

Marked up version

SUSY Les Houches Accord 2

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Abstract

The Supersymmetry Les Houches Accord (SLHA) provides a universal set of conventions for conveying spectral and decay information for supersymmetry analysis problems in high energy physics. Here, we propose extensions of the conventions of the first SLHA to include various generalisations: the minimal supersymmetric standard model with violation of CP, R-parity, and flavour, as well as the simplest next-to-minimal model.

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1 Introduction

Supersymmetric (SUSY) extensions of the Standard Model rank among the most promising and well-explored scenarios for New Physics at the TeV scale. Given the long history of supersymmetry and the number of people working in the field, several different conventions for defining supersymmetric theories have been proposed over the years, many of which have come into widespread use. At present, therefore, no unique set of conventions prevails. In principle, this is not a problem. As long as everything is clearly and consistently defined, a translation can always be made between two sets of conventions.

However, the proliferation of conventions does have some disadvantages. Results obtained by different authors or computer codes are not always directly comparable. Hence, if author/code A wishes to use the results of author/code B in a calculation, a consistency check of all the relevant conventions and any necessary translations must first be made – a tedious and error-prone task.

To deal with this problem, and to create a more transparent situation for non-experts, the original SUSY Les Houches Accord (SLHA1) was proposed [1]. This accord uniquely defines a set of conventions for supersymmetric models together with a common interface between codes. The most essential fact is not what the conventions are in detail (they largely resemble those of [2]), but that they are consistent and unambiguous, hence reducing the problem of translating between conventions to a linear, rather than a factorial, dependence on the number of codes involved. At present, these codes can be categorised roughly as follows (see [3, 4] for a review and on-line repository):

- Spectrum calculators [5–8], which calculate the supersymmetric mass and coupling spectrum, assuming some (given or derived) SUSY-breaking terms and a matching to known data on the Standard Model parameters.
- Observables calculators [9–19]; packages which calculate one or more of the following: collider production cross sections (cross section calculators), decay partial widths (decay packages), relic dark matter density (dark matter packages), and indirect/precision observables, such as rare decay branching ratios or Higgs/electroweak observables (constraint packages).
- Monte-Carlo event generators [20–28], which calculate cross sections through explicit statistical simulation of high-energy particle collisions. By including resonance decays, parton showering, hadronisation, and underlying-event effects, fully exclusive final states can be studied, and, for instance, detector simulations interfaced.
- SUSY and CKM fitting programs [29–32] which fit model parameters to collider-type data.

At the time of writing, the SLHA1 has already, to a large extent, obliterated the need for separately coded (and maintained and debugged) interfaces between many of these codes. Moreover, it has provided users with input and output in a common format, which is more readily comparable and transferable. Finally, the SLHA convention choices are also being

adapted for other tasks, such as the SPA project [33]. We believe, therefore, that the SLHA project has been useful, solving a problem that, for experts, is trivial but frequently occurring and tedious to deal with, and which, for non-experts, is an unnecessary headache.

However, SLHA1 was designed exclusively with the MSSM with real parameters and R-parity conservation in mind. Some recent public codes [6, 7, 17, 18, 34–38] are either implementing extensions to this base model or are anticipating such extensions. It therefore seems prudent at this time to consider how to extend SLHA1 to deal with more general supersymmetric theories. In particular, we will consider R-parity violation (RPV), flavour violation (FLV), and CP-violating (CPV) phases in the minimal supersymmetric standard model (MSSM). We will also consider next-to-minimal models (i.e., models in which the MSSM field content is augmented by a gauge singlet chiral superfield) which we shall collectively label by the acronym NMSSM.

Rather than giving exhaustive historical references for all concepts used in this article, we provide a list of useful and pedagogical reviews to whose contents and references in turn we refer. For the various topics treated in the article, these reviews are:

- SUSY [39],
- FLV [40],
- Neutrinos [41],
- RPV [42, 43],
- CPV [44],
- NMSSM [45],
- SUSY Tools [3, 4].

There is clearly some tension between the desirable goals of generality of the models, ease of implementation in programs, and practicality for users. A completely general accord would be useless in practice if it was so complicated that no one would implement it. We have agreed on the following for SLHA2: for the MSSM, we will here restrict our attention to *either* CPV or RPV, but not both. For RPV and flavour violation, we shall work in the Super-CKM/PMNS basis, as defined in sections 4.1 and 4.2. For the NMSSM, we define one catch-all model and extend the SLHA1 mixing only to include the new states, with CP, R-parity, and flavour still assumed conserved.

To make the interface independent of programming languages, compilers, platforms etc, the SLHA1 is based on the transfer of three different ASCII files (or potentially a character string containing identical ASCII information): one for model input, one for spectrum calculator output, and one for decay calculator output. We believe that the advantage of implementation independence outweighs the disadvantage of codes using SLHA1 having to parse input. Indeed, there are tools to assist with this task [46–48].

Care was taken in SLHA1 to provide a framework for the MSSM that could easily be extended to the cases listed above. The conventions and switches described here are designed to be a *superset* of those of the original SLHA1 and so, unless explicitly mentioned in

the text, we will assume the conventions of the original accord [1] implicitly. For instance, all dimensionful parameters quoted in the present paper are assumed to be in the appropriate power of GeV, all angles are in radians, and the output formats for SLHA2 data BLOCKs follow those of SLHA1. In a few cases it will be necessary to replace the original conventions. This is clearly remarked upon in all places where it occurs, and the SLHA2 conventions then supersede the SLHA1 ones.

2 Extensions of SLHA1

Since its first publication, a few useful extensions to the SLHA1 have been identified. These are collected here for reference and are independent of the more general SUSY models discussed in subsequent sections. (Also note the recent proposal for a joint SLHA+LHEF format for BSM event generation [49, 50].)

Firstly, we introduce additional optional entries in the SLHA1 block EXTPAR to allow for using either the A^0 or H^+ pole masses as input instead of the parameter $m_A^2(M_{\text{input}})$ defined in [1].

Secondly, to allow for different parameters to be defined at different scales (e.g., μ defined at M_{EWSB} , the remaining parameters defined at M_{input}) we introduce a new optional block QEXTPAR which, if present, overrides the default MINPAR and EXTPAR scale choices for specific parameters, as defined below.

While there is no obligation on codes to implement these extensions, we perceive it as useful that the accord allows for them, enabling a wider range of input parameter sets to be considered. The entries defined in EXTPAR and QEXTPAR in the SLHA2 are thus (repeating unchanged EXTPAR entries for completeness):

BLOCK EXTPAR

ours is one of these.

Optional input parameters for non-minimal/non-universal models. This block may be entirely absent from the input file, in which case a minimal type of the selected SUSY breaking model will be used. When block EXTPAR is present, the starting point is still a minimal model with parameters as given in MINPAR [1] but with each value present in EXTPAR replacing the minimal model value of that parameter, as applicable. If MINPAR is not present, then *all* model parameters must be specified explicitly using EXTPAR. All scale-dependent parameters are understood to be given in the $\overline{\text{DR}}$ scheme.

question: is it used in TG's code? Probably.

Input scale

0 : M_{input} . Input scale for EXTPAR entries in SUGRA, AMSB, and general MSSM models. If absent, the GUT scale derived from gauge unification will be used as input scale. Note that this parameter has no effect in GMSB scenarios where the input scale by definition is identical to the messenger scale, M_{mess} . A special case is when $Q = M_{\text{EWSB}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ is desired as input scale, since this scale is not known beforehand. This choice can be invoked by giving the special value $M_{\text{input}} = -1$. To define an alternative input scale for one or more specific parameters, see QEXTPAR below.

Gaugino Masses

- 1 : $M_1(M_{\text{input}})$. $U(1)_Y$ gaugino (Bino) mass.
- 2 : $M_2(M_{\text{input}})$. $SU(2)_L$ gaugino (Wino) mass.
- 3 : $M_3(M_{\text{input}})$. $SU(3)_C$ gaugino (gluino) mass.

Trilinear Couplings

- 11 : $A_t(M_{\text{input}})$. Top trilinear coupling.
- 12 : $A_b(M_{\text{input}})$. Bottom trilinear coupling.
- 13 : $A_\tau(M_{\text{input}})$. Tau trilinear coupling.

Higgs Parameters

— Only one of the parameter sets $(m_{H_1}^2, m_{H_2}^2)$, (μ, m_A^2) , (μ, m_{A^0}) , or (μ, m_{H^\pm}) should be given, they merely represent different ways of specifying the same parameters.

