Soft Physics in PYTHIA8

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QCD@LHC 2024-10-10

Outline

- The Lund approach to hadronic collisions
  - Multi-parton interactions
  - String formation and hadronisation
  - Heavy ions
- The Lund model reloaded
  - Colour reconnections
  - String interactions
  - Rope hadronisation
  - Hadronic rescattering

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

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there is *soft* QCD everywhere @LHC

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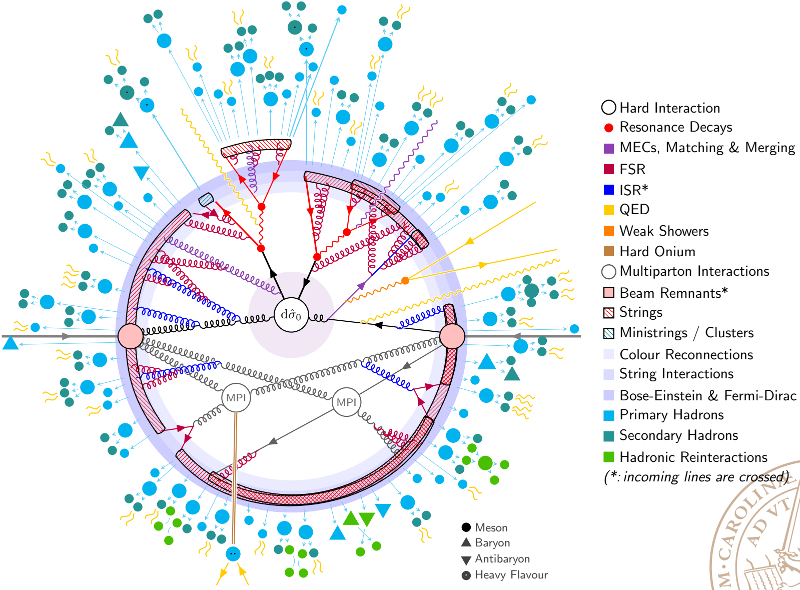
$d\hat{\sigma}_0$
MPI
MPI
Meson
Baryon
Antibaryon
Heavy Flavour
Hard Interaction
Resonance Decays
MECs, Matching & Merging
FSR
ISR*
QED
Weak Showers
Hard Onium
Multiparton Interactions
Beam Remnants*
Strings
Ministrings / Clusters
Colour Reconnections
String Interactions
Bose-Einstein & Fermi-Dirac
Primary Hadrons
Secondary Hadrons
Hadronic Reinteractions
(*: incoming lines are crossed)

(Semi-) Hard Multiple Interactions

Starting Point in PYTHIA:

$$\frac{d\sigma^H}{dk_\perp^2} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{ij}^H}{dk_\perp^2}$$

The QCD $2 \to 2$ cross section is divergent $\propto \alpha_S^2(k_\perp^2)/k_\perp^4$

$\int_{k_{\perp c}^2} d\sigma^H$ will exceed the total (non-diffractive) *pp* cross section at the LHC for $k_{\perp c} \lesssim 5$ GeV.

There are more than one partonic interaction per *pp*-collision

$$\langle N_H \rangle (k_{\perp c}) = \frac{\int_{k_{\perp c}^2} d\sigma^H}{\sigma^{\mathrm{ND}}}$$

The trick in PYTHIA is to treat everything as if it is perturbative.

$$\frac{d\hat{\sigma}_{ij}^{H}}{dk_{\perp}^{2}} \to \frac{d\hat{\sigma}_{ij}^{H}}{dk_{\perp}^{2}} \times \left(\frac{\alpha_S(k_{\perp}^{2} + k_{\perp 0}^{2})}{\alpha_S(k_{\perp}^{2})} \cdot \frac{k_{\perp}^{2}}{k_{\perp}^{2} + k_{\perp 0}^{2}} \right)^{2}$$

Where $k_{\perp 0}^{2}$ is motivated by colour screening (saturation) and is dependent on collision energy.

$$k_{\perp 0}(E_{\mathrm{CM}}) = k_{\perp 0}(E_{\mathrm{CM}}^{\mathrm{ref}}) \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^{\epsilon \sim 0.16}$$

(using handwaving about the the rise of the total cross section)

The total and non-diffractive cross section is put in by hand (or with a Donnachie—Landshoff parameterization).

