Constraints on the *R*-parity violating minimal supersymmetric standard model with neutrino masses from multilepton studies at the LHC

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In a recent paper, we proposed a hierarchical ansatz for the lepton-number-violating trilinear Yukawa couplings of the *R*-parity-violating minimal supersymmetric standard model. As a result, the number of free parameters in the lepton-number-violating sector was reduced from 36 to 6. Neutrino oscillation data fixes these six parameters, which also uniquely determines the decay modes of the lightest supersymmetric particle and thus governs the collider signature at the LHC. A typical signature of our model consists of multiple leptons in the final state and significantly reduced missing transverse momentum compared to models with *R*-parity conservation. In this work, we present exclusion limits on our model based on multilepton searches performed at the Large Hadron Collider with a 7 TeV center-of-mass energy in 2011 while accommodating a 125 GeV Higgs.

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I. INTRODUCTION

Recently, the Large Hadron Collider (LHC) experiments announced the discovery of a Higgs-like particle with a mass around 125 GeV [1,2]. To all appearances, the properties of this Higgs-like particle seem to agree well with the standard model (SM) Higgs boson. It is essential to probe whether the Higgs-like particle is embedded in the SM or whether electroweak symmetry breaking is realized in an extended framework of the SM. However, it is also equally important to look for extensions of the SM in direct collider searches for phenomena of physics beyond the SM. Supersymmetry (SUSY) [3,4] is a popular extension of the SM, and the lightest supersymmetric particle (LSP) is most commonly stabilized by imposing *R*-parity conservation. Many SUSY searches at the LHC focus on collider signatures with a low SM background by demanding large missing transverse momentum [5,6]. So far, the searches for large missing transverse momentum in association with multiple hard jets provide the strictest bounds on supersymmetric models, where the lightest neutralino is assumed to be the LSP.

In *R*-parity-violating models, the LSP is unstable and its decay products may be detected within the detector. Thus, less missing transverse momentum is produced on average, and it is interesting to investigate how strict the resulting bounds are compared to the *R*-parity-conserving case. The decay properties of the LSP are determined by the *R*-parity-violating couplings. *A priori*, there is a large number of trilinear and bilinear *R*-parity-violating parameters. However, simultaneous lepton- and baryon-number violation leads to experimentally unobserved proton decay [7]. As an equally well-motivated alternative to *R*-parity, one can impose the discrete symmetry baryon triality (B_3) [8,9], which forbids the baryon-number-violating terms but allows for lepton-number violation. Then, massive neutrinos arise in the mass spectrum [10,11], and the neutrino oscillation data [12,13] can be used to constrain the lepton-number-violating sector. In a previous publication, we proposed a hierarchical structure of the *R*-parity-violating trilinear Yukawa couplings similar to the SM Yukawa couplings [14]. As a consequence, there remain only six independent lepton-number-violating parameters, which can be completely fixed by the neutrino oscillation data, uniquely determining the decay properties of the LSP. Characteristic collider signatures contain multiple leptons, third-generation particles, several hard jets and, most importantly, reduced missing transverse momentum.

In a recent study [15], we examined the impact of the three most important *R*-parity-conserving searches from ATLAS [16–18] with missing transverse momentum and multijets on our hierarchical *R*-parity-violating model, assuming a constrained soft-breaking sector, the constrained minimal supersymmetric standard model (cMSSM) [19–21]. In the light of the recent little hierarchy problem [22–24], the cMSSM seems to have become somewhat unnatural, since in order to obtain a 125 GeV Higgs boson, large radiative corrections to the tree-level Higgs mass from scalar top quarks are needed, resulting in large fine-tuning in cMSSM models. However, a 125 GeV Higgs boson can still be obtained with percent-level fine-tuning in the focus point region of a (slightly modified) cMSSM [25] or in the focal curve region [26]; hence for simplicity we continue to present our results in the cMSSM framework.

