Fermilab FERMILAB-CONF-05-517-T

Status of the SUSY Les Houches Accord II Project

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Abstract

Supersymmetric (SUSY) spectrum generators, decay packages, Monte-Carlo programs, dark matter evaluators, and SUSY fitting programs often need to communicate in the process of an analysis. The SUSY Les Houches Accord provides a common interface that conveys spectral and decay information between the various packages. Here, we propose extensions of the conventions of the first SUSY Les Houches Accord to include various generalisations: violation of CP, R-parity and flavour as well as the simplest next-to-minimal supersymmetric standard model (NMSSM).

1. Introduction

Supersymmetric 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 both theorists and experimentalists 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, there is not one unique definition of supersymmetric theories which prevails. Rather, different conventions are adopted by different groups for different applications. In principle, this is not a problem. As long as everything is clearly and completely defined, a translation can always be made between two sets of conventions, call them A and B.

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 complete and unambiguous, hence reducing the problem of translating between conventions to a linear, rather than a quadratic, 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 online 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 [9–15]; 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 [16–22], 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 [23, 24] which fit MSSM models 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 [25]. We believe therefore, that the SLHA project has been useful, solving a problem that, for experts, is trivial but oft-encountered 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, 26–29] 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, flavour violation and CP-violating phases in the MSSM. We will also consider the next-to-minimal supersymmetric standard model (NMSSM).

For the MSSM, we will here restrict our attention to *either* CPV or RPV, but not both. For the NMSSM, we extend the SLHA1 mixing only to include the new states, with CP, R-parity and flavour still assumed conserved.

Since there is a clear motivation to make the interface as independent of programming languages, compilers, platforms etc, as possible, the SLHA1 is based on the transfer of three different ASCII files (or potentially a character string containing identical ASCII information, if CPU-time constraints are crucial): one for model input, one for spectrum calculator output, and one for decay calculator output. We believe that the advantage of platform, and indeed language independence, outweighs the disadvantage of codes using SLHA1 having to parse input. Indeed, there are tools to assist with this task [30].

Much 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 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.

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.
- `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 3.1 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 extra SUSY phases assumed zero.
- `2` : CP is violated. Completely general CP phases allowed. If flavour is not simultaneously violated (see below), imaginary parts corresponding to the entries in the SLHA1 block `EXTPAR` can be given in `IMEXTPAR` (together with the CKM phase). In the general case, imaginary parts of the blocks defined in Section 3.2 should be given, which supersede the corresponding entries in `EXTPAR`.

`6` : (Default=0) Flavour violation. Switches defined are:
- `0` : No (SUSY) flavour violation. This corresponds to the SLHA1.
- `1` : Flavour is violated. The blocks defined in Section 3.2 should be present.

3. General MSSM

3.1 R-Parity Violation

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

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

where $x, y, z = 1, \ldots, 3$ are fundamental SU(3)$_C$ indices and ϵ^{xyz} is the totally antisymmetric tensor in 3 dimensions with $\epsilon^{123} = +1$. In eq. (1), $\lambda_{ijk}, \lambda'_{ijk}$ 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 $i, j, k = 1, 2, 3$.

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

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

T, T' and T'' may often be written as

$$\frac{T_{ijk}}{\lambda_{ijk}} \equiv A_{\lambda,ijk}, \qquad \frac{T'_{ijk}}{\lambda_{ijk}} \equiv A_{\lambda',ijk}, \qquad \frac{T''_{ijk}}{\lambda_{ijk}} \equiv A_{\lambda'',ijk}; \qquad \text{no sum over } i,j, \quad (3)$$

The additional bilinear soft SUSY-breaking potential terms are

$$V_{RPV2} = -\epsilon_{ab}D_i\tilde{L}^a_{iL}H^b_2 + \tilde{L}^\dagger_{iaL}m^2_{\tilde{L}_iH_1}H^a_1 + \mathrm{h.c.} \quad (4)$$

and are all lepton number violating.

