# Part II
# The SUSY Les Houches Accord Project

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**Abstract**
An accord specifying a unique set of conventions for supersymmetric extensions of the Standard Model together with generic file structures for (1) supersymmetric model specifications and input parameters, (2) electroweak scale supersymmetric mass and coupling spectra, and (3) decay tables is defined, to provide a universal interface between spectrum calculation programs, decay packages, and high energy physics event generators.

## 1. INTRODUCTION

An increasing number of advanced programs for the calculation of the supersymmetric (SUSY) mass and coupling spectrum are appearing [1–5] in step with the more and more refined approaches which are taken in the literature. Furthermore, these programs are often interfaced to specialized decay packages, [6–8], relic density calculations [9, 10], and (parton–level) event generators [11–18], in themselves fields with a proliferation of philosophies and, consequentially, programs.

At present, a small number of specialized interfaces exist between various codes. Such tailor-made interfaces are not easily generalized and are time-consuming to construct and test for each specific implementation. A universal interface would clearly be an advantage here. However, since the codes involved are not all written in the same programming language, the question naturally arises how to make such an interface work across languages. At this point, we deem an inter–language runtime linking solution too fragile to be set loose among the particle physics community. Instead, we advocate a less elegant but more robust solution, exchanging information between FORTRAN and C(++) codes via three ASCII files, one for model input, one for model input plus spectrum output, and one for model input plus spectrum output plus decay information. The detailed structure of these files is described in [27]. Briefly stated, the purpose of this Accord is thus the following:

1. To present a set of generic definitions for an input/output file structure which provides a universal framework for interfacing SUSY spectrum calculation programs.
2. To present a generic file structure for the transfer of decay information between decay calculation packages and event generators.

Note that different codes may have different implementations of how SUSY Les Houches Accord (SLHA) input/output is *technically* achieved. The details of how to 'switch on' SLHA input/output with a particular program should be described in the manual of that program and are not covered here.

## 2. CONVENTIONS

One aspect of supersymmetric calculations that has often given rise to confusion and consequent inconsistencies in the past is the multitude of ways in which the parameters can be, and are being, defined. Hoping to minimize both the extent and impact of such confusion, we have chosen to adopt one specific set of self-consistent conventions for the parameters appearing in this Accord. These conventions are described in the following subsections. As yet, we only consider R–parity and CP conserving scenarios, with the particle spectrum of the MSSM.

## 2.1 STANDARD MODEL PARAMETERS

In general, the SUSY spectrum calculations impose low–scale boundary conditions on the renormalization group equation (RGE) flows to ensure that the theory gives correct predictions for low–energy observables. Thus, experimental measurements of masses and coupling constants at the electroweak scale enter as inputs to the spectrum calculators.

In this Accord, we choose a specific set of low–scale input parameters, letting the electroweak sector be fixed by

1. The conventional electromagnetic coupling at the $Z$ pole, $\alpha_{\mathrm{em}}(m_Z)$:

$$\alpha_{\mathrm{em}}(m_Z) = \frac{\alpha}{1 - \Delta\alpha_{\mathrm{lep}}(m_Z) - \Delta\alpha^{(5)}_{\mathrm{had}}(m_Z) - \Delta\alpha_{\mathrm{top}}(m_Z)}, \tag{1}$$

   where $\alpha$ is the fine structure constant, $\Delta\alpha_{\mathrm{lep}}(m_Z)$ and $\Delta\alpha_{\mathrm{top}}(m_Z)$ represent the quantum corrections coming from leptons and top quarks, respectively (see [19, 20]), and $\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z)$ is the contribution from the five light quark flavours (see e.g. [21]).
2. The Fermi constant determined from muon decay, $G_F$.
3. The $Z$ boson pole mass, $m_Z$.

All other electroweak parameters, such as $m_W$ and $\sin^2\theta_W$, should be derived from these inputs if needed.

The strong interaction strength is fixed by $\alpha_s(m_Z)^{\overline{\mathrm{MS}}}$ (five–flavour), and the third generation Yukawa couplings are obtained from the top and tau pole masses, and from $m_b(m_b)^{\overline{\mathrm{MS}}}$, see [21]. The reason we take $m_b(m_b)^{\overline{\mathrm{MS}}}$ rather than a pole mass definition is that the latter suffers from infra-red sensitivity problems, hence the former is the quantity which can be most accurately related to experimental measurements. If required, relations between running and pole quark masses may be found in [22, 23].

