Hadronisation in PYTHIA8:

string junctions, strangeness and beyond

Javira Altmann - Monash University, visiting University of Oxford

PhD Supervisor - Peter Skands

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

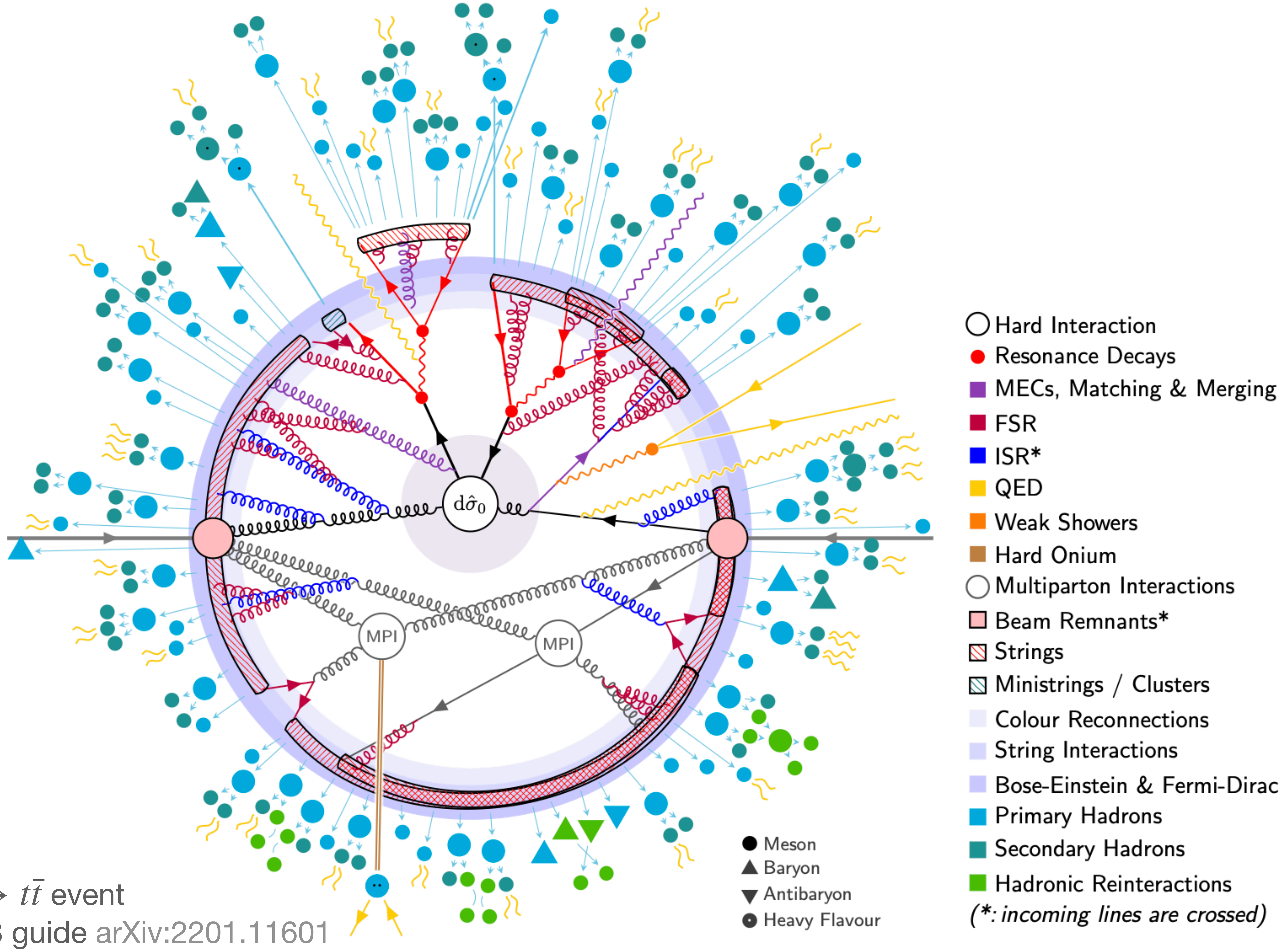
Confinement in high energy collisions

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

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?

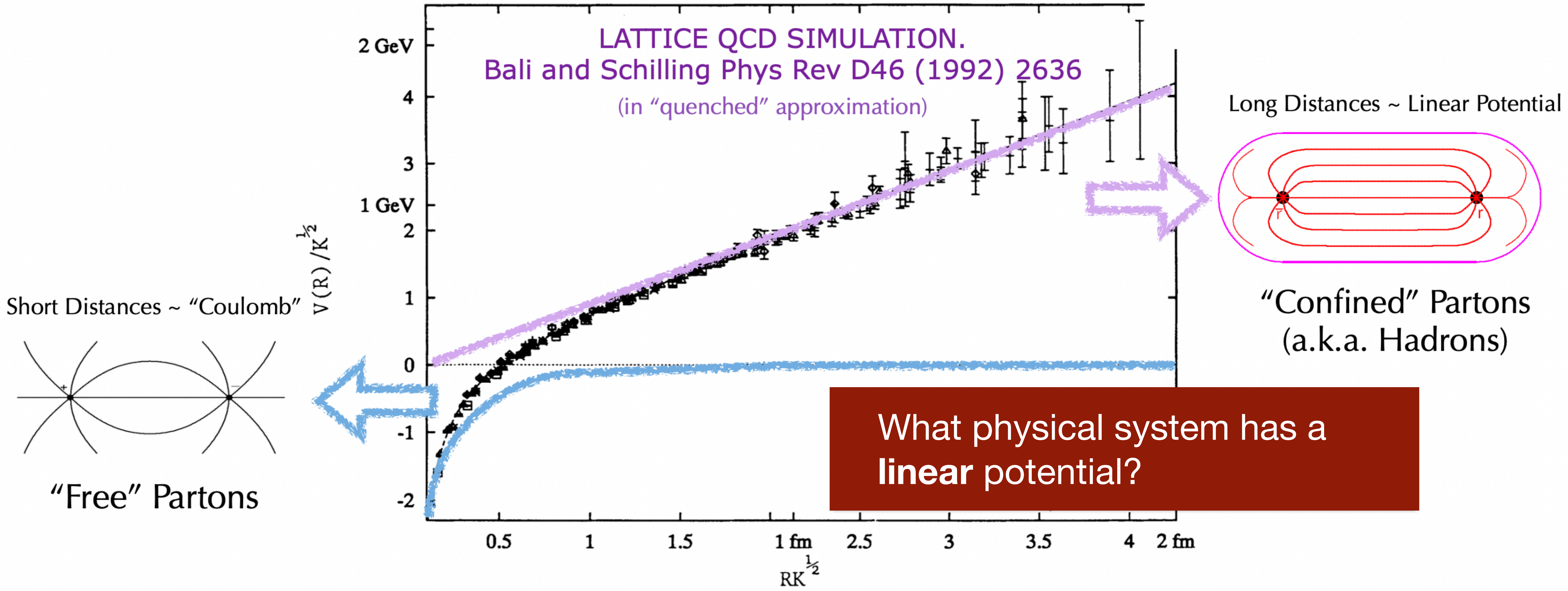
Colour neutralisation

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

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?

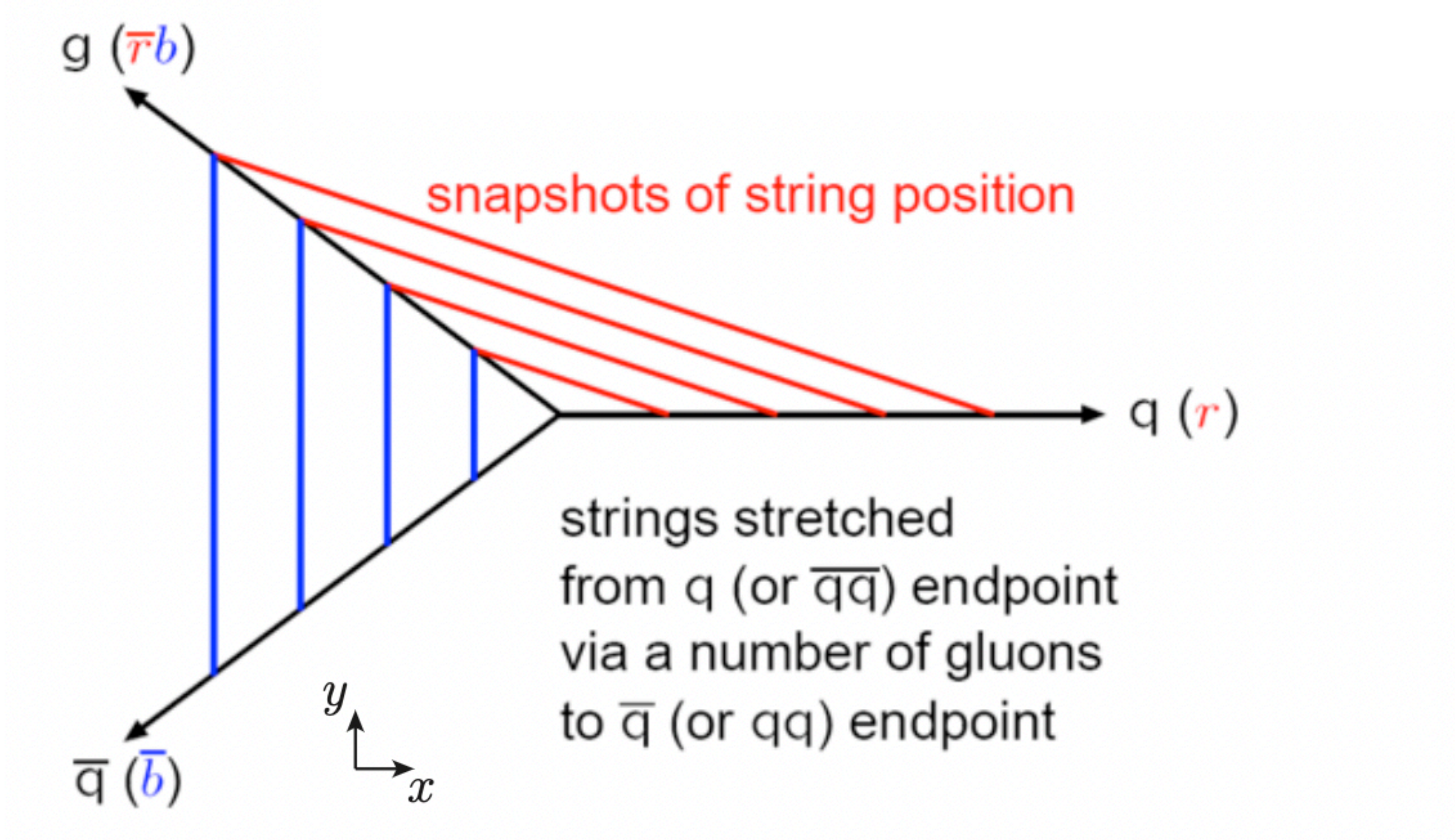
Lund String Model

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

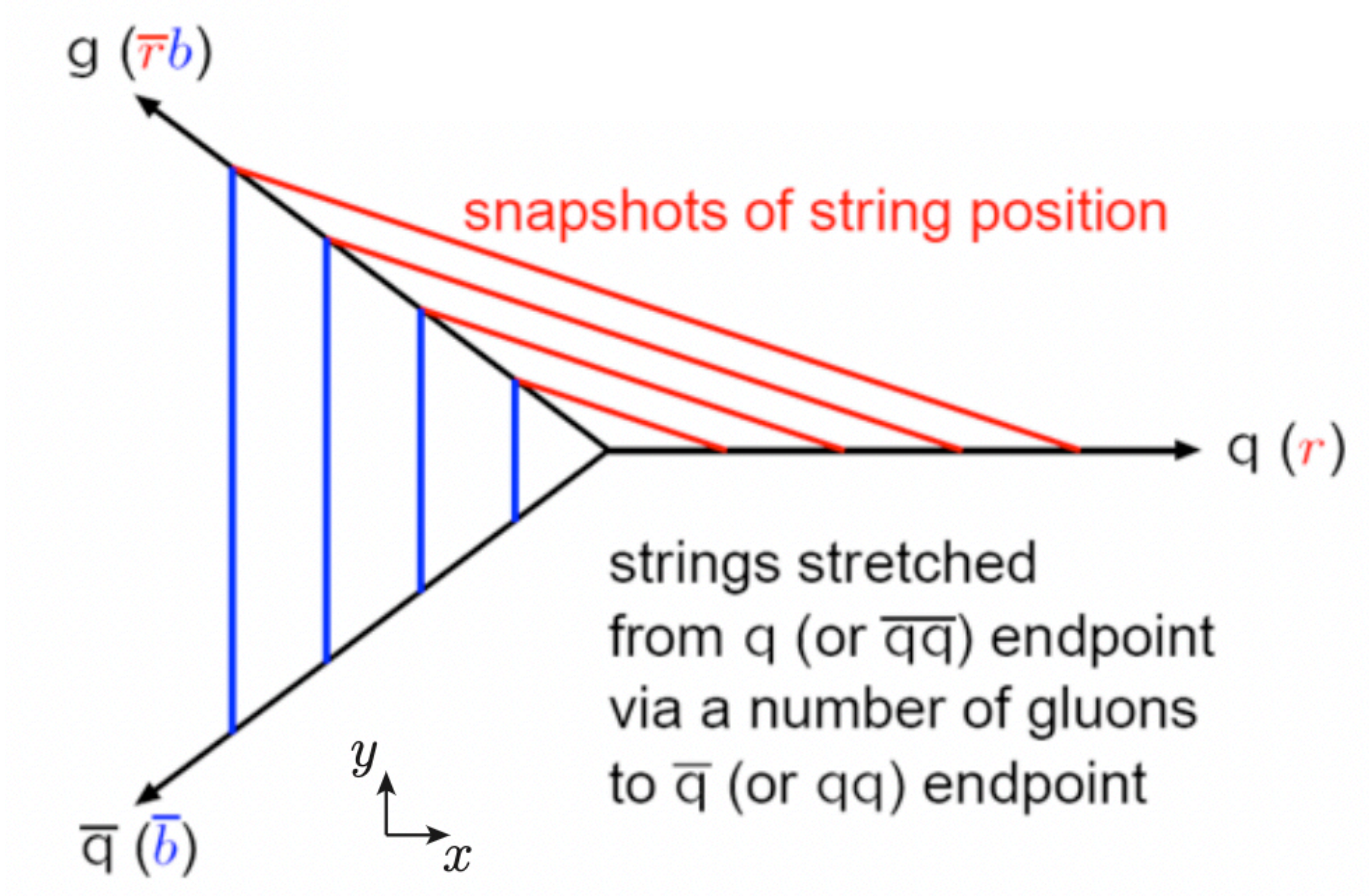
Lund String Model

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

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")**

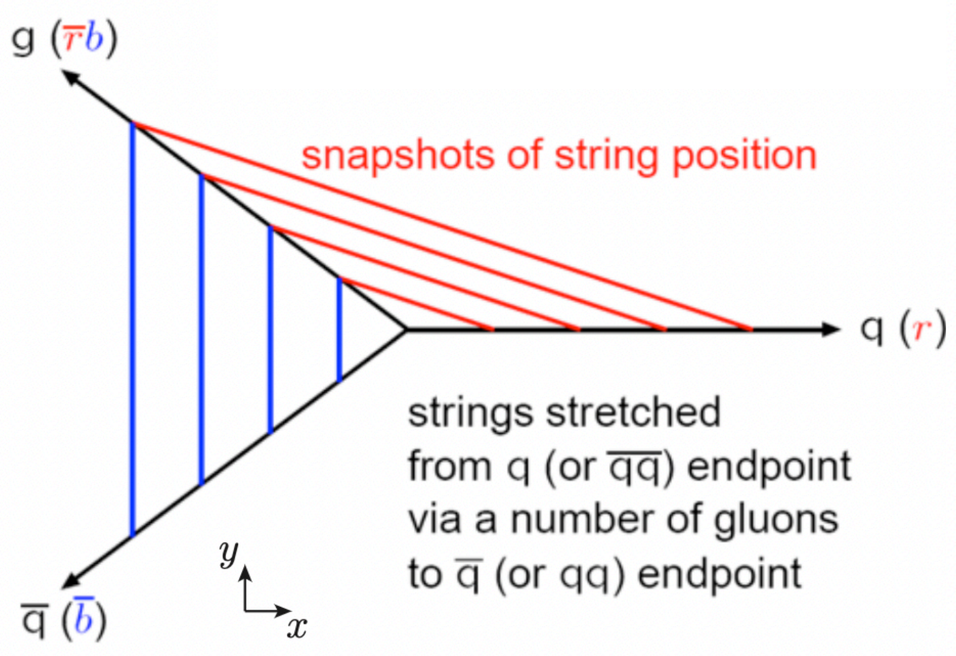
Lund String Model

Lund String Model:

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

Collapse the colour field into a **narrow flux tube**
sheet) with uniform energy density

$\kappa \sim 1$ GeV/fm

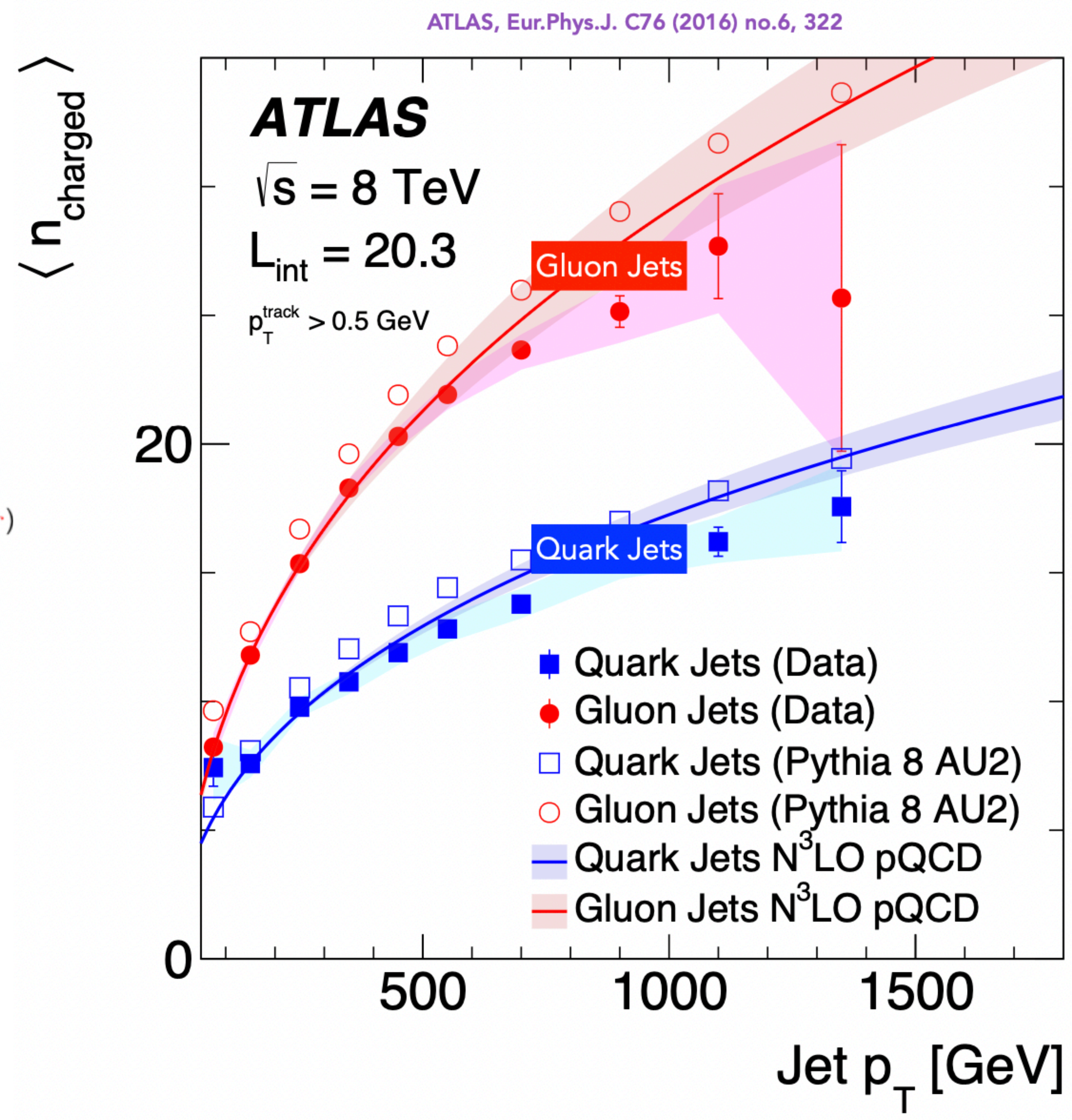


Quarks / antiquarks

(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")**



Signatures of gluon-kinks have been seen
Factor ~ 2 more particles in gluon jets

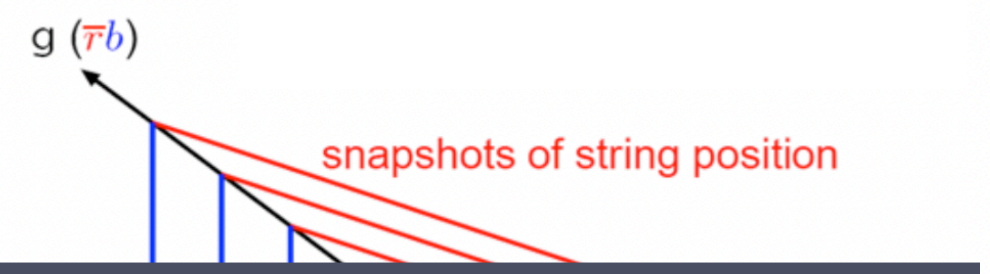
Lund String Model

Lund String Model:

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

Collapse the colour field into a **narrow flux tube** sheet) with uniform energy density

$\kappa \sim 1$ GeV/fm



Quarks / antiquarks

(anti)triplet → carry (ant

→ connected via a strin

→ string **endpoints**

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

String fragmentation!

