String hadronization in PYTHIA8:

from e^+e^- to pp and beyond

Javira Altmann - Monash University, visiting University of Oxford

- ➢ **Confinement** in High-Energy Collisions
- ➢ String **Hadronisation** → Modelling in PYTHIA (QCD Colour Reconnections)
- ➢ String **Junctions**
- ➢ Strings from vacuum → small systems → heavy ion collisions

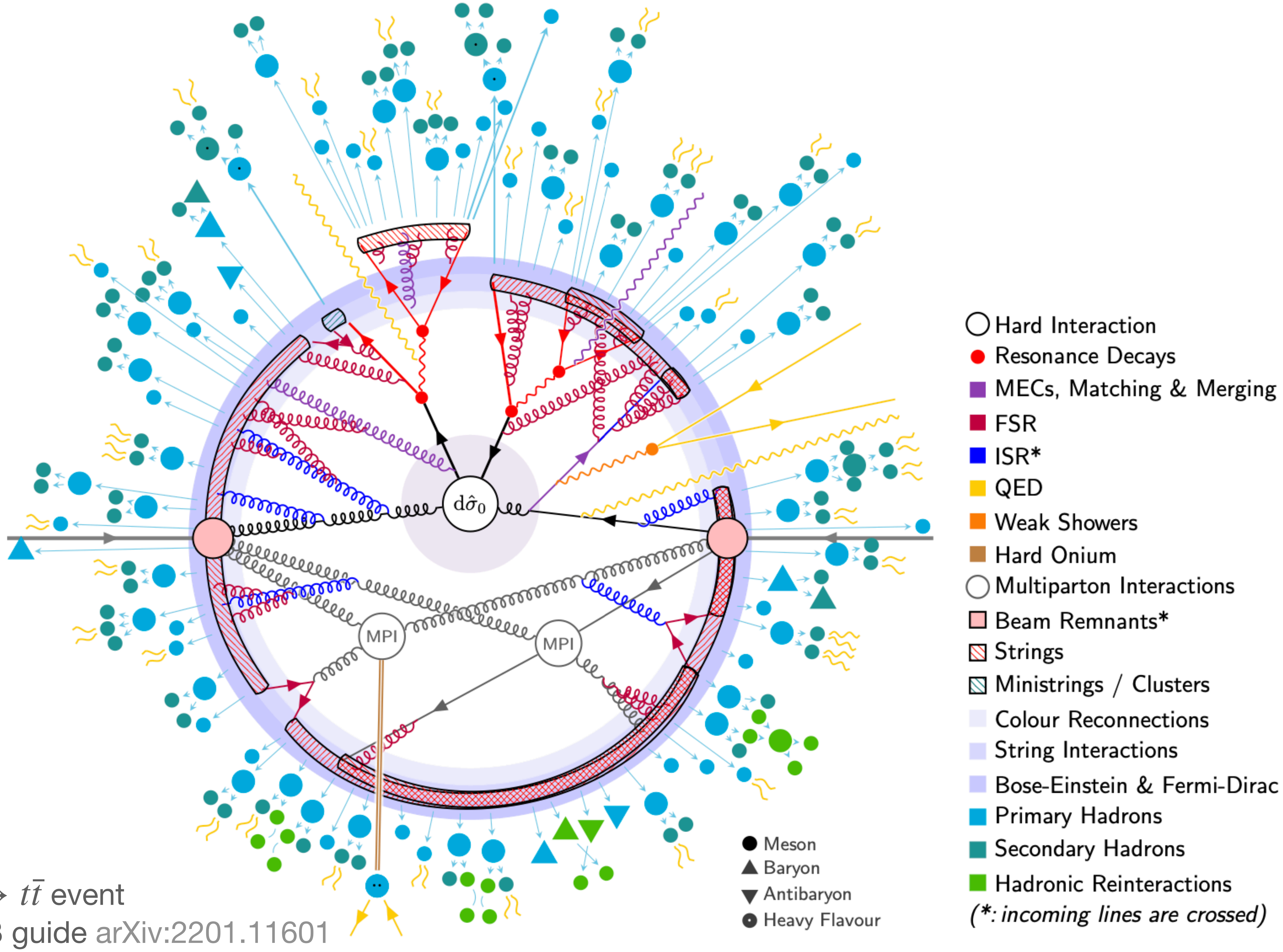
Confinement in high energy collisions

Consider "hard" processes with large momentum transfers $Q^2 \gg \Lambda^2_{QCD}$

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

Need a dynamical process to ensure partons (**quarks and gluons**) 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

Colour neutralisation

Require colour neutralisation:

- ➢ The point of confinement is that partons are **coloured** → a physical model needs two or more partons to create **colour neutral** objects

What does this **confinement field** look like?

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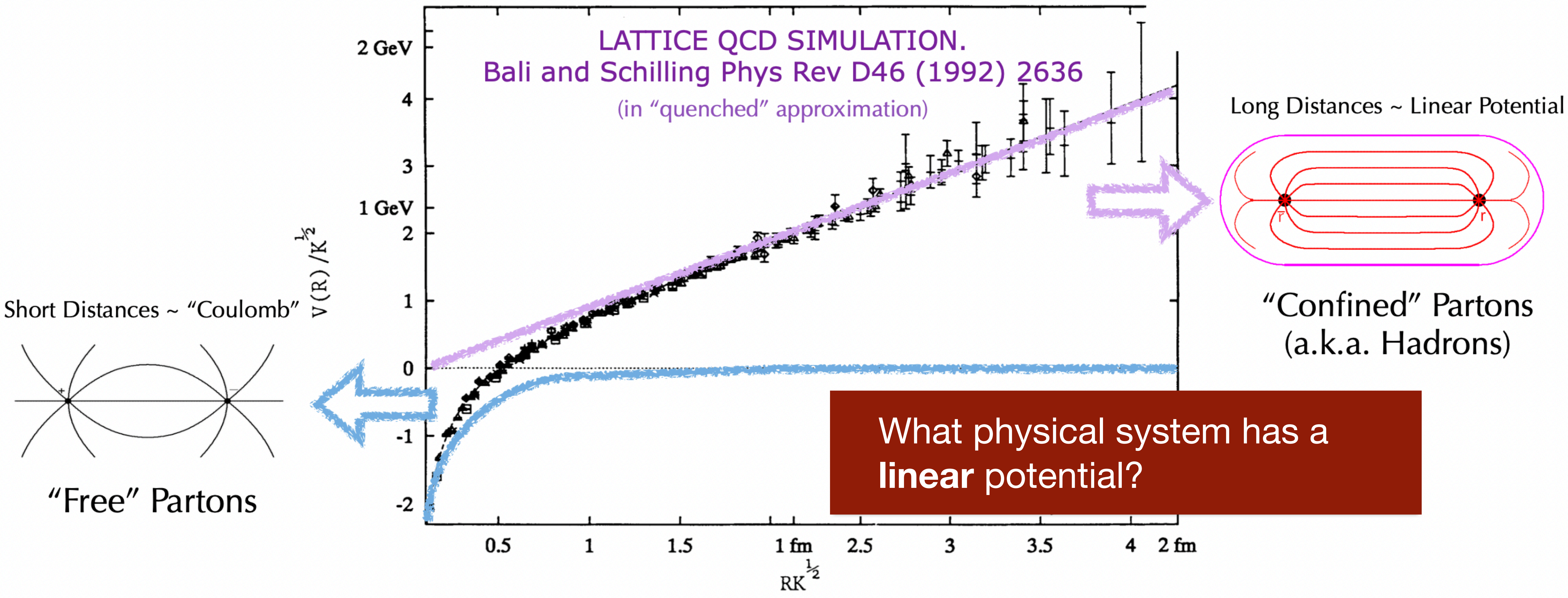
Lattice QCD **"Cornell potential"** $V(r) = -\frac{a}{r} + \kappa r$ with $\kappa \sim 1$ GeV/fm

shows us the potential energy of a colour singlet $q\bar{q}$ at separation distance r



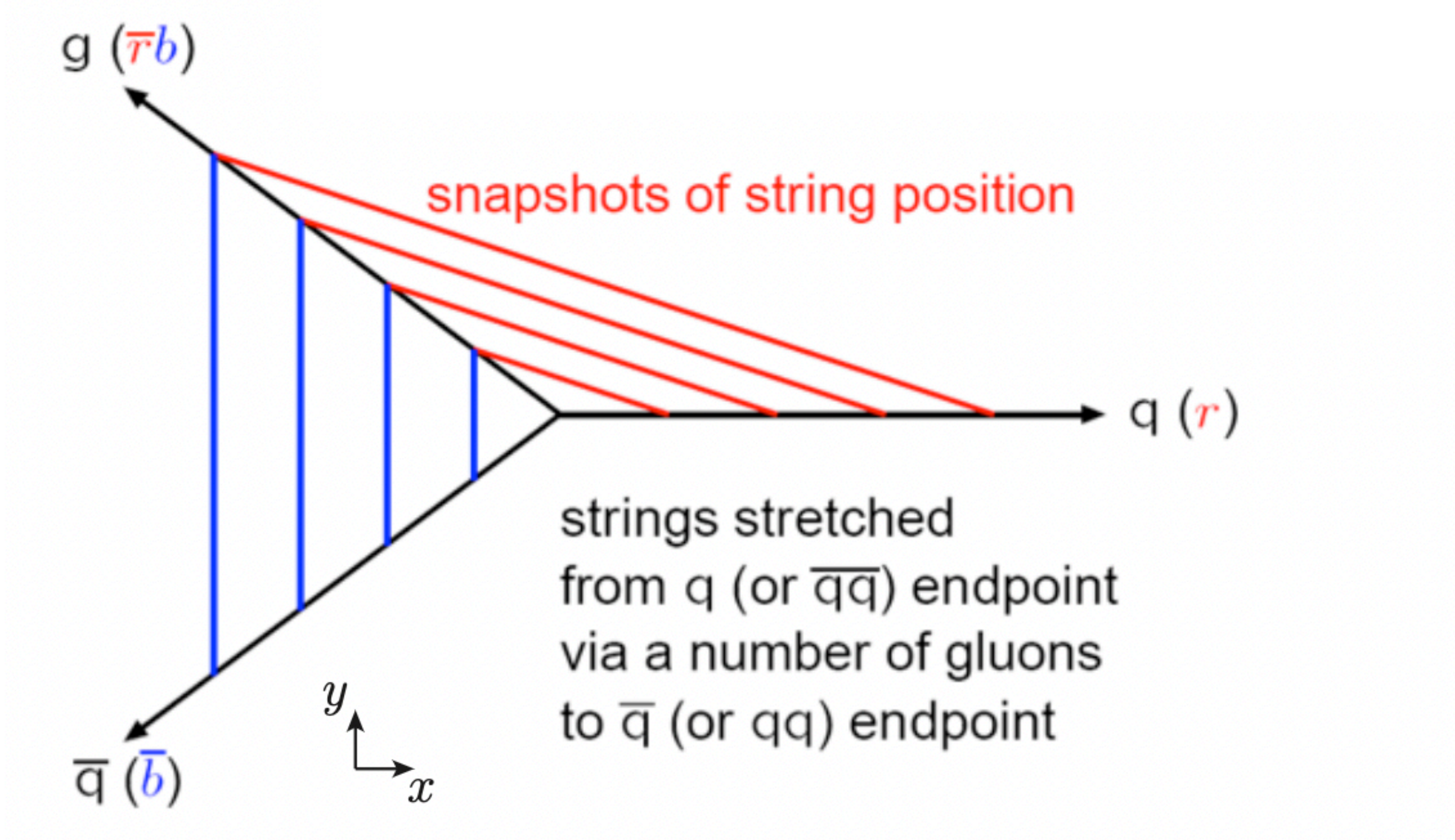
What physical system has a **linear** potential?

Lund String Model

Lund String Model:

Model the **confining field** between colour charges as a **string**

- Collapse the colour field into a **narrow flux tube** (relativistic 1+1 dimensional world sheet) with uniform energy density
  - $\kappa \sim 1$ GeV/fm



Example of a **"dipole"** string

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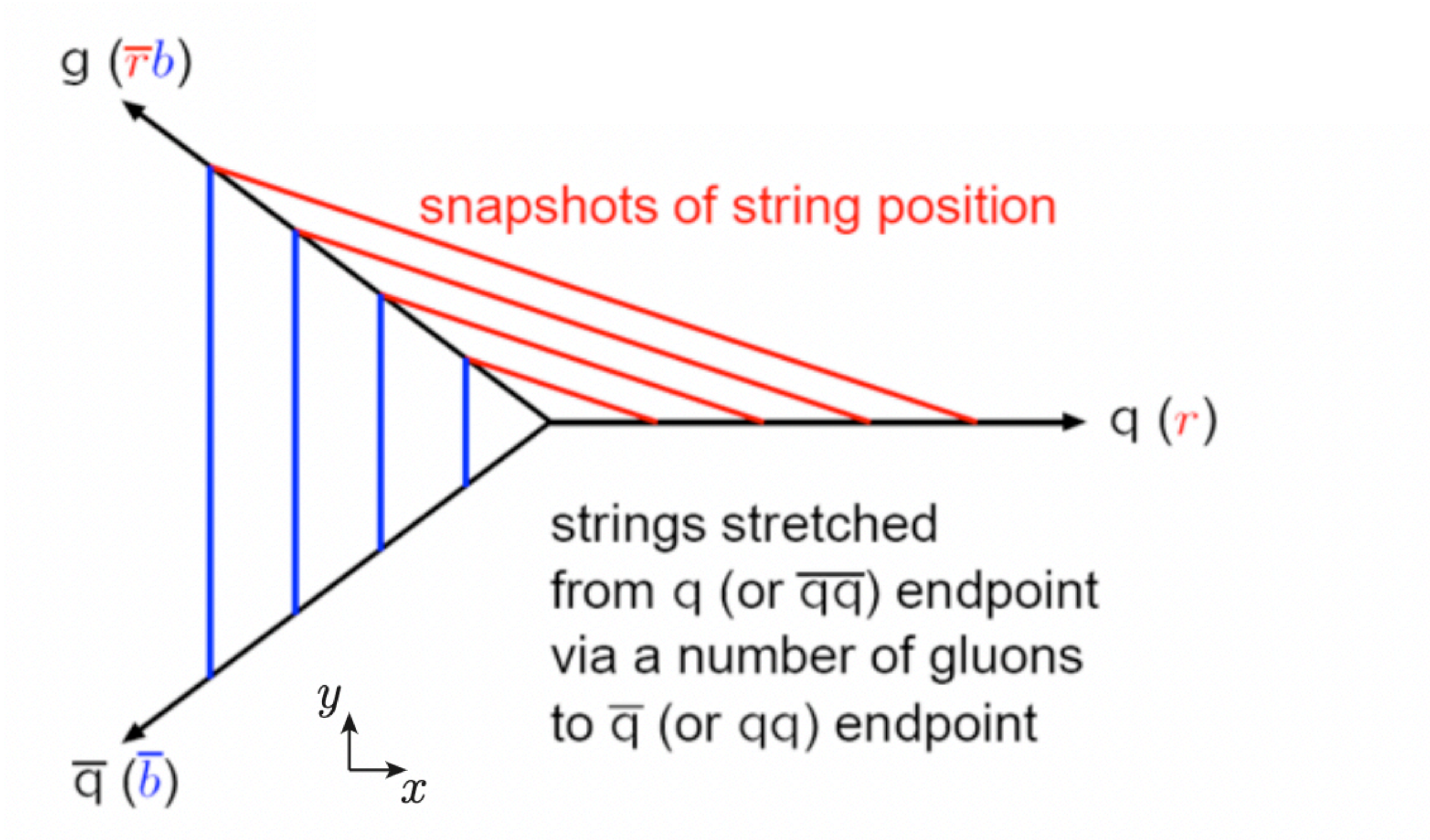

Example of a **"dipole"** string

Quarks / antiquarks

(anti)triplet → carry (anti)**colour**
→ connected via a string to an anticolour charge
→ string **endpoints**

Gluons

Octet → carry a **colour** and an **anticolour**
→ connected via a string to both a colour and an anticolour charge
→ transverse excitations on the **string ("kinks")**

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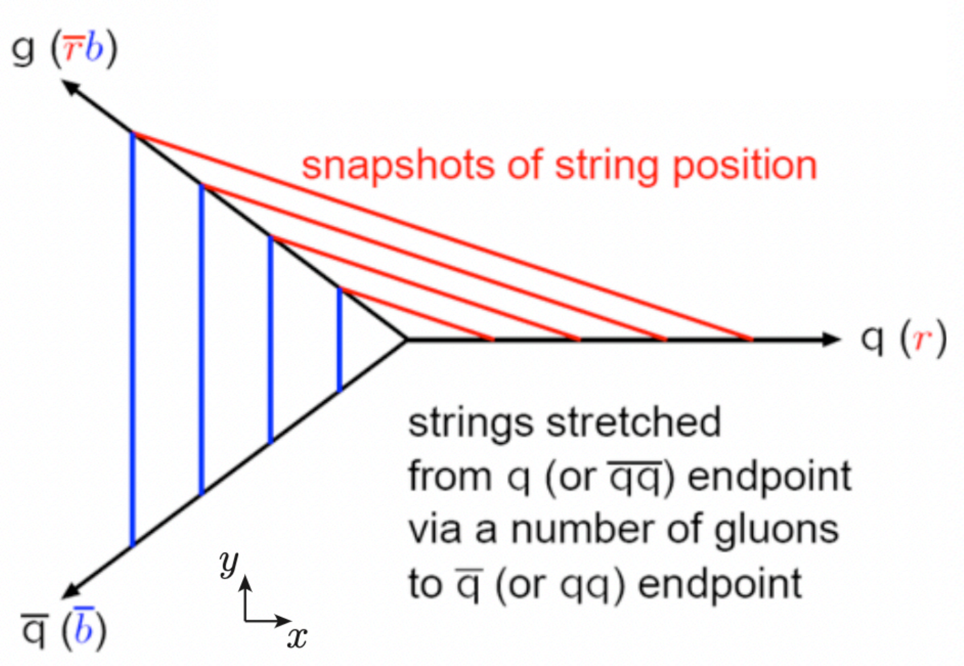

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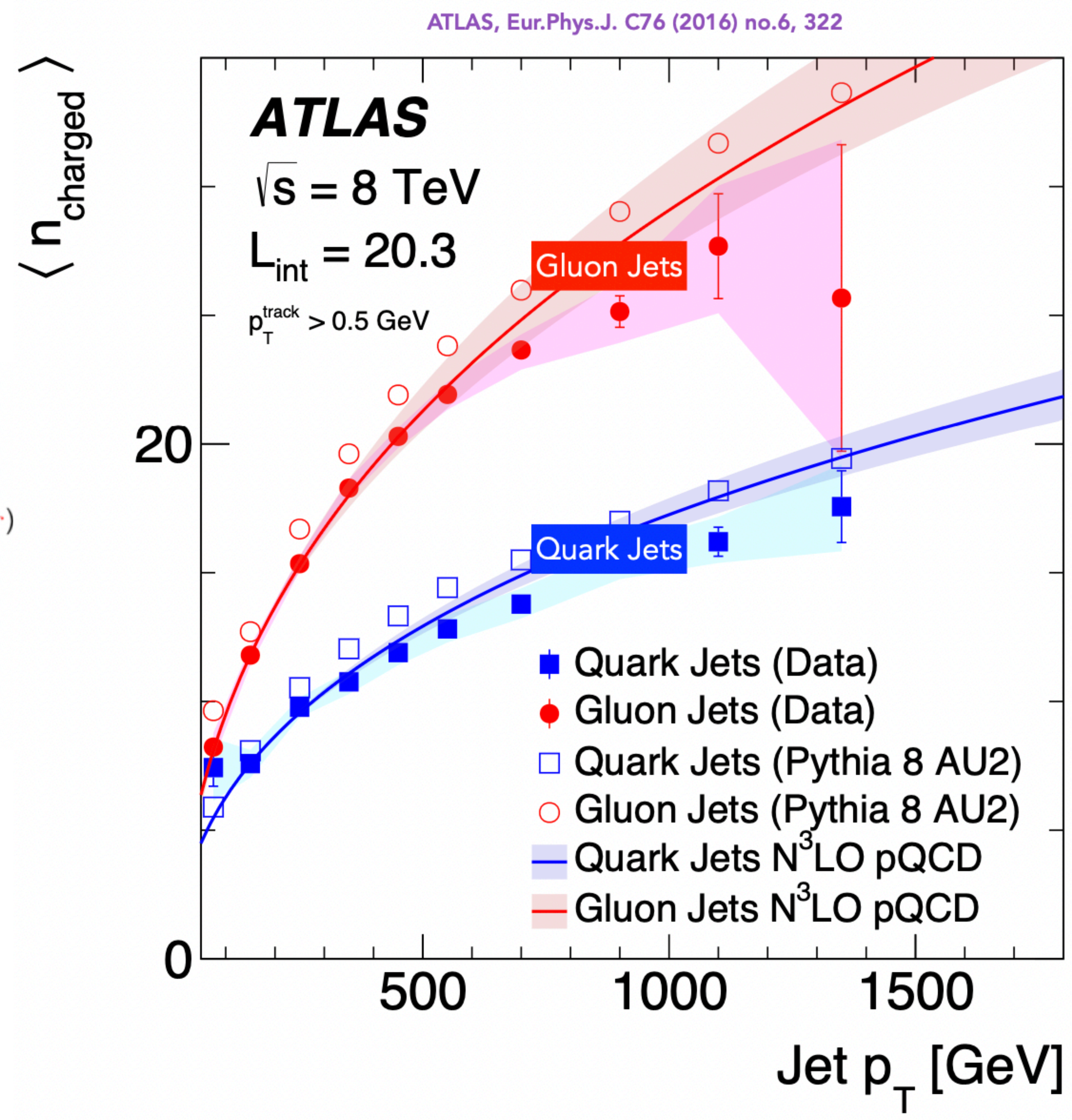

Signatures of gluon-kinks have been seen

Factor ~ 2 more particles in gluon jets

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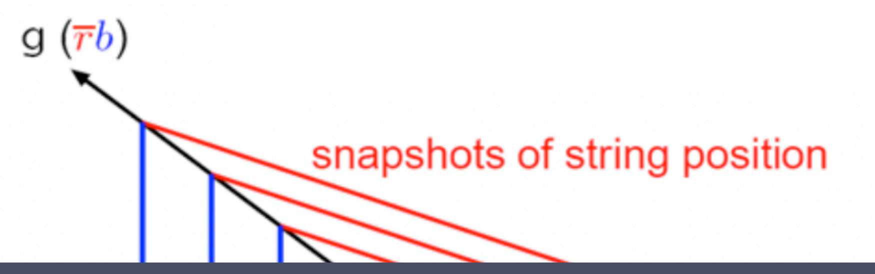

Quarks / antiquarks

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How does this **map partons onto hadrons** in high-energy collisions?

String fragmentation!

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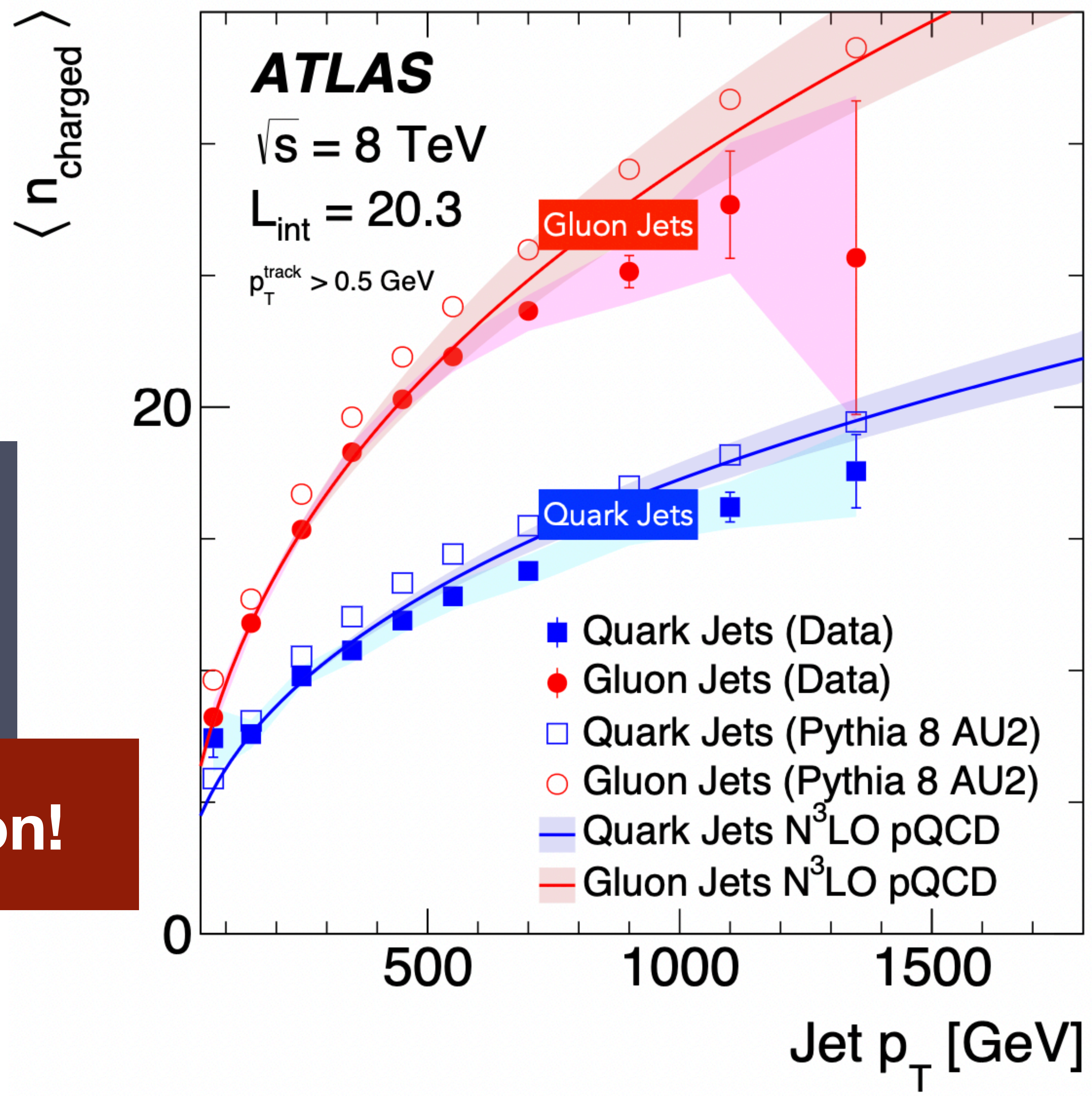
ATLAS, Eur.Phys.J. C76 (2016) no.6, 322



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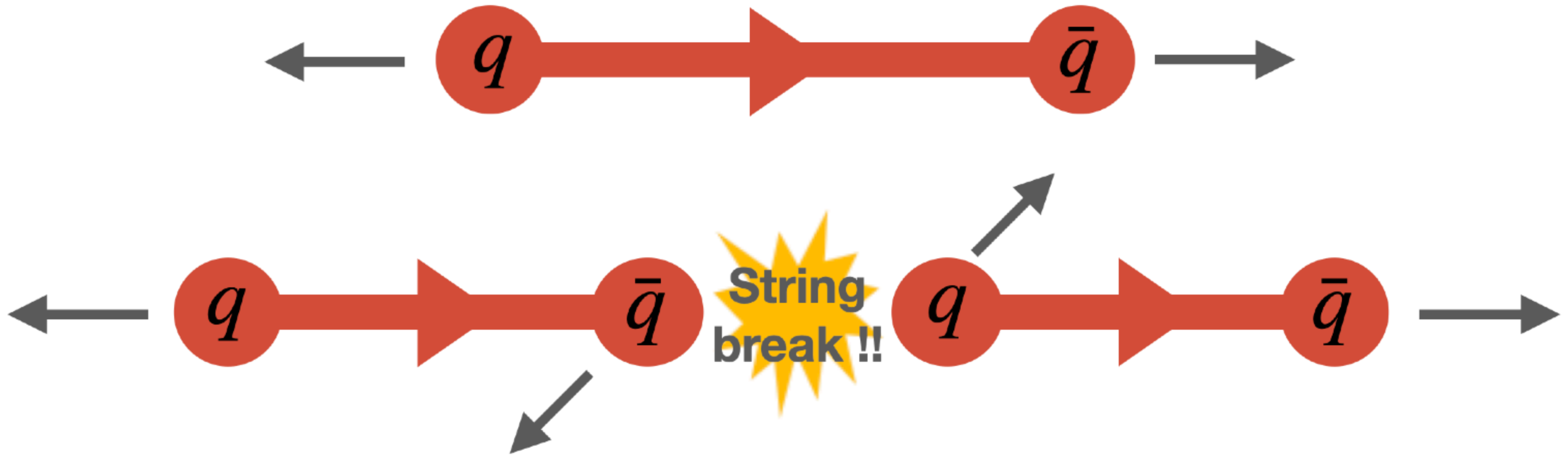
Partons → Hadrons

Hadronisation:

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

These happen at **non-perturbative** scales, can't use $P_{g\to q\bar{q}}(z)$

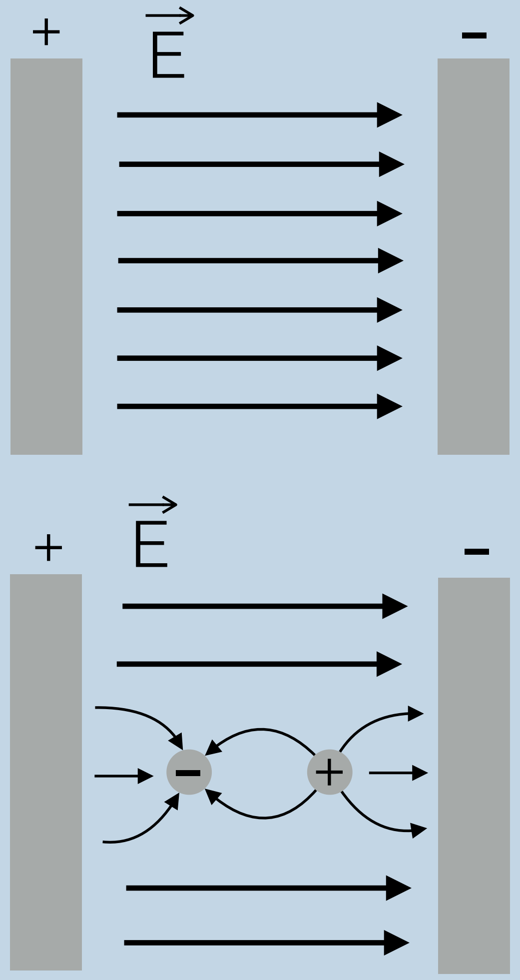
Instead use the **Schwinger mechanism**



Schwinger → **Gaussian** $p_\perp$ **spectrum** and heavy flavour suppression **Prob(u:d:s)** $\approx$ **1 : 1 : 0.2**

Heavy quarks 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

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

Gaussian suppression of high $m_\perp = \sqrt{m_q^2 + p_\perp^2}$

Baryons formed from beam remnants or **diquark-antidiquark** pair creation

Partons → Hadrons

Hadronisation:

Schwinger → **Gaussian $p_\perp$ spectrum** and heavy flavour suppression **Prob(u:d:s) ≈ 1 : 1 : 0.2**

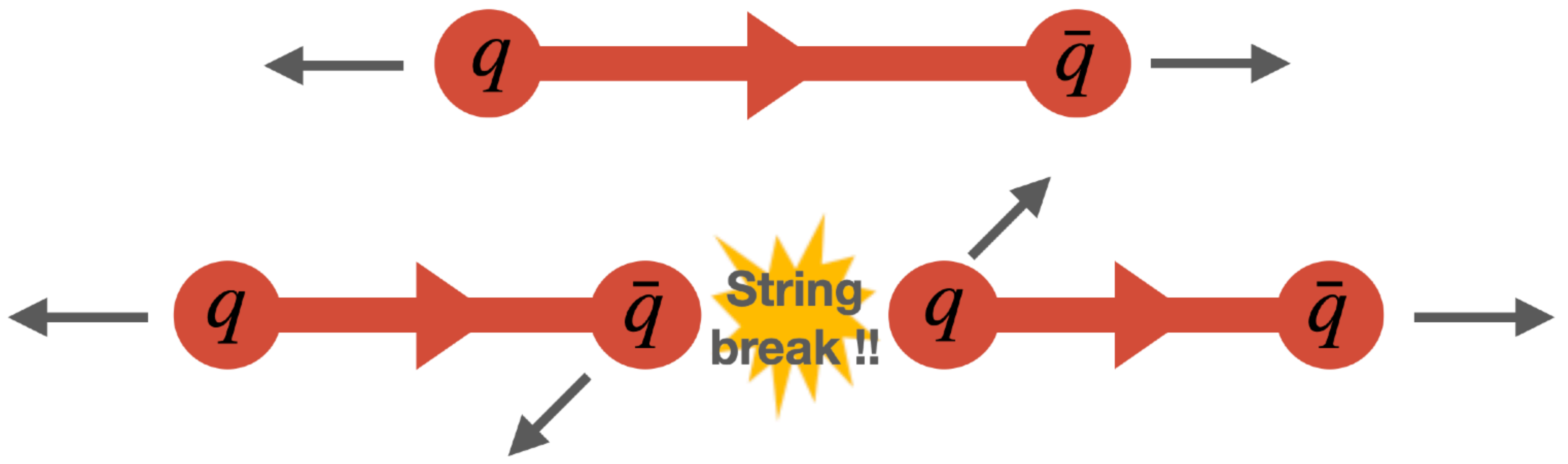
String breaks are **causally disconnected**

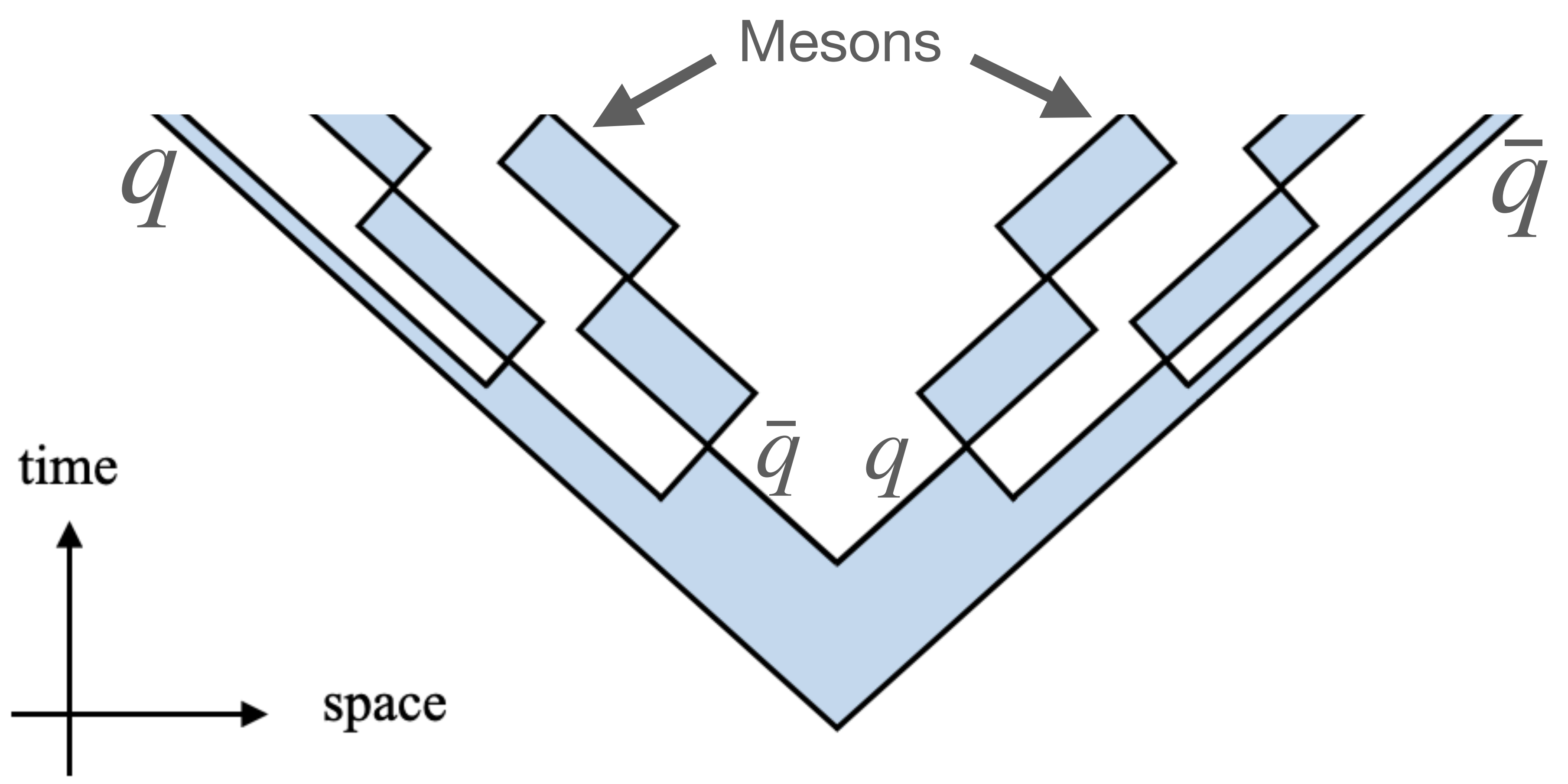
→ can fragment off hadrons from either end of the string

Probability distribution for the **fraction of quark momenta, z,** the hadron will take is parametrised by the **Lund Symmetric Fragmentation Function**

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Free tuneable parameters a and b





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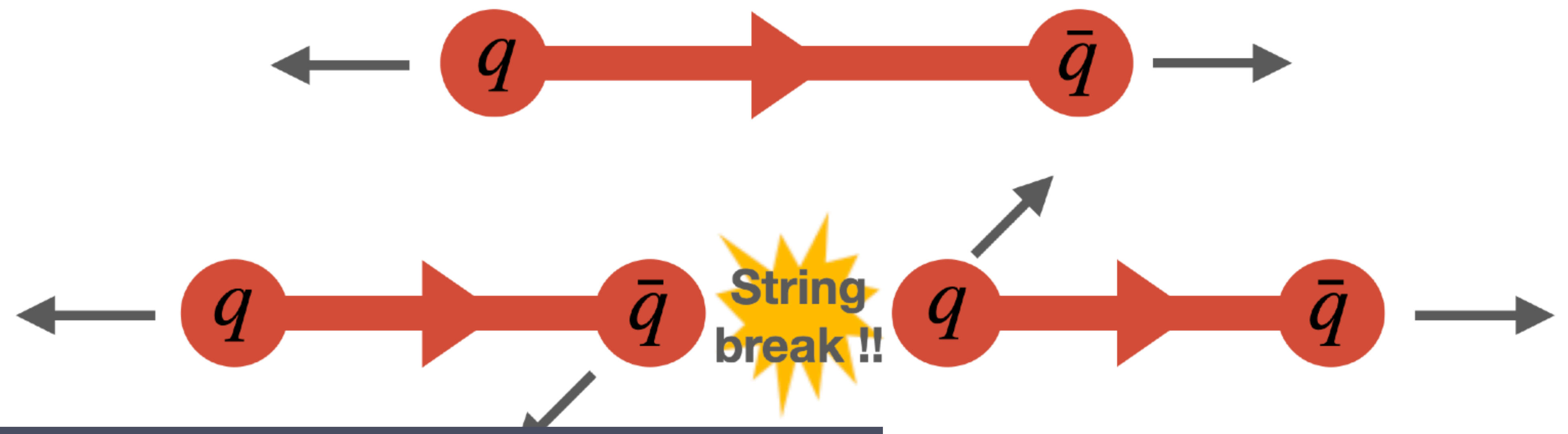
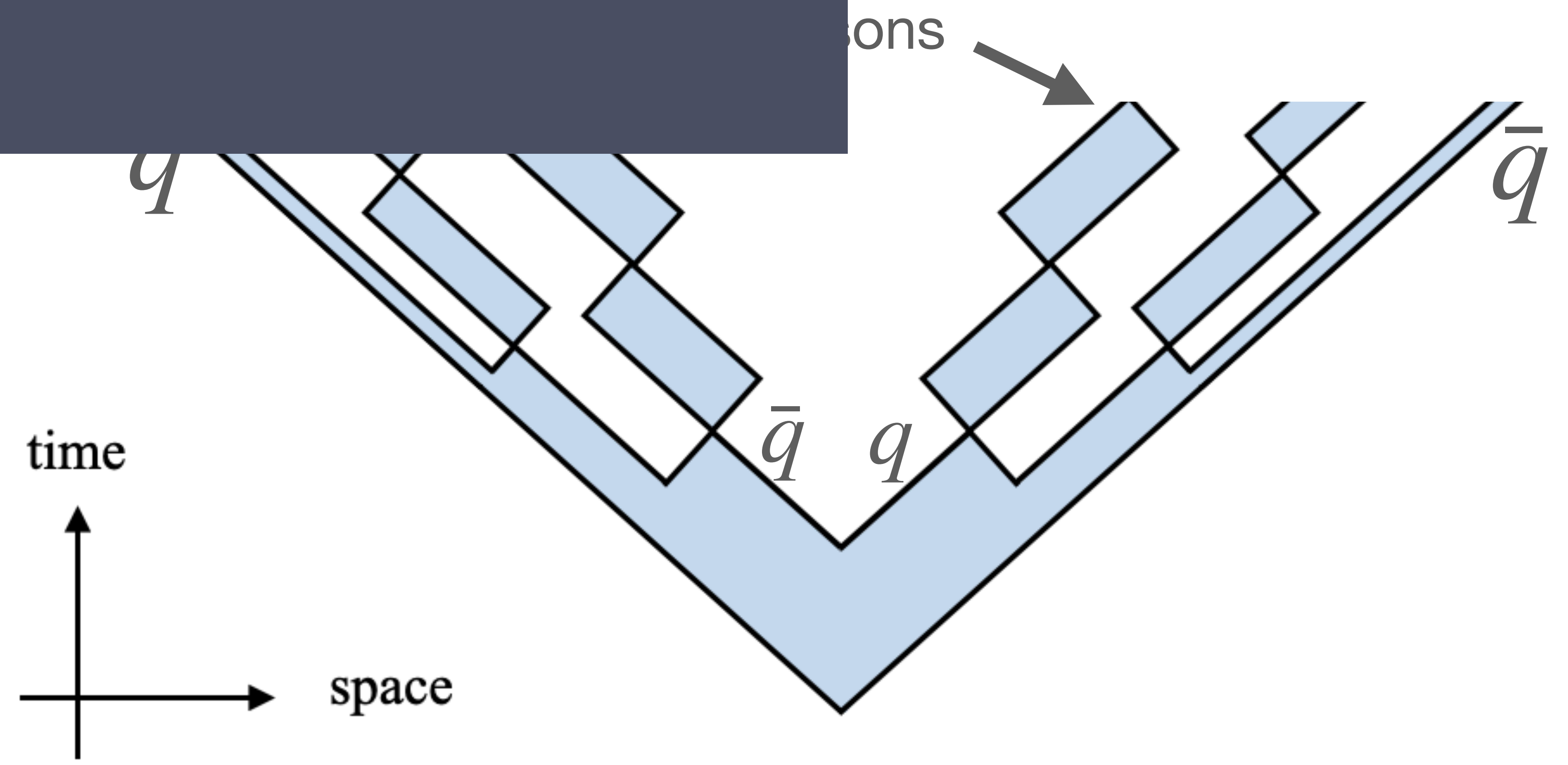
Probability c

momenta, z

Lund Symmetric Fragmentation Function

So far we have notion of hadron flavour and momentum
What about colour?





