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SUSY Les Houches Accord 2

B.C. Allanach[1], C. Balázs[2], G. Bélanger[3], M. Bernhardt[4], F. Boudjema[3], D. Choudhury[5], K. Desch[4], U. Ellwanger[6], P. Gambino[7], R. Godbole[8], T. Goto[9], J. Guasch[10], M. Guchait[11], T. Hahn[12], S. Heinemeyer[13], C. Hugonie[14], T. Hurth[15,16], S. Kraml[15], S. Kreiss[17], J. Lykken[18], F. Moortgat[19], S. Moretti[20], S. Peñaranda[21], T. Plehn[17], W. Porod[22], A. Pukhov[23], P. Richardson[24], M. Schumacher[25], L. Silvestrini[26], P. Skands[15,18†], P. Slavich[3,15], M. Spira[27], G. Weiglein[24], P. Wienemann[4]

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Abstract

The Supersymmetry Les Houches Accord (SLHA) [1] 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.

1 *DAMTP, CMS, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom*
2 *School of Physics, Monash University, Melbourne VIC 3800, Australia*
3 *LAPTH, CNRS, UMR 5108, Chemin de Bellevue BP110, F-74941, Annecy-le-Vieux, France*
4 *University of Bonn, Physics Insitute, Nussallee 12, D-53115 Bonn, Germany*
5 *Harish Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211019, India*
6 *Laboratoire de Physique Théorique, Université de Paris Sud XI, Bât. 210, F-91405, Orsay, France*
7 *Università di Torino and INFN, sez. di Torino, 10125 Torino, Italy*
8 *Indian Institute of Science, Center for Theoretical Studies, Bangalore 560012, Karnataka, India*
9 *Theory Group, IPNS, KEK, Tsukuba, 305-0801, Japan*
10 *Universitat de Barcelona, Dept. de Fisica Fonamental, Diagonal 647, E-08028 Barcelona, Spain*
11 *Tata Institute for Fundamental Research, Homi Bhabha Road, Mumbai, India*
12 *MPI, Werner Heisenberg Inst., Föhringer Ring 6, D-80805 Munich, Germany*
13 *IFCA (CSIC–UC), Avda. de los Castros s/n, 39005 Santander, Spain*
14 *LPTA, Université Montpellier II, F-34095 Montpellier,Cedex 5, France*
15 *CERN, Department of Physics, Theory Unit, CH-1211, Geneva 23, Switzerland*
16 *SLAC, Stanford University, Stanford, CA 94309, USA*
17 *The University of Edinburgh, School of Physics, James Clerk Maxwell Building, King's Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom*
18 *Theoretical Physics, Fermilab, P.O. Box 500, Batavia, IL 60510-0500, USA*
19 *ETH Zurich, CH-8093 Zurich, Switzerland*
20 *University of Southampton, School of Physics and Astronomy, Highfield, Southampton S017 1BJ, United Kingdom*

†skands@fnal.gov; see `http://home.fnal.gov/∼skands/slha/` for updates and examples.

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21 Departamento de Física Teórica, Universidad de Zaragoza, E-50009, Zaragoza, Spain
22 Institut für Theoretische Physik und Astrophysik, Universität Würzburg, 97074 Würzburg, Germany
23 M.V. Lomonosov Moscow State University (MSU) Faculty of Physics 1, building 2, GSP-2, Leninskiye Gory, Moscow, 119992, Russia
24 Durham University Inst. for Particle Physics Phenomenology Ogden Centre for Fundamental Physics South Road Durham DH1 3LE, United Kingdom
25 Univ. Göttingen, Inst. für Theoretische Physik, Friedreich-Hund-Platz 1, D-37077 Göttingen, Germany
26 Univ. degli Studi di Roma, La Sapienza, Dipt. di Fisica G. Marconi, Piazzale Aldo Moro 2, I-00185 Rome, Italy
27 Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Contents

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 quick 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 [9–17]; 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 [18–26], 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 fitting programs [27, 28] 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 [29]. 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 head-ache.

However, SLHA1 was designed exclusively with the MSSM with real parameters and R-parity conservation in mind. Some recent public codes [6, 7, 17, 30–34] 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 the violation of R-parity (RPV), flavour violation, and CP-violating (CPV) phases in the minimal supersymmetric standard model (MSSM). We will also consider next-to-minimal models which we shall collectively label by the acronym NMSSM.

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. We shall work in the Super-CKM/MNS basis throughout (defined in Section 3.1), except in the RPV case where input parameters are supposed to be in the interaction basis. 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 [35–37].

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 SLHA1 [1] implicitly. For instance, all dimensionful parameters quoted in the present paper are assumed to be in the appropriate power of GeV and all angles are in radians. 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 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:
- `0` : MSSM. This corresponds to SLHA1.
- `1` : NMSSM. As defined here.

`4` : (Default=`0`) R-parity violation. Switches defined are:
- `0` : R-parity conserved. This corresponds to the SLHA1.
- `1` : R-parity violated. The blocks defined in Section 3.2 should be present.

`5` : (Default=`0`) CP violation. Switches defined are:
- `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 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 3.1 should be given, again with the prefix `IM`, which supersede the corresponding entries in `IMEXTPAR`.

`6` : (Default=`0`) Flavour violation. Switches defined are:
- `0` : No (SUSY) flavour violation. This corresponds to the SLHA1.
- `1` : Quark flavour is violated. The blocks defined in Section 3.1.1 should be present.
- `2` : Lepton flavour is violated. The blocks defined in Section 3.1.2 should be present.
- `3` : Lepton and quark flavour is violated. The blocks defined in Sections 3.1.1 and 3.1.2 should both be present.

3 General MSSM

3.1 Flavour Violation

3.1.1 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 [38] 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

$$D^o \;=\; V_d\, D\,, \qquad U^o \;=\; V_u\, U\,, \qquad \bar{D}^o = \; U_d^*\, \bar{D}\,, \qquad \bar{U}^o = \; U_u^*\, \bar{U}\,, \tag{1}$$

of all matter superfields in the superpotential

$$W_Q \;=\; \epsilon_{ab}\left[(Y_D)_{ij}\, H_1^a Q_i^{b\,o} \bar{D}_j^{\,o} + (Y_U)_{ij}\, H_2^b Q_i^{a\,o} \bar{U}_j^{\,o} - \mu H_1^a H_2^b\right] \tag{2}$$

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

$$d_L^o = V_d d_L\,, \qquad u_L^o = V_u u_L\,, \qquad d_R^o = U_d d_R\,, \qquad u_R^o = U_u u_R\,, \tag{3}$$

