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Swinging dipoles – the colour reconnection and spacetime

BY TORBJÖRN LUNDBERG 2025 SUPERVISED BY LEIF LÖNNBLAD

Outline

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Colour reconnections
Spacetime
Major swing points
Some results
Outlook

A spacetime model for the perturbative swing

"A new colour reconnection model [...] where the full spacetime separation between partons constrains the reconnection probability throughout the final-state radiative shower. [...] our objective is to introduce realistic spatially-based colour reconnections within the Angantyr model for heavy-ion collisions."
[Lundberg and Lönnblad, 2025]

- Colour reconnections, quickly
- A spacetime picture
- Our points of concern
- ...and attempt at a solution.
- Some results
- Summary and outlook

Colour reconnections

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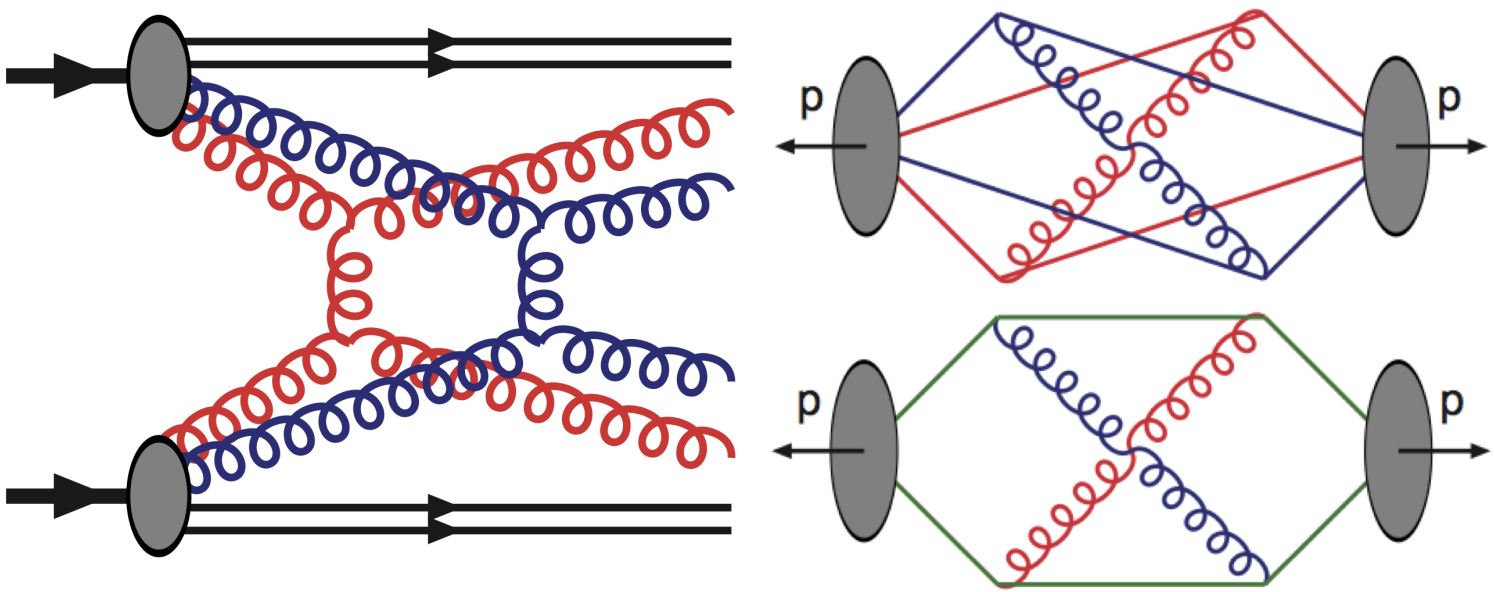
Already when the first *multi-parton interaction* (MPI) model was introduced in PYTHIA, the need for a *colour reconnection* (CR) mechanism was recognised.

[Sjöstrand and van Zijl, 1987]

"The choice of color flow structure is only a first attempt."



Adapted from talk by T. Sjöstrand.

