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General MSSM signatures at the LHC with and without R-parity

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We present the possible signatures appearing in general realizations of the MSSM based on 14 unrelated mass parameters at the SUSY scale. The parameters of the general MSSM are reduced by assuming a degeneracy of the sfermions of the first two generations with the same quantum numbers. We also assume no mass-splitting between neutral and charged Higgsinos. We do allow for separate soft breaking terms for the third generation sfermions. We consider all possible resulting $14! \approx 9{\cdot}10^{10}$ relevant mass orderings and check for the dominant decay cascades and the corresponding collider signatures. In determining the dominant decay modes we assume that mixing between sparticles is sub-dominant. As preferred signatures, we consider charged leptons, missing transverse momentum, jets, and W, Z or Higgs bosons. We include also the cases of bi- and trilinear R-parity violation and show that specific signatures can be used to distinguish the different scenarios.

I. INTRODUCTION

The ATLAS [1] and CMS [2] experiments at the LHC have collected about 5 fb^{-1} of data. Among other extensions of the Standard Model of particle physics (SM) they have searched for supersymmetry (SUSY) [3, 4], however so far to no avail. For the published 1 fb^{-1} data see Refs. [5–10]. The more recent analyses have been presented in preliminary form in Refs. [11]. For a recent best-fit to the CMSSM, including the most recent LHC data, see also [12, 13]. The present searches are largely based on the assumption of conserved R-parity [14], where the lightest supersymmetric particle (LSP) is stable. For cosmological reasons it must be electrically and color neutral. All produced supersymmetric particles are typically expected to cascade decay to the LSP promptly within the detector; the LSP itself escapes detection leading to missing transverse energy, $\not{E}_T$, as a typical signature. Thus most searches include a more or less strict lower cut on $\not{E}_T$.

The minimal supersymmetric standard model (MSSM) has in its most general form 124 free parameters [15]. Most of these arise from the supersymmetry breaking sector. In particular there is a free mass parameter for each of the new supersymmetric particles. Thus in the most general case any mass ordering of the spectrum is possible. However it is difficult to get a meaningful interpretation of the experimental searches in terms of 124 parameters. Thus simplifying assumptions are made which dramatically reduce the number of parameters. The most widely considered case is the CMSSM, often also called the mSUGRA model. This has five free parameters. Other popular reduced parameter scenarios include: gauge mediated SUSY breaking (GMSB), anomaly mediated SUSY breaking (AMSB) or mirage mediation. For the collider phenomenology see for example [16–19].

The reduction to a significantly smaller set of free parameters comes at the price of a significant loss of generality. The central point of this paper is to analyse in general the possible mass orderings of the spectrum and determine the resulting *dominant* LHC signatures. The dominant signature will be determined by the dominant decay modes of the supersymmetric particles. We discuss these decays in detail below and show our results for the dominant modes in Tables II, III and IV. Consider the CMSSM as an example, which has five free parameters. These are fixed at the unification scale ($\sim 10^{16}$ GeV). The low-energy supersymmetric spectrum and the particlecouplings are computed

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using the renormalization group equations (RGEs) via publically available codes [20–23]. This leads to very specific features in the spectrum. For example typically the gluinos and squarks are the heaviest particles and the right-handed sleptons and the lightest neutralino are the lightest. Overall 47 different mass hierarchies are possible [24]. This is a very small number compared to the general MSSM. Within the general MSSM, if one assumes a degeneracy of the sfermions with the same quantum numbers and no mass-splitting between neutral and charged Higgsinos, there are nine mass parameters. These lead to $9! = 362\,880$ mass hierarchies, as discussed in Konar *et al.* [24]. We go one step beyond this work and separate the soft-breaking terms of the third generation sfermions from the other two generations resulting in 14 free parameters and $14! = 87\,178\,291\,200 \approx 9 \cdot 10^{10}$ possible hierarchies.[1]

We extend the study [24] by several other aspects: we allow for a mass-splitting between charged and neutral components of Higgsinos and Winos. Since this breaks $SU(2)$ invariance, we distinguish explicitly between charged leptons and missing transverse energy ($\not{E}_T$) as a signature. We start with the case of R-parity conservation (RpC). Later we also consider bi- and trilinear R-parity violating (RpV) parameters in detail, significantly going beyond the work in [24]. Our goal is to determine the widest possible set of distinct signatures, which we can still compute. These can then be employed to determine a broad based search for supersymmetry at the LHC. They can also be used to find ways of distinguishing RpV from RpC.

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 minimal supersymmetric standard model (MSSM) [3, 4], extended to include R-parity violation [27–34]. The MSSM particle content consists of the chiral superfields $\hat{q}_a\,(\mathbf{3},\mathbf{2},\frac{1}{6})$, $\hat{\ell}_a\,(\mathbf{1},\mathbf{2},-\frac{1}{2})$, $\hat{H}_d\,(\mathbf{1},\mathbf{2},-\frac{1}{2})$, $\hat{H}_u\,(\mathbf{1},\mathbf{2},\frac{1}{2})$, $\hat{d}^c_a\,(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$, $\hat{u}^c_a\,(\bar{\mathbf{3}},\mathbf{1},\frac{2}{3})$, $\hat{e}^c_a\,(\mathbf{1},\mathbf{1},1)$ and the vector superfields $\tilde{g}_\alpha\,(\mathbf{8},\mathbf{1},0)$, $\tilde{W}^i\,(\mathbf{1},\mathbf{3},0)$, $\tilde{B}\,(\mathbf{1},\mathbf{1},0)$. In parentheses we give the SM gauge quantum numbers with respect to $SU(3)_c \times SU(2)_L \times U(1)_Y$. $a = 1,2,3$ is a generation index. The most general renormalizable and SM gauge invariant superpotential is

$$W = Y_e^{ab}\,\hat{\ell}^j_a\,\hat{e}^c_b\,\hat{H}^i_d\,\epsilon_{ij} + Y_d^{ab}\,\hat{q}^{j\alpha}_a\,\hat{d}^c_{\alpha b}\,\hat{H}^i_d\,\epsilon_{ij} + Y_u^{ab}\hat{q}^{i\alpha}_a\,\hat{u}^c_{\alpha b}\,\hat{H}^j_u\,\epsilon_{ij} + \mu\,\hat{H}^i_u\,\hat{H}^j_d\epsilon_{ij} + W_{\not{R}}\,. \tag{1}$$

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. $W_{\not{R}}$ contains the well-known R-parity violating terms, which are discussed below. The soft SUSY breaking potential reads

$$\mathcal{V}_{\rm SB} = \mathcal{V}_{{\rm SB},R} + \mathcal{V}_{{\rm SB},\not{R}}\,, \tag{2}$$

with the RpC part given in a hopefully clear notation based on the conventions of ref. [35]

$$\begin{aligned}\mathcal{V}_{{\rm SB},R} \;=\; & m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + \tilde{q}^\dagger m^2_{\tilde{q}}\tilde{q} + \tilde{l}^\dagger m^2_{\tilde{l}}\tilde{l} + \tilde{d}^\dagger m^2_{\tilde{d}}\tilde{d} + \tilde{u}^\dagger m^2_{\tilde{u}}\tilde{u}\\ & + \frac{1}{2}\left(M_1\,\tilde{B}\tilde{B} + M_2\,\tilde{W}_i\tilde{W}^i + M_3\,\tilde{g}_\alpha\tilde{g}^\alpha + h.c.\right)\\ & - H_u\tilde{q}T_u\tilde{u}^\dagger + H_d\tilde{q}T_d\tilde{d}^\dagger + H_d\tilde{l}T_e\tilde{e}^\dagger + B_\mu H_u H_d\,.\end{aligned} \tag{3}$$

We do not specify the R-parity violating soft SUSY breaking soft terms in $\mathcal{V}_{{\rm SB},\not{R}}$, for simplicity.

In general, the SUSY particles (sparticles) mix after electroweak symmetry breaking (EWSB) giving rise to 28 mass eigenstates. (12 squarks, 6 charged sleptons, 3 neutral sleptons, 4 neutralinos, 2 charginos and 1 gluino; we identify all particles in $SU(3)_c \times U(1)_{em}$ irreducible representations.) With no *a priori* model explaining the masses, these 28 states lead to $28! \simeq 3 \cdot 10^{29}$ possible mass orderings or *hierarchies*. Unfortunately, it is computationally impossible to classify this general setup. Therefore, we shall make some assumptions, which we consider reasonable, to reduce the number of hierarchies to a manageable amount. In the following we shall be interested in *dominant* effects on the spectrum and the decays. We make two major simplifications:

(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.

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[1] See also related work in Ref. [25] where, in the same spirit of generality as in our work, complete scans of the pMSSM [26] were performed.

Particle	Name	Mass
Bino-like neutralino	$\tilde{B}$	M_1
Wino-like neutralino	$\tilde{W}^0$	M_2
Higgsino-like neutralinos	$\tilde{H}^0$	μ
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.