- Pick a hardest scattering according to

$$\frac{1}{\sigma^{\mathrm{ND}}}\frac{d\sigma^H}{dk_\perp^2} \times \exp\left(-\int_{k_\perp^2} dq_\perp^2 \frac{1}{\sigma^{\mathrm{ND}}}\frac{d\sigma^H}{dq_\perp^2}\right)$$

- Pick an impact parameter, b, from the overlap function (high $k_\perp$ gives bias for small b).
- Generate additional scatterings with decreasing $k_\perp$ using $1/\sigma^{\mathrm{ND}}\ d\sigma^H(b)/dk_\perp$

- Most of the energy of a proton continues along the beam direction.
- Any scattering will give accelerated colour charges, and also bremsstrahlung (parton showers).
- Each parton pinches a hole in the QCD vacuum condensate, like a magnetic field line in a superconductor.
- Confinement means that each and every accelerated colour charge must be individually neutralised.

The Lund model

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

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$(d : u : s : c \quad \sim \quad 1 : 1 : 0.3 : 10^{-11})$

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

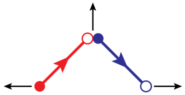
$$p(z) \propto \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

(z is the energy fraction of the string end taken by the hadron)

The role of Gluons

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

The role of Gluons



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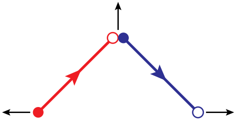

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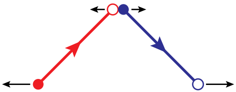

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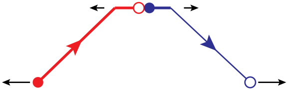

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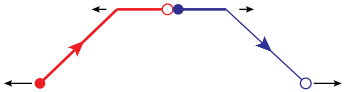

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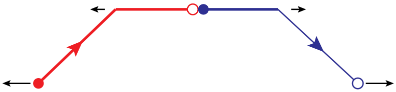

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Baryons and Popcorn

The simplest 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.

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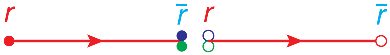

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This would give strong $B\bar{B}$ correlations.

- 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
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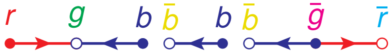

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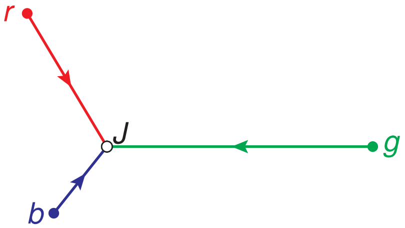
Multiple Scattering and Remnants

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)
- …

Junction hadronization



Performed in the junction rest frame, but normal string breaks.

- First the *shortest* leg
- then the second shortest
- finally the longest with a di-quark end

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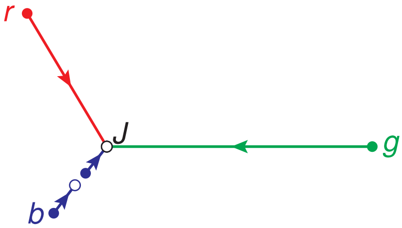

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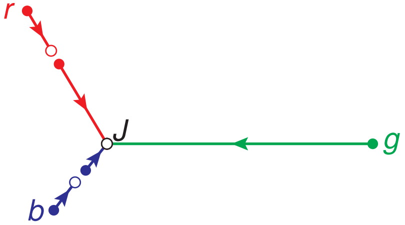

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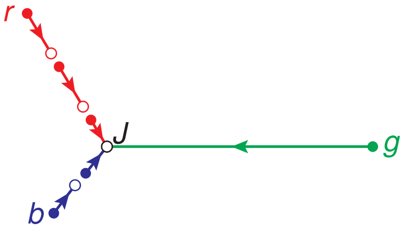

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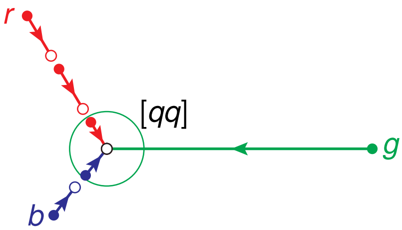

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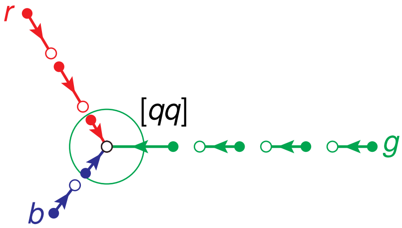

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- The sub-collisions are then simply stacked together.
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- How hot?
- How dense?

