Collectivity in the absence of QGP

Javira Altmann, Monash University

Overview

QGP "signatures" in small systems e.g. strangeness and baryon enhancement, flow

➢ QGP formation via **core-corona** picture e.g. EPOS

➢ Model **without QGP**?

Aim to consider a **purely string model**

➢ Natural transition from $e^+e^- \rightarrow pp \rightarrow AA$

➢ Challenge what is considered a QGP signature

Review of collectivity with strings arXiv:2401.07585

Review of strings can be found in recent heavy quark hadronisation review arXiv:2405.19137

Pythia - e^+e^- to pp

Angantyr - pA to AA

1. **Lund string hadronization**
2. **Colour reconnections (CR)**
3. **Shoving**
4. **Ropes**

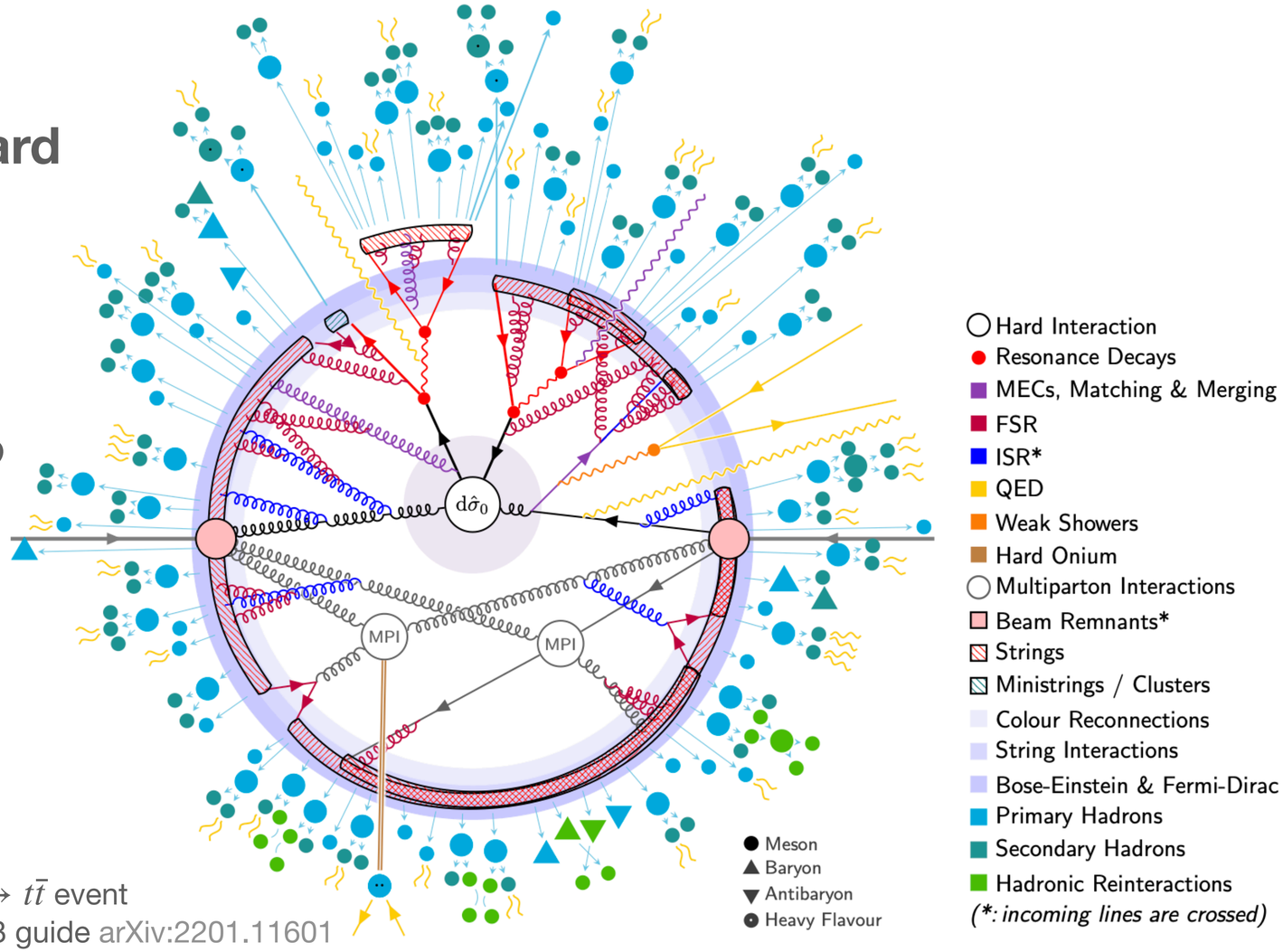
String Hadronization

Starting point is partons formed in **hard collisions** and subsequent partons radiated off in **parton showers**

At wavelengths $\sim r_{proton} \sim 1/\Lambda_{QCD}$

Need a dynamical process to ensure partons become **confined** within hadrons

i.e. non-perturbative
parton → hadron map



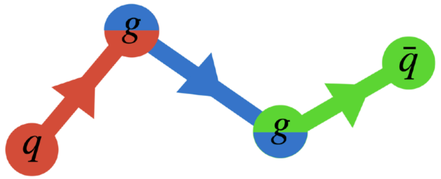
Example of $pp \to t\bar{t}$ event
From PYTHIA 8.3 guide arXiv:2201.11601

Partons → Hadrons

Strings

Colour confinement field with **constant tension**

Form between **colour-connected** partons i.e. partons that form an overall colour singlet

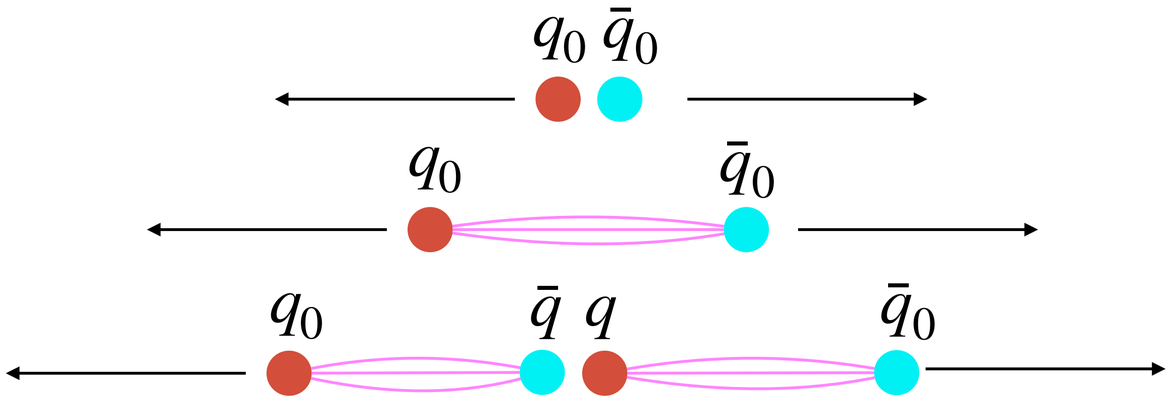


e.g. a dipole string configuration which make use of the **colour-anticolour** singlet state

Hadronization

Partons move apart and stretch the string → **string breaks**

→ creates light **quark-antiquark pairs** (or diquark-antidiquark)



standard procedure is all in momentum space

Details of the modelling

Lund symmetric fragmentation function

→ longitudinal momentum

Schwinger mechanism

→ transverse momentum

→ flavour (u/d vs s vs diquarks)

Colour Reconnections

Recent brief review on CR arXiv:2405.19137

Starting point for Monte Carlo is **leading colour** $N_C \to \infty$ i.e. unique colour singlet configurations determined by colour tracing in hard processes

CR restores missing colour correlations from $SU(3)$ assuming **string "length" minimisation**

