Searching Neutrino Physics through Displaced Vertices at Colliders

M. B. Magro
Centro Universitário Fundação Santo André, Santo André – SP, Brazil.
E-mail: magro@if.usp.br

Abstract. We present a brief review on the features of bilinear R-parity violation in mSUGRA models at the LHC. These kind of models can provied a way of probing neutrino oscillation physics at colliders. We show that the LHC will be able to cover such models for a large fraction of the parameter space.

The Large Hadron Collider (LHC) will probe a new land of physics by accessing a new scale of energy, and it is expected that the LHC will shed light upon some of the main open problems in actual particle physics, such as the origin of mass and the nature of the electroweak symmetry breaking. One of the most popular models for breaking electroweak symmetry is supersymmetry (SUSY) which provides an elegant way to solve the hierarchy problem [1] that appears in the symmetry breaking mechanism. On the other hand, extensions for the standard model of particle physics are in evidence nowadays after the discovery of neutrino masses and oscillations [2].

In SUSY models one define a new multiplicative quantum number called R-parity that is even for the standard model particles and odd for their supersymmetrical partners. One natural way of generating masses and mixings for neutrinos compatible with recent neutrino oscillation data is through R-parity breaking by violating leptonic number. We then assume that R-parity is broken by a bilinear R-parity breaking supergravity model (BRpV–mSUGRA) in which the MSSM superpotential is supplemented by the following terms [3]

\[
W_{\text{BRpV}} = W_{\text{MSSM}} + \varepsilon_{ab} \tilde{L}_{i}^{a} \tilde{H}_{u}^{b},
\]

with three extra parameters (\(\varepsilon_{i}\)), one for each fermion generation. In addition to these bilinear terms, we must also include new soft supersymmetry breaking terms (\(B_{i}\)).

\[
V_{\text{soft}} = V_{\text{MSSM}} - \varepsilon_{ab} \left( B_{i} \varepsilon_{i} \tilde{L}_{i}^{a} \tilde{H}_{u}^{b} \right).
\]

Taken together, the new terms in the BRpV Lagrangian (the three bilinear \(\varepsilon_{i}\) and the \(B_{i}\)) lead to the explicit violation of lepton number as well as R-parity. These terms also induce vevs \(v_{i} \equiv v_{L_{i}}, i = 1, 2, 3\) for the three left-type sneutrinos.

The basic difference between BRpV–mSUGRA and the conventional R-parity conserving mSUGRA scenario is that the lightest supersymmetric particle is no longer stable and it decays, typically inside the detector, consequently modifying the SUSY phenomenology at colliders.

This model contains eleven free parameters: \(m_{0}\) and \(m_{1/2}\) being the scalar soft SUSY breaking masses and the common gaugino mass at the unification scale; \(A_{0}\), the common trilinear term;
tan \beta, \text{ the ratio between the Higgs field vev's; sign(}\mu) ; \epsilon_i \text{ and } \Lambda_i. \text{ We trade the soft parameters } B_i \text{ by the "alignment" parameters } \Lambda_i = \epsilon_i v_d + \mu v_i \text{ which are directly related to the neutrino–neutralino properties [4].}

While the BRpV parameters \epsilon_i \text{ and } \Lambda_i \text{ have no effect in the production cross sections of supersymmetric states, they affect the LSP decay length and branching ratios. In Fig. 1 we illustrate the LSP decay length as a function of its mass in its rest frame. As we can see, for a large region of the parameter space the LSP decay length will be large enough to produce displaced vertices at the LHC.}

