Testing neutrino masses in the R–parity violating minimal supersymmetric standard model with LHC results

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Within the R–parity violating minimal supersymmetric standard model (MSSM), we use a hierarchical ansatz for the lepton–number violating trilinear Yukawa couplings by relating them to the corresponding Higgs–Yukawa couplings. This ansatz reduces the number of free parameters in the lepton–number violating sector from 36 to 6. Baryon–number violating terms are forbidden by imposing the discrete gauge symmetry Baryon Triality. We fit the lepton–number violating parameters to the most recent neutrino oscillation data, including the mixing angle $\theta_{13}$ found by Daya Bay. We find that we obtain phenomenologically viable neutrino masses and mixings only in the case of normal ordered neutrino masses and that the lepton–number violating sector is unambiguously determined by neutrino oscillation data. We discuss the resulting collider signals for the case of a neutralino as well as a scalar tau lightest supersymmetric particle. We use the ATLAS searches for multi–jet events and large transverse missing momentum in the 0, 1 and 2 lepton channel with 7 TeV center–of–mass energy in order to derive exclusion limits on the parameter space of this R–parity violating supersymmetric model.

I. INTRODUCTION

A main objective of both multi–purpose experiments ATLAS and CMS at the Large Hadron Collider (LHC) is the search for new physics beyond the Standard Model (SM). Many of these extensions, in particular supersymmetry (SUSY) \[1,2\], include new heavy colored states and a weakly interacting lightest new particle escaping detection. Thus the most generic signal among these models are several hard jets and large transverse missing momentum ($p_{T}$). ATLAS and CMS grouped their multi–jet and missing transverse momentum searches into 0, 1, 2 lepton studies \[3,14\] in order to be sensitive to different SUSY models and to avoid an overlap between these studies. Most studies were recently updated to the full dataset of about 5 fb$^{-1}$ recorded in 2011 at a center–of–mass energy of 7 TeV. So far, no excess above SM expectations has been observed and strict bounds on any supersymmetric model or another relevant new physics model providing a similar collider signal can be derived. ATLAS and CMS mainly concentrate on SUSY searches which are based on R–parity conserving ($R_{p}$) supersymmetric extensions of the SM \[13\]. An equally well motivated scenario is a R–parity violating ($R_{p}$) supersymmetric SM \[15\], where the discrete symmetry baryon triality ($B_{3}$) \[17\] is imposed in order to avoid baryon–number violation and proton decay. The particle spectrum is the same as for $R_{p}$ models. However, lepton (L–) number is violated and the lightest supersymmetric particle (LSP) is not stable any more.
signatures or displaced vertices \[^{30, 31}\]. However, most of these studies constrain models where the L-violating couplings are either very large (for single slepton production), very small (for displaced vertices) or where we have single coupling dominance and four body decays (4 lepton signature) \[^{27}\]. Neither of these criteria is the case in most regions of the hierarchical B\(_3\) MSSM parameter space. Apart from these studies, the results of the ATLAS 1 lepton, multi-jet and \(p_T\) study with 1 fb\(^{-1}\) of data were used to restrict a bi-linear R–parity violating model \[^{38}\], which takes into account constraints from neutrino data \[^{22}\].

In this study, we would like to re–interpret the ATLAS studies with jets, \(p_T\) and 0, 1 or 2 isolated leptons \[^{3, 12}\] in the light of the hierarchical B\(_3\) MSSM. The trilinear \(R\)–parity violating model \[^{38}\], which imposes simplifying assumptions on the scalar and gaugino masses and couplings at the unified (GUT) scale. It turns out that only specific regions of the cMSSM parameter space are phenomenologically viable when taking into account neutrino data \[^{20}\], and we focus on these parameter regions. As a result, there are 4 free parameters in the SUSY breaking sector besides the six L–violating parameters.

In Sect. \[^{II}\], we shortly discuss how neutrino masses are generated in the hierarchical B\(_3\) MSSM. We then describe how we fit the L–violating parameters in order to obtain the correct masses and mixing angles of the neutrino sector at any parameter point in the hierarchical B\(_3\) cMSSM parameter space. In Sect. \[^{III}\] we examine the arising collider signatures for the case of stau LSP and neutralino LSP scenarios. In Sect. \[^{IV}\] we present bounds on the hierarchical B\(_3\) cMSSM neutrino model derived from SUSY ATLAS searches. We conclude in Sect. \[^{V}\].

II. HIERARCHICAL BARYON TRIALITY

CMSSM AND MASSIVE NEUTRINOS

A. Hierarchical Baryon Triality (B\(_3\)) cMSSM

The B\(_3\) MSSM allows for additional, L–violating terms in the superpotential compared to the \(R\)\(_p\) MSSM \[^{41, 43}\],

\[
W_{B_3} = W_{R_p} + \epsilon_{ab} \left[ \frac{1}{2} \lambda_{ijk} L_i^a L_j^b E_k^c + \lambda'_{ijk} L_i^a Q_j^b D_k^c - \kappa_{ijk} L_i^a H_u^b \right].
\]

(1)

Where \(L_i, Q_i, E_i, D_i\) correspond to the SU(2) doublet lepton and quark superfields. \(E_i, D_i\) are the SU(2) singlet lepton and down-type quark superfields, respectively. \(i, j, k \in \{1, 2, 3\}\) are generation indices, \(a, b \in \{1, 2\}\) \((\epsilon_{12} = 1)\) are indices of the SU(2)\(_f\) fundamental representation, while the corresponding SU(3)\(_c\) indices are suppressed. The trilinear couplings \(\lambda_{ijk}\) correspond to nine independent parameters due to the antisymmetry of the first two indices \(i, j\), whereas the trilinear couplings \(\lambda'_{ijk}\) denote 27 independent parameters. The bilinear couplings \(\kappa_{ijk}\) are 3 dimensionful couplings.

For universal supersymmetry breaking, the bilinear L–violating couplings and the corresponding soft–breaking terms can be simultaneously rotated to zero at the unification (GUT) scale via a basis transformation of the lepton and Higgs superfields \[^{39, 40}\]. However, non–vanishing \(\kappa\) terms (and non–aligned soft–breaking terms) are generated at the electroweak scale via the renormalization group equations \[^{44}\].

