— Physics Landscapes Session —

The SUSY Les Houches Accord

Peter Skands (Fermilab)

- I: SUSY Conventions and the emergence of SLHA.
  (+ Quick overview of SUSY RGE/ME/MC/... codes.)
- II: Results of the Durham meeting.
  (NMSSM & towards CPV)

SuSy Conventions & emergence of SLHA

- ∃ Increasing no. of sophisticated codes for calculating the SuSy mass & coupling spectrum ('RGE codes').
- Often (desired) interfaced to specialized codes for calculating e.g. cross sections, decay widths, or relic densities.
- Also, general-purpose Monte Carlo Event generators interface RGE codes and/or decay packages for SuSy spectra and decays.

Previously, was necessary to write tailor-made interfaces between each set of programs (+ keep up-to-date!). Cumbersome, and error-prone.

$\rightarrow$ Idea to have general interface instead.

What is the SLHA?

SUSY model → **Spectrum Calculator** → **Event Gen./ XS Calc.**

SUSY model

- MSSM
- SUGRA
- GMSB
- AMSB
- RPV
- CPV
- NMSSM
- ...

Spectrum Calculator

- FEYNHIGGS
- ISASUSY
- (PYTHIA)
- SOFTSUSY
- SPHENO
- SUSPECT
- ...

Event Gen./ XS Calc.

- COMPHEP
- AF'S SLEPTONS
- GRACE
- HERWIG
- ISAJET
- PROSPINO
- PYTHIA
- SHERPA
- SUSYGEN
- WHIZARD
- ...

CDM Package

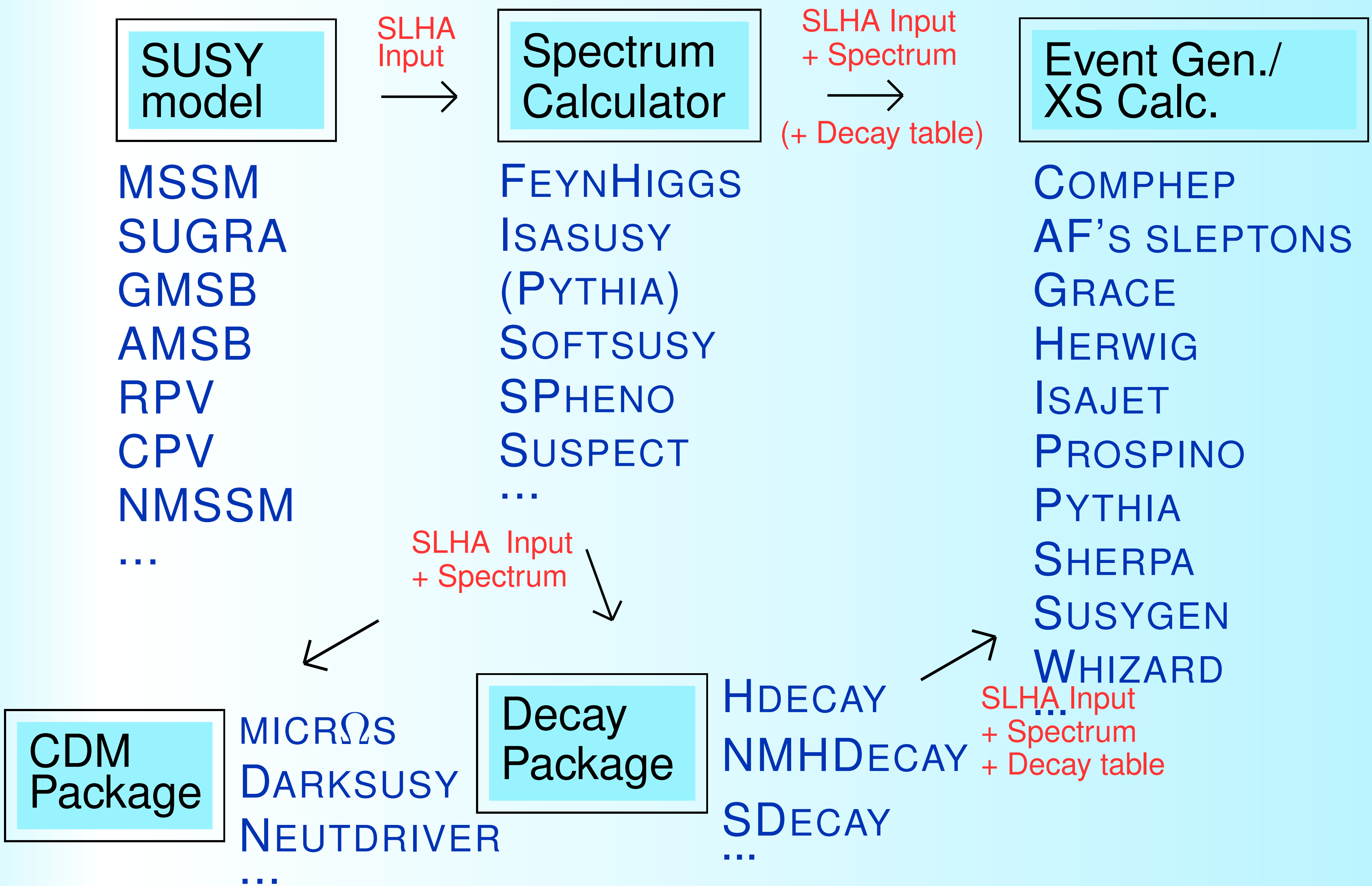
- MICRΩS
- DARKSUSY
- NEUTDRIVER
- ...