(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

$$\begin{aligned} m_{\tilde{e}L} &= m_{\tilde{\mu}L} = m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} = m_{\tilde{\ell},11} && (4)\\ m_{\tilde{e}R} &= m_{\tilde{\mu}R} = m_{\tilde{e},11} && (5)\\ m_{\tilde{\tau}L} &= m_{\tilde{\nu}_\tau} = m_{\tilde{\ell},33} && (6)\\ m_{\tilde{\tau}R} &= m_{\tilde{e},33}\,, && (7) \end{aligned}$$

and analogously for the squarks. These two assumptions leave us with 14 relevant mass parameters,

$$\begin{gathered} M_1, M_2, M_3, \mu \qquad (8)\\ m_{\tilde{e},11}, m_{\tilde{e},33}, m_{\tilde{\ell},11}, m_{\tilde{\ell},33} \qquad (9)\\ m_{\tilde{d},11}, m_{\tilde{d},33}, m_{\tilde{u},11}, m_{\tilde{u},33}, m_{\tilde{q},11}, m_{\tilde{q},33} \quad , \qquad (10) \end{gathered}$$

and thus 14! different hierarchies.[2] 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 combine them because, by assumption, they lead to the same signatures:

$$\begin{aligned} (\tilde{e}_L/\tilde{\mu}_L) &\to \tilde{\ell},\\ (\tilde{e}_R/\tilde{\mu}_R) &\to \tilde{e},\\ (\tilde{d}_L/\tilde{s}_L/\tilde{u}_L/\tilde{c}_L) &\to \tilde{q},\\ (\tilde{d}_R/\tilde{s}_R) &\to \tilde{d},\\ (\tilde{u}_R/\tilde{c}_R) &\to \tilde{u},\\ (\tilde{\nu}_e/\tilde{\nu}_\mu) &\to \tilde{\nu}, \qquad (11) \end{aligned}$$

[2] In fact, as explained in the next section, this will imply $2^4 \cdot 14!$ possibilities due to the consideration of decay chains where we make the distinctions $\tilde{W}^0/\tilde{W}^\pm$, $\tilde{H}^0/\tilde{H}^\pm$, $\tilde{\ell}/\tilde{\nu}$ and $\tilde{\tau}/\tilde{\nu}_\tau$.

as well as the two Higgsino-like neutralinos[3]. A collection of the considered states as well as of the relevant mass parameters is given in Table I.

Going beyond this, we also study the impact of the different RpV superpotential couplings [27–29, 33, 34]

$$W_{\not{R}} = \epsilon_i \hat{\ell}_i \hat{H}_u + \frac{1}{2}\lambda_{ijk}\hat{\ell}_i\hat{\ell}_j\hat{e}^c_k + \frac{1}{2}\lambda^{'}_{ijk}\hat{q}_i\hat{d}^c_j\hat{\ell}_k + \frac{1}{2}\lambda^{''}_{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k\,, \tag{12}$$

where we have suppressed the $SU(2)_L$ and $SU(3)_c$ gauge indices. The two main phenomenological effects of RpV are

(i) SUSY particles can decay directly to SM particles. In particular, the LSP is unstable.

(ii) SUSY particles can be produced singly; resonant or in associated production [27, 36–39].

Furthermore, the additional interactions in Eq. (12) break either lepton (L) or baryon number (B). There is thus a large set of experimental bounds on the parameters ϵ_i, λ, λ', λ'' [28–34, 40–44], which are typically very strict. The Yukawa couplings are then significantly smaller than the gauge couplings[4]. For our analysis of the mass hierarchies, the effect of the RpV couplings in the RGEs is typically small, since the couplings are small [28, 32, 45]. However, we consider here general mass hierarchies. Since the LSP is not stable, any particle can now be the LSP.

The RpV couplings can also lead to additional decays of all SUSY particles, see for example the decay tables in [46]. However, since the couplings are small, we consider this effect *sub-dominant* for all sparticles, other than the LSP.

III. STRATEGY FOR THE ANALYSIS

In total, we have $14! = 87,178,291,200 \approx 9 \cdot 10^{10}$ hierarchies. Each one can be denoted as a chain of fields in decreasing order of mass from left to right:

$$i_1 \ldots i_n C r_1 \ldots r_m \tag{13}$$

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 and thus important for our analysis. As in Ref. [24], 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. In order to find them we apply the same algorithm as in Ref. [24]:

1. Find those SUSY particles which are lighter than the LCP and have the largest coupling to it.[5] In general, that may apply to more than one particle.

2. For each of those particles, search for the lighter particles with the largest coupling to it. Again, several possibilities can exist and have to 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*,[6] represent the experimentally relevant result of our study. They are obtained by summing up the decay products of all steps in the decay chain. These are given, together with the coupling strengths, in Tables II-IV. We have considered as final state particles in our analysis

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[3] We note that all signatures in our final results would appear $2^6 \cdot 4 = 256$ times more often if we consider all possible combinations of the fields affected by this simplifying assumption. However, since the relative importance will not change, we do not include this factor to keep the numbers as low as possible.

[4] Note that for large supersymmetric masses, the bounds on the RpV typically become weaker, although this is not always the case [42]. Bounds from neutrino masses on the L-violating couplings typically have a weaker mass dependence.

[5] See Tables II-IV for the coupling strengths and the corresponding decay products.

[6] If different signatures can be the result of a given decay chain we have chosen the one with the largest number of charged leptons. See also the remarks at the end of this section. Therefore, both *dominant signatures* and *dominant and best visible signatures* will be used as equivalent concepts in the following.

1. charged leptons (l),
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.

In Table II we see for example that the $SU(2)_L$ singlet down-like squark, $\tilde{d}$, can dominantly decay to a gluino or a bino, if either is lighter. If not, it has a wide range of decays which are all suppressed, in our sense, but must be considered, if the dominant decays are kinematically blocked. Similarly, the $\tilde{e}$ field only has an unsuppressed decay to the bino, if allowed. Whereas the $\tilde{l}$ has three unsuppressed modes, to the bino, neutral and charged wino. The charged Higgsino, $\tilde{H}^{\pm}$, has unsuppressed decays to the third generation scalars due to the large Yukawa couplings.

While the case of a neutral LSP might be favored because it could also give a valid dark matter candidate, we have included explicitly also the two possibilities of a charged or colored LSP since these are not necessarily ruled out: the relic density of the SUSY LSP could be tiny enough to be cosmologically negligible and dark matter is formed by other fields like the axion [47–49] or the axino [50]. In case of the gravitino, which we have not mentioned so far, it may be the LSP, and thus the lightest SUSY particle discussed here would be the NLSP. In such scenarios, the NLSP would decay outside the detector into a gravitino [51, 52]. We will nevertheless call this particle the LSP, since the real LSP would not be discovered at the LHC in such a case. We refer the interested reader to [53] for a summary of dark matter candidates in supersymmetry. For our discussion in the following the nature of dark matter is not relevant. However, we want to point out that detailed studies for a charged or a colored LSP exist in the literature [54–58] which have motivated us to discuss these scenarios here.

As for the dominant decay chains, one can have more than one dominant signature for a given hierarchy. This would happen if two dominant decay chains have different signatures. However, if two dominant decay chains have the same signature, this signature is only counted once.

We exemplify this method with the hierarchy

$$i_1 \dots i_8 \tilde{G}\tilde{b}\tilde{H}^0\tilde{W}^0\tilde{l}\tilde{B} \tag{14}$$

For the first two transitions only one possibility exists because the largest couplings are $\tilde{G} \to \tilde{b}$ and $\tilde{b} \to \tilde{H}^0$. However, the higgsino couples with the same strength to the wino and to the bino, and therefore both branches have to be considered. Moreover, the wino will always take the way via the slepton to decay into the LSP. In conclusion, there are two dominant decay chains and two different dominant signatures:

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{B}: \quad 2j + v \tag{15}$$

$$\tilde{G} \to \tilde{b} \to \tilde{H}^0 \to \tilde{W}^0 \to \tilde{l} \to \tilde{B}: \quad 2j + v + 2l \tag{16}$$

Both dominant signatures will appear 8! times because of all possible permutations of the fields heavier than the gluino LCP.

This method of classifying all possible signatures will be applied to two different cases: (i) R-parity conservation and (ii) R-parity violation. In the first case we will assume that all couplings in the superpotential Eq. (12) vanish exactly and thus the LSP is stable. If neutral, it will contribute to the signature as missing transverse energy, $\not{E}_T$. If colored or electrically charged, the LSP interacts with the detector, leading to visible tracks. Thus it cannot be regarded as $\not{E}_T$. We do not consider a stable massive electrically or colored charged particle as a separate signature.

In the second case, R-parity violation, the LSP is no longer stable. Here we shall assume it decays in the detector. However, due to the typically small RpV couplings, that is the only step of the decay chain where these coupling play a role. The rest is exactly the same as in the R-parity conserving case. Furthermore, we will assume that one RpV coupling dominates the decay of the LSP. Therefore, we treat separately four R-parity violating scenarios: ϵ, λ, λ' or λ'' dominance.[7] Our choices for the R-parity violating decay modes are given in Table V. For completeness we note that in case of RpV the couplings can be so small that displaced vertices can be measured at the LHC [59–64]. However, as this depends on the details of the model we did not include it as a signature here.