It is also important to note that all the parameters mentioned here should be the 'ordinary' ones obtained from SM fits, i.e. with no SUSY corrections included. The spectrum calculators themselves are then assumed to convert these parameters into ones appropriate to an MSSM framework.

Finally, while we assume $\overline{\mathrm{MS}}$ running quantities with the SM as the underlying theory as input, all running parameters in the *output* of the spectrum calculations are defined in the modified dimensional reduction ($\overline{\mathrm{DR}}$) scheme [24–26], with different spectrum calculators possibly using different prescriptions for the underlying effective field content. More on this in section 2.5.

## 2.2 SUPERSYMMETRIC PARAMETERS

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

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

Then, the superpotential (omitting RPV terms) is written as

$$W = \epsilon_{ab}\left[(Y_E)_{ij} H_1^a L_i^b \bar{E}_j + (Y_D)_{ij} H_1^a Q_i^b \bar{D}_j + (Y_U)_{ij} H_2^b Q_i^a \bar{U}_j - \mu H_1^a H_2^b\right]. \tag{3}$$

We denote $SU(2)_L$ fundamental representation indices by $a, b = 1, 2$ and generation indices by $i, j = 1, 2, 3$. Colour indices are everywhere suppressed. $\epsilon_{ab}$ is the antisymmetric tensor, with $\epsilon_{12} = \epsilon^{12} = 1$. Lastly, we will use $t, b, \tau$ to denote the $i = j = 3$ entries of mass or coupling matrices (top, bottom and tau).

The Higgs vacuum expectation values (VEVs) are $\langle H_i^0 \rangle = v_i/\sqrt{2}$, and $\tan\beta = v_2/v_1$. We also use the notation $v = \sqrt{v_1^2 + v_2^2}$. Different choices of renormalization scheme and scale are possible for defining $\tan\beta$. For the input to the spectrum calculators, we adopt by default the commonly encountered definition

$$\tan\beta(m_Z)^{\overline{\mathrm{DR}}}, \tag{4}$$

i.e. the $\tan\beta$ appearing in the input is defined as a $\overline{\mathrm{DR}}$ running parameter given at the scale $m_Z$. However, an option is included to allow $\tan\beta$ to be input at a different scale, $\tan\beta(M_{\mathrm{input}} \neq m_Z)^{\overline{\mathrm{DR}}}$. Lastly, the spectrum calculator may be instructed to write out one or several values of $\tan\beta(Q)^{\overline{\mathrm{DR}}}$ at various scales $Q_i$, see [27].

Finally, the MSSM $\overline{\mathrm{DR}}$ gauge couplings are: $g'$ (hypercharge gauge coupling in Standard Model normalization), $g$ ($SU(2)_L$ gauge coupling) and $g_3$ (QCD gauge coupling).

### 2.3 SUSY BREAKING PARAMETERS

We now tabulate the notation of the soft SUSY breaking parameters. The trilinear scalar interaction potential is

$$V_3 = \epsilon_{ab}\sum_{ij}\left[(T_E)_{ij}H_1^a\tilde{L}_{i_L}^b\tilde{e}_{j_R}^* + (T_D)_{ij}H_1^a\tilde{Q}_{i_L}^b\tilde{d}_{j_R}^* + (T_U)_{ij}H_2^b\tilde{Q}_{i_L}^a\tilde{u}_{j_R}^*\right] + \mathrm{h.c.}\,, \tag{5}$$

where fields with a tilde are the scalar components of the superfield with the identical capital letter. In the literature the T matrices are often decomposed as

$$\frac{T_{ij}}{Y_{ij}} = A_{ij} \quad ;(\text{no sum over } i,j)\,, \tag{6}$$

where $Y$ are the Yukawa matrices and A the soft supersymmetry breaking trilinear couplings.

The scalar bilinear SUSY breaking terms are contained in the potential

$$\begin{aligned} V_2 \;=\; & m_{H_1}^2 H_{1a}^* H_1^a + m_{H_2}^2 H_{2a}^* H_2^a + \tilde{Q}_{iLa}^*(m_{\tilde{Q}}^2)_{ij}\tilde{Q}_{jL}^a + \tilde{L}_{iLa}^*(m_{\tilde{L}}^2)_{ij}\tilde{L}_{jL}^a + \\ & \tilde{u}_{iR}(m_{\tilde{u}}^2)_{ij}\tilde{u}_{jR}^* + \tilde{d}_{iR}(m_{\tilde{d}}^2)_{ij}\tilde{d}_{jR}^* + \tilde{e}_{iR}(m_{\tilde{e}}^2)_{ij}\tilde{e}_{jR}^* - (m_3^2\epsilon_{ab}H_1^aH_2^b + \mathrm{h.c.})\,. \end{aligned} \tag{7}$$

Instead of $m_3^2$ itself, we use the more convenient parameter $m_A$, defined by:

$$m_A^2 = \frac{m_3^2}{\sin\beta\cos\beta}, \tag{8}$$

which is identical to the pseudoscalar Higgs mass at tree level in our conventions.