Decay Package

- HDECAY
- NMHDECAY (NEW!)
- SDECAY
- ...

Ellwanger+Gunion+Hugonie
hep-ph/0406215
NMSSM Higgs sector

What is the SLHA?



What is the SLHA?

SUSY model —SLHA Input→ Spectrum Calculator —SLHA Input + Spectrum (+ Decay table)→ Event Gen./ XS Calc.

SUSY model
- MSSM✔
- SUGRA✔
- GMSB✔
- AMSB✔
- RPV
- CPV(...)
- NMSSM(✔)
- ...

Spectrum Calculator
- FeynHiggs✔
- IsaSUSY✔
- (Pythia)✔
- SoftSUSY✔
- SPheno✔
- SuSpect(✔)
- ...

Event Gen./ XS Calc.
- CompHEP
- AF's sleptons
- Grace
- Herwig
- Isajet
- Prospino✔
- Pythia✔
- Sherpa
- Susygen
- Whizard✔
- ...

SLHA Input + Spectrum → CDM Package, Decay Package

CDM Package
- MicrΩs✔
- DarkSUSY
- NeutDriver
- ...

Decay Package
- HDecay
- NMHDecay✔
- SDecay✔
- ...

Decay Package —SLHA Input + Spectrum + Decay table→ Event Gen./ XS Calc.

Conventions and Consistency

What is needed to 'specify' a SUSY model?

1. Specify experimental boundary conditions.

   "SM" gauge couplings g_i^{SM} & Yukawas Y_{ijk}^{SM} ('measured')
   $\rightarrow$ "MSSM" couplings g_i and Yukawas Y_{ijk} (not the same, since different field content $\rightarrow$ different quantum corrections).

2. Define the Superpotential.

   Y_{ijk}, μ (+ RPV/NMSSM terms) (HO: at scale Q, e.g. in $\overline{\mathrm{DR}}$ scheme) $\rightarrow W$.

3. Define the SUSY breaking terms.

   Soft breaking gaugino masses M_i, scalar masses m_{ij}, b_{ij}, and trilinear A_{ijk} terms (HO: at scale Q, e.g. in $\overline{\mathrm{DR}}$ scheme).

4. Work out the physical spectrum.

   Pole masses (for kinematics), and couplings (for ME's), incl. mass $\leftrightarrow$ current eigenstate transl., and for HO calcs all def in a useful and well–defined renormalization scheme/scale.

SUSY: Conventions and Consistency

All these steps $\rightarrow$ potential pitfalls when doing (and esp. combining) calculations.

Need to be careful with:

- Signs, factors $\sqrt{2}$, etc.
- Mixing angles: clockwise or counter? Reflections?
- (Eigen)state decompositions.
- Renormalization schemes/scales.
- Effective field content (sparticles integrated out or not)
- Your favourite headache.