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 $\hat{Y}_U$:

$$(\hat{Y}_D)_{ii} = (U_d^\dagger Y_D^T V_d)_{ii} = \sqrt{2}\frac{m_{d\,i}}{v_1}\,, \qquad (\hat{Y}_U)_{ii} = (U_u^\dagger Y_U^T V_u)_{ii} = \sqrt{2}\frac{m_{u\,i}}{v_2}\,. \tag{4}$$

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 [39, 40]

$$V_{\rm CKM} = V_u^\dagger V_d\ , \tag{5}$$

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

$$\mathcal{L}_{\tilde{q}}^{\rm mass} \;=\; -\,\Phi_u^\dagger\, \mathcal{M}_{\tilde{u}}^2\, \Phi_u - \Phi_d^\dagger\, \mathcal{M}_{\tilde{d}}^2\, \Phi_d\ , \tag{6}$$

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:

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} V_{\rm CKM}\, \hat{m}^2_{\tilde{Q}}\, V^\dagger_{\rm CKM} + m_u^2 + D_{u\,LL} & v_2 \hat{T}^\dagger_U - \mu m_u \cot\beta \\ v_2 \hat{T}_U - \mu^* m_u \cot\beta & \hat{m}^2_{\tilde{u}} + m_u^2 + D_{u\,RR} \end{pmatrix}, \quad (7)$$

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_{\tilde{Q}} + m_d^2 + D_{d\,LL} & v_1 \hat{T}^\dagger_D - \mu m_d \tan\beta \\ v_1 \hat{T}_D - \mu^* m_d \tan\beta & \hat{m}^2_{\tilde{d}} + m_d^2 + D_{d\,RR} \end{pmatrix}. \quad (8)$$

In the equations above we introduced the 3×3 matrices

$$\hat{m}^2_{\tilde{Q}} \equiv V_d^\dagger\, m^2_{\tilde{Q}}\, V_d\,, \quad \hat{m}^2_{\tilde{u}} \equiv U_u^\dagger\, m^{2\,T}_{\tilde{u}}\, U_u\,, \quad \hat{m}^2_{\tilde{d}} \equiv U_d^\dagger\, m^{2\,T}_{\tilde{d}}\, U_d\,, \quad (9)$$

$$\hat{T}_U \equiv U_u^\dagger\, T_U^T\, V_u\,, \quad \hat{T}_D \equiv U_d^\dagger\, T_D^T\, V_d\,, \quad (10)$$

where the un-hatted mass matrices $m^2_{Q,u,d}$ and trilinear interaction matrices $T_{U,D}$ are given in the electroweak basis of [1, eqs. (5) and (7)]. The matrices $m_{u,d}$ are the diagonal up-type and down-type quark masses and $D_{f\,LL,RR}$ are the D-terms given by:

$$D_{f\,LL,RR} = \cos 2\beta\, m_Z^2 \left(T_f^3 - Q_f \sin^2\theta_W\right) 1\!\!1_3\,, \quad (11)$$

which are also flavour diagonal. Note that the up-type and down-type squark mass matrices in eqs. (7) and (8) cannot be simultaneously flavour-diagonal unless $\hat{m}^2_{\tilde{Q}}$ is flavour-universal (i.e. proportional to the identity in flavour space).

3.1.2 The lepton sector and the super-MNS basis

For the lepton sector, we adopt a super-MNS basis. 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 [41–43]. 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)

$$\mathcal{L} = -\frac{1}{2} \nu^{oT} (m_\nu) \nu^o + \text{h.c.}, \quad (12)$$

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

$$\nu^o = V_\nu \nu, \quad (13)$$

reducing the mass matrix m_ν to its diagonal form $\hat{m}_\nu$

$$(\hat{m}_\nu)_{ii} = (V_\nu^T m_\nu V_\nu)_{ii} = m_{\nu_i}. \tag{14}$$

The charged lepton fields have a 3×3 Yukawa coupling matrix defined in the superpotential piece [1]

$$W_E = \epsilon_{ab} (Y_E)_{ij} H_1^a L_i^{bo} \bar{E}_j^o, \tag{15}$$

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

$$e_L^o = V_e e_L \qquad \text{and} \qquad e_R^o = U_e e_R. \tag{16}$$

The equivalent diagonalised charged lepton Yukawa matrix is

$$(\hat{Y}_E)_{ii} = (U_e^\dagger Y_E^T V_e)_{ii} = \sqrt{2} \frac{m_{ei}}{v_1} \quad . \tag{17}$$

Lepton mixing in the charged current interaction can then be characterised by the MNS matrix [44, 45]

$$U_{MNS} = V_e^\dagger V_\nu \ , \tag{18}$$

which is proportional to the tree-level $\bar{e}_{Li} \nu_j W^-$ and $\bar{e}_{Li} \nu_j H^-$ 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-MNS basis for the charged sleptons and the sneutrinos, described by the Lagrangian[1]

$$\mathcal{L}_{\tilde{l}}^{mass} = -\Phi_e^\dagger \mathcal{M}_{\tilde{e}}^2 \Phi_e - \Phi_\nu^\dagger \mathcal{M}_{\tilde{\nu}}^2 \Phi_\nu, \tag{19}$$

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

$$\mathcal{M}_{\tilde{e}}^2 = \begin{pmatrix} \hat{m}_{\tilde{L}}^2 + m_e^2 + D_{eLL} & v_1 \hat{T}_E^\dagger - \mu m_e \tan\beta \\ v_1 \hat{T}_E - \mu^* m_e \tan\beta & \hat{m}_{\tilde{e}}^2 + m_e^2 + D_{eRR} \end{pmatrix}. \tag{20}$$

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

$$\mathcal{M}_{\tilde{\nu}}^2 = U_{MNS}^\dagger \ \hat{m}_{\tilde{L}}^2 \ U_{MNS} + D_{\nu LL}, \tag{21}$$

where D_{eLL} and $D_{\nu LL}$ are given in eq. (11). In the equations above we introduced the 3×3 matrices

$$\hat{m}_{\tilde{L}}^2 \equiv V_e^\dagger \, m_{\tilde{L}}^2 \, V_e \,, \quad \hat{m}_{\tilde{e}}^2 \equiv U_e^\dagger \, m_{\tilde{e}}^{2\,T} \, U_e \,, \tag{22}$$

$$\hat{T}_E \equiv U_e^\dagger \, T_E^T \, V_e \,, \tag{23}$$

where the un-hatted mass matrices $m_{\tilde{L},e}^2$ and the trilinear interaction matrix T_E are given in the interaction basis of ref. [1, eqs. (5) and (7)]. We diagonalise the charged slepton and sneutrino mass matrices via the 6×6 and unitary 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.

[1]We neglect the possible term $\Phi_\nu^T \hat{\mathcal{M}}_{\tilde{\nu}}^2 \Phi_\nu$. Neutrino mass constraints usually imply that it is highly suppressed and has negligible effect on collider phenomenology.

