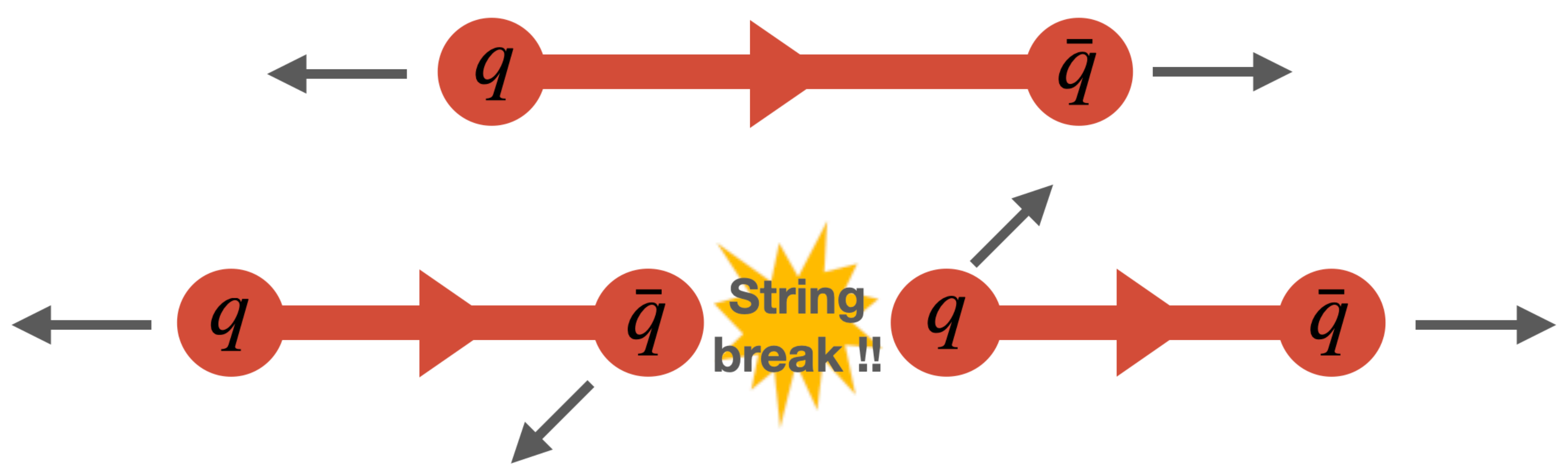
# Updates on junctions in PYTHIA and describing strangeness

Javira Altmann, Monash University

# Hadronisation and the Lund String Model

**Hadronisation in PYTHIA:**

- ➢ Maps **partons to hadrons** using the **Lund String Model**
- ➢ Represent the **colour-confinement field** between colour-connected partons (i.e. form overall colour singlet state) as **strings**
- ➢ Partons move apart and "break" the string, creating new **light** quark-antiquark pairs (or diquark-antidiquark pairs)



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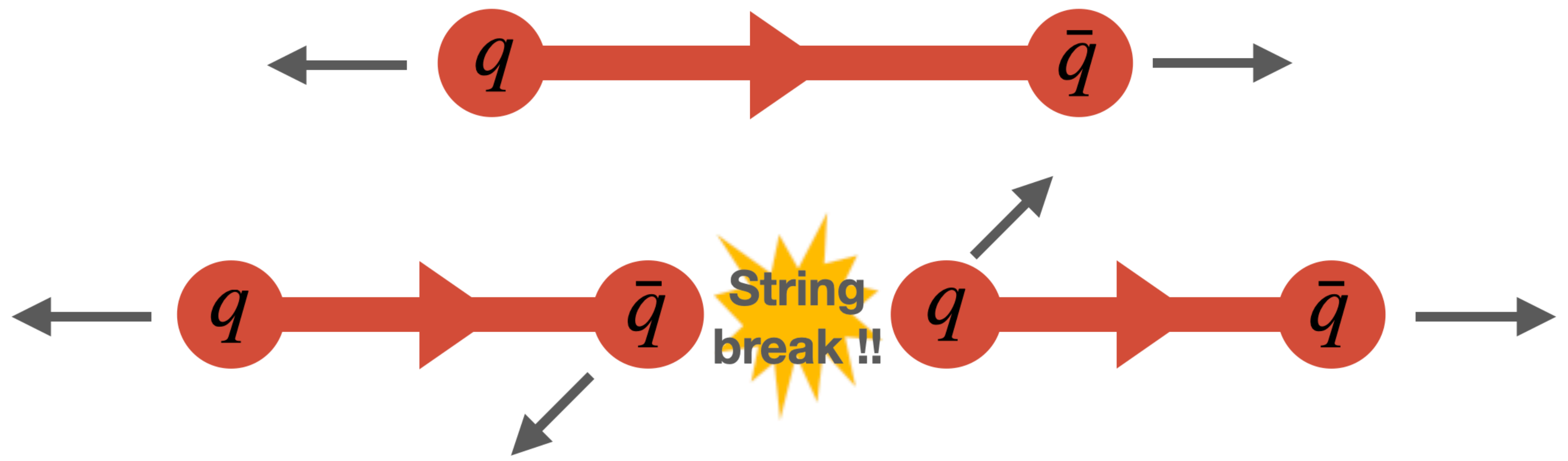
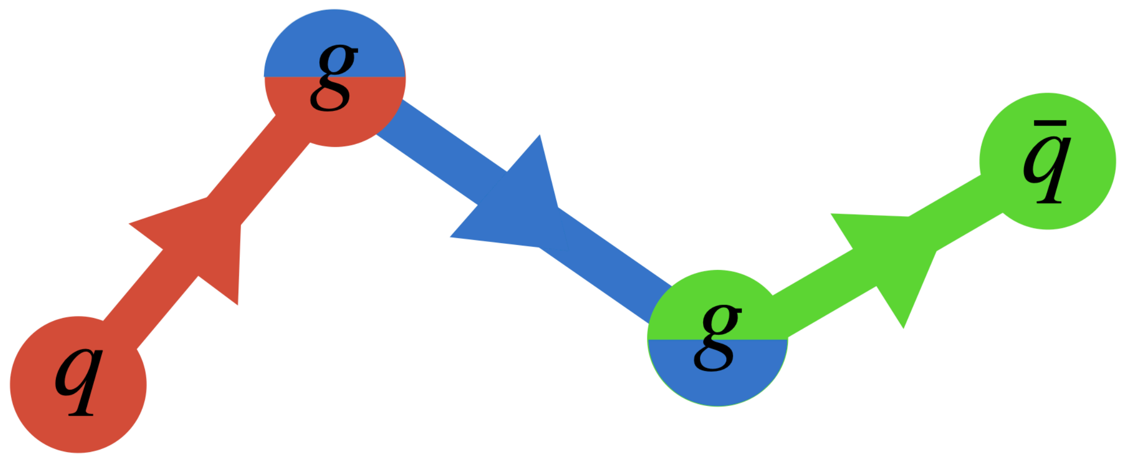



