General NMSSM signatures at the LHC

H. K. Dreiner* and F. Staub†

Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn, Nußallee 12, 53115 Bonn, Germany

A. Vicente‡

Laboratoire de Physique Théorique, CNRS – UMR 8627, Université de Paris-Sud 11 F-91405 Orsay Cedex, France

We study the possible LHC collider signatures in the next-to-minimal supersymmetric Standard Model (NMSSM). The general NMSSM consists of 29 supersymmetric (SUSY) particles which can be mass ordered in $29! \simeq 9 \cdot 10^{30}$ ways. To reduce the number of hierarchies to a more manageable amount we assume a degeneracy of the sfermions of the first two generations with the same quantum numbers. Further assumptions about the neutralino and chargino masses leave 15 unrelated parameters. We check all $15! \approx 10^{12}$ relevant mass orderings for the dominant decay chains and the corresponding collider signatures at the LHC. As preferred signatures, we consider charged leptons, missing transverse momentum, jets, and W, Z or Higgs bosons. We present the results for three different choices of the singlet to Higgs coupling λ: (a) small: $O(\lambda) < O(Y_\tau)$, (b) large: $O(\lambda) \simeq O(Y_{top}, Y_b, Y_\tau)$ and (c) dominant: $O(\lambda) > O(Y_{top})$. We compare these three scenarios with the MSSM expectations as well as among each other. We also mention a possible mass hierarchy leading to 7 jets plus 1 lepton signatures at the LHC and comment briefly on the consequence of possible R-parity violation.

I. INTRODUCTION

There is strong evidence that a particle similar to the Standard Model Higgs boson exists with a mass in the range between 122 and 128 GeV [1, 2]. Assuming this is the Higgs boson, this has significant implications for supersymmetric extensions of the Standard Model (SM) capable of ameliorating the (little) hierarchy problem [3]. In particular, in the Constrained Minimal Supersymmetric Standard Model (CMSSM) the fine tuning needed to achieve this Higgs mass is large,

*Electronic address: dreiner@uni-bonn.de
†Electronic address: fnstaub@physik.uni-bonn.de
‡Electronic address: avelino.vicente@th.u-psud.fr

requiring a cancellation between (in the CMSSM) uncorrelated parameters of order 1 part in 300 [4–7]. The overall fit of the CMSSM to the low-energy and LHC data, including the Higgs, is also poor [7–10]. In the context of the more general MSSM, allowing for non-universal supersymmetry breaking parameters, defined close to the electroweak scale it is easier to find valid regions of parameter space to explain the Higgs mass. However, still large stop masses and A-terms are needed [11]. This tension gets significantly reduced if a new gauge singlet is added to the particle content which has a superpotential coupling to the MSSM doublet Higgs fields. The easiest example of this kind of model is the next-to-minimal, supersymmetric Standard Model (NMSSM) [12–15]. New F-Term contributions already at tree-level help to increase the Higgs mass which is bounded in the MSSM (at tree-level) to $m_h \leq M_Z$. This makes it much easier to obtain Higgs masses in the preferred mass range in much larger areas of parameter space and thus reduces the fine-tuning [16].

However, the new singlet state might not only have an impact on the mass of the light Higgs boson but also on the collider phenomenology: for instance, an additional light, singlino-like neutralino can appear in the SUSY cascade decays. Therefore, we shall compare all possible signatures of the general NMSSM with those possible in the general MSSM. Previously, the general signatures of the MSSM based on 9 and 14 free mass parameters at the SUSY scale have been studied in [17] and [18], respectively. In the latter case the third generation was treated separately. We take the scenario with 14 mass parameters and add a 15th parameter, the singlino mass. This leads in general to $15! \sim 1.3 \cdot 10^{12}$ mass hierarchies. We categorize all signatures by the number of charged leptons, jets, massive bosons and the presence or absence of missing transverse energy ($\not{E}_T$, which is actually missing transverse momentum, $\not{p}_T$). In this context we study three different NMSSM scenarios: dominant λ, large λ and small λ, where λ denotes the singlet Higgs coupling, *cf.* Eq. (1). In the first case, λ is even larger than the top Yukawa coupling, while in the second case it is comparable to the size of the third generation Yukawa couplings. In the third case it is not larger than a second generation Yukawa coupling and we are in the MSSM limit.

The rest of the paper is organized as follows: In sec. II we give the basic definitions and conventions used throughout the paper. We explain in detail our approach and the underlying assumptions in sec. III. In sec. IV we discuss our results before we conclude in sec. V.

II. MODEL DEFINITIONS

In the following we consider the next-to-minimal supersymmetric standard model (NMSSM). For a detailed introduction to the NMSSM we refer the interested reader to Ref. [15]. In the NMSSM the particle content of the MSSM is extended by one chiral superfield which is a gauge singlet: $\hat{S}\,(\mathbf{1},\mathbf{1},0)$. In parentheses we give the SM gauge quantum numbers with respect to $SU(3)_c\times SU(2)_L\times U(1)_Y$. The other chiral superfields of the supersymmetric SM read $\hat{q}_a\,(\mathbf{3},\mathbf{2},\frac{1}{6})$, $\hat{\ell}_a\,(\mathbf{1},\mathbf{2},-\frac{1}{2})$, $\hat{H}_d\,(\mathbf{1},\mathbf{2},-\frac{1}{2})$, $\hat{H}_u\,(\mathbf{1},\mathbf{2},\frac{1}{2})$, $\hat{d}^c_a\,(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$, $\hat{u}^c_a\,(\bar{\mathbf{3}},\mathbf{1},\frac{2}{3})$, $\hat{e}^c_a\,(\mathbf{1},\mathbf{1},1)$, where $a=1,2,3$ is a generation index. The vector superfields are the same as in the MSSM: $\tilde{g}_\alpha\,(\mathbf{8},\mathbf{1},0)$, $\tilde{W}^i\,(\mathbf{1},\mathbf{3},0)$, $\tilde{B}\,(\mathbf{1},\mathbf{1},0)$. Using these superfields and demanding an additional Z_3 symmetry[1] it is possible to write down a scale invariant superpotential

$$W = Y_e^{ab}\,\hat{\ell}^j_a\,\hat{e}^c_b\,\hat{H}^i_d\,\epsilon_{ij} + Y_d^{ab}\,\hat{q}^{j\alpha}_a\,\hat{d}^c_{\alpha b}\,\hat{H}^i_d\,\epsilon_{ij} + Y_u^{ab}\hat{q}^{i\alpha}_a\,\hat{u}^c_{\alpha b}\,\hat{H}^j_u\,\epsilon_{ij} + \lambda\,\hat{S}\,\hat{H}^i_u\,\hat{H}^j_d\epsilon_{ij} + \frac{1}{3}\kappa\,\hat{S}\,\hat{S}\,\hat{S}\,. \tag{1}$$

