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Signatures of Spontaneous Breaking of R-parity in Gluino Cascade Decays at LHC

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Abstract

We study the pattern of gluino cascade decays in a class of supersymmetric models where R-parity is spontaneously broken. We give a detailed discussion of the R-parity violating decays of the lightest neutralino, the second lightest neutralino and the lightest chargino. The multi-lepton and same-sign dilepton signal rates expected in these models are compared with those predicted in the Minimal Supersymmetric Standard Model. We show that these rates can be substantially enhanced in broken R-parity models.

1 Introduction

The search for supersymmetry (SUSY) will play an important rôle in the experimental program of LHC which will explore the mass range of supersymmetric particles up to TeV energies [1]. Due to the high production cross section of gluinos and squarks at hadron colliders, their signals are expected to be well above the Standard Model (SM) background.

Up to now most studies of gluino production and decays [1, 2] have been carried out within the framework of the *Minimal Supersymmetric Standard Model (MSSM)* [3]. In the MSSM R-parity is conserved implying that the lightest supersymmetric particle (LSP) is stable, giving rise to the missing energy ($\not{E}_T$) signal. There are already some studies where the effects of R-parity breaking have been explored [4]. However, most of them are in the context of models with explicit breaking of R-parity.

Although the MSSM is by far the most well studied realization of supersymmetry, there is considerable theoretical as well as phenomenological interest in studying the implications of alternative scenarios without R-parity conservation [5]. The violation of R-parity could arise explicitly [6] as a residual effect of some larger unified theory [7], or spontaneously, through nonzero vacuum expectation values (VEV's) for scalar neutrinos [8]. In the first case there is a large number of unknown parameters characterizing the superpotential of these models. For simplicity these effects are usually studied assuming that there is only one dominant term which breaks R-parity explicitly. In contrast, models with spontaneous R-parity breaking [9, 10, 11, 12] depend on much fewer parameters, which allow a more systematic study of R-parity breaking signals. Moreover, in these models the scale of R-parity violation is expected to lie in the TeV range [9]. This leads to effects that can be large enough to be experimentally observable, for a wide range of parameter choices consistent with observations, including astrophysics and cosmology [5, 11, 13].

There are two generic cases of spontaneous R-parity breaking models. If lepton number is part of the gauge symmetry there is a new gauge boson Z' which gets mass via the Higgs mechanism [12]. In this model the lightest SUSY particle (LSP) is in general a neutralino which decays mostly into visible states, therefore breaking R-parity. The main decay modes are decays such as

$$\tilde{\chi}_1^0 \to Z^{(*)}\nu \to f\bar{f}\nu, \tag{1}$$

where the Z-boson can be either virtual or real and f denotes a charged fermion. Its invisible decay modes are in the channels $\tilde{\chi}_1^0 \to 3\nu$. Alternatively, if spontaneous R-parity violation occurs in the absence of any additional gauge symmetry, it leads to the existence of a physical massless Nambu-Goldstone boson, called majoron (J). In this case *the lightest SUSY particle is the majoron* which is massless and therefore stable [1]. As a consequence the lightest neutralino $\tilde{\chi}_1^0$ may decay invisibly as

$$\tilde{\chi}_1^0 \to \nu + J. \tag{2}$$

This decay conserves R-parity since the majoron has a large R-odd singlet sneutrino component [9, 10].

We also consider a specific class of models with explicit R-parity breaking characterized by a single bilinear superpotential term of the type ℓH_u [15]. These models mimic in many respects the features of models with spontaneous breaking of R-parity containing an additional gauge boson. Since they do not contain the majoron, the lightest neutralino has only decays into Standard Model fermions. In the following the class of models containing a majoron will be denoted by the majoron-model, whereas the models without a majoron will be denoted generically by the ϵ-model [15].

Although in these broken R-parity models supersymmetric particles may be produced singly (see ref. [16]), it is most likely that gluinos at the LHC will be produced in pairs, and that R-parity violation will affect only the structure of their cascade decays. The most obvious modification of these cascade decays with respect to the one expected in the MSSM comes from the fact that the lightest neutralino now can decay.

In this paper we concentrate on cascade decays of the gluino assuming that it is lighter than the squarks. We pay special attention to the impact of R-parity violation in the the multi-lepton (ML) signals and the same-sign dilepton (SSD) signals.The gluino has the following R-parity conserving decays:

$$\tilde{g} \quad \to \quad q\bar{q}\tilde{\chi}_i^0 \ ; \ q\bar{q}'\tilde{\chi}_j^\pm \ ; \ g\tilde{\chi}_i^0 \tag{3}$$

where $\tilde{\chi}_i^0$ denotes the neutralinos and $\tilde{\chi}_j^\pm$ the charginos. In eq. (3) we also include the decays into top quarks, which give important contributions to the ML and SSD signals. If R-parity is violated spontaneously one has in principle also the decay modes $\tilde{g} \to q + \bar{q}' + l$, $q + \bar{q} + \nu_l$. We have neglected these decays in the following because their branching ratios are expected to be much smaller.

In order to characterize the complicated pattern of gluino cascade decays in broken R-parity models, we will first discuss the decays of the gluinos into charginos and neutralinos (Section 2). Then we will discuss the decay pattern of the lightest neutralino, the second lightest neutralino and the lightest chargino, paying particular

[1] The majoron may have a small mass due to explicit breaking effects at the Planck scale. In this case it may decay into neutrinos and photons. However, the time scales are only of cosmological interest and do not change the signal expected in laboratory experiments [14].

attention to R-parity violating decays (Section 4). We calculate the rates for the 3-, 4-, 5- and 6-lepton signals and the same-sign dilepton signal in the two classes of broken R-parity models described above and compare them with the corresponding rates predicted in the MSSM (Section 5).

2 Gluino decays into charginos and neutralinos

At $p\bar{p}$ and pp colliders gluinos are produced through gg and $q\bar{q}$ fusion [17]. Here we will assume that squarks are heavier than gluinos, so that pair production of gluinos dominates. As an example we will consider a gluino with a mass of 500 GeV. At the LHC with a centre of mass energy of 14 TeV the production cross section will be ~ 25 pb, which corresponds to 2.5 million gluino-pairs per year for an integrated luminosity of $10^5 pb^{-1}$.

As the multi-lepton signal is the result of a complicated decay chain, one has to calculate the branching ratio of each step in the gluino cascade decays. For the computation of the decays in eq. (3) we have used the formulae given in [18]. As these formulae have been developed in the framework of the MSSM, one has to make appropriate replacements as given in Appendix A in order to be consistent with the models described in the next section.

We will consider a low $\tan\beta$ scenario ($\tan\beta = 2$) and a high $\tan\beta$ scenario ($\tan\beta = 30$). These choices are theoretically motivated by renormalization group studies in some unified supergravity models [19]. Moreover we will vary μ between -1000 GeV and 1000 GeV. In Fig. 1 we show the gluino decay branching ratios. We have summed over all quark flavours and included the contribution coming from the decay into a gluon and a neutralino. As already mentioned, the R-parity violating decays of the gluino can be neglected. Because of kinematics (the masses of the heavier neutralinos $\tilde{\chi}^0_3$ and $\tilde{\chi}^0_4$ and the heavier chargino $\tilde{\chi}^-_2$ is of order μ if $|\mu| > M_2$) for $|\mu| > m_{\tilde{g}}/2$ we have only decays into the lightest chargino $\tilde{\chi}^-_1$ ($\sim 50\%$) and the two lightest neutralinos $\tilde{\chi}^0_1$ ($\sim 20\%$) and $\tilde{\chi}^0_2$ ($\sim 30\%$). For $|\mu| < m_{\tilde{g}}/2$ the decay into the heavier chargino becomes important ($\gtrsim 25\%$).