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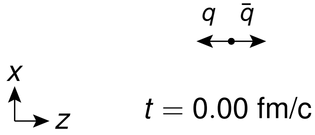

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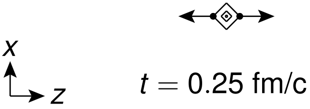

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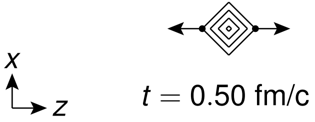

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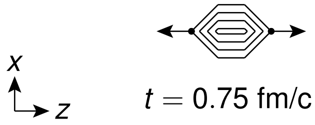

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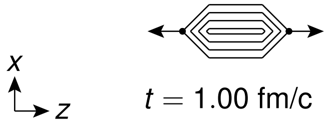

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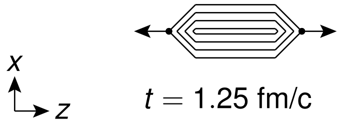

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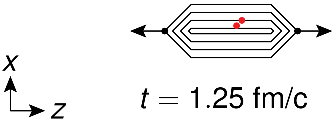

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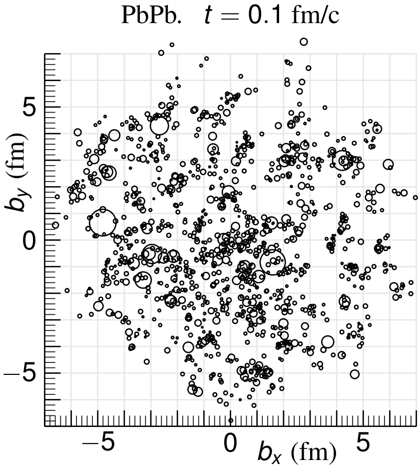
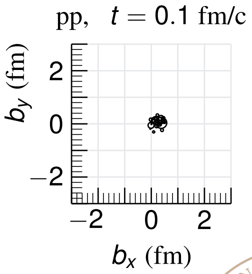
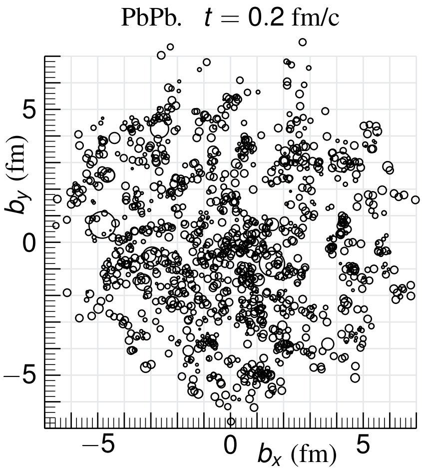
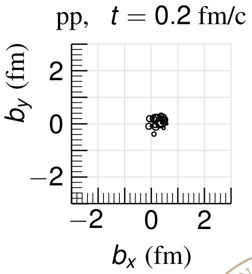