Here $a,b=1,2,3$ are generation indices and $i,j=1,2$ are $SU(2)_L$ gauge indices of the fundamental representation. ϵ_{ij} is the totally anti-symmetric tensor. Y_e, Y_d, Y_u are dimensionless 3x3 matrices of Yukawa couplings. The soft SUSY breaking potential consists of masses for the scalar components of the chiral superfields, gaugino mass terms as well as trilinear-scalar couplings:

$$\begin{aligned}\mathcal{V}_{\rm SB} \;=\;& m_S^2|S|^2 + m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + \tilde{q}^\dagger m_{\tilde{q}}^2\tilde{q} + \tilde{l}^\dagger m_{\tilde{l}}^2\tilde{l} + \tilde{d}^\dagger m_{\tilde{d}}^2\tilde{d} + \tilde{u}^\dagger m_{\tilde{u}}^2\tilde{u}\\ &+\frac{1}{2}\Big(M_1\,\tilde{B}\tilde{B} + M_2\,\tilde{W}_i\tilde{W}^i + M_3\,\tilde{g}_\alpha\tilde{g}^\alpha + h.c.\Big)\\ &-H_u\tilde{q}T_u\tilde{u}^\dagger + H_d\tilde{q}T_d\tilde{d}^\dagger + H_d\tilde{l}T_e\tilde{e}^\dagger + T_\lambda S H_u H_d + \frac{1}{3}T_\kappa SSS\,.\end{aligned} \tag{2}$$

One of the appealing features of the NMSSM is that it solves the μ problem of the MSSM [20]: after SUSY breaking the scalar component of $\hat{S}$, S, receives a vacuum expectation value (VEV), denoted v_s, which leads to an effective mass term of the Higgsinos

$$\mu_{\rm eff} = \frac{1}{\sqrt{2}}\lambda v_s\,. \tag{3}$$

Here, we have used the decomposition

$$S = \frac{1}{\sqrt{2}}\left(\phi_s + i\sigma_s + v_s\right)\,. \tag{4}$$

Since v_s and thus also $\mu_{\rm eff}$ are a consequence of SUSY breaking one finds that $\mu_{\rm eff}$ is naturally of the order of the SUSY breaking scale.

ϕ_s and σ_s mix together with the neutral Higgs boson of the MSSM to form three CP even and two CP odd eigenstates, while the fermionic component of $\hat{S}$ mixes after EWSB with the other four neutralinos of the MSSM. In total, there are 29 mass eigenstates in the NMSSM with R-parity -1, called sparticles: 12 squarks, 6 charged sleptons, 3 neutral sleptons, 5 neutralinos, 2 charginos and

[1] For a discussion of the potential cosmological problems see for example [19].

1 gluino. With no *a priori* model explaining the masses, these 29 states lead to $29! \simeq 8.8 \cdot 10^{30}$ possible mass orderings or *hierarchies*. Unfortunately, it is computationally impossible to classify the dominant signatures of this general setup. Therefore, we make the same assumptions to reduce the number of hierarchies to a manageable amount as for the MSSM in Ref. [18]:

(i) The mixing between sparticles is sub-dominant, so we can identify the mass eigenstates with the corresponding gauge eigenstates. The only exception are the Higgsinos, which we assume to be maximally mixed.

(ii) The first and second generations of sfermions of the same kind are degenerate in mass. We consider the third generation masses as independent parameters, *e.g.* for the sleptons

$$m_{\tilde{e}L} = m_{\tilde{\mu}L} = m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} \equiv m_{\tilde{\ell},11} \tag{5}$$

$$m_{\tilde{e}R} = m_{\tilde{\mu}R} \equiv m_{\tilde{e},11} \tag{6}$$

$$m_{\tilde{\tau}L} = m_{\tilde{\nu}_\tau} \equiv m_{\tilde{\ell},33} \tag{7}$$

$$m_{\tilde{\tau}R} \equiv m_{\tilde{e},33}\,, \tag{8}$$

and analogously for the squarks.

(iii) The Higgsino mass mixing term is given by

$$\mu_{\text{eff}} = \frac{1}{\sqrt{2}}\lambda v_s\,, \tag{9}$$

and the singlet mass is given by

$$M_S = \frac{1}{\sqrt{2}}\kappa v_s\,. \tag{10}$$

These three assumptions leave us with 15 relevant mass parameters,

$$M_1, M_2, M_3, \mu_{\text{eff}}, M_S \tag{11}$$

$$m_{\tilde{e},11}, m_{\tilde{e},33}, m_{\tilde{\ell},11}, m_{\tilde{\ell},33} \tag{12}$$

$$m_{\tilde{d},11}, m_{\tilde{d},33}, m_{\tilde{u},11}, m_{\tilde{u},33}, m_{\tilde{q},11}, m_{\tilde{q},33}\,, \tag{13}$$

and thus 15! different hierarchies. Furthermore, the identification of the first and second generation sfermions allows us to reduce the number of fields we need to take into account in our analysis. We

Particle	Name	Mass
Singlino-like neutralino	$\tilde{S}$	M_S
Bino-like neutralino	$\tilde{B}$	M_1
Wino-like neutralino	$\tilde{W}^0$	M_2
Higgsino-like neutralinos	$\tilde{H}^0$	$\mu_{\rm eff}$
Gluino	$\tilde{G}$	M_3
Wino-like chargino	$\tilde{W}^\pm$	M_2
Higgsino-like chargino	$\tilde{H}^\pm$	μ
left-Squarks (1./2. generation)	$\tilde{q}_{1,2} \equiv \tilde{q}$	$m_{\tilde{q},11}$
down-right Squarks (1./2. generation)	$\tilde{d}, \tilde{s} \equiv \tilde{d}$	$m_{\tilde{d},11}$
up-right Squarks (1./2. generation)	$\tilde{u}, \tilde{c} \equiv \tilde{u}$	$m_{\tilde{u},11}$
left charged sleptons (1./2. generation)	$\tilde{e}_L, \tilde{\mu}_L \equiv \tilde{l}$	$m_{\tilde{l},11}$
sneutrinos (1./2. generation)	$\tilde{\nu}_e, \tilde{\nu}_\mu \equiv \tilde{\nu}$	$m_{\tilde{l},11}$
right sleptons (1./2. generation)	$\tilde{e}_R, \tilde{\mu}_R \equiv \tilde{e}$	$m_{\tilde{e},11}$
left-Squarks (3. generation)	$\tilde{q}_3$	$m_{\tilde{q},33}$
down-right Squarks (3. generation)	$\tilde{b}$	$m_{\tilde{d},33}$
up-right Squarks (3. generation)	$\tilde{t}$	$m_{\tilde{u},33}$
left staus (3. generation)	$\tilde{\tau}_L$	$m_{\tilde{l},33}$
sneutrinos (3. generation)	$\tilde{\nu}_\tau$	$m_{\tilde{l},33}$
right sleptons (3. generation)	$\tilde{\tau}_R$	$m_{\tilde{e},33}$

TABLE I: Particle content and relevant mass parameters.

combine them because, by assumption, they lead to the same signatures:

$$\begin{aligned} (\tilde{e}_L/\tilde{\mu}_L) &\rightarrow \tilde{\ell}, \\ (\tilde{e}_R/\tilde{\mu}_R) &\rightarrow \tilde{e}, \\ (\tilde{d}_L/\tilde{s}_L/\tilde{u}_L/\tilde{c}_L) &\rightarrow \tilde{q}, \\ (\tilde{d}_R/\tilde{s}_R) &\rightarrow \tilde{d}, \\ (\tilde{u}_R/\tilde{c}_R) &\rightarrow \tilde{u}, \\ (\tilde{\nu}_e/\tilde{\nu}_\mu) &\rightarrow \tilde{\nu}, \end{aligned} \tag{14}$$

as well as the two Higgsino-like neutralinos. A collection of the considered states as well as of the relevant mass parameters is given in Table I.