Both ATLAS and CMS have recently published multilepton searches where the cut on missing transverse momentum is significantly reduced or even replaced by a cut on the scalar sum (S_T) of the transverse momentum of all reconstructed objects [27,28]. These searches are expected to be more sensitive to our model than the *R*-parity-conserving studies because the LSP decays reduce missing transverse momentum but not S_T. ATLAS interprets their null result in a simplified model of chargino pair production with a neutralino LSP decaying via an R-parity-violating coupling into two leptons and a neutrino, and a scenario with a stau LSP candidate, considering final state signatures with four or more leptons. In our framework, the LSP decay modes are different due to the presence of neutralino-neutrino mixing terms, which tend to reduce the number of final-state leptons. Therefore, we find that the CMS study is more effective in setting exclusion limits on our model, because they also present signal regions with three or more leptons. Thus, we will, in the following, focus on the CMS study, presenting exclusion limits on our framework, while also taking into account a 125 GeV Higgs in the focus point region. Our results can be interpreted in terms of bounds on the lighter chargino mass.

Our analysis is structured as follows: In Sec. II, we shortly discuss how neutrino masses arise in the hierarchical B_3 cMSSM, and in Sec. III we outline our numerical procedure. In Sec. IV, we constrain the parameter space of the hierarchical B_3 cMSSM using the multilepton ATLAS and CMS searches. We conclude in Sec. V.

II. HIERARCHICAL BARYON TRIALITY AND NEUTRINO MASSES

The hierarchical B_3 minimal supersymmetric standard model (MSSM) allows for additional, L-violating terms in the superpotential compared to the R_p MSSM superpotential ($\mathcal{W}_{R_p}$) [19–21]:

$$\mathcal{W}_{B_3} = \mathcal{W}_{R_p} + \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k - \kappa_iL_iH_u. \quad (1)$$

Here L_i and Q_i denote the $SU(2)$ doublet lepton and quark superfields. $\bar{E}_i$ and $\bar{D}_i$ are the $SU(2)$ singlet lepton and down-type quark superfields, respectively. i, j, k are the family indices, while the $SU(2)_L$ and $SU(3)_c$ indices are suppressed. We work in a basis where the bilinear R-parity-violating superpotential term and the corresponding soft-breaking term are rotated away by a field redefinition at the unification scale [29,30]. Note that these terms reemerge at lower scales via the renormalization group equations.

The hierarchical ansatz implies that the trilinear L-violating couplings have the following form [14]:

$$\lambda_{ijk} \equiv \ell_i \cdot (Y_E)_{jk} - \ell_j \cdot (Y_E)_{ik}, \quad (2)$$

$$\lambda'_{ijk} \equiv \ell'_i \cdot (Y_D)_{jk}, \quad (3)$$

where ℓ_i, ℓ'_i are c numbers. Equation (2) has the required form to maintain the antisymmetry of the λ_{ijk} in the first two indices. Assuming a specific form of the Higgs-Yukawa couplings $Y_{E/D}$, the trilinear L-violating couplings are fully determined by the six independent parameters ℓ_i, ℓ'_i.

In the hierarchical B_3-cMSSM, the number of free parameters in the soft-breaking sector is constrained to five, and thus the model is described by 11 independent parameters at the unification scale [29]:

$$M_0,\, M_{1/2},\, A_0,\, \mathrm{sgn}(\mu),\, \tan\beta,\, \ell_i,\, \ell'_i. \quad (4)$$

M_0, $M_{1/2}$ and A_0 denote the universal scalar mass, universal gaugino mass and universal trilinear scalar coupling, respectively. The parameter $\mathrm{sgn}(\mu)$ is the sign of the superpotential Higgs mixing parameter, and $\tan\beta$ is the ratio between the two Higgs vacuum expectation values (VEVs).