Some subtleties may arise when finding the dominant decay chains. Our choice for the coupling strengths and the decay products for the different steps of the decay chains also contain some additional assumptions. Therefore, some remarks are required:

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[7] We assume the LSP couples to the dominant RpV operator, see also [28, 46].

transition	strength	signature	transition	strength	signature	transition	strength	signature
$\tilde{G} \leftrightarrow \tilde{d}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{q}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{u}$	not sup.	j
$\tilde{G} \leftrightarrow \tilde{W}^0$	sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{W}^\pm$	sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{e}$	str. sup.	$2j+l$
$\tilde{G} \leftrightarrow \tilde{H}^0$	str. sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{H}^\pm$	str. sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{l}$	str. sup.	$2j+l$
$\tilde{G} \leftrightarrow \tilde{\nu}$	str. sup.	$2j+l$	$\tilde{G} \leftrightarrow \tilde{t}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{b}$	not sup.	j
$\tilde{G} \leftrightarrow \tilde{q}_3$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{\tau}_R$	str. sup.	$3j$	$\tilde{G} \leftrightarrow \tilde{\tau}_L$	str. sup.	$3j$
$\tilde{G} \leftrightarrow \tilde{\nu}_\tau$	str. sup.	$2j+\not\!\!E_T$	$\tilde{G} \leftrightarrow \tilde{B}$	sup.	$2j$			
$\tilde{d} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{d} \leftrightarrow \tilde{q}$	sup.	$2j$	$\tilde{d} \leftrightarrow \tilde{u}$	sup.	$2j$
$\tilde{d} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{d} \leftrightarrow \tilde{W}^\pm$	sup.	j	$\tilde{d} \leftrightarrow \tilde{e}$	sup.	$j+l$
$\tilde{d} \leftrightarrow \tilde{H}^0$	sup.	j	$\tilde{d} \leftrightarrow \tilde{H}^\pm$	sup.	j	$\tilde{d} \leftrightarrow \tilde{l}$	sup.	$j+l$
$\tilde{d} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{d} \leftrightarrow \tilde{t}$	sup.	$2j$	$\tilde{d} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{d} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{d} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{d} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{d} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{d} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{q} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{q} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{q} \leftrightarrow \tilde{u}$	sup.	$2j$
$\tilde{q} \leftrightarrow \tilde{W}^0$	not sup.	j	$\tilde{q} \leftrightarrow \tilde{W}^\pm$	not sup.	j	$\tilde{q} \leftrightarrow \tilde{e}$	sup.	$j+l$
$\tilde{q} \leftrightarrow \tilde{H}^0$	sup.	j	$\tilde{q} \leftrightarrow \tilde{H}^\pm$	sup.	j	$\tilde{q} \leftrightarrow \tilde{l}$	sup.	$j+l$
$\tilde{q} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{q} \leftrightarrow \tilde{t}$	sup.	$2j$	$\tilde{q} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{q} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{q} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{q} \leftrightarrow \tilde{\tau}_L$	sup.	$j+\not\!\!E_T$
$\tilde{q} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{q} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{u} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{u} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{u} \leftrightarrow \tilde{W}^\pm$	sup.	j	$\tilde{u} \leftrightarrow \tilde{e}$	sup.	$j+l$
$\tilde{u} \leftrightarrow \tilde{H}^0$	sup.	j	$\tilde{u} \leftrightarrow \tilde{H}^\pm$	sup.	j	$\tilde{u} \leftrightarrow \tilde{l}$	sup.	$j+l$
$\tilde{u} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{u} \leftrightarrow \tilde{t}$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{u} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{t} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{t} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{t} \leftrightarrow \tilde{W}^\pm$	sup.	j
$\tilde{t} \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{t} \leftrightarrow \tilde{H}^\pm$	not sup.	j
$\tilde{t} \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{t} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{b} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{b} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{b} \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{b} \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{b} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{b} \leftrightarrow \tilde{W}^\pm$	sup.	j
$\tilde{b} \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{b} \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{b} \leftrightarrow \tilde{H}^\pm$	not sup.	j
$\tilde{b} \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{b} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{b} \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{b} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{b} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{b} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{b} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{b} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{q}_3 \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{q}_3 \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{q}_3 \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{q}_3 \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{q}_3 \leftrightarrow \tilde{W}^0$	not sup.	j	$\tilde{q}_3 \leftrightarrow \tilde{W}^\pm$	not sup.	j
$\tilde{q}_3 \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{q}_3 \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{q}_3 \leftrightarrow \tilde{H}^\pm$	not sup.	j
$\tilde{q}_3 \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{q}_3 \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{q}_3 \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{q}_3 \leftrightarrow \tilde{b}$	sup.	$2j$	$\tilde{q}_3 \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{q}_3 \leftrightarrow \tilde{\tau}_L$	sup.	$j+\not\!\!E_T$
$\tilde{q}_3 \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{q}_3 \leftrightarrow \tilde{B}$	not sup.	j			

TABLE II: Interactions for colored particles. We have considered for our analysis charged lepton (l), jets (j), massive bosons (v) and missing transversal energy ($\not\!\!E_T$) as signatures.

transition	strength	signature	transition	strength	signature	transition	strength	signature
$\tilde{e} \leftrightarrow \tilde{G}$	str. sup.	$2j+l$	$\tilde{e} \leftrightarrow \tilde{d}$	sup.	$j+l$	$\tilde{e} \leftrightarrow \tilde{q}$	sup.	$j+l$
$\tilde{e} \leftrightarrow \tilde{u}$	sup.	$j+l$	$\tilde{e} \leftrightarrow \tilde{W}^0$	sup.	l	$\tilde{e} \leftrightarrow \tilde{W}^{\pm}$	sup.	$\not\!\!E_T$
$\tilde{e} \leftrightarrow \tilde{H}^0$	sup.	l	$\tilde{e} \leftrightarrow \tilde{H}^{\pm}$	sup.	$\not\!\!E_T$	$\tilde{e} \leftrightarrow \tilde{l}$	sup.	$2l$
$\tilde{e} \leftrightarrow \tilde{\nu}$	sup.	$l+\not\!\!E_T$	$\tilde{e} \leftrightarrow \tilde{t}$	sup.	$j+l$	$\tilde{e} \leftrightarrow \tilde{b}$	sup.	$j+l$
$\tilde{e} \leftrightarrow \tilde{q}_3$	sup.	$j+l$	$\tilde{e} \leftrightarrow \tilde{\tau}_R$	sup.	$j+l$	$\tilde{e} \leftrightarrow \tilde{\tau}_L$	sup.	$j+l$
$\tilde{e} \leftrightarrow \tilde{\nu}_\tau$	sup.	$l+\not\!\!E_T$	$\tilde{e} \leftrightarrow \tilde{B}$	not sup.	l			
$\tilde{l} \leftrightarrow \tilde{G}$	str. sup.	$2j+l$	$\tilde{l} \leftrightarrow \tilde{d}$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{q}$	sup.	$j+l$
$\tilde{l} \leftrightarrow \tilde{u}$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{W}^0$	not sup.	l	$\tilde{l} \leftrightarrow \tilde{W}^{\pm}$	not sup.	$\not\!\!E_T$
$\tilde{l} \leftrightarrow \tilde{e}$	sup.	$2l$	$\tilde{l} \leftrightarrow \tilde{H}^0$	sup.	l	$\tilde{l} \leftrightarrow \tilde{H}^{\pm}$	str. sup.	$\not\!\!E_T$
$\tilde{l} \leftrightarrow \tilde{t}$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{b}$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{q}_3$	sup.	$j+l$
$\tilde{l} \leftrightarrow \tilde{\tau}_R$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{\tau}_L$	sup.	$j+l$	$\tilde{l} \leftrightarrow \tilde{\nu}_\tau$	sup.	$l+\not\!\!E_T$
$\tilde{l} \leftrightarrow \tilde{B}$	not sup.	l						
$\tilde{\nu} \leftrightarrow \tilde{G}$	str. sup.	$2j+l$	$\tilde{\nu} \leftrightarrow \tilde{d}$	sup.	$j+l$	$\tilde{\nu} \leftrightarrow \tilde{q}$	sup.	$j+l$
$\tilde{\nu} \leftrightarrow \tilde{u}$	sup.	$j+l$	$\tilde{\nu} \leftrightarrow \tilde{W}^0$	not sup.	$\not\!\!E_T$	$\tilde{\nu} \leftrightarrow \tilde{W}^{\pm}$	not sup.	l
$\tilde{\nu} \leftrightarrow \tilde{e}$	sup.	$l+\not\!\!E_T$	$\tilde{\nu} \leftrightarrow \tilde{H}^0$	str. sup.	$\not\!\!E_T$	$\tilde{\nu} \leftrightarrow \tilde{H}^{\pm}$	sup.	l
$\tilde{\nu} \leftrightarrow \tilde{t}$	sup.	$j+l$	$\tilde{\nu} \leftrightarrow \tilde{b}$	sup.	$j+l$	$\tilde{\nu} \leftrightarrow \tilde{q}_3$	sup.	$j+l$
$\tilde{\nu} \leftrightarrow \tilde{\tau}_R$	sup.	$j+\not\!\!E_T$	$\tilde{\nu} \leftrightarrow \tilde{\tau}_L$	sup.	$j+\not\!\!E_T$	$\tilde{\nu} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+l$
$\tilde{\nu} \leftrightarrow \tilde{B}$	not sup.	$\not\!\!E_T$						
$\tilde{\tau}_R \leftrightarrow \tilde{G}$	str. sup.	$3j$	$\tilde{\tau}_R \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{\tau}_R \leftrightarrow \tilde{W}^{\pm}$	sup.	$\not\!\!E_T$
$\tilde{\tau}_R \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{\tau}_R \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{\tau}_R \leftrightarrow \tilde{H}^{\pm}$	not sup.	$\not\!\!E_T$
$\tilde{\tau}_R \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{\tau}_R \leftrightarrow \tilde{\nu}$	sup.	$j+\not\!\!E_T$	$\tilde{\tau}_R \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{b}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not\!\!E_T$	$\tilde{\tau}_R \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{\tau}_L \leftrightarrow \tilde{G}$	str. sup.	$3j$	$\tilde{\tau}_L \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{q}$	sup.	$j+\not\!\!E_T$
$\tilde{\tau}_L \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{W}^0$	not sup.	j	$\tilde{\tau}_L \leftrightarrow \tilde{W}^{\pm}$	not sup.	$\not\!\!E_T$
$\tilde{\tau}_L \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{\tau}_L \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{\tau}_L \leftrightarrow \tilde{H}^{\pm}$	sup.	$\not\!\!E_T$
$\tilde{\tau}_L \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{\tau}_L \leftrightarrow \tilde{\nu}$	sup.	$j+\not\!\!E_T$	$\tilde{\tau}_L \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{\tau}_L \leftrightarrow \tilde{b}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{q}_3$	sup.	$j+\not\!\!E_T$	$\tilde{\tau}_L \leftrightarrow \tilde{\tau}_R$	sup.	$2j$
$\tilde{\tau}_L \leftrightarrow \tilde{B}$	not sup.	j						
$\tilde{\nu}_\tau \leftrightarrow \tilde{G}$	str. sup.	$2j+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{d}$	sup.	$j+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{q}$	sup.	$j+\not\!\!E_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{u}$	sup.	$j+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{W}^0$	not sup.	$\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{W}^{\pm}$	not sup.	j
$\tilde{\nu}_\tau \leftrightarrow \tilde{e}$	sup.	$l+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{H}^0$	sup.	$\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{H}^{\pm}$	not sup.	j
$\tilde{\nu}_\tau \leftrightarrow \tilde{l}$	sup.	$l+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{\nu}_\tau \leftrightarrow \tilde{t}$	sup.	$j+\not\!\!E_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{b}$	sup.	$j+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{q}_3$	sup.	$j+\not\!\!E_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{\tau}_R$	sup.	$j+\not\!\!E_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{B}$	not sup.	$\not\!\!E_T$						

TABLE III: Interactions for uncolored scalars. The same definitions as in Table II are used.