The charginos and neutralinos arising from gluino decays will subsequently decay as discussed above, leading to the various multi-lepton signals we will discuss in Section 5. Another important source of leptons are the top quarks produced in $\tilde{g} \to tb\tilde{\chi}^\pm_j$ with the top quark decaying into a W-boson. The branching ratio of this decay is at least 5%.

For the case $\tan\beta = 30$ there are some changes in the area $|\mu| < m_{\tilde{g}}/2$ compared to the case $\tan\beta = 2$. Because of larger bottom Yukawa couplings the decays $\tilde{g} \to b\bar{b}\tilde{\chi}_i^0$ are enhanced. However, for the multi-lepton signal these changes are only important for a parameter region which is already excluded by experimental data. For further details about gluino decays see ref. [18].

3 Lepton-Gaugino-Higgsino Mixing

The basic tools in our subsequent discussion are the chargino and neutralino mass matrices. The chargino mass matrix may be written as [9]

$$\begin{array}{c|ccc} & e_j^+ & \tilde{H}_u^+ & -i\tilde{W}^+ \\ \hline e_i & h_{eij}v_d & -h_{\nu ij}v_{Rj} & \sqrt{2}g_2v_{Li} \\ \tilde{H}_d^- & -h_{eij}v_{Li} & \mu & \sqrt{2}g_2v_d \\ -i\tilde{W}^- & 0 & \sqrt{2}g_2v_u & M_2 \end{array} \tag{4}$$

Its diagonalization requires two unitary matrices U and V

$$\chi_i^+ = V_{ij}\psi_j^+ \tag{5}$$

$$\chi_i^- = U_{ij}\psi_j^-, \tag{6}$$

where the indices i and j run from 1 to 5 and $\psi_j^+ = (e_1^+, e_2^+, e_3^+, \tilde{H}_u^+, -i\tilde{W}^+)$ and $\psi_j^- = (e_1^-, e_2^-, e_3^-, \tilde{H}_d^-, -i\tilde{W}^-)$.

The details of the neutralino mass matrix are rather model dependent. However, for our purposes it will be sufficient to use the following effective form given in [9]

$$\begin{array}{c|ccccc} & \nu_i & \tilde{H}_u & \tilde{H}_d & -i\tilde{W}_3 & -i\tilde{B} \\ \hline \nu_i & 0 & h_{\nu ij}v_{Rj} & 0 & g_2v_{Li} & -g_1v_{Li} \\ \tilde{H}_u & h_{\nu ij}v_{Rj} & 0 & -\mu & -g_2v_u & g_1v_u \\ \tilde{H}_d & 0 & -\mu & 0 & g_2v_d & -g_1v_d \\ -i\tilde{W}_3 & g_2v_{Li} & -g_2v_u & g_2v_d & M_2 & 0 \\ -i\tilde{B} & -g_1v_{Li} & g_1v_u & -g_1v_d & 0 & M_1 \end{array} \tag{7}$$

This matrix is diagonalised by a 7×7 unitary matrix N,

$$\chi_i^0 = N_{ij}\psi_j^0, \tag{8}$$

where $\psi_j^0 = (\nu_i, \tilde{H}_u, \tilde{H}_d, -i\tilde{W}_3, -i\tilde{B})$, with ν_i denoting the three weak-eigenstate neutrinos.

In the above equations v_R is the VEV of the right sneutrino mostly responsible for the spontaneous violation of R-parity [2]. The VEV's v_u and v_d are the usual ones

[2] There is also a small seed of R-parity breaking in the doublet sector, $v_L = \langle\tilde{\nu}_{L\tau}\rangle$, whose magnitude is related to the Yukawa coupling h_ν. Since this vanishes as $h_\nu \to 0$, we can naturally obey the limits from stellar energy loss [20]

responsible for the breaking of the electroweak symmetry and the generation of fermion masses, with the combination $v^2 = v_u^2 + v_d^2$ fixed by the W, Z masses. Moreover, $M_{1,2}$ denote the supersymmetry breaking gaugino mass parameters and $g_{1,2}$ are the $SU(2) \otimes U(1)$ gauge couplings divided by $\sqrt{2}$. In the following we assume the GUT relation $\frac{3}{5}M_1/M_2 = \tan^2\theta_W$. Note that the effective Higgsino mixing parameter μ may be given in some models as $\mu = h_0 \langle \Phi \rangle$, where $\langle \Phi \rangle$ is the VEV of an appropriate singlet scalar. In the ϵ-model the term $h_\nu v_R$ in eq. (4) and (7) is replaced by a mass parameter ϵ [15].

There are restrictions on these parameters that follow from searches for SUSY particles at LEP [21, 22] and at TEVATRON [25]. In addition, we take into account the constraints from neutrino physics and weak interactions phenomenology [16], which are more characteristic of R-parity breaking models. These are important, as they exclude many parameter choices that are otherwise allowed by the constraints from the collider data, while the converse is not true. Due to these constraints R-parity violation effects manifest themselves mainly in the third generation. We therefore assume $v_{L_1} = v_{L_2} = v_{R_1} = v_{R_2} = 0$.

Most of our subsequent analysis will be general enough to cover a wide class of $SU(2) \otimes U(1)$ models with spontaneously broken R-parity, such as those of ref. [9, 10], as well as models where the majoron is absent due to an enlarged gauge structure [12]. Many of the phenomenological features relevant for the LHC studies discussed here are already present in the ϵ-model which effectively mimics the spontaneous violation of R-parity through an explicit R-parity-breaking bilinear superpotential term ℓH_u [15].

In the following we will need the mass eigenstates of (4) and (7). In order to use the same notation as in the MSSM, l, ν_l denote the mass eigenstates for charged leptons and neutrinos, $\tilde{\chi}^0_i$ (i=1,..,4) the mass eigenstates for neutralinos and $\tilde{\chi}^\pm_j$ (j=1,2) the mass eigenstates for charginos.

4 Neutralino and Chargino Decays

In this section we shall discuss in detail the decays of charginos and neutralinos which occur in the cascade decays of the gluino. The neutralinos have the following R-parity conserving two-body decay modes:

$$\tilde{\chi}^0_i \quad \to \quad \tilde{\chi}^\pm_j W^\mp \; ; \; \tilde{\chi}^0_k Z. \qquad (9)$$

One has in principle also decays into Higgs bosons, squarks and sleptons which we neglect. Insofar as squarks and sleptons are concerned, we simply assume them to be too heavy to be important. A notable exception for the case of the *majoron model* considered in this paper is that of the majoron, which is a linear combination of the $SU(2)\otimes U(1)$ singlet sneutrinos and is massless (or very light) because it is a Goldstone boson. Indeed, in this case the decay $\tilde{\chi}_j^\pm \to \tau^\pm + J$ can have a sizeable branching ratio. We have taken into account the existence of such decays in the evaluation of the multi-lepton (ML) and same-sign dilepton (SSD) rates presented in this paper. We have, however, not studied the corresponding signals for the LHC, because they involve the detection of taus in the final state. For the case of LEP2 these signals have been already considered in the literature [23], although more work is needed [24].

