All Possible Lightest Supersymmetric Particles in R-Parity Violating mSUGRA Models and their Signals at the LHC

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Abstract. We consider minimal supergravity (mSUGRA) models with an additional R-parity violating operator at the grand unification scale. This can change the supersymmetric spectrum leading on the one hand to a sneutrino, smuon or squark as the lightest supersymmetric particle (LSP). On the other hand, a wide parameter region is reopened, where the scalar tau is the LSP. It is vital to know the nature of the LSP, because supersymmetric particles normally cascade decay down to the LSP at collider experiments. We investigate in detail the conditions leading to non-neutralino LSP scenarios. We also present some typical LHC signatures.

Keywords: Renormalization group, mSUGRA, R-parity violation, LHC phenomenology

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INTRODUCTION

In the minimal supersymmetric standard model (MSSM) the LSP is stable guaranteed by the discrete symmetry R-parity, $R_p$. The LSP must then be the lightest neutralino for cosmological reasons. However, if we drop $R_p$, further renormalizable operators are allowed in the superpotential [1]

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \frac{1}{2} \lambda''_{ijk} \tilde{U}_i \tilde{U}_j \tilde{D}_k + \kappa_i L_i H_d.$$  (1)

To ensure the stability of the proton we must either suppress the lepton- or the baryon-number violating operators in Eq. (1). These terms violate $R_p$ and thus the LSP is no longer stable [2]. It can be in principle any supersymmetric particle (sparticle) [2]

$$\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\ell}_{L/R}^\pm, \tilde{\tau}_i, \tilde{\tilde{\nu}}_i, \tilde{\tilde{q}}_{L/R j}, \tilde{\tilde{b}}_1, \tilde{\tilde{t}}_1, \tilde{\tilde{g}}.$$  (2)

It is vital to know the nature of the LSP, because sparticles normally cascade decay down to the LSP at collider experiments.

However, due the bewildering array of LSP candidates in Eq. (2), it is difficult to perform detailed phenomenological studies. We therefore need a guiding principle. As a first step, we investigate the $R_p$ violating ($\neq R_p$) minimal supergravity model [1]:

$$M_0, M_{1/2}, A_0, \tan \beta, \text{sgn}(\mu), \Lambda \quad \text{with} \quad \Lambda \in \{\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}\}.$$  (3)

1 Potential other dark matter candidates are for example the axino or the lightest U-parity particle [4].
Here, $M_0$ ($M_{1/2}$) is the universal softbreaking scalar (gaugino) mass and $A_0$ is the universal softbreaking trilinear scalar interaction at the grand unification scale $M_{\text{GUT}}$. $\tan \beta$ is the ratio of the two vacuum expectation values and $\mu$ is the Higgs mixing parameter. The effects of $R_p$ are incorporated by assuming one non-vanishing trilinear coupling $\Lambda$ at $M_{\text{GUT}}$ at a time, cf. Eq. (1).

We now have a simple and well-motivated framework, in which we can systematically investigate the nature of the LSP and its phenomenology at the LHC.

**LSP CANDIDATES IN $R_p$ VIOLATING MSUGRA MODELS**

In most of the $R_p$ mSUGRA parameter space the lightest neutralino $\tilde{\chi}_1^0$ or the lightest scalar tau $\tilde{\tau}_1$ is the LSP as can be seen in Fig. 1a, b. According to Fig. 1a, we can obtain a $\tilde{\tau}_1$ LSP instead of the $\tilde{\chi}_1^0$ LSP by increasing $M_{1/2}$. Increasing $M_{1/2}$ increases the mass of the (bino-like) $\tilde{\chi}_1^0$ faster than the mass of the (mainly right-handed) $\tilde{\tau}_1$. Apart from that, we can also get a $\tilde{\tau}_1$ LSP by increasing $\tan \beta$. Increasing $\tan \beta$ increases on the one hand the magnitude of the tau Yukawa coupling, $\tilde{\tau}$, which increases its (negative) effect on the running of the $\tilde{\tau}_1$ mass. On the other hand, $\tan \beta$ increases the mixing between $\tilde{\tau}_L$ and $\tilde{\tau}_R$. We conclude that a $\tilde{\tau}_1$ LSP is as well motivated as a $\tilde{\chi}_1^0$ LSP in $R_p$ mSUGRA.