- 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. This is beyond what has been done in [24], and is motivated by the fact that we distinguish between charged leptons and $\not\!\!E_T$ as a signature. Moreover, the charge of the LSP is correlated with the charge of the particles produced in the decay chain. Hence, it is not possible to choose them arbitrarily as charged lepton or $\not\!\!E_T$ when restricting to a chargeless LSP. The easiest example to illustrate this is the $\tilde{B} \to \tilde{L}$ transition, where $\tilde{L}$ is a scalar $SU(2)_L$ doublet containing a charged slepton and a sneutrino. The decay product of the transition can be either a charged lepton, for $\tilde{L} \equiv \tilde{l}$, or $\not\!\!E_T$, for $\tilde{L} \equiv \tilde{\nu}$. Similar correlations are important in order to correctly include the RpV decays. For instance, in the λ-dominated scenario a $\tilde{W}^{\pm}$ LSP will decay into $3l$. (We consider the decay to $2\nu + l$ less visible.) On the other hand, a $\tilde{W}^0$ LSP will decay into $\not\!\!E_T + 2l$. This distinction between fields of different electric charge leads to $16 \cdot 14! = 1,394,852,659,200 \approx 10^{12}$ different field insertions in the 14! hierarchies. We also note that this distinction is not required for squarks, since their electric charge is reabsorbed in that of the jets.

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

TABLE IV: Interactions for uncolored fermions. The same definitions as in Table II are used.

- 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 have always chosen $\not{E}_T$. For example, the transition $\tilde{B} \leftrightarrow \tilde{W}^0$ can either emit two jets, two charged leptons or two neutrinos, and we choose two charged leptons.
- 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.

IV. RESULTS

A. Introduction and RpC Case

We present our results in terms of how large the percentage of models is leading to the signature considered. We have categorized the signatures by the nature of the LSP: (a) neutral ($\tilde{B}$, $\tilde{W}^0$, $\tilde{H}^0$, $\tilde{\nu}$, $\tilde{\nu}_\tau$), (b) charged ($\tilde{l}$, $\tilde{e}$, $\tilde{\tau}_L$, $\tilde{\tau}_R$, $\tilde{W}^+$, $\tilde{H}^+$) and (c) colored ($\tilde{g}$, $\tilde{d}$, $\tilde{u}$, $\tilde{q}$, $\tilde{b}_R$, $\tilde{t}_R$, $\tilde{q}_3$). In each case the sum over the relevant LSPs is taken for the

	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^-	$q\bar{q}$	$qq'q''\nu$
$\tilde{\tau}_R$	$\tau\nu$	$l^\pm\nu$	$l^\pm\nu q\bar{q}$	$qq'q''\tau$

TABLE V: R-parity violating decay modes of the LSP [29, 34, 65, 66]. 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.

	$n_v=0$			$n_v=1$			$n_v=2$		
n_l	$n_j=1$	$n_j=2$	$n_j>2$	$n_j=1$	$n_j=2$	$n_j>2$	$n_j=1$	$n_j=2$	$n_j>2$
0	31.16	11.76	16.48	4.03	1.82	1.27	0.39	0.11	0.02
1	6.69	3.47	5.72	0.42	0.1	0.36	0.02	$7\cdot10^{-3}$	0.02
2	6.5	1.85	5.09	0.22	0.11	0.23	$5\cdot10^{-3}$	$2\cdot10^{-3}$	$7\cdot10^{-3}$
3	0.16	0.25	1.09	0.02	$4\cdot10^{-3}$	0.03	$2\cdot10^{-4}$	$2\cdot10^{-4}$	$2\cdot10^{-3}$
4	0.25	0.05	0.29	$4\cdot10^{-3}$	$2\cdot10^{-3}$	$8\cdot10^{-3}$	$3\cdot10^{-4}$	$5\cdot10^{-5}$	$5\cdot10^{-4}$

TABLE VI: Results for R-parity conservation and a neutral LSP. 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. All numbers in this table refer to percentages of a specific signature.

results in the Tables. For the R-parity conserving cases these three LSP scenarios are presented in Tables VI-VIII, respectively. We list in each Table how often a specific signature appears, classified by the number of charged leptons, jets and massive vector bosons, respectively. Thus in Table VI, we show in the top row 0, 1 or 2 bosons in the event, $n_v=0,1,2$, dividing the Table into three big columns. In the second row we distinguish the number of jets, n_j, dividing each of the big columns into 3 smaller columns. The first column distinguishes the number of charged leptons, n_l, in the event, yielding five further rows. Since we are considering the initial production of a colored particle for each decay chain, we always have at least one jet. Thus we do not consider $n_j=0$. For a neutral LSP we see that for one boson, $n_v=1$, two jets, $n_j=2$, and three charged leptons, $n_l=3$, we have 39 029 940 hierarchies and dominant decay scenarios for a given cascade. This corresponds to a relative fraction of $\sim 0.004\%$, which we have entered in the Table.

In Tables VII and VIII, we have in addition distinguished between signatures without $\not{E}_T$ (upper part of each cell) and with $\not{E}_T$ (lower part of the cell). In Table VI, we have $\not{E}_T$ in each case due to the neutral and stable LSP.

We can see from the numbers in Tables VI-VIII that in the RpC case many hierarchies lead to monojet signatures with and without $\not{E}_T$ and without any charged lepton or massive boson. The transverse momentum is balanced by the charged LSP. The case without $\not{E}_T$, without a charged lepton, but with one vector boson is unique for a charged, colorless LSP and also does not appear in any of the RpV scenarios, as can be seen below. There are also other scenarios which are specific to R-parity conservation. In some cases it is also possible to determine the kind of LSP. A collection of distinctive signatures is given in Table IX. Note that these signatures are expected to be unique if no other signal for SUSY is discovered: we have focused here on the dominant and best visible signatures but, of course,

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	6.45 3.88	14.17 4.35	13.98 4.5	1.77 0.75	0.79 0.31	0.91 0.37	0.13 0.05	0.07 0.01	0.03 0.01
1	10.32 3.2	3.33 2.19	7.36 3.64	0.22 0.16	0.1 0.17	0.46 0.23	0.04 $4 \cdot 10^{-3}$	$8 \cdot 10^{-3}$ 0.01	0.03 0.01
2	0.53 0.55	2.7 0.93	3.78 1.74	0.09 0.05	0.03 0.03	0.16 0.09	0 $2 \cdot 10^{-3}$	$6 \cdot 10^{-3}$ $1 \cdot 10^{-3}$	$8 \cdot 10^{-3}$ $5 \cdot 10^{-3}$
3	1.21 0.37	0.28 0.26	1.49 0.84	0.02 $7 \cdot 10^{-3}$	$8 \cdot 10^{-3}$ 0.02	0.06 0.04	$2 \cdot 10^{-3}$ $5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$ $9 \cdot 10^{-4}$	$3 \cdot 10^{-3}$ $2 \cdot 10^{-3}$
4	0 0	0.2 0.03	0.34 0.09	$1 \cdot 10^{-3}$ $3 \cdot 10^{-4}$	$1 \cdot 10^{-3}$ $7 \cdot 10^{-5}$	0.01 $3 \cdot 10^{-3}$	0 0	$4 \cdot 10^{-4}$ $4 \cdot 10^{-5}$	$8 \cdot 10^{-4}$ $2 \cdot 10^{-4}$

TABLE VII: Result for R-parity conservation and a charged, colorless LSP. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

sub-dominant signatures of other scenarios can lead to the same signal. However, in that case it is most likely that the corresponding *dominat and best visible* signature of the other sceneario is detected first. Looking at the case of a neutral LSP given in Table VI, we see that monojet events can at most be accompanied by four charged leptons as already been pointed out in [24]. This means that our modified treatment of third generation particles does not affect this result. The main reason is that we have treated τs as jets. Chains like $\tilde{g} \to \tilde{t}_R \to \tilde{H}^0 \to \tilde{\tau}_R \to \tilde{B} \to \tilde{e}_R \to \tilde{l} \to \tilde{\nu}_\tau$ lead to 4 charged leptons, 2 jets, 2 τs and $\not{E}_T$. And we treat the τs as additional jets. One example for a decay chain with $n_l = 4$ and $n_j = 1$ is

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \,. \tag{17}$$

All three decay channels of the $SU(2)_L$ singlet $\tilde{d}$ into $\tilde{l}$, $\tilde{e}$ or $\tilde{W}^0$ are equally suppressed (see Table II) and have therefore be considered. Obviously, the transition $\tilde{e} \to \tilde{l}$ which emits two charged leptons is important for this signature. It is much easier to obtain with a wino instead of a bino LSP. For the latter, $\tilde{e}$ would directly decay to the LSP, as would the $\tilde{d}$. Hence, the observation of this signature would support theories which lead to a wino LSP, like AMSB.