Starting point is **Leading Colour** limit $N_C \to \infty$

- ➢ Each colour is unique → only one way to make colour singlets




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

## In $e^+e^-$ collisions (LEP):

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

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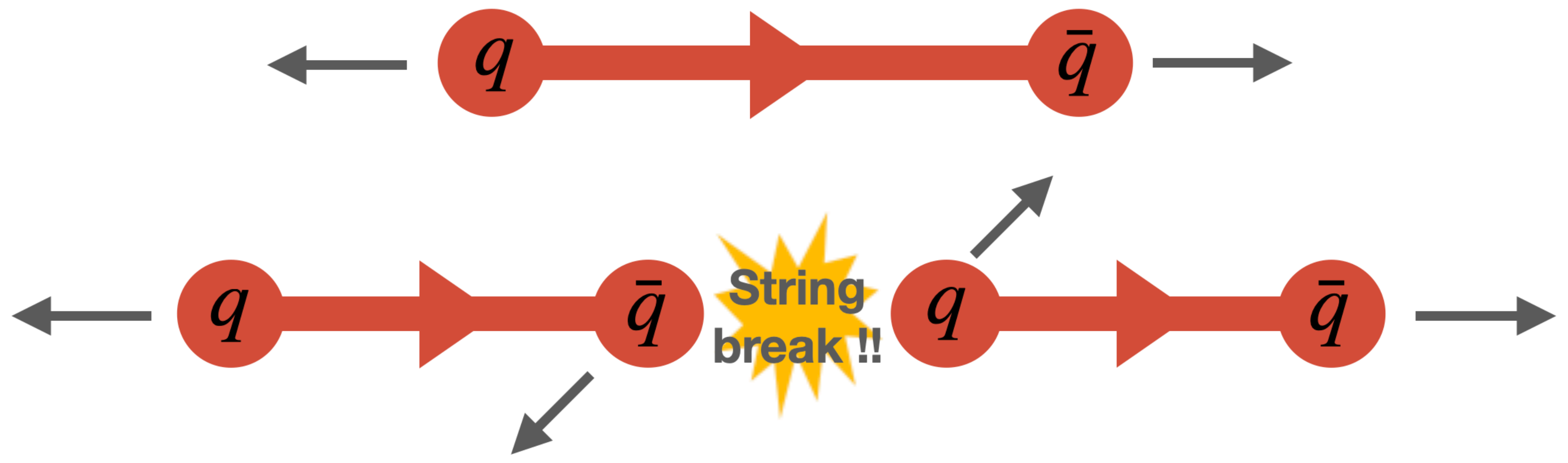


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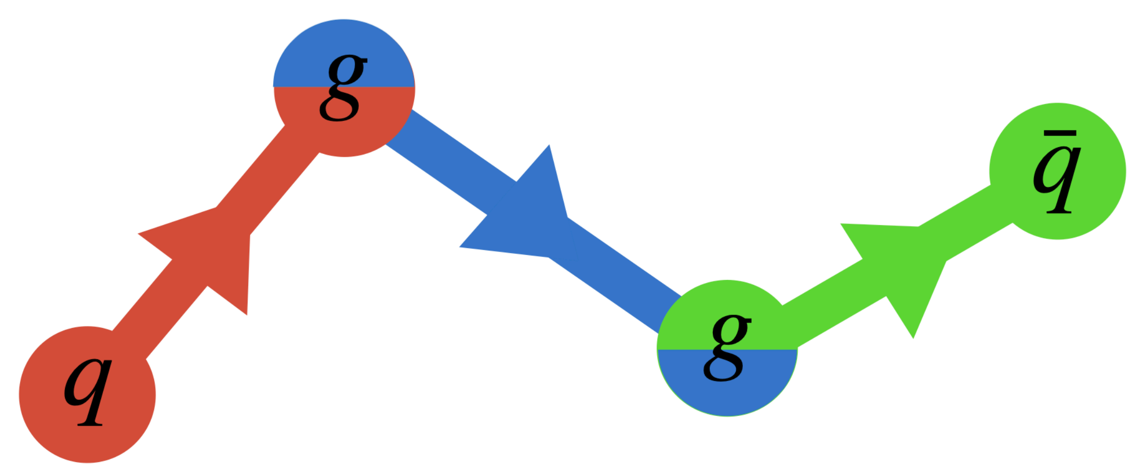



e.g. a dipole string configuration which make use of the **colour-anticolour** singlet state

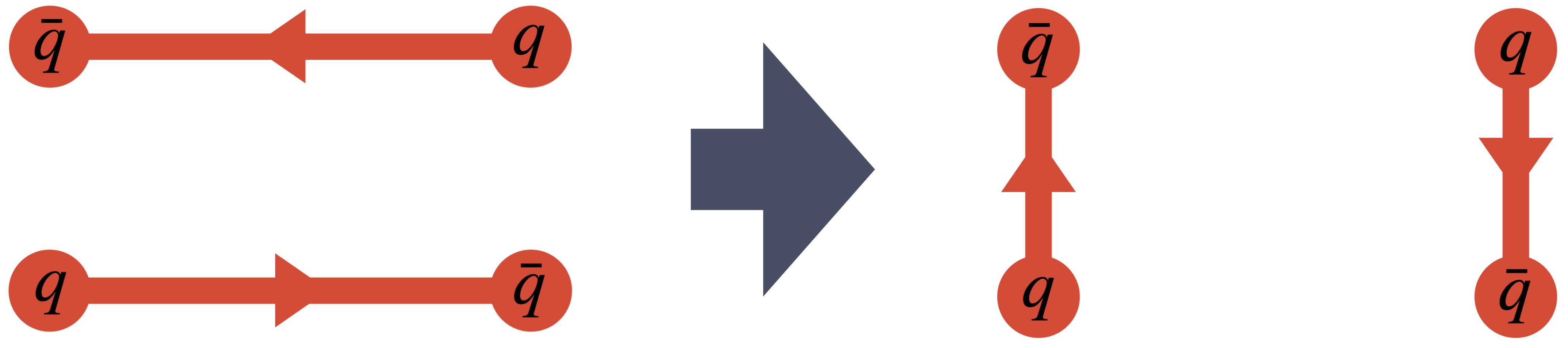
But high-energy pp collisions involve **very many** coloured partons with significant **phase space overlaps**

