilepton branching ratio for a  $\chi_2^0\chi_1^\pm$  pair gets reduced by about one order for  $\lambda'_{221} = 0.2$ , and by a factor of nearly 50 for  $\lambda'_{221} = 0.4$ . The consequent dilution of the trilepton signals at the LHC may cost one dearly in the exclusive search for a chargino-neutralino pair. On the other hand, the modes available in this case lead to *lepton + jets +  $\cancel{E}_T$*  and *dilepton + jets* events. Similar final states are also possible from cascade decays of squarks and gluinos which are produced much more copiously at hadron colliders. Estimates of such (*n jets + m leptons +  $\cancel{E}_T$* ) event rates already exist for both the Tevatron and the LHC [10], and cascades originating from coloured superparticles are likely to dominate there. Therefore, the exclusive production modes in the chargino-neutralino sector, which are so clean and distinctive at LHC for MSSM, lose much of their cleanliness over a sizable region of the allowed parameter space in a scenario with broken R-parity.

In cases like the above, it is hardly necessary to emphasize the importance of new production

channels in unravelling the non-strongly interacting sector of SUSY, which is so essential to obtain a clear picture about the particle spectrum and the different interactions. One direction to explore in this connection is the production of charginos and neutralinos through gauge boson fusion at the LHC. We take this up in the next section.

### 3 Neutralino and chargino production via vector boson fusion

The vector boson fusion channel has so far been studied mainly with a view to Higgs searches. The salient features of this class of processes are [11]:

- Two highly energetic forward jets (originating from the two quarks from which the gauge bosons are emitted) moving in opposite directions, with the pseudorapidity ( $\eta$ ) of each jet peaking in the region  $\eta = 3 - 4$ .
- Decay products of the particle(s) produced via VBF lying in the rapidity interval between the two forward jets.
- Suppression of hadronic activity (arising from coloured particle exchange) in the rapidity interval between the forward jets.

If neutralinos and charginos are also produced via VBF, then the above event characteristics enable us to eliminate similar effects originating from gluinos and squarks. This can be achieved by demanding a high ( $\gtrsim 650 \text{ GeV}$ ) invariant mass for the forward jet pair. Consequently, when R-parity violating decays for  $\chi_2^0$  and  $\chi_1^\pm$  dominate, the centrally produced charginos and neutralinos should give rise to events of the type

$$\textit{Like- or Unlike-Sign Dileptons} + \geq 2 \textit{ Jets}$$

in the rapidity interval between the two high invariant mass forward jets. With our particular choice of the  $\lambda'$ -coupling, the leptons actually turn out to be muons. Such events are largely free from standard model backgrounds, too, especially after applying the cuts that we shall discuss shortly.

Signals of the above type can be obtained from  $\chi_i^0 \chi_j^0$ ,  $\chi_i^\pm \chi_j^\pm$ ,  $\chi_i^+ \chi_j^-$  as well as  $\chi_i^0 \chi_j^\pm$ . Of these, the largest contributions come from  $\chi_1^+ \chi_1^-$  and  $\chi_2^0 \chi_1^\pm$ , so long as one adheres to a gaugino mass unification scheme. Out of the large number of diagrams leading to final states mentioned above, only those involving  $W$ ,  $Z$  and  $\gamma$ -fusion contribute to events with the characteristics laid down here. We have numerically calculated all the helicity amplitudes (for  $pp$  collision with  $\sqrt{s} = 14 \text{ TeV}$  corresponding to these diagrams using the HELAS package [12]. CTEQ4L distributions [13] have been used in our parton level Monte Carlo calculation, with the factorization scale set at the sum of the masses of the neutralino/chargino pair-produced via VBF.

It should be noted that the signals under consideration here can come not only from direct R-parity violating decays of heavier neutralinos and charginos but also from, say,  $\chi_2^0$  or  $\chi_1^\pm$  decaying hadronically through MSSM interactions to the  $\chi_1^0$ , and the latter decaying through  $\lambda'$ -type couplings. Such cascade processes are included in our calculation; they are especially important in cases where the R-violating couplings are relatively small. In such cases, MSSM interactions override them in  $\chi_2^0$  or  $\chi_1^\pm$  decays, but their presence is reflected in the decay channels of the lightest neutralino.