III. STRATEGY FOR THE ANALYSIS

We use for our analysis the same approach as for the MSSM in Ref. [18] which we summarize here. In total, we have $15! = 1.307.674.368.000 \approx 1.3 \cdot 10^{12}$ hierarchies. Each one can be denoted as a chain of fields in decreasing order of mass from left to right:

$$i_1 \dots i_n C r_1 \dots r_m \tag{15}$$

C denotes the lightest colored particle (LCP), excluding the third generation. So C is the lightest of the four fields $\tilde{G}$, $\tilde{q}$, $\tilde{d}$ and $\tilde{u}$. The particles $\{i_k\}$ (i for irrelevant) are all heavier, and contain among others the remaining colored particles, other than possible third generation squarks. The particles $\{r_k\}$ (r for relevant) are all lighter than C and are potentially involved in the cascade decay of C and thus important for our analysis. We assume that C is the only directly produced particle at the LHC. We do not impose any restrictions on the LSP, denoted r_m above.

We are interested in the determination of the *dominant decay chains* for all hierarchies. These are the decay chains $C \to r_i \to \cdots \to r_m =$ LSP that will dominantly happen at the LHC for each hierarchy. Not all $r_j,\ j \in \{1, ..., m\}$ are necessarily involved. In order to find them we apply the same algorithm as in Refs. [17, 18]:

1. Find the SUSY particles which are lighter than the LCP and have the largest coupling to it.
2. For each of these, search for the lighter particles with the largest coupling to it. The existing possibilities must be considered independently.
3. Iterate step 2 until the LSP is reached.

In principle, one can have more than one dominant decay chain for a given hierarchy. That situation would correspond to decay chains with similar rates at the LHC. Once the dominant decay chains are found, one can determine their signature. These signatures, denoted here as *dominant signatures*,[2] represent the main result of our study. They are obtained by summing up the decay products of all steps in the decay chain[3].

We have considered as final state particles in our analysis

1. charged leptons (l),

[2] If different signatures can be the result of a given decay chain we have chosen the one with the largest number of charged leptons.

[3] See Ref. [18] for the coupling strengths and the corresponding decay products in the MSSM, the NMSSM transitions are discussed below.

transition	strength	signature	transition	strength	signature	transition	strength	signature
$\tilde{S} \leftrightarrow \tilde{H}^0$	A	v	$\tilde{S} \leftrightarrow \tilde{H}^\pm$	A	v	$\tilde{S} \leftrightarrow \tilde{l}$	C	$v+l$
$\tilde{S} \leftrightarrow \tilde{d}$	C	$j+v$	$\tilde{S} \leftrightarrow \tilde{q}$	C	$j+v$	$\tilde{S} \leftrightarrow \tilde{u}$	C	$j+v$
$\tilde{S} \leftrightarrow \tilde{W}^0$	C	$2j+v$	$\tilde{S} \leftrightarrow \tilde{W}^\pm$	C	$2j+v$	$\tilde{S} \leftrightarrow \tilde{e}$	C	$v+l$
$\tilde{S} \leftrightarrow \tilde{\nu}$	C	$l+v$	$\tilde{S} \leftrightarrow \tilde{t}$	B	$j+v$	$\tilde{S} \leftrightarrow \tilde{b}$	B	$j+v$
$\tilde{S} \leftrightarrow \tilde{q}_3$	B	$j+v$	$\tilde{S} \leftrightarrow \tilde{\tau}_R$	B	$\not{E}_T+v$	$\tilde{S} \leftrightarrow \tilde{\tau}_L$	B	$j+v$
$\tilde{S} \leftrightarrow \tilde{\nu}_\tau$	C	$l+v$	$\tilde{S} \leftrightarrow \tilde{B}$	C	$2j+v$	$\tilde{S} \leftrightarrow \tilde{G}$	C	$2j+v$

TABLE II: Interactions of the singlino. We have considered for our analysis charged lepton (l), jets (j), massive bosons (v) and missing transversal energy ($\not{E}_T$) as signatures. The coupling strengths A, B and C depend on the value taken for λ, see text.

2. jets (j),
3. massive bosons (v)
4. missing transverse energy ($\not{E}_T$) (neutrinos and neutralino and sneutrino LSP, for RpC).

Note that *massive bosons* stands for both gauge and Higgs bosons including the scalar and pseudoscalar singlets. For the signatures and coupling strengths of the MSSM particle we refer to Ref. [18], where three different categories have been introduced to quantize the coupling strength

- *not suppressed*: a two body decay mode which does not suffer from any mixing suppression
- *suppressed*: a two body decay mode which is mixing suppressed or a three body decay without additional suppression
- *strongly suppressed*: a three body decay with mixing suppression or a four body decay

Note that some additional assumptions enter the definition of the dominant signature for each transition. These have an impact on our final results:

- We distinguish $\tilde{W}^0/\tilde{W}^\pm$, $\tilde{H}^0/\tilde{H}^\pm$, $\tilde{l}/\tilde{\nu}$ and $\tilde{\tau}/\tilde{\nu}_\tau$ in the decay chains because we differentiate between charged leptons and $\not{E}_T$ as a signature.
- Emitted τ's are regarded as ordinary jets.
- When, for a given transition, two different decay products with similar strengths are possible, we always choose the one with the largest amount of charged leptons. When the choice is between τs and $\not{E}_T$, we always choose $\not{E}_T$.

- We disregard the possibility of degeneracies among fields of different types (with the exceptions mentioned above concerning first and second generation sfermions). Therefore, 2-body decays have no phase space suppression.

- We do not treat jets originating from third generation quarks separately.

For the singlino we distinguish three categories of couplings (A,B,C) to the other SUSY particles, see Table II. The relative order between (A,B,C) and the strengths relative to the MSSM transitions depend on the value taken for λ. In the following we study three different cases:

1. **Small** λ: λ is smaller than the electroweak gauge couplings. We can identify

   - A = suppressed
   - B = strongly suppressed
   - C $<$ strongly suppressed

2. **large** λ: λ is not larger or smaller than the third generation Yukawa couplings. This leads to the following size of singlino couplings:

   - A = not suppressed
   - B = suppressed
   - C = strongly suppressed

3. **dominant** λ: λ is larger than all other couplings. In that case we have

   - A $>$ not suppressed
   - not suppressed $>$ B $>$ suppressed
   - suppressed $>$ C $>$ strongly suppressed

We exemplify this method with the hierarchy

$$i_1 \ldots i_8 \tilde{G} \tilde{b} \tilde{H}^0 \tilde{S} \tilde{W}^0 \tilde{l} \tilde{B} \tag{16}$$

For the first transition only one possibility exists because the largest coupling is $\tilde{G} \to \tilde{b}$. For the second transition there are two dominant possibilities: $\tilde{b} \to \tilde{H}^0$, $\tilde{B}$. Furthermore, the higgsino couples with the same strength to the wino and to the bino, while the coupling to the singlino depends on our choice of λ. If we assume a dominant λ, the Higgsino will only decay into the singlino. For large λ, the Higgsino decays with the same probability into the wino, bino and singlino. Therefore, all three branches have to be considered. For small λ, the Higgs decays dominantly only to the Wino or Bino.