We have assumed in Fig. 1a that $\Lambda$ at $M_{\text{GUT}}$ is at least one order of magnitude smaller than the gauge couplings, i.e. it has no significant impact on the running of the sparticle masses. However, for $\Lambda = \mathcal{O}(10^{-1})$, we need to take into account the $R_p$ contributions to the renormalization group equations (RGEs). If a sparticle directly couples to $\Lambda$, the dominant contributions to the RGE of the running sparticle mass $\tilde{m}$ are [1, 2, 3, 4]:

$$16\pi^2 \frac{d(\tilde{m}^2)}{dt} = -a_i g_i^2 M_i^2 - b g_1^2 \mathcal{J} + \Lambda^2 \mathcal{F} + c h_A^2, \quad h_A \equiv \Lambda \times A_0 \text{ at } M_{\text{GUT}}. \quad (4)$$

Here, $g_i (M_i)$, $i = 1, 2, 3$, are the gauge couplings (soft breaking gaugino masses). $t = \ln Q$ with $Q$ the renormalization scale and $a_i$, $b$, $c$ are constants of $\mathcal{O}(10^{-1} - 10^1)$. $\mathcal{J}$ and $\mathcal{F}$ are linear functions of products of two softbreaking scalar masses.

The sum of the first two $R_p$ terms in Eq. (4) is negative and thus increases $\tilde{m}$ when running from $M_{\text{GUT}}$ to the electroweak scale. In contrast, the last two $R_p$ terms proportional to $\Lambda^2$, $h_A^2$, are always positive and therefore decrease $\tilde{m}$. We thus expect new LSP candidates beyond $\tilde{\chi}_1^0$, $\tilde{\tau}_1$ if these latter terms contribute substantially, i.e. $\Lambda = \mathcal{O}(g_i)$ [2, 5]. We can strengthen the (negative) contribution of $h_A^2$, by choosing a negative $A_0$ with a large magnitude; for moderate positive $A_0$ there is a cancellation in the RGE evolution of $h_A$ [5].

As a first example, we show in Fig. 1b the case of a right-handed $\tilde{\mu}_R$ LSP which we obtain via $\lambda_{132} |_{\text{GUT}} = 0.09$ [2]. We see that the $\tilde{\mu}_R$ LSP exists in an extended region of

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2 All sparticle mass spectra have been calculated with SOFTSUSY 3.0 [5].

3 For third generation sparticles we also need to take into account the contributions from the Higgs-Yukawa interactions. Their effect is similar to $\Lambda$ and $h_A$ in Eq. (4).
FIGURE 1. Mass difference, $\Delta M$, between the next-to-lightest LSP (NLSP) and LSP. The LSP candidates are explicitly mentioned. The blackened out region corresponds to parameter points, which possess a tachyon or which violate other experimental constraints; see Ref. [2, 5] for details.

- Fig. 1(a): $\tilde{\tau}_1$ LSP region; $M_0 = 100$ GeV, $A_0 = -100$ GeV, $\text{sgn}(\mu) = +1$, $\Lambda < \mathcal{O}(10^{-1})$.
- Fig. 1(b): $\tilde{\mu}_R$ LSP via $\lambda_{132}|_\text{GUT} = 0.09$; $M_0 = 170$ GeV, $A_0 = -1500$ GeV, $\text{sgn}(\mu) = +1$. Fig. 1(c): $\tilde{\nu}_\mu$ LSP via $\lambda'_{231}|_\text{GUT} = 0.11$; $A_0 = -600$ GeV, $\tan\beta = 10$, $\text{sgn}(\mu) = +1$. Fig. 1(d): $\tilde{t}_1$ LSP via $\lambda''_{323}|_\text{GUT} = 0.35$; $M_0 = 120$ GeV, $M_{1/2} = 480$ GeV, $\text{sgn}(\mu) = +1$.

$R_p$ mSUGRA. We find a $\tilde{\mu}_R$ LSP for all $M_{1/2} > 480$ GeV, because $M_{1/2}$ increases the mass of the (bino-like) $\tilde{\chi}_1^0$ faster than the mass of the $\tilde{\mu}_R$ [2].

