Tevatron signatures of an R-parity violating supersymmetric theory

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Abstract

We show that an R-parity violating supersymmetric scenario which can account for the atmospheric $\nu_\mu$ deficit has testable signals at the Fermilab Tevatron with upgraded energy and luminosity. The explanation of neutrino masses and maximal $\nu_\mu - \nu_\tau$ oscillation in terms of bilinear R-violating terms in the superpotential associates comparable numbers of muons and tau’s resulting from decays of the lightest neutralino. We show that this should lead to like-sign dimuons and ditaus with substantial rates, in a form that separates them from standard model backgrounds and other signals of supersymmetry. One here also has the possibility of completely reconstructing the lightest neutralino.

Existing data strongly point towards nondegenerate, massive neutrinos and large mixing between $\nu_\mu$ and $\nu_\tau$ (or, perhaps, a sterile state to which $\nu_\mu$ oscillates). To decide on which extension of the standard model fits this picture best, one also needs to think of other testable consequences of any suggested scenario. In this spirit, here we predict some signals of one such candidate theory: a supersymmetric (SUSY) scenario where R-parity breaking bilinear terms mix neutrinos and neutralinos, and thence lead to massive neutrinos.

Admitting of lepton number violation, the superpotential for the minimal SUSY standard model (MSSM) can be extended to include the following terms:

$$W_L = \epsilon_1 \hat{L}_i \hat{H}_2 + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k$$

(1)

Here we take the most economical approach and consider only the bilinear terms in the second and third generations, viz. $\epsilon_{2,3} L_2, L_3 H_2$. These terms can be responsible for generating one tree-level neutrino mass; also, the retention of the bilinears in the second and third generations ensures $\nu_\mu - \nu_\tau$ mixing of the kind suggested by the atmospheric neutrino data.

Performing a rotation we remove them from the superpotential, and reabsorb them in $\mu' H_1^0 H_2^0$ (where $\mu' = (\mu^2 + \epsilon_2^2 + \epsilon_3^2)^{1/2}$, and $H_1$ is a linear combination of $H_1, L_2$ and $L_3$). But the effects of $\epsilon_2$ and $\epsilon_3$ are still manifest; apart from newly produced trilinear terms, they show up through the scalar potential, where non-zero sneutrino vev’s $\nu_\mu$ and $\nu_\tau$ are in general induced. These vev’s give rise to neutrino-gaugino cross terms, that change the structure of the neutralino mass matrix

$$\frac{1}{2} \Psi^t C^{-1} \begin{pmatrix} 0 & -\mu' & \frac{g_{\nu_2}}{\sqrt{2}} & -\frac{g_{\nu_3}}{\sqrt{2}} & 0 & 0 \\ -\mu' & 0 & -\frac{g_{\nu_2}}{\sqrt{2}} & \frac{g_{\nu_3}}{\sqrt{2}} & 0 & 0 \\ \frac{g_{\nu_2}}{\sqrt{2}} & -\frac{g_{\nu_3}}{\sqrt{2}} & M & 0 & -\frac{g_{\nu_2}}{\sqrt{2}} & -\frac{g_{\nu_3}}{\sqrt{2}} \\ -\frac{g_{\nu_2}}{\sqrt{2}} & \frac{g_{\nu_3}}{\sqrt{2}} & 0 & M' & \frac{g_{\nu_2}}{\sqrt{2}} & \frac{g_{\nu_3}}{\sqrt{2}} \\ 0 & 0 & -\frac{g_{\nu_2}}{\sqrt{2}} & \frac{g_{\nu_3}}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -\frac{g_{\nu_2}}{\sqrt{2}} & \frac{g_{\nu_3}}{\sqrt{2}} & 0 & 0 \end{pmatrix} \Psi,$$

with $\Psi = \begin{pmatrix} \hat{H}_2 \\ \hat{H}_1 \\ -i \hat{W}_3 \\ -i \hat{B} \\ \nu_\tau \\ \nu_\mu \end{pmatrix}$