We show in Fig. 2 the main LSP branching ratios as a function of \(m_0\) for several values of \(m_{1/2}\). When it is kinematically allowed the LSP decays via two body decays into \(W\ell, Z\nu\) and \(h\nu\) with the gauge bosons further decaying into quarks and leptons. We can see from Fig 2 that \(\tilde{\chi}_1^0\) does have a sizeable branching ratio into \(\nu_b \bar{b}\), specially for heavier LSP and larger \(m_0\). Notice that the main contribution for this decay is via higgs production. From the figures we can also learn that the leptonic decays modes \(\nu\tau^+\tau^-\) and \(\nu\tau^+\ell^\mp\) vary from \(\approx 40\%\) at small \(m_0\) to a few percent at large \(m_0\). At moderate and large \(m_0\), these decays originate from the lightest neutralino decaying into the two–body modes \(\tau^\pm W^\mp\), \(\mu^\pm W^\mp\) and \(\nu Z\), followed by the leptonic decay of the weak gauge bosons. In general, semi-leptonic decays of the LSP are suppressed at small \(m_0\) and they dominate at large \(m_0\) due to two–body decays.

As can be seen from the previous figures, the LHC will be able to probe the BRpV-mSUGRA model both using standard SUSY searches looking for displaced vertices. We employed PYTHIA version 6.409 [5] to generate the signal and backgrounds, using the SPheno program [6] to generate all BRpV branching ratios in the SLHA format [7].

We searched for SUSY looking for standard signals at the LHC using the same strategy used in [8]. Fig. 3 displays the LHC reach in the three–(multi–)lepton (right–(left–)panel) channels with/without R–parity for integrated luminosity of 100 fb\(^{-1}\), which constitutes the best standard channel for BRpV discovery. For the reach of other topologies, see our full analysis in [9].

The decay of the LSP has an impact of reducing the LHC reach for SUSY when we take into account only the main all inclusive channel. Notwithstanding, the new BRpV interactions lead to a substantial increase in the final states containing isolated charged leptons, specially for pairs of same sign leptons and trileptons, compensating the losses in the inclusive channel [9]. Nevertheless, The existence of long decay lengths is an important feature of the BRpV models since detached vertices are a smoking gun of SUSY with R–parity violation. Furthermore, displaced vertices provide an additional handle that makes possible the SUSY search at the LHC. Since the neutralino decay length is large enough to be detached from the primary vertex of LHC, we expect it to decay producing a displaced vertex inside the ATLAS/CMS detectors.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{lsp_decay_length.png}
\caption{\(\tilde{\chi}_1^0\) decay length for several values of \(m_0\) as a function of its mass, for \(A_0 = -100\) GeV, \(\tan \beta = 10, \mu > 0\).}
\end{figure}
Figure 2. Lightest neutralino branching ratios as a function of $m_0$ for several values of $m_{1/2}$ and $A_0 = -100$ GeV, $\tan \beta = 10$, and $\mu > 0$.

Figure 3. LHC discovery potential in the three lepton channel (left panel) and the multilepton one (right panel) for an integrated luminosity of 100 fb$^{-1}$ [9].

In principle, this topology has little, if none, background expected at LHC.

In Fig. 4 we present the displaced vertex reach. As one can see, the LHC will be able to look for the displaced vertex signal up to $m_{1/2} \sim 800$ (1000) GeV for a large range of $m_0$ values and an integrated luminosity of 10 (100) fb$^{-1}$. Notice that the reach in this channel is rather independent of $m_0$ as expected from Fig. 1. Moreover, this signal for BRpV–mSUGRA disappears in the region where the stau is the LSP due to its rather short lifetime.

Since the LHCb experiment has excellent vertex capabilities, it is natural to conclude that it can also play a role in the displaced vertex search for SUSY. Taking into account that the LHCb experiment already has a dimuon trigger, we started our analysis looking for displaced vertices associated to $\tilde{\chi}^0 \to \nu \mu^+ \mu^-$. Despite the smallness of this branching ratio this is a very clean signal. Since the LHCb has very good vertex system we have also studied its discovery potential using all LSP decays that allow vertex reconstruction, i.e. the decays exhibiting two or more charged particles that can be reconstructed as emanating from the same point.