Our next example is a muon sneutrino $\tilde{\nu}_\mu$ LSP via $\lambda'_{231}|_\text{GUT} = 0.11$ [5], cf. Fig. 1(c). We again observe that the $\tilde{\nu}_\mu$ LSP exists in large regions of the mSUGRA parameter space. We can get a $\tilde{\tau}_1$ LSP instead of a $\tilde{\nu}_\mu$ LSP if we increase $M_{1/2}$, because the left-handed $\tilde{\nu}_\mu$ LSP couples stronger to the gauginos than the (mainly right-handed) $\tilde{\tau}_1$. If we choose $M_0$ large enough we can always reobtain the $\tilde{\chi}_1^0$ LSP.

Finally, we show in Fig. 1(d) that also squark LSPs are possible via a non-vanishing baryon number violating operator, cf. Eq. (1). Fig. 1(d) gives the example of a stop $\tilde{t}_1$ LSP via $\lambda''_{323}|_\text{GUT} = 0.35$ [2]. We observe that the $\tilde{t}_1$ LSP parameter space is more restricted compared to the aforementioned LSP candidates. We can also see in Fig. 1(d) that $A_0 = \mathcal{O}(-1\text{TeV})$ is vital to obtain a $\tilde{t}_1$ LSP. On the one hand this $A_0$ increases left-right mixing. On the other hand it increases the negative effect of the top Yukawa
coupling and of $\lambda''_{323}$ on the running of the $\tilde{t}_1$ mass; see Ref. [2] for further details.

Beside the $\tilde{\tau}_1$, $\tilde{\mu}_R$, $\tilde{\nu}$ and $\tilde{t}_1$ we also found the $\tilde{e}_R$, $\tilde{s}_R$, $\tilde{d}_R$ and $\tilde{b}_1$ as (the only possible) further non-$\tilde{\chi}_1^0$ LSP candidates in $R_p$ mSUGRA [2].

**HADRON COLLIDER PHENOMENOLOGY**

We have found in the last section many new candidates for the LSP in $R_p$ mSUGRA models. As an obvious next step, we will now investigate the hadron collider phenomenology of some of these new scenarios.

The collider phenomenology of $\tilde{\tau}_1$ LSP scenarios is mainly driven by the different decay modes of the $\tilde{\tau}_1$ LSP. It can either decay via a 4-body decay or via a 2-body decay; see Refs. [1, 6, 7] for more details and explicit examples.

The $\tilde{\mu}_R$ LSP in Fig. 1b will decay via $\lambda_{132}$, i.e. $\tilde{\mu}_R \rightarrow e\nu_\tau, \tau \nu_e$. One typical and simple supersymmetric process at the LHC will therefore be

$$PP \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \rightarrow (q\mu\tilde{\mu}_R)(q\mu\tilde{\mu}_R) \rightarrow (q\mu e\nu_\tau)(q\mu \tau \nu_e).$$ (5)

Even this simple supersymmetric process leads to four charged leptons in the final state; two muons from the decay of the $\tilde{\chi}_1^0$ non-LSP into the $\tilde{\mu}_R$ LSP and an electron and a tau from the $\tilde{\mu}_R$ LSP decays. Due to the large number of charged leptons, we expect discovery of $\tilde{\mu}_R$ LSP scenarios at LHC to be relatively easy.

One of the most striking signatures of $\tilde{\nu}_\mu$ LSP scenarios, Fig. 1c, are high-$p_T$ muons, i.e. muons with a transverse momentum of a few hundred GeV [5]. At the same time we have a quark with roughly the same energy, which is expected to be back-to-back to the muon. The high-$p_T$ muons stem from the decay of a (heavy) squark via $\lambda'_{231}$, e.g. $\tilde{d}_R \rightarrow \mu t$. The large squark mass is in this case transformed into the momenta of the standard model particles. High-$p_T$ muons can be found in roughly 10% of all sparticle pair production events at the LHC, because $\lambda'_{231} = o(g_i)$.

In general, we expect the discovery of squark LSP scenarios at the LHC to be more difficult compared to $R_p$ conserving scenarios. Instead of large amounts of missing energy we have many jets in the final state from the LSP decays [3]. However, it was claimed in Ref. [9] that the complete $\tilde{t}_1$ LSP region in Fig. 1d should be testable at the Tevatron with the available data. But this analysis has not been done so far.

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