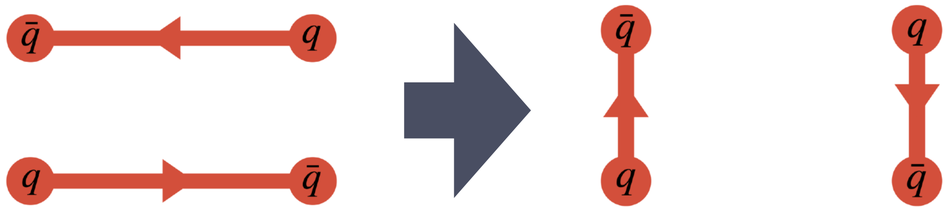
Aims to **stochastically restore** these colour correlations using $SU(3)$ algebra

$$3 \otimes \bar{3} = 8 \oplus 1 \text{ (colour-anticolour)}$$

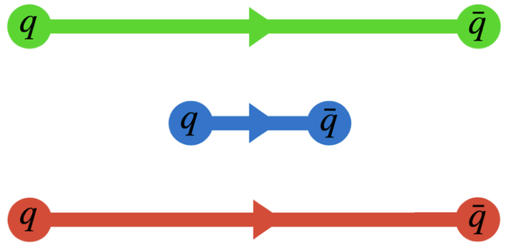
$$3 \otimes 3 = 6 \oplus \bar{3} \text{ (colour-colour)}$$

"string length" is **not** a spatial measure but measure of approx how many hadrons a string can make e.g. rapidity-type measure or invariant mass of the dipole

Dipole-type reconnection: colour-anticolour



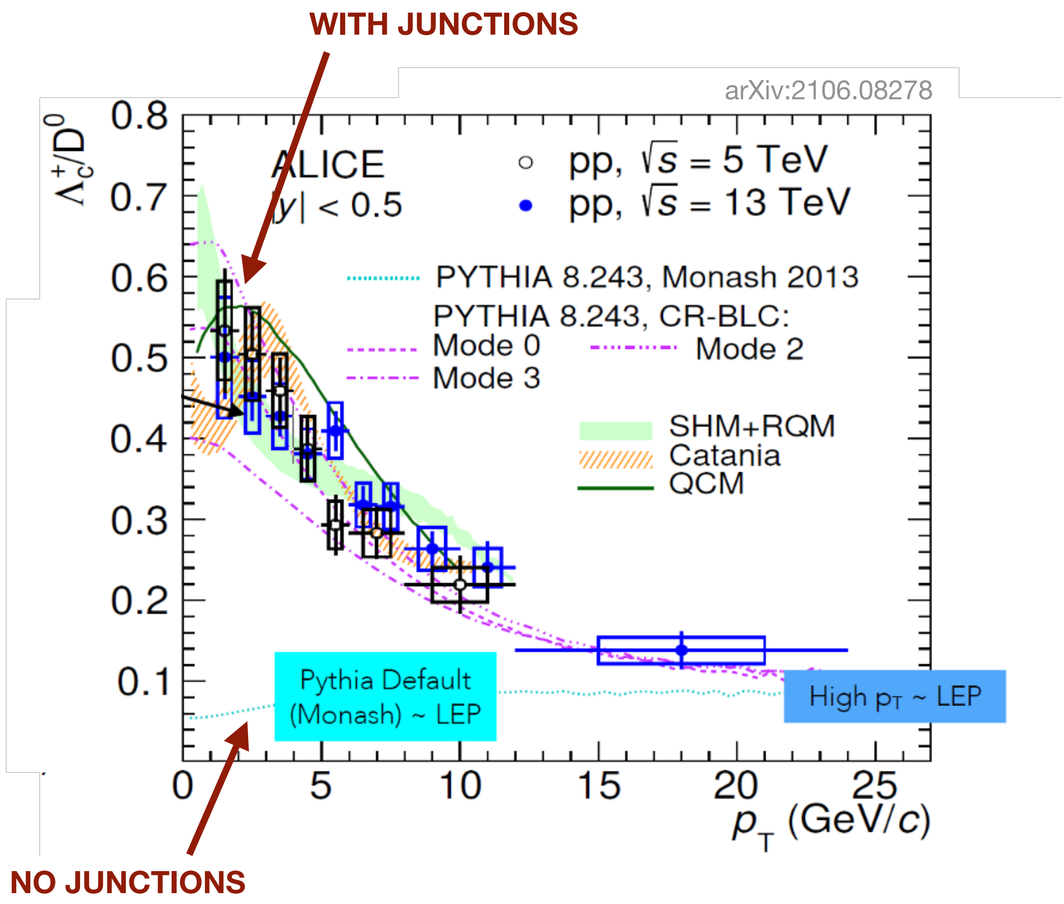
Junction-type reconnection: red-green-blue



Independently hadronising MPI does not result in **increasing** $\langle p_\perp \rangle$ **with multiplicity**

Colour Reconnections

Recent brief review on CR arXiv:2405.19137



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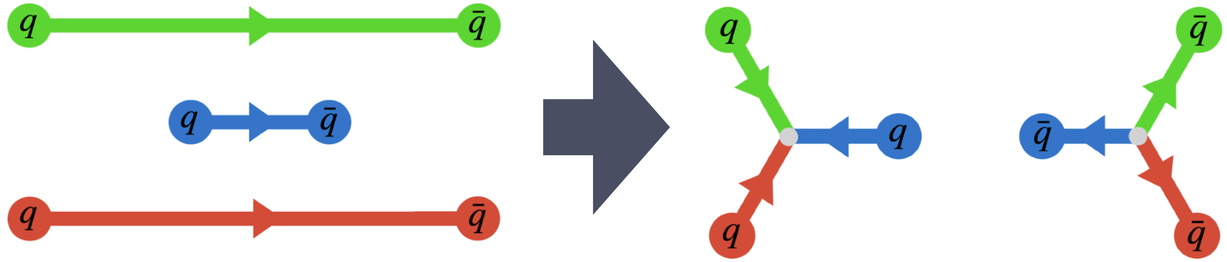

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Junctions result in baryons → increase in **baryon-to-meson ratio**

Colour Reconnections

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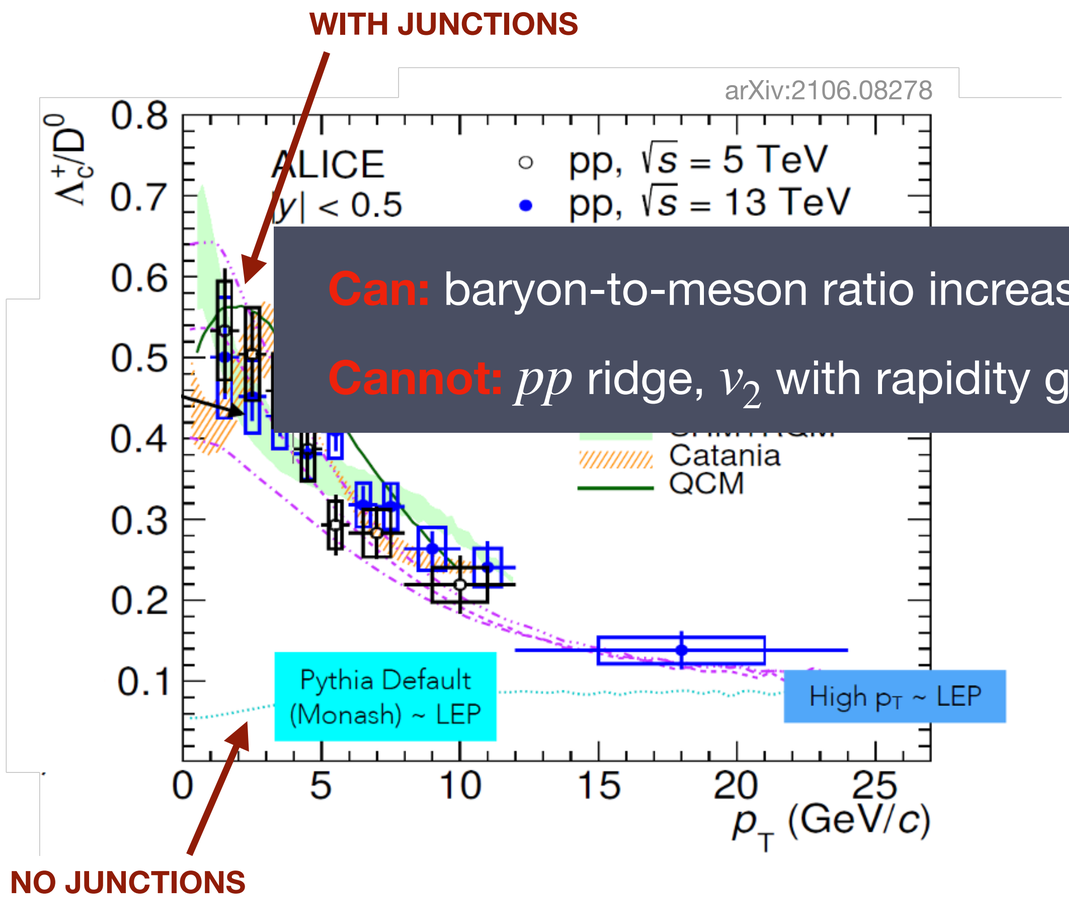
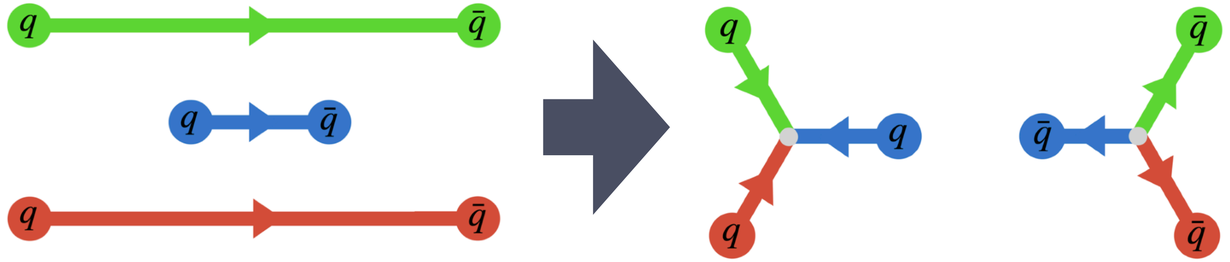