**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




**Dipole-type reconnection**

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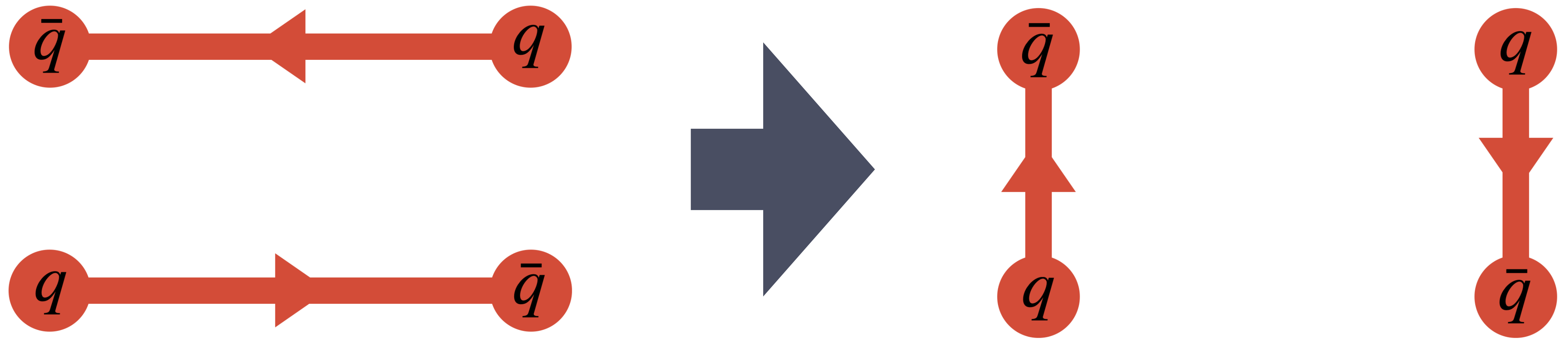
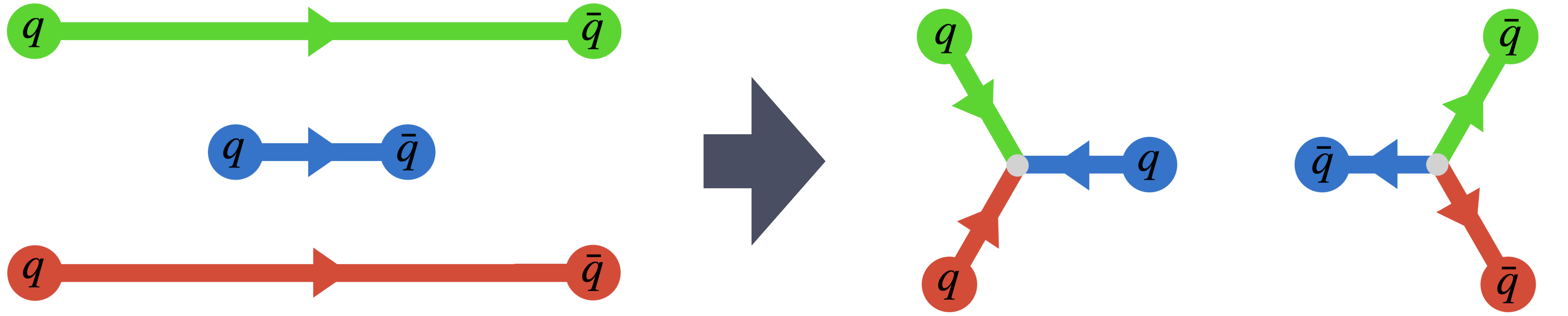