Since R-parity is violated one has the additional decay modes:

$$\tilde{\chi}_i^0 \quad\to\quad l_j^\pm W^\mp \;;\; \nu_l Z \tag{10}$$

In case these two-body decays into gauge bosons are kinematically forbidden the neutralinos have the following three-body decay modes:

$$\tilde{\chi}_i^0 \quad\to\quad \tilde{\chi}_j^0 f\bar{f} \;;\; \tilde{\chi}_j^\pm f'\bar{f} \;;\; \nu_k f\bar{f} \;;\; l_k^\pm f'\bar{f} \tag{11}$$

where $f, f' = l_i, \nu_i, d_i, u_i$. The first two decays conserve R-parity whereas the other ones violate R-parity. In addition, in $SU(2)\otimes U(1)$ models with spontaneous R-parity violation one has also the decay into a majoron J

$$\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 J, \nu_k J. \tag{12}$$

It is important to notice that the decays into a standard neutrino conserve R-parity, since the majoron is mainly a right sneutrino, and thus R-odd.

Turning now to charginos, the lightest one has the following R-parity conserving two-body decay:

$$\tilde{\chi}_1^+ \to \tilde{\chi}_i^0 W^+ \tag{13}$$

Again we assume that decays into scalars are kinematically forbidden. In addition it has the following R-parity-violating decay modes:

$$\tilde{\chi}_1^+ \quad\to\quad \nu_j W^+ \;; l_j^+ Z \tag{14}$$

In models with majoron the chargino can decay according to [11]

$$\tilde{\chi}_1^+ \to l_j J \tag{15}$$

In case two-body decays into gauge bosons are kinematically forbidden, the chargino decays as:

$$\tilde{\chi}_1^+ \quad\to\quad \tilde{\chi}_j^0 f'\bar{f} \;;\; \nu_k f'\bar{f} \;;\; l_k^+ f\bar{f} \tag{16}$$

where the first decay conserves and the others break R-parity. The formulae for two- and three-body decay widths relevant for our study are given in Appendix B.

As already mentioned in the previous section R-parity violating effects manifest themselves mainly through the mixing of the third generation leptons with charginos and neutralinos. In order to show typical examples of neutralino and chargino decays we have fixed the following set of parameters: $M_2 = 170$ GeV, $m_A = 500$ GeV, $h_{\nu 33} = 0.01$, $v_R \equiv v_{R3} = 100$ GeV and $v_L \equiv v_{L3} = 10^{-5}$ GeV. In the ϵ-model this corresponds to $\epsilon = 1$ GeV. As we already mentioned, we have considered $\tan\beta$ in both low and high value scenarios, $\tan\beta = 2$ and $\tan\beta = 30$, as suggested by renormalization group studies [19]. The μ parameter has been varied between -1000 GeV and 1000 GeV.

In contrast to the MSSM, in models where R-parity is broken the lightest neutralino will decay. Let us first focus on the majoron-model. In Fig. 2 we show the branching ratios for the lightest neutralino for $\tan\beta = 2$. The decay into the majoron dominates for two reasons: first, the decay of the lightest neutralino into a neutrino and a majoron is R-parity conserving, while the decays into W and Z bosons are R-parity violating. Moreover, the decays into gauge-bosons are either phase space suppressed two-body decays or three-body decays. Note that the decays into a majoron and a neutrino and into three neutrinos are invisible decays thus leading to the same missing transverse momentum signature characteristic of a stable neutralino in the MSSM. The importance of the decays into the majoron increases for larger $\tan\beta$. We found that in the case of $\tan\beta = 30$ the decay into the majoron is practically 100 % in the parameter range which will not be covered by LEP2.

Let us now turn to the ϵ-model. In Fig. 3a (b) we present the branching ratios for the lightest neutralino for $\tan\beta = 2$ (30). We can see that for most μ values the W channel dominates over Z channel. The reason for this behaviour is the fact that for our parameter choices, very often the neutralino has charged-current two-body decays and neutral current three-body decays. Another important fact is that the Z-boson only couples to the Higgsino components of the neutralino which are rather small in our case.

In the MSSM, the second lightest neutralino will mainly decay into a Z-boson and the lightest neutralino due to kinematics. In Fig. 4 we show the branching ratios for the second lightest neutralino for $\tan\beta = 2$ in the majoron-model. Notice that, the νZ and τW decay modes are sizeable, even though they violate R-parity, since they are kinematically favoured with respect to the R-parity conserving MSSM decay mode $\tilde{\chi}^0_1 Z^*$ (the case where the second lightest neutralino is lighter than the W-boson will be completely covered by LEP2, for our choice of parameters). On the other hand the $\tilde{\chi}^0_2 \to J\nu_\tau$ channel, although R-parity conserving, is smaller since the underlying

Yukawa coupling is relatively small (10^{-2}). This is in sharp contrast to the situation in $\tilde{\chi}_1^0$ decay (Fig. 2) where the charged and neutral current induced decays are suppressed by phase space. Note also that here we do not show the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^- W$, because it is only important in a small range which will be covered by LEP2. For $\tan\beta = 30$ the R-parity breaking decays are negligible. For the case of the ϵ-model the R-parity violating decays into gauge-bosons are again significant if $\tan\beta$ is small, as can be seen in Fig. 5 (again we do not show the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^- W$). For $\tan\beta = 30$ they become negligible.

In the MSSM the lightest chargino decays mainly into the lightest neutralino and a W-boson, since the decays into the second lightest neutralino are suppressed by phase space. In Fig. 6a (b) we show the branching ratios in the majoron-model of the lightest chargino as a function of μ for $M_2 = 170$ GeV and $\tan\beta = 2(30)$. In contrast, for the case of the ϵ-model all decays of the lightest chargino are induced by W and Z boson exchange. For the ranges of M_2 and μ considered in this paper, all of these decays are two-body. As a result the R-parity violating decay branching ratios are all negligible.

Although our discussion has been quite general, we have neglected, as already mentioned, chargino and neutralino decays mediated by scalar particles, including Higgs bosons. In this approximation, neutralinos and charginos produced by gluino decays have only decays mediated by W or Z bosons, except for the two-body majoron decays, characteristic of the spontaneous R-parity breaking models with the minimum $SU(2) \otimes U(1)$ gauge symmetry.

5 Multi-lepton and same-sign dilepton rates

In the following we calculate the multi-lepton (ML) and same-sign dilepton (SSD) rates in gluino pair production for the MSSM, the majoron-model and the ϵ-model. We have counted all leptons coming from charginos, neutralinos, t-quarks, W- and Z-bosons, summing over electrons and muons. We again take $m_{\tilde{g}} = 500$ GeV, and all other parameters as in Section 4.

