The Theory of R-parity, Unification and SUSY at the LHC

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Abstract. The simplest gauge theories for the conservation of R-parity in supersymmetry are discussed. We show how the minimal theory based on the B-L gauge symmetry predicts that R-parity must be spontaneously broken at the TeV scale. The most striking signals of these theories at the Large Hadron Collider are discussed. We present a realistic theory where the local baryon and lepton numbers are spontaneously broken at the supersymmetry breaking scale. The possibility to understand the conservation of R-parity in grand unified theories defined in four dimensions is mentioned.

Keywords: Supersymmetric Theories, Collider Physics, Grand Unified Theories.

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INTRODUCTION

The idea of supersymmetry has been considered for more than thirty five years as one of the most interesting ideas with application to particle physics. The minimal supersymmetric standard model (MSSM) could be tested soon at the Large Hadron Collider. However, it is very difficult to test its predictions because we know nothing about the supersymmetric spectrum, and about the presence of the lepton (L) and baryon (B) number violating interactions, which can modify most of the MSSM predictions for collider physics and cosmology. In this short review I will discuss the new results presented in Refs. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

It is well-known that the MSSM superpotential is given by

\[ W_{\text{MSSM}} = Y_u \hat{Q} \hat{H}_u \hat{d} + Y_d \hat{Q} \hat{H}_d \hat{u} + Y_e \hat{L} \hat{H}_d \hat{e} + \mu \hat{H}_u \hat{H}_d + W_{BL} + W_5^{(BL)}, \]

with

\[ W_{BL} = \epsilon \hat{L} \hat{H}_u + \lambda \hat{L} \hat{L} \hat{e} + \lambda' \hat{Q} \hat{L} \hat{d} + \lambda'' \hat{u} \hat{d} \hat{d} \hat{d}, \]

and

\[ W_5^{(BL)} = \frac{c_L}{\Lambda} \hat{Q} \hat{Q} \hat{L} + \frac{c_R}{\Lambda} \hat{u} \hat{d} \hat{e} \hat{e}, \]

where the first three terms in \( W_{BL} \) break L, the last term violates B, and the interactions in \( W_5^{(BL)} \) break both symmetries. There are several phenomenological constraints on the B and L violating interactions, but the most important one is coming from proton decay. For example, if we assume that the couplings \( \lambda' \) and \( \lambda'' \) are of order one and the squark mass around TeV, the lifetime of the proton is about \( \tau_p^{(4)} \sim 10^{-20} \) years. Therefore, in order to satisfy the experimental bounds on the proton decay lifetime, \( \tau_p > 10^{32-34} \) years, it is important to understand the possible absence of these interactions. The operators in \( W_5^{(BL)} \), Eq.(3), mediate the so-called dimension five contributions to proton decay [12] and the scale \( \Lambda \) should be larger than \( 10^{17} \) GeV in order to satisfy the experimental bounds. Therefore, one has to assume a desert between the TeV scale and grand unified scale.

In order to avoid the interactions in \( W_{BL} \), Eq.(2), it is often assumed the discrete symmetry, \( R = (-1)^{2S} M \), where \( S \) is the spin and

\[ M = (-1)^{3(B-L)}, \]

is called matter parity. Notice that in this case the interactions in \( W_5^{(BL)} \) are allowed and still the scale \( \Lambda \) has to be very large. Unfortunately, in most of the studies the conservation of this symmetry is enforced or the explicit breaking is considered [13]. Only a few groups have studied the dynamical origin of these interactions, see for example Refs. [14, 15, 16, 17, 18, 19, 20, 21, 22, 1, 2, 3, 4, 5, 6, 7, 8, 9, 11]. The main goal of this review is to discuss the different theories where we can understand the conservation or violation of matter parity in supersymmetry.
In order to understand the origin of the B and L violating interactions in the MSSM we can consider a theory defined at the TeV scale or we can discuss this issue in the context of a grand unified theory in four dimensions. Before we study any particular theory we have to notice the relation between matter parity and B-L. It is obvious that if we consider a theory where B-L is part of the gauge symmetry, at the B-L scale matter parity is conserved, but when the gauge symmetry is broken one has (non) conservation of $M$ if the field responsible for symmetry breaking has an (odd) even number of B-L. Therefore, we can say that the theories based on the B-L gauge symmetry are the simplest frameworks where we can investigate this issue.