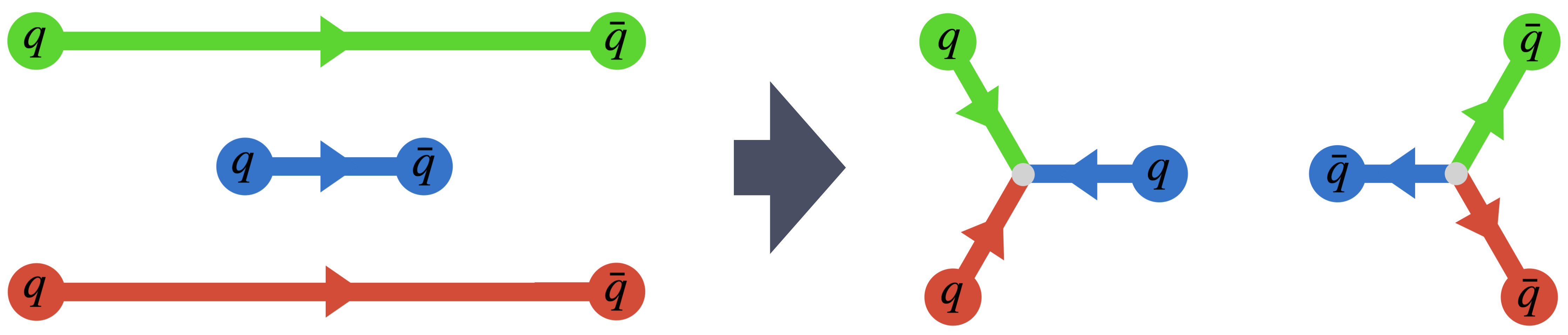

Dipole-type reconnection

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




**Junctions!**

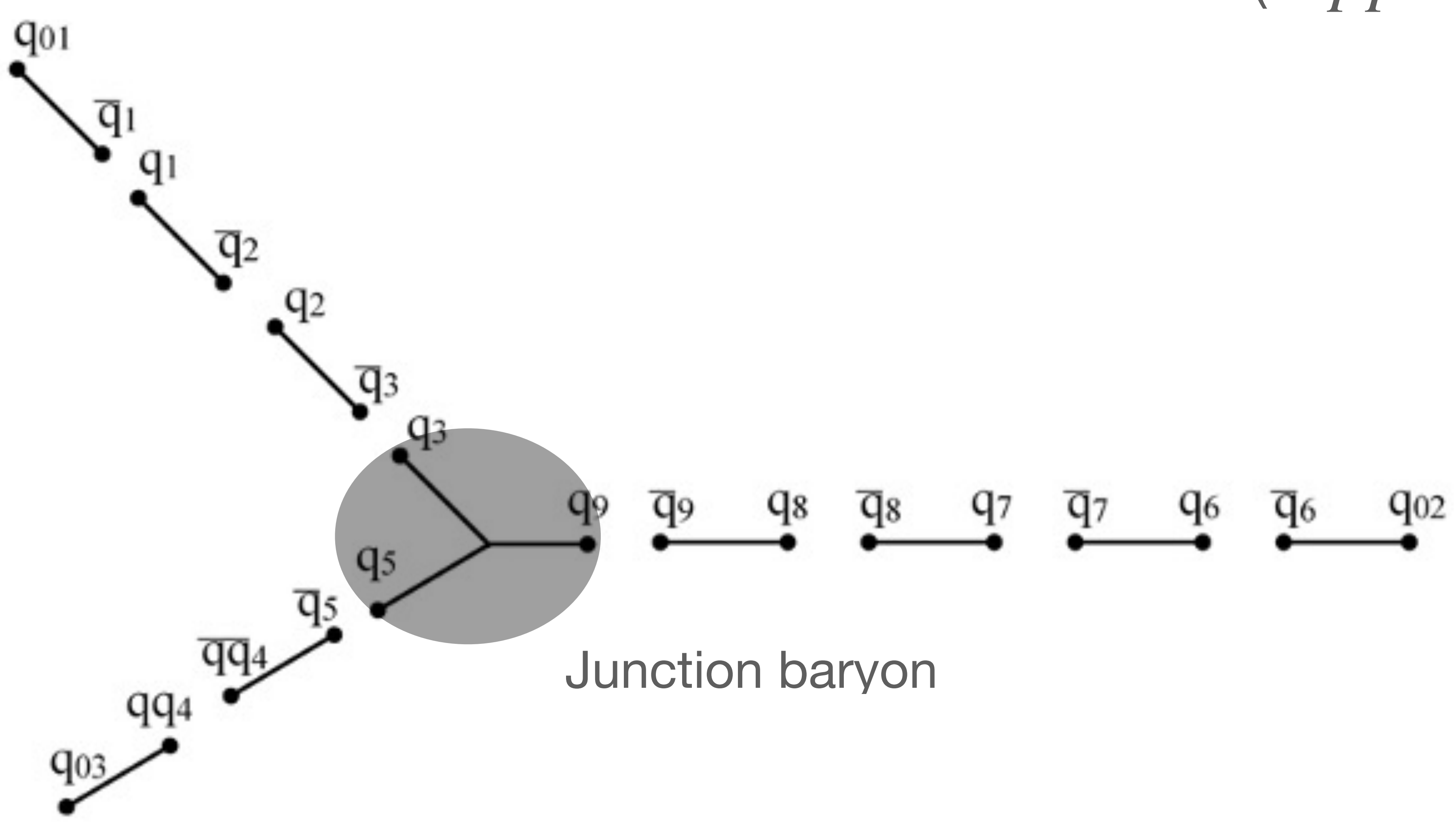
# Junctions

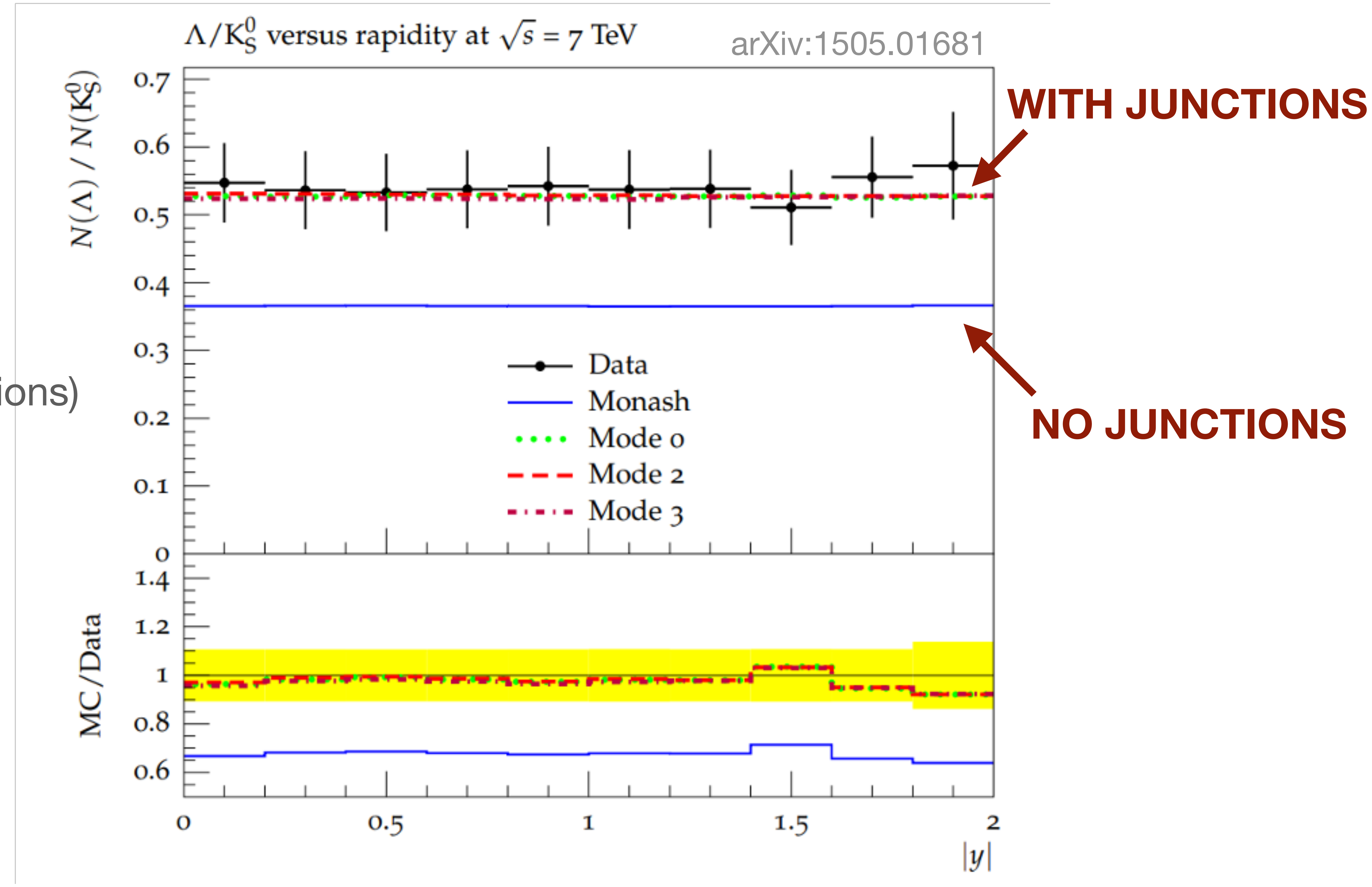


Mechanism for **baryon production**