3.1.3 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 ($\overline{\mathrm{DR}}$) scheme. The basis is the super-CKM/MNS basis as defined above, that is the one in which the Yukawa couplings of the SM fermions, given in the $\overline{\mathrm{DR}}$ scheme, are diagonal. Note that the masses and vacuum expectation values (VEVs) in eqs. (4), (14), and (17) must thus be the running ones in the $\overline{\mathrm{DR}}$ scheme.

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

- All input SUSY parameters are given at the scale M_{input} as defined in the SLHA1 block `EXTPAR`, except for `EXTPAR 26`, which, if present, is the *pole* pseudoscalar Higgs mass[2]. If no M_{input} is present, the GUT scale is used.

- 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 $m_c(m_c)^{\overline{\mathrm{MS}}}$, $m_b(m_b)^{\overline{\mathrm{MS}}}$ and $m_t^{\mathrm{on-shell}}$. 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` : $\alpha_{\mathrm{em}}^{-1}(m_Z)^{\overline{\mathrm{MS}}}$. Inverse electromagnetic coupling at the Z pole in the $\overline{\mathrm{MS}}$ scheme (with 5 active flavours).

  `2` : G_F. Fermi constant (in units of GeV^{-2}).

  `3` : $\alpha_s(m_Z)^{\overline{\mathrm{MS}}}$. Strong coupling at the Z pole in the $\overline{\mathrm{MS}}$ scheme (with 5 active flavours).

  `4` : m_Z, pole mass.

  `5` : $m_b(m_b)^{\overline{\mathrm{MS}}}$. b quark running mass in the $\overline{\mathrm{MS}}$ 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` : $m_d(2\ \mathrm{GeV})^{\overline{\mathrm{MS}}}$. d quark running mass in the $\overline{\mathrm{MS}}$ scheme.

  `22` : $m_u(2\ \mathrm{GeV})^{\overline{\mathrm{MS}}}$. u quark running mass in the $\overline{\mathrm{MS}}$ scheme.

  `23` : $m_s(2\ \mathrm{GeV})^{\overline{\mathrm{MS}}}$. s quark running mass in the $\overline{\mathrm{MS}}$ scheme.

[2] This is an evolution of the SLHA1 which is not present in the journal version of ref. [1].

24 : $m_c(m_c)^{\overline{\rm MS}}$. c quark running mass in the $\overline{\rm MS}$ scheme.

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

- $V_{\rm CKM}$: the input CKM matrix in the PDG parametrisation [46] (exact to all orders), 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 and CKMFitter, the main collaborations that extract the CKM parameters) refer to SM $\overline{\rm MS}$ quantities defined at $Q = m_Z$, to avoid any possible ambiguity. `VCKMIN` should have the following entries (all in radians):

  1 : θ_{12} (the Cabibbo angle)

  2 : θ_{23}

  3 : θ_{13}

  4 : δ_{13}

  The FORTRAN format is the same as that of `SMINPUTS` above. Note that the three θ angles can all be made to lie in the first quadrant by appropriate rotations of the quark phases.

- $U_{\rm MNS}$: the input MNS matrix, in the block `UMNSIN`. It should have the PDG parameterisation in terms of rotation angles [46] (all in radians):

  1 : $\bar\theta_{12}$ (the solar angle)

  2 : $\bar\theta_{23}$ (the atmospheric mixing angle)

  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, $\beta\beta 0\nu$ decay of nuclei [46].

- $(\hat m^2_{\tilde Q})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde u})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde d})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde L})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde e})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at the input scale in the super-CKM/MNS 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`

- $(\hat{T}_U)^{\overline{\rm DR}}_{ij}$, $(\hat{T}_D)^{\overline{\rm DR}}_{ij}$, and $(\hat{T}_E)^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking trilinear couplings at the input scale in the super-CKM/MNS basis, 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, and the $\overline{\rm DR}$ and mixing parameters as follows:

- $(\hat{m}^2_{\tilde{Q}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{u}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{d}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{L}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{e}})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at scale Q in the super-CKM/MNS 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.

- $(\hat{T}_U)^{\overline{\rm DR}}_{ij}$, $(\hat{T}_D)^{\overline{\rm DR}}_{ij}$, and $(\hat{T}_E)^{\overline{\rm DR}}_{ij}$: The squark and slepton soft SUSY-breaking trilinear couplings in the super-CKM/MNS basis. Given in the new blocks `TU Q=...`, `TD Q=...`, `TE Q=...`, which supersede the SLHA1 blocks `AD`, `AU`, and `AE`, see [1].

- $(\hat{Y}_U)^{\overline{\rm DR}}_{ii}$, $(\hat{Y}_D)^{\overline{\rm DR}}_{ii}$, $(\hat{Y}_E)^{\overline{\rm DR}}_{ii}$: the diagonal $\overline{\rm DR}$ Yukawas in the super-CKM/MNS basis, with $\hat{Y}$ defined by eqs. (4) and (17), 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/MNS rotation.

- The $\overline{\rm DR}$ CKM matrix at the scale Q, in the PDG parametrisation [46]. Will be given in the new block(s) `VCKM Q=...`, with entries defined as for the input block `VCKMIN` above.

- The $\overline{\rm DR}$ MNS matrix at the scale Q, again in the PDG parameterisation in the new block `UMNS Q=...` with entries defined as for the input block `UMNSIN` 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 $\tilde{e}$ mixing matrices to the 6×6 case. More specifically, the new blocks R_u =`USQMIX` R_d =`DSQMIX`, R_e =`SELMIX` and the 3 by 3 matrix for R_ν =`SNUMIX` connect the particle codes (=mass-ordered basis) with the super-CKM basis according to the following definition:

$$\begin{pmatrix} 1000001 \\ 1000003 \\ 1000005 \\ 2000001 \\ 2000003 \\ 2000005 \end{pmatrix} = \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix}_{\rm mass-ordered} = \mathtt{DSQMIX}_{ij} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}_{\rm super-CKM} , \tag{24}$$

$$\begin{pmatrix} 1000002 \\ 1000004 \\ 1000006 \\ 2000002 \\ 2000004 \\ 2000006 \end{pmatrix} = \begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix}_{\mathrm{mass-ordered}} = \mathtt{USQMIX}_{ij} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}_{\mathrm{super-CKM}} . \tag{25}$$

$$\begin{pmatrix} 1000011 \\ 1000013 \\ 1000015 \\ 2000011 \\ 2000013 \\ 2000015 \end{pmatrix} = \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \\ \tilde{e}_3 \\ \tilde{e}_4 \\ \tilde{e}_5 \\ \tilde{e}_6 \end{pmatrix}_{\mathrm{mass-ordered}} = \mathtt{SELMIX}_{ij} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}_{\mathrm{super-MNS}} , \tag{26}$$

$$\begin{pmatrix} 1000012 \\ 1000014 \\ 1000016 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \\ \tilde{\nu}_3 \end{pmatrix}_{\mathrm{mass-ordered}} = \mathtt{SNUMIX}_{ij} \begin{pmatrix} \tilde{\nu}_{e_L} \\ \tilde{\nu}_{\mu_L} \\ \tilde{\nu}_{\tau_L} \end{pmatrix}_{\mathrm{super-MNS}} . \tag{27}$$

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.