Can: baryon-to-meson ratio increase, $\langle p_\perp \rangle$ increase with multiplicity, some flow-like effects

Cannot: pp ridge, v_2 with rapidity gap between particles of interest

Junction-type reconnection: red-green-blue



Independently hadronising MPI does not result in **increasing $\langle p_\perp \rangle$ with multiplicity**

Junctions result in baryons → increase in **baryon-to-meson ratio**

Shoving

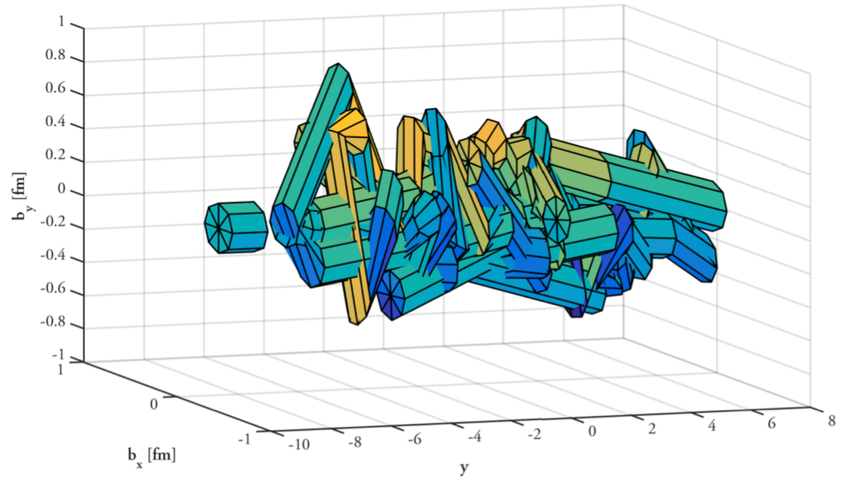
arXiv:2010.07595

After the string has had time after its initial creation to expand to its full **transverse size**, strings will start **“shoving”**

CR has already occurred with string minimisation choosing singlet configurations

→ only octet states would likely be near one another

→ only **repulsion** left



e.g. $\sqrt{s} = 7$ TeV collision example

*uses string radius of 0.2 fm for illustration purposes but in reality can be much larger

Force calculable from the field $E = N\exp(-\rho^2/2R^2)$

Energy per unit length of two strings overlapping $\int d^2\rho \frac{(E_1+E_2)^2}{2}$

Force between two strings transversely separated by $d_\perp$ is then $f(d_\perp) = \frac{g\kappa d_\perp}{R^2}\exp\left(-\frac{d_\perp^2}{4R^2}\right)$

ρ is the radius in cylindrical coordinates

R is the equilibrium radius

N is a normalization factor, determined by letting the energy in the field correspond to a **fraction g of the total string tension**.

Monte Carlo implementation details

➢ Use parallel dogbone frame

➢ Ordered in $p_\perp$ in similar spirit to parton shower ordering

Requires space-time picture of strings

Shoving in pp

arXiv:2010.07595

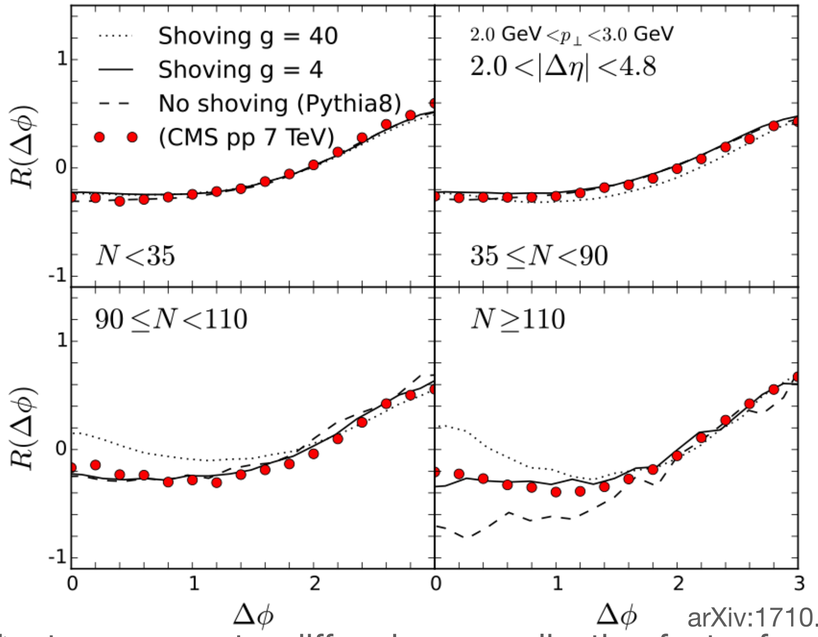
After the string has had time after its initial creation to expand to its full **transverse size**, strings will start **“shoving”**

CR has already occurred with string minimisation choosing singlet configurations

→ only octet states would likely be near one another

→ only **repulsion** left

Generate anisotropic flow as a response to the **spatial initial conditions**

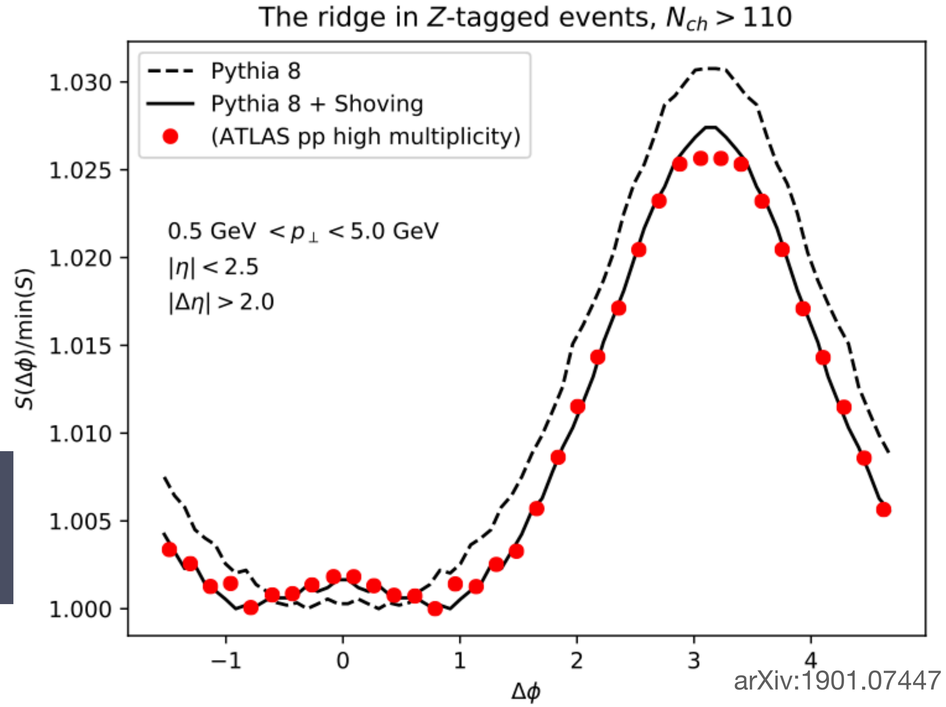


arXiv:1710.09725

*note g parameter differs by normalisation factor from g in equation

Z-tagged results - m_Z scale as the largest hard scale of the collision, which could alter the distribution in $p_\perp$ of MPIs w.r.t minimum bias

