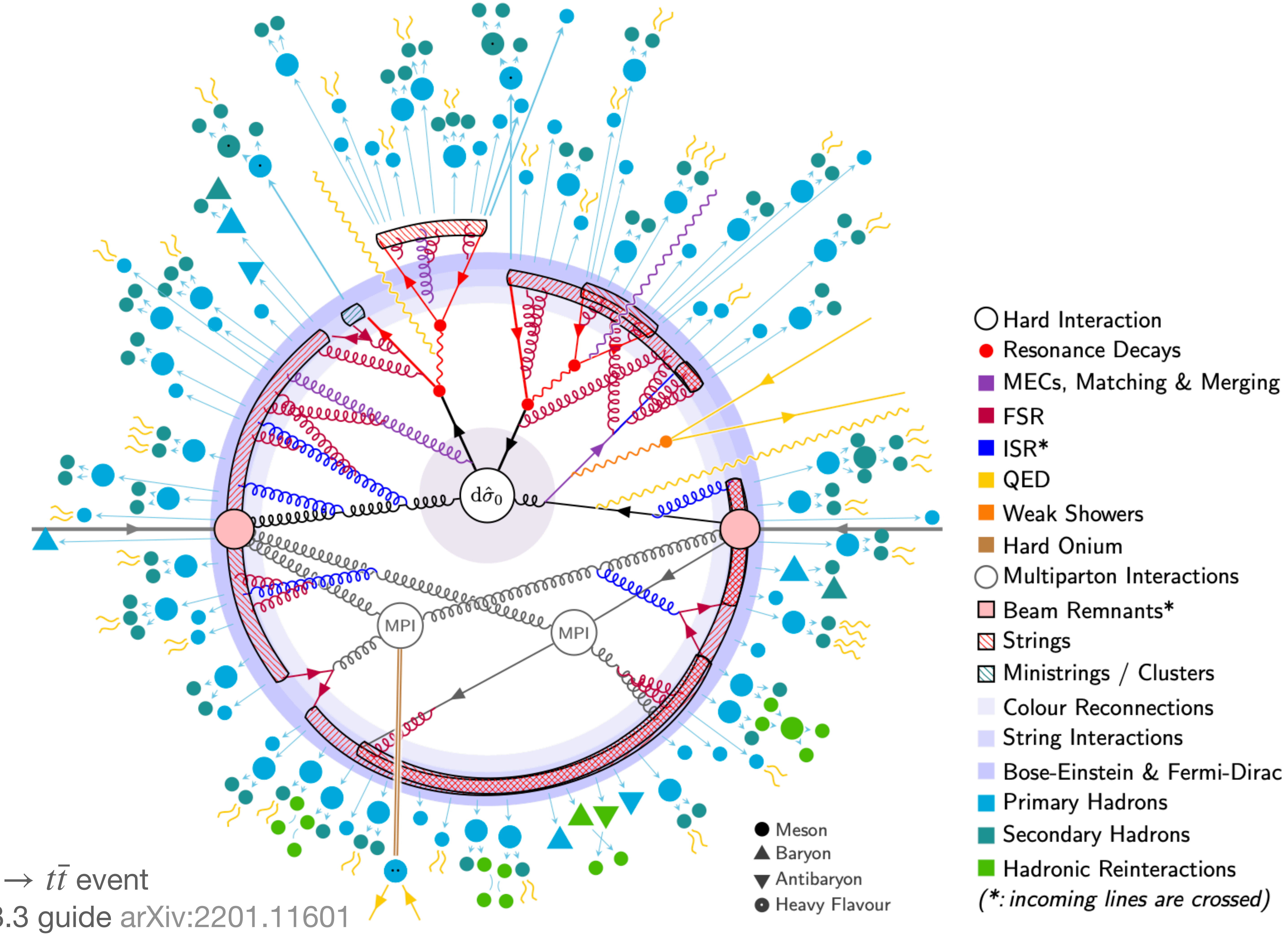
# Hadronisation in PYTHIA8

Javira Altmann, Monash University

# Overview

- ➢ Brief recap of hadronisation using the Lund String Model
- ➢ Colour reconnections
  - ➢ Junctions
  - ➢ Impact on heavy-flavour baryon production
- ➢ What needs to be explored further?
- ➢ What about pA and AA?




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

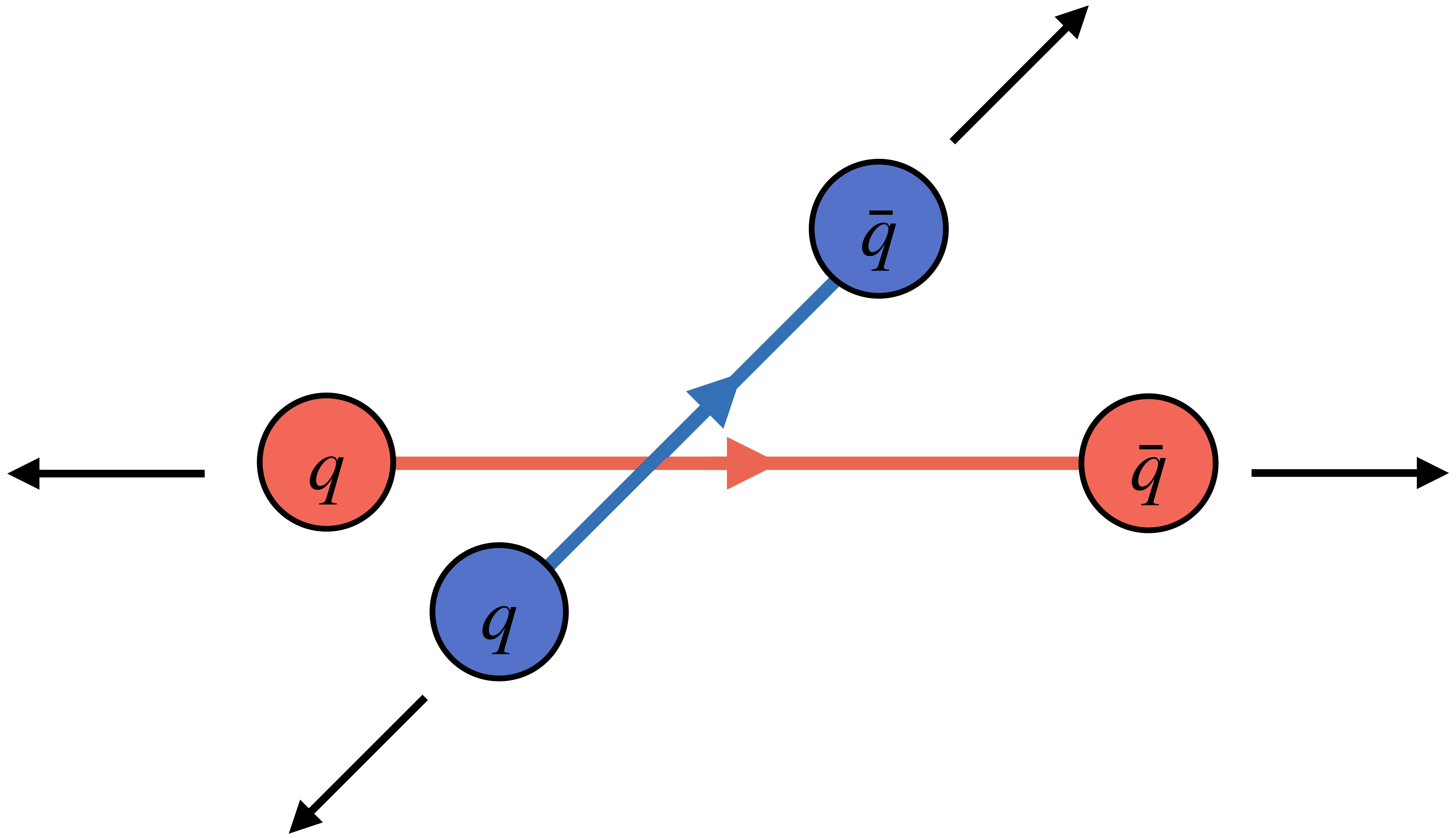
# Hadronisation and the Lund String Model

What is a **"string"**?

- **Colour confinement field** stretched between partons
- Defined by fundamental parameter, the constant string tension $\kappa$ ~ 1 GeV/fm

**Key features:**

- *String configuration* : scattering of colour charges
- *String breaks* : map partons to hadrons



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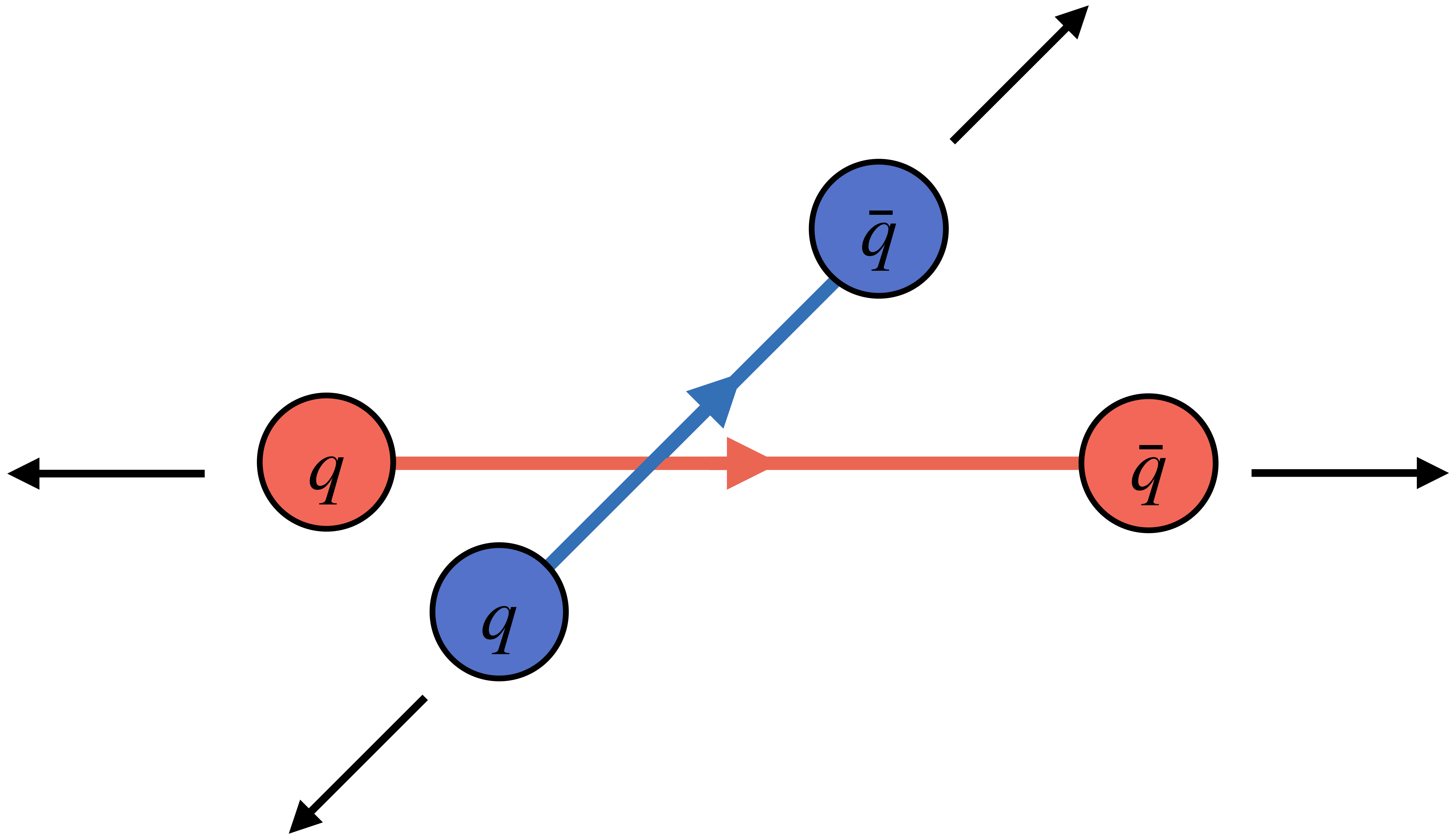
Governed by perturbative partonic scattering of colour charges (QCD 2→2 ME)

Confinement fields (strings) will form between a parton with its closest colour connected parton to form an overall singlet state

e.g. a **red** colour charge will stretch a confinement field to the nearest **anti-red** charge that makes a singlet state



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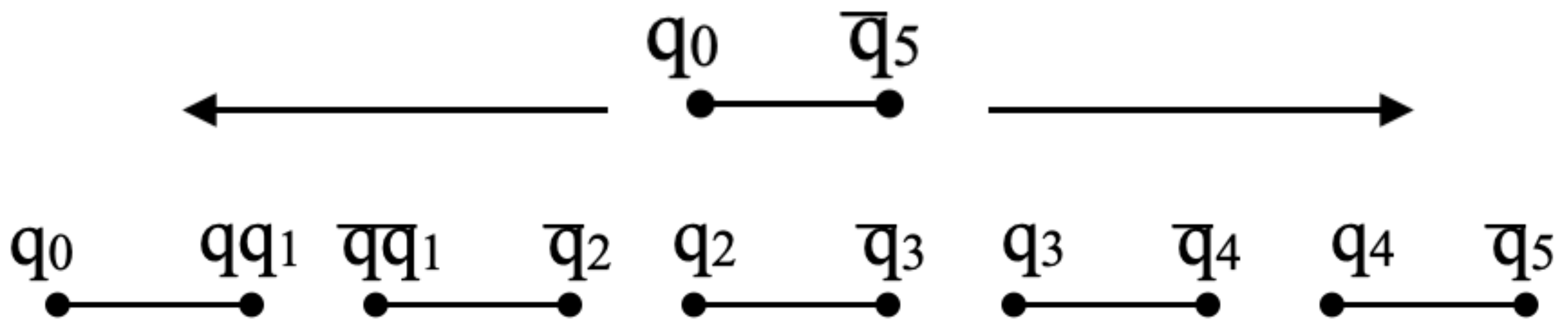
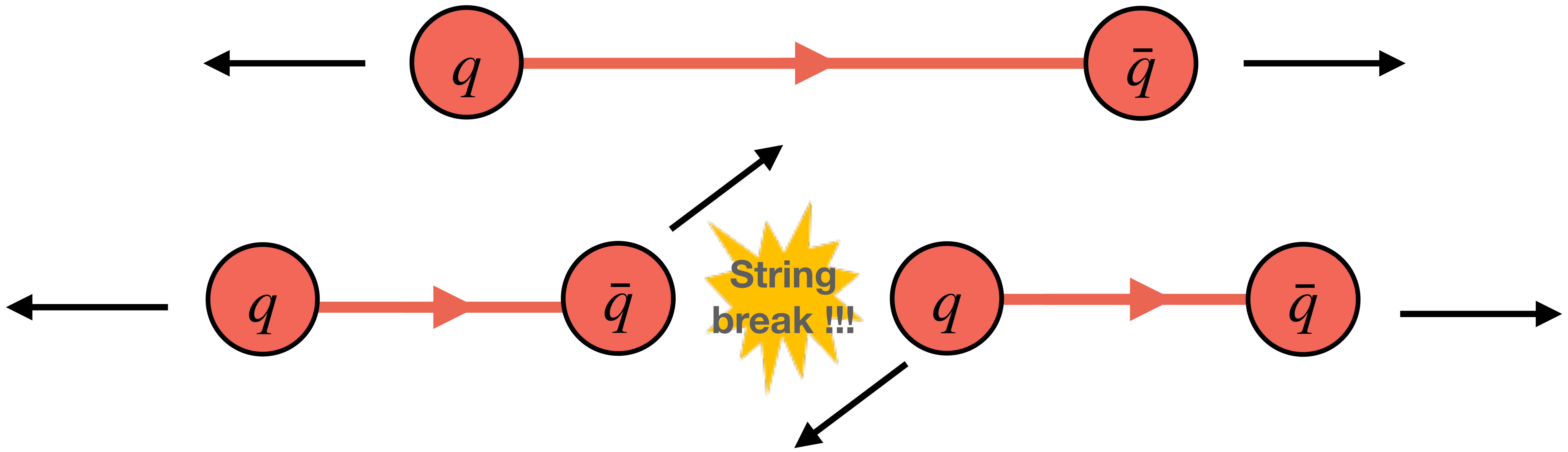



What happens when a **string breaks**?

- ➢ spontaneous **pair creation** at the site of string breaks modelled as a quantum tunnelling process




Only light quark-antiquark, or diquark-antidiquark pairs can be created via string fragmentation.
Any $b$ or $c$ quarks must come from hard processes

# Colour Flow

Starting point for PYTHIA is the **Leading Colour** (LC) limit $N_C \to \infty$

➢ Simplified version to trace where do the colours scatter, giving unambiguous string topologies

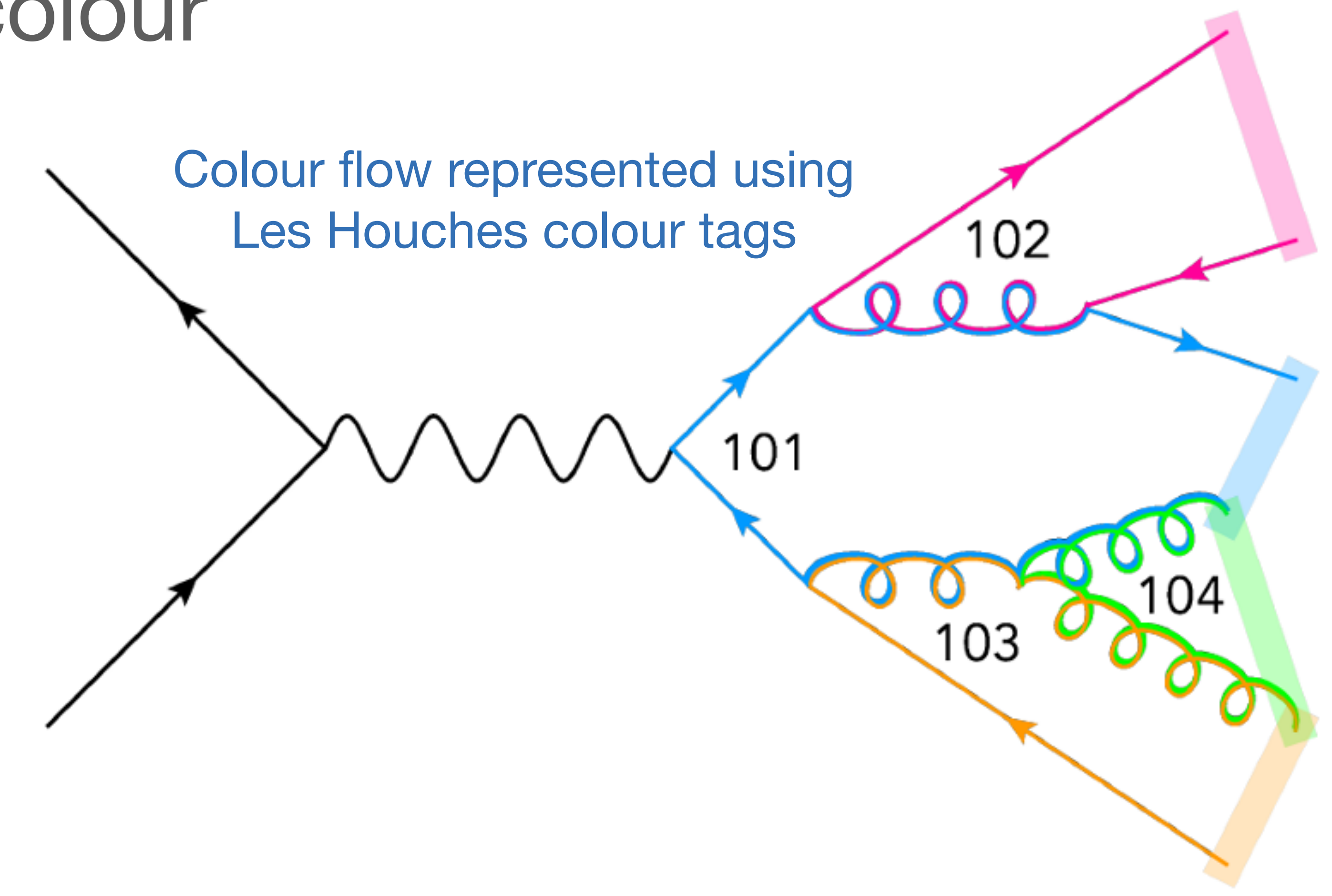
➢ Allows dipole strings only

➢ Each new colour pair is given a new tag

  ➢ Colours uniquely matched to an anticolour

Expect corrections to be suppressed by $1/N_C^2 \sim 10\,\%$

Example from Pythia 8.3 manual :
$e^+e^- \to Z_0 \to q\bar{q}$ + parton shower



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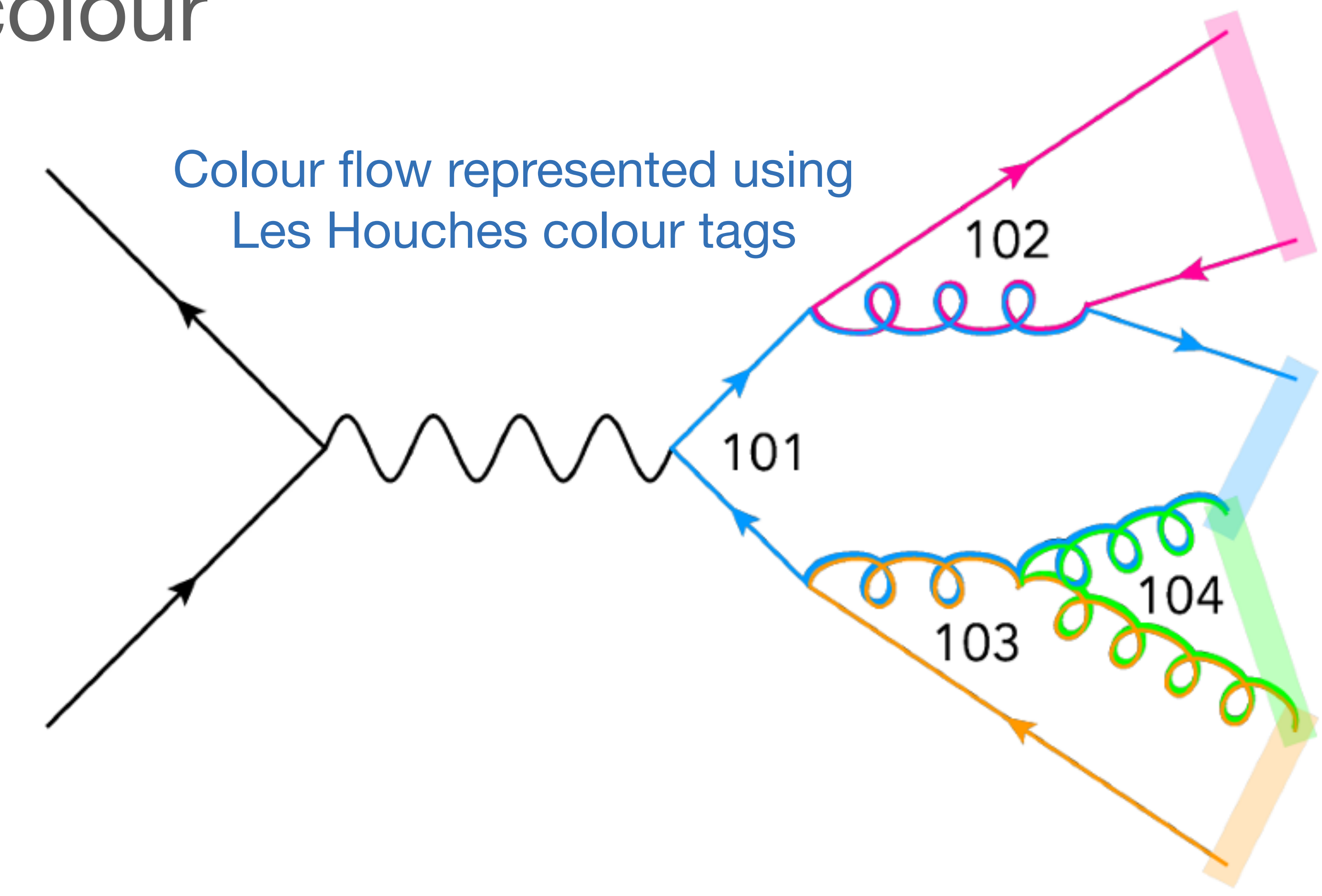


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Colour is represented by the **SU(3) group**, thus finite number of colours!
What happens if we introduce this colour-space ambiguity?