(2)
$M$ and $M'$ are the SU(2) and U(1) gaugino masses, and $v_1' = (H'_1)$, $v_2 = (H_2)$. Thence, the state 

$$\nu_3 = \nu_\tau \cos \theta + \nu_\mu \sin \theta$$

where \(\tan \theta = v_\mu/v_\tau\) (3) acquires a tree-level mass. For \(m_Z \ll \mu'\), this mass is

$$m_{\nu_3} \approx -g^2(v_\mu^2 + v_\tau^2) 2M \times \frac{M^2}{M'M' - m_Z^2 M/\mu' \sin 2\beta}$$ (4)

where \(g^2 M = g^2 M' + g^2 M\), and \(\tan \beta = v_2/v_1'\). The parameter \(v_0 = (v_\tau^2 + v_\mu^2)^{1/2}\) is a basis-independent measure of R-parity violation; if \(v_0 \sim 100\) keV (say, for \(\mu' = -500\) GeV, \(\tan \beta = 5\) and \(m_{\chi_0^0} \simeq 100\) GeV) the atmospheric neutrino problem can be explained in terms of oscillations.\(^1\) The decay of the lightest neutralino \(\chi_1^0\) (assumed to be the LSP–lightest SUSY particle) could provide the crucial test of this model: In fact, if enough massive, \(\chi_1^0\) has two-body decays of the type \(\chi_1^0 \rightarrow lW\) and \(\chi_1^0 \rightarrow \nu_\tau Z\); \(l = \mu, \tau\) (Roy-Mukhopadhyaya in [2]; [8, 11]).

The production and cascade decays of superparticles at a hadronic collider (till the LSP is reached) is expected to be controlled by R-parity conserving interactions. Thus all SUSY processes at the Tevatron will end up in \(\chi_1^0\) pairs. Two-body decays of a neutralino will lead often to lepton-$W$ final states; a conservative estimate predicts \(B(\chi_1^0 \rightarrow \mu W) \approx B(\chi_1^0 \rightarrow \tau W) \approx 35\%\) for maximal mixing angle.\(^2\) Half of these events contain like-sign dileptons (LSD) due to the Majorana character of neutralinos (Roy-Mukhopadhyaya in [2]; [8, 11]). It is this real $W$ + LSD signal (with correlated numbers of dimuons and ditaus, but a depletion of dielectrons) that can help us testing the proposed model. Such a signal is of particular interest for the CDF detector, sensitive to LSD’s; it has already been used to look for R-parity violation of other types with $107\, pb^{-1}$ data sample obtained at $\sqrt{s} = 1.8$ TeV [13]. Here we present our results for the upgraded Tevatron running at $\sqrt{s} = 2$ TeV, with a luminosity of $10\, fb^{-1}$.

We assumed that the only QCD process that leads to LSP pairs is the pair-production of squarks (of five degenerate flavours) whose lower mass limit is approaching 300 GeV [14]. The effective decoupling of the gluino can be indeed derived from the condition that the lightest neutralino heavier than the $W$, assuming gaugino mass unification (that we use to reduce the number of parameters). We retained all possible cascade channels in our calculation, and took particular note of the small but non-negligible contributions from $\chi_2^0 \chi_1^\pm$ and $\chi_1^+ \chi_1^-$ ($\chi_2^0$ and $\chi_1^\pm$ are the second lightest neutralino and the lighter chargino). Also, we have not restricted ourselves to a supergravity (SUGRA) scenario but considered squark and slepton masses as free parameters within existing experimental bounds (this is a common practice in Tevatron SUSY analyses; see also Ref. [14]).

The signals involving leptons get enhanced considerably if one remembers that the cascades leading to LSP pairs also produce single- or multi-leptons simultaneously. For example, heavier neutralinos (mainly $\chi_2^0$) and the lighter chargino ($\chi_1^\pm$) can cause cascades where sleptons giving large contributions if they are so light as to be produced on-shell. On the whole, LSP pairs are in general produced in final states of the following types:

$$\chi_1^0 \chi_1^0 + 0, 1, 2 \text{ or } 3 \ l \ + \ X \quad \text{with } l = e, \mu, \tau$$ (5)

Charged leptons can be produced in the cascade, or in the decay $\chi_1^0$-pair; $X$ denotes other states, possibly produced in association (jets, neutrinos).

