QCD for BSM in PYTHIA

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QCD at LHC

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,

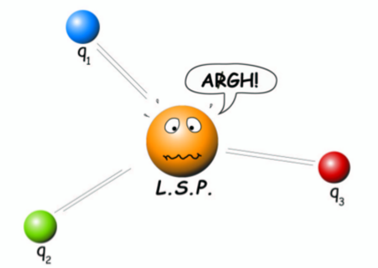
all implemented in PYTHIA 8.

1. *R*-parity violation in SUSY

Baryon number violation (BNV) is allowed in SUSY superpotential

$$W_{\mathrm{BNV}} = \lambda''_{ijk}\epsilon_{abc}\overline{U}_{ia}\overline{D}_{jb}\overline{D}_{kc}$$

(where ijk = generation, abc = colour).
Alternatively lepton number violation, but proton unstable if both.



λ''_{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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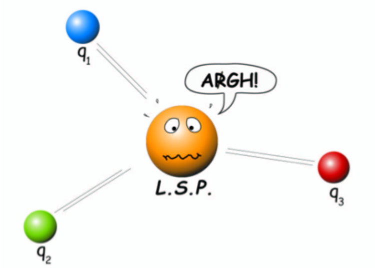

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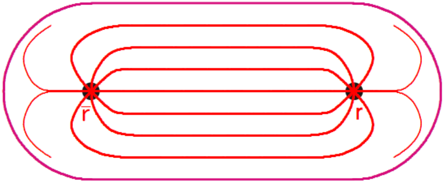
What about showers and hadronization in decays?

P. Skands & TS, Nucl. Phys. B659 (2003) 243; N. Desai & P. Skands, in preparation

The Lund string

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

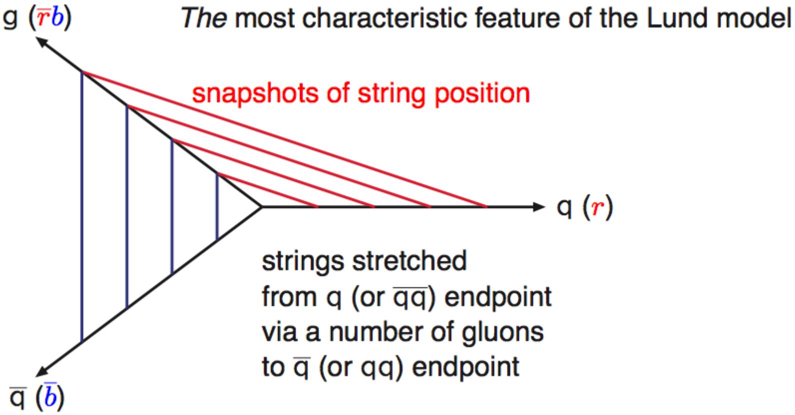


by self-interactions among soft gluons in the "vacuum".

Gives linear confinement with string tension:
$F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

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

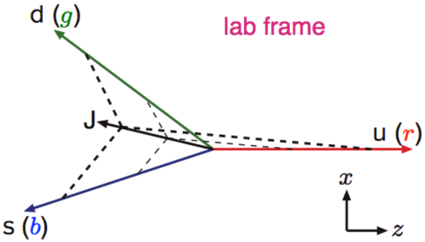


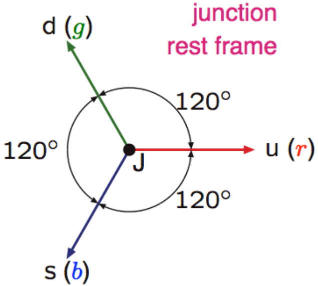
Gluon = kink on string, carrying energy and momentum

Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, $\rightarrow 2$ for $N_C \rightarrow \infty$

The junction

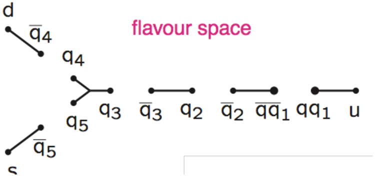
What string topology for 3 quarks in overall colour singlet?
One possibility is to introduce a **junction** (Artru, 't Hooft, ...).