**What about $pp$ collisions?**

$pp$ collisions have dense environments
→ subleading colour ambiguities become more significant

# QCD-based Colour Reconnections

**Restore missing colour correlations stochastically**

Approximate LC-unconnected partons as uncorrelated and use SU(3) rules

- ➢ Assign partons **"colour indices"** from 0 to 8 to reproduce probabilities given by these SU(3) rules
- ➢ Choose the **"lowest-energy"** configuration

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**Dipole CR**

$3 \otimes \bar{3} = 8 \oplus 1$ for uncorrelated colour-anticolour pairs

**Junction CR**

$3 \otimes 3 = 6 \oplus \bar{3}$ for uncorrelated colour-colour pairs

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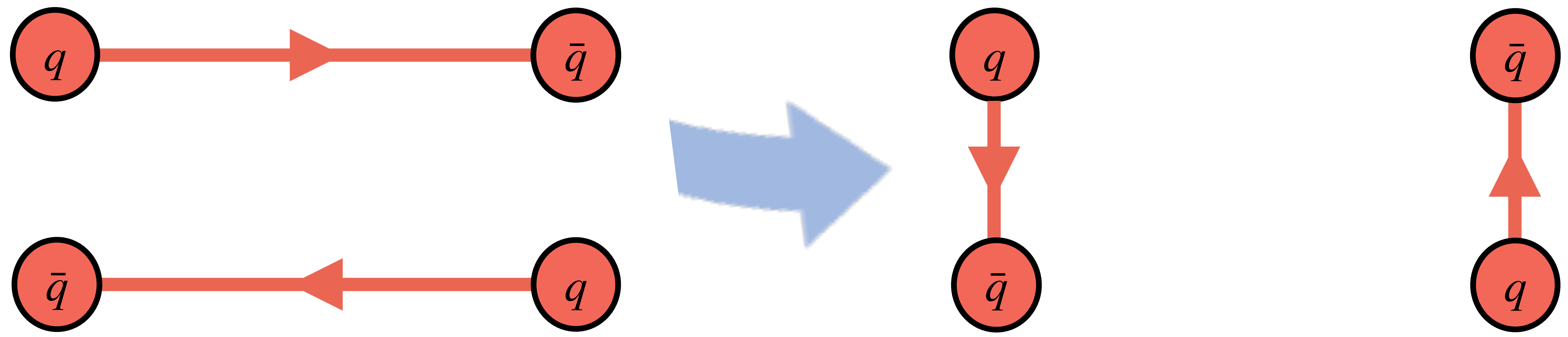
- ➢ Confined with **anti-index 0**

(giving 1/9 probability from equation above)

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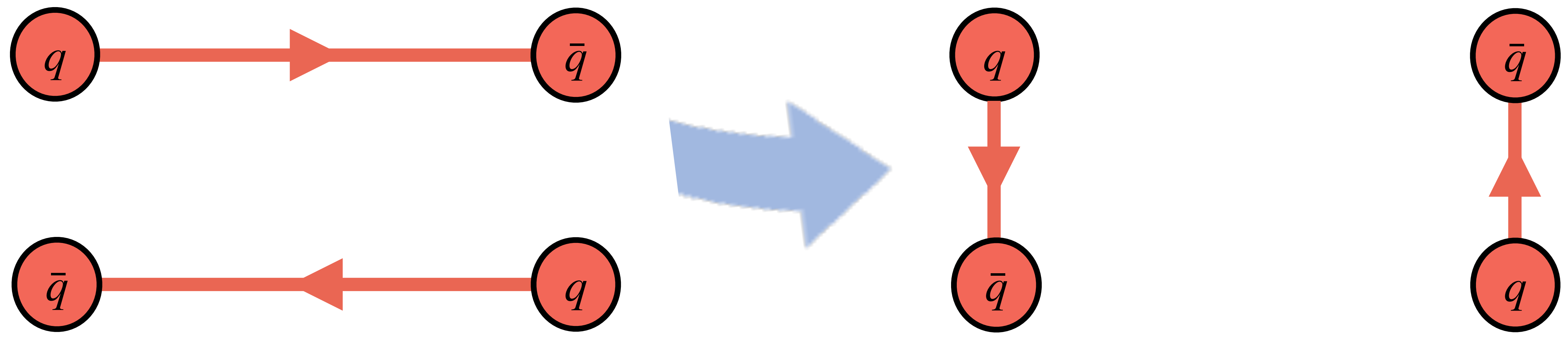



**Junction CR**

$3 \otimes 3 = 6 \oplus \bar{3}$ for uncorrelated colour-colour pairs

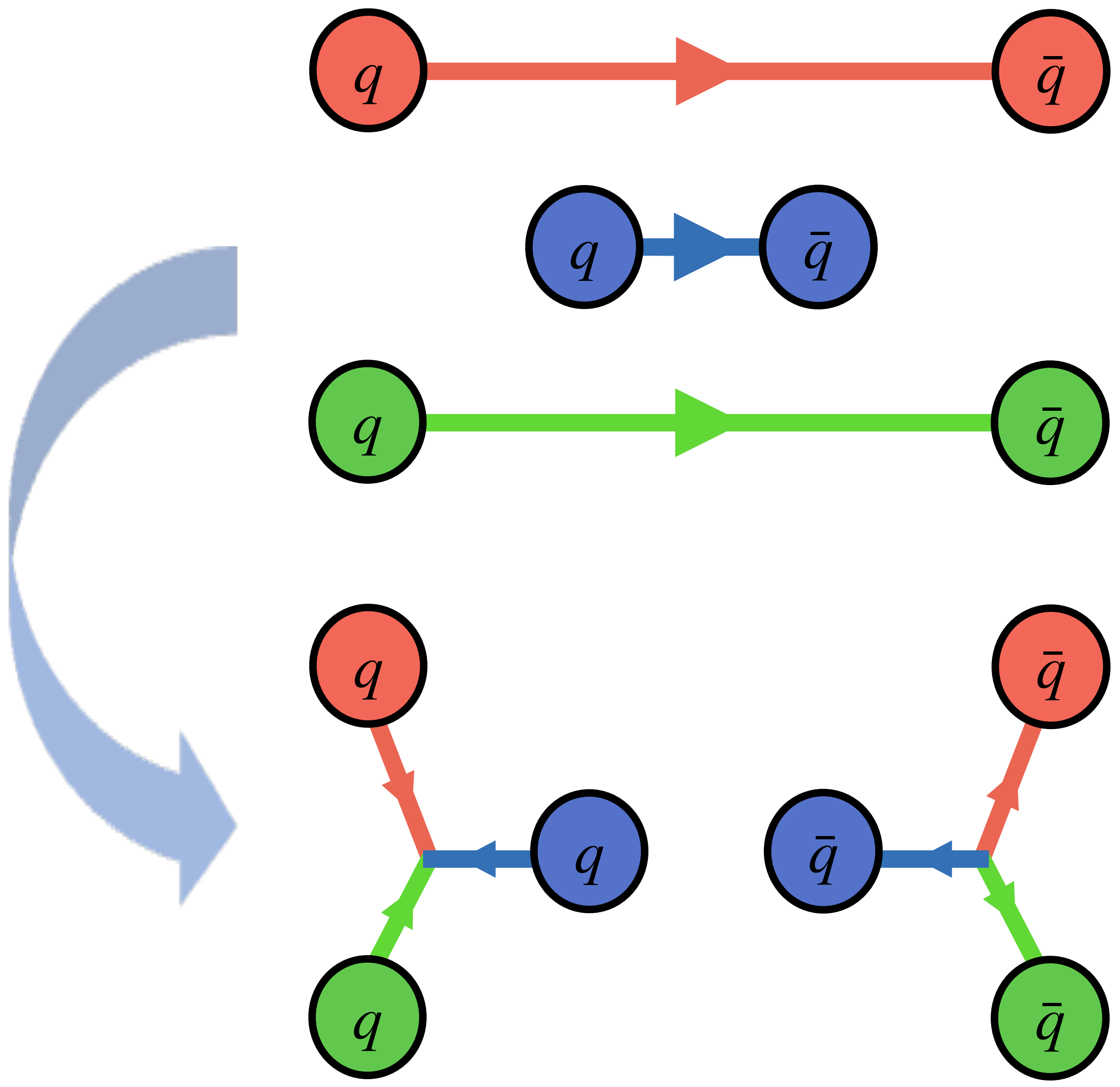
- ➢ Confined with indices **3** and **6** to form colour-neutral combination of **R**, **G**, and **B**

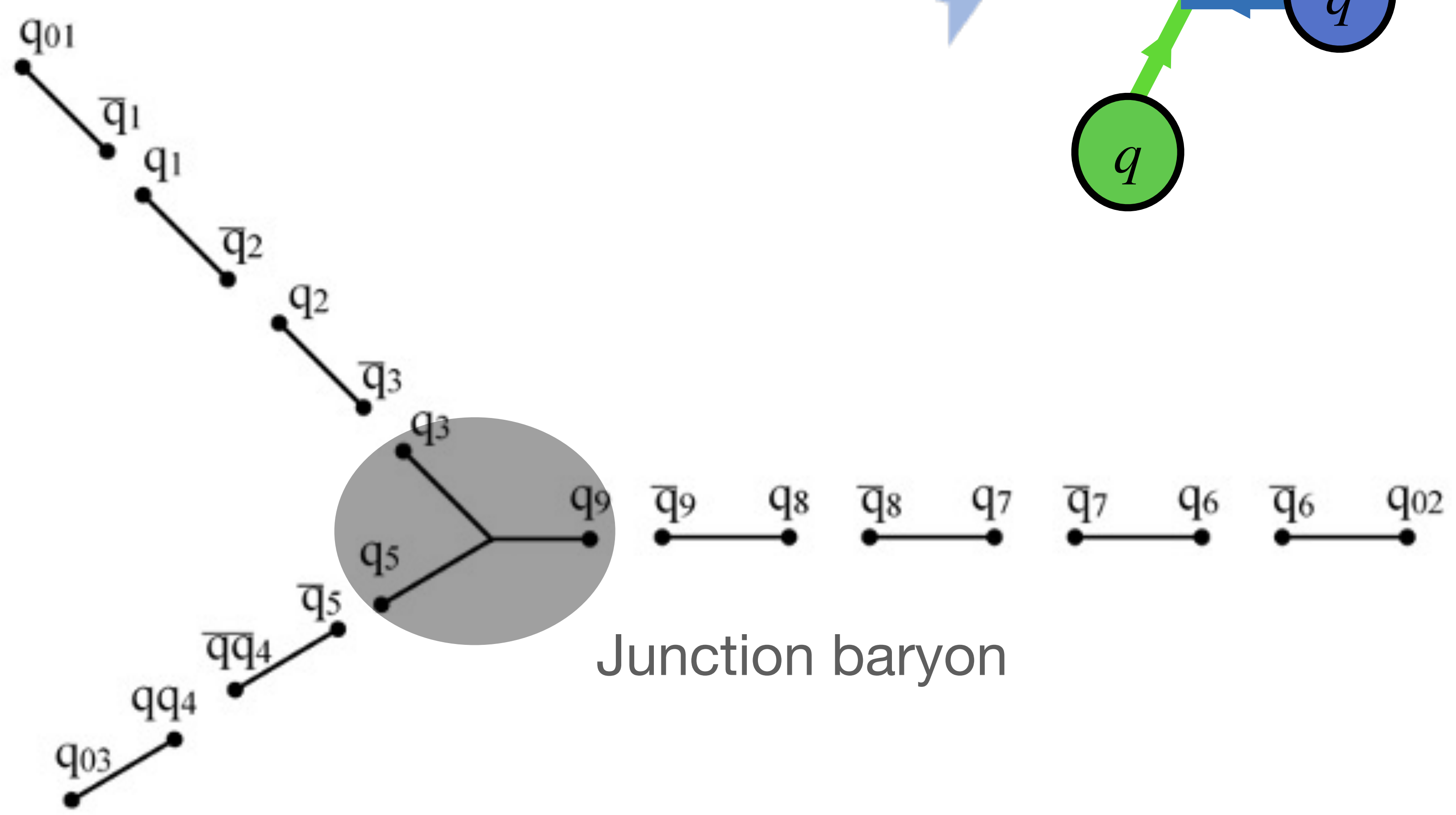
(giving approx. 3/9 probably in equation above) represented by **“string junctions”** → **baryons!**

# Junction Topologies

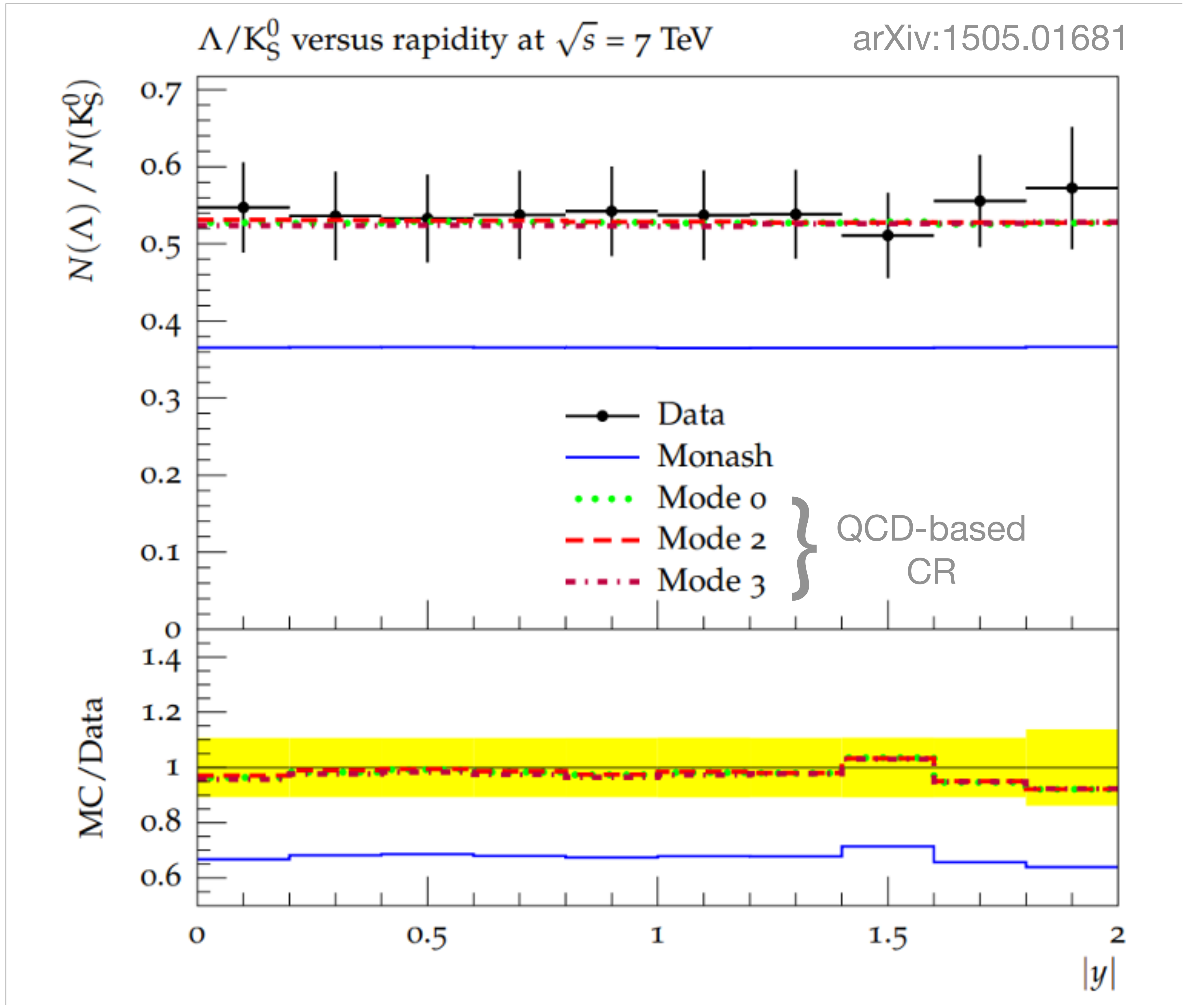
**Junction CR**

Choose "shortest" string configuration




Increased ratio of baryons to mesons



# Junction Topologies

## Junction CR

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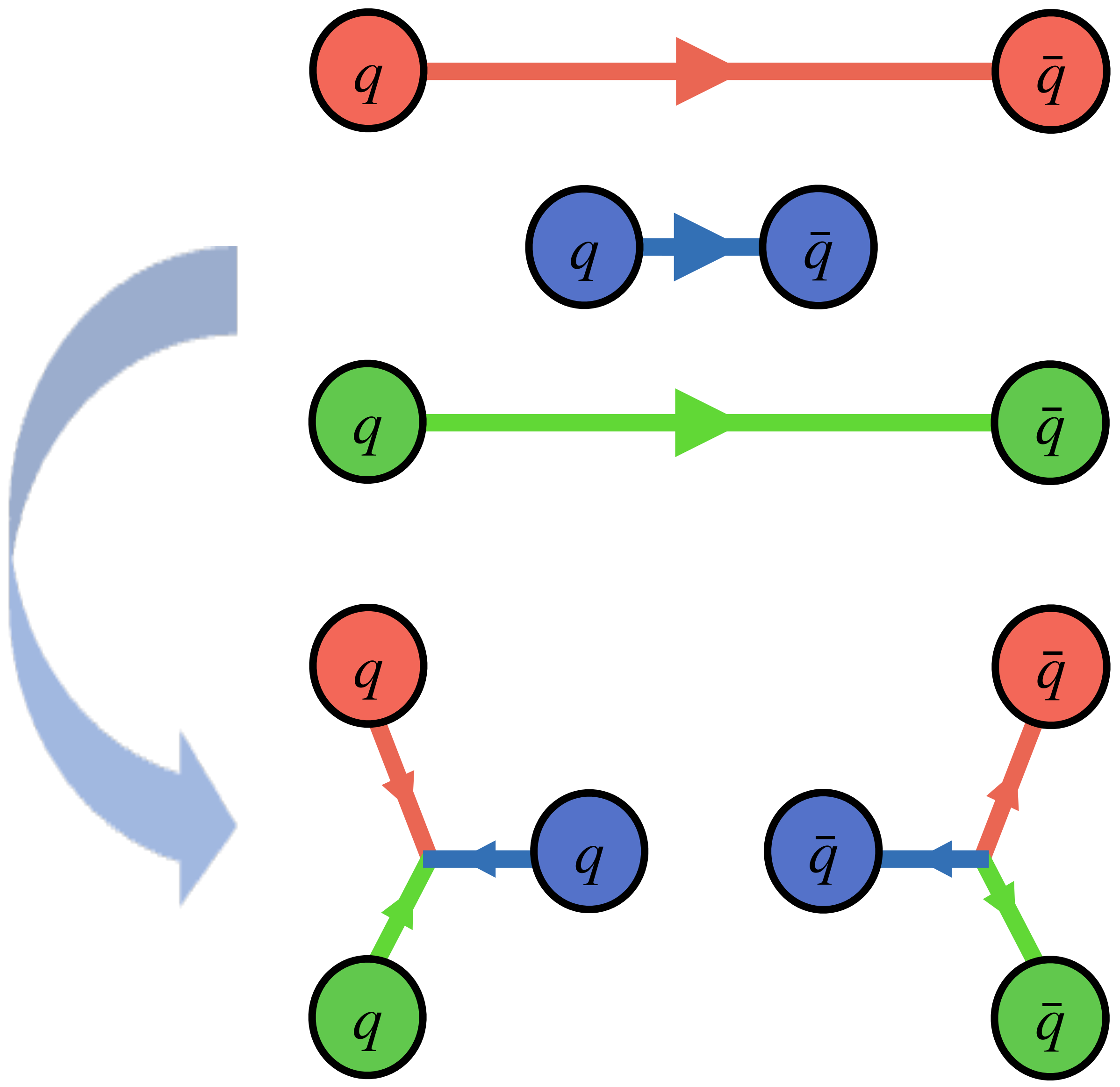

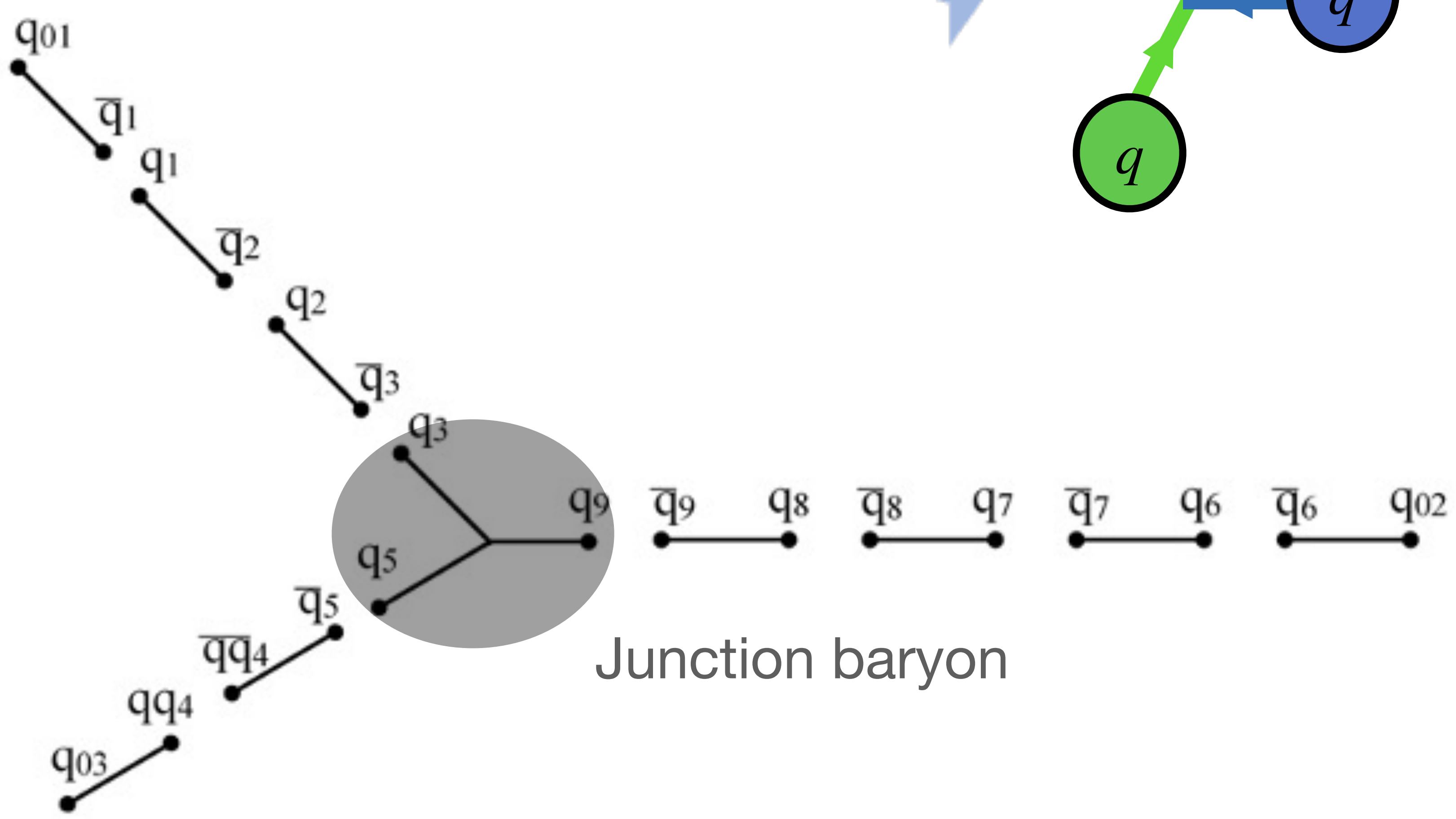


**Junctions come with anti-junctions**
→ Increase total baryonic final states ($\Sigma|B|$) but doesn’t violate total baryon number ($\Sigma B$) conservation.

