The SUSY Les Houches Accord, and SUSY/PYTHIA News

Peter Skands (Fermilab)

- I: SUSY Conventions and the emergence of SLHA.
  (+ Quick overview of SUSY RGE/ME/MC/... codes.)
- II: BSM/Exotics news in PYTHIA.
  (Special focus: Baryon Number Violating SUSY.)

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 terms if any) (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 $\longrightarrow$ potential pitfalls when doing (and esp. combining) calculations.

- 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.

NB: Problem especially acute since *many* models out there, and *many* codes to do *many* types of calculations.

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
- 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?

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
GRACE
HERWIG
ISAJET
PROSPINO
PYTHIA
SHERPA
SUSYGEN
WHIZARD
...

Spectrum Calculator → 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.

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
- 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

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

$\mathrm{sgn}(\mu)$	$W_\mu = \epsilon_{ab}\left[-\mu H_1^a H_2^b\right]$, $(\epsilon_{12} = 1)$
$\tan\beta(m_Z)^{\overline{\mathrm{DR}}}$	v_2/v_1 (can also be given at $Q \neq m_Z$)
$V_3(M_{\mathrm{input}})$	$\epsilon_{ab}\sum_{ij}\left[(T_E)_{ij}H_1^a\tilde{L}_{i_L}^b\tilde{e}_{j_R}^* + (T_D)_{ij}H_1^a\tilde{Q}_{i_L}^b\tilde{d}_{j_R}^* + (T_U)_{ij}H_2^b\tilde{Q}_{i_L}^a\tilde{u}_{j_R}^*\right] + \mathrm{h.c.}$, $A_{ij} = T_{ij}/Y_{ij}$
$V_2(M_{\mathrm{input}})$	$m_{H_j}^2 H_{j\,a}^* H_j^a + \tilde{Q}_{i_L a}^*(m_{\tilde{Q}}^2)_{ij}\tilde{Q}_{j_L}^a + \tilde{L}_{i_L a}^*(m_{\tilde{L}}^2)_{ij}\tilde{L}_{j_L}^a + \tilde{q}_{i_R}(m_{\tilde{q}}^2)_{ij}\tilde{q}_{j_R}^* + \tilde{e}_{i_R}(m_{\tilde{e}}^2)_{ij}\tilde{e}_{j_R}^* - (m_3^2\epsilon_{ab}H_1^a H_2^b + \mathrm{h.c.})$ ∘ Either $(m_{H_1}^2, m_{H_2}^2)$ or $(\mu, m_A^2 = \frac{m_3^2}{\sin\beta\cos\beta})$
$\mathcal{L}_G(M_{\mathrm{input}})$	$\frac{1}{2}\left(M_1\tilde{b}\tilde{b} + M_2\tilde{w}^A\tilde{w}^A + M_3\tilde{g}^X\tilde{g}^X\right) + \mathrm{h.c.}$

Conventions and Consistency

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

$W(Q_i)^{\overline{\mathrm{DR}}}$	$\epsilon_{ab}\left[(Y_E)_{ij}H_1^a L_i^b \bar{E}_j + (Y_D)_{ij}H_1^a Q_i^b \bar{D}_j + (Y_U)_{ij}H_2^b Q_i^a \bar{U}_j - \mu H_1^a H_2^b\right]$
$\tan\beta(Q_i)^{\overline{\mathrm{DR}}}$	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 $v^2 = (v_1^2 + v_2^2) = (246\ \text{GeV})^2$
$M_j(Q_i)^{\overline{\mathrm{DR}}}$	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)