Massive neutrinos emerge in the mass spectrum of the hierarchical B_3 cMSSM because the neutrinos mix with the neutralinos via the L-violating terms [29]. However, it is well known that at tree-level, only one neutrino mass eigenstate obtains a mass [11]. The global fit results to the neutrino oscillation data [12,13] show that we need at least one further massive neutrino, which arises at the one-loop level. Full one-loop contributions to the neutrino-neutralino mass matrix are implemented in SOFTSUSY [31]. As described in Refs. [32,33], the ratio between the tree-level neutrino mass and the radiative contributions is $\mathcal{O}(100)$ in large regions of the cMSSM parameter space, contradicting the experimental observation of a neutrino mass hierarchy of $\mathcal{O}(1)$. However, neutrino masses with the correct neutrino mass hierarchy can be obtained if the trilinear universal scalar coupling is fixed to

$$A_0^{(\lambda')} \approx 2M_{1/2}. \quad (5)$$

This approximation holds until $M_0 \gg 2M_{1/2}$. Then, $A_0^{(\lambda')}$ grows linearly with M_0.

III. NUMERICAL PROCEDURE

The low-energy mass spectrum and couplings including neutrino masses are calculated with SOFTSUSY3.3 [31]. The L-violating parameters ℓ_i and ℓ'_i are determined by a fitting procedure using the most recent experimental neutrino data [15] with the root package MINUIT2. We assume $\tan\beta = 25$ and the Higgs mixing parameter $\mu > 0$, while A_0 is determined by Eq. (5), leaving only M_0 and $M_{1/2}$ as free parameters. For the derivation of exclusion limits on our model, we perform a scan in the M_0-$M_{1/2}$ plane.

The decay widths of the relevant sparticles are obtained with IsaJet7.64 [34] and IsaWig1.200. Because neutralino LSP decays via the sneutrino VEVs and the κ_i terms are not implemented in IsaWig1.200, we evaluate these with SPheno3.1 [35]. We use the parton distribution functions MRST2007 LO modified [36]. Our signal events [37] are generated with Herwig6.510 [38]. The cross sections are normalized with the next-to-leading order calculations from Prospino2.1 [39], assuming an equal renormalization and factorization scale. We take into account detector effects by using the fast detector simulation Delphes1.9 [40]. Our event samples are then analyzed with the program package ROOT [41], and we calculate the 95% and 68% confidence levels (C.L.) of the exclusion limits by the Rolke test [42].

In the following section, we investigate the implications of multilepton LHC searches for our model.

IV. MULTILEPTON SEARCHES AT THE LHC

In this section, we derive exclusion limits on the M_0-$M_{1/2}$ plane in the hierarchical B_3 cMSSM from a recent multilepton search at the LHC with 2011 data. We discussed the collider signatures of the hierarchical B_3 cMSSM in detail in Ref. [15], for both the neutralino and the stau LSP case. There, we concluded that we expect three or more leptons from neutralino LSP decays in $\mathcal{O}(10\%)$ of the events, and two leptons in up to 30% of events. Stau LSP decays result in two leptons in 40% of events. Apart from the LSP decays, the decay chains are identical to the R-parity-conserving case, since the L-violating couplings are quite small [$\mathcal{O}(10^{-5})$]. Within the decay chain, additional leptons from, e.g., chargino decays can arise, so that we expect a sizable fraction of events with three or more leptons.

In the following, we discuss the CMS study [28] at $\sqrt{s} = 7$ TeV with an integrated luminosity of 4.98 fb^{-1} and then present our numerical results taking a 125 GeV Higgs into account.

The CMS study is divided into many mutually exclusive search channels with either three or four isolated leptons in the final state (including hadronically decaying tau leptons) and for three different S_T regions ($S_T < 300$ GeV, 300 GeV $< S_T < 600$ GeV, and $S_T > 600$ GeV). The CMS study uses the S_T of the transverse momentum of all reconstructed objects as a selection cut. Since missing transverse momentum ($\not{p}_T$) is not a powerful discriminating observable in R-parity-violating models as opposed to R-parity-conserving models, the overall mass scale of the process is here certainly the more appropriate observable. CMS also considers search channels with a mild missing transverse momentum cut. However, these search channels yield much weaker constraints on our R-parity-violating models compared to the S_T search channels. Events are further categorized according to the number of Drell-Yan pairs with either Z-boson veto or acceptance. Any new physics model is allowed to have an excess in a limited amount of channels, which are defined as the signal region, and the remaining channels with no excess are designated as control regions.