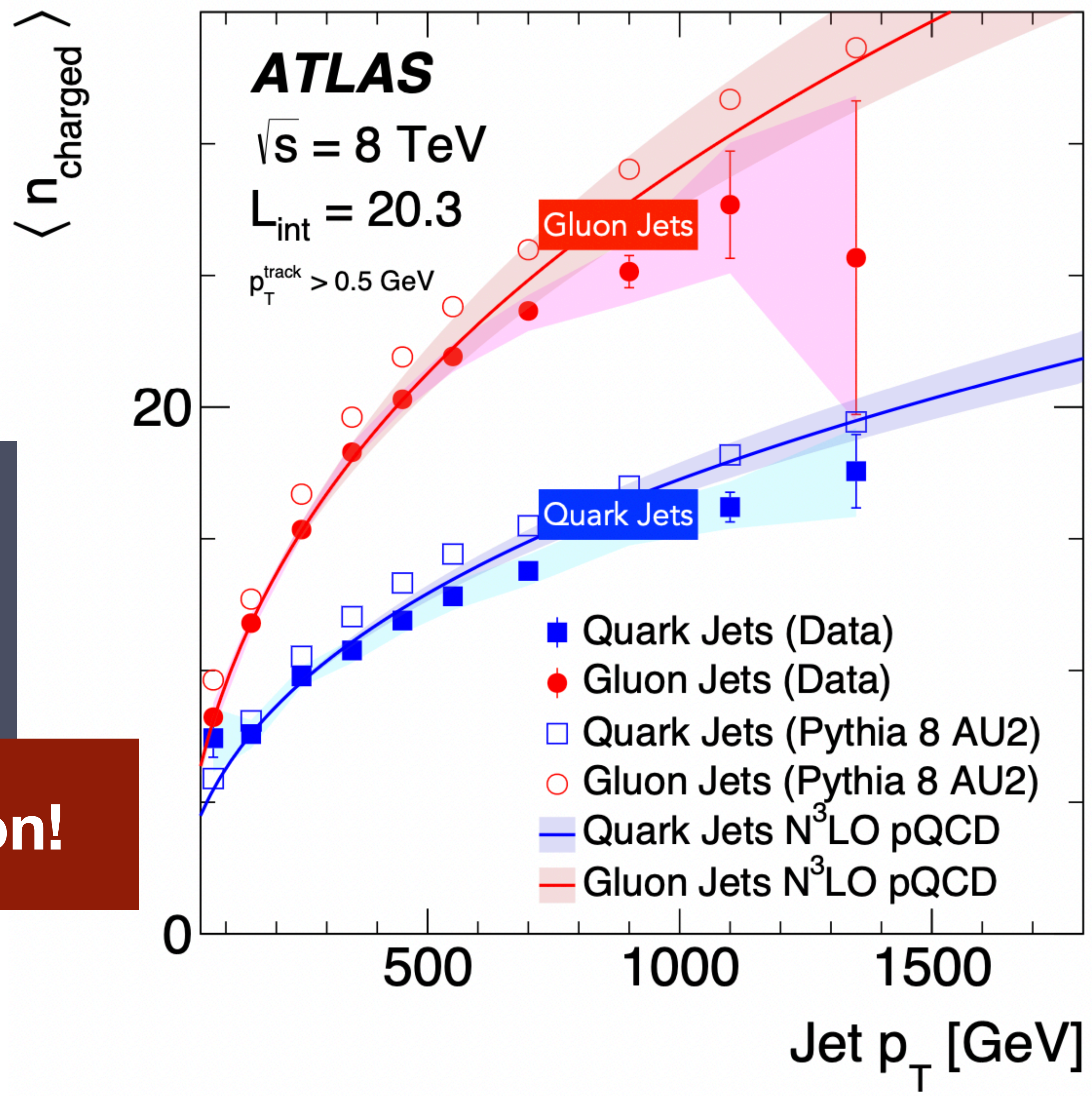
Gluons

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")**

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



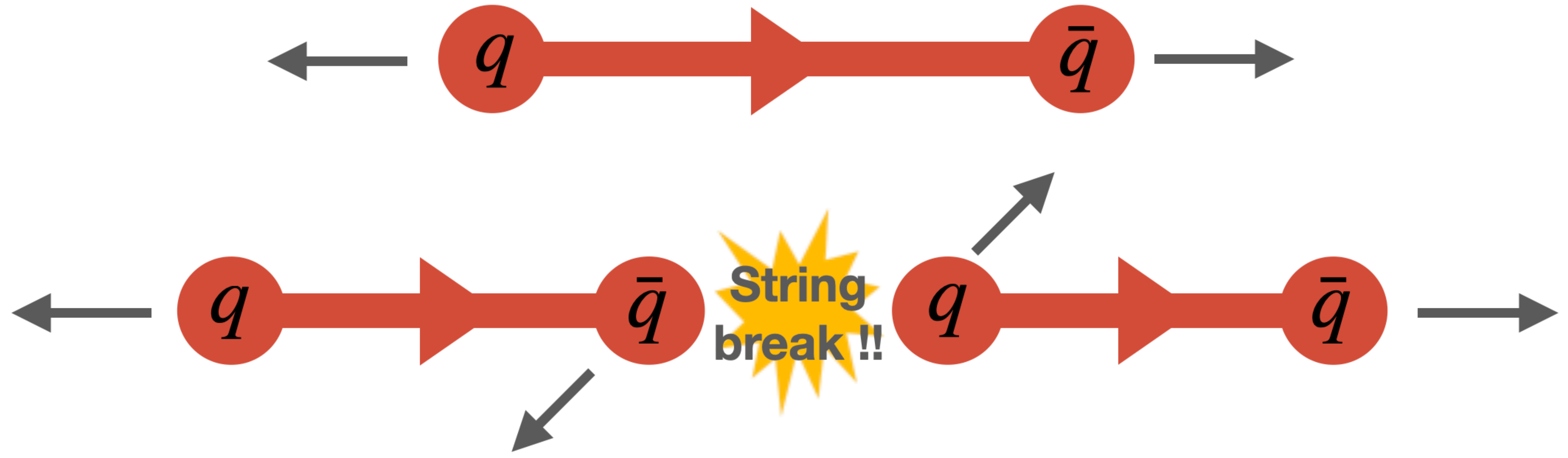
Signatures of gluon-kinks have been seen
Factor ~ 2 more particles in gluon jets

Hadronisation:

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

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

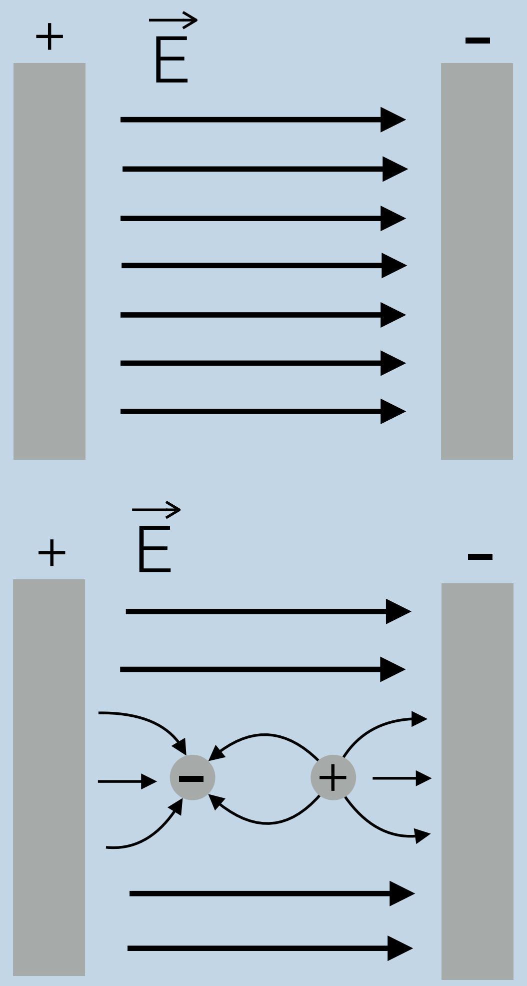
Instead use the **Schwinger mechanism**



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 $m_\perp = \sqrt{m_q^2 + p_\perp^2}$

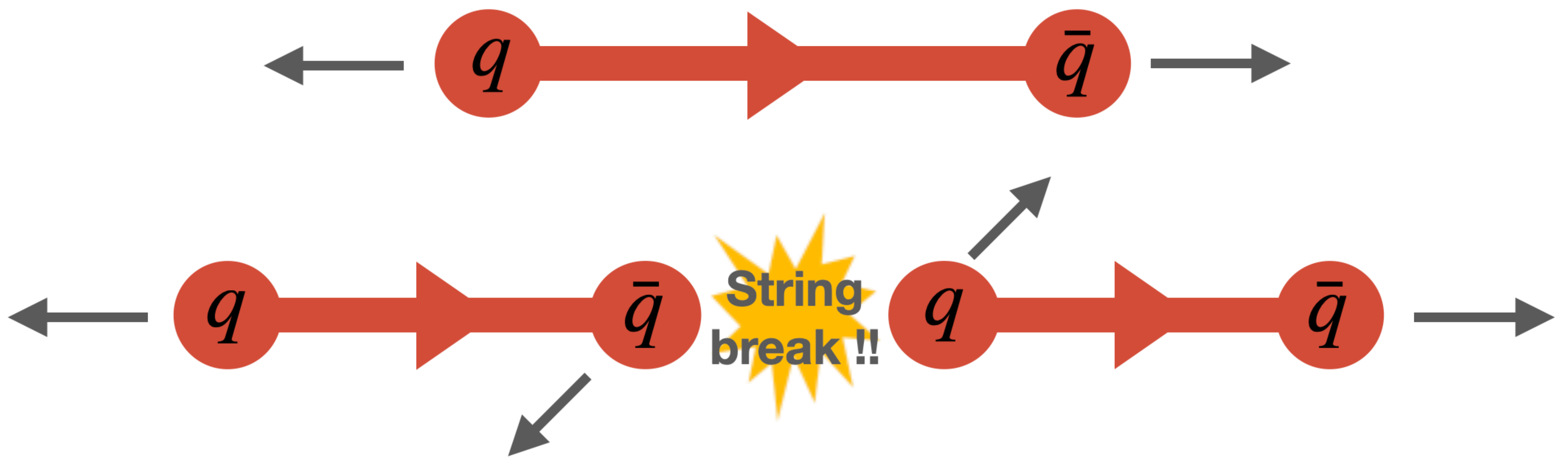
Partons → Hadrons

Hadronisation:

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

String breaks are **causally disconnected**

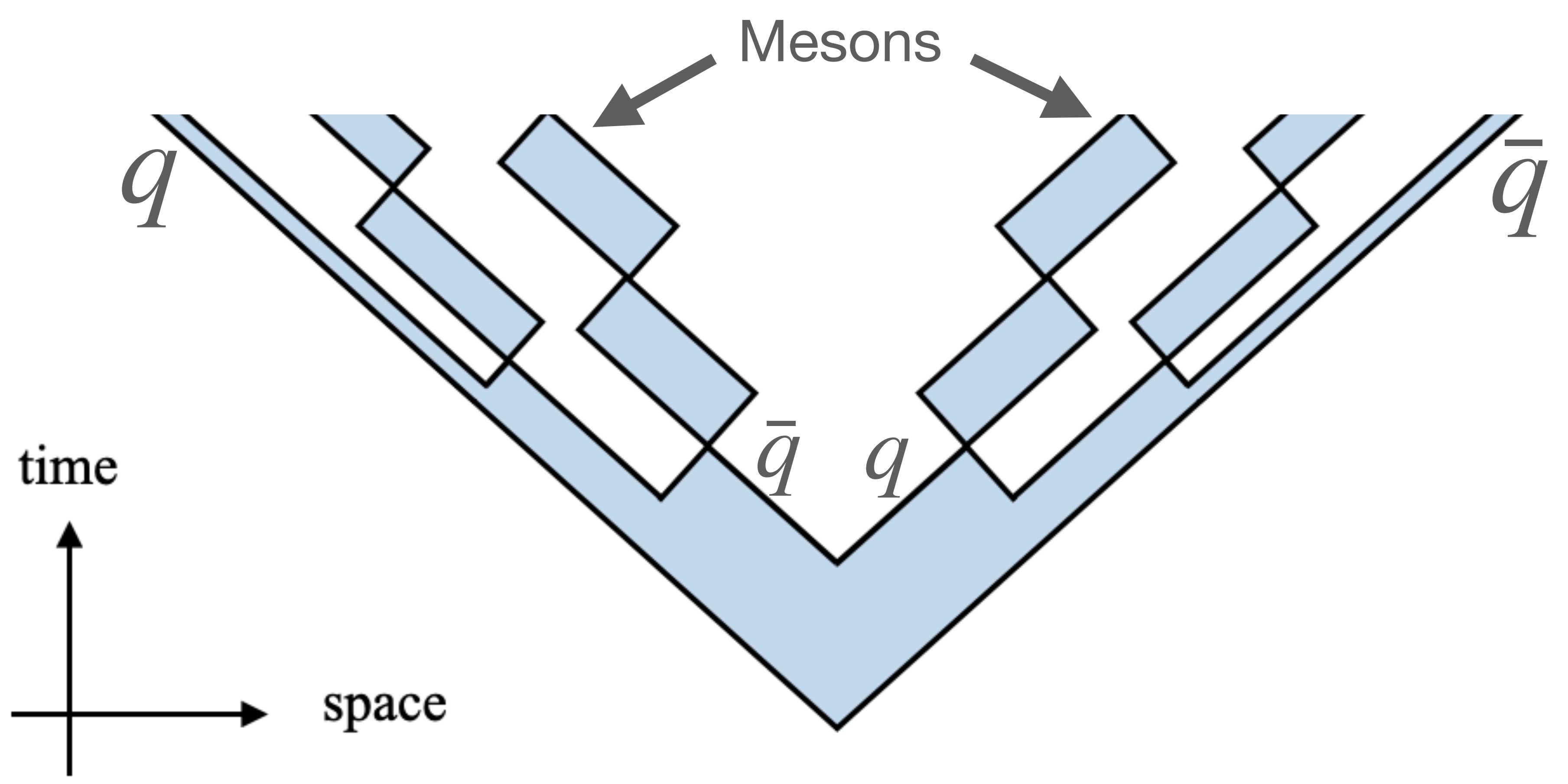
→ can fragment off hadrons from either end of the string



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



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 fragme

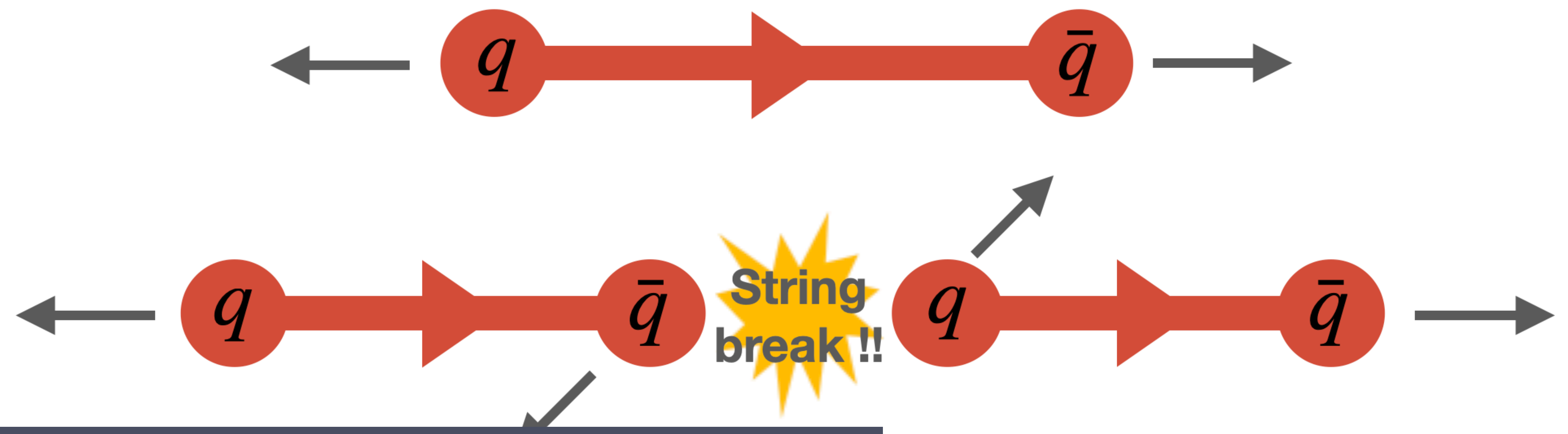
Probability c

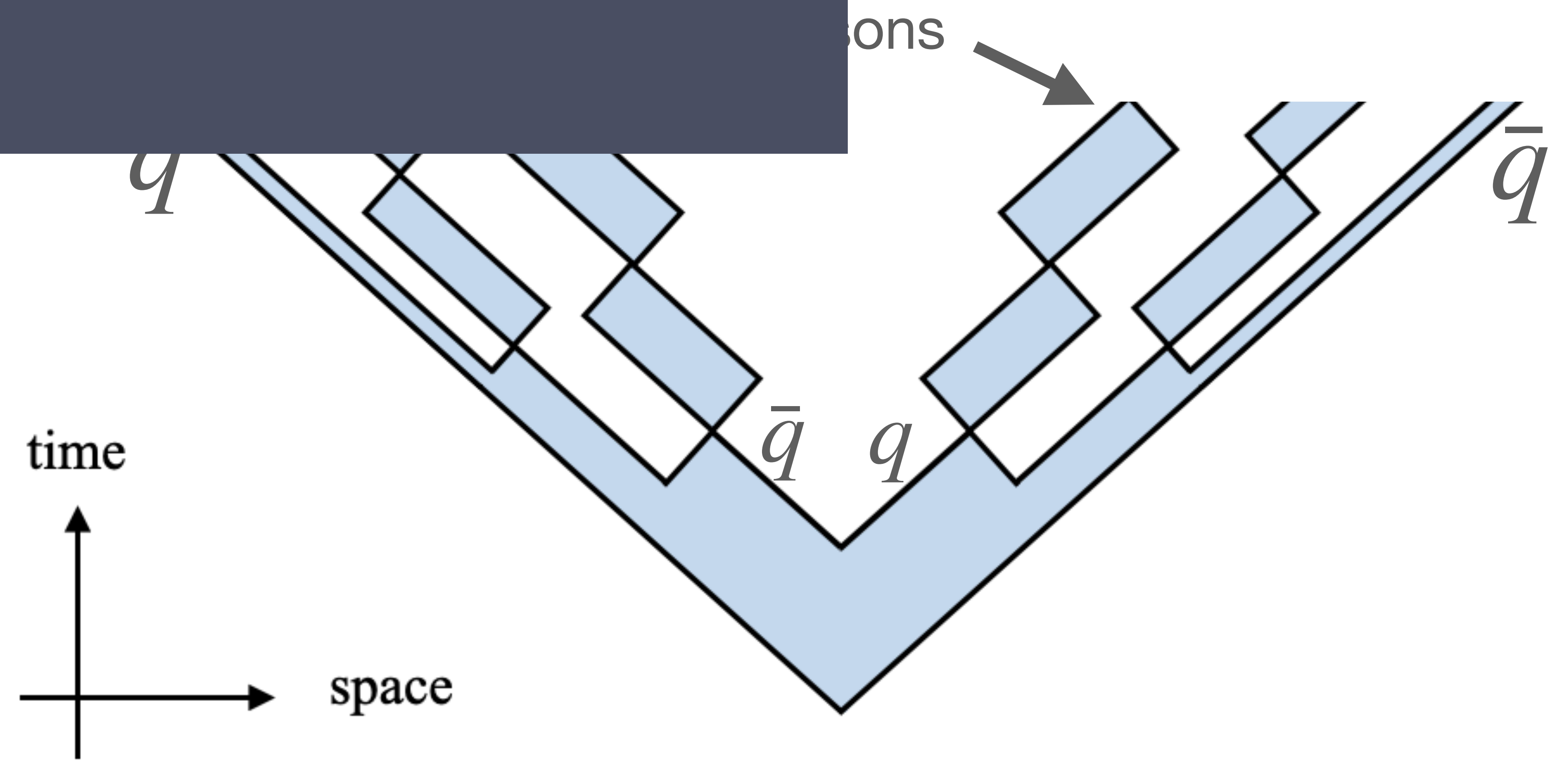
momenta, z

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





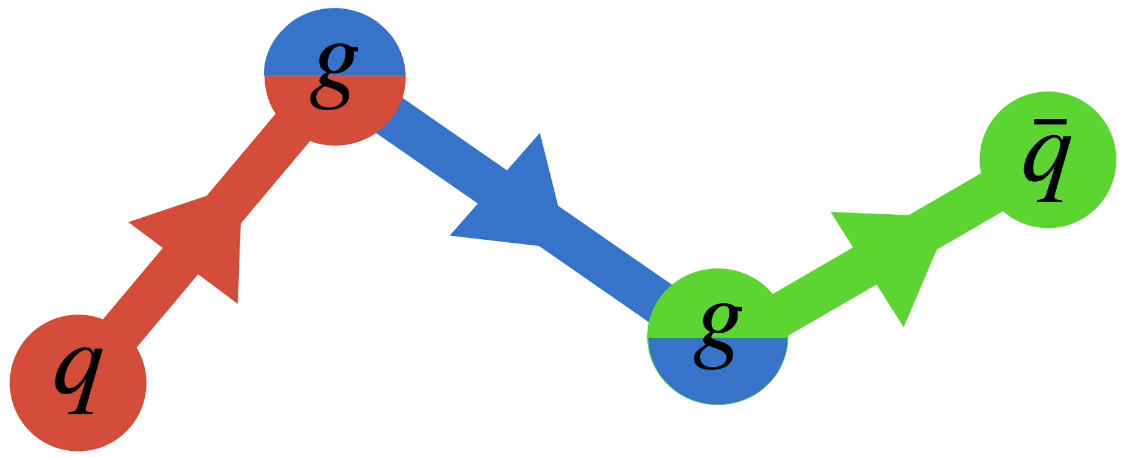
So far we have notion of hadron flavour and momentum
What about colour?

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 :

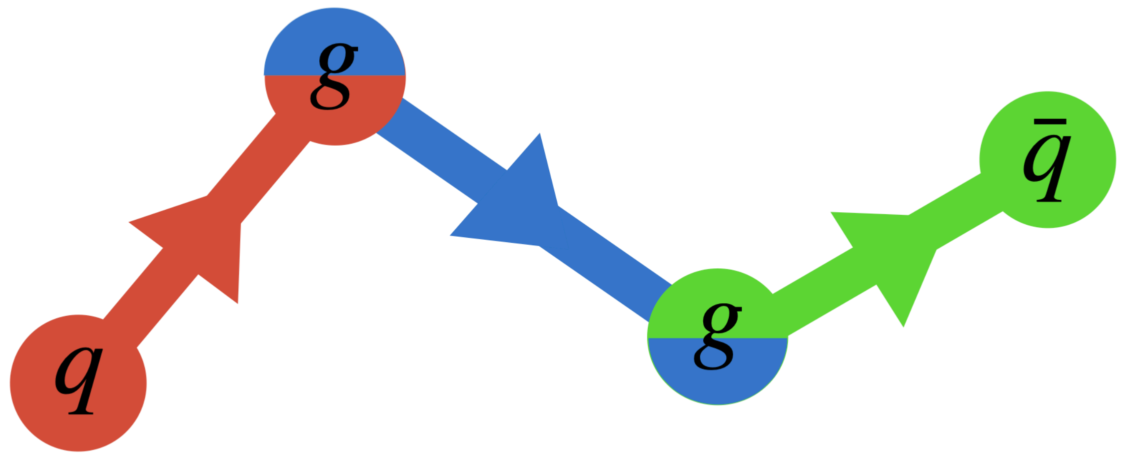
- ➢ Corrections suppressed by $1/N_C^2 \sim 10\,\%$
- ➢ Not much overlap in phase space

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

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

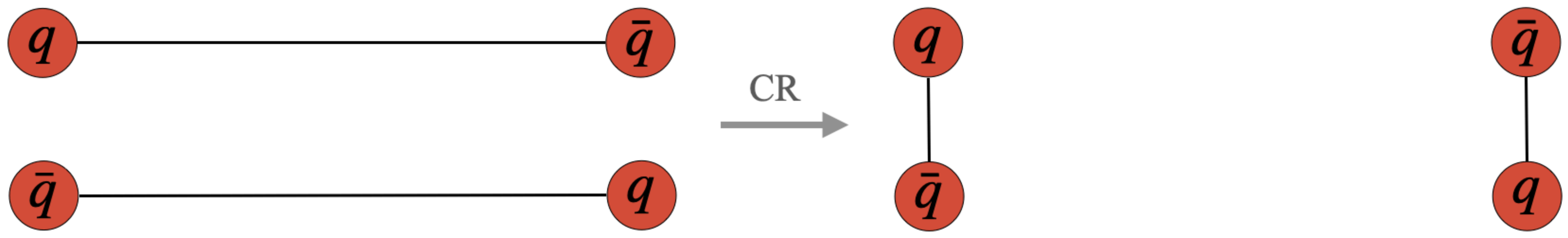
QCD Colour Reconnection (CR) model

QCD Colour Reconnections

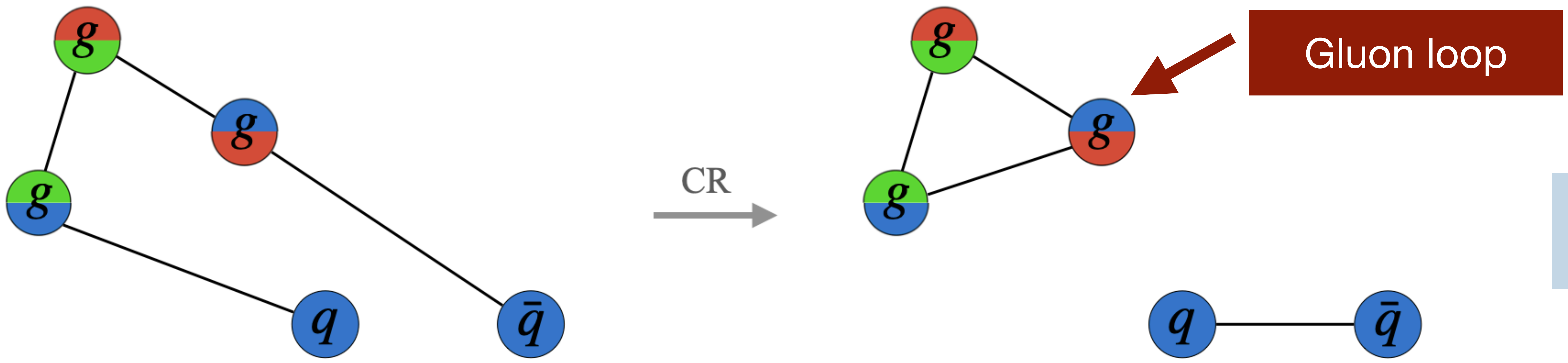
Stochastically restores colour-space ambiguities according to **SU(3) algebra**