- 21 : $m_{H_1}^2(M_{\text{input}})$. Down type Higgs mass squared.
- 22 : $m_{H_2}^2(M_{\text{input}})$. Up type Higgs mass squared.
- 23 : $\mu(M_{\text{input}})$. μ parameter.
- 24 : $m_A^2(M_{\text{input}})$. Tree-level pseudoscalar Higgs mass parameter squared, as defined in [1].

- 25 : $\tan \beta(M_{\text{input}})$. If present, this value of $\tan \beta$ overrides the one in MINPAR, and the input scale is taken as M_{input} rather than m_Z .
- 26 : m_{A^0} . Pseudoscalar Higgs pole mass. May be given instead of $m_A^2(M_{\text{input}})$.
- 27 : m_{H^+} . Charged Higgs pole mass. May be given instead of $m_A^2(M_{\text{input}})$.

Sfermion Masses

- 31 : $m_{\tilde{e}_L}(M_{\text{input}})$. Left 1stgen. scalar lepton mass.
- 32 : $m_{\tilde{\mu}_L}(M_{\text{input}})$. Left 2ndgen. scalar lepton mass.
- 33 : $m_{\tilde{\tau}_L}(M_{\text{input}})$. Left 3rdgen. scalar lepton mass.
- 34 : $m_{\tilde{e}_R}(M_{\text{input}})$. Right scalar electron mass.
- 35 : $m_{\tilde{\mu}_R}(M_{\text{input}})$. Right scalar muon mass.
- 36 : $m_{\tilde{\tau}_R}(M_{\text{input}})$. Right scalar tau mass.
- 41 : $m_{\tilde{q}_{1L}}(M_{\text{input}})$. Left 1stgen. scalar quark mass.
- 42 : $m_{\tilde{q}_{2L}}(M_{\text{input}})$. Left 2ndgen. scalar quark mass.
- 43 : $m_{\tilde{q}_{3L}}(M_{\text{input}})$. Left 3rdgen. scalar quark mass.
- 44 : $m_{\tilde{u}_R}(M_{\text{input}})$. Right scalar up mass.
- 45 : $m_{\tilde{c}_R}(M_{\text{input}})$. Right scalar charm mass.
- 46 : $m_{\tilde{t}_R}(M_{\text{input}})$. Right scalar top mass.
- 47 : $m_{\tilde{d}_R}(M_{\text{input}})$. Right scalar down mass.
- 48 : $m_{\tilde{s}_R}(M_{\text{input}})$. Right scalar strange mass.
- 49 : $m_{\tilde{b}_R}(M_{\text{input}})$. Right scalar bottom mass.

Other Extensions

- 51 : N_1 (GMSB only). $U(1)_Y$ messenger index (defined as in ref. [51]).
- 52 : N_2 (GMSB only). $SU(2)_L$ messenger index (defined as in ref. [51]).
- 53 : N_3 (GMSB only). $SU(3)_C$ messenger index (defined as in ref. [51]).

(1,1,1)

N_1 gpt ~~Pythia~~ $\Phi_I + \bar{\Phi}_I$
 $\Phi_I + \bar{\Phi}_I$ (p91 of hep-ph/9709356)

BLOCK QEXTPAR

Optional alternative input scales for specific parameters. This block should normally be absent, in which case the default input scale or M_{input} (see EXTPAR 0) will be used for all parameters. We stress that most codes cannot be expected to allow for multiple arbitrary scale choices, so the relevant manual and output should be carefully checked to make sure the desired behaviour is obtained. Currently defined entries are:

- 1 : Q_{M_1} . Input scale for M_1 .
- 2 : Q_{M_2} . Input scale for M_2 .
- 3 : Q_{M_3} . Input scale for M_3 .
- 11 : Q_{A_u} . Input scale for up-type squark trilinear couplings.
- 12 : Q_{A_d} . Input scale for down-type squark trilinear couplings.
- 13 : Q_{A_ℓ} . Input scale for charged slepton trilinear couplings.
- 21 : $Q_{m_{H_1}^2}$. Input scale for $m_{H_1}^2$.
- 22 : $Q_{m_{H_2}^2}$. Input scale for $m_{H_2}^2$.
- 23 : Q_μ . Input scale for μ .
- 24 : $Q_{m_A^2}$. Input scale for m_A^2 , as defined in [1].
- 25 : $Q_{\tan\beta}$. Input scale for $\tan\beta$.
- 31 : $Q_{m_{\tilde{t}_L}}$. Input scale for all left-handed slepton mass terms.
- 34 : $Q_{m_{\tilde{t}_R}}$. Input scale for all right-handed slepton mass terms.
- 41 : $Q_{m_{\tilde{q}_L}}$. Input scale for all left-handed squark mass terms.
- 44 : $Q_{m_{\tilde{u}_R}}$. Input scale for all right-handed up-type squark mass terms.
- 47 : $Q_{m_{\tilde{d}_R}}$. Input scale for all right-handed down-type squark mass terms.

3 Model Selection

To define the general properties of the model, we propose to introduce global switches in the SLHA1 model definition block MODSEL, as follows. Note that the switches defined here are in addition to the ones in [1].

BLOCK MODSEL

Switches and options for model selection. The entries in this block should consist of an index, identifying the particular switch in the listing below, followed by another integer or real number, specifying the option or value chosen:

3 : (Default=0) Choice of particle content. Switches defined are:

\rightarrow 0 : MSSM. This corresponds to SLHA1.

1 : NMSSM. The blocks defined in section 5 should be present.

4 : (Default=0) R-parity violation. Switches defined are:

\rightarrow 0 : R-parity conserved. This corresponds to the SLHA1.

1 : R-parity violated. The blocks defined in section 4.2 should be present.

5 : (Default=0) CP violation. Switches defined are:

\rightarrow 0 : CP is conserved. No information even on the CKM phase is used. This corresponds to the SLHA1.

1 : CP is violated, but only by the standard CKM phase. All other phases are assumed zero.

2 : CP is violated. Completely general CP phases allowed. Imaginary parts corresponding to the entries in the SLHA1 block EXTPAR can be given in IMEXTPAR (together with the CKM phase). In the case of additional SUSY flavour violation, imaginary parts of the blocks defined in section 4.1 should be given, again with the prefix IM, which supersede the corresponding entries in IMEXTPAR.

6 : (Default=0) Flavour violation. Switches defined are:

\rightarrow 0 : No (SUSY) flavour violation. This corresponds to the SLHA1.

1 : Quark flavour is violated. The blocks defined in section 4.1 should be present.

or
2 : Lepton flavour is violated. The blocks defined in section 4.1 should be present.

\rightarrow 3 : Lepton and quark flavour is violated. The blocks defined in section 4.1 should be present.

4 General MSSM

For convenience, we here repeat the definitions of the field content, superpotential and soft SUSY-breaking potential of the MSSM in the notation of [1].

Specifically, the chiral superfields of the MSSM have the following $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ quantum numbers

$$\begin{aligned} L &: (1, 2, -\frac{1}{2}), & \bar{E} &: (1, 1, 1), & Q &: (3, 2, \frac{1}{6}), & \bar{U} &: (\bar{3}, 1, -\frac{2}{3}), \\ \bar{D} &: (\bar{3}, 1, \frac{1}{3}), & H_1 &: (1, 2, -\frac{1}{2}), & H_2 &: (1, 2, \frac{1}{2}), \end{aligned} \quad (1)$$

the superpotential (omitting RPV terms, see section 4.2) is written as

$$W_{MSSM} = \epsilon_{ab} [(Y_E)_{ij} H_1^a L_i^b \bar{E}_j + (Y_D)_{ij} H_1^a Q_i^b \bar{D}_j + (Y_U)_{ij} H_2^b Q_i^a \bar{U}_j - \mu H_1^a H_2^b], \quad (2)$$

and the trilinear and bilinear soft SUSY-breaking potentials V_3 and V_2 are

$$V_3 = \epsilon_{ab} \sum_{ij} \left[(T_E)_{ij} H_1^a \tilde{L}_{iL}^b \tilde{e}_{jR}^* + (T_D)_{ij} H_1^a \tilde{Q}_{iL}^b \tilde{d}_{jR}^* + (T_U)_{ij} H_2^b \tilde{Q}_{iL}^a \tilde{e}_{jR}^* \right] + \text{h.c.} , \quad (3)$$