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 alpha
         -1.146864127e-01   # alpha
Block hmix Q= 4.520624648e+02   # DRbar Higgs mix
     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)
```

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://www.thep.lu.se/~zeiler/slha/`

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

BSM News in PYTHIA...

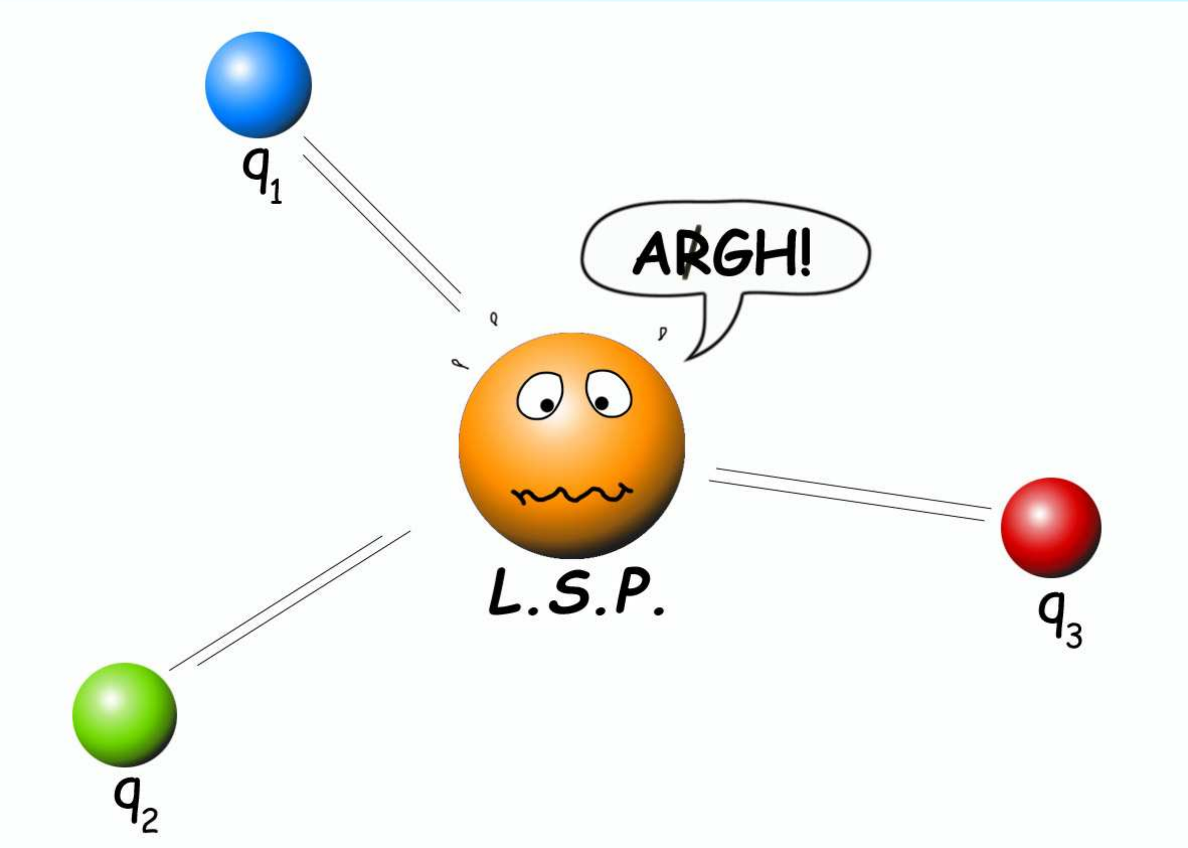
BSM News in PYTHIA

1. R–parity violating SUSY decays.
2. Other SUSY news.
3. (News from extra dimensions.)
4. (News in Technicolor.)
5. (Left–Right Symmetry, Z', compositeness.)

R–parity violating SUSY decays

LNV: [PS, hep-ph/0108207 & Eur.Phys.J.C23:173(2002)]

BNV: [T. Sjöstrand + PS, Nucl.Phys.B659:243(2003) & hep-ph/0209199]



Focus: the Smoking Gun of BNV

2. R-parity violating SUSY