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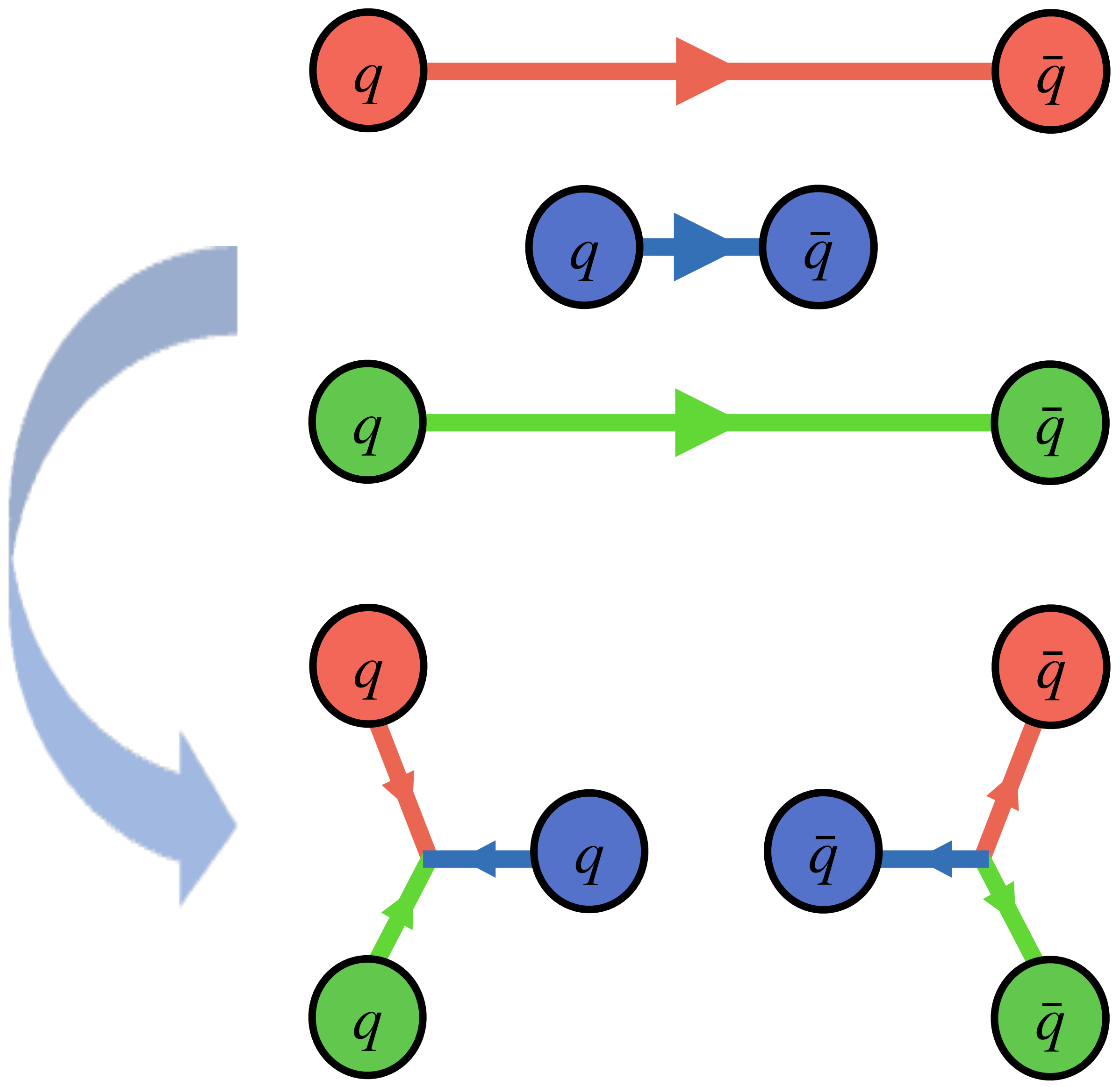
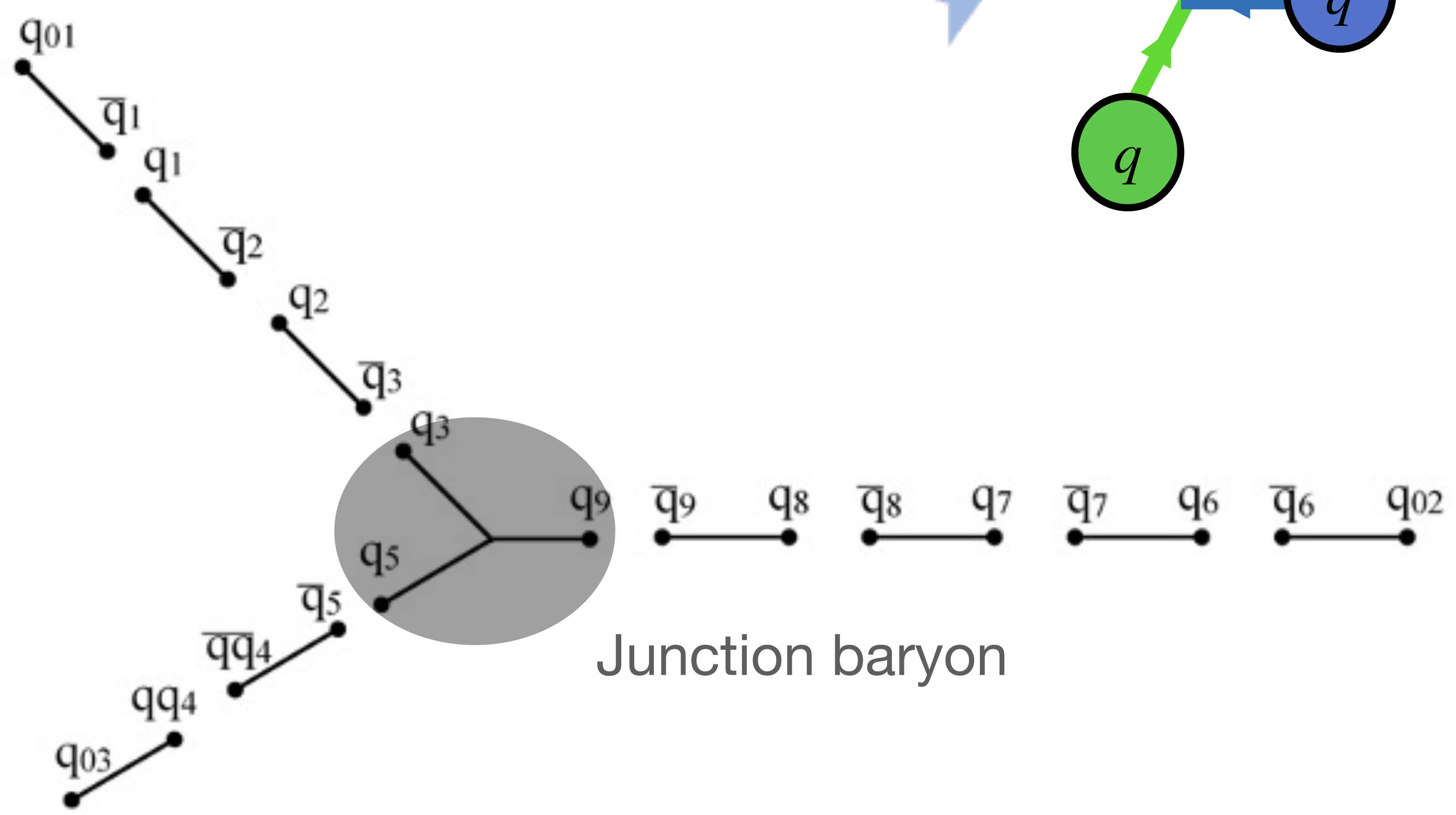


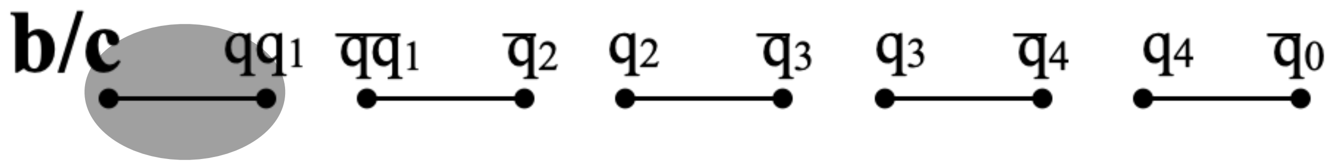
Junction baryon

**Junctions come with anti-junctions**
→ Increase total baryonic final states $(\Sigma|B|)$ but doesn't violate total baryon number $(\Sigma B)$ conservation.

Junctions will predominantly sit at low $p_\perp$
→ increase production of **low $p_\perp$ baryons**

# Heavy Flavour Baryons

**Diquark creation**
(does not require junction topology)



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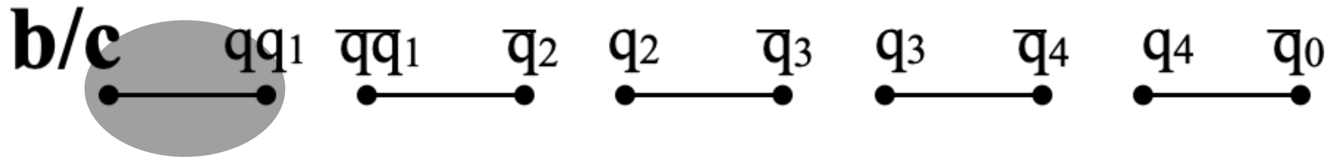
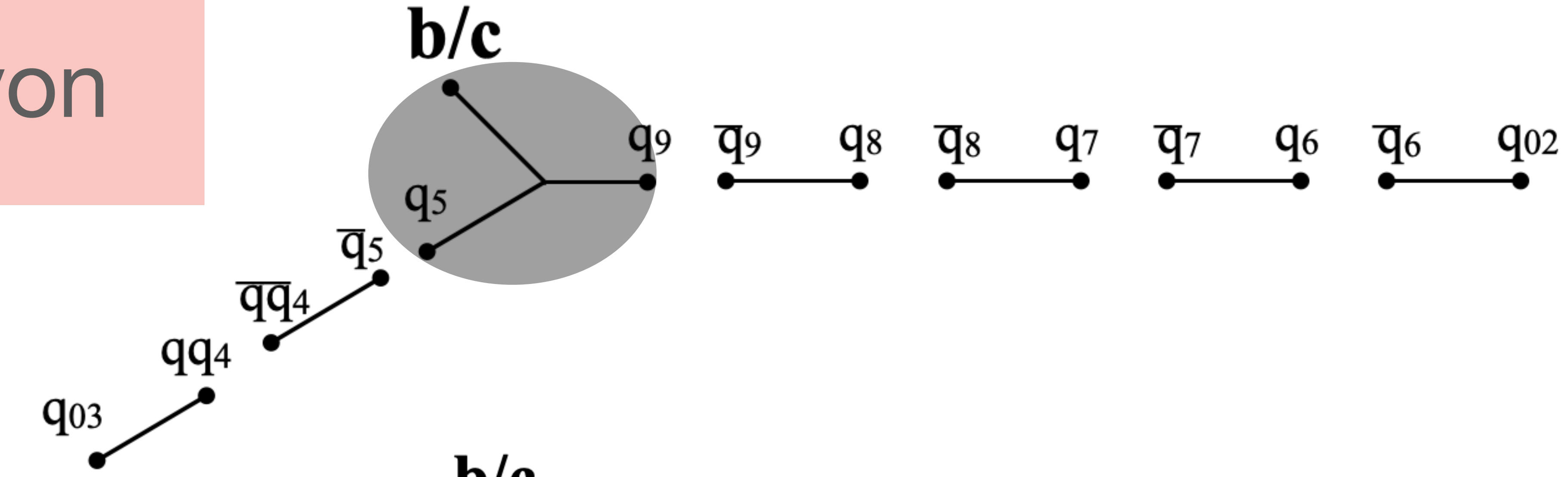
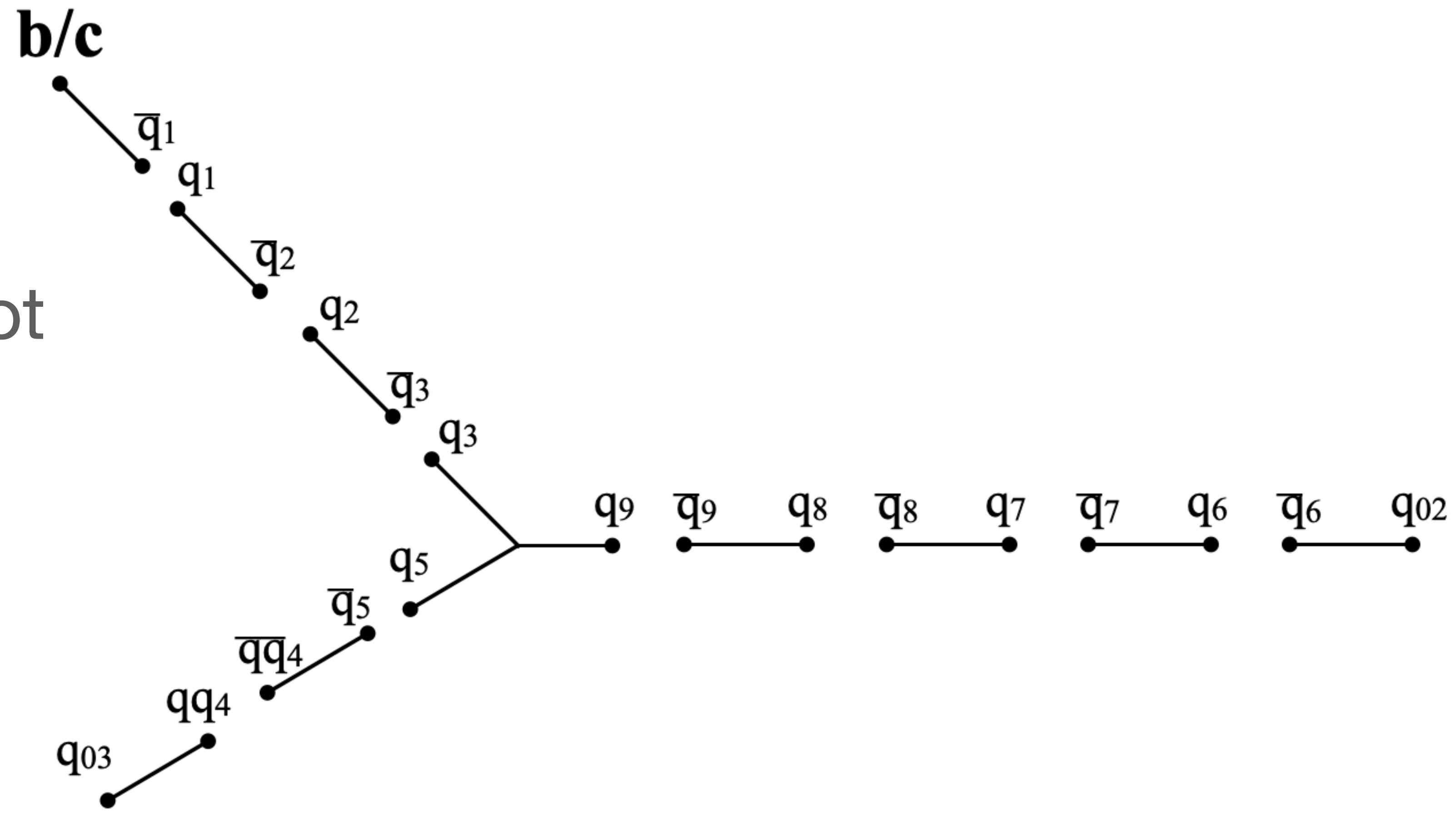



**Junction baryon**




High $p_\perp$ $b/c$ quark typically will not contribute to a junction baryon
→ less likely to get high $p_\perp$ heavy flavour baryons

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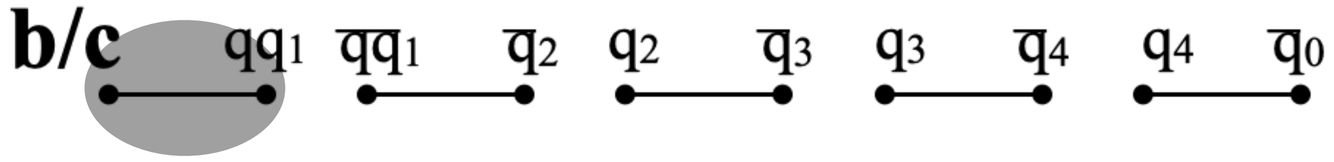


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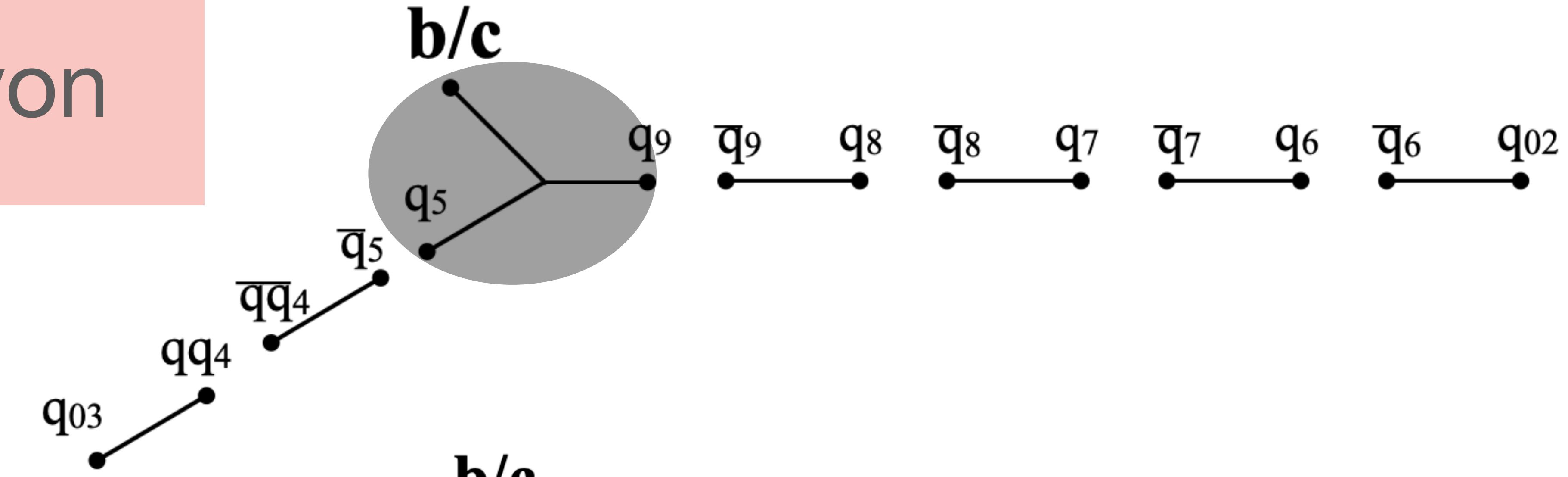


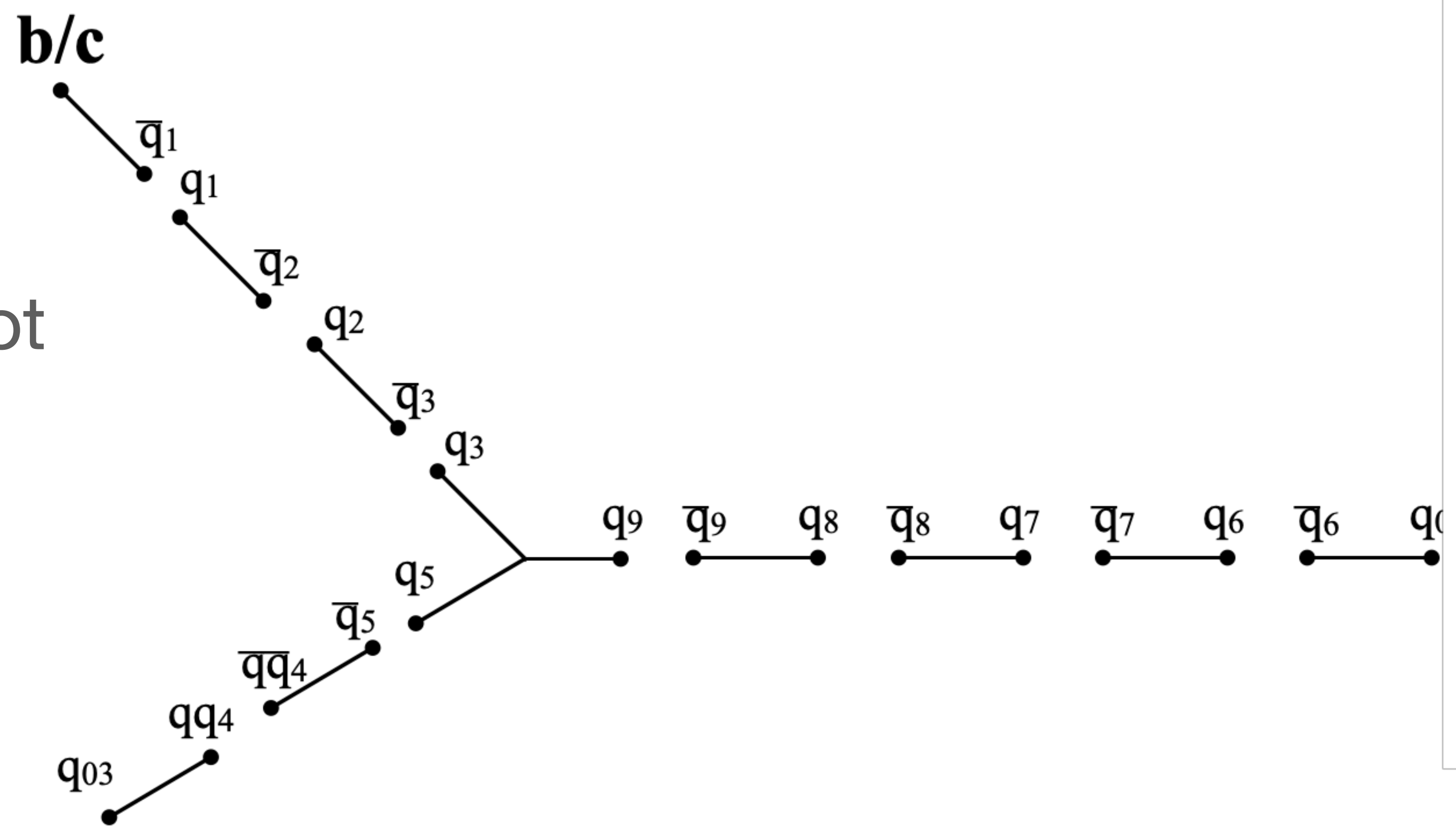


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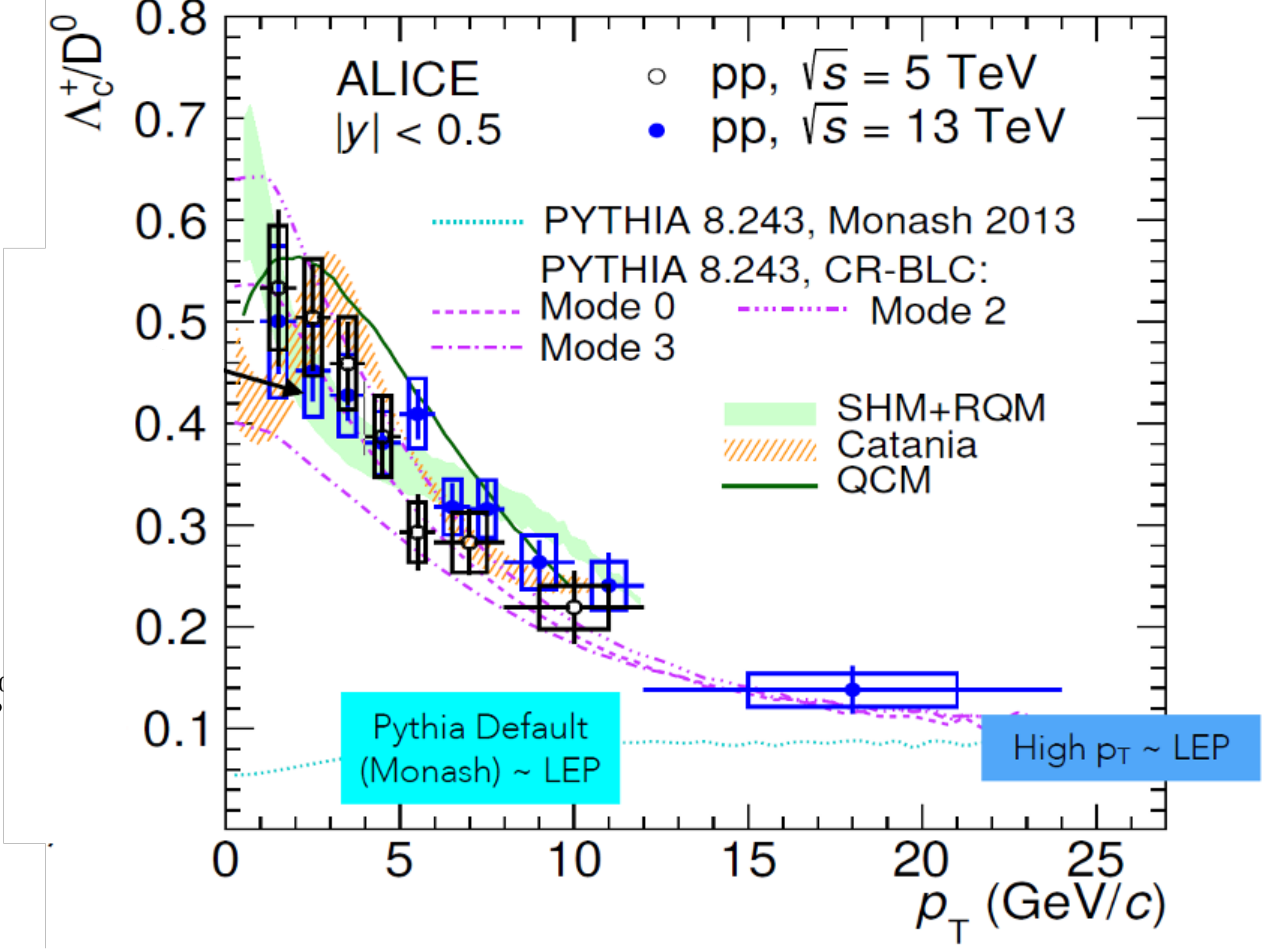
**Charm**
ALICE 2021:

**QCD CR model:**
Inclusion of junctions leads to order-of-magnitude increase in $\Lambda_c/D^0$ at low $p_\perp$

arXiv:2011.06079 arXiv:2106.08278



# Heavy Flavour Baryons

## $\Lambda_b$ asymmetry

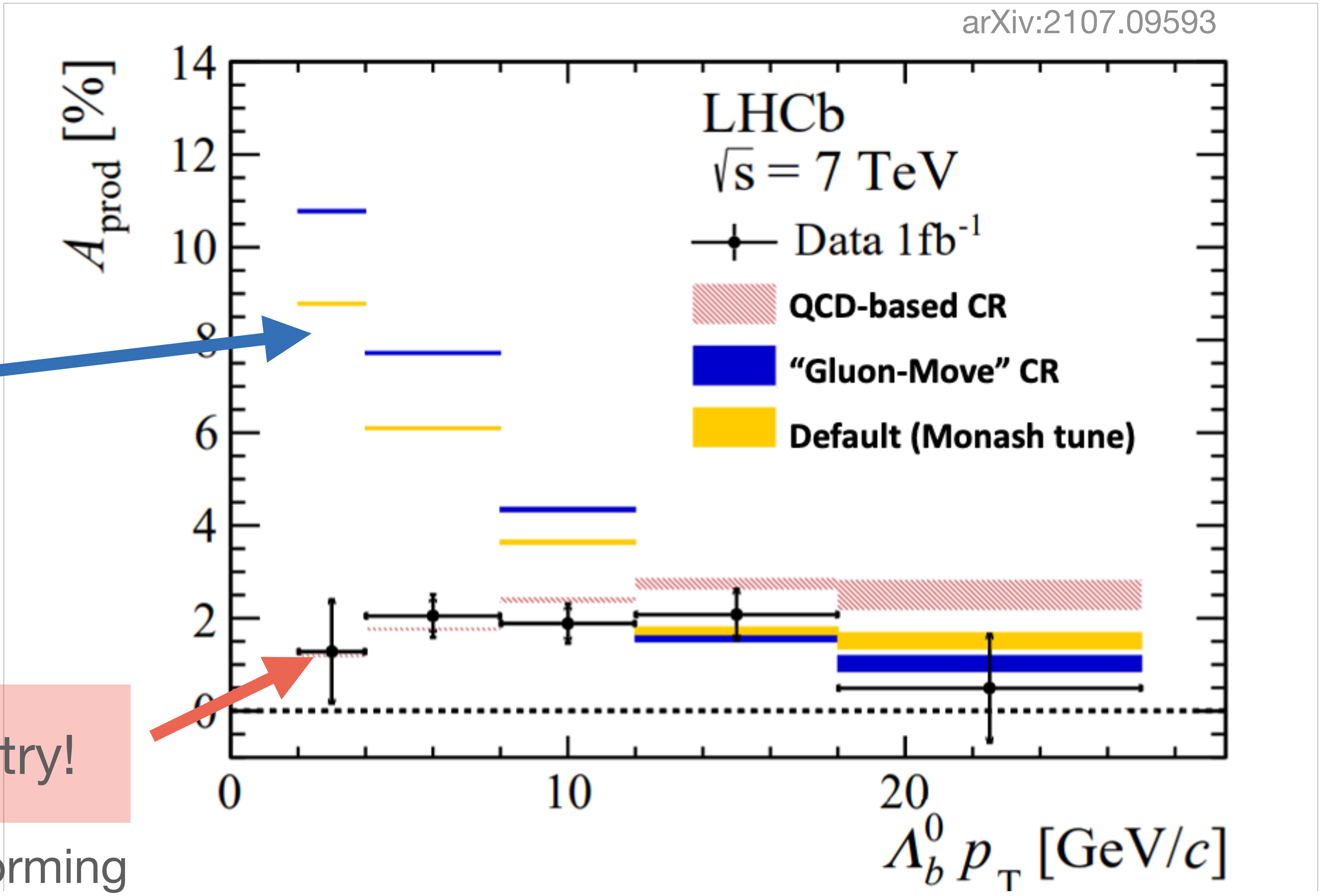
$$A = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$$

**Without junction CR**

Key source of low $p_\perp$ $\Lambda_b$ production is the combination of a **b quark** with the **proton beam remnant**

Same does not apply for $\bar{\Lambda}_b$ as there is **no $\bar{p}$ remnant** at the LHC.