Writing the bino as $\tilde{b}$, the unbroken $SU(2)_L$ gauginos as $\tilde{w}^{A=1,2,3}$, and the gluinos as $\tilde{g}^{X=1\ldots8}$, the gaugino mass terms are contained in the Lagrangian

$$\mathcal{L}_G = \frac{1}{2}\left(M_1\tilde{b}\tilde{b} + M_2\tilde{w}^A\tilde{w}^A + M_3\tilde{g}^X\tilde{g}^X\right) + \mathrm{h.c.}\,. \tag{9}$$

### 2.4 MIXING MATRICES

In the following, we describe in detail our conventions for neutralino, chargino, sfermion, and Higgs mixing. Essentially all SUSY spectrum calculators on the market today work with mass matrices which include higher–order corrections. Consequentially, a formal depencence on the renormalization scheme and scale, and on the external momenta appearing in the corrections, enters the definition of the corresponding mixing matrices. Since, at the moment, no consensus exists on the most convenient definition to use here, the mixing matrices should be thought of as 'best choice' solutions, at the discretion of each spectrum calculator. For example, one program may output on–shell parameters at vanishing external momenta in these blocks while another may be using $\overline{\mathrm{DR}}$ definitions at certain 'characteristic' scales. For details on specific prescriptions, the manual of the particular spectrum calculator should be consulted.

Nonetheless, for obtaining loop–improved tree–level results, these parameters can normally be used as is. They can also be used for consistent cross section and decay width calculations at higher orders, but then the renormalization prescription employed by the spectrum calculator must match or be consistently matched to that of the intended higher order calculation.

Finally, different spectrum calculators may disagree on the overall sign of one or more rows in a mixing matrix, owing to different diagonalization algorithms. Such differences do not lead to inconsistencies, only the relative sign between entries on the same row is physically significant, for processes with interfering amplitudes.

### *2.41 NEUTRALINO MIXING*

The Lagrangian contains the (symmetric) neutralino mass matrix as

$$\mathcal{L}^{\mathrm{mass}}_{\tilde\chi^0} = -\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 + \mathrm{h.c.}\ , \tag{10}$$

in the basis of 2–component spinors $\tilde\psi^0 = (-i\tilde b, -i\tilde w^3, \tilde h_1, \tilde h_2)^T$. We define the unitary 4 by 4 neutralino mixing matrix $N$, such that:

$$-\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 = -\frac{1}{2}\underbrace{\tilde\psi^{0T}N^T}_{\tilde\chi^{0T}}\underbrace{N^*\mathcal{M}_{\tilde\psi^0}N^\dagger}_{\mathrm{diag}(m_{\tilde\chi^0})}\underbrace{N\tilde\psi^0}_{\tilde\chi^0}\ , \tag{11}$$

where the (2–component) neutralinos $\tilde\chi^0_i$ are defined such that their absolute masses increase with increasing $i$. Generically, the resulting mixing matrix $N$ may yield complex entries in the mass matrix, $\mathrm{diag}(m_{\tilde\chi^0})_i = m_{\tilde\chi^0_i}e^{i\varphi_i}$. If so, we absorb the phase into the definition of the corresponding eigenvector, $\tilde\chi^0_i \to \tilde\chi^0_i e^{i\varphi_i/2}$, making the mass matrix strictly real:

$$\mathrm{diag}(m_{\tilde\chi^0}) \equiv \left[N^*\mathcal{M}_{\tilde\psi^0}N^\dagger\right]_{ij} = m_{\tilde\chi^0_i}\delta_{ij}. \tag{12}$$

Note, however, that a special case occurs when CP violation is absent and one or more of the $m_{\tilde\chi^0_i}$ turn out to be negative. In this case, we allow for maintaining a strictly real mixing matrix $N$, instead writing the *signed* mass eigenvalues in the output. Thus, a negative $m_{\tilde\chi^0_i}$ in the output implies that the physical field is obtained by the rotation $\tilde\chi^0_i \to \tilde\chi^0_i e^{i\pi_i/2}$.