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

Colour - anticolour singlet state



Dipole reconnection



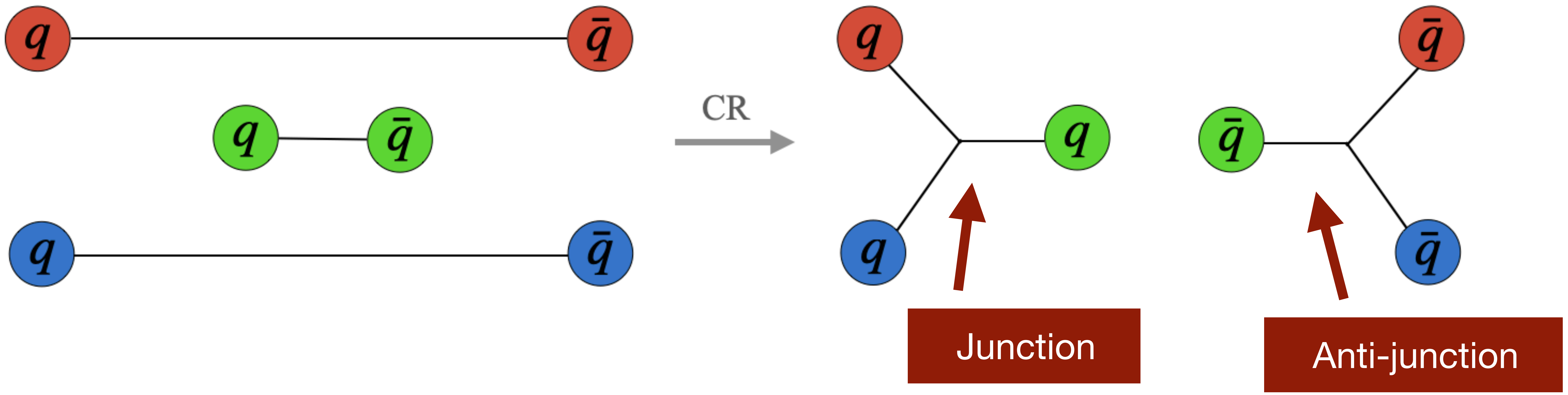
Gluon loop formation

QCD Colour Reconnections

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

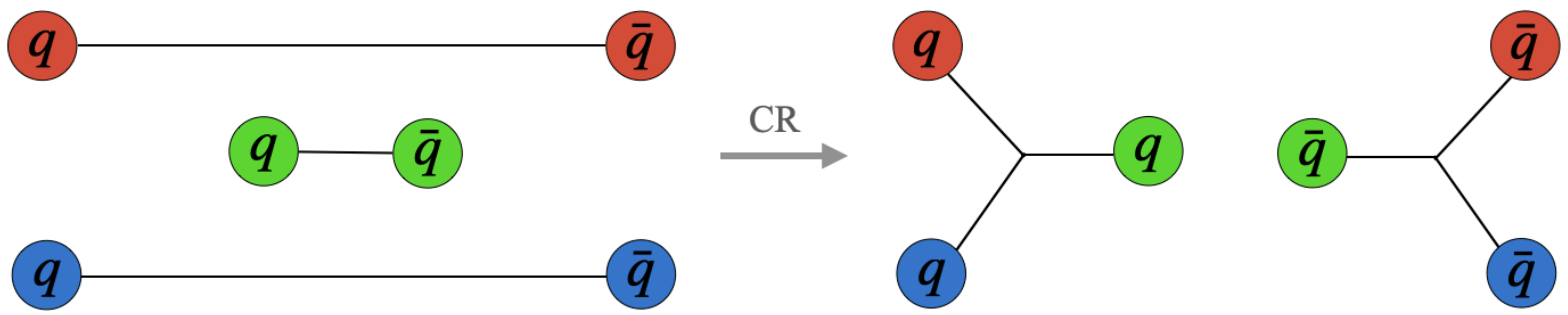
➢ Allows for reconnections to **minimise string lengths**

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



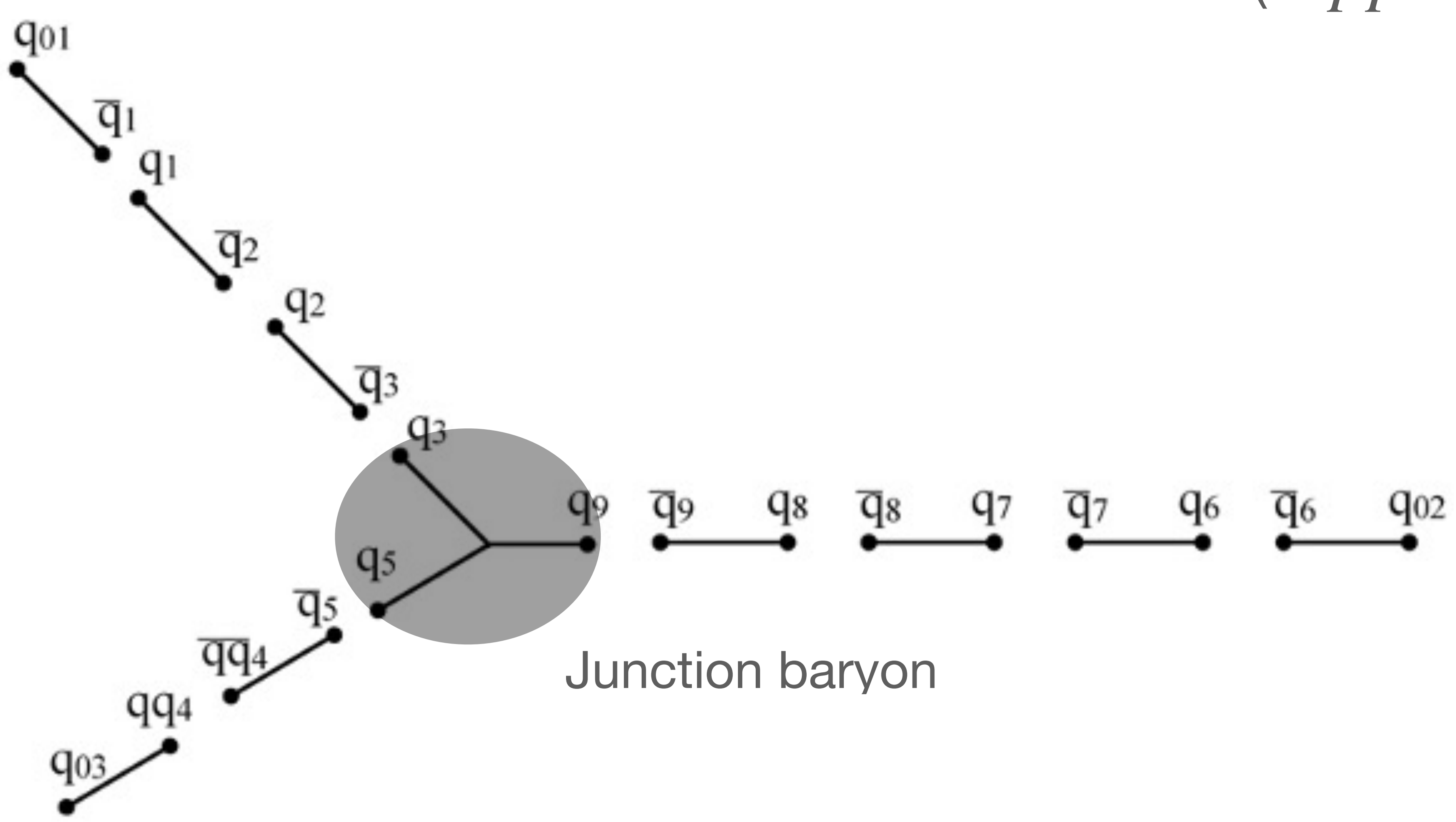
Junction reconnection

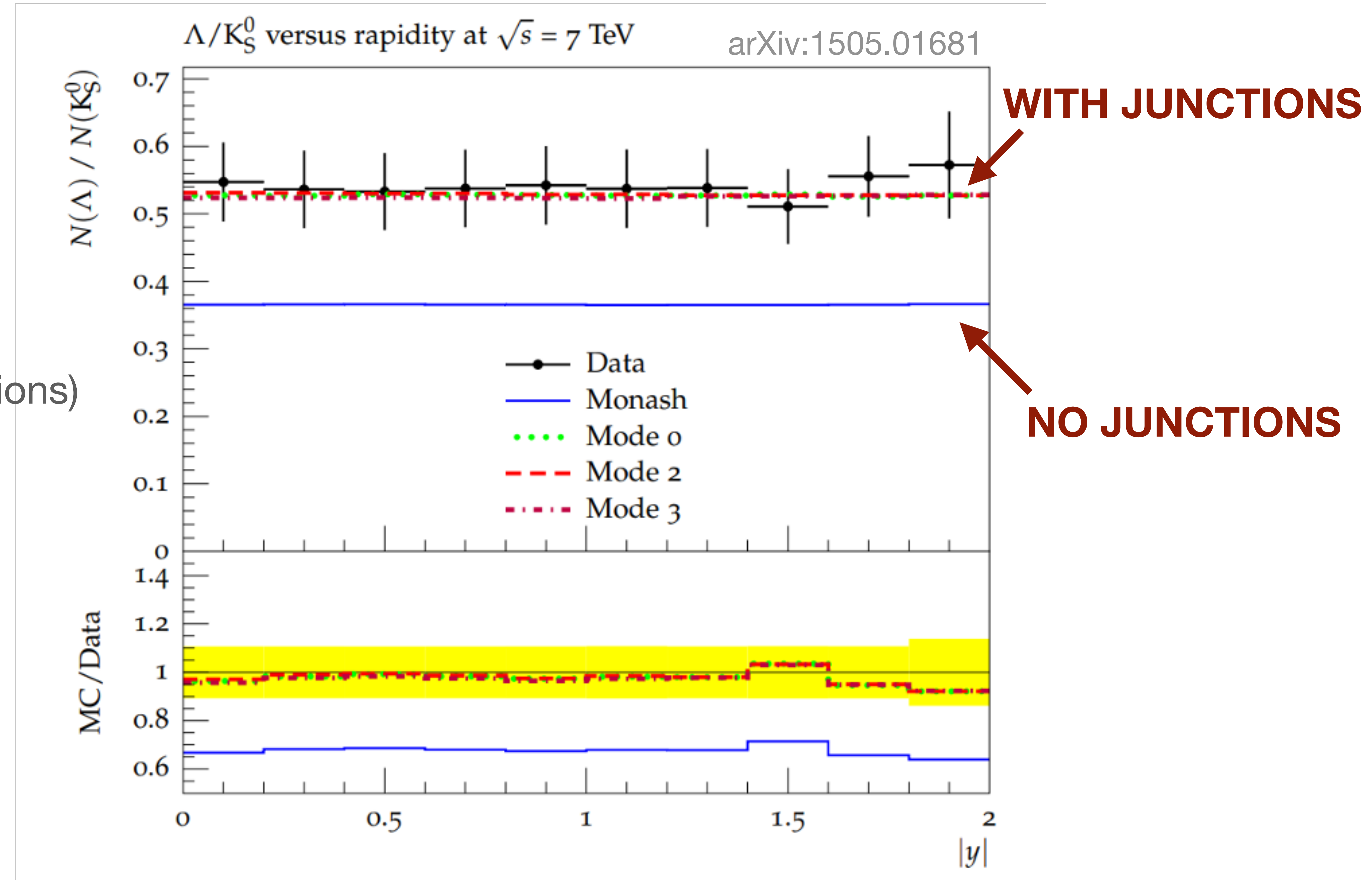
Junctions



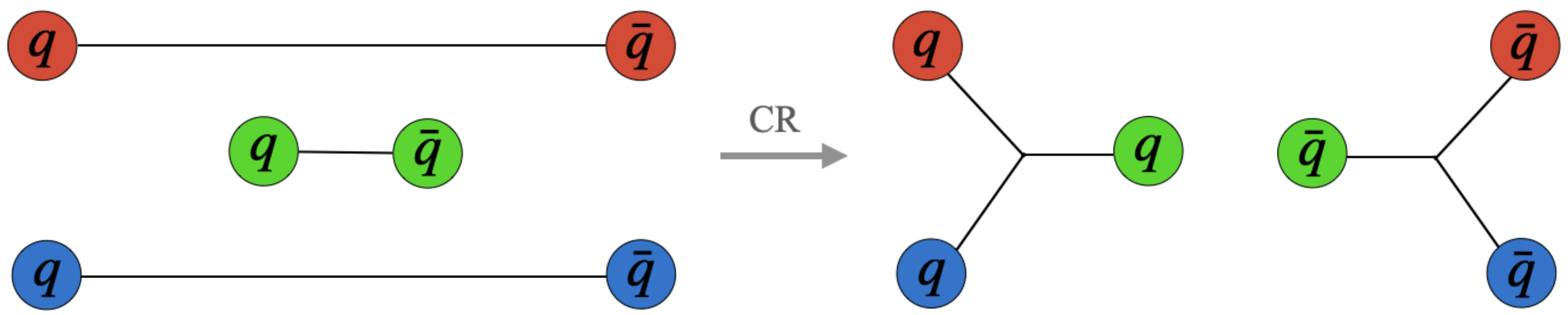
Mechanism for **baryon production**

- ~40% of baryons are from junctions in PYTHIA (in pp collisions)





Junctions



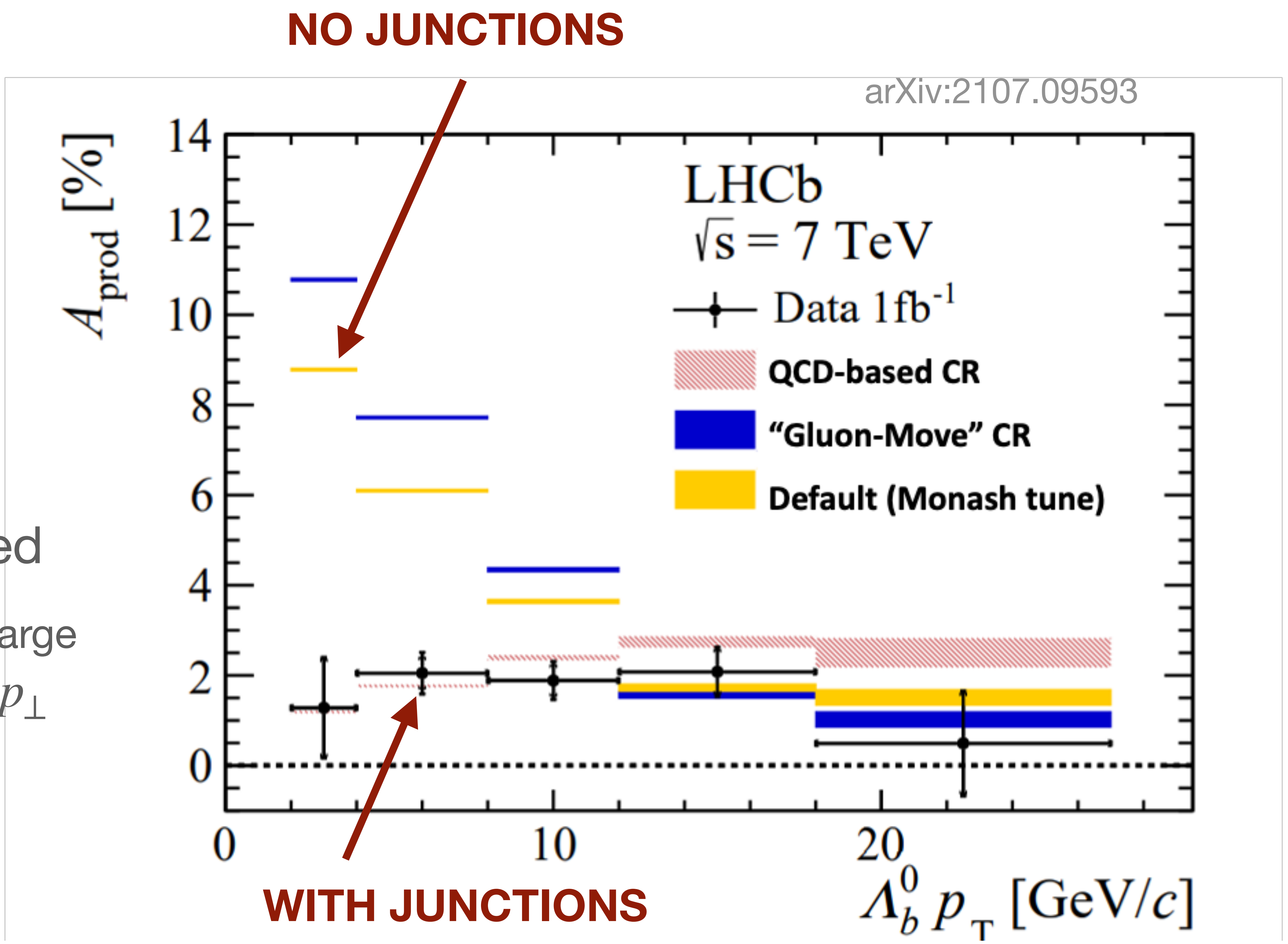
Mechanism for **baryon production**

- ➢ ~40% of baryons are from junctions in PYTHIA

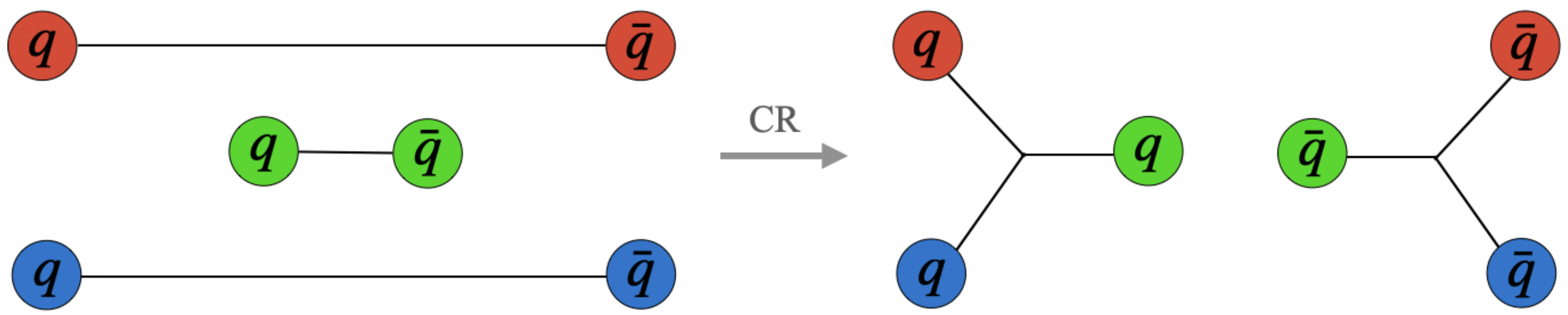
Asymmetries

- ➢ 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** $p_\perp$



Junctions



Mechanism for **baryon production**

- ➢ ~40% of baryons are from junctions in PYTHIA

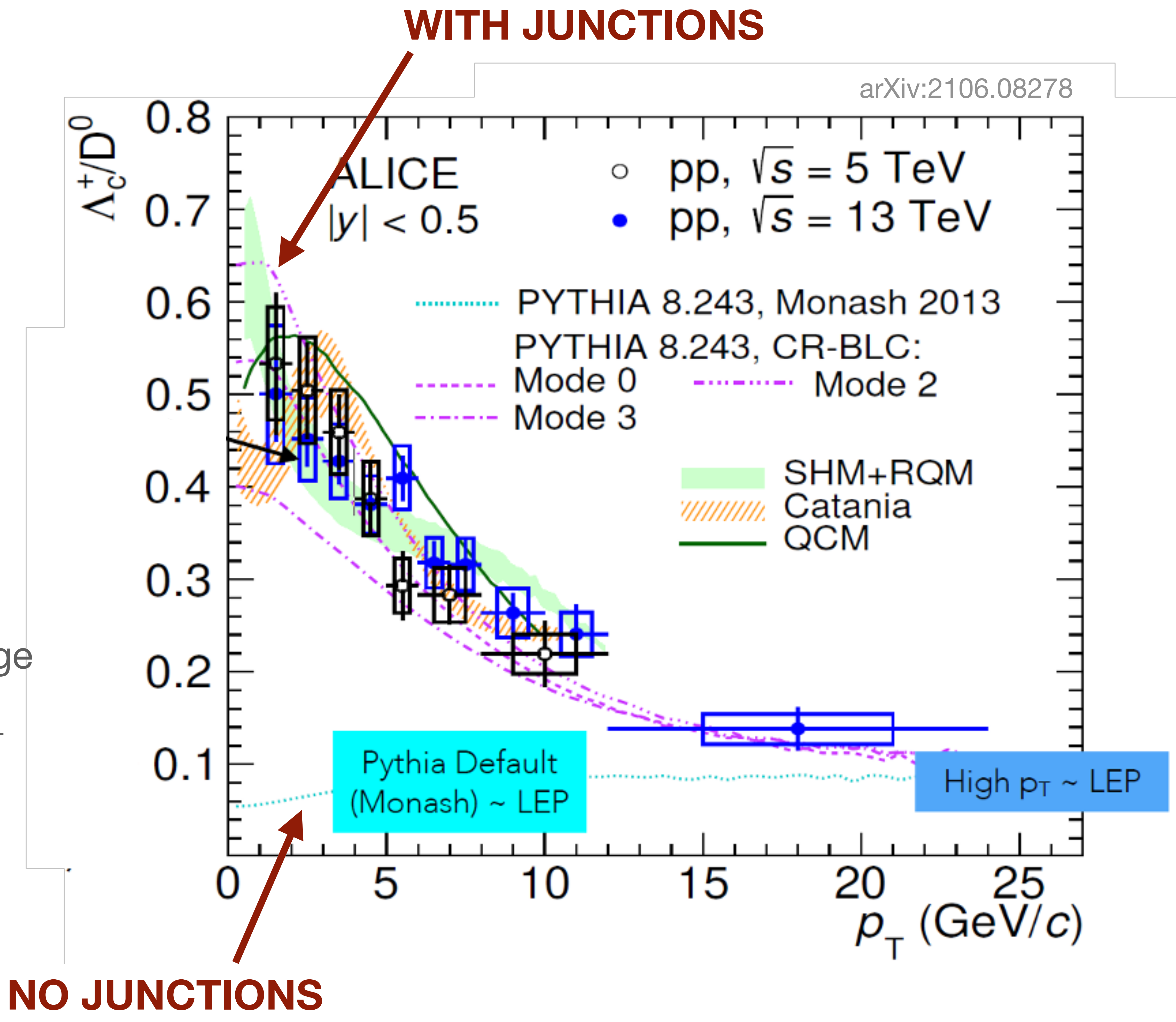
Asymmetries

- ➢ Equal amount of junctions and anti junctions are formed

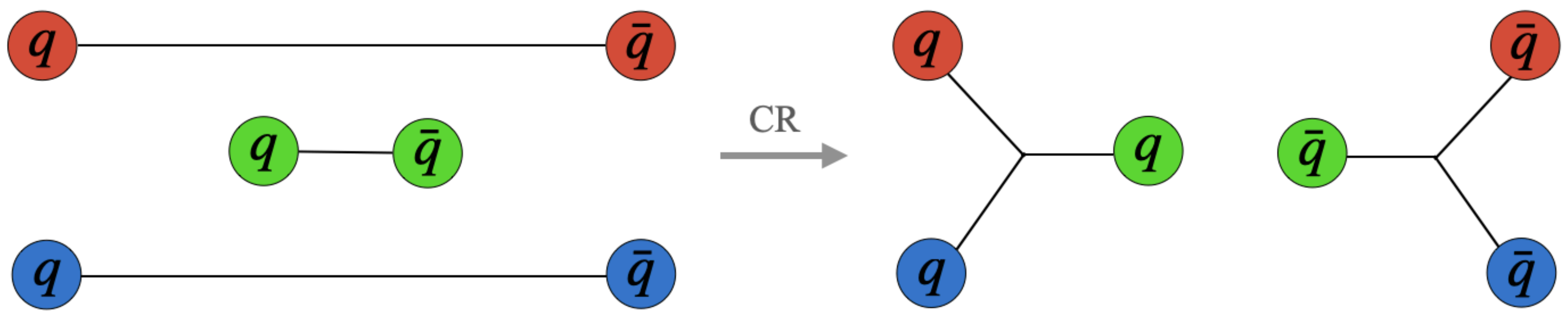
Junctions typically **form between jets** → as jets are likely to have large opening angles due to available phase space, **junction sits at low $p_{\perp}$**