What you get from SLHA is unique and well-defined!

Conventions and Consistency

1. Experimental Boundary Conditions

$\alpha_{\mathrm{em}}(m_{\mathrm{Z}})^{\overline{\mathrm{MS}}}$	$\frac{\alpha}{1-\Delta\alpha(m_{\mathrm{Z}})^{\overline{\mathrm{MS}}}}$
G_F	The Fermi constant determined from μ decay
m_{Z}	The Z boson pole mass
$\alpha_s(m_{\mathrm{Z}})^{\overline{\mathrm{MS}}}$	The 5–flavour $\overline{\mathrm{MS}}$ strong coupling at m_{Z}
$m_{\mathrm{b}}(m_{\mathrm{b}})^{\overline{\mathrm{MS}}}$	The $\overline{\mathrm{MS}}$ b quark running mass at m_{b}
m_{t}	Top pole mass
m_τ	Tau pole mass

Note: no SUSY corrections here!

Conventions and Consistency

2. & 3. Defining the SUSY Model

$\mathrm{sgn}(\mu)$ $\quad W_\mu = \epsilon_{ab}\left[-\mu H_1^a H_2^b\right],\ (\epsilon_{12}=1)$

$\tan\beta(m_Z)^{\overline{\mathrm{DR}}}$ $\quad v_2/v_1$ (can also be given at $Q \neq m_Z$)

$V_3(M_{\mathrm{input}})$

$$\epsilon_{ab}\sum_{ij}\Big[(T_E)_{ij}H_1^a\tilde{L}_{i_L}^b\tilde{e}_{j_R}^* + (T_D)_{ij}H_1^a\tilde{Q}_{i_L}^b\tilde{d}_{j_R}^* + (T_U)_{ij}H_2^b\tilde{Q}_{i_L}^a\tilde{u}_{j_R}^*\Big] + \mathrm{h.c.},\quad A_{ij} = T_{ij}/Y_{ij}$$

$V_2(M_{\mathrm{input}})$

$$m_{H_j}^2 H_{j\,a}^* H_j^a + \tilde{Q}_{i_L a}^*(m_{\tilde{Q}}^2)_{ij}\tilde{Q}_{j_L}^a + \tilde{L}_{i_L a}^*(m_{\tilde{L}}^2)_{ij}\tilde{L}_{j_L}^a + \tilde{q}_{i_R}(m_{\tilde{q}}^2)_{ij}\tilde{q}_{j_R}^* + \tilde{e}_{i_R}(m_{\tilde{e}}^2)_{ij}\tilde{e}_{j_R}^* - (m_3^2\epsilon_{ab}H_1^aH_2^b + \mathrm{h.c.})$$

- Either $(m_{H_1}^2, m_{H_2}^2)$ or $(\mu, m_A^2 = \frac{m_3^2}{\sin\beta\cos\beta})$

$\mathcal{L}_G(M_{\mathrm{input}})$

$$\frac{1}{2}\left(M_1\tilde{b}\tilde{b} + M_2\tilde{w}^A\tilde{w}^A + M_3\tilde{g}^X\tilde{g}^X\right) + \mathrm{h.c.}$$

(NB: Extensions to NMSSM have already been agreed upon)

Conventions and Consistency

2. & 3. Defining the SUSY Model

$\Longrightarrow$ Now all parameters unambiguously defined. E.g. for the neutralino sector, with $\tilde{\psi}^{0T} = (-i\tilde{b}, -i\tilde{w}^0, \tilde{h}_1^0, \tilde{h}_2^0)^T$:

$$\text{Mass terms} = -\tfrac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\tfrac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0} \; ,$$

At tree level:

$$\mathcal{M}_{\tilde{\psi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z\cos\beta\sin\theta_W & m_Z\sin\beta\sin\theta_W \\ 0 & M_2 & m_Z\cos\beta\cos\theta_W & -m_Z\sin\beta\cos\theta_W \\ -m_Z\cos\beta\sin\theta_W & m_Z\cos\beta\cos\theta_W & 0 & -\mu \\ m_Z\sin\beta\sin\theta_W & -m_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

Generically complex entries $\mathrm{diag}(m_{\tilde{\chi}^0})_i = m_{\tilde{\chi}_i^0}e^{i\varphi_i}$, phases removed by redef. $\tilde{\chi}_i^0 \to \tilde{\chi}_i^0 e^{i\varphi_i/2} \to$ real positive masses.