When lepton number is broken, 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

$$v = \sqrt{v_1^2 + v_2^2 + v_e^2 + v_\mu^2 + v_\tau^2}\,. \quad (5)$$

The addition of sneutrino VEVs allow various different definitions of $\tan\beta$, but we here choose to keep the SLHA1 definition $\tan\beta = v_2/v_1$. If one rotates the fields to a basis with zero sneutrino VEVs, one must take into account the effect upon $\tan\beta$.

3.11 Input/Output Blocks

For R-parity violating parameters and couplings, the input will occur in `BLOCK RV#IN`, where the '#' character should be replaced by the name of the relevant output block given below (thus, for example, `BLOCK RVLAMBDAIN` would be the input block for λ_{ijk}). Default inputs for all R-parity violating couplings are zero. The inputs are given at scale M_{input}, as described in SLHA1, and follow the output format given below, with the omission of `Q= ....` The dimensionless couplings $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ are included in the SLHA2 conventions as `BLOCK RVLAMBDA, RVLAMBDAP, RVLAMBDAPP 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 to the coupling itself. $A_{ijk}, A'_{ijk}, A''_{ijk}$ are included as `BLOCK RVA, RVAP, RVAPP Q= ...` in the same conventions as $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ (except for the fact that they are measured in GeV). The bilinear superpotential and soft SUSY-breaking terms κ_i, D_i, and $m^2_{\tilde{L}_iH_1}$ are contained in `BLOCK RVKAPPA, RVD, RVMLH1SQ Q= ...` respectively as

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

in FORTRAN format. Sneutrino VEV parameters v_i are given as `BLOCK SNVEV Q= ...` in an identical format, where the integer labels `1`=e, `2`=μ, `3`=τ respectively and the double

Table 1: Summary of R-parity violating SLHA2 data blocks. Input/output data are denoted by i for an integer, f for a floating point number. See text for precise definition of the format.

Input block	Output block	data
RVLAMBDAIN	RVLAMBDA	$i\ j\ k\ \lambda_{ijk}$
RVLAMBDAPIN	RVLAMBDAP	$i\ j\ k\ \lambda'_{ijk}$
RVLAMBDAPPIN	RVLAMBDAPP	$i\ j\ k\ \lambda''_{ijk}$
RVKAPPAIN	RVKAPPA	$i\ \kappa_i$
RVAIN	RVA	$i\ j\ k\ A_{ijk}$
RVAPIN	RVAP	$i\ j\ k\ A'_{ijk}$
RVAPPIN	RVAPP	$i\ j\ k\ A''_{ijk}$
RVDIN	RVD	$i\ D_i$
RVSNVEVIN	RVSNVEV	$i\ v_i$
RVMLH1SQIN	RVMLH1SQ	$i\ m^2_{\tilde{L}_i H_1}$

precision number gives the numerical value of the VEV in GeV. The input and output blocks for R-parity violating couplings are summarised in Table 1.

As for the R-conserving MSSM, the bilinear terms (both SUSY breaking and SUSY respecting ones, and 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 input parameters in Tab. 1 can be given simultaneously. At the present time we are not able to present an agreement on a specific convention/procedure here, and hence restrict ourselves to merely noting the existence of the problem. An elaboration will follow in the near future.

3.12 Particle Mixing

The mixing of particles can change when L is violated. Phenomenological constraints can often mean 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 neutralinos. This requires a change in the definition of the 4 by 4 neutralino mixing matrix N to a 7 by 7 matrix. The Lagrangian contains the (symmetric) neutralino mass matrix as

$$\mathcal{L}^{\mathrm{mass}}_{\tilde{\chi}^0} = -\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 + \mathrm{h.c.}\ , \tag{6}$$

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 by 7 neutralino mixing matrix N (block RVNMIX), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{7}$$

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 ν_{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 $\tilde{\chi}_i^0$ 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

$$\mathcal{L}^{\mathrm{mass}}_{\tilde{\chi}^+} = -\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ + \mathrm{h.c.}\ , \tag{8}$$

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 $\tilde{w}^\pm = (\tilde{w}^1 \mp \tilde{w}^2)/\sqrt{2}$, and the primed fields are in the weak interaction basis.