Heavy flavour baryons

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



Junctions



Mechanism for **baryon production**

➢ ~40% of baryons are from junctions in PYTHIA

Asymmetries

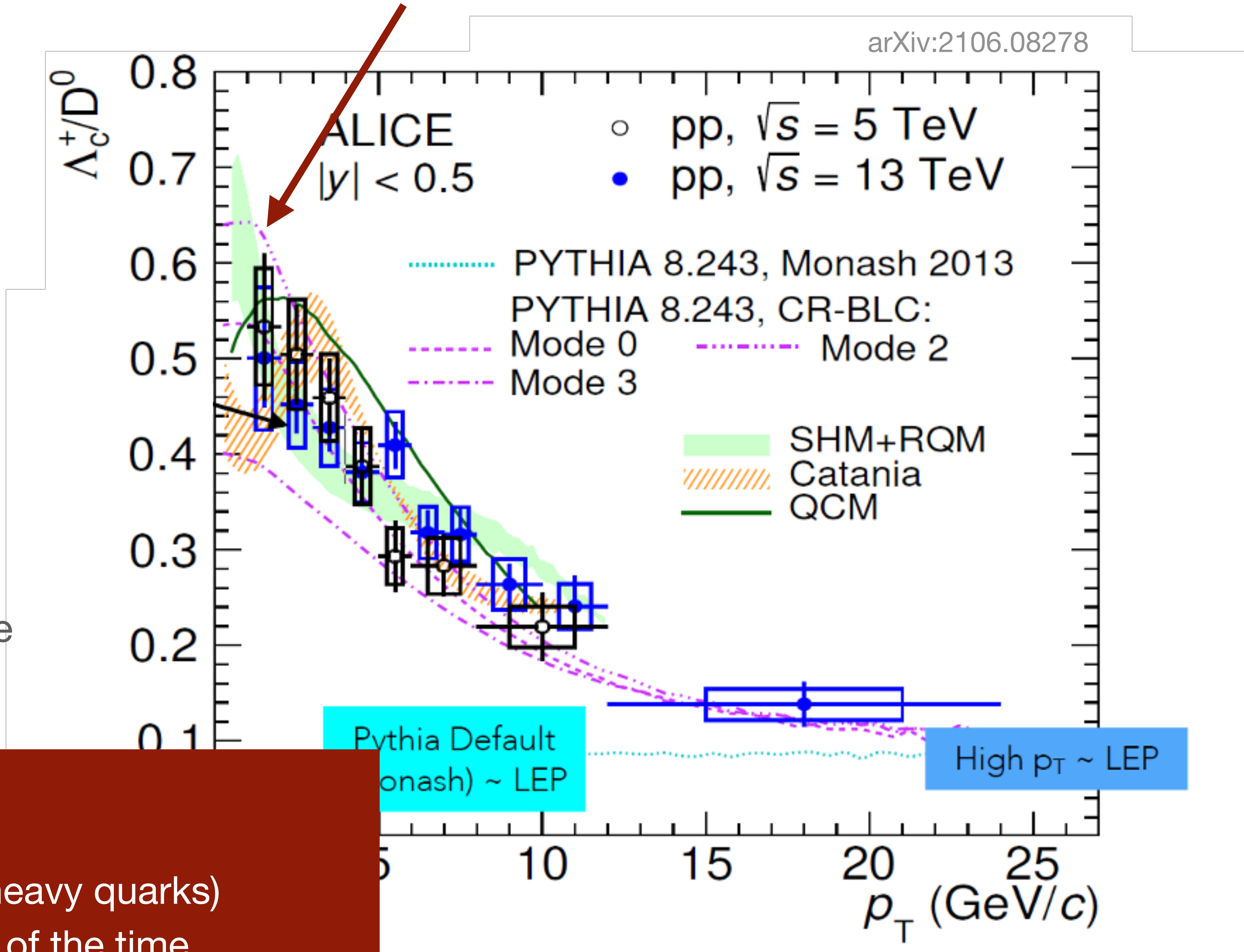
➢ Equal amount of junctions and anti junctions are formed

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

Heavy flavour ba

➢ **~70% of hea**

WITH JUNCTIONS



Current implementation

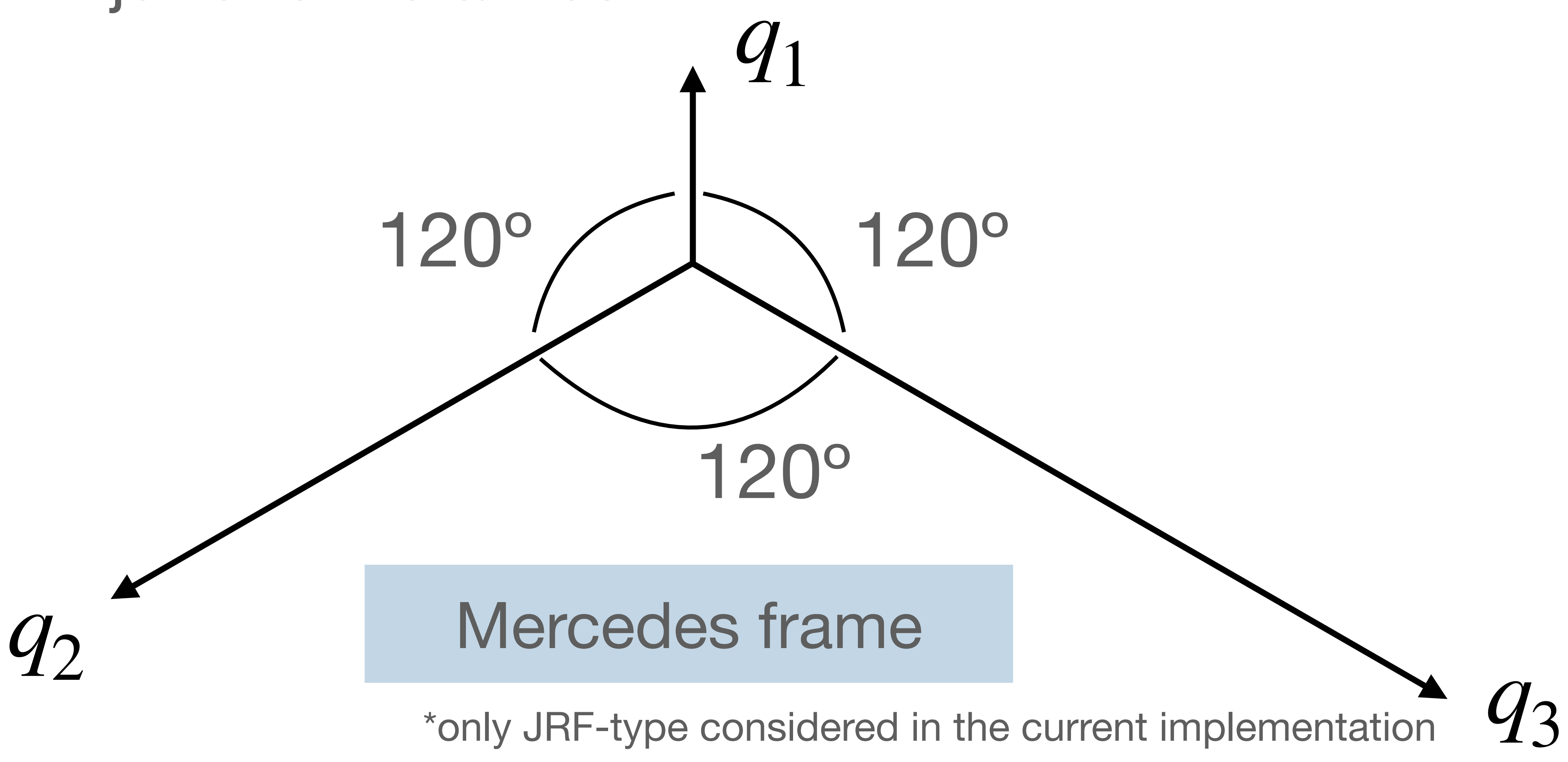
➢ Runs into cases with no solution (particularly for heavy quarks)

➢ 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



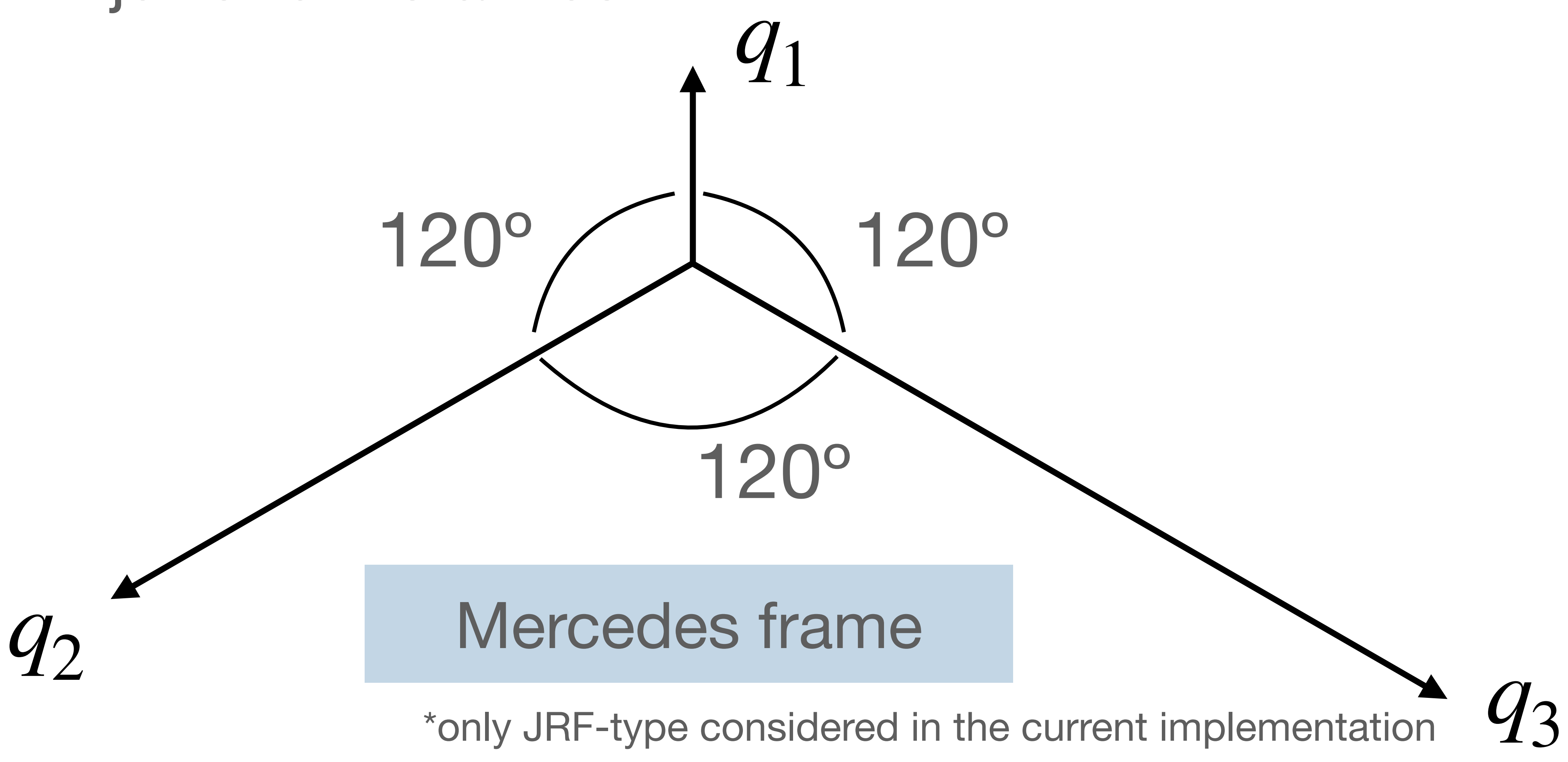
Mercedes frame

*only JRF-type considered in the current implementation

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



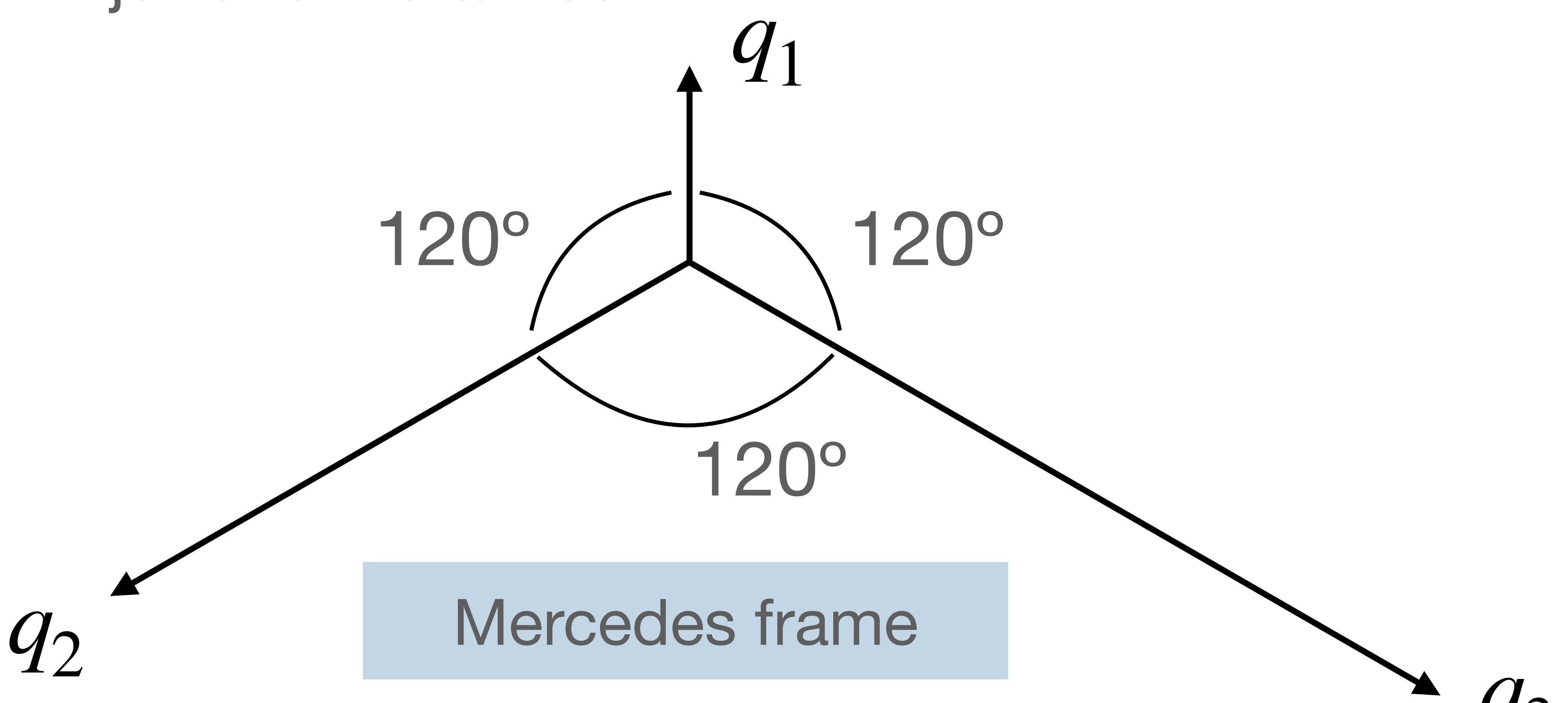
*only JRF-type considered in the current implementation

Does a boost to the mercedes frame always exist?

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



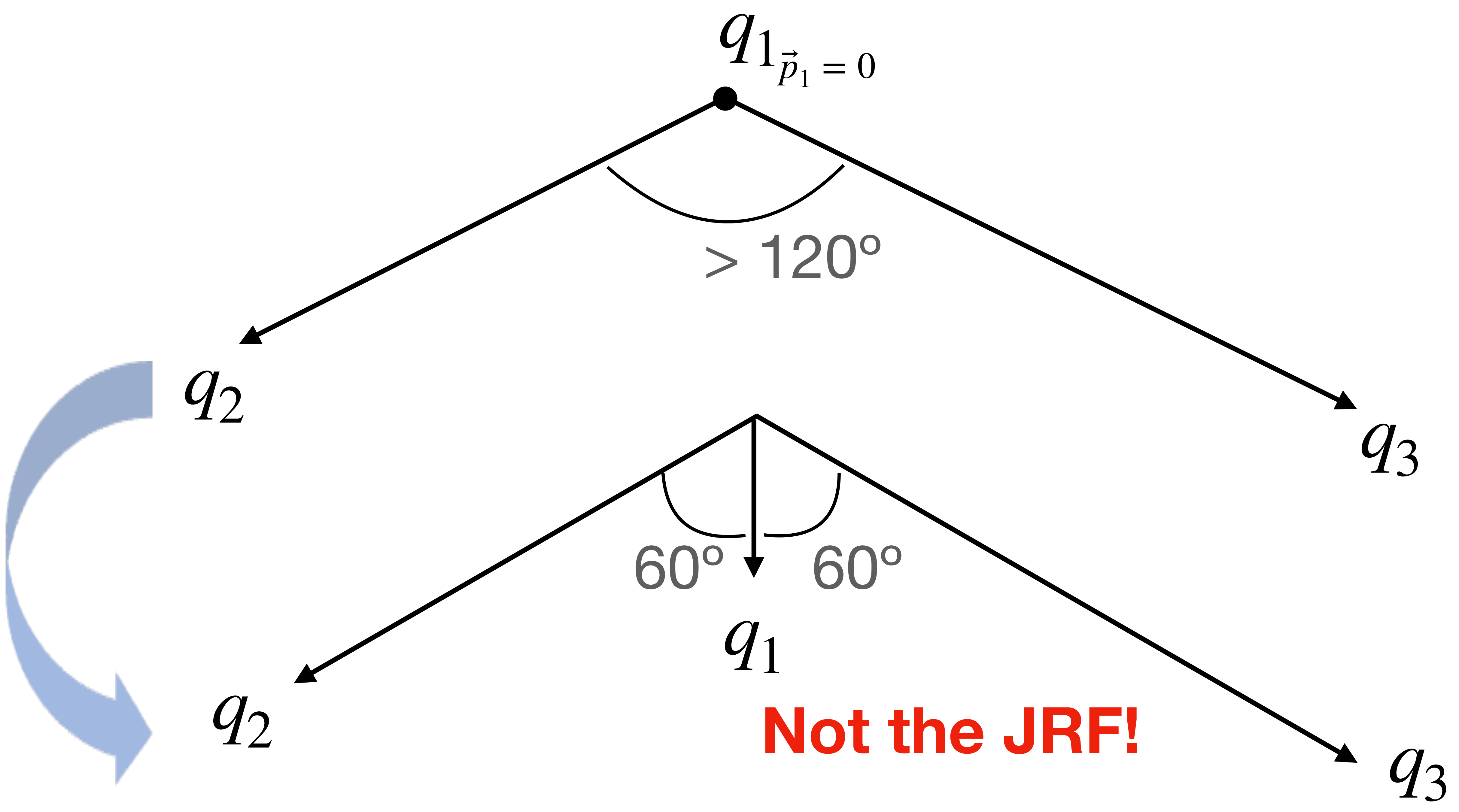
*only JRF-type considered in the current implementation