Conventions and Consistency

4. Communicating the Spectrum: $\overline{\mathrm{DR}}$ parameters

- Firstly, copies of all the input parameters, for consistency (e.g. so next calculation uses same m_{t}).
- Secondly, all the (non-input) sparticle and Higgs boson pole masses, also e.g. m_{W}.
- Thirdly, all the Lagrangian parameters at given scale(s) Q_i in the $\overline{\mathrm{DR}}$ scheme.
- Fourthly, (less well defined) mixing matrices, for loop-improved tree–level calculations.

Conventions and Consistency

4. Communicating the Spectrum: $\overline{\mathrm{DR}}$ parameters

$W(Q_i)^{\overline{\mathrm{DR}}}$	$\epsilon_{ab}\left[(Y_E)_{ij}H_1^aL_i^b\bar{E}_j+(Y_D)_{ij}H_1^aQ_i^b\bar{D}_j+(Y_U)_{ij}H_2^bQ_i^a\bar{U}_j-\mu H_1^aH_2^b\right]$
$\tan\beta(Q_i)^{\overline{\mathrm{DR}}}$	v_2/v_1
$g_j(Q_i)^{\overline{\mathrm{DR}}}$	g', g, and g_3: gauge couplings
$A_j(Q_i)^{\overline{\mathrm{DR}}}$	Soft breaking trilinear couplings
$v_j(Q_i)^{\overline{\mathrm{DR}}}$	$\sqrt{2}\langle H_j^0\rangle$, so $v^2=(v_1^2+v_2^2)=(246\ \mathrm{GeV})^2$
$M_j(Q_i)^{\overline{\mathrm{DR}}}$	Soft breaking gaugino masses
$m_j(Q_i)^{\overline{\mathrm{DR}}}$	Soft breaking sfermion masses
$m_A(Q_i)^{\overline{\mathrm{DR}}}$	Running A mass.

In v1 writeup / In v2 writeup (& JHEP): JHEP 0407:036,2004

Conventions and Consistency

3. Communicating the Spectrum: mixing matrices

- mixing angles avoided, matrix elements given instead.

$$T = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}$$

- No consensus on best 'scheme' $\rightarrow$ Effective 'best choice' definitions, at the discretion of each spectrum calculator.

E.g. α: Diagonalizes loop–corrected mass matrices, but not a $\overline{\mathrm{DR}}$ or $\overline{\mathrm{MS}}$ parameter. Still, not scale independent. On–shell scheme has scale fixed by renormalization conditions, and external propagators still carry some momentum, which momentum?

Some Examples...