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

$$-\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ = -\frac{1}{2}\underbrace{\tilde{\psi}^{-T}U^T}_{\tilde{\chi}^{-T}}\underbrace{U^*\mathcal{M}_{\tilde{\psi}^+}V^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^+})}\underbrace{V\tilde{\psi}^+}_{\tilde{\chi}^+}\ , \tag{9}$$

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, V are be 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 $\phi_i^0 \equiv \sqrt{2}\mathrm{Re}\left\{(H_1^0, H_2^0, \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T\right\}$

$$\mathcal{L} = -\frac{1}{2}\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 \tag{10}$$

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

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

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}\aleph^T}_{\Phi^{0T}}\underbrace{\aleph^*\mathcal{M}^2_{\phi^0}\aleph^\dagger}_{\mathrm{diag}(m^2_{\Phi^0})}\underbrace{\aleph\phi^0}_{\Phi^0}\ , \tag{11}$$

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 labeled the states by what they should tend to in the R-parity conserving limit, and that this ordering is still under debate, hence should be considered preliminary for the time being).

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

$$\mathcal{L} = -\frac{1}{2}\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 \tag{12}$$

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

$$-\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 = -\underbrace{\bar{\phi}^{0T}\bar{\aleph}^T}_{\bar{\Phi}^{0T}}\underbrace{\bar{\aleph}^*\mathcal{M}^2_{\bar{\phi}^0}\bar{\aleph}^\dagger}_{\mathrm{diag}(m^2_{\bar{\Phi}^0})}\underbrace{\bar{\aleph}\bar{\phi}^0}_{\bar{\Phi}^0}\,, \tag{13}$$

where $\bar{\Phi}^0 \equiv (G^0, A^0, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$ are the mass eigenstates. G^0 denotes the Goldstone boson. As for the CP-even sector this specific choice of basis ordering is still preliminary.

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 by 8 mass squared matrix $\mathcal{M}^2_{\phi^\pm}$ by an 8 by 8 unitary matrix C (block `RVLMIX`):

$$\mathcal{L} = -\underbrace{(h_1^-, h_2^{+*}, \tilde{e}_{L_i}, \tilde{e}_{R_j})C^T}_{(G^-, H^-, \tilde{e}_\alpha)}\underbrace{C^*\mathcal{M}^2_{\phi^\pm}C^T}_{\mathrm{diag}(\mathcal{M}^2_{\Phi^\pm})}C^*\begin{pmatrix} h_1^{-*} \\ h_2^+ \\ \tilde{e}^*_{L_k} \\ \tilde{e}^*_{R_l}\end{pmatrix} \tag{14}$$

where in eq. (14), $i, j, k, l \in \{1, 2, 3\}$, $\alpha, \beta \in \{1, \ldots, 6\}$, $G^\pm$ are the Goldstone bosons and the non-braced product on the right hand side is equal to $(G^+, H^+, \tilde{e}_\beta)$.

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 3.2 (along with other forms of flavour mixing).

3.2 Flavour Violation

3.21 The Super CKM basis

Within the minimal supersymmetric standard model (MSSM), there are two new sources of flavour changing neutral currents (FCNC), namely 1) contributions arising from quark mixing as in the SM and 2) generic supersymmetric contributions arising through the squark mixing. These generic new sources of flavour violation are a direct consequence of a possible misalignment of quarks and squarks. 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 [31] 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 (see also Sect.III in [32])

$$D^o \;=\; V_d\,D\,, \qquad U^o \;=\; V_u\,U\,, \qquad \bar{D}^o = \;U_d^*\,\bar{D}\,, \qquad \bar{U}^o = \;U_u^*\,\bar{U}\,, \tag{15}$$

of all matter superfields in the superpotential

$$W \;=\; \epsilon_{ab}\left[(Y_D)_{ij}\,H_1^a Q_i^{b\,o}\bar{D}_j^{\,o} + (Y_U)_{ij}\,H_2^b Q_i^{a\,o}\bar{U}_j^{\,o} - \mu H_1^a H_2^b\,,\right] \tag{16}$$

brings fermions from the current eigenstate basis $\{d^o_L, u^o_L, d^o_R, u^o_R\}$ to their mass eigenstate basis $\{d_L, u_L, d_R, u_R\}$:

$$d^o_L = V_d d_L\,, \qquad u^o_L = V_u u_L\,, \qquad d^o_R = U_d d_R\,, \qquad u^o_R = U_u u_R\,, \tag{17}$$