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

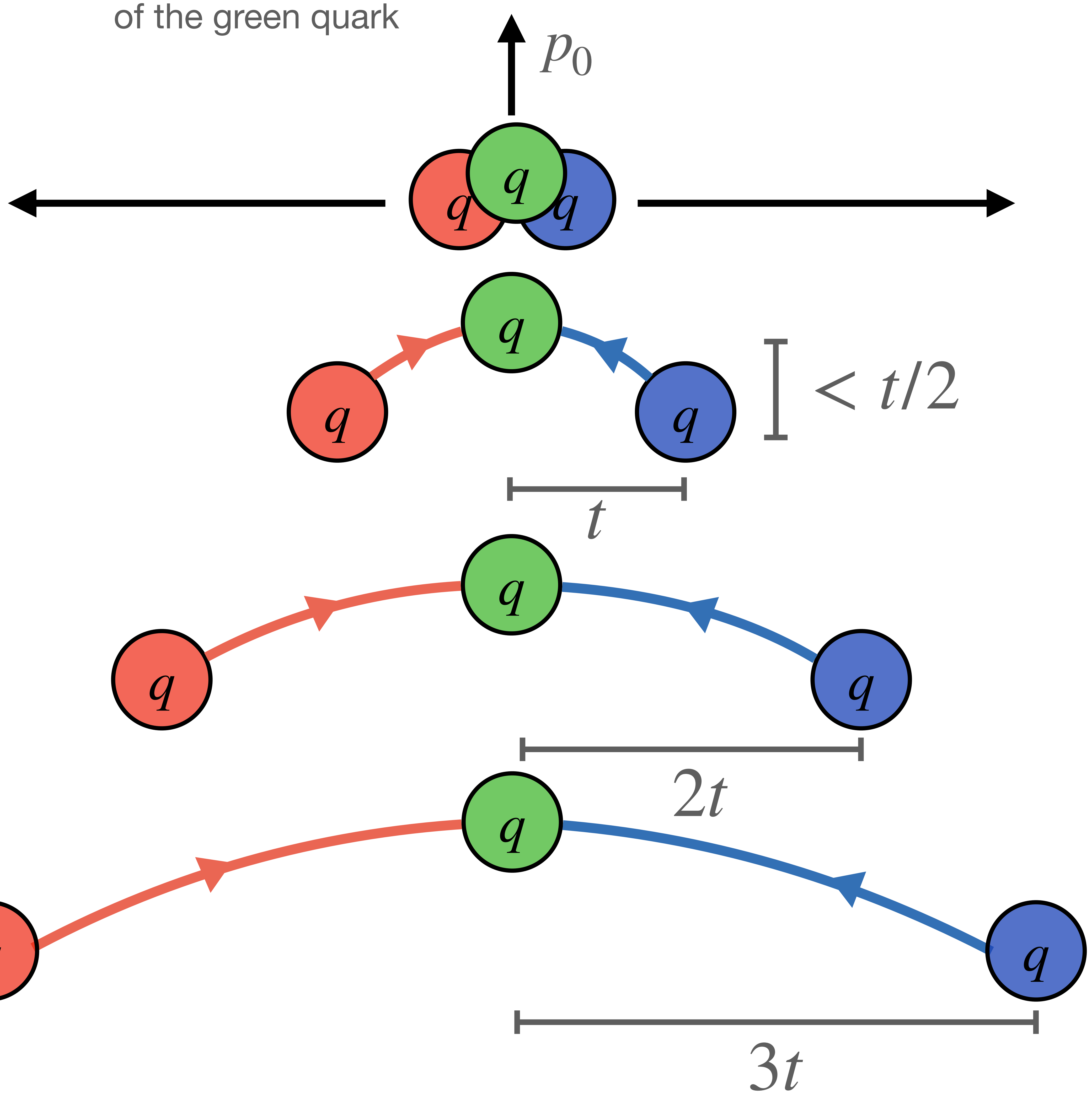


Pearl-on-a-string

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



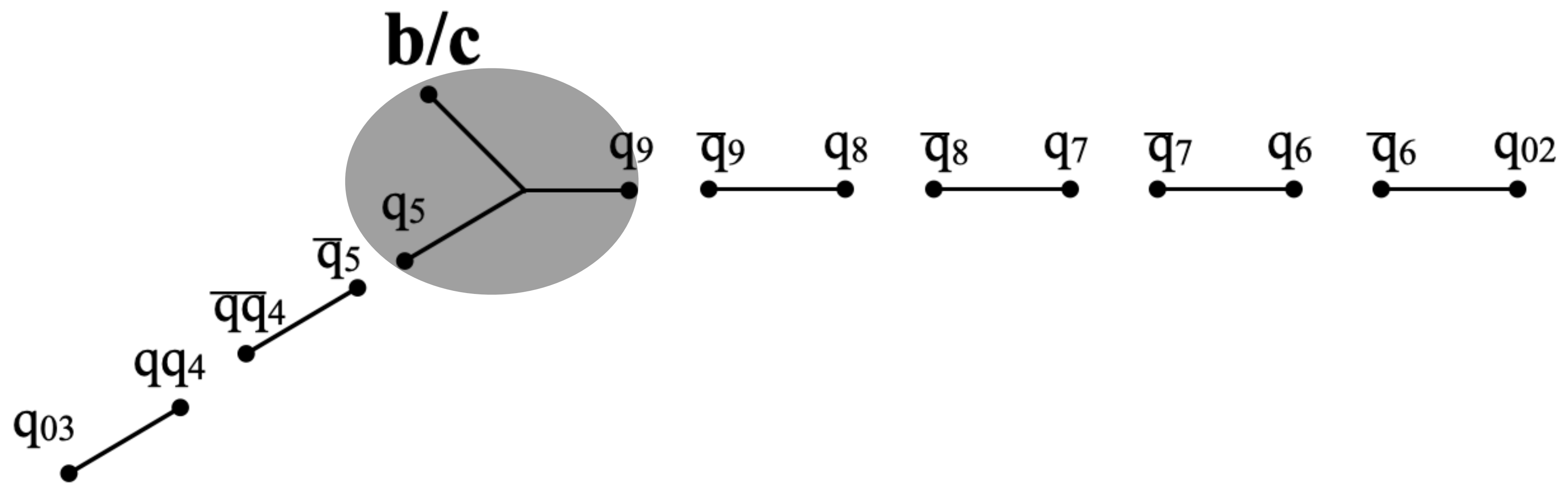
Special thanks to Gösta Gustafson

Pearl-on-a-string

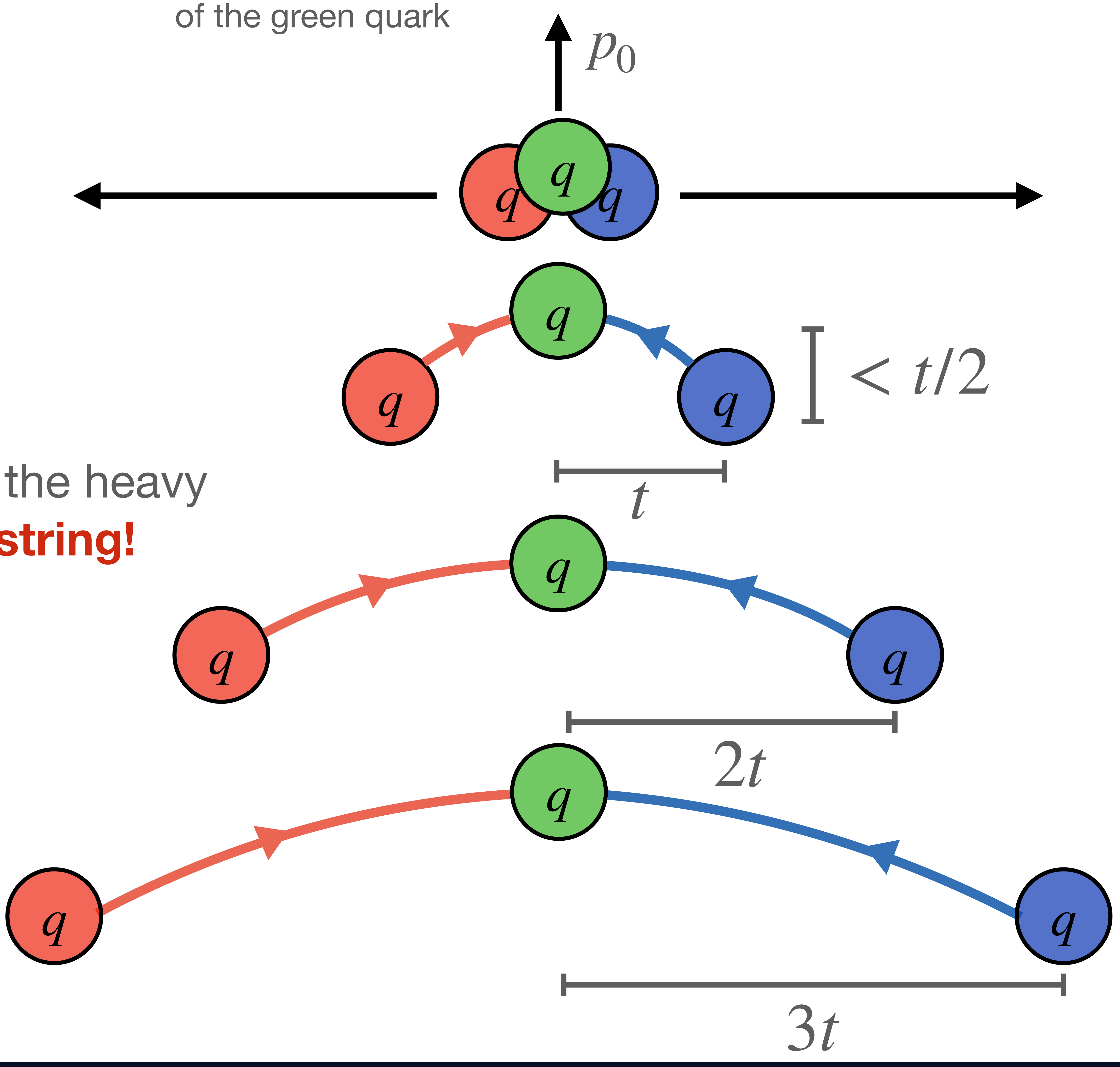
The **junction gets "stuck"** to the soft quark, which we call a **pearl-on-a-string**

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

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!**

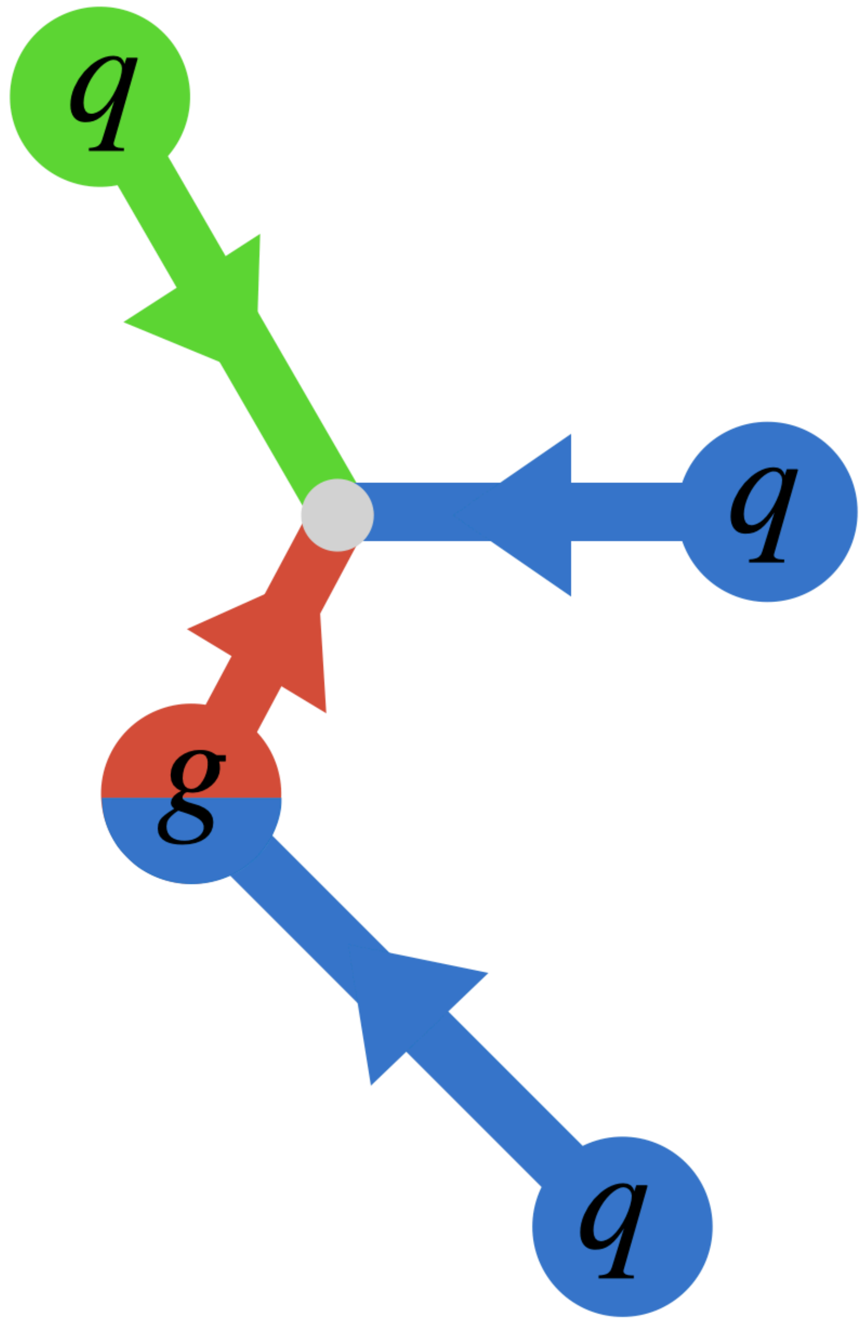


Example of pearl-on-a-string viewed in the Ariadne frame of the green quark



Special thanks to Gösta Gustafson

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

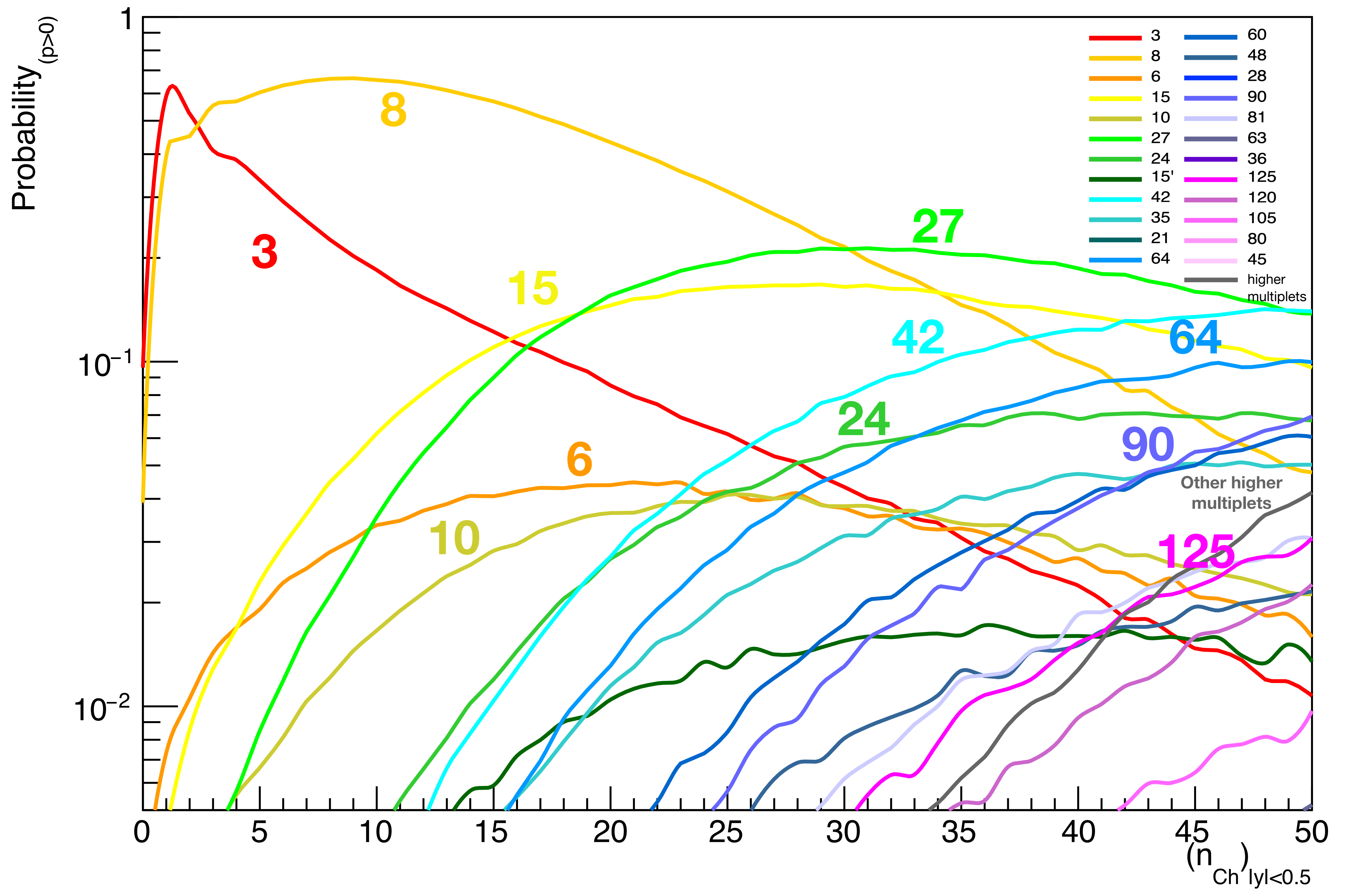
What about strange baryons?

Junctions

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

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

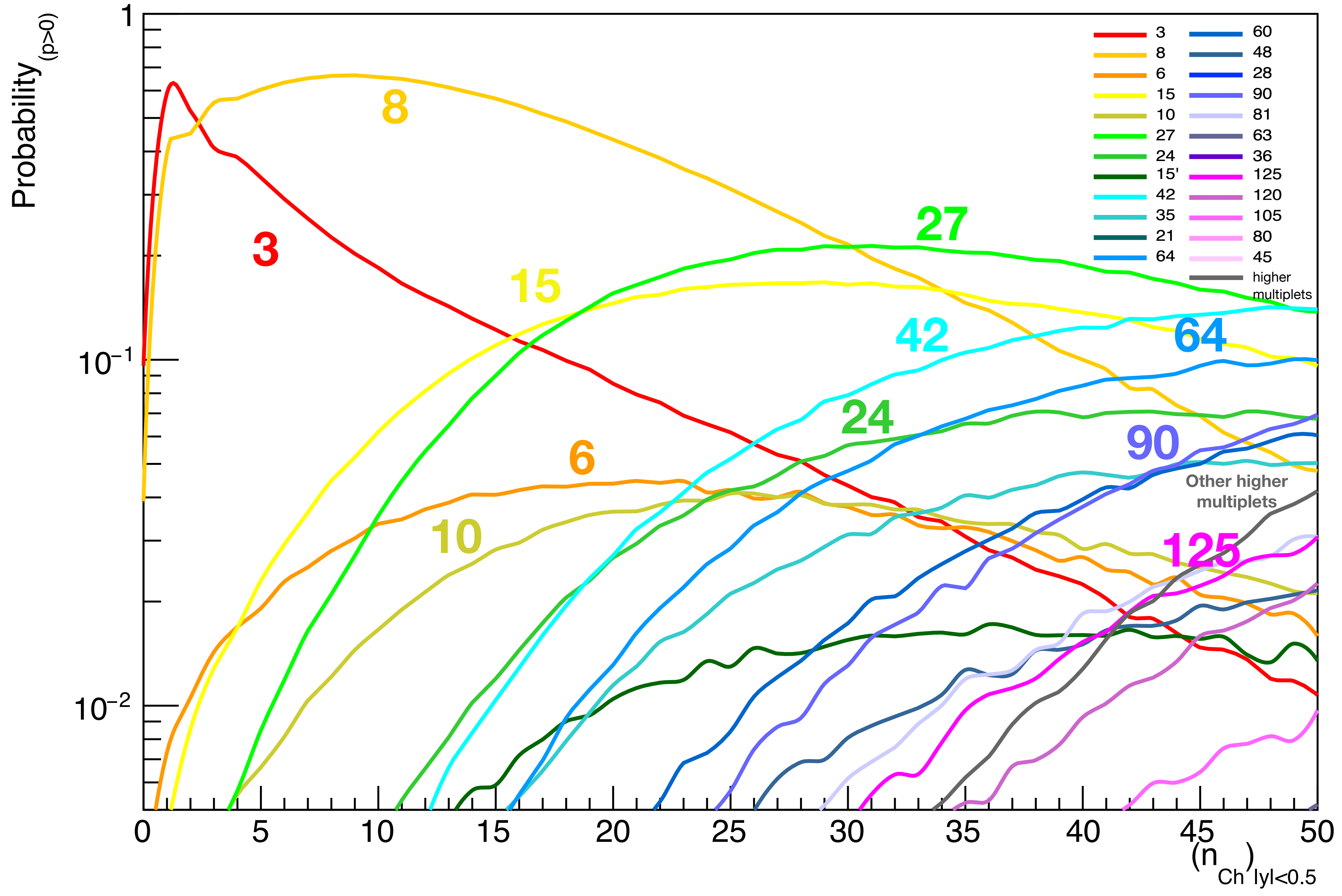
Strangeness enhancement with charged multiplicity suggests **higher multiplicity** string systems act **different to the vacuum case**

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

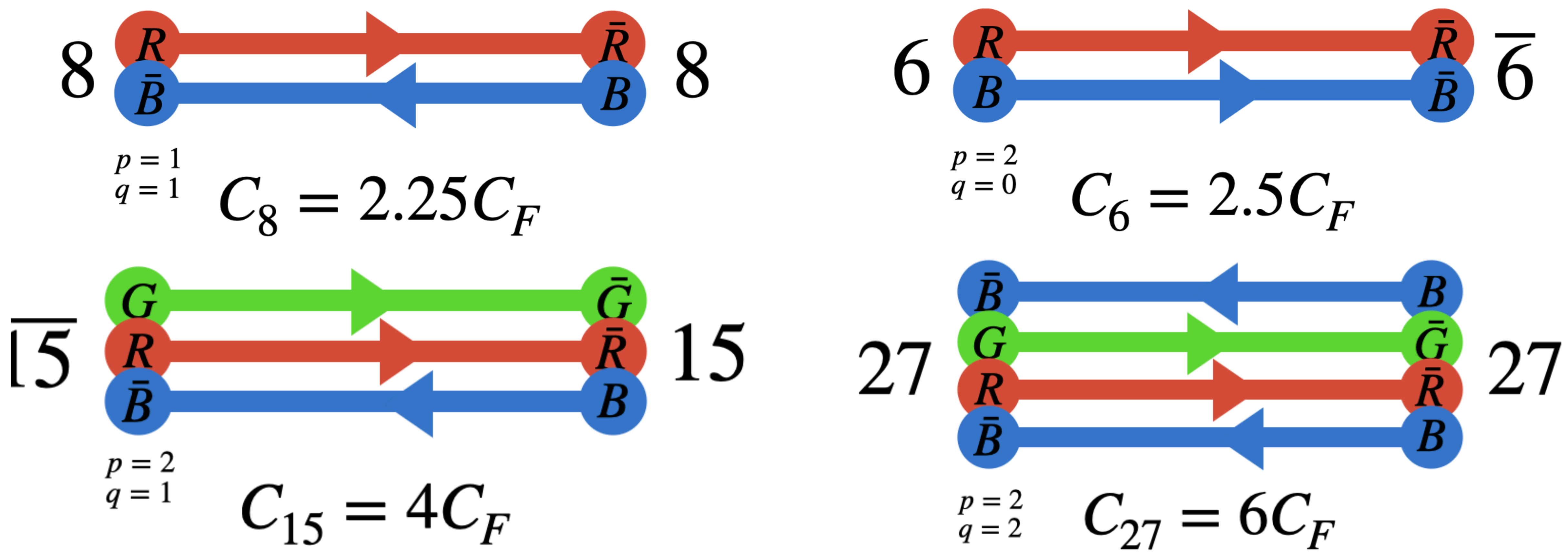
Strangeness Enhancement

Multiplets (y=0, pp 7 TeV)



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

Close-packing + Ropes



Dense string environments

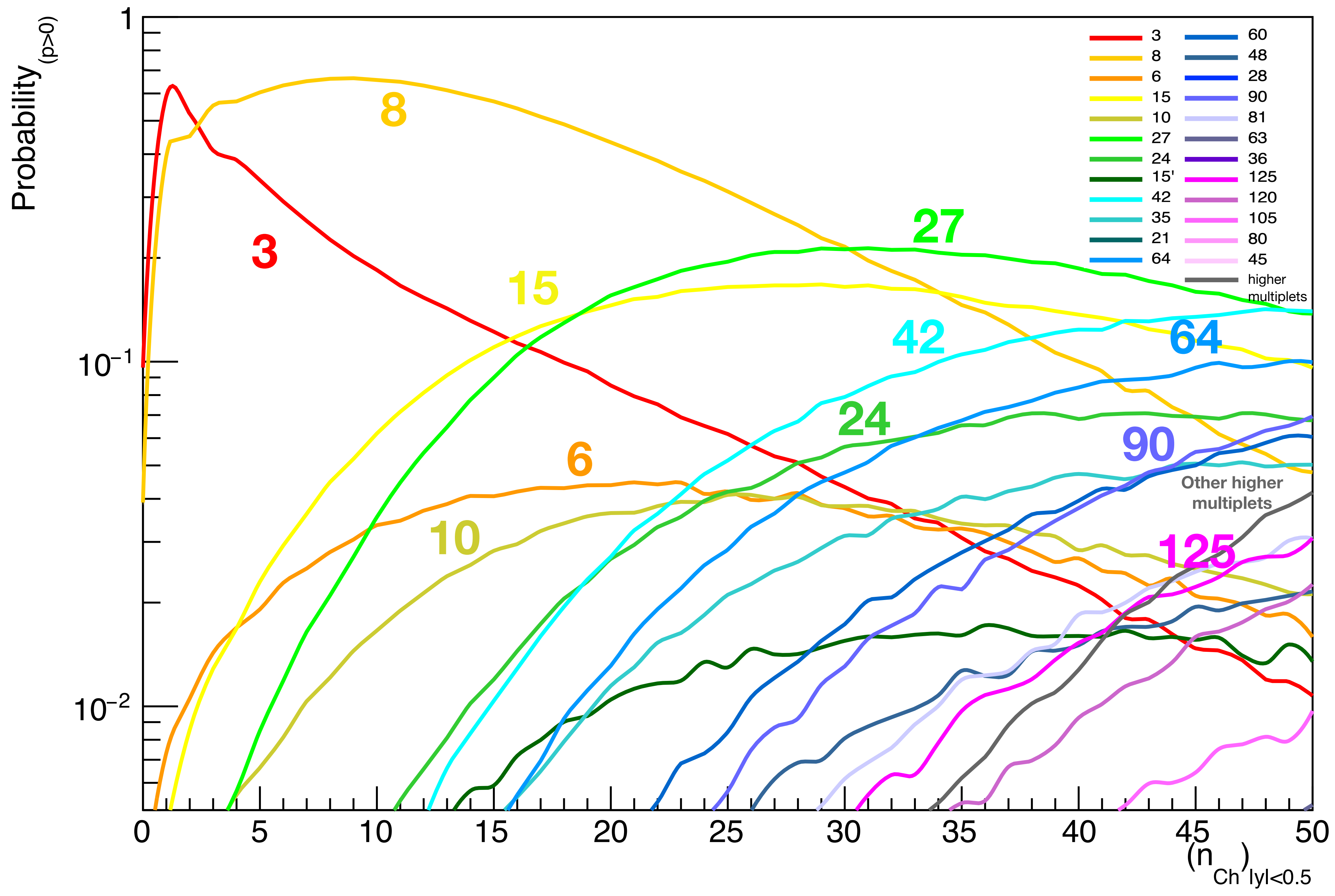
→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