PbPb. $t = 0.1$ fm/c
b_y (fm)
b_x (fm)
5
0
−5
−5
0
5


pp, $t = 0.1$ fm/c
b_y (fm)
b_x (fm)
2
0
−2
−2
0
2


PbPb. t = 0.2 fm/c
b_y (fm)
5
0
−5
−5
0
5
b_x (fm)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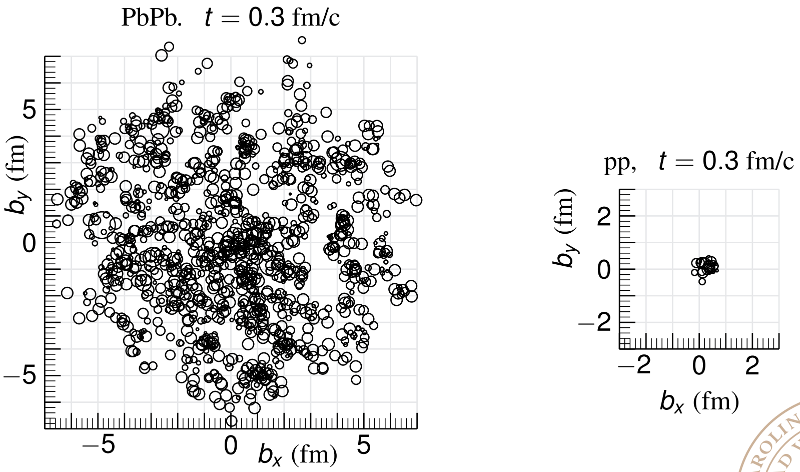
PbPb. $t = 0.3$ fm/c
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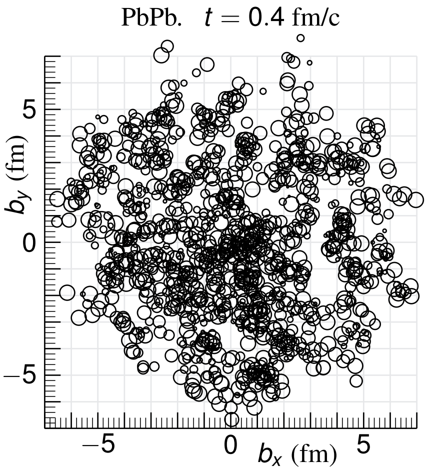
PbPb. $t = 0.4$ fm/c
b_y (fm)
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0
−5
−5
0
5
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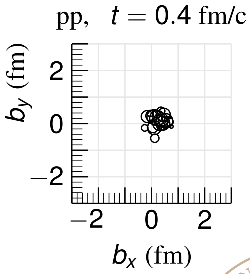
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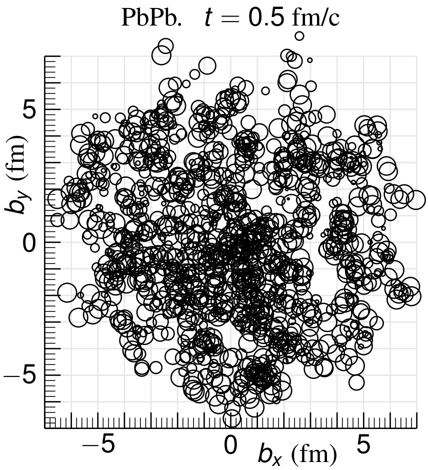
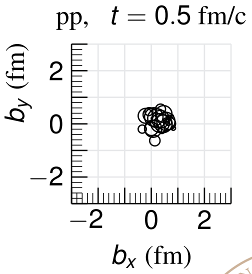

PbPb. $t = 0.5$ fm/c
b_y (fm)
b_x (fm)
5
0
−5
−5
0
5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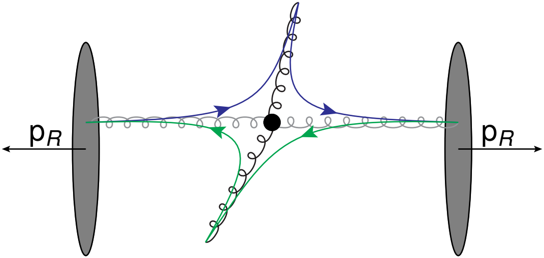

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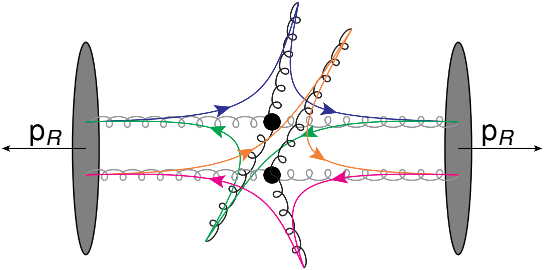

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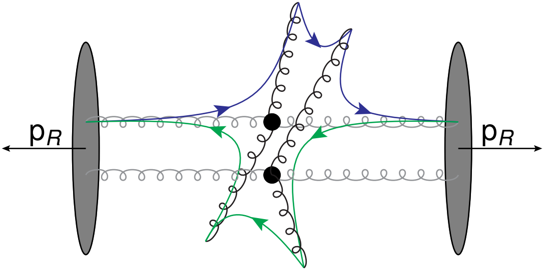

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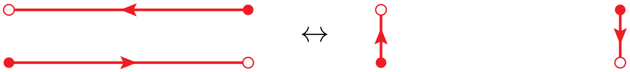
To be able to describe observables such as $\langle p_\perp \rangle (n_{\rm ch})$ we need (a lot of) colour (re-)connections.

Colour reconnections

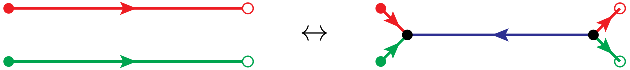
The cases where two (anti-) parallel strings forms triplets or singlets are treated with ***Colour reconnections***.

The singlet case is straight forward.



The general idea is that nature prefers shorter strings.