(Examples)

```
# SUSY Les Houches Accord 1.0
# Example spectrum file - Snowmass point 1a
Block SPINFO          # Program information
     1   SOFTSUSY     # spectrum calculator
     2   1.8.4        # version number
Block MODSEL  # Select model
     1   1  # sugra
Block MINPAR  # Input parameters
     1   1.000000000e+02  # m0
     2   2.500000000e+02  # m12
     3   1.000000000e+01  # tanb
     4   1.000000000e+00  # sign(mu)
     5  -1.000000000e+02  # A0
Block SMINPUTS # SM parameters
     1   1.279340000e+02  # 1/alpha(MZ)[MSbar]
     2   1.166370000e-05  # Gmu [GeV**-2]
     3   1.172000000e-01  # alphas(MZ)[MSbar]
     4   9.118760000e+01  # Z pole mass
     5   4.250000000e+00  # mb(mb)[MSbar]
     6   1.743000000e+02  # t pole mass
     7   1.777000000e+00  # tau pole mas
Block MASS   # Mass spectrum (pole masses)
         24     8.024639840e+01   # W
         25     1.106368320e+02   # h0
         35     4.008746040e+02   # H0
         36     4.005062720e+02   # A0
         37     4.087847760e+02   # H+
    1000001     5.537379281e+02   # sd(L)
    1000002     5.480648005e+02   # su(L)
    1000003     5.536689385e+02   # ss(L)
    1000004     5.479950083e+02   # sc(L)
    1000005     4.990864878e+02   # sb(1)
    1000006     3.866681125e+02   # st(1)
    1000011     2.005077001e+02   # se(L)
    1000012     1.844822029e+02   # snue(L)
    1000013     2.005050044e+02   # smu(L)
    1000014     1.844792730e+02   # snumu(L)
    1000015     1.339969762e+02   # stau(1)
    1000016     1.836242253e+02   # snu(tau(L))
    1000021     5.934756712e+02   # gluino
    1000022     9.701573617e+01   # neutralino(1)
    1000023     1.788864799e+02   # neutralino(2)
    1000024     1.782649096e+02   # chargino(1)
```

```
    1000025    -3.536102287e+02   # neutralino(3)
    1000035     3.733417082e+02   # neutralino(4)
    1000037     3.736128390e+02   # chargino(2)
    2000001     5.269676664e+02   # sd(R)
    2000002     5.311251030e+02   # su(R)
    2000003     5.269652151e+02   # ss(R)
    2000004     5.309795680e+02   # sc(R)
    2000005     5.257115262e+02   # sb(2)
    2000006     5.704560875e+02   # st(2)
    2000011     1.430886701e+02   # se(R)
    2000013     1.430810123e+02   # smu(R)
    2000015     2.043832731e+02   # stau(2)
Block alpha # Effective Higgs mixing angle alph
         -1.146864127e-01   # alpha
Block hmix Q= 4.520624648e+02   # DRbar Higgs mi
     1     3.439934743e+02   # mu
Block stopmix   # stop mixing matrix
  1  1     5.443784304e-01   # O(1,1)
  1  2     8.388397490e-01   # O(1,2)
  2  1     8.388397490e-01   # O(2,1)
  2  2    -5.443784304e-01   # O(2,2)
Block sbotmix   # sbottom mixing matrix
  1  1     9.355024721e-01   # O(1,1)
  1  2     3.533201449e-01   # O(1,2)
  2  1    -3.533201449e-01   # O(2,1)
  2  2     9.355024721e-01   # O(2,2)
Block staumix   # stau mixing matrix
  1  1     2.810947184e-01   # O(1,1)
  1  2     9.596800297e-01   # O(1,2)
  2  1     9.596800297e-01   # O(2,1)
  2  2    -2.810947184e-01   # O(2,2)
# Gaugino-higgsino mixing
Block nmix   # neutralino mixing matrix
  1  1     9.849417415e-01   # N(1,1)
  1  2    -5.795970738e-02   # N(1,2)
  1  3     1.526931274e-01   # N(1,3)
  1  4    -5.670314904e-02   # N(1,4)
  2  1     1.090115410e-01   # N(2,1)
  2  2     9.374300545e-01   # N(2,2)
  2  3    -2.852021039e-01   # N(2,3)
  2  4     1.673354023e-01   # N(2,4)
...
```