Dilutes asymmetry!

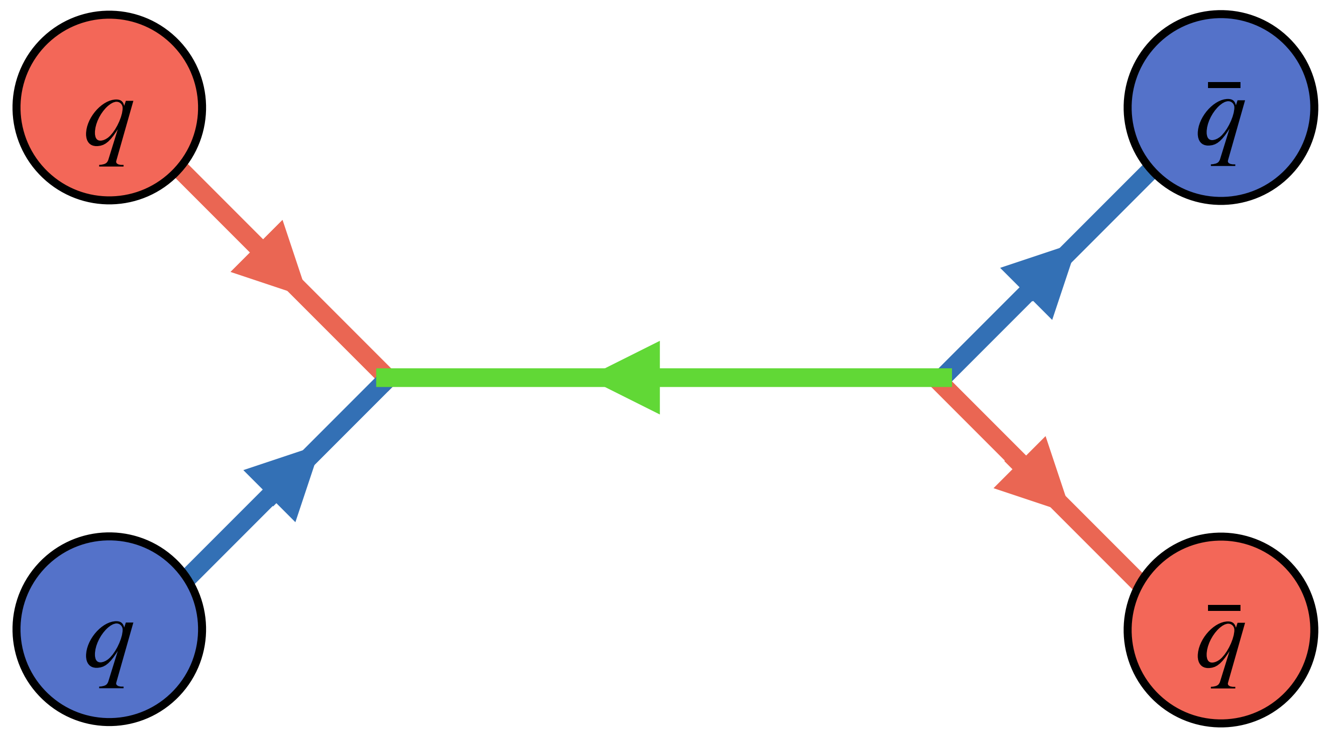



QCD CR adds large amounts of low-$p_\perp$ junctions, forming more $\Lambda_b$ and $\bar{\Lambda}_b$ baryons in equal amounts

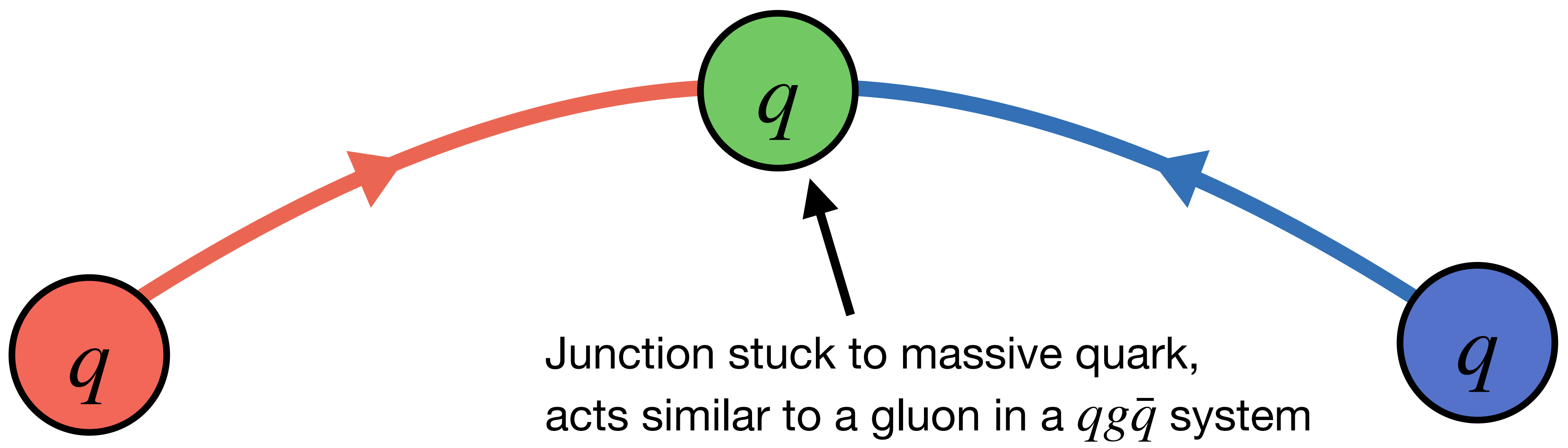
# Complicated Junction Topologies

Lots more we can explore!

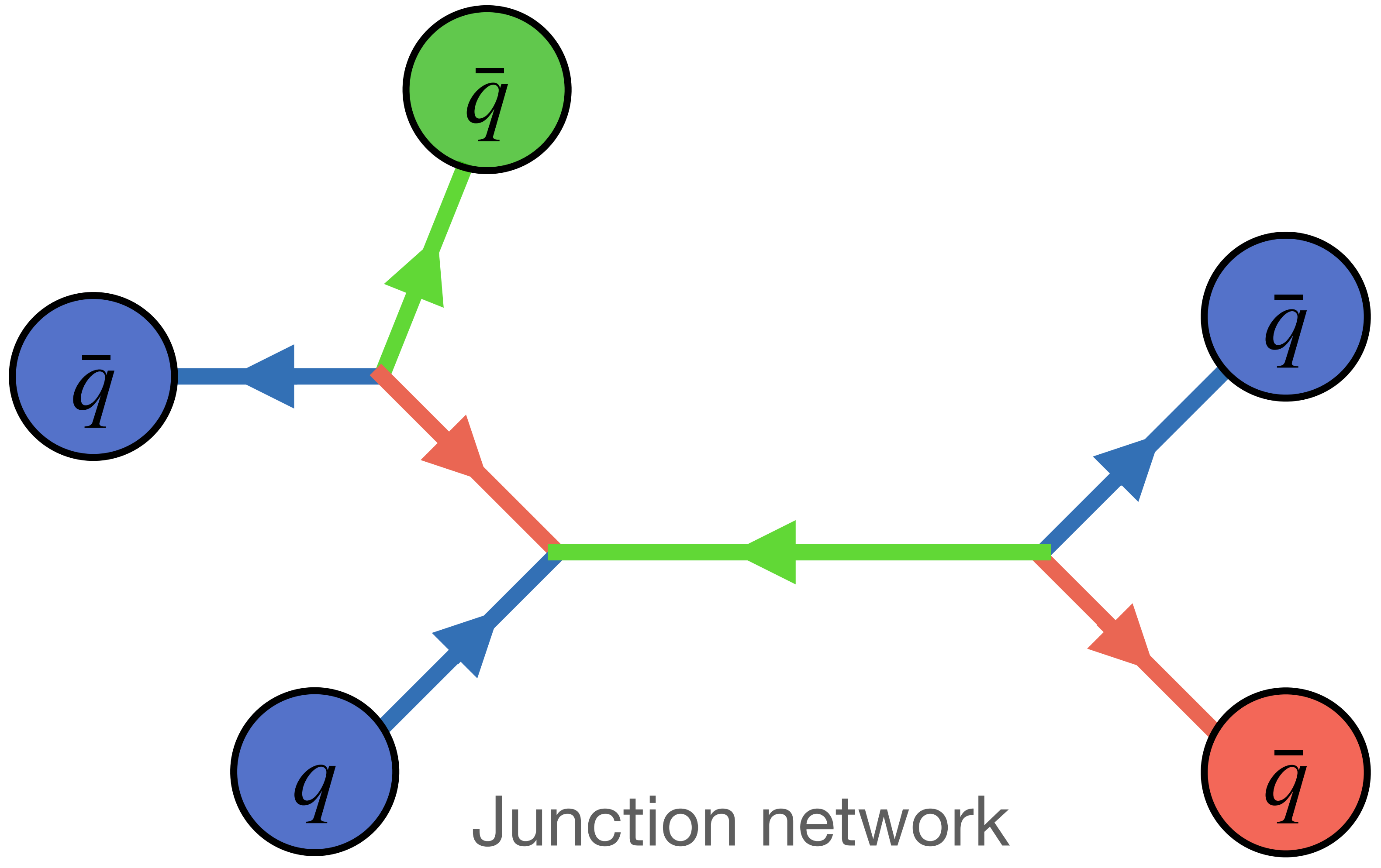
- ➢ PYTHIA currently returns many convergence errors when dealing with junction topologies, particularly with heavy quarks
- ➢ How do “gluon kinks” move through junctions?
- ➢ How do heavy quarks effect junction motion?
- ➢ Could “junction networks” be possible representations for structures such as tetraquarks, pentaquarks, *etc.*




Junction-antijunction system
Possible tetraquark?




Important for heavy-quark junctions topologies !!!

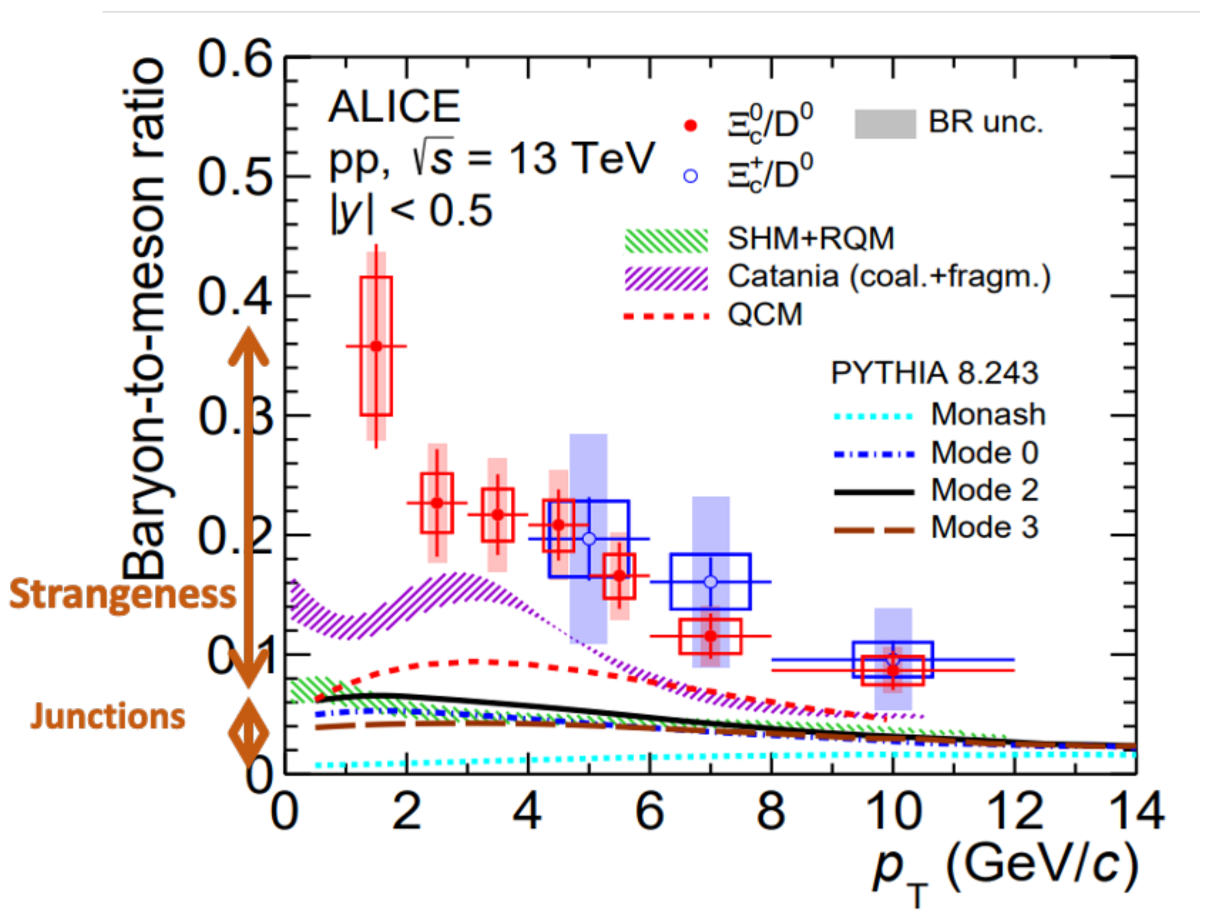


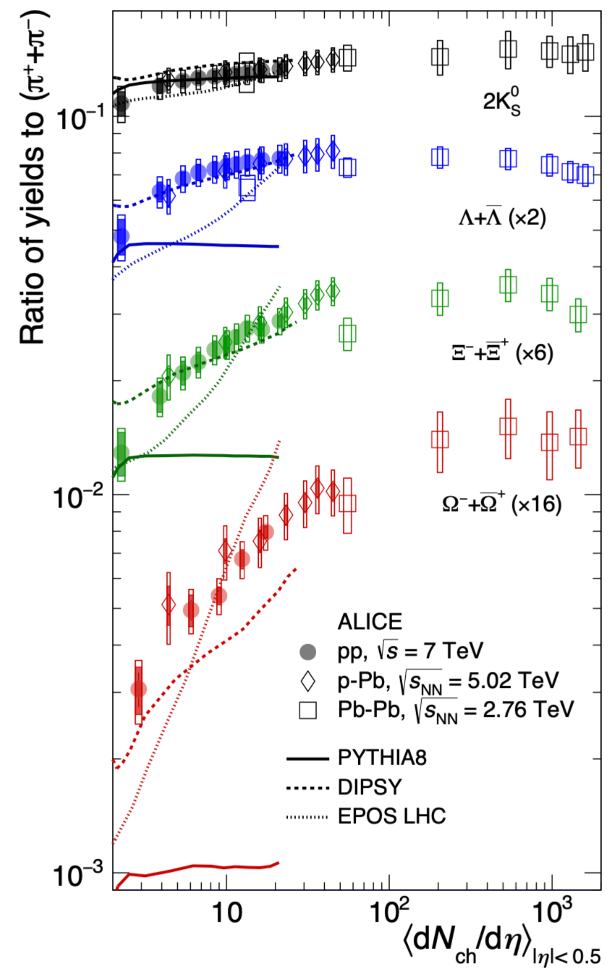

Junction network
Possible pentaquark?

# Lingering Questions...

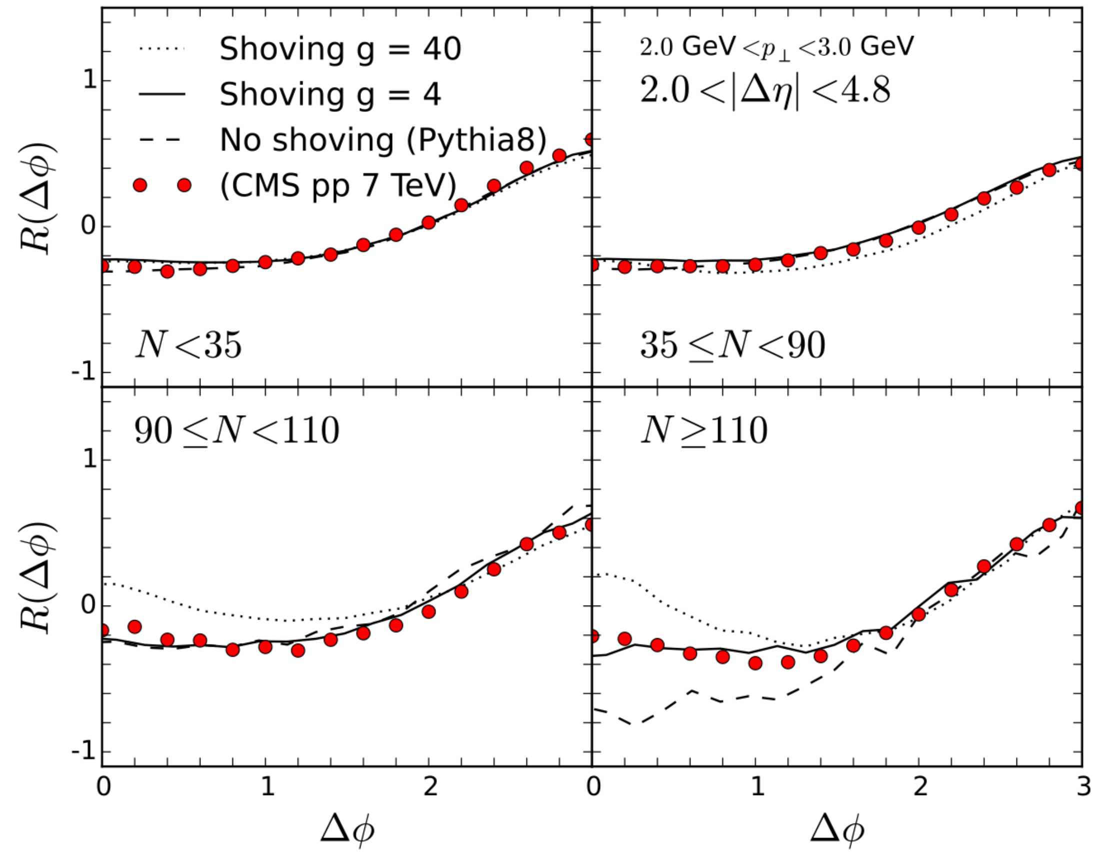
What does default PYTHIA + QCD-based CR not fully describe?

## Strangeness Enhancement

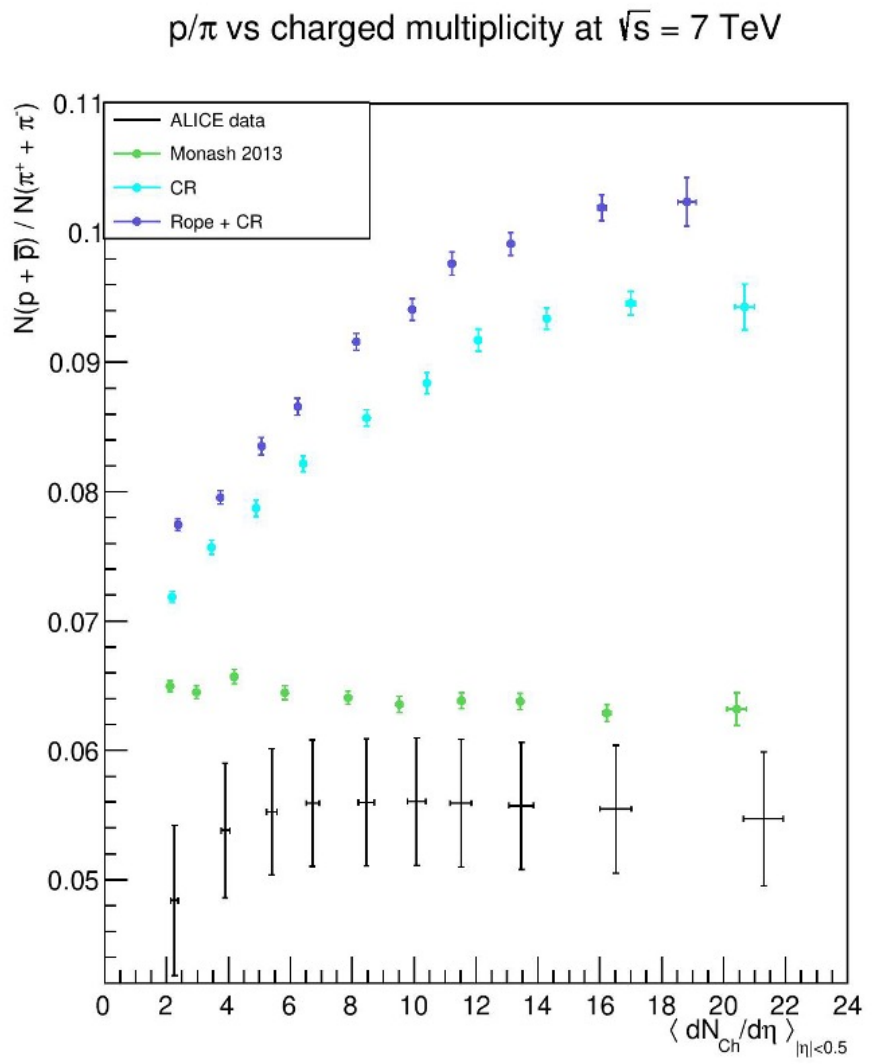



## Near-sided Ridge




## Proton-to-pion ratio




## Strings or QGP?

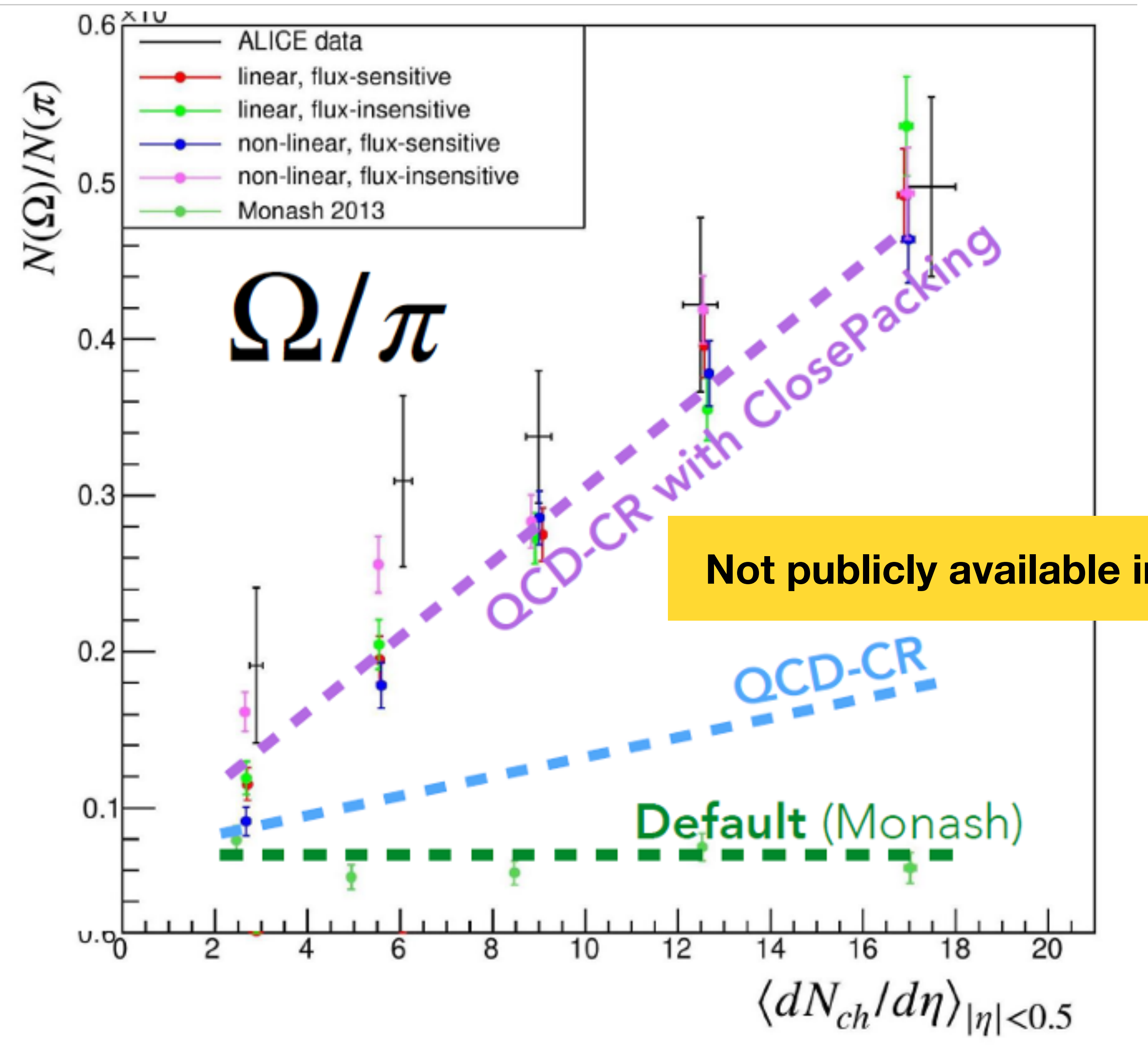
How can we expand the Lund String Model to its furthest consequence?