Moreover, the wino will always take the way via the slepton to decay into the LSP. In contrast, as can be seen in Table II the singlino couples to the wino, bino and slepton with the same strength. Hence, all three possibilities have to be considered. In conclusion, depending on the choice of λ different decay chains are possible:

- small λ: there are three dominant decay chains and two different dominant signatures:

$$\tilde{G} \to \tilde{b} \to \tilde{B}: \quad 2j \tag{17}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{B}: \quad 2j + v \tag{18}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{W}^0 \to \tilde{l} \to \tilde{B}: \quad 2j + v + 2l \tag{19}$$

- large λ: there are six dominant decay chains

$$\tilde{G} \to \tilde{b} \to \tilde{B}: \quad 2j \tag{20}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{B}: \quad 2j + v \tag{21}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{W}^0 \to \tilde{l} \to \tilde{B}: \quad 2j + v + 2l \tag{22}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{B}: \quad 4j + 2v \tag{23}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{l} \to \tilde{B}: \quad 2j + 2v + 2l \tag{24}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{W}^0 \to \tilde{l} \to \tilde{B}: \quad 4j + 2v + 2l \tag{25}$$

- dominant λ: there are four dominant decay chains

$$\tilde{G} \to \tilde{b} \to \tilde{B}: \quad 2j \tag{26}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{B}: \quad 4j + 2v \tag{27}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{l} \to \tilde{B}: \quad 2j + 2v + 2l \tag{28}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{S} \to \tilde{W}^0 \to \tilde{l} \to \tilde{B}: \quad 4j + 2v + 2l \tag{29}$$

IV. RESULTS

Here we present our results on whether a given signature appears in a given setup or not. We have gone through the various sparticle hierarchies and used only the dominant decay modes. We have categorized the signatures by the nature of the LSP: (a) neutral ($\tilde{S}$, $\tilde{B}$, $\tilde{W}^0$, $\tilde{H}^0$, $\tilde{\nu}$, $\tilde{\nu}_\tau$), (b) charged ($\tilde{l}$, $\tilde{e}$, $\tilde{\tau}_L$, $\tilde{\tau}_R$, $\tilde{W}^+$, $\tilde{H}^+$) and (c) colored ($\tilde{g}$, $\tilde{d}$, $\tilde{u}$, $\tilde{q}$, $\tilde{b}_R$, $\tilde{t}_R$, $\tilde{q}_3$). As in our previous MSSM study [18], we have not restricted ourselves to the case of a neutral LSP which could provide a valid dark matter candidate. There are at least three motivations to study also the case of a colored or charged LSP. (i) The relic density of the SUSY LSP could be so small to be cosmologically negligible and dark matter is formed by other fields like the axion [21–24] or the axino [25, 26]. (ii) There are detailed experimental and theoretical collider studies for a charged or a colored LSP in the literature [27–32]. (iii) Searches for R-hadrons have been performed at the Tevatron [33–35] and at the LHC [36].

For the R-parity conserving case we present our results in Tables III – VI. We state in each table whether a specific signature classified by the number of charged leptons, jets and massive vector bosons appears dominantly or not. Unlike in Ref. [18], we do not list the numerical frequency. In the case of a colored or charged LSP, we distinguish also between signatures without $\not{E}_T$ (upper part of each cell) and with $\not{E}_T$ (lower part of the cell). For a neutral LSP like in the first part of Table III, $\not{E}_T$ is always present and we do not have to split the cells.

A. MSSM

Before we discuss the NMSSM, we recall in Table III all possible signatures for the MSSM given in Ref. [18]. The table has to be read as follows: we separate the results in three big columns depending on the number of massive bosons (n_v) in the final state. Each column is again divided into four smaller columns giving the number of jets (n_j) appearing in the signatures. We distinguish the values $n_j = 0, 1, 2$ and $n_j > 2$. The rows show the number of charged leptons (n_l). As already mentioned, while in the case of a neutral LSP $\not{E}_T$ is always present in each cascade, we have to distinguish for a colored and charged LSP between events with and without $\not{E}_T$. For that reason, the cells in the part of the table giving the results for colored and charged are divided into an upper and lower part. The upper gives the results for events without $\not{E}_T$, while the lower one includes $\not{E}_T$.

We can see from Table III that in the R-parity conserving MSSM up to 2 massive vector bosons and up to 4 charged leptons per cascade are possible. Furthermore, it is obvious that in the case of a neutral or charged LSP at least one jet is emitted while for a colored LSP also events without jets, charged leptons and bosons are possible. This is the case when the LSP is the gluino or a squark of the first two generations: in these scenarios the LSP is directly dominantly produced at

	$n_v = 0$				$n_v = 1$				$n_v = 2$			
n_j	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2
n_l	neutral LSP											
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
4	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
n_l	charged LSP											
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
4	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
n_l	colored LSP											
0	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
1	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
2	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
3	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
4	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓

TABLE III: Results for the MSSM: n_v denotes the number of bosons, n_j the number of jets and n_l the number of charged leptons from the single cascade chain. In the case of a charged and colored LSP, the upper entry in a given cell of the Table refers to no $\not{E}_T$ the lower entry to $\not{E}_T$ also being present. A neutral LSP is always counted as $\not{E}_T$. Signatures marked with ✓appear due to the dominant and best visible decay chains, while ✗ could only be reached in subdominant cascades.

the LHC.

Interesting signatures for a neutral LSP are those with a large number of charged leptons and a small number of jets. For instance, events with $n_l = 4$, $n_v = 0$ and $n_j = 1$ as well as a neutral LSP can be the result of the decay chain

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \,. \tag{30}$$

Recently, there have been some hints for events at the LHC with 7 jets and one lepton that cannot be explained by SM background [37]. This signature can be, for instance, a consequence of a bino LSP and the following hierarchy:

$$\tilde{G}\,\tilde{q}_3\,\tilde{W}^+\,\tilde{\nu}\,\tilde{\tau}_L\,\tilde{H}^+\,\tilde{t}\,\tilde{B}\,. \tag{31}$$

For this mass ordering, the following five cascades appear dominantly

$$\tilde{G} \to \tilde{q}_3 \to \tilde{B}: \;2j \tag{32}$$

$$\tilde{G} \to \tilde{q}_3 \to \tilde{H}^+ \to \tilde{B}: \;2j + v \tag{33}$$

$$\tilde{G} \to \tilde{q}_3 \to \tilde{H}^+ \to \tilde{t} \to \tilde{B}: \;4j \tag{34}$$

$$\tilde{G} \to \tilde{t} \to \tilde{B}: \;2j \tag{35}$$

$$\tilde{G} \to \tilde{q}_3 \to \tilde{W}^+ \to \tilde{\nu} \to \tilde{\tau}_R \to \tilde{H}^+ \to \tilde{t} \to \tilde{B}: \;l + 5j\,. \tag{36}$$

Combining the first or the fourth cascade with the fifth can explain the excess in this channel. See also [38].

In contrast, for a charged LSP, monojet events and four lepton tracks are only possible if accompanied by exactly one massive boson. Possible hierarchies for these signatures can easily be derived from Eq. (30) by adding a stau or a charged Higgsino to the end of the cascade:

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \to \tilde{\tau}_L \;:\; 4l + 2j \tag{37}$$

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \to \tilde{H}^+ \;:\; 4l + j + v \tag{38}$$

Another important feature of a charged LSP is that it provides *three* signatures beside the four lepton monojet events which can neither be reached by the other RpC cases nor by RpV scenarios: $(n_v, n_j, n_l) = (0,1,2)$, $(1,1,0)$ and $(2,1,0)$. Possible cascades to obtain these signatures are

$$(0,1,2) \;:\; \tilde{d} \to \tilde{\nu} \to \tilde{W}^+ \tag{39}$$

$$(1,1,0) \;:\; \tilde{q} \to \tilde{B} \to \tilde{H}^+ \tag{40}$$

$$(2,1,0) \;:\; \tilde{q} \to \tilde{B} \to \tilde{H}^+ \to \tilde{W}^+ \tag{41}$$

We summarize briefly the case of a colored LSP in the MSSM. The events with one jet but nothing else are caused by a squark of the third generation as the LSP and a produced gluino. As soon as one lepton or one massive boson is involved there have to be at least two jets: the produced colored particle at the beginning of the cascade as well as the stable colored particle at the end have to interact with non-colored particles. Due to baryon number conservation at each vertex at least two jets will appear. The reason that all events with one or three charged leptons will also include neutrinos is, of course, lepton number conservation.