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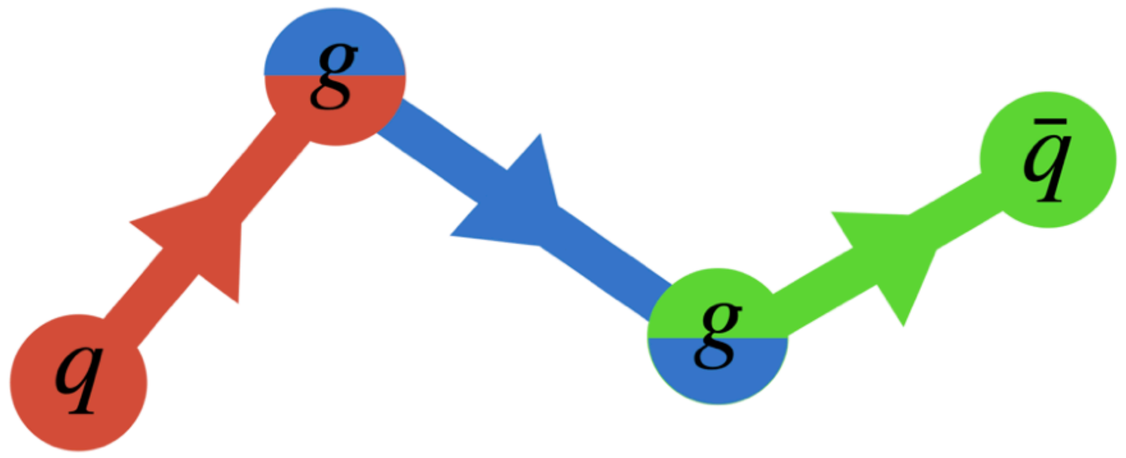
Modelling Colour

Leading Colour limit:

Starting point for Monte Carlo event generators $N_C \to \infty$

- ➢ Each **colour is unique** → only one way to make colour singlets
- ➢ Only **dipole** strings
- ➢ Used by PYTHIA in the default (Monash 2013) tune



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

In e^+e^- collisions :

- ➢ Corrections suppressed by $1/N_C^2 \sim 10\,\%$
- ➢ Not much overlap in phase space

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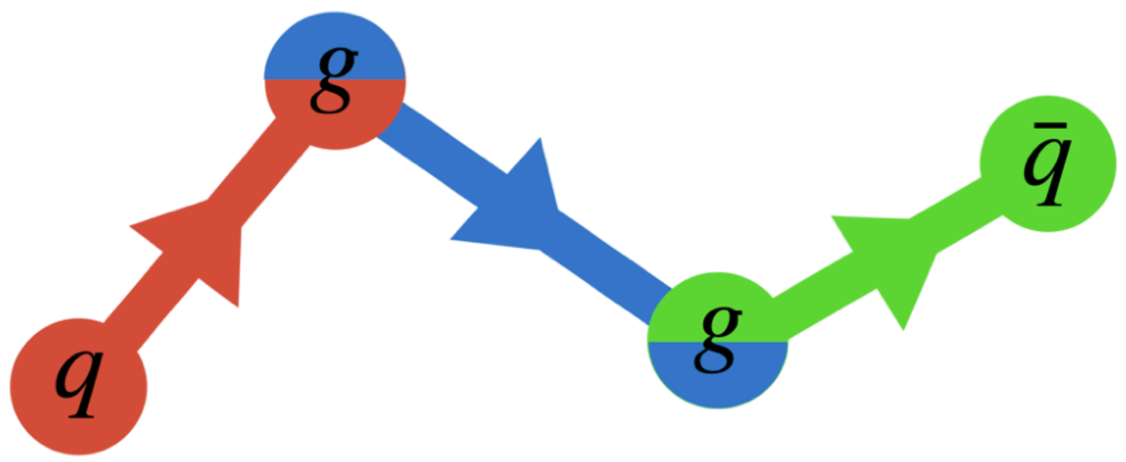

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But high-energy pp collisions involve **very many** coloured partons with significant **phase space overlaps**

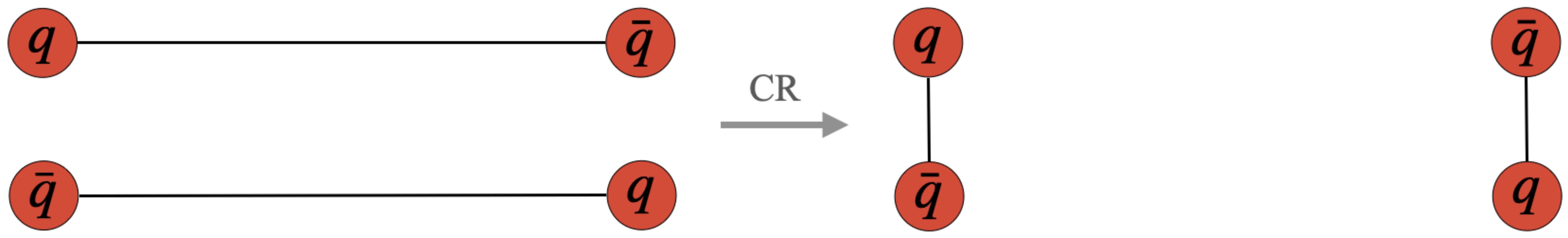
QCD Colour Reconnection (CR) model

QCD Colour Reconnections

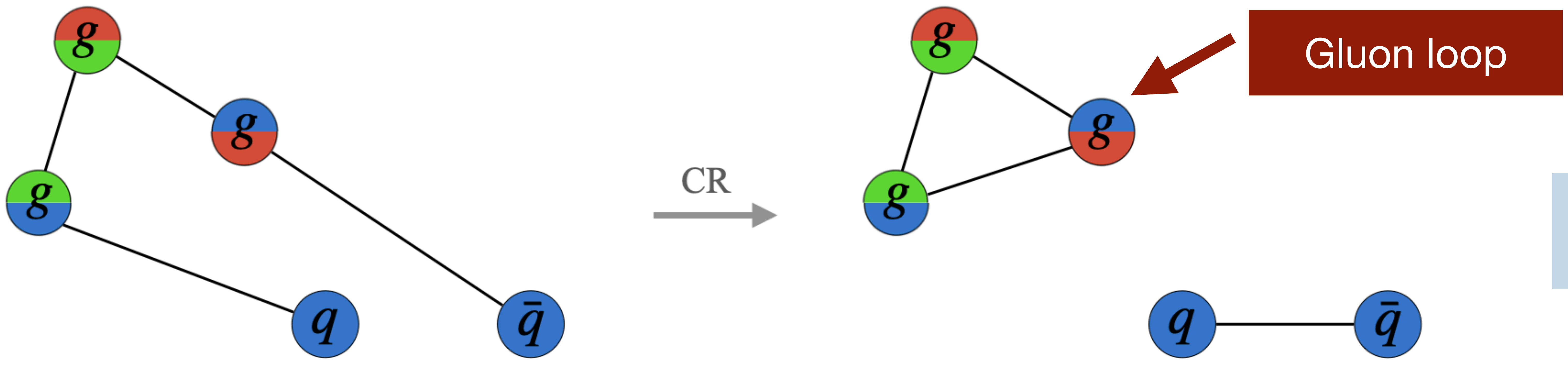
Stochastically restores colour-space ambiguities according to **SU(3) algebra**

➢ Allows for reconnections to **minimise string lengths**

Colour - anticolour singlet state



Dipole reconnection



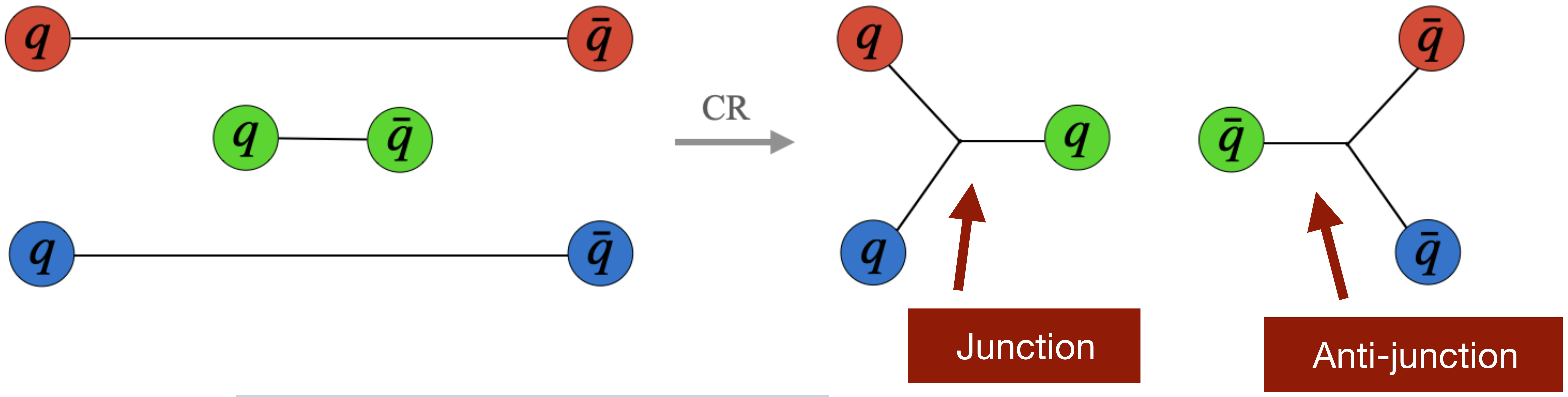
Gluon loop formation

QCD Colour Reconnections

Stochastically restores colour-space ambiguities according to **SU(3) algebra**

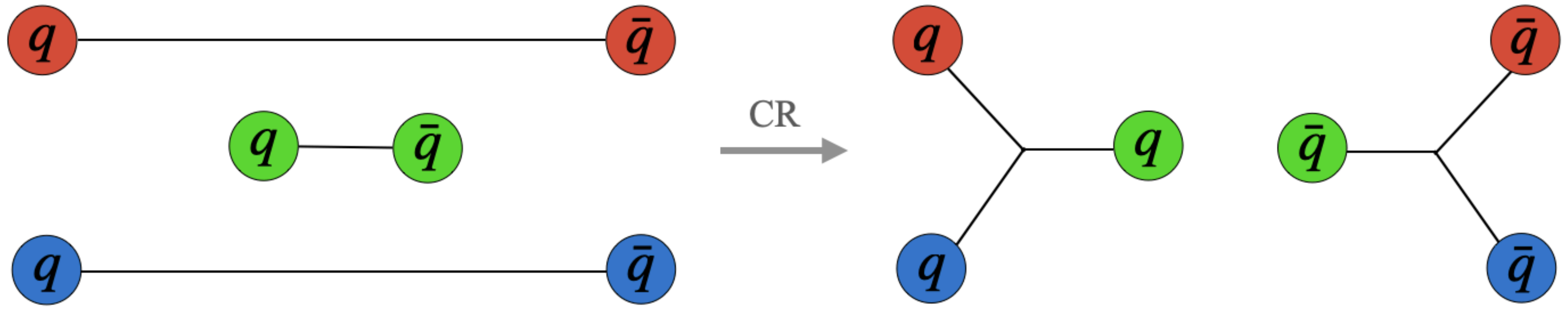
- ➢ Allows for reconnections to **minimise string lengths**

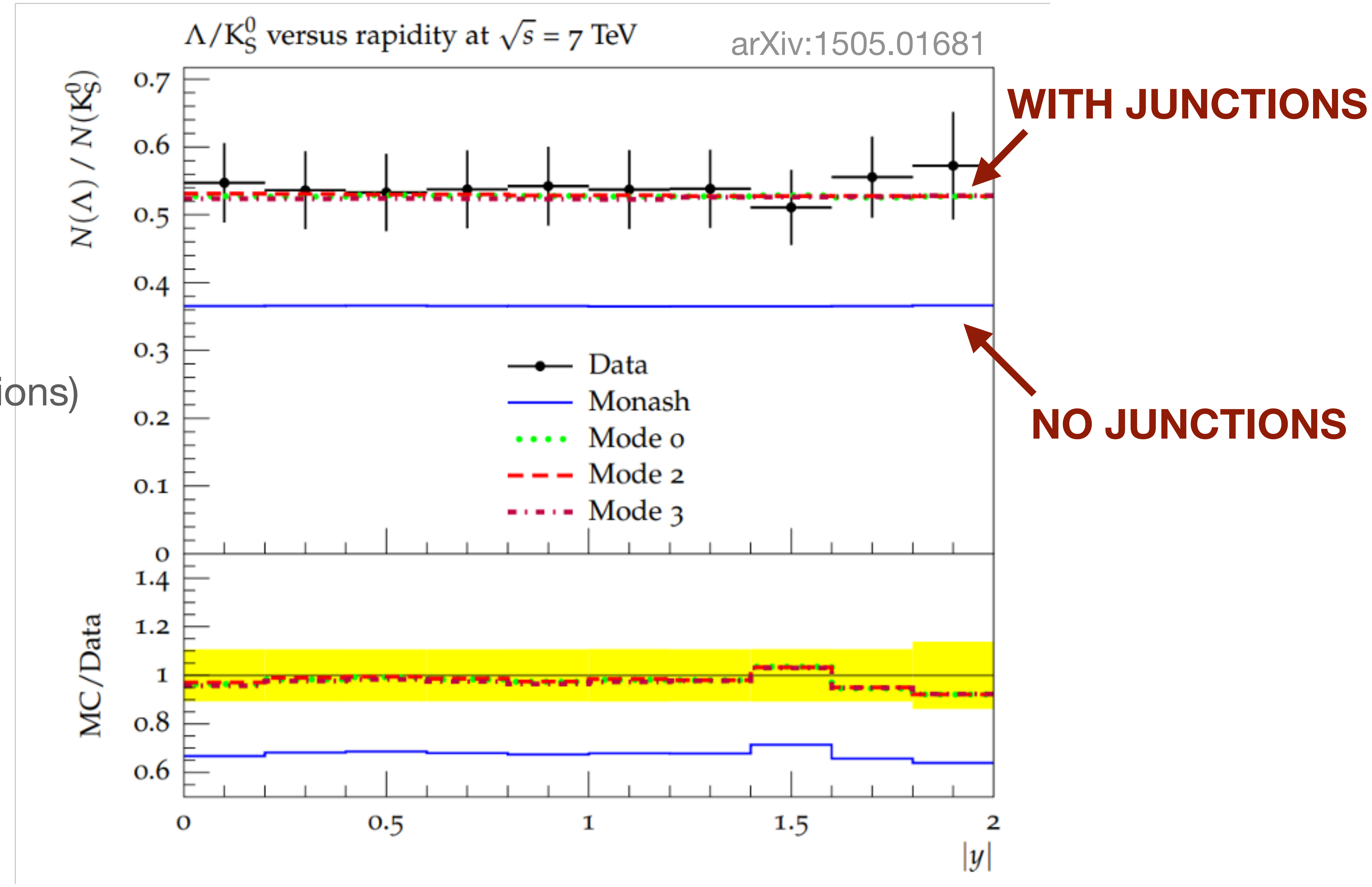
What about the red-green-blue colour singlet state?



Junction reconnection

Junctions

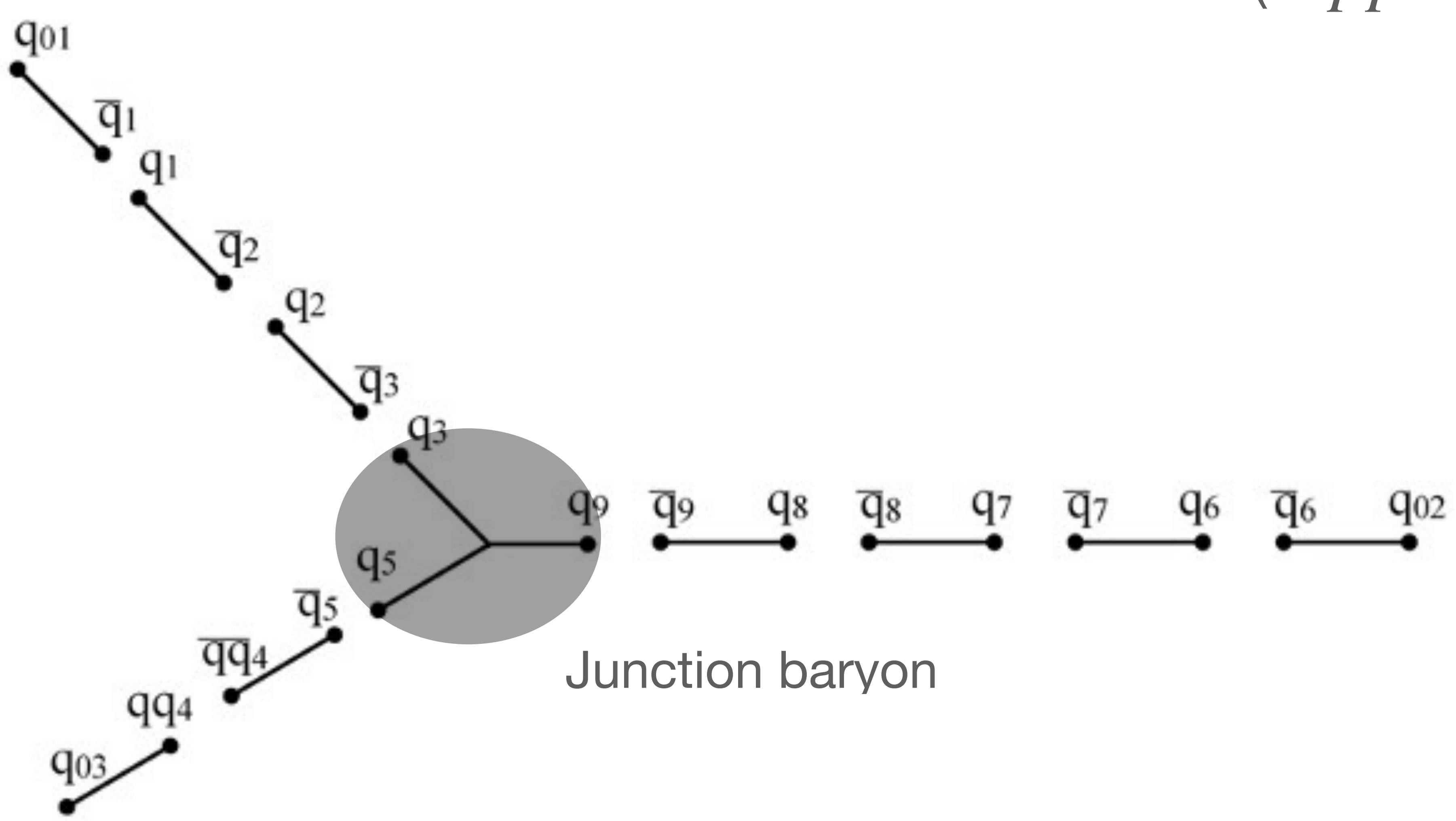




Mechanism for **baryon production**

➢ ~40% of baryons are from junctions in PYTHIA

(in *pp* collisions)



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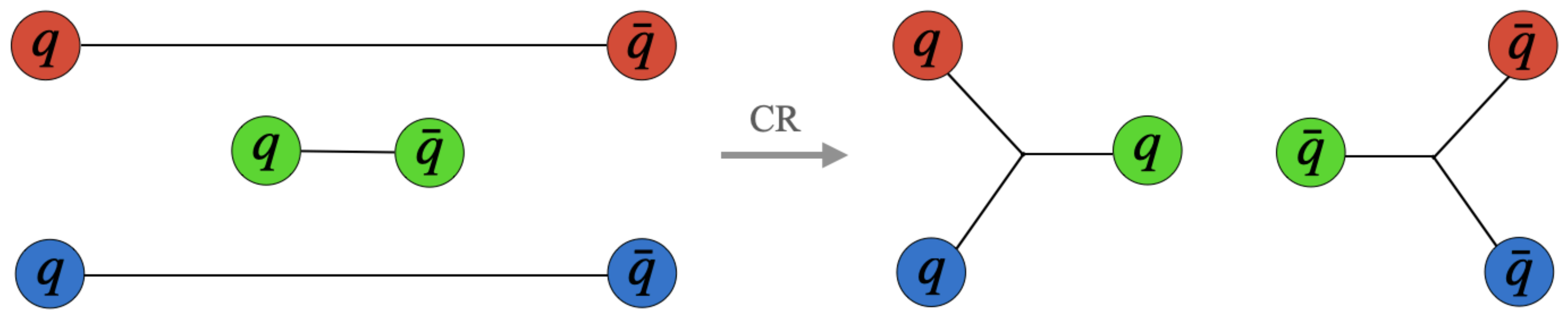

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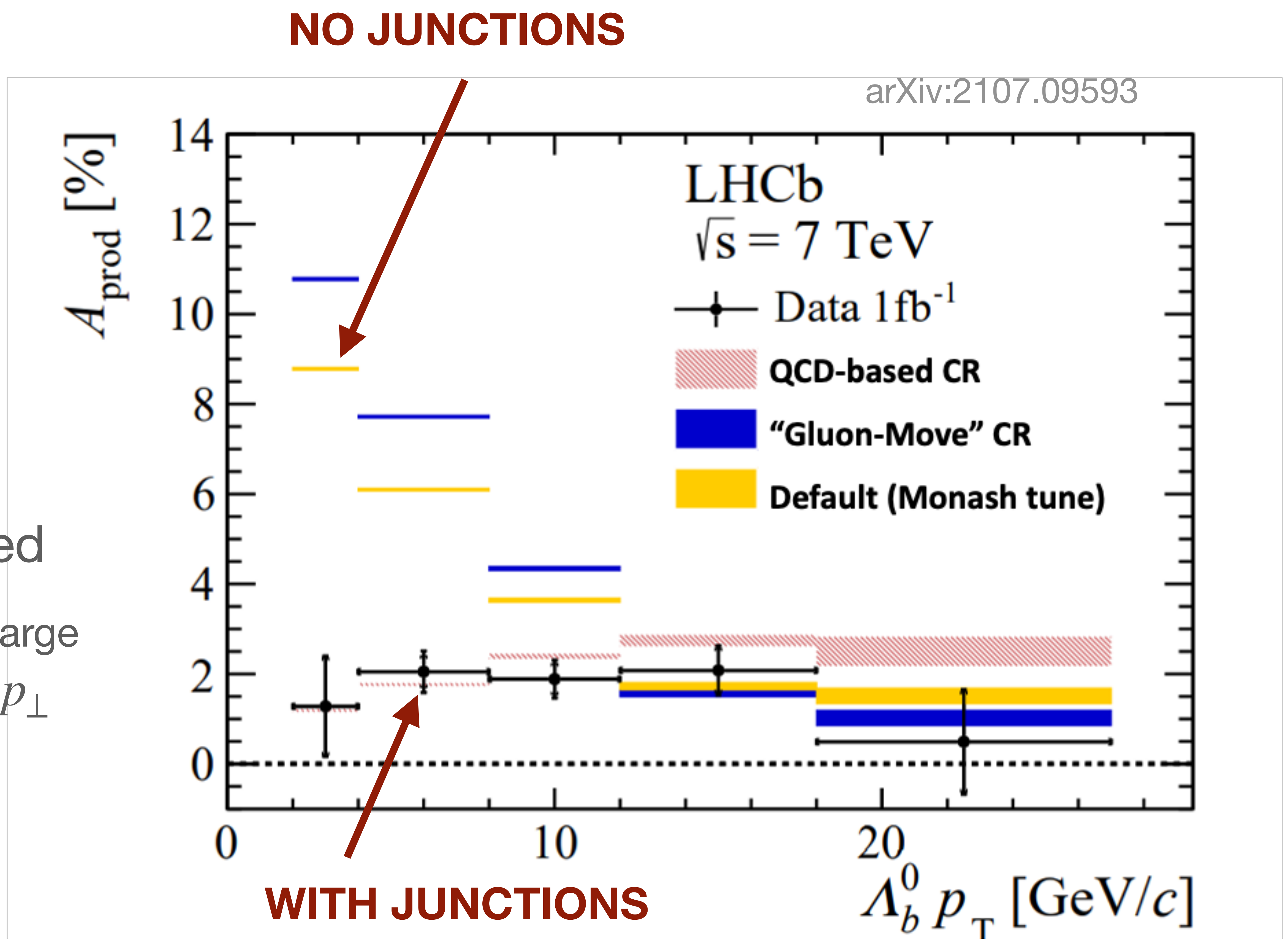
Asymmetries

- Equal amount of junctions and anti junctions are formed

Junctions typically **form between jets** → as jets are likely to have large opening angles due to available phase space, **junction sits at low** $p_\perp$



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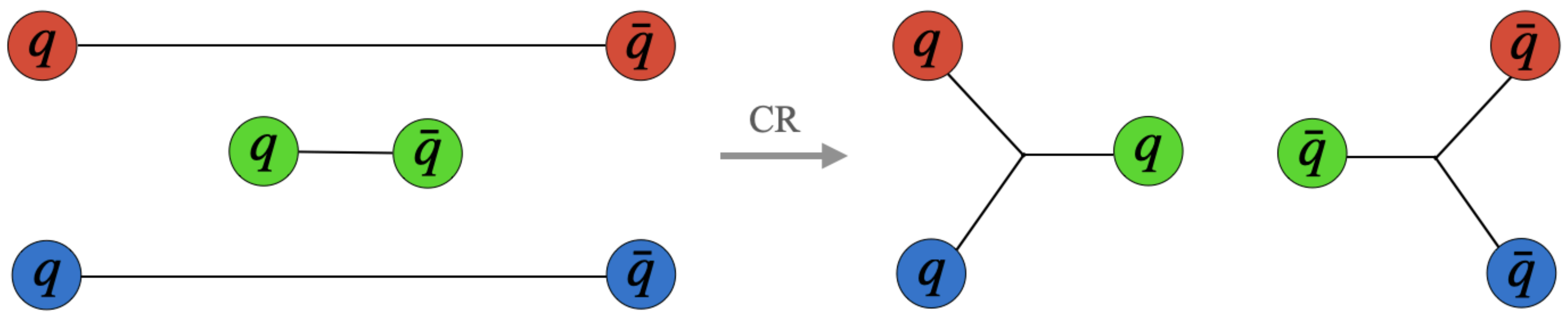

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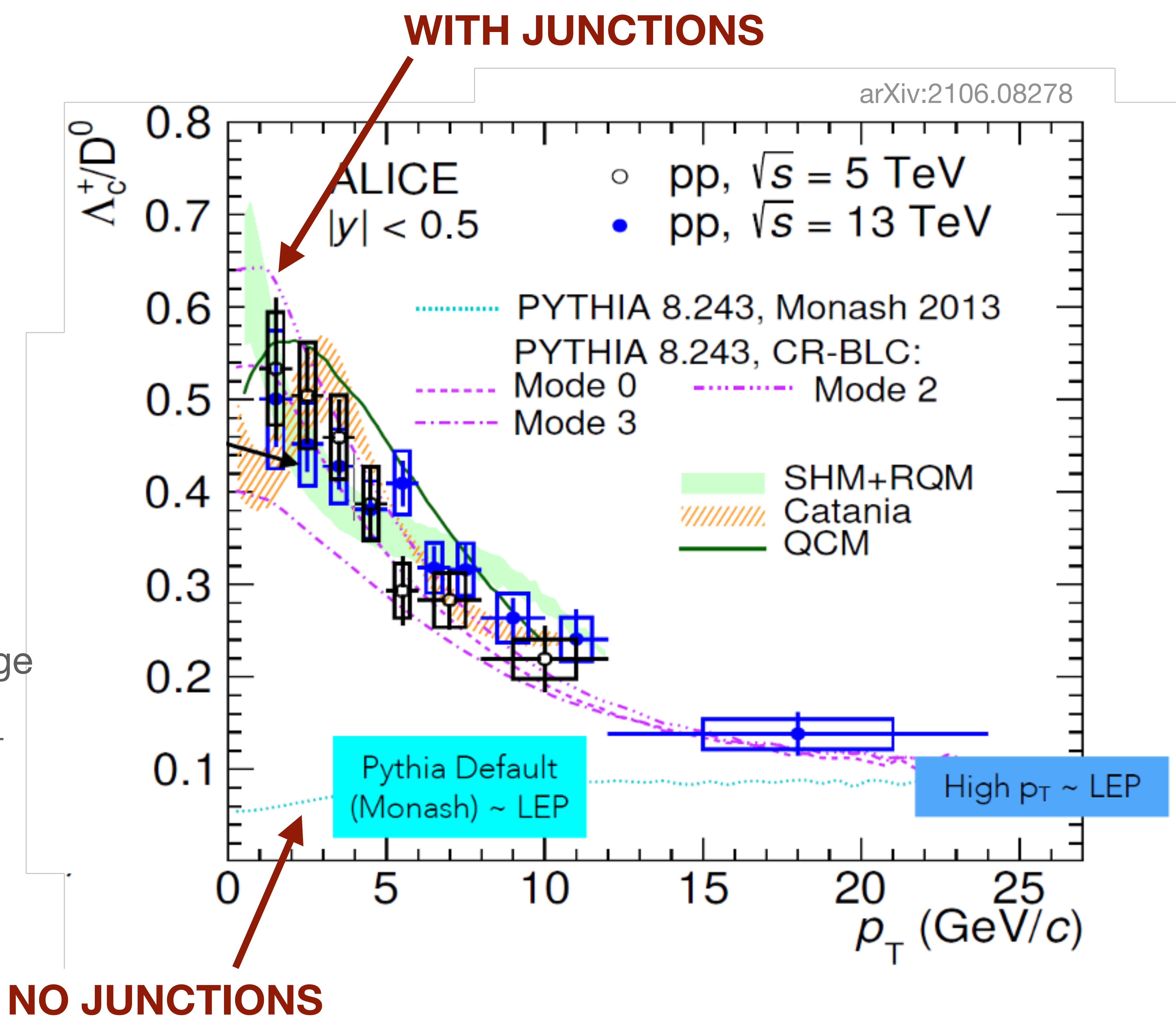
Heavy flavour baryons

- ➢ **~70% of heavy baryons** are from junctions in PYTHIA



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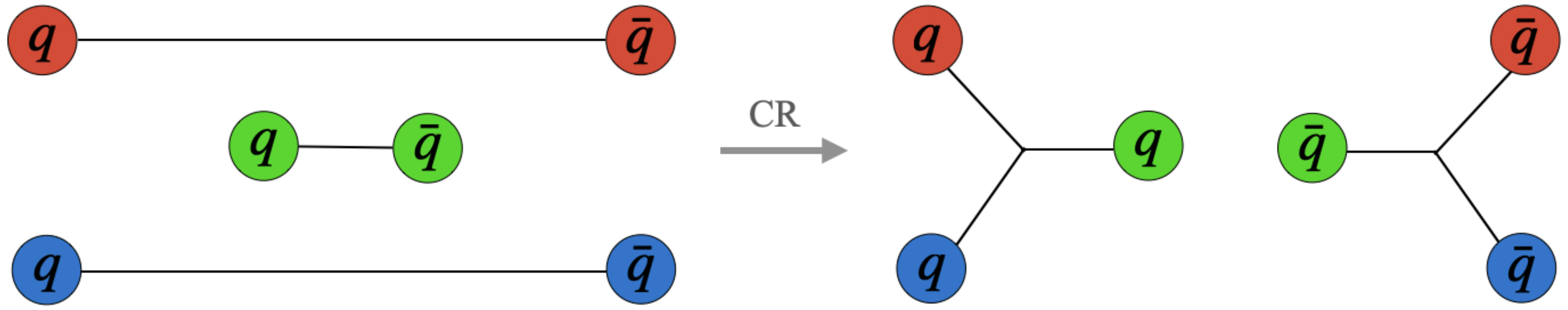