$\not{L} \Rightarrow >$ 1200 new decay chanels, $\not{B} \Rightarrow \sim$ 200 new decay chanels.

LLE (λ):

- $\tilde{e}_j^- \to \bar{\nu}_i \ell_k^-, \ \nu_k \ell_i^-$
- $\tilde{\nu}_j \to \ell_i^+ \ell_k^-$
- $\tilde{\chi}_n^0 \to \bar{\nu}_i \ell_j^+ \ell_k^-, \ \nu_i \ell_j^- \ell_k^+$
- $\tilde{\chi}_n^+ \to \ell_i^+ \ell_j^+ \ell_k^-$
- $\tilde{\chi}_n^+ \to \bar{\nu}_i \ell_j^+ \nu_k, \ \nu_i \nu_j \ell_k^+$

LQD (λ'):

- $\tilde{e}_i^- \to \bar{u}_j d_k$
- $\tilde{\nu}_i \to \bar{d}_j d_k$
- $\tilde{u}_j \to e_i^+ d_k$
- $\tilde{d}_k \to \nu_i d_j, \ \bar{\nu}_j d_i, \ \ell_i^- u_j$
- $\tilde{\chi}_n^0 \to$ $\bar{\nu}_i \bar{d}_j d_k, \ \ell^+ \bar{u}_j d_k, \ + \text{c.c.}$
- $\tilde{\chi}_n^+ \to \bar{\nu}_i \bar{d}_j u_k, \ \nu_i \bar{d}_k u_j$
- $\tilde{\chi}_n^+ \to \ell_i^+ \bar{u}_j u_k, \ \ell_i^+ \bar{d}_j d_k$

UDD (λ''):

- $\tilde{d}_j \to \bar{u}_i \bar{d}_k$