*model of shoving used here is old implementation that manifests the “shove” as soft gluons



arXiv:1901.07447

*results from old implementation of shoving w.r.t to the beam axis rather than the dog-bone implementation

Shoving in AA

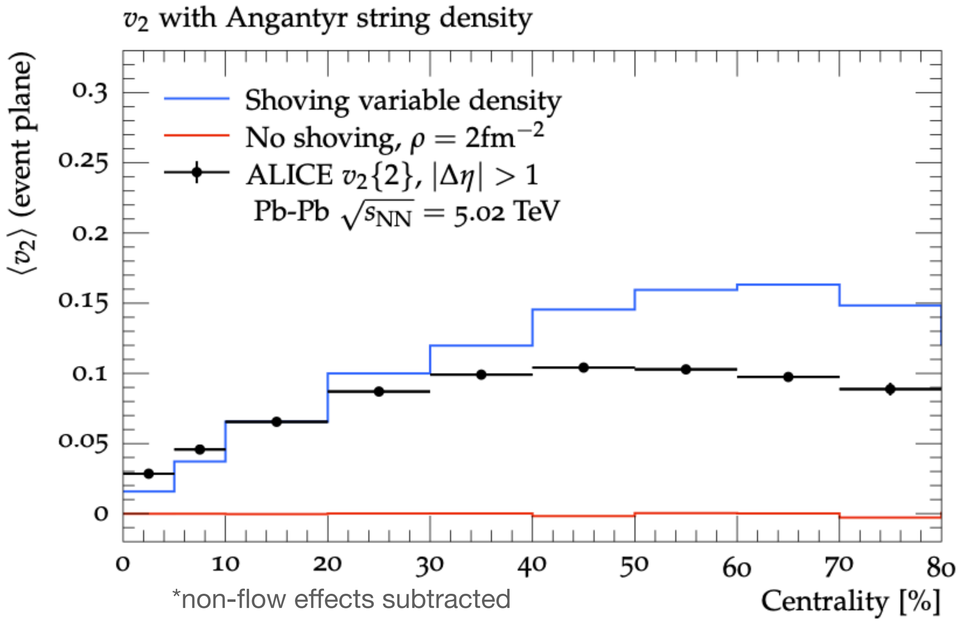
arXiv:2010.07595

First look at **toy case**

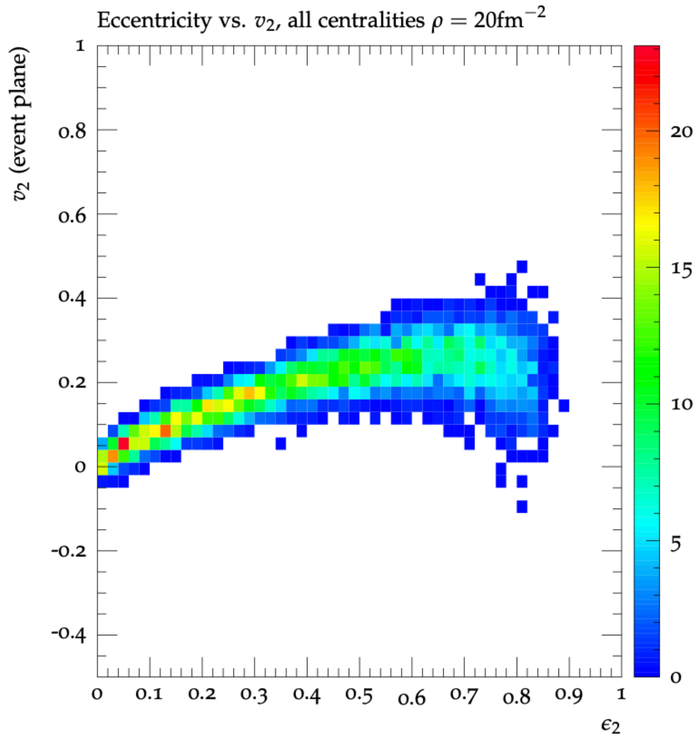
- ➢ Multiplicity generated by a single string well known (approx one hadron per unit of rapidity)
- ➢ System of **straight strings (no gluon kinks)** that corresponds to the multiplicity of AA collisions in a given centrality interval

Not perfect agreement however is only a toy model and uses **same parameters as pp collision systems**

source of flow can be the same across collision systems!!!



Correlation between initial state ϵ_2 and final state v_2 is linear in hydrodynamic deconfined QGP phase - **similarly with shoving** → **hydrodynamic behaviour is not limited to deconfined systems**



Shoving in AA

arXiv:2010.07595

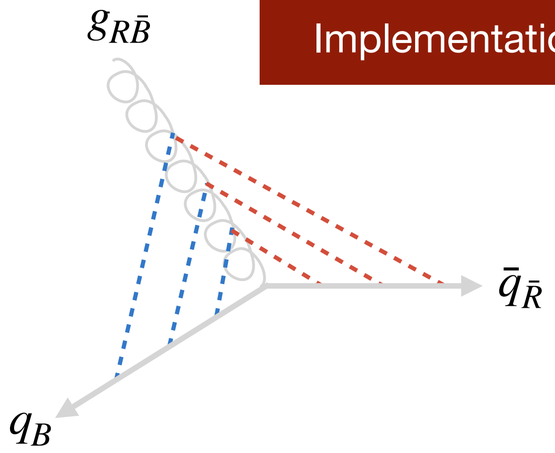
Full **Pb-Pb collision in Angantyr**

- ➢ Implementation issues

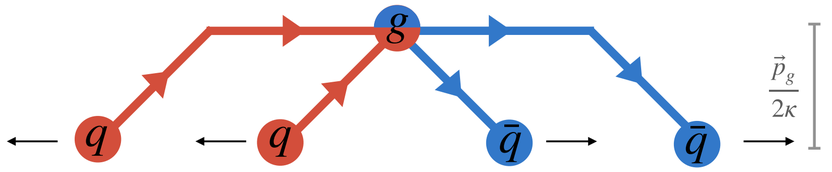
  Many **soft gluons** → **short interaction time** for shoving mechanism as the mechanism does not consider the region formed from soft gluons → insufficient level of shoving

- ➢ Trend is in the correct direction but insufficient, also lacks curved shape

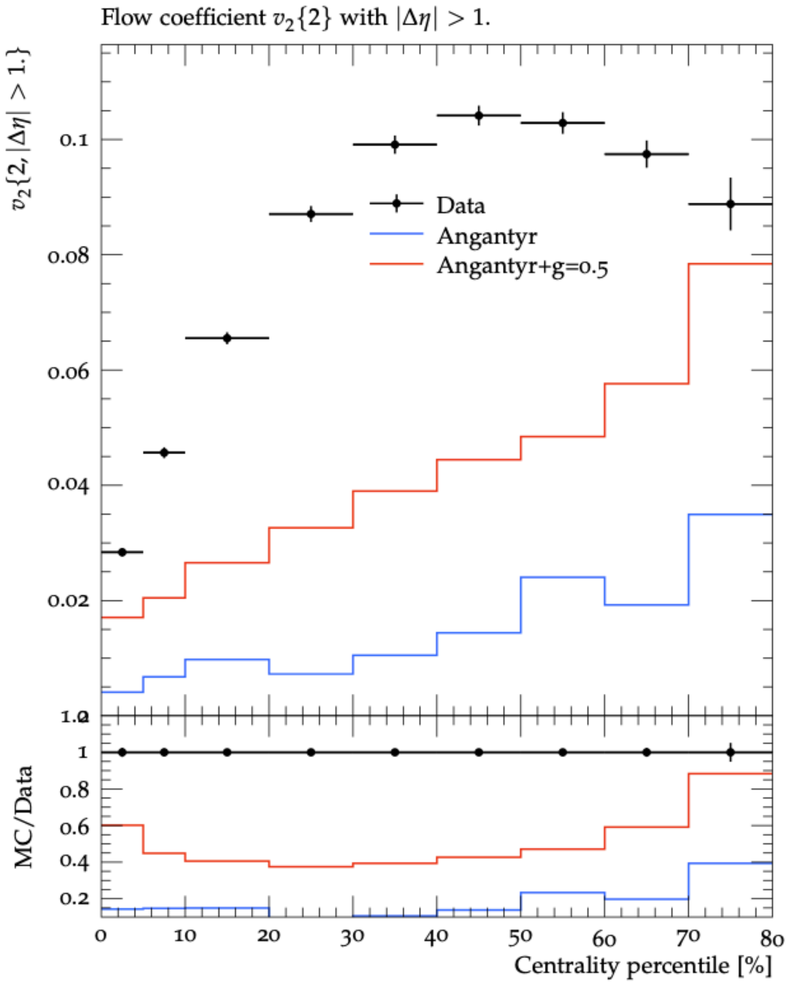
Implementation issues in the model prevent concrete conclusions