The sample results\(^2\) shown in Table 1 demonstrate that, of the different final states mentioned above, the ‘pure jet + LSP pair’ and the ‘single lepton’ final state have the highest rates in general,
the dominant channel being determined by whether a slepton is light enough to be produced on-shell. These rates are followed by that of the di-lepton final state. In the latter cases, however, our signals can receive significant contributions because, if one of the leptons ($\mu$ or $\tau$) pairs up with one of identical flavour and sign coming from LSP decay, the overall rate gets suppressed only by a single power of the LSP branching fraction rather than its square. Thus, by reconstructing one $\chi^0_1$ and letting the other one decay in any allowed channel, one may get an enhancement by about a factor of 6 so long as it is enough to look for just one reconstructed $W$ in the final state. The most convenient mode for reconstructing the $W$ and hence, checking the mass-shell condition of $\chi^0_1$ seems to be $\chi^0_1 \rightarrow lW$ ($l=\mu,\tau$) followed by $W \rightarrow jj$, since all the decay products are visible here.

The standard model backgrounds to this kind of a final state ($W + LSD$) are quite suppressed. This is because the neutralino decay length in our case can be as large as between 0.1 cm$^2$ and 1 cm$^2$ when the decaying neutralino is of mass around 100 GeV or above. Such decay gaps result from the smallness of the R-parity violating coupling driving decays of the LSP. This coupling is determined by the basis-independent parameter $\tan \beta$ which also controls the tree-level neutrino mass. The resultant displaced vertex– to which the $W$ needs to be reconstructed– will distinguish our signals. For example, LSD backgrounds from $t\bar{t}$-production followed by semileptonic decay of one of the bottom quarks produced in top-decay can be eliminated by proper identification of the primary and secondary vertices together with suitable isolation cuts on the leptons. Though most MSSM cascades potentially faking our signals are suppressed at some stage or other, there are processes like $p\bar{p} \rightarrow b\bar{b}^{*}$ followed by decays of the $b$-squarks to a top, where both $W$'s and like-sign dileptons can be observed. However, the decay gap typical of our scenario can cause the latter to stand out. When R-parity is violated by trilinear terms, LSP's produced via the decay $\chi^+_1 \rightarrow \chi^0_1 W$, followed by three-body leptonic decay of each LSP, can in principle give rise to $LSD + W$, where a similar decay gap as above can occur if the trilinear R-violating couplings are appropriately small. In order to avoid faking by signals of this kind, one could test whether one lepton in the $LSD$ pair and the $W$ originate from the same displaced vertex. In addition, here as well as for the $t\bar{t}$ backgrounds mentioned above, one can use the neutralino mass scale condition to suppress the backgrounds.

### Table 1: Lowest order (LO) cross sections in pb at $\sqrt{s} = 2$ TeV for various final states and model parameters ($\mu' = -250$ GeV). $\sigma_n$'s ($n = 0, 1, 2, 3$) are the cross sections for $n$-lepton + jets + $\chi^0_1 \chi^0_1 + E_T$ (carried by neutrinos) final states; $\sigma_{nl}$ is the cross section for hadronically quiet $n$-lepton event. The numbers shown as .000 are insignificant up to three decimal places. We used CTEQ-4L parametrization (from PDFLIB, [17]) evaluated at $Q = (m_i + m_j)/2$ ($m_{i,j}$ are the masses of the particles produced in the hard scattering). Next-to-LO corrections enhance $\sigma_0$ and $\sigma_1$ by $\sim 20\%$ .