- $\tilde{u}_i \to \bar{d}_j \bar{d}_k$
- $\tilde{\chi}_n^0 \to u_i d_j d_k, \ + \text{c.c.}$
- $\tilde{\chi}_n^+ \to u_i u_j d_k, \ \bar{d}_i \bar{d}_j \bar{d}_k$
- $\tilde{g} \to u_i d_j d_k, \ + \text{c.c.}$

$\Rightarrow$ Junctions!

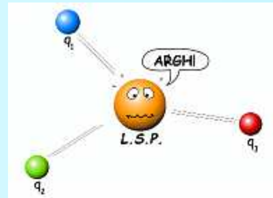
- Partial widths: tree-level ME's, massive t and b.
- Momentum distributions: isotropic 3-body phase space: good when intermediate propagators way off shell, worse if only slightly off shell.
- Final state parton multiplicity increased by subsequent showers.
- Only MSSM pair production, and no BRPV.

Colour topologies

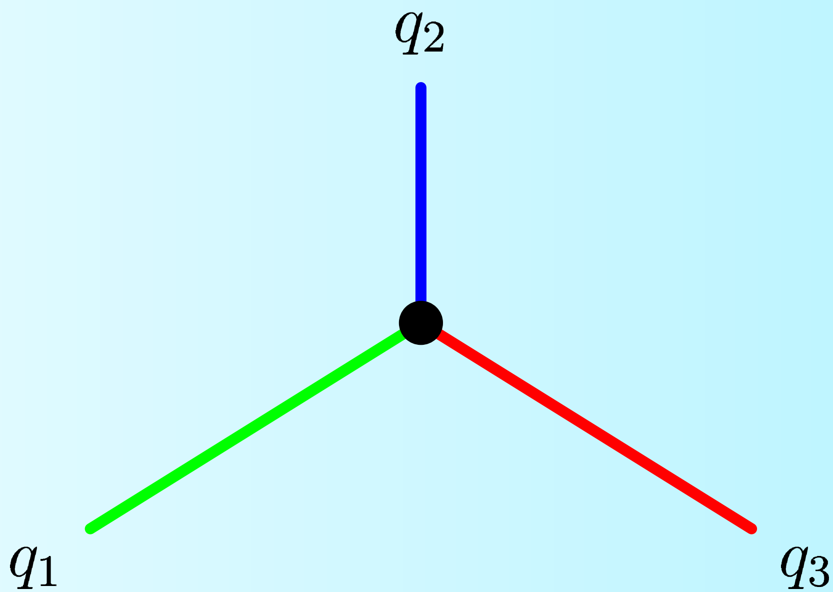
'Ordinary' colour topology

(e.g. $Z^0 \to q\bar{q}$):

'Baryonic' colour topology

(e.g. 

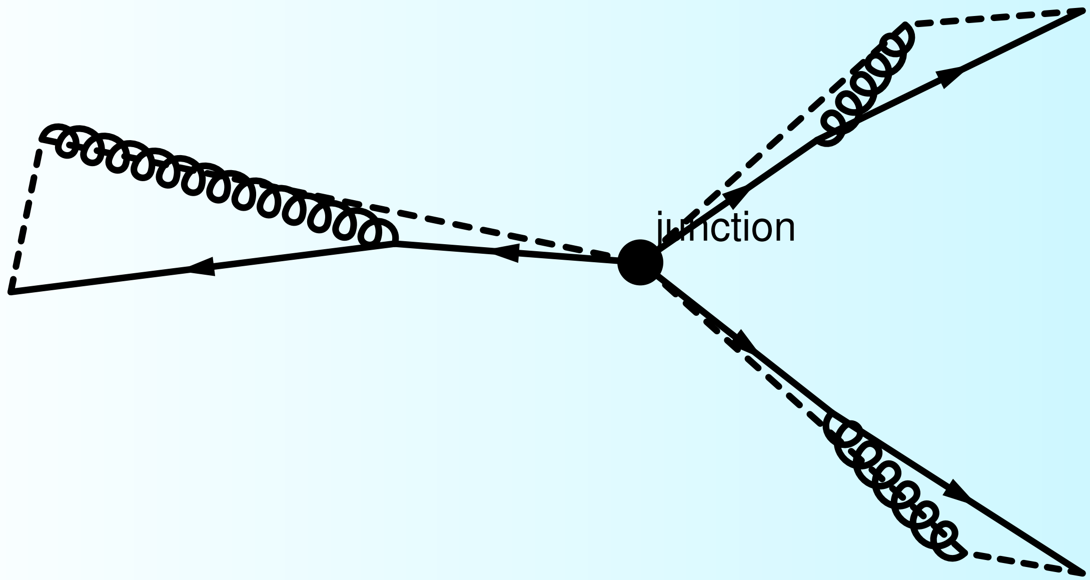
):



- How does such a system fragment?
- Could a Baryon excess be observed?