$$\begin{aligned} V_2 = & m_{H_1}^2 H_{1a}^* H_1^a + m_{H_2}^2 H_{2a}^* H_2^a + \tilde{Q}_{iL}^*(m_{\tilde{Q}}^2)_{ij} \tilde{Q}_{jL}^a + \tilde{L}_{iL}^*(m_{\tilde{L}}^2)_{ij} \tilde{L}_{jL}^a + \\ & \tilde{u}_{iR}(m_{\tilde{u}}^2)_{ij} \tilde{u}_{jR}^* + \tilde{d}_{iR}(m_{\tilde{d}}^2)_{ij} \tilde{d}_{jR}^* + \tilde{e}_{iR}(m_{\tilde{e}}^2)_{ij} \tilde{e}_{jR}^* - (m_3^2 \epsilon_{ab} H_1^a H_2^b + \text{h.c.}) , \end{aligned} \quad (4)$$

where a tilde over the symbol for a quark or lepton superfield denotes its scalar component (note however that we define, e.g., \tilde{u}_R^* as the scalar component of \bar{U}). Throughout this section, we denote $SU(2)_L$ fundamental representation indices by $a, b = 1, 2$ and generation indices by $i, j = 1, 2, 3$. Colour indices are everywhere suppressed, since only trivial contractions are involved. ϵ_{ab} is the totally antisymmetric tensor, with $\epsilon_{12} = \epsilon^{12} = 1$.

4.1 Flavour Violation

4.1.1 The quark sector and the super-CKM basis

Within the MSSM there are in general new sources of flavour violation arising from a possible misalignment of quarks and squarks in flavour space. The severe experimental constraints on flavour violation have no direct explanation in the structure of the unconstrained MSSM which leads to the well-known supersymmetric flavour problem.

The Super-CKM basis of the squarks is very useful in this context because in that basis only physically measurable parameters are present. In the Super-CKM basis the quark mass matrix is diagonal and the squarks are rotated in parallel to their superpartners. Actually, once the electroweak symmetry is broken, a rotation in flavour space

$$D^o = V_d D, \quad U^o = V_u U, \quad \bar{D}^o = U_d^* \bar{D}, \quad \bar{U}^o = U_u^* \bar{U}, \quad (5)$$

of all matter superfields in the (s)quark superpotential

$$W_Q = \epsilon_{ab} \left[(Y_D)_{ij} H_1^a Q_i^{bo} \bar{D}_j^o + (Y_U)_{ij} H_2^b Q_i^{ao} \bar{U}_j^o \right] \quad (6)$$

brings fermions from the interaction eigenstate basis $\{d_L^o, u_L^o, d_R^o, u_R^o\}$ to their mass eigenstate basis $\{d_L, u_L, d_R, u_R\}$:

$$d_L^o = V_d d_L, \quad u_L^o = V_u u_L, \quad d_R^o = U_d d_R, \quad u_R^o = U_u u_R, \quad (7)$$

and the scalar superpartners to the basis $\{\tilde{d}_L, \tilde{u}_L, \tilde{d}_R, \tilde{u}_R\}$. Through this rotation, the Yukawa matrices Y_D and Y_U are reduced to their diagonal form \hat{Y}_D and \hat{Y}_U :

$$(\hat{Y}_D)_{ii} = (U_d^\dagger Y_D^T V_d)_{ii} = \sqrt{2} \frac{m_{di}}{v_1}, \quad (\hat{Y}_U)_{ii} = (U_u^\dagger Y_U^T V_u)_{ii} = \sqrt{2} \frac{m_{ui}}{v_2}. \quad (8)$$

Tree-level mixing terms among quarks of different generations are due to the misalignment of V_d and V_u , expressed via the CKM matrix

$$V_{\text{CKM}} = V_u^\dagger V_d, \quad (9)$$

$$V_{CKM} \left(\begin{pmatrix} \hat{m}_Q^2 \\ \hat{m}_{\tilde{Q}}^2 \end{pmatrix} \right) = \left(\begin{pmatrix} V_d & m_u^2 \\ V_d^\dagger & \hat{m}_{\tilde{Q}}^2 \end{pmatrix} \right) V_{CKM} = \begin{matrix} \text{LHS} \\ V_{CKM} V_d^\dagger m_u^2 V_d V_{CKM} \\ V_u V_d^\dagger V_d^\dagger m_{\tilde{Q}}^2 V_d V_d^\dagger V_u \\ = V_u m_{\tilde{Q}}^2 V_u \end{matrix}$$

(rotate to
diag
quark
basis)

which is proportional to the tree-level $\bar{u}_{Li} d_{Lj} W^+$, $\bar{u}_{Li} d_{Rj} H^+$, and $\bar{u}_{Ri} d_{Lj} H^+$ couplings ($i, j = 1, 2, 3$). This is also true for the supersymmetric counterparts of these vertices, in the limit of unbroken supersymmetry.

In the super-CKM basis the 6×6 mass matrices for the up-type and down-type squarks are defined as

$$\mathcal{L}_{\tilde{q}}^{\text{mass}} = -\Phi_u^\dagger \mathcal{M}_{\tilde{u}}^2 \Phi_u - \Phi_d^\dagger \mathcal{M}_{\tilde{d}}^2 \Phi_d , \quad (10)$$

where $\Phi_u = (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T$ and $\Phi_d = (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T$. We diagonalise the squark mass matrices via 6×6 unitary matrices $R_{u,d}$, such that $R_{u,d} \mathcal{M}_{\tilde{u},\tilde{d}}^2 R_{u,d}^\dagger$ are diagonal matrices with increasing mass squared values. The flavour-mixed mass matrices read:

$$\mathcal{M}_{\tilde{u}}^2 = \begin{pmatrix} V_{CKM} \hat{m}_{\tilde{Q}}^2 V_{CKM}^\dagger + m_u^2 + D_{uLL} & \frac{v_2}{\sqrt{2}} \hat{T}_U^\dagger - \mu m_u \cot \beta \\ \frac{v_2}{\sqrt{2}} \hat{T}_U - \mu^* m_u \cot \beta & \hat{m}_{\tilde{u}}^2 + m_u^2 + D_{uRR} \end{pmatrix} , \quad (11)$$

$$\mathcal{M}_{\tilde{d}}^2 = \begin{pmatrix} \hat{m}_{\tilde{Q}}^2 + m_d^2 + D_{dLL} & \frac{v_1}{\sqrt{2}} \hat{T}_D^\dagger - \mu m_d \tan \beta \\ \frac{v_1}{\sqrt{2}} \hat{T}_D - \mu^* m_d \tan \beta & \hat{m}_{\tilde{d}}^2 + m_d^2 + D_{dRR} \end{pmatrix} . \quad (12)$$

In the equations above we introduced the 3×3 matrices

$$\hat{m}_{\tilde{Q}}^2 \equiv V_d^\dagger m_{\tilde{Q}}^2 V_d, \quad \hat{m}_{\tilde{u}}^2 \equiv U_u^\dagger m_{\tilde{u}}^{2T} U_u, \quad \hat{m}_{\tilde{d}}^2 \equiv U_d^\dagger m_{\tilde{d}}^{2T} U_d , \quad (13)$$

$$\hat{T}_U \equiv U_u^\dagger T_U^T V_u, \quad \hat{T}_D \equiv U_d^\dagger T_D^T V_d , \quad (14)$$

where the un-hatted mass matrices $m_{Q,u,d}^2$ and trilinear interaction matrices $T_{U,D}$ are given in the interaction basis.

The matrices $m_{u,d}$ are the diagonal up-type and down-type quark masses and $D_{fLL,RR}$ are the D-terms given by:

$$D_{fLL,RR} = \cos 2\beta m_Z^2 (T_f^3 - Q_f \sin^2 \theta_W) \mathbb{1}_3, \quad \rightarrow \text{electroweak corrections} \quad (15) \quad (\text{usually small})$$

which are also flavour diagonal. Here, Q_f is the electric charge of the left-handed chiral supermultiplet to which the squark belongs, i.e., it is $2/3$ for U and $-2/3$ for U^c . Note that the up-type and down-type squark mass matrices in eqs. (11) and (12) cannot be simultaneously flavour-diagonal unless $\hat{m}_{\tilde{Q}}^2$ is flavour-universal (i.e., proportional to the identity in flavour space).