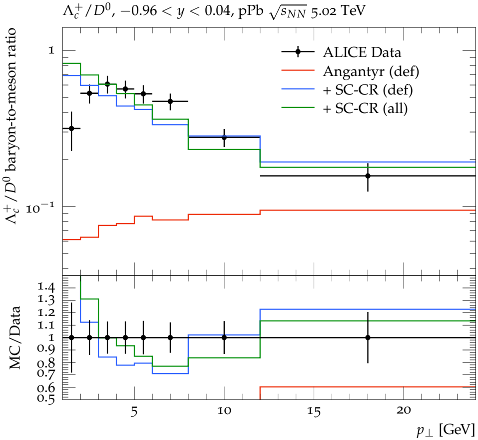
The anti-triplet case is trickier and is only treated in the "QCD-based" model:



We get junctions, potentially well separated in rapidity.

[arXiv:1505.01681]

These junction reconnections also allow for more heavy baryons



[arXiv:2309.12452]

String Interactions

- Overlapping (anti-)parallel strings may attenuate each other
- Overlapping strings may repel each other
- Overlapping strings will have an increased string tension, making it easier to produce eg. strange hadrons.

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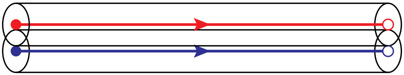

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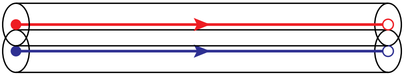


String repulsion: Shoving

The string endpoints (quarks and gluons) carry longitudinal momentum, but the string itself cannot.

The shoving between parallel strings gives a transverse push according to

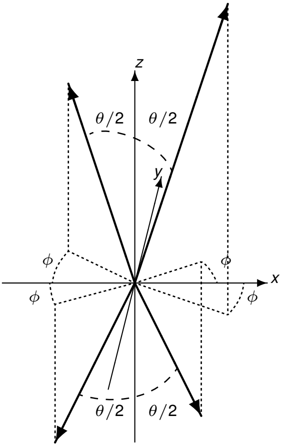
$$\frac{dp_\perp}{dt\,dz} = \frac{g\kappa\delta_\perp(t)}{R^2}\exp\left(-\frac{\delta_\perp^2(t)}{4R^2}\right).$$

This push must be parallel to both string pieces.

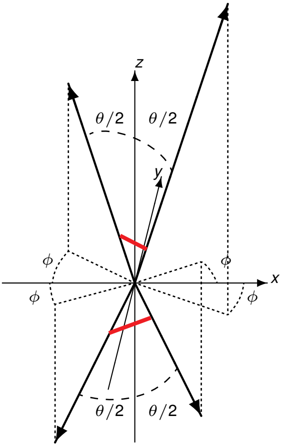
There is no frame where two random string pieces are parallel.

But there is always a frame where they lie in parallell planes at any given time.

The parallel string frame



The parallel string frame



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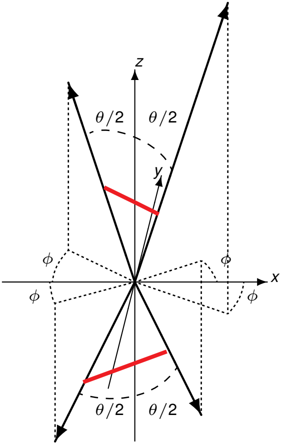

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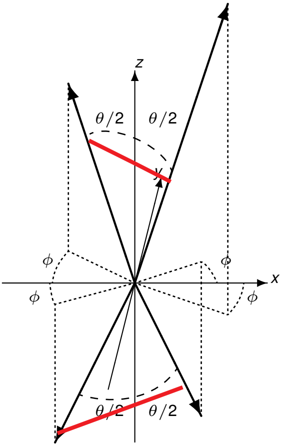
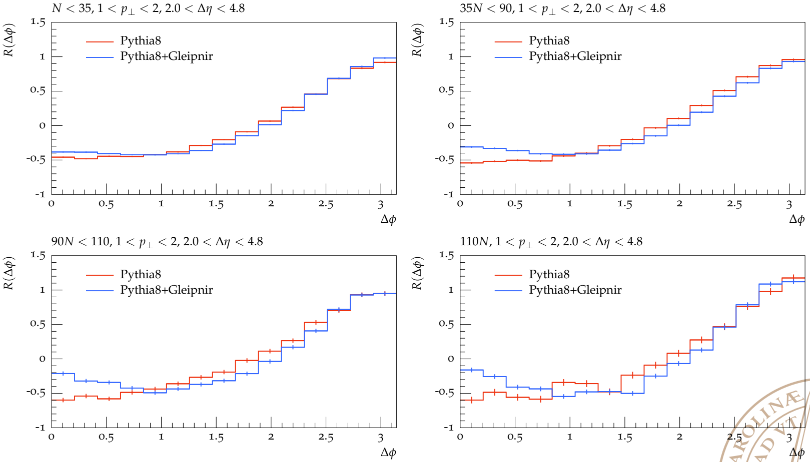