In the B\(_3\) constrained MSSM (cMSSM), the number of free parameters in the soft–breaking sector is constrained. We end up with 5 + \(n\) independent parameters at the GUT scale \[^{39}\].

\[
M_0, M_{1/2}, A_0, \text{sgn}(\mu), \tan \beta, \Lambda. \quad (2)
\]

\(M_0, M_{1/2}\) and \(A_0\) denote the universal scalar mass, universal gaugino mass and universal trilinear scalar coupling, respectively. \(\text{sgn}(\mu)\) is the sign of the superpotential Higgs mixing parameter and \(\tan \beta\) is the ratio between the two Higgs vacuum expectation values. \(\Lambda\) denotes a subset of \(n\) independent dimensionless trilinear L–violating couplings.

In this work, we further restrict the number of free L–violating parameters: In the B\(_3\) cMSSM, the down–type Higgs superfield and the SU(2) doublet lepton superfield have the same gauge quantum numbers \[^{41}\]. They are indistinguishable because lepton number is broken. Thus, the L–violating trilinear terms in Eq. \[^{4}\] resemble terms in the R–parity conserving superpotential,

\[
W_{R_p} > \epsilon_{ab} \left[ (Y_E)_{jk} H_u^a L_j^b E_k + (Y_D)_{jk} H_u^a Q_j^b D_k \right], \quad (3)
\]

where \((Y_E)_{jk}\) and \((Y_D)_{jk}\) are the Higgs–Yukawa couplings of the lepton and the down–type quarks, respectively. We therefore proposed the following ansatz at the GUT scale \[^{22}\], which can be motivated in the framework of Froggatt-Nielsen models \[^{10}\].

\[
\lambda_{ijk} \equiv \ell_i \cdot (Y_E)_{jk} - \ell_j \cdot (Y_E)_{ik}, \quad \lambda'_{ijk} \equiv \ell'_i \cdot (Y_D)_{jk}. \quad (4)
\]

Here, \(\ell_i, \ell'_i\) are c-numbers. Eq. \[^{4}\] has the required form to maintain the anti-symmetry of the \(\lambda_{ijk}\) in the first two indices. Assuming a specific form of the Higgs–Yukawa couplings, the number of L–violating parameters reduces to six complex numbers. We have given our ansatz in the weak–current basis. However, after EW symmetry breaking, we must rotate to the mass–eigenstate basis. Experimentally, only the PMNS and the CKM matrix are known \[^{46, 47}\]. The explicit lepton and quark mixing matrices are therefore not fully determined. In the following, we assume that the lepton Higgs–Yukawa matrix is diagonal.
we assume mixing only in the leptonic sector. In the quark sector, we assume left-right symmetric mixing. Additionally, we work in the limit where the down-type Higgs–Yukawa matrix is diagonal whereas the up-type is non-diagonal. Hence our specific form of the Higgs–Yukawa couplings implies mixing only in the up-type sector. In Ref. [21], it was shown that the choice of quark mixing (e.g. mixing in the up-type versus mixing in the down-type sector) does not significantly influence the numerical results at the low energy scale.

B. B3 neutrino masses

Since lepton number is violated, the neutrinos mix with the neutralinos, resulting in a 7×7 neutralino-neutrino mass matrix of rank 5. As a result, we obtain one massive neutrino at tree level [39],

\[ m_{\nu}^{\text{tree}} = -\frac{16\pi\alpha_{\text{GUT}}}{5} \sum_{i=1}^{3} \left( v_i - \nu_i \delta_{\mu} \right)^2 \frac{1}{M_{1/2}} \]  

(6)

Here \( v_d, v_u \) and \( v_i \) denote the vacuum expectation values of the \( H_d, H_u \) and sneutrino fields. However, experimental neutrino oscillation data suggests that we need at least two massive neutrinos. Since there is only one massive neutrino at tree-level, higher-order corrections need to be taken into account. Full 1-loop corrections to the neutrino-neutralino mass matrix have been discussed in Ref. [21]. A good estimate of the size of these radiative corrections is given by the slepton–lepton and down-type quark–squark loop contribution, which are proportional to \( \frac{1}{M_{1/2}} \)

\[ (m_{\nu}^{cMSSM})_{ij} \propto \lambda_{ikn} \lambda_{jn} \ m_{\ell_k} \ m_{\ell_n}, \]  

(7)

\[ (m_{\nu}^{cMSSM})_{ij} \propto \lambda_{n} \lambda_{ikn} \ m_{d_k} \ m_{d_n}, \]  

(8)

The proportionality of the loop contributions to the exchanged SM fermion mass in the loop further increases the effect that trilinear couplings with indices ijk are dominant over all other indices \( ijk \), as is clear from the hierarchical ansatz in Eqs. (4) and (5).

Ref. [20] noted that in large regions of cMSSM parameter space the ratio between the tree-level neutrino mass and the radiative contributions is too large too yield a phenomenologically viable neutrino mass hierarchy. However, due to RGE effects in the running of L-violating parameters, the tree-level neutrino mass has a global minimum at

\[ A_{0}^{(3)} = 2 M_{1/2}, \]  

(9)

\[ A_{0}^{(5)} = \frac{M_{1/2}}{2}, \]  

(10)

for non-zero \( \lambda_{ijk} \) or \( \lambda_{ij} \), respectively. We choose \( A_0 \) such that it minimizes the \( \lambda \) contribution to neutrino masses [Eq. (9)], as explained in more detail in the next paragraph. Thus, in the hierarchical B3 cMSSM a set of 10 free parameters,

\[ M_{1/2}, M_0, \ sgn(\mu), \ tan(\beta), \ \ell_1, \ \ell_2, \]  

(11)

fixes the full B3 cMSSM.

As described in Ref. [21], it is possible to obtain the experimentally measured neutrino mass squared differences and mixing angles by independently generating each neutrino mass with a set of three L-violating free parameters. This means that 6 or 9 independent couplings are necessary in order to obtain the full spectrum with either two or three massive neutrinos. However, in the case of neutrinos in normal hierarchy mass ordering with a massless lightest neutrino, it turns out that one can do with only 2 couplings to explain the heaviest neutrino mass, \( m_{\nu_3} \), cf. Ref. [21]. This is fortunate, because due to our hierarchical ansatz only \( \ell_1, \ell_1, \ell_2 \) and \( \ell_2 \) have a significant impact on the neutrino sector whereas \( \ell_3 \) generates only a negligible contribution to the neutrino masses if it is of the same order of magnitude as the other couplings [71]. Therefore, we generate \( m_{\nu_3} \) at tree-level via the \( \lambda_{ijk} \) couplings, which are in turn determined by \( \ell_1 \) and \( \ell_2 \). The second neutrino mass, \( m_{\nu_2} \) is generated via \( \lambda_{ijk} \) (determined by \( \ell_1 \)) at one-loop level, whereas the lightest neutrino must remain massless, \( m_{\nu_1} \approx 0 \).