Or can we make a smooth limit between strings and QGP?

# Strangeness Enhancement

QCD-based CR is **NOT** a mechanism for **strangeness enhancement.**
Therefore look to **collective effects** *i.e.* QCD string interactions
Increase string tension → increase strangeness (and baryons)

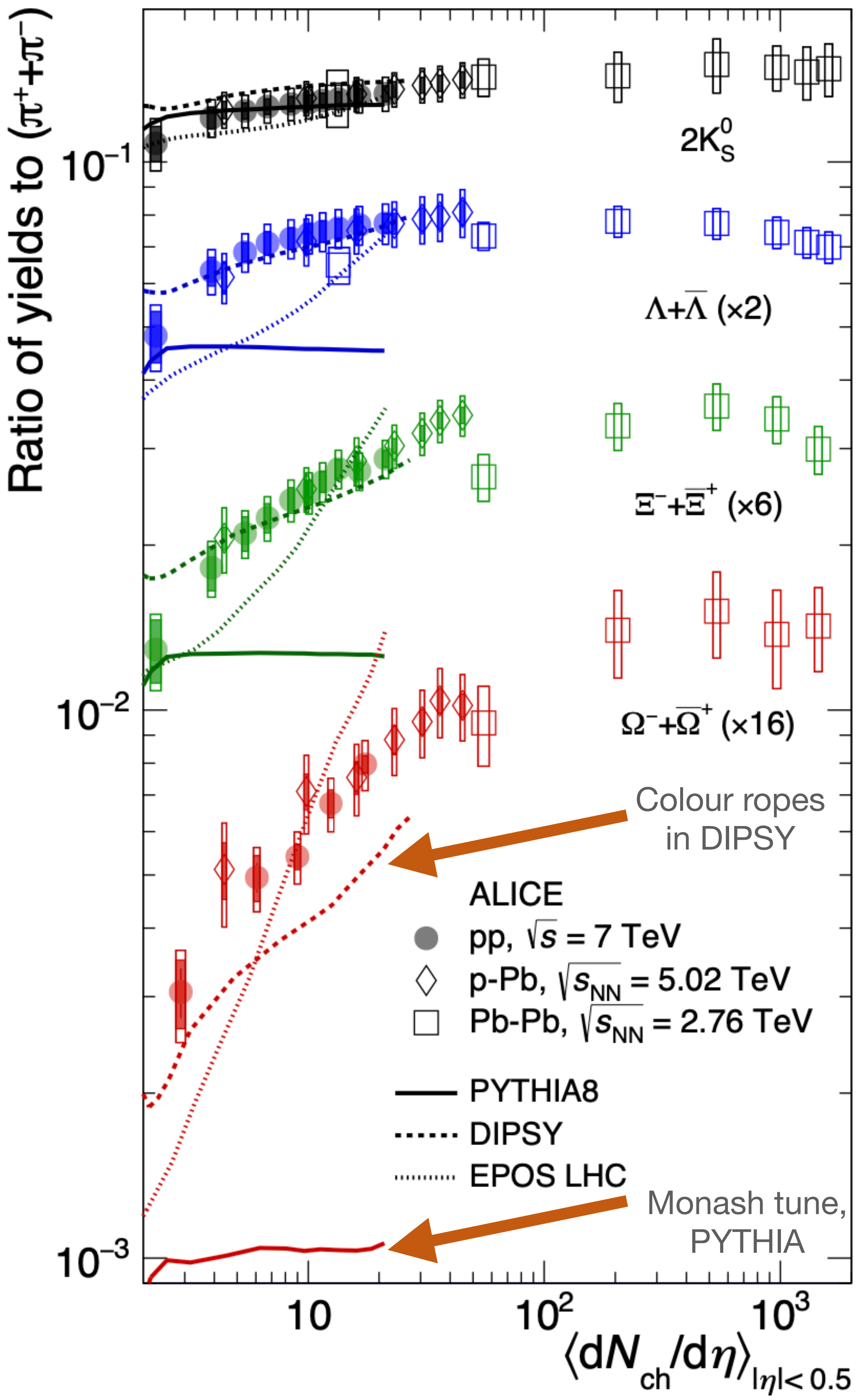
Preliminary results from my honours thesis implementing close-packing model with standard Gaussian string breaks




➢ **Colour ropes:** already implemented in PYTHIA. Requires space-time evolution of strings.

➢ **Close packing model:** simpler mechanism than rope hadronisation, that more naturally compatible with junctions. Current implementation publicly available in PYTHIA only for "thermal" string-breaking model arXiv:1610.09818

arXiv:1606.07424



# Ridge

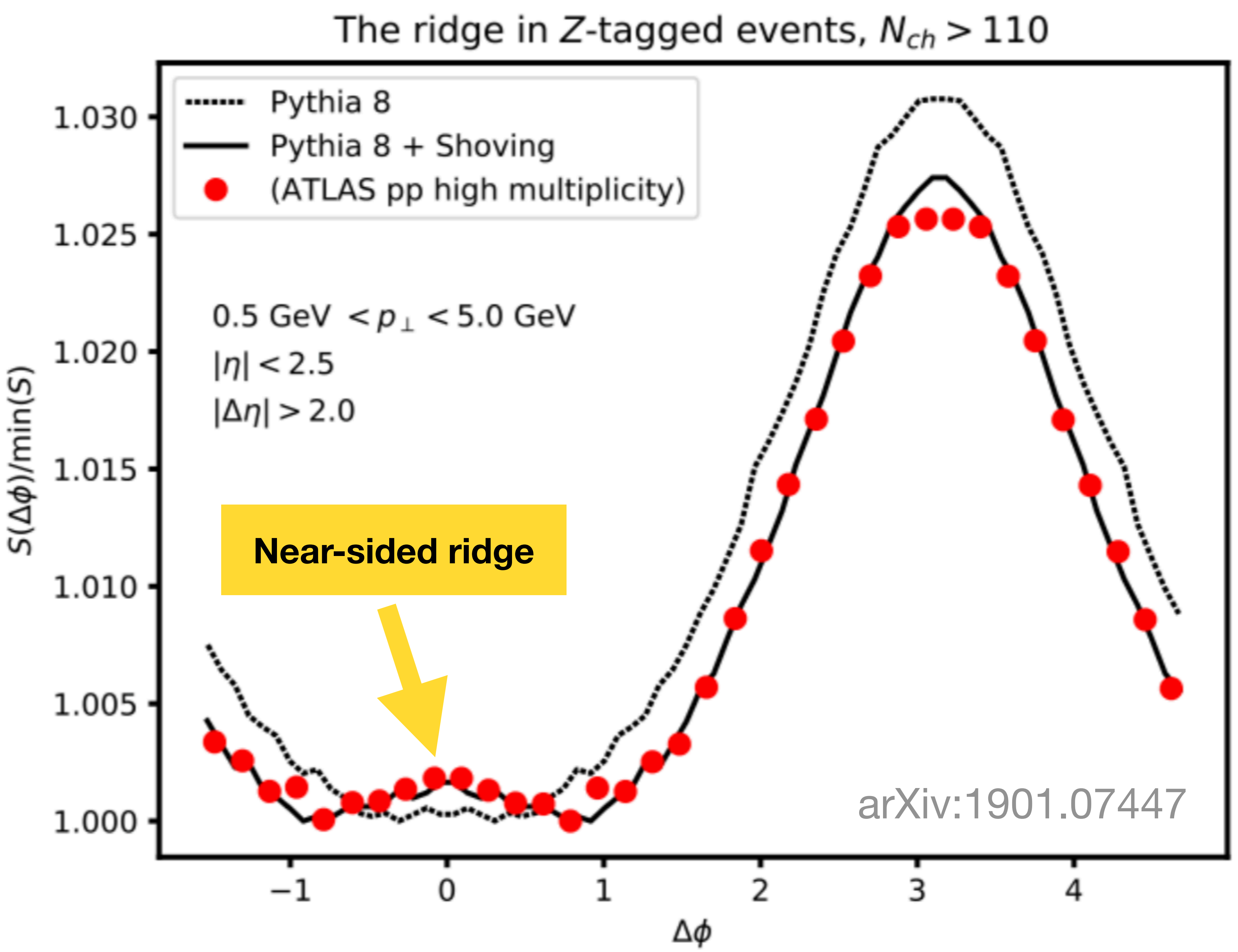
Another sign of collective effects is the **near-sided ridge** seen in high multiplicity events

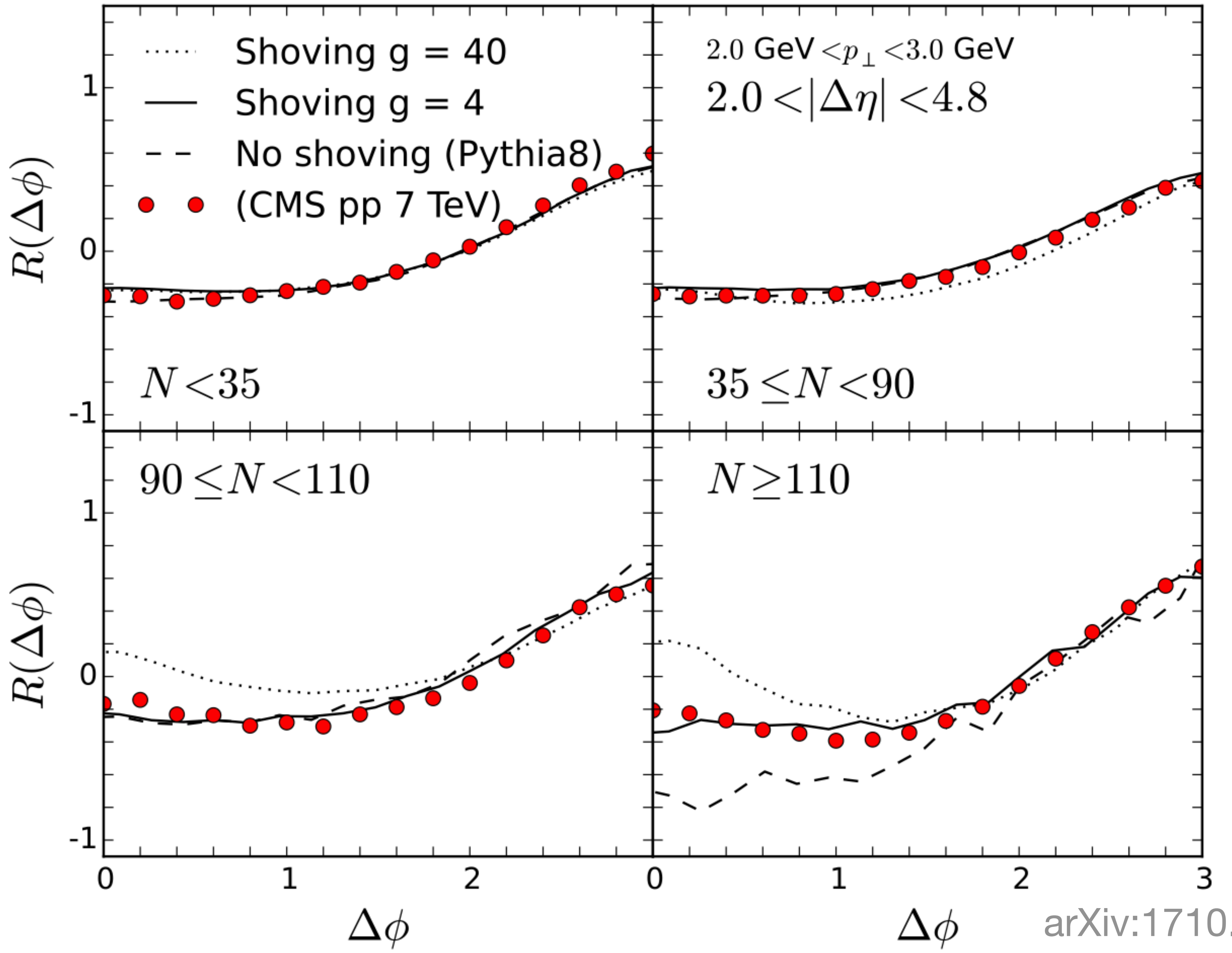
Need to introduce some **azimuthal angular dependence**

➢ Consider repulsive string-string effects, similar to a Lorentz force on wires → **String shoving**

Attractive effects assumed to be mostly taken care of by CR. Based on explicit space-time evolution of strings

Governed by strength parameter *g*



# Proton-to-Pion Ratio

Default tune is tuned to the LEP data and describes the $p/\pi$ ratio well, however **overpredicts** this ratio for $pp$ collisions.

➢ QCD-based CR increases baryon production and describes low pT baryon production

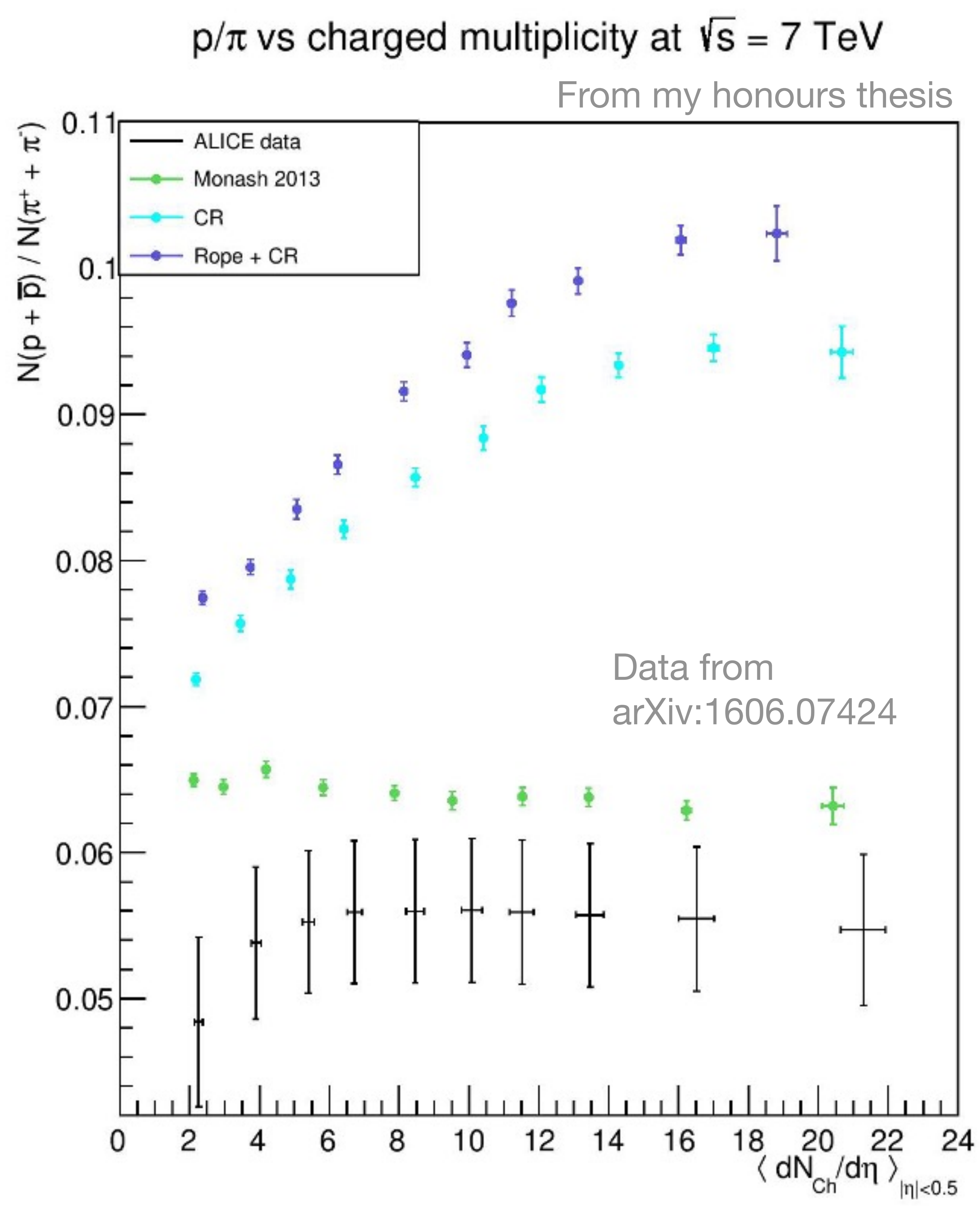
➢ increases baryon production overall

➢ Ropes and close-packing describes strangeness enhancement

➢ increases both strangeness AND baryon production

**Therefore further over predict the $p/\pi$ ratio !!!**

Need to introduce a new mechanism to deal with this:



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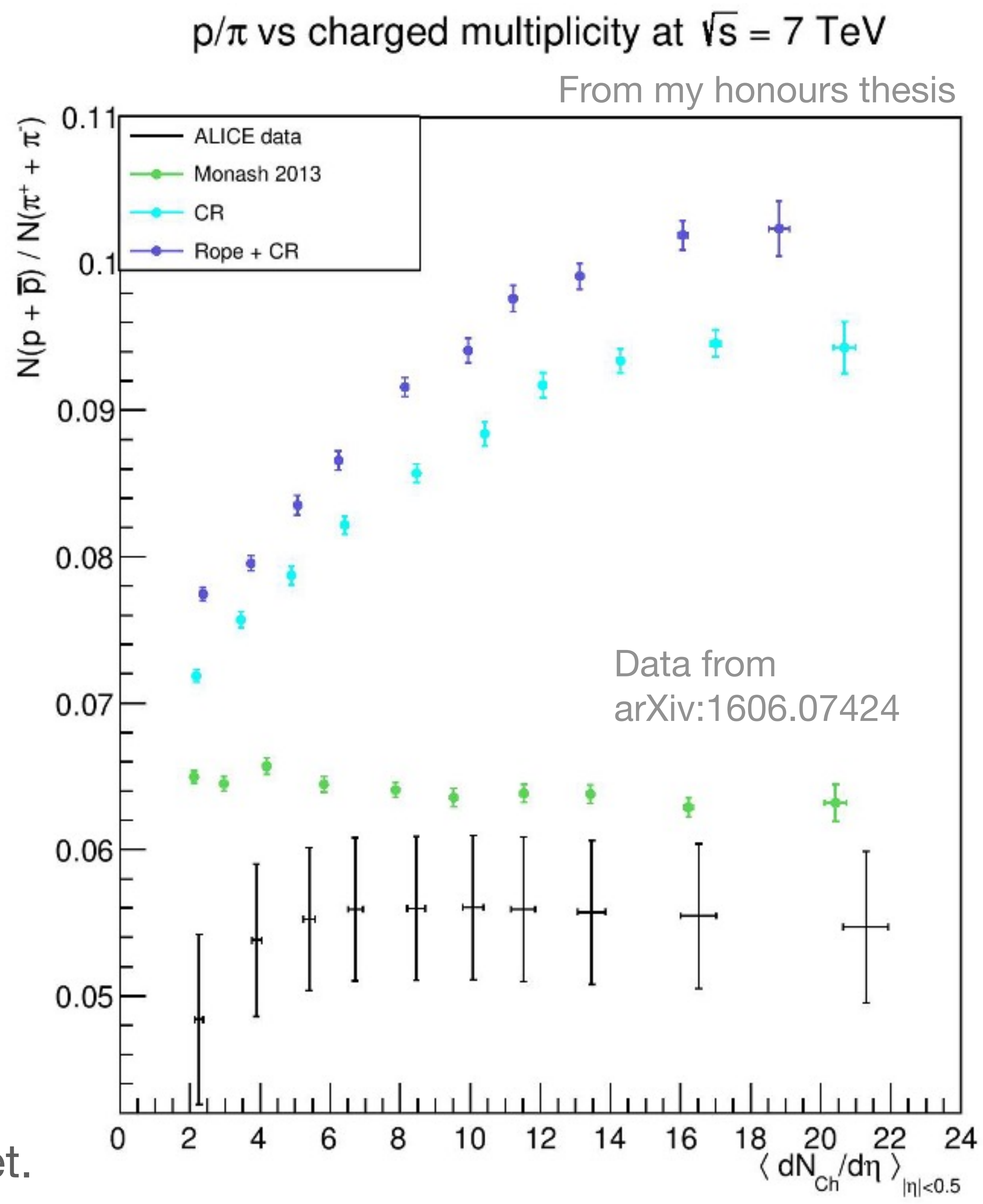
**Therefore further over predict the $p/\pi$ ratio !!!**
Need to introduce a new mechanism to deal with this:

**Hadron rescattering** can decrease number of final state protons and antiprotons via annihilation

$$p\bar{p} \rightarrow \pi^+\pi^-\pi^0$$

Do not have results of this data implementing both CR and hadron rescattering yet.