The perturbative swing

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To get fewer hadrons, a CR scheme may minimise the *string length*:

$$\lambda_{q\bar{q}} \propto \log\left(\frac{m_{q\bar{q}}^2}{m_0^2}\right).$$

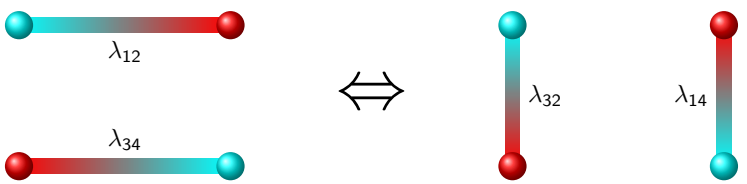
$m_{q\bar{q}}$: invariant mass of $q\bar{q}$-pair, m_0: a hadronic mass scale [Andersson et al., 1988].

Note: CR all through FSR

The perturbative swing is applied continually during the final-state radiative shower.

$$\omega = \frac{m_{12}^2 m_{34}^2}{m_{14}^2 m_{32}^2}$$

Dipoles are allowed to *swing* back and forth in between shower emissions. [Lönnblad, 1996]



Vertices and positions

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PYTHIA can assign parton vertices in spacetime. (With blurring!) [Bierlich et al., 2018a]

We use this functionality to assign a production vertex v_i to every parton i, based on the *position* of its mother at the time of emission. The position is simply

$$p_i(t) = v_i + (t - v_{it})\frac{q_i}{e_i}$$

with parton momentum and energy q_i, e_i.

The separation (squared) between two partons is

$$\delta r_{ij}^2(t) \equiv -\big(p_i(t) - p_j(t)\big)^2.$$

This will be important when replacing the momentum-only dependent relative probability!

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The parallel frame (a quick note)

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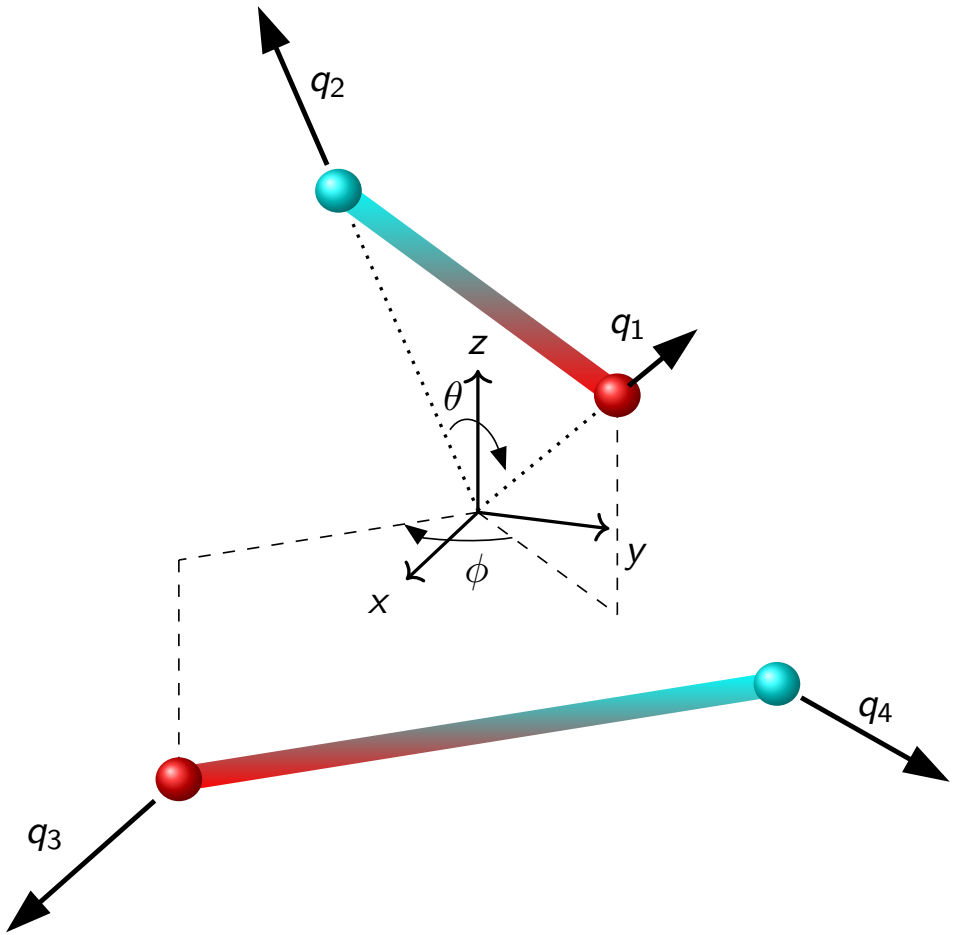