### I. The Minimal Theory for R-parity Violation

Let us consider the simplest supersymmetric theory based on the B-L gauge symmetry [2]

$$G_{B-L} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$$

where we have the MSSM superfields, $\hat{Q}$, $\hat{u}^c$, $\hat{d}^c$, $\hat{L}$, $\hat{e}^c$, $\hat{H}_u$, $\hat{H}_d$, and the right-handed neutrinos needed to cancel the B-L anomalies, $\tilde{\nu}^c$. In this context the superpotential has a simple form

$$\mathcal{W}_{B-L} = Y_u \hat{Q} \hat{H}_u \tilde{\nu}^c + Y_d \hat{Q} \hat{H}_d \tilde{d}^c + Y_e \hat{L} \hat{H}_d \tilde{e}^c + Y_d \hat{L} \hat{H}_u \nu^c + \mu \hat{H}_u \hat{H}_d + W_{B-L}^{(5)}$$

with

$$W_{B-L}^{(5)} = \frac{\lambda_1}{\Lambda} \hat{Q} \hat{L} \tilde{\nu}^c + \frac{\lambda_2}{\Lambda} \hat{u}^c \tilde{d}^c \tilde{\nu}^c + \frac{\lambda_3}{\Lambda} \hat{L} \hat{L} \tilde{e}^c \tilde{\nu}^c.$$

As one expects, the R-parity violating terms in $\mathcal{W}_{BL}$, Eq.(2), are not allowed before symmetry breaking.

Now, in the context of the minimal theory there is only one possibility to break the gauge symmetry, $G_{B-L}$, to the SM symmetry. We have to give a vacuum expectation value to the fields which can be responsible for B-L symmetry breaking, the right-handed sneutrinos $\tilde{\nu}^c$. Therefore, one can say that R-parity must be spontaneously broken and one expects lepton number violating signatures at the LHC. Here the scale for B-L and R-parity violation is defined by the supersymmetric scale. It is easy to prove that we can give a vev to the fields $\tilde{\nu}^c$ in a consistent way, using the superpotential $\mathcal{W}_{B-L}$, the D-terms and the soft terms in

$$V_{soft} \supset M_{\tilde{L}}^2 |\tilde{L}|^2 + M_{\tilde{\nu}}^2 |\tilde{\nu}^c|^2 + (A_v \hat{L} \hat{H}_u \nu^c + h.c.).$$

One finds that the VEV for the right-handed sneutrinos is given by

$$\langle \tilde{\nu}^c \rangle = \sqrt{-\frac{8 M_{\tilde{\nu}}^2}{g_{BL}^2}},$$

with $M_{\tilde{\nu}}^2 < 0$, and

$$\langle \nu \rangle = \frac{\langle \tilde{\nu}^c \rangle Y_v \mu v_d - A_v v_u}{\sqrt{2} \left( M_{\tilde{\nu}}^2 - \frac{g_{BL}^2}{2} \langle \tilde{\nu}^c \rangle^2 \right)}.$$

Here $g_{BL}$ is the B-L gauge coupling. The sfermion masses are different in this scenario because we have new contributions from the $B-L$ D-term and we can have tachyonic slepton masses if the $Z_{B-L}$ mass is large. Therefore, in order to have a realistic spectrum we have to impose the relation $M_{Z_{BL}} < \sqrt{2} M_{\tilde{\nu}}$ [3]. The spectrum for neutrinos is peculiar in this theory. We have shown in Ref [4] (see also Refs. [17, 23]) that the spectrum for neutrinos is different because there are five light neutrinos, the SM neutrinos and two sterile neutrinos. It has been pointed out in Ref. [3] that the invisible decay of the $Z_{BL}$ is modified and maybe one can test this property at the LHC.

It is important to mention that after symmetry breaking one obtains the bilinear lepton number violating terms at the renormalizable level, while the baryon number violating interactions are suppressed by the cutoff scale. Then, assuming a large cutoff, $\Lambda \sim 10^{17}$ GeV, one can satisfy the bounds on the proton decay lifetime.