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 $\hat{Y}_U$:

$$(\hat{Y}_D)_{ii} = (U^\dagger_d Y_D V_d)_{ii} = \sqrt{2}\frac{m_{d\,i}}{v_1}\,, \qquad (\hat{Y}_U)_{ii} = (U^\dagger_u Y_U V_u)_{ii} = \sqrt{2}\frac{m_{u\,i}}{v_2}\,. \tag{18}$$

Tree-level mixing terms among quarks of different generations are due to the misalignment of V_d and V_u which can be expressed via the CKM matrix $V_{\rm CKM} = V^\dagger_u V_d$ [33, 34]; all the vertices $\bar{u}_{L\,i}$–$d_{L\,j}$–W^+ and $\bar{u}_{L\,i}$–$d_{R\,j}$–H^+, $\bar{u}_{R\,i}$–$d_{L\,j}$–H^+ $(i, j = 1, 2, 3)$ are weighted by the elements of the CKM matrix. This is also true for the supersymmetric counterparts of these vertices, in the limit of unbroken supersymmetry.

In this basis the squark mass matrices are given as:

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} V_{\rm CKM}\hat{m}^2_{\tilde{Q}}V^\dagger_{\rm CKM} + m^2_u + D_{u\,LL} & v_2\hat{T}_U - \mu^* m_u \cot\beta \\ v_2\hat{T}^\dagger_U - \mu m_u \cot\beta & \hat{m}^2_{\tilde{u}} + m^2_u + D_{u\,RR} \end{pmatrix}\,, \tag{19}$$

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_{\tilde{Q}} + m^2_d + D_{d\,LL} & v_1\hat{T}_D - \mu^* m_d \tan\beta \\ v_1\hat{T}^\dagger_D - \mu m_d \tan\beta & \hat{m}^2_{\tilde{d}} + m^2_d + D_{d\,RR} \end{pmatrix}\,. \tag{20}$$

where we have defined the matrix

$$\hat{m}^2_Q \equiv V^\dagger_d m^2_{\tilde{Q}} V_d \tag{21}$$

where $m^2_{\tilde{Q}}$ is given in the electroweak basis of [1]. 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:

$$D_{f\,LL,RR} = \cos 2\beta\, m^2_Z \left(T^3_f - Q_f \sin^2\theta_W\right) \mathbb{1}_3\,, \tag{22}$$

which are also flavour diagonal.

3.22 *Lepton Mixing*

The authors regret that there is not yet a final agreement on conventions for the charged and neutral lepton sectors in the presence of flavour violation. We do not, however, perceive this as a large problem, and expect to remedy this omission in the near future.

3.23 *Explicit proposal for SLHA*

We take eq. (18) as the starting point. In view of the fact that higher order corrections are included, one has to be more precise in the definition. In the SLHA [1], we have agreed to use $\overline{\rm DR}$ parameters. We thus propose to define the super-CKM basis in the output spectrum file as the one, where the u- and d-quark Yukawa couplings, given in the $\overline{\rm DR}$ scheme, are diagonal. The masses and the VEVs in eq. (18) must thus be the running ones in the $\overline{\rm DR}$ scheme.