We want to give here one example for a decay chain with the maximal amount of charged leptons and massive bosons but the minimal amount of jets: four leptons together with two massive bosons and two jets follows from the decay chain

$$\tilde{q} \to \tilde{B} \to \tilde{H}^0 \to \tilde{W}^0 \to \tilde{l} \to \tilde{e} \to \tilde{\tau}_R \tag{42}$$

B. NMSSM, Small λ

We leave the MSSM and turn to the NMSSM. We start with the case of a small coupling between the Higgs doublets and the gauge singlet. The corresponding results are given in Table IV. Since this case is the MSSM limit of the NMSSM we do not expect large deviations from the MSSM results presented in Table III. This assumption holds exactly for a colored LSP where there is no difference between the NMSSM and the MSSM. For a neutral and charged LSP the MSSM and NMSSM agree in all possible signatures with $n_v < 3$. However, while it is not possible to get $n_v = 3$ in the MSSM, there are such events in the NMSSM. For instance, in the case of a neutral LSP, $n_v = 3$, $n_j = n_l = 1$ can be a result of the decay chain

$$\tilde{q} \to \tilde{W}^0 \to \tilde{H}^0 \to \tilde{S} \to \tilde{\nu} \tag{43}$$

while the same signature for a charged LSP appears in

$$\tilde{q} \to \tilde{W}^0 \to \tilde{H}^0 \to \tilde{S} \to \tilde{e}\,. \tag{44}$$

One might wonder why $n_v = 3$ events are not possible for a colored LSP. The point is that a colored LSP which is not the LCP can only be a third generation squark. These squarks couple, for small λ, stronger to the Higgs fields than the singlet does. Therefore, the Higgs decays directly to the LSP while for events with three bosons the cascade $\tilde{H} \to \tilde{S} \to LCP$ is needed.

Another interesting observation is the fact that $n_v = 3$ is only possible for a charged LSP if at least one charged lepton is present, while this is not the case for $n_v < 3$. To understand this,

	$n_v=0$				$n_v=1$				$n_v=2$				$n_v=3$			
n_j	$=0$	$=1$	$=2$	>2	$=0$	$=1$	$=2$	>2	$=0$	$=1$	$=2$	>2	$=0$	$=1$	$=2$	>2
n_l	neutral LSP															
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
4	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
n_l	charged LSP															
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
4	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
n_l	colored LSP															
0	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
1	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
2	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
3	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
4	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗

TABLE IV: Results for the NMSSM assuming small λ. The notation is as in Table III. In the case of a charged and colored LSP, the upper entry in a given cell of the Table refers to no $\not{E}_T$ the lower entry to $\not{E}_T$ also being present. A neutral LSP is always counted as $\not{E}_T$.

one must know that all events with $n_l = 0$ and $n_v = 2$ have a charged Wino as LSP. For instance, $n_j = 1$, $n_l = 0$ and $n_v = 2$ appears due to the cascade

$$\tilde{q} \to \tilde{B} \to \tilde{H}^0 \to \tilde{W}^+ . \tag{45}$$

To get a third boson $\tilde{S}$ must be present in the cascade. However, $\tilde{H}^0$ couples stronger to the charged wino than the singlino. Therefore, even if the the singlino is present the Higgs decays dominantly to the LSP. Therefore, $n_v = 3$ demands another LSP with a weaker coupling to the Higgs fields. That is the case for $\tilde{e}$ or $\tilde{l}$, and lepton number conservation explains therefore the presence of at least on charged lepton track.

C. NMSSM, Large λ

As a next scenario we assume that λ is comparable to the third generation Yukawa couplings. In this case, the Higgsinos decay dominantly into the singlet and the third generation squarks with the same probability if both are lighter than μ_{eff}. The resulting dominant signatures are given in Table V. The main result is that signatures with up to four massive bosons are possible. This observation is independent of the nature of the LSP.

For a neutral LSP the dominant signatures with $n_v < 3$ agree completely with the MSSM results, while this is not the case for a charged or colored LSP. We will explain this below. First, some words about the neutral LSP: the NMSSM with large λ and a neutral LSP can produce all signatures dominantly with $n_j \geqslant 2$, $n_v \leq 4$ and $n_l \leq 4$. One important result for the $n_v = 4$ signatures is that they can only be obtained by the transition $LCP \to \tilde{B} \to \tilde{H} \to \tilde{W} \to \tilde{S} \to LSP$ or $LCP \to \tilde{W} \to \tilde{H} \to \tilde{B} \to \tilde{S} \to LSP$, *i.e.* $\tilde{W}$ and $\tilde{B}$ have to be heavier than the singlino and therefore the LSP must be a neutral slepton.

Finally, we want to point out that there is also one signature for a neutral LSP and large λ which can not be reached by any other configuration in the NMSSM: $(n_v, n_j, n_l) = (4, 2, 4)$ (with $\not{E}_T$). Let us give a possible hierarchy which leads to the corresponding cascade:

$$(4,2,4): \quad \tilde{q} \to \tilde{W} \to \tilde{H} \to \tilde{B} \to \tilde{e} \to \tilde{S} \to \tilde{\tau}_R \to \tilde{l} \to \tilde{\nu}_\tau \tag{46}$$

The case of a charged LSP is even more interesting. Not only are signatures with $n_v > 2$ present, while they were impossible in the MSSM, but also for $n_v \leq 2$ a new signature with five charged lepton tracks arises. In the MSSM there was an upper limit of four. The signature $(n_v, n_j, n_l) = (2, 2, 5)$

	$n_v = 0$				$n_v = 1$				$n_v = 2$				$n_v = 3$				$n_v = 4$			
n_j	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2
n_l	neutral LSP																			
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
4	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
n_l	charged LSP																			
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓
	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓
4	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓
	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓
5	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
n_l	colored LSP																			
0	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓
1	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
2	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
3	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
4	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓

TABLE V: Results for the NMSSM assuming large λ. The notation is as in Table III. In the case of a charged and colored LSP, the upper entry in a given cell of the Table refers to no $\not{E}_T$ the lower entry to $\not{E}_T$ also being present. A neutral LSP is always counted as $\not{E}_T$.

without $\not{E}_T$ can be for instance produced via the cascade:

$$(2,2,5): \quad \tilde{G} \to \tilde{S} \to \tilde{l} \to \tilde{W}^0 \to \tilde{B} \to \tilde{e} \tag{47}$$

But even for less than four charged leptons there are signatures with $n_v = 2$ which do not appear dominantly in the MSSM with a charged LSP, but which are present in the NMSSM: $(n_v, n_j, n_l) = (2,1,2), (2,1,4), (2,1,4) + \not{E}_T$. Cascades resulting in these signatures are the following:

$$(2,1,2): \quad \tilde{q} \to \tilde{H}^0 \to \tilde{S} \to \tilde{\nu} \to \tilde{W}^+ \tag{48}$$

$$(2,1,4): \quad \tilde{q} \to \tilde{W}^0 \to \tilde{l} \to \tilde{B} \to \tilde{e} \to \tilde{S} \to \tilde{H}^+ \tag{49}$$

$$(2,1,4) + \not{E}_T: \quad \tilde{q} \to \tilde{H}^0 \to \tilde{S} \to \tilde{\nu} \to \tilde{W}^+ \to \tilde{B} \to \tilde{e} \tag{50}$$

The only remaining case for large λ is the one with a colored LSP. The results are presented in the last part of Table V. Also in this setup up to four massive bosons are possible. However, each of them is accompanied by at least two jets. The reason is the same as for the MSSM: there are at least two colored vertices and baryon number is conserved. As in the scenario with a neutral LSP, all signatures with $n_v < 3$ agree exactly with those of the MSSM. Furthermore, all possible dominantly appearing signatures with $n_v \geqslant 3$ can also be obtained in the case of a neutral or charged LSP. Hence, it is difficult to find a smoking gun signature for the NMSSM with large λ and a colored LSP.