In our case, the most promising channel is the three-lepton channel with $S_T > 600$ GeV, without hadronically decaying taus and without Drell-Yan pairs. This is because a strict S_T cut suppresses the SM background most effectively and because of the limited tau tagging efficiency of Delphes [43]. Less than $\mathcal{O}(1\%)$ of our events

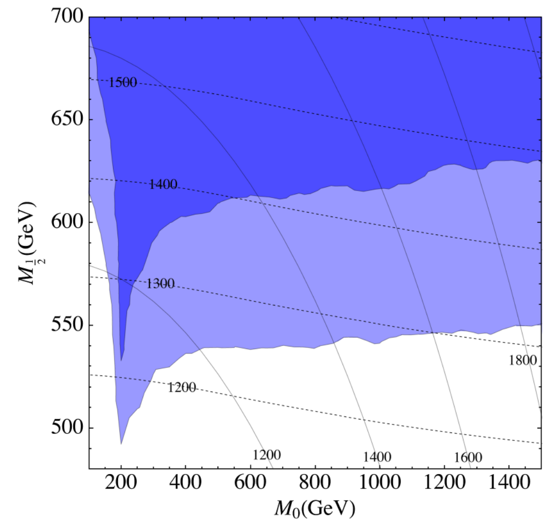

FIG. 1 (color online). Exclusion limit on our benchmark region, where $\tan\beta = 25$, $\mathrm{sgn}(\mu) = 1$ and $A_0^{(\lambda')} \approx 2M_{1/2}$, from the three-lepton CMS study. The white region is excluded at the 95% C.L., while the light blue is excluded at the 68% C.L. The grey lines denote the squark masses, and the dashed black lines denote the gluino masses (each in GeV).

contain Drell-Yan pairs from Z-boson decays (cf. our discussion in Ref. [15]). In Fig. 1, we present the exclusion limits in the M_0-$M_{1/2}$ plane. We also show the contours of constant squark and gluino masses, which range from 1 to 2 TeV. Thus, the production of colored states is heavily suppressed in large regions of parameter space compared to the production of electroweak gauginos. The lighter chargino is mostly wino-like, and typically chargino-neutralino and chargino pair production are the dominant production channels for large M_0, $M_{1/2}$.

The exclusion limits have a peak at small M_0 values. Here, the stau is the LSP and slepton pair production yields a sizable contribution to the total sparticle cross section besides colored sparticle and chargino production. The stau LSP always decays in a two-body final state. As long as the channel $\tilde{\tau}^- \to b\bar{t}$ is kinematically suppressed or closed, the dominant decay modes are $\tilde{\tau}^- \to \ell^- \nu_\ell$. We can obtain additional leptons from the cascade decay chain, and thus we often have three isolated leptons in the final state. With increasing M_0, the exclusion limits sharply drop. In this region, the stau decay into a top and a bottom is kinematically open and becomes dominant, strongly reducing the number of isolated leptons in the final state.

For $M_0 \gtrsim 200$ GeV, the stau becomes heavier than the neutralino. Initially, the three-body decay mode $\chi_1^0 \to \nu b\bar{b}$ dominates, resulting in poor efficiency of the trilepton study. Then, the exclusion limit moves again towards higher values of $M_{1/2}$, since with increasing M_0 the two-body neutralino decay modes via bilinear L-violating couplings or sneutrino vacuum expectation values quickly become dominant. Thus, a sizable fraction decays into W's and charged leptons. Additional leptons arise from

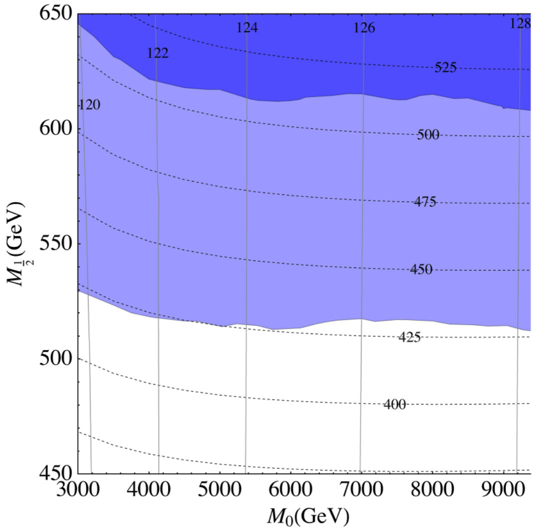

FIG. 2 (color online). Exclusion limit as in Fig. 1, but for the focus point region, M_0, $A_0 \gg M_{1/2}$. The grey lines denote the lightest Higgs mass, and the dashed black lines denote the lighter chargino mass (each in GeV).