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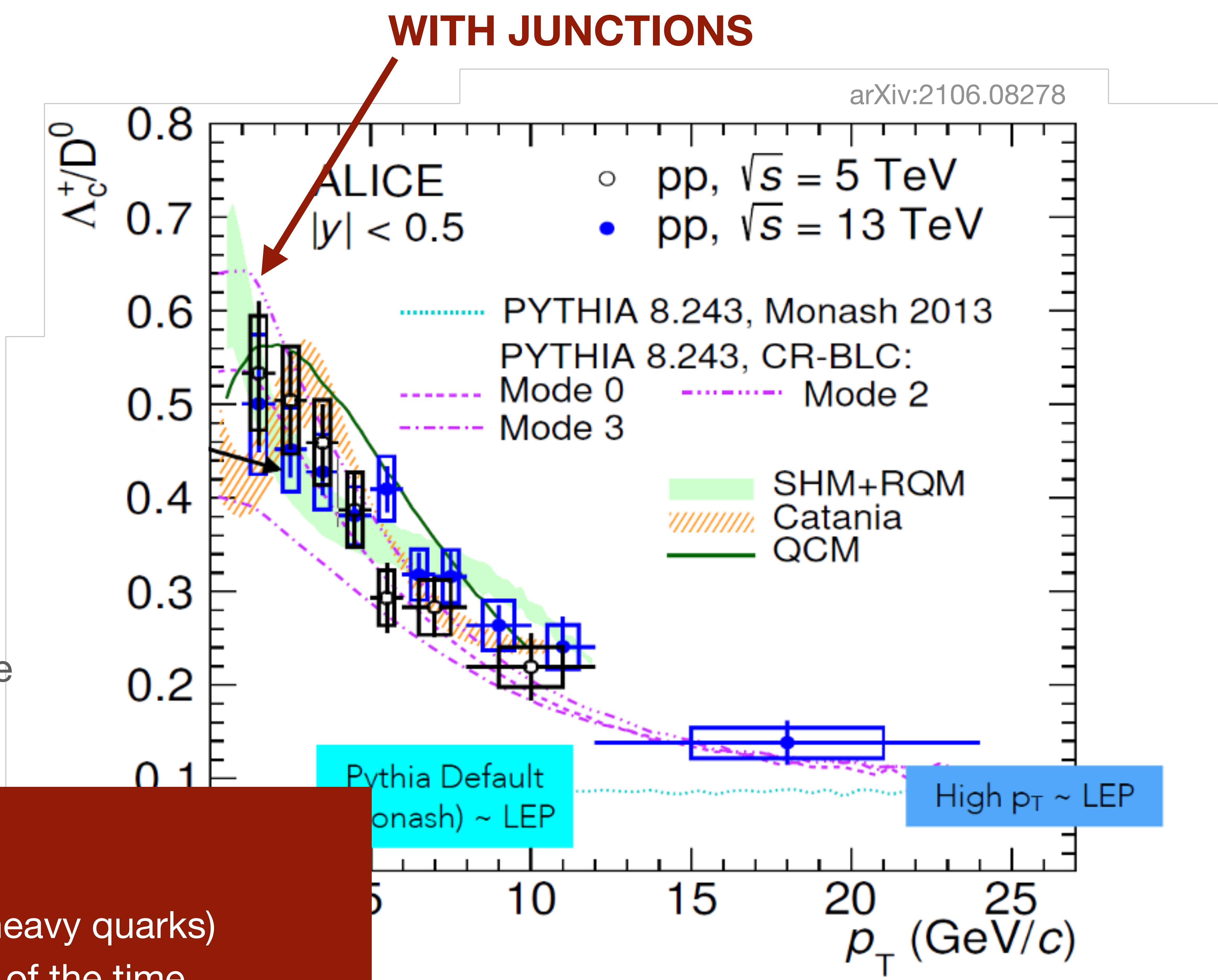


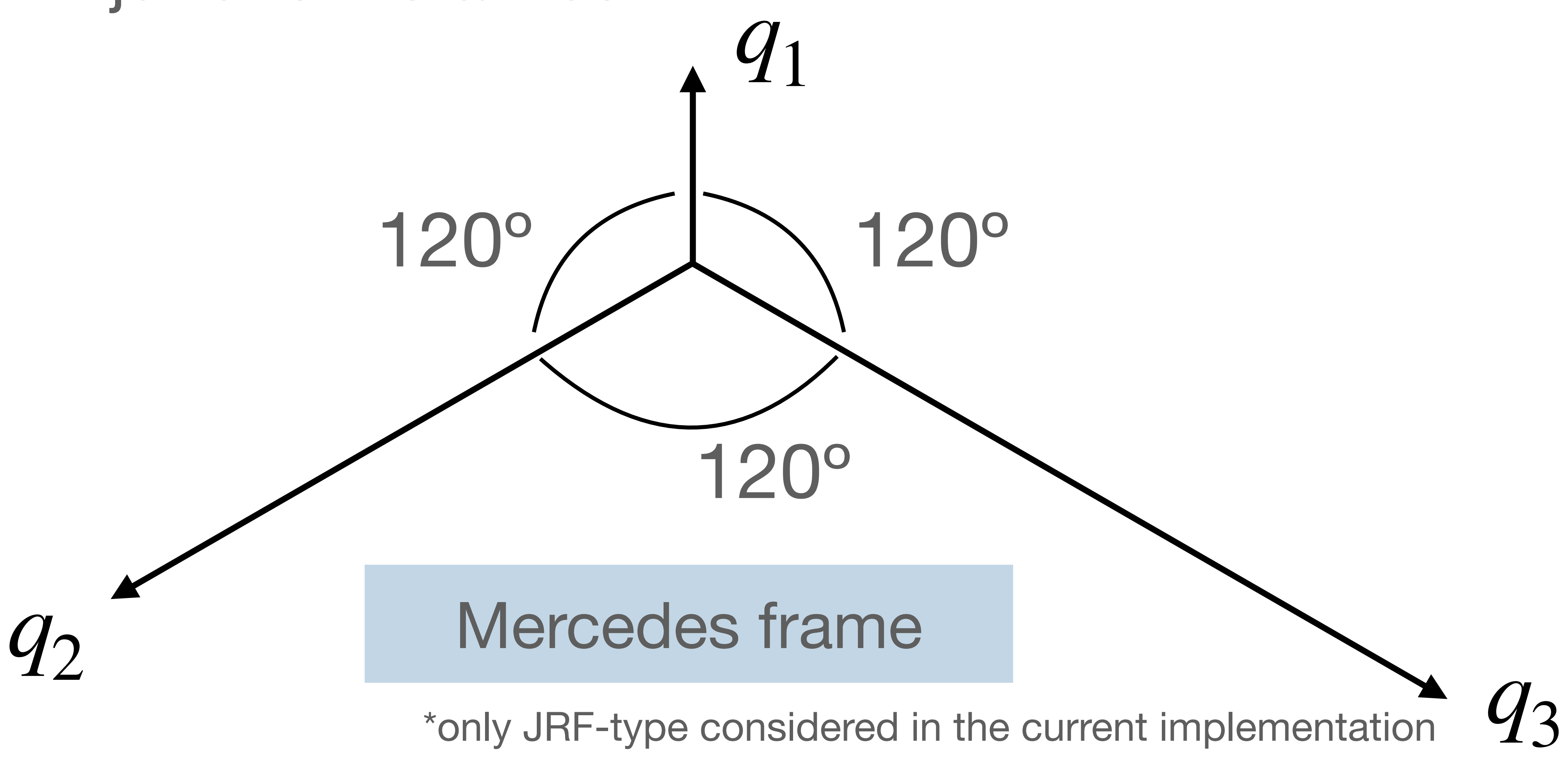
Current implementation

- ➢ Runs into cases with no solution (particularly for heavy quarks)
- ➢ Relies on convergence procedure that fails ~10% of the time

Junction Rest Frame

What is the junction rest frame?

If the momenta of the junction legs are at 120º angles
→ the pull in each direction on the junction is equal
→ junction is at rest



*only JRF-type considered in the current implementation

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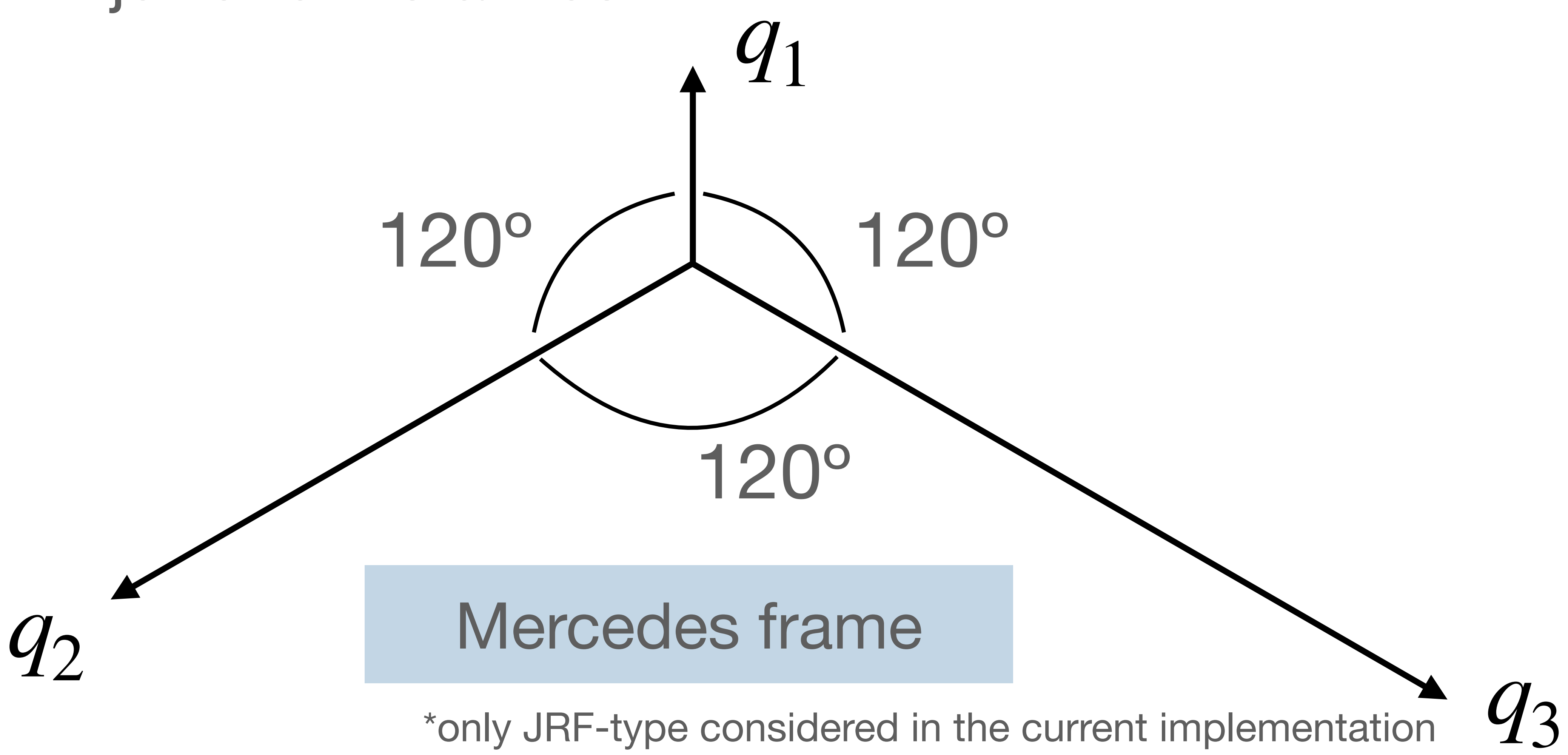

Mercedes frame

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Does a boost to the mercedes frame always exist?

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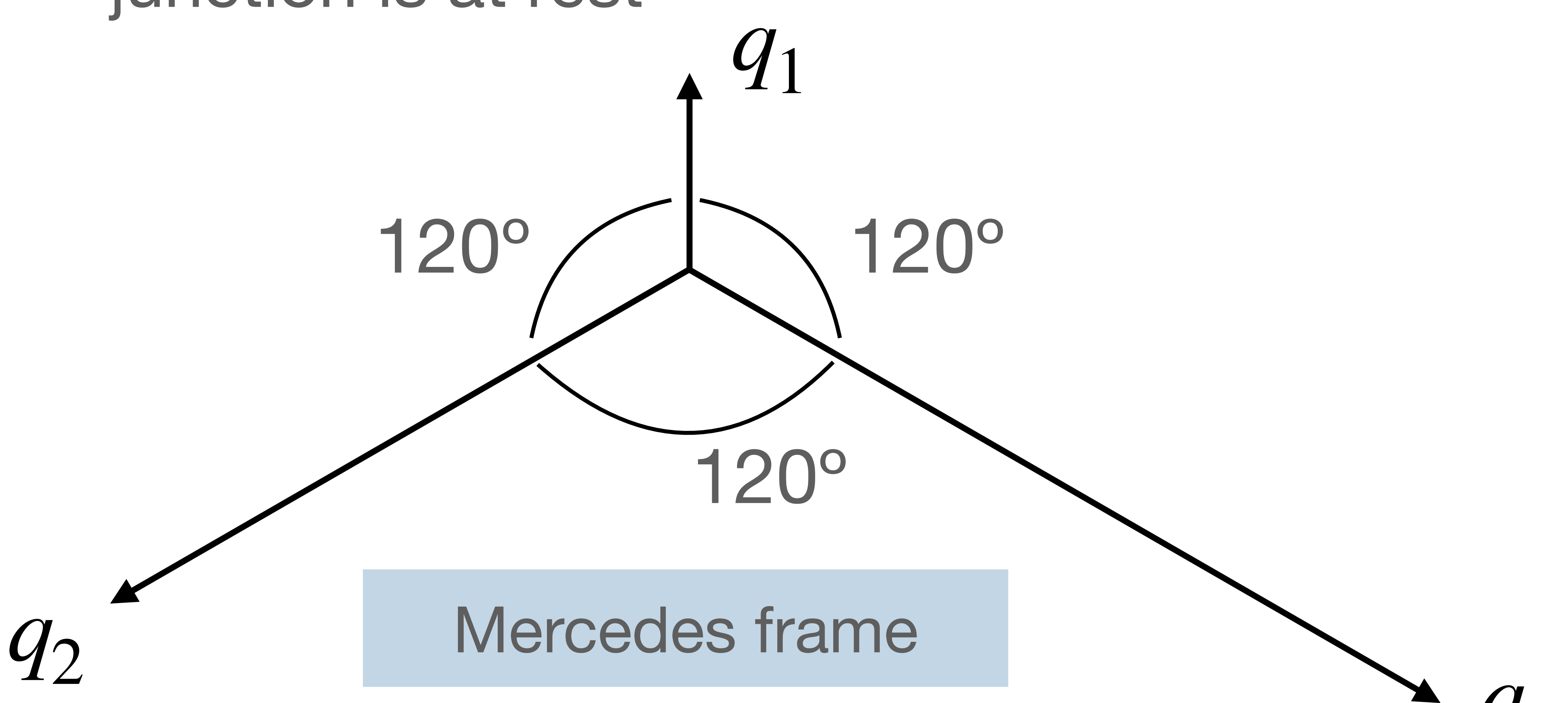

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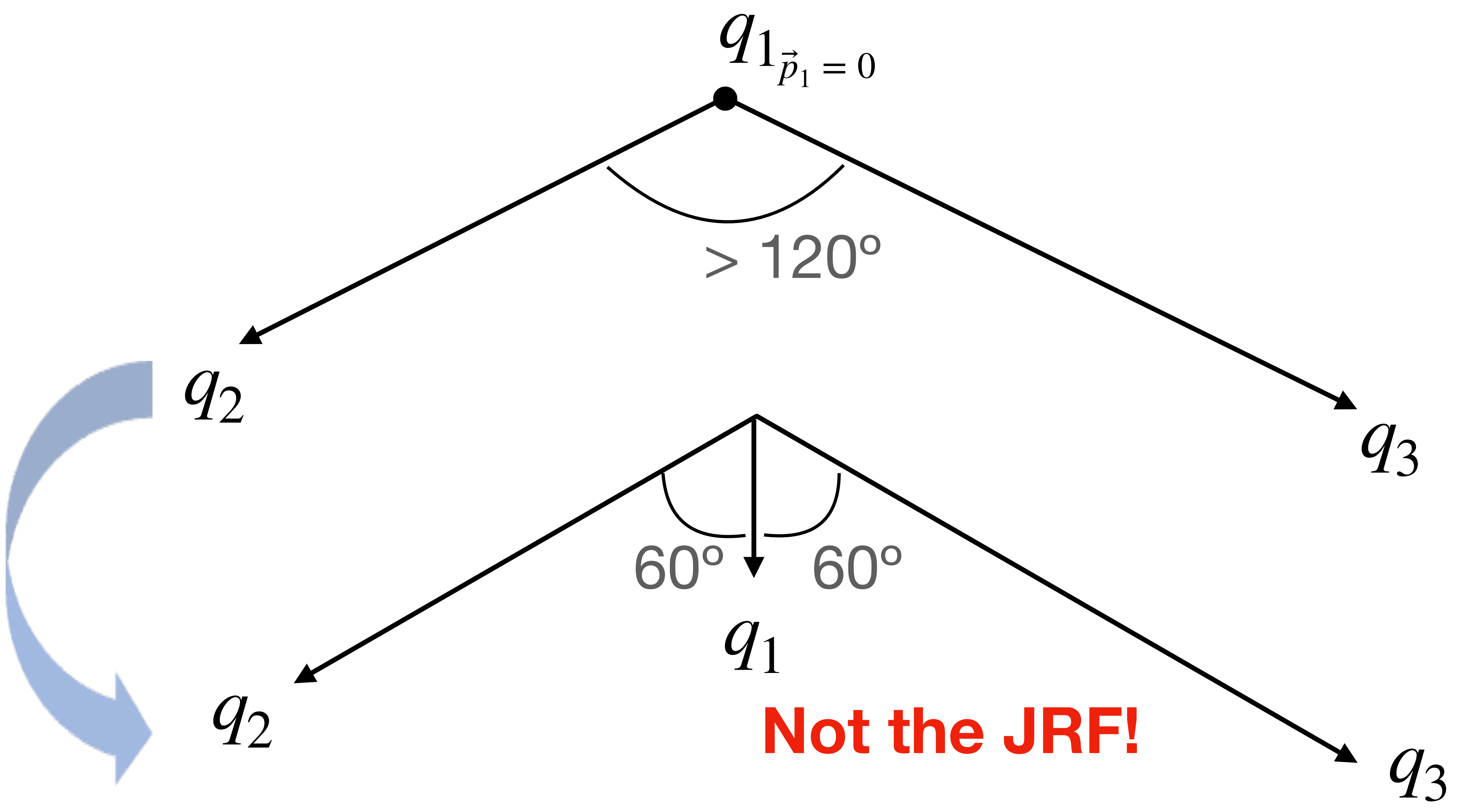
Does a boost to the mercedes frame always exist?

Consider the following:

In the **rest frame of one of the partons**, and the angle between the other two partons is **greater than 120º**

*no special consideration for these cases in current implementation

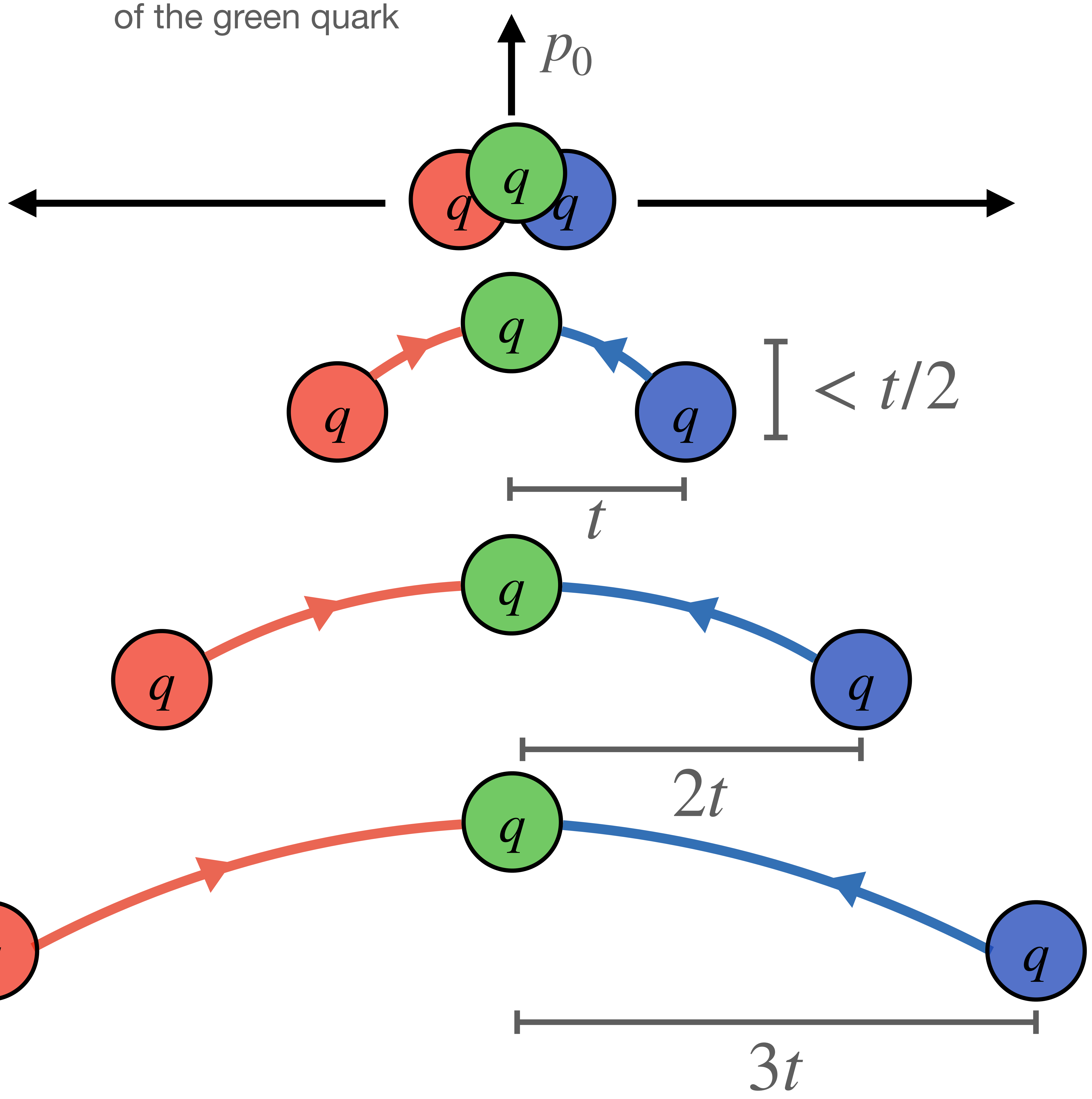


Pearl-on-a-string

The **junction gets "stuck"** to the soft quark, which we call a **pearl-on-a-string**

- ➢ More likely to occur for junctions with heavy flavour endpoints

Example of pearl-on-a-string viewed in the Ariadne frame of the green quark



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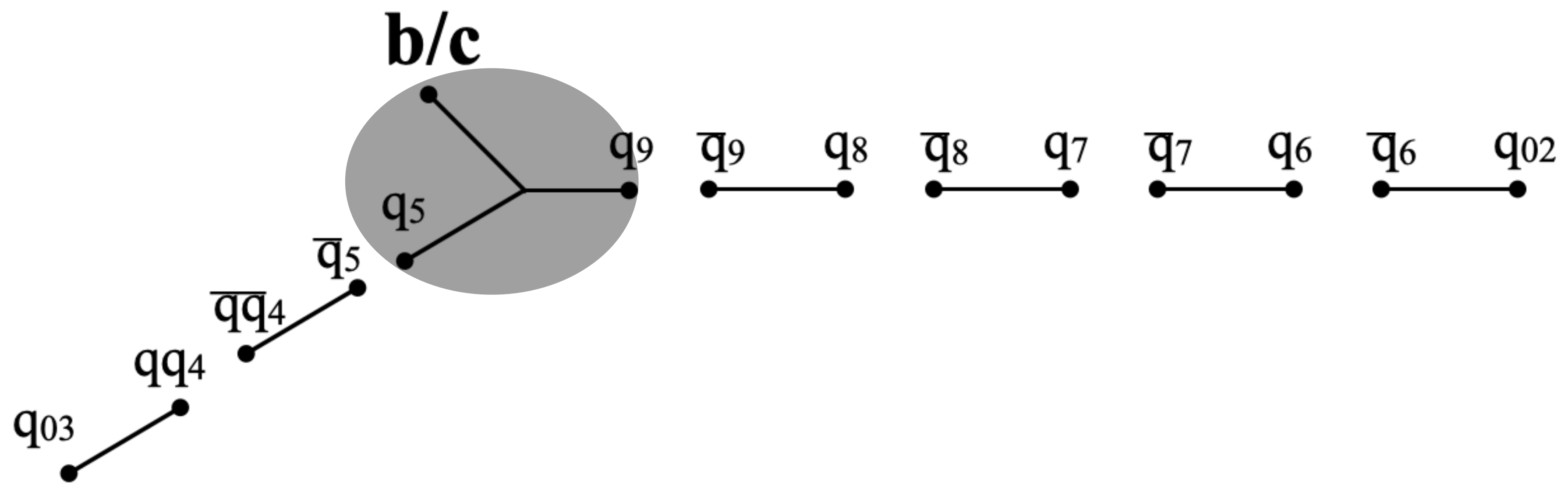
For a junction to make a **heavy baryon**, the junction leg with the heavy quark can't fragment (*i.e.* a "soft" junction leg) = **pearl-on-a-string!**



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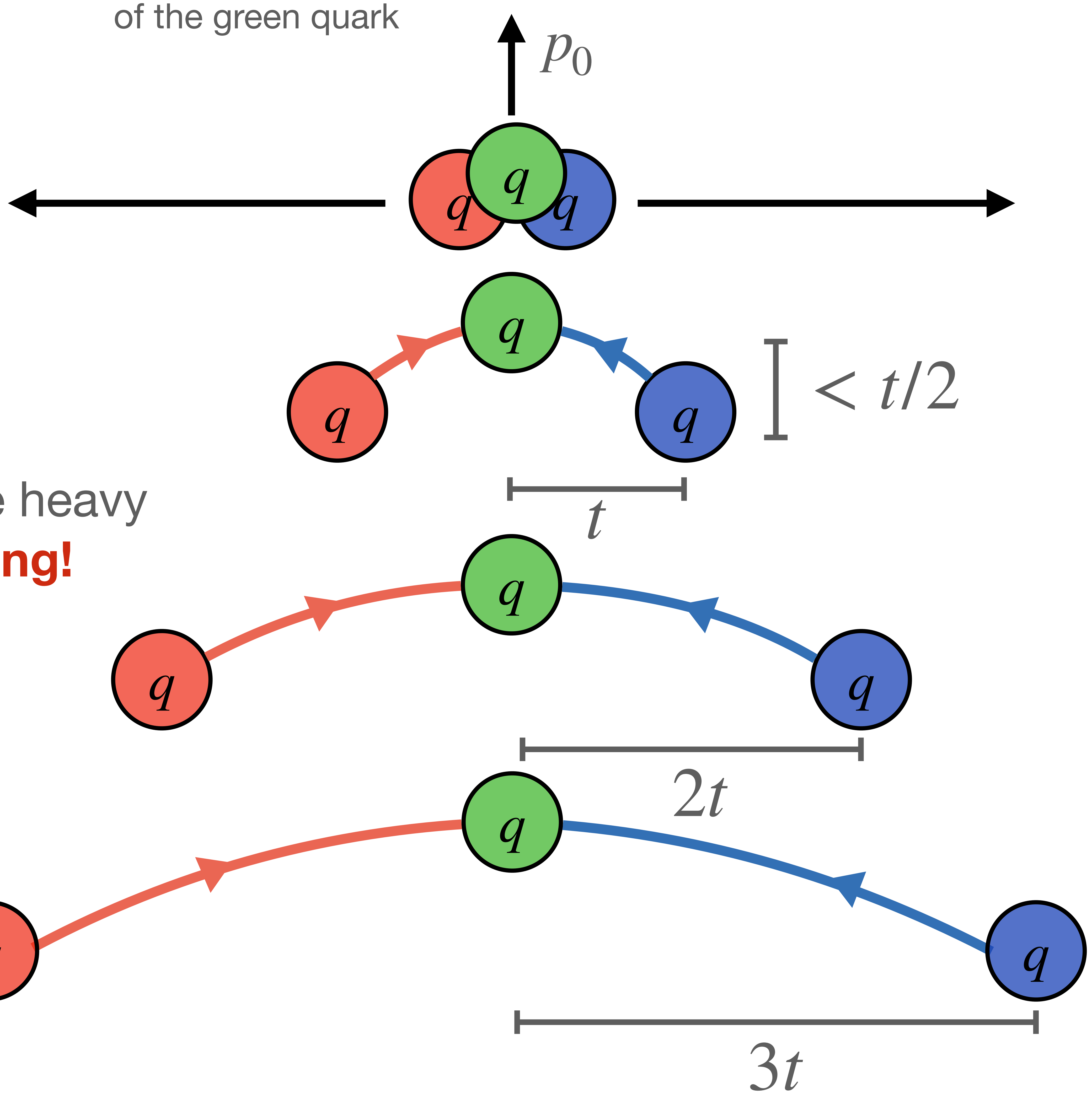
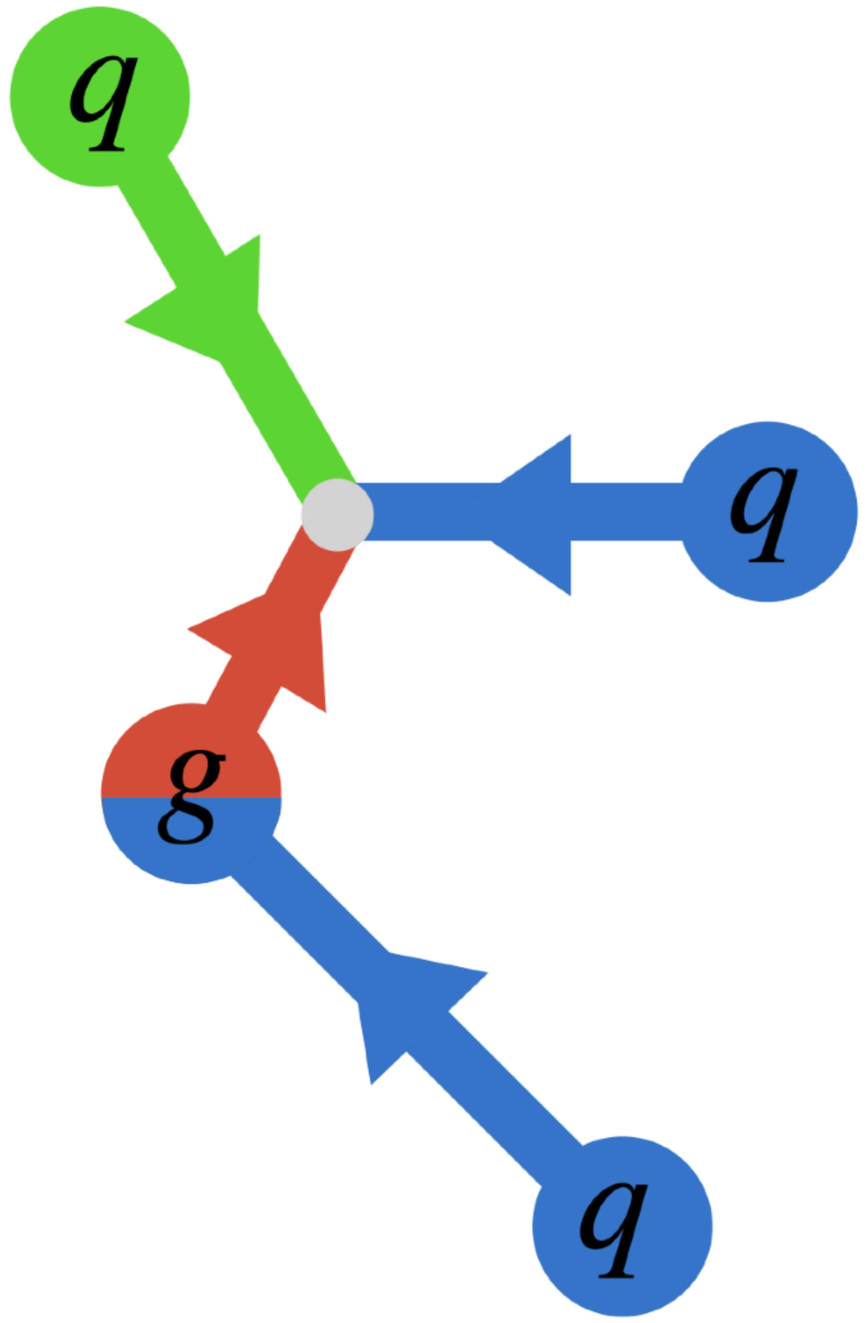


Updates to averaging



Use an **"average" JRF**

Current procedure assumes the **average is the mercedes frame**

- ➢ Uses energy weighted sum of momenta on each junction leg
- ➢ Relies on convergence procedure that fails ~10% of cases

New treatment:

- ➢ Considers pull on junction over time and average over junction motion
- ➢ Includes pearl-on-a-string
- ➢ Allow endpoint oscillations
- ➢ No reliance on convergence

- ➢ Early time JRF defined by the first parton on each leg
  - ➢ Use smallest leg momentum as a measure of effective time for the JRF
- ➢ When softest parton has lost its momentum, the next parton dominates the pull

Junctions

arXiv:2106.08278

Junctions


arXiv:2105.05187
arXiv:2106.08278
Preliminary
ALICE pp 13 TeV
Monash
CR new
CR new with gluon-approx
CR old
WITH JUNCTIONS
NO JUNCTIONS
LiveDisplays
Theory/Data
Λ_c^+/D^0
Ξ_c^0 / D_0
$3/2 * \Sigma_c^{0,+,++} / D^0$
$p_\perp$
What about strange baryons?

Junctions

What about strange baryons?