D. NMSSM, Dominant λ

If one drops the assumption that λ is perturbative up to the GUT scale and assumes instead a λSUSY scenario [39], it is possible that λ is even much larger than the top Yukawa coupling. We now discuss this case. The corresponding results are given in Table VI. It can be seen that only signatures with at most three massive bosons show up dominantly. This is a bit surprising because for large λ four bosons have been possible. However, we have already seen that the case of $n_v = 4$ demands the transitions $\tilde{B} \to \tilde{H} \to \tilde{W} \to (\cdots \to)\tilde{S}$ or $\tilde{W} \to \tilde{H} \to \tilde{B} \to (\cdots \to)\tilde{S}$. These transitions are highly suppressed for dominant λ because the Higgsino will decay prominently directly to the singlino.

Comparing Table VI with Table V it turns out that exactly the same signatures with $n_v < 4$ appear in the case of a large and of a dominant λ. That means that there is no unique setup which would be a strong indication for the NMSSM with a dominant λ coupling between the singlet and the Higgs fields.

	$n_v = 0$				$n_v = 1$				$n_v = 2$				$n_v = 3$			
n_j	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2	$= 0$	$= 1$	$= 2$	> 2
n_l	neutral LSP															
0	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
1	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
2	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
3	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
4	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
n_l	charged LSP															
0	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✗ ✓	✗ ✓	✓ ✓
1	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓
2	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓
3	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✗	✗ ✓	✓ ✓	✓ ✓	✓ ✓
4	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✓ ✓	✓ ✓	✓ ✓	✗ ✗	✗ ✓	✗ ✓	✓ ✓
5	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✓ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✗ ✗
n_l	colored LSP															
0	✓ ✗	✓ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓
1	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓
2	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓
3	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓	✗ ✗	✗ ✗	✗ ✓	✗ ✓
4	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✗ ✗	✗ ✗	✓ ✓	✓ ✓

TABLE VI: Results for the NMSSM assuming dominant λ. The notation is as in Table III. In the case of a charged and colored LSP, the upper entry in a given cell of the Table refers to no $\not{E}_T$ the lower entry to $\not{E}_T$ also being present. A neutral LSP is always counted as $\not{E}_T$.

To summarize the main results for the possible signatures in the NMSSM: we have seen that for a small value of λ the case of a colored LSP is exactly as in the MSSM, while for neutral and charged LSPs signatures with $n_v = 3$ are possible. The upper limit on charged lepton tracks in this scenario is four. In contrast, for a large or dominant λ up to 5 charged leptons can be emitted during the cascade decays. However, this happens dominantly only for $n_v = 2$. While it is possible to get $n_v = 3$ for all three kinds of LSPs for a dominant λ, for a large singlino coupling even $n_v = 4$ is possible. Finally, comparing Table IV to VI, one can see that events with $n_l = 4$, $n_j = 1$ and without a massive boson ($n_v = 0$) are only possible for a neutral LSP independent of the assumed order of λ.

E. NMSSM with R-parity violation

We have also derived all possible signatures in the case of R-parity violation [40–47]. For this purpose we used the dominant decay modes already presented in Ref. [18]. While a detailed discussion of the data is beyond the scope of this paper, we want to point out some unique signatures[4]. The four possible types of couplings in the general, R-parity violating NMSSM are the same as for the MSSM[5] and read

$$W_{\not R} = \epsilon_i \hat{\ell}_i \hat{H}_u + \frac{1}{2}\lambda_{ijk}\hat{\ell}_i\hat{\ell}_j\hat{e}^c_k + \frac{1}{2}\lambda'_{ijk}\hat{q}_i\hat{d}^c_j\hat{\ell}_k + \frac{1}{2}\lambda''_{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k\,. \tag{51}$$

In the following we assume that only one of these couplings is present at once. In addition, we assume that only the LSP decays through an RpV operator. The decay modes are listed in Table VII.

1. $\epsilon_i \hat{\ell}_i \hat{H}_u$

In the MSSM with bilinear RpV at most 5 charged leptons and two massive scalars are possible in a cascade. In contrast, in the NMSSM it is possible to get six or seven leptons for a large or dominant λ. Six leptons are also possible for the RpC NMSSM but only without $\not{E}_T$. Including

[4] A pdf file with the tables of all possible RpV-NMSSM signatures can be obtained by email from the authors.

[5] The singlet superfield $\hat{S}$ allows for additional R-parity violating terms. This is for example the case of $\hat{S}\hat{\ell}_i\hat{H}_u$, as in the $\mu\nu$SSM [48]. After electroweak symmetry breaking this operator leads to the NMSSM with an effective bilinear term. Therefore, the collider phenomenology of the $\mu\nu$SSM cannot be distinguished from that of the NMSSM with an explicit $\epsilon_i\hat{\ell}_i\hat{H}_u$ superpotential term [49, 50]. Similarly, the bilinear term can also be generated in models with spontaneous R-parity violation [51] where, in contrast, the phenomenology can be altered due to the presence of a majoron [52].

	ϵ	λ	λ'	λ''
$\tilde{B}$	$h^0\nu$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{W}^\pm$	$Z^0l^\pm$	$3l^\pm$	$l^\pm q\bar{q}$	$qq'q''$
$\tilde{W}^0$	$W^\pm l^\mp$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{G}$	$q\bar{q}'l^\pm$	$q\bar{q}l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{H}^\pm$	$Z^0l^\pm$	$3l^\pm$	$l^\pm q\bar{q}$	$qq'q''$
$\tilde{H}^0$	$W^\pm l^\mp$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{q}$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	$4q$
$\tilde{d}$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	qq'
$\tilde{u}$	$q\nu$	$ql^+l^-\nu$	$l^\pm q\bar{q}'q''$	qq'
$\tilde{l}$	$q\bar{q}'$	$l^\pm\nu$	$q\bar{q}'$	$qq'q''l^\pm$
$\tilde{\nu}$	$q\bar{q}$	l^+l^-	$q\bar{q}$	$qq'q''\nu$
$\tilde{e}$	$l^\pm\nu$	$l^\pm\nu$	$l^\pm l^\pm q\bar{q}'$	$qq'q''l^\pm$
$\tilde{q}_3$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	$4q$
$\tilde{b}_R$	$q\nu$	$ql^+l^-\nu$	$q\nu$	qq'
$\tilde{t}_R$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q\bar{q}'q''$	qq'
$\tilde{\tau}_L$	$q\bar{q}'$	$l^\pm\nu$	$q\bar{q}'$	$qq'q''\tau$
$\tilde{\nu}_\tau$	$q\bar{q}$	l^+l^-	$q\bar{q}$	$qq'q''\nu$
$\tilde{\tau}_R$	$\tau\nu$	$l^\pm\nu$	$l^\pm\nu q\bar{q}$	$qq'q''\tau$
$\tilde{S}$	$W^\pm l^\mp$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$