For a given string, the collective of surrounding strings provides an **effective background**

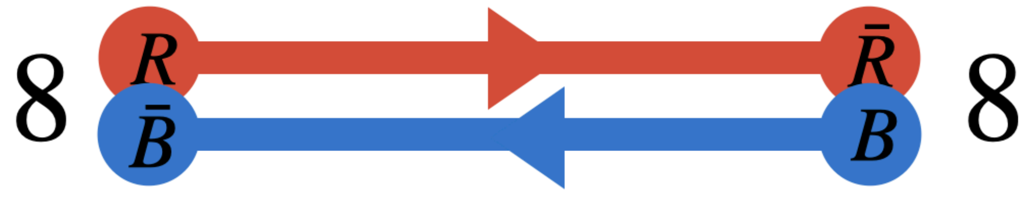
Strangeness Enhancement

Multiplets (y=0, pp 7 TeV)



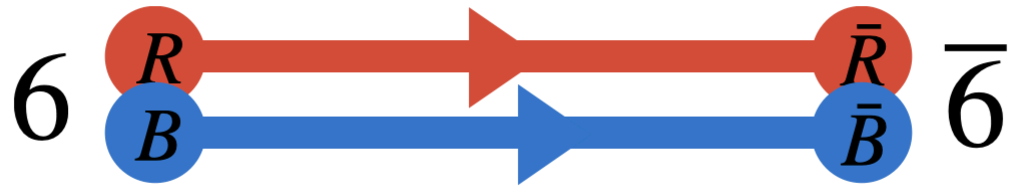
Clear observations of strangeness enhancement with respect to charged multiplicity [e.g. ALICE Nature Pays. 13, 535 (2017)]

Close-packing + Ropes



$p = 1$
$q = 1$

$C_8 = 2.25 C_F$



$p = 2$
$q = 0$

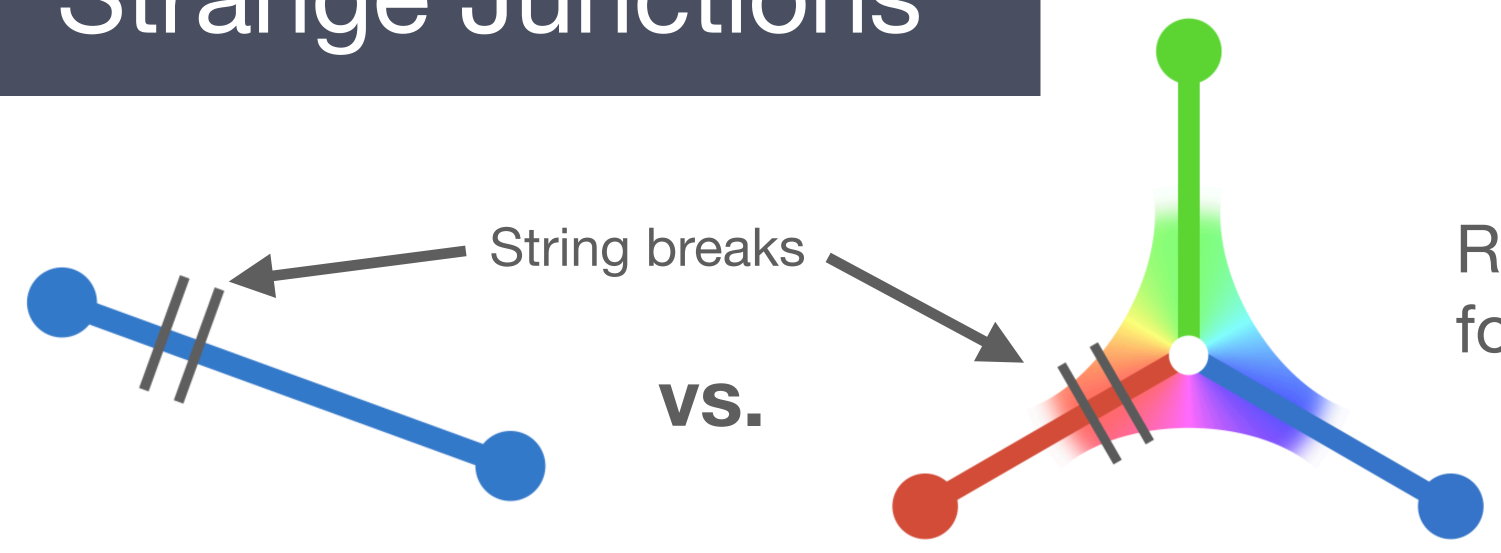
$C_6 = 2.5 C_F$

Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

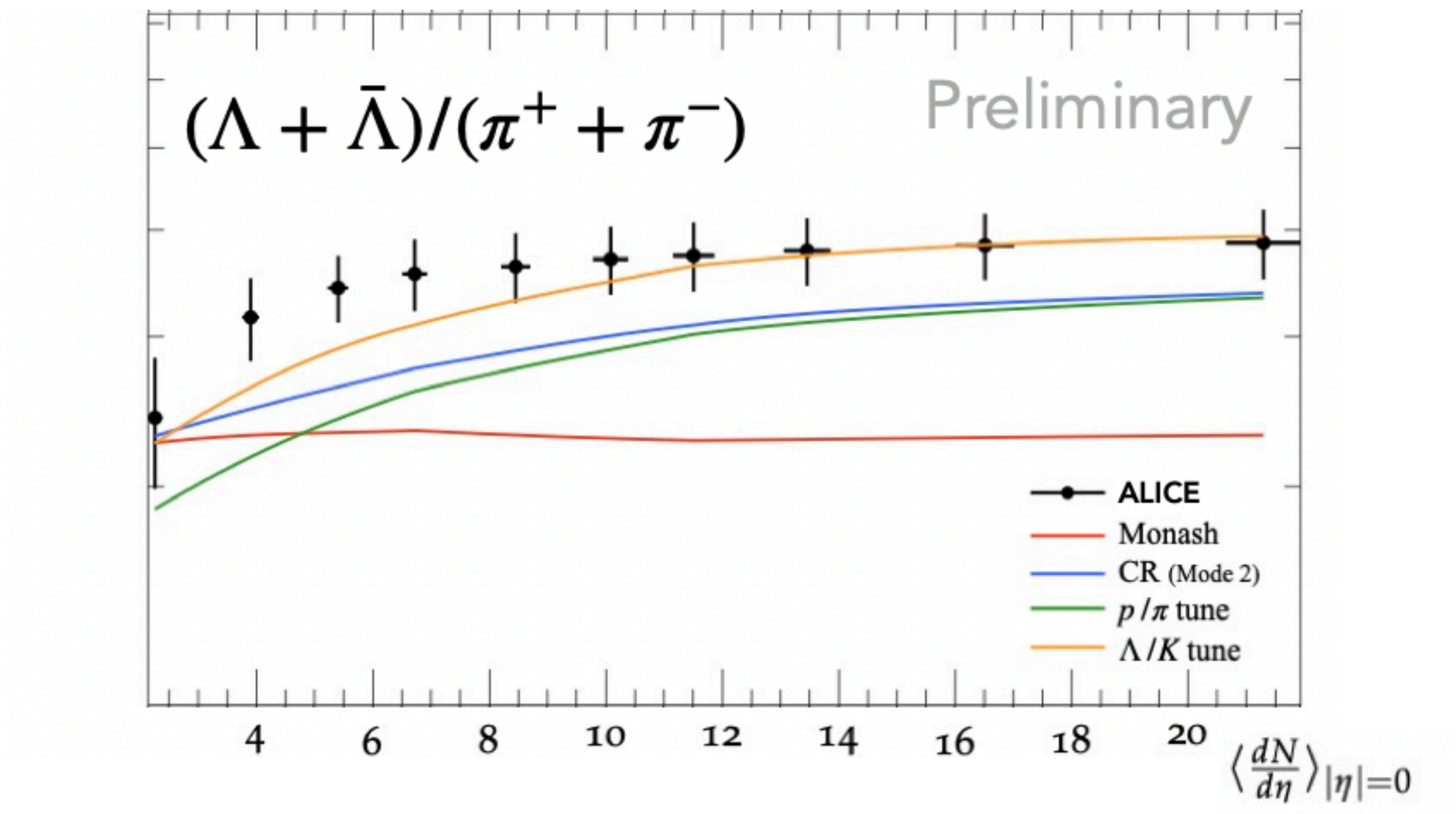
Strange Junctions

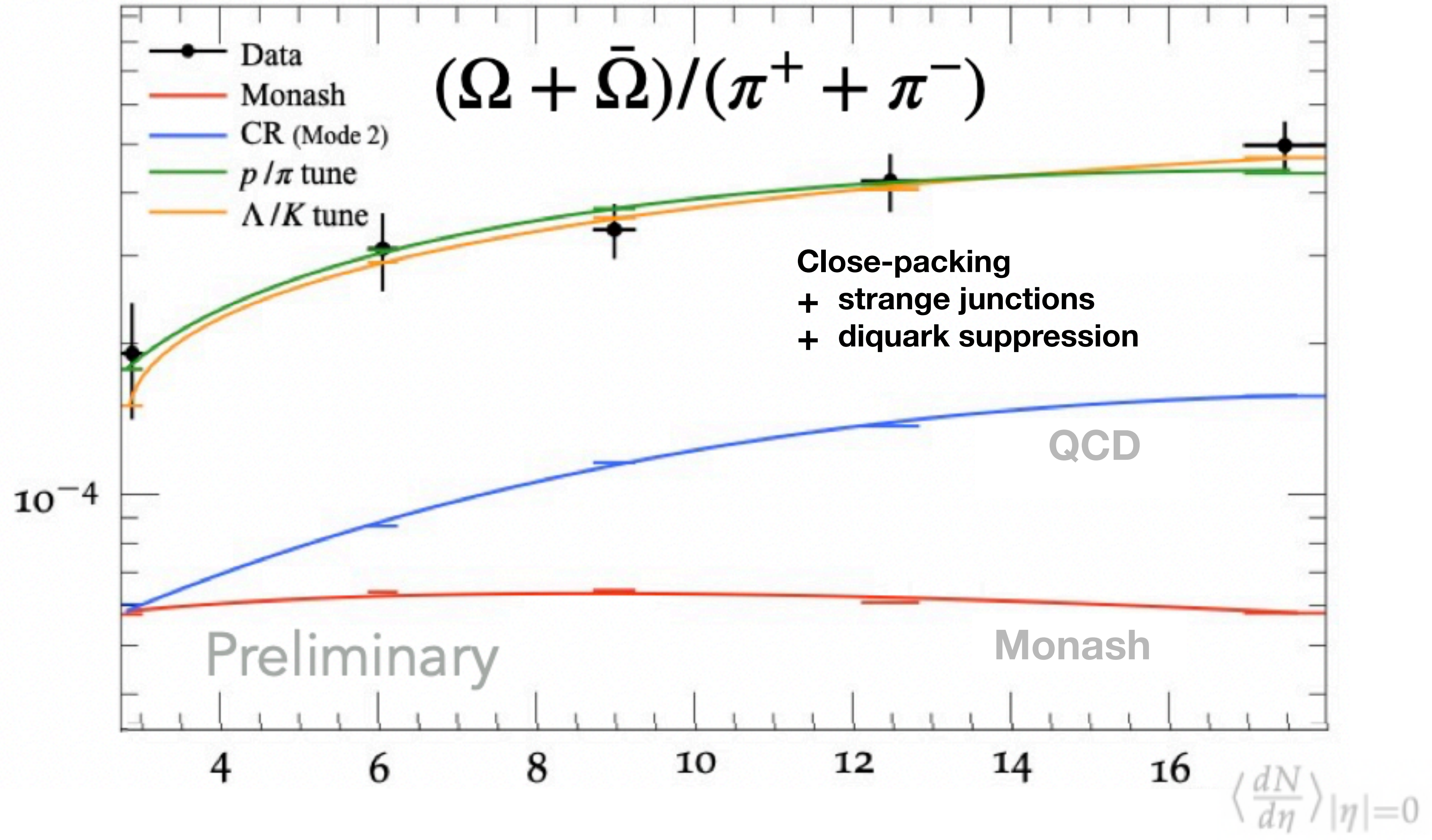


Results in strangeness enhancement focused in baryon sector

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

Strangeness Enhancement





Close-packing + Ropes

$p = 1$, $q = 1$: $C_8 = 2.25C_F$

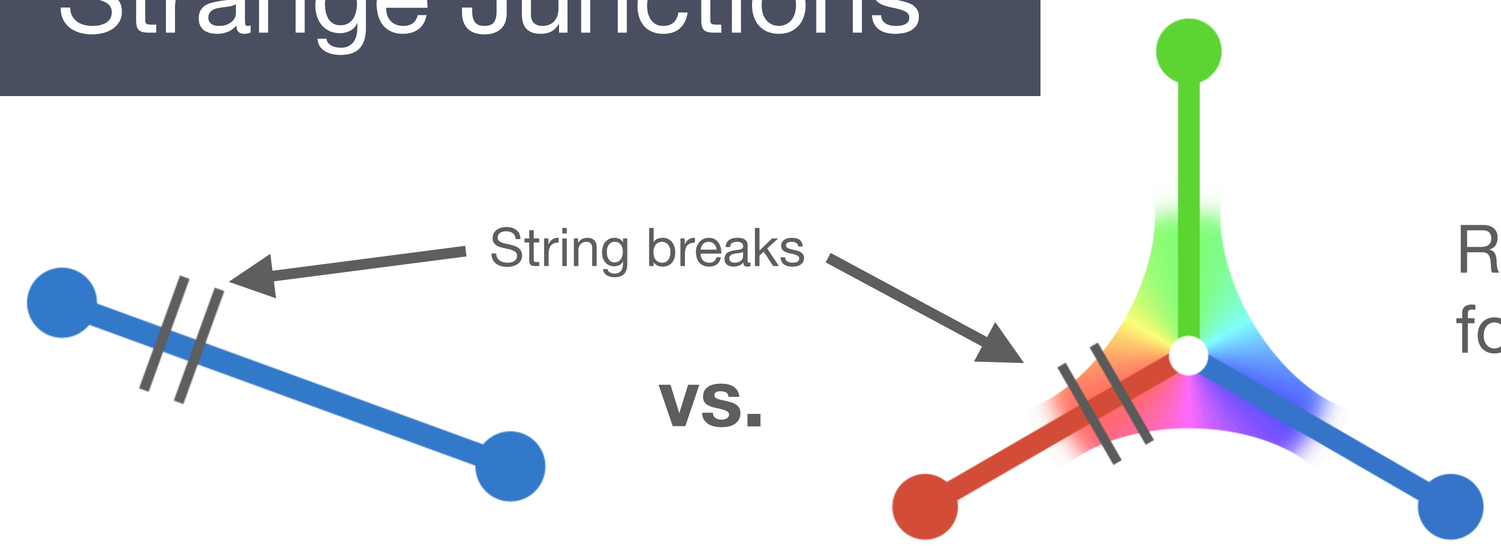
$p = 2$, $q = 0$: $C_6 = 2.5C_F$

Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

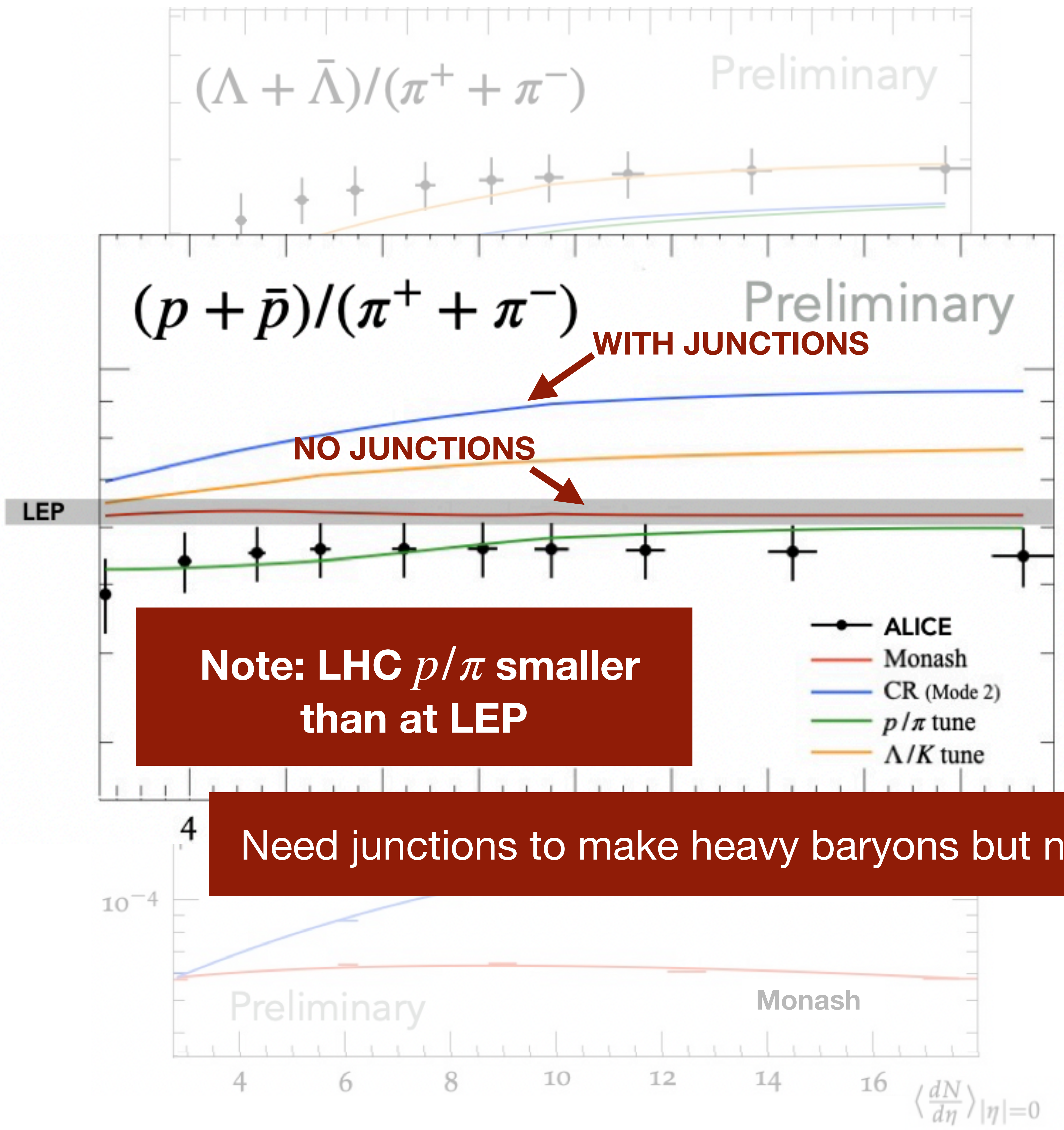
Strange Junctions



Results in strangeness enhancement focused in baryon sector

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

Strangeness Enhancement



Note: LHC p/π smaller than at LEP

Need junctions to make heavy baryons but need less protons?

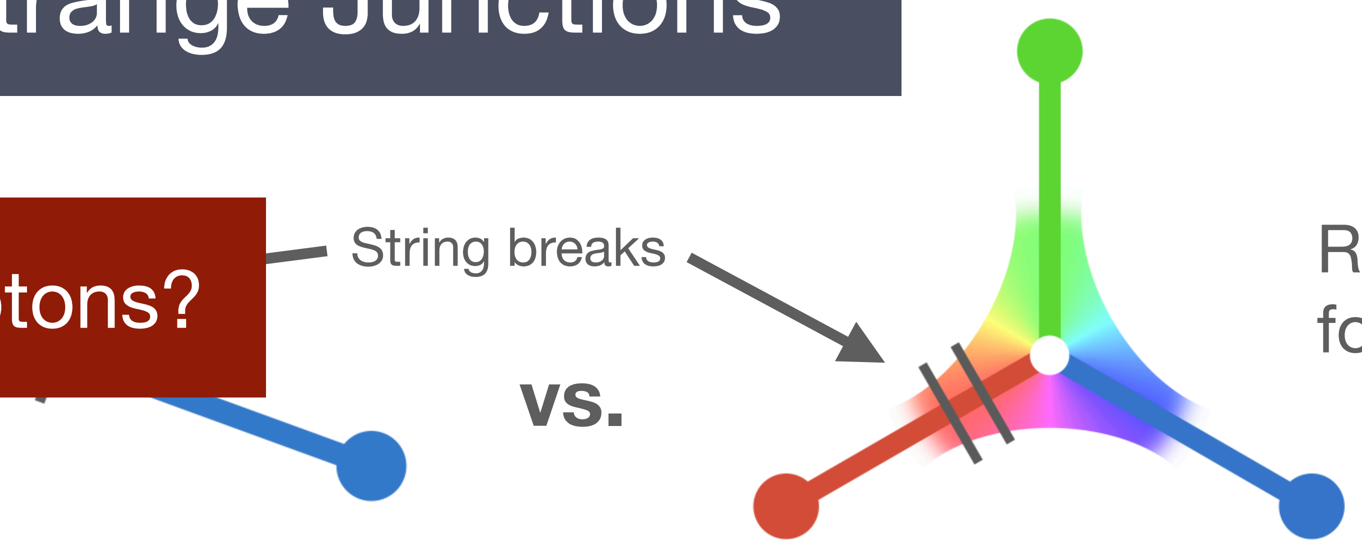
Close-packing + Ropes

Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

Strange Junctions



Results in strangeness enhancement focused in baryon sector

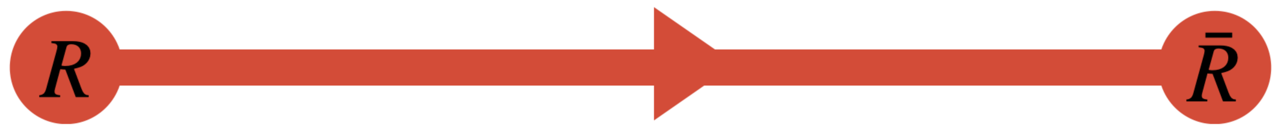
String tension could be different from the vacuum case compared to near a junction