We present in Figure 5 the region of the $m_0 \otimes m_{1/2}$ plane where we expect 5 or more displaced vertices for integrated luminosity of 2 fb$^{-1}$, $A_0 = -100$ GeV, $\tan \beta = 10$, and $\mu > 0$ for both di–muon and all visible modes. For further details, see [10].
Figure 4. Discovery reach for displaced vertices channel in the $m_0 \otimes m_{1/2}$ plane for $\tan \beta = 10$, $\mu > 0$, $A_0 = -100$ GeV. The stars (squares) stand for points where there are more than 5 displaced vertex signal events for an integrated luminosity of 10 (100) fb$^{-1}$ [9].

Figure 5. The left(right) panel contains the LHCb discovery potential of BRpV–mSUGRA using dimuons(all visible modes) coming from a detached vertex [10]. We assumed $A_0 = -100$ GeV, $\tan \beta = 10$, and $\mu > 0$. The blue squares stand for the points with 5 or more events for $\mathcal{L} = 2$ fb$^{-1}$. The magenta areas correspond to a cross section larger than 10 fb$^{-1}$.

It is interesting to contrast the LHCb discovery potential with the ATLAS/CMS ones in the low luminosity initial run in order to estimate the contribution to BRpV searches that the different experiments can give. There are two main difference between the LHCb and ATLAS/CMS experiments: first of all, the ATLAS/CMS will have a luminosity 5 times the LHCb one in this period. Secondly, ATLAS/CMS vertex detectors have a larger pseudo-rapidity coverage, ranging from $-2.5 < \eta < 2.5$. We can see that ATLAS/CMS reach is a factor of 2 larger than the LHCb reach in the di–muon channel. This larger ATLAS/CMS discovery potential originates mainly from the larger planned integrated luminosity for these detectors.

We also analyze the two–body LSP decay into the lightest Higgs boson $h^0$ as a Higgs discovery channel $\tilde{\chi}^0_1 \rightarrow h\nu$. If the LSP lives long enough it will be detached from the primary interaction point leaving a displaced vertex as signal at the LHC. Since the Higgs boson decays mostly into b–quark pairs we expect a displaced vertex with two b–jets as a characteristic signature for Higgs production. Therefore, we looked for events with at least one displaced vertex containing at least one jet tagged as a b–jet. We considered a b–tagging efficiency up to 50% [11].

For our analysis the Higgs mass lies in the range 110 GeV $\lesssim M_h \lesssim 120$ GeV when we vary $M_0$ and $M_{1/2}$. Since we are only interested in detached jets coming from Higgs decays, we have further required that the jet–jet invariant mass is around the Higgs mass value. Physical SM processes do not lead to sizeable backgrounds to the detached Higgs searches due to to large difference in the invariant mass of the visible products. However, BRpV LSP decays into $\nu Z$ are a potential source of background for the Higgs signal.

From Fig. 6 one can see that the ATLAS and CMS experiments will be able to look for the
signal up to $M_{1/2} \sim 700$ (900) GeV for a LHC integrated luminosity of 10 (100) fb$^{-1}$, for the full analysis see [11]. Notice that the LHC Higgs discovery potential is almost independent of $M_0$. We have also estimated the reach expected at LHCb for our Higgs search proposal. The hatched region in Fig. 6 indicates the LHCb reach for 10 fb$^{-1}$. Due to the strong cut on the pseudo–rapidity required by this experiment the reach for 2 fb$^{-1}$ is severely depleted and only a small region of the parameter space is covered.