4.1.2 The lepton sector and the super-PMNS basis

For the lepton sector, we adopt a super-PMNS basis, as defined in this section.

Neutrino oscillation data have provided a strong indication that neutrinos have masses and that there are flavour-changing charged currents in the leptonic sector. One popular model to produce such effects is the see-saw mechanism, where right-handed neutrinos have both Majorana masses as well as Yukawa couplings with the left-handed leptons. When the heavy neutrinos are integrated out of the effective field theory, one is left with three light approximately left-handed neutrinos which are identified with the ones observed experimentally. There are other models of neutrino masses, for example involving SU(2) Higgs

triplets, that, once the triplets have been integrated out, also lead to effective Majorana masses for the neutrinos. Here, we cover all cases that lead to a low energy effective field theory with Majorana neutrino masses and one sneutrino per family. In terms of this low energy effective theory, the lepton mixing phenomenon is analogous to the quark mixing case and so we adapt the conventions defined above to the leptonic case.

After electroweak symmetry breaking, the neutrino sector of the MSSM contains the Lagrangian pieces (in 2-component notation)

$$\mathcal{L} = -\frac{1}{2}\nu^{oT}(m_\nu)\nu^o + \text{h.c.}, \quad (16)$$

where m_ν is a 3×3 symmetric matrix. The interaction eigenstate basis neutrino fields ν^o are related to the mass eigenstate ones ν by

$$\nu^o = V_\nu \nu, \quad (17)$$

reducing the mass matrix m_ν to its diagonal form \hat{m}_ν

$$(\hat{m}_\nu)_{ii} = (V_\nu^T m_\nu V_\nu)_{ii} = m_{\nu_i}. \quad (18)$$

The charged lepton fields have a 3×3 Yukawa coupling matrix defined in the (s)lepton superpotential

$$W_E = \epsilon_{ab}(Y_E)_{ij} H_1^a L_i^{bo} \bar{E}_j^o, \quad (19)$$

where the charged lepton interaction eigenstates $\{e_L^o, e_R^o\}$ are related to the mass eigenstates $\{e_L, e_R\}$ by

$$e_L^o = V_e e_L \quad \text{and} \quad e_R^o = U_e e_R. \quad (20)$$

The equivalent diagonalised charged lepton Yukawa matrix is

$$(\hat{Y}_E)_{ii} = (U_e^\dagger Y_E^T V_e)_{ii} = \sqrt{2} \frac{m_{ei}}{v_1} \quad . \quad (21)$$

Lepton mixing in the charged current interaction can then be characterised by the PMNS matrix

$$U_{PMNS} = V_e^\dagger V_\nu, \quad (22)$$

which is proportional to the tree-level $\bar{e}_{Li} \nu_j W^-$ and $\bar{e}_{Ri} \nu_j H^-$ couplings ($i, j = 1, 2, 3$). This is also true for the supersymmetric counterparts of these vertices, in the limit of unbroken supersymmetry.

Rotating the interaction eigenstates of the sleptons identically to their leptonic counterparts, we obtain the super-PMNS basis for the charged sleptons and the sneutrinos, described by the Lagrangian¹

$$\mathcal{L}_{\tilde{l}}^{mass} = -\Phi_e^\dagger \mathcal{M}_e^2 \Phi_e - \Phi_\nu^\dagger \mathcal{M}_\nu^2 \Phi_\nu, \quad (23)$$

¹We here neglect the possible term $\Phi_\nu^T \hat{\mathcal{M}}_\nu^2 \Phi_\nu$.

where $\Phi_\nu = (\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T$ and $\Phi_e = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)^T$. $\mathcal{M}_{\tilde{e}}^2$ is the 6×6 matrix

$$\mathcal{M}_{\tilde{e}}^2 = \begin{pmatrix} \hat{m}_L^2 + m_e^2 + D_{eLL} & \frac{v_1}{\sqrt{2}} \hat{T}_E^\dagger - \mu m_e \tan \beta \\ \frac{v_1}{\sqrt{2}} \hat{T}_E - \mu^* m_e \tan \beta & \hat{m}_{\tilde{e}}^2 + m_e^2 + D_{eRR} \end{pmatrix}, \quad (24)$$

and $\mathcal{M}_{\tilde{\nu}}^2$ is the 3×3 matrix

$$\mathcal{M}_{\tilde{\nu}}^2 = U_{PMNS}^\dagger \hat{m}_L^2 U_{PMNS} + D_{\nu LL}, \quad (25)$$

where D_{eLL} and $D_{\nu LL}$ are given in eq. (15). In the equations above we introduced the 3×3 matrices

$$\hat{m}_L^2 \equiv V_e^\dagger m_L^2 V_e, \quad \hat{m}_{\tilde{e}}^2 \equiv U_e^\dagger m_{\tilde{e}}^{2T} U_e, \quad (26)$$

$$\hat{T}_E \equiv U_e^\dagger T_E^T V_e, \quad (27)$$

where the un-hatted mass matrices $m_{L,e}^2$ and the trilinear interaction matrix T_E are given in the interaction basis. We diagonalise the charged slepton and sneutrino mass matrices via the unitary 6×6 and 3×3 matrices $R_{e,\nu}$ respectively. Thus, $R_{e,\nu} \mathcal{M}_{\tilde{e},\tilde{\nu}}^2 R_{e,\nu}^\dagger$ are diagonal with increasing entries toward the bottom right of each matrix.

4.1.3 Explicit proposal for SLHA2

As in the SLHA1 [1], for all running parameters in the output of the spectrum file, we propose to use definitions in the modified dimensional reduction (\overline{DR}) scheme. The basis is the super-CKM/PMNS basis as defined above, that is the one in which the Yukawa couplings of the SM fermions, given in the \overline{DR} scheme, are diagonal. Note that the masses and vacuum expectation values (VEVs) in eqs. (8), (18), and (21) must thus also be the running ones in the \overline{DR} scheme.

The input for an explicit implementation in a spectrum calculator consists of the following information:

- By default, all SUSY parameters are given at the scale M_{input} as defined in the SLHA1 block EXTPAR (see above). In principle, advanced codes may also allow for separate input scales for the sfermion mass matrices and trilinear couplings, via the block QEXTPAR defined above, but we emphasise that this should be regarded as non-standard.
- For the SM input parameters, we take the Particle Data Group (PDG) definition: lepton masses are all on-shell. The light quark masses $m_{u,d,s}$ are given at 2 GeV, and the heavy quark masses are given as $m_c(m_c)^{\overline{MS}}$, $m_b(m_b)^{\overline{MS}}$ and $m_t^{\text{on-shell}}$. The latter two quantities are already in the SLHA1. The others are added to SMINPUTS in the following manner (repeating the SLHA1 parameters for convenience):

- 1 : $\alpha_{\text{em}}^{-1}(m_Z)^{\overline{MS}}$. Inverse electromagnetic coupling at the Z pole in the \overline{MS} scheme (with 5 active flavours).
- 2 : G_F . Fermi constant (in units of GeV^{-2}).

- 3 : $\alpha_s(m_Z)^{\overline{\text{MS}}}$. Strong coupling at the Z pole in the $\overline{\text{MS}}$ scheme (with 5 active flavours).
- 4 : m_Z , pole mass.
- 5 : $m_b(m_b)^{\overline{\text{MS}}}$. b quark running mass in the $\overline{\text{MS}}$ scheme.
- 6 : m_t , pole mass.
- 7 : m_τ , pole mass.
- 8 : m_{ν_3} , pole mass.
- 11 : m_e , pole mass.
- 12 : m_{ν_1} , pole mass.
- 13 : m_μ , pole mass.
- 14 : m_{ν_2} , pole mass.
- 21 : $m_d(2 \text{ GeV})^{\overline{\text{MS}}}$. d quark running mass in the $\overline{\text{MS}}$ scheme.
- 22 : $m_u(2 \text{ GeV})^{\overline{\text{MS}}}$. u quark running mass in the $\overline{\text{MS}}$ scheme.
- 23 : $m_s(2 \text{ GeV})^{\overline{\text{MS}}}$. s quark running mass in the $\overline{\text{MS}}$ scheme.
- 24 : $m_c(m_c)^{\overline{\text{MS}}}$. c quark running mass in the $\overline{\text{MS}}$ scheme.