### *2.42 CHARGINO MIXING*

We make the identification $\tilde w^\pm = (\tilde w^1 \mp i\tilde w^2)/\sqrt{2}$ for the charged winos and $\tilde h_1^-, \tilde h_2^+$ for the charged higgsinos. The Lagrangian contains the chargino mass matrix as

$$\mathcal{L}^{\mathrm{mass}}_{\tilde\chi^+} = -\frac{1}{2}\tilde\psi^{-T}\mathcal{M}_{\tilde\psi^+}\tilde\psi^+ + \mathrm{h.c.}\ , \tag{13}$$

in the basis of 2–component spinors $\tilde\psi^+ = (-i\tilde w^+,\ \tilde h_2^+)^T,\ \tilde\psi^- = (-i\tilde w^-,\ \tilde h_1^-)^T$. We define the unitary 2 by 2 chargino mixing matrices, $U$ and $V$, such that:

$$-\frac{1}{2}\tilde\psi^{-T}\mathcal{M}_{\tilde\psi^+}\tilde\psi^+ = -\frac{1}{2}\underbrace{\tilde\psi^{-T}U^T}_{\tilde\chi^{-T}}\underbrace{U^*\mathcal{M}_{\tilde\psi^+}V^\dagger}_{\mathrm{diag}(m_{\tilde\chi^+})}\underbrace{V\tilde\psi^+}_{\tilde\chi^+}\ , \tag{14}$$

where the (2–component) charginos $\tilde\chi^+_i$ are defined such that their absolute masses increase with increasing $i$ and such that the mass matrix, $m_{\tilde\chi^+_i}$, is strictly real:

$$\mathrm{diag}(m_{\tilde\chi^+}) \equiv \left[U\mathcal{M}_{\tilde\psi^+}V^T\right]_{ij} = m_{\tilde\chi^+_i}\delta_{ij}\ . \tag{15}$$

### *2.43 SFERMION MIXING*

At present, we restrict our attention to left–right mixing in the third generation sfermion sector only. The convention we use is, for the interaction eigenstates, that $\tilde{f}_L$ and $\tilde{f}_R$ refer to the $SU(2)_L$ doublet and singlet superpartners of the fermion $f \in \{t, b, \tau\}$, respectively, and, for the mass eigenstates, that $\tilde{f}_1$ and $\tilde{f}_2$ refer to the lighter and heavier mass eigenstates, respectively. With this choice of basis, the spectrum output should contain the elements of the following matrix:

$$\left( \begin{array}{c} \tilde{f}_1 \\ \tilde{f}_2 \end{array} \right) = \left[ \begin{array}{cc} F_{11} & F_{12} \\ F_{21} & F_{22} \end{array} \right] \left( \begin{array}{c} \tilde{f}_L \\ \tilde{f}_R \end{array} \right) , \tag{16}$$

whose determinant should be $\pm 1$. We here deliberately avoid notation involving mixing angles, to prevent misunderstandings which could arise due to the different conventions for these angles used in the literature. The mixing matrix elements themselves are unambiguous, apart from the overall signs of rows in the matrices, see above.

### *2.44 HIGGS MIXING*

The conventions for $\mu$, $v_1$, $v_2$, $v$, $\tan\beta$, and $m_A^2$ were defined above in sections 2.2 and 2.3. The angle $\alpha$ we define by the rotation matrix:

$$\left( \begin{array}{c} H^0 \\ h^0 \end{array} \right) = \left[ \begin{array}{cc} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{array} \right] \left( \begin{array}{c} H_1^0 \\ H_2^0 \end{array} \right) , \tag{17}$$

where $H_1^0$ and $H_2^0$ are the CP–even neutral Higgs scalar interaction eigenstates, and $h^0$ and $H^0$ the corresponding mass eigenstates (including any higher order corrections present in the spectrum calculation), with $m_{h^0} < m_{H^0}$ by definition.

## **2.5 RUNNING COUPLINGS**

In contrast to the effective definitions adopted above for the mixing matrices, we define the gauge couplings, the Yukawa couplings, and the soft breaking Lagrangian terms which appear in the output as $\overline{\mathrm{DR}}$ running parameters, computed at a user–specifiable scale $Q$ (or grid of scales $Q_i$, see below).

That the $\overline{\mathrm{DR}}$ scheme is adopted for the output of running parameters is simply due to the fact that this scheme substantially simplifies many SUSY calculations (and hence all spectrum calculators use it). However, it does have drawbacks which for some applications are serious. For example, the $\overline{\mathrm{DR}}$ scheme violates mass factorization as used in QCD calculations [28]. For consistent calculation beyond tree–level of processes relying on this factorization, e.g. cross sections at hadron colliders, the $\overline{\mathrm{MS}}$ scheme is the only reasonable choice. At the present level of calculational precision, this is fortunately not an obstacle, since at one loop, a set of parameters calculated in either of the two schemes can be consistently translated into the other [29], see also [27] for explicit prescriptions.