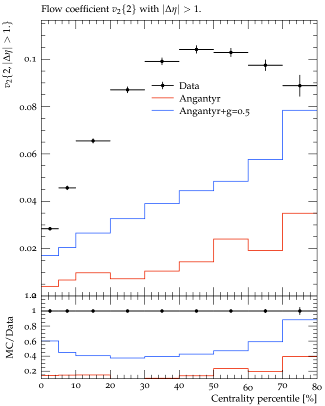
- Use (simplified) space-time information of all partons.
- Transform to parallel frame for every pair of string pieces.
- Calculate and collect small nudges, ordered in time.
- Apply the nudges to the produced primary hadrons (both position and momenta).

We have a ridge!



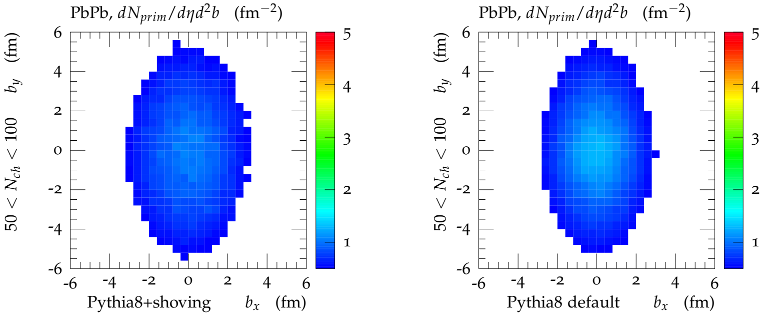
[arXiv:1009.4122]

We have v_2 in PbPb



(but not enough . . .)

[arXiv:2010.07595, arXiv:1602.01119]


PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
$50 < N_{ch} < 100$ b_y (fm)
Pythia8+shoving b_x (fm)
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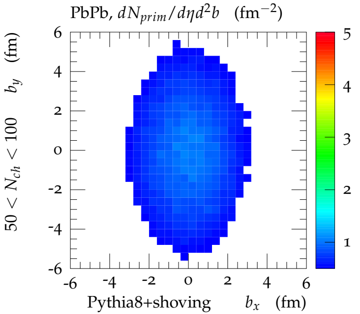
PbPb, $dN_{prim}/d\eta d^2b$ (fm^{-2})
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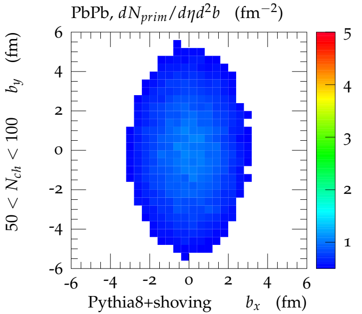
6
4
2
0
-2
-4
-6
5
4
3
2
1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6
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Rope hadronisation

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 we can use the parallel frame) ...

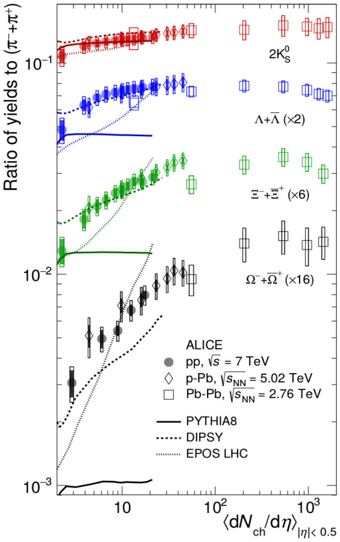
From the tunnelling probability

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

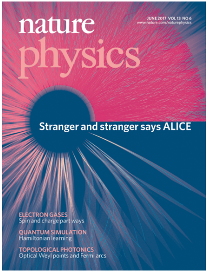
We see that strange quarks will be relatively less suppressed compared to u/d.