3.2 R-Parity Violation

We write the superpotential of R-parity violating interactions in the notation of [1] as

$$\begin{aligned} W_{\mathrm{RPV}} &= \epsilon_{ab} \left[\frac{1}{2} \lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^{bx} \bar{D}_{kx} - \kappa_i L_i^a H_2^b \right] \\ & \quad + \frac{1}{2} \lambda''_{ijk} \epsilon^{xyz} \bar{U}_{ix} \bar{D}_{jy} \bar{D}_{kz}, \end{aligned} \tag{28}$$

where $x, y, z = 1, \ldots, 3$ are fundamental $\mathrm{SU}(3)_C$ indices and ϵ^{xyz} is the totally antisymmetric tensor in 3 dimensions with $\epsilon^{123} = +1$. In eq. (28), $\lambda_{ijk}, \lambda'_{ijk}$ 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 $i, j, k = 1, 2, 3$. In the treatment of R-parity violation, we do *not* generalise the flavour discussion in Section 3.1 as it would lead to excessive complication. We use known charged fermion masses for input along with interaction basis R-parity violating couplings and neglect (s)quark/(s)lepton flavour mixing effects in the same spirit as SLHA1.

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

$$\begin{aligned} V_{3,\mathrm{RPV}} &= \epsilon_{ab}\left[\frac{1}{2}(T)_{ijk}\tilde{L}^a_{iL}\tilde{L}^b_{jL}\tilde{e}^*_{kR} + (T')_{ijk}\tilde{L}^a_{iL}\tilde{Q}^b_{jL}\tilde{d}^*_{kR}\right] \\ &\quad + \frac{1}{2}(T'')_{ijk}\epsilon_{xyz}\tilde{u}^{x*}_{iR}\tilde{d}^{y*}_{jR}\tilde{d}^{z*}_{kR} + \mathrm{h.c.} \quad . \end{aligned} \tag{29}$$

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.

When lepton number is broken, additional bilinear soft SUSY-breaking potential terms can appear,

$$V_{\mathrm{RPV2}} = -\epsilon_{ab} D_i \tilde{L}^a_{iL} H^b_2 + \tilde{L}^\dagger_{iaL} m^2_{\tilde{L}_i H_1} H^a_1 + \mathrm{h.c.}\ , \tag{30}$$

and 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

$$v = \sqrt{v_1^2 + v_2^2 + v_e^2 + v_\mu^2 + v_\tau^2}\ . \tag{31}$$

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

3.2.1 Input/Output Blocks

For R-parity violating parameters and couplings, the naming convention for input blocks is `BLOCK RV#IN`, where the '#' character represents the name of the relevant output block given below (thus, for example, the "LLE" couplings λ_{ijk} would be given in `BLOCK RVLAMLLEIN`).

Default inputs for all R-parity violating couplings are zero. The inputs are given at scale M_{input}, as described in SLHA1 (again, if no M_{input} is given, the GUT scale is assumed), and follow the output format given below (with the omission of `Q= ...`).

The dimensionless couplings λ_{ijk}, λ'_{ijk}, and λ''_{ijk} are given in `BLOCK RVLAMLLE, RVLAMLQD, RVLAMUDD Q= ...` respectively. The output standard should correspond to the FORTRAN format

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

where the first three integers in the format correspond to i, j, and k and the double precision number is the coupling.

T_{ijk}, T'_{ijk}, and T''_{ijk} are given in `BLOCK RVTLLE, RVTLQD, RVTUDD Q= ...` in the same format as for the λ couplings above.

The bilinear superpotential and soft SUSY-breaking terms κ_i, D_i, and $m^2_{\tilde{L}_i H_1}$ and the sneutrino VEVs are given in `BLOCK RVKAPPA, RVD, RVM2LH1, RVSNVEV Q= ...` respectively, in the format

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

Input block	Output block	data
RVLAMLLEIN	RVLAMLLE	$i\ j\ k\ \lambda_{ijk}$
RVLAMLQDIN	RVLAMLQD	$i\ j\ k\ \lambda'_{ijk}$
RVLAMUDDIN	RVLAMUDD	$i\ j\ k\ \lambda''_{ijk}$
RVTLLEIN	RVTLLE	$i\ j\ k\ T_{ijk}$
RVTLQDIN	RVTLQD	$i\ j\ k\ T'_{ijk}$
RVTUDDIN	RVTUDD	$i\ j\ k\ T''_{ijk}$
NB: One of the following RV...IN blocks must be left out: (which one up to user and RGE code)		
RVKAPPAIN	RVKAPPA	$i\ \kappa_i$
RVDIN	RVD	$i\ D_i$
RVSNVEVIN	RVSNVEV	$i\ v_i$
RVM2LH1IN	RVM2LH1	$i\ m^2_{\tilde{L}_i H_1}$

Table 1: Summary of R-parity violating SLHA2 data blocks. All output parameters are to be given in the Super-CKM/MNS basis, but input parameters should be given in the interaction eigenstate basis. Only 3 out of the last 4 blocks are independent. Which block to leave out of the input is in principle up to the user, with the caveat that a given spectrum calculator may not accept all combinations. See text for a precise definition of the format.

The input and output blocks for R-parity violating couplings are summarised in Tab. 1.

As for the R-conserving MSSM, the bilinear terms (both SUSY-breaking and SUSY-respecting ones, including μ) and the VEVs are not independent parameters. They become related by the condition of electroweak symmetry breaking. Thus, in the SLHA1, one had the possibility *either* to specify $m^2_{H_1}$ and $m^2_{H_2}$ *or* μ and m^2_A. This carries over to the RPV case, where not all the parameters in the input blocks RV...IN in Tab. 1 can be given simultaneously. Specifically, of the last 4 blocks only 3 are independent. One block is determined by minimising the Higgs-sneutrino potential. We do not here insist on a particular choice for which of RVKAPPAIN, RVDIN, RVSNVEVIN, and RVM2LH1IN to leave out, but leave it up to the spectrum calculators to accept one or more combinations.