TABLE VII: Dominant R-parity violating decay modes of the LSP [42, 47, 53–55]. Note that we have chosen charged lepton final states over $\not{E}_T$ and thus neglected the decay $\tilde{B} \to \nu q\bar{q}'$, for example.

the ϵ term, we can get them also with $\not{E}_T$:

$$(2, > 2, 6) + \not{E}_T : \qquad \tilde{G} \to \tilde{e} \to \tilde{H}^0 \to \tilde{S} \to \tilde{l} \to \tilde{W}^0 \to \tilde{B} \to \tilde{\tau}_R \to \tau + \nu\,, \tag{52}$$

where the τ in the final state is counted as an additional jet. For small and dominant λ also signatures with $n_v = 4$ are possible. This is interesting because $n_v = 4$ without RpV is only possible for large λ, as we have seen. The reason is that the RpV decays of a wino, bino or Higgsino LSP produce additional bosons. On the other hand, $n_v = 5$ is not possible for large λ despite what one might expect. The point is that $n_v = 4$ in the RpC case is only possible if $\tilde{B}$, $\tilde{W}$ and $\tilde{H}$ are heavier than the singlino as we have discussed in sec. IV C. Therefore, they cannot be the LSP and their RpV decay modes play only a sub-leading role.

2. $\lambda_{ijk}\hat{\ell}_i\hat{\ell}_j\hat{e}^c_k$

The lepton number violating interaction $\hat{\ell}_i\hat{\ell}_j\hat{e}^c_k$ can cause up to seven leptons in a cascade, but only two bosons in the MSSM. In contrast, in the NMSSM extended by this operator, it is possible to obtain up to four massive bosons and seven leptons. Four bosons are only possible for large λ

$$(4,1,6)+\not{E}_T: \quad \tilde{q}\to\tilde{B}\to\tilde{H}\to\tilde{W}^0\to\tilde{l}\to\tilde{S}\to\tilde{e}\to\tilde{\nu}_\tau\to ll \tag{53}$$

while three bosons are emitted dominantly for all λ's. A signature not dominantly arising in the RpC case but present here for all values of λ is the one with six lepton tracks:

$$(3,1,6)+\not{E}_T: \quad \tilde{q}\to\tilde{B}\to\tilde{H}^0\to\tilde{W}^0\to\tilde{l}\to\tilde{e}\to\tilde{S}\to\nu ll \tag{54}$$

The case of seven leptons also exists for all λ's and can occur for large λ as a result of

$$(2,>2,7)+\not{E}_T: \quad \tilde{G}\to\tilde{t}\to\tilde{H}^0\to\tilde{S}\to\tilde{e}\to\tilde{B}\to\tilde{W}^0\to\tilde{\nu}\to\tilde{\nu}_\tau\to ll \tag{55}$$

3. $\lambda'_{ijk}\hat{q}_i\hat{d}^c_j\hat{\ell}_k$

The operator $\hat{q}_i\hat{d}^c_j\hat{\ell}_k$ produces in general additional jets. In the MSSM the number of charged leptons is restricted to at most five, and of massive bosons to two. In contrast, we can find in the NMSSM with the same operator

$$(2,>2,7)\quad(\text{large, dominant}\,\lambda): \quad \tilde{G}\to\tilde{S}\to\tilde{l}\to\tilde{W}^0\to\tilde{B}\to\tilde{e}\to llq\bar{q}' \tag{56}$$

$$(3,>2,5)+\not{E}_T\quad(\text{all}\,\lambda): \quad \tilde{q}\to\tilde{t}\to\tilde{H}^0\to\tilde{W}^0\to\tilde{l}\to\tilde{S}\to\tilde{e}\to\tilde{\tau}_R\to l\nu q\bar{q} \tag{57}$$

$$(4,>2,5)+\not{E}_T\quad(\text{large}\,\lambda): \quad \tilde{q}\to\tilde{B}\to\tilde{H}^0\to\tilde{W}^0\to\tilde{l}\to\tilde{S}\to\tilde{e}\to\tilde{\tau}_R\to l\nu q\bar{q} \tag{58}$$

4. $\lambda''_{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k$

Cascades involving $\lambda''_{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k$ can produce even more jets than in the case of $\lambda'_{ijk}\hat{q}_i\hat{d}^c_j\hat{\ell}_k$, but the number of charged leptons and massive bosons in the MSSM are limited as in the R-parity conserving case: only $n_l \leq 4$ and $n_v leq 2$ is possible. If we go to the NMSSM, we can find for all possible values of λ also signatures with $n_v = 3$, while for large λ also $n_v = 4$ is possible. However, the signatures are the same as for RpC, except for the additional jets. The same holds for signatures with six charged leptons, which do not appear for small λ, but in the other two cases the same results as for R-parity conservation are obtained.

V. CONCLUSION

We have discussed in this paper the collider signatures dominantly appearing in a very general realization of the NMSSM. It is based on 15 unrelated mass parameters which lead to $15! \simeq 1.3 \cdot 10^{12}$ possible particle mass orderings. We have studied three possible scenarios for the singlet-Higgs coupling λ. We checked possible signatures to discriminate these three scenarios among each other but also from the MSSM. For small λ, the signatures for all LSPs are identical to the MSSM as long as less than 3 massive bosons are present. Signatures with 3 bosons are not possible in the MSSM, but can appear in the NMSSM for all possible ranges of λ. Furthermore, in the case of a large but not dominant λ, even up to four massive bosons can be emitted during the cascade decays. This is also the only difference between the case of a large and dominant λ: all signatures with less bosons are identical. On the other side, for both setups, signatures with less than three massive bosons arise and these do not appear dominantly in the MSSM. For instance, in the MSSM there can be at most four charged lepton tracks if R-parity is conserved, while we find also hierarchies in the NMSSM which can dominantly emit five charged leptons.

We pointed out a hierarchy which can dominantly lead to seven jets and one lepton, which could explain the observed excess at the LHC.

We briefly commented on the NMSSM with R-parity violation and the possible signatures. We found that, depending on the R-parity violating parameters, outstanding signatures with up to five massive bosons or seven charged leptons are possible.

Acknowledgements

We thank Werner Porod for discussions and collaboration in the early stage of this project. AV acknowledges support from the ANR project CPV-LFV-LHC NT09-508531. HKD acknowledges support from BMBF grant 00160200.

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] E. Gildener, Phys. Rev. D **14** (1976) 1667.

[4] C. Balazs, A. Buckley, D. Carter, B. Farmer and M. White, arXiv:1205.1568 [hep-ph].

[5] D. Ghosh, M. Guchait, S. Raychaudhuri and D. Sengupta, arXiv:1205.2283 [hep-ph].

[6] S. Cassel, D. M. Ghilencea, S. Kraml, A. Lessa and G. G. Ross, JHEP **1105**, 120 (2011) [arXiv:1101.4664 [hep-ph]]; D. M. Ghilencea and G. G. Ross, arXiv:1208.0837 [hep-ph].

