QCD for BSM in PYTHIA

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LHC is a QCD machine:

- hard processes initiated by partons (quarks, gluons),
- associated with initial-state QCD corrections (showers etc.),
- underlying event by QCD mechanisms (MPI, colour flow),
- even in BSM scenarios production of new coloured states often favoured (squarks, Kaluza–Klein gluons, excited quarks, leptoquarks, ...).
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BSM physics can raise “new”, specific QCD aspects, here

1. $R$-parity violation in SUSY,
2. $R$-hadron formation in SUSY,
3. parton showers and hadronization in Hidden Valleys,

all implemented in PYTHIA 8.
1. *R*-parity violation in SUSY

Baryon number violation (BNV) is allowed in SUSY superpotential

\[ W_{\text{BNV}} = \lambda''_{ijk} \epsilon_{abc} \overline{U}_i a \overline{D}_j b \overline{D}_k c \]

(where \(ijk\) = generation, \(abc\) = colour).

Alternatively lepton number violation, but proton unstable if both.

\( \lambda''_{ijk} \) should not be too big, or else large loop corrections \( \Rightarrow \) relevent for LSP (Lightest Supersymmetric Particle).

Long-lived \( \Rightarrow \) secondary vertex.
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What about showers and hadronization in decays?

The Lund string

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

by self-interactions among soft gluons in the “vacuum”.

Gives linear confinement with string tension:

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]

Separation of transverse and longitudinal degrees of freedom

$\Rightarrow$ simple description as 1+1-dimensional object – **string** –

with Lorentz invariant formalism
The Lund gluon picture

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Force ratio gluon/ quark = 2, cf. QCD \( \frac{N_C}{C_F} = \frac{9}{4} \), \( \to 2 \) for \( N_C \to \infty \)

The most characteristic feature of the Lund model

snapshots of string position

strings stretched from q (or \( \bar{q}q \)) endpoint via a number of gluons to \( \bar{q} \) (or \( qq \)) endpoint
The junction

What string topology for 3 quarks in overall colour singlet? One possibility is to introduce a junction (Artru, ’t Hooft, ...).

Junction rest frame = where string tensions $T_i = \kappa \frac{p_i}{|p_i|}$ balance = $120^\circ$ separation between quark directions.

This is not the CM frame where momenta $p_i$ balance, but in BNV decay no collinear singularity between quarks, so normally junction is slowly moving in LSP rest frame.
Each string piece can break, mainly to give mesons. Always one baryon around junction; junction “carries” baryon number.

Junction baryon slow $\Rightarrow$ ”smoking-gun” signal.
The junction and dipole showers

Normal showers: each parton can radiate.

Dipole showers: each *pair* of partons, with matching colour–anticolour, can radiate, with recoil inside system. But here no simply matching colours!

Solution: let each three possible dipoles radiate, but with half normal strength. Gives correct answer collinear to each parton, and reasonable interpolation in between.
Now different tack: $R$-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino. Squarks and gluinos are unstable and decay to LSP, e.g. $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow q\tilde{\chi}q$.

Alternative SUSY: gluino LSP, or long-lived for another reason. E.g. Split SUSY (Dimopoulos & Arkani-Hamed): scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.
2. \textit{R}-hadron motivation

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More generally, many BSM models contain colour triplet or octet particles that can be (pseudo)stable: extra-dimensional excitations with odd KK-parity, leptoquarks, excited quarks, . . . . $\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:
- colour octet uncharged state, like $\tilde{g}$,
- colour triplet charge $+2/3$ state, like $\tilde{t}$,
- colour triplet charge $-1/3$ state, like $\tilde{b}$. 
A number of states predefined:

\[
\begin{array}{cccccccccccccccc}
\tilde{b}d & \tilde{b}ud_{1} & \tilde{t}d & \tilde{t}ud_{1} & \tilde{g}g & \tilde{g}c\tilde{d} & \tilde{g}c\tilde{b} & \tilde{g}suu & \tilde{g}csu \\
\tilde{b}\tilde{u} & \tilde{b}uu_{1} & \tilde{t}\tilde{u} & \tilde{t}uu_{1} & \tilde{g}d\tilde{d} & \tilde{g}c\tilde{u} & \tilde{g}bb & \tilde{g}ssd & \tilde{g}css \\
\tilde{b}\tilde{s} & \tilde{b}sd_{0} & \tilde{t}\tilde{s} & \tilde{t}sd_{0} & \tilde{g}ud\tilde{d} & \tilde{g}c\tilde{s} & \tilde{g}ddd & \tilde{g}ssu & \tilde{g}bdd \\
\tilde{b}\tilde{c} & \tilde{b}sd_{1} & \tilde{t}\tilde{c} & \tilde{t}sd_{1} & \tilde{g}u\tilde{u} & \tilde{g}c\tilde{c} & \tilde{g}udd & \tilde{g}sss & \tilde{g}bud \\
\tilde{b}\tilde{b} & \tilde{b}su_{0} & \tilde{t}\tilde{b} & \tilde{t}su_{0} & \tilde{g}d\tilde{s} & \tilde{g}d\tilde{b} & \tilde{g}uud & \tilde{g}cdd & \tilde{g}buu \\
\tilde{b}dd_{1} & \tilde{b}su_{1} & \tilde{t}dd_{1} & \tilde{tsu}_{1} & \tilde{g}u\tilde{s} & \tilde{g}u\tilde{b} & \tilde{g}uuu & \tilde{g}cud & \tilde{g}bsd \\
\tilde{b}ud_{0} & \tilde{b}ss_{1} & \tilde{t}ud_{0} & \tilde{t}ss_{1} & \tilde{g}s\tilde{s} & \tilde{g}s\tilde{b} & \tilde{g}ssd & \tilde{g}cuu & \tilde{g}bsu \\
\end{array}
\]