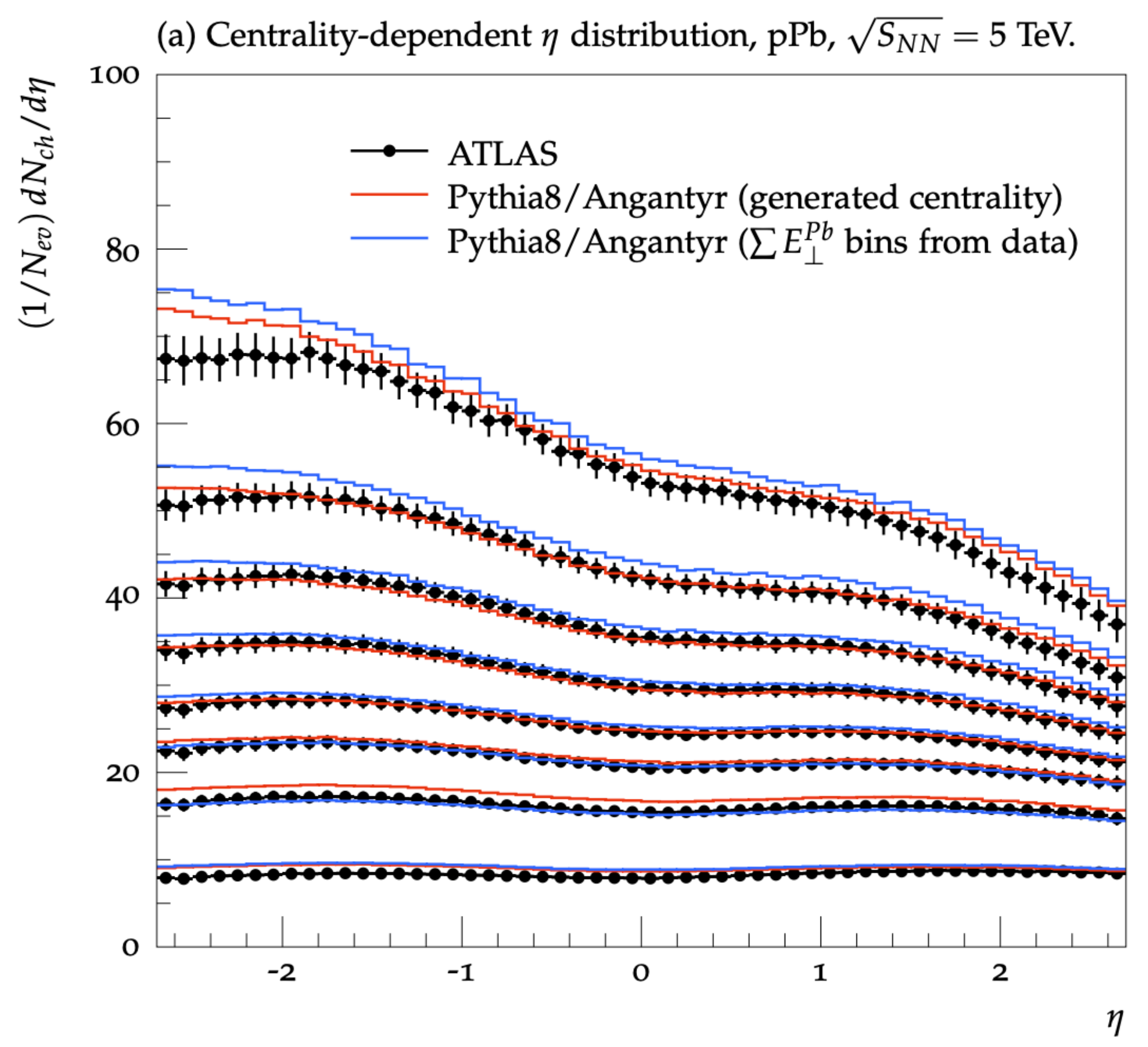
# pA and AA collisions - Angantyr

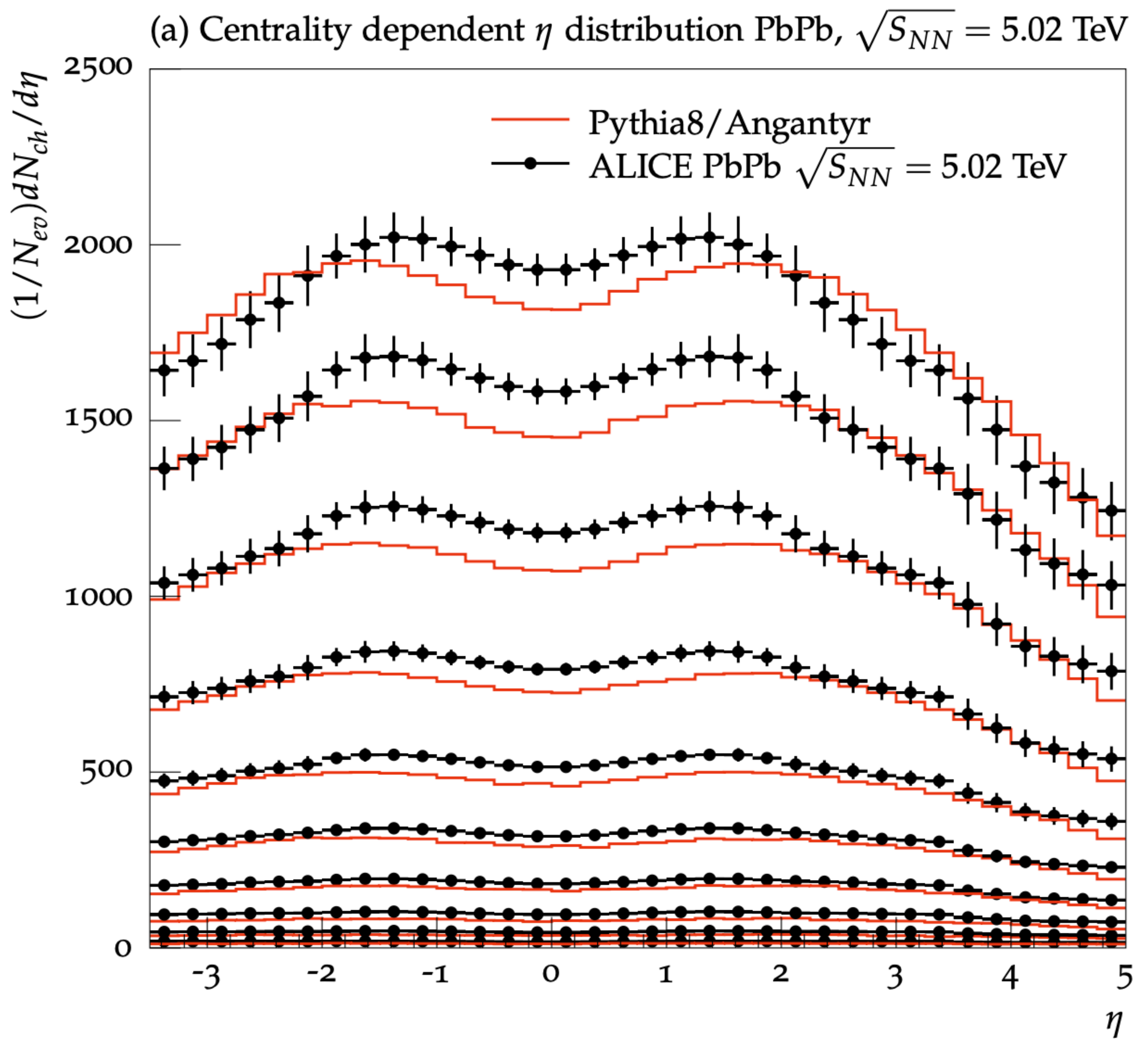
**Angantyr** uses PYTHIA as its base to do pA and AA collisions.

Does so with **no QGP**, instead keeps using strings.

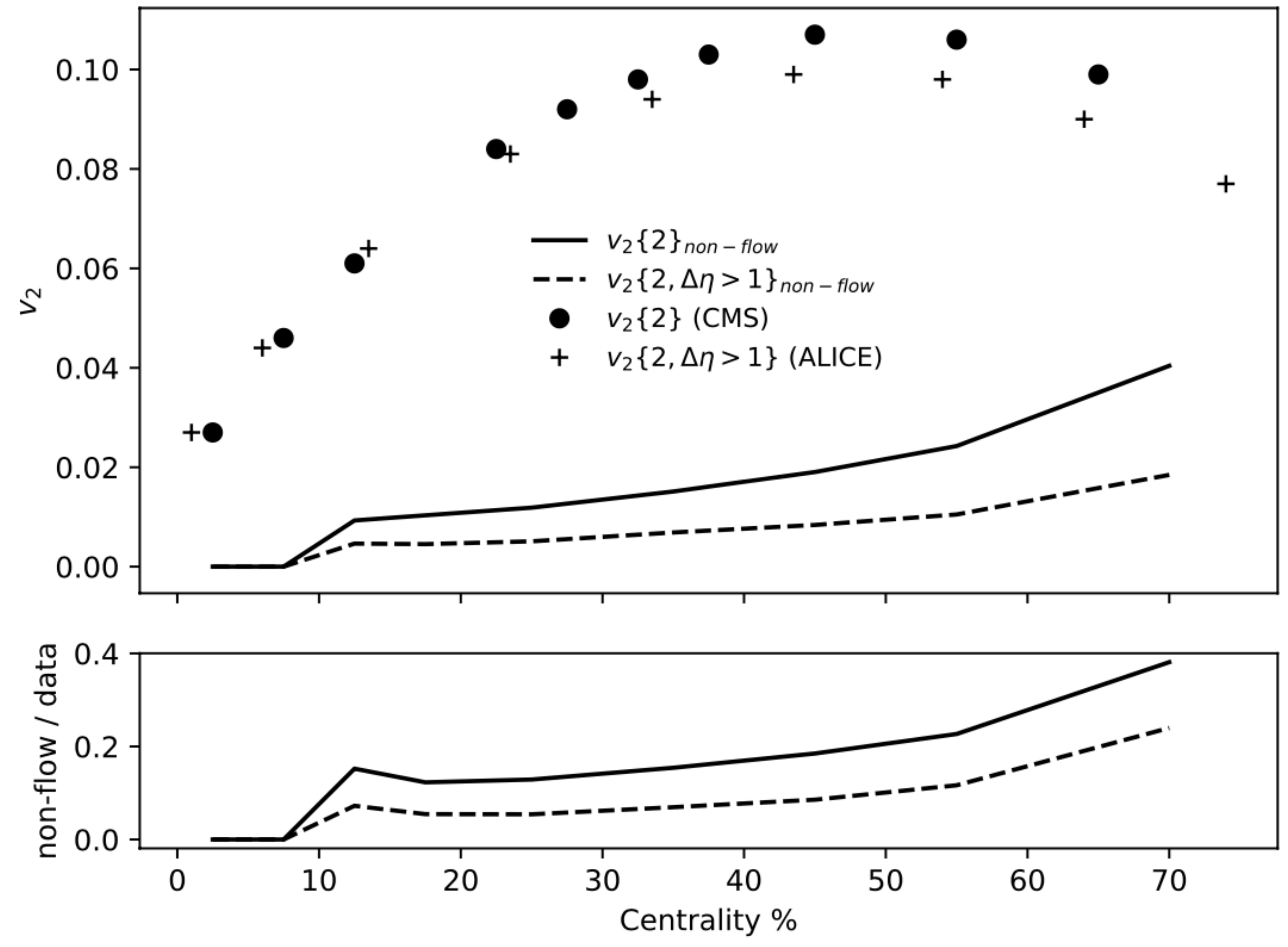
Initial results of the centrality dependent charged multiplicities are promising (considering no tuning to AA collision data).

➢ Requires collective effects to describe pA or AA data fully: *e.g.* cannot reproduce elliptic flow coefficient. Further work and testing required.




arXiv:1806.10820



# pA and AA collisions - Angantyr

**Angantyr** uses PY

Does so with **no**

**Questions to explore:**

Can strings + string collective effects describe collision events from pp to AA?

*OR*

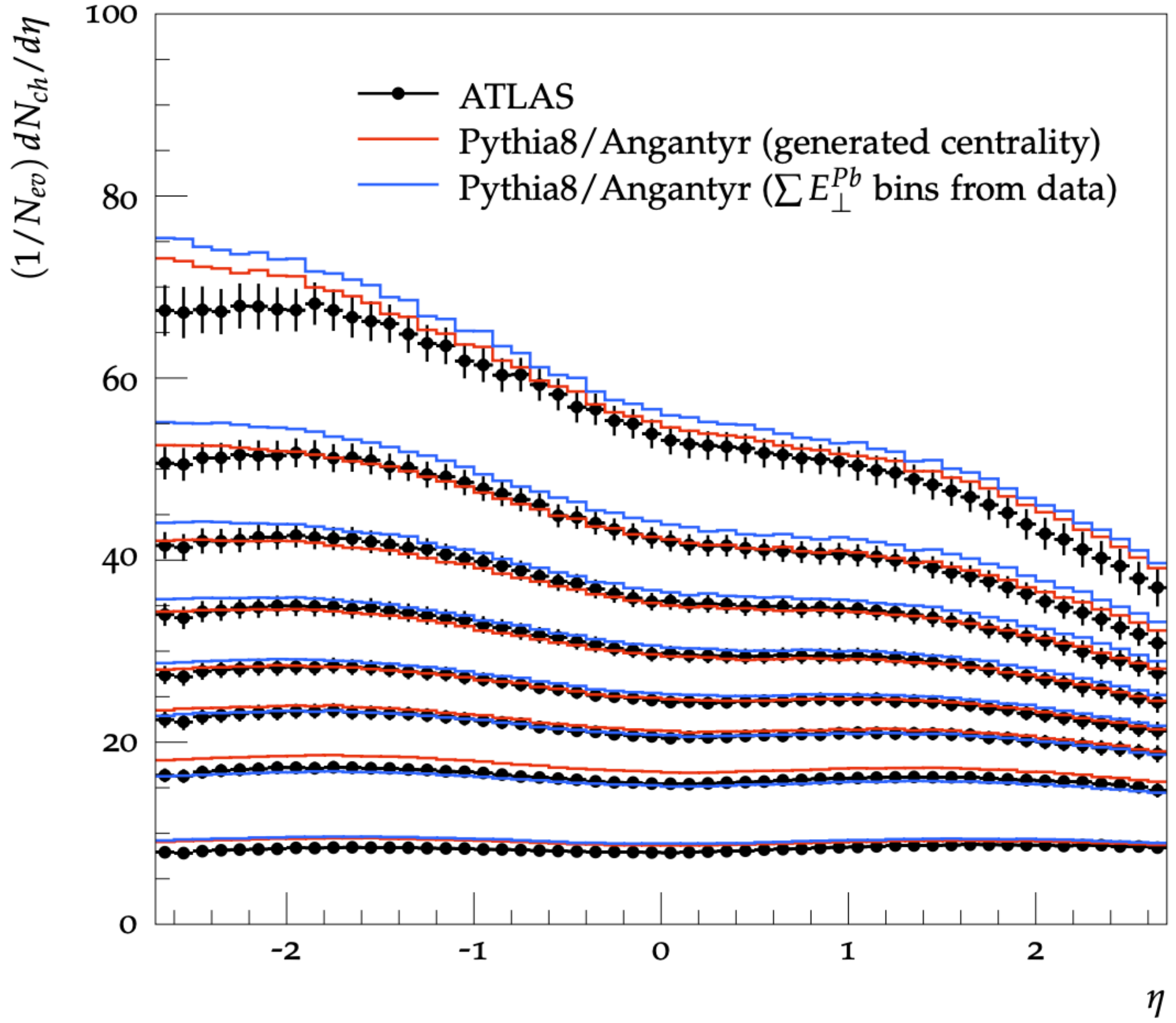
Can we create a smooth transition between strings and QGP?

Initial results of the … collision data).

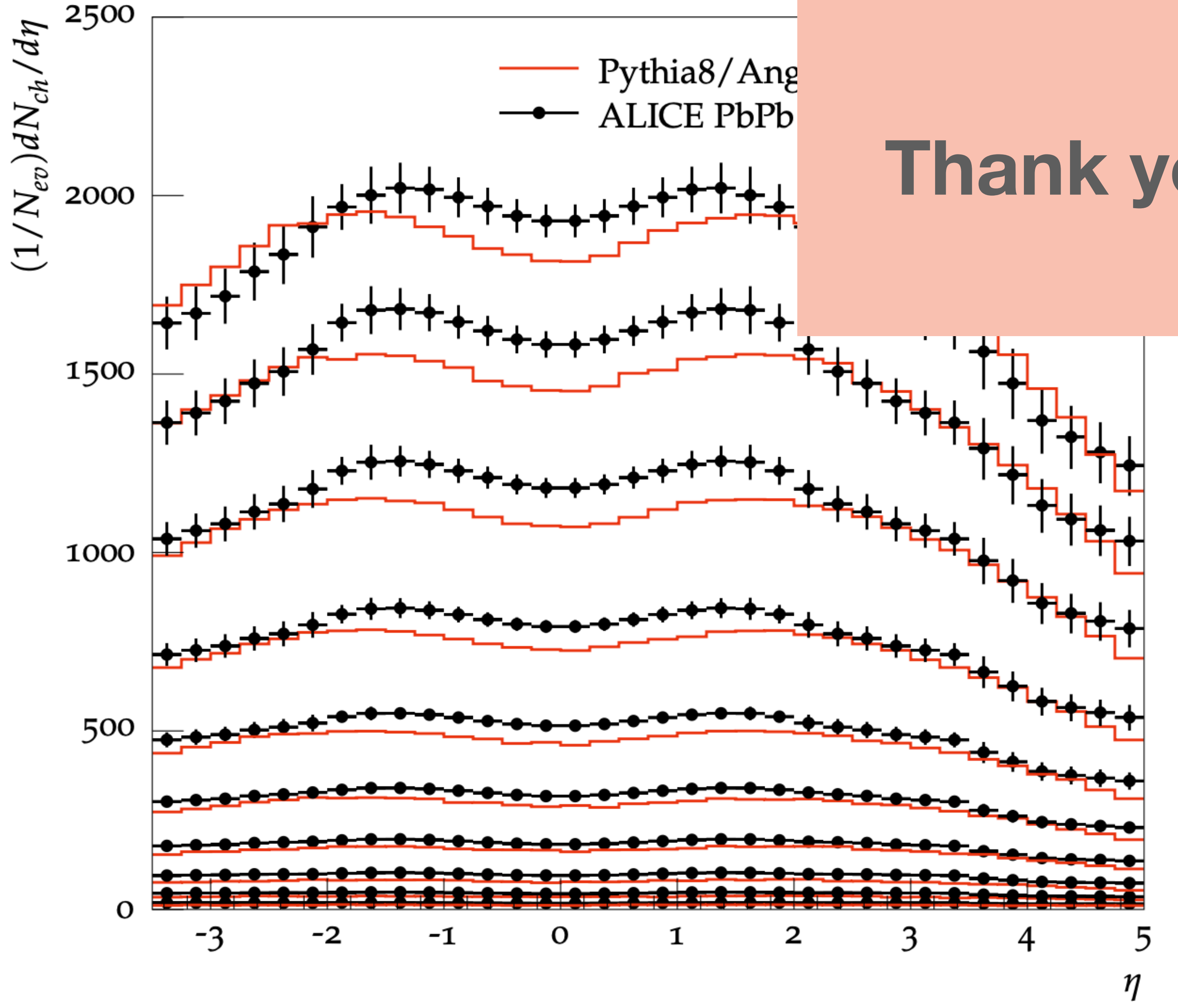
➢ Requires col … efficient.

Further work

(a) Centrality-dependent $\eta$ distribution, pPb, $\sqrt{S_{NN}} = 5$ TeV.




(a) Centrality dependent $\eta$ distribution PbPb, $\sqrt{S_{NN}} = 5.02$ TeV

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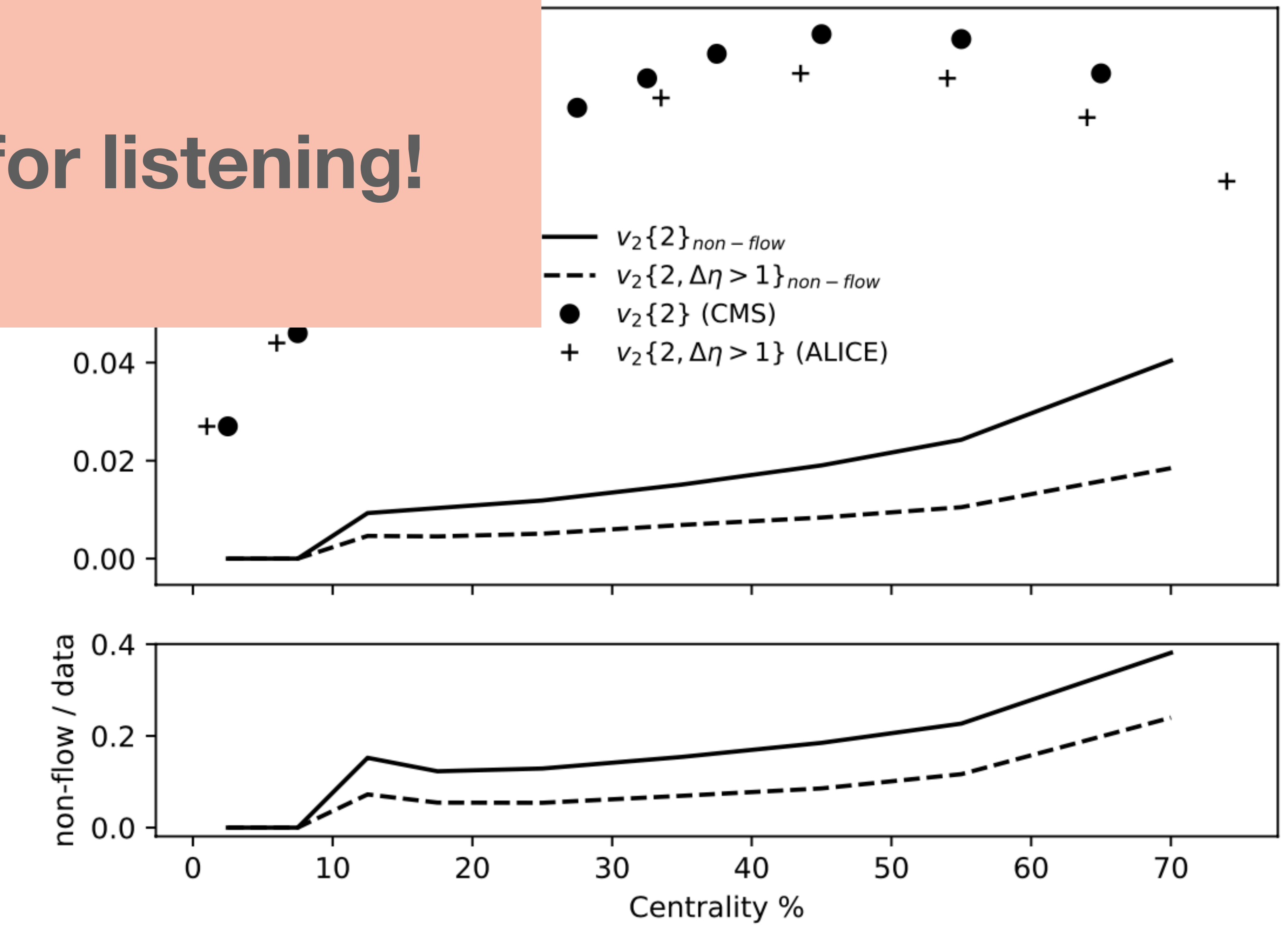
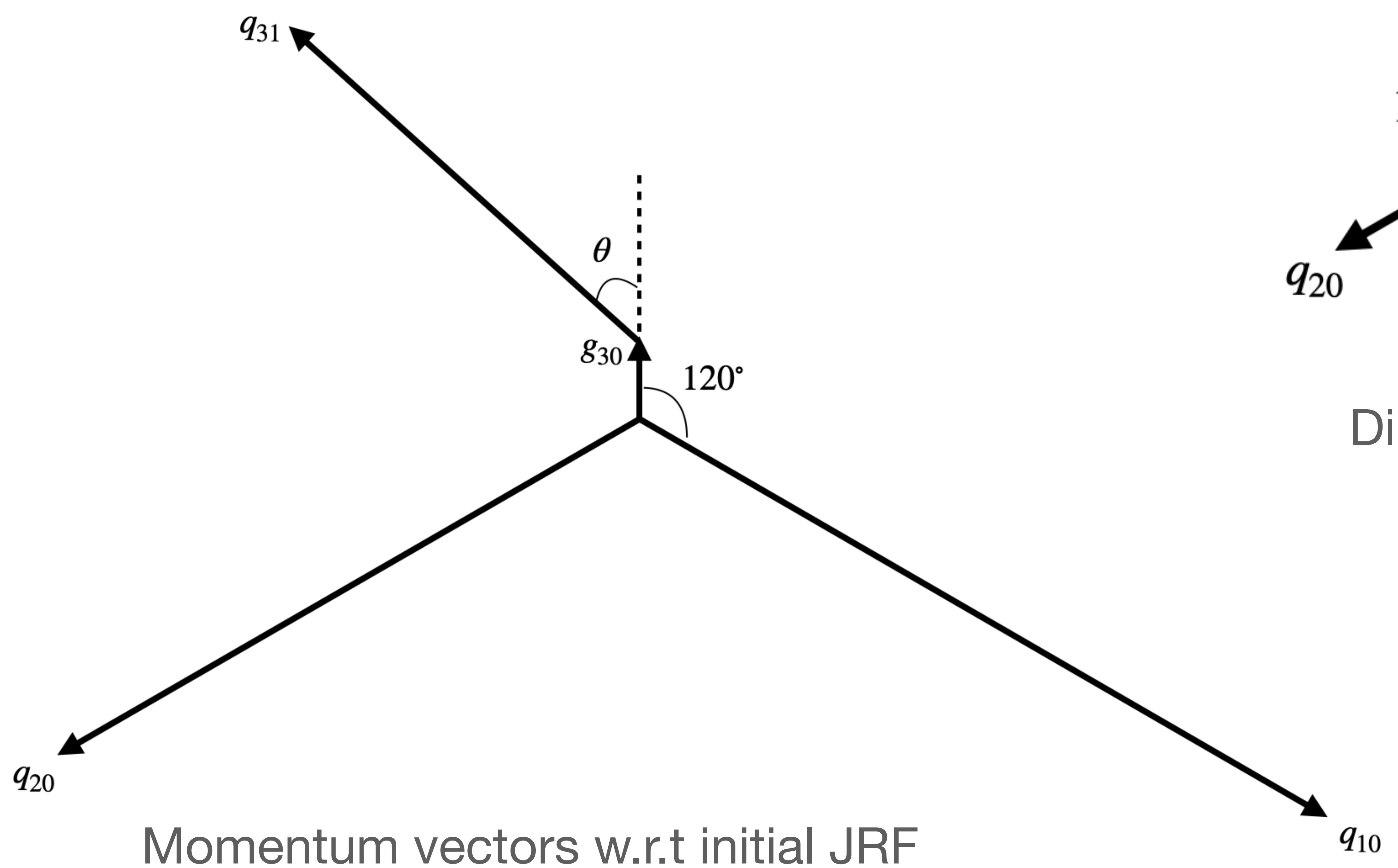