For the explicit implementation one has to give, thus, the following information:

- $(\hat{Y}_U)_{ii}^{\overline{\rm DR}}$, $(\hat{Y}_D)_{ii}^{\overline{\rm DR}}$: the diagonal $\overline{\rm DR}$ Yukawas in the super-CKM basis, with $\hat{Y}$ defined by eq. (18), at the scale 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 rotation.
- $V_{\rm CKM}$: the $\overline{\rm DR}$ CKM matrix at the scale Q, in the PDG parametrisation [35] (exact to all orders). Will be given in the new block `VCKM Q=...`, with entries:

  `1` : θ_{12} (the Cabibbo angle)

  `2` : θ_{23}

  `3` : θ_{13}

  `4` : δ_{13}

  Note that the three θ angles can all be made to lie in the first quadrant by appropriate rotations of the quark phases.
- $(\hat{m}^2_{\tilde{Q}})_{ij}^{\overline{\rm DR}}$, $(\hat{m}^2_{\tilde{u}})_{ij}^{\overline{\rm DR}}$, $(\hat{m}^2_{\tilde{d}})_{ij}^{\overline{\rm DR}}$: the squark soft SUSY-breaking masses in the super-CKM basis, with $\hat{m}_Q$ defined by eq. (21). Will be given in the new blocks `MSQ Q=...`, `MSU Q=...`, `MSD Q=...`
- $(\hat{T}_U)_{ij}^{\overline{\rm DR}}$ and $(\hat{T}_D)_{ij}^{\overline{\rm DR}}$: The squark soft SUSY-breaking trilinear couplings in the super-CKM basis, see [1].
- The squark masses and mixing matrices should be defined as in the existing SLHA1, e.g. extending the $\tilde{t}$ and $\tilde{b}$ mixing matrices to the 6×6 case. Will be given in the new blocks `USQMIX` and `DSQMIX`, respectively.

A further question is how the SM in the model input file shall be defined. Here we propose to take the PDG definition: the light quark masses $m_{u,d,s}$ are given at 2 GeV, $m_c(m_c)^{\overline{\rm MS}}$, $m_b(m_b)^{\overline{\rm MS}}$ and $m_t^{\rm on-shell}$. The latter two quantities are already in the SLHA1. The others can easily be added to the block `SMINPUTS`.

Finally, we need of course the input CKM matrix. Present CKM studies do not define precisely the CKM matrix because 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. Analogously to the RPV parameters, we specify the input CKM matrix in a separate input block `VCKMINPUTS`, with the same format as the output block `VCKM` above.

3.3 CP Violation

When adding CP violation to mixing matrices and MSSM parameters, 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.

The Higgs sector mixing changes when CP symmetry is broken, since the CP-even and CP-odd Higgs states mix. Writing the neutral scalars as $\phi_i^0 \equiv \sqrt{2}({\rm Re}\left\{H_1^0\right\}, {\rm Re}\left\{H_2^0\right\}, {\rm Im}\left\{H_1^0\right\},$

$\mathrm{Im}\left\{H_2^0\right\})$ we define the unitary 4 by 4 mixing matrix S (blocks `CVHMIX` and `IMCVHMIX`) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}S^T}_{\Phi^{0T}}\underbrace{S^*\mathcal{M}^2_{\phi^0}S^\dagger}_{\mathrm{diag}(m^2_{\Phi^0})}\underbrace{S\phi^0}_{\Phi^0}\ , \tag{23}$$

where $\Phi^0 \equiv (G^0, H_1^0, H_2^0, H_3^0)$ are the mass eigenstates. G^0 denotes the Goldstone boson. We associate the following PDG codes with these states, in strict mass order *regardless* of CP-even/odd composition: H_1^0: 25, H_2^0: 35, H_3^0: 36. That is, even though the PDG reserves code 36 for the CP-odd state, we do not maintain such a labeling here, nor one that reduces to it. This means one does have to exercise some caution when taking the CP conserving limit.

Whether and how to include the mixing in the charged Higgs sector (specifying the make-up of (G^+, H^+) in terms of their (H_1^+, H_2^+) components) has not yet been agreed upon.