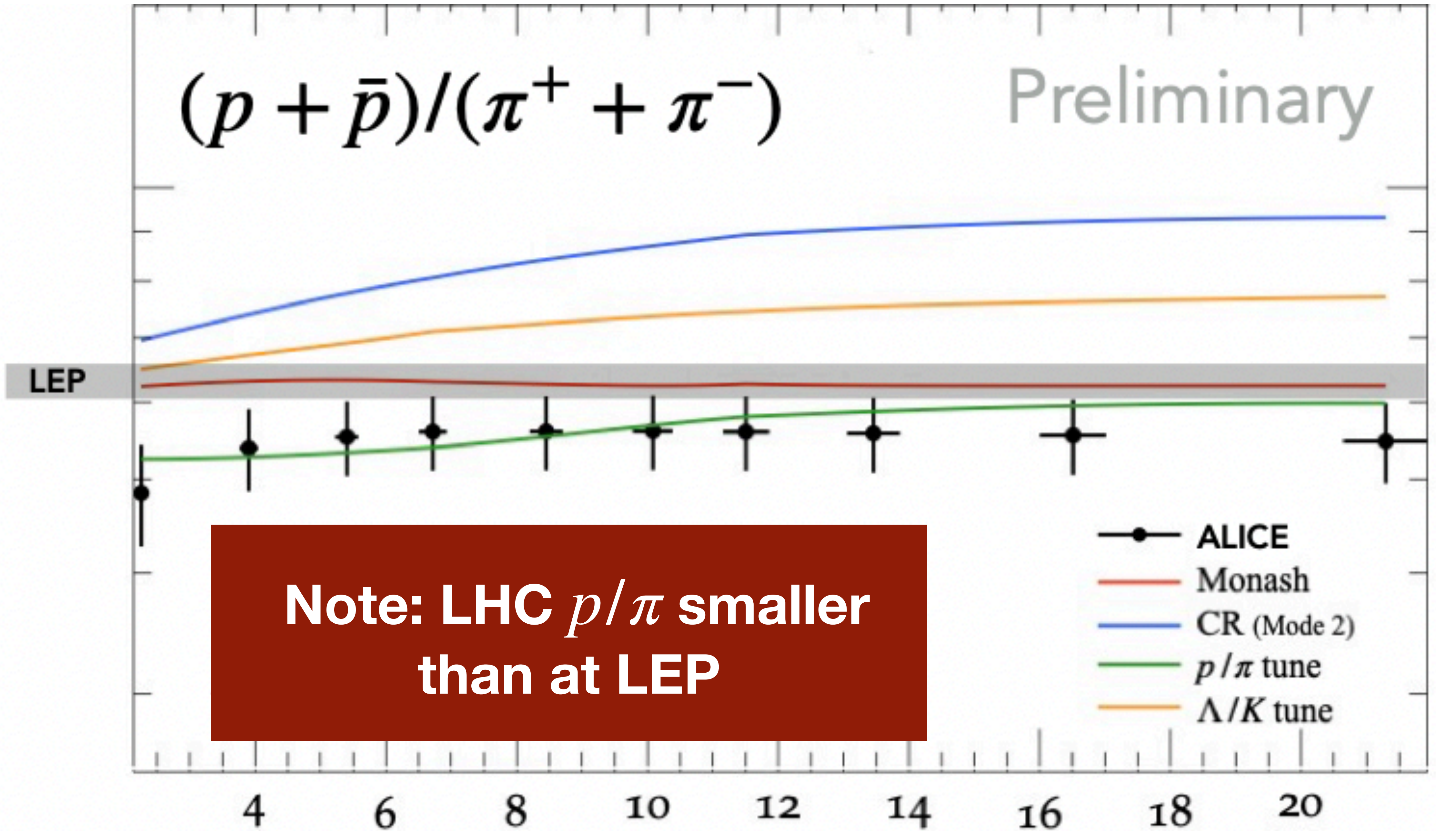
Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**





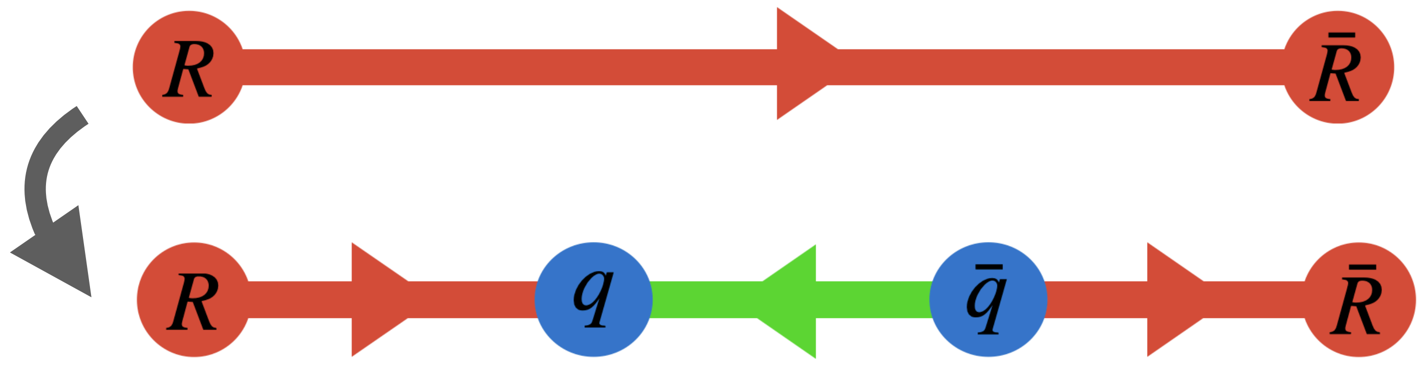
Note: LHC p/π smaller than at LEP

Popcorn mechanism

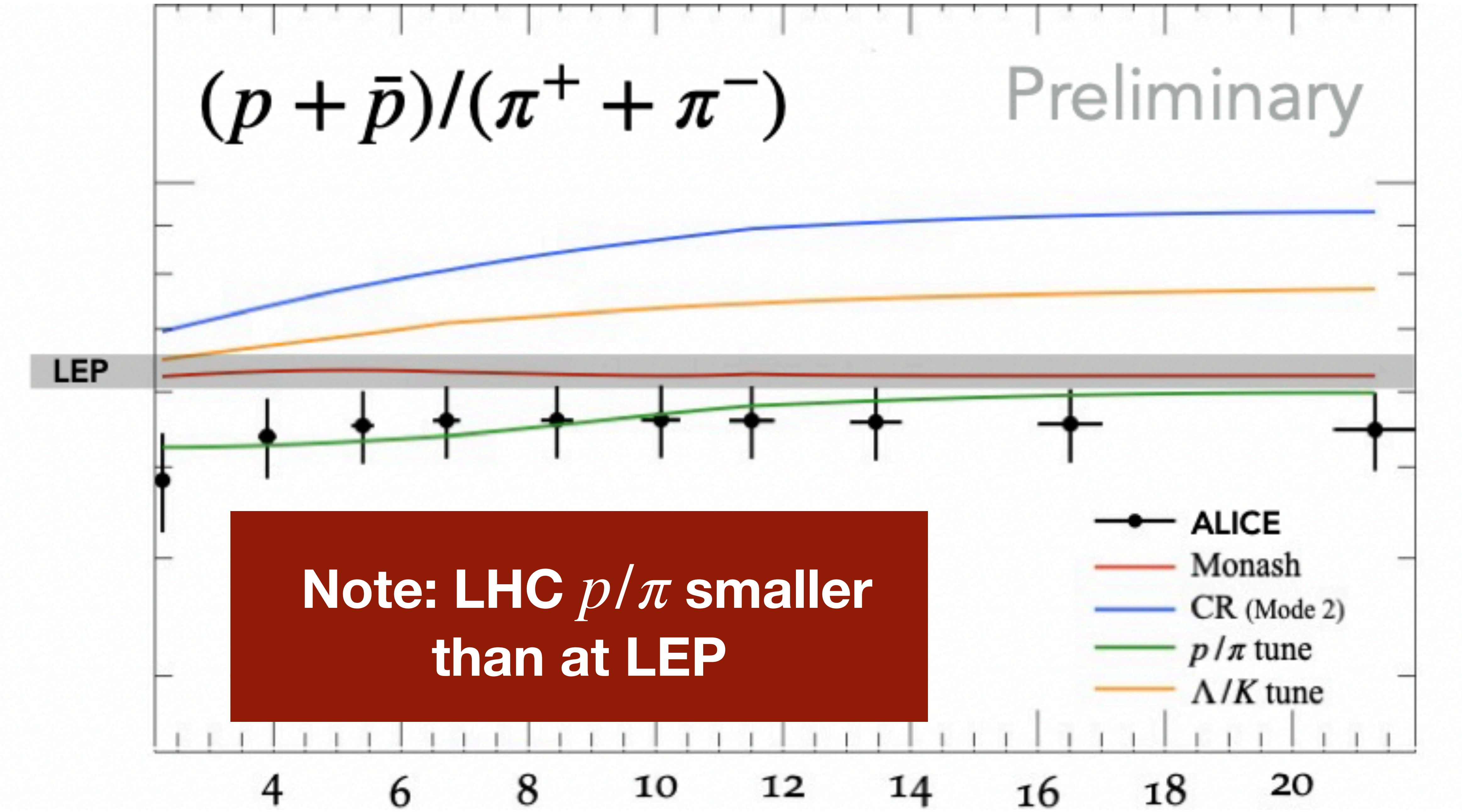
Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**



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



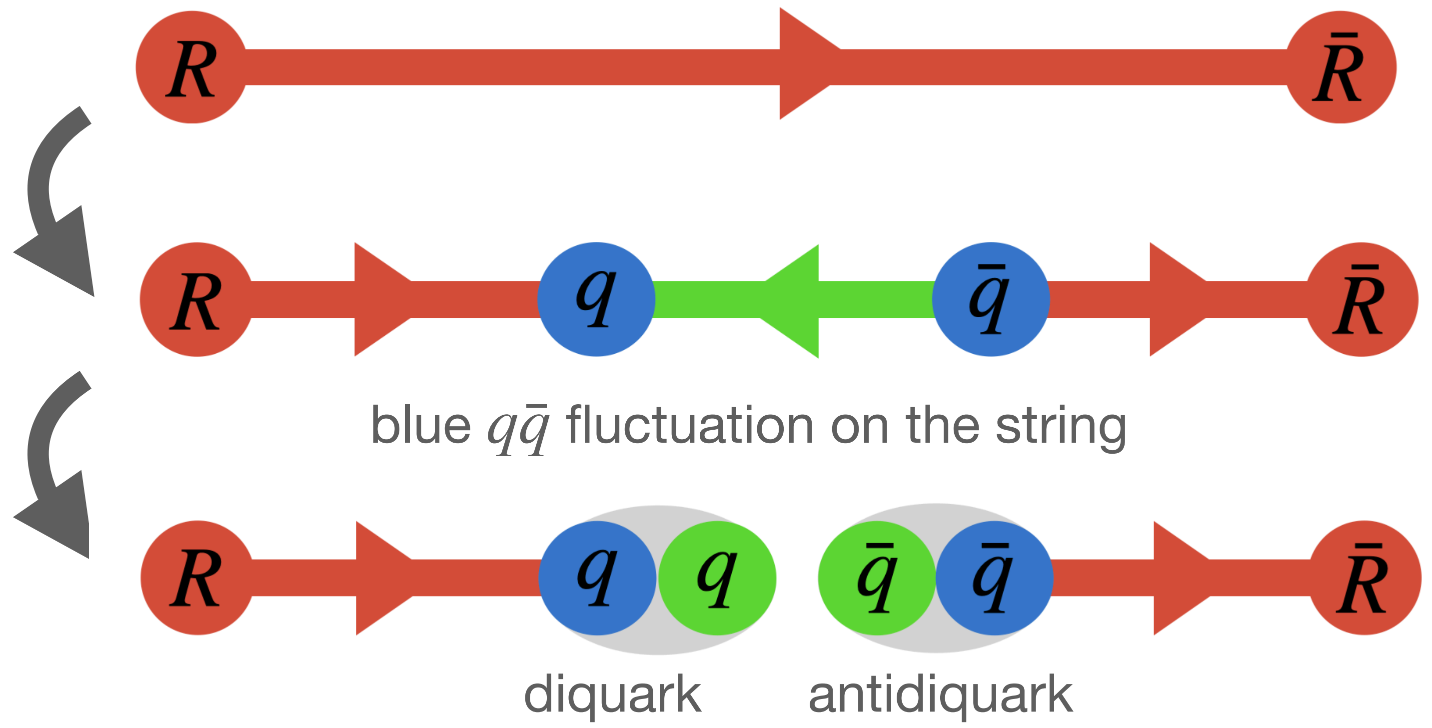
Note: LHC p/π smaller than at LEP

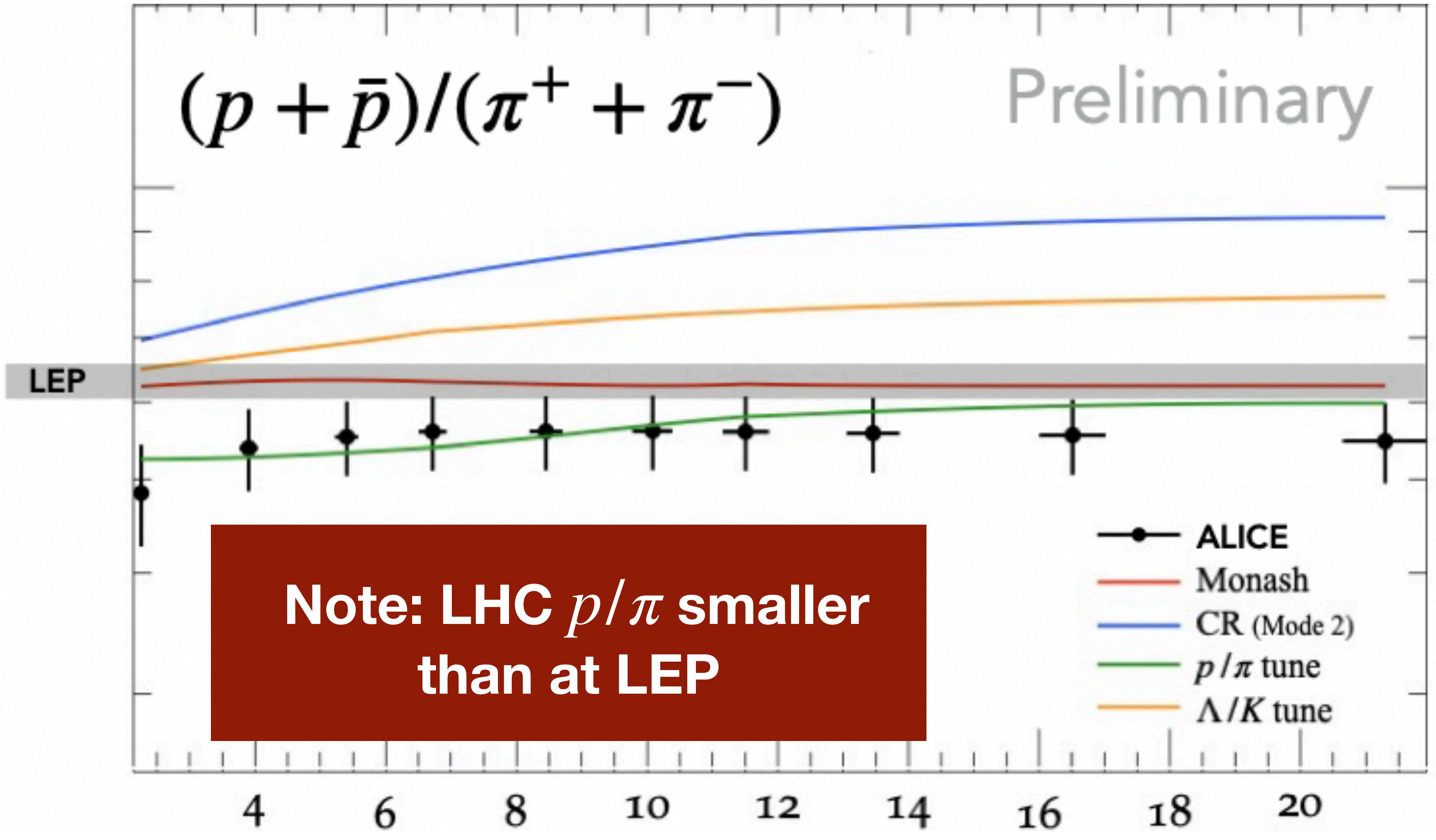
Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**





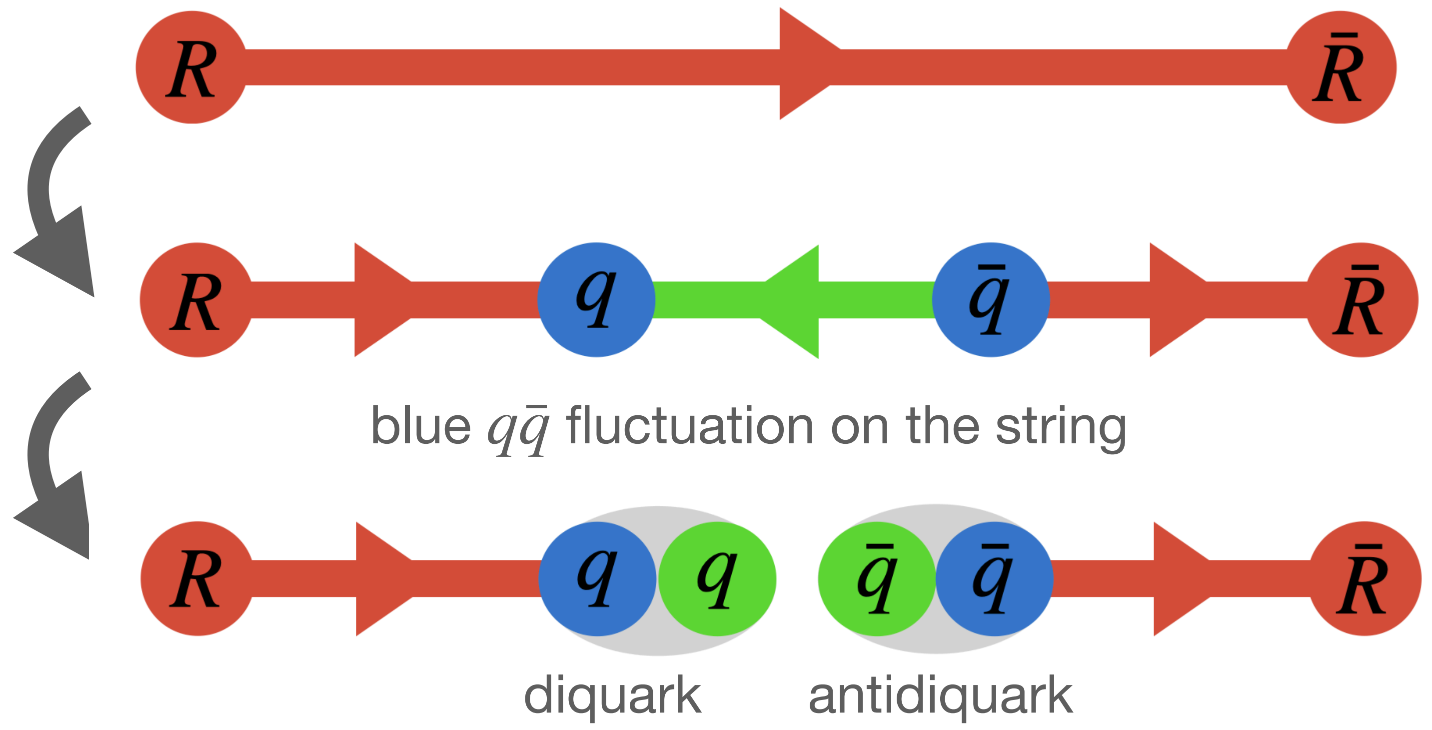
Note: LHC p/π smaller than at LEP

Popcorn mechanism

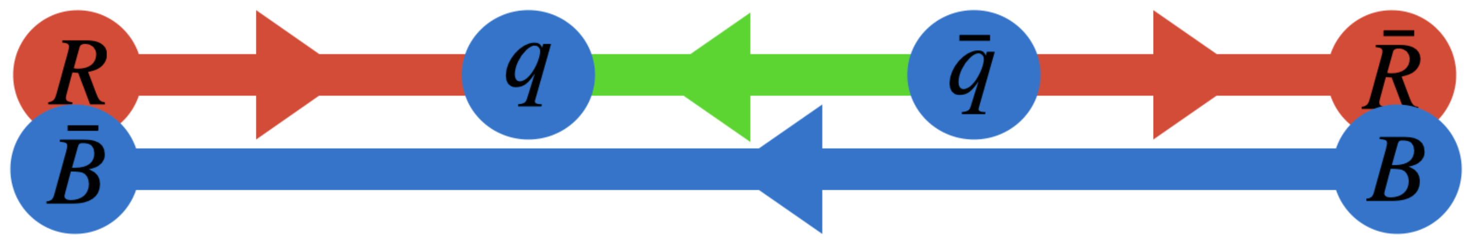
Popcorn Mechanism

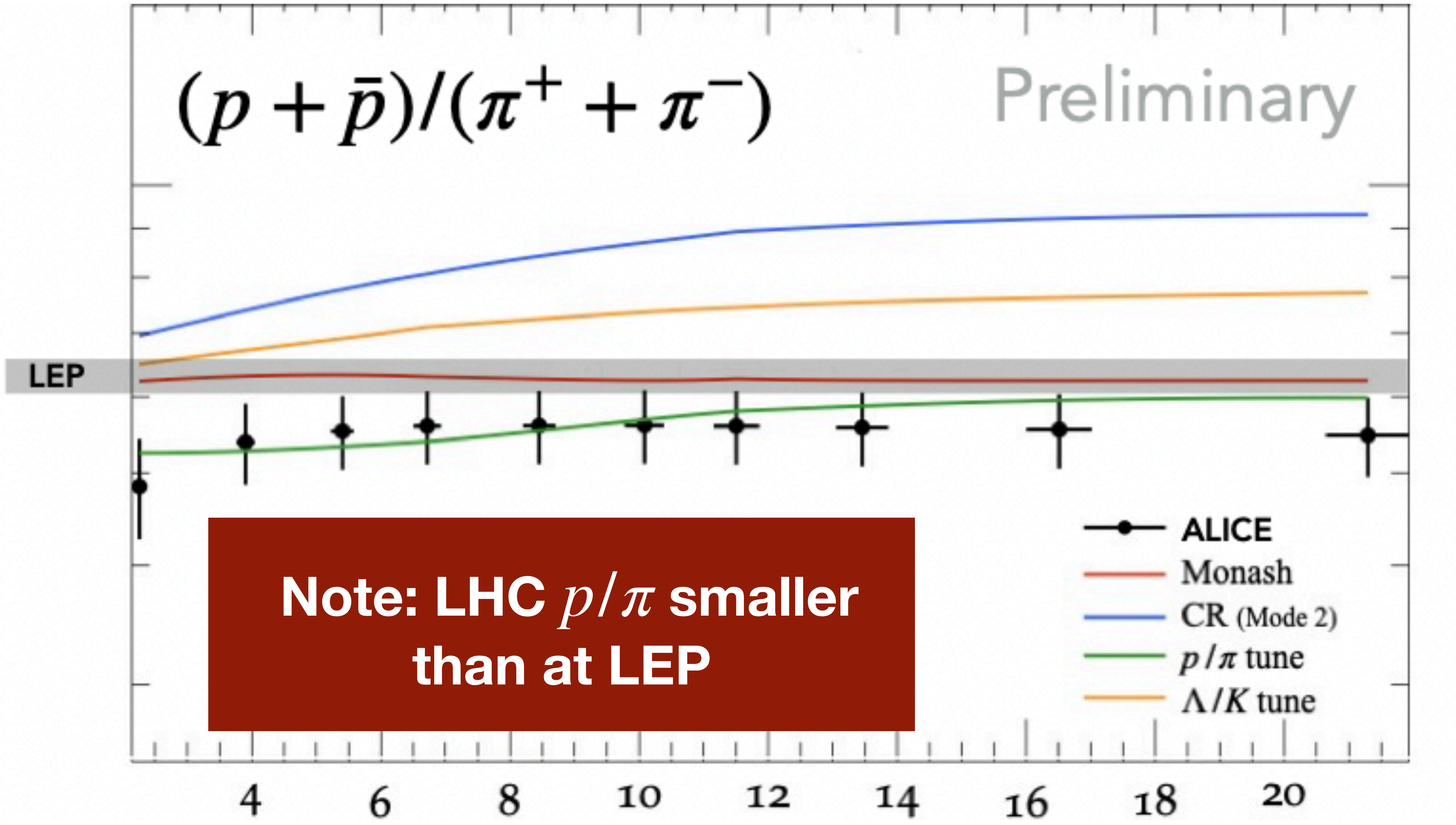
arXiv:hep-ph/9606454

Diquark formation via **successive colour fluctuations**



What if there's a blue string nearby?