Quite generally, the various ML rates in the R-parity violating models can be different from those in the MSSM for two reasons: (i) The lightest neutralino $\tilde{\chi}_1^0$ can decay leptonicaly as $\tilde{\chi}_1^0 \to Z^{(*)}\nu_\tau \to l^+l^-\nu_\tau$, $\tilde{\chi}_1^0 \to W^{(*)}\tau \to l^+\nu_l\tau$, leading to an enhancement of the multi-lepton rates. (ii) The R-parity violating decays of the lightest chargino $\tilde{\chi}_1^\mp$ and the second lightest neutralino $\tilde{\chi}_2^0$ may reduce the leptonic signal, $\tilde{\chi}_2^0 \to W^{(*)}\tau$, $J\nu_\tau$, $\tilde{\chi}_1^- \to J\tau$. Depending on which of these two effects is dominant, one has an overall enhancement or a reduction of the leptonic rates compared to those expected in the MSSM. A summary of the effects of the most important R-parity breaking decay modes is given in Table 1.

In Fig. 7 we show the branching ratios for the 3-, 4-, 5- and 6-lepton events for $\tan\beta = 2$. In comparison with the MSSM, the majoron-model exhibits the feature that the overall rates for the ML signals are enhanced for $\mu < 0$ and suppressed for $\mu > 0$. This is due to the fact that the R-parity violating decays of the lightest neutralino into gauge bosons have a larger branching ratio for $\mu < 0$ than for $\mu > 0$, and that the R-parity violating decays of the second lightest neutralino are larger for $\mu > 0$ than for $\mu < 0$. Note that for $\mu < 0$ the 5-lepton signal is much larger in the majoron-model than in the MSSM, giving about 30 to 1200 events per year for a luminosity of $10^5 pb^{-1}$. The 6-lepton signal has a rate up to 5×10^{-5} in the range -300 GeV$< \mu < -80$ GeV giving 125 events per year.

For the case of the ϵ-model the ML rates are enhanced compared to the MSSM and the majoron-model for all μ. The reason is that the lightest neutralino always decays into a gauge boson (either real or virtual) which further decays into leptons. This over-compensates the reduction of leptons coming from the second lightest neutralino. In this model the 3- and 4-lepton signals are enhanced by an order of magnitude compared to the MSSM. The branching ratio for the 5-lepton signal is larger than 2×10^{-4} and the branching ratio for the 6-lepton signal goes up to 5×10^{-4}.

In Fig. 8 we show the ML signal rates for $\tan\beta = 30$. As one can see, for the 6-lepton signal they are larger than for $\tan\beta = 2$. For $|\mu| > 200$ GeV the majoron-model and the MSSM give similar results because the lightest neutralino decays mainly invisibly and the R-parity violating decays of the second lightest neutralino are somewhat smaller than the conventional ones. In the ϵ-model again all ML signals are enhanced compared to the MSSM. For example the 5-lepton rate is larger than 3×10^{-4}.

In Fig. 9 we show the SSD signal for $\tan\beta = 2$ and 30. In the case of $\tan\beta = 2$ the signal is enhanced in the majoron-model for $\mu \lesssim -100$ GeV or $\mu \gtrsim 200$ GeV. This is due to the fact that now at least one of the neutralinos has a sizeable branching ratio into a W, leading to the enhancement of the signal (see Table 1). In the ϵ-model the signal is larger by an order of magnitude except for $|\mu| \lesssim 200$ GeV. In the case of $\tan\beta = 30$ again the majoron-model and the MSSM give similar results whereas in the ϵ-model the signal is one order of magnitude larger than in the MSSM.

6 Conclusions

We have studied the effects of R-parity violation in gluino cascade decays for two different classes of models, the majoron-model and the ϵ-model. We have calculated the rates for the ML and SSD signals. These processes are interesting from the experimental point of view since for example, the 4-, 5-, 6-lepton signal are practically free of background from Standard Model processes.

In order to understand the complex decay pattern a detailed analysis of the decays of neutralinos and charginos has been performed. In particular, it has been shown that not only the R-parity violating decays of the lightest neutralino, but also those of the second lightest neutralino and the lightest chargino are important. Comparing the majoron-model with the MSSM, the ML and SSD signals can increase or decrease depending on the model parameters. Especially for small $\tan\beta$ and negative μ the MSSM and the majoron-model give different results. In the ϵ-model all signals are enhanced by one order of magnitude for most of the parameter ranges considered.

The results found in this paper should encourage one to perform detailed Monte Carlo simulations in order to take into account all the detector features relevant in an experiment.

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decay mode	ML signal	SSD signal
$\tilde{\chi}_1^0 \rightarrow Z^{(*)}\nu_\tau$	+	0
$\tilde{\chi}_1^0 \rightarrow W^{(*)}\tau$	+	+
$\tilde{\chi}_1^0 \rightarrow J\nu_\tau$	0	0
$\tilde{\chi}_i^0 \rightarrow Z^{(*)}\nu_\tau$	0	0
$\tilde{\chi}_i^0 \rightarrow W^{(*)}\tau$	-	+
$\tilde{\chi}_i^0 \rightarrow J\nu_\tau$	-	-
$\tilde{\chi}_1^- \rightarrow W^{(*)}\nu_\tau$	0	0
$\tilde{\chi}_1^- \rightarrow J\tau$	-	-

Table 1: Influence of the most important R-parity violating decays on the multi-lepton and same-sign dilepton signals. As reference model we take the MSSM. For neutralino decays one has to distinguish between the lightest neutralino and the heavier ones. We therefore list first the decays of the lightest one and afterwards the decays of the heavy ones (i=2,3,4). Here + (−) denotes an enhancement (suppression) of the signal with respect to that expected in the MSSM, whereas 0 denotes that there is no difference compared to the MSSM.

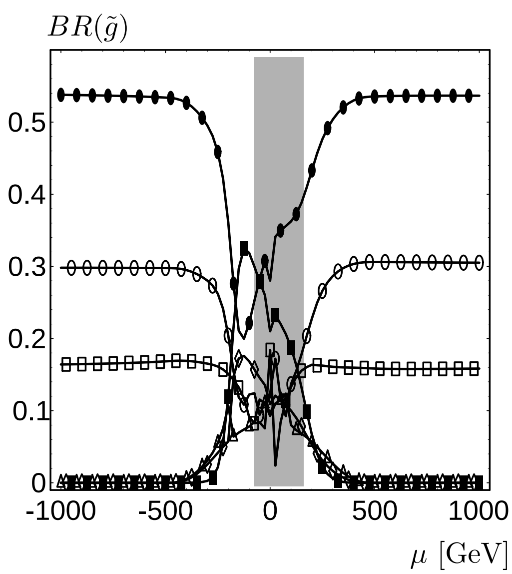

Fig. 1: The branching ratios for $\tilde{g} \rightarrow \tilde{\chi}_i^0 + q + \bar{q}, \tilde{\chi}_i^0 + g$ and $\tilde{g} \rightarrow \tilde{\chi}_j^{\pm} + q + \bar{q}'$ (summed over all quark flavours) as a function of μ. We have taken $m_{\tilde{g}} = 500$ GeV, $m_{\tilde{q}_i} = 2\, m_{\tilde{g}}$, $\tan\beta = 2$, $m_t = 175$ GeV and $m_b = 5$ GeV. The curves correspond to the following transitions: $\square$ into $\tilde{\chi}_1^0$,$\circ$ into $\tilde{\chi}_2^0$, $\triangle$ into $\tilde{\chi}_3^0$, $\diamondsuit$ into $\tilde{\chi}_4^0$, $\bullet$ into $\tilde{\chi}_1^{\mp}$ and $\blacksquare$ into $\tilde{\chi}_2^{\mp}$. The shaded area will be covered by LEP2.