4. The Next-to-Minimal Supersymmetric Standard Model

4.1 Conventions

In the notation of SLHA1 the conventions for the Lagrangian of the CP conserving NMSSM are as follows: The NMSSM specific terms in the superpotential W are given by

$$W = -\epsilon_{ab}\lambda S H_1^a H_2^b + \frac{1}{3}\kappa S^3\ . \tag{24}$$

Hence a VEV $\langle S\rangle$ of the singlet generates an effective μ term $\mu_{\mathrm{eff}} = \lambda\langle S\rangle$. (Note that the sign of the λ term in eq. (24) coincides with the one in [15, 29] where the Higgs doublet superfields appear in opposite order.) The new soft SUSY-breaking terms are

$$V_{\mathrm{soft}} = m_{\mathrm{S}}^2|S|^2 + \left(-\epsilon_{ab}\lambda A_\lambda S H_1^a H_2^b + \frac{1}{3}\kappa A_\kappa S^3 + \mathrm{h.c.}\right)\ . \tag{25}$$

The input parameters relevant for the Higgs sector of the NMSSM (at tree level) are

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta\ =\ \langle H_2\rangle / \langle H_1\rangle\ ,\ \mu_{\mathrm{eff}} = \lambda\langle S\rangle\ . \tag{26}$$

One can choose sign conventions such that λ and $\tan\beta$ are positive, while κ, A_λ, A_κ and μ_{eff} must be allowed to have either sign.

4.2 Input/Output Blocks

The `BLOCK MODSEL` should contain the switch 3 (corresponding to the choice of the model) with value 1, as attributed to the NMSSM already in SLHA1. The `BLOCK EXTPAR` contains the NMSSM specific SUSY and soft SUSY-breaking parameters. The new entries are:

61	for λ
62	for κ
63	for A_λ
64	for A_κ
65	for $\mu_{\mathrm{eff}} = \lambda\langle S\rangle$
65	for ξ

Note that the meaning of the switch 23 (the MSSM μ parameter) is maintained which allows, in principle, for non zero values for both μ and $\mu_{\rm eff}$. The reason for choosing $\mu_{\rm eff}$ 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 Section 5.) are

45	for the third CP-even Higgs boson,
46	for the second CP-odd Higgs boson,
1000045	for the fifth neutralino.

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 weak eigenstates are numbered by $\phi^0_i \equiv \sqrt{2}\mathrm{Re}\left\{(H^0_1, H^0_2, S)^T\right\}$. If Φ_i are the mass eigenstates (ordered in mass), the convention is $\Phi_i = S_{ij}\phi^0_j$. 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 $h_3 \sim S_R$) the elements of the first 2×2 sub-matrix of S_{ij} are related to the MSSM angle α as

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

In the CP-odd sector the weak eigenstates are $\bar\phi^0_i \equiv \sqrt{2}\mathrm{Im}\left\{(H^0_1, H^0_2, S)^T\right\}$. We define the orthogonal 3 by 3 mixing matrix P (block `NMAMIX`) by

$$
-\bar\phi^{0T}\mathcal{M}^2_{\bar\phi^0}\bar\phi^0 = -\underbrace{\bar\phi^{0T}P^T}_{\bar\Phi^{0T}}\underbrace{P\mathcal{M}^2_{\bar\phi^0}P^T}_{\mathrm{diag}(m^2_{\bar\Phi^0})}\underbrace{P\bar\phi^0}_{\bar\Phi^0}\,, \tag{27}
$$

where $\bar\Phi^0 \equiv (G^0, A^0_1, A^0_2)$ are the mass eigenstates ordered in mass. G^0 denotes the Goldstone boson. Hence, $\bar\Phi_i = P_{ij}\bar\phi^0_j$. (Note that some of the P_{ij} are redundant since $P_{11} = \cos\beta$, $P_{12} = -\sin\beta$, $P_{13} = 0$, and the present convention does not quite coincide with the one in [15] where redundant information has been omitted. An updated version of [29] will include the SLHA2 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 by 4 neutralino mixing matrix N to a 5 by 5 matrix. The Lagrangian contains the (symmetric) neutralino mass matrix as

$$
\mathcal{L}^{\rm mass}_{\tilde\chi^0} = -\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 + \mathrm{h.c.}\,, \tag{28}
$$