(Examples)

```
# SUSY Les Houches Accord 1.0
# Example decay file - Gluino decays
Block DCINFO     # Program information
     1     SDECAY   # Decay package
     2     1.0      # version number
#          PDG             Width
DECAY    1000021     1.01752300e+00    # gluino decays
#           BR            NDA      ID1         ID2
     4.18313300E-02     2      1000001        -1    # BR(sg -> sd(L) dbar)
     1.55587600E-02     2      2000001        -1    # BR(sg -> sd(R) dbar)
     3.91391000E-02     2      1000002        -2    # BR(sg -> su(L) ubar)
     1.74358200E-02     2      2000002        -2    # BR(sg -> su(R) ubar)
     4.18313300E-02     2      1000003        -3    # BR(sg -> ss(L) sbar)
     1.55587600E-02     2      2000003        -3    # BR(sg -> ss(R) sbar)
     3.91391000E-02     2      1000004        -4    # BR(sg -> sc(L) cbar)
     1.74358200E-02     2      2000004        -4    # BR(sg -> sc(R) cbar)
     1.13021900E-01     2      1000005        -5    # BR(sg -> sb(1) bbar)
     6.30339800E-02     2      2000005        -5    # BR(sg -> sb(2) bbar)
     9.60140900E-02     2      1000006        -6    # BR(sg -> st(1) tbar)
     0.00000000E+00     2      2000006        -6    # BR(sg -> st(2) tbar)
     4.18313300E-02     2     -1000001         1    # BR(sg -> sdbar(L) d)
     1.55587600E-02     2     -2000001         1    # BR(sg -> sdbar(R) d)
     3.91391000E-02     2     -1000002         2    # BR(sg -> subar(L) u)
     1.74358200E-02     2     -2000002         2    # BR(sg -> subar(R) u)
     4.18313300E-02     2     -1000003         3    # BR(sg -> ssbar(L) s)
     1.55587600E-02     2     -2000003         3    # BR(sg -> ssbar(R) s)
     3.91391000E-02     2     -1000004         4    # BR(sg -> scbar(L) c)
     1.74358200E-02     2     -2000004         4    # BR(sg -> scbar(R) c)
     1.13021900E-01     2     -1000005         5    # BR(sg -> sbbar(1) b)
     6.30339800E-02     2     -2000005         5    # BR(sg -> sbbar(2) b)
     9.60140900E-02     2     -1000006         6    # BR(sg -> stbar(1) t)
     0.00000000E+00     2     -2000006         6    # BR(sg -> stbar(2) t)
```

News and Updates...

News

- NMHDecay: [U. Ellwanger et al., hep-ph/0406215]
  - NMSSM Higgs sector: masses, couplings + decays.
- CPSuperH: [J. Lee et al., CPC 156(2004)283, hep-ph/0307377]
  - CPV MSSM Higgs sector: masses, mixings + decays.
- SDecay updated: [M. Mühlleitner et al., hep-ph/0311167]
  - 3-body sbottom decays, QCD corrections for gaugino $\to \tilde{q}q'$ and $\tilde{q} \to \tilde{q}'V$, and SLHA spectrum read-in. (SLHA output already there.)
- ISAJET updated (v 7.69): [C. Balazs]
  - Routine `ISALHA.F` writes out SLHA spectrum.

News

- AF's sleptons:

  [A. Freitas et al., Eur.Phys.J.C34:487-512,2004 + addendum]

  - NLO slepton production at e^+e^- machines.

- Sfitter and Fittino: [R. Lafaye et al., hep-ph/0404282], [P. Bechtle et al.]
  - MSSM parameter fitting from cross sections etc.

- SLHAlib-1.0 [T. Hahn, hep-ph/0408283]
  - F77 SLHA Read-Write libraries.

Summary of Durham Discussions

Towards including CPV, RPV etc.

Theory errors?

Cross sections?

Summary of Durham Discussions

We have agreed to: Conserve colour, charge, and spin!

- $\rightarrow$ add (optional) new LARGE mixing blocks which in principle can deal with all possible consequences of CPV, RPV, etc. (normally will be block-diagonal to a large extent.)
- Include (option for) giving either effective (loop-improved) mixing matrices OR mixing in $\overline{\mathrm{DR}}$ scheme at a given scale.
- Include imaginary parts in new mixing structure.
- Conventions for NMSSM adopted, for CPV underway.
- Theory errors: highly non-trivial issue. Sub-group organised by K. Desch & W. Porod to investigate solutions.
- Cross sections: even more thorny issue. No general concensus yet — but strong interest from SPA project for $\mathrm{e}^+\mathrm{e}^-$ case.

SLHA: Where to find more info:

- The SUSY Les Houches Accord:
  PS et al., JHEP 0407:036 (hep-ph/0311123)

- SLHA Latest News, codes, examples, workshops, ...:
  `http://home.fnal.gov/~skands/slha/`

- The SLHA and PYTHIA (+ much other good stuff!):
  See CDF/D0 Pythia Tutorial:
  `www-cdf.fnal.gov/`
  `physics/lectures/pythia_Dec2004.html`