Neutrino masses and leptonic mixing are considered as an *output* of the spectrum generator: providing interaction basis lepton number violating couplings in the input will, in general, generate neutrino masses and lepton mixing, which codes may output.

3.2.2 Particle Mixing

The mixing of particles can change when L is violated. Phenomenological constraints can often imply that any such mixing has to be small. It is therefore possible that some programs may ignore the mixing in their output. In this case, the mixing matrices from SLHA1 should suffice. However, in the case that mixing is considered to be important and included in the output, we here present extensions to the mixing blocks from SLHA1 appropriate to the more general case.

In general, the neutrinos mix with the neutralinos. This requires a change in the definition of the 4×4 neutralino mixing matrix N to a 7×7 matrix. The Lagrangian contains the (symmetric) neutralino mass matrix as

$$\mathcal{L}^{\rm mass}_{\tilde{\chi}^0} = -\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 + \text{h.c.} \ , \tag{32}$$

in the basis of 2–component spinors $\tilde{\psi}^0 = (\nu_e, \nu_\mu, \nu_\tau, -i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2)^T$. We define the unitary 7×7 neutralino mixing matrix N (block `RVNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\text{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0} \ , \tag{33}$$

where the 7 (2–component) generalised neutralinos $\tilde{\chi}_i$ are defined strictly mass-ordered, i.e. with the 1^{st},2^{nd},3^{rd} lightest corresponding to the mass entries for the PDG codes `12`, `14`, and `16`, and the four heaviest to the PDG codes `1000022`, `1000023`, `1000025`, and `1000035`.

Note! although these codes are normally associated with names that imply a specific flavour content, such as code `12` being $\nu_{\rm e}$ and so forth, it would be exceedingly complicated to maintain such a correspondence in the context of completely general mixing, hence we do not make any such association here. The flavour content of each state, i.e. of each PDG number, is in general only defined by its corresponding entries in the mixing matrix `RVNMIX`. Note, however, that the flavour basis is ordered so as to reproduce the usual associations in the trivial case (modulo the unknown flavour composition of the neutrino mass eigenstates).

In the limit of CP conservation, the default convention is that N be a real symmetric matrix and the neutralinos may have an apparent negative mass. The minus sign may be removed by phase transformations on $\tilde{\chi}^0_i$ as explained in SLHA1 [1].

Charginos and charged leptons may also mix in the case of L-violation. In a similar spirit to the neutralino mixing, we define

$$\mathcal{L}^{\rm mass}_{\tilde{\chi}^+} = -\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ + \text{h.c.} \ , \tag{34}$$

in the basis of 2–component spinors $\tilde{\psi}^+ = (e^+, \mu^+, \tau^+, -i\tilde{w}^+, \tilde{h}_2^+)^T$, $\tilde{\psi}^- = (e^-, \mu^-, \tau^-, -i\tilde{w}^-, \tilde{h}_1^-)^T$ where $\tilde{w}^\pm = (\tilde{w}^1 \mp \tilde{w}^2)/\sqrt{2}$. Note that, in the limit of no RPV the lepton fields are mass eigenstates.

We define the unitary 5×5 charged fermion mixing matrices U, V, blocks `RVUMIX`, `RVVMIX`, such that:

$$-\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ = -\frac{1}{2}\underbrace{\tilde{\psi}^{-T}U^T}_{\tilde{\chi}^{-T}}\underbrace{U^*\mathcal{M}_{\tilde{\psi}^+}V^\dagger}_{\text{diag}(m_{\tilde{\chi}^+})}\underbrace{V\tilde{\psi}^+}_{\tilde{\chi}^+} \ , \tag{35}$$

where $\tilde{\chi}_i^\pm$ are defined as strictly mass ordered, i.e. with the 3 lightest states corresponding to the PDG codes `11`, `13`, and `15`, and the two heaviest to the codes `1000024`, `1000037`. As for neutralino mixing, the flavour content of each state is in no way implied by its PDG number, but is only defined by its entries in `RVUMIX` and `RVVMIX`. Note, however, that the flavour basis is ordered so as to reproduce the usual associations in the trivial case.

In the limit of CP conservation, U and V are chosen to be real by default.

CP-even Higgs bosons mix with sneutrinos in the limit of CP symmetry. We write the neutral scalars as $\phi^0 \equiv \sqrt{2}\text{Re}\left\{(H_1^0, H_2^0, \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T\right\}$, with the mass term

$$\mathcal{L} = -\frac{1}{2}\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 \ , \tag{36}$$

where $\mathcal{M}^2_{\phi^0}$ is a 5×5 symmetric mass matrix.

One solution is to define the unitary 5×5 mixing matrix $\aleph$ (block RVHMIX) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}\aleph^T}_{\Phi^{0T}}\underbrace{\aleph^*\mathcal{M}^2_{\phi^0}\aleph^\dagger}_{\text{diag}(m^2_{\Phi^0})}\underbrace{\aleph\phi^0}_{\Phi^0} \ , \tag{37}$$

where $\Phi^0 \equiv (H^0, h^0, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$ are the mass eigenstates (note that we have here labelled the states by what they should tend to in the R-parity conserving limit).

CP-odd Higgs bosons mix with the imaginary components of the sneutrinos: We write these neutral pseudo-scalars as $\bar{\phi}^0 \equiv \sqrt{2}\text{Im}\left\{(H_1^0, H_2^0, \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T\right\}$, with the mass term

$$\mathcal{L} = -\frac{1}{2}\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 \ , \tag{38}$$

where $\mathcal{M}^2_{\bar{\phi}^0}$ is a 5×5 symmetric mass matrix. We define the 4×5 mixing matrix $\bar{\aleph}$ (block RVAMIX) by

$$-\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 = -\underbrace{\bar{\phi}^{0T}\bar{\aleph}^T}_{\bar{\Phi}^{0T}}\underbrace{\bar{\aleph}^*\mathcal{M}^2_{\bar{\phi}^0}\bar{\aleph}^\dagger}_{\text{diag}(m^2_{\bar{\Phi}^0})}\underbrace{\bar{\aleph}\bar{\phi}^0}_{\bar{\Phi}^0} \ , \tag{39}$$

where $\bar{\Phi}^0 \equiv (A^0, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$ are the mass eigenstates. The Goldstone boson G^0 (the "5th component") has been explicitly left out and the remaining 4 rows form a set of orthonormal vectors.

If the blocks RVHMIX, RVAMIX are present, they *supersede* the SLHA1 ALPHA variable/block.