In summary, we have 5 free L-violating parameters which control the neutrino sector, \( \ell_1, \ell_2 \). These can be used to generate non-zero \( m_{\nu_2} \) and \( m_{\nu_3} \), respectively, in accordance with the two mass squared difference and three mixing angles from experiment. It is not easily possible to obtain inverse hierarchy or degenerate neutrino masses in the hierarchical B3 cMSSM unless \( \ell_3 \) becomes several orders of magnitude larger than the other L-violating parameters.

C. Experimental neutrino oscillation data

Assuming three active oscillating neutrinos, the best global fit values of the neutrino masses and mixing parameters at 1σ C.L. are given by [49, 50, 51],

\[ \sin^2[\theta_{12}] = 0.31 \pm 0.02, \]  

\[ \sin^2[\theta_{23}] = 0.51 \pm 0.06, \]  

\[ \sin^2[\theta_{13}] = 0.09 \pm 0.02, \]  

\[ \Delta m^2_{21} = 7.59 \pm 0.2 \times 10^{-5} \text{eV}^2, \]  

\[ \Delta m^2_{31} = \{ -2.34 \pm 0.1 \times 10^{-3} \text{eV}^2, 2.45 \pm 0.1 \times 10^{-3} \text{eV}^2 \} \]  

(12)

where

\[ \Delta m^2_{ij} \equiv m_{\nu_i}^2 - m_{\nu_j}^2. \]  

(13)

\( m_{\nu_1}, m_{\nu_2}, m_{\nu_3} \) denote the neutrino masses in order of largest electron-neutrino admixture. There are two large mixing angles \( \theta_{12} \) and \( \theta_{23} \). Deviating from Ref [49], we use in Eq. (12) for \( \theta_{13} \) the best fit value recently measured...
by Daya Bay and RENO \cite{DayaBay:2012,RENO:2012}. The neutrino oscillation data implies at least two non-vanishing neutrino masses $m_{\nu_i}$. In this work, we usually consider the so-called Normal Hierarchy (NH) scenario, where $\Delta m^2_{31} > 0$ and $m_{\nu_1} \approx 0$.

D. Numerical results

For each cMSSM point we fit the L-violating parameters $\ell_i$ and $\ell'_i$ to the best-fit Normal Hierarchy neutrino mass data in Eq. (12). We perform this fit by minimizing the $\chi^2$ function

$$
\chi^2 = \frac{1}{N_{\text{obs}}} \sum_{i=1}^{N_{\text{obs}}} \left( \frac{f_{\text{susy}} - f_{\text{obs}}}{\delta_i} \right)^2,
$$

where $f_{\text{obs}}$ are the central values of the $N_{\text{obs}}$ experimental observables in Eq. (12), $f_{\text{susy}}$ are the corresponding numerical predictions and $\delta_i$ are the 1σ uncertainties. We calculate the low energy mass spectrum and couplings with SOFTSUSY3.3 \cite{Allanach:2001}. The numerical minimization of our $\chi^2$ function is done with the program package MINUIT2 \cite{James:1994}. Details of our numerical procedure can be found in Ref. \cite{Ambrogi:2014}. Here, we present an example solution where we translate the best fit values $\ell_i$ and $\ell'_i$ into the corresponding values of the trilinear L-violating couplings at the unification scale:

$$
\begin{align*}
\lambda_{133} &= 1.72 \cdot 10^{-6} \\
\lambda_{233} &= 2.74 \cdot 10^{-6} \\
\lambda'_{133} &= 1.13 \cdot 10^{-5} \\
\lambda'_{233} &= 3.89 \cdot 10^{-5} \\
\lambda_{333} &= 3.11 \cdot 10^{-5}
\end{align*}
$$

We have used $M_0 = 100$ GeV, $M_{1/2} = 500$ GeV, $\tan\beta = 25$, $\text{sgn}(\mu)$ and $A^{(X)}_0 \approx 2M_{1/2}$. As one can see, the $\lambda_{333}$ and $\lambda'_{333}$ couplings are at least one order of magnitude smaller, below $O(10^{-5})$. The couplings $\lambda'_{233}$ and $\lambda'_{133}$ tend to be the largest trilinear L-violating couplings. In Fig. 1 we display the best fit value of $\lambda'_{233}$ in the $M_0 - M_{1/2}$ plane. We see that the magnitude of the L-violating couplings does not strongly depend on $M_0$ and $M_{1/2}$. Furthermore, the relative magnitude of the L-violating couplings to each other remains roughly the same throughout the parameter space.

Recall that the parameter $\ell_3$ is not fixed by the neutrino oscillation data in the normal hierarchy scenario. However, we assume that $\ell_3$ is of the same order of magnitude as $\ell_1$ and $\ell_2$, setting $\ell_3 = \ell_2$ in the rest of our paper \cite{Ambrogi:2014}.

We have checked all low energy constraints on the L-violating trilinear couplings \cite{Ambrogi:2014,Allanach:2001}. However, in our case the couplings are too small to have an observable impact on any low energy observables.

III. COLLIDER SIGNATURES

In this section, we investigate possible collider signatures of the hierarchical B$_3$ cMSSM at the LHC. The best-fit values of the L-violating couplings to neutrino data are too small to have an observable effect on the resonant production of supersymmetric particles. Thus, pair production of colored sparticles via strong interactions is the dominant production channel at the LHC. Only if sleptons and gauginos are much lighter than the colored sparticles, their production rate becomes comparable. The produced sparticles cascade decay into the LSP. In our parameter space, we can have either a stau LSP or a neutralino LSP \cite{Ambrogi:2014}. The final state collider signature is determined by the decay properties of the LSP candidate. In the B$_3$ cMSSM, the LSP is almost always short-lived and decays within the detector via the L-violating interactions \cite{Ambrogi:2014}. We now describe the final state signatures of stau LSP and neutralino LSP scenarios separately after describing the numerical tools used. Then we go on to discuss in which regions of $M_0 - M_{1/2}$ parameter space they occur.