The testability of this theory at the LHC has been investigated in Ref. [3], where we have discussed the most interesting signatures at the LHC in different LSP scenarios. Here we will mention the most striking signals which can help us to test the lepton number and spontaneous R-parity violation. We focus on the case where the lightest supersymmetric particle is the neutralino. In this case one can have the following signals:
FIGURE 1. Signals with four leptons and two W’s. In order to observe lepton number violation we use the jets from the W decays.

\[ pp \rightarrow \gamma^* Z^* Z_{BL} \rightarrow \tilde{e}_i^+ \tilde{e}_i^- \rightarrow e_i^\pm e_j^\mp 4j. \]

These signals with four leptons, three of them with the same electric charge, and four jets are background free. See Fig. 1 for the topology of these events. We have investigated in detail the neutralino decays taking into account the constraints coming from neutrino physics and the slepton decays, showing that with a luminosity of 10 fb\(^{-1}\) we can have several events. We have shown in Ref. [3] that there are many solutions where the neutralino is long lived giving raise to displaced vertices. In Fig. 2 we can see that the production cross section can be above 1 fb when the slepton mass is below 400 GeV. In order to understand the discovery reach at the LHC we show in Fig. 2 (right panel) the number of events for different values of the slepton mass and branching ratios. In this way we can see the possibility to have a few events in large region of the parameter space, for more details see Ref. [3].

In summary, we can say that the minimal supersymmetric B-L theory [2] predicts:

- R-parity must be spontaneously broken.
- The B-L and R-parity violating scales are determined by the supersymmetry breaking scale.
- The theory predicts two light sterile neutrinos.
- Lepton number violating signals and displaced vertices at the LHC.

We would like to mention that these results are valid for the simplest theories where B-L is part of gauge symmetry and the idea was realized for the first time in Ref. [1]. It is important to emphasize again that in this case one needs to
assume a large cutoff, i.e. a desert, in order to satisfy the constraints from proton decay. In the next sections we will
discuss a model where one can break B and L at the low scale without generating any contribution to proton decay.

II. R-parity Conservation at the LHC

Now we discuss the minimal theory where one can explain dynamically the conservation of R-parity. We have
discussed in the previous section that in the simplest B-L theory one should break R-parity. Then, in order to have
R-parity conservation we need to go beyond the minimal model and add extra Higgses to give mass to the new neutral
gauge boson in the theory. The superpotential of a simple theory for R-parity conservation is given by

\[ W_{\text{RPC}} = W_{\text{B-L}} + \mu \bar{X} \tilde{X} + f \tilde{\nu} c \tilde{\nu} \]

(10)

We also could have two different scenarios: In the first case the new Higgses do not generate neutrino mass [6], or we
can generate the mass for the $Z_{\text{BL}}$ gauge boson through the Stueckelberg mechanism [8]. Here we discuss the scenario
where the neutrinos are Majorana fermions and have the implementation of the radiative symmetry mechanism to
break the local B-L gauge symmetry.

![FIGURE 3](image-url)

**FIGURE 3.** The state of the $B-L$ breaking vacuum in the $f_1 - f_2 - f_3$ space with $M_0 = 2 \text{ TeV}$, $M_{1/2} = 200 \text{ GeV}$ and $A_0 = 0$. Blue dots indicate R-parity conservation while red dots R-parity violation, the latter appears five times more often. The key point is
that only fairly degenerate values of $f_i$ (and therefore the right-handed neutrino masses) allow for R-parity conservation [7].

In this theory we can have two different vacua which break B-L. a) R-parity Conserving Vacua: In this case
only the Higgses get a VEV, $\langle X \rangle \neq 0$ and $\langle \tilde{X} \rangle \neq 0$. b) R-parity Violating Vacua: The right-handed sneutrinos get
a VEV. In Fig. 3 we show the possible solutions in the 3D $f_1 - f_2 - f_3$ space assuming boundary conditions [5],
$A_0 = 0$, $M_0 = 2 \text{ TeV}$, $M_{1/2} = 200 \text{ GeV}$. The blue and red points correspond to the solutions when R-parity is conserved
and violated, respectively. Therefore, one can appreciate in Fig. 3 that if we stick to the radiative symmetry mechanism
and universal boundary conditions R-parity is spontaneously broken in the majority of the parameter space. This is
an interesting result which hints at the possibility that R-parity violation is present in this theory. We should mention
that this simple theory for R-parity conservation predicts that the B-L symmetry breaking scale and the right-handed
neutrino masses are determined by the SUSY scale, and one expects lepton number violating signals from the Higgs
decays.