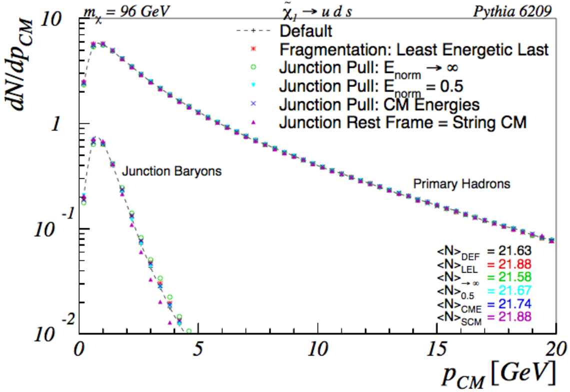


Junction rest frame = where string tensions $\mathbf{T}_i = \kappa\, \mathbf{p}_i / |\mathbf{p}_i|$ balance
$= 120^\circ$ separation between quark directions.
This is not the CM frame where momenta $\mathbf{p}_i$ balance,
but in BNV decay no collinear singularity between quarks,
so normally junction is slowly moving in LSP rest frame.

Junction hadronization

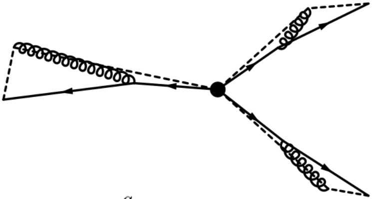


Each string piece can break, mainly to give mesons. Always one baryon around junction; junction "carries" baryon number.

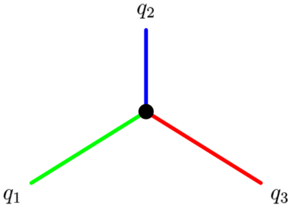


Junction baryon slow $\Rightarrow$ "smoking-gun" signal.

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.

2. *R*-hadron motivation

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. $\tilde{g} \to \tilde{q}\overline{q} \to q\tilde{\chi}\overline{q}$.

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.

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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 $\tilde{b}$.

R-hadron states

A number of states predefined:

$\tilde{\mathrm{b}}\bar{\mathrm{d}}$	$\tilde{\mathrm{b}}\mathrm{ud}_1$	$\tilde{\mathrm{t}}\bar{\mathrm{d}}$	$\tilde{\mathrm{t}}\mathrm{ud}_1$	$\tilde{\mathrm{g}}\mathrm{g}$	$\tilde{\mathrm{g}}\mathrm{c}\bar{\mathrm{d}}$	$\tilde{\mathrm{g}}\mathrm{c}\bar{\mathrm{b}}$	$\tilde{\mathrm{g}}\mathrm{suu}$	$\tilde{\mathrm{g}}\mathrm{csu}$
$\tilde{\mathrm{b}}\bar{\mathrm{u}}$	$\tilde{\mathrm{b}}\mathrm{uu}_1$	$\tilde{\mathrm{t}}\bar{\mathrm{u}}$	$\tilde{\mathrm{t}}\mathrm{uu}_1$	$\tilde{\mathrm{g}}\mathrm{d}\bar{\mathrm{d}}$	$\tilde{\mathrm{g}}\mathrm{c}\bar{\mathrm{u}}$	$\tilde{\mathrm{g}}\mathrm{b}\bar{\mathrm{b}}$	$\tilde{\mathrm{g}}\mathrm{ssd}$	$\tilde{\mathrm{g}}\mathrm{css}$
$\tilde{\mathrm{b}}\bar{\mathrm{s}}$	$\tilde{\mathrm{b}}\mathrm{sd}_0$	$\tilde{\mathrm{t}}\bar{\mathrm{s}}$	$\tilde{\mathrm{t}}\mathrm{sd}_0$	$\tilde{\mathrm{g}}\mathrm{u}\bar{\mathrm{d}}$	$\tilde{\mathrm{g}}\mathrm{c}\bar{\mathrm{s}}$	$\tilde{\mathrm{g}}\mathrm{ddd}$	$\tilde{\mathrm{g}}\mathrm{ssu}$	$\tilde{\mathrm{g}}\mathrm{bdd}$
$\tilde{\mathrm{b}}\bar{\mathrm{c}}$	$\tilde{\mathrm{b}}\mathrm{sd}_1$	$\tilde{\mathrm{t}}\bar{\mathrm{c}}$	$\tilde{\mathrm{t}}\mathrm{sd}_1$	$\tilde{\mathrm{g}}\mathrm{u}\bar{\mathrm{u}}$	$\tilde{\mathrm{g}}\mathrm{c}\bar{\mathrm{c}}$	$\tilde{\mathrm{g}}\mathrm{udd}$	$\tilde{\mathrm{g}}\mathrm{sss}$	$\tilde{\mathrm{g}}\mathrm{bud}$
$\tilde{\mathrm{b}}\bar{\mathrm{b}}$	$\tilde{\mathrm{b}}\mathrm{su}_0$	$\tilde{\mathrm{t}}\bar{\mathrm{b}}$	$\tilde{\mathrm{t}}\mathrm{su}_0$	$\tilde{\mathrm{g}}\mathrm{d}\bar{\mathrm{s}}$	$\tilde{\mathrm{g}}\mathrm{d}\bar{\mathrm{b}}$	$\tilde{\mathrm{g}}\mathrm{uud}$	$\tilde{\mathrm{g}}\mathrm{cdd}$	$\tilde{\mathrm{g}}\mathrm{buu}$
$\tilde{\mathrm{b}}\mathrm{dd}_1$	$\tilde{\mathrm{b}}\mathrm{su}_1$	$\tilde{\mathrm{t}}\mathrm{dd}_1$	$\tilde{\mathrm{t}}\mathrm{su}_1$	$\tilde{\mathrm{g}}\mathrm{u}\bar{\mathrm{s}}$	$\tilde{\mathrm{g}}\mathrm{u}\bar{\mathrm{b}}$	$\tilde{\mathrm{g}}\mathrm{uuu}$	$\tilde{\mathrm{g}}\mathrm{cud}$	$\tilde{\mathrm{g}}\mathrm{bsd}$
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						$\tilde{\mathrm{g}}\mathrm{sud}$	$\tilde{\mathrm{g}}\mathrm{csd}$	$\tilde{\mathrm{g}}\mathrm{bss}$