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 by 5 neutralino mixing matrix N (block `NMNMIX`), such that:

$$
-\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 = -\frac{1}{2}\underbrace{\tilde\psi^{0T}N^T}_{\tilde\chi^{0T}}\underbrace{N^*\mathcal{M}_{\tilde\psi^0}N^\dagger}_{\mathrm{diag}(m_{\tilde\chi^0})}\underbrace{N\tilde\psi^0}_{\tilde\chi^0}\,, \tag{29}
$$

where the 5 (2–component) neutralinos $\tilde\chi_i$ are defined such that their absolute masses (which are not necessarily positive) increase with i, cf. SLHA1.

Table 2: SM fundamental particle codes, with extended Higgs sector. Names in parentheses correspond to the MSSM labeling of states.

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)		

5. PDG Codes and Extensions

Listed in Table 2 are the PDG codes for extended Higgs sectors and Standard Model particles, extended to include the NMSSM Higgs sector. Table 3 contains the codes for the spectrum of superpartners, extended to include the extra NMSSM neutralino as well as a possible mass splitting between the scalar and pseudoscalar sneutrinos. 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 [35, chp. 33].

6. Conclusion and Outlook

This is a preliminary proof-of-concept, containing a summary of proposals and agreements reached so far, for extensions to the SUSY Les Houches Accord, relevant for CP violation, R-parity violation, flavour violation, and the NMSSM. These proposals are not yet final, but should serve as useful starting points. A complete writeup, containing the finalised agreements, will follow at a later date. Several other aspects, which were not entered into here, are foreseen to also be included in the long writeup, most importantly agreements on a way of parametrising theoretical uncertainties, on passing inclusive cross section information, and on a few other minor extensions of SLHA1.

Acknowledgments

The majority of the agreements and conventions contained herein resulted from the workshops "Physics at TeV Colliders", Les Houches, France, 2005, and "Flavour in the Era of the LHC", CERN, 2005–2006. B.C.A. and W.P. would like to thank enTapP 2005, Valencia, Spain, 2005 for hospitality offered during working discussions of this project. This work has been partially supported by PPARC and by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy. W.P. is supported by a MCyT Ramon y Cajal contract.

Table 3: Sparticle codes in the extended MSSM. Note that two mass eigenstate numbers are assigned for each of the sneutrinos $\tilde{\nu}_{iL}$, corresponding to the possibility of a mass splitting between the pseudoscalar and scalar components.

Code	Name	Code	Name	Code	Name
1000001	$\tilde{d}_L$	1000011	$\tilde{e}_L$	1000021	$\tilde{g}$
1000002	$\tilde{u}_L$	1000012	$\tilde{\nu}_{1\mathrm{e}L}$	1000022	χ_1^0
1000003	$\tilde{s}_L$	1000013	$\tilde{\mu}_L$	1000023	χ_2^0
1000004	$\tilde{c}_L$	1000014	$\tilde{\nu}_{1\mu L}$	1000024	$\chi_1^\pm$
1000005	$\tilde{b}_1$	1000015	$\tilde{\tau}_1$	1000025	χ_3^0
1000006	$\tilde{t}_1$	1000016	$\tilde{\nu}_{1\tau L}$	1000035	χ_4^0
		1000017	$\tilde{\nu}_{2\mathrm{e}L}$	1000045	χ_5^0
		1000018	$\tilde{\nu}_{2\mu L}$	1000037	$\chi_2^\pm$
		1000019	$\tilde{\nu}_{2\tau L}$	1000039	$\tilde{G}$ (gravitino)
2000001	$\tilde{d}_R$	2000011	$\tilde{e}_R$		
2000002	$\tilde{u}_R$				
2000003	$\tilde{s}_R$	2000013	$\tilde{\mu}_R$		
2000004	$\tilde{c}_R$				
2000005	$\tilde{b}_2$	2000015	$\tilde{\tau}_2$		
2000006	$\tilde{t}_2$				

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