Baryons in PYTHIA8

Leif Lönnblad
On behalf of the PYTHIA8 collaboration

Department of Physics
Lund University

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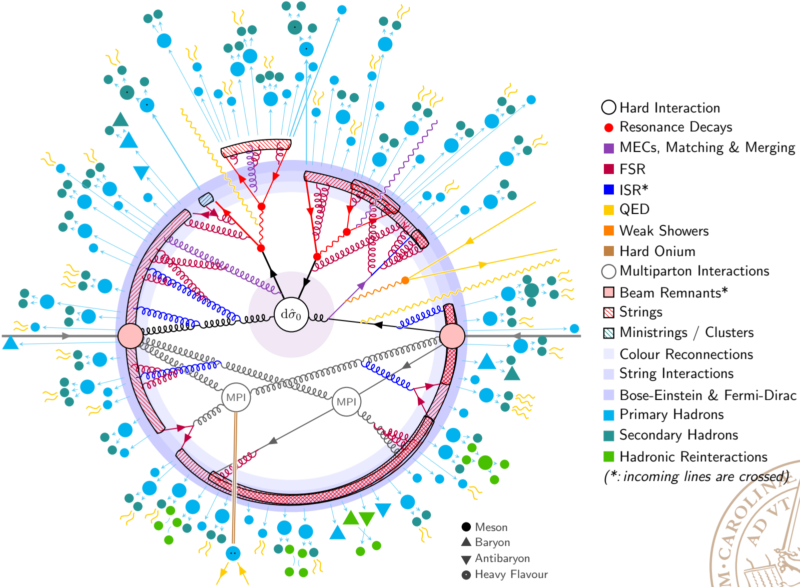
Outline

- Introduction - The Lund model
- Diquarks vs. the popcorn model
- Rope hadronisation
- Colour reconnections
- Baryons vs. gluons (jets)

[arXiv:2203.11601, A comprehensive guide to the physics and usage of PYTHIA8]


dσ̂₀
MPI
MPI
Hard Interaction
Resonance Decays
MECs, Matching & Merging
FSR
ISR*
QED
Weak Showers
Hard Onium
Multiparton Interactions
Beam Remnants*
Strings
Ministrings / Clusters
Colour Reconnections
String Interactions
Bose-Einstein & Fermi-Dirac
Primary Hadrons
Secondary Hadrons
Hadronic Reinteractions
(*: incoming lines are crossed)
Meson
Baryon
Antibaryon
Heavy Flavour

The Lund model

All partons in an event is connected with (one-dimensional, massless relativistic) string pieces.

As partons separates, energy is stored in the strings, with tension $\kappa \approx 1$ GeV/fm.

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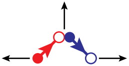
A virtual $q\bar{q}$ pair can neutralise the field and use the released string tension to tunnel on-shell and break the string, with probability

$$P \propto e^{-\frac{\pi(m_q^2+p_\perp^2)}{\kappa}}$$

Operationally in PYTHIA, hadrons are chopped off sequentially from string ends. Left–right symmetry constrains the form of the resulting fragmentation function.

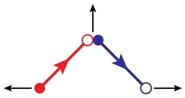
$$p(z) \propto \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

The role of Gluons



- A gluon act like a kink on the string
- As a gluon is connected with two string pieces,
- it looses energy faster than a quark ...
- ...and will eventually stop ...
- ...stretching out new string region.

The role of Gluons



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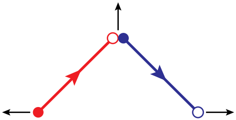

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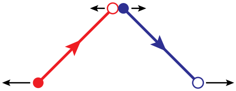

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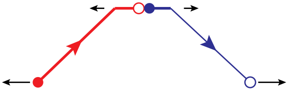

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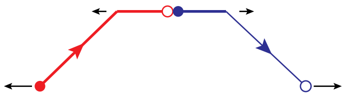

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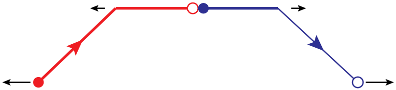

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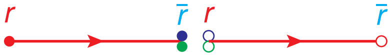
Diquarks and Popcorn

The default way of producing baryons in PYTHIA8 is to have string breaking due to have virtual diquark–anti-diquark pairs tunnelling out to become on-shell.