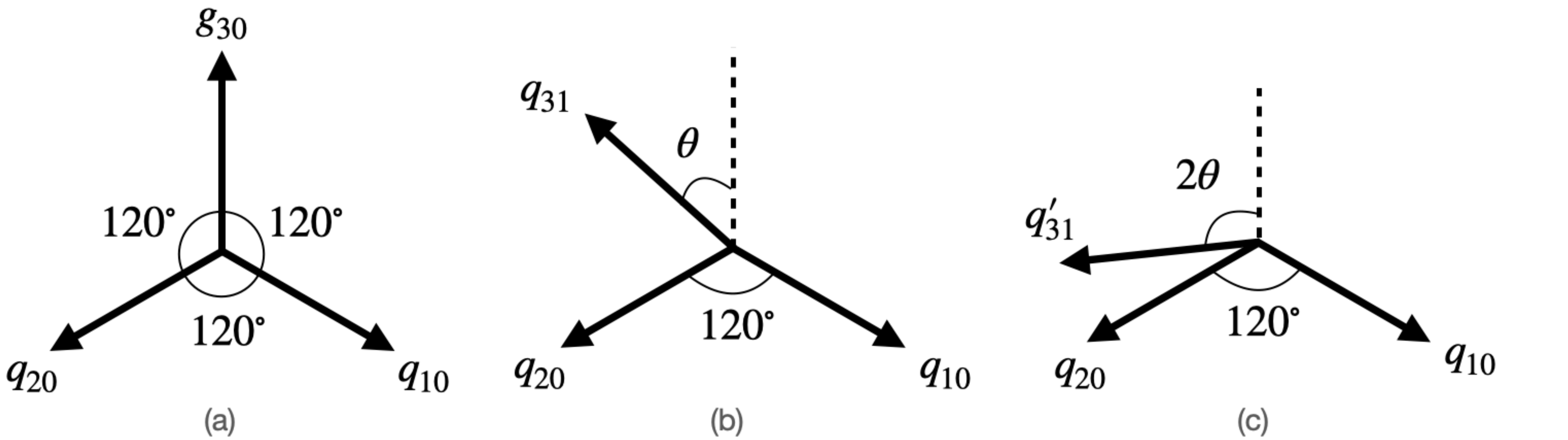

**Thank you for listening!**

# Backup Slides

# Gluon hitting junction

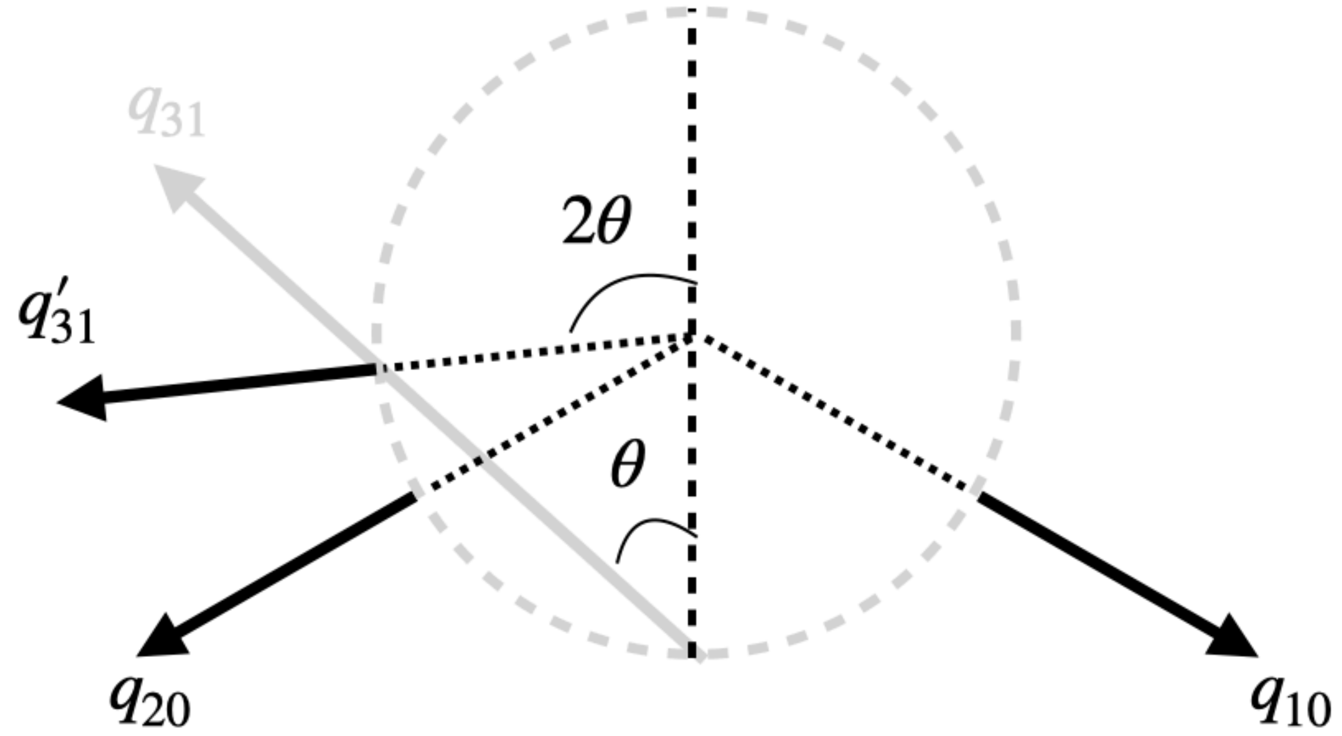



Momentum vectors w.r.t initial JRF
(3-momenta assumed to be on a single plane for simplicity)




Direction of 3-momentum that defines pull on junction w.r.t initial JRF

Diagram used to calculate 3-momentum in (c):



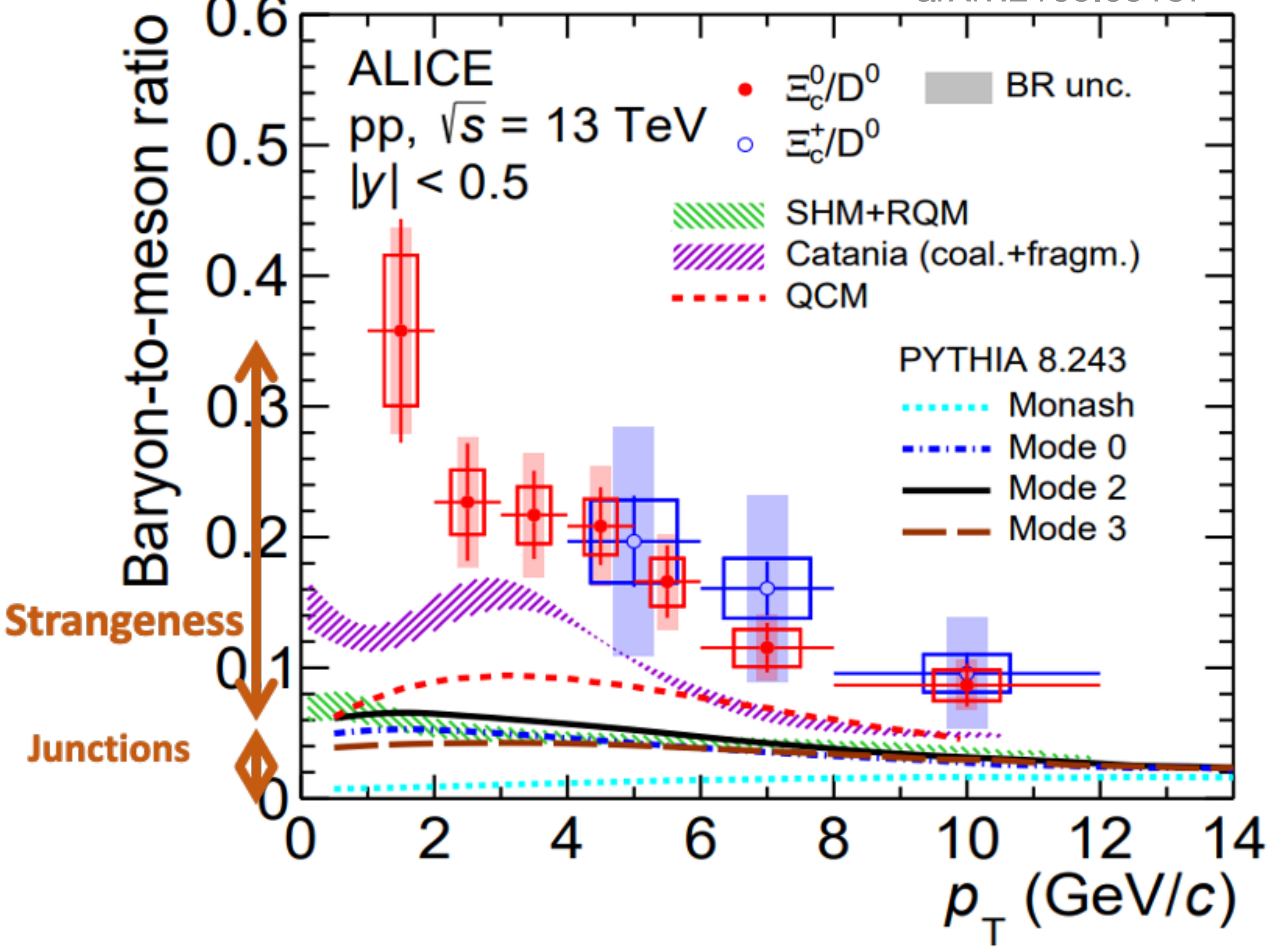
# Strangeness Enhancement

QCD-based CR is **NOT** a mechanism for **strangeness enhancement.**

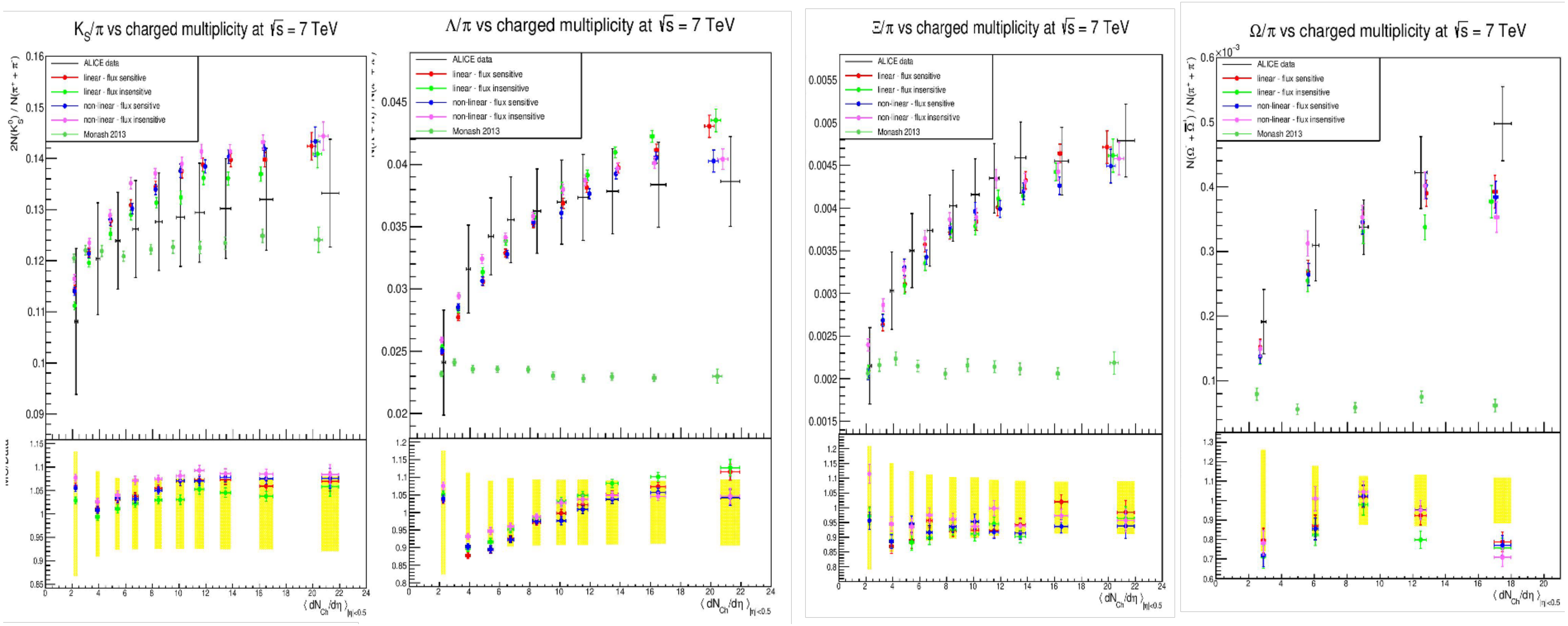
Therefore look to **collective effects** *i.e.* QCD string interactions

Increase string tension → increase strangeness (and baryons)

arXiv:2105.05187



# Close-packing



# Lund String Model

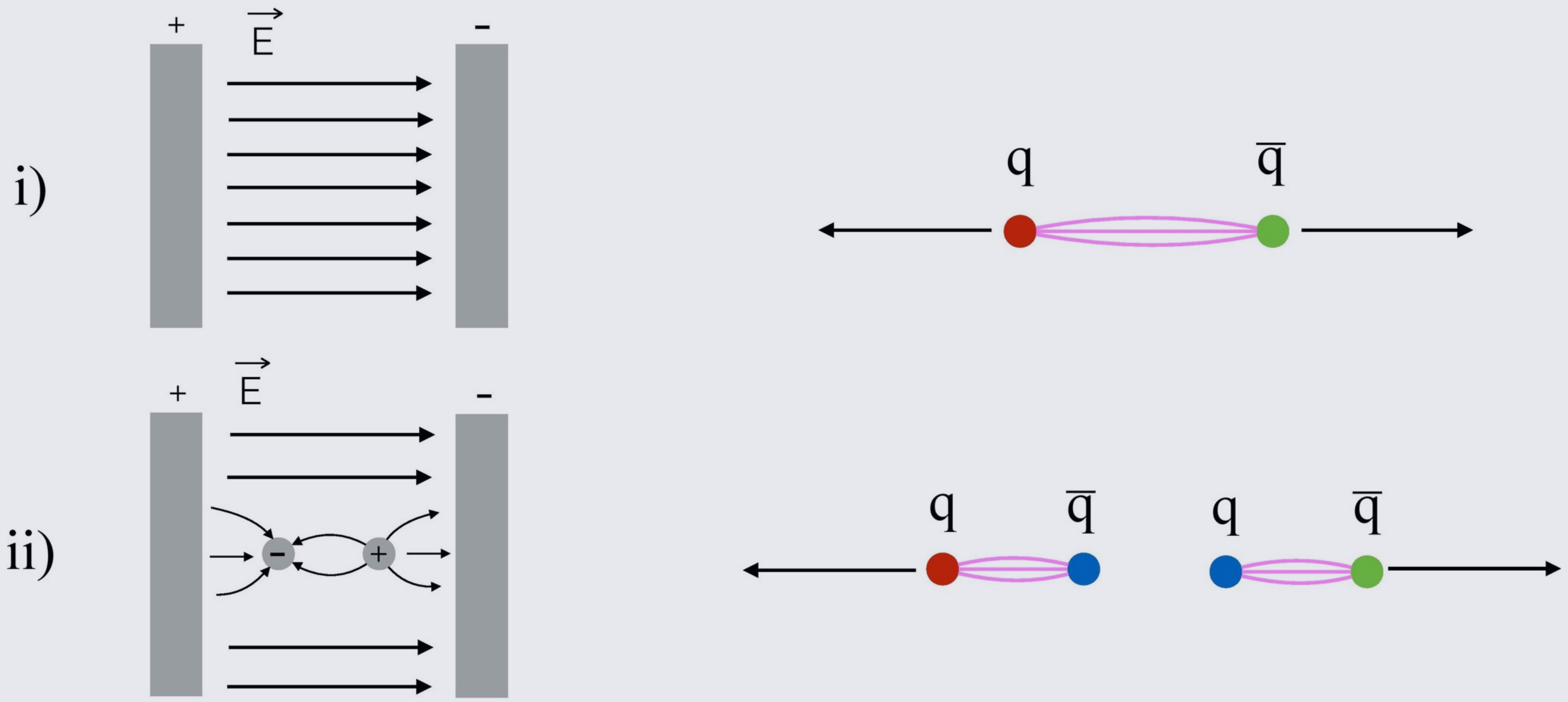
## Symmetric Fragmentation Function[3]

- Longitudinal component of fragmentation
- Probability hadron will have fraction z of the total energy

$$f(z) = N\,\frac{1}{z}(1-z)^{a}\exp\left(\frac{-b\,m_{\perp}^{2}}{z}\right)$$

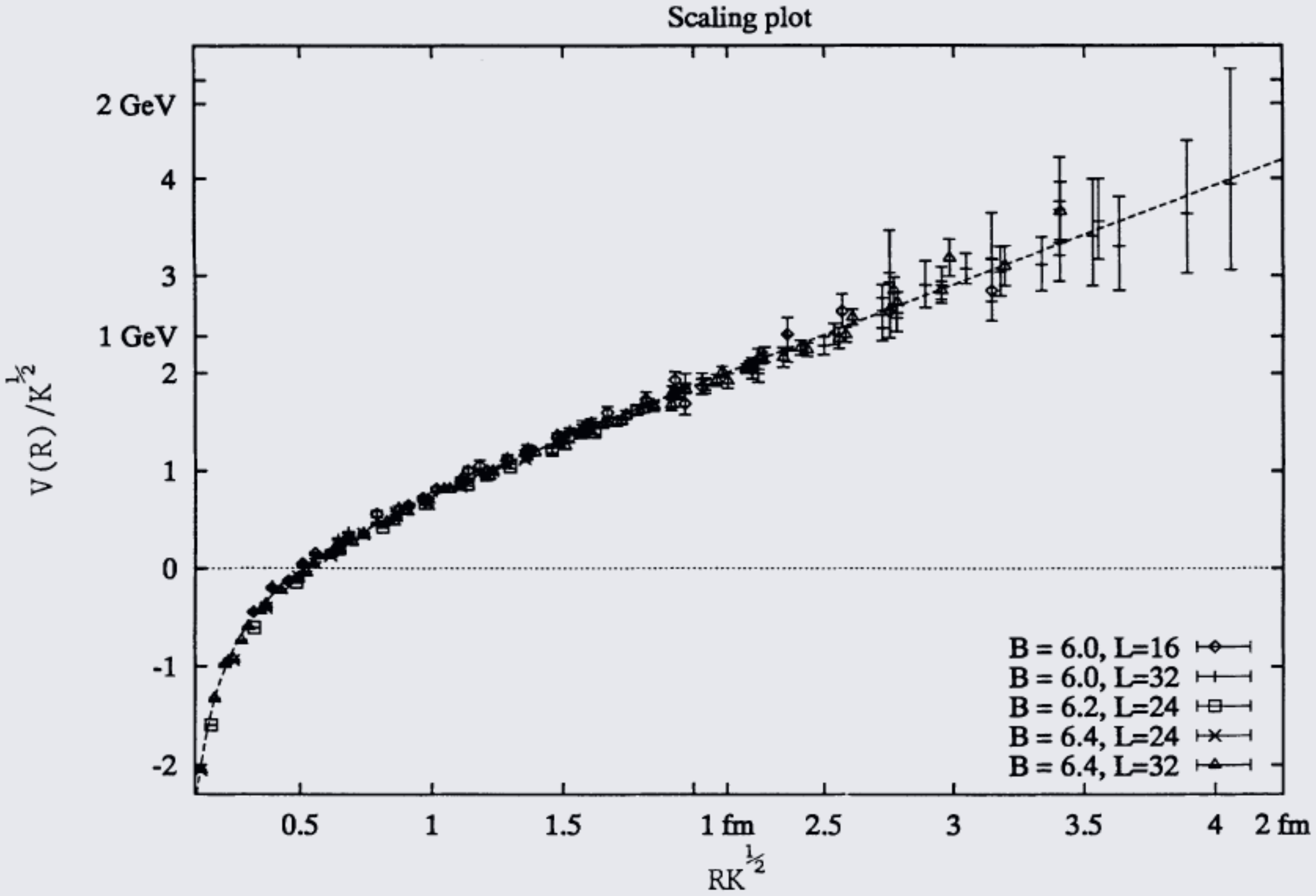
## Schwinger Mechanism[4, 5]

- Transverse component of fragmentation
- Tunnelling probability for spontaneous creation of quark/antiquark pair due to string break



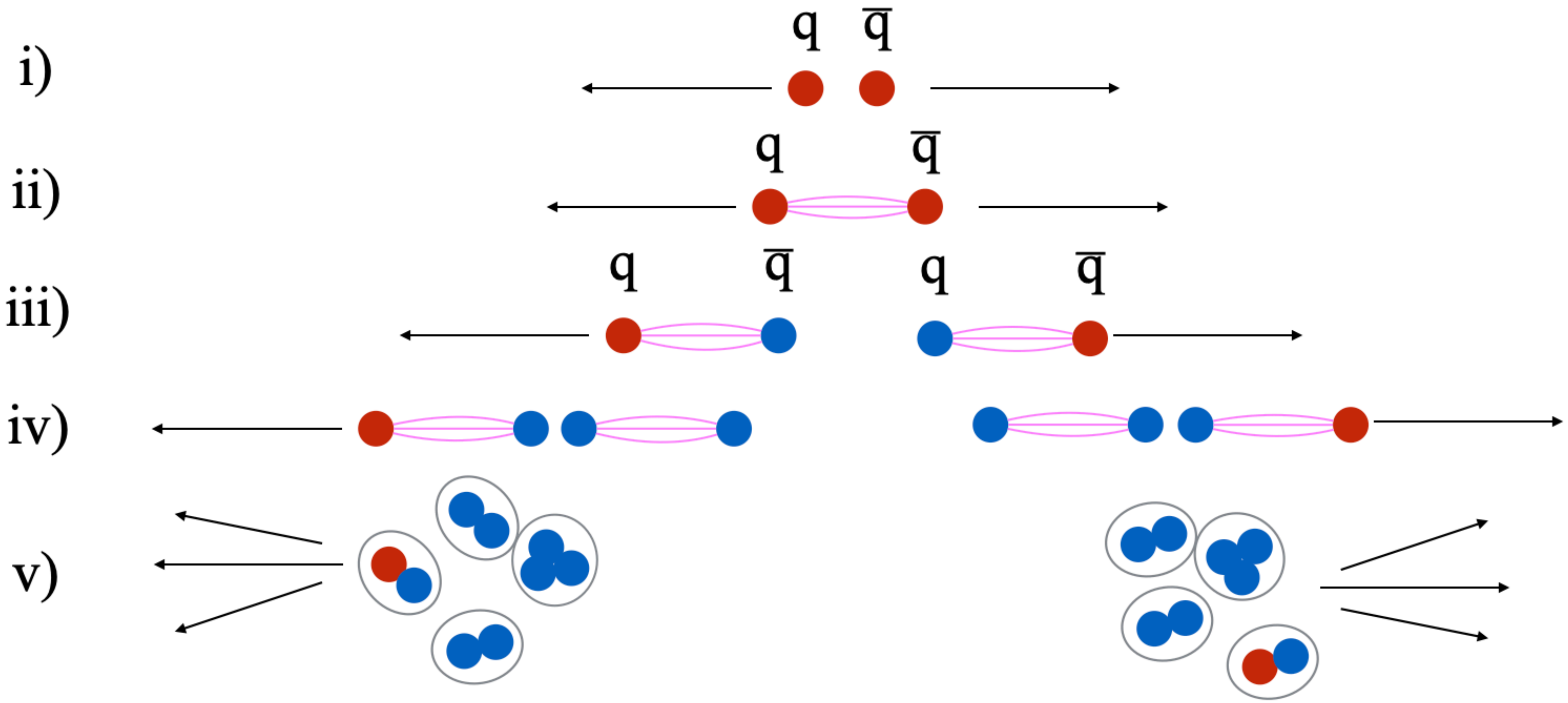

$$\exp\left(\frac{-\pi\,m_{q}^{2}}{\kappa}\right)\exp\left(\frac{-\pi\,p_{\perp q}^{2}}{\kappa}\right) = \exp\left(\frac{-\pi\,m_{\perp q}^{2}}{\kappa}\right)$$

# Lund Strings – Coulomb Potential



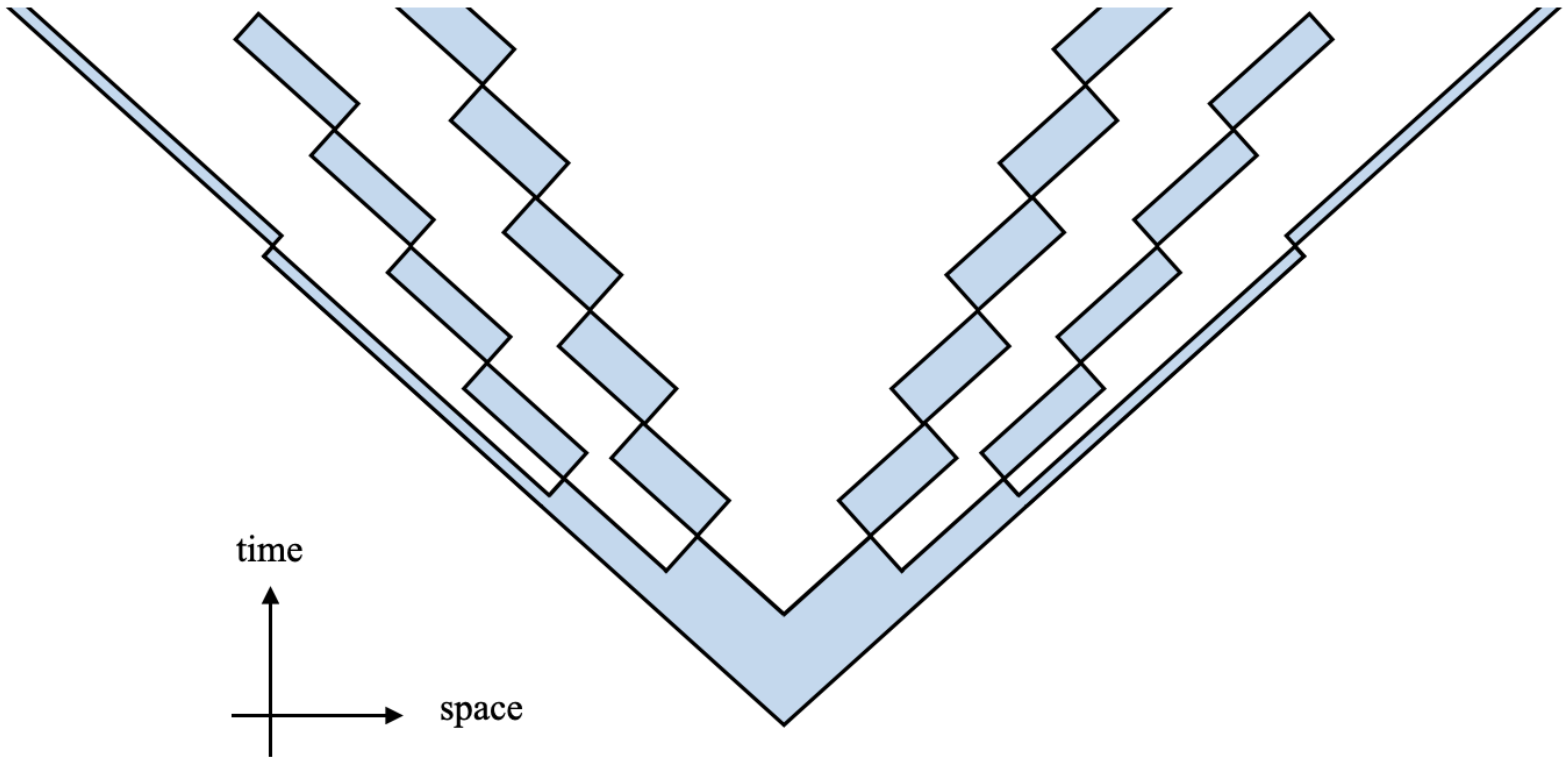

G. S. Bali and K. Schilling, Static quark - anti-quark potential: Scaling behavior and finite size effects in SU(3) lattice gauge theory, Phys. Rev. D 46 (1992) 2636.