➢ ~40% of baryons are from junctions in PYTHIA

(in *pp* collisions)



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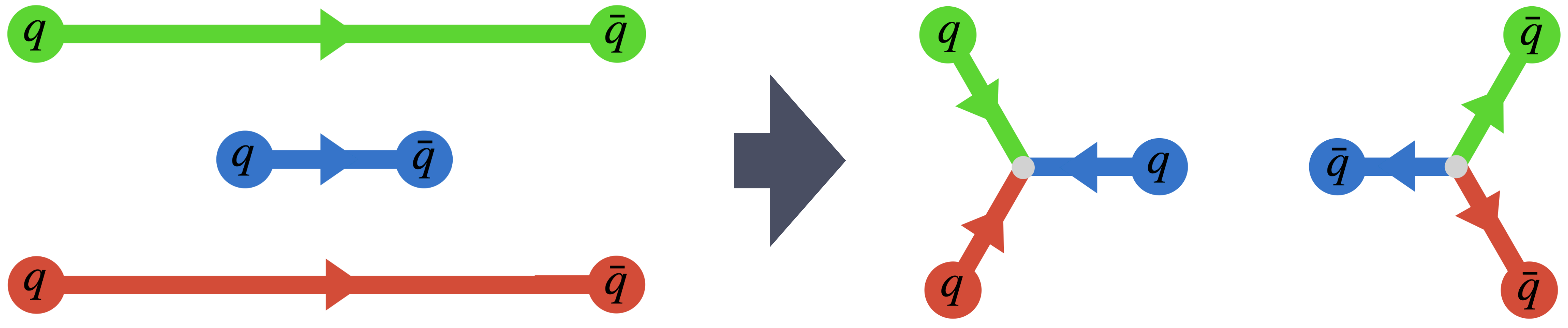


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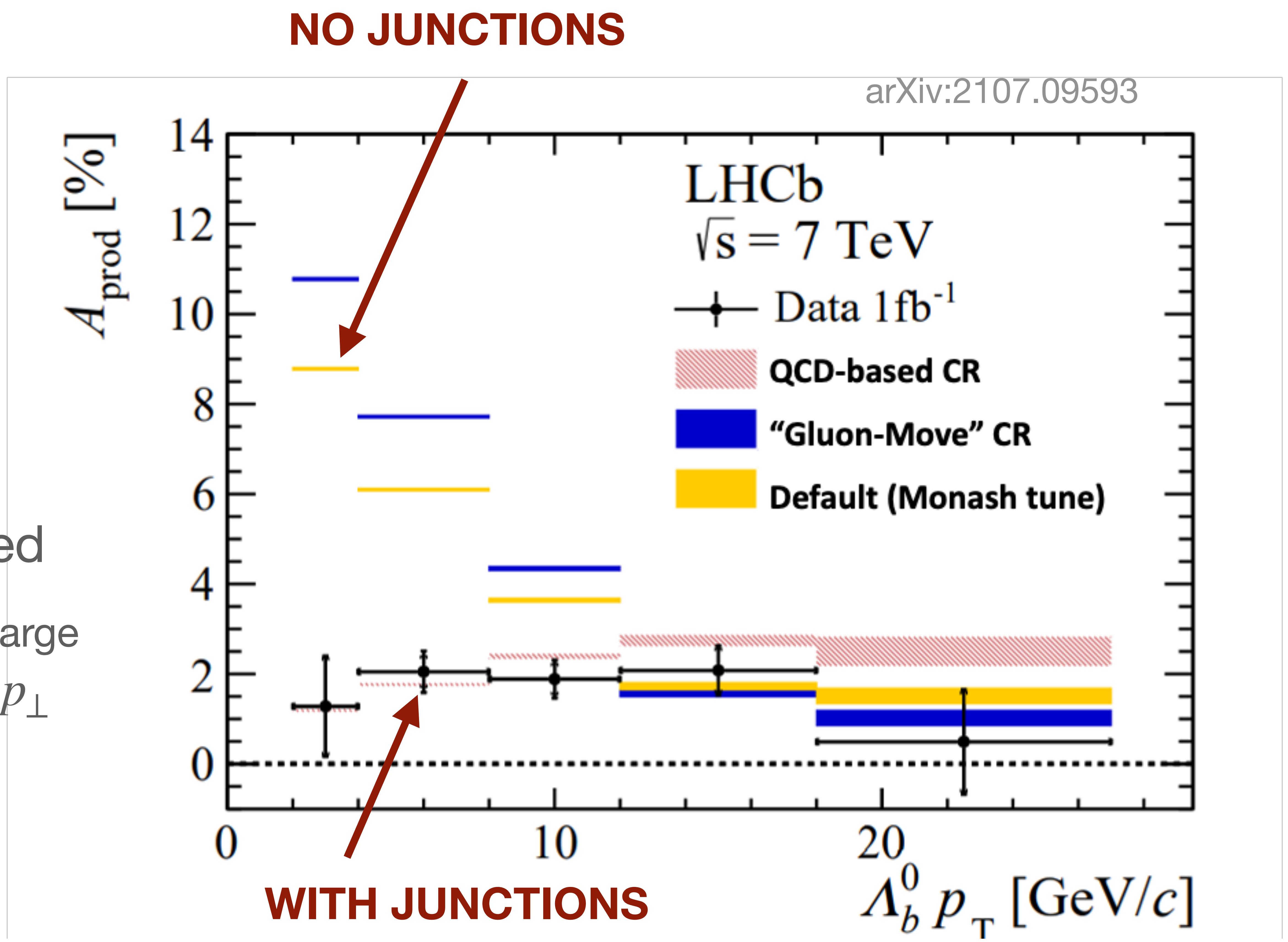
**Asymmetries**