A. Numerical tools

The low energy mass spectrum and couplings are calculated with SOFTSUSY3.3 \cite{Allanach:2001}. The decay widths of the relevant sparticles are obtained with Isajet7.64 \cite{Isajet:2013} and Isawig1.200. However, the decay channels of the neutralino LSP via the sneutrino vevs and the $\kappa_i$ term are absent in Isawig1.200. Therefore, we calculate decays via the bilinear L-violating couplings with SPheno3.1 \cite{Porod:2003}. We combined...
all decay widths in order to calculate the branching ratio of the sparticles. We use the parton distribution functions MRST2007 LO modified [58]. Our signal events are generated with Hervig6.510 [59]. The cross sections are normalized with the NLO calculations from Prospino2.1 [60] assuming equal renormalization and factorization scale. Our events are stored in the Monte Carlo event record format StdHep5.6.1. We take into account detector effects by using the fast detector simulation Delphes1.9 [61], where we choose the default ATLAS-like detector settings. Our event samples are then analyzed with the program package ROOT [62] and we calculate the 95% and 68% confidence levels (CL) of the exclusion limits with TRolke [63].

B. Stau LSP decay

In the parameter region where the lighter stau $\tilde{\tau}_1$ is the LSP, pair produced squarks and gluinos at the LHC cascade decay into the LSP, producing jets and taus (tau–neutrinos) along the way,

$$pp \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow jj \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow jj \tau \tilde{\tau}_1,$$

where $j$ and $X$ denote jets and additional particles of the process (such as $\tau$ or $\nu$), respectively. Note that we can have more than 2 jets in the final state if the process involves gluinos. These additional jets are included in $X$, which we discuss in more detail in Sect. IIIB. For example, right-handed squarks decay into a jet and the lightest neutralino, which then typically decays into a stau and a tau with a branching ratio of one,

$$\tilde{q}_R \tilde{q}_R \rightarrow jj \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow jj \tau \tilde{\tau}_1.$$

The stau then directly decays into two SM fermions via the trilinear $L$–violating couplings $\lambda_{133}$, $\lambda_{233}$ and $\lambda_{ijk}$, cf. Fig 2. Decays via the $A_{333}$ couplings are dominant, even though the decay width via $\lambda_{ijk}$ is enhanced by a factor of $N_C = 3$ and the $\lambda_{ijk}$ couplings are generally larger. However, the lightest stau is mostly right–handed and thus the coupling of the stau via $\lambda'$ is suppressed due to the small admixture with the left–handed stau. Additionally, the stau decay via $\lambda'_{333}$ into a top and bottom quark is kinematically forbidden or suppressed in large regions of parameter space. Stau decays via $\lambda'_{311}$ and $\lambda'_{322}$ are heavily suppressed due to the smallness of the couplings.

In principle, the stau can also mix with the charged Higgs boson via $\kappa_3$ and decay via the two–body decay mode $\tilde{\tau} \rightarrow \tau \nu$. However, we have numerically checked that stau decays via bilinear operators are always sub–dominant in our model. We define a

- benchmark point BP1 in the stau LSP region with $M_0 = 100$ GeV, $M_{1/2} = 500$ GeV, $\tan \beta = 25$, $\text{sgn}(\mu) = 1$ and $A_0^{(\mu)} \approx 2 M_{1/2}$

Note that the branching ratios into different decay channels are roughly independent of the stau mass as long as the final state masses are negligible.

Roughly half of the staus decay into a charged lepton and neutrino, the other half decays into a tau and neutrino. Note that we only denote electrons or muons as leptons in this paper. Since one third of tau decays leptonically, we expect final state collider signatures with either 0, 1 or 2 leptons from the decaying stau LSPs, for 12%, 46% and 42% of events, respectively:

$$0\ell + 2\nu + 2\tau_{\text{had}} + 2j + X,$$

$$1\ell + 2(4)\nu + 1\tau_{\text{had}} + 2j + X,$$

$$2\ell + 2(4, 6)\nu + 2j + X$$

where $\ell$ denotes an electron or muon and $\tau_{\text{had}}$ denotes a hadronically decaying tau. If the lepton[s] in the $1\ell$ or $2\ell$ channel come from a leptonically decaying tau, the number of neutrinos increases from 2 to 4 [6], as shown in brackets in Eq. (19). Due to the Majorana character of the neutralino, both neutralinos can decay into like–charged taus and hence we can have same–sign leptons in the final state.

C. Neutralino LSP decay

In the hierarchical B3 cMSSM, the lightest neutralino eigenstate is generally bino–like. The production process is given by

$$pp \rightarrow \tilde{q} \tilde{q}/\tilde{g} \tilde{g} \rightarrow \chi_1^0 \chi_1^0 + 2j + X.$$

The neutralino LSP can either decay via a trilinear $L$–violating operator into three SM fermions or via neutralino–neutrino mixing (proportional to the bilinear $L$–violating couplings and the sneutrino vevs) into a gauge/Higgs boson and a lepton, cf. Fig. 3.
For relatively low sfermion masses in the propagator, the trilinear three-body decay modes dominate because the bilinear L–violating couplings are only generated radiatively via RGE running and the sneutrino vevs are determined to be relatively small from radiative electroweak symmetry breaking. However, in parameter regions with heavy sfermions, the bilinear two-body decay mode becomes dominant because the three body decay mode suffers from phase space suppression and heavy virtual sfermions in the propagator.

First, we discuss the case where the lightest neutralino dominantly decays via the trilinear LNV couplings, for which we define