| $\tan \beta$ | $M_2$ | $m_{\tilde{g}}$ | $m_{\chi^0_1}$ | $m_i$ | $\sigma_0$ | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ | $\sigma_{nl}$ | $\sigma_{2l}$ | $\sigma_{3l}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 200 | 698 | 102 | 150 | 0.218 | 0.233 | 0.078 | 0.012 | 0.045 | 0.013 | 0.021 |
| | | | | 225 | 0.479 | 0.118 | 0.017 | 0.001 | 0.002 | 0.001 | 0.001 |
| | | | | 300 | 0.477 | 0.117 | 0.019 | 0.001 | 0.003 | 0.001 | 0.002 |
| | 400 | 150 | 0.016 | 0.023 | 0.006 | 0.001 | 0.045 | 0.018 | 0.021 |
| | | 225 | 0.086 | 0.034 | 0.004 | 0.000 | 0.003 | 0.002 | 0.001 |
| | | 300 | 0.085 | 0.033 | 0.005 | 0.000 | 0.003 | 0.002 | 0.002 |
| 30 | 200 | 698 | 97 | 150 | 0.163 | 0.217 | 0.119 | 0.029 | 0.031 | 0.023 | 0.075 |
| | | | | 225 | 0.496 | 0.124 | 0.036 | 0.002 | 0.001 | 0.002 | 0.004 |
| | | | | 300 | 0.518 | 0.126 | 0.015 | 0.001 | 0.003 | 0.002 | 0.002 |
| | 400 | 150 | 0.012 | 0.021 | 0.010 | 0.002 | 0.031 | 0.031 | 0.075 |
| | | 225 | 0.111 | 0.048 | 0.014 | 0.000 | 0.001 | 0.003 | 0.005 |
| | | 300 | 0.120 | 0.048 | 0.005 | 0.000 | 0.003 | 0.003 | 0.002 |
Thus the finally suggested signals are of the form

\[ \text{like-sign dimuons/ditaus} + \text{displaced vertex} + \text{a real W paired with one } \mu/\tau. \]  

(6)

The condition of having one displaced vertex forces us to leave out those events where both leptons have their origins in cascades rather than in $\chi_1^0$ decays.

In figures 1-3 we show some plots of the predicted number of signal events (of both like-sign dimuons and ditaus) expected at the Tevatron Run II ($\sqrt{s} = 2$ TeV, with an integrated luminosity of $10 \, \text{fb}^{-1}$), once the above set of criteria are specified. The Higgsino mass parameter $\mu$ is taken to be $-250$ GeV in all the cases. No drastic effect in the nature of these curves are observed due to variations in $\mu$. A common low-energy slepton mass has been assumed in each case. In addition, the physical stau masses are determined by left-right mixing depending on the value of $\tan\beta$. Each curve is truncated at the point where the lightest neutralino ceases to be lighter than all the sleptons.

Let us discuss the most prominent features of these results:

(i) For slepton masses of 150 GeV, leptonic final states can be observed via decays of on-shell sleptons produced in the preceding decays of neutralinos or charginos in the cascades. For low $\tan\beta$, like-sign dimuon and ditau events rates are closely comparable. As $\tan\beta$ increases, mixing in the stau sector lowers the mass of one physical state while still keeping it consistent with the current search limits[20]. This results in larger event rates with ditaus and a consequent splitting between the dimuon and ditau curves as seen from figures 1, 2 and 3. Also, $\mu\tau$-events with similar kinematic characteristics as our already described signals are expected in this scenario. The $\mu\tau$-type LSD event plots should correspond approximately to the sum of the dimuon and ditau curves for each combination of parameters.

(ii) With the slepton masses on the higher side (225 GeV and 300 GeV), the event rates are mostly controlled by the all-jet channel for relatively low masses of the lightest neutralino. In these regions, for low $\tan\beta$, the numbers of muonic and tau events are very close together, and are relatively insensitive to the above variation in the slepton masses. However, with large enough gaugino masses, two-body decays of $\chi^0_2$ and $\chi^+_1$ in the cascades become possible, whereby rates for the single-and dilepton + $\chi^0_1$ - pair events get enhanced. This causes both the muonic and tau-events to go up comparably for lower values of $\tan\beta$ for which there is no substantial mass-splitting between the smuon and stau mass eigenstates. For larger values of $\tan\beta$ ($\tan\beta = 10, 30$) in this region (see figures 2 and 3) there is a rather early onset of the two-body decays of $\chi^0_2$ and $\chi^+_1$ leading to a sharp enhancement in tauonic events while a relatively minor rise of this type is noticed for the corresponding muonic events at a larger value of gaugino masses. The difference is attributed primarily to the fact that for same $\tan\beta$ the lighter $\tau$ mass eigenstate is less massive than its muonic counterpart. This in turn implies that the two-body decays of gauginos involving muons open up for somewhat higher gaugino masses which suppress the signals from the production level as well. The rise in the events rates due to the above effects is offset by the fall in the rate of $\chi^0_2$ and $\chi^+_1$ production when the masses of the latter (and therefore that of $\chi^0_1$) go on increasing. That is why the curves showing the tau-rates as shooting up also show a fall following a peaking behaviour.