➢ 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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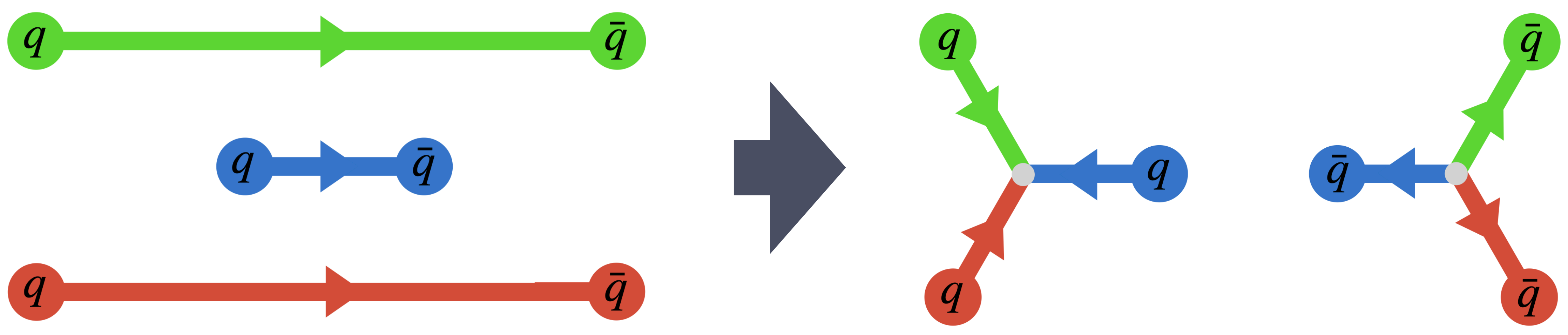

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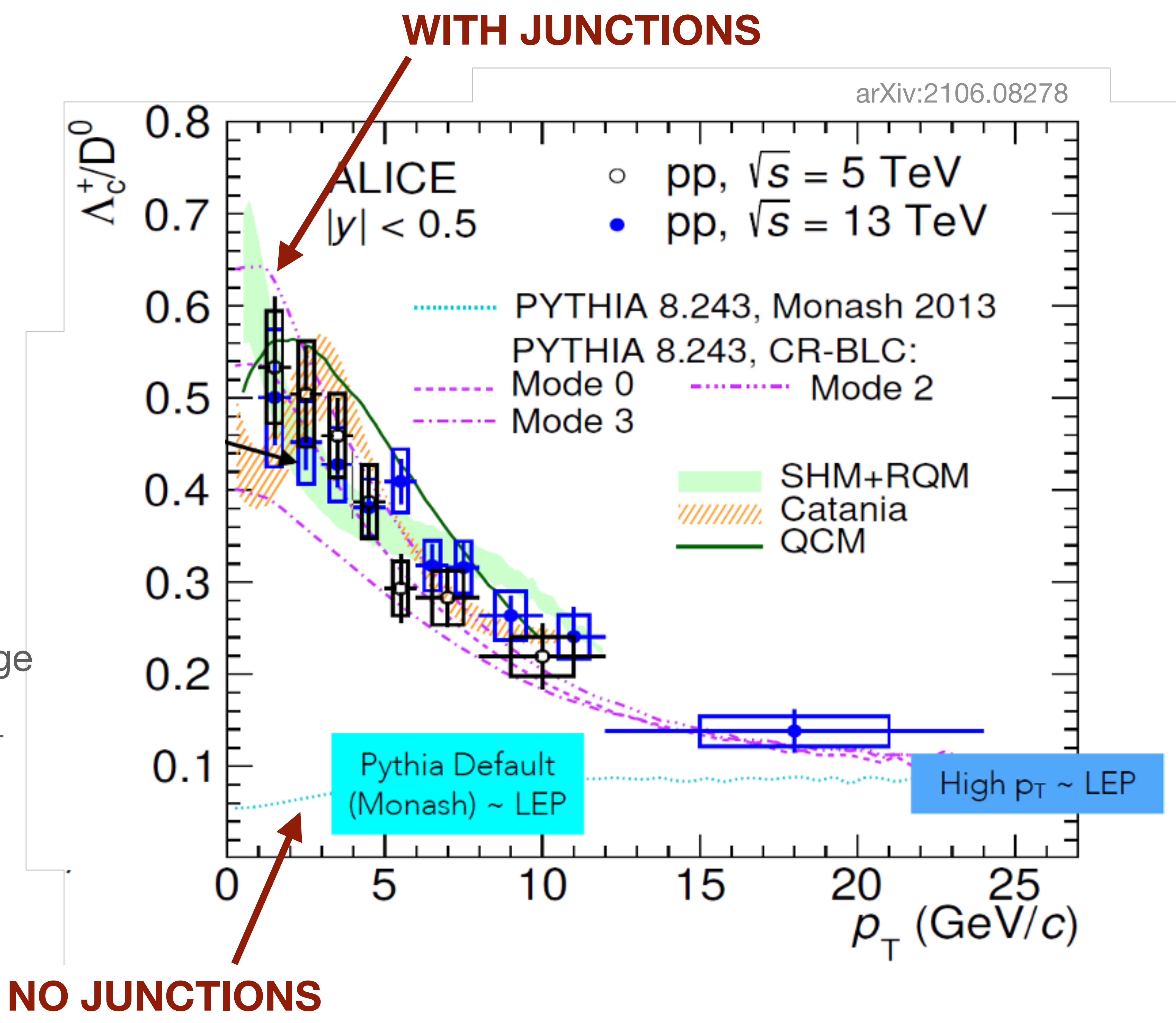
**Heavy flavour baryons**