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

Strangeness enhancement

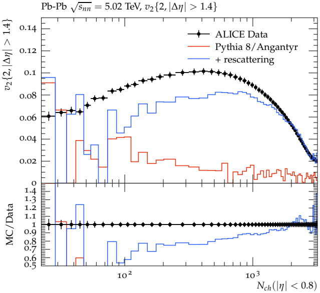


Looks like a common mechanism



Nature Phys. 13 (2017) 535-539

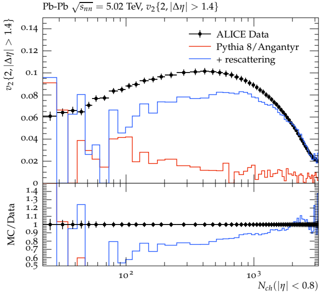
Hadronic Rescattering



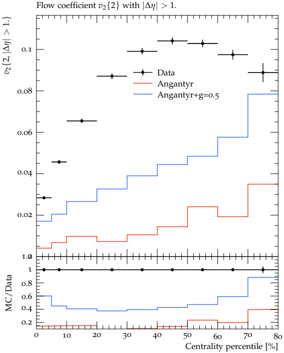
[arXiv:2103.09665]

PYTHIA8 includes a full machinery for hadron rescattering, with parametrisation of any hadronic cross section.
Including $2 \to n$ but not $3 \to n$.

Hadronic Rescattering vs. Shoving



[arXiv:2103.09665]



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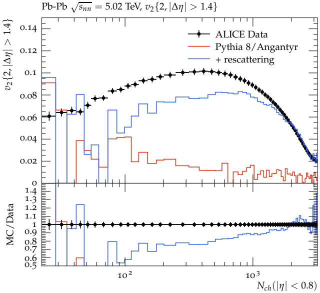

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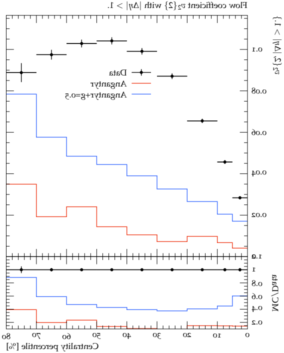

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Towards a new picture of dense systems

- Particle production is driven my multiple semi-hard parton interactions.
- Accelerated colour charges need to form colour-singlet hadrons.
- Colours can combine (reconnect) but we are left with colour fields that are confined into *fluxtubes* (strings).
- The strings repel each other causing flow (shoving).
- The remaining overlap gives increased string tension (ropes, strangeness enhancement).
- After hadronisation, the produced hadrons may rescatter (giving more flow).

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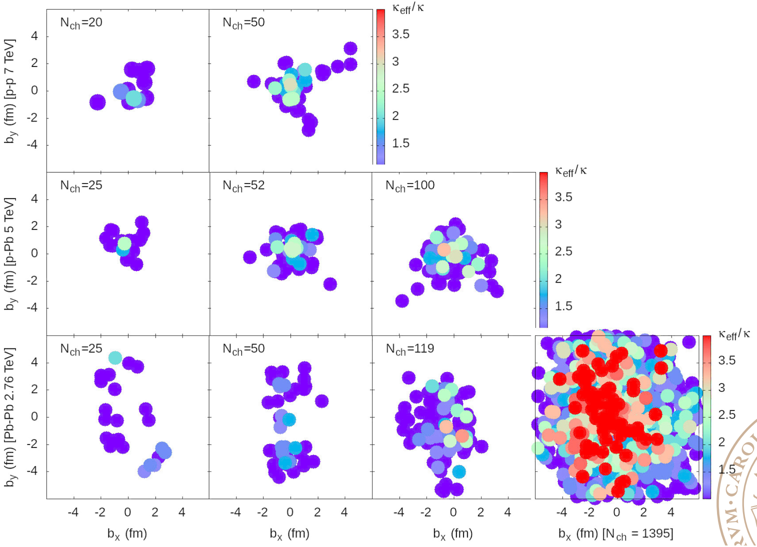
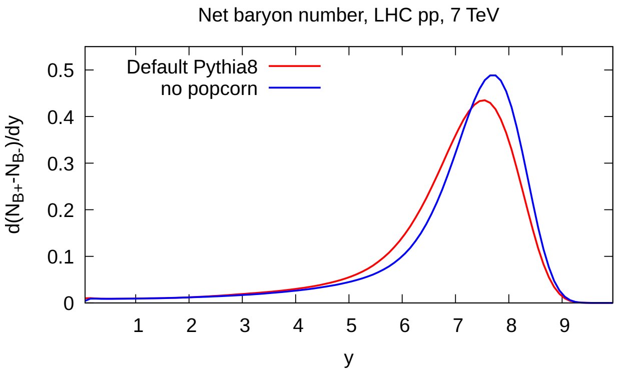
Unfortunately we are still not ready to use reconnections + shoving + ropes + rescattering together.