Diquarks and Popcorn



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This would give strong $B\bar{B}$ correlations.

- What happens if we have a $q\bar{q}$ fluctuation that does ***not*** break the colour field?
- If the quark moves in the original quark direction, there is no net force acting on it, so it could live for a while
- long enough for a new fluctuation to break the string
- maybe even twice, reducing the $B\bar{B}$ correlations.

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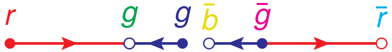

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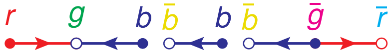

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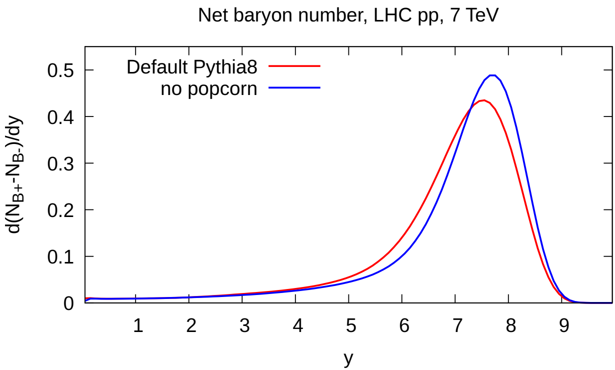

Net baryon number, LHC pp, 7 TeV
Default Pythia8
no popcorn
d(N_B+-N_B-)/dy
y
0
0.1
0.2
0.3
0.4
0.5
1
2
3
4
5
6
7
8
9

Multiple Scattering and junctions

The Multi-parton scattering model in PYTHIA allows for several strings connecting to the proton remnant.

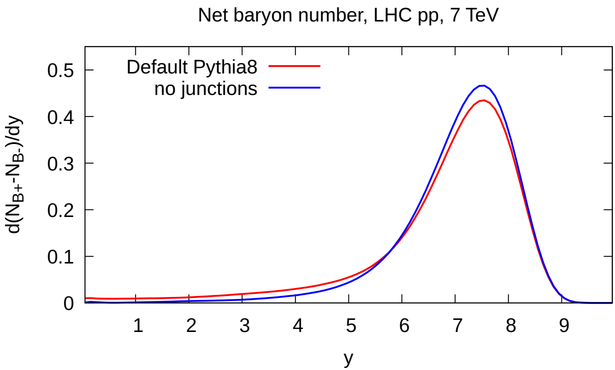
If you kick out

- a valence quark, you get a diquark remnant
- a gluon ⇒ quark + diquark
- an anti-quark ⇒ two quarks + diquark
- two gluons ⇒ quark + diquark
- two valence quarks ⇒ quark (connected via a junction)
- ...

PYTHIA hadronises junctions one juction leg at the time, starting with the two lowest energy ones (in the Junction rest frame).

After these two, the longest leg gets a diquark end and is hadronised as a normal string.

Junction hadronisation has been a bit shaky in events with many junctions, but that will be improved in the upcoming release

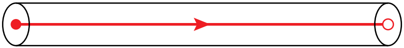

Net baryon number, LHC pp, 7 TeV
Default Pythia8
no junctions
d(N_B+-N_B-)/dy
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
y

Rope hadronisation

- The original Lund Model assumed one-dimensional strings
- In reality (on the lattice) they have a thickness $\sim 0.25 - 1$ fm
- What happens if strings (or flux tubes) overlap?

[arXiv:1412.6259]

Rope hadronisation



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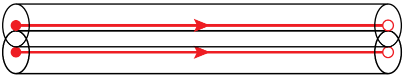


- The original Lund Model assumed one-dimensional strings
- In reality (on the lattice) they have a thickness $\sim 0.25 - 1$ fm
- What happens if strings (or flux tubes) overlap?