Colour topologies and hadronization

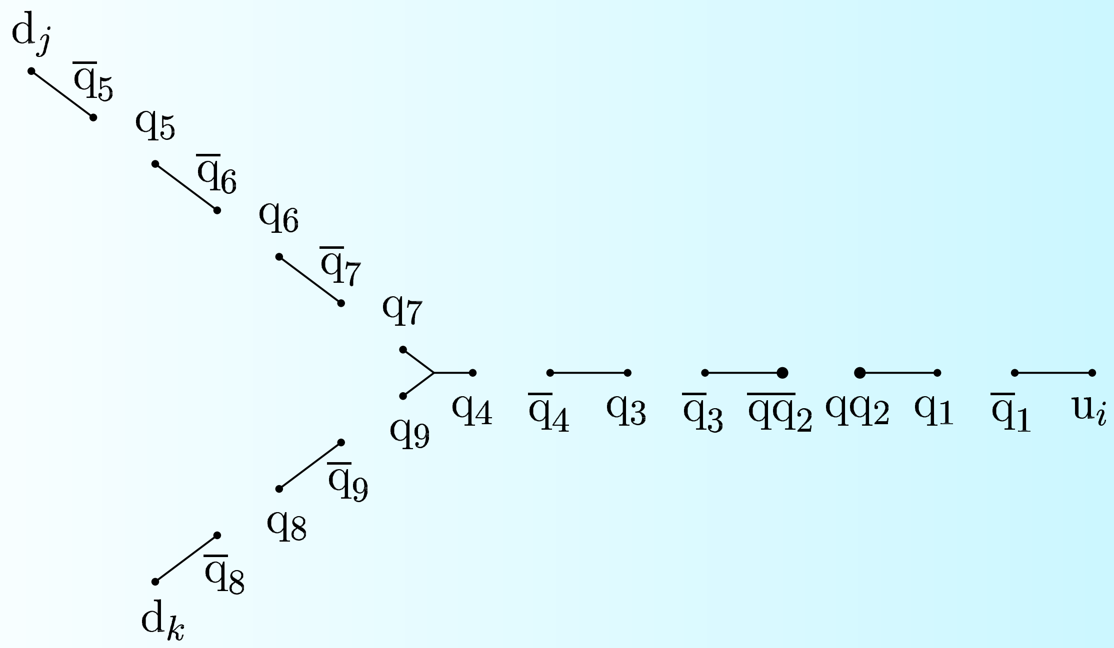
- Fundamental properties of QCD vacuum suggest string picture still applicable.
- String energy minimization + dipole picture $\Longrightarrow$ picture of 3 string pieces meeting at a 'string junction'.



(Warning: This picture was drawn in a "pedagogical projection" where distances close to the center are greatly exaggerated!)

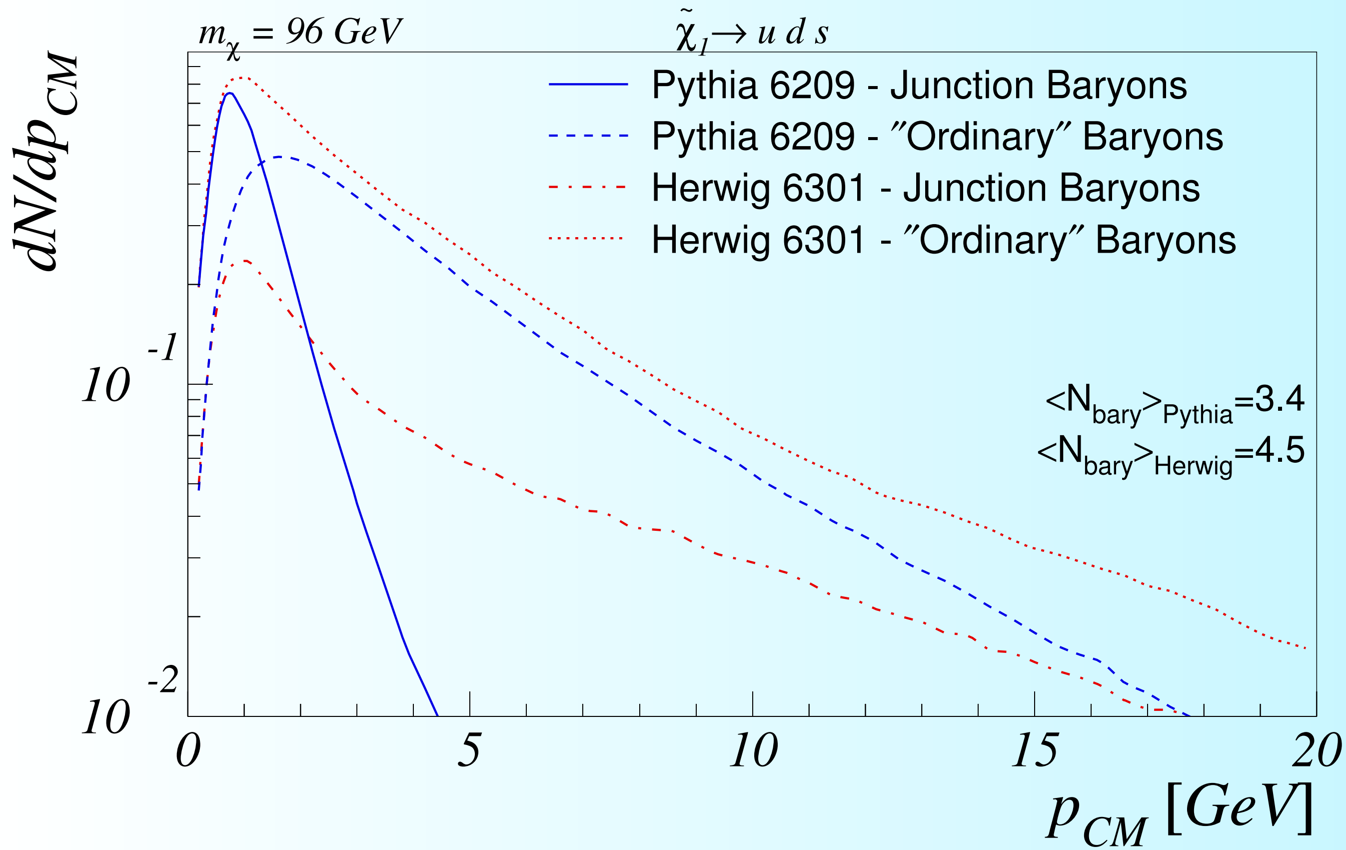
Fragmentation

- The movement of the string junction is crucial, it is the smoke of the BNV gun!
- Using eqs. of motion and string potential, the junction-rest-frame can be determined. Then motion is known, and we can hadronize the system:



Properties and Predictions

Junction fragmentation implies:



- if leading jets are well separated, junction will be slow, and junction baryon will be at low momenta:

BNV-SUSY summary

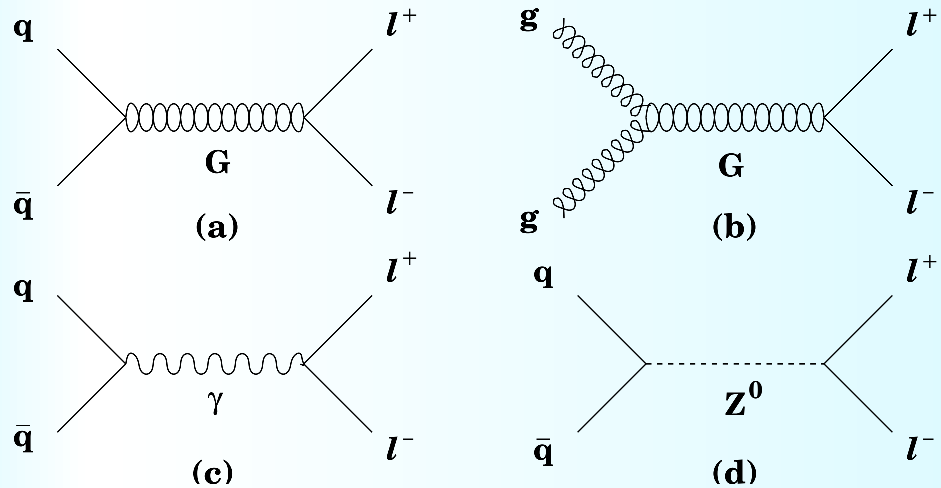
- A model for BNV-SUSY allowing detailed studies available in PYTHIA (6.2 and 6.3)
- Special attention given to the non-perturbative aspects. Hadronization based on physical picture shows new features.
- Generic prediction (apologies to particle ID people!):

  The smoking Gun — slow baryons.
- (Some features not mentioned: junction–junction strings and junction–junction annihilation, colour flow in gluino decays. + Bonus!: junction fragmentation recycled for improved description of beam remnants in hadron collisions!)

2. Other SUSY News

- Complex phases in gaugino and gluino sectors. [Mrenna]
- ME weighting in 3-body decays (not $R\!\!\!/$). [Mrenna]
- Higgs mass calculation corrected at large $\tan\beta$. [Carena, Quiros, Wagner]