The events have been required to pass the following cuts:

- A minimum invariant mass of 650  $GeV$  on the two forward jets ( $j_1, j_2$ ).
- $2 \leq |\eta| \leq 5$  for each forward jet, with  $\eta(j_1) \eta(j_2) < 0$ .
- $|\Delta\eta_{j_1 j_2}| \geq 4$ .
- $E_T \geq 15 GeV$  for all jets.
- The central jets and leptons to lie in the rapidity interval between  $j_1$  and  $j_2$ .
- $\Delta R(l, j_{1(2)}) \geq 0.6$ .
- $\Delta R(\text{central jet}, j_{1(2)}) \geq 0.6$ .
- $p_T \geq 10 GeV$  for the central muons.
- The dilepton invariant mass lying outside the region  $m_Z \pm 15 GeV$  for unlike-sign dileptons.
- Total missing  $E_T \leq 10 GeV$ .

The rapidity and isolation cuts separate the central events arising from neutralino and chargino decays. The large invariant mass demanded of the forward jets sets the signal events apart from potential backgrounds from squarks and gluinos. This combination of cuts eliminates practically all standard model backgrounds as well as those arising in R-conserving MSSM. In the case of unlike-sign leptons, the invariant mass cut on the lepton pair takes care of faking by a  $Z$ -boson. And finally, an upper limit set on the missing transverse momentum (obtained after applying a Gaussian smear [14] on the momenta of the final-state partons and leptons) is expected to take care of such backgrounds as those from a  $t\bar{t}$  pairs, with semileptonic b-decays giving rise to like-sign dileptons. For unlike-sign dileptons, the two b's from a top-antitop pair can also in principle be a potential source of backgrounds. A stiff isolation cut between the leptons and jets in the central region is one cure for this problem; however, the signal strength then gets reduced by upto a factor of 10. Instead of applying such a cut, we have noticed that the upper limit set on the missing  $E_T$  comes to our rescue in reducing this background. Since the leptons and neutrinos have similar  $E_T$  distributions, those background events which pass the lepton  $E_T$  cuts set by us mostly carry large

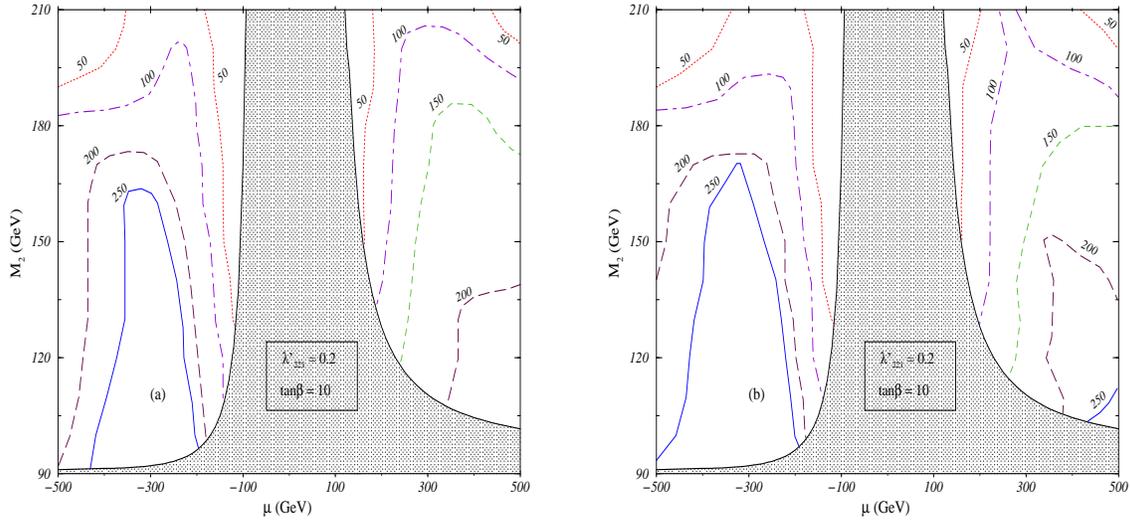


Figure 3: Event contours for (a) like-sign dilepton (LSD) production and (b) unlike-sign dilepton (USD) production in  $M_2 - \mu$  plane, with  $\lambda'_{221} = 0.2$  and  $\tan \beta = 10$ . Other features are same as in fig. 1.

missing  $E_T$  as well, and thus they get eliminated by the  $\cancel{E}_T$ -cut. Thus the demand that our final state particles are ‘visible’ makes the signal background-free.