- Separation in what frame?
- Consider two dipoles.
- The parallel frame can always be found for *massless* vectors q_i. [Bierlich et al., 2021a]
- It is the "most" symmetric frame.
- Convenient to reduce to normal CR.

We have been thinking about...

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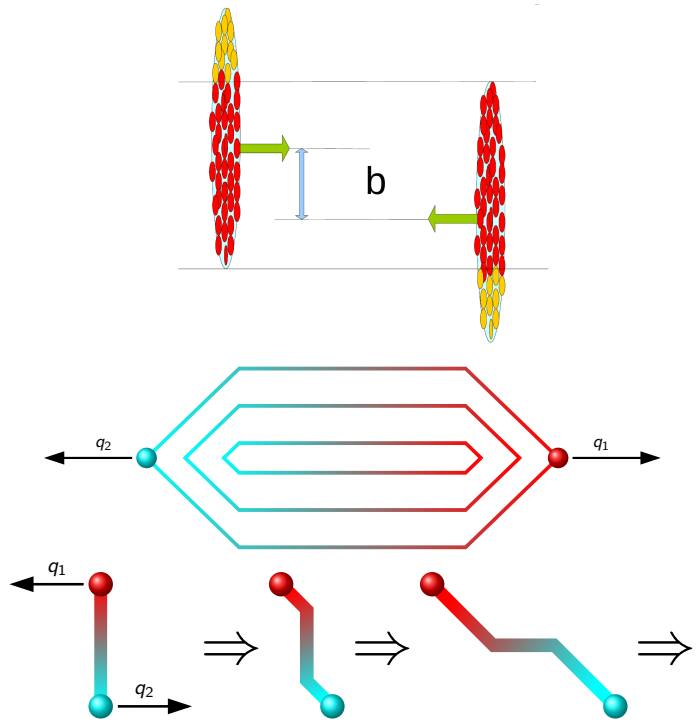
- Impact parameter (b) separation.
- *Where* dipoles come from.
- The "thickness" of a dipole.
- The expansion of reconnected colour fields.
- *When* do dipoles overlap?
- The ordering of reconnections.

Adapted from J-P. Lansberg.



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The proper time

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It can be shown in the parallel frame that

$$\tau_{12}(t) = (t - v_{12t})\sqrt{1 - \mathrm{v}_z^2}.$$

$\tau_{12}(t)$ is the *maximum proper time* along the dipole.

Note: proper time and separation

The proper time can be closely related to the physical expansion of of the field.

$$\tau_{ij}(t) \propto \sqrt{\delta r_{ij}^2(t)}.$$

Where do *dipoles* come from?

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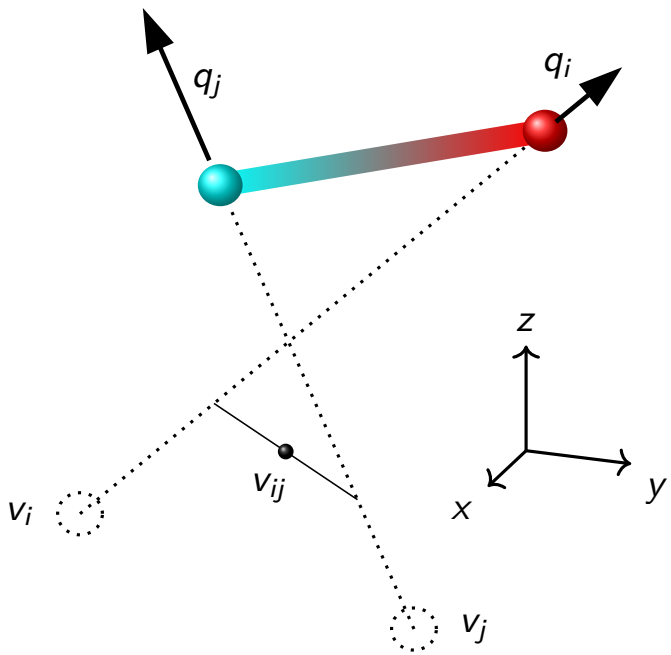
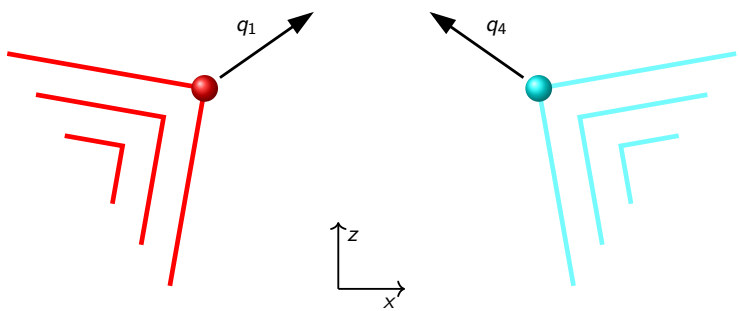
We need to think seriously about separated dipoles.