Clear observations of strangeness enhancement with respect to charged multiplicity [e.g. ALICE Nature Pays. 13, 535 (2017)]

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**

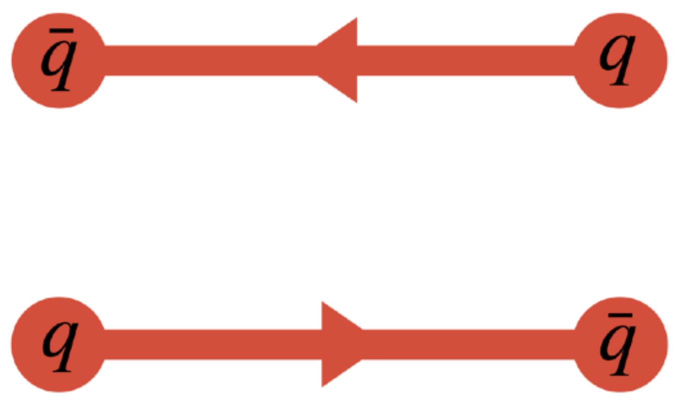
Aims to **stochastically restore** these colour correlations using $SU(3)$ algebra

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

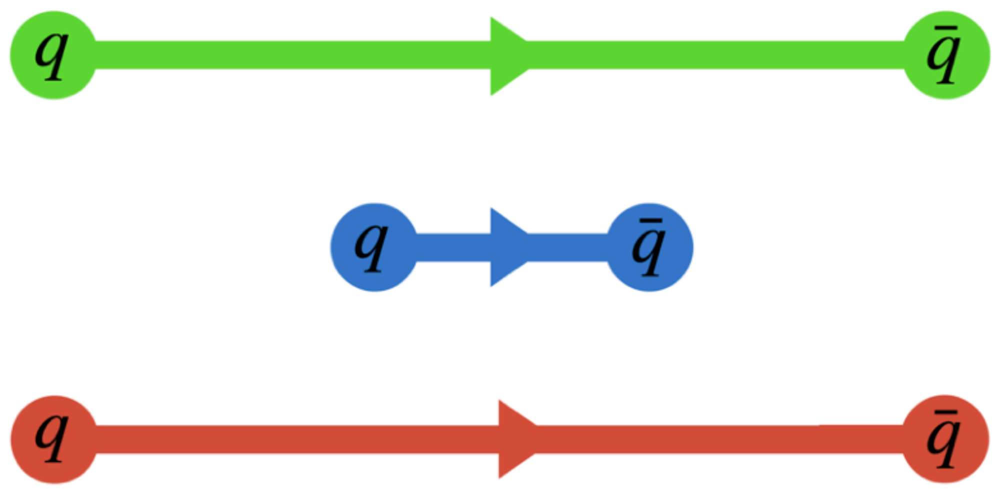
$$3 \otimes 3 = 6 \oplus \bar{3} \text{ (colour-colour)}$$

"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



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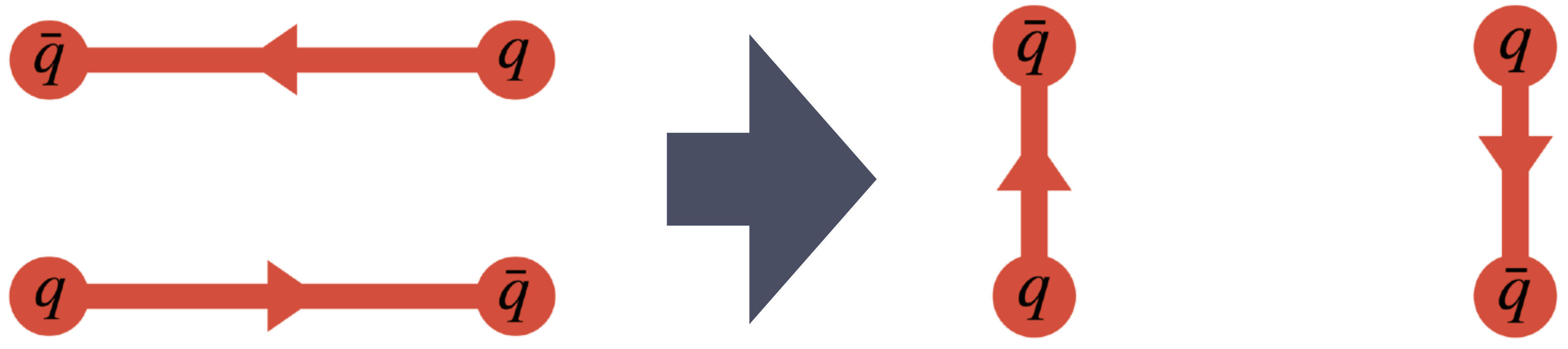

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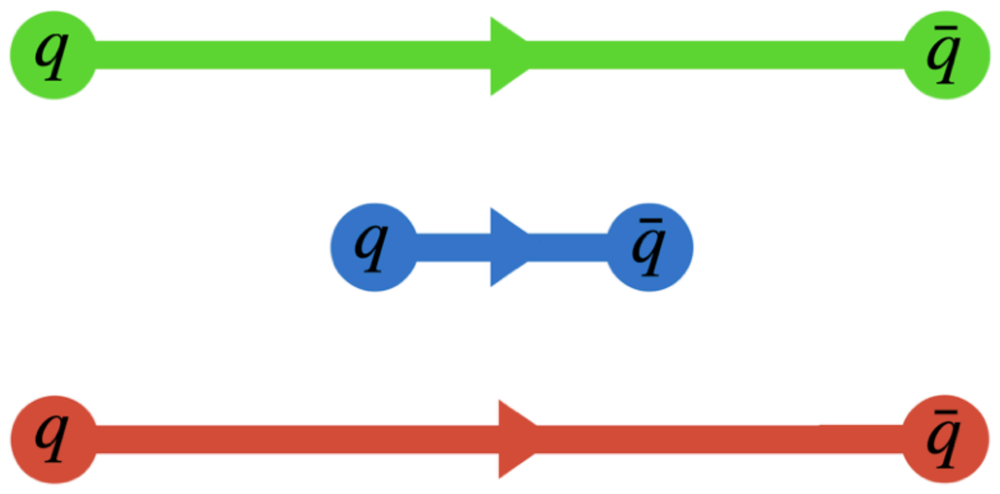

Independently hadronising MPI does not result in **increasing $\langle p_\perp \rangle$ with multiplicity**

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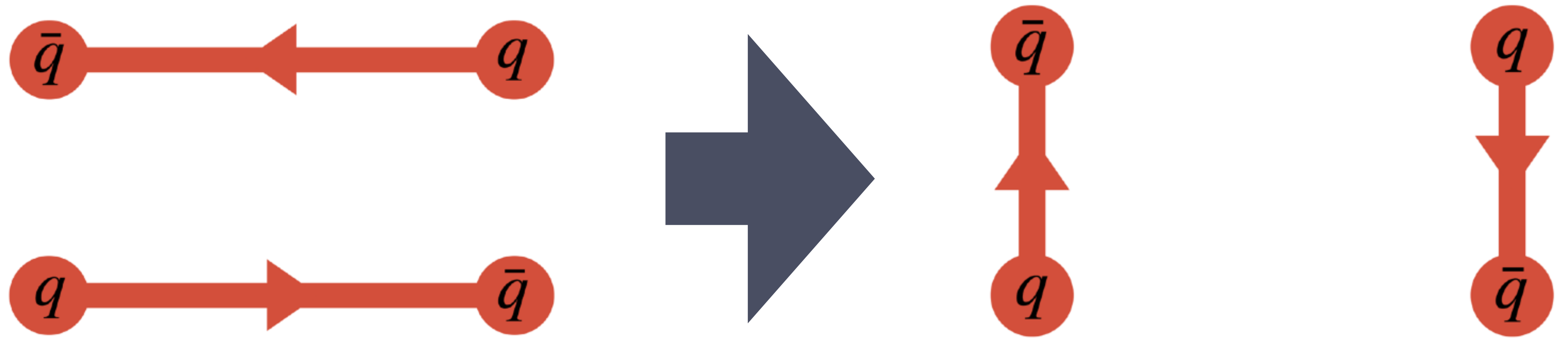
Aims to **stochastically restore** these colour correlations using $SU(3)$ algebra

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

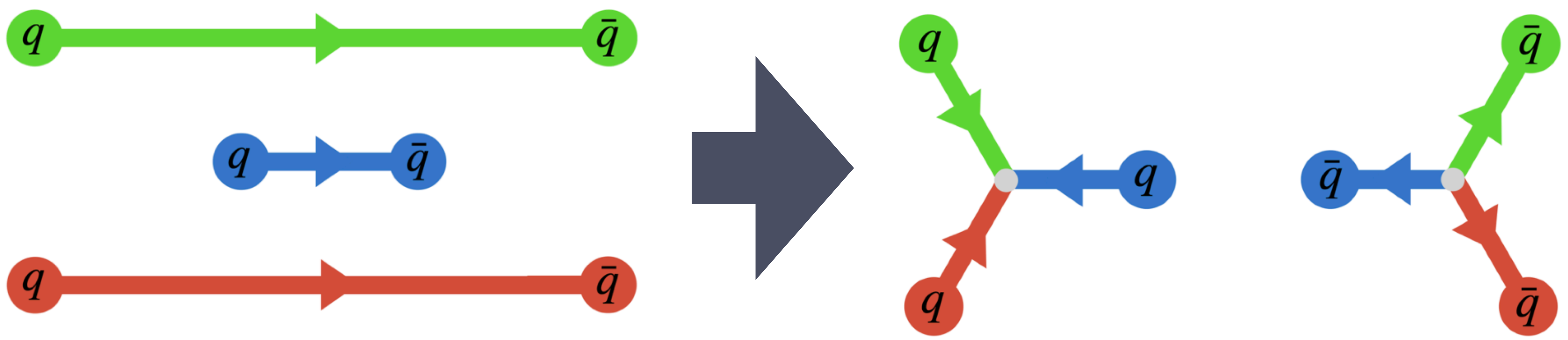
$$3 \otimes 3 = 6 \oplus \bar{3} \text{ (colour-colour)}$$

"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



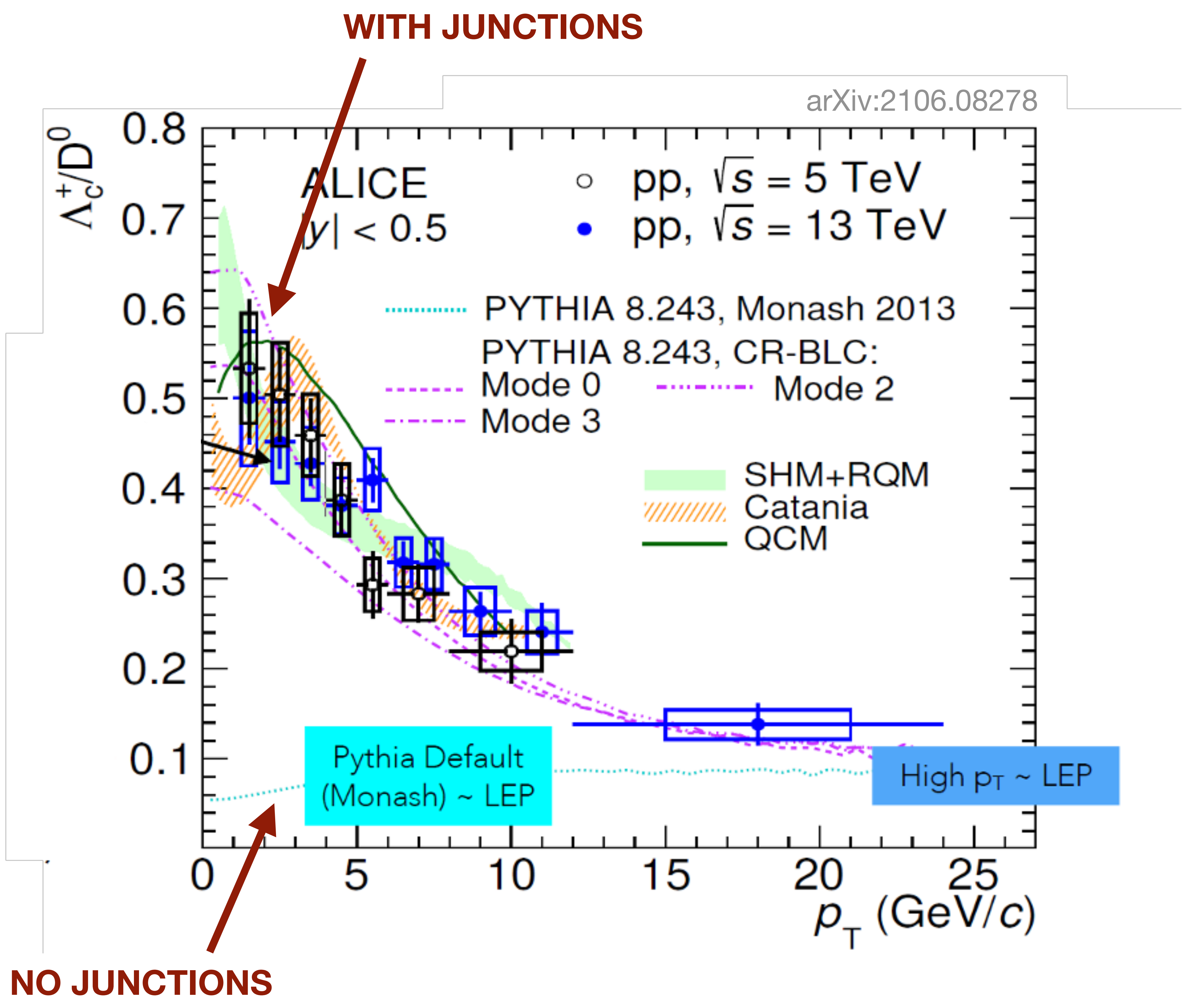
Junction-type reconnection: red-green-blue



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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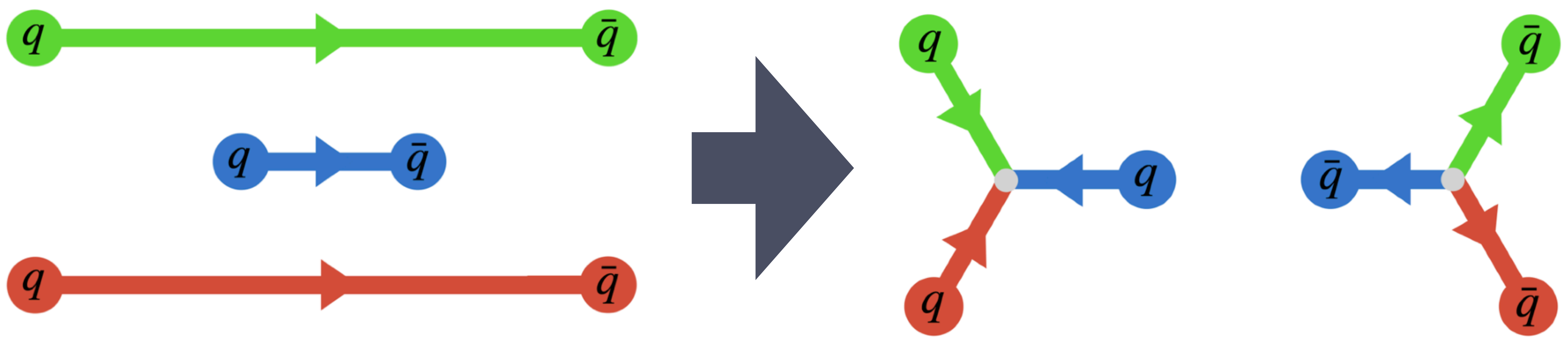

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Junctions result in baryons → increase in **baryon-to-meson ratio**

Colour Reconnections

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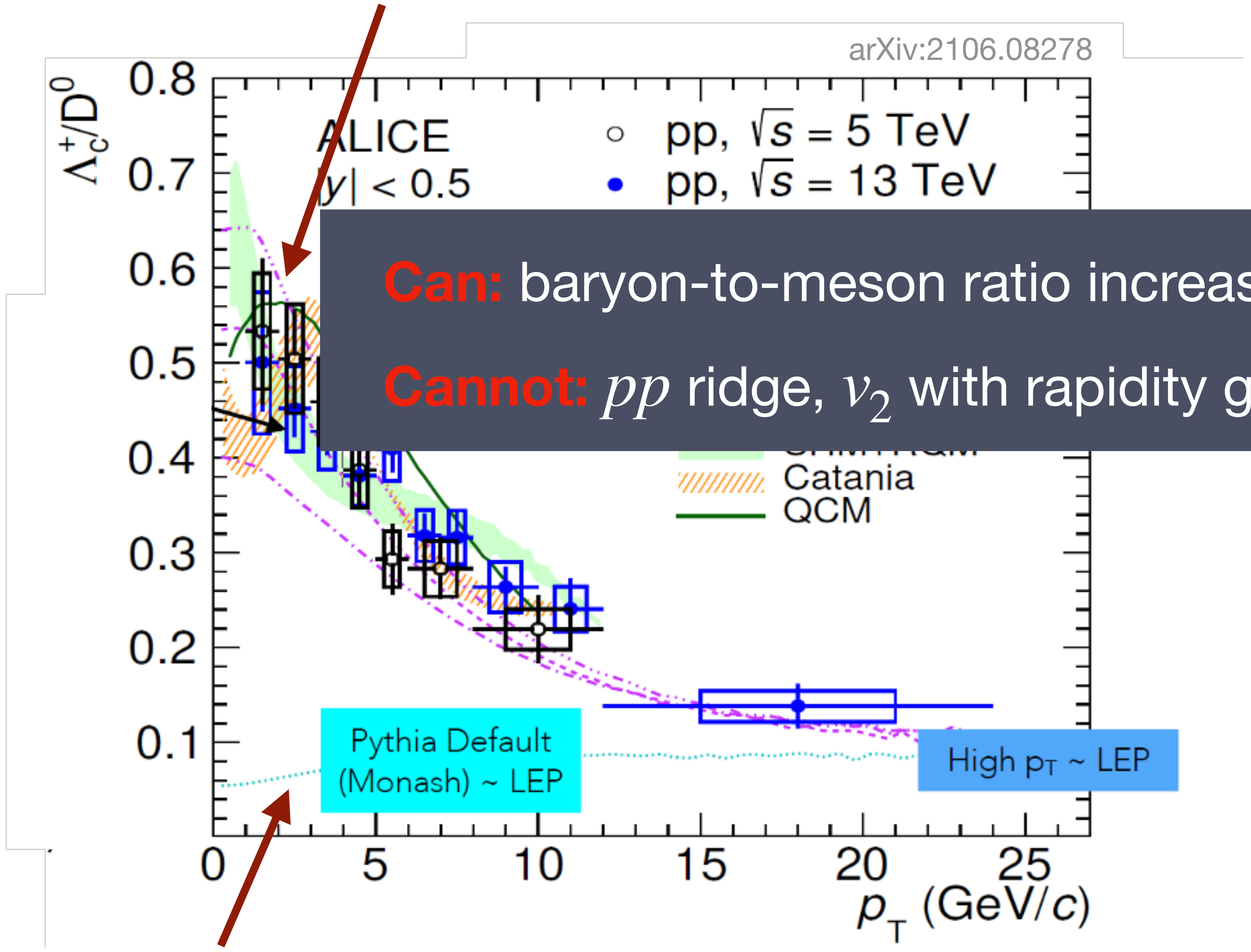
WITH JUNCTIONS

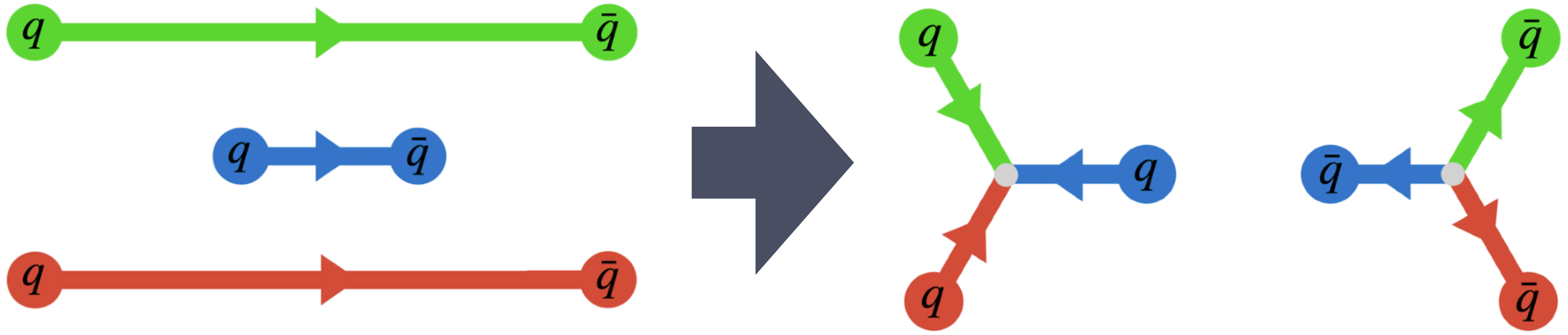


NO JUNCTIONS

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



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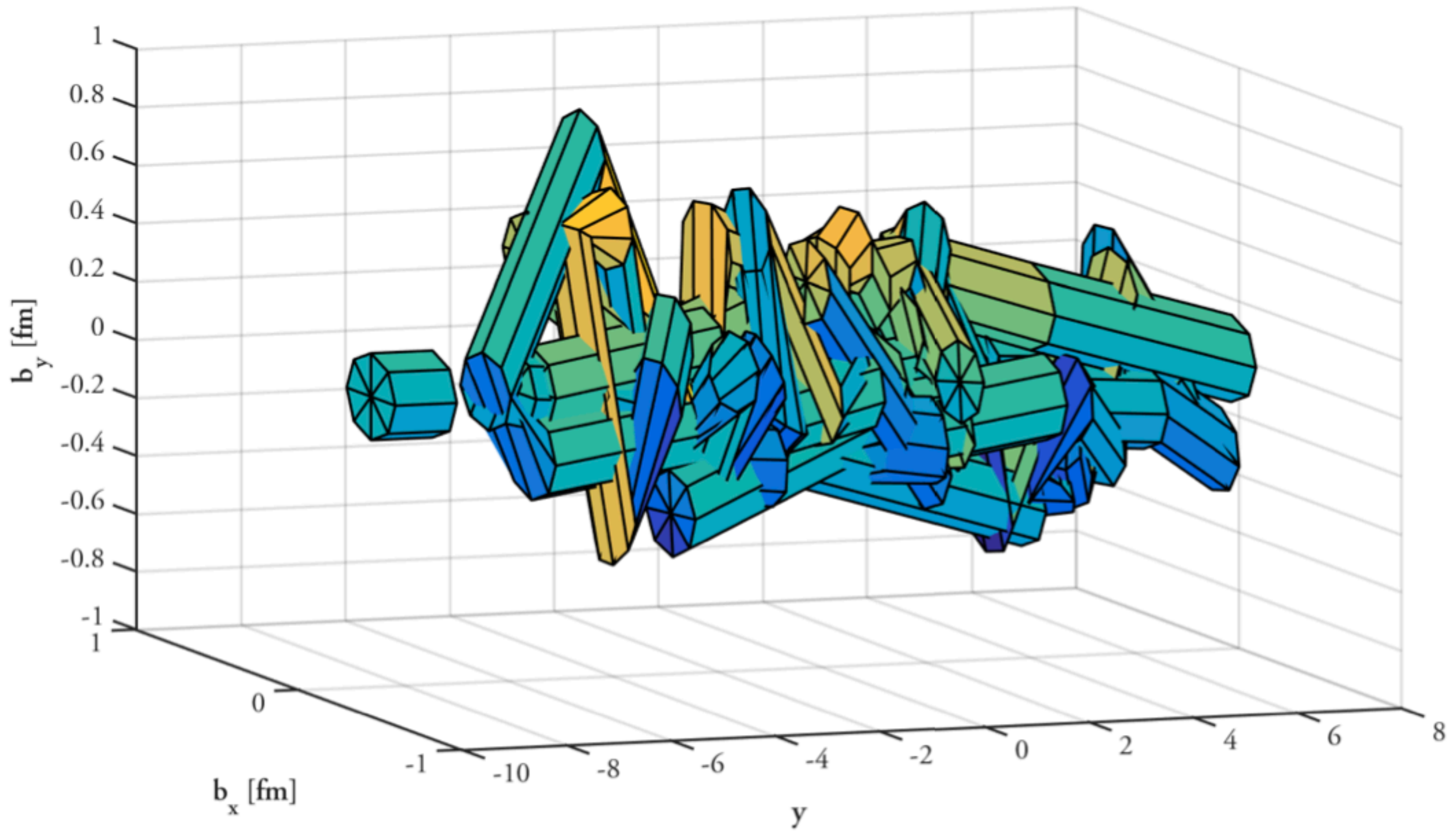
Shoving

arXiv:2010.07595

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



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

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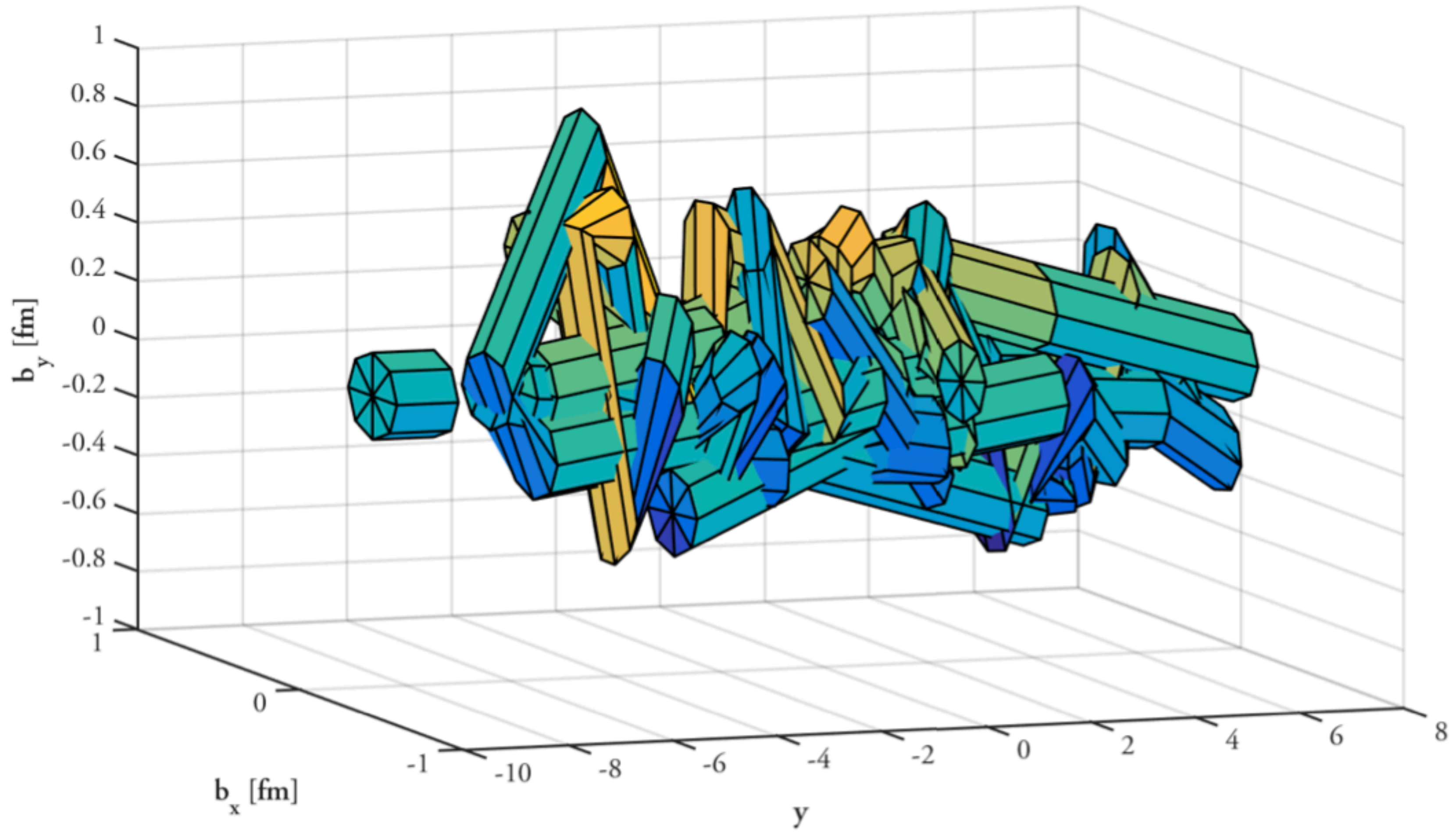
CR has already occurred with string minimisation choosing singlet configurations

→ only octet states would likely be near one another

→ only **repulsion** left



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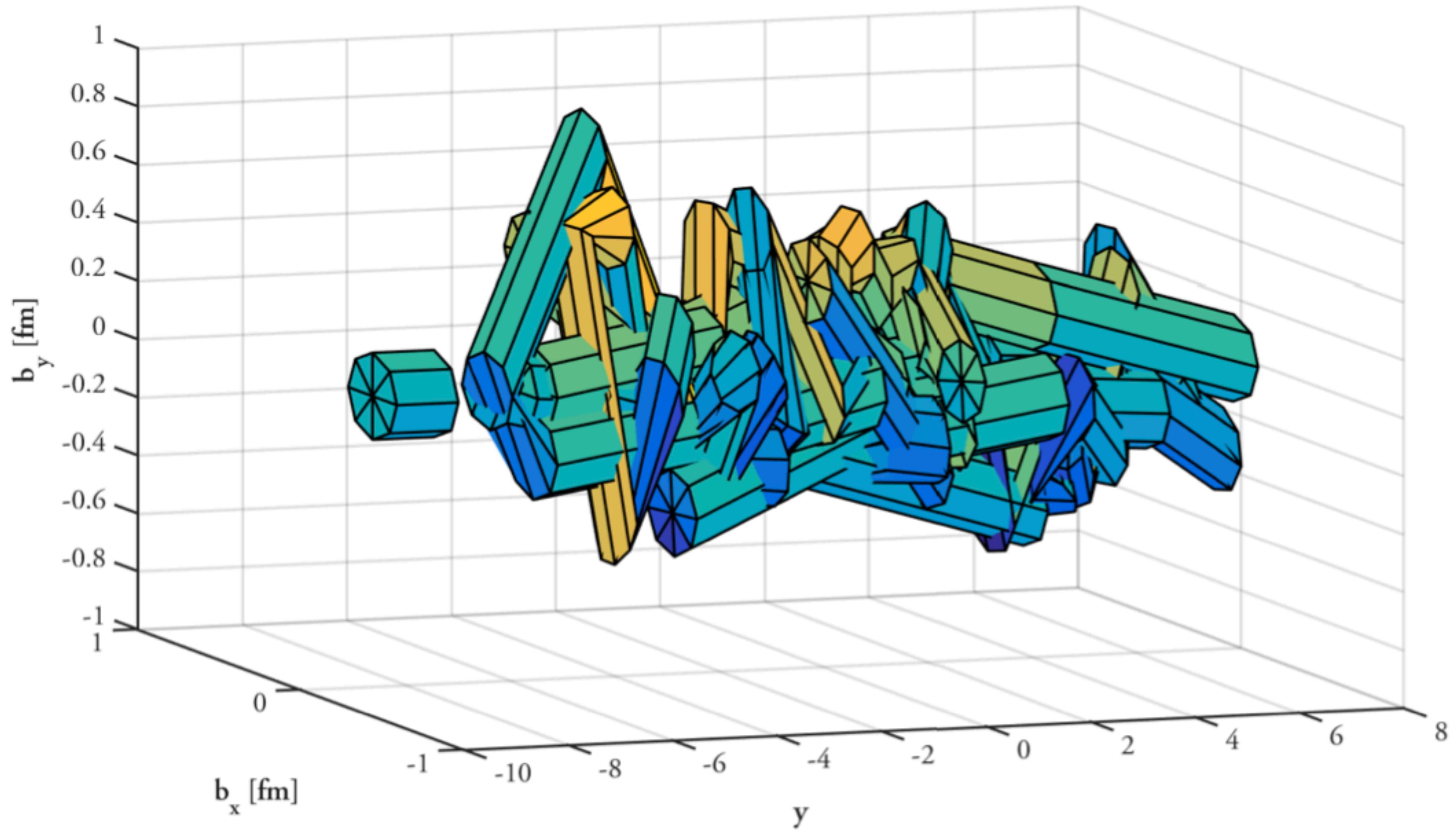

e.g. $\sqrt{s} = 7$ TeV collision example

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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.**

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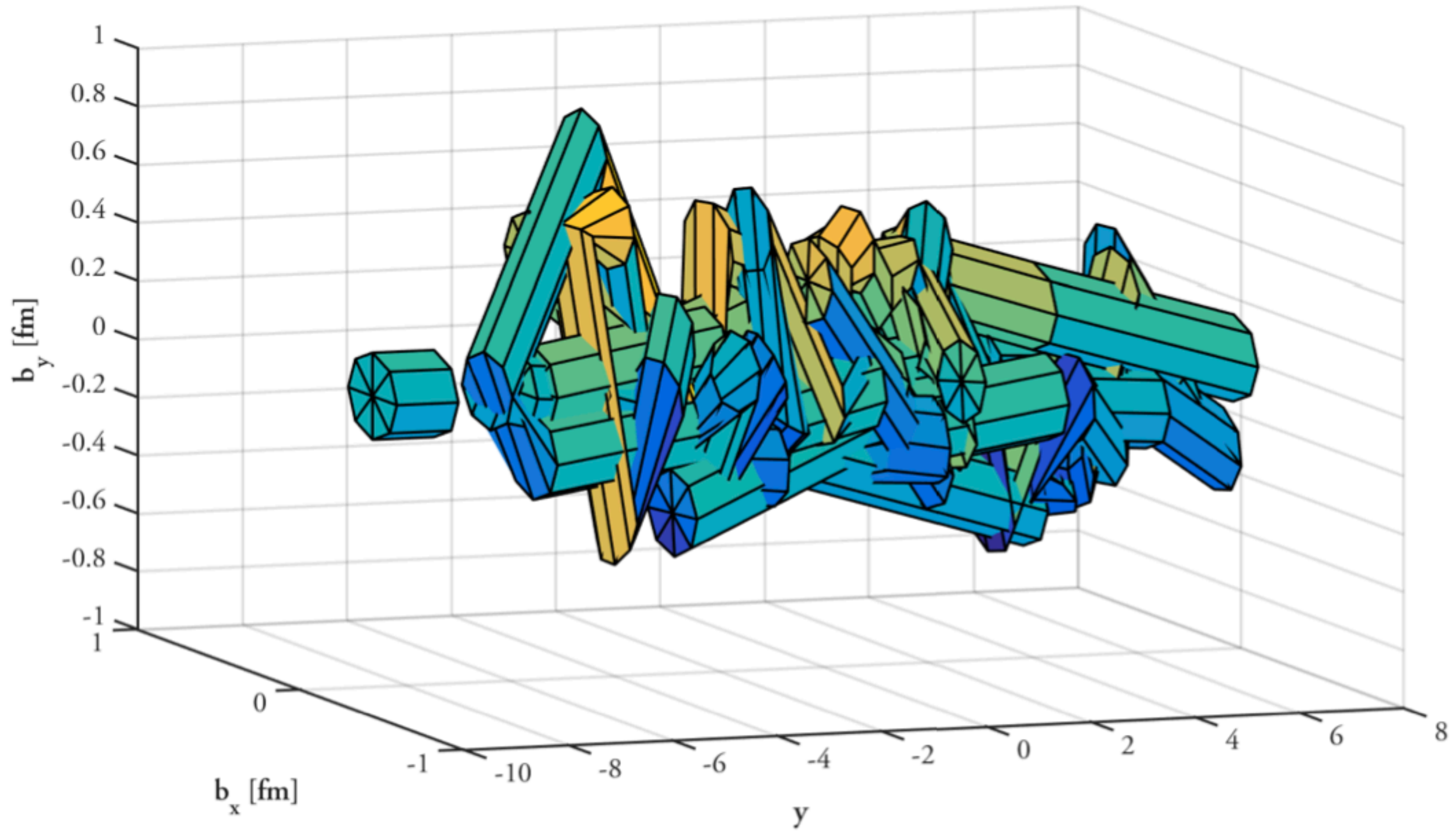

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Monte Carlo implementation details

➢ 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

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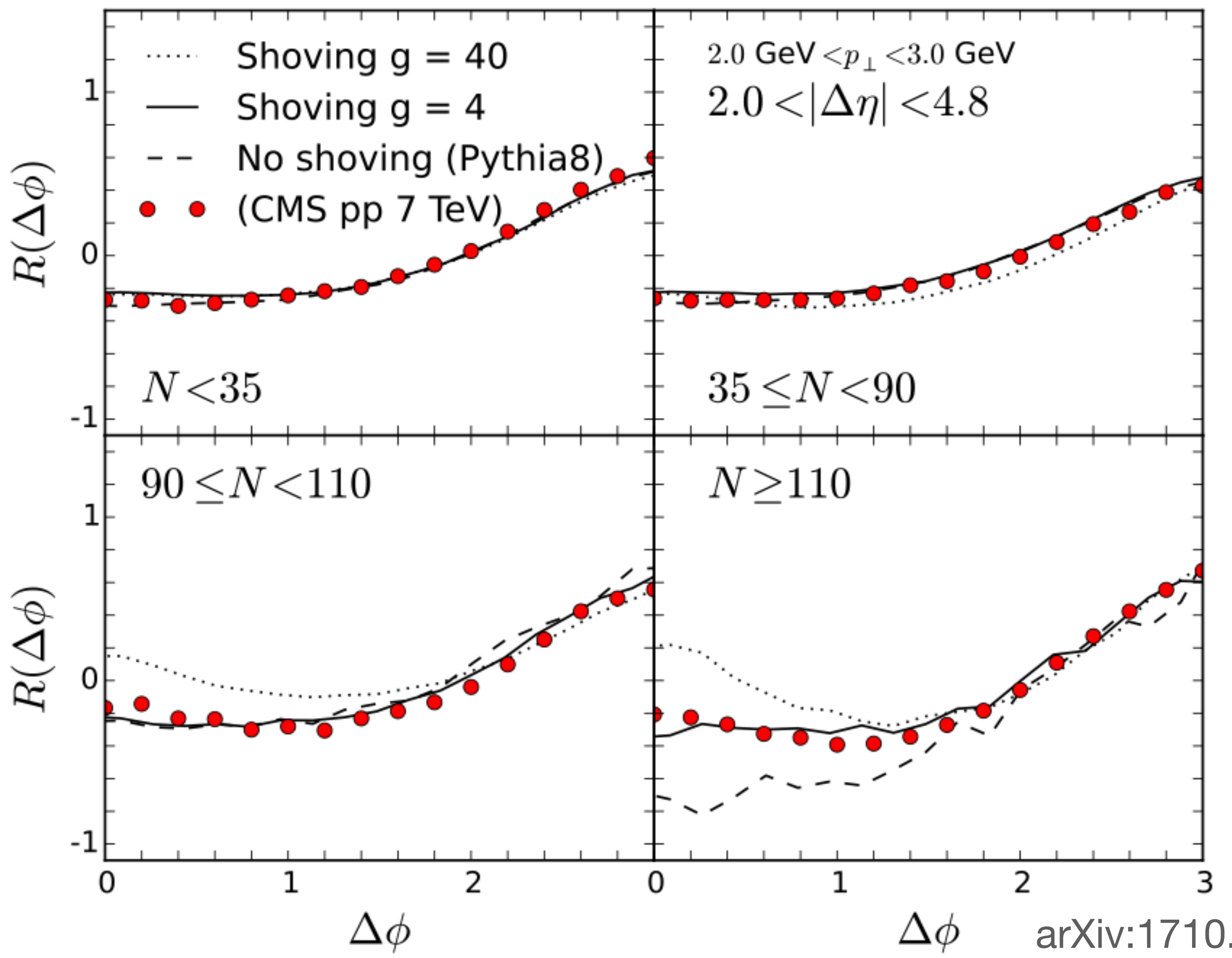
Generate anisotropic flow as a response to the **spatial initial conditions**