- **benchmark point BP2** with
  \[ M_0 = 200 \text{ GeV}, \quad M_{1/2} = 400 \text{ GeV}, \quad \tan \beta = 25, \]
  \[ \text{sgn}(\mu) = 1 \quad \text{and} \quad A_{0}^{(N)} \approx 2M_{1/2}. \]
  This benchmark point is characterized by lightest neutralino, lighter stau, gaugino and squark masses of 163 GeV, 213 GeV, 937 GeV and 846 GeV, respectively. We obtain the following LSP branching ratios for **BP2**:  
  \[ \begin{align*}
  \text{Br}(\tilde{\chi}_1^0 \rightarrow \tilde{\nu}_1^0 bb) &= 0.31 \\
  \text{Br}(\tilde{\chi}_1^0 \rightarrow \tilde{\nu}_1^0 bb) &= 0.20 \\
  \text{Br}(\tilde{\chi}_1^0 \rightarrow W^\pm \ell^\mp) &= 0.21 \\
  \text{Br}(\tilde{\chi}_1^0 \rightarrow W^\pm \ell^\mp) &= 0.05 \\
  \text{Br}(\tilde{\chi}_1^0 \rightarrow \ell^\pm Z^0) &= 0.13 \\
  \text{Br}(\tilde{\chi}_1^0 \rightarrow \ell^\pm h^0) &= 0.08
  \end{align*} \]  
  The branching ratio of the three-body decay modes (the \[ \tilde{\chi}_1^0 \rightarrow \nu \ell^{-} \nu \ell^{+} \] channel) is roughly 51%. However, for this benchmark point the two-body L–violating decays via bilinear L–violating couplings already have a sizable contribution to the LSP decays. The electron (electron-neutrino) channel is suppressed compared to the muon decay channel because \( \lambda_{133} \sim 0.3 \lambda_{233} \), cf. Eq. (12). Therefore, about 90% of our leptons are muons. Summing up the various decay channels and including the gauge boson branching ratios, roughly 72% of neutralinos decay without leptons, 19% with one lepton and 7% with two leptons. This leads to 52%, 27% and 14% of events with 0, 1 and 2 leptons from LSP decays, respectively.

Assuming the cascade decay processes of Eq. (20), dominant final state signatures are then given by

\[ \begin{align*}
  0\ell + 2\nu + 2\ell^{-} + 2j + X \\
  1\ell + 1\nu + \ell^{-} + W_{\text{had}} + 2j + X \\
  2\ell + 2\nu + \ell^{-} + 2j + X
  \end{align*} \]

Next, we discuss the decay properties of the lightest neutralino in a region where the two–body decays dominate,

- **benchmark point BP3** with
  \[ M_0 = 600 \text{ GeV}, \quad M_{1/2} = 400 \text{ GeV}, \quad \tan \beta = 25, \]
  \[ \text{sgn}(\mu) = 1 \quad \text{and} \quad A_{0}^{(N)} \approx 2M_{1/2}. \]

The lightest neutralino, lighter stau, gluino and squark masses of **BP2** are 164 GeV, 579 GeV, 961 GeV and 1010 GeV, respectively. Here, the LSP decay channels are the same as for **BP2**; however, the branching ratios differ drastically:

\[ \begin{align*}
  \text{Br}(\tilde{\chi}_1^0 \rightarrow \ell^\pm h^0) &= 0.12
  \end{align*} \]

Since here the scalar masses \( (M_0) \) are fairly large, the two–body neutralino decay modes via bilinear L–violating couplings or sneutrino vevs dominate, amounting to 93%. Therefore, there are only half as many neutralinos decaying into the 0ℓ channel as for **BP2**; twice as many decay into the 1ℓ channel and 7% with two leptons. This results in final state signatures with 0, 1 or 2 leptons at 24, 37 and 27%, respectively. Typical final state signatures are given by

\[ \begin{align*}
  0\ell + 2\nu + 2Z_{\text{had}} + 2j + X \\
  1\ell + 1\nu + Z_{\text{had}} + 2j + X \\
  2\ell + 2\nu + 2Z_{\text{had}} + 2j + X
  \end{align*} \]

As mentioned before, the electron decay channel is suppressed by roughly a factor of 10 compared to the muon decay channel. Additionally to the channels mentioned in Eq. (21), there are 12% of events with 3 or 4 leptons from LSP decay.

D. **Scan in the \( M_0 - M_{1/2} \) plane and kinematical distributions**

In the subsequent numerical analysis, we perform a scan in the \( M_0 - M_{1/2} \) plane. For this, we define a benchmark region (BR) which contains the three benchmark points defined above (**BP1, BP2, BP3**):

![Schematic characterization of the three-body (left) and two-body (right) decay modes of the neutralino LSP in the hierarchical B3 cMSSM.](image-url)
In Sect. [11]3 we discussed that the absolute magnitude of the L-violating parameters as well as the relative magnitude between them does not vary significantly with $M_0$ and $M_{1/2}$. This implies that the LSP decay branching ratios are hardly affected by variations of the L-violating parameters within our BR. However, the decay modes are importantly affected by two points, as illustrated in Fig. 4

(A) Whether we are in the stau or neutralino LSP region

(B) The ratio between three- and two-body decay modes within the neutralino LSP region.

In the stau LSP region, the 1 and 2 lepton channels are dominant for large regions of parameter space. The 0 lepton channel only becomes significant once the stau becomes heavier than the top-quark. Then, hadronic stau decays via $\lambda_{33}'$ contribute significantly and the 1 and 2 lepton studies perform much worse, resulting in a “cutoff” of the sensitive region for stau masses above the top mass. Now, the 0 lepton channel could further exclude parameter space; however, since this region extends well above $M_{1/2} \approx 500$ GeV, we expect that the amount of data collected is not yet large enough to make exclusion possible. In the neutralino LSP region dominated by three-body decays, we expect the 0 lepton channel to be the best, whereas in the case of two-body decays, the 2 lepton channel should perform better.

We now come to a discussion of possible additions to the final state particles from “X” [as contained in Eqs. (16) and (20)] and the most important distributions for our benchmark region.

Additional jets can arise from gluinos in the hard process, since the gluino decays into quark and (virtual) squark, leading to more jets in the final state. Besides gluino pair and gluino–squark production, gluinos can occur in squark decays if $M_{1/2} \ll M_0$. For example, in BP3 the gluinos are lighter than the squarks and a sizable fraction of the squarks decay into a gluino and a quark which then decays via virtual squark and quark. Thus, we expect a higher jet multiplicity than for BP1 or BP2, where $m_\tilde{g} < m_\tilde{g}$. This is illustrated in Fig. 6 (i). There, we show the distribution of the number of jets for our three benchmark points as well as for a $R_p$-conserving version of BP2 and BP3 with a stable LSP (denoted “BP2 RPC” and “BP3 RPC”, respectively). One can see that for BP2 RPC, there are on average only 2-3 jets because here squarks typically decay into a neutralino/chargino and a quark, whereas for BP3 RPC, there are 3-4 jets. Comparing BP2 RPC to BP2, we expect up to 4 additional b-jets from the neutralino LSP decays [Eq. (22)], and thus the distribution peaks around $N_{\text{jet}} = 5 - 6$, cf. Fig. 5 (i). Similar observations can be made for BP3. Here, there are more jets from the (R-parity conserving) decay chain involving gluinos. However, on average there are less jets from neutralino LSP decays, Eq. (24), such that the distribution also peaks at $N_{\text{jet}} = 5 - 6$. In the stau LSP case (BP1), the distribution peaks at $N_{\text{jet}} = 3 - 4$. Here there are only few jets which can be attributed to X (ie. gluino decays), as discussed above.