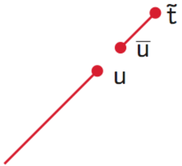
Approximate mass spectrum:

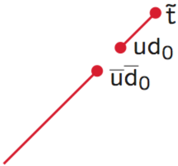
$$m_{\mathrm{hadron}} = \sum_i m_i + k \sum_{i \neq j} \frac{\langle \mathbf{F}_i \cdot \mathbf{F}_j \rangle \langle \mathbf{S}_i \cdot \mathbf{S}_j \rangle}{m_i m_j}$$

($\mathbf{F}_i$ colour vectors, $\mathbf{S}_i$ spin vectors)

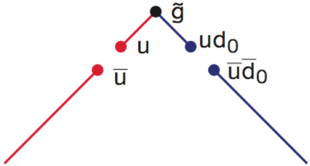
so heavy particle decouples, $m(\tilde{\mathrm{b}}\bar{\mathrm{d}}_0) \approx m(\tilde{\mathrm{b}}\bar{\mathrm{d}}_1)$ (cf. $m_\pi \neq m_{rho}$).

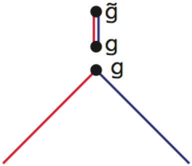
R-hadron formation





Squark fragmenting to meson or baryon





Gluino fragmenting to baryon or glueball

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:

- $\tilde{\mathrm{b}}/\tilde{\mathrm{t}}/\tilde{\mathrm{g}}$ massive $\Rightarrow$ slow-moving, $v \sim 0.7c$.
- In R-hadron rest frame the detector has $v \sim 0.7c$
  $\Rightarrow E_{\mathrm{kin,p}} \sim 1$ 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.
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{d}\overline{\mathrm{d}}) + \mathrm{p}$.
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{udd}) + \pi^+$,
  since (a) kinematically disfavoured (π exceptionally light)
  and (b) few pions in matter.

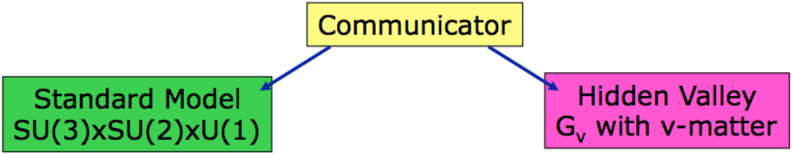
. . . but part of detector simulation (GEANT), not PYTHIA.

A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1

3. Hidden Valleys: motivation

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .

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



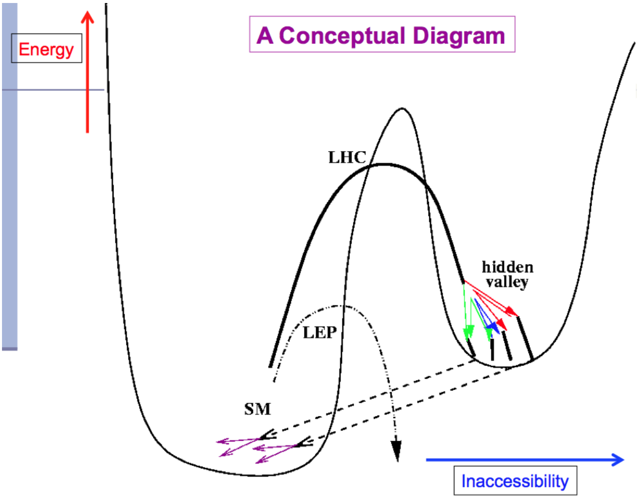
Hidden Valleys (secluded sectors) experimentally interesting if