This theory could be tested at the LHC if we understand the production mechanisms and decays of the new B-L
Higgses, $X_1, X_2$ and $A_{\text{BL}}$. We have investigated the testability of this model at the LHC in Ref. [7] and found that the
signals with same-sign leptons and two jets can be observed if we have high luminosity:

\[ pp \rightarrow X_1 \rightarrow N \ N \rightarrow WW \ e_i^{+} e_j^{-} \rightarrow e_i^{+} e_j^{-} 4j \]

In this case the number of events with two muons and four jets can be estimated as

\[ N_{2\mu 4j} = \sigma(pp \rightarrow X_1) \times \text{Br}(X_1 \rightarrow \text{NN}) \times 2\text{Br}(N \rightarrow W\mu)^2 \times \text{Br}(W \rightarrow 2j)^2 \times \mathcal{L} \]

(11)

\[ \approx 5 \text{ fb} \times (1/3) \times 2(1/4)^2 \times (6/9)^2 \times 100 \text{ fb}^{-1} \approx 9. \]

(12)
In Fig. 4 we show the cross section for the single Higgs production (left panel) and the decay length of the right-handed neutrinos (right panel). We can see that one has displaced vertices in a large fraction of the parameter space. Therefore, we can have signals with two same-sign leptons and displaced vertices which are background free. The Higgs pair production: $pp \rightarrow Z_{BL}^* \rightarrow X_1 A_{BL} \rightarrow NNNN$, is very important to test this model and its prediction is independent of the supersymmetric spectrum. See also Ref. [24] for the study of the full spectrum assuming boundary conditions at the high scale.

Now, we can say that it is very easy to write down a theory for R-parity conservation at the TeV scale and as in the previous model we can have interesting lepton number violating signals. In this context we can have the implementation of the radiative symmetry mechanism for the electroweak symmetry and the B-L gauge symmetry. The testability of this theory at the LHC could shed light on the connection between the cold dark matter in the universe and the possible observation of missing energy at the LHC.

III. B and L as Local Gauge Symmetries

In the previous sections we have discussed the simplest theory where one can understand the conservation or violation of $R$-parity. Unfortunately, in these theories we have to postulate the desert between the TeV scale and the grand unified scale in order to suppress the dimension five operators for proton decay. Now, we would like to discuss a simple theory where the local baryon and lepton numbers are local symmetries spontaneously broken at the TeV scale. This theory is based on the gauge symmetry [9]

$$G_{BL} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

We refer to this model as the “BLMSSM”. In this context there are no dangerous operators mediating proton decay because the lepton number is broken in an even number while the baryon number violating operators can change $B$ by one unit. In this context the anomaly cancellation requires the presence of new families. In this context there is no flavour violation at tree level and in order to avoid Landau poles at the low scale we generate vector-like masses for the new quarks. We have investigated the predictions for the light Higgs boson mass showing that we can satisfy the experimental bounds without assuming a large stop mass and left-right mixing [10]. Also we can modify the current LHC bounds on the supersymmetric spectrum due to the presence of the baryon number violating interactions.

In this model we have the chiral superfields of the MSSM, and in order to cancel the B and L anomalies we need a vector-like family: $\hat{Q}_4, \hat{u}_4^c, \hat{d}_4^c, \hat{L}_4, \hat{e}_4^c, \hat{V}_4^c, \hat{Q}_5, \hat{u}_5^c, \hat{d}_5^c, \hat{L}_5^c, \hat{e}_5^c, \hat{V}_5^c$. The superpotential of the model is given by

$$W^L_B = W_0 + W_B + W_L + W_X + W_S,$$  \(13\)
sector one has the following interactions

\[ W_0 = Y_u \hat{Q}_u \hat{u} \hat{c} + Y_d \hat{Q}_d \hat{d} \hat{c} + Y_e \hat{L}_e \hat{c} \hat{\nu} + \mu \hat{H}_u \hat{H}_d, \]  