![Figure 6. LHC reach for Higgs search in displaced vertices for the BRpV–mSUGRA model in the plane $M_{1/2} \otimes M_0$ assuming $\tan \beta = 10$, $A_0 = -100$ GeV, and $\mu > 0$. The yellow stars (blue squares) represent the reach for an integrated luminosity of 10 (100) fb$^{-1}$ while the hatched region corresponds to the reach of the LHCb experiment for an integrated luminosity of 10 fb$^{-1}$ [11]. Note that the black lines delimit different regimes of LSP decay length.](image)

Finally we analyze the correlation presented in the BRpV-mSUGRA model between neutralino decay properties at LHC and neutrino mixing angles determined in low energy neutrino oscillation experiments. In [12] it is shown that the atmospheric angle is related to the neutralino branching ratios as

$$\tan^2 \theta_{\text{atm}} \simeq \frac{BR(\tilde{\chi}_0^0 \rightarrow \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \rightarrow \tau^\pm W^\mp)} = R.$$  \hspace{1cm} (3)

We present a quantitative analysis of the precision that the LHC can achieve in measuring the ratio $R$ through the reconstruction of the LSP branching ratios, see [13].

We present in Fig. 7 the attainable precision $\sigma(R)/R$ with which the correlation $R$ can be measured as a function of $m_0 \otimes m_{1/2}$ for $A_0 = -100$ GeV, $\tan \beta = 10$ and $\text{sgn}(\mu) = +1$ for an integrated luminosity of 100 fb$^{-1}$ and a center-of-mass energy of 14 TeV. We require in all plots that at least 5 events of reconstructed taus are observed. In the left panel of this figure we present the expected statistical error on the ratio $R$ assuming no systematic errors on the determination of the reconstruction efficiencies, while in the right panel we consider a more conservative scenario, where we anticipate a systematic error of 10% in each of the reconstruction efficiencies. One can see from this panel that the precision drops as $m_{1/2}$ grows since the neutralino production rates from squark/gluino cascade decays also decrease with increasing $m_{1/2}$ values. Therefore, if the systematic errors of the efficiency determination are negligible the LHC collaborations should be able to probe with a very good precision ($\lesssim 10\%$) the ratio $R$ for $m_{1/2} \lesssim 650$ GeV, that correspond to an LSP mass up to $\simeq 270$ GeV. The inclusion of systematic errors at the level assumed in the right panel of Fig. 7 increases the uncertainty in $R$, however, it is still possible to perform an accurate test of RmSUGRA scenario.

Note that in Fig. 7 we also present results for the 7 TeV run of the LHC. One can see that the LHC has a much more limited capability of probing the ratio $R$, since the reach of this run covers only up to $m_{1/2} \lesssim 300$ GeV. Still, although large, the statistical errors in this region...
Figure 7. Precision in the determination of the ratio $R$ in the plane $m_{1/2} \times m_0$ for a luminosity of 100 fb$^{-1}$, center-of-mass energy of 14 TeV, $A_0 = -100$ GeV, $\tan \beta = 10$ and $\text{sgn}(\mu) = +1$. In the right (left) panel we did (not) include a possible systematic uncertainty in the extraction of the efficiencies for the channels $\mu W$ and $\tau W$. The stars in the right panel represent the results for the 7 TeV run with an integrated luminosity of 1 fb$^{-1}$ [13].

$(0.3 \lesssim \sigma(R)/R \lesssim 0.5)$, due mainly to the small anticipated integrated luminosity of 1 fb$^{-1}$, allow a determination of the atmospheric angle comparable to that obtained at low energies.

In conclusion, we have shown that the LHC will be able to probe the features of the BRpV-mSUGRA model for a sizeable range of the parameter space. SUSY standard searches will be supressed by the high multiplicity of final states due to the LSP decaying into the detectors and the difficulty of isolating the final leptons, while the displaced vertex signal, since it has no background, will be the best channel of probing such models. Looking for displaced vertices at LHC will provide a important tool for probing R-partity in SUSY models. On top of that, measuring accurately the neutralino branching ratios can connect the high energy physics at LHC with the neutrino oscillation data from low energy experiments. We have shown here that the error in the determination of the atmospheric angle by the LHC in the BRpV-mSUGRA model is comparable with the errors presented in the regular neutrino oscillation experiments.

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