the lighter chargino decay into $W^{\pm}$ and $\tilde{\chi}_1^0$. As mentioned before, squark and gluino production decreases with increasing M_0 and $M_{1/2}$, such that electroweak gaugino pair production is dominant for $M_0 \gtrsim 400$ GeV. The electroweak gaugino pair production cross section then increases slightly with M_0 (for constant $M_{1/2} \sim 550$ GeV), as destructive interference terms become more suppressed due to heavier sfermion masses. But for very large M_0 values, the chargino gets heavier, and thus the cross section falls off again.

We want to conclude the numerical discussion by commenting on the Higgs mass in our scenario. As already mentioned, both experiments at CERN discovered a 125 GeV resonance, which is consistent with a SM-like Higgs. This puts strong constraints on our model, since A_0 is fixed to be positive and similar in magnitude to $M_{1/2}$ or M_0 [44]. We obtain a Higgs mass of the order of 125 ± 3 GeV only if $M_0 \gtrsim 5$ TeV for $M_{1/2} \sim 550$ GeV, as displayed in Fig. 2. In this region of parameter space, the only sub-TeV sparticles are neutralinos and charginos, whereas the gluinos have a mass of $\sim$1.4 TeV. The scalars with masses around 3–6 TeV are beyond the reach of the current run of the LHC.

In the region $M_{1/2} \ll M_0, A_0$ is similar to the focus point region with large A terms studied in Ref. [25]. Even though heavy scalars are disfavored by fine-tuning studies, we can still have small fine-tuning of 1% in the focus point region. However, the soft-breaking sector of the cMSSM must be slightly modified [25,45], allowing for $\mathcal{O}(10\%)$ deviations in the stop soft-breaking terms. Note that demanding radiative electroweak symmetry breaking sets a relatively weak lower bound on $M_{1/2}$ of roughly 50 (200) GeV for $M_0 = 5(10)$ TeV. (Recall that for $M_0 \gg M_{1/2}$, viable neutrino masses require $A_0 \sim M_0$.)

V. CONCLUSION

We considered a hierarchical ansatz for the L-violating trilinear Yukawa couplings in the B_3 cMSSM, which enables us to unambiguously determine the numerical values of all L-violating couplings from experimental neutrino data. An important feature of this ansatz is that it uniquely fixes the decay channels of the LSP, and thus the collider signature at the LHC. In light of the 125 GeV Higgs and neutrino oscillation data, the hierarchical B_3 cMSSM predicts heavy squarks and sleptons beyond the reach of the LHC, as well as normal mass ordering in the neutrino sector. This seems to be consistent with null results from direct collider searches at the LHC. Naively, one would expect large fine-tuning due to the heavy stop masses. However, our parameter space is similar to the focus point region, with large A terms resulting in less fine-tuning if one allows for $\mathcal{O}(10\%)$ deviations in the third-generation squark sector. In our model, electroweak gaugino pair production is the dominant sparticle production process. We confronted our model with a multilepton search from CMS. We showed that the three-lepton final state with high S_T and no $\not{p}_T$ requirement provides the best exclusion limits. We demonstrated that the CMS multilepton search with data collected in 2011 already excludes large regions of the parameter space up to values of $M_{1/2}$ close to 550 GeV. This bound is mostly independent of M_0, corresponding to bounds on wino-like charginos and neutralinos with masses around 430 GeV and squark and gluino masses well above 1 TeV. Previously obtained exclusion limits from $\not{p}_T$ and multijet studies with 2011 data are much weaker, as described in a previous publication, confirming that the use of S_T is a very powerful observable for R-parity-violating models.

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