The FORTRAN format is the same as that of **SMINPUTS** in SLHA1 [1].

- V_{CKM} : the input CKM matrix in the Wolfenstein parameterisation², in the block VCKMIN. Note that present CKM studies do not precisely define a renormalisation scheme for this matrix since the electroweak effects that renormalise it are highly suppressed and generally neglected. We therefore assume that the CKM elements given by PDG (or by UTFIT [31] and CKMFITTER [32], the main collaborations that extract the CKM parameters) refer to SM $\overline{\text{MS}}$ quantities defined at $Q = m_Z$, to avoid any possible ambiguity. VCKMIN should have the following entries

- 1 : λ
- 2 : A
- 3 : $\bar{\rho}$
- 4 : $\bar{\eta}$

The FORTRAN format is the same as that of **SMINPUTS** above.

ignore →

- U_{PMNS} : the input PMNS matrix, in the block UPMNSIN. It should have the PDG parameterisation in terms of rotation angles [52] (all in radians):

- 1 : $\bar{\theta}_{12}$ (the solar angle)
- 2 : $\bar{\theta}_{23}$ (the atmospheric mixing angle)

²For the Wolfenstein parameters we use the PDG definition, eq.(11.4) of [52], which is exact to all orders in λ .

- 3 : $\bar{\theta}_{13}$ (currently only has an upper bound)
- 4 : $\bar{\delta}_{13}$ (the Dirac CP-violating phase)
- 5 : α_1 (the first Majorana CP-violating phase)
- 6 : α_2 (the second CP-violating Majorana phase)

The FORTRAN format is the same as that of **SMINPUTS** above. Majorana phases have no effect on neutrino oscillations. However, they have physical consequences in the case of, for example, $\beta\beta0\nu$ decay of nuclei.

- $(\hat{m}_Q^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{u}}^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{d}}^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_L^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{e}}^2)_{ij}^{\overline{\text{DR}}}$: the squark and slepton soft SUSY-breaking masses at the input scale in the super-CKM/PMNS basis, as defined above. They will be given in the new blocks **MSQ2IN**, **MSU2IN**, **MSD2IN**, **MSL2IN**, **MSE2IN**, with the FORTRAN format

`(1x,I2,1x,I2,3x,1P,E16.8,0P,3x,'#',1x,A).`

where the first two integers in the format correspond to i and j and the double precision number to the soft mass squared. Only the “upper triangle” of these matrices should be given. If diagonal entries are present, these supersede the parameters in the SLHA1 block **EXTPAR**.

- $(\hat{T}_U)_{ij}^{\overline{\text{DR}}}$, $(\hat{T}_D)_{ij}^{\overline{\text{DR}}}$, and $(\hat{T}_E)_{ij}^{\overline{\text{DR}}}$: the squark and slepton soft SUSY-breaking trilinear couplings at the input scale in the super-CKM/PMNS basis. They will be given in the new blocks **TUIN**, **TDIN**, **TEIN**, in the same format as the soft mass matrices above. If diagonal entries are present these supersede the A parameters specified in the SLHA1 block **EXTPAR** [1].

For the output, the pole masses are given in block **MASS** as in SLHA1 (note, however, that some PDG numbers have different assignments in SLHA2, see below) and the $\overline{\text{DR}}$ and mixing parameters as follows:

- $(\hat{m}_Q^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{u}}^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{d}}^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_L^2)_{ij}^{\overline{\text{DR}}}$, $(\hat{m}_{\tilde{e}}^2)_{ij}^{\overline{\text{DR}}}$: the squark and slepton soft SUSY-breaking masses at scale Q in the super-CKM/PMNS basis. Will be given in the new blocks **MSQ2 Q=...**, **MSU2 Q=...**, **MSD2 Q=...**, **MSL2 Q=...**, **MSE2 Q=...**, with formats as the corresponding input blocks **MSX2IN** above.
- $(\hat{T}_U)_{ij}^{\overline{\text{DR}}}$, $(\hat{T}_D)_{ij}^{\overline{\text{DR}}}$, and $(\hat{T}_E)_{ij}^{\overline{\text{DR}}}$: The squark and slepton soft SUSY-breaking trilinear couplings in the super-CKM/PMNS basis. Given in the new blocks **TU Q=...**, **TD Q=...**, **TE Q=...**, which supersede the SLHA1 blocks **AD**, **AU**, and **AE**, see [1].
- $(\hat{Y}_U)_{ii}^{\overline{\text{DR}}}$, $(\hat{Y}_D)_{ii}^{\overline{\text{DR}}}$, $(\hat{Y}_E)_{ii}^{\overline{\text{DR}}}$: the diagonal $\overline{\text{DR}}$ Yukawas in the super-CKM/PMNS basis, with \hat{Y} defined by eqs. (8) and (21), at the scale Q . Given in the SLHA1 blocks **YU Q=...**, **YD Q=...**, **YE Q=...**, see [1]. Note that although the SLHA1 blocks provide for off-diagonal elements, only the diagonal ones will be relevant here, due to the CKM/PMNS rotation.

- The entries of the $\overline{\text{DR}}$ CKM matrix at the scale Q . The real and imaginary parts are given in `VCKM Q=...` and `IMVCKM Q=...`, respectively. The format of the individual entries is the same as for mixing matrices in the SLHA1. Note that the complete matrix should be output, i.e., all entries should be included.
- The entries of the $\overline{\text{DR}}$ PMNS matrix at the scale Q . The real and imaginary parts are given in `UPMNS Q=...` and `IMUPMNS Q=...`, respectively, with entries defined as for the V_{CKM} output blocks above.
- The squark and slepton masses and mixing matrices should be defined as in the existing SLHA1, e.g. extending the \tilde{t} , \tilde{b} and $\tilde{\tau}$ mixing matrices to the 6×6 case. More specifically, the new blocks $R_u = \text{USQMIX}$, $R_d = \text{DSQMIX}$, $R_e = \text{SELMIX}$ and the 3×3 matrix for $R_\nu = \text{SNUMIX}$ specify the composition of the mass eigenstates in terms of the super-CKM/PMNS basis states according to the following definitions:

$$\begin{pmatrix} 1000001 \\ 1000003 \\ 1000005 \\ 2000001 \\ 2000003 \\ 2000005 \end{pmatrix} = \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix}_{\text{mass-ordered}} = \text{DSQMIX}_{ij} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}_{\text{super-CKM}}, \quad (28)$$

$$\begin{pmatrix} 1000002 \\ 1000004 \\ 1000006 \\ 2000002 \\ 2000004 \\ 2000006 \end{pmatrix} = \begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix}_{\text{mass-ordered}} = \text{USQMIX}_{ij} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}_{\text{super-CKM}}. \quad (29)$$

$$\begin{pmatrix} 1000011 \\ 1000013 \\ 1000015 \\ 2000011 \\ 2000013 \\ 2000015 \end{pmatrix} = \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \\ \tilde{e}_3 \\ \tilde{e}_4 \\ \tilde{e}_5 \\ \tilde{e}_6 \end{pmatrix}_{\text{mass-ordered}} = \text{SELMIX}_{ij} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}_{\text{super-PMNS}}, \quad (30)$$

$$\begin{pmatrix} 1000012 \\ 1000014 \\ 1000016 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \\ \tilde{\nu}_3 \end{pmatrix}_{\text{mass-ordered}} = \text{SNUMIX}_{ij} \begin{pmatrix} \tilde{\nu}_e \\ \tilde{\nu}_\mu \\ \tilde{\nu}_\tau \end{pmatrix}_{\text{super-PMNS}}. \quad (31)$$

Note! A potential for inconsistency arises if the masses and mixings are not calculated in the same way, e.g. if radiatively corrected masses are used with tree-level mixing matrices. In this case, it is possible that the radiative corrections to the masses shift the mass ordering relative to the tree-level. This is especially relevant when near-degenerate masses occur in the spectrum and/or when the radiative corrections are large. In these cases, explicit care must be taken especially by the program writing

the spectrum, but also by the one reading it, to properly arrange the rows in the order of the mass spectrum actually used.

