MEASURING NEUTRINO MIXING ANGLES AT LHC

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Abstract
We study an MSSM model with bilinear R-parity violation which is capable of explaining neutrino data while leading to testable predictions for ratios of LSP decay rates. Further, we estimate the precision with which such measurements could be carried out at the LHC.

1. INTRODUCTION

Recent neutrino experiments [1–4] clearly show that neutrinos are massive particles and that they mix. In supersymmetric models these findings can be explained by the usual seesaw mechanism [5–7]. However, supersymmetry allows for an alternative which is intrinsically supersymmetric, namely the breaking of R-parity. The simplest way to realize this idea is to add bilinear terms to the superpotential W:

$$W = W_{\rm MSSM} + \epsilon_i \hat{L}_i \hat{H}_u \tag{1}$$

For consistency one has also to add the corresponding bilinear terms to soft SUSY breaking which induce small vacuum expectation values (vevs) for the sneutrinos. These vevs in turn induce a mixing between neutrinos and neutralinos, giving mass to one neutrino at tree level. The second neutrino mass is induced by loop effects (see [8–10] and references therein). The same parameters that induce neutrino masses and mixings are also responsible for the decay of the lightest supersymmetric particle (LSP). This implies that there are correlations between neutrino physics and LSP decays [11–14].

In this note we investigate how well LHC can measure ratios of LSP branching ratios that are correlated to neutrino mixing angles in a scenario where the lightest neutralino $\tilde\chi^0_1$ is the LSP. In particular we focus on the semi-leptonic final states $l_i \mathrm{q}'\bar{\mathrm{q}}$ ($l_i = e, \mu, \tau$). There are several more examples which are discussed in [12]. In the model specified by Eq. (1) the atmospheric mixing angle at tree level is given by

$$\tan\theta_{\rm atm} = \frac{\Lambda_2}{\Lambda_3} \tag{2}$$

$$\Lambda_i = \epsilon_i v_d + \mu v_i \tag{3}$$

where v_i are the sneutrino vevs and v_d is the vev of H^0_d. It turns out that the dominant part of the $\tilde\chi^0_1$-W-l_i coupling O^L_i is given by

$$O^L_i = \Lambda_i f(M_1, M_2, \mu, \tan\beta, v_d, v_u) \tag{4}$$

where the exact form of f can be found in Eq. (20) of ref. [12]. The important point is that f only depends on MSSM parameters but not on the R-parity violating parameters. Putting everything together one finds:

$$\tan^2\theta_{\rm atm} \simeq \left|\frac{\Lambda_2}{\Lambda_3}\right|^2 \simeq \frac{BR(\tilde\chi^0_1 \to \mu^\pm \mathrm{W}^\mp)}{BR(\tilde\chi^0_1 \to \tau^\pm \mathrm{W}^\mp)} \simeq \frac{BR(\tilde\chi^0_1 \to \mu^\pm \bar{\mathrm{q}}\mathrm{q}')}{BR(\tilde\chi^0_1 \to \tau^\pm \bar{\mathrm{q}}\mathrm{q}')}, \tag{5}$$

where the last equality is only approximate due to possible (small) contributions from three body decays of intermediate sleptons and squarks. The restriction to the hadronic final states of the W is necessary for the identification of the lepton flavour. Note that Eq. (5) is a prediction of the bilinear model independent of the R-parity conserving parameters.