- 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



Courtesy
M. Strassler

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

Production

Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive γ_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

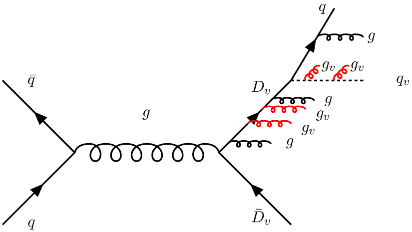
1. massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive F_v charged under both SM and hidden group, so e.g. $\mathrm{gg} \to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

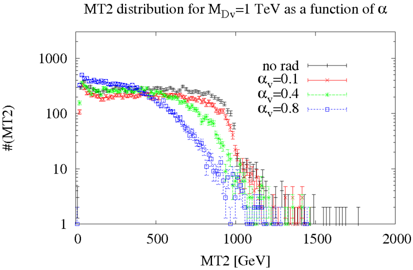
Showers

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

HV $U(1)$: add $\mathrm{q}_v \to \mathrm{q}_v \gamma_v$ and $\mathrm{F}_v \to \mathrm{F}_v \gamma_v$.

HV $SU(N)$: add $\mathrm{q}_v \to \mathrm{q}_v \mathrm{g}_v$, $\mathrm{F}_v \to \mathrm{F}_v \mathrm{g}_v$ and $\mathrm{g}_v \to \mathrm{g}_v \mathrm{g}_v$.



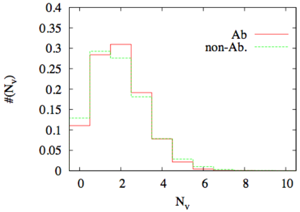


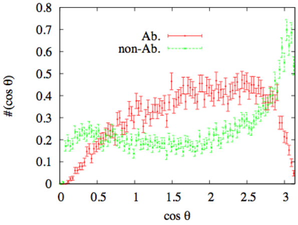
Recoil effects in visible sector also of invisible emissions!

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back, $\gamma_v \to \gamma \to \mathrm{f\bar{f}}$ 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 $\mathrm{q}_v\bar{\mathrm{q}}_v$ mesons, but for now assumed degenerate in mass, so only distinguish
  - off-diagonal, flavour-charged, stable & invisible
  - diagonal, can decay back $\mathrm{q}_v\bar{\mathrm{q}}_v \to \mathrm{f\bar{f}}$

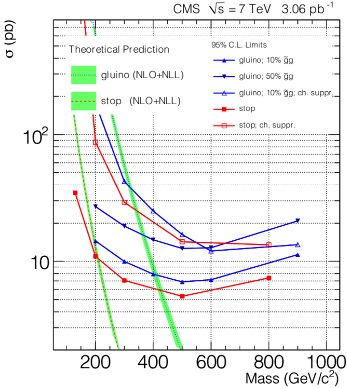
Even when tuned to same average activity, hope to separate $U(1)$ and $SU(N)$:

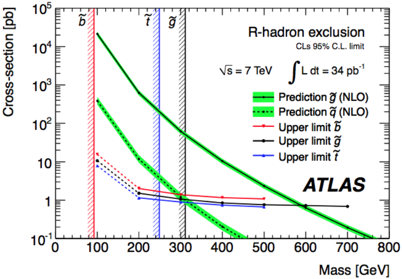




Summary

QCD physics tools can be essential also for BSM searches!





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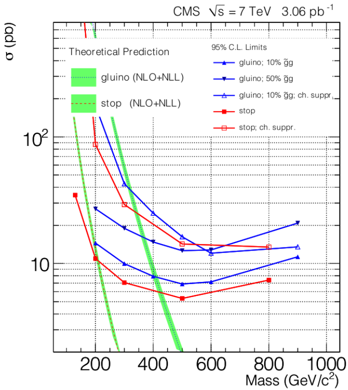

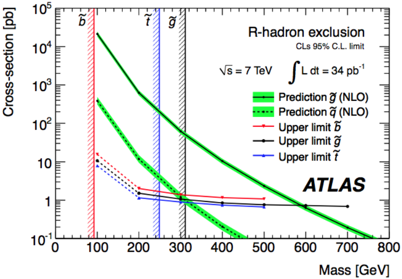

. . . and, hopefully, for upcoming discoveries!