In figures 3(a) and 3(b), we present the event contours for both like-and unlike-sign dileptons (LSD,USD), for  $\lambda'_{221} = 0.2$  and  $\tan \beta = 10$ . The event rates have been calculated for an integrated luminosity of  $100 \text{ fb}^{-1}$ . It is found that as far as USD events are concerned, the dominant contributions come from  $\chi_1^+ \chi_1^-$  production and R-parity violating decay of each of them. Also, the  $\chi_1^\pm \chi_2^0$  production channel contributes appreciably. For LSD, on the other hand, a  $\chi_1^+ \chi_1^-$  pair contributes only if at least one chargino has an R-conserving decay into a  $\chi_1^0$  which subsequently gives one lepton via the  $\lambda'$ -type coupling. In any case, one can easily have upto about 250 events of both USD and LSD types surviving the cuts for the choice of parameters shown here. This includes regions in the parameters space for both positive and negative values of  $\mu$ ; it may be noted here that the region of our interest is compatible with the SUSY solution recently measured excess in muon anomalous magnetic moments, so long as  $\mu$  is positive [15].

Signals of the said type can be measurable even for much smaller values of  $\lambda'_{221}$ . For example, if it has a value of 0.02, then the R-parity violating decays of  $\chi_1^\pm$  and  $\chi_2^0$  are severely suppressed. However, this is where the two-stage decays, boosted by the 100% branching ratio for R-violating  $\chi_1^0$  decay, come to be of use. As is shown in figures 4(a) and 4(b), one can expect up to about 40 events of both USD and LSD types with the given integrated luminosity even with such a small value of the R-parity violating interaction. This leads us to the conclusion that such signals are worthwhile to investigate at the LHC even for a situation where R-parity violation is miniscule.

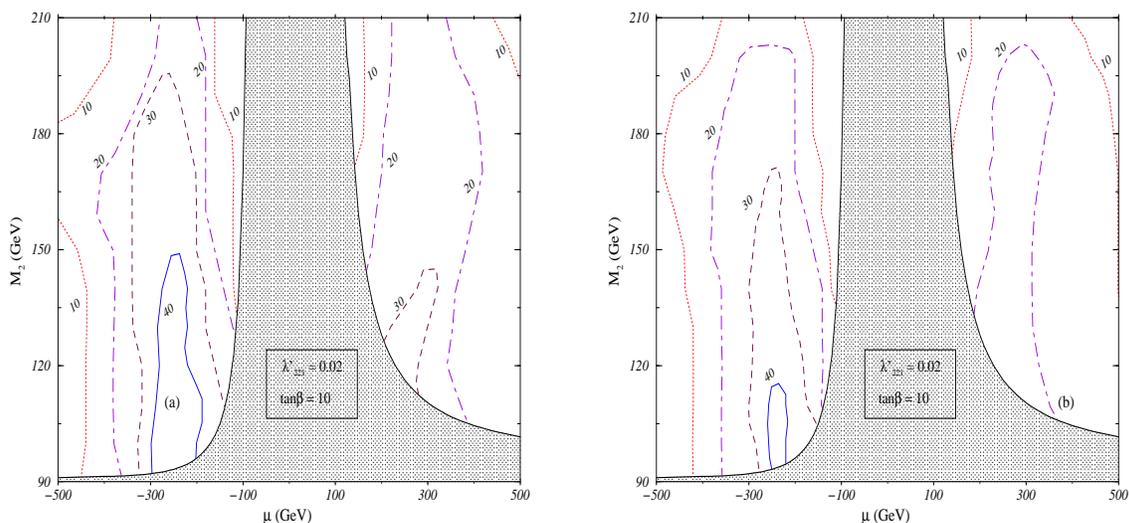


Figure 4: Event contours for (a) like-sign dilepton (LSD) production and (b) unlike-sign dilepton (USD) production in  $M_2 - \mu$  plane, with  $\lambda'_{221} = 0.02$  and  $\tan\beta = 10$ . Other features are same as in fig. 1.

We have presented our results in the  $\mu - M_2$  plane. From figure 4 it is evident that for  $\lambda'_{221} = 0.02$ , one can have 20 signal events, for values of  $M_2$  upto about 200 GeV. Figure 3, on the higher hand, shows the corresponding number of events to be around 50. In terms of neutralino chargino masses, this means that we can probe upto a lighter chargino and second lightest neutralino mass upto about 200 GeV. The lightest chargino mass reach is nearly half of the above value. This is indicative of how much improvement over the LEP results is possible through the VBF technique in probing the chargino-neutralino sector of an R-parity violating scenario.

The signals suggested here can also be mimicked by the production of charged-higgs boson pairs via VBF channel [16]. The production cross-section for the latter can reach upto 10 fb. Further decay of  $H^\pm$  to  $\chi_1^\pm \chi_1^0$  or  $W^\pm h^0$ ,  $tb$  may lead to final states comprising unlike-sign dileptons associated with jets. Following reference [17], charged-higgs branching ratio to  $\chi_1^\pm \chi_1^0$  can be as big as 0.7. Leptonic decay of the charginos would make the effective branching ratio of a charged-higgs pair to unlike sign dileptons around 2%. Cuts on the leptons and jets in the central region will further reduce the signal strength and we may be left with a maximum of 10 such events coming from this channel. Moreover, R-conserving decays of the charginos would produce a large amount of missing  $E_T$  caused by the lightest neutralino. So our missing  $E_T$  cut ( $< 10$  GeV) can control this ‘background’ quite efficiently.