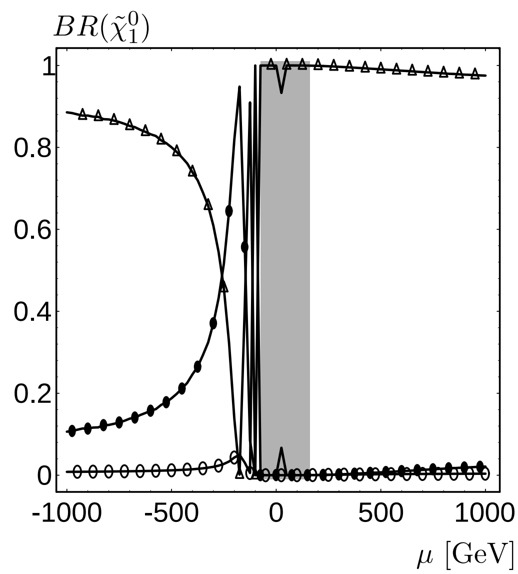

Fig. 2: Branching ratios of the lightest neutralino in the majoron-model. We have taken $M_2 = 170$ GeV, $h_{\nu 33} = 0.01$, $v_R = 100$ GeV, $v_L = 10^{-5}$ GeV and $\tan\beta = 2$. The curves correspond to the following transitions: $\circ$ into $\nu_\tau Z$, $\triangle$ into $\nu_\tau J$ and $\bullet$ into τW. The shaded area will be covered by LEP2.

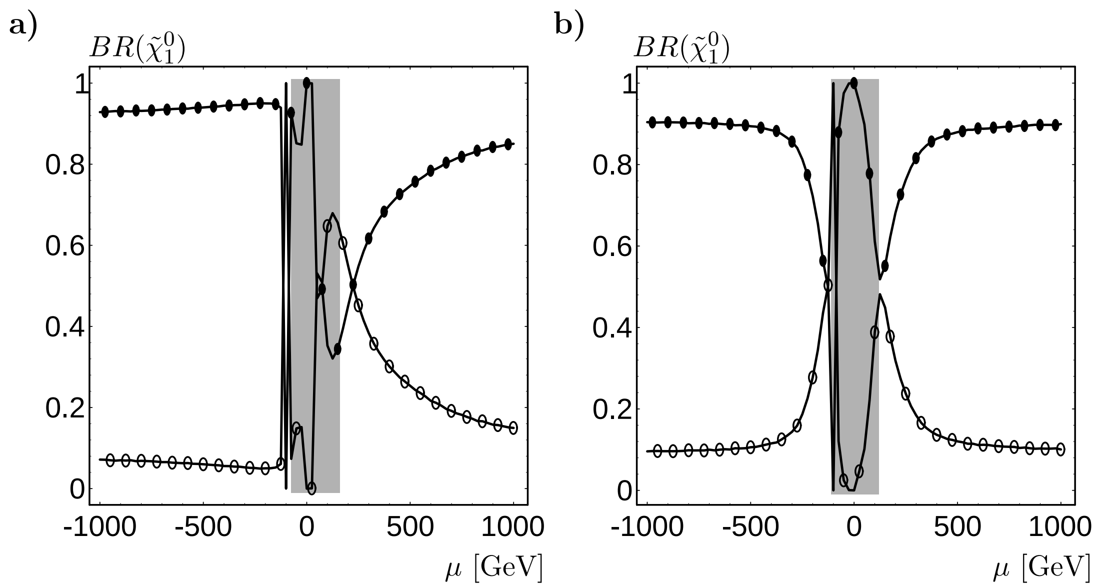

Fig. 3: Branching ratios of the lightest neutralino in the ϵ-model. We have taken $M_2 = 170$ GeV, $\epsilon = 1$ GeV, a) $\tan\beta = 2$ and b) $\tan\beta = 30$. The curves correspond to the following transitions: $\circ$ into $\nu_\tau Z$ and $\bullet$ into τW. The shaded area will be covered by LEP2.

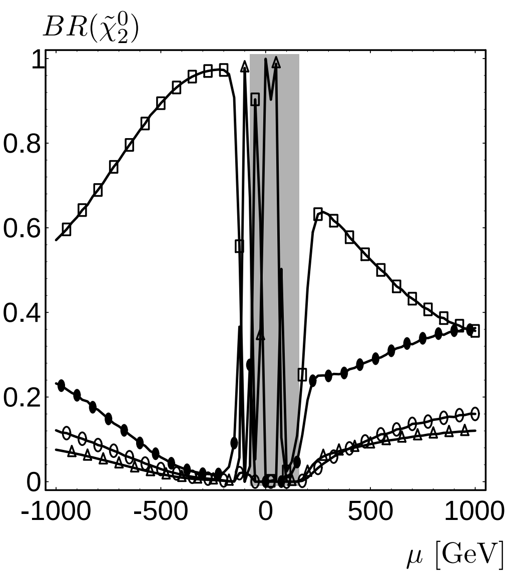

Fig. 4: Branching ratios of the second lightest neutralino in the majoron-model. We have taken $M_2 = 170$ GeV, $h_{\nu 33} = 0.01$, $v_R = 100$ GeV, $v_L = 10^{-5}$ GeV and $\tan\beta = 2$. The curves correspond to the following transitions: $\square$ into $\tilde{\chi}^0_1 Z^{(*)}$, $\circ$ into $\nu_\tau Z$, $\triangle$ into $\nu_\tau J$ and $\bullet$ into τW. The shaded area will be covered by LEP2.

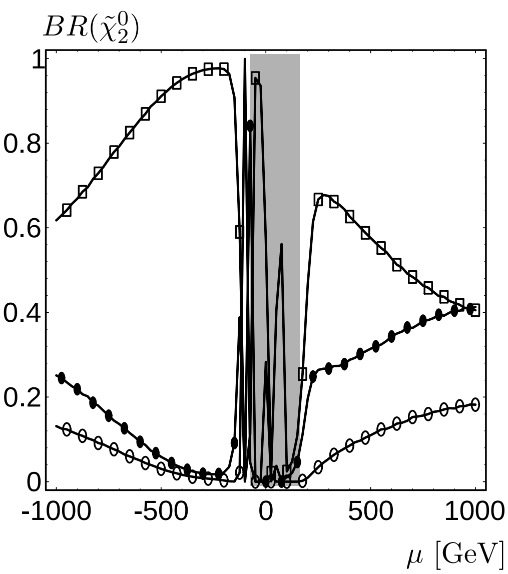

Fig. 5: Branching ratios of the second lightest neutralino in the ϵ-model. We have taken $M_2 = 170$ GeV, $\epsilon = 1$ GeV and $\tan\beta = 2$. The curves correspond to the following transitions: $\square$ into $\tilde{\chi}^0_1 Z^{(*)}$, $\circ$ into $\nu_\tau Z$, and $\bullet$ into τW. The shaded area will be covered by LEP2.