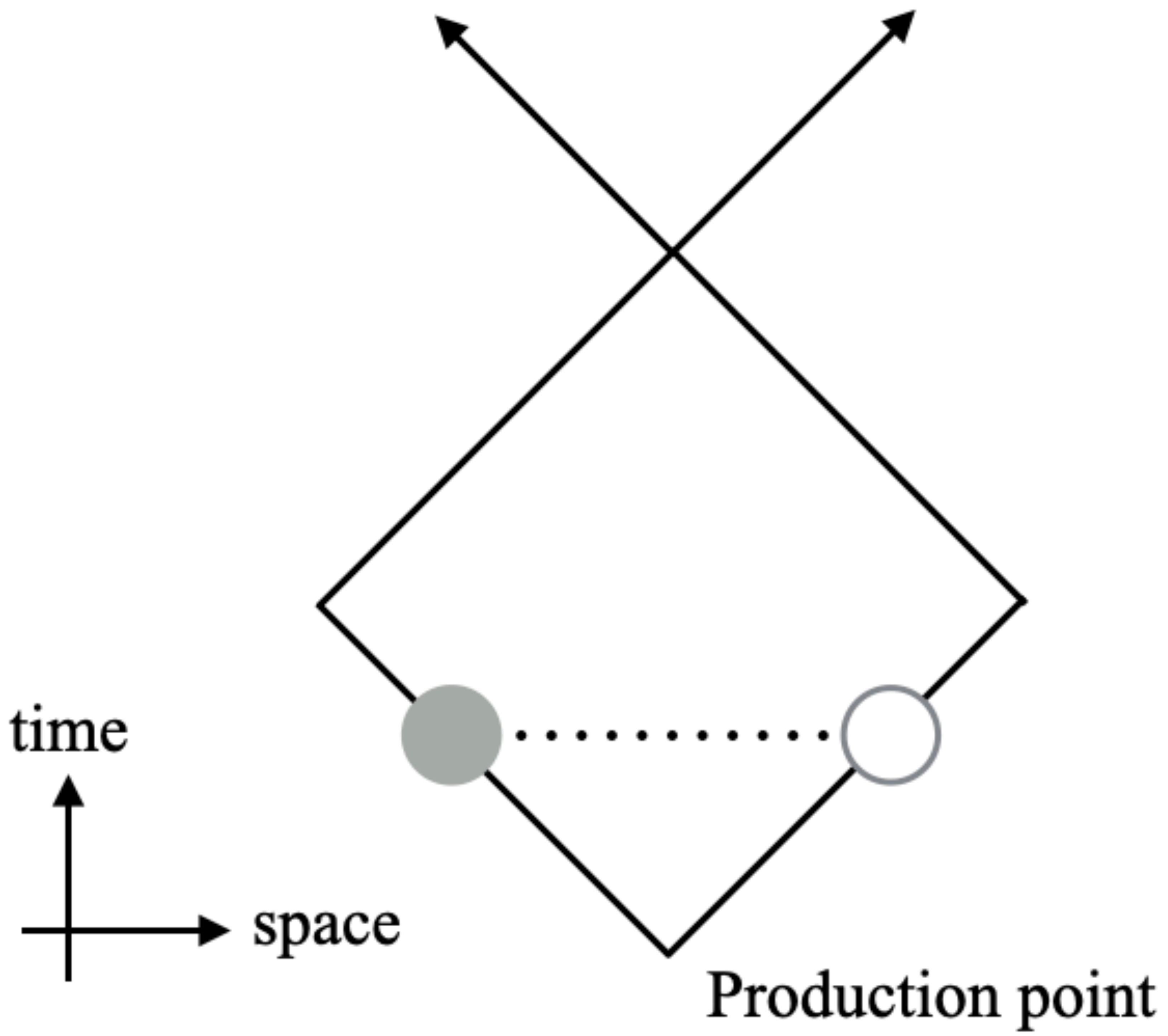
# Hadronisation and the Lund String Model




Note: colours here are not SU(3) colours, but simply to keep track of initial $q\bar{q}$ pair

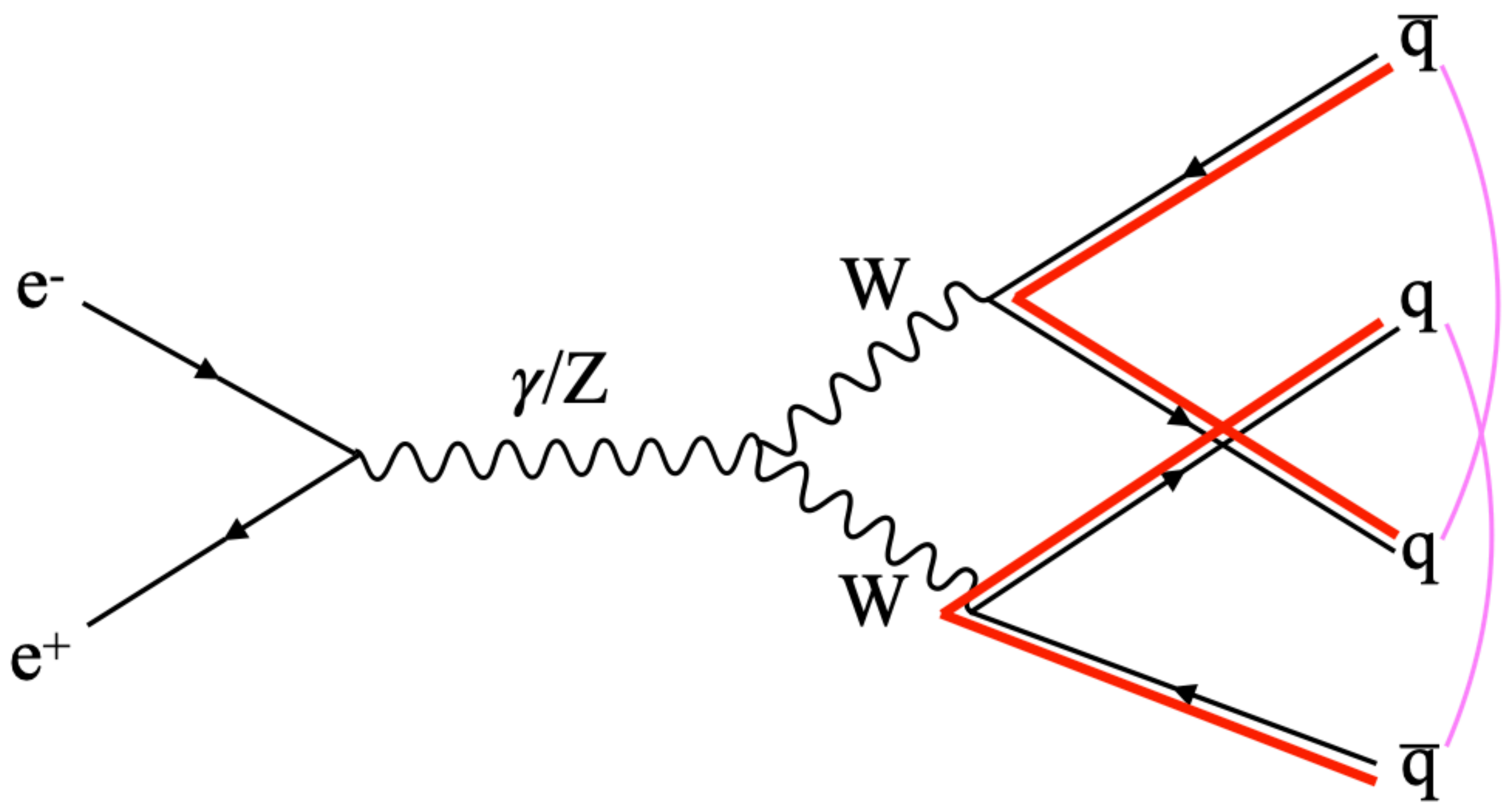
# Lund String Model



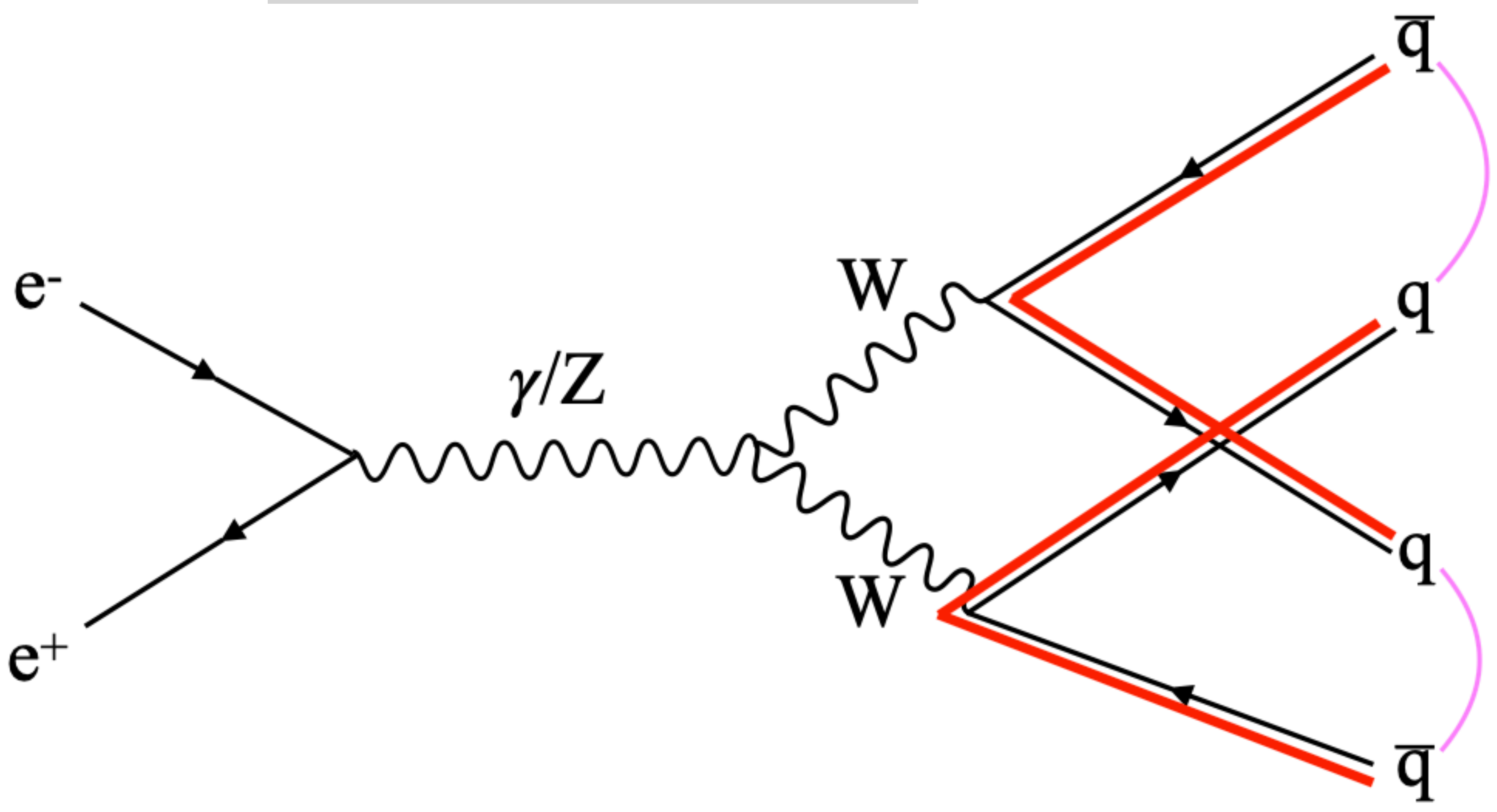



# QCD-based Colour Reconnections

Leading Colour




Alternative Topology



# Implementation in PYTHIA

## ProbStoUD

The probability of the ratio of strange to up/down quarks, is determined by the **Schwinger mechanism**

**Schwinger mechanism**

$$\exp\left(\frac{-\pi\, m_q^2}{\kappa}\right)\exp\left(\frac{-\pi\, p_{\perp q}^2}{\kappa}\right) = \exp\left(\frac{-\pi\, m_{\perp q}^2}{\kappa}\right)$$

$$P'(s{:}\,u/d) = P(s{:}\,u/d)^{\frac{\kappa_0}{\kappa_{eff}}}$$

There are other parameters that also scale with an effective string tension, but **ProbStoUD** is the main one that governs strangeness

# Close Packing

**Collective effect of strings:** multiple strings in the near vicinity contributing to an effective string tension

- Strings counted if they have rapidity overlap with the hadron resulting from the fragmented string
- Increase string tension -> **increase strangeness** (due to the Schwinger mechanism)

$$\kappa_{eff} = \left(1 + \frac{k_P p + k_A q}{1 + \frac{p_{\perp Had}^2}{p_{\perp 0}^2}}\right)^{2r} \kappa_0$$

$p$ = parallel strings, $q$ = antiparallel strings

$k_P$ = tension strength of parallel strings

$k_A$ = strength of antiparallel strings

## Casimir scaling is determined by lattice QCD

- Determines the altered string tension of overlapping strings
- $k_P$ = **0.25** , $k_A$ = **0.125**

**Flux sensitivity :** can either be flux sensitive (i.e. follows **Casimir scaling**) or flux insensitive ( $\frac{k_A}{k_P} = 1$ )

**Scaling :** either **linear** scaling (via altering $k_P$) or **non-linear** scaling (via altering $r$)

# Close Packing

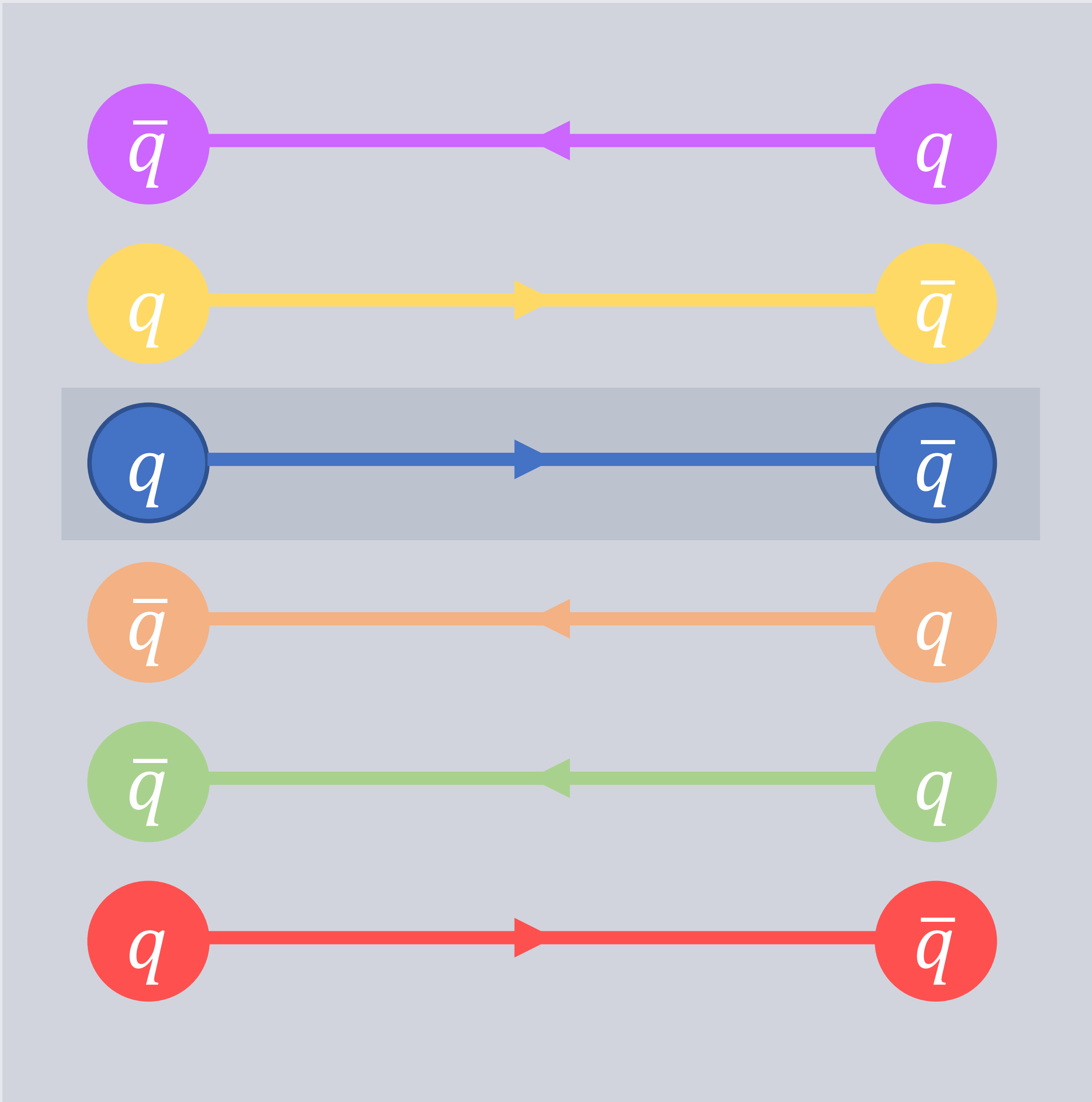
**Collective effect of strings:** multiple strings in vicinity contribute to effective string tension

- Strings counted by rapidity overlap
- Increase string tension → **increase strangeness** (Schwinger mechanism)

$$\kappa_{eff} = \kappa_0 + \varepsilon_\kappa n_{NSP}$$
$$\kappa_{eff} = (1 + \varepsilon\, n_{NSP})\, \kappa_0$$

$n_{NSP}$ = number of near string pieces

$\varepsilon$ = weight of effect of near string pieces




$p$ = parallel strings = 2; $q$ = antiparallel strings = 3

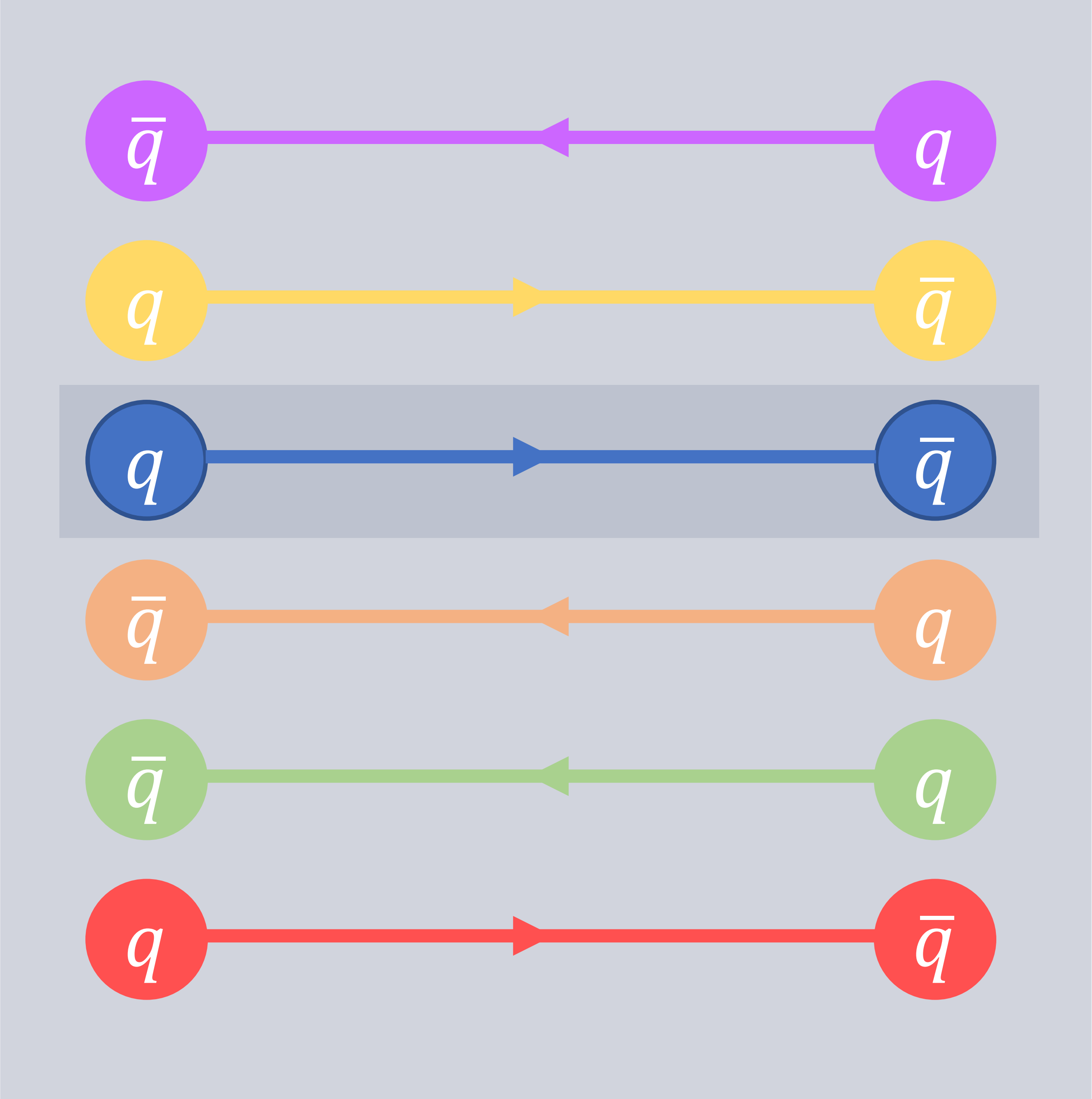
**Flux sensitivity :** can either be flux sensitive (i.e. follows **Casimir scaling**) or flux insensitive

**Scaling :** either **linear** scaling (linear weight of p and q) or **non-linear** scaling (raise power of $r$)

# Close Packing

**Collective effect of strings:** multiple strings in vicinity contribute to effective string tension

- Strings counted by rapidity overlap
- Increase string tension → **increase strangeness** (Schwinger mechanism)




$p$ = 2; $q$ = 3

## **Casimir scaling** is determined by lattice QCD

$$\kappa_{eff} = (1 + 0.25p + 0.125q)\,\kappa_0$$

$p$ = parallel strings, $q$ = antiparallel strings

**Flux sensitivity :** can either be flux sensitive (i.e. follows **Casimir scaling**) or flux insensitive

**Scaling :** either **linear** scaling (linear weight of p and q) or **non-linear** scaling (raise power of $r$)

# Modified Probabilities

## ProbStoUD

The ratio of probabilities of strange to up/down quarks, is determined by the **Schwinger mechanism**

**Schwinger mechanism**

$$\exp\left(\frac{-\pi\, m_q^2}{\kappa}\right)\exp\left(\frac{-\pi\, p_{\perp q}^2}{\kappa}\right) = \exp\left(\frac{-\pi\, m_{\perp q}^2}{\kappa}\right)$$

$$P(s:u/d) = \frac{P(m_s^2)}{P\left(m_{u/d}^2\right)} = \frac{\exp\left(-\frac{\pi\, m_s^2}{\kappa_0}\right)}{\exp\left(-\frac{\pi\, m_{u/d}^2}{\kappa_0}\right)} \quad \Rightarrow \quad P'(s:u/d) = \exp\left(-\frac{\pi\,(m_s^2 - m_{u/d}^2)}{\kappa_{eff}}\right) = \exp\left(-\frac{\pi\,(m_s^2 - m_{u/d}^2)}{\kappa_0}\frac{\kappa_0}{\kappa_{eff}}\right)$$

The modified probabilities due to an effective string tension is thus given by:

$$P'(s:u/d) = P(s:u/d)^{\frac{\kappa_0}{\kappa_{eff}}}$$

Same form of modification for ProbSQtoQQ and ProbQQ1toQQ0.

However **ProbQQtoQ** is a global probability and thus has a different form of modification.

# Modified Probabilities

**ProbQQtoQ** is a global probability modified by:

**Diquark to quark probability**

$$P(qq{:}\,q) = \frac{\sum_{qq_s} P_{qq_s}}{\sum_q P_q} = \alpha \frac{P_{ud0}}{P_u}$$

Where α is dependent on the other probabilities.

$$\kappa_{ratioQQ} = 1 + \text{facQQ}^2 \left( \frac{\kappa_0}{\kappa_{eff}} - 1 \right)$$

$$P'(qq{:}\,q) = \tilde{\alpha} \left( \frac{P(qq{:}\,q)}{\alpha} \right)^{\kappa_{ratioQQ}}$$

- Limit facQQ $\rightarrow 1$; $\frac{P_{ud0}}{P_u}$ scales directly with $\frac{\kappa_0}{\kappa_{eff}}$
- Limit facQQ $\rightarrow 0$; $\frac{P_{ud0}}{P_u}$ doesn't scale

## pT Distribution

The width of the $p_\perp$ spectrum is given by $\sigma^2$, which is the average value of $p_\perp$.

$$\langle p_\perp^2 \rangle = \frac{\pi}{\kappa_0} \int_0^\infty p_\perp^2 \exp\left( -\frac{\pi\, p_\perp^2}{\kappa_0} \right) dp_\perp^2 = \frac{\kappa_0}{\pi}$$

$$\sigma'^2 = \frac{\kappa_{eff}}{\pi} = \frac{\kappa_0}{\pi} \frac{\kappa_{eff}}{\kappa_0} = \sigma^2 \frac{\kappa_{eff}}{\kappa_0}$$

Therefore increased effective kappa

→ increased width of the pT spectrum

→ higher probability of high pT