- SUSY Les Houches Accord (see previous).
- Old (pre-SLHA) Run–time interface to ISASUSY (PYSUGI) extended to include GMSB, AMSB etc.

Randall-Sundrum graviton excitations, G^*:

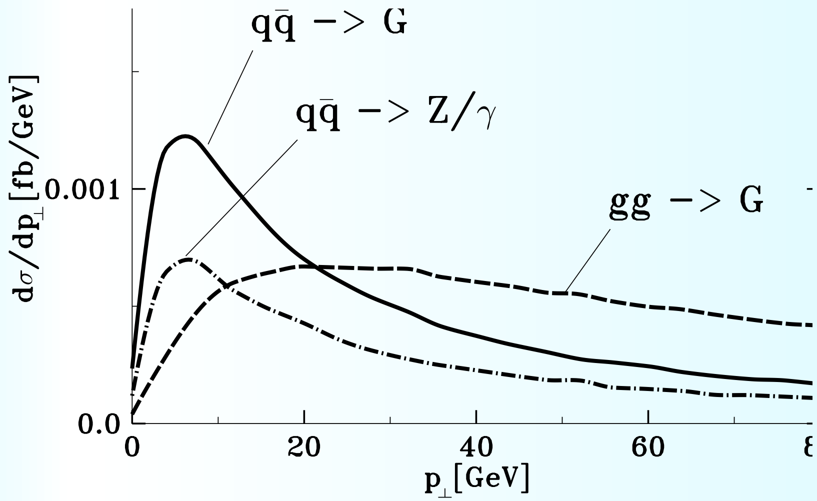


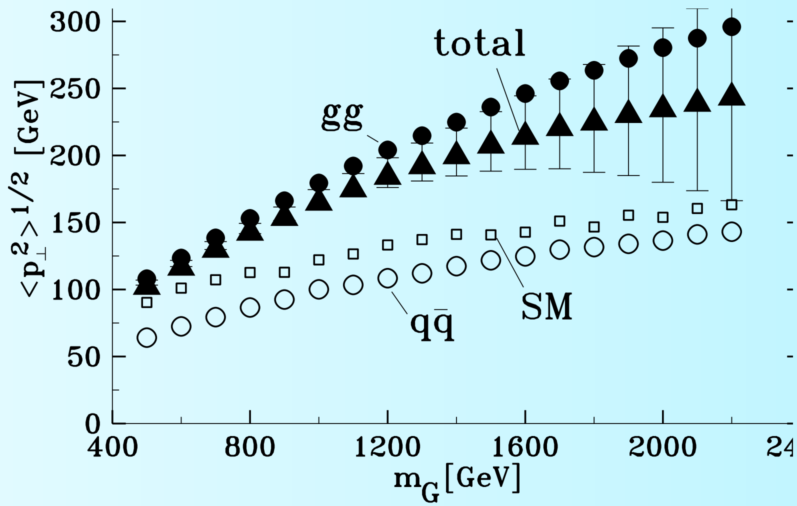
Lowest order:

$q\bar{q} \to G^*$
$gg \to G^*$

γ^*/Z^0 backgr.

Higher $p_\perp$ for gg fusion $\Rightarrow$ extra signal/check (in addition to spin-2 angular decay distribution)





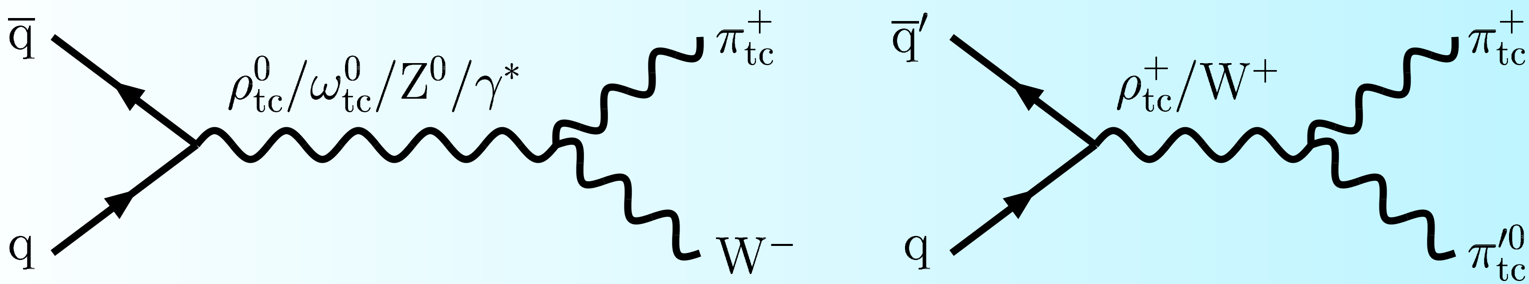
Also NLO ($q\bar{q} \to gG^*$, $qg \to qG^*$, $gg \to gG^*$) confirms PS.

(4. Technicolor) [Mrenna]

✧ Interferences, e.g. for $\rho^0_{\mathrm{tc}}/\omega^0_{\mathrm{tc}}/Z^0/\gamma^*$ and ρ^+_{tc}/W^+

$\Rightarrow$ new set of pair productions of $\pi^\pm_{\mathrm{tc}}/\pi^0_{\mathrm{tc}}/\pi'^0_{\mathrm{tc}}/W^\pm_{\mathrm{L}}/Z^0_{\mathrm{L}}/W^\pm/Z^0/\gamma$:

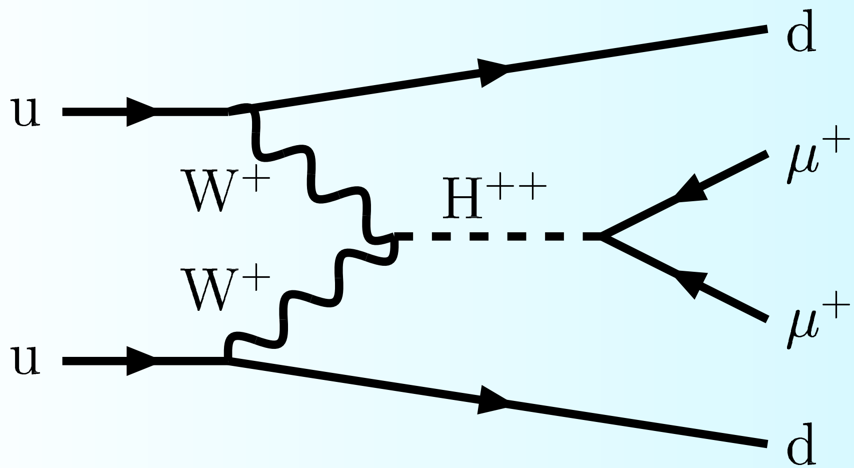
E.g.:



(5. L–R symmetry, Z', compositeness)

✧ LR symmetry: Higgs triplets [Huitu et al.]

E.g.:



$\mathrm{H}^{\pm\pm}_{L,R}$ production

$\mathrm{H}^{\pm\pm}_{L,R} \to \ell^\pm\ell^\pm/\mathrm{W}^\pm_{L,R}\mathrm{W}^\pm_{L,R}$

$\mathrm{W}^+_R \to \mathrm{q}_i\overline{\mathrm{q}}_j/\ell^+\nu_R$

✧ Z'^0: flavour dependent couplings.

✧ Compositeness: some new $2 \to 2$, e.g. $q_iq_j \to d^*q_k$.

PYTHIA 6.2/6.3:

- ★ Major news is development of complete model for BNV topologies. Some new BSM procs added, but...
- ★ Trend is to increase use of external, specialized parton level event generators (e.g. CompHEP, Madgraph, etc) interfaced via the Les Houches Accord (#1).
- ★ Alternatively, SUSY spectrum and decay tables from specialized packages may be interfaced using the SUSY Les Houches Accord.