(14)

is the R-parity conserving MSSM superpotential and

\[ W_B = \lambda_B \hat{Q}_4 \hat{Q}_4 \hat{S}_B + \lambda_u \hat{u} \hat{S}_B \hat{S}_B + \lambda_d \hat{d} \hat{S}_B \hat{S}_B + \mu_B \hat{S}_B \hat{S}_B \\
+ \ Y_u \hat{Q}_4 \hat{H}_u \hat{u}_5 + Y_d \hat{Q}_4 \hat{H}_d \hat{d}_5 + Y_e \hat{Q}_5 \hat{H}_e \hat{\nu}_5 + Y_5 \hat{L}_5 \hat{H}_d \hat{\nu}_5. \]  

(15)

The new quark superfields acquire TeV scale masses once the \( S_B \) and \( \hat{S}_B \) Higgs fields acquire a VEV. In the leptonic sector one has the following interactions

\[ W_L = \ Y_e \hat{L}_e \hat{c}_4 + \ Y_4 \hat{L}_4 \hat{c}_5 + \ Y_5 \hat{L}_5 \hat{c}_5 + \ Y_5 \hat{L}_5 \hat{d}_5 \hat{\nu}_5 + \mu_L \hat{S}_L \hat{S}_L. \]  

(16)

Here we have an implementation of the seesaw mechanism for the light neutrino masses once the \( \hat{S}_L \) field acquires a VEV, while the new neutrinos have Dirac mass terms. In order to avoid the stability for the new quarks we add the fields, \( \hat{X} \) and \( \hat{X} \), which have the following interactions

\[ W_X = \lambda_1 \hat{Q}_4 \hat{Q}_5 \hat{X} + \lambda_2 \hat{u} \hat{S}_B \hat{X} + \lambda_3 \hat{d} \hat{S}_B \hat{X} + \mu_X \hat{X} \hat{X}, \]  

(17)

where the baryon number for the new fields are: \( B_X = 2/3 + B_A = -B_X \), and if we assume that they do not get a VEV the lightest one can be a dark matter candidate even if R-parity is violated, see Ref. [11] for details. For any value of the baryonic charges of the new fermions, which satisfy the anomaly conditions, the Higgses \( \hat{S}_B \) and \( \hat{S}_B \) have charges 1 and \(-1\), respectively. Then, one can write the following dimension five operator which gives rise to baryon number violation once the local baryonic symmetry is broken through the VEV of \( S_B \):

\[ W_S = \ \frac{a_1}{\Lambda} \hat{u} \hat{d} \hat{d} \hat{S}_B. \]  

(18)

Therefore, after breaking \( U(1)_B \) we find the so-called \( \lambda' \) MSSM interactions which can modify the current LHC bounds on the supersymmetric mass spectrum.

The B violating interactions can modify the signatures at the LHC. For example if the squark is the LSP it can be long-lived and form bounded states. Now, if we compute the decay length of a squark one finds

\[ \text{L}(\tilde{q}_i \to q_{jk}) > 1 \text{ mm} \left( \frac{10^2 \text{ GeV}}{M_{\tilde{q}}} \right) \left( \frac{10^{-7}}{\lambda'} \right)^2. \]  

(19)

Therefore, the squark will form bounded states but it will decay inside the detector. In this case we have used the bound from cosmology [11], and it is possible to have displaced vertices as well when the stop (sbottom) has mass around 100 GeV. For example, we can have signals with four jets from the decays of a stop or a sbottom

\[ pp \to \tau^+ \tau^- \to 4j, \ \text{pp} \to \tilde{b} \tilde{b} \to 4j. \]

Therefore, one can avoid the LHC constraints coming from the searches for multijets and missing energy [11].

This theory also predicts light leptons which modify the predictions for the Higgs mass. In Fig. 5 we show the constraints on the stop mass and the left-right mixing in the stop sector in the MSSM and in the BLMSSM. Here we use \( \tan \beta \) between 2 and 6 and see Ref. [11] for the other input parameters. Thanks to the existence of these new leptons one can satisfy the experimental bounds on the Higgs bosons even when the left-right mixing in the stop sector is small. The Higgs decays have been investigated in great details in Ref. [11], where we have shown that the Higgs decay into two photons is suppressed and one could rule out this model in the near future if the recent Higgs signals, around \( M_H \approx 125 \text{ GeV} \), are confirmed by the LHC experiments.