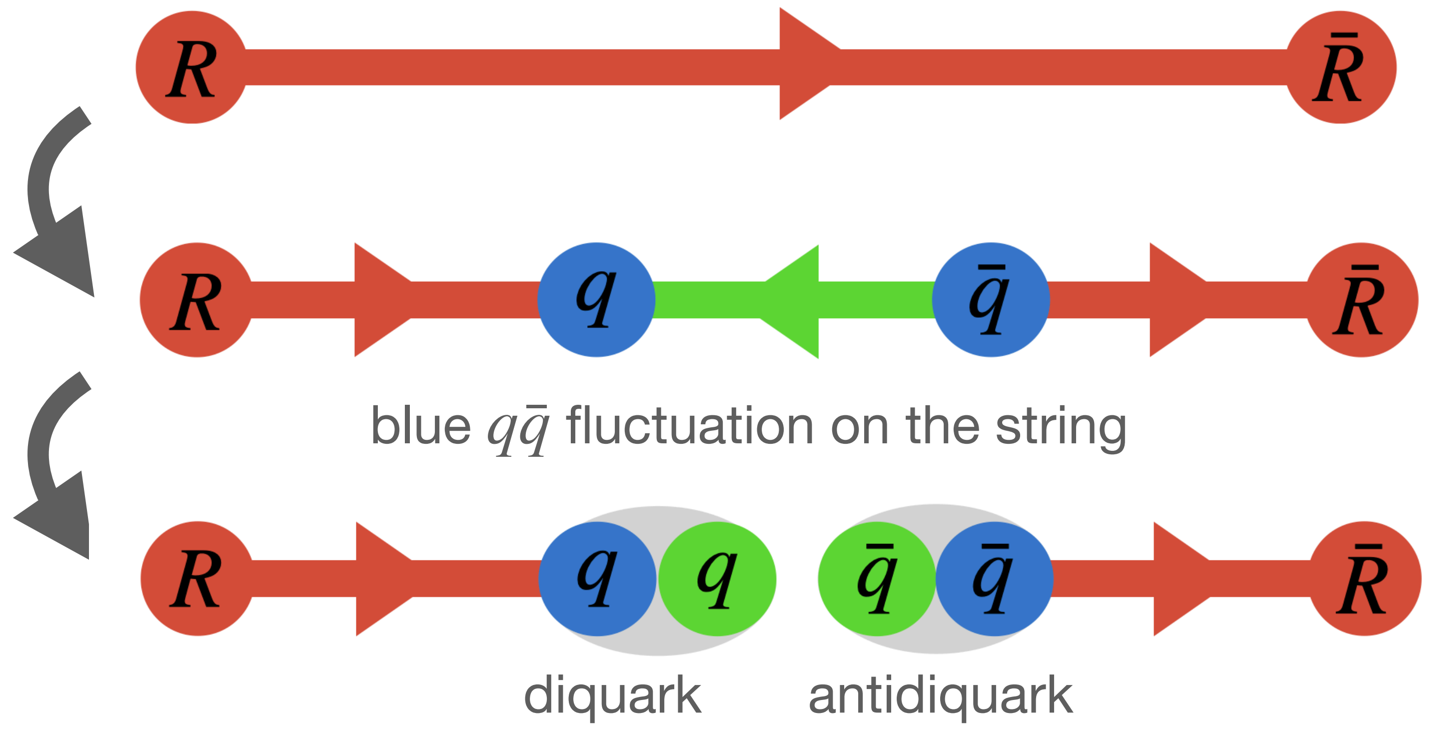


Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

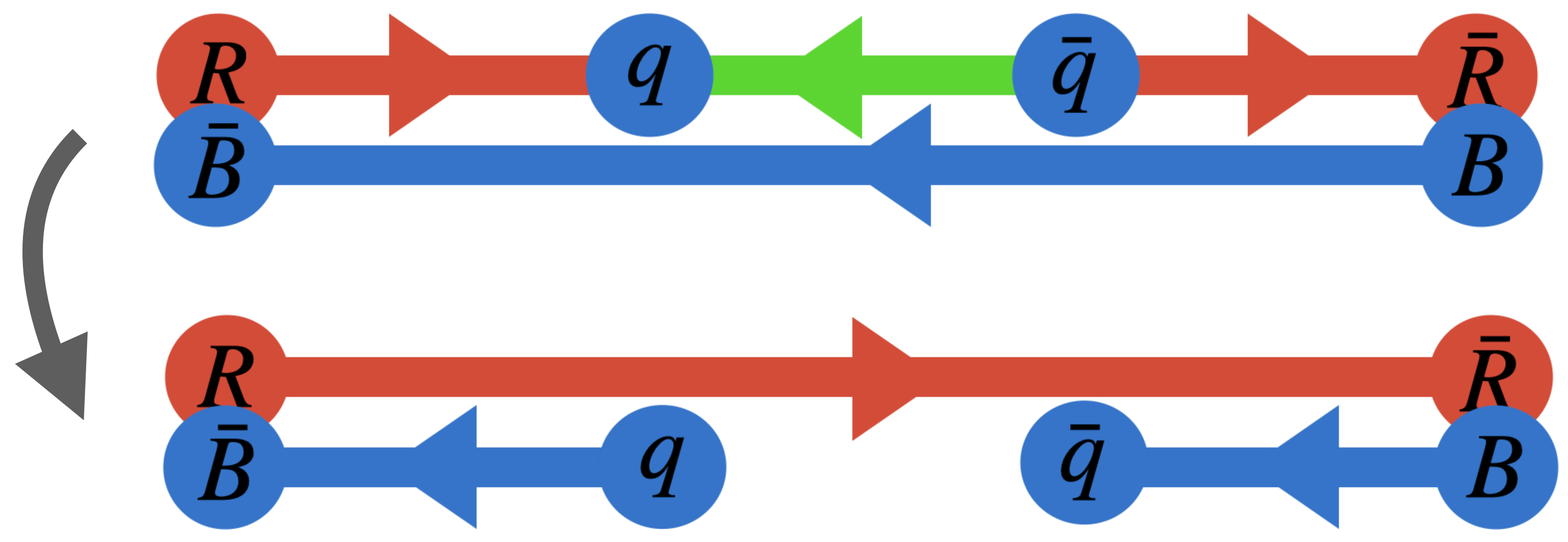
Diquark formation via **successive colour fluctuations**



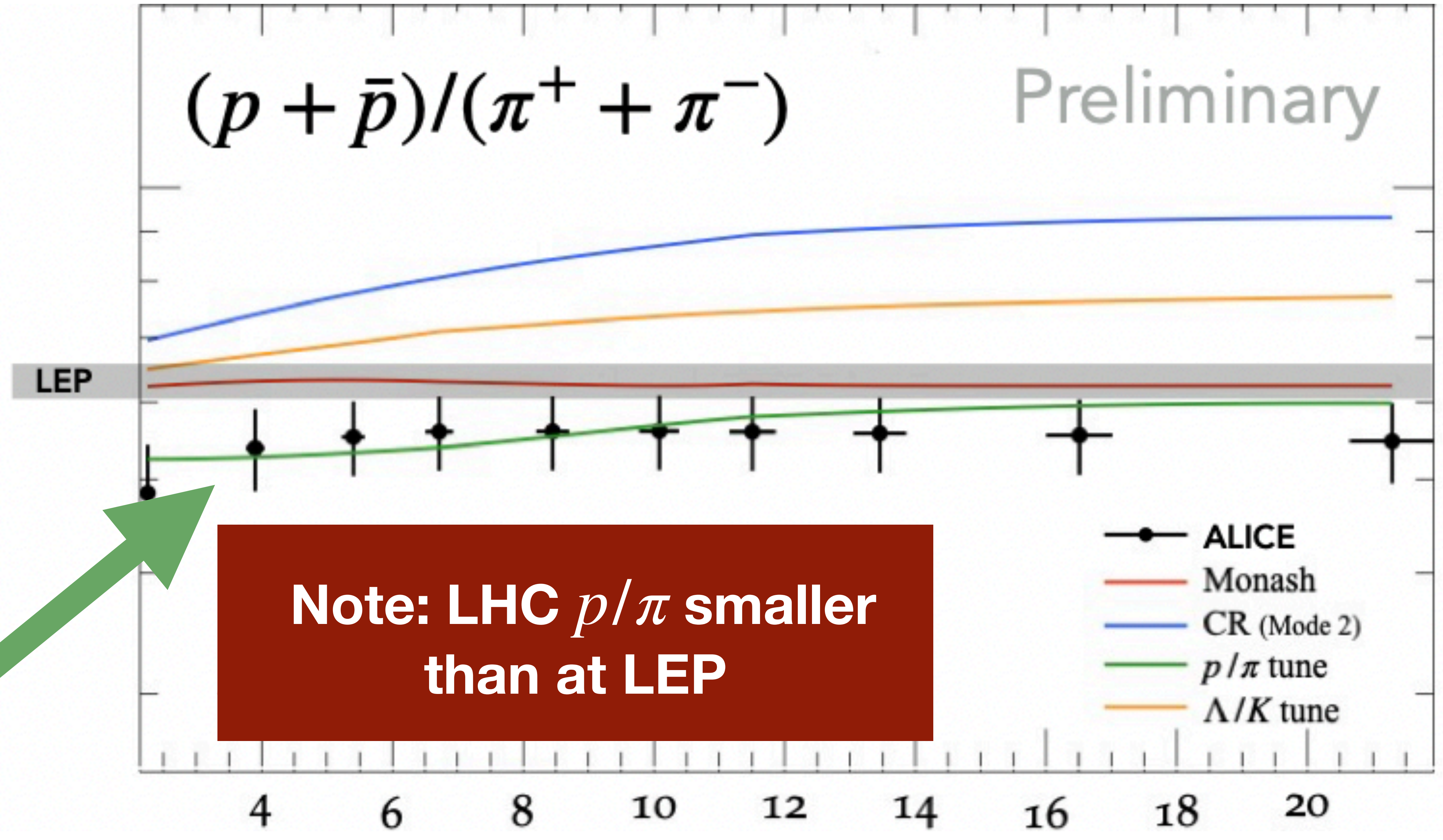
What if there's a blue string nearby?

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

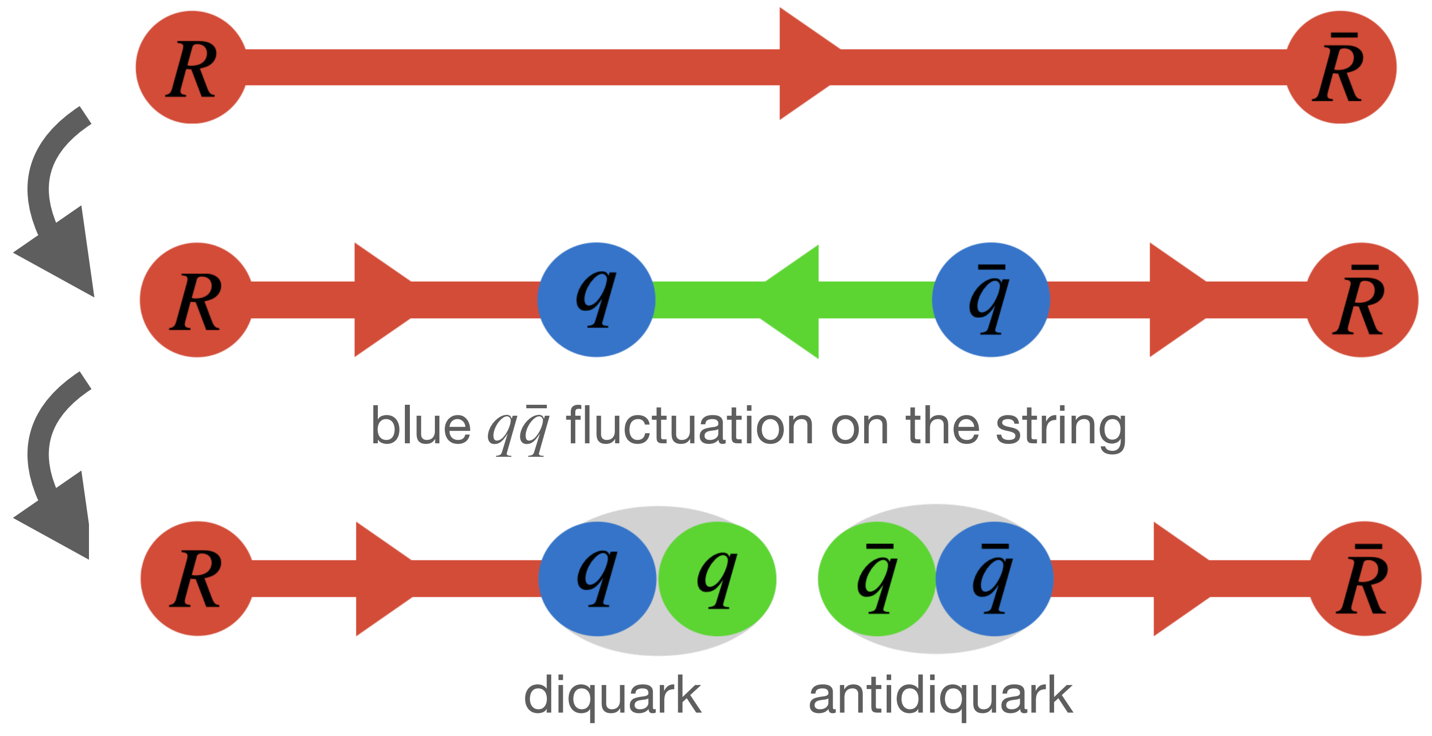
Only basic model implemented thus far, further improvements on the modelling still happening!

Popcorn mechanism

Popcorn Mechanism

arXiv:hep-ph/9606454

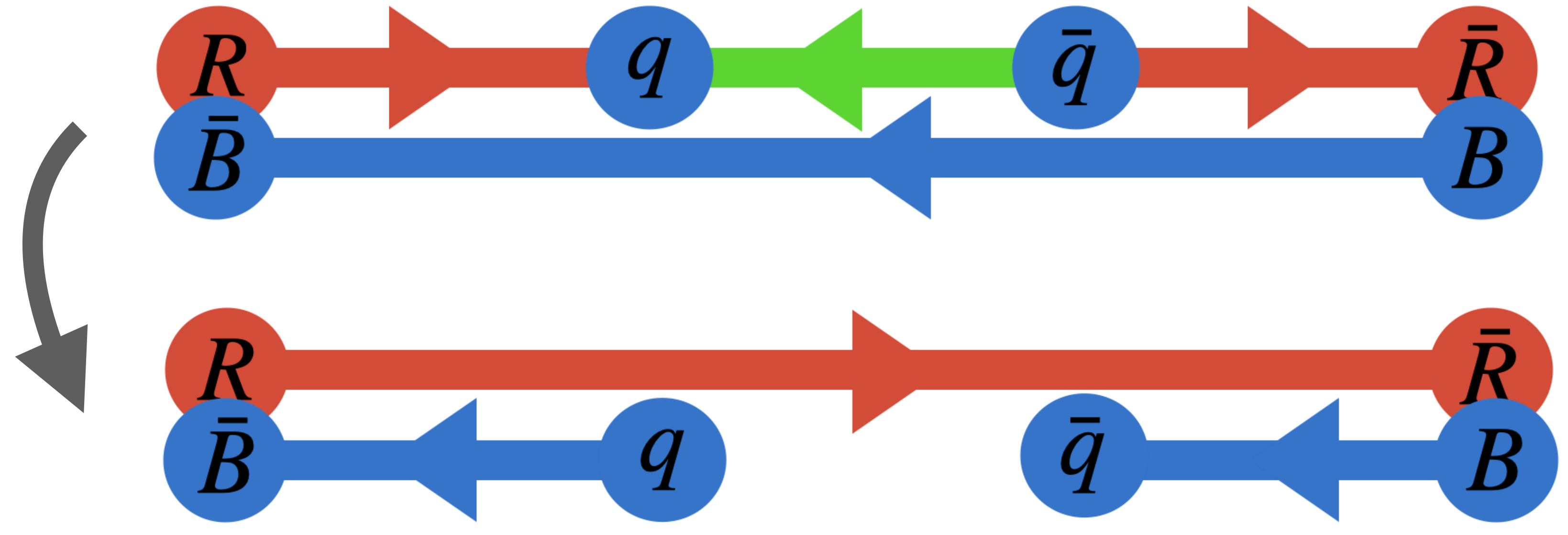
Diquark formation via **successive colour fluctuations**



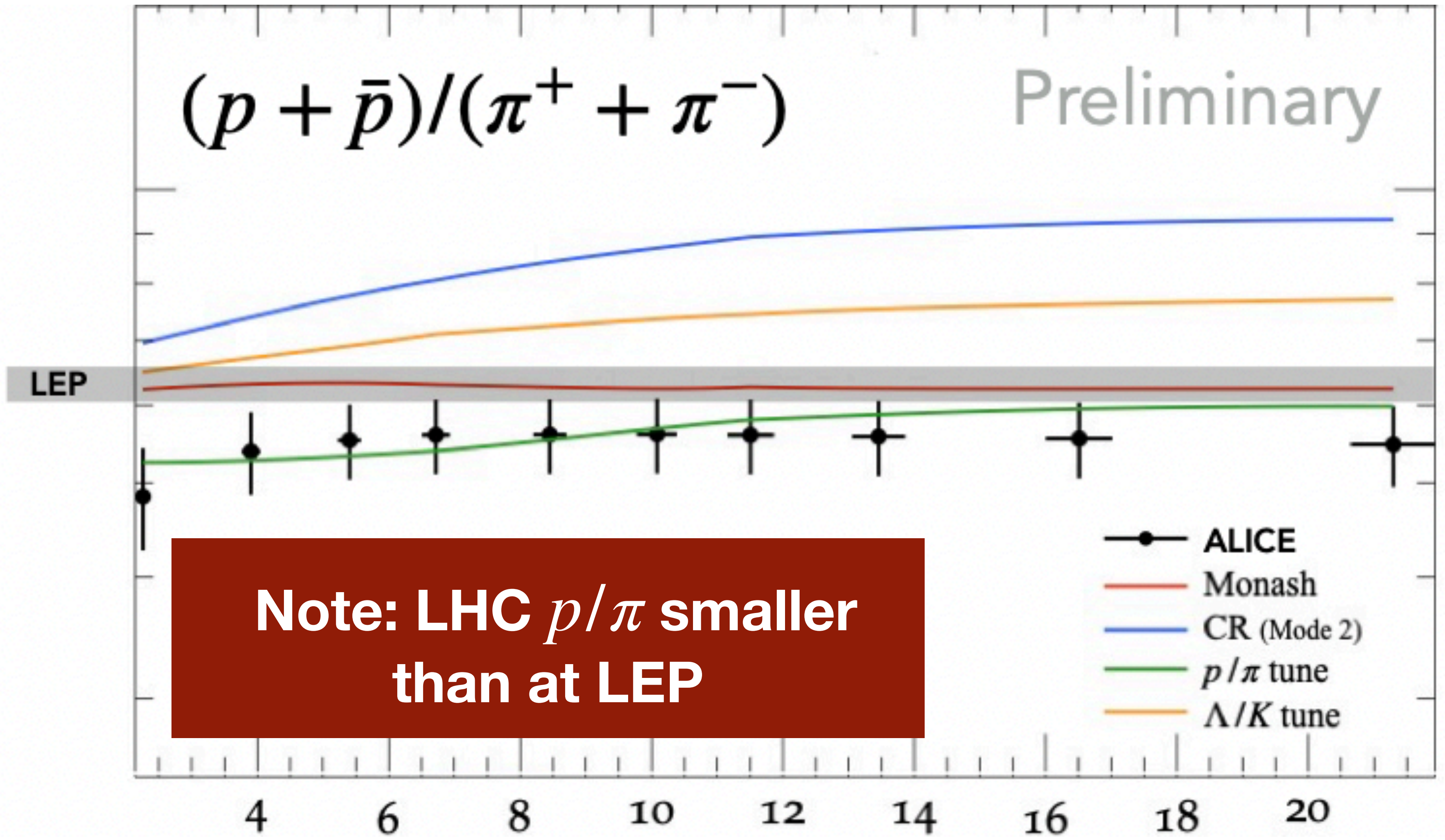
What if there's a blue string nearby?

NEW

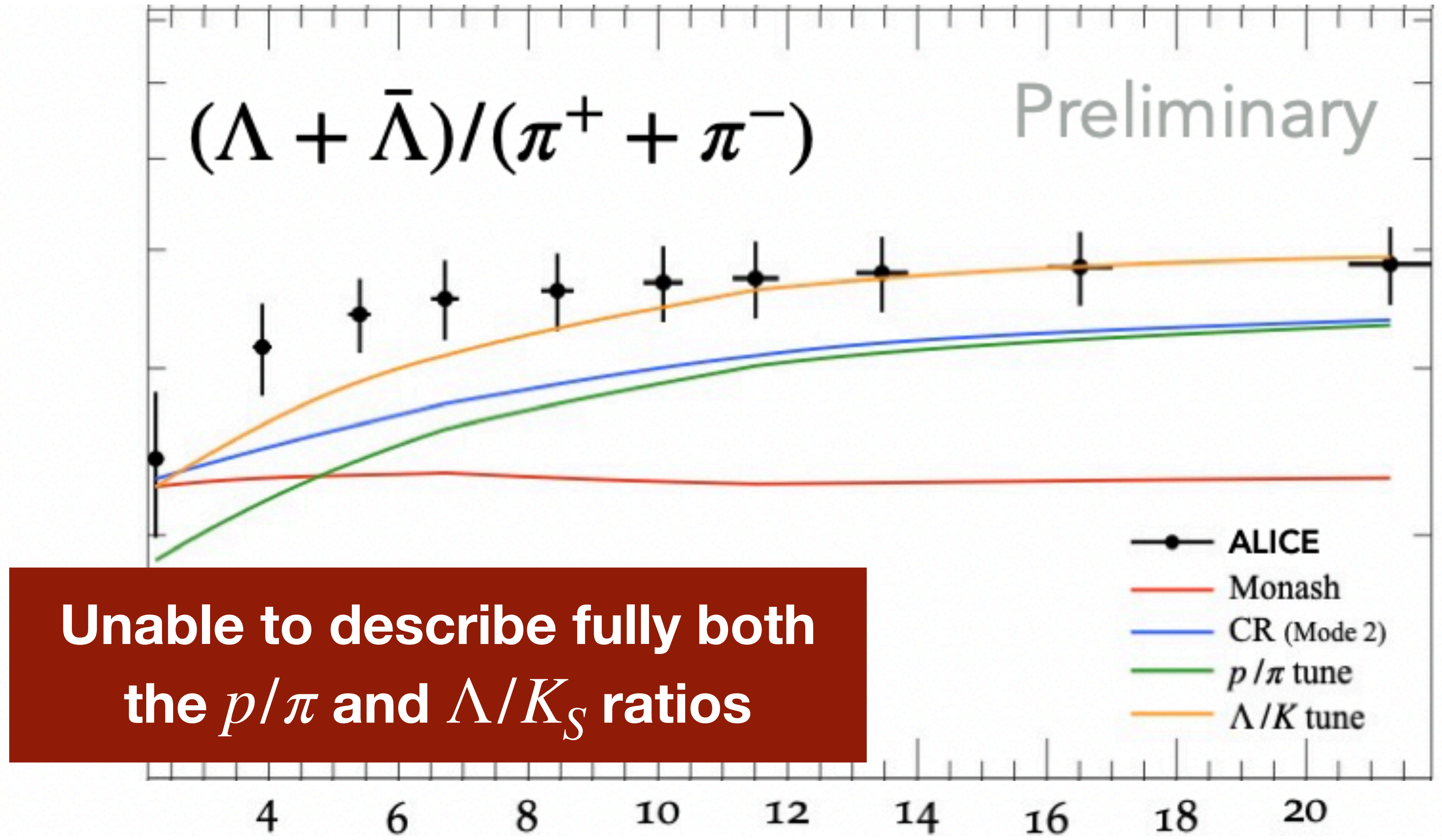
Destructive interference of popcorn mechanism



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



Note: LHC p/π smaller than at LEP



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!