2. NUMERICAL RESULTS

We take the SPS1a mSUGRA benchmark point [15] as a specific example, characterized by $m_0 = 100$ GeV, $m_{\frac{1}{2}} = 250$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$, and $\mathrm{sign}(\mu) = 1$[1]. The low–energy parameters were derived using SPHENO 2.2 [16] and passed to PYTHIA 6.3 [17] using the recently defined SUSY Les Houches Accord [18]. The R-parity violating parameters (in MeV) at the low scale are given by: $\epsilon_1 = 43$, $\epsilon_2 = 100$, $\epsilon_3 = 10$, $v_1 = -2.9$, $v_2 = -6.7$ and $v_3 = -0.5$. For the neutrino sector we find $\Delta m^2_{\mathrm{atm}} = 3.8 \cdot 10^{-3}$ eV^2, $\tan^2\theta_{\mathrm{atm}} = 0.91$, $\Delta m^2_{\mathrm{sol}} = 2.9 \cdot 10^{-5}$ eV^2, $\tan^2\theta_{\mathrm{sol}} = 0.31$. Moreover, we find that the following neutralino branching ratios are larger than 1%:

$$\begin{array}{lll}
\mathrm{BR}(\mathrm{W}^{\pm}\mu^{\mp}) = 2.2\%, & \mathrm{BR}(\mathrm{W}^{\pm}\tau^{\mp}) = 3.2\%, & \mathrm{BR}(\bar{\mathrm{q}}\mathrm{q}'\mu^{\mp}) = 1.5\%, \\
\mathrm{BR}(\bar{\mathrm{q}}\mathrm{q}'\tau^{\mp}) = 2.1\%, & \mathrm{BR}(\mathrm{q}\bar{\mathrm{q}}\nu_i) = 4.7\%, & \mathrm{BR}(\mathrm{b}\bar{\mathrm{b}}\nu_i) = 15.6\%, \\
\mathrm{BR}(e^{\pm}\tau^{\mp}\nu_i) = 5.9\%, & \mathrm{BR}(\mu^{\pm}\tau^{\mp}\nu_i) = 30.3\%, & \mathrm{BR}(\tau^{+}\tau^{-}\nu_i) = 37.3\%,
\end{array}$$

where we have summed over the neutrino final states as well as over the first two generations of quarks. Moreover, there are 0.2% of neutralinos decaying invisibly into three neutrinos. In the case that such events can be identified they can be used to distinguish this model from a model with trilinear R-parity violating couplings because in the latter case they are absent.

We now turn to the question to what extent the ratio, Eq. (5), could be measurable at an LHC experiment. The intention here is merely to illustrate the phenomenology and to give a rough idea of the possibilities. For simplicity, we employ a number of shortcuts; e.g. detector energy resolution effects are ignored and events are only generated at the parton level. Thus, we label a final-state quark or gluon which has $p_\perp > 15$ GeV and which lies within the fiducial volume of the calorimeter, $|\eta| < 4.9$, simply as 'a jet'. Charged leptons are required to lie within the inner detector coverage, $|\eta| < 2.5$, and to have $p_\perp > 5$ GeV (electrons), $p_\perp > 6$ GeV (muons), or $p_\perp > 20$ GeV (taus). The assumed efficiencies for such leptons are [19] 75% for electrons, 95% for muons, and 85% for taus decaying in the 3–prong modes (we do not use the 1–prong decays), independent of $p_\perp$.

For SPS1a, the total SUSY cross section is $\sigma_{\mathrm{SUSY}} \sim 41$ pb. This consists mainly of gluino and squark pair production followed by subsequent cascades down to the LSP, the $\tilde{\chi}^0_1$. With an integrated luminosity of 100 fb^{-1}, approximately 8 million $\tilde{\chi}^0_1$ decays should thus have occurred in the detector.

An important feature of the scenario considered here is that the $\tilde{\chi}^0_1$ width is sufficiently small to result in a potentially observable displaced vertex. By comparing the decay length, $c\tau = 0.5$ mm, with an estimated vertex resolution of about 20 microns in the transverse plane and 0.5 mm along the beam axis, it is apparent that the two neutralino decay vertices should exhibit observable displacements in a fair fraction of events. Specifically, we require that both neutralino decays should occur outside an ellipsoid defined by 5 times the resolution. For at least one of the vertices (the 'signal' vertex), all three decay products ($\mu\mathrm{q}\bar{\mathrm{q}}'$ or $\tau\mathrm{q}\bar{\mathrm{q}}'$) must be reconstructed, while we only require one reconstructed decay product (jet in the inner detector or lepton in the inner detector whose track does not intersect the 5σ vertex resolution ellipsoid) for the second vertex (the 'tag' vertex).