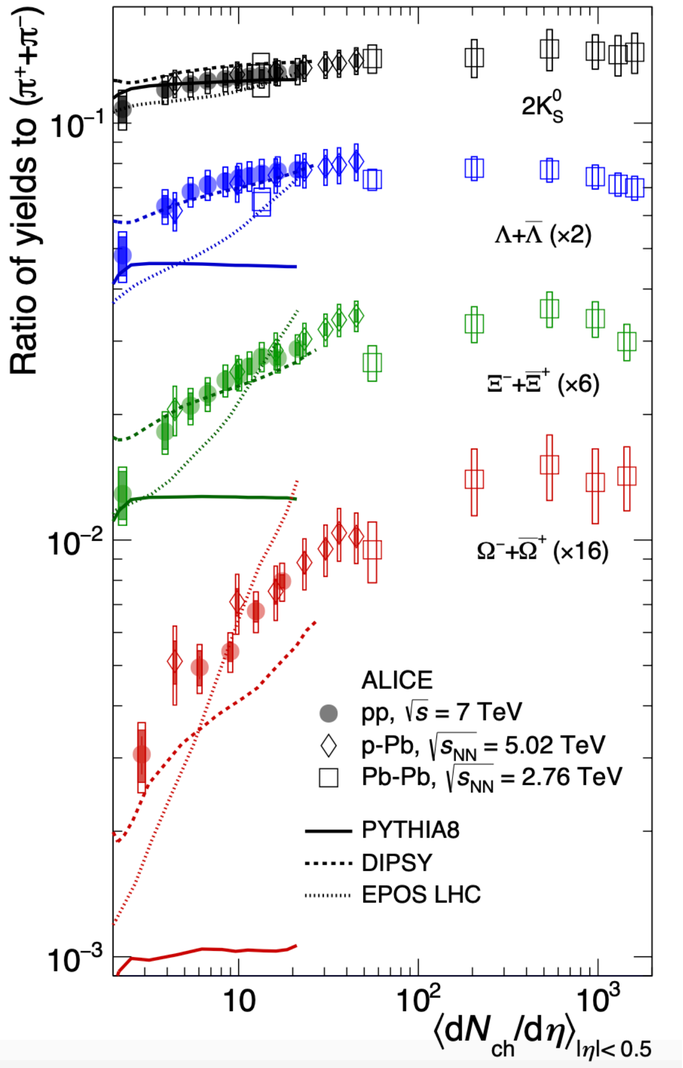
Gluon-kink picture



Soft gluon-kink

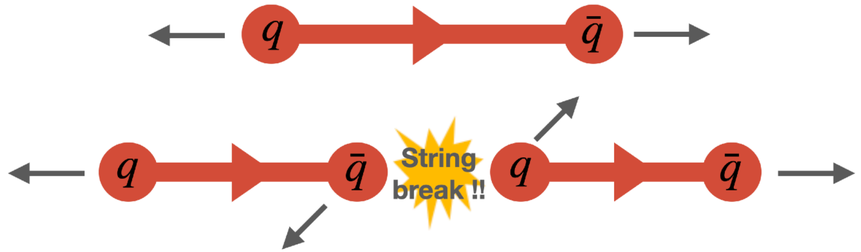


Strangeness Enhancement



Strange production in the string picture

Use **Schwinger mechanism** to model **tunnelling of quark-antiquark pairs** created by string breaks

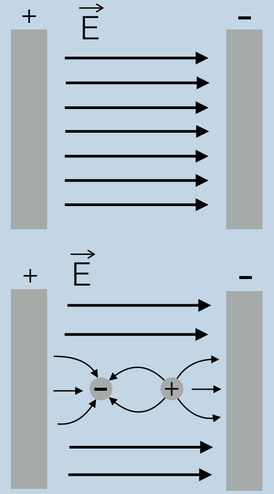


Schwinger → **Gaussian $p_\perp$ spectrum** and heavy flavour suppression

Prob(u:d:s) ≈ 1 : 1 : 0.2

Heavy quarks (charm and bottom) are only produced from hard processes → must be **string endpoints**