Surprisingly in Table VI there are more hierarchies which lead to monojet events together with four than with three leptons for a neutral LSP and in the absence of additional massive bosons. This is related to the right-handedness of the produced squark. $\tilde{d}/\tilde{u} \to \tilde{e}$ will always lead to a jet and a charged lepton because the transition happens dominantly due to an off-shell bino and not a charged wino or higgsino. This changes when one looks at two or more jets because chains like $\tilde{d} \to \tilde{e} \to \tilde{\tau}_R \to \tilde{H}^+ \to \tilde{\nu}$ are possible.

If we compare these results with Table VII which contains the number of hierarchies with a charged LSP, one can see that monojet events and four leptons are only possible in case of exactly one massive boson. Possible hierarchies for these signatures can easily be derived from Eq. (17) by adding a stau or a charged Higgsino to the end of the cascade:

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \to \tilde{\tau}_L \;:\; 4l + 2j \tag{18}$$

$$\tilde{d} \to \tilde{e} \to \tilde{l} \to \tilde{W}^0 \to \tilde{H}^+ \;:\; 4l + j + v \tag{19}$$

One might wonder a bit about the zero entry for the $2l + 2v + 1j$-signature (no $\not{E}_T$) in Table VII. Two bosons come from a $\tilde{B} - \tilde{H} - \tilde{W}$ transition, and therefore $n_v = 2$ events are based on

$$C \to \tilde{B} \to \tilde{H} \to \tilde{W}^0/\tilde{W}^+ \to \tilde{l}/\tilde{\nu} \to \tilde{e} \tag{20}$$

If C is a squark, this will lead to one jet events. All possible combinations of the last three particles always involve three external lepton doublets because of lepton number conservation, so only the combinations $l + \not{E}_T$, $2l + \not{E}_T$ and $3l$ are possible, but not just $2l$. If one allows more jets the picture changes because $\tilde{\tau}_R$ can be inserted between $\tilde{l}/\tilde{\nu} \to \tilde{e}$ leading to the possibility of two charged leptons with $\not{E}_T$. Again, the special properties of the emitted τs play an important role.

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

	$n_v = 0$				$n_v = 1$			$n_v = 2$		
n_l	$n_j = 0$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j \leq 1$	$n_j = 2$	$n_j > 2$	$n_j \leq 1$	$n_j = 2$	$n_j > 2$
0	35.75	6.7	19.87	12.63	0	1.35	0.85	0	0.11	0.04
	0	0	1.58	4.02	0	0.03	0.37	0	$6 \cdot 10^{-3}$	0.02
1	0	0	0	0	0	0	0	0	0	0
	0	0	1.05	1.44	0	0.08	0.09	0	0.01	$6 \cdot 10^{-3}$
2	0	0	5.1	4.33	0	0.08	0.19	0	0.01	0.01
	0	0	0.55	1.55	0	$7 \cdot 10^{-3}$	0.09	0	$2 \cdot 10^{-3}$	$5 \cdot 10^{-3}$
3	0	0	0	0	0	0	0	0	0	0
	0	0	0.41	0.47	0	$7 \cdot 10^{-3}$	0.02	0	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
4	0	0	0.39	0.51	0	$3 \cdot 10^{-3}$	0.01	0	$8 \cdot 10^{-4}$	$1 \cdot 10^{-3}$
	0	0	0.06	0.17	0	$2 \cdot 10^{-4}$	$8 \cdot 10^{-3}$	0	$1 \cdot 10^{-4}$	$4 \cdot 10^{-4}$

TABLE VIII: Result for R-parity conservation and a colored LSP. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

$(1,1,0)$ and $(2,1,0)$. Possible cascades to obtain these signatures are[8]:

$$(0,1,2) : \ \tilde{d} \to \tilde{\nu} \to \tilde{W}^+ \tag{21}$$
$$(1,1,0) : \ \tilde{q} \to \tilde{B} \to \tilde{H}^+ \tag{22}$$
$$(2,1,0) : \ \tilde{q} \to \tilde{B} \to \tilde{H}^+ \to \tilde{W}^+ \tag{23}$$

Next, we consider a colored LSP in the RpC case, *i.e.* a gluino or a squark. These particles might form 'R-hadrons' and come to rest in the calorimeters. Searches for these signals have been performed at LEP, the Tevatron [67–69] and the LHC [70]. If the LSP is the gluino or a squark of the first two generations it will be produced and will not decay. This leads to the large number in the $n_j = n_l = n_v = 0$ entry because they come with a huge combinatorial factor of 13! taking all possible hierarchies of the heavier particles into account. The events with one jet but nothing else are caused by a squark of the third generation as 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. Because of 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. However, it is interesting to see that this also holds when considering the emitted τs as jets.

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 appear for instance in

$$\tilde{q} \to \tilde{B} \to \tilde{H} \to \tilde{W}^0 \to \tilde{l} \to \tilde{e} \to \tilde{t}_R \tag{24}$$

The produced squark has not necessarily to be left-handed and the LSP can also be left-handed or a sbottom.

In compiling the RpC scenarios we first compared with Ref. [24] and found agreement. The results presented above differ, since we have treated the third generation leptons separately and have also treated the two leptons in the $SU(2)_L$ doublets separately.

Summary for RpC

We have distinguished three RpC cases: (i) for a neutral LSP always $\not{E}_T$ is present and monojet events can be accompanied with at most four charged leptons. Interestingly, there are more hierarchies leading to four than to three charged leptons and one jet. (ii) In the case of a charged and colorless LSP monojet events with four charged

[8] In this decay chain, the only unsuppressed $\tilde{d}$ decay is to a bino. Here the bino is heavier and thus this becomes a suppressed 3-body decay. Therefore in Eq. (21) the decay $\tilde{d} \to \tilde{\nu}$ with $1j$, $1l$ is allowed.

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	R			c	R		c	R	
							R		
1									
	R								
2	c			ø			ø		
3									
							R		
4	ø			c			ø		
5	λ	λ	$\not R$	$\not R$	$\not R$	$\not R$	$\not R$	$\not R$	$\not R$
	λ	λ	$\not R$	$\not R$	$\not R$	$\not R$	λ	$\not R$	$\not R$
6	ø	ø	λ	ø	λ	λ	ø	ø	λ
	λ	λ	λ	λ	λ	λ	λ	λ	λ
7	ø	ø	λ	λ	λ	λ	ø	ø	ø
	ø	λ	λ	ø	ø	λ	ø	ø	ø

TABLE IX: The *dominant and best visible signatures* which appear only in a given scenario. We used here R for R-parity conservation in general and n (neutral), c (charged), h (colored) if also the kind of LSP can be determined. When a specific signal is just possible R-parity violation, we used $\not R$, while we give the corresponding coupling this is only possible for one scenario. In addition, we use ø for cases which are neither covered in the RpV nor RpC case and therefore unique in that sense that they demand an extension of the MSSM. The upper line in a cell is for the case without $\not E_T$, the lower part with $\not E_T$. Note, this table does not include a column for $n_j = 0$, but we point out that $n_j = 0$, $n_l = 0$, $n_\nu = 1$ without $\not E_T$ is unique for a colored LSP in the RpC case.

leptons can only appear for $n_v = 1$. The $n_j = n_v = 1, n_l = 4$ with $\not E_T$ is unique and can neither appear in any other RpV nor RpC scenario. In addition, there are three other unique signatures for a charged, coloreless LSP: $(n_v, n_j, n_l) = (0, 1, 2), (1, 1, 0)$ and $(2, 1, 0)$. (iii) The most often appearing hierarchies for a colored LSP are either $n_j = n_v = n_l = 0$ if the LSP a gluino or a squark of the first two generations. For a squark of the third generation there are only signatures with at least two jets. For all three cases it turned out that the treatment of the τs is crucial: the results of Ref. [24], which did not differ between the third and the other two generations, are only recovered because τs are counted as jets.

B. Bilinear RpV

We turn now to the results for bilinear RpV given in Table X[9]. Since the LSP decays, we present in each entry in the table the sum of the hierarchies for all possible LSPs. Here, the maximal number of charged lepton tracks is five. This is more than in the RpC case. Five charged leptons can be reached for instance due to the decay channels listed in Table V and the signatures given in Eq. (17) for a wino LSP or Eq. (24) for a squark LSP.

There are two other interesting results: *(i)* the signal $v+j+l$ ($n_v = n_j = n_l = 1$) without $\not E_T$ can only be generated in bilinear RpV with a general LSP as well as in RpC with a charged LSP. Thus if this signature is observed and if the LSP is found and uncharged, bilinear R-parity violation is the best candidate to explain this within supersymmetry. *(ii)* Monojet events with $\not E_T$ and zero or one massive boson appear much more often in bilinear RpV than in the other cases.

In Table X, the origin of the $n_v = n_j = n_l = 1$ entries without $\not E_T$ are the hierarchies with a wino LSP. As long as the produced squark is left-handed it will always decay dominantly into the LSP independently of the mass ordering of the other states. However, if the produced squark is right-handed then for this signature ($n_v = n_j = n_l = 1$) the bino cannot be lighter because then the squark would not decay directly to the LSP.

[9] This also covers models which contain the bilinear model when integrating out heavy additional states, e.g. spontaneous R-parity violation [71, 72] or the $\mu\nu$SSM [73, 74].