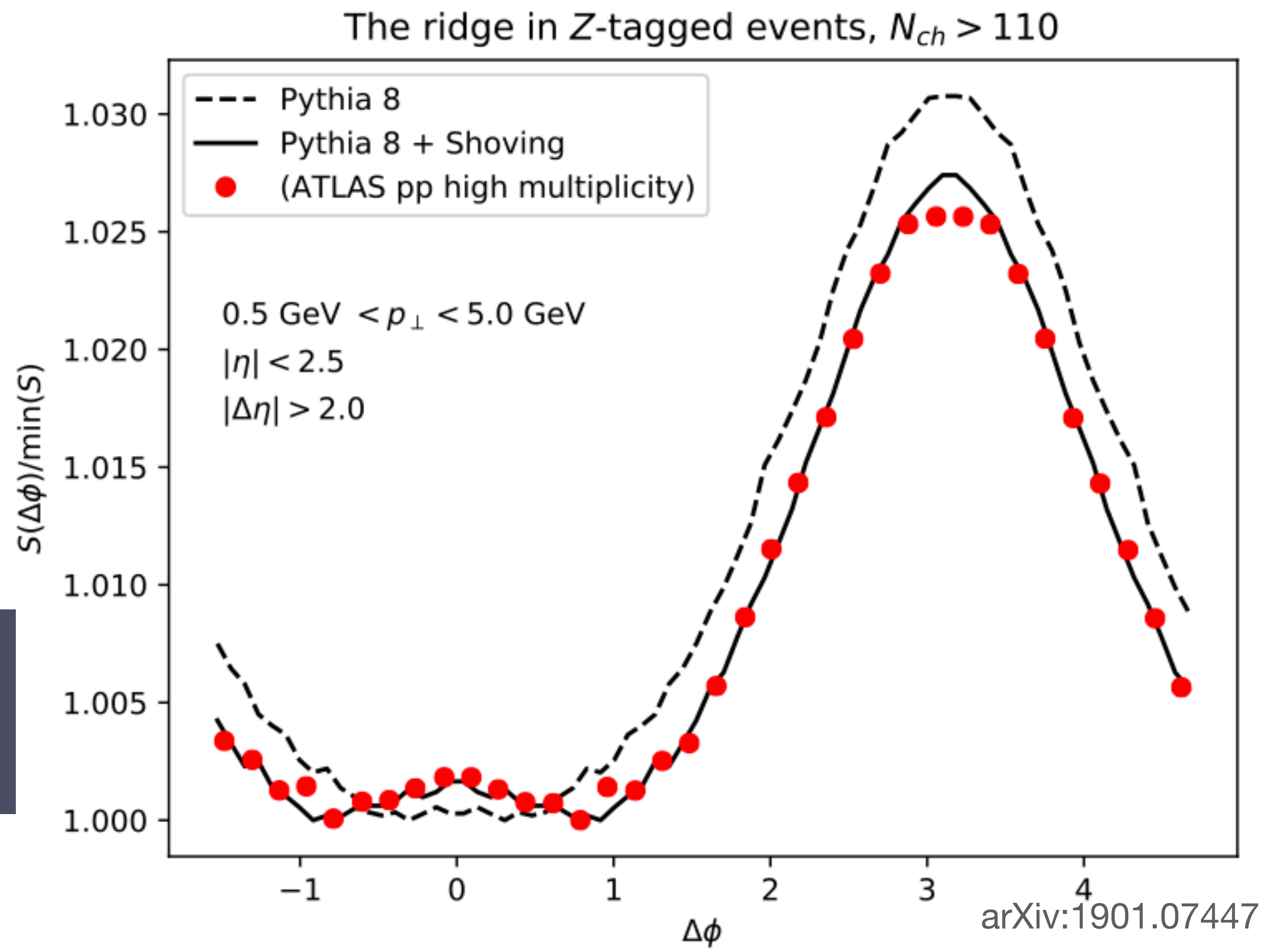


arXiv:1710.09725

*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

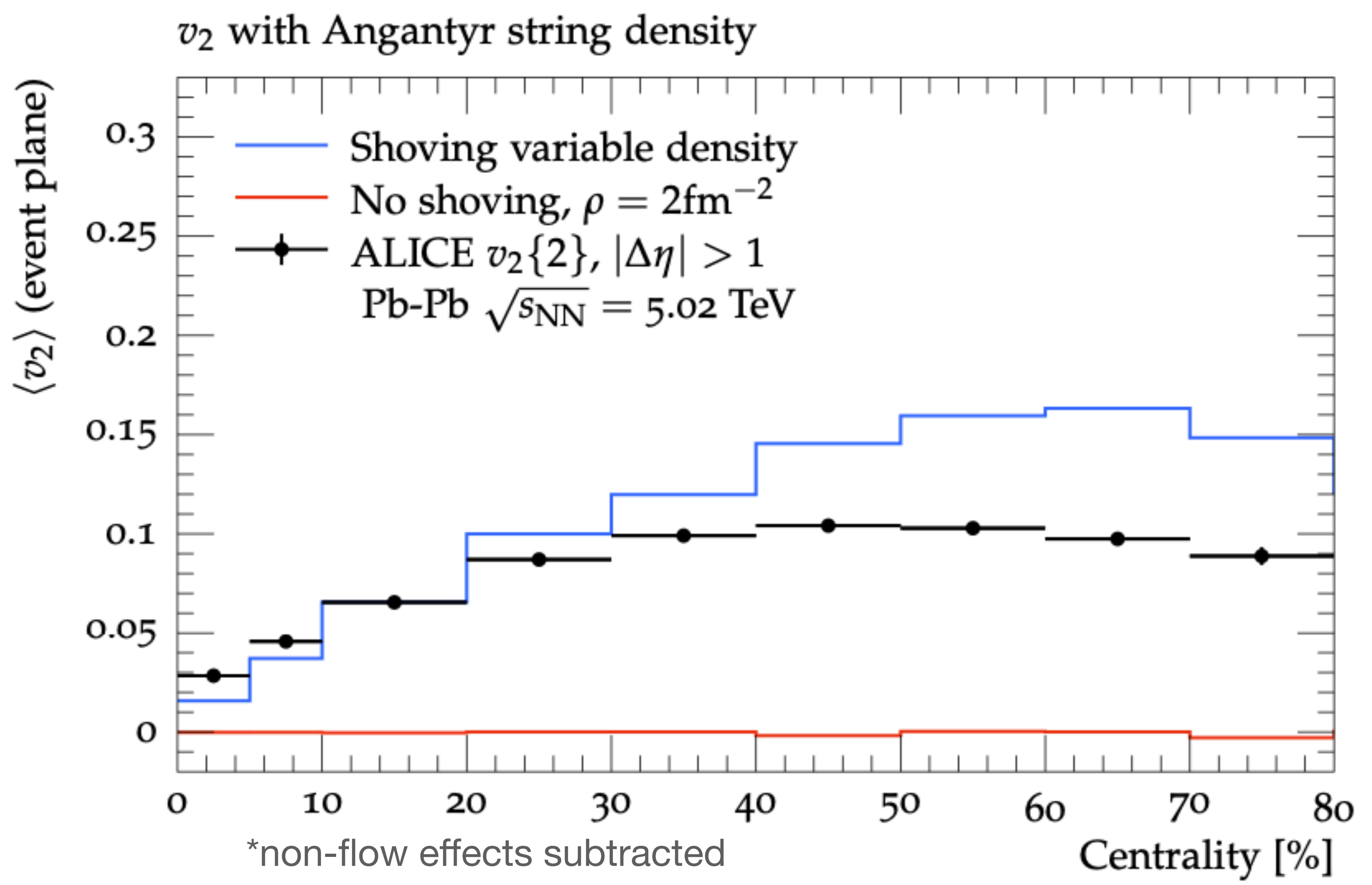
arXiv:2010.07595

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

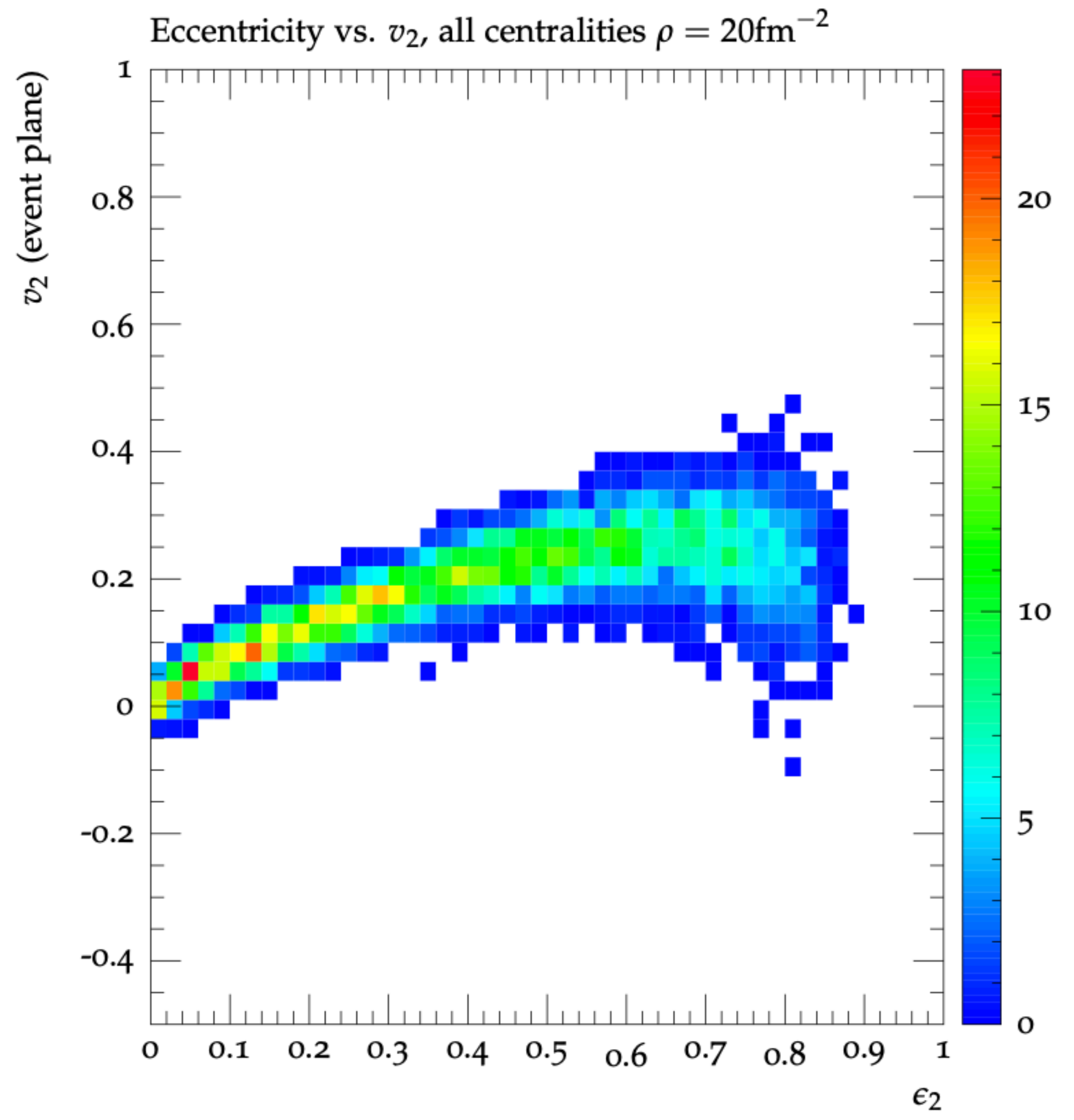
Not perfect agreement however is only a toy model and uses **same parameters as pp collision systems**

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



*non-flow effects subtracted

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

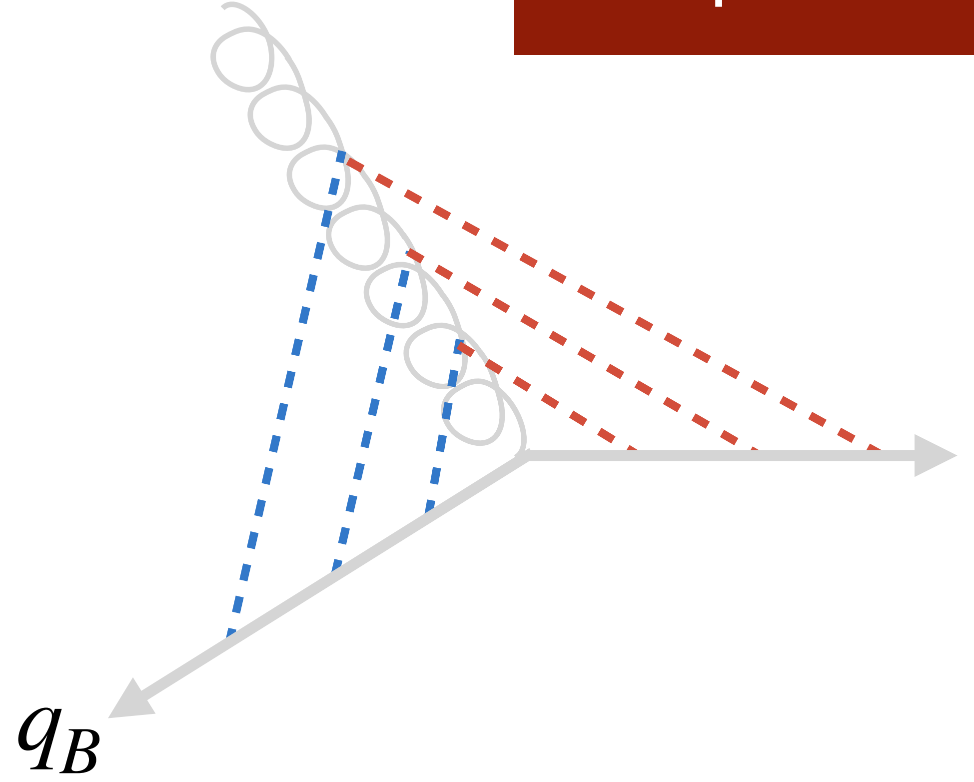
Full **Pb-Pb collision in Angantyr**

- ➢ Implementation issues

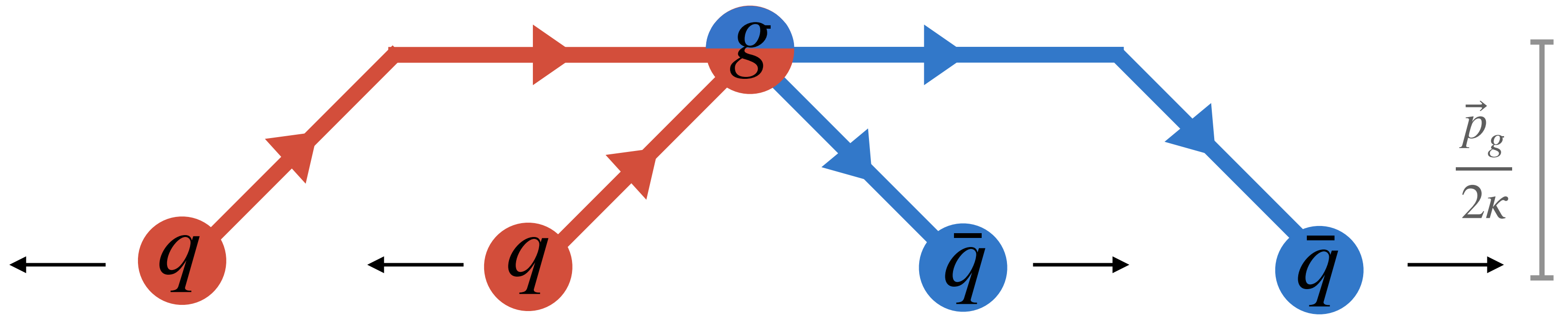
  Many **soft gluons** → **short interaction time** for shoving mechanism as the mechanism does not consider the region formed from soft gluons → insufficient level of shoving

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

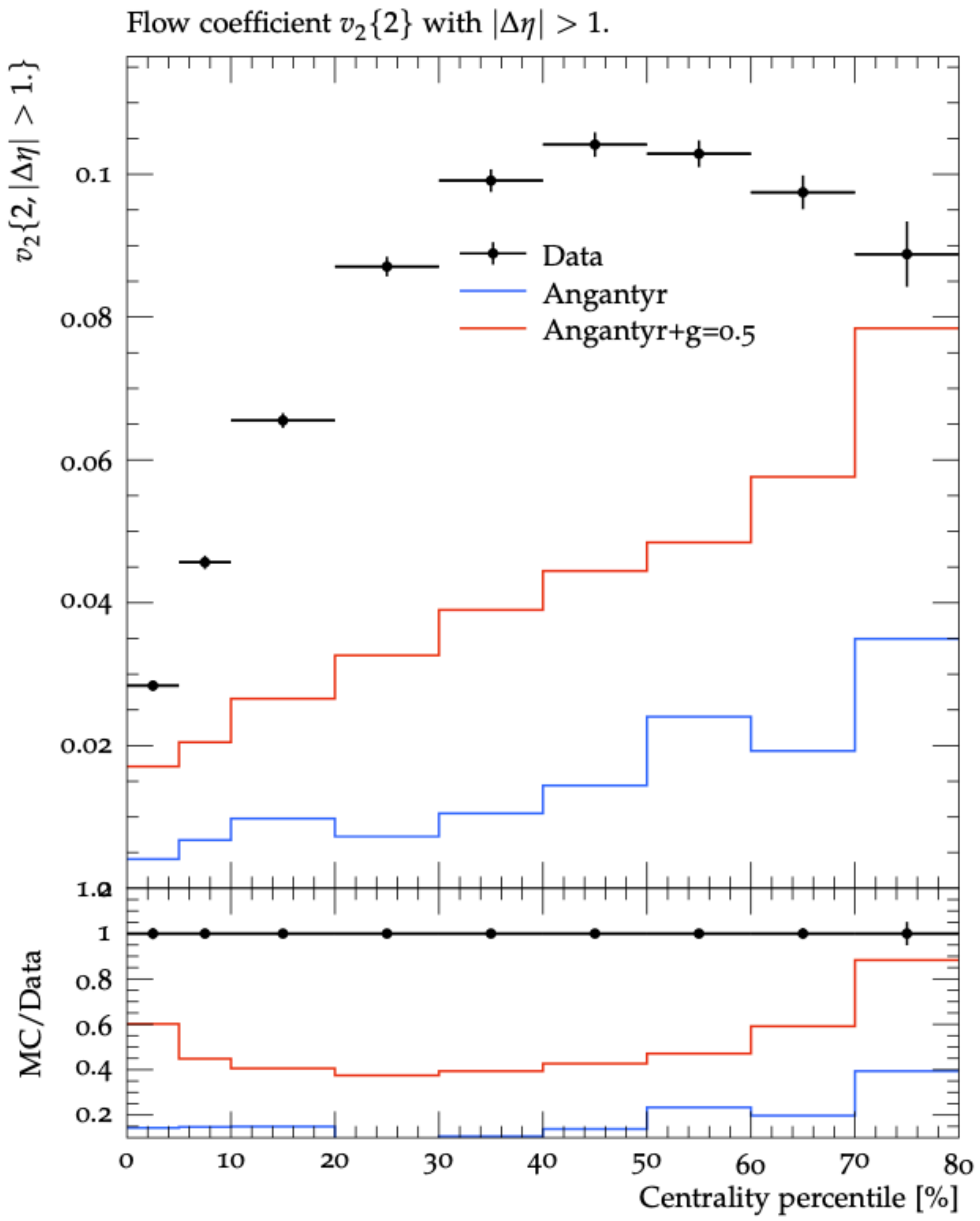
Implementation issues in the model prevent concrete conclusions



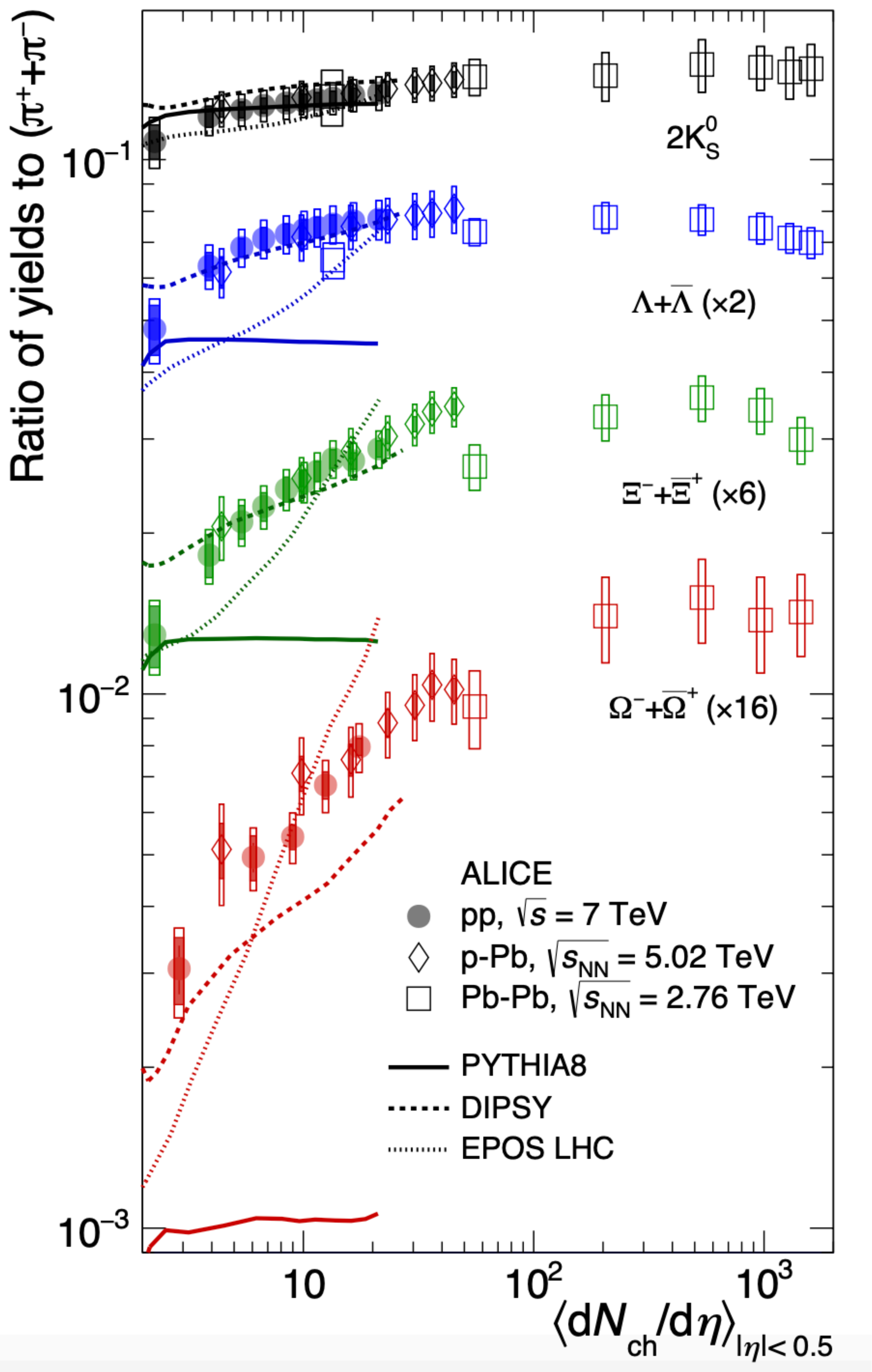
Gluon-kink picture



Soft gluon-kink

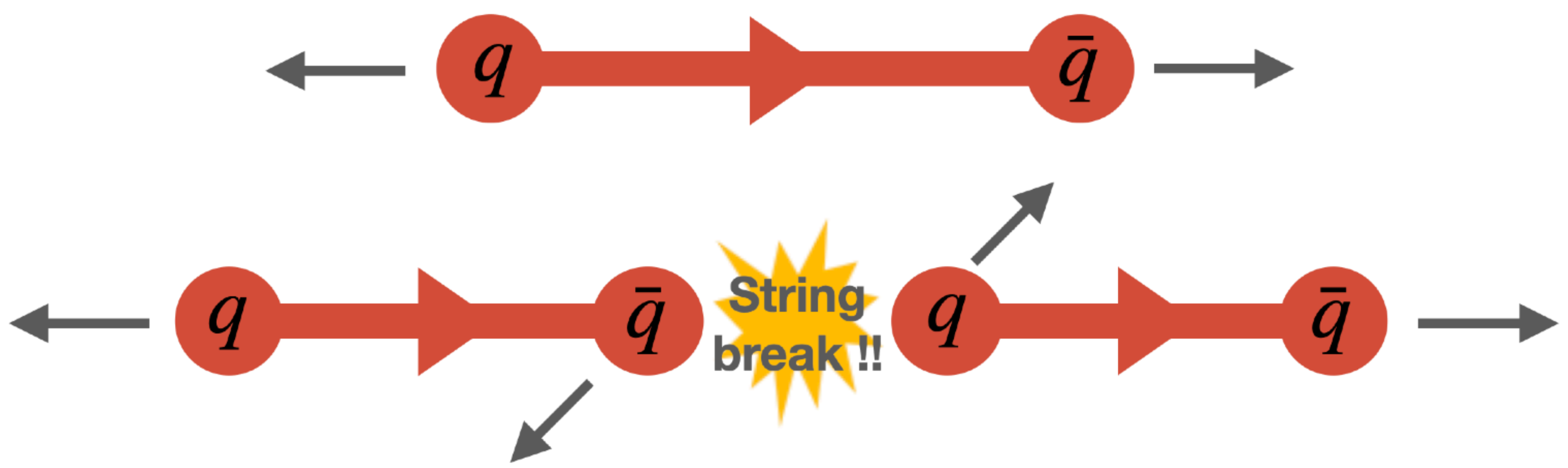


Strangeness Enhancement



Strange production in the string picture

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



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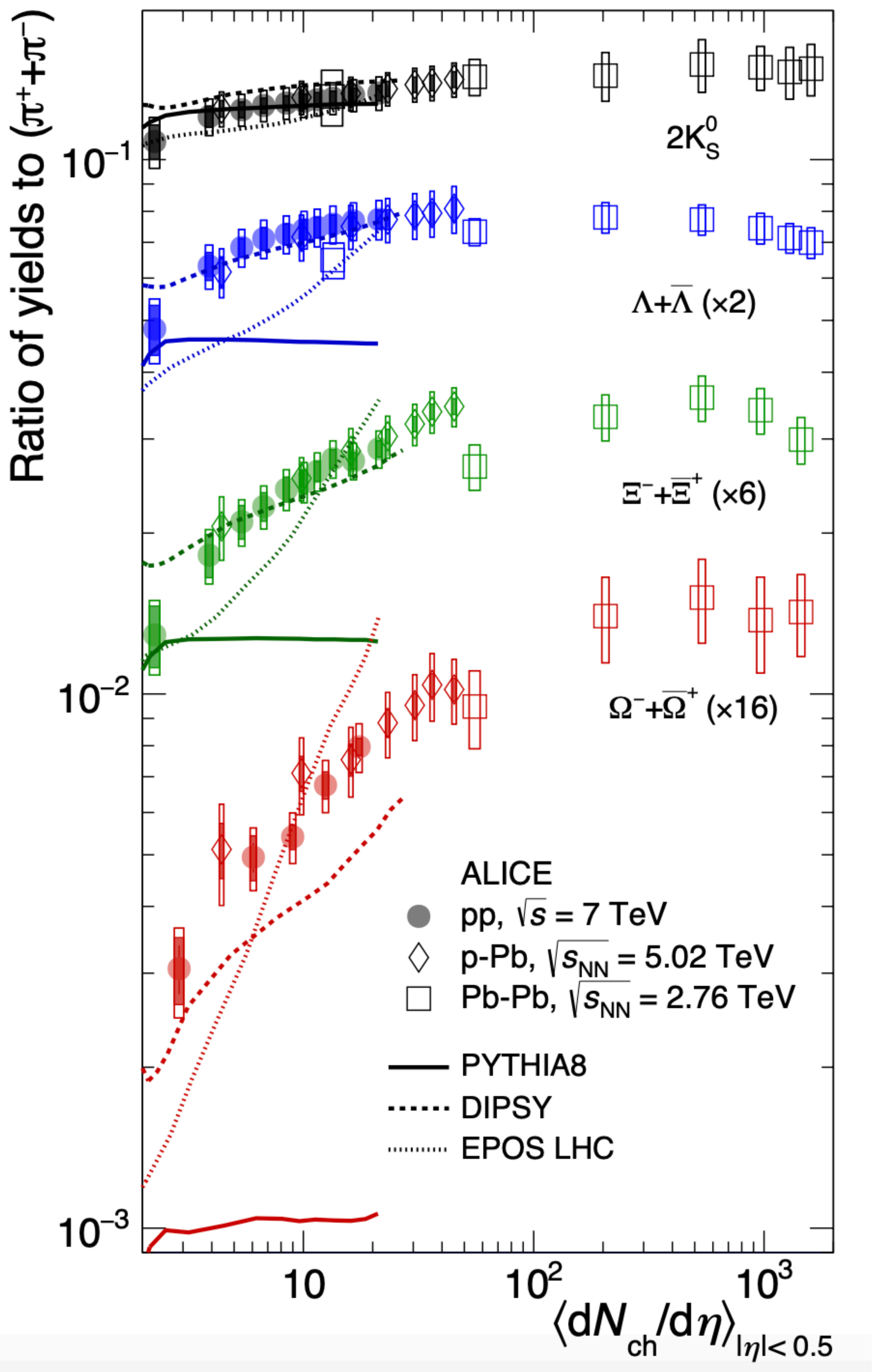

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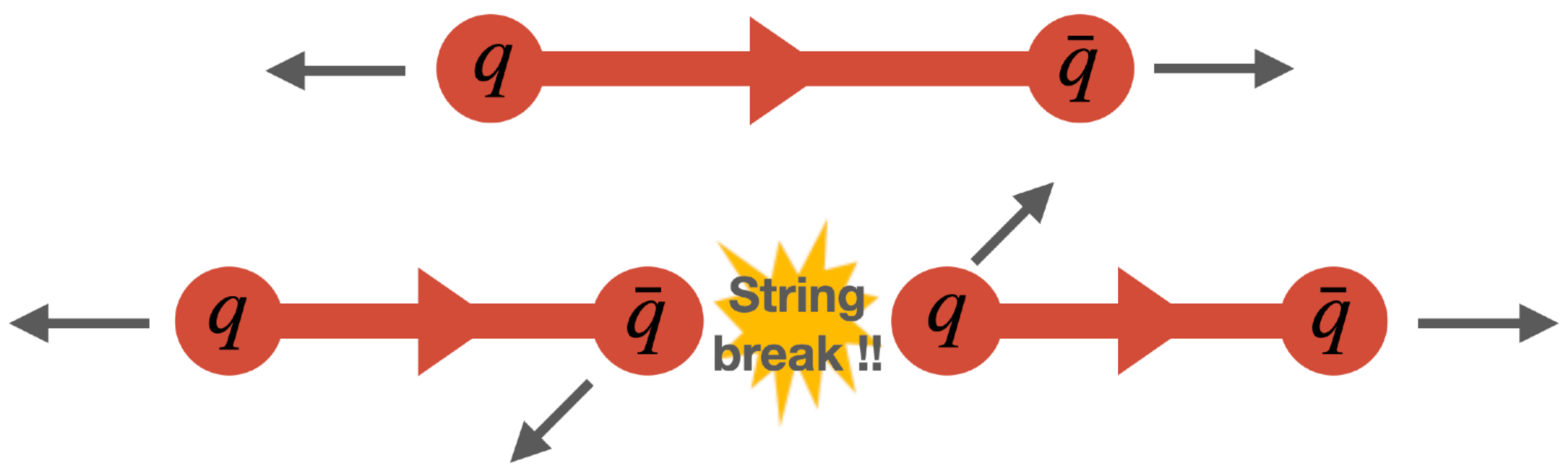
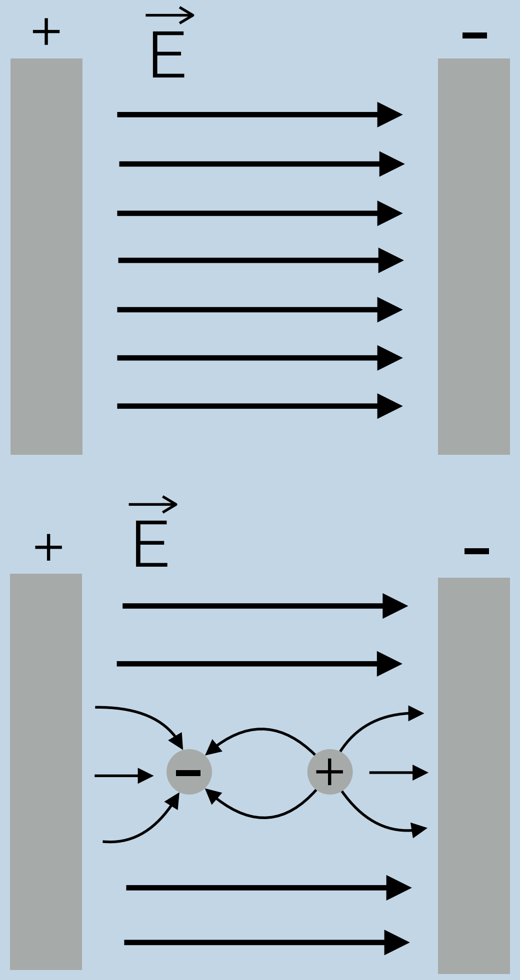


Schwinger mechanism QED



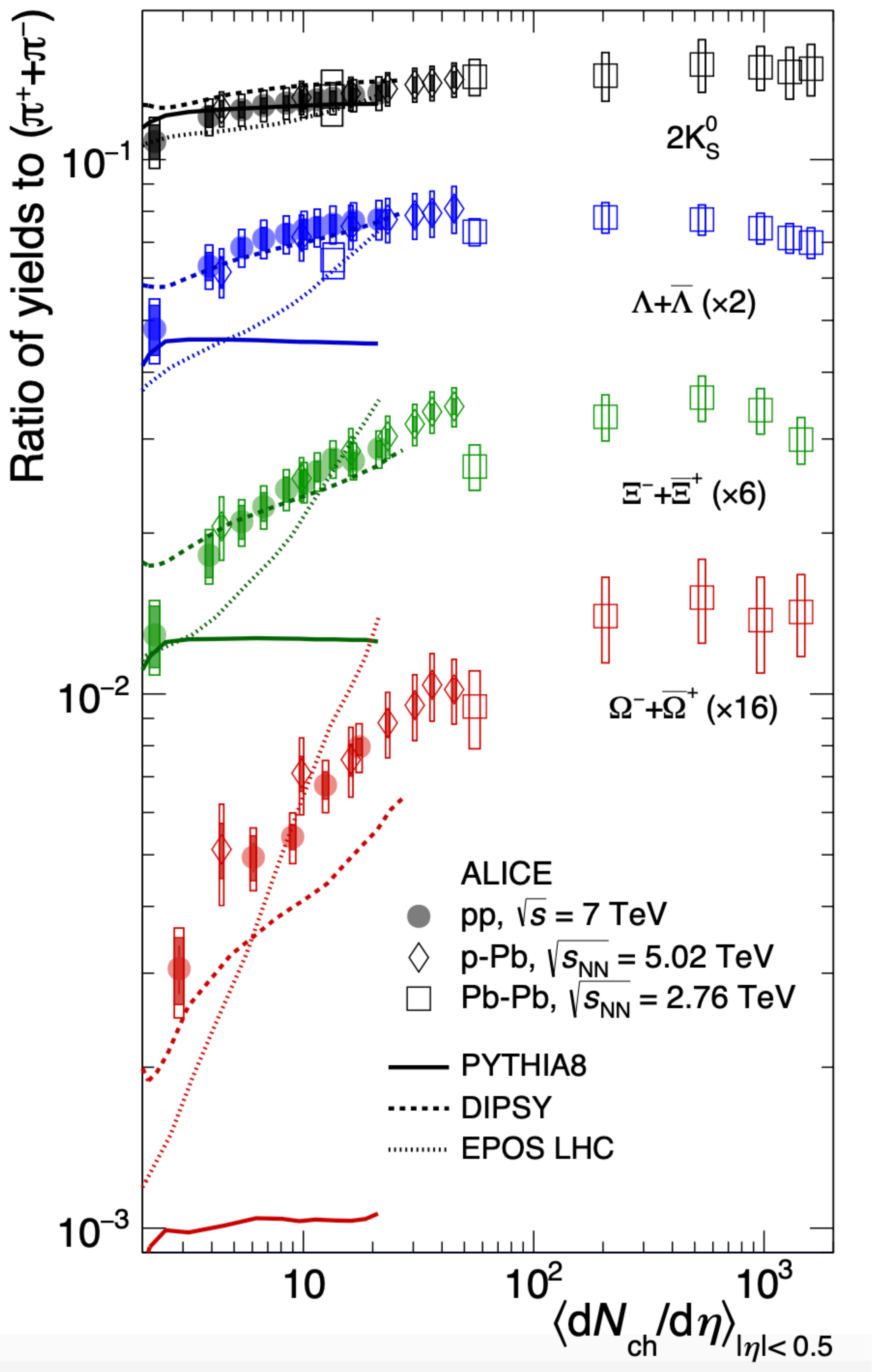
Non-perturbative creation of e^+e^- pairs in a string electric field

Probability from tunnelling factor

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

κ = string tension

Strangeness Enhancement



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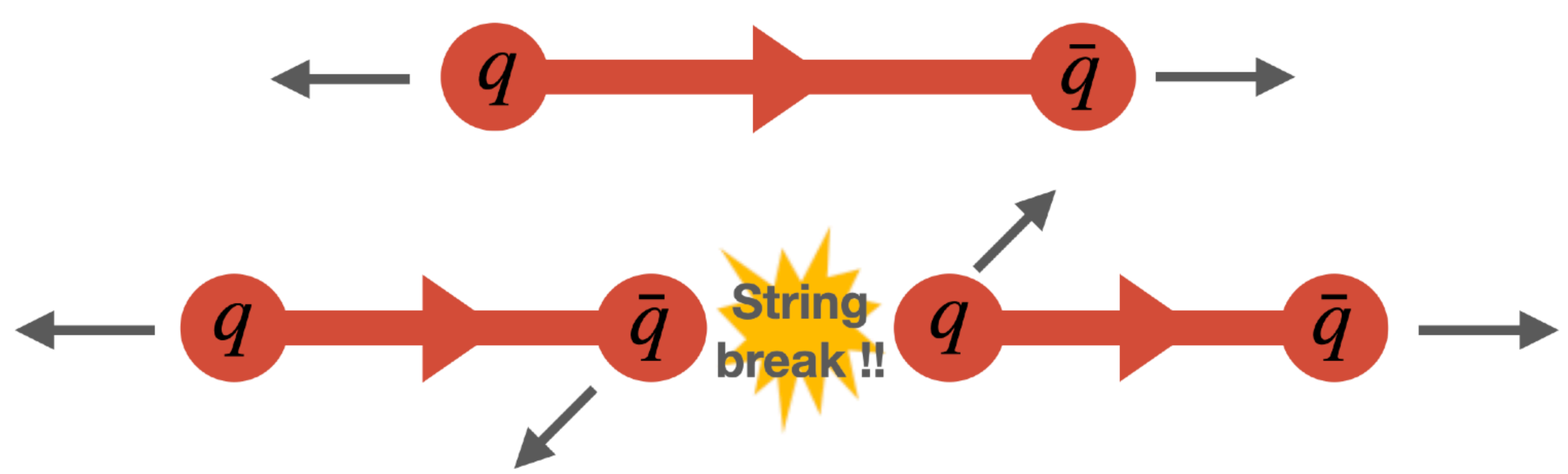
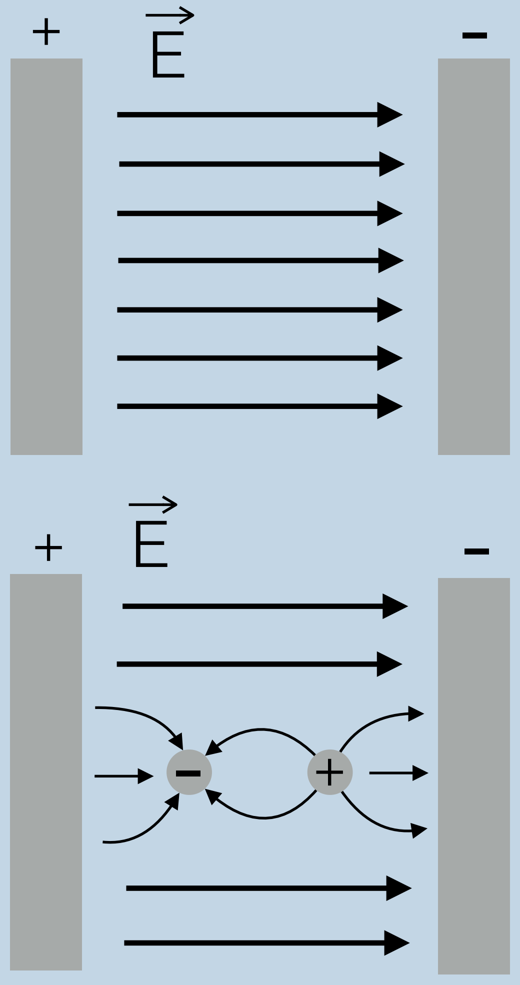


Schwinger → **Gaussian $p_\perp$ spectrum** and heavy flavour suppression

Prob(u:d:s) ≈ 1 : 1 : 0.2

Schwinger mechanism QED



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Probability from tunnelling factor