- **Optionally**, we allow for the possibility of the scalar and pseudoscalar components of the sneutrinos to be treated separately. In this case, we define separate PDG codes and mixing matrices for the scalar and pseudoscalar sneutrinos, as follows:

$$\begin{pmatrix} 1000012 \\ 1000014 \\ 1000016 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_{1S} \\ \tilde{\nu}_{2S} \\ \tilde{\nu}_{3S} \end{pmatrix}_{\text{mass-ordered}} = \text{SNSMIX}_{ij} \begin{pmatrix} \sqrt{2}\text{Re}\{\tilde{\nu}_e\} \\ \sqrt{2}\text{Re}\{\tilde{\nu}_\mu\} \\ \sqrt{2}\text{Re}\{\tilde{\nu}_\tau\} \end{pmatrix}_{\text{super-PMNS}}, \quad (32)$$

$$\begin{pmatrix} 1000017 \\ 1000018 \\ 1000019 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_{1A} \\ \tilde{\nu}_{2A} \\ \tilde{\nu}_{3A} \end{pmatrix}_{\text{mass-ordered}} = \text{SNAMIX}_{ij} \begin{pmatrix} \sqrt{2}\text{Im}\{\tilde{\nu}_e\} \\ \sqrt{2}\text{Im}\{\tilde{\nu}_\mu\} \\ \sqrt{2}\text{Im}\{\tilde{\nu}_\tau\} \end{pmatrix}_{\text{super-PMNS}}. \quad (33)$$

If present, SNSMIX and SNAMIX supersede SNUMIX.

~~skip~~ 4.2 R-Parity Violation

We write the R-parity violating superpotential in the interaction basis as

$$W_{\text{RPV}} = \epsilon_{ab} \left[\frac{1}{2} \lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^{bx} \bar{D}_{kx} - \kappa_i L_i^a H_2^b \right] + \frac{1}{2} \lambda''_{ijk} \epsilon_{xyz} \bar{U}_i^x \bar{D}_j^y \bar{D}_k^z, \quad (34)$$

where $x, y, z = 1, \dots, 3$ are fundamental $SU(3)_C$ indices and ϵ_{xyz} is the totally antisymmetric tensor in 3 dimensions with $\epsilon_{123} = +1$. In eq. (34), λ_{ijk} , λ'_{ijk} and κ_i break lepton number, whereas λ''_{ijk} violate baryon number. To ensure proton stability, either lepton number conservation or baryon number conservation is usually still assumed, resulting in either $\lambda_{ijk} = \lambda'_{ijk} = \kappa_i = 0$ or $\lambda''_{ijk} = 0$ for all $i, j, k = 1, 2, 3$.

The trilinear R-parity violating terms in the soft SUSY-breaking potential are

$$V_{3,\text{RPV}} = \epsilon_{ab} \left[\frac{1}{2} (T)_{ijk} \tilde{L}_{iL}^a \tilde{L}_{jL}^b \tilde{e}_{kR}^* + (T')_{ijk} \tilde{L}_{iL}^a \tilde{Q}_{jL}^b \tilde{d}_{kR}^* \right] + \frac{1}{2} (T'')_{ijk} \epsilon_{xyz} \tilde{u}_{iR}^{x*} \tilde{d}_{jR}^{y*} \tilde{d}_{kR}^{z*} + \text{h.c.} \quad . \quad (35)$$

Note that we do not factor out the λ couplings (e.g. as in $T_{ijk}/\lambda_{ijk} \equiv A_{\lambda,ijk}$) in order to avoid potential problems with $\lambda_{ijk} = 0$ but $T_{ijk} \neq 0$. This usage is consistent with the convention for the R-conserving sector elsewhere in this report.

The bilinear R-parity violating soft terms (all lepton number violating) are

$$V_{2,\text{RPV}} = -\epsilon_{ab} D_i \tilde{L}_{iL}^a H_2^b + \tilde{L}_{iaL}^\dagger m_{\tilde{L}_i H_1}^2 H_1^a + \text{h.c.} \quad . \quad (36)$$

When lepton number is not conserved the sneutrinos may acquire vacuum expectation values (VEVs) $\langle \tilde{\nu}_{e,\mu,\tau} \rangle \equiv v_{e,\mu,\tau}/\sqrt{2}$. The SLHA1 defined the VEV v , which at tree level is equal to $2m_Z/\sqrt{g^2 + g'^2} \sim 246$ GeV; this is now generalised to

$$v = \sqrt{v_1^2 + v_2^2 + v_e^2 + v_\mu^2 + v_\tau^2} \quad . \quad (37)$$

The addition of sneutrino VEVs allows for various different definitions of $\tan \beta$, but we here choose to keep the SLHA1 definition $\tan \beta = v_2/v_1$.

For input/output, we use the super-CKM/PMNS basis throughout, as defined in section 4.1 with the following considerations specific to the R-parity violating case.

Firstly, the d -quark mass matrices are given by

$$\sqrt{2}(m_d)_{ij} = (Y_D)_{ij}v_1 + \lambda'_{kij}v_k . \quad (38)$$

where v_k are the sneutrino VEVs. Secondly, in the lepton number violating case, the PMNS matrix can only be defined consistently by taking into account the 1-loop contributions induced by the lepton-number violating couplings (see, e.g., [43]). We here restrict our attention to scenarios in which there are no right-handed neutrinos and, thus, neutrino masses are generated solely by the lepton number violating couplings. In this case, the PMNS matrix is not an independent input but an output.

For definiteness, and to keep the changes with respect to the R-parity conserving case as limited as possible, we define the super-CKM basis as the one where the Yukawa couplings Y_D and Y_U are diagonal. The PMNS basis is defined as the basis where Y_E is diagonal and the loop-induced neutrino mass matrix is diagonalised. In this way one obtains a uniquely defined set of parameters:

$$\hat{\lambda}_{ijk} \equiv \lambda_{rst}V_{\nu,ri}V_{e,sj}U_{e,tk}^\dagger , \quad (39)$$

$$\hat{\lambda}'_{ijk} \equiv \lambda'_{rst}V_{\nu,ri}V_{d,sj}U_{d,tk}^\dagger , \quad (40)$$

$$\hat{\kappa}_i \equiv \kappa_r V_{e,ri} , \quad (41)$$

$$\hat{\lambda}''_{ijk} \equiv \lambda''_{rst}U_{u,ri}^\dagger U_{d,sj}^\dagger U_{d,tk}^\dagger , \quad (42)$$

where the fermion mixing matrices are defined in section 4.1. The Lagrangian for the quark-slepton interactions then takes the following form:

$$\mathcal{L} = -\hat{\lambda}'_{ijk}\tilde{\nu}_i\bar{d}_{Rk}d_{Lj} + \hat{\lambda}'_{rsk}U_{PMNS,ri}^\dagger V_{CKM,sj}^\dagger \tilde{l}_{L,i}\bar{d}_{Rk}u_{Lj} + \text{h.c.} . \quad (43)$$

Similarly one obtains the soft SUSY breaking couplings in this basis by replacing the superpotential quantities in eqs. (39)–(42) by the corresponding soft SUSY breaking couplings. In addition we define:

$$\hat{m}_{\tilde{L}_i H_1}^2 \equiv V_{e,ir}^\dagger m_{\tilde{L}_r H_1}^2 . \quad (44)$$

4.2.1 Input/Output Blocks

As mentioned above, we use the super-CKM/PMNS basis throughout, for both superpotential and soft SUSY-breaking terms. This applies to both input and output³. The naming convention for input blocks is **BLOCK RV#IN**, where the '#' character represents the name

³A code may need to convert internally the parameters to the interaction basis. In this case it must supply – or take as additional inputs – the individual rotation matrices of quark and lepton superfields entering eqs. (39)–(42).

Important note: only 12 of the parameters listed in eq. (60) should be given as input at any one time (including explicit zeroes for parameters desired “switched off”), the remaining ones being determined by the minimisation of the effective potential. Which combinations to accept is left up to the individual spectrum calculator programs. Alternatively, for minimal models, 6 parameters of those listed in eq. (61) should be given.

For non-zero values, signs can be either positive or negative. As noted above, the meaning of the already existing entries EXTPAR 23 and 24 (the MSSM μ parameter and corresponding soft term) are maintained, which allows, in principle, for non-zero values for both μ and $\langle S \rangle$. The reason for choosing $\lambda \langle S \rangle$ rather than $\langle S \rangle$ as input parameter 65 is that it allows more easily to recover the MSSM limit $\lambda, \kappa \rightarrow 0, \langle S \rangle \rightarrow \infty$ with $\lambda \langle S \rangle$ fixed.