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	0 2.99	0 0.75	4.25 15.72	0 2.24	0 0.75	0.27 1.02	0 0	0 0.06	0.02 0.09
1	5.98 0	4.49 0	15.28 3.42	7.28 0.8	2.73 0.91	4.73 0.9	1.99 0.04	0.49 0.17	0.43 0.04
2	0 2.17	0 0.7	1.29 6.31	0 1.11	0 0.3	0.03 0.63	0 0.14	0 0.02	$3 \cdot 10^{-3}$ 0.03
3	0 0	0 0	3.16 0.95	1.38 0.23	0.24 0.18	0.98 0.22	0.09 $7 \cdot 10^{-3}$	0.01 0.02	0.05 $6 \cdot 10^{-3}$
4	0 0.17	0 0.04	0.12 0.78	0 0.1	0 0.03	$3 \cdot 10^{-3}$ 0.1	0 $5 \cdot 10^{-3}$	0 $4 \cdot 10^{-4}$	$3 \cdot 10^{-4}$ $2 \cdot 10^{-3}$
5	0 0	0 0	0.2 0.05	0.03 $4 \cdot 10^{-3}$	$3 \cdot 10^{-3}$ $8 \cdot 10^{-3}$	0.03 $7 \cdot 10^{-3}$	$1 \cdot 10^{-3}$ 0	$7 \cdot 10^{-5}$ $2 \cdot 10^{-5}$	$6 \cdot 10^{-4}$ $1 \cdot 10^{-4}$

TABLE X: Results for bilinear R-parity violation. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
1	0 0	0 4.28	0 4.15	0 0	0 0.17	0 0.22	0 0	0 0.02	0 0.01
2	0 24.17	0.4 10.63	0.31 20.16	0 1.32	0.08 0.45	0.03 1.4	0 0.15	$5 \cdot 10^{-3}$ 0.03	$1 \cdot 10^{-3}$ 0.07
3	5.98 0.39	2.18 2.25	3.32 2.21	1.13 0.04	0.28 0.12	0.29 0.1	0.09 $4 \cdot 10^{-4}$	0.02 $4 \cdot 10^{-3}$	$4 \cdot 10^{-3}$ $5 \cdot 10^{-3}$
4	0 3.3	0.15 0.74	0.14 5.82	0 0.15	$4 \cdot 10^{-3}$ 0.03	$6 \cdot 10^{-3}$ 0.2	0 $3 \cdot 10^{-3}$	$3 \cdot 10^{-4}$ $6 \cdot 10^{-4}$	$3 \cdot 10^{-4}$ 0.01
5	0.58 0.11	0.1 0.31	0.68 0.38	0.05 $4 \cdot 10^{-3}$	$5 \cdot 10^{-3}$ 0.01	0.03 0.01	$6 \cdot 10^{-5}$ $8 \cdot 10^{-5}$	$1 \cdot 10^{-5}$ $3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$ $7 \cdot 10^{-4}$
6	0 0.15	0 0.03	0.01 0.46	0 $4 \cdot 10^{-3}$	$1 \cdot 10^{-4}$ $6 \cdot 10^{-4}$	$2 \cdot 10^{-4}$ $9 \cdot 10^{-3}$	0 $9 \cdot 10^{-5}$	0 $1 \cdot 10^{-5}$	$2 \cdot 10^{-5}$ $8 \cdot 10^{-4}$
7	0 0	0 $6 \cdot 10^{-3}$	0.01 $2 \cdot 10^{-3}$	$7 \cdot 10^{-4}$ 0	$2 \cdot 10^{-5}$ 0	$2 \cdot 10^{-5}$ $5 \cdot 10^{-6}$	0 0	0 0	0 0

TABLE XI: Results for R-parity violation: λ term. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

The large number of monojet events with $\not{E}_T$ and one charged lepton comes from the direct decays of right-handed squarks. Therefore, its amount is exactly half of the $n_v = n_j = n_l = 0$-entry in Table VIII.

The zero entries in Table X indicate that there are many scenarios which can disfavor bilinear RpV. For instance, an even number of charged leptons is only (dominantly) possible together with $\not{E}_T$ as long as less than three jets are present. The reason is again the special properties of the τ, *e.g.*

$$\tilde{q} \to \tilde{e} \to \tilde{l} \to \tilde{\tau}_L \tag{25}$$

leads to 4 jets and 4 charged leptons.Two jets arise from the $\tilde{\tau}$-LSP decay.

Summary for bilinear RpV

Bilinear RpV can often be disfavored because many signatures are only sub-dominant. This is for instance the case for a even number of charged leptons and $\not{E}_T$ and less than three jets. However, monojet events with $\not{E}_T$ and less than two massive vector bosons appear much more often in bilinear RpV than in all other cases. Furthermore,

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	0	0	4.17	0	0	0.26	0	0	0.02
	0	0.73	11.41	0	0	0.75	0	0	0.06
1	5.87	3.67	35.35	0	0	3.64	0	0	0.26
	0	0	9.75	0	0	0.65	0	0	0.03
2	0	0	1.27	0	0	0.03	0	0	$3 \cdot 10^{-3}$
	0	0	5.66	0	0	0.38	0	0	0.01
3	0	0	10.05	0	0	0.4	0	0	0.02
	0	0	3.24	0	0	0.15	0	0	$9 \cdot 10^{-3}$
4	0	0	0.11	0	0	$3 \cdot 10^{-3}$	0	0	$2 \cdot 10^{-4}$
	0	0	0.99	0	0	0.03	0	0	$3 \cdot 10^{-3}$
5	0	0	0.71	0	0	0.02	0	0	$2 \cdot 10^{-3}$
	0	0	0.27	0	0	$8 \cdot 10^{-3}$	0	0	$7 \cdot 10^{-4}$

TABLE XII: Results for R-parity violation: λ' term. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

signatures with one jet, one charged lepton, one massive vector boson and without $\not{E}_T$ are only possible for bilinear RpV or RpC with a colored LSP.

C. Trilinear RpV

Next we consider the trilinear RpV scenario $\lambda\hat{l}\hat{l}\hat{e}$. This interaction leads to an increase in the number of charged leptons in the final states. Up to seven lepton tracks with and without $\not{E}_T$ are possible, *c.f.* Table XI. This is found for the mass hierarchies

$$\tilde{q} \to \tilde{B} \to \tilde{e} \to \tilde{l} \to \tilde{\nu}_\tau \to \tilde{H}^\pm \tag{26}$$

thanks to the three leptons in the final decay of the LSP, $\tilde{H}^\pm \to l^\pm l^+ l^-$ (the $\tilde{l} \to \tilde{\nu}_\tau$ should go through a neutral wino). However, even in the unconstrained version of the MSSM it is hard to obtain a chargino LSP, consistent with the LEP constraints. Therefore, this signature might not only point to R-parity violation but also to some other extension of the MSSM. In contrast, events with 6 charged leptons, which are still outstanding, are possible for a neutral LSP as well as for a stop LSP, which is possible within RpV mSUGRA [75]. A potential spectrum hierarchy leading to 6 leptons is

$$\tilde{q} \to \tilde{B} \to \tilde{e} \to \tilde{l} \to \tilde{H}^0/\tilde{t}_L \tag{27}$$

Of course, also the cascades in Eqs. (17) and (24) do the job.

The reason that there are no seven jets events possible with two massive bosons is that the bino and the wino have to be present and have to couple to the higgsino. Therefore, the transitions $\tilde{C} - \tilde{B}/\tilde{W} - \tilde{l}/\tilde{e}_R$ are not possible. Another remarkable signature is the one with seven charged leptons but only one jet and one massive boson. This signature can be obtained by replacing $\tilde{\nu}_\tau$ by $\tilde{W}^0$ in Eq. (26).

On the other hand, the λ-interaction can be easily disfavored by the observation of supersymmetric events with less than two leptons. The only possibility to get one-lepton events are due to the decay of τs, for example in the chains

$$\tilde{q} \to \tilde{\tau}_L\,, \qquad \tilde{q} \to \tilde{B} \to \tilde{H}^0 \to \tilde{\tau}_L\,, \qquad \tilde{q} \to \tilde{B} \to \tilde{H}^0 \to \tilde{W}^0 \to \tilde{\tau}_L \tag{28}$$

with two jets and zero, one or two massive vector bosons.

The second lepton number violating coupling, λ', usually leads to multi-jet events. The only exception is the case without any massive boson and without $\not{E}_T$ but with just one charged lepton. Such an event happens if the LSP is a squark of the first two generations ($\tilde{d}$, $\tilde{u}$ or $\tilde{q}$). In that case, the LSP is produced and decays directly due to a R-parity violating channel without any intermediate cascade, *e.g.* $\tilde{u}_L \to l^+ + d_R$. Note that $\tilde{u}$ does not directly interact via the lqd operator. Thus the decay proceeds via two off-shell particles leading to three jets and one charged lepton. The

	$n_v=0$			$n_v=1$			$n_v=2$		
n_l	$n_j=2$	$n_j=3$	$n_j>3$	$n_j=2$	$n_j=3$	$n_j>3$	$n_j=2$	$n_j=3$	$n_j>3$
0	9.38	4.69	37.98	0	0	4.21	0	0	0.3
	0	0	7.87	0	0	0.76	0	0	0.03
1	0	0	0	0	0	0	0	0	0
	0	0	8.19	0	0	0.56	0	0	0.03
2	0	0	17.45	0	0	0.65	0	0	0.05
	0	0	3.71	0	0	0.22	0	0	0.01
3	0	0	0	0	0	0	0	0	0
	0	0	1.42	0	0	0.06	0	0	$3\cdot10^{-3}$
4	0	0	1.92	0	0	0.05	0	0	$4\cdot10^{-3}$
	0	0	0.44	0	0	0.02	0	0	$1\cdot10^{-3}$

TABLE XIII: Results for R-parity violation: λ'' term. The notation is as in Table VI. 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. All numbers in this table refer to percentages of a specific signature.

two jet events in Table XII are a consequence of a gluino LSP. On the other side, theoretically up to eleven jets can be caused by the cascade

$$\tilde{d} \to \tilde{\tau}_L \to \tilde{W}^0 \to \tilde{b}_L \to \tilde{b}_R \to \tilde{t}_R\,. \tag{29}$$

The stop LSP decays into three jets and a charged lepton.