[arXiv:1412.6259]

For completely overlapping parallel strings we get an increased tension proportional to the second Casimir operator for the resulting colour multiplet in the string ends.

For two random parallel string we can either get an sextet or an (anti-) triplet. while for the anti-parallel case we get an octet or a singlet.

$$\kappa^{(6)} = \frac{5}{2}\kappa^{(3)}, \qquad \kappa^{(8)} = \frac{9}{4}\kappa^{(3)}$$

Breaking such a "rope" with a $q\bar{q}$ breakup will happen with an increased effective string tension, e.g.

$$\kappa_{eff} = \kappa^{(6)} - \kappa^{(3)} = \frac{3}{2}\kappa^{(3)}$$

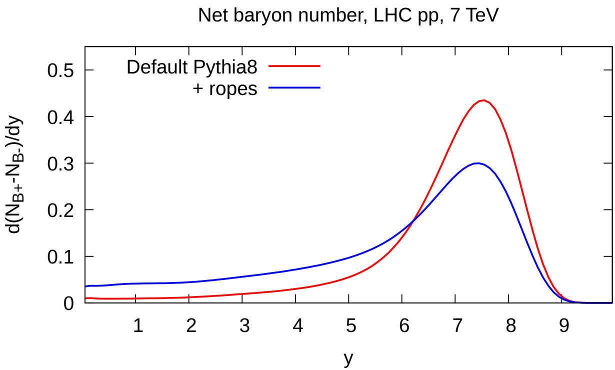
In general strings are not exactly parallel, nor are they completely overlapping, but still . . .

From the tunnelling probability

$$P \propto e^{-\frac{\pi(m_q^2+p_\perp^2)}{\kappa}}$$

We see that strange quarks will be relatively less suppressed compared to u/d.

The same will be true for diquarks - so we expect more (anti-) baryons.


Net baryon number, LHC pp, 7 TeV
Default Pythia8
+ ropes
d(N_{B+}-N_{B-})/dy
0.5
0.4
0.3
0.2
0.1
0
1
2
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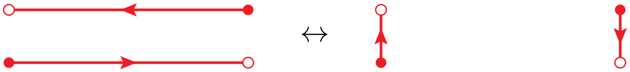
Colour reconnections

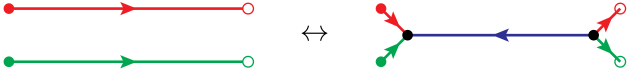
The cases where two (anti-) parallel stings forms triplets or singlets are treated with ***Colour reconnections***.

The singlet case is straight forward.



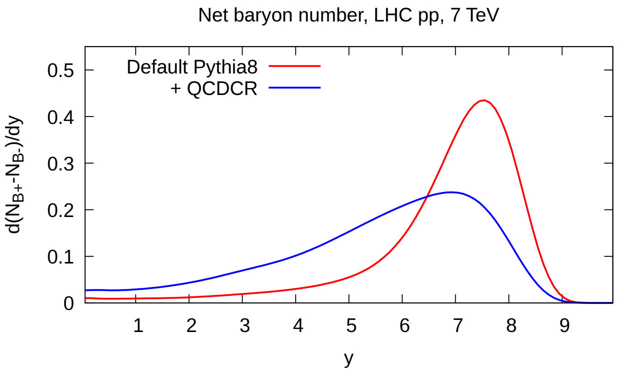
The general idea is that nature prefers shorter strings.