Further leptons in the final state can emerge in the cascade decays of the SU(2) doublet squarks. The latter decay into charginos and neutralinos with dominant SU(2) gaugino composition, which are typically $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in the cMSSM. $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ subsequently decay either into slepton and lepton or gauge boson/Higgs and the lightest neutralino. However, this
leads to isolated leptons in only $\sim 15\%$ of events in our case, as is illustrated in Fig. (ii) by the $N_\ell$ distributions for BP2 RPC and BP3 RPC. The reason for this is that in BP2, the $\tilde{\tau}_1$ is much lighter than the other sleptons, whereas the latter are heavier than $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$. Thus $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ dominantly decay into $\tau\tau$ and $\tau\nu$, respectively. About one third of these $\tau$’s decay leptonically, leading to final state leptons. In BP3, all sleptons are heavier than $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ and hence the latter preferably decay into a gauge/Higgs boson and the lightest neutralino. Comparing BP2 RPC and BP3 RPC with the corresponding $R_p$ scenarios, we clearly see that there are significantly more leptons for BP2 and BP3 due to leptonic decays of $\tilde{\chi}_1^0$. However, there are more entries in the 0 lepton bin for BP2 and BP3 than expected from Eqs. (22) and (23), because some of the leptons are non-isolated or too soft or do not fall into the acceptance region of the tracking system. The same holds for BP1, which has overall the largest number of isolated leptons; nevertheless the ratio between events with 1 lepton and 0 leptons is still less than predicted from Eq. (10).

In Fig. (iii), we present the missing transverse momentum distribution. Here, we clearly see that BP1 has the hardest distribution among all $R_p$ violating distributions. Note that for the two other $R_p$ violating scenarios the missing transverse energy distribution is much softer compared to the respective $R_p$ conserving scenarios, due to the LSP decays.

IV. NUMERICAL RESULTS: EXCLUSION LIMITS ON HIERARCHICAL $B_3$ CMSSM PARAMETER SPACE

In this section, we further constrain the hierarchical $B_3$ CMSSM parameter space using data from the LHC at $\sqrt{s} = 7$ TeV with an integrated luminosity of up to $5$ fb$^{-1}$. We focus on recent ATLAS studies with 0, 1 or 2 isolated leptons, several jets and large missing transverse momentum. A short overview over the ATLAS studies used is given in Table I. Full details of objects reconstruction, definitions of all kinematical observables and event selection cuts of all three analyses can be found in the respective ATLAS publications 8, 9, 10 (0 lepton), 11, 12 (1 lepton) and 13 (2 leptons). We have chosen these analyses because they only rely on simple objects such as electrons, muons, jets and missing transverse momentum in the final state. Thus, we do not rely on complicated tau reconstruction and $b$-tagging algorithms, which are difficult to simulate with the detector simulation Delphes1.9 61. In particular, difficulties arise in reconstructing hadronically decaying taus 28. Also, the published ATLAS studies for supersymmetry involving taus 64 or $b$-jets 65 in the final states have smaller cross-sections or smaller efficiencies than the multi-jet, large $p_T$ and lepton searches. Thus, we expect the “simple” 0-2 lepton analyses to perform better with the current amount of data. So far, the experimental data is in agreement with the SM background expectations. We use their results in order to derive the 68% and 95% CL exclusion regions in the $M_0$--$M_{1/2}$ parameter space. We plan to investigate exclusion limits arising from third generation studies and multi-lepton studies in a future publication.
for each grid point in the model, we checked that the Monte Carlo tools are correct.

A. 0 lepton channel

ATLAS has used the 0 lepton channel as one of the first search channels for supersymmetry [3,5]. So far, they have collected a total luminosity of about 4.7 fb$^{-1}$ at the center of mass energy of $\sqrt{s} = 7$ TeV. From the non-observation of an excess, we can derive exclusion limits on the hierarchical B$_3$ cMSSM. The ATLAS 0 lepton channel is divided into several signal regions (SR). For all signal regions, the cut on $p_T^*$ and the minimum requirement on $p_T^\text{jet}$ of the first two most-energetic jets are identical. However, the number of jets and the minimum $p_T^\text{jet}$ cut for the remaining jets as well as the cut on $m_{\text{inc}}^\text{jet}$ and on the ratio $p_T^*/m_{\text{eff}}$ differ for the different signal regions.

We have examined all signal regions after applying the object reconstruction described in their study and found that we obtain the strictest exclusion limits for the “SRE–m” signal region, which demands 6 jets, $m_{\text{inc}}^\text{jet} > 1200$ GeV and $p_T^*/m_{\text{eff}} > 0.15$, cf. Table I. We show the resulting plot in the $M_0$–$M_{1/2}$ plane in Fig. 6. The exclusion limit peaks at $M_0 \approx 200$ GeV. This is the region where the neutralino LSP decays dominantly via three–body decays $\tilde{\chi}_1^0 \to \nu b\bar{b}$, c. f. Fig. 4. It was to be expected that the “SRE–m” signal region gives good exclusion limits for this type of scenario, because if both neutralinos decay via $\tilde{\chi}_1^0 \to \nu b\bar{b}$, and therefore more events survive in the “SRE–m” than in the “SRE–t” scenario (where $m_{\text{inc}}^\text{jet} > 1500$ GeV). Finally, leptons from the cascade decays of SU(2) doublet squarks into $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are suppressed, since the latter dominantly decay into $\tilde{\chi}_1^0 \to \tau\nu$ and $\tilde{\chi}_2^0 \to \tilde{\tau}$. For increasing $M_0$, the exclusion region decreases to lower $M_{1/2}$ values. We can see in Fig. 4 that the two–body decay mode of the neutralino becomes more important here. Thus, an increasing number of the neutralino LSPs decay into a gauge boson and a lepton and less $b$–jets are expected in the final state, so that less events pass the kinematical cuts on the final state jets. Another effect is that for larger $M_0$, the production cross section decreases. Directly to the left of the peak at $M_0 \approx 200$ GeV, the limit drops off sharply because here the LSP becomes the $\tilde{\tau}_1$ and there are significantly less events with 6 jets and no leptons. However, $M_{1/2} \lesssim 350$ GeV can still be excluded at 95% CL. We would like to point out that in principle, it is possible to obtain better exclusion limits (up to $M_{1/2} \lesssim 400$ GeV) in the stau LSP case by using a signal region with only 4 or 5 jets. However, the 1 lepton study performs even better and therefore we go not into detail about the results from these signal regions here.