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

κ = string tension

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

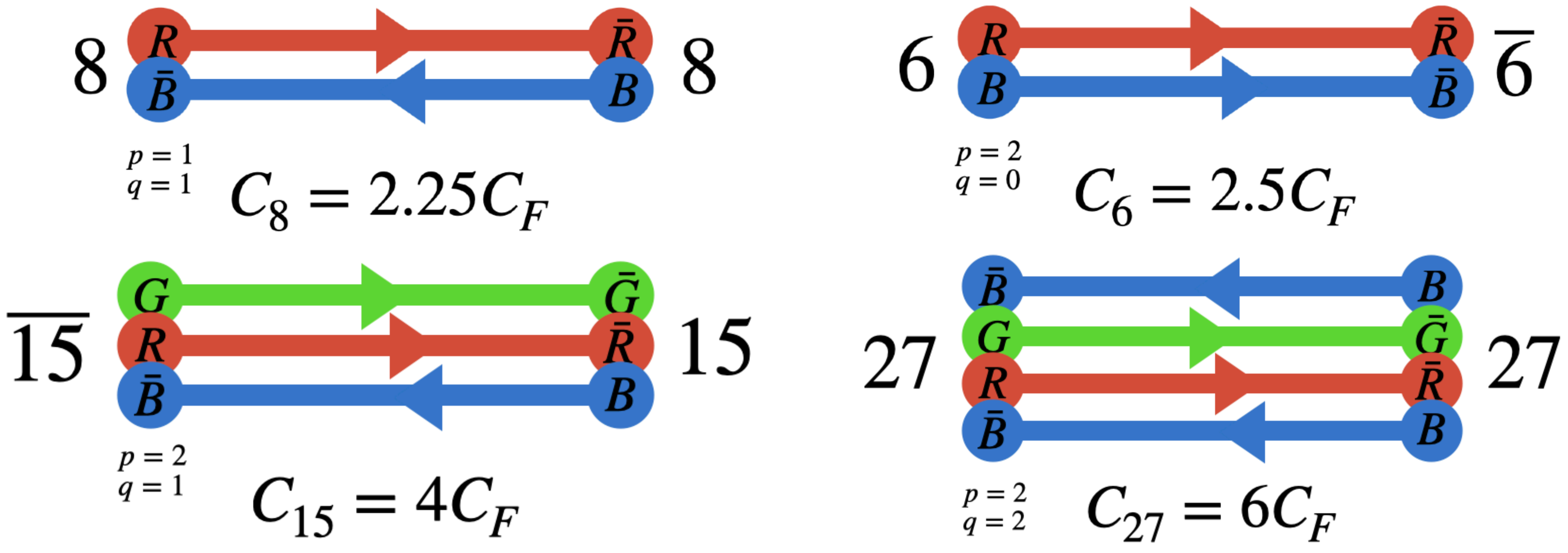
Strangeness Enhancement

Rope hadronisation

arXiv:1412.6259

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

Enhance string tension for higher multiplets

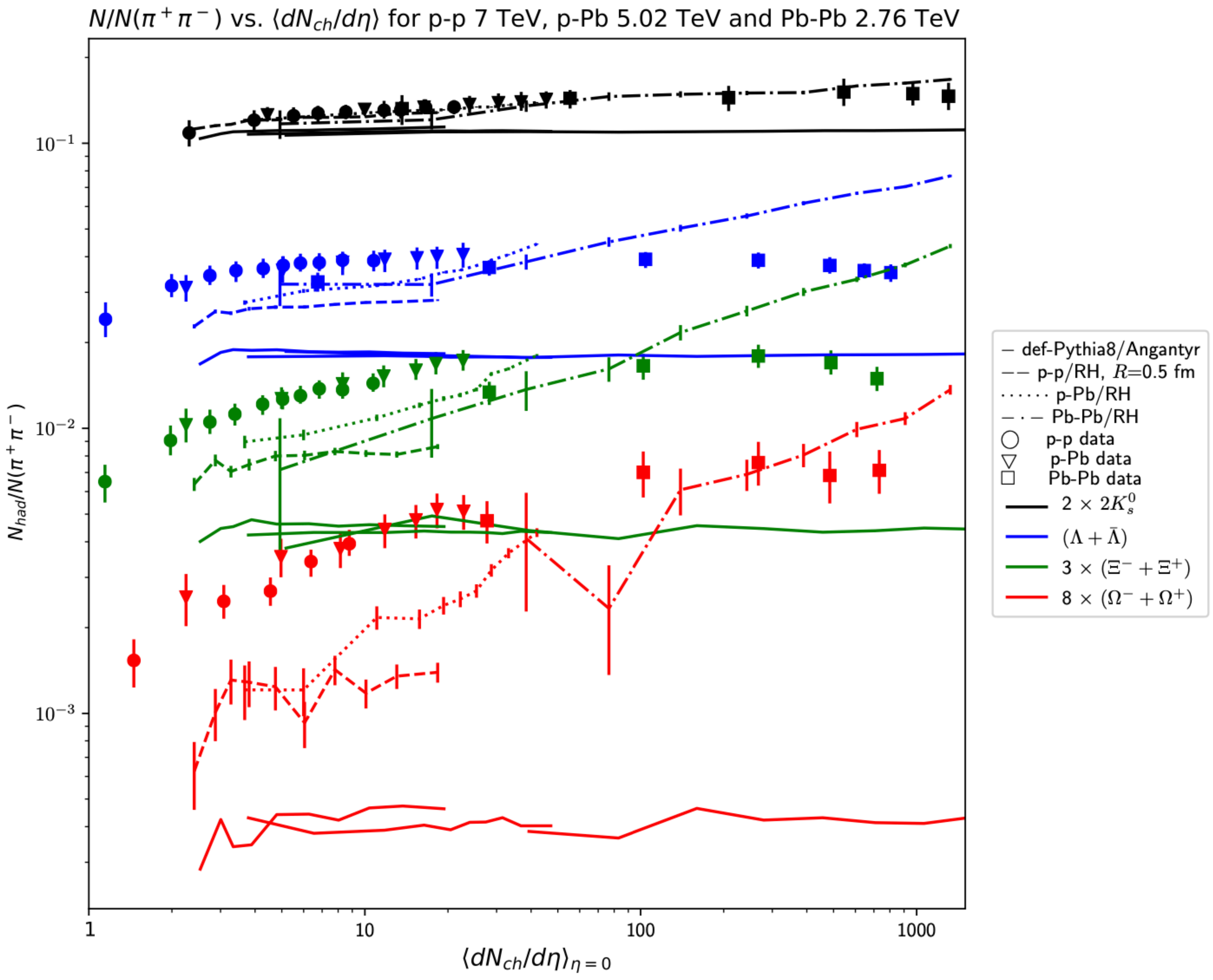


Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

Higher κ → lower strangeness suppression



Strangeness Enhancement

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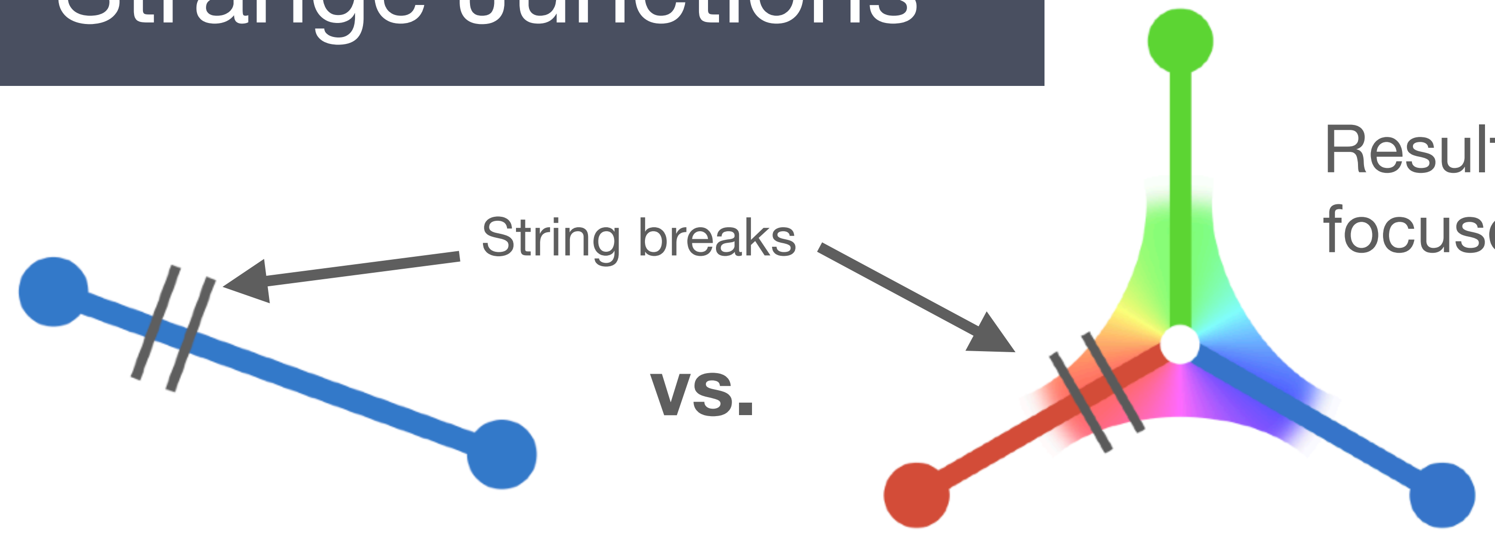
Enhance string tension for higher multiplets

Close-packing

Simpler implementation of ropes fully in momentum space

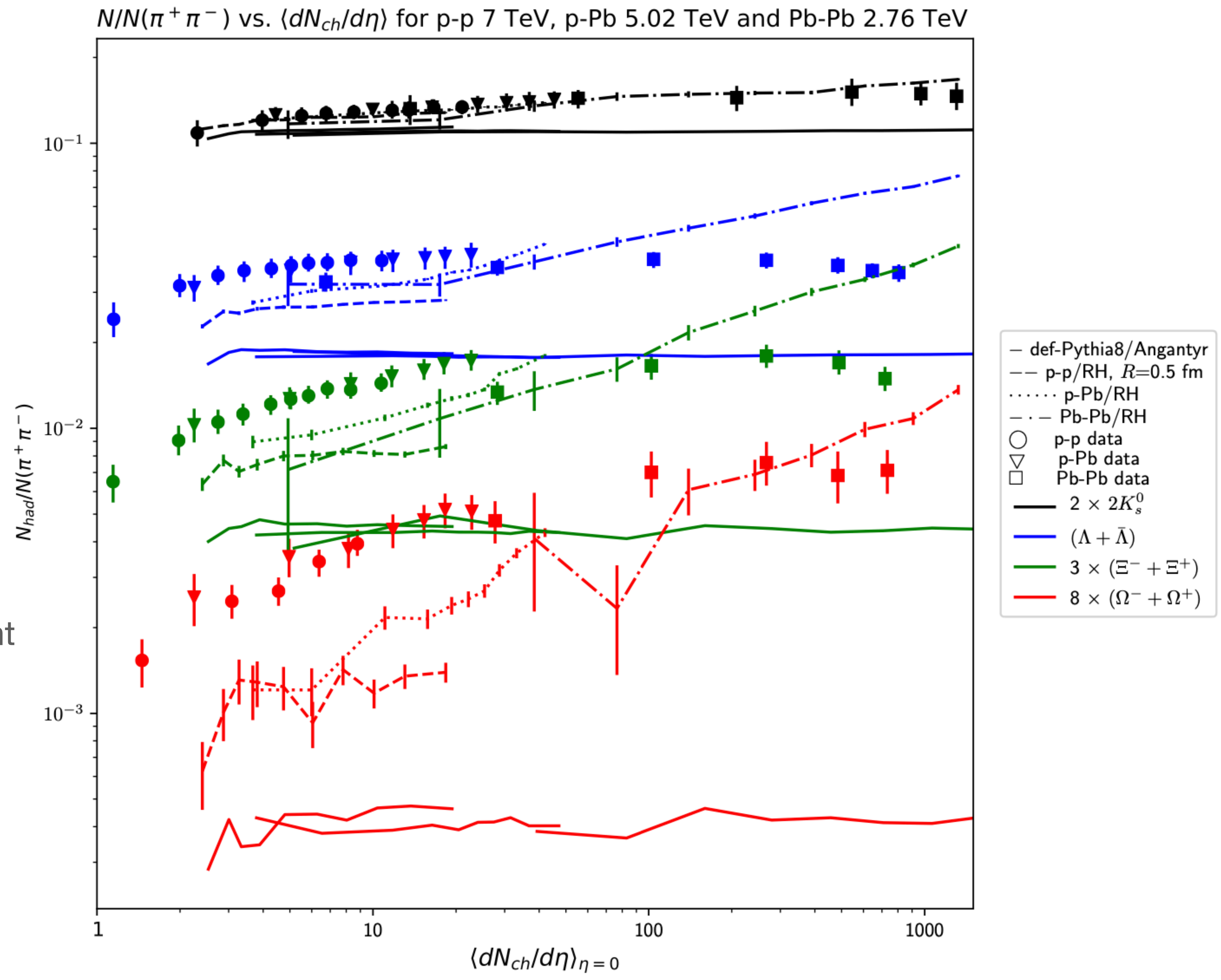
→ not in conjunction with shoving

Strange Junctions



Results in strangeness enhancement focused in baryon sector

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



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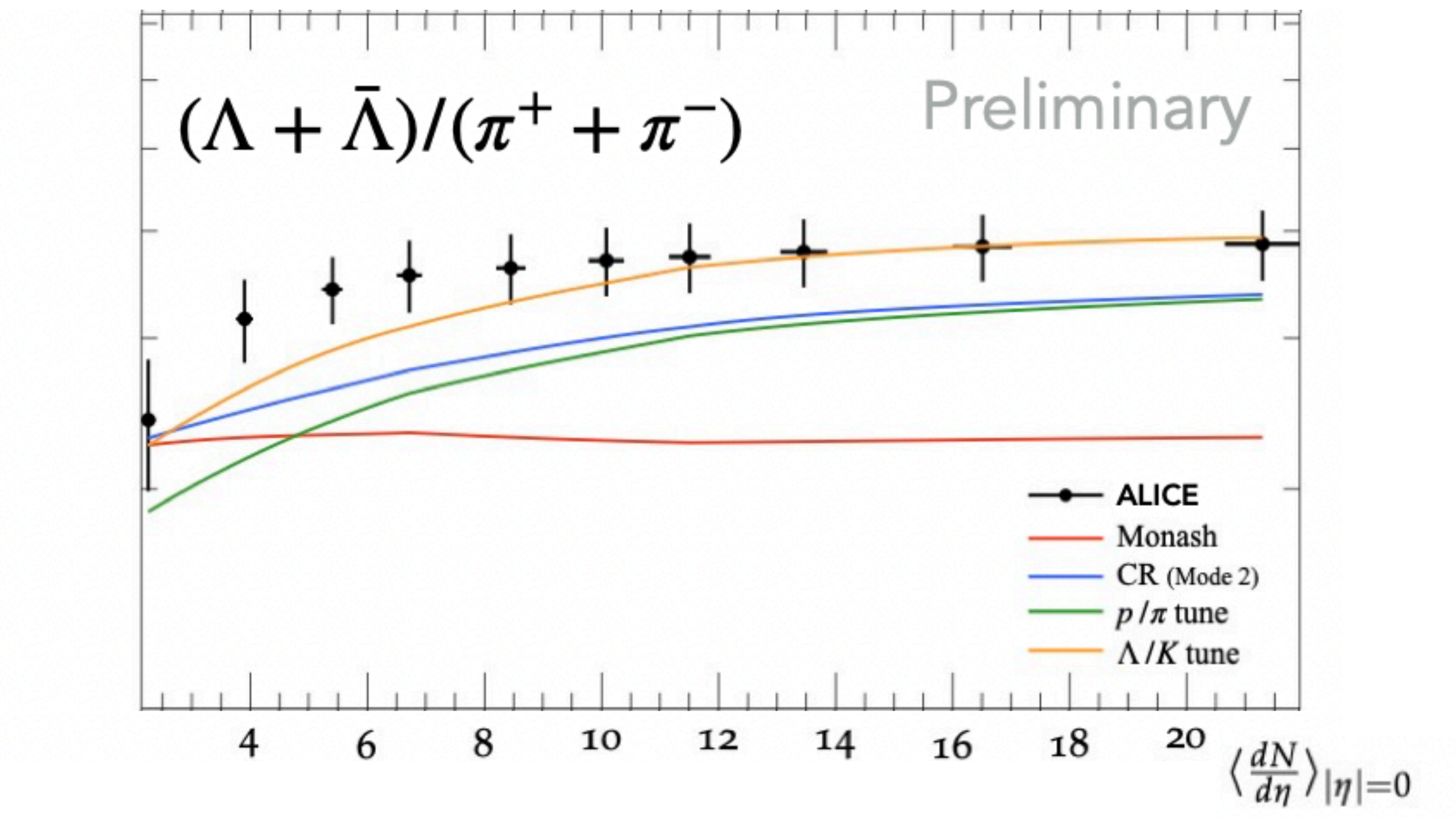
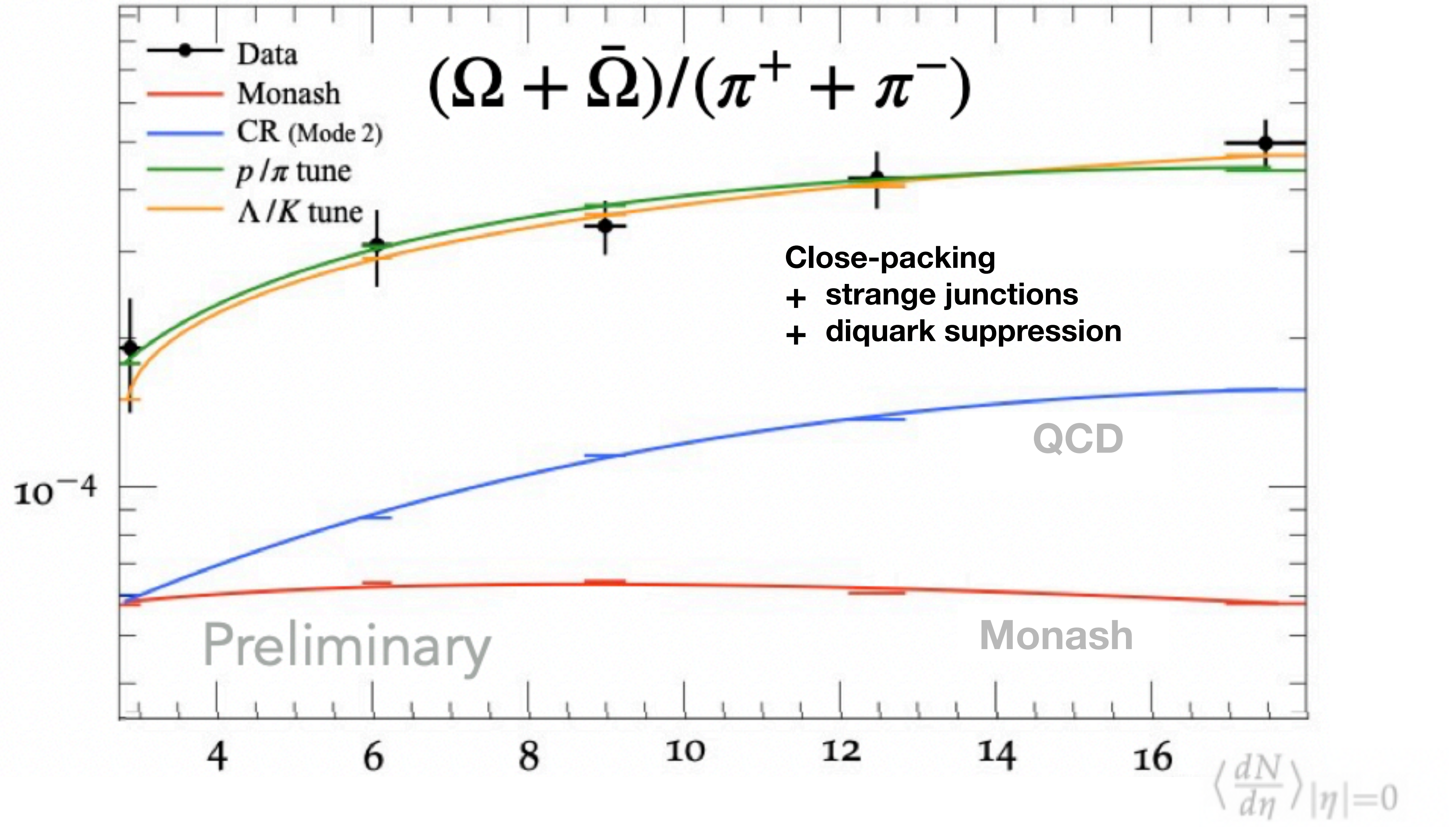
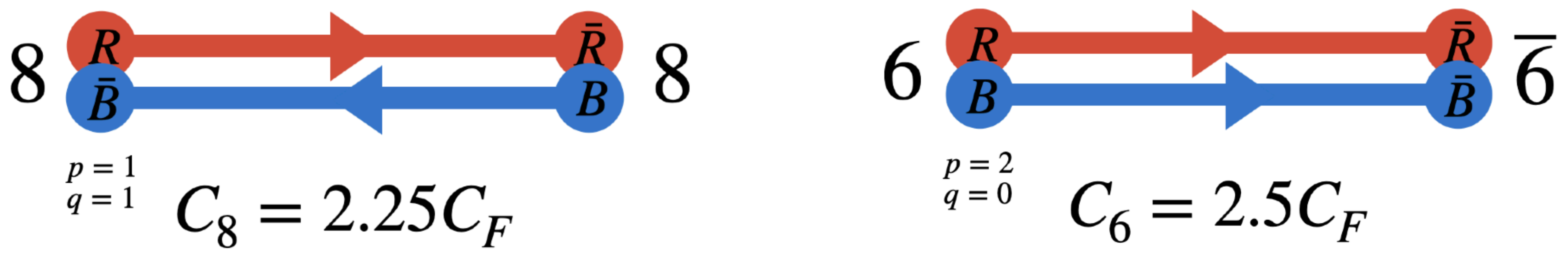




Close-packing + Ropes



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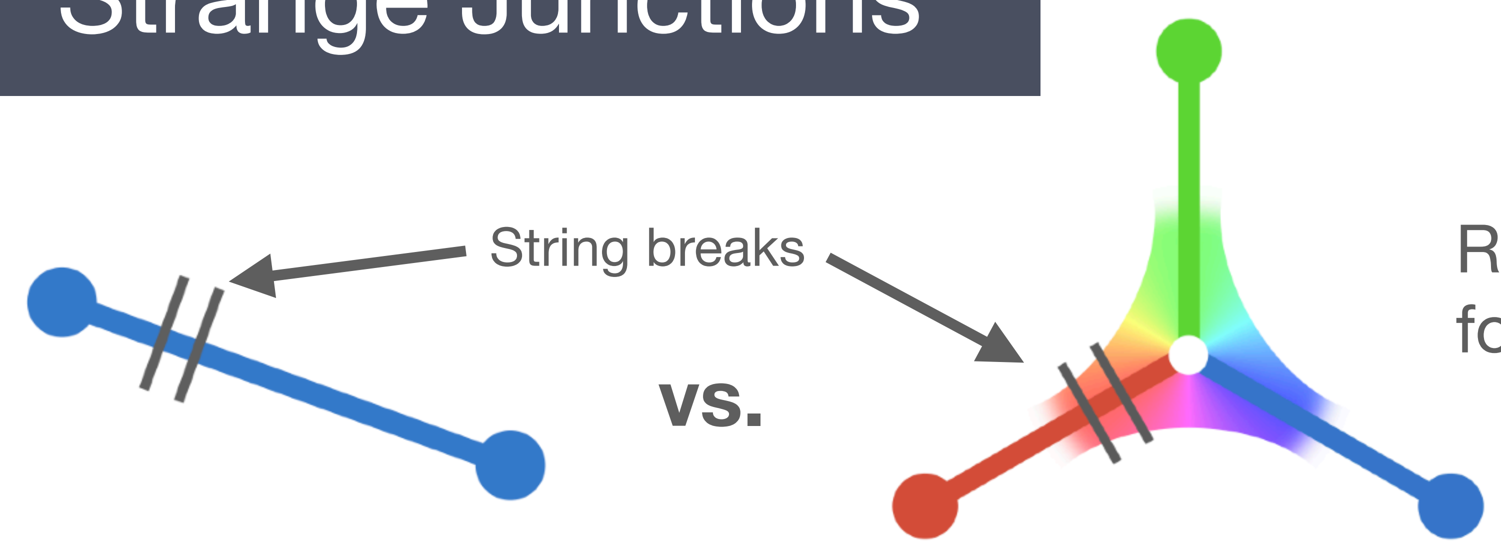
Strange Junctions



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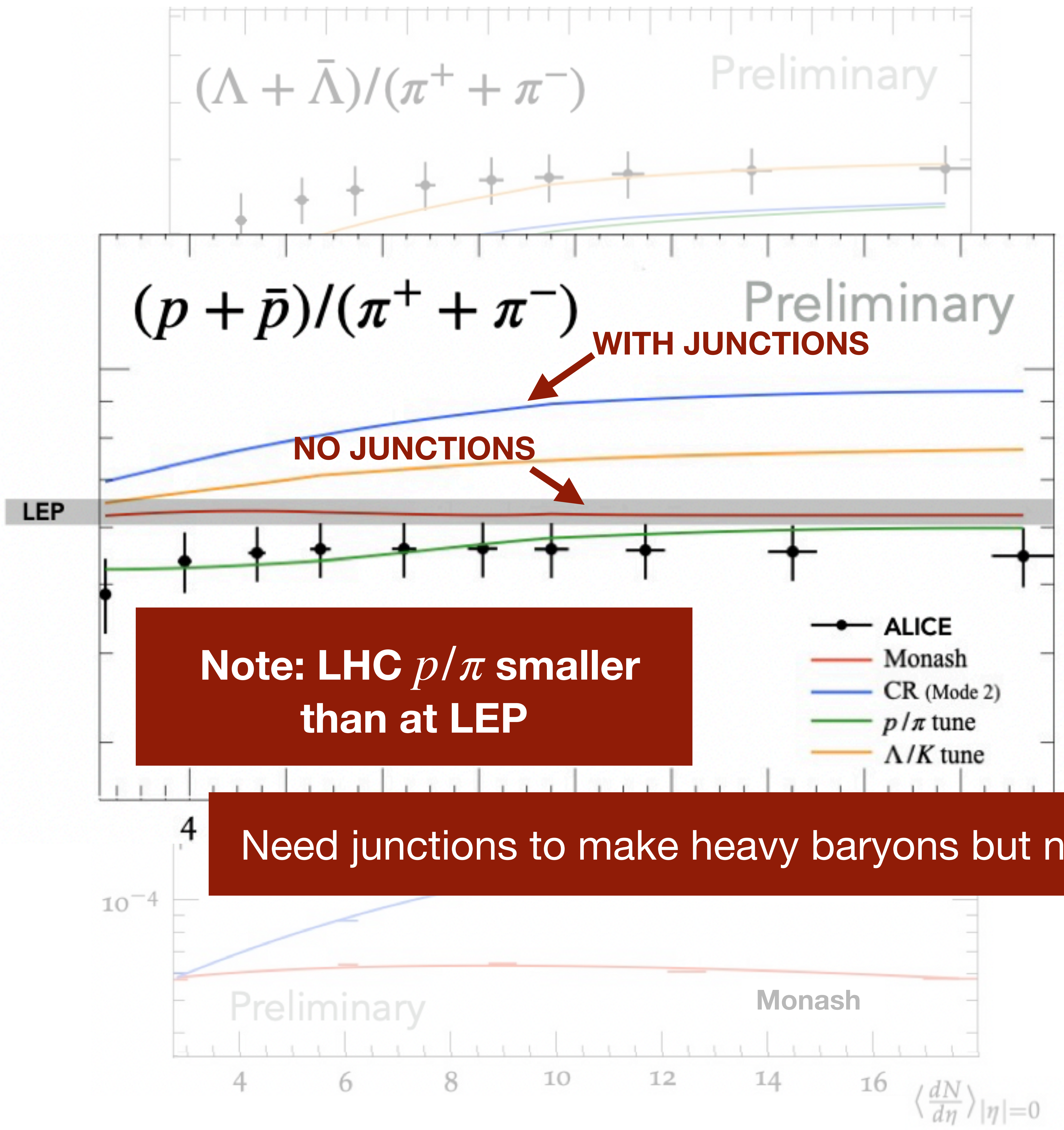
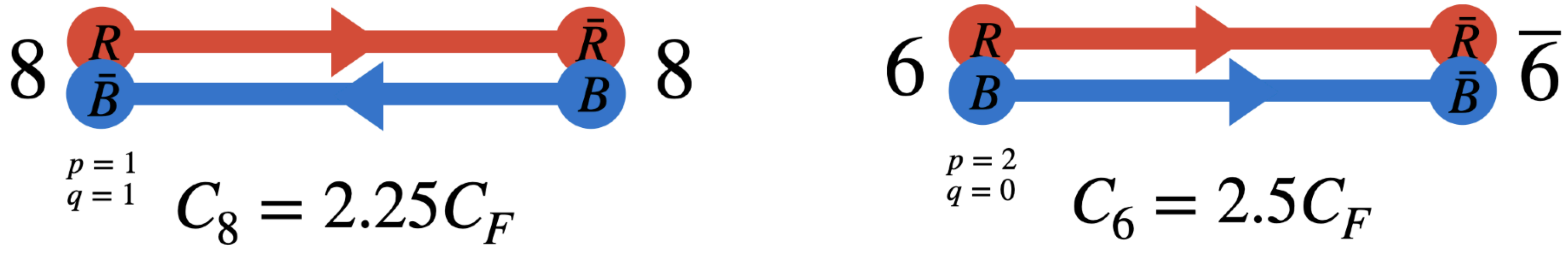


Note: LHC p/π smaller than at LEP

Need junctions to make heavy baryons but need less protons?

Close-packing + Ropes



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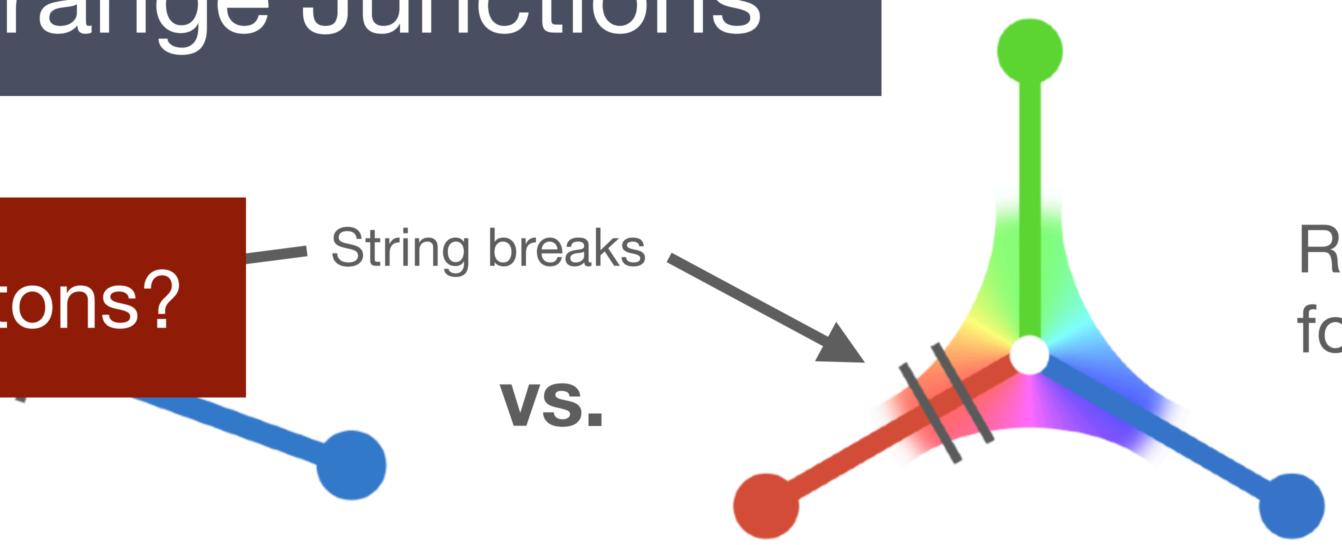

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Strangeness Enhancement

Rope hadronisation

arXiv:1412.6259

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

Enhance string tension fo

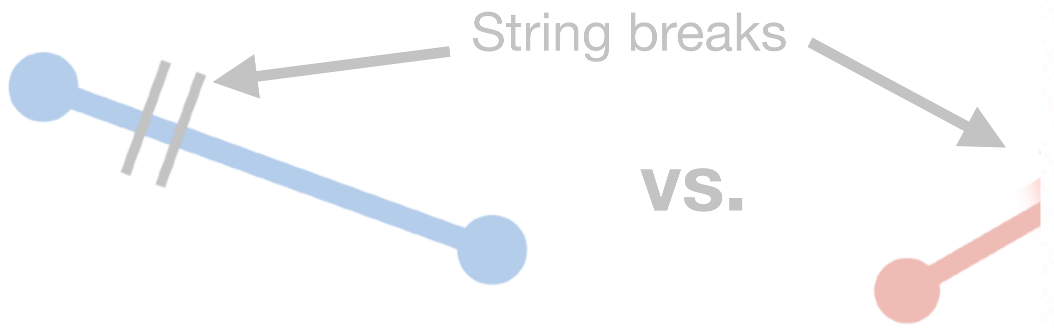
What about the non-strange baryon-to-meson ratio p/π ?