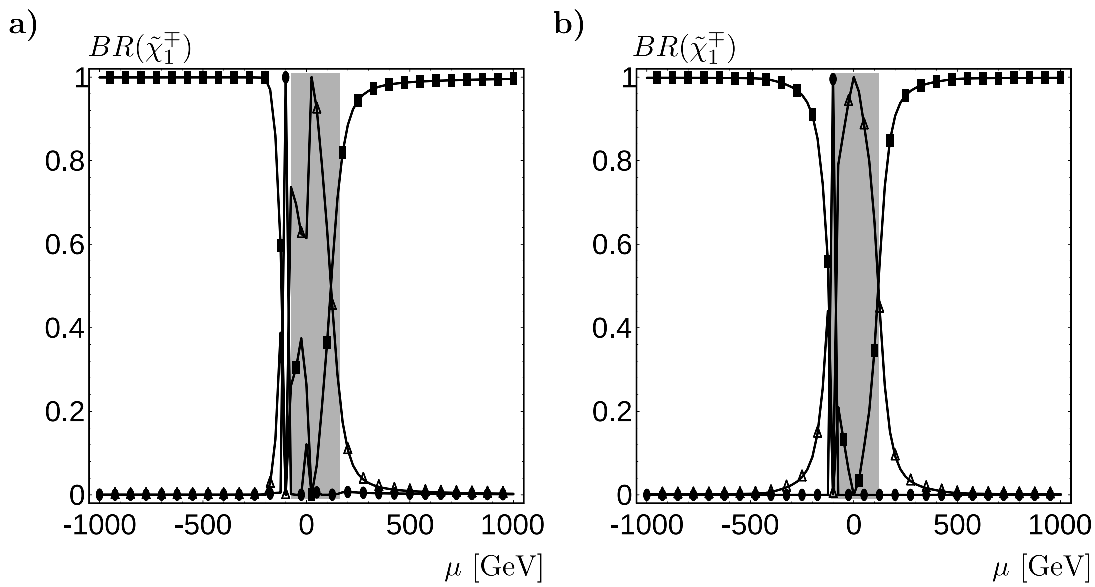

Fig. 6: Branching ratios of the lightest chargino in the majoron-model. We have taken $M_2 = 170$ GeV, $h_{\nu 33} = 0.01$, $v_R = 100$ GeV, $v_L = 10^{-5}$ GeV, a) $\tan\beta = 2$ and b) $\tan\beta = 30$. The curves correspond to the following transitions: ■ into $\tilde{\chi}_1^0 W^{(*)}$, $\triangle$ into τJ and • into $\nu_\tau W$. The shaded area will be covered by LEP2.

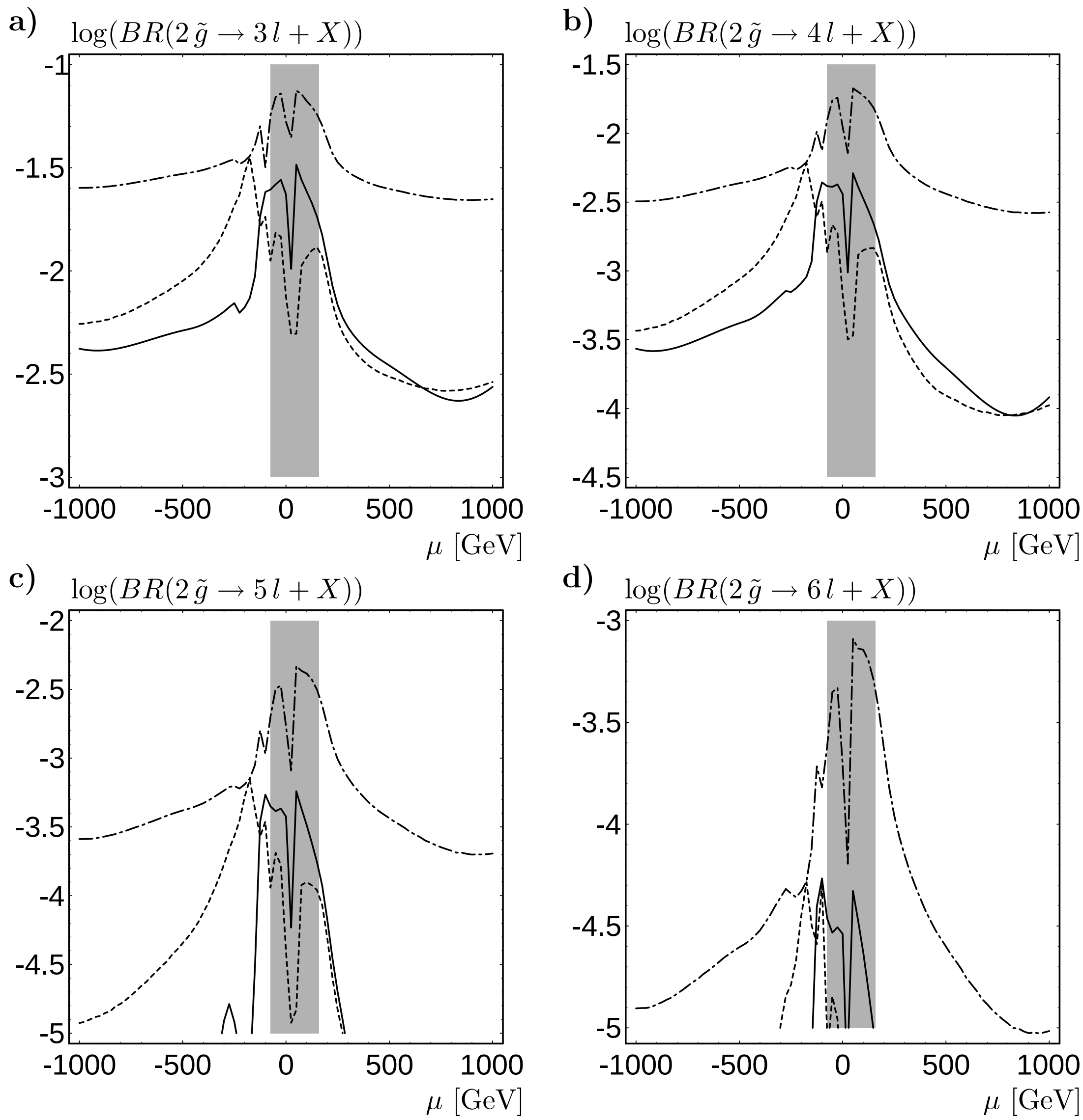

Fig. 7: Multi-lepton signals (summed over electrons and muons) for $\tan\beta = 2$, with other parameters chosen as described before. We show a) the 3-lepton, b) the 4-lepton, c) the 5-lepton and d) the 6-lepton signal for the MSSM (full line), the majoron-model (dashed line) and the ϵ-model (dashed-dotted line). The shaded area will be covered by LEP2.