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



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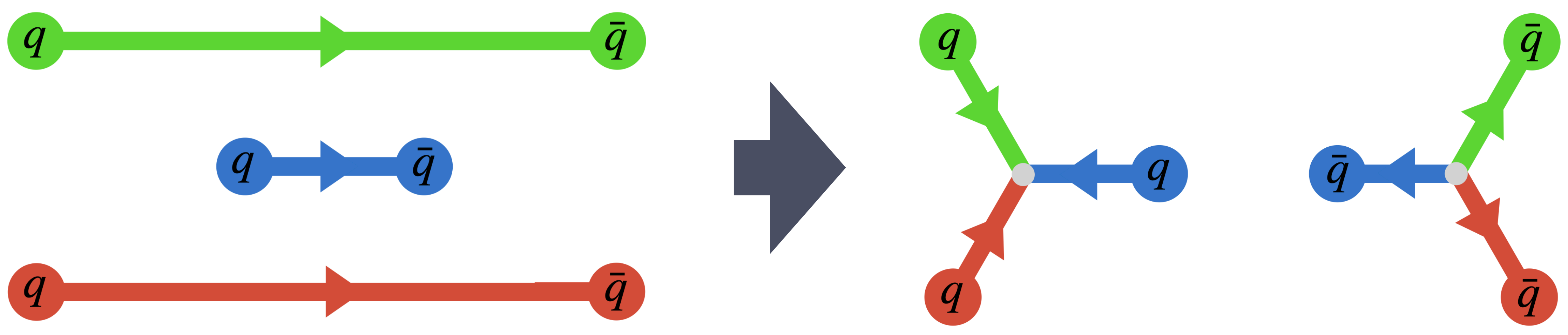