Close-packing

Simpler implementation of ro

→ not in conjunction with sho

Strange Junctions



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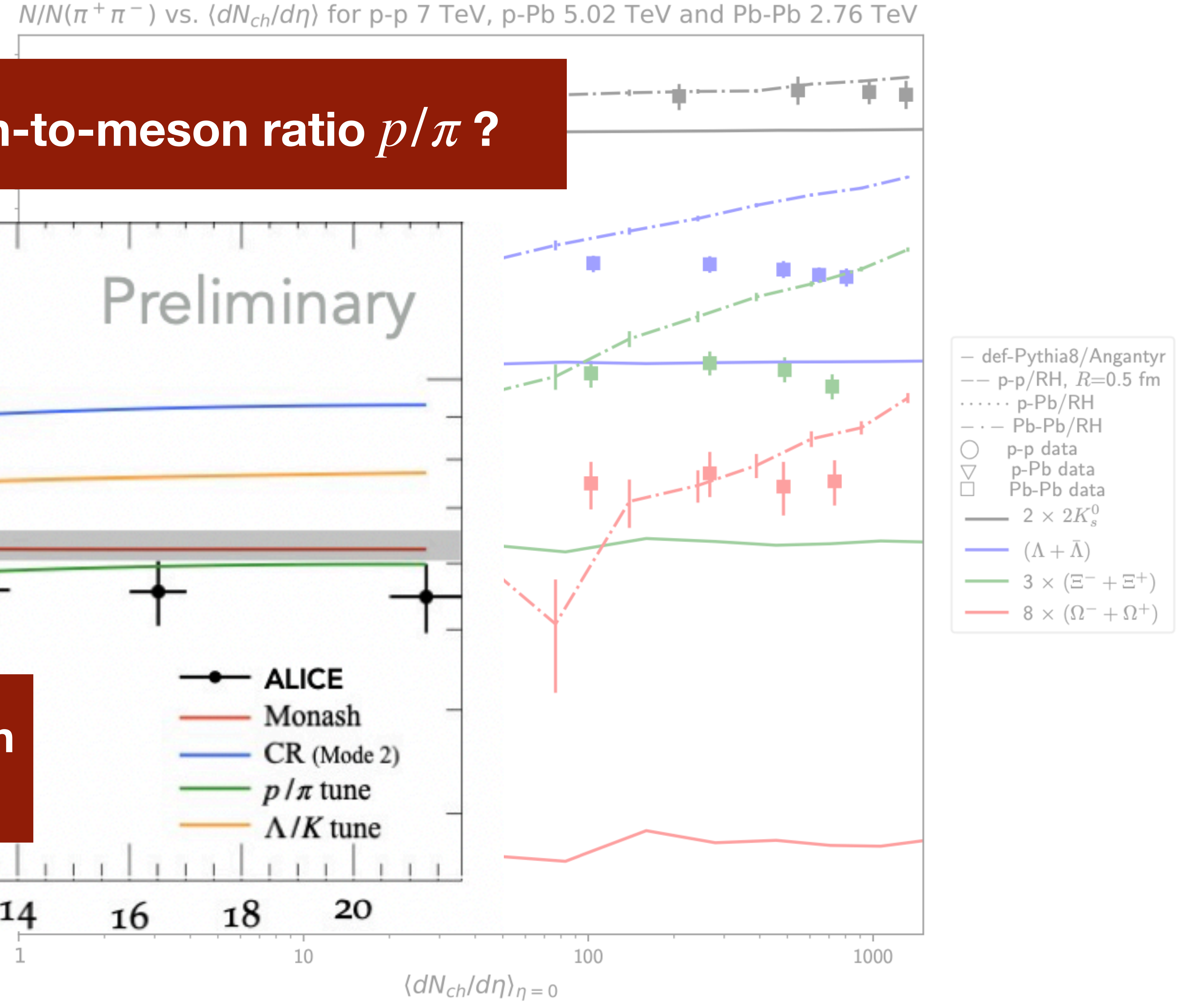
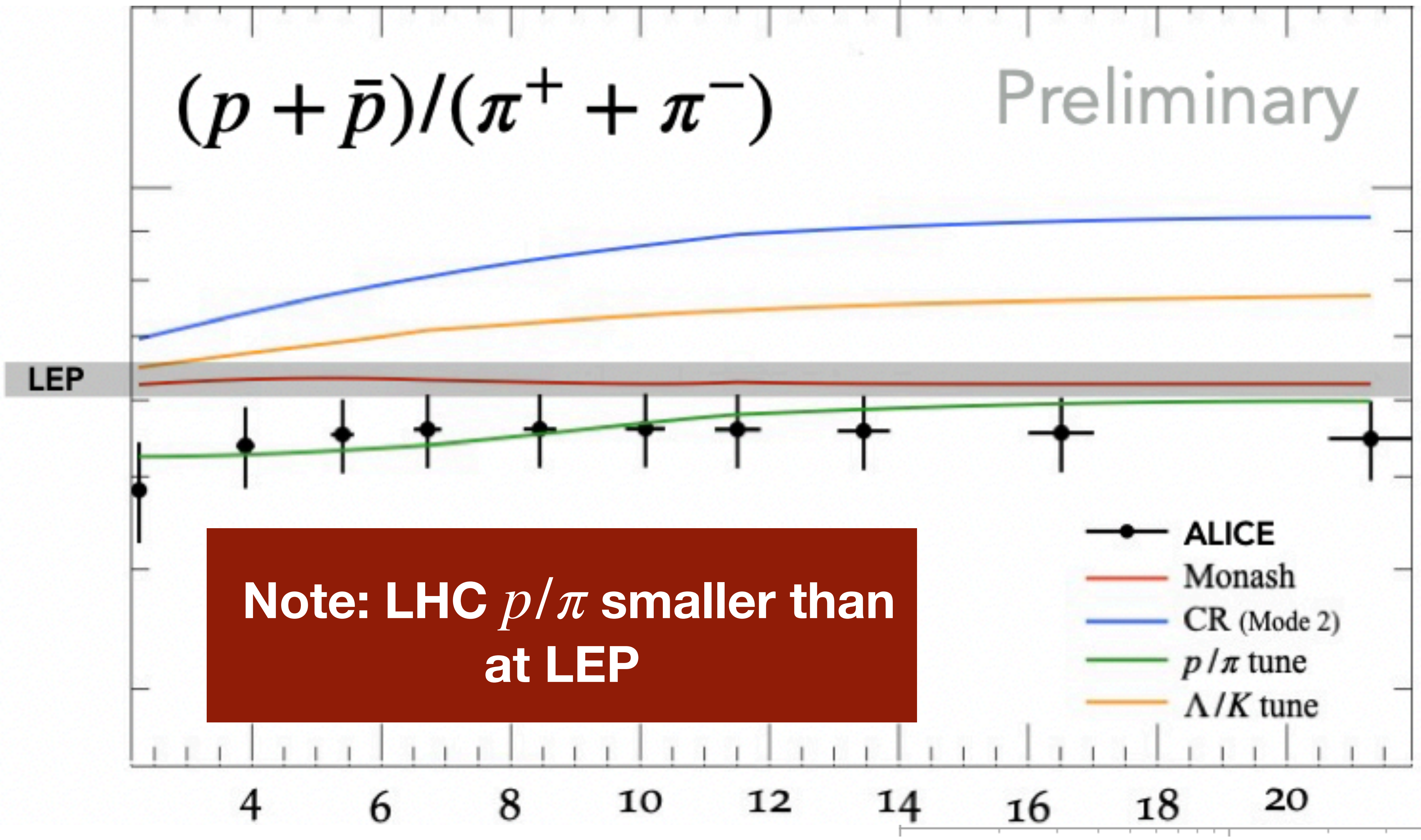


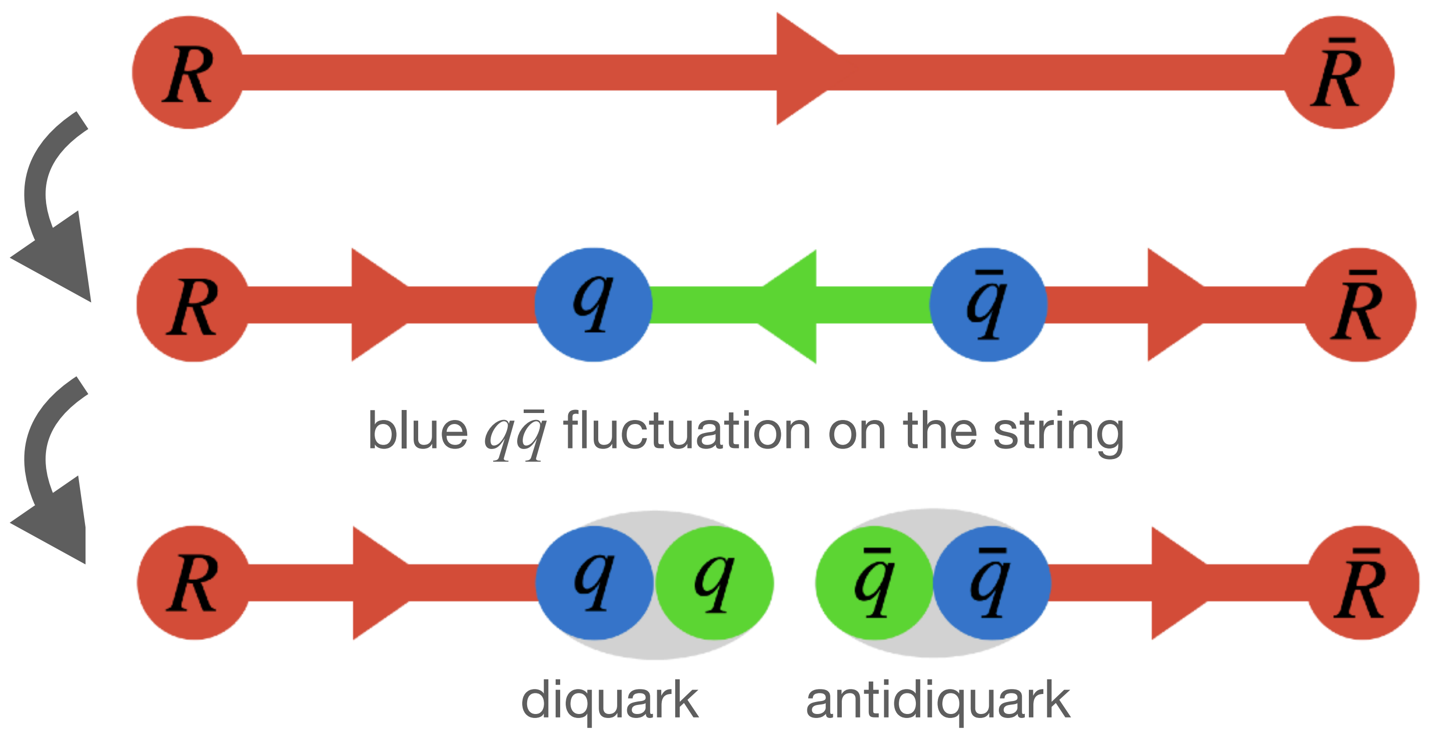


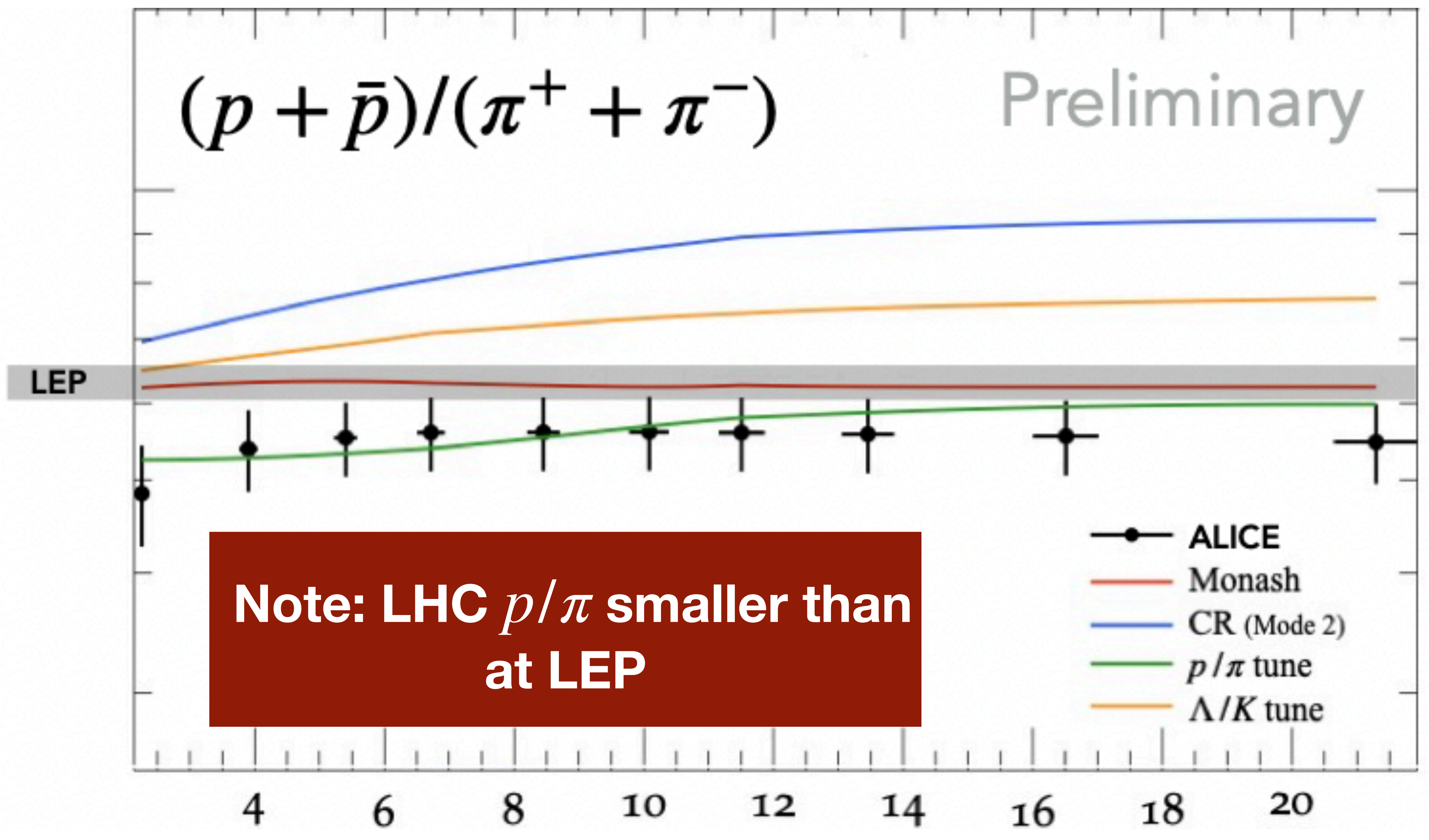
Note: LHC p/π smaller than at LEP

Proton problem

Popcorn mechanism for diquark production

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





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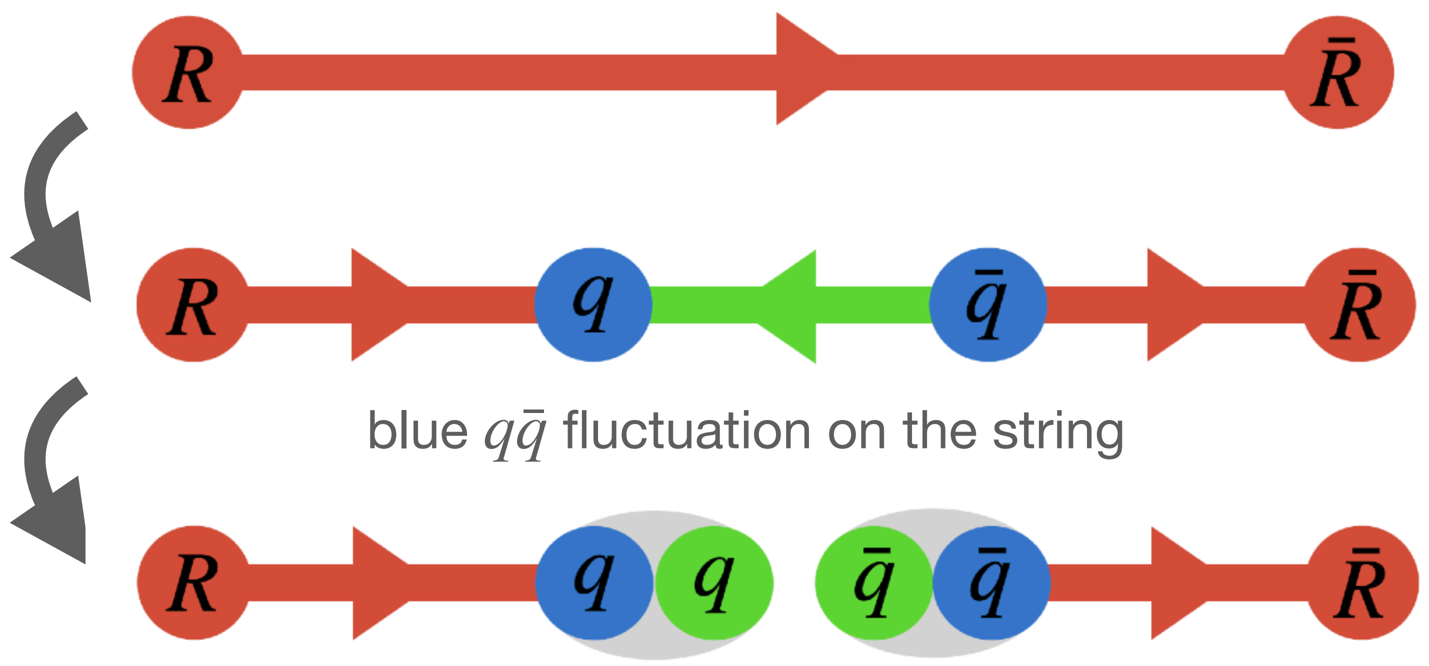
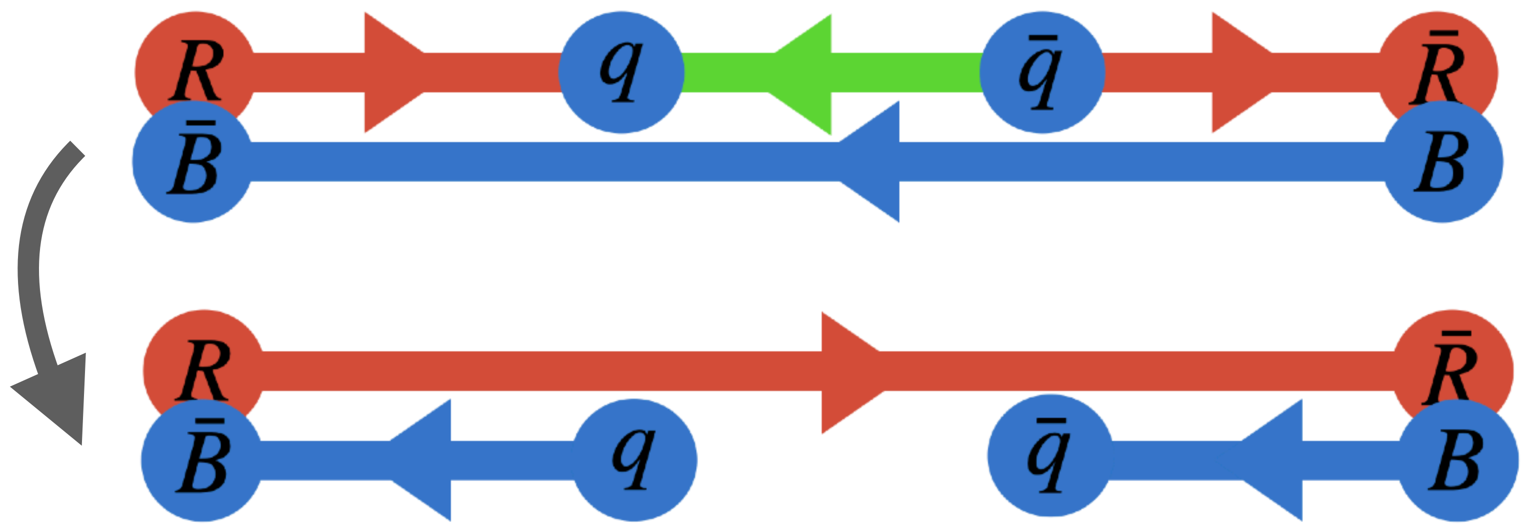


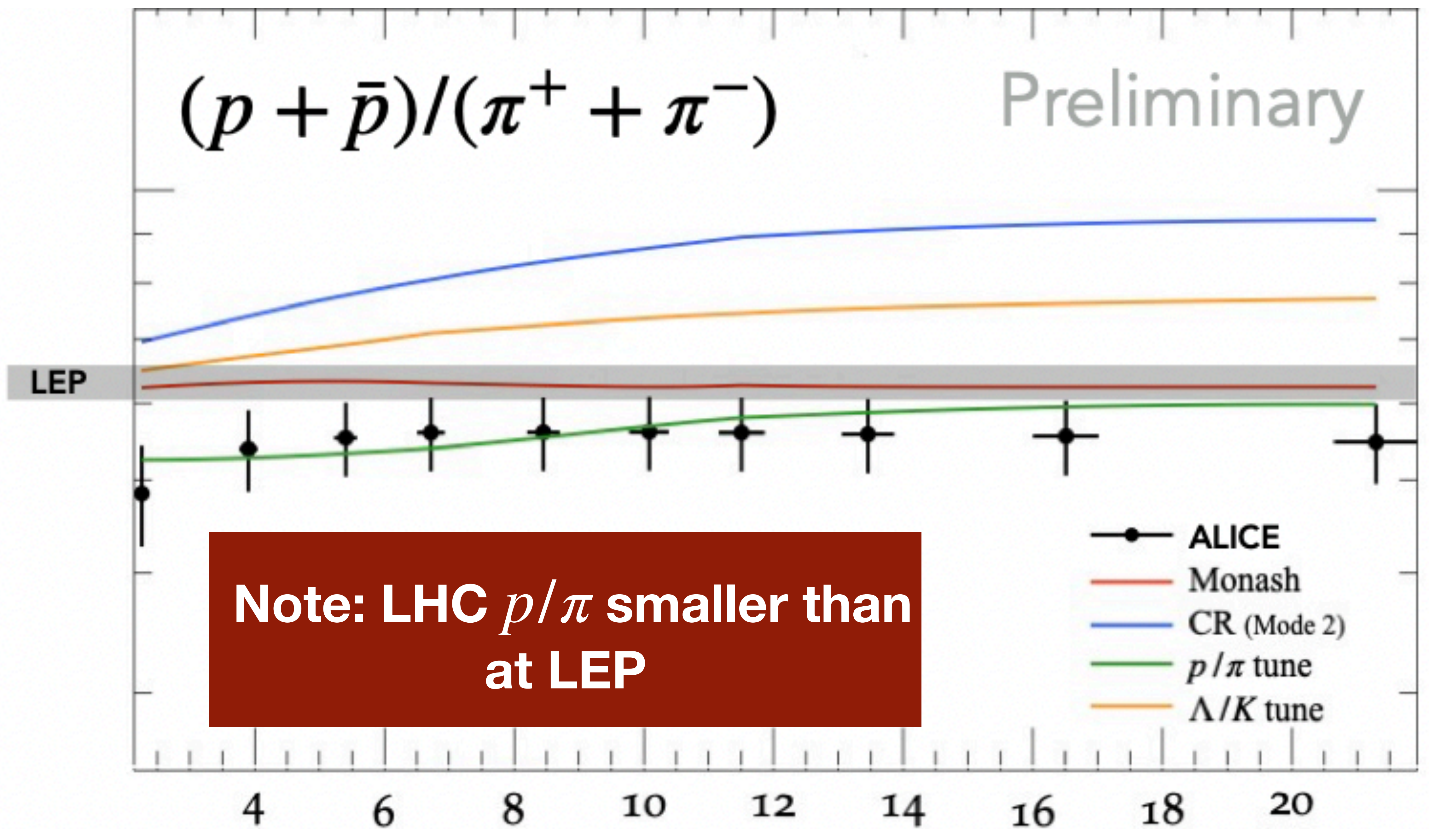
Popcorn destructive interference

NEW

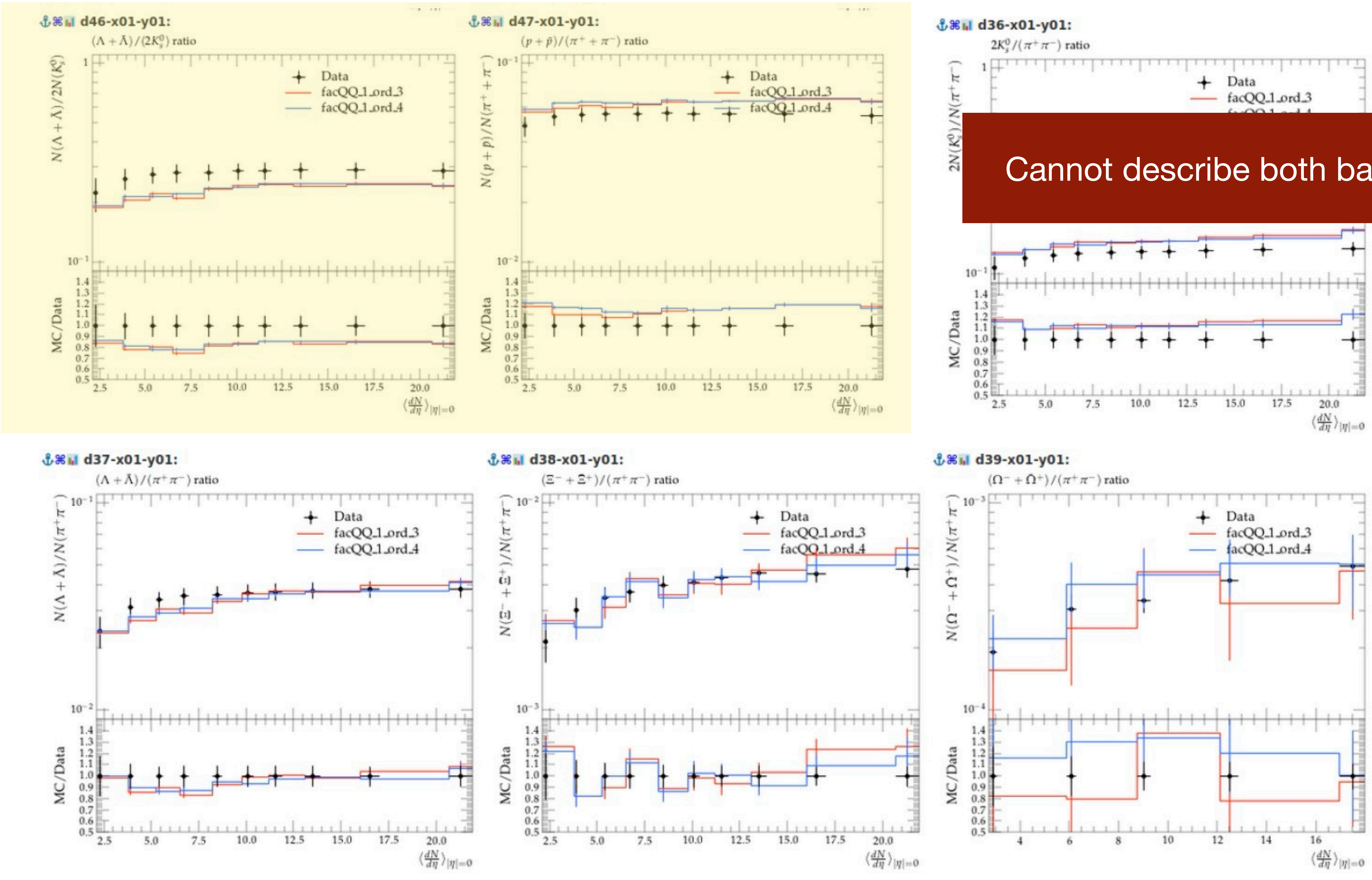
What if there's a blue string nearby?



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

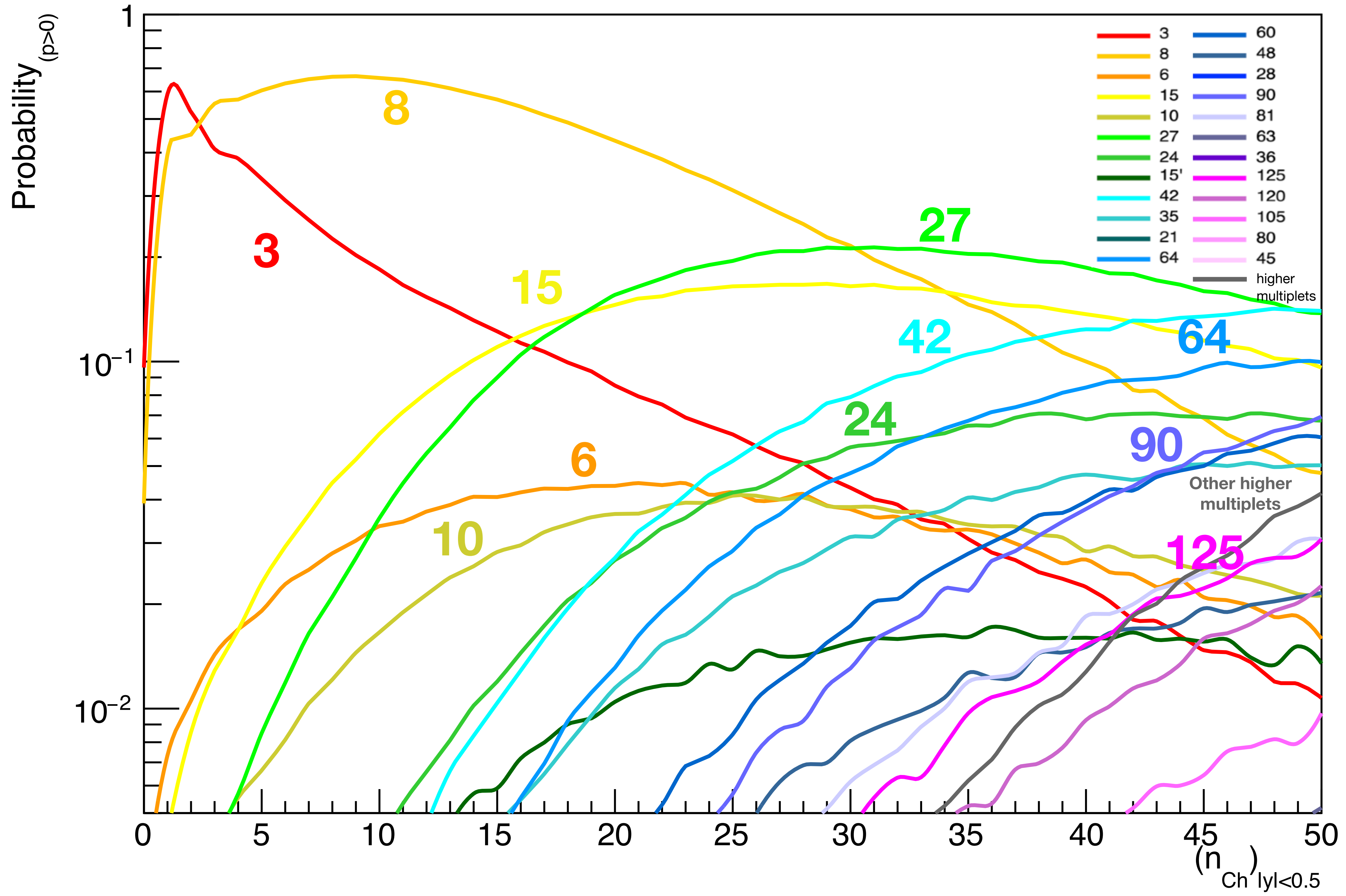
→ strangeness enhancement

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)

Vacuum → High multiplicities

Multiplets (y=0, pp 7 TeV)



Clear observations of strangeness enhancement with respect to charged multiplicity [e.g. ALICE Nature Pays. 13, 535 (2017)]

Protons are composite

→ lots of quarks and gluons inside

→ multiple parton-parton interactions

→ lots of colour charges

Strangeness enhancement with charged multiplicity suggests **higher multiplicity** string systems act **different to the vacuum case**

Number of fundamental and anti-fundamental flux lines at central rapidity in *pp* collisions give us **effective multiplet representation**

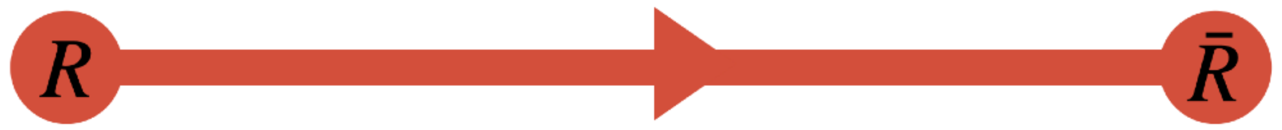
Reach higher than simple quark-antiquark triplet string

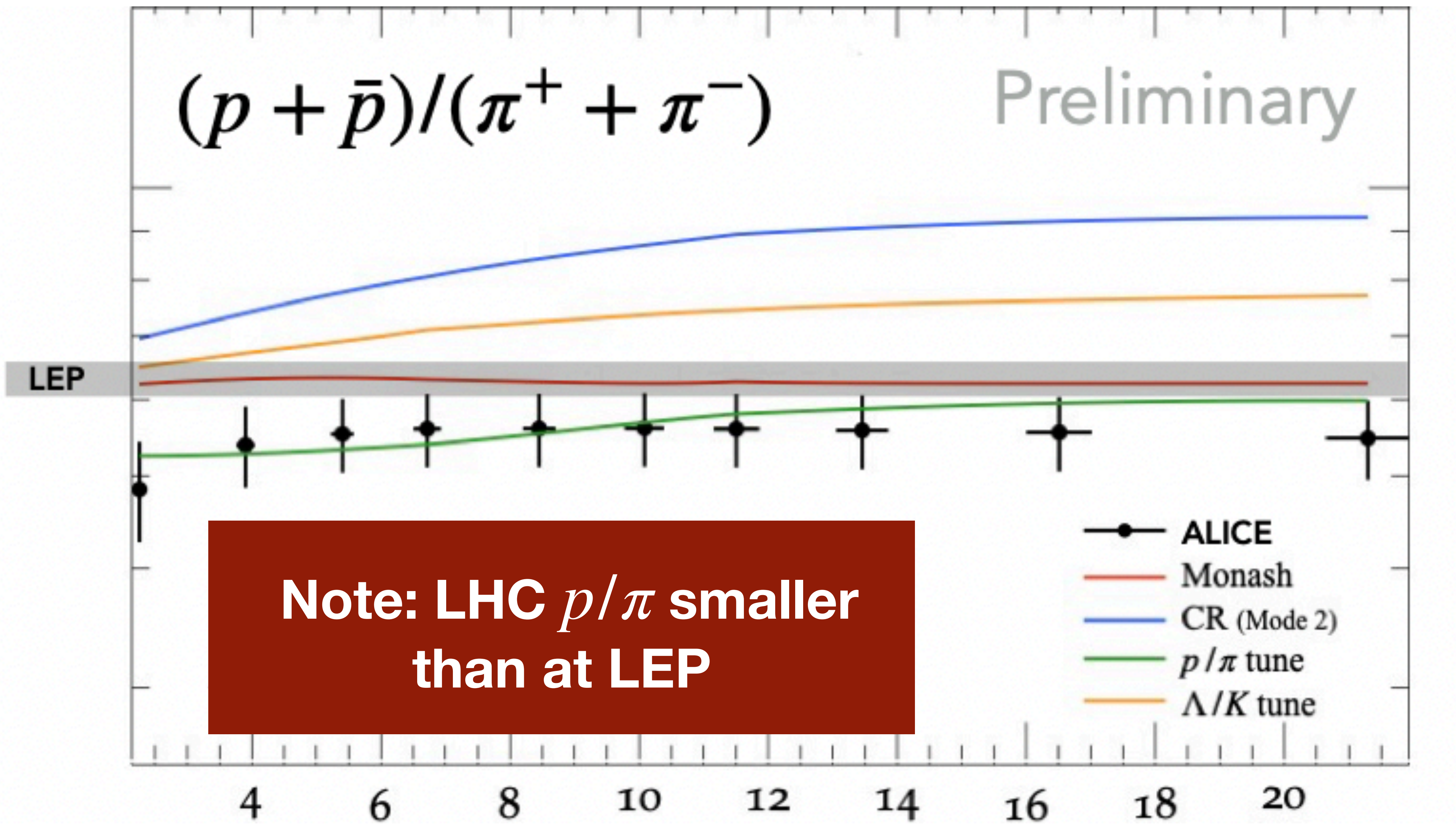
Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**





Popcorn mechanism

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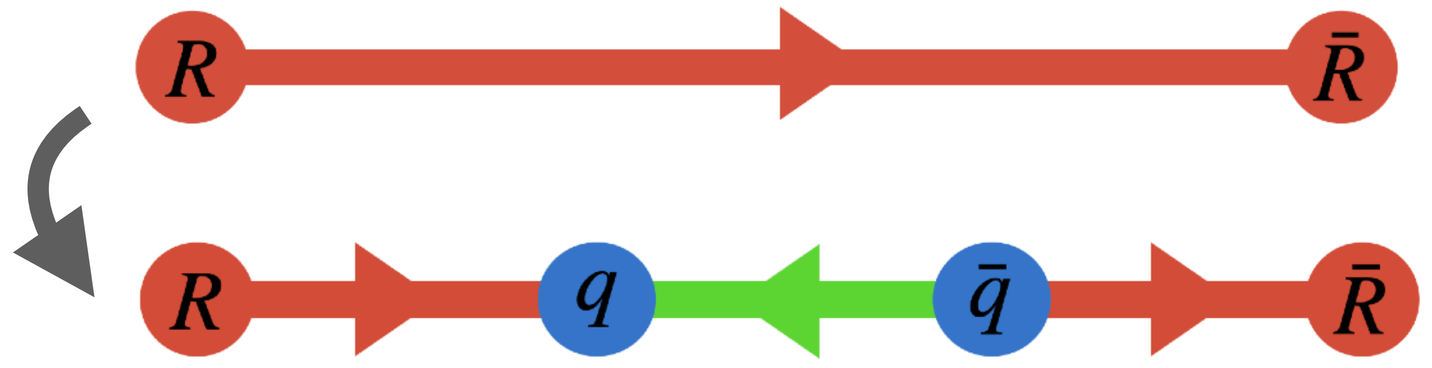
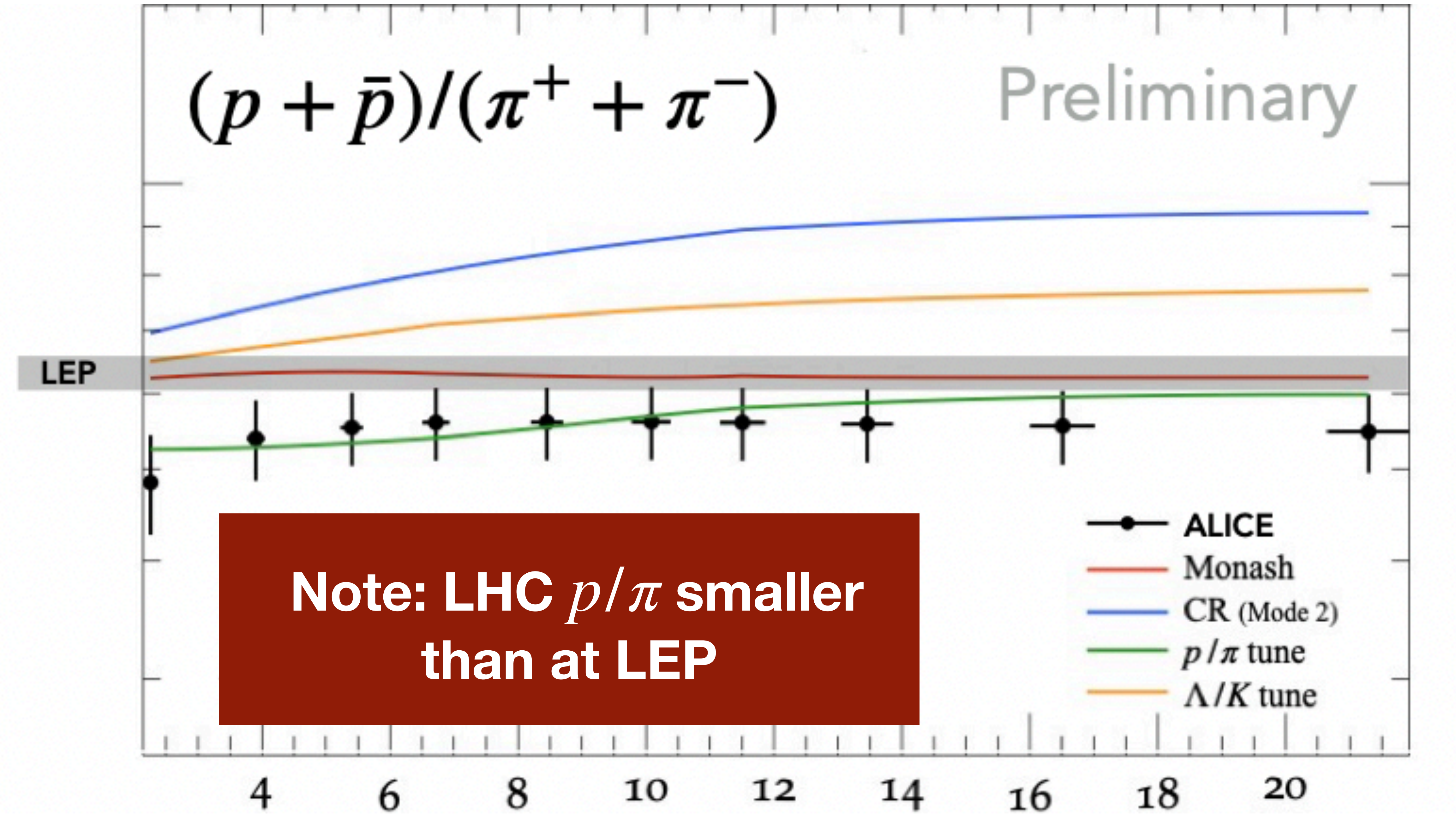