In summary, we can say that it is possible to define a simple theory for the spontaneous breaking of B and L at the TeV scale in agreement with the experiments. The theory predicts baryon number at the low scale which could modify LHC bounds on sfermion masses. The lepton number is broken in an even number and one also expects lepton number violating signals at colliders. The new light leptons change the prediction for the Higgs mass and we could have a light supersymmetric spectrum.
FIGURE 5. Allowed parameter space in the MSSM and BLMSSM in the plane of lightest stop mass versus the left-right mixing in the stop sector. We use as input parameters $M_{q_4} = M_{q_5} = 90$ GeV and $M_{u_4} = M_{u_5} = 100$ GeV. In the MSSM we compute the Higgs mass at two-loops and in the BLMSSM we have the extra one-loop contributions. The red points correspond to the range when the Higgs mass is between 115 GeV and 122 GeV, while the blue points correspond to the range, 122 GeV - 128 GeV. We use $M_{\tilde{g}} = 1$ TeV as the gluino mass [11].

IV. 4D GUTs and R-parity Conservation

In the context of a SUSY GUT in four dimensions based on the SU(5) gauge symmetry is not possible to understand the conservation of R-parity. In this context we can write the following interactions

$$W_{SU(5)} \supset \epsilon \hat{\bar{5}}_i \bar{5}_H + \lambda_{ijk} \hat{\bar{10}}_i \hat{\bar{5}}_j \hat{\bar{5}}_k + \eta \hat{\bar{5}}_i 24_H 5_H,$$

which break matter parity. Here $\hat{\bar{5}}_i$ and $\hat{\bar{10}}_i$ are the matter superfields, while $\hat{5}_H, \hat{\bar{5}}_H$ and $\bar{24}_H$ are the Higgs superfields.

Some of the SO(10) scenarios provide a framework to understand the conservation of R-parity. Unfortunately, one cannot use the $16_H$ Higgs to generate fermion masses and explain why the right-handed sneutrino does not get a vacuum expectation value. In the context of SO(10) we need to use large representations, $\hat{126}_H, \hat{\bar{126}}$, and $\hat{210}_H$ (or $\hat{54}_H$ and $\hat{45}_H$) to show that R-parity is conserved and one can generate fermion masses at the renormalizable level. See Ref. [25] for a discussion of this issue in SO(10). We can say that there is no a simple grand unified theory in four dimensions where we can understand the conservation of matter parity.

SUMMARY

We have presented the simplest gauge theories for the conservation of R-parity in supersymmetry. It has been shown that the minimal theory based on the B-L gauge symmetry predicts that R-parity must be spontaneously broken at the TeV scale. The B-L and R-parity violating scales are determined by the supersymmetry breaking scale and the theory predicts two light sterile neutrinos. In this context we expect lepton number violating signals and displaced vertices at the LHC, the most striking signals are the channels with four leptons, three of them with the same electric charge, and four jets.

The minimal theory for R-parity conservation provides a framework to implement the radiative symmetry mechanism and dynamically generate neutrino masses. In this case, assuming universal boundary conditions for the soft terms, we have shown that R-parity is spontaneously broken in the majority of the parameter space. Here the B-L symmetry breaking scale and the right-handed neutrinos masses are determined by the SUSY scale. Also one expects lepton number violating signals from the Higgs decays and displaced vertices from the right-handed neutrino decays.

In order to avoid a desert between the TeV scale and the grand unified scale, but still satisfy the bounds on the proton decay lifetime, we have defined an interesting theory where the local baryon and lepton numbers are spontaneously broken at the supersymmetric scale. This theory predicts baryon number violation at the low scale which can modify the LHC bounds on the supersymmetric spectrum. The new light leptons in the theory increase the Higgs mass without
assuming very heavy stops or a large left-right mixing in the stop sector. The possibility to understand the conservation of R-parity in grand unified theories was mentioned.

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