[7] P. Bechtle, T. Bringmann, K. Desch, H. Dreiner, M. Hamer, C. Hensel, M. Kramer and N. Nguyen *et al.*, JHEP **1206** (2012) 098 [arXiv:1204.4199 [hep-ph]].

[8] A. Fowlie, M. Kazana, K. Kowalska, S. Munir, L. Roszkowski, E. M. Sessolo, S. Trojanowski and Y. -L. S. Tsai, Phys. Rev. D **86** (2012) 075010 [arXiv:1206.0264 [hep-ph]].

[9] P. Bechtle *et al.*, Phys. Rev. D **84** (2011) 011701 [arXiv:1102.4693 [hep-ph]]; O. Buchmueller *et al.*, Eur. Phys. J. C **72** (2012) 1878 [arXiv:1110.3568 [hep-ph]]; B. C. Allanach, Phys. Rev. D **83** (2011) 095019 [arXiv:1102.3149 [hep-ph]]; A. Fowlie *et al.*, Phys. Rev. D **85** (2012) 075012 [arXiv:1111.6098 [hep-ph]].

[10] O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M. J. Dolan, J. R. Ellis, H. Flacher and S. Heinemeyer *et al.*, arXiv:1207.7315 [hep-ph].

[11] S. Heinemeyer, O. Stal and G. Weiglein, Phys. Lett. B **710**, 201 (2012) [arXiv:1112.3026 [hep-ph]].

[12] P. Fayet, Nucl. Phys. B **90** (1975) 104.

[13] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B **120** (1983) 346.

[14] J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D **39** (1989) 844.

[15] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. **496**, 1 (2010) [arXiv:0910.1785 [hep-ph]].

[16] G. G. Ross, K. Schmidt-Hoberg and F. Staub, JHEP **1208**, 074 (2012) [arXiv:1205.1509 [hep-ph]].

[17] P. Konar, K. T. Matchev, M. Park and G. K. Sarangi, Phys. Rev. Lett. **105** (2010) 221801 [arXiv:1008.2483 [hep-ph]].

[18] H. K. Dreiner, F. Staub, A. Vicente and W. Porod, Phys. Rev. D **86**, 035021 (2012) [arXiv:1205.0557 [hep-ph]].

[19] S. A. Abel, S. Sarkar and P. L. White, Nucl. Phys. B **454** (1995) 663 [hep-ph/9506359]; S. A. Abel, Nucl. Phys. B **480** (1996) 55 [hep-ph/9609323]; C. Panagiotakopoulos and K. Tamvakis, Phys. Lett. B **446** (1999) 224 [hep-ph/9809475].

[20] J. E. Kim and H. P. Nilles, Phys. Lett. B **138** (1984) 150; G. F. Giudice and A. Masiero, Phys. Lett. B **206** (1988) 480; A. H. Chamseddine and H. K. Dreiner, Phys. Lett. B **389** (1996) 533 [hep-ph/9607261].

[21] S. Weinberg, Phys. Rev. Lett. **40** (1978) 223; F. Wilczek, Phys. Rev. Lett. **40** (1978) 279.

[22] J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. B **120** (1983) 127.

[23] L. F. Abbott and P. Sikivie, Phys. Lett. B **120** (1983) 133.

[24] M. Dine and W. Fischler, Phys. Lett. B **120** (1983) 137.

[25] K. Rajagopal, M. S. Turner and F. Wilczek, Nucl. Phys. B **358** (1991) 447.

[26] L. Covi, J. E. Kim and L. Roszkowski, Phys. Rev. Lett. **82** (1999) 4180 [hep-ph/9905212].

[27] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **102** (2009) 161802 [arXiv:0809.4472 [hep-ex]].

[28] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103** (2009) 021802 [arXiv:0902.1266 [hep-ex]].

[29] S. Raby, Phys. Lett. B **422**, 158 (1998) [hep-ph/9712254].

[30] H. Baer, K. -m. Cheung and J. F. Gunion, Phys. Rev. D **59** (1999) 075002 [hep-ph/9806361].

[31] S. Raby and K. Tobe, Nucl. Phys. B **539** (1999) 3 [hep-ph/9807281].

[32] H. K. Dreiner and S. Grab, Phys. Lett. B **679** (2009) 45 [arXiv:0811.0200 [hep-ph]]; H. K. Dreiner, S. Grab and M. K. Trenkel, Phys. Rev. D **79** (2009) 016002 [Erratum-ibid. **79** (2009) 019902] [arXiv:0808.3079 [hep-ph]]; H. K. Dreiner, S. Grab and T. Stefaniak, Phys. Rev. D **84** (2011) 015005 [arXiv:1103.1883 [hep-ph]].

[33] A. Heister *et al.* [ALEPH Collaboration], Eur. Phys. J. C **31** (2003) 327 [hep-ex/0305071].

[34] A. Arvanitaki *et al.*, Phys. Rev. D **76** (2007) 055007 [hep-ph/0506242].

[35] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **99** (2007) 131801 [arXiv:0705.0306 [hep-ex]].

[36] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **701** (2011) 1 [arXiv:1103.1984 [hep-ex]].

[37] T. J. Khoo [ATLAS Collaboration], Talk given at *Hadron Collider Physics Symposium*, Kyoto, 2012

[38] M. Lisanti, P. Schuster, M. Strassler and N. Toro, JHEP **1211** (2012) 081 [arXiv:1107.5055 [hep-ph]].

[39] R. Barbieri, L. J. Hall, Y. Nomura and V. S. Rychkov, Phys. Rev. D **75**, 035007 (2007) [hep-ph/0607332].

[40] L. J. Hall and M. Suzuki, Nucl. Phys. B **231** (1984) 419.

[41] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **69** (2004) 115002 [Erratum-ibid. D **72** (2005) 079902] [hep-ph/0309196].

[42] H. K. Dreiner, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 565-583 [hep-ph/9707435].

[43] G. Bhattacharyya, In *Tegernsee 1997, Beyond the desert 1997* 194-201 [hep-ph/9709395].

[44] V. D. Barger, G. F. Giudice and T. Han, Phys. Rev. D **40** (1989) 2987.

[45] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **60** (1999) 075014 [arXiv:hep-ph/9906209].

[46] M. Hirsch *et al.*, Phys. Rev. D **62** (2000) 113008 [Erratum-ibid. D **65** (2002) 119901] [hep-ph/0004115].

[47] R. Barbier *et al.*, Phys. Rept. **420**, 1 (2005) [hep-ph/0406039].

[48] D. E. Lopez-Fogliani and C. Munoz, Phys. Rev. Lett. **97** (2006) 041801 [hep-ph/0508297].

[49] P. Ghosh and S. Roy, JHEP **0904** (2009) 069 [arXiv:0812.0084 [hep-ph]].

[50] A. Bartl *et al.*, JHEP **0905** (2009) 120 [arXiv:0903.3596 [hep-ph]].

[51] A. Masiero and J. W. F. Valle, Phys. Lett. B **251** (1990) 273.

[52] M. Hirsch, A. Vicente and W. Porod, Phys. Rev. D **77** (2008) 075005 [arXiv:0802.2896 [hep-ph]].

[53] W. Porod, M. Hirsch, J. Romao and J. W. F. Valle, Phys. Rev. D **63** (2001) 115004 [hep-ph/0011248].

[54] M. Hirsch and W. Porod, Phys. Rev. D **68** (2003) 115007 [hep-ph/0307364].

[55] H. K. Dreiner and G. G. Ross, Nucl. Phys. B **365** (1991) 597.