Approximate mass spectrum:

\[
m_{\text{hadron}} = \sum_{i} m_{i} + k \sum_{i \neq j} \frac{\langle F_{i} \cdot F_{j} \rangle \langle S_{i} \cdot S_{j} \rangle}{m_{i}m_{j}}
\]

\[(F_{i}; \text{colour vectors, } S_{i}; \text{spin vectors})\]

so heavy particle decouples, \(m(\tilde{b}d_{0}) \approx m(\tilde{b}d_{1})\) (cf. \(m_{\pi} \neq m_{\rho}\)).
Most hadronization properties by analogy with normal string fragmentation, but glueball formation new aspect, assumed $\sim 10\%$ of time (or less).
$R$-hadron interactions

$R$-hadron interactions with matter involve interesting aspects:

- $\tilde{b}/\tilde{t}/\tilde{g}$ massive $\Rightarrow$ slow-moving, $\nu \sim 0.7c$.
- In $R$-hadron rest frame the detector has $\nu \sim 0.7c$ $\Rightarrow E_{\text{kin,p}} \sim 1 \text{ GeV}$: low-energy (quasi)elastic processes.
- Cloud of light quarks and gluons interact with hadronic rate; sparticle is inert reservoir of kinetic energy.
- Charge-exchange reactions allowed, e.g.
  \[ R^+(\tilde{g}\bar{u}\bar{d}) + n \rightarrow R^0(\tilde{g}\bar{d}\bar{d}) + p. \]
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way, 
  \[ R^+(\tilde{g}\bar{u}\bar{d}) + n \rightarrow R^0(\tilde{g}udd) + \pi^+, \]
  since (a) kinematically disfavoured ($\pi$ exceptionally light) and (b) few pions in matter.

...but part of detector simulation (GEANT), not PYTHIA.

Many BSM models contain new sectors (≡ new gauge groups and matter content). These new sectors may decouple from our own at low energy:

Hidden Valleys (secluded sectors) experimentally interesting if
- coupling not-too-weakly to our sector, and
- containing not-too-heavy particles.

Here: no attempt to construct a specific model, but to set up a reasonably generic framework.

L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091
Experimental relevance

Models only interesting if they can give observable consequences at the LHC!

A Conceptual Diagram

Energy

LEP

LHC

SM

hidden valley

Inaccessibility

Courtesy M. Strassler
Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive $\gamma_v$),
2. non-Abelian $SU(N)$, unbroken ($N^2 - 1$ massless $g_v$'s),

with matter $q_v$'s in fundamental representation.
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Three alternative production mechanisms

1. massive $Z'$: $q\bar{q} \rightarrow Z' \rightarrow q_v \bar{q}_v$,
2. kinetic mixing: $q\bar{q} \rightarrow \gamma \rightarrow \gamma_v \rightarrow q_v \bar{q}_v$,
3. massive $F_v$ charged under both SM and hidden group, so e.g. $gg \rightarrow F_v \bar{F}_v$. Subsequent decay $F_v \rightarrow f q_v$. 
**Showers**

*Interleaved shower* in QCD, QED and HV sectors: emissions arranged in one common sequence of decreasing emission $p_\perp$ scales.

**HV $U(1)$**: add $q_v \rightarrow q_v \gamma_v$ and $F_v \rightarrow F_v \gamma_v$.

**HV $SU(N)$**: add $q_v \rightarrow q_v g_v$, $F_v \rightarrow F_v g_v$ and $g_v \rightarrow g_v g_v$.

Recoil effects in visible sector also of invisible emissions!
Hidden Valley particles may remain invisible, or

- **Broken $U(1)$**: $\gamma_v$ acquire mass, radiated $\gamma_v$s decay back, $\gamma_v \rightarrow \gamma \rightarrow f\bar{f}$ with BRs as photon ($\Rightarrow$ lepton pairs!)
- **$SU(N)$**: hadronization in hidden sector, with full string fragmentation setup, permitting up to 8 different $q_v$ flavours and 64 $q_v\bar{q}_v$ mesons, but for now assumed degenerate in mass, so only distinguish
  - off-diagonal, flavour-charged, stable & invisible
  - diagonal, can decay back $q_v\bar{q}_v \rightarrow f\bar{f}$

Even when tuned to same average activity, hope to separate $U(1)$ and $SU(N)$:

![Graphs showing distributions](image-url)
QCD physics tools can be essential also for BSM searches!
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...and, hopefully, for upcoming discoveries!