The charged sleptons and charged Higgs bosons also mix in the 8×8 mass squared matrix $\mathcal{M}^2_{\phi^\pm}$ by a 7×8 matrix C (block RVLMIX):

$$\mathcal{L} = -\underbrace{(h_1^-, h_2^{+*}, \tilde{e}_{L_i}, \tilde{e}_{R_j})C^T}_{(H^-,\tilde{e}_\alpha)}\underbrace{C^*\mathcal{M}^2_{\phi^\pm}C^T}_{\text{diag}(\mathcal{M}^2_{\Phi^\pm})}C^*\begin{pmatrix} h_1^{-*} \\ h_2^+ \\ \tilde{e}^*_{L_k} \\ \tilde{e}^*_{R_l}\end{pmatrix} \ , \tag{40}$$

where $i,j,k,l \in \{1,2,3\}$, $\alpha,\beta \in \{1,\ldots,6\}$, the non-braced product on the right hand side is equal to $(H^+, \tilde{e}^*_\beta)$, and the Goldstone bosons $G^\pm$ (the "8th components") have been explicitly left out and the remaining 7 rows form a set of orthonormal vectors.

There may be contributions to down-squark mixing from R-parity violation. However, this only mixes the six down-type squarks amongst themselves and so is identical to the effects of flavour mixing. This is covered in Section 3.1 (along with other forms of flavour mixing).

3.3 CP Violation

When adding CP violation to the MSSM model parameters and mixing matrices[3], the SLHA1 blocks are understood to contain the real parts of the relevant parameters. The imaginary parts should be provided with exactly the same format, in a separate block of the same name but prefaced by `IM`. The defaults for all imaginary parameters will be zero. Thus, for example, `BLOCK IMAU, IMAD, IMAE, Q= ...` would describe the imaginary parts of the trilinear soft SUSY-breaking scalar couplings. For input, `BLOCK IMEXTPAR` may be used to provide the relevant imaginary parts of soft SUSY-breaking inputs. In cases where the definitions of the current paper supersedes the SLHA1 input and output blocks, completely equivalent statements apply.

One special case is the μ parameter. When the real part of μ is given in `EXTPAR 23`, the imaginary part should be given in `IMEXTPAR 23`, as above. However, when $|\mu|$ is determined by the conditions for electroweak symmetry breaking, only the phase φ_μ is taken as an input parameter. In this case, SLHA2 generalizes the entry `MINPAR 3` to contain the cosine of the phase (as opposed to just $\mathrm{sign}(\mu)$ in SLHA1), and we further introduce a new block `IMMINPAR` whose entry `3` gives the sine of the phase, that is:

`BLOCK MINPAR`

`3` : CP conserved: $\mathrm{sign}(\mu)$.
CP violated: $\cos\varphi_\mu = \mathrm{Re}\,\{\mu\}\,/|\mu|$.

`BLOCK IMMINPAR`

`3` : CP conserved: n/a.
CP violated: $\sin\varphi_\mu = \mathrm{Im}\,\{\mu\}\,/|\mu|$.

Note that $\cos\varphi_\mu$ coincides with $\mathrm{sign}(\mu)$ in the CP-conserving cases.

When CP symmetry is broken, quantum corrections cause mixing between the CP-even and CP-odd Higgs states. Writing the neutral scalar interaction eigenstates as $\phi^0 \equiv \sqrt{2}(\mathrm{Re}\,\{H_1^0\}\,, \mathrm{Re}\,\{H_2^0\}\,, \mathrm{Im}\,\{H_1^0\}\,, \mathrm{Im}\,\{H_2^0\})^T$ we define the 3×4 mixing matrix S (blocks `CVHMIX` and `IMCVHMIX`) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}S^T}_{\Phi^{0T}}\underbrace{S^*\mathcal{M}^2_{\phi^0}S^\dagger}_{\mathrm{diag}(m^2_{\Phi^0})}\underbrace{S\phi^0}_{\Phi^0}\ , \tag{41}$$

where $\Phi^0 \equiv (H_1^0, H_2^0, H_3^0)^T$ are the mass eigenstates.

The matrix S thus gives the decomposition of the three physical mass eigenstates in terms of the four interaction eigenstates, all in one go, with the Goldstone boson G^0 explicitly projected out.

For comparison, in the literature, the projecting-out of the Goldstone boson is often done as a separate step, by first performing a rotation by the angle β. (This is, for instance, the

[3]For a recent review, see, e.g., the CPNSH report [47].

prescription followed by CPsuperH [13, 48]). In such an approach, our matrix S would be decomposed as:

$$S\phi^0 = \left(\begin{array}{cc} \mathcal{O}_{3\times 3} & \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \end{array} \right) \underbrace{\left(\begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -\sin\beta & \cos\beta \\ 0 & 0 & \cos\beta & \sin\beta \end{array} \right) \phi^0}_{\sqrt{2}(\mathrm{Re}\left\{H_1^0\right\},\mathrm{Re}\left\{H_2^0\right\},A^0_{\mathrm{tree}},G^0_{\mathrm{tree}})^T} \ , \tag{42}$$

where $\mathcal{O}_{3\times 3}$ gives the decomposition of the three physical mass eigenstates in terms of the intermediate basis $\tilde{\phi}^0 = \sqrt{2}(\mathrm{Re}\left\{H_1^0\right\}, \mathrm{Re}\left\{H_2^0\right\}, A^0_{\mathrm{tree}})^T$, with A^0_{tree} denoting the tree-level MSSM non-Goldstone pseudoscalar mass eigenstate. Note that a simple rotation by β suffices to translate between the two conventions, so whichever is the more practical can easily be used.

A second alternative convention, e.g. adopted by FeynHiggs [34, 49], is to also rotate the CP-even states by the angle α as part of the first step. In this case, our matrix S would be decomposed as:

$$S\phi^0 = \left(\begin{array}{cc} \mathcal{R}_{3\times 3} & \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \end{array} \right) \underbrace{\left(\begin{array}{cccc} -\sin\alpha & \cos\alpha & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 & 0 \\ 0 & 0 & -\sin\beta & \cos\beta \\ 0 & 0 & \cos\beta & \sin\beta \end{array} \right) \phi^0}_{(h^0,H^0,A^0,G^0)^T_{\mathrm{tree}}} \ , \tag{43}$$

with α defined as the mixing angle in the CP-even Higgs sector at tree-level and $\mathcal{R}_{3\times 3}$ giving the decomposition of the three physical mass eigenstates in terms of the intermediate basis $\tilde{\Phi}^0 = (h^0, H^0, A^0)^T_{\mathrm{tree}}$, that is in terms of the the tree-level mass eigenstates. In order to translate between S and $\mathcal{R}_{3\times 3}$, the tree-level angle α would thus also be needed. This should be given in the SLHA1 `BLOCK ALPHA`:

`BLOCK ALPHA`

CP conserved: α; precise definition up to spectrum calculator, see SLHA1.
CP violated: α_{tree}. Must be accompanied by the matrix S, as described above, in the blocks `CVHMIX` and `IMCVHMIX`.