Also,  $H^\pm \rightarrow W^\pm h^0$  decay can have a maximum branching ratio of 0.6 for low  $\tan\beta$  and for higgs mass less than  $tb$  threshold. The  $tb$  channel, once allowed, becomes dominant. Effective branching ratios of these channels to unlike sign di-leptons are around 0.025 and 0.04 respectively. Both these channels will produce missing energy due to the leptonic decays of the  $W$  bosons. Again

our missing  $E_T$  cut is effective in reducing these backgrounds compared to our signals. Finally, the direct  $H^\pm$  pair-production via  $q\bar{q}$  or  $gg$  fusion has a large cross-section. Gluon radiation from initial states in such cases may produce two forward jets. But demanding a high invariant mass of the forward jets and  $E_T^j > 15$  GeV, we can successfully kill this background also.

## 4 Concluding remarks

We have considered the production of charginos and neutralinos at the LHC via VBF in an R-parity violating scenario. We have seen that over a substantial part of the parameter space, a  $\lambda'$ -type interaction can cause the  $\chi_2^0$  or the  $\chi_1^\pm$  to decay predominantly into a lepton and two quarks, thereby suppressing the hadronically quiet trilepton mode and giving instead signals which can be faked by gluino and squark cascades. In these cases, charginos and neutralinos, produced in pairs through VBF, can give rise to large event rates, after filtration through cuts that should remove standard model backgrounds and residual effects of the strongly interacting sector of the SUSY spectrum. We have also noted that the signals suggested here can be clearly detectable after all cuts even for very small values of the R-parity violating couplings.

In the context of (R-parity conserving) MSSM, too, the VBF channel could be interesting. For example, VBF provides the unique channel for the production of a  $\chi_i^\pm \chi_j^\pm$  pair. This will lead to dileptons plus missing  $E_T$  in the central region. However, the like-sign chargino pair-production cross-section in this manner is rather low ( $\sim 5-7$  fb) and the corresponding signals are considerably smaller than those coming from the VBF production of like-sign W's. On the other hand, unlike-sign dilepton event rates from  $\chi_i^+ \chi_j^-$  production in the same manner fare much better compared to the corresponding rate from  $W^+W^-$  production. For example, with  $\mu = 400$  GeV,  $M_2 = 150$  GeV and  $\tan\beta = 5$ , and with the same cuts on the forward jets and central leptons as those described in the previous section, 191 *unlike-sign dileptons* +  $\cancel{E}_T$  events are predicted from a  $\chi_i^+ \chi_j^-$  pair produced via VBF for an integrated luminosity of  $100$  fb $^{-1}$ , as against 86 from a  $W$ -pair produced in the same fashion. Since forward jet tagging is going to be a part of LHC experiments anyway, this might be looked upon as an additional process that can be exploited to uncover hadronically quiet signals of the chargino-neutralino sector in MSSM.

Also, in cases with  $\lambda$ -type interactions, although the R-violating decays of  $\chi_2^0$  or  $\chi_1^\pm$  will still give hadronically quiet events, the VBF channels will lead to spectacular multilepton signals in the central region. Such central multilepton signals can also arise from the cascade process mentioned in the previous section when the second lightest neutralino or the lighter chargino decays leptonically into the lightest neutralino. Similarly, decays of  $\chi_2^0$  or  $\chi_1^\pm$  into real gauge bosons and leptons might be the sources of interesting signals of the bilinear R-parity violating term shown in equation (1). A detailed study of such signals (including those within the MSSM) will be presented in a subsequent paper [18].

Finally we want to point out that signals similar to those described here can also arise from the

production of the lightest neutral Higgs boson and its subsequent decay into a pair of neutralinos which might decay via the  $\lambda'$ -type couplings [19]. In such a case, however, the total invariant mass of the products lying in the region in between the two forward jets is equal to the Higgs mass, and should thus lie within about 130  $GeV$ . On the other hand, the signals from the chargino-neutralino pair have considerably higher invariant mass so long as the chargino and neutralino masses satisfy the LEP constraints. Thus the signals discussed here are in a way complementary to the ones that can be observed if the lightest neutral scalar has a substantial branching ratio for the  $\chi_1^0\chi_1^0$  channel.

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