We do not consider the region with a LSP lifetime exceeding $\tau = 15$ mm, since the ATLAS searches for supersymmetry require prompt LSP decays. In Fig.

| $N_{\ell}$ | 0lept–SRE–m | 1lept–3j | 2lept–OS–4j |
|---|---|---|---|
| 0 | 1 | 2 |
| 6 | 3 | $\geq 4$ |
| $p_T^{\text{jets}}$ | $(130, 60, 60, 60, 40, 40)$ | $(100, 25, 25)$ | $(100, 70, 70, 70)$ |
| $p_T^*$ | $> 160$ | $> 250$ | $> 100$ |
| $m_{\text{inc}}^\text{jet}$ | $> 1200$ | $> 1200$ | $-$ |
| $L$ | $4.7$ fb$^{-1}$ | $4.7$ fb$^{-1}$ | $1.0$ fb$^{-1}$ |

TABLE I. The main cuts used in the ATLAS studies used in this collider study. More details concerning the cuts can be found in the relevant ATLAS studies (0 lepton [3, 1 lepton [5] and 2 lepton [12]). $N_{\ell}$ denotes the number of isolated leptons, $N_{\text{jet}}$ the number of jets and $p_T^{\text{jets}}$ specifies the minimal transverse momentum which is required for these jets. $p_T^*$ gives the minimal value of missing transverse momentum of the event, $m_{\text{inc}}^\text{jet}$ the minimal (inclusive) effective mass and $L$ denotes the total integrated luminosity at 7 TeV.
B. 1 lepton channel

Refs. [6, 10] search for multi–jet events with large missing transverse momentum and exactly one isolated lepton. Similarly to the 0 lepton channel in the previous subsection, the 1 lepton channel was one of the first supersymmetry search channels and the current integrated luminosity is 4.7 fb$^{-1}$ at the center of mass energy of 7 TeV. They consider signal regions with 3– or 4–jets with different kinematic configurations, which are optimized for the $R_p$ cMSSM with a large mass difference between the gluino and the LSP. Additionally, they include a soft–lepton signal region which is sensitive to scenarios with small mass splitting between the sparticles.

Comparing the results for the different signal regions, we observe that the 3–jet signal region (“1lept–3j”) provides us with the best overall exclusion limits in the stau LSP region up to $M_{1/2} \sim 500$ GeV (i.e. better than the limits from any other signal region in the 0 to 2 lepton channels). The main kinematic cuts of the 1lept–3j signal region are listed in Table I and the resulting plot is shown in Fig. 7. Almost half of the events in the stau LSP region decay into final states with 1 lepton, cf. Sect. III B. Note also that the 1 lepton study [11] demands the most stringent cut on $p_T$, among the 0, 1 and 2 lepton studies. In the stau LSP region with direct (two–body) leptonic decays, much more missing transverse momentum is produced than in the neutralino LSP region. In particular in the neutralino LSP region with dominant three–body decays into $\nu\nu\ell$ (i.e. $R_p$), the amount of $p_T$ is greatly reduced compared to the stau LSP region. Moreover, much less charged leptons arise from the neutralino decay. Additional leptons from the cascade decays are also heavily suppressed. Thus, we have a sharp drop of the acceptance in the crossover region between the stau and neutralino LSP region. For larger $M_p$ values, eventually the two–body neutralino decay modes become dominant over the three–body decay mode. However, the hard cut on $p_T$ still rejects many signal events in this region.

Note that the ATLAS signal region with 1 lepton and 4–jets is also sensitive to the neutralino LSP region besides the stau LSP region. This explains why the old 4–jet signal region with 1 fb$^{-1}$ in the muon channel, ATLAS was able to constrain the bilinear $R_p$ model presented in Ref. [6] (with two–body neutralino decays) quite well. However, having in mind that in our case we have additional three–body decays and in the new 5 fb$^{-1}$ study, the cuts are more stringent cuts than the 1 fb$^{-1}$ version and not optimized for our type of scenario, the resulting exclusion limits on the neutralino LSP region are weaker than the limits derived in the 2 lepton channel as shown below.

C. 2 lepton channel

The ATLAS study based on final states with two leptons and missing transverse momentum [12] has not yet been updated to include more than 1 fb$^{-1}$ of data. The search is divided into opposite–sign (OS), same–sign (SS) and flavour–subtraction (FS) signal regions where up to 4 jets are demanded besides exactly 2 leptons and a cut on $p_T$. We find that we obtain the best exclusion limits with the OS signal regions. The three OS regions differ in the $p_T$ cut, the number of jets and the corresponding minimal $p_T$ cut. As in the case of the 1 lepton channel, the OS studies with the hardest transverse missing momentum cut (“2lept–OS–2j”, $p_T > 250$ GeV) are quite sensitive to the stau LSP region where two staus decay leptonically. However, in the 2 lepton channel the obtained exclusion limits are $\sim 50$ GeV weaker than in the “1lept–3j” study. This is due to the stringent cuts on $m^\text{soft}$ and on the ratio $p_T/m^\text{soft}$ in the “1lept–3j” search channel, which yield better signal isolation and background suppression.

The OS and 4–jet channel with a moderate $p_T$ cut of...
100 GEV ("2lept–OS–4j"), described in Table I provides us with the best exclusion limits for $M_0 \gtrsim 300$ GeV, where the neutralino LSP decays dominantly via two–body decays as shown in Fig. 8. We notice a slight dip for smaller $M_0$ ($M_0 \sim 200$ GeV), where there are dominant three–body neutralino decays. Here, as discussed in the previous subsections, parton–level leptons from the neutralino LSP decays or from the cascade decays of the SU(2) doublet squarks are heavily suppressed and the exclusion limits from the 0 lepton channel are more stringent. For even smaller values of $M_0$, we are in the stau LSP region and the exclusion limits improve again. However, as discussed in the last paragraph, the cuts are not optimized for a stau LSP scenario. The $E_T^{miss}$ cut is the weakest among all three analyses in Table I and the kinematic requirements on the jets are harder compared to the "1lept–3j" search channel.