- Partons traverse the collision region.
- The dipole expands between them.
- Small scale $\rightarrow$ larger scale.

Note: dipole vertex

v_{ij} is the spacetime midpoint at the closest approach.



How do dipoles look?

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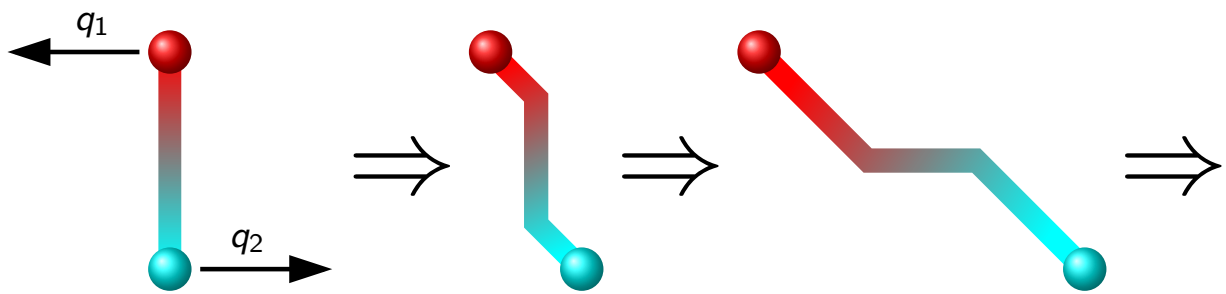
When dipole endpoints come from different spacetime vertices, dipoles are a bit weird...



Note: initial field content

There can be an initial separation (above): a "primordial" colour field $\Rightarrow \bar{\tau}_{ij}(t) = \tau_{ij}(t) + \tau_{ij,0}$.

$\tau_{ij,0}$ looses significance as a Lund string-like object forms.

How to order reconnections?

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Ordering variable

$$\tau_{ij}(t)$$

τ_{ij} (the maximum proper time along a dipole)

- is positively definite (following closest approach).
- is Lorentz invariant.
- directly gives a handle for how "long" the dipole has expanded.
- is related to the physical extension of the dipole.
- naturally provides a maximum scale for when to stop (hadronise).
- may be compared between parallel frames as well as to the inverse shower ordering variable $p_\perp$.

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The swing strength function

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...or the *weight*

$$\omega(t) \propto \frac{\max\left[\bar{\tau}_{12}(t), \tau_{12,0}\right]^2 \max\left[\bar{\tau}_{34}(t), \tau_{34,0}\right]^2}{\max\left[\bar{\tau}_{14}(t), \tau_{14,0}\right]^2 \max\left[\bar{\tau}_{32}(t), \tau_{32,0}\right]^2}$$

$[\bar{\tau}_{ij}(t) = \tau_{ij}(t) + \tau_{ij,0}]$

$\omega(t)$ is a weight in the sense that we use it in a veto algorithm to generate a time $t \to \tau$ that in turn may be used as the instance of when two dipoles will reconnect.

C.f. perturbative swing $\omega = \frac{m_{12}^2 m_{34}^2}{m_{14}^2 m_{32}^2}$.