For the three physical mass eigenstates (which are independent of convention) we associate the following PDG codes, in strict mass order regardless of CP-even/odd composition:

25	H_1^0	for the lightest Higgs boson,
35	H_2^0	for the second Higgs boson,
36	H_3^0	for the heaviest Higgs boson.

That is, even though the PDG reserves code 36 for the CP-odd state, we do not maintain such a labelling here, nor one that reduces to it. This means one does have to exercise some caution when taking the CP conserving limit.

For the neutralino and chargino mixing matrices, the default convention in SLHA1 (and hence for the CP conserving case) is that they be real symmetric matrices. One or more mass eigenvalues may then have an apparent negative sign, which can be removed by a phase transformation on $\tilde{\chi}_i$ as explained in SLHA1 [1]. When going to CPV, the reason for introducing the negative-mass convention in the first place, namely maintaining the mixing matrices strictly real, disappears. We therefore here take all masses real and positive, with N, U, and V complex. This does lead to a nominal dissimilarity with SLHA1 in the limit of vanishing CP violation, but we note that the explicit CPV switch in `MODSEL` can be used to decide unambiguously which convention to follow.

4 The Next-to-Minimal Supersymmetric SM

The first question to be addressed in defining universal conventions for the next-to-minimal supersymmetric standard model is just what field content and which couplings this name should apply to. The field content is already fairly well agreed upon; we shall here define the next-to-minimal case as having exactly the field content of the MSSM with the addition of one gauge singlet chiral superfield. As to couplings and parameterisations, several definitions exist in the literature [50–57]. Rather than adopting a particular one, or treating each special case separately, below we choose instead to work at the most general level. Any particular special case can then be obtained by setting different combinations of couplings to zero. For the time being, however, we do specialise to the SLHA1-like case without CP violation, R-parity violation, or flavour violation. Below, we shall use the acronym NMSSM for this class of models, but we emphasise that we understand it to relate to field content only, and not to the presence or absence of specific couplings.

4.1 Conventions

In addition to the MSSM terms, the most general CP conserving NMSSM superpotential is (extending the notation of SLHA1):

$$W_{NMSSM} = W_{MSSM} - \epsilon_{ab}\lambda S H_1^a H_2^b + \frac{1}{3}\kappa S^3 + \mu' S^2 + \xi_F S \ , \tag{44}$$

where W_{MSSM} is the MSSM superpotential, in the conventions of ref. [1, eq. (3)]. A non-zero λ in combination with a VEV $\langle S \rangle$ of the singlet generates a contribution to the effective μ term $\mu_{\mathrm{eff}} = \lambda \langle S \rangle + \mu$, where the MSSM μ term is normally assumed to be zero in NMSSM constructions, yielding $\mu_{\mathrm{eff}} = \lambda \langle S \rangle$. The sign of the λ term in eq. (44) coincides with the one in [16,33] where the Higgs doublet superfields appear in opposite order. The remaining terms represent a general cubic potential for the singlet; κ is dimensionless, μ' has dimension of mass, and ξ_F has dimension of mass squared. The soft SUSY-breaking terms relevant to the NMSSM are

$$V_{\mathrm{soft}} = V_{2,MSSM} + V_{3,MSSM} + m_{\mathrm{S}}^2|S|^2 + (-\epsilon_{ab}\lambda A_\lambda S H_1^a H_2^b + \frac{1}{3}\kappa A_\kappa S^3 + B'\mu' S^2 + \xi_S S + \mathrm{h.c.}) \ , \tag{45}$$

where $V_{i,MSSM}$ are the MSSM soft terms, in the conventions of ref. [1, eqs. (5) and (7)].

At tree level, there are thus 15 parameters (in addition to m_Z) which are relevant for the Higgs sector of the R-parity and CP-conserving NMSSM:

$$\tan\beta,\ \mu,\ m_{H_1}^2,\ m_{H_2}^2,\ m_3^2,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu',\ B',\ \xi_F,\ \xi_S,\ \lambda\langle S\rangle,\ m_S^2\ . \tag{46}$$

The minimization of the effective potential imposes 3 conditions on these parameters, such that only 12 of them can be considered independent. For the time being, we leave it up to each spectrum calculator to decide on which combinations to accept. For the purpose of this accord, we note only that to specify a general model exactly 12 parameters from eq. (46) should be provided in the input, including explicit zeroes for parameters desired "switched off". However, since $\mu = m_3^2 = \xi_F = \xi_S = \mu' = B' = 0$ in the majority of phenomenological constructions, for convenience we also allow for a six-parameter specification in terms of the reduced parameter list:

$$\tan\beta,\ m_{H_1}^2,\ m_{H_2}^2,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \lambda\langle S\rangle,\ m_S^2\ . \tag{47}$$

To summarize, in addition to m_Z, the input to the accord should contain either 12 parameters from the list given in eq. (46), including zeroes for parameters not present in the desired model, or it should contain 6 parameters from the list in eq. (47), in which case the remaining 6 "non-standard" parameters, will be assumed to be zero; in both cases the 3 unspecified parameters (as, e.g., $m_{H_1}^2$, $m_{H_2}^2$, and m_S^2) are assumed to be determined by the minimization of the effective potential.

4.2 Input/Output Blocks

Firstly, as described above in Section 2, `BLOCK MODSEL` should contain the switch 3 with value 1, corresponding to the choice of the NMSSM particle content.

Secondly, for the parameters that are also present in the MSSM, we re-use the corresponding SLHA1 entries. That is, m_Z should be given in `SMINPUTS` entry `4` and $m_{H_1}^2, m_{H_2}^2$ can be given in the `EXTPAR` entries `21` and `22`. $\tan\beta$ should either be given in `MINPAR` entry 3 (default) or `EXTPAR` entry 25 (user-defined input scale), as in SLHA1. If μ should be desired non-zero, it can be given in `EXTPAR` entry `23`. The corresponding soft parameter m_3^2 can be given in `EXTPAR` entry `24`, in the form $m_3^2/(\cos\beta\sin\beta)$, see [1]. The notation m_A^2 that was used for that parameter in the SLHA1 is no longer relevant in the NMSSM context, but by keeping the definition in terms of m_3^2 and $\cos\beta\sin\beta$ unchanged, we maintain an economical and straightforward correspondence between the two cases.

Further, new entries in `BLOCK EXTPAR` have been defined for the NMSSM specific input parameters, as follows. As in the SLHA1, these parameters are all given at the common scale M_{input}, which can either be left up to the spectrum calculator or given explicitly using `EXTPAR 0` (see [1]):

`BLOCK EXTPAR`

Input parameters specific to the NMSSM (i.e., in addition to the entries defined in [1])

61 : λ. Superpotential trilinear Higgs SH_2H_1 coupling.