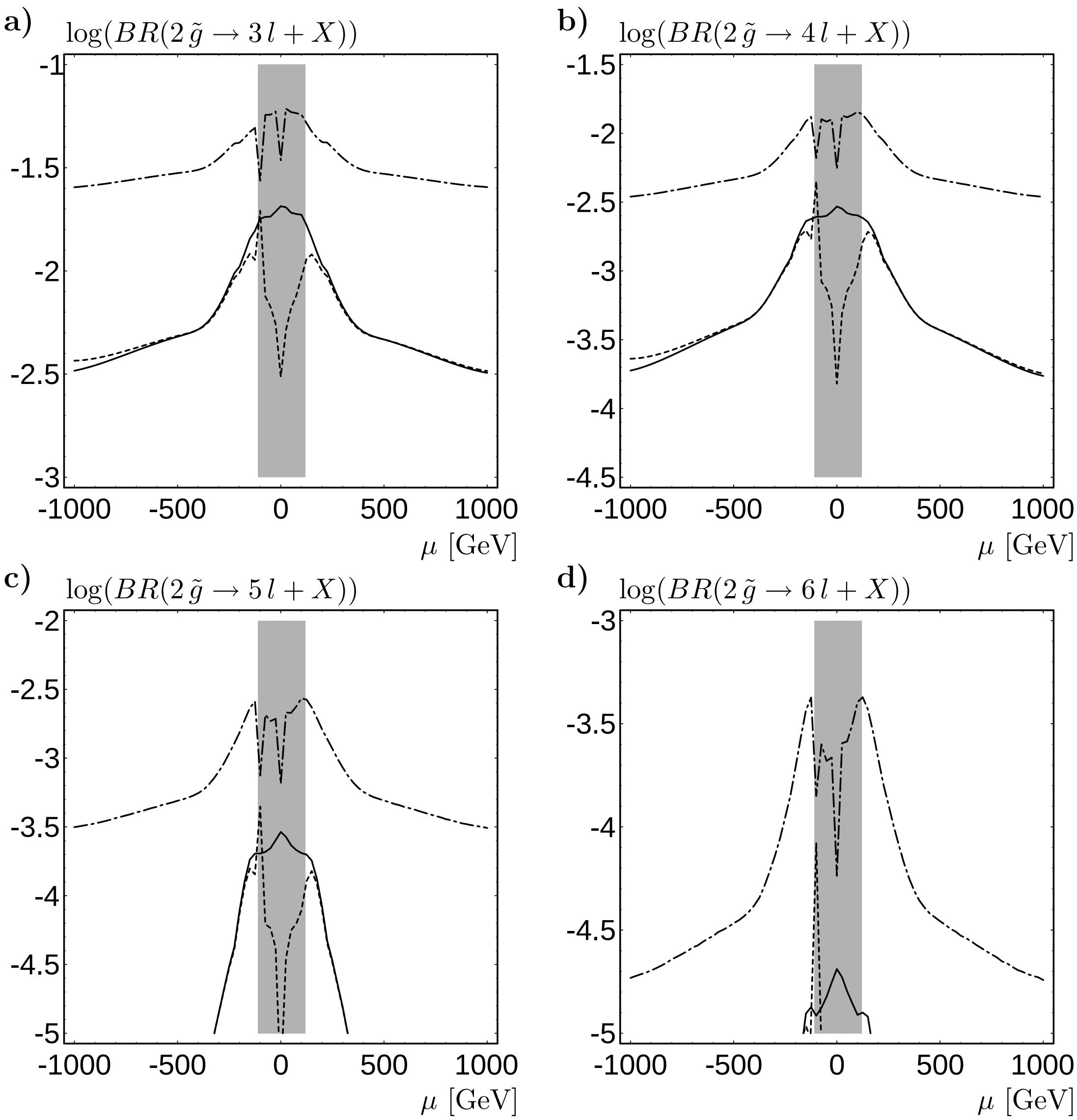

Fig. 8: Multi-lepton signals (summed over electrons and muons) for $\tan\beta = 30$ with other parameters chosen as described before. We show a) the 3-lepton, b) the 4-lepton, c) the 5-lepton and d) the 6-lepton signal for the MSSM (full line), the majoron-model (dashed line) and the ϵ-model (dashed dotted line). The shaded area will be covered by LEP2.

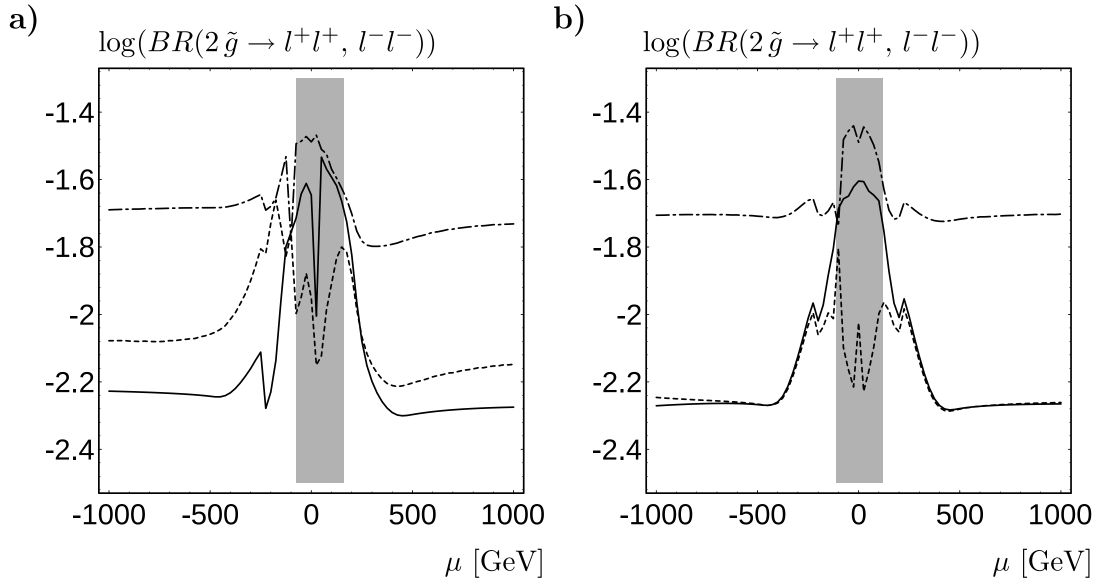

Fig. 9: The same-sign dilepton signal (summed over electrons and muons) for a) $\tan\beta = 2$ and b) $\tan\beta = 30$ with other parameters chosen as described before. We show situation for the MSSM (full line), the majoron-model (dashed line) and the ϵ-model (dashed dotted line). The shaded area will be covered by LEP2.

A Squark Couplings

To get the couplings of the squarks to neutralinos (charginos) and quarks of [18] in the notation used in this paper one has to do the following replacements: $U_{j1} \to U_{j+3,5}$, $U_{j2} \to U_{j+3,4}$, $V_{j1} \to V_{j+3,5}$, $V_{j2} \to V_{j+3,4}$, $N_{j1} \to N_{j+3,7}\cos\theta_W + N_{j+3,6}\sin\theta_W$, $N_{j2} \to -N_{j+3,7}\sin\theta_W + N_{j+3,6}\cos\theta_W$, $N_{j3} \to N_{j+3,5}\cos\beta - N_{j+3,4}\sin\beta$ and $N_{j4} \to N_{j+3,5}\sin\beta + N_{j+3,4}\cos\beta$.