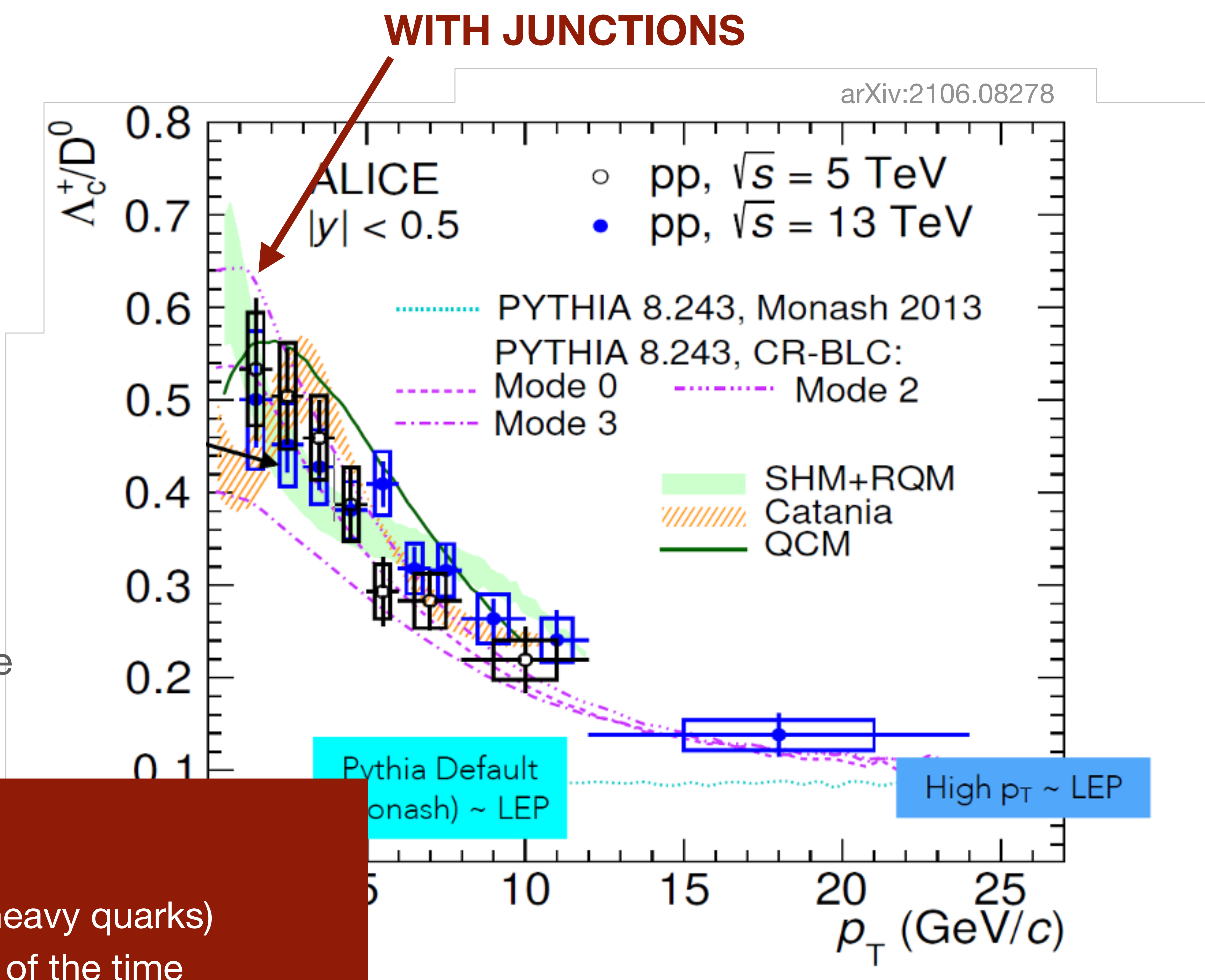


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**Heavy flavour ba**

- ➢ **~70% of hea**

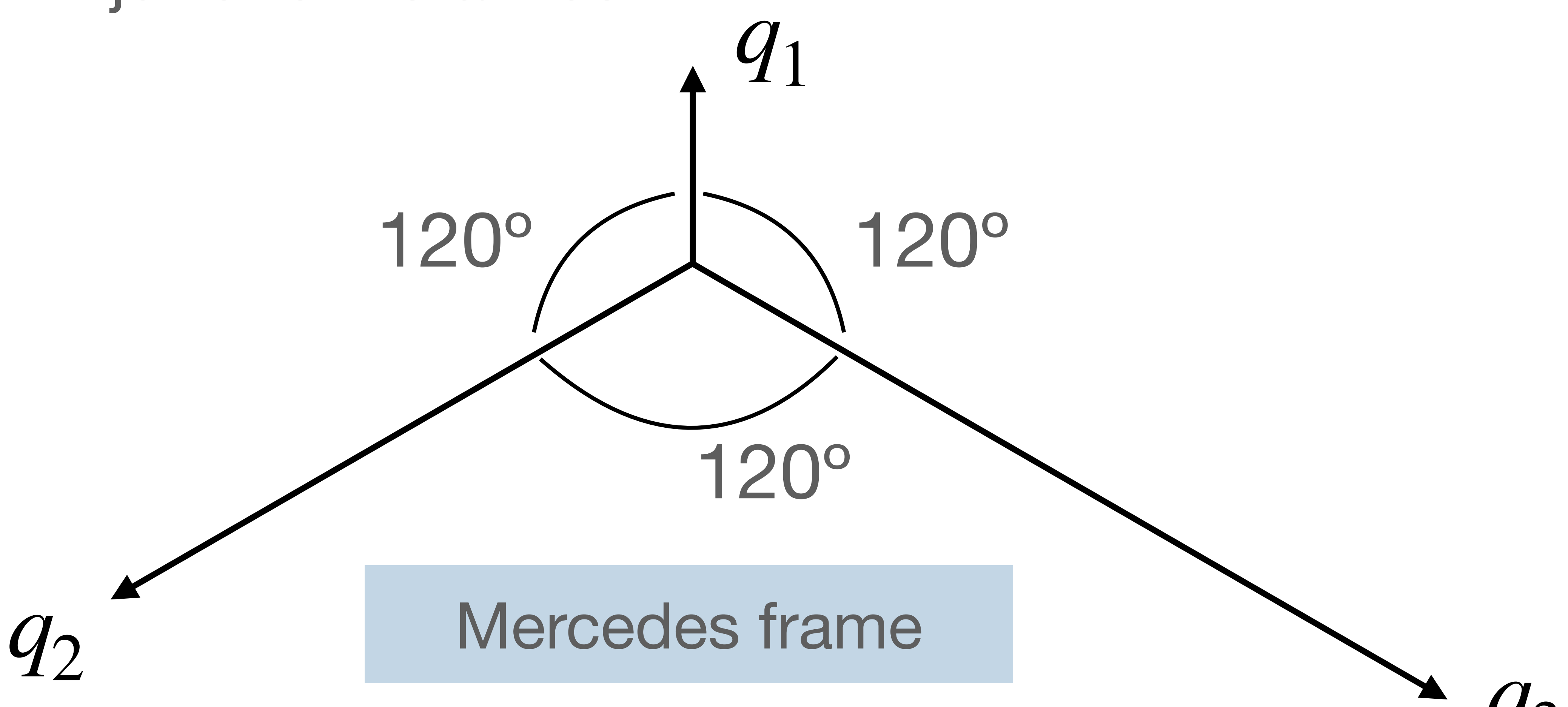
**Current implementation**

- ➢ 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

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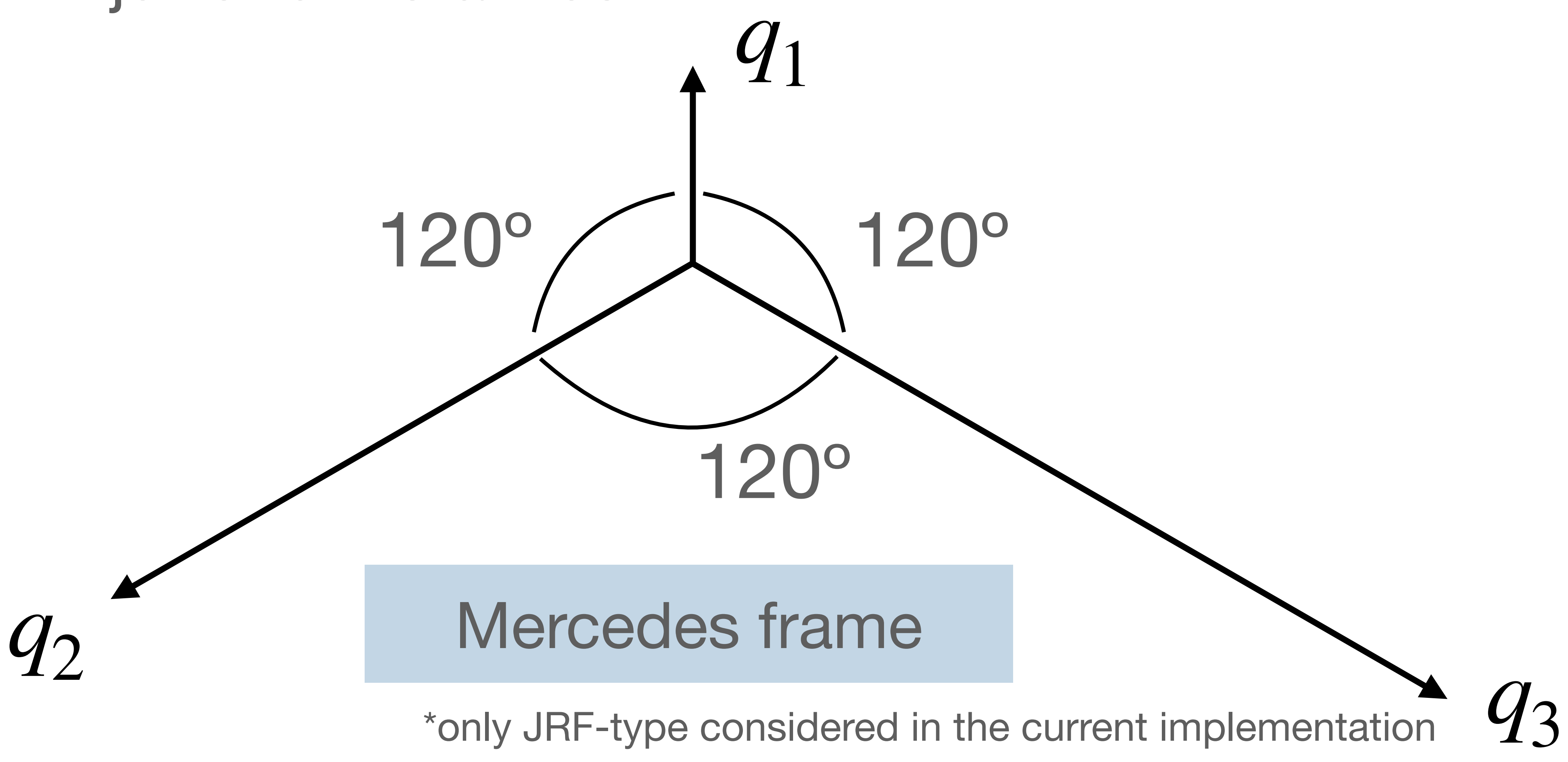


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