Note, however, that different spectrum calculators use different choices for the underlying particle content of the effective theory. The programs SOFTSUSY (v. 1.8), SPHENO (v. 2.1), and SUSPECT (v. 2.2) use the full MSSM spectrum at all scales, whereas in ISAJET (v. 7.69) a more involved prescription is followed, with different particles integrated out of the effective theory at different scales. Whatever the case, these couplings should *not* be used 'as is' in calculations performed in another renormalization scheme or where a different effective field content is assumed.

Unfortunately, ensuring consistency of the field content assumed in the effective theory must still be done on a per program basis, though information on the prescription used by a particular spectrum calculator may conveniently be given as comments, when running parameters are provided.

Technically, we treat running parameters in the output in the following manner: since programs outside the spectrum calculation will not normally be able to run parameters with the full spectrum included, or at least less precisely than the spectrum calculators themselves, an option is included to allow the spectrum calculator to write out values for each running parameter at a user–defined number of logarithmically spaced scales, i.e. to give output on running parameters at a grid of scales, $Q_i$, where the lowest point in the grid will normally be $m_Z$ and the highest point is user–specifiable. A complementary possibility is to let the spectrum calculator give output for the running couplings at one or more scales equal to specific sparticle masses in the spectrum.

## 3. DEFINITIONS OF THE INTERFACES

The following general structure for the SLHA files is proposed:

- All quantities with dimensions of energy (mass) are implicitly understood to be in GeV (GeV/$c^2$).
- Particles are identified by their PDG particle codes. See [27] for lists of these, relevant to the MSSM.
- The first character of every line is reserved for control and comment statements. Data lines should have the first character empty.
- In general, formatted output should be used for write-out, to avoid "messy-looking" files, while a free format should be used on read-in, to avoid misalignment etc. leading to program crashes.
- A "`#`" mark anywhere means that the rest of the line is intended as a comment to be ignored by the reading program.
- All input and output is divided into sections in the form of named "blocks". A "`BLOCK xxxx`" (with the "`B`" being the first character on the line) marks the beginning of entries belonging to the block named "`xxxx`". E.g. "`BLOCK MASS`" marks that all following lines until the next "`BLOCK`" (or "`DECAY`") statement contain mass values, to be read in a specific format, intrinsic to the `MASS` block. The order of blocks is arbitrary, except that input blocks should always come before output blocks.
- Reading programs should skip over blocks that are not recognized, issuing a warning rather than crashing. Thereby, stability is increased and private blocks can be constructed, for instance `BLOCK MYCODE` could contain some parameters that only the program MyCode (or a special hack of it) needs, but which are not recognized universally.
- A line with a blank first character is a data statement, to be interpreted according to what data the current block contains. Comments and/or descriptions added after the data values, e.g. "` ... # comment`", should always be added, to increase readability of the file for human readers.

Finally, program authors are advised to check that any parameter relations they assume in their code (implicit or explicit) are obeyed by the parameters in the files. For instance, tree–level relations should not be used with loop–corrected parameters.

For the technical specifications of the blocks contained in the SUSY Les Houches Accord files the full writeup [27] should be consulted.

## 4. OUTLOOK

The present Accord [27] specifies a unique set of conventions together with ASCII file formats for model input and spectrum output for most commonly investigated supersymmetric models, as well as a decay table file format for use with decay packages.

With respect to the model parameter input file, mSUGRA, mGMSB, and mAMSB scenarios can be handled, with some options for non-universality. However, this should not discourage users desiring to investigate alternative models; the definitions for the spectrum output file are at present capable of handling any CP and R–parity conserving supersymmetric model, with the particle spectrum of the MSSM. Specifically, this includes the so-called SPS points [30].

Also, these definitions are not intended to be static solutions. Great efforts have gone into ensuring that the Accord may accomodate essentially any new model or new twist on an old one with minor modifications required and full backwards compatibility. Planned issues for future extensions of the Accord are, for instance, to include options for R–parity violation and CP violation, and possibly to include definitions for an NMSSM. Topics which are at present only implemented in a few codes, if at all, will be taken up as the need arises. Handling RPV and CPV should require very minor modifications to the existing structure, while the NMSSM, for which there is at present not even general agreement on a unique definition, will require some additional work.

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