The anti-triplet case is trickier and is only treated in the "QCD-based model":

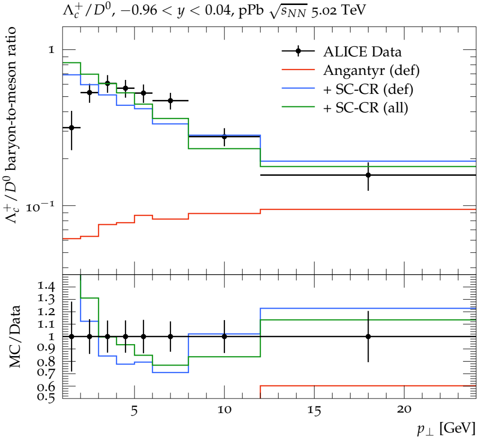


We get junctions, potentially well separated in rapidity.

[arXiv:1505.01681]


Net baryon number, LHC pp, 7 TeV
Default Pythia8
+ QCDCR
d(N_B+-N_B-)/dy
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
y

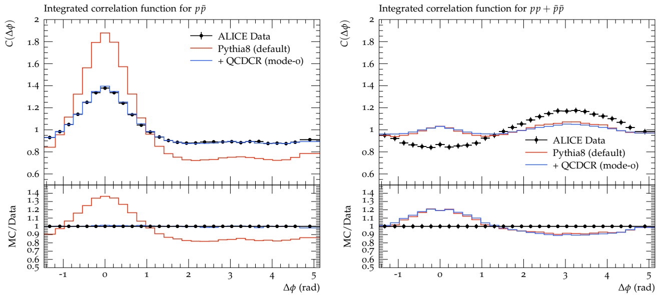
These junction reconnections also allows for more heavy baryons



[arXiv:2309.12452]

Popcorn vs. Gluons

ALICE found some weird baryon correlation effects

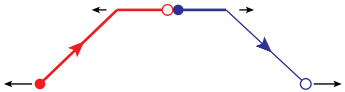


There is no jet peak for like-sign baryons!

Do baryons not like (gluon) jets?

[arXiv:1401.4306, arXiv:1612.08975]

Maybe the answer is related to the popcorn model.



- A non-breaking $q\bar{q}$ pair can still be formed
- But travelling across a kink corresponds to the quark acquiring a transverse momentum, which must be exponentially suppressed.

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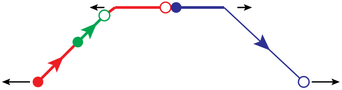

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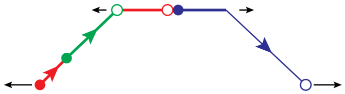

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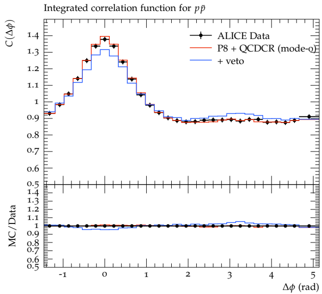
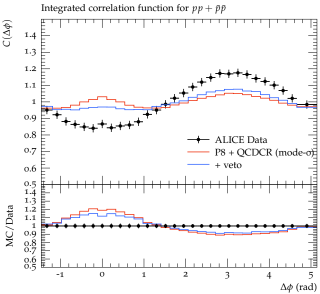
Popcorn suppression in jets is not properly implemented yet, but a toy model with a simple veto looks promising:

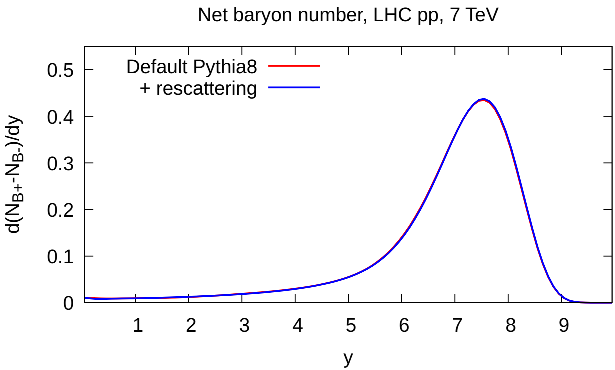




[arXiv:2309.01557]

Conclusions

- Baryon production is tricky in event generators
- There are several baryon production mechanisms in PYTHIA8
- Most of them also available for heavy ions
- And we will continue to improve them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