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The final algorithm

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1. Consider all dipole pairs but for dipoles that share a parton.
2. Compute the parallel frame.
3. In this frame, veto all pairs that are disallowed to reconnect (not overlapping in τ.
4. Attempt generation of a reconnection scale τ for the pair.

During FSR shower

Compare the (inverse of the) *upcoming* reconnection scale to the shower $p_\perp$. Perform the "earliest".

Note: whenever a parton is radiated or a reconnection is performed, the dipole collection is altered. We rerun steps 1–4 above for affected dipoles.

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Multiplicities

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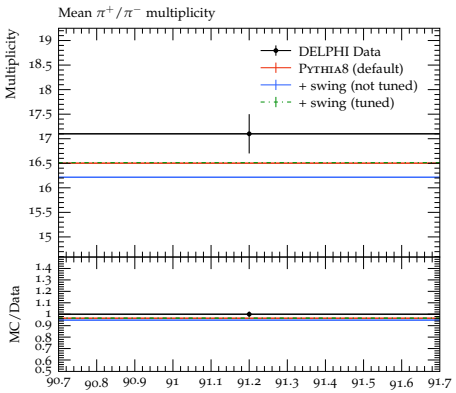

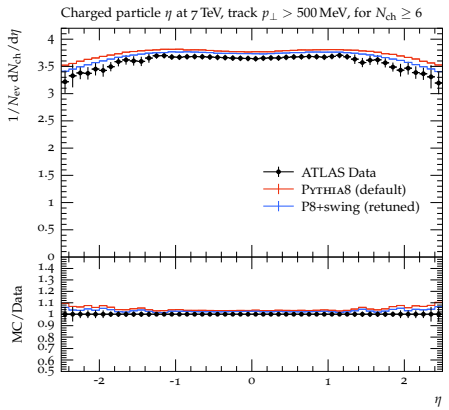

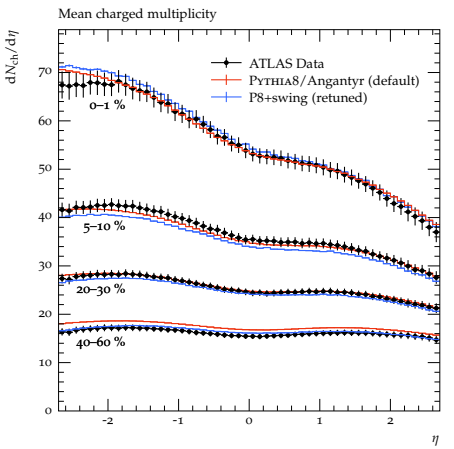

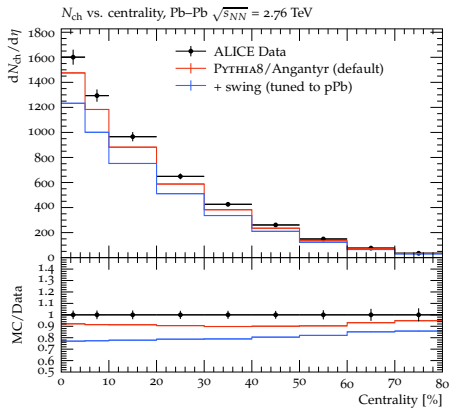

Multiplicities for

- e^+e^- [Abreu et al., 1997]
- pp [Aad et al., 2011]
- pPb [Aad et al., 2016]
- PbPb [Aamodt et al., 2011]

Note 1

We can tune multiplicities from lepton-lepton to pA!

Note 2

For central PbPb, too few particles are produced. Maybe hadronic rescattering? [Bierlich et al., 2021b]