B Neutralino and Chargino Widths

Here we collect all the expressions for neutralino and chargino widths. The decay widths of the two body decays into gauge bosons have the generic form

$$\Gamma(\tilde{\chi}_i \to \tilde{\chi}_j + V) = \frac{g^2 \sqrt{\lambda(m_i^2, m_j^2, m_V^2)}}{16\pi \cos^2\theta_W \, m_i^3} \Big[(d_L^2 + d_R^2) f_V(m_i^2, m_j^2, m_V^2) \tag{17}$$

$$-6 d_L d_R \epsilon_i \epsilon_j m_i m_j \Big] \tag{18}$$

with

$$\lambda(x, y, z) = (x - y - z)^2 - 4yz \tag{19}$$

and

$$f_V(x, y, z) = \frac{(x-y)^2 - 2z^2 + xz + yz}{2z}. \tag{20}$$

The corresponding couplings d_L, d_R are given in the table.

For neutralinos, the first three R-parity conserving widths that appear in (11) are given by [16]

$$\Gamma_{\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f \bar{f}} = 8(v_f^2 + a_f^2) \Gamma^{3b}(M_{\tilde{\chi}_i^0}, \tilde{\chi}_j^0, M_Z, O''_{L4j}, O''_{R4j}) \tag{21}$$

and the last three R-parity breaking neutralino widths, which are given in [22], have the generic form

$$\Gamma_{\tilde{\chi}_i^0 \to \nu_j f \bar{f}} = \Gamma^{3b\prime}(M_i, O''_L, O''_R, O'_R, O'_L, K_L, K_R) \tag{22}$$

For the Majoron model the width of eq. (12) is given by

$$\Gamma_{\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 J} = \frac{1}{16\pi} m_i \left(1 - \frac{m_j^2}{m_i^2}\right) O_L^2 \left(1 + \frac{m_j^2}{m_i^2} - 2\epsilon_i \epsilon_j \frac{m_j}{m_i}\right) \tag{23}$$

For the lightest chargino, we have the following expressions for the three body decays given in eq. (16):

$$\Gamma_{\tilde{\chi}_1^+ \to \tilde{\chi}_j^0 u \bar{d}} = \Gamma^{3b}(M_{\tilde{\chi}^+}, M_{\tilde{\chi}_j^0}, M_W, K_{L44}, K_{R44}) \tag{24}$$

$$\Gamma_{\tilde{\chi}_1^+ \to \tilde{\chi}_j^0 \nu_k l_k^+} = \Gamma^{3b\prime\prime}(M_{\tilde{\chi}_1^+}, M_{\tilde{\chi}_j^0}, M_W, K_{L4j}, K_{R4j}) \tag{25}$$

conserving R-parity and

$$\Gamma_{\tilde{\chi}_1^+ \to l_j^+ f \bar{f}} = 8(v_f^2 + a_f^2) \Gamma^{3b}(M_{\tilde{\chi}^+}, 0, M_Z, O'_{L4j}, O'_{R4j}) \tag{26}$$

$$\Gamma_{\tilde{\chi}_1^+ \to \bar{\nu}_j u \bar{d}} = \Gamma^{3b}(M_{\tilde{\chi}^+}, 0, M_W, K_{L4j}, K_{R4j}) \tag{27}$$

$$\Gamma_{\tilde{\chi}_1^+ \to \bar{\nu}_j \nu_k l_k^+} = \Gamma^{3b\prime}(M_{\tilde{\chi}^+}, K_{L4j}, K_{R4j}, O'_{L4j}, O'_{R4j}) \tag{28}$$

for the R-parity-breaking decays. The expressions of Γ^{3b} and $\Gamma^{3b\prime}$ are presented in [16]. $\Gamma^{3b\prime\prime}$ is given by

$$\begin{aligned}\Gamma^{3b\prime\prime}(m_i, m_j, m_b, d_L, d_R) &= \frac{e^4\ m_i}{256\ \pi^3\ \sin^4\theta_W\ \beta^4}\ (d_L^2 + d_R^2)\ f_1(\beta^2 - \delta^2) \\ &+ 2\ d_L\ d_R\ \beta\ \delta\ f_2(\beta^2 - \delta^2)\end{aligned} \tag{29}$$

with

$$f_1(x) = -\frac{x^3}{6} - \frac{x^2}{2} + x + (1-x)\ln(1-x) \tag{30}$$

$$f_2(x) = 2x + (2-x)\ln(1-x) \tag{31}$$

and $\beta = \frac{m_i}{m_b}$; $\delta = \frac{m_j}{m_b}$. The couplings O'', O' and K are the same as in the table.

In the majoron model, the width for eq. (15) is given by

$$\Gamma_{\tilde{\chi}_1^+ \to l_j^+ J} = \frac{1}{32} m_{\tilde{\chi}_1^+} (C_{Lj4}^2 + C_{Rj4}^2) \tag{32}$$

with

$$C_{Lj4} = \frac{v_R}{\sqrt{2}V} \sum_{k=1}^{3} h_{\nu k3} \eta_4 U_{4k} V_{j4}, \quad C_{Rj4} = \frac{v_R}{\sqrt{2}V} \sum_{k=1}^{3} h_{\nu k3} \eta_j U_{jk} V_{44} \quad . \tag{33}$$

$\tilde{\chi}^0_i \to \tilde{\chi}^0_j + Z^0$	d_L	$\frac{1}{\cos\theta_W} O''_{Lij} = \frac{1}{2\,\cos\theta_W}\left[N_{i4}N_{j4} - N_{i5}N_{j5} - \sum_{m=1}^{3} N_{im}N_{jm}\right]$
	d_R	$\frac{1}{\cos\theta_W} O''_{Rij} = -\frac{1}{\cos\theta_W} O''_{Lij}$
$\tilde{\chi}^0_i \to \tilde{\chi}^+_j + W^-$	d_L	$K_{Lji} = \eta_j \left[-\sqrt{2}U_{j5}N_{i6} - U_{j4}N_{i5} - \sum_{m=1}^{3} U_{jm}N_{im}\right]$
	d_R	$K_{Rji} = \epsilon_i \left[-\sqrt{2}V_{j5}N_{i6} + V_{j4}N_{i4}\right]$
$\tilde{\chi}^+_i \to \tilde{\chi}^0_j + W^+$	d_L	K_{Lij}
	d_R	K_{Rij}
$\tilde{\chi}^+_i \to \tilde{\chi}^+_j + Z^0$	d_L	$O'_{Lij} = \frac{1}{2}U_{i4}U_{j4} + U_{i5}U_{j5} + \frac{1}{2}\sum_{m=1}^{3} U_{im}U_{jm} - \delta_{ij}\sin^2\theta_W$
	d_R	$O'_{Rij} = \frac{1}{2}V_{i4}V_{j4} + V_{i5}V_{j5} - \delta_{ij}\sin^2\theta_W$

Table 2: Couplings for neutralino and chargino Charged and Neutral Current decays.

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