For $M_0 \gg M_{1/2}$, the gluino is generally lighter than the squarks and thus we expect a higher jet multiplicity and in general more jets passing the kinematic cuts. However, much less transverse momentum is generated compared to the R–parity conserving case or the stau LSP region. Thus, the "2lept–OS–4j" yields the better overall exclusion region in the neutralino LSP region with dominant bilinear RPV decays due to the softer $E_T^{miss}$ cut compared to "0lept–SREm". One further remark on the number of leptons in the final state: for $M_{1/2} \ll M_0$, the SU(2) doublet squarks decay via a wino–like gaugino is quite sizable, although we have the competing decay channel via an off–shell gluino. These wino–like gauginos again dominantly decay into gauge bosons providing additional leptons in the final state.

V. SUMMARY AND CONCLUSION

We introduced a hierarchical ansatz for the L–violating trilinear Yukawa couplings in the B3 cMSSM. Here, the trilinear LNV Yukawa couplings are related to the Higgs Yukawa parameters $\lambda_i$ and $\lambda_i'$. We have then determined the best fit values of the $\ell_i$ and $\ell_i'$ in order to obtain phenomenologically viable neutrino masses and mixing angles. It is possible to quasi unambiguously determine the L–violating sector as well as the value of the SUSY breaking scalar coupling $A_0$ from neutrino oscillation data. We discussed the final collider signatures in the stau LSP and neutralino LSP scenarios at the LHC and finally used the ATLAS searches in jets and large missing transverse momentum with 0, 1 and 2 isolated leptons in order to find the 95% and 68% CL exclusion limits in the $M_0$–$M_{1/2}$ plane for fixed $\text{sgn}(\mu)$ and
We can exclude squark masses below 800 GeV, and gluino masses below 700 GeV (for squark masses below 1 TeV) at 95%. These limits become more stringent at 68% CL, by roughly 100 GeV. Compared to the case of the R–parity conserving cMSSM, we obtain weaker limits because generally we have more jets and leptons and less $p_T$ due to the LSP decays.

We want to conclude with a short discussion of how we can improve a future collider study for our model or similar R–parity violating models. There are a number of studies in which R–parity violating collider signatures are investigated, as mentioned in the introduction. Many of these studies consider multilepton ($N_l \geq 3$) signatures in association with much less missing transverse energy than in our study. They typically assume, however, a single non–zero $\lambda_{ijk}$ without third generation indices, i.e. $i,j,k \in \{1,2\}$, so that the number of lepton is enhanced. In our model, the LSP dominantly decays via $\lambda_{ijk}$ or $\lambda_{i3j}$ couplings involving third generation decay products, or via neutralino–neutrino mixing involving gauge boson decay products. However, the branching ratio of the LSP into leptons is still considerably large (between 19% and 47%) and therefore the lepton multiplicity is higher than in R–parity conserving models. Also, the average $p_T$ distribution of the signal leptons will be relatively hard due to the large phase space of the two body decay channels of the LSP into SM fermions. For example, in BP2 the hardest lepton has on average $p_T = 80$ GeV. In BP2 RPC, the hardest lepton has a mean value of $p_T = 60$ GeV. Demanding one (two) lepton(s) with moderate $p_T$ cuts might be advantageous to isolate the signal. As an alternative, we can also apply a kinematical cut on the scalar sum of all the leptons’ $p_T$.

Decays via trilinear couplings with third generation indices are dominant in large regions of parameter space in our model. Therefore, we expect a substantial proportion of events with third generation SM particles in this parameter region. For example, we expect a large number of taus and b–jets in BC1 and BC2, respectively. In BP2, about 50% of all events have at least one b–jet. This is in sharp contrast to BP2 RPC where only 13% of all events have a b–jet in the final state. Requiring hadronically decaying taus or b–jets in the final state should help to suppress the SM background. However, for the parameter region around BP3, the LSP dominantly decays via neutralino–neutrino mixing. Here, we do not expect third generation particles in the final state in abundance.

The increase in jet and lepton multiplicities due to LSP decays in our model happens at the cost of less missing transverse momentum compared to the R–parity conserving case. For example, in BP3 RPC we have on average $p_T = 213$ GeV because the stable neutralino LSP escapes detection. In BP3 we obtain a mean value of $p_T = 123$ GeV due to neutrinos from the LSP decay. In many studies the effective mass,

$$M_{\text{eff}} = p_T + \sum p_T^T,$$

is used to “measure” the effective SUSY mass scale. However, they assume a stable LSP and thus $M_{\text{eff}}$ receives a sizable contribution from $p_T$. Our signatures tend to look softer than those of most R–parity conserving scenarios because some of the decay products of the LSP are not included in the sum in Eq. (26). A useful discriminating variable to increase the significance of our signal could be the scalar sum of missing transverse momentum, all jets, leptons and hadronic taus,

$$S_T = p_T + \sum p_T^T + \sum p_T^T + \sum p_T^T_{\text{had}}.$$  

For example, the ratio of Eq. (26) and Eq. (27) is 0.85 for BP3.

Finally, it is difficult to constrain the region $M_{1/2} \lesssim 230$ GeV in our model due to the finite lifetime of the LSP, since many supersymmetry searches only reconstruct leptons and jets which originate from the primary vertex. We thus conclude that allowing events with displaced vertices would certainly be advantageous to establish bounds in the low $M_{1/2}$ region.

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Because of the antisymmetry of $\lambda_{ijk}$, $\lambda_{333} = 0$ and $\ell_3$ could only contribute to neutrino masses via $\lambda_{233}$. This means that for a sizable contribution, $\ell_3$ must be several orders of magnitude larger than $\ell_1$ or $\ell_2$. $\ell_3$ has no relevance for the collider signatures as long as it doesn’t become several orders of magnitude larger than $\ell_1$ and $\ell_2$. In principle, any sparticle could here be the LSP in $R_p$ models since it is unstable. However, since the $L$-violating couplings in the hierarchical $R_\chi$ cMSSM are small, the particle spectrum remains very similar to the $R_p$ cMSSM and thus the lighter stau is always the lightest sfermion due to large left–right mixing. Only in a small part of the neutralino LSP region, where $M_{1/2} \lesssim 240$ GeV, the lifetime of the LSP can become larger than $c\tau \gtrsim 15$ mm. Note that additional jets can also arise from QCD Bremsstrahlung.