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pT distributions

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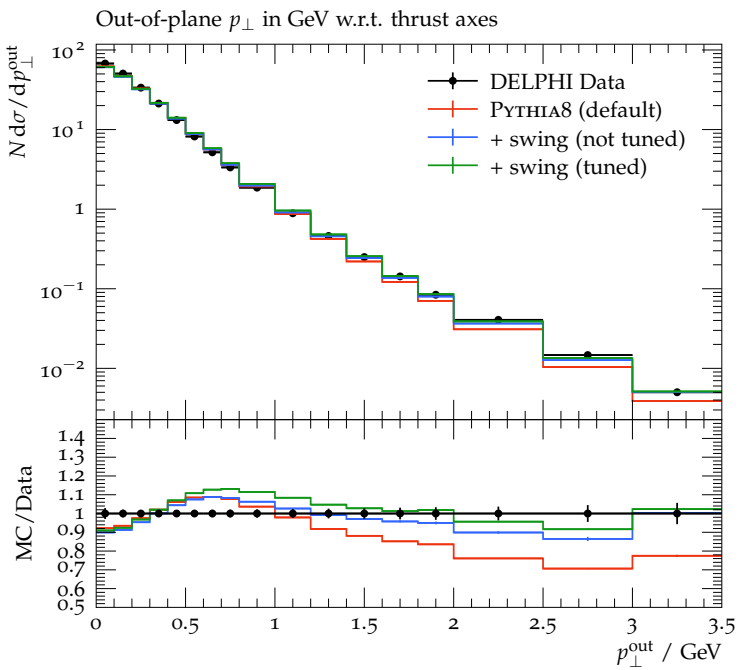
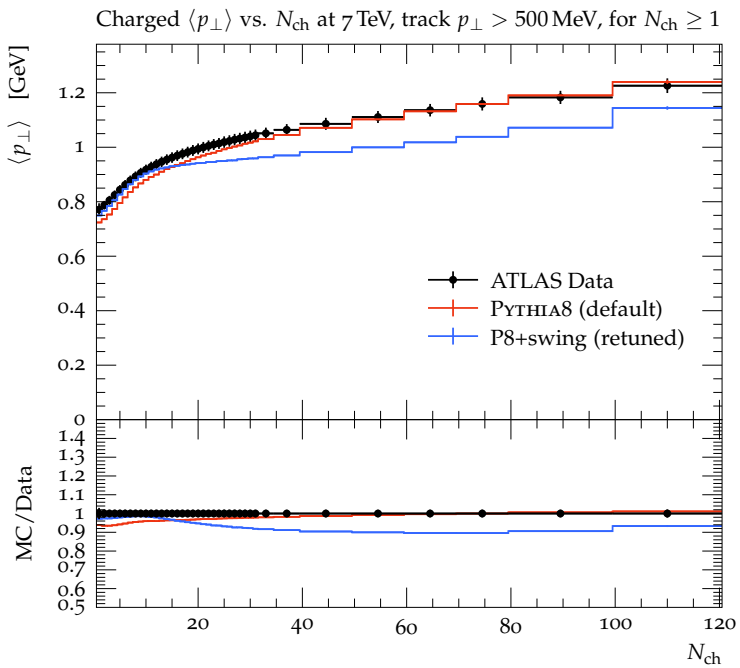
A puzzle

The transverse momentum poses an issue for our simulations.





Data from [Abreu et al., 1997, Aad et al., 2011]

So, what does this mean?

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We have:

- A new colour reconnection algorithm: the swing mechanism.
- That can be applied to any collision system: inside the FSR.
- So that dipoles from the entire collision can interact.
- Giving reasonable descriptions of multiplicities.

The prospects of the swing are to:

- Provide a novel source of collective effects.
- Include formation of junction structures $\Rightarrow$ baryons. (coming)
- Help momentum spectra with junctions. (how much?)
- Help central PbPb with hadronic rescattering effects. (enough?)
- Effects on jet shapes in heavy ion collisions?

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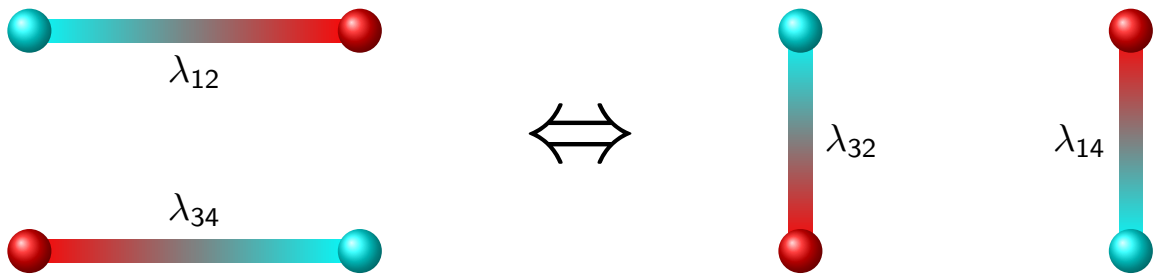
BACKUP