Naturally, since the decay occurs within the detector, the standard SUSY missing $E_\perp$ triggers are ineffective. Avoiding a discussion of detailed trigger menus (cf. [20]), we have approached the issue by requiring that each event contains either four jets, each with $p_\perp > 100$ GeV, or two jets with $p_\perp > 100$ GeV together with a lepton (here meaning muon or electron) with $p_\perp > 20$ GeV, or one jet with $p_\perp > 100$ GeV together with two leptons with $p_\perp > 20$ GeV. Further, since the Standard Model background will presumably be dominated by $\mathrm{t}\bar{\mathrm{t}}$ events, we impose an additional parton–level b jet veto.

To estimate the efficiency with which decays into each channel can be reconstructed, a sample of 7.9 million SUSY events were generated with PYTHIA, and the above trigger and reconstruction cuts were imposed. To be conservative, we only include the resonant decay channels, where the quark pair at the signal vertex has the invariant mass of the W. The number of generated decays into

[1] Strictly speaking, the SPS points should be defined by their low-energy parameters as calculated with ISAJET 7.58.

mode	N_{gen}	$\epsilon_{\rm rec}$	$N_{\rm rec}(100\ {\rm fb}^{-1})$
$\tilde{\chi}^0_1 \to \mu{\rm W} \to \mu{\rm q}\bar{\rm q}'$	235000	0.10	12500
$\tilde{\chi}^0_1 \to \tau{\rm W} \to \tau_{3-{\rm prong}}{\rm q}\bar{\rm q}'$	51600	0.054	1400

Table 1: Statistical sample, estimated reconstruction efficiencies, and expected event numbers.

each channel, the fractions remaining after cuts, and the expected total number of reconstructed events scaled to an integrated luminosity of $100\ {\rm fb}^{-1}$ are given in table 1. The comparatively small efficiencies owe mainly to the requirement that *both* neutralino decays should pass the 5σ vertex resolution cut. Nonetheless, using these numbers as a first estimate, the expected statistical accuracy of the ratio, $R = BR(\tilde{\chi}^0_1 \to \mu^\pm{\rm W}^\mp)/BR(\tilde{\chi}^0_1 \to \tau^\pm{\rm W}^\mp)$, appearing in Eq. (5) becomes $\frac{\sigma(R)}{R} \simeq 0.028$.

3. CONCLUSIONS

We have studied neutralino decays in a model where bilinear R-parity violating terms are added to the usual MSSM Lagrangian. This model can successfully explain neutrino data and leads at the same time to *predictions* for ratios of the LSP decay branching ratios. In particular we have considered a scenario where the lightest neutralino is the LSP. In this case the ratio $BR(\tilde{\chi}^0_1 \to \mu^\pm{\rm W}^\mp)/BR(\tilde{\chi}^0_1 \to \tau^\pm{\rm W}^\mp)$ is directly related to the atmospheric neutrino mixing angle. Provided R-parity violating SUSY is discovered, the measurement of this ratio at colliders would thus constitute an important test of the hypothesis of a supersymmetric origin of neutrino masses.

We have investigated the possibility of performing this measurement at a 'generic' LHC experiment, using PYTHIA to generate LHC SUSY events at the parton level and imposing semi-realistic acceptance and reconstruction cuts. Within this simplified framework, we find that the LHC should be sensitive to a possible connection between R-parity violating LSP decays and the atmospheric mixing angle, at least for scenarios with a fairly light sparticle spectrum and where the neutralino decay length is sufficiently large to give observable displaced vertices. Obviously, the numbers presented here represent crude estimates and should not be taken too literally. A more refined experimental analysis would be necessary for more definitive conclusions to be drawn.

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