Schwinger mechanism QED



Non-perturbative creation of e^+e^- pairs in a string electric field

Probability from tunnelling factor

$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

κ = string tension

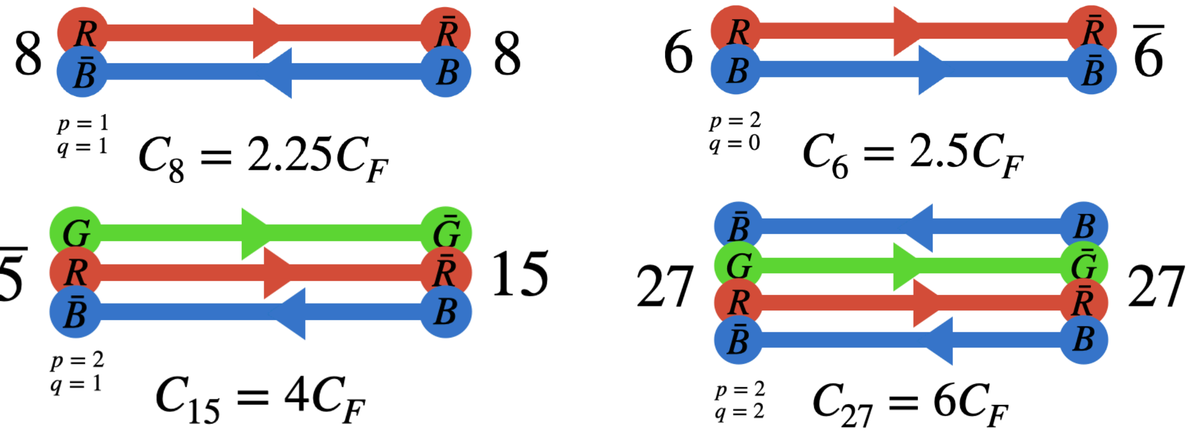
Strangeness Enhancement

Rope hadronisation

arXiv:1412.6259

After shoving, if strings are still overlapping → form a rope

Enhance string tension for higher multiplets

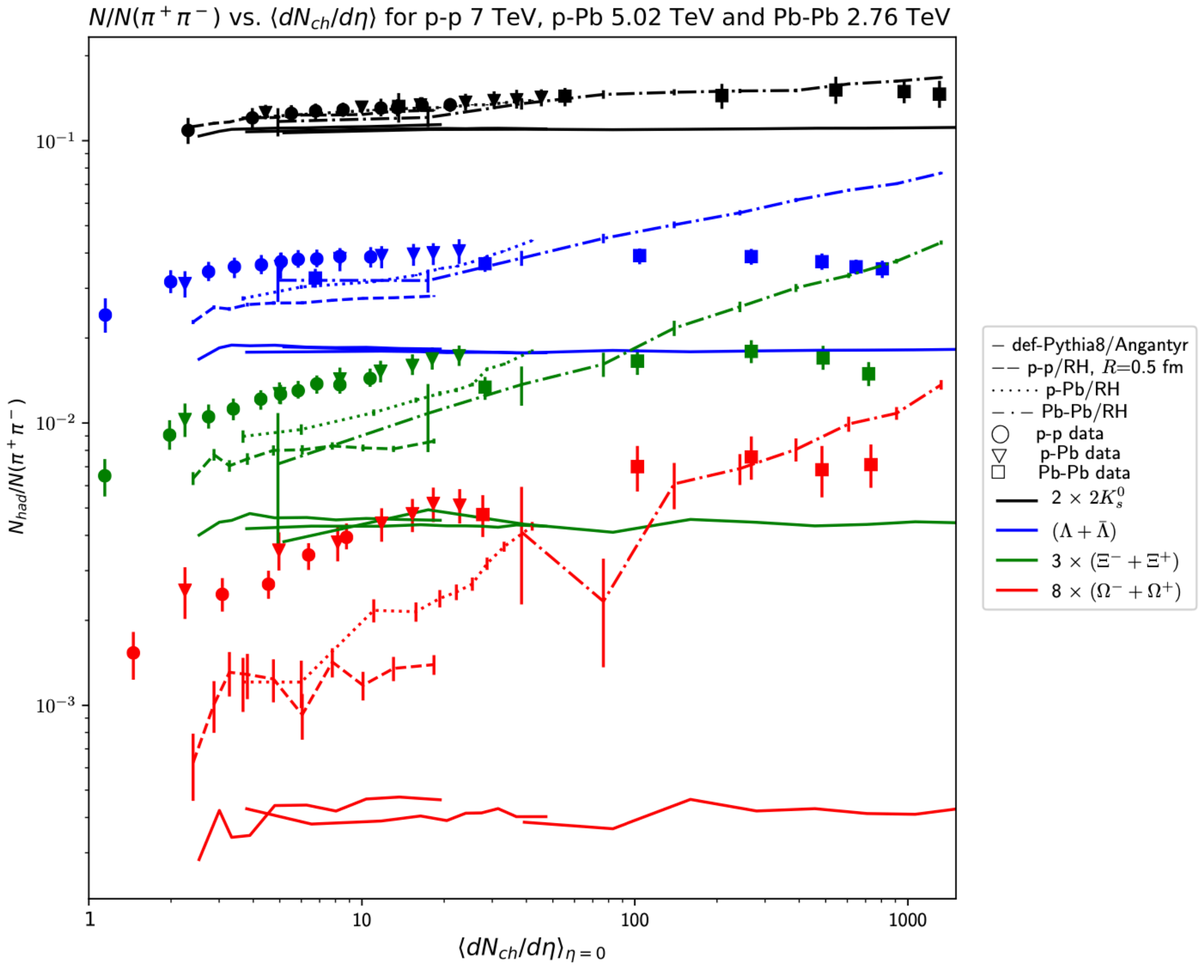


Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

Higher κ → lower strangeness suppression



Strangeness Enhancement

Rope hadronisation

arXiv:1412.6259

After shoving, if strings are still overlapping → form a rope

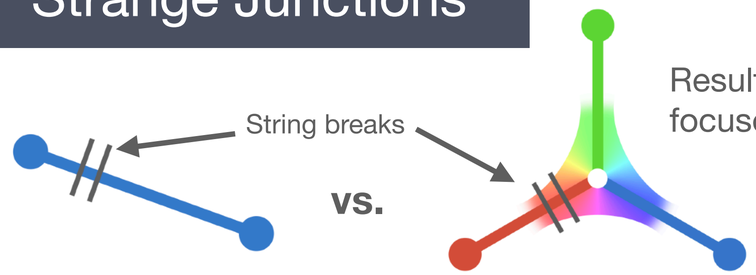
Enhance string tension for higher multiplets

Close-packing

Simpler implementation of ropes fully in momentum space

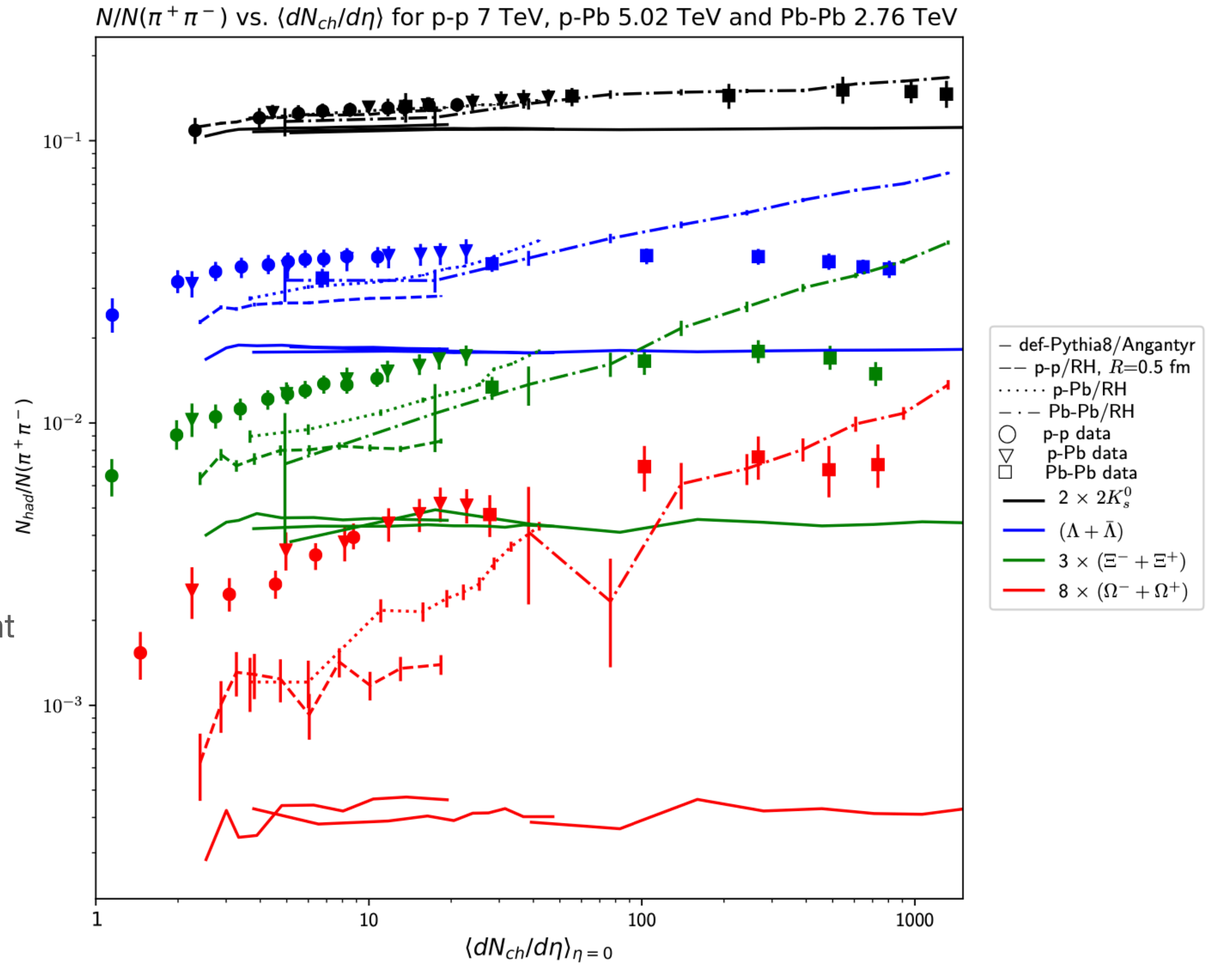
→ not in conjunction with shoving

Strange Junctions



Results in strangeness enhancement focused in baryon sector

String tension could be different from the vacuum case compared to near a junction



Strangeness Enhancement

Rope hadronisation

arXiv:1412.6259

After shoving, if strings are still overlapping → form a rope

Enhance string tension fo

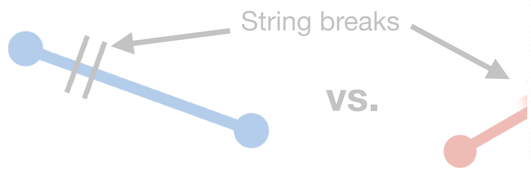
What about the non-strange baryon-to-meson ratio p/π ?