62 : κ. Superpotential cubic S coupling.

63 : A_λ. Soft trilinear Higgs SH_2H_1 coupling.

64 : A_κ. Soft cubic S coupling.

65 : $\lambda \langle S \rangle$. Vacuum expectation value of the singlet (scaled by λ).

66 : ξ_F. Superpotential linear S coupling.

67 : ξ_S. Soft linear S coupling.

68 : μ'. Superpotential quadratic S coupling.

69 : B'. Soft quadratic S coupling.

70 : m_S^2. Soft singlet mass squared.

Important note: only 12 of the parameters listed in eq. (46) should be given as input at any one time (including explicit zeroes for parameters desired "switched off"), the remaining ones being determined by the minimization 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. (47) 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 λ, $\kappa \to 0$, $\langle S \rangle \to \infty$ with $\lambda \langle S \rangle$ fixed.

Proposed PDG codes for the new states in the NMSSM (to be used in the `BLOCK MASS` and the decay files, see also Appendix A) are

45	H_3^0	the third CP-even Higgs boson,
46	A_2^0	the second CP-odd Higgs boson,
1000045	$\tilde{\chi}_5^0$	the fifth neutralino.

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 $\overline{\mathrm{DR}}$ 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, but at least one should always be present. See corresponding entries in `EXTPAR` above for definitions.

1 : $\lambda(Q)^{\overline{\mathrm{DR}}}$.

2 : $\kappa(Q)^{\overline{\mathrm{DR}}}$.

3 : $A_\lambda(Q)^{\overline{\rm DR}}$.

4 : $A_\kappa(Q)^{\overline{\rm DR}}$.

5 : $\mu_{\rm eff}(Q)^{\overline{\rm DR}}$.

6 : $\xi_F(Q)^{\overline{\rm DR}}$.

7 : $\xi_S(Q)^{\overline{\rm DR}}$.

8 : $\mu'(Q)^{\overline{\rm DR}}$.

9 : $B'(Q)^{\overline{\rm DR}}$.

10 : $m_S^2(Q)$.

4.3 Particle Mixing

In the CP-conserving NMSSM, the diagonalisation of the 3×3 mass matrix in the CP-even Higgs sector can be performed by an orthogonal matrix S_{ij}. The (neutral) CP-even Higgs interaction eigenstates are numbered by $\phi^0 \equiv \sqrt{2}{\rm Re}\left\{(H_1^0, H_2^0, S)^T\right\}$. If Φ_i are the mass eigenstates (ordered in mass), the convention is $\Phi_i = S_{ij}\phi_j^0$. The elements of S_{ij} should be given in a `BLOCK NMHMIX`, in the same format as the mixing matrices in SLHA1.

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

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

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

$$-\bar\phi^{0T}\mathcal{M}^2_{\bar\phi^0}\bar\phi^0 = -\underbrace{\bar\phi^{0T}P^T}_{\bar\Phi^{0T}}\underbrace{P\mathcal{M}^2_{\bar\phi^0}P^T}_{{\rm diag}(m^2_{\bar\Phi^0})}\underbrace{P\bar\phi^0}_{\bar\Phi^0}\ , \tag{48}$$

where $\bar\Phi^0 \equiv (A_1^0, A_2^0)$ are the mass eigenstates ordered in mass and the Goldstone boson G^0 (the "3rd component") has been explicitly left out and the remaining 2 rows form a set of orthonormal vectors. Hence, $\bar\Phi_i = P_{ij}\bar\phi_j^0$. An updated version `NMSSMTools` [33] 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

$$\mathcal{L}^{\rm mass}_{\tilde\chi^0} = -\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 + {\rm h.c.}\ , \tag{49}$$

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 `NMNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{50}$$

where the 5 (2–component) neutralinos $\tilde{\chi}_i$ are defined such that the absolute value of their masses increase with i, cf. SLHA1 [1].

5 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 finalization 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

Listed in Tab. 2 are the PDG codes for Standard Model particles and extended Higgs sectors, including the NMSSM content. Tab. 3 defines the extra neutralino in the NMSSM and generalises the PDG codes for the MSSM spectrum of superpartners to apply to the flavour violating case. Note that these extensions are not officially endorsed by the PDG at this time — however, neither are they currently in use for anything else. Codes for other particles may be found in [46, chp. 33].

Table 2: Particle codes for the SM, MSSM, and NMSSM (see Tab. 3 for superpartners). Names in parentheses correspond to the MSSM labelling of states [1].

Code	Name	Code	Name	Code	Name
1	d	11	e^-	21	g
2	u	12	ν_e	22	γ
3	s	13	μ^-	23	Z^0
4	c	14	ν_μ	24	W^+
5	b	15	τ^-		
6	t	16	ν_τ		
25	H_1^0 (h^0)	35	H_2^0 (H^0)	45	H_3^0
36	A_1^0 (A^0)	46	A_2^0		
37	H^+	39	G (graviton)		

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Table 3: Superpartner particle codes for the NMSSM and for the general MSSM. Note that one mass eigenstate number is assigned for each of the sneutrinos $\tilde{\nu}_{1,2,3}$, corresponding to the neglect of tiny splittings between the pseudoscalar and scalar components.

NMSSM: SLHA1 codes [1] plus				1000045	$\tilde{\chi}_5^0$
General MSSM:					
1000001	$\tilde{d}_1$	1000011	$\tilde{e}_1$	1000021	$\tilde{g}$
1000002	$\tilde{u}_1$	1000012	$\tilde{\nu}_1$	1000022	$\tilde{\chi}_1^0$
1000003	$\tilde{d}_2$	1000013	$\tilde{e}_2$	1000023	$\tilde{\chi}_2^0$
1000004	$\tilde{u}_2$	1000014	$\tilde{\nu}_2$	1000024	$\tilde{\chi}_1^\pm$
1000005	$\tilde{d}_3$	1000015	$\tilde{e}_3$	1000025	$\tilde{\chi}_3^0$
1000006	$\tilde{u}_3$	1000016	$\tilde{\nu}_3$	1000035	$\tilde{\chi}_4^0$
2000001	$\tilde{d}_4$	2000011	$\tilde{e}_4$		
2000002	$\tilde{u}_4$			1000037	$\tilde{\chi}_2^\pm$
2000003	$\tilde{d}_5$	2000013	$\tilde{e}_5$	1000039	$\tilde{G}$ (gravitino)
2000004	$\tilde{u}_5$				
2000005	$\tilde{d}_6$	2000015	$\tilde{e}_6$		
2000006	$\tilde{u}_6$				

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