QCD-based colour reconnection

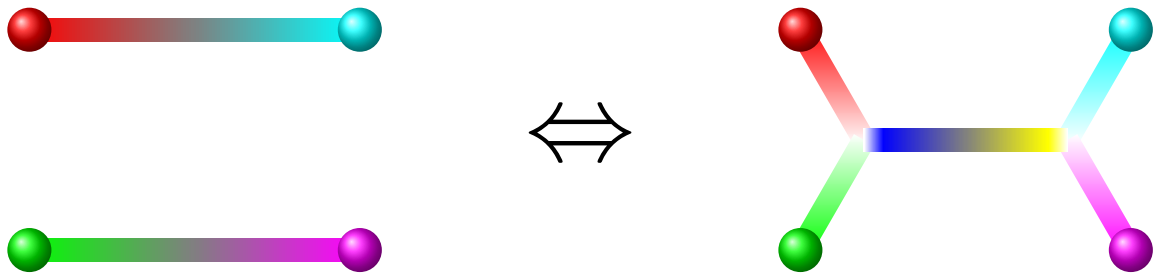
As implemented in PYTHIA, this CR scheme takes into account the SU(3) colour algebra when reconnecting.

The parton shower (of interest to us) employs the limit $N_C \to \infty$.

Not only the following reconnections



are allowed but also the formation of junction structures.



“Tuning”

Tuning is of course important: we have opted for a very rudimentary dialling of a few parameters.

- `TimeShower:alphaSvalue` 0.1365 $\rightarrow$ 0.14
- `MultipartonInteractions:pT0Ref` 2.28 $\rightarrow$ 2.60

Further, a novel mode of handling *secondary absorptive* nucleon-nucleon interactions have been used. These are, as in the default Angantyr model, simulated as *non-diffractive* Pomeron-nucleon subevent [Bierlich et al., 2018b] but with a cut so as to remove the proton remnant [Rosenkvist, 2023].

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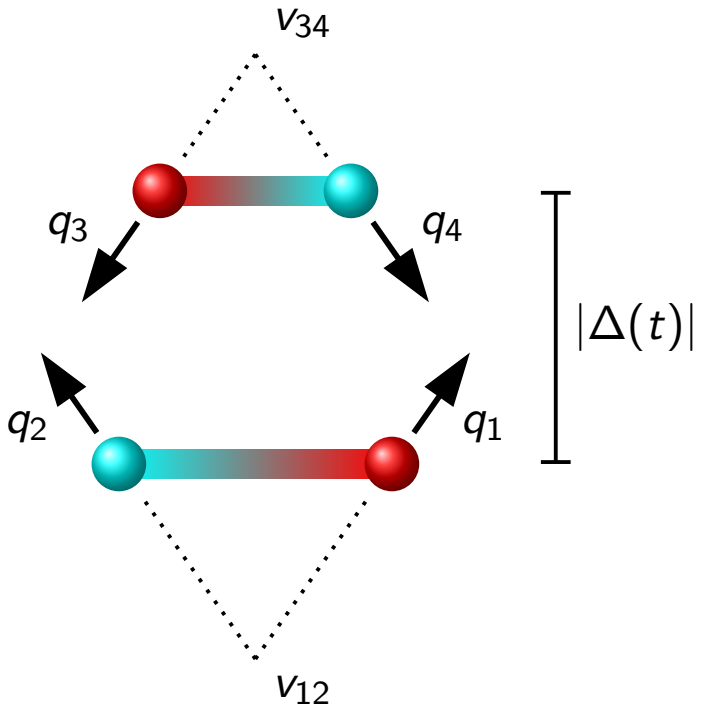
When do *dipoles* touch?



- Created apart, touching later.
- The maximum proper time gives the "thickness".
- Dipole vertices gives separation.
- Dipoles at different stages of expansion.

Note: limited interval

There is only a limited interval in t (τ) in which the two dipoles overlap and may reconnect.

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