Close-packing

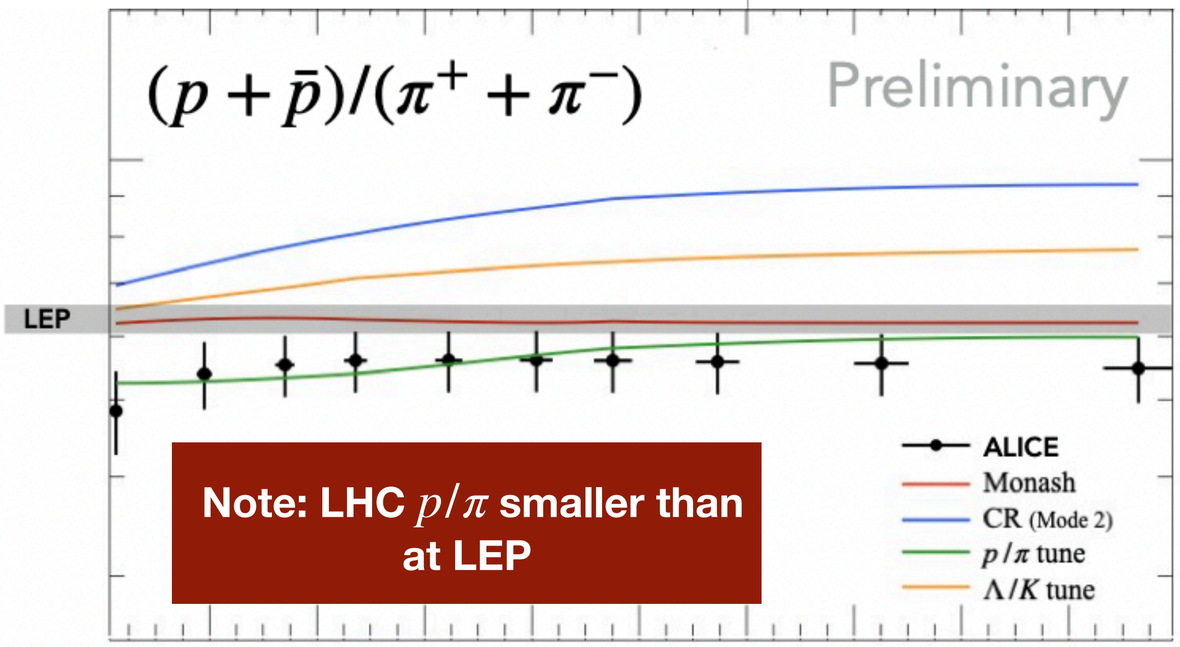
Simpler implementation of ro

→ not in conjunction with sh

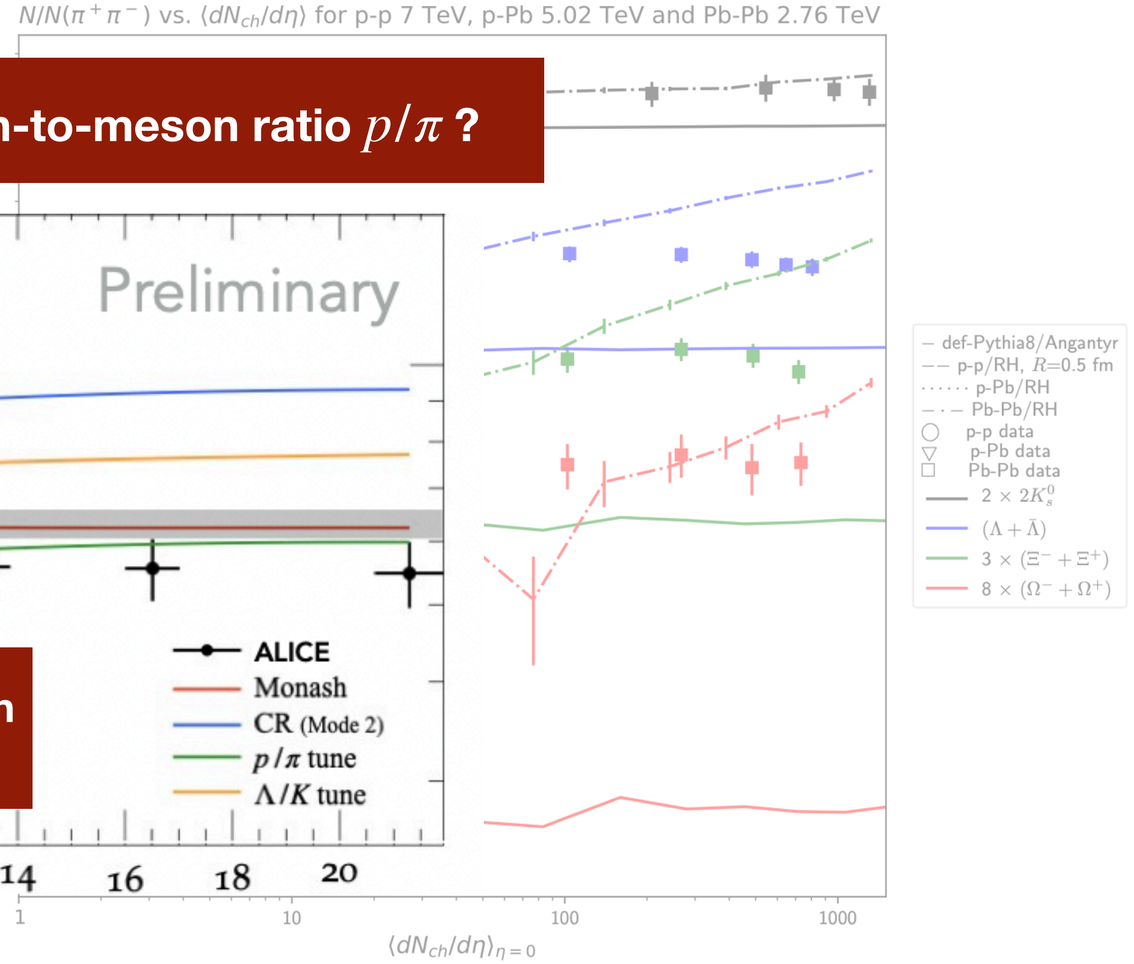
Strange Junctions



String tension could be diffe
case compared to near a junction



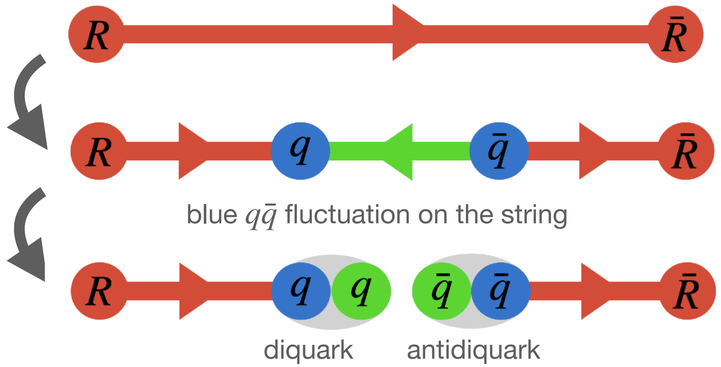
Note: LHC p/π smaller than at LEP



Proton problem

Popcorn mechanism for diquark production

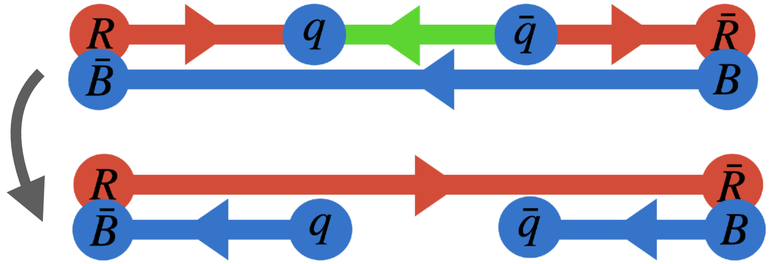
Diquark formation via **successive colour fluctuations** — popcorn mechanism