(iii) However, for a slepton mass of 300 GeV these features are not clear from the graphs. The relevant cross sections surely get diminished due to heavier sleptons and LSPs in the processes leading to a smaller number of events. These, when plotted with the curves for lower slepton masses, fail to attain the required resolution due to obvious reasons.

Our results indicate that rather copious numbers of uncut signal events\(^3\), unlikely to be faked by backgrounds, are expected over a large part of the parameter space. Comparing the upper and lower panels of each of of figures 1,2 and 3 it is seen that the number of events fall with a rise in the squark masses, since, as we have already mentioned, squark pairs form the main source of cascades here. Apart from that the general features of the events remain unaltered for fixed $\mu$ and $\tan\beta$.

\[^3\text{Actual analyses need to consider ID-efficiencies for } \mu, \tau \text{ and W’s, and isolation and } p_T \text{ cuts for } \mu, \tau.\]
In fig. 4 we show the muon $p_T$-distributions in some sample cases. We have separately plotted the distributions coming from decays of the LSP (i.e. the ones emerging from displaced vertices) and those produced in earlier stages of the cascades (i.e. the ones that would be there even if R-parity were conserved). Increasing the LSP mass, the leptons from the cascades are less important for the overall signal strength, while the muons originating from the LSP tend to be harder. We have used a slepton mass of 150 GeV in these plots; the cascades, as demonstrated in Table 1, are considerably less significant for higher slepton masses. These conservative estimates show that a large number of muons in each case survive an $p_T$-cut of the order of 15 GeV, usually adopted in Tevatron experiments [9]. Taking the overall detection efficiencies into account, we expect that well above 50 % of the events predicted in figures 1-3 can be salvaged after the experimental cuts employed at the Tevatron.

In conclusion, the decays of the lightest neutralino can have quite distinctive signatures in the considered R-parity violating scenario. The characteristic signals are final states comprising of like-sign dimuons and ditaus, together with a real $W$, with a measurable decay gaps ($O(1mm)$ or larger). These criteria eliminate any backgrounds, and distinguish the signal from those of other R-parity breaking models. An effective $W$-reconstruction leads to observation of the lightest neutralino mass peak. These considerations motivate to a certain extent the urge for further refinement of the techniques of such reconstruction as well as of the resolution of displaced vertices at Run-II of the Tevatron.

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Figure 1: The predicted numbers of like-sign dimuon and ditau events (indicated by the labels $\mu$ and $\tau$ on the respective curves) with a real $W$ and a displaced vertex, as a function of mass of the lightest neutralino (LSP) at the upgraded Tevatron with an integrated luminosity of $10 \, fb^{-1}$. Three values of the low energy slepton mass parameter (in GeV) have been used. Other parameters are: $\mu' = -250$ GeV, $\tan \beta = 3$. The degenerate squark mass $m_\tilde{q}$ is 300 GeV in the upper panel, 400 GeV in the lower one. Notice the different vertical scale.
Figure 2: Same as in Figure 1, but with $\tan \beta = 10$. 
Figure 3: Same as in Figure 1, but with $\tan \beta = 30$. 
Figure 4: $p_T$ distributions of muons for various values of $\tan \beta$. The upper panel shows the distributions for muons from a displaced vertex due to $R$-parity violating decays of the lightest neutralino (the LSP). The bottom panel illustrates those for muons originating from usual MSSM cascades. The values of the MSSM parameters used are $m_{\tilde{q}} = 300$ GeV, $m_{\tilde{t},\tilde{b}} \approx 150$ GeV, $m_{\chi_1^0} = 100$ GeV, $\mu' = -250$ GeV.