In the spectrum output, running NMSSM parameters corresponding to the EXTPAR entries above can be given in the block NMSSMRUN Q=...:

BLOCK NMSSMRUN Q=...

Output parameters specific to the NMSSM, given in the $\overline{\text{DR}}$ scheme, at the scale Q . As in the SLHA1, several of these blocks may be given simultaneously in the output, each then corresponding to a specific scale. See corresponding entries in EXTPAR above for definitions.

- 1 : $\lambda(Q)^{\overline{\text{DR}}}$.
- 2 : $\kappa(Q)^{\overline{\text{DR}}}$.
- 3 : $A_\lambda(Q)^{\overline{\text{DR}}}$.
- 4 : $A_\kappa(Q)^{\overline{\text{DR}}}$.
- 5 : $\lambda \langle S \rangle(Q)^{\overline{\text{DR}}}$.
- 6 : $\xi_F(Q)^{\overline{\text{DR}}}$.
- 7 : $\xi_S(Q)^{\overline{\text{DR}}}$.
- 8 : $\mu'(Q)^{\overline{\text{DR}}}$.
- 9 : $m_S'^2(Q)^{\overline{\text{DR}}}$.
- 10 : $m_S^2(Q)^{\overline{\text{DR}}}$.

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5.3 Particle Mixing

In the CP-conserving NMSSM, the CP-even interaction eigenstates are $\phi^0 \equiv \sqrt{2} \text{Re} \{(H_1^0, H_2^0, S)^T\}$. We define the orthogonal 3×3 mixing matrix S (block NMHMIX) by

$$-\phi^{0T} \mathcal{M}_{\phi^0}^2 \phi^0 = -\underbrace{\phi^{0T} S^T}_{\Phi^{0T}} \underbrace{S \mathcal{M}_{\phi^0}^2 S^T}_{\text{diag}(m_{\Phi^0}^2)} \underbrace{S \phi^0}_{\Phi^0}, \quad (62)$$

where $\Phi^0 \equiv (h_1^0, h_2^0, h_3^0)$ are the mass eigenstates ordered in mass. These states are numbered sequentially by the PDG codes (25, 35, 45). The format of **BLOCK NMHMIX** is the same as for the mixing matrices in SLHA1.

In the MSSM limit ($\lambda, \kappa \rightarrow 0$, and parameters such that $h_3^0 \sim \text{Re}\{S\}$) the elements of the first 2×2 sub-matrix of S_{ij} are related to the MSSM angle α as

$$\begin{aligned} S_{11} &\sim -\sin \alpha, & S_{21} &\sim \cos \alpha, \\ S_{12} &\sim \cos \alpha, & S_{22} &\sim \sin \alpha. \end{aligned}$$

In the CP-odd sector the interaction eigenstates are $\bar{\phi}^0 \equiv \sqrt{2}\text{Im}\{(H_1^0, H_2^0, S)^T\}$. We define the 2×3 mixing matrix P (block **NMAMIX**) by

$$-\bar{\phi}^{0T} \mathcal{M}_{\bar{\phi}^0}^2 \bar{\phi}^0 = -\underbrace{\bar{\phi}^{0T} P^T}_{\bar{\Phi}^{0T}} \underbrace{P \mathcal{M}_{\bar{\phi}^0}^2 P^T}_{\text{diag}(m_{\bar{\Phi}^0}^2)} \underbrace{P \bar{\phi}^0}_{\bar{\Phi}^0}, \quad (63)$$

where $\bar{\Phi}^0 \equiv (A_1^0, A_2^0)$ are the mass eigenstates ordered in mass. These states are numbered sequentially by the PDG codes (36, 46). The Goldstone boson G^0 (the “3rd component”) has been explicitly left out and the 2 rows of P form a set of orthonormal vectors. An updated version **NMSSMTools** [37] will follow these conventions.

If **NMHMIX**, **NMAMIX** blocks are present, they *supersede* the SLHA1 ALPHA variable/block.

The neutralino sector of the NMSSM requires a change in the definition of the 4×4 neutralino mixing matrix N to a 5×5 matrix. The Lagrangian contains the (symmetric) neutralino mass matrix as

$$\mathcal{L}_{\tilde{\chi}^0}^{\text{mass}} = -\frac{1}{2} \tilde{\psi}^{0T} \mathcal{M}_{\tilde{\psi}^0} \tilde{\psi}^0 + \text{h.c.}, \quad (64)$$

in the basis of 2-component spinors $\tilde{\psi}^0 = (-i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2, \tilde{s})^T$. We define the unitary 5×5 neutralino mixing matrix N (block **NMNMX**), such that:

$$-\frac{1}{2} \tilde{\psi}^{0T} \mathcal{M}_{\tilde{\psi}^0} \tilde{\psi}^0 = -\frac{1}{2} \underbrace{\tilde{\psi}^{0T} N^T}_{\tilde{\chi}^{0T}} \underbrace{N^* \mathcal{M}_{\tilde{\psi}^0} N^\dagger}_{\text{diag}(m_{\tilde{\chi}^0}^2)} \underbrace{N \tilde{\psi}^0}_{\tilde{\chi}^0}, \quad (65)$$

where the 5 (2-component) neutralinos $\tilde{\chi}_i$ are defined such that the absolute value of their masses increase with i . As in SLHA1, our convention is that N be a real matrix. One or more mass eigenvalues may then have an apparent negative sign, which can be removed by a phase transformation on $\tilde{\chi}_i$. The states are numbered sequentially by the PDG codes (1000022, 1000023, 1000025, 1000035, 1000045).

6 Conclusion and Outlook

At the time of writing of the SLHA1, a large number of computer codes already existed which used MSSM spectrum and coupling information in one form or another. This had several advantages: there was a high motivation from program authors to produce and

implement the accord accurately and quickly, and perhaps more importantly, the SLHA1 was tested “in anger” in diverse situations as it was being written.

We find ourselves in a slightly different situation in terms of the SLHA2. There are currently few programs that utilise information in any of the NMSSM or CP-violating, R-parity violating, or non-trivial flavour violating MSSM scenarios. Thus we do not have the benefit of comprehensive simultaneous testing of the proposed accord and the strong motivation that was present for implementation and writing of the original one. What we do have are the lessons learned in connection with the SLHA1 itself, and also several almost-finished codes which are now awaiting the finalisation of SLHA2 in order to publish their first official releases. Concrete tests involving several of these were thus possible in connection with this writeup.

We have adhered to the principle of backward compatibility wherever feasible. We therefore expect that the conventions and agreements reached within this paper constitute a practical solution that will prove useful for SUSY particle phenomenology in the future.

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A PDG Codes and Extensions

The existing PDG nomenclature for (s)particle names is based on the limit of the MSSM in which CP, R-parity, and flavour are conserved. Several of the mass eigenstates are therefore labeled to indicate definite R, CP, and/or flavour quantum numbers. When the corresponding symmetries are broken, such a labeling becomes misleading. Throughout this paper we have adopted the convention of assigning a common label to all states which carry identical conserved quantum numbers in the given model. We then re-use the existing PDG codes for those states, arranged in strictly increasing mass order.

This implies that, while the PDG numbers remain unaltered, their labels change, depending on which scenario is considered. The PDG codes and labels are discussed in detail in the individual sections on flavour violation, R-parity violation, CP violation, and the NMSSM. In the tables below, we summarise the PDG numbers and suggested labels relevant to each distinct scenario, for squarks (Tab. 2), charged colour-singlet fermions (Tab. 3), neutral colour-singlet fermions (Tab. 4), charged colour-singlet scalars (Tab. 5), and neutral colour-singlet scalars (Tab. 6), respectively. Note that these extensions are not officially endorsed by the PDG at this time. Codes for other particles can be found in [52, chp. 33].