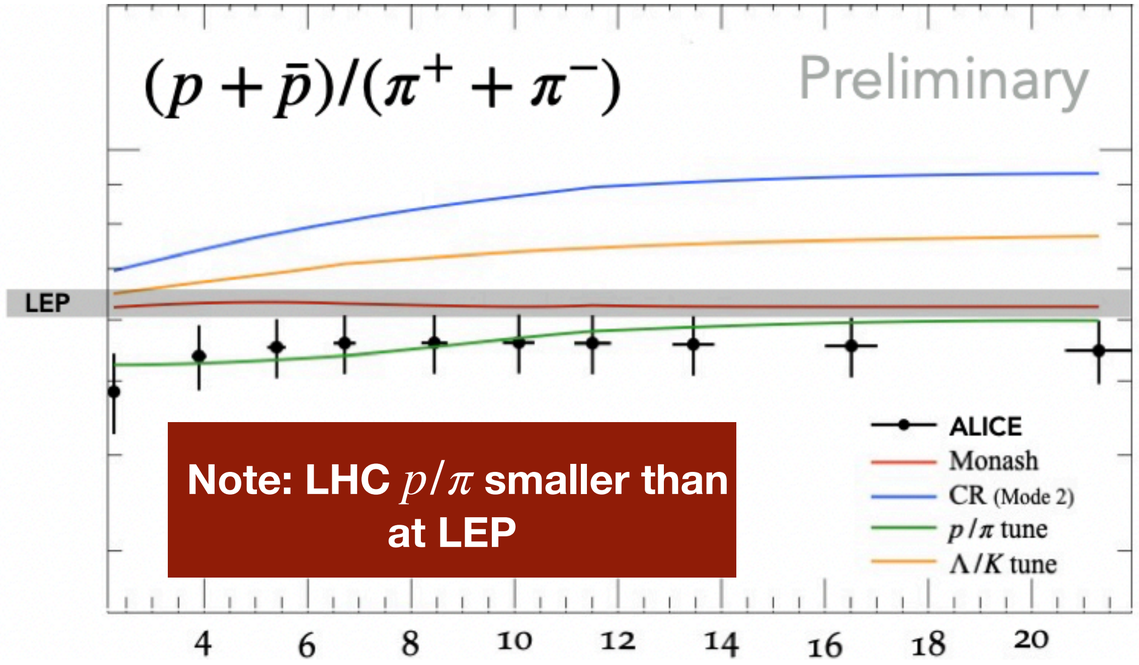
Popcorn destructive interference

NEW

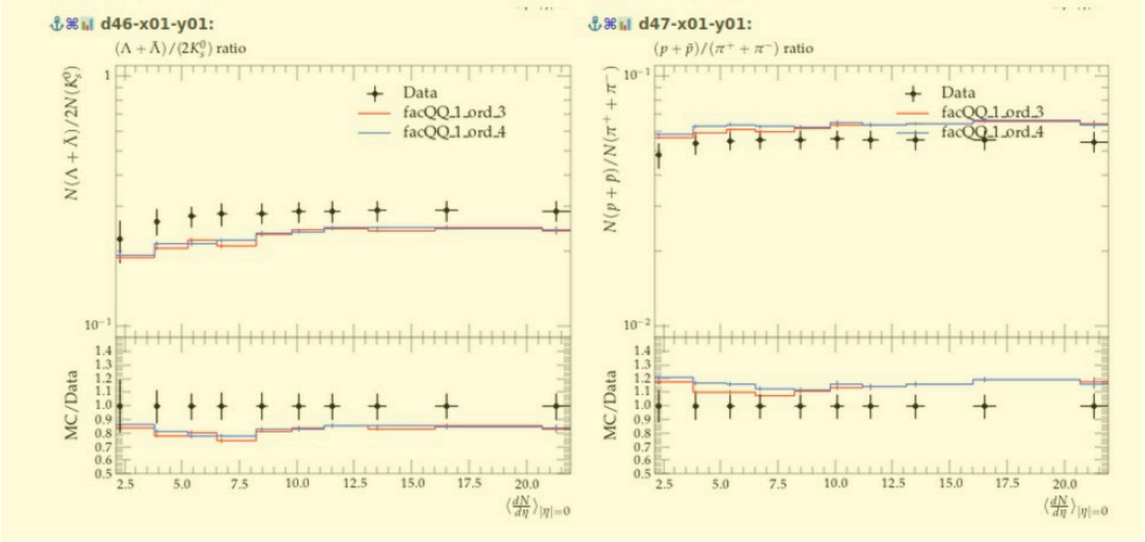
What if there's a blue string nearby?

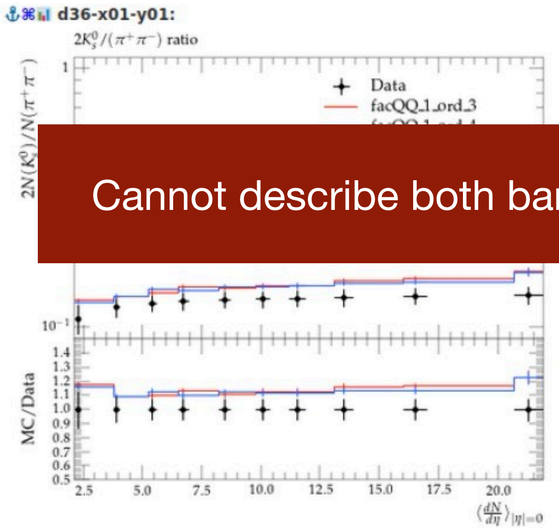


blue $q\bar{q}$ fluctuation breaks nearby blue string, preventing diquark formation



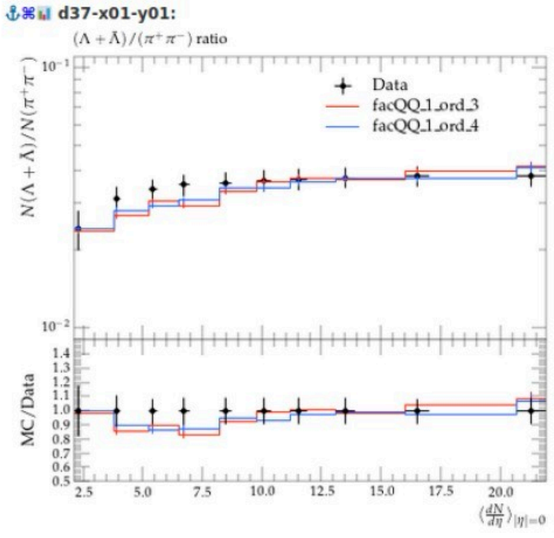
Results — ongoing

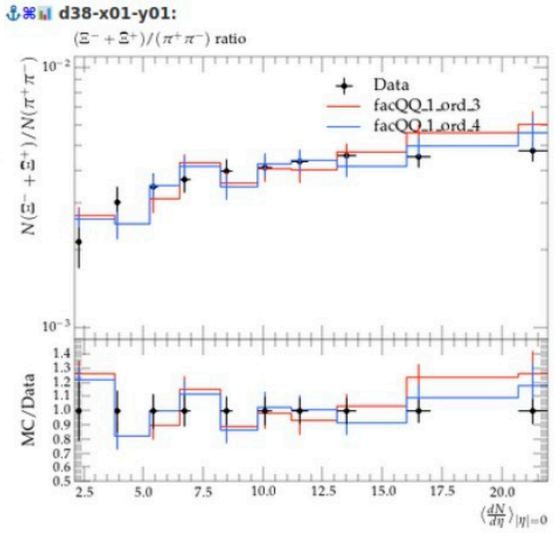


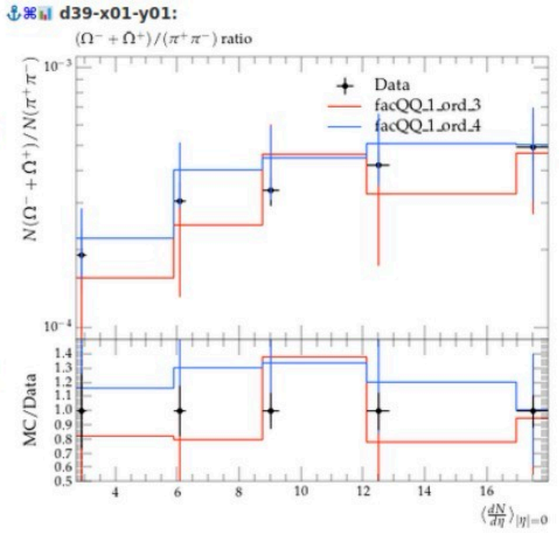


Cannot describe both baryon-to-meson ratios simultaneously

Taken from slide by Lorenzo Bernadinis: masters student currently undertaking tuning project with the model







Summary

Evidence that **collective effects can arise from non-QGP** sources

CR restores $SU(3)$ colour correlations

→ baryons-to-meson ratio enhancement, $\langle p_\perp \rangle$ increase with multiplicity, some flow-like

Angantyr allows for pA and AA using strings instead of QGP

→ multiplicity distributions for AA

Shoving string interactions before hadronisation

→ near-sided ridge in pp, some v_2 with full description hindered by implementation technicality issues

Ropes

→ strangeness enhancement

Unmentioned: jet quenching, hadron rescattering

Future studies: shoving **considering regions formed by soft gluons**, reexamination of results given **updates to CR in Angantyr** (previous modelling only included CR within each nucleon-nucleon collision, now CR is allowed between nucleon-nucleon collisions)

Thank you for listening!