blue $q\bar{q}$ fluctuation on the string

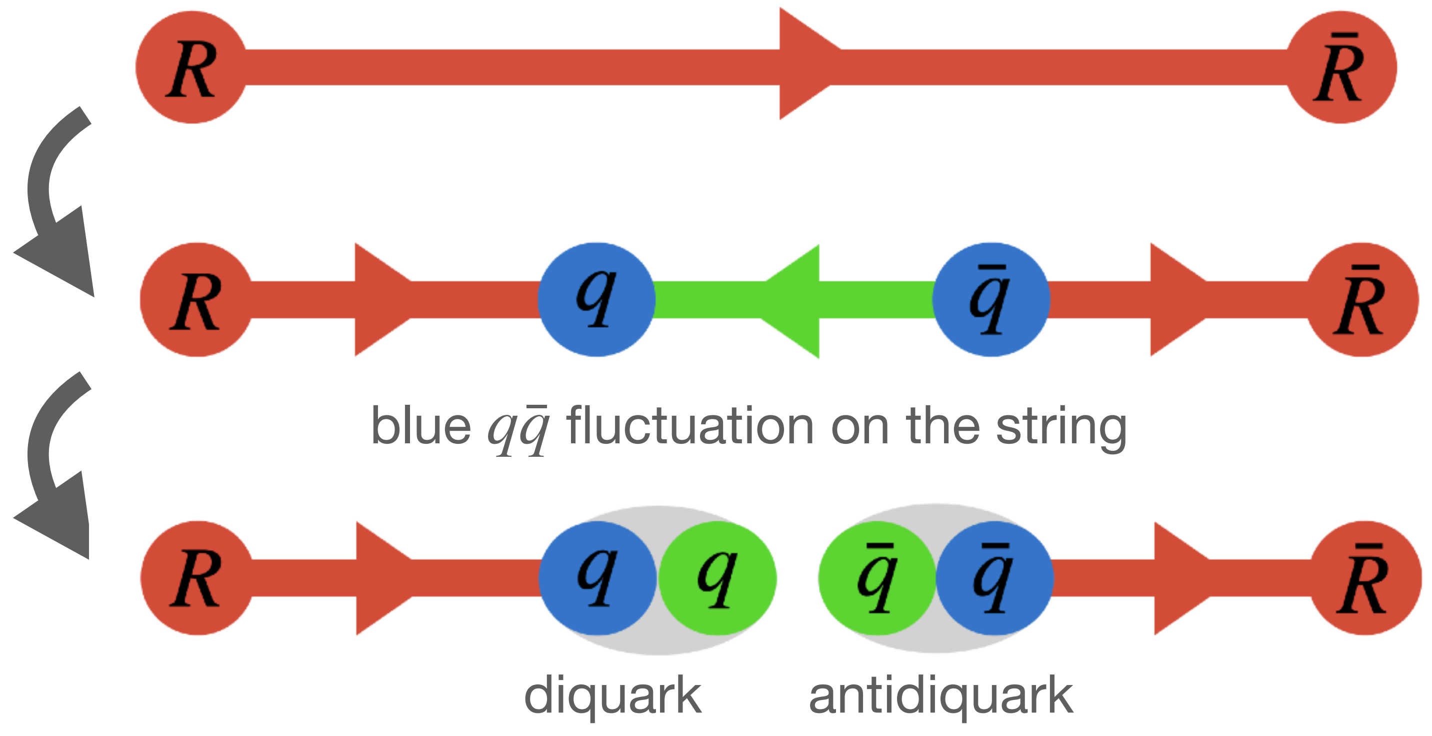


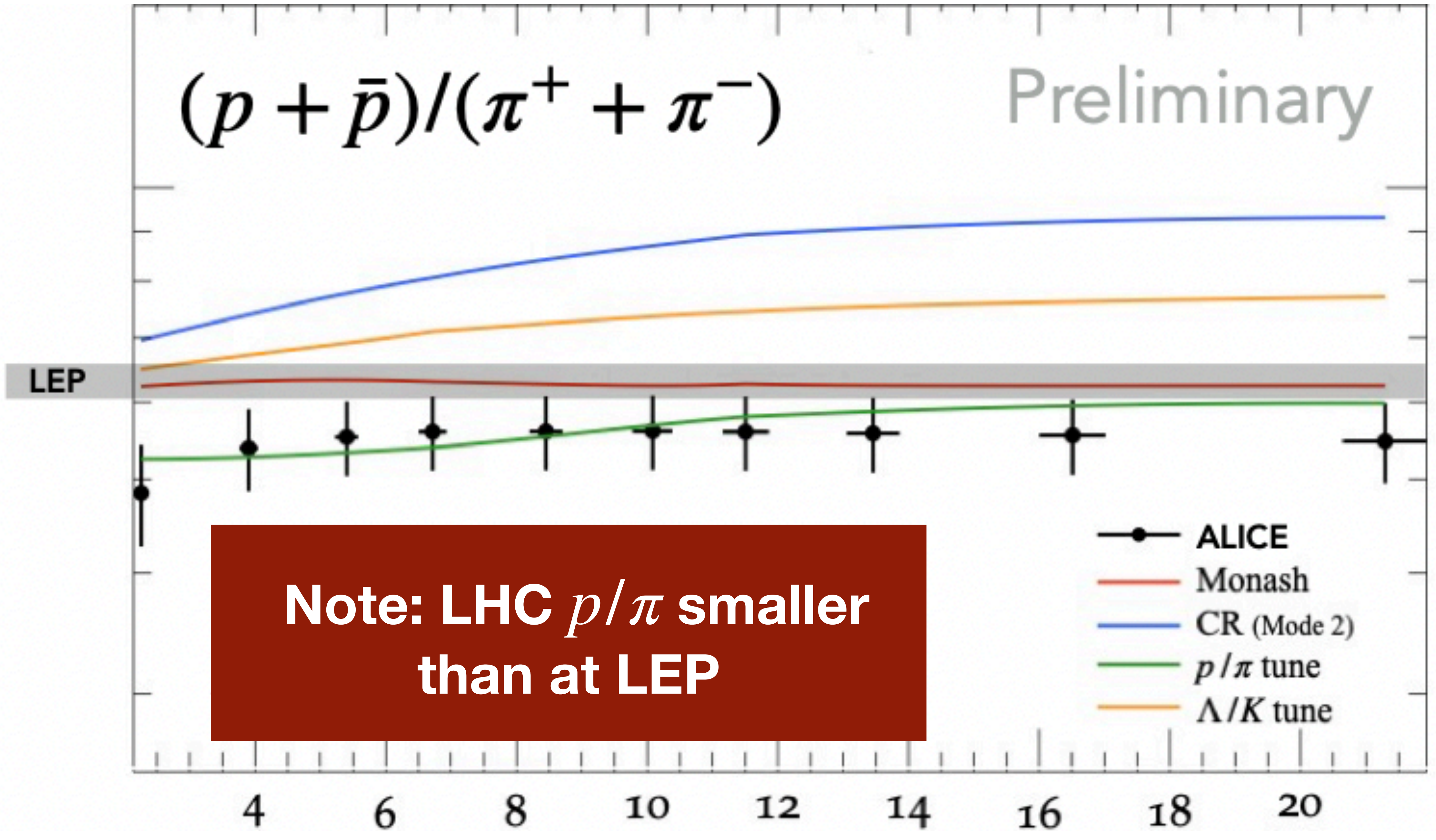
Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**





Note: LHC p/π smaller than at LEP

Popcorn mechanism

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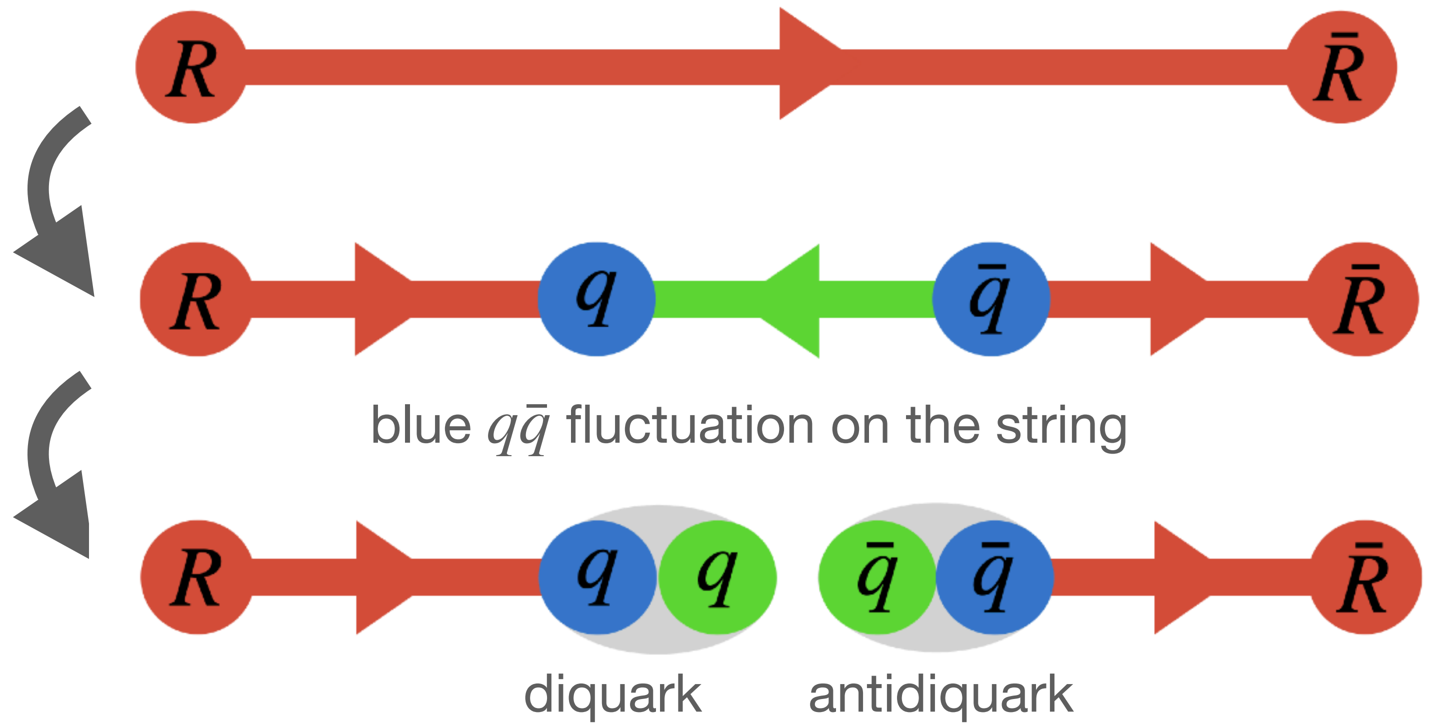
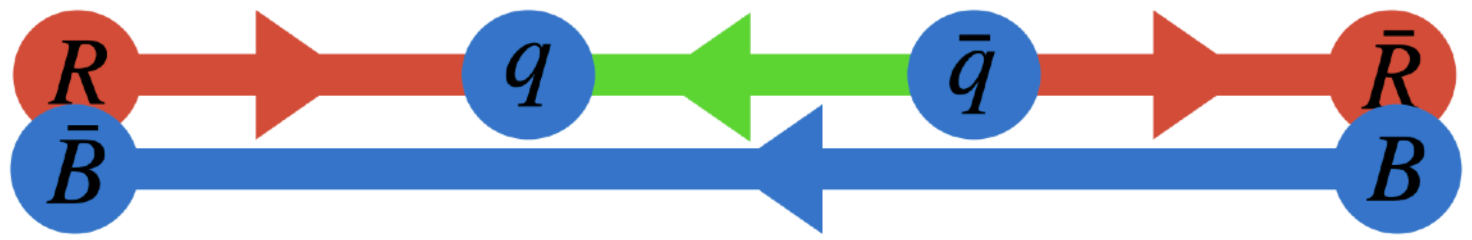
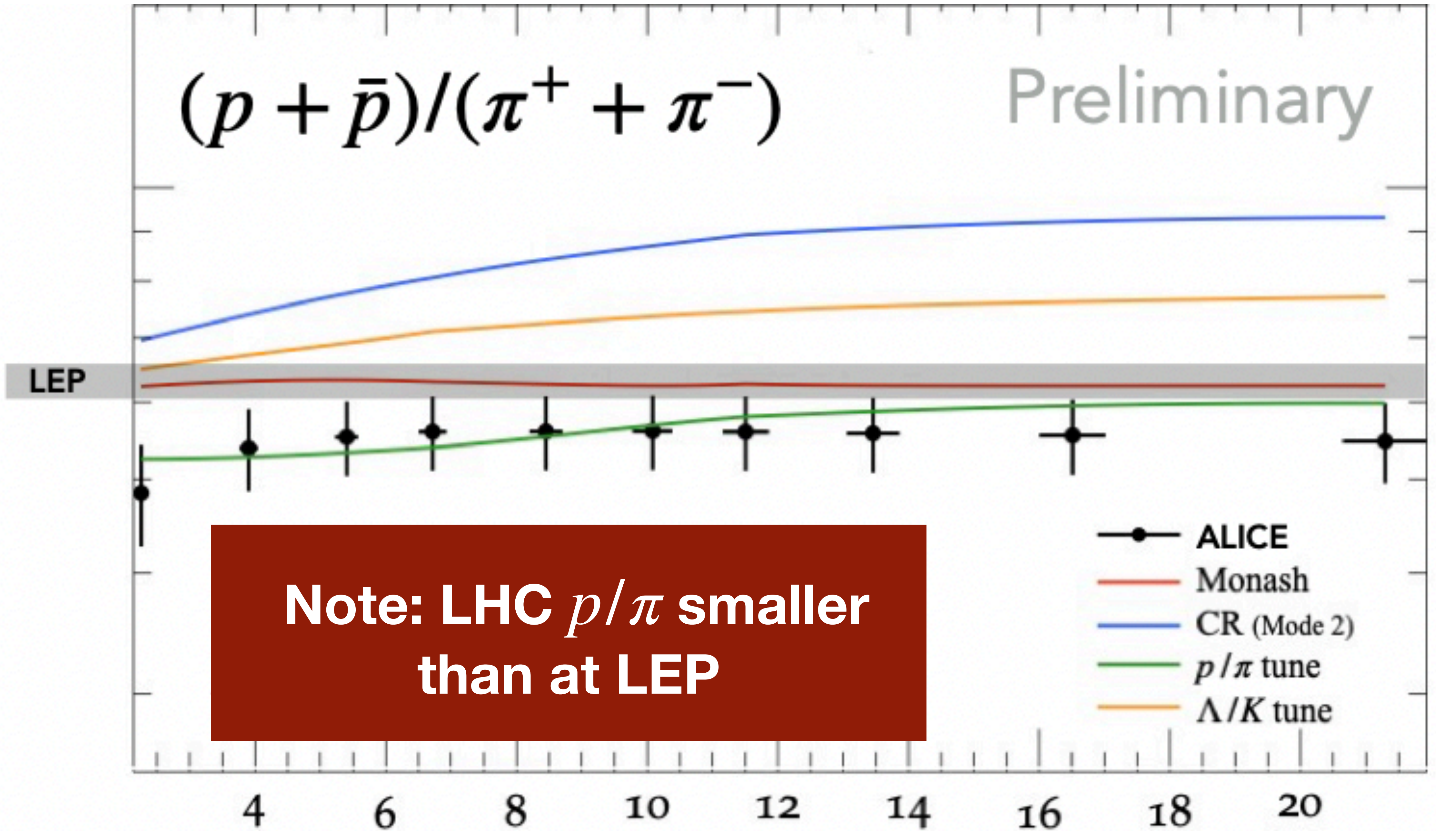


What if there's a blue string nearby?





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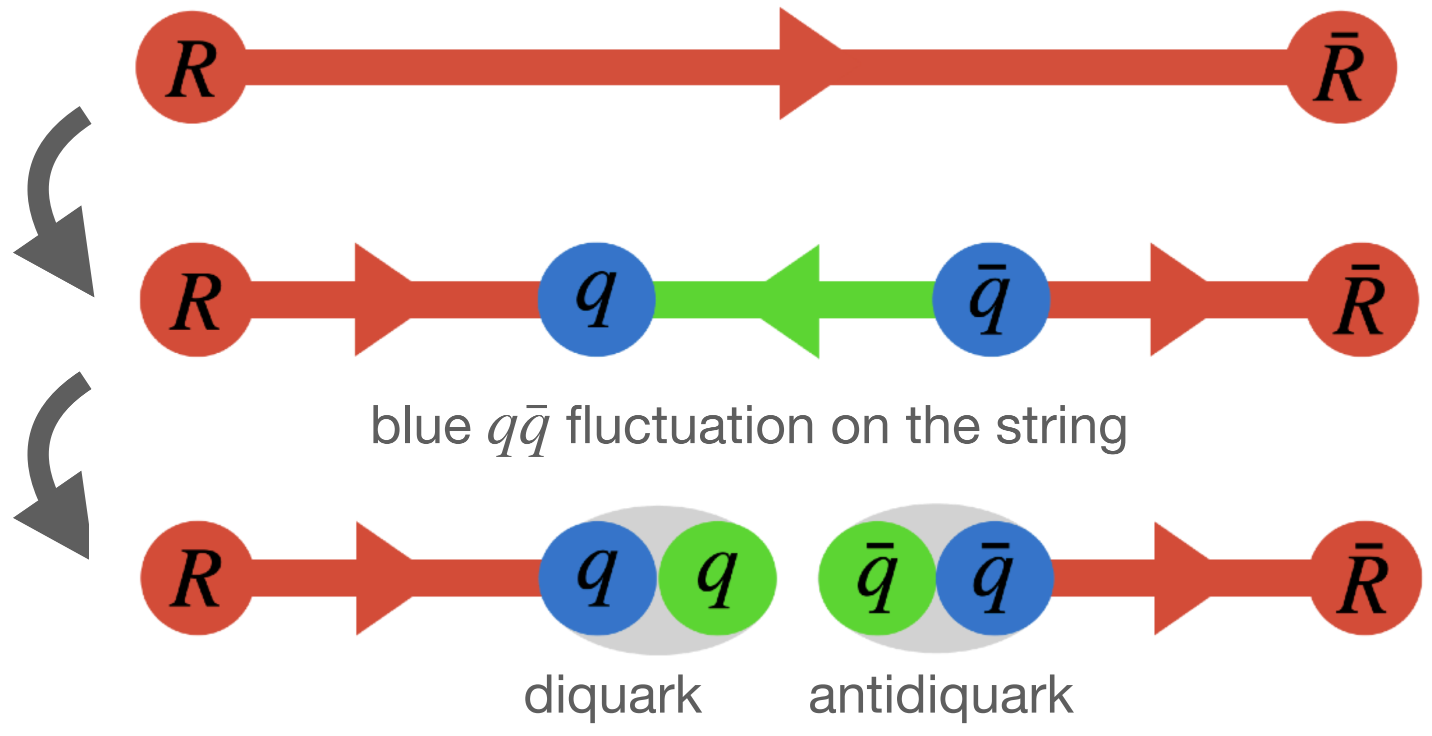
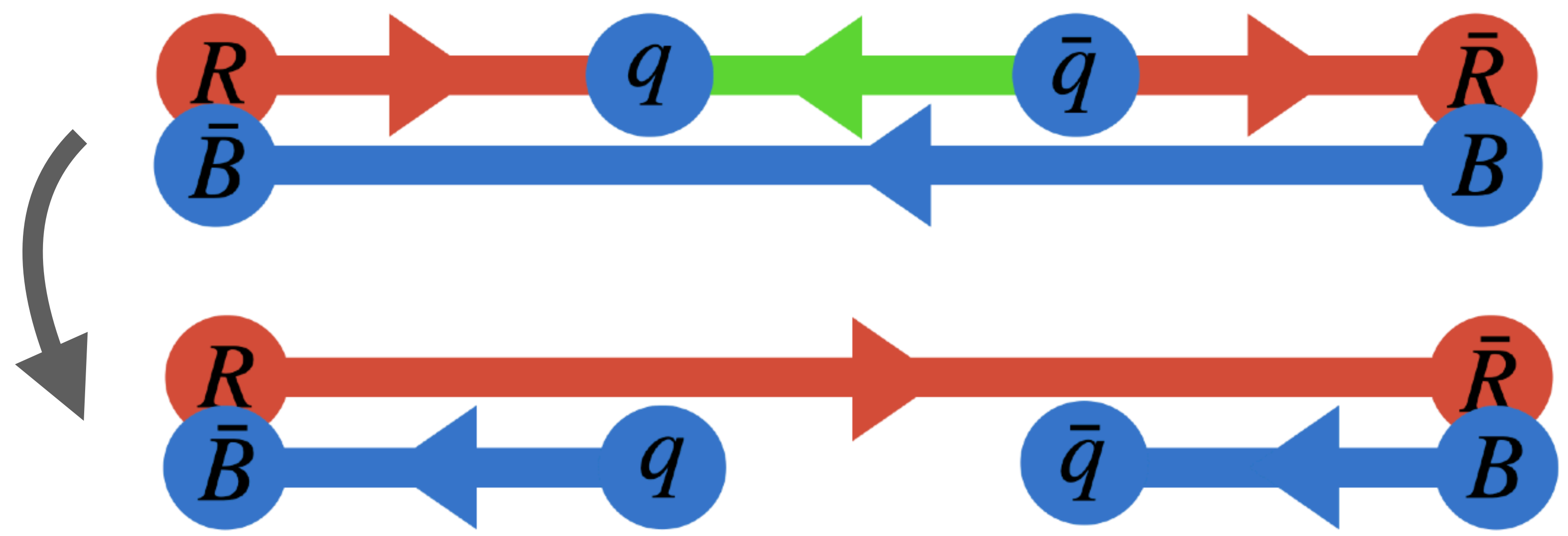


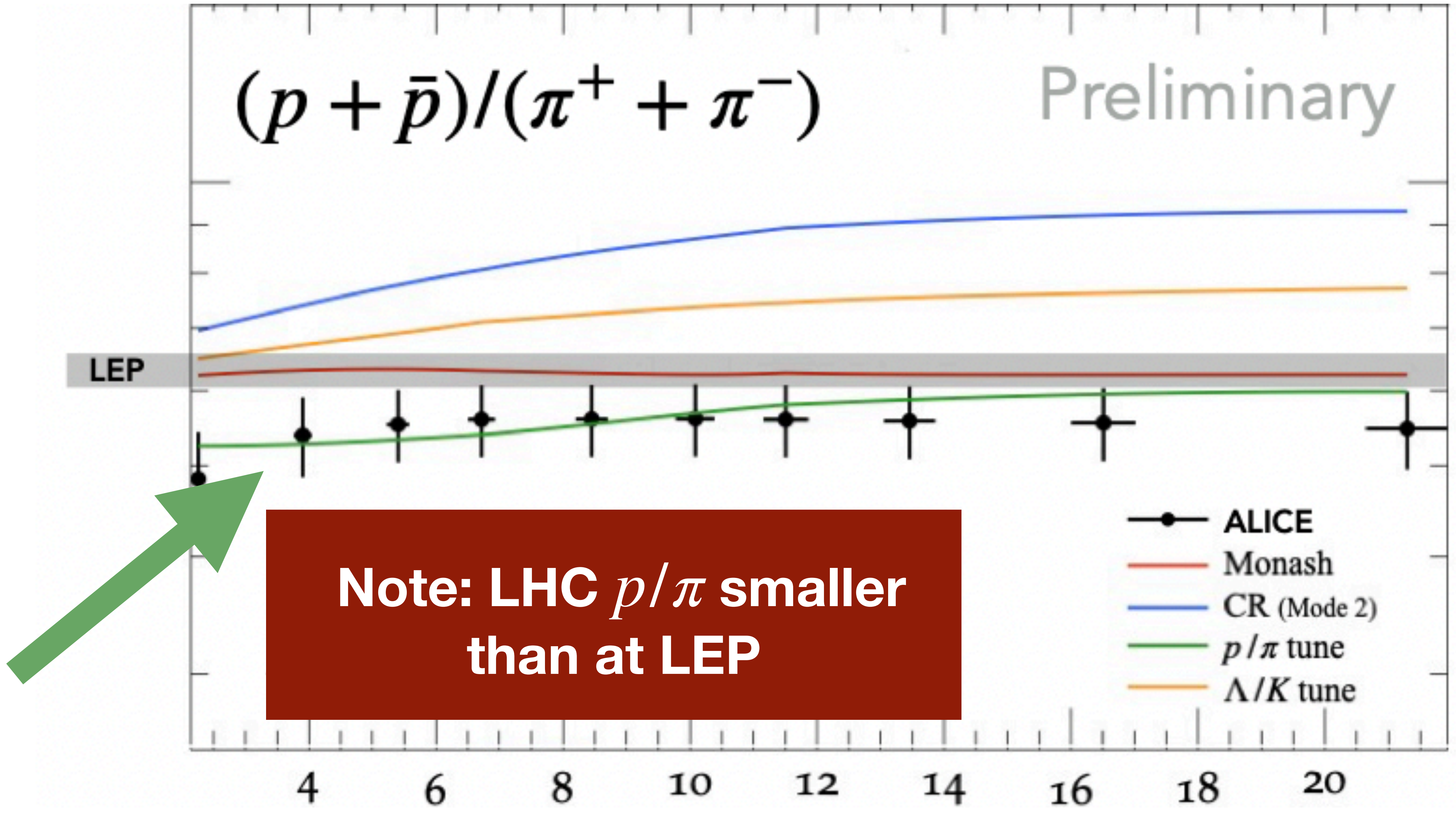
What if there's a blue string nearby?

NEW

Destructive interference of popcorn mechanism



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



Note: LHC p/π smaller than at LEP

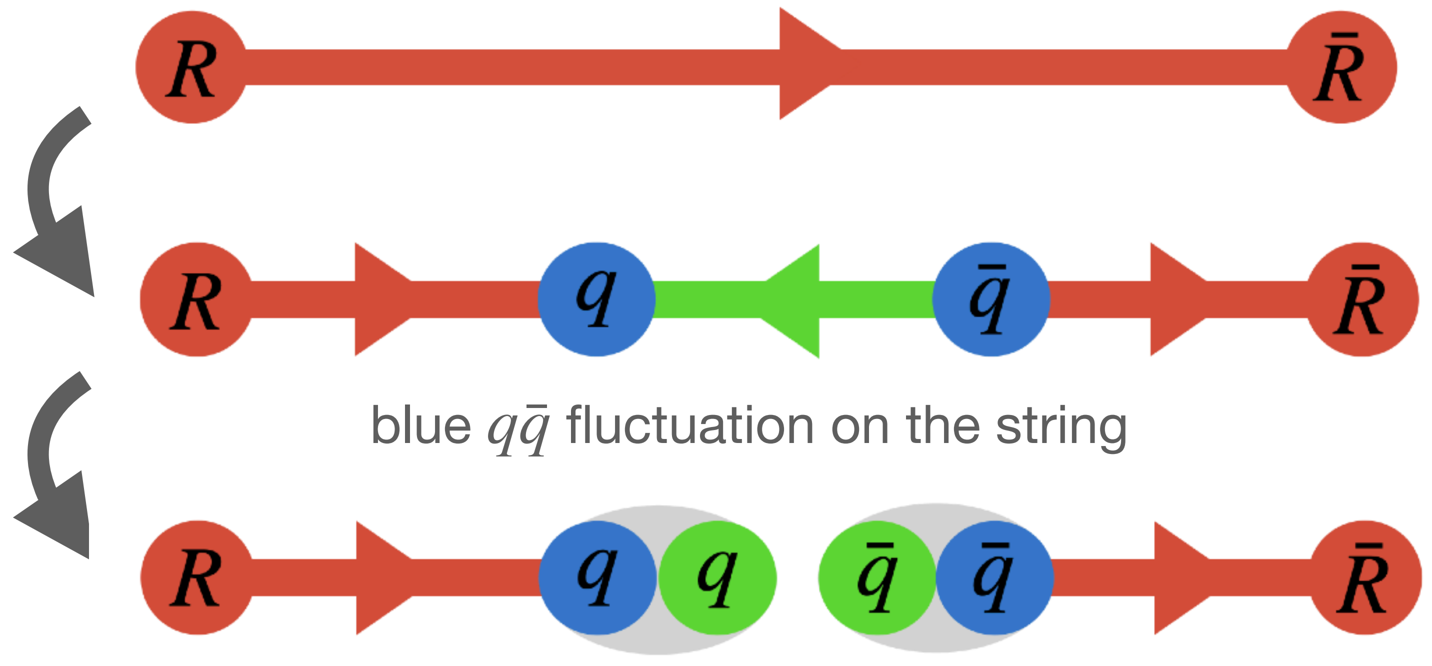
Only basic model implemented thus far, further improvements on the modelling still happening!

Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**



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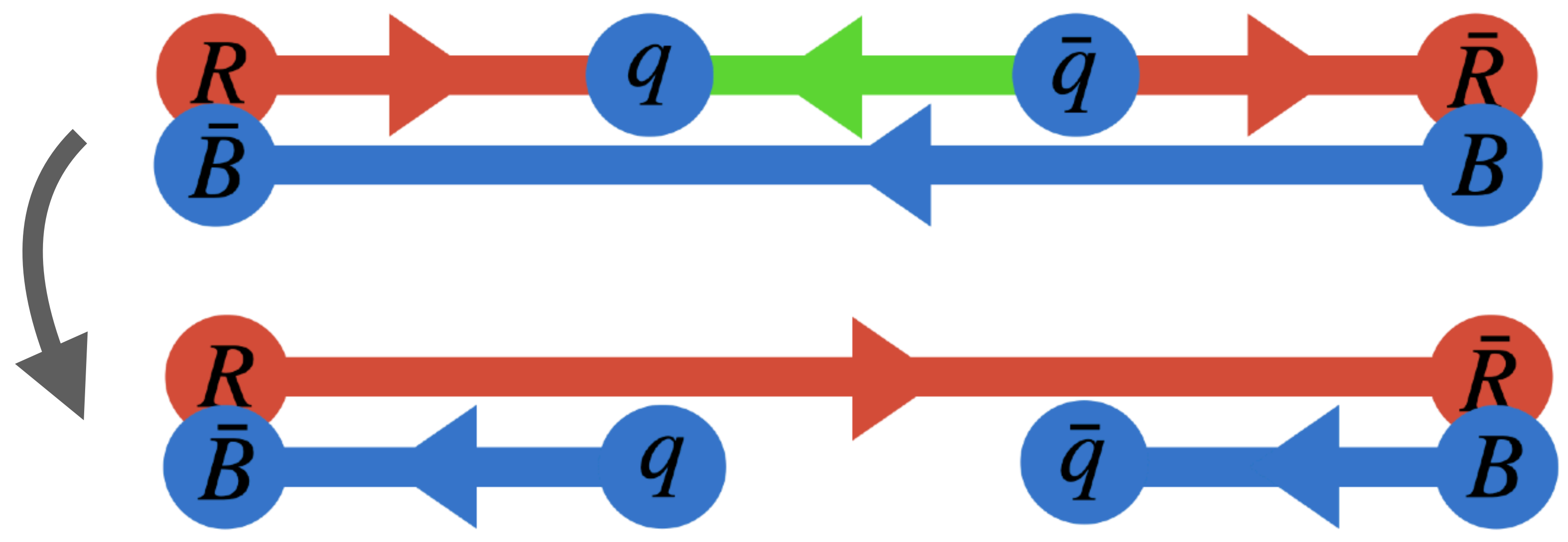

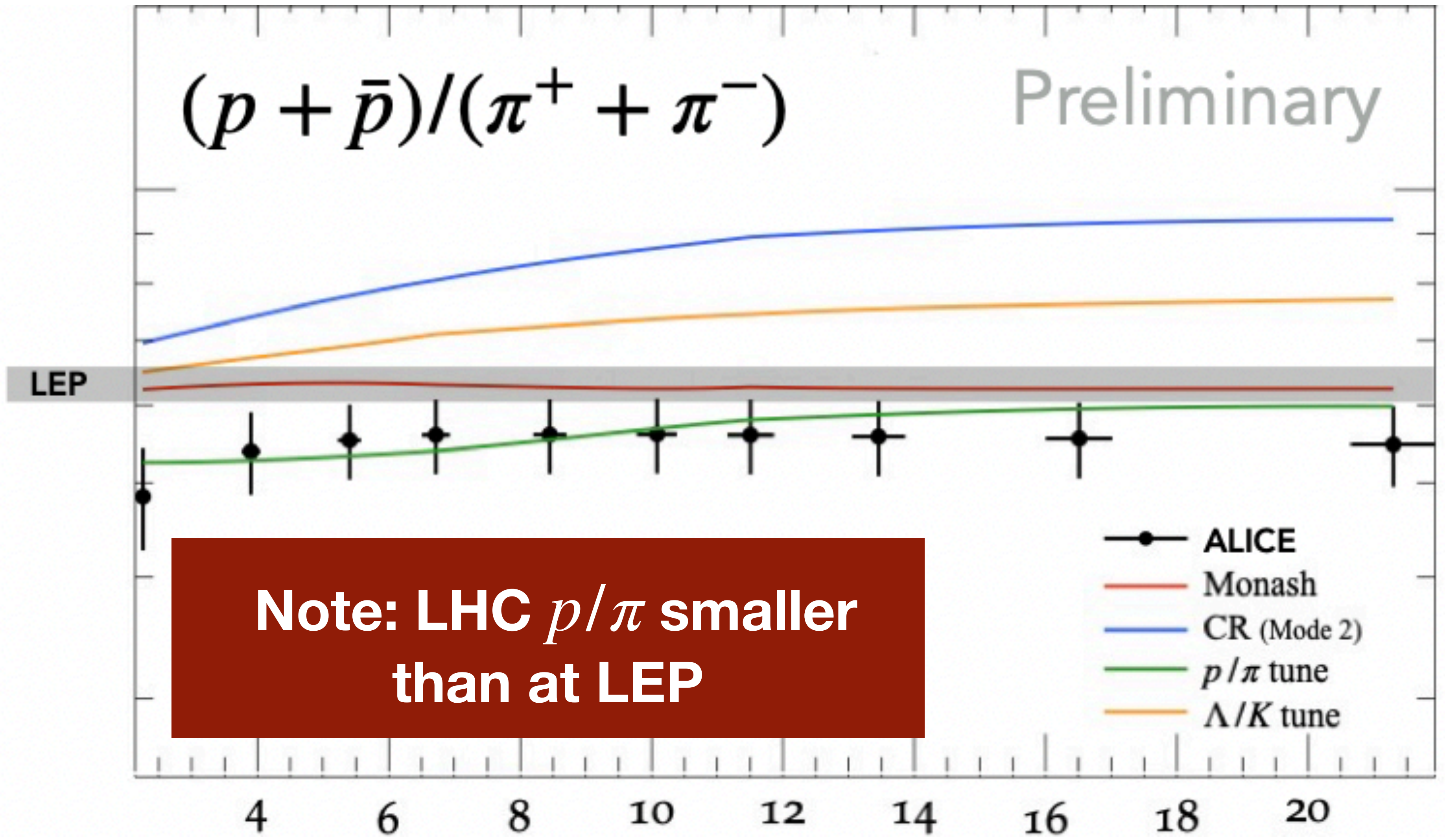

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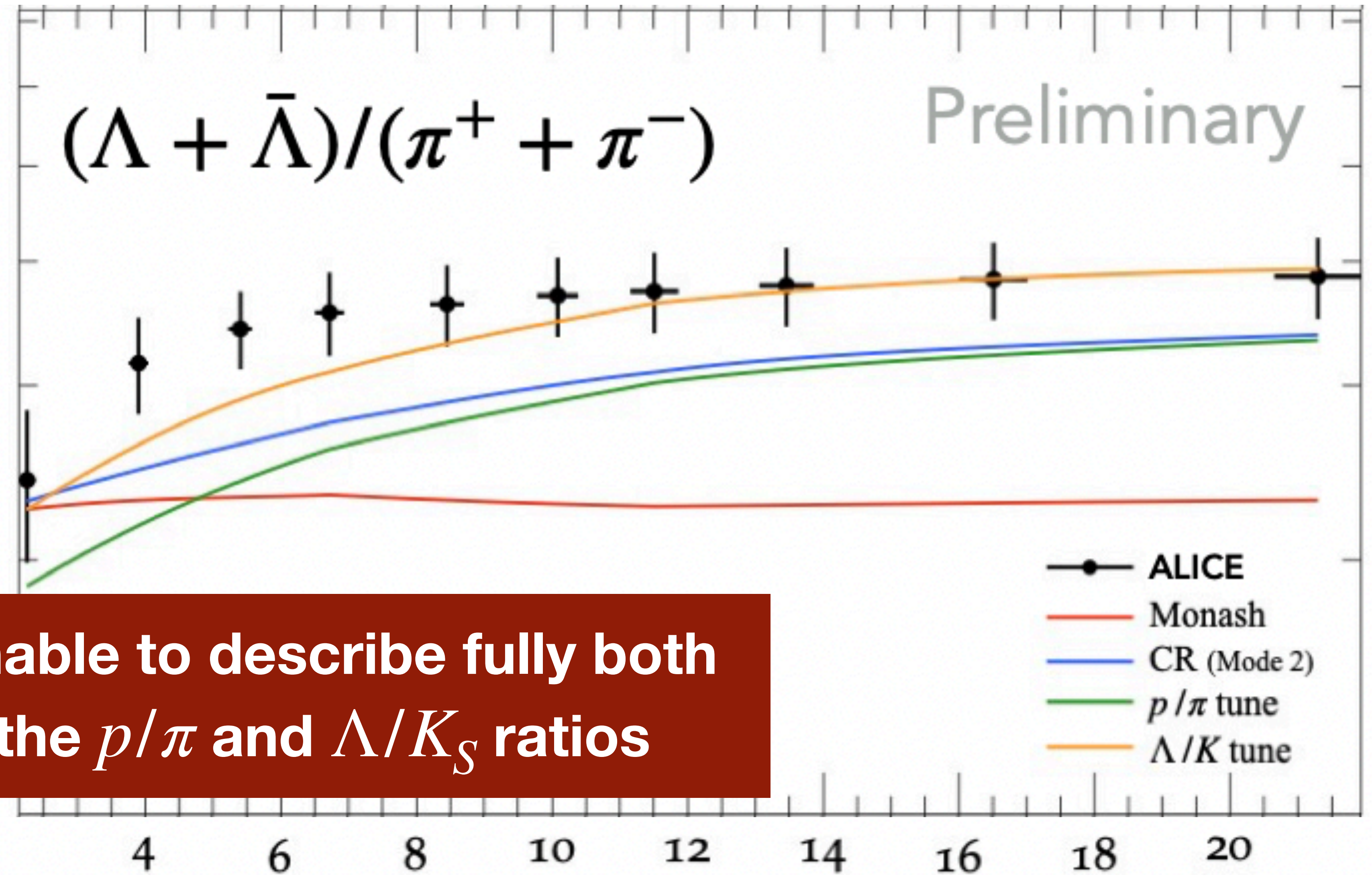

Unable to describe fully both the p/π and Λ/K_S ratios

Vacuum → Small Systems → Heavy Ion

String model has well described e^+e^- **systems** (i.e. cases with not many strings), and we've explored **high multiplicity small systems**, but what about **heavy ion systems?**

Do we still have strings? Do we have QGP? Is it a mix of both, or is there a smooth transition between the strings and QGP?

How far can we push the string model?

Angantyr uses PYTHIA as its base to do pA and AA collisions, using only strings (**no QGP** formation)

Collective effects of strings can describe features that are typically described as signature of QGP

- ➢ Near-sided ridge → string shoving
- ➢ v_2 → string repulsion?
- ➢ Strangeness enhancement → ropes/close-packing

Thank you for listening!