Scalar Quarks							
FLV	No	YES	No	No	YES	YES	NMSSM
RPV	No	No	YES	No	YES	No	
CPV	No	No	No	YES	No	YES	
1000001	\tilde{d}_L	\tilde{d}_1	\tilde{d}_1	\tilde{d}_L	\tilde{d}_1	\tilde{d}_1	\tilde{d}_L
1000002	\tilde{u}_L	\tilde{u}_1	\tilde{u}_1	\tilde{u}_L	\tilde{u}_1	\tilde{u}_1	\tilde{u}_L
1000003	\tilde{s}_L	\tilde{d}_2	\tilde{d}_2	\tilde{s}_L	\tilde{d}_2	\tilde{d}_2	\tilde{s}_L
1000004	\tilde{c}_L	\tilde{u}_2	\tilde{u}_2	\tilde{c}_L	\tilde{u}_2	\tilde{u}_2	\tilde{c}_L
1000005	\tilde{b}_1	\tilde{d}_3	\tilde{d}_3	\tilde{b}_1	\tilde{d}_3	\tilde{d}_3	\tilde{b}_1
1000006	\tilde{t}_1	\tilde{u}_3	\tilde{u}_3	\tilde{t}_1	\tilde{u}_3	\tilde{u}_3	\tilde{t}_1
2000001	\tilde{d}_R	\tilde{d}_4	\tilde{d}_4	\tilde{d}_R	\tilde{d}_4	\tilde{d}_4	\tilde{d}_R
2000002	\tilde{u}_R	\tilde{u}_4	\tilde{u}_4	\tilde{u}_R	\tilde{u}_4	\tilde{u}_4	\tilde{u}_R
2000003	\tilde{s}_R	\tilde{d}_5	\tilde{d}_5	\tilde{s}_R	\tilde{d}_5	\tilde{d}_5	\tilde{s}_R
2000004	\tilde{c}_R	\tilde{u}_5	\tilde{u}_5	\tilde{c}_R	\tilde{u}_5	\tilde{u}_5	\tilde{c}_R
2000005	\tilde{b}_2	\tilde{d}_6	\tilde{d}_6	\tilde{b}_2	\tilde{d}_6	\tilde{d}_6	\tilde{b}_2
2000006	\tilde{t}_2	\tilde{u}_6	\tilde{u}_6	\tilde{t}_2	\tilde{u}_6	\tilde{u}_6	\tilde{t}_2

Table 2: Particle codes and corresponding labels for squarks. The labels in the first column correspond to the current PDG nomenclature.

Charged Leptons and Charginos

	FLV	No	YES	No	No	YES	YES	NMSSM
	RPV	No	No	YES	No	YES	No	
	CPV	No	No	No	YES	No	YES	
11		e^-	e^-	e_1^-	e^-	e_1^-	e^-	e^-
13		μ^-	μ^-	e_2^-	μ^-	e_2^-	μ^-	μ^-
15		τ^-	τ^-	e_3^-	τ^-	e_3^-	τ^-	τ^-
1000024		$\tilde{\chi}_1^+$	$\tilde{\chi}_1^+$	e_4^+	$\tilde{\chi}_1^+$	e_4^+	$\tilde{\chi}_1^+$	$\tilde{\chi}_1^+$
1000037		$\tilde{\chi}_2^+$	$\tilde{\chi}_2^+$	e_5^+	$\tilde{\chi}_2^+$	e_5^+	$\tilde{\chi}_2^+$	$\tilde{\chi}_2^+$

Table 3: Particle codes and corresponding labels for charged colour-singlet fermions. The labels in the first column correspond to the current PDG nomenclature. Note that, for historical reasons, codes 11, 13, and 15 pertain to negatively charged fields while codes 1000024 and 1000037 pertain to the opposite charge.

Neutrinos and Neutralinos

	FLV	No	YES	No	No	YES	YES	NMSSM
	RPV	No	No	YES	No	YES	No	
	CPV	No	No	No	YES	No	YES	
12		ν_e	ν_1	ν_1	ν_e	ν_1	ν_1	ν_e
14		ν_μ	ν_2	ν_2	ν_μ	ν_2	ν_2	ν_μ
16		ν_τ	ν_3	ν_3	ν_τ	ν_3	ν_3	ν_τ
1000022		$\tilde{\chi}_1^0$	$\tilde{\chi}_1^0$	ν_4	$\tilde{\chi}_1^0$	ν_4	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^0$
1000023		$\tilde{\chi}_2^0$	$\tilde{\chi}_2^0$	ν_5	$\tilde{\chi}_2^0$	ν_5	$\tilde{\chi}_2^0$	$\tilde{\chi}_2^0$
1000025		$\tilde{\chi}_3^0$	$\tilde{\chi}_3^0$	ν_6	$\tilde{\chi}_3^0$	ν_6	$\tilde{\chi}_3^0$	$\tilde{\chi}_3^0$
1000035		$\tilde{\chi}_4^0$	$\tilde{\chi}_4^0$	ν_7	$\tilde{\chi}_4^0$	ν_7	$\tilde{\chi}_4^0$	$\tilde{\chi}_4^0$
1000045		-	-	-	-	-	-	$\tilde{\chi}_5^0$

Table 4: Particle codes and corresponding labels for neutral colour-singlet fermions. The labels in the first column correspond to the current PDG nomenclature.

Charged Higgs Boson and Charged Scalar Leptons

	FLV	No	YES	No	No	YES	YES	NMSSM
	RPV	No	No	YES	No	YES	No	
	CPV	No	No	No	YES	No	YES	
37		H^+	H^+	h_1^+	H^+	h_1^+	H^+	H^+
1000011		\tilde{e}_L^+	\tilde{e}_1^+	h_2^+	\tilde{e}_L^+	h_2^+	\tilde{e}_1^+	\tilde{e}_L^+
1000013		$\tilde{\mu}_L^+$	\tilde{e}_2^+	h_3^+	$\tilde{\mu}_L^+$	h_3^+	\tilde{e}_2^+	$\tilde{\mu}_L^+$
1000015		$\tilde{\tau}_1^+$	\tilde{e}_3^+	h_4^+	$\tilde{\tau}_1^+$	h_4^+	\tilde{e}_3^+	$\tilde{\tau}_1^+$
2000011		\tilde{e}_R^+	\tilde{e}_4^+	h_5^+	\tilde{e}_R^+	h_5^+	\tilde{e}_4^+	\tilde{e}_R^+
2000013		$\tilde{\mu}_R^+$	\tilde{e}_5^+	h_6^+	$\tilde{\mu}_R^+$	h_6^+	\tilde{e}_5^+	$\tilde{\mu}_R^+$
2000015		$\tilde{\tau}_2^+$	\tilde{e}_6^+	h_7^+	$\tilde{\tau}_2^+$	h_7^+	\tilde{e}_6^+	$\tilde{\tau}_2^+$

Table 5: Particle codes and corresponding labels for charged colour-singlet scalars. The labels in the first column correspond to the current PDG nomenclature.

$$\epsilon \\ \times$$

Neutral Higgs Bosons and Scalar Neutrinos

	FLV	No	YES	No	No	YES	YES	NMSSM
	RPV	No	No	YES	No	YES	No	
	CPV	No	No	No	YES	No	YES	
25		h^0	h^0	h_1^0	h_1^0	h_1^0	h_1^0	h_1^0
35		H^0	H^0	h_2^0	h_2^0	h_2^0	h_2^0	h_2^0
36		A^0	A^0	A_1^0	h_3^0	A_1^0	h_3^0	A_1^0
45		-	-	-	-	-	-	h_3^0
46		-	-	-	-	-	-	A_2^0
1000012		$\tilde{\nu}_{eL}$	$\tilde{\nu}_1 (\tilde{\nu}_{1S})$	h_3^0	$\tilde{\nu}_{eL}$	h_3^0	$\tilde{\nu}_1$	$\tilde{\nu}_{eL}$
1000014		$\tilde{\nu}_{\mu L}$	$\tilde{\nu}_2 (\tilde{\nu}_{2S})$	h_4^0	$\tilde{\nu}_{\mu L}$	h_4^0	$\tilde{\nu}_2$	$\tilde{\nu}_{\mu L}$
1000016		$\tilde{\nu}_{\tau L}$	$\tilde{\nu}_3 (\tilde{\nu}_{3S})$	h_5^0	$\tilde{\nu}_{\tau L}$	h_5^0	$\tilde{\nu}_3$	$\tilde{\nu}_{\tau L}$
1000017		-	$(\tilde{\nu}_{1A})$	A_2^0	-	A_2^0	-	-
1000018		-	$(\tilde{\nu}_{2A})$	A_3^0	-	A_3^0	-	-
1000019		-	$(\tilde{\nu}_{3A})$	A_4^0	-	A_4^0	-	-

Table 6: Particle codes and corresponding labels for neutral colour-singlet scalars. The labels in the first column correspond to the current PDG nomenclature. The labels in parenthesis denote the optional separation of sneutrinos into separate scalar and pseudoscalar components.

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