The last remaining RpV case is the baryon number violating term $\lambda''\hat{u}\hat{d}\hat{d}$. This interaction causes a large number of additional jets and therefore monojet events are not possible. Events with exactly two jets can only occur if the LSP is the directly produced squark. In case of a gluino LSP three jets are emitted in the RpV decay.

As a consequence of this, this scenario would be under pressure by the observation of events with less then 4 jets accompanied by some charged leptons or an amount of charged leptons which is larger than expected already for the RpC case. In contrast, multi-jet events can also appear easily in the R-parity conserving case as well as for lepton-number violating operators. This renders it rather difficult to find a signature which privileges the λ'' case, since we have seen that already in the $\hat{l}\hat{q}\hat{d}$ scenario up to eleven jets are possible.

Finally, we have here treated each final state quark as a separate jet. This need not be the case. If the jets resulting from a decaying particle are clumped, they can manifest an interesting substructure [76]. This is particularly relevant for the $\hat{u}\hat{d}\hat{d}$ case [77]. See also the recent work in Ref. [78].

Summary for trilinear RpV

The three cases of trilinear RpV have very different features: (i) in case of $\lambda\hat{l}\hat{l}\hat{e}$ signatures with up to seven charged leptons are possible while in all other setups at most five are possible. However, $n_l = 7$ is only possible for a chargino LSP what is usually hard to reach in the MSSM, $n_l = 6$ works also for a Higgsino or stau LSP. (ii) If the LSP is not a squark of the first two generations, and therefore directly produced, $\lambda'\hat{l}\hat{q}\hat{d}$ leads to multi-jet events. Therefore, it is very hard to distinguish this case from the one with RpC and a colored LSP. The main difference between both is the possibility of five charged leptons. (iii) Finally, $\lambda''\hat{u}\hat{d}\hat{d}$ might be the scenario which is the hardest one to be proven correct. The reason is that only in 14% of all hierarchies it is possible to get events with less than 4 jets while events with zero or one jet are not possible at all.

D. Exclusion Summary

We have collected in Table XIV all scenarios which can be disfavored by the observation of a specific signature. Obviously, especially events with just one or two jets as well as multi-lepton events are a very effective selection criterion. Thus for $n_v = 2$ and $n_l = 7$ we have written 'all' in the three boxes for $n_j = 1$, $n_j = 2$ and $n_j > 2$. This means that *no* model predicts this signature dominantly. In the box for $n_v = 0$, $n_j > 2$ and $n_l = 4$ we have the entry 'n' meaning this signature does *not* appear dominantly if the LSP is neutral.

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	$n,\not{R}$ $h,\lambda,\lambda',\lambda''$	$n,\epsilon,\lambda,\lambda'$ λ,λ''	n,λ λ	$n,h,\not{R}$ $h,\lambda,\lambda',\lambda''$	$n,\epsilon,\lambda,\lambda''$ $\lambda,\lambda',\lambda''$	n,λ,λ' λ	$n,h,\epsilon,\lambda,\lambda''$ $h,\not{R}$	$n,\epsilon,\lambda',\lambda,\lambda',\lambda''$ $\lambda,\lambda',\lambda''$	n,λ λ
1	n,h,λ,λ'' $h,\not{R}$	n,h,λ,λ'' $\epsilon,\lambda',\lambda''$	n,h,λ,λ''	$n,h,\lambda,\lambda',\lambda''$ $h,\lambda,\lambda',\lambda''$	$n,h,\lambda,\lambda',\lambda''$ λ',λ''	n,h,λ,λ''	$n,h,\ \lambda,\lambda',\lambda''$ $h,\lambda,\lambda',\lambda''$	$n,h,\ \lambda,\lambda',\lambda''$ λ',λ''	n,h,λ,λ''
2	$n,h,\not{R}$ h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	$n,h,\not{R}$ h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	all h,λ',λ''	$n,\ \epsilon,\lambda',\lambda''$ λ',λ''	n
3	$n,h,\epsilon,\lambda',\lambda''$ $h,\epsilon,\lambda',\lambda''$	$n,h,\epsilon,\lambda',\lambda''$ $\epsilon,\lambda',\lambda''$	n,h,λ''	n,h,λ',λ'' h,λ',λ''	n,h,λ',λ'' λ',λ''	n,h,λ''	$n,h,\ \lambda',\lambda''$ $h,\not{R}$	n,h,λ',λ'' λ',λ''	n,h,λ''
4	all c,h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	$n,\ h,\not{R}$ h,λ',λ''	$c,\epsilon,\lambda',\lambda''$ λ',λ''	n	all c,h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n
5	R,ϵ,λ' R,ϵ,λ'	R,ϵ,λ' R,ϵ,λ'	R R	R,λ' R,λ'	R,λ' R,λ'	R R	R,λ' R,ϵ,λ'	R,λ' R,λ'	R R
6	all $R,\epsilon,\ \lambda',\ \lambda''$	all $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$	all $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$	all $R,\epsilon,\ \lambda',\ \lambda''$	all $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$
7	all all	all $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$	$R,\epsilon,\ \lambda',\ \lambda''$ all	$R,\epsilon,\ \lambda',\ \lambda''$ all	$R,\epsilon,\ \lambda',\ \lambda''$ $R,\epsilon,\ \lambda',\ \lambda''$	all all	all all	all all

TABLE XIV: Signatures which do not appear dominantly in a given model. We used here R for R-parity conservation in general and n (neutral), c (charged), h (colored) if also the kind of LSP can be determined. When a specific signal is just possible R-parity violation, we used $\not{R}$, while we give the corresponding coupling this is only possible for one scenario. The upper line in a cell is for the case without $\not{E}_T$, the lower part with $\not{E}_T$. Note, this table does not include a column for $n_j = 0$, but we point out that $n_j = 0$, $n_l = 0$, $n_\nu = 1$ without $\not{E}_T$ would exclude all cases but h, while any other combination with $n_j = 0$ would disfavor all scenarios discussed here.

A word of caution should be added here. This table applies in case that one signature is observed at the LHC. However, we emphasize that other signatures, which do not belong to the set of *dominant and best visible signatures* considered here, are possible. Nevertheless, in those cases it is very likely that the most visible signature is detected first.

Furthermore, there are also signatures which cannot be reached dominantly in any of the presented scenarios. Such an observation would directly point to an extension of the MSSM. It might be a surprise that not only events with four or more charged leptons are hard to produce in the MSSM with and without R-parity violation, but also one jet, two charged leptons and two massive bosons is not a result of the dominant decay chain of any of the 14! hierarchies considered here.

V. CONCLUSION

We have presented in this work the collider signatures appearing in a very general realization of the MSSM based on 14 unrelated mass parameters. These mass parameters lead to $14! \approx 9 \cdot 10^{10}$ particle orderings. We go beyond previous work to allow for separate third generation soft supersymmetry breaking parameters. For each mass ordering of the supersymmetric fields, we have determined the dominant decay modes. We imagine this as a chain of decays giving a cascade overall. Each supersymmetric particle can decay to all other lighter supersymmetric particles, fixed by that mass ordering. For these we consider decays involving the mixing between sparticles to be subdominant. If a 2-body decay mode exists, then 3-body decays are subdominant. For all sfermions other than the third generation, Higgs(ino) couplings are subdominant. We can thus classify all decays for each supersymmetric particle which are summarized in Tables II-IV.

These tables are the basis for all our results. Each dominant decay leads to a specific signature. For our signatures we consider: charged leptons, jets, massive bosons ($W^\pm$, Z, Higgs) and $\not{E}_T$. We have then systematically gone through all possible mass ordering and determined the dominant decay signatures. We have summarized the results for several supersymmetric models, both R-parity conserving and R-parity violating, in a series of tables.

In Table VI, we consider the case of R-parity conservation with a neutralino LSP. This closely resembles the previous work in [24]. We go beyond their work to consider the third generation parameters as separate. In the table, we list the relative frequency with which the various signatures occur.

In Tables VII and VIII we perform the analogous analysis for a possible electrically charged or color charged stable LSP. Here we have in addition determined whether the final state signature includes $\not{E}_T$ or not.

We found signatures which are specific for a particular RpV scenario or for the RpC case. However, it has also been shown that there is no hierarchy in the case of the $\hat{l}\hat{q}\hat{d}$ couplings which leads to a signature that cannot be reached by another setup as well. This makes it a bit difficult to favor one of these possibilities by looking just at the signatures produced at the LHC. However, not only pure monojet events are only possible with conserved R-parity, but also other signatures like two jets and one massive vector boson will not appear dominantly in RpV scenarios while they do in RpC. In addition, there is at least one signature which is dominant only in trilinear RpV and many multi-lepton signatures which are outstanding for $\hat{l}\hat{l}\hat{e}$ couplings. Furthermore, we also found several signatures which can, at least, highly disfavor some of the scenarios considered here due to the impossibility to find hierarchies that can produce such a signal in its dominant decay mode.