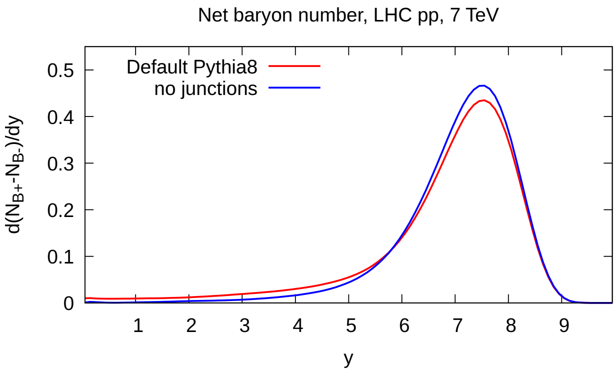
PYTHIA8 News flashes for QCD

- Quarkonium states can now be produced in the shower, using NRQCD [arXiv:2312.05203]
- String fragmentation now comes with weight variations [arXiv:2308.13459]
- Variable beams (soon also in Heavy Ions) allows for modelling cosmic rays, and could even be used in detector simulations. [arXiv:2108.03481]

pp vs. pPb vs. PbPb




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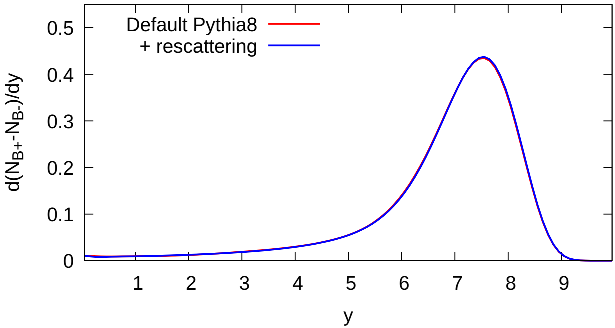
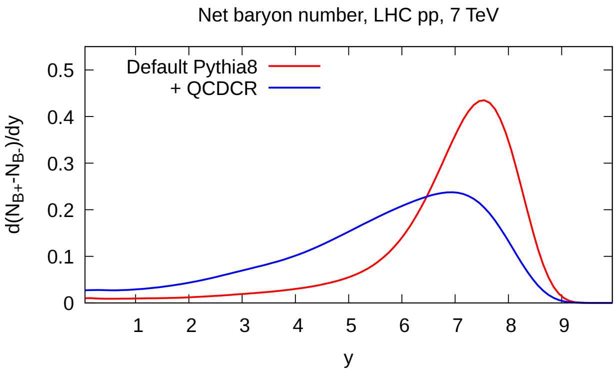
Default Pythia8
no junctions
d(NB+-NB-)/dy
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
y

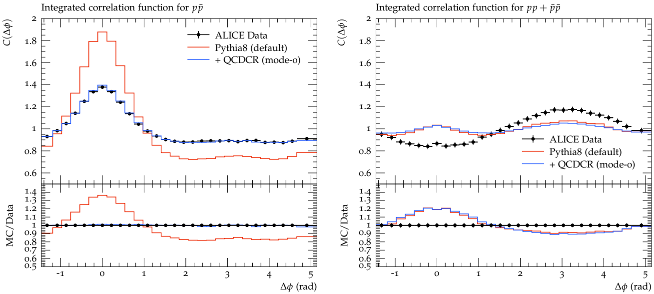
Net baryon number, LHC pp, 7 TeV




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

Popcorn vs. Gluons

ALICE found some weird baryon correlation effects

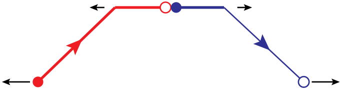


There is no jet peak for like-sign baryons!

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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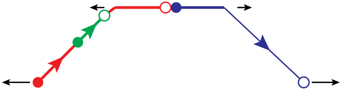

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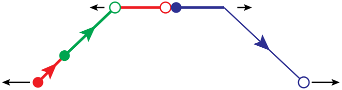

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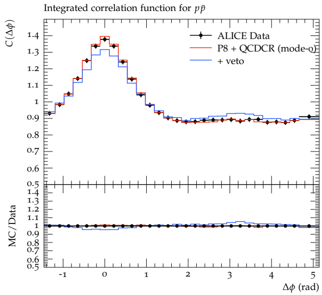
Popcorn suppression in jets is not properly implemented yet, but a toy model with a simple veto looks promising:



[arXiv:2309.01557]