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[1] G. Aad *et al.* [The ATLAS Collaboration], arXiv:0901.0512 [hep-ex].
[2] S. Chatrchyan *et al.* [CMS Collaboration], JINST **3** (2008) S08004.
[3] S. P. Martin, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].
[4] H. P. Nilles, Phys. Rept. **110** (1984) 1.
[5] G. Aad *et al.* [ATLAS Collaboration], arXiv:1109.6572 [hep-ex].
[6] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **85** (2012) 012006 [arXiv:1109.6606 [hep-ex]].
[7] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **709** (2012) 137 [arXiv:1110.6189 [hep-ex]].
[8] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. D **85** (2012) 012004 [arXiv:1107.1279 [hep-ex]].
[9] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1108**, 156 (2011) [arXiv:1107.1870 [hep-ex]].
[10] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **107** (2011) 221804 [arXiv:1109.2352 [hep-ex]].
[11] See the talk by Steve Lowette on behalf of the `Atlas` and `CMS` collaborations at the conference Rencontres de Moriond 2012 `http://indico.in2p3.fr/getFile.py/access?contribId=96&sessionId=5&resId=0&materialId=slides&confId=6001`.
[12] P. Bechtle *et al.*, arXiv:1204.4199 [hep-ph].
[13] 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]].
[14] G. R. Farrar and P. Fayet, Phys. Lett. B **76** (1978) 575.
[15] H. E. Haber, Nucl. Phys. Proc. Suppl. **62** (1998) 469 [hep-ph/9709450].
[16] G. F. Giudice and R. Rattazzi, Phys. Rept. **322**, 419 (1999) [hep-ph/9801271].
[17] F. E. Paige and J. D. Wells, hep-ph/0001249.
[18] H. Baer, E. -K. Park, X. Tata and T. T. Wang, JHEP **0706** (2007) 033 [hep-ph/0703024].
[19] J. A. Conley, H. K. Dreiner, L. Glaser, M. Kramer and J. Tattersall, JHEP **1203** (2012) 042 [arXiv:1110.1287 [hep-ph]].
[20] F. E. Paige, S. D. Protopopescu, H. Baer and X. Tata, hep-ph/0312045.
[21] B. C. Allanach, Comput. Phys. Commun. **143** (2002) 305 [hep-ph/0104145].
[22] A. Djouadi, J. -L. Kneur and G. Moultaka, Comput. Phys. Commun. **176** (2007) 426 [hep-ph/0211331].
[23] W. Porod, Comput. Phys. Commun. **153** (2003) 275 [hep-ph/0301101].
[24] P. Konar, K. T. Matchev, M. Park and G. K. Sarangi, Phys. Rev. Lett. **105** (2010) 221801 [arXiv:1008.2483 [hep-ph]].
[25] C. F. Berger, J. S. Gainer, J. L. Hewett and T. G. Rizzo, JHEP **0902** (2009) 023 [arXiv:0812.0980 [hep-ph]].
[26] For the pMSSM see Ref. [22] and P. Bechtle, K. Desch and P. Wienemann, Comput. Phys. Commun. **174** (2006) 47 [hep-ph/0412012].
[27] L. J. Hall and M. Suzuki, Nucl. Phys. B **231** (1984) 419.
[28] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **69** (2004) 115002 [Erratum-ibid. D **72** (2005) 079902] [hep-ph/0309196].
[29] H. K. Dreiner, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 565-583 [hep-ph/9707435].
[30] G. Bhattacharyya, In *Tegernsee 1997, Beyond the desert 1997* 194-201 [hep-ph/9709395].
[31] V. D. Barger, G. F. Giudice and T. Han, Phys. Rev. D **40** (1989) 2987.
[32] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **60** (1999) 075014 [arXiv:hep-ph/9906209].

[33] M. Hirsch *et al.*, Phys. Rev. D **62** (2000) 113008 [Erratum-ibid. D **65** (2002) 119901] [hep-ph/0004115].
[34] R. Barbier *et al.*, Phys. Rept. **420**, 1 (2005) [hep-ph/0406039].
[35] B. C. Allanach *et al.*, Comput. Phys. Commun. **180** (2009) 8 [arXiv:0801.0045 [hep-ph]].
[36] B. C. Allanach, H. K. Dreiner, P. Morawitz and M. D. Williams, Phys. Lett. B **420** (1998) 307 [hep-ph/9708495].
[37] M. A. Bernhardt, H. K. Dreiner, S. Grab and P. Richardson, Phys. Rev. D **78** (2008) 015016 [arXiv:0802.1482 [hep-ph]].
[38] S. Dimopoulos, R. Esmailzadeh, L. J. Hall and G. D. Starkman, Phys. Rev. D **41** (1990) 2099.
[39] H. K. Dreiner, P. Richardson and M. H. Seymour, Phys. Rev. D **63** (2001) 055008 [hep-ph/0007228].
[40] Y. Kao and T. Takeuchi, arXiv:0910.4980 [hep-ph].
[41] H. K. Dreiner, M. Hanussek and S. Grab, Phys. Rev. D **82** (2010) 055027 [arXiv:1005.3309 [hep-ph]].
[42] H. K. Dreiner, K. Nickel, F. Staub and A. Vicente, Phys. Rev. D 86, **015003** (2012) [arXiv:1204.5925 [hep-ph]].
[43] H. K. Dreiner, G. Polesello and M. Thormeier, Phys. Rev. D **65** (2002) 115006 [hep-ph/0112228].
[44] H. K. Dreiner, M. Kramer and B. O'Leary, Phys. Rev. D **75** (2007) 114016 [hep-ph/0612278].
[45] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **60** (1999) 056002 [hep-ph/9902251].
[46] B. C. Allanach *et al.*, Phys. Rev. D **75** (2007) 035002 [hep-ph/0609263].
[47] J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. B **120** (1983) 127.
[48] L. F. Abbott and P. Sikivie, Phys. Lett. B **120** (1983) 133.
[49] M. Dine and W. Fischler, Phys. Lett. B **120** (1983) 137.
[50] L. Covi, J. E. Kim and L. Roszkowski, Phys. Rev. Lett. **82** (1999) 4180 [hep-ph/9905212].
[51] J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **588** (2004) 7 [hep-ph/0312262].
[52] J. R. Ellis, A. R. Raklev and O. K. Oye, JHEP **0610** (2006) 061 [hep-ph/0607261].
[53] F. D. Steffen, Eur. Phys. J. C **59** (2009) 557 [arXiv:0811.3347 [hep-ph]].
[54] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **102** (2009) 161802 [arXiv:0809.4472 [hep-ex]].
[55] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103** (2009) 021802 [arXiv:0902.1266 [hep-ex]].
[56] S. Raby, Phys. Lett. B **422**, 158 (1998) [hep-ph/9712254].
[57] H. Baer, K. -m. Cheung and J. F. Gunion, Phys. Rev. D **59** (1999) 075002 [hep-ph/9806361].
[58] S. Raby and K. Tobe, Nucl. Phys. B **539** (1999) 3 [hep-ph/9807281].
[59] F. de Campos *et al.*, JHEP **0805** (2008) 048 [arXiv:0712.2156 [hep-ph]].
[60] F. de Campos *et al.*, Phys. Rev. D **77** (2008) 115025 [arXiv:0803.4405 [hep-ph]].
[61] F. De Campos *et al.*, Phys. Rev. D **82** (2010) 075002 [arXiv:1006.5075 [hep-ph]].
[62] K. Desch, S. Fleischmann, P. Wienemann, H. K. Dreiner and S. Grab, Phys. Rev. D **83** (2011) 015013 [arXiv:1008.1580 [hep-ph]].
[63] H. K. Dreiner, M. Hanussek, J. -S. Kim and C. H. Kom, Phys. Rev. D **84** (2011) 113005 [arXiv:1106.4338 [hep-ph]].
[64] P. W. Graham, D. E. Kaplan, S. Rajendran and P. Saraswat, arXiv:1204.6038 [hep-ph].
[65] W. Porod, M. Hirsch, J. Romao and J. W. F. Valle, Phys. Rev. D **63** (2001) 115004 [hep-ph/0011248].
[66] M. Hirsch and W. Porod, Phys. Rev. D **68** (2003) 115007 [hep-ph/0307364].
[67] A. Heister *et al.* [ALEPH Collaboration], Eur. Phys. J. C **31** (2003) 327 [hep-ex/0305071].
[68] A. Arvanitaki *et al.*, Phys. Rev. D **76** (2007) 055007 [hep-ph/0506242].
[69] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **99** (2007) 131801 [arXiv:0705.0306 [hep-ex]].
[70] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **701** (2011) 1 [arXiv:1103.1984 [hep-ex]].
[71] A. Masiero and J. W. F. Valle, Phys. Lett. B **251** (1990) 273.
[72] M. Hirsch, A. Vicente and W. Porod, Phys. Rev. D **77** (2008) 075005 [arXiv:0802.2896 [hep-ph]].
[73] D. E. Lopez-Fogliani and C. Munoz, Phys. Rev. Lett. **97** (2006) 041801 [hep-ph/0508297].
[74] A. Bartl *et al.*, JHEP **0905** (2009) 120 [arXiv:0903.3596 [hep-ph]].
[75] H. K. Dreiner and S. Grab, Phys. Lett. B **679** (2009) 45 [arXiv:0811.0200 [hep-ph]]; H. K. Dreiner and S. Grab, AIP Conf. Proc. **1200** (2010) 358 [arXiv:0909.5407 [hep-ph]].
[76] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. **100** (2008) 242001 [arXiv:0802.2470 [hep-ph]].
[77] J. M. Butterworth, J. R. Ellis, A. R. Raklev and G. P. Salam, Phys. Rev. Lett. **103** (2009) 241803 [arXiv:0906.0728 [hep-ph]].
[78] B. C. Allanach and B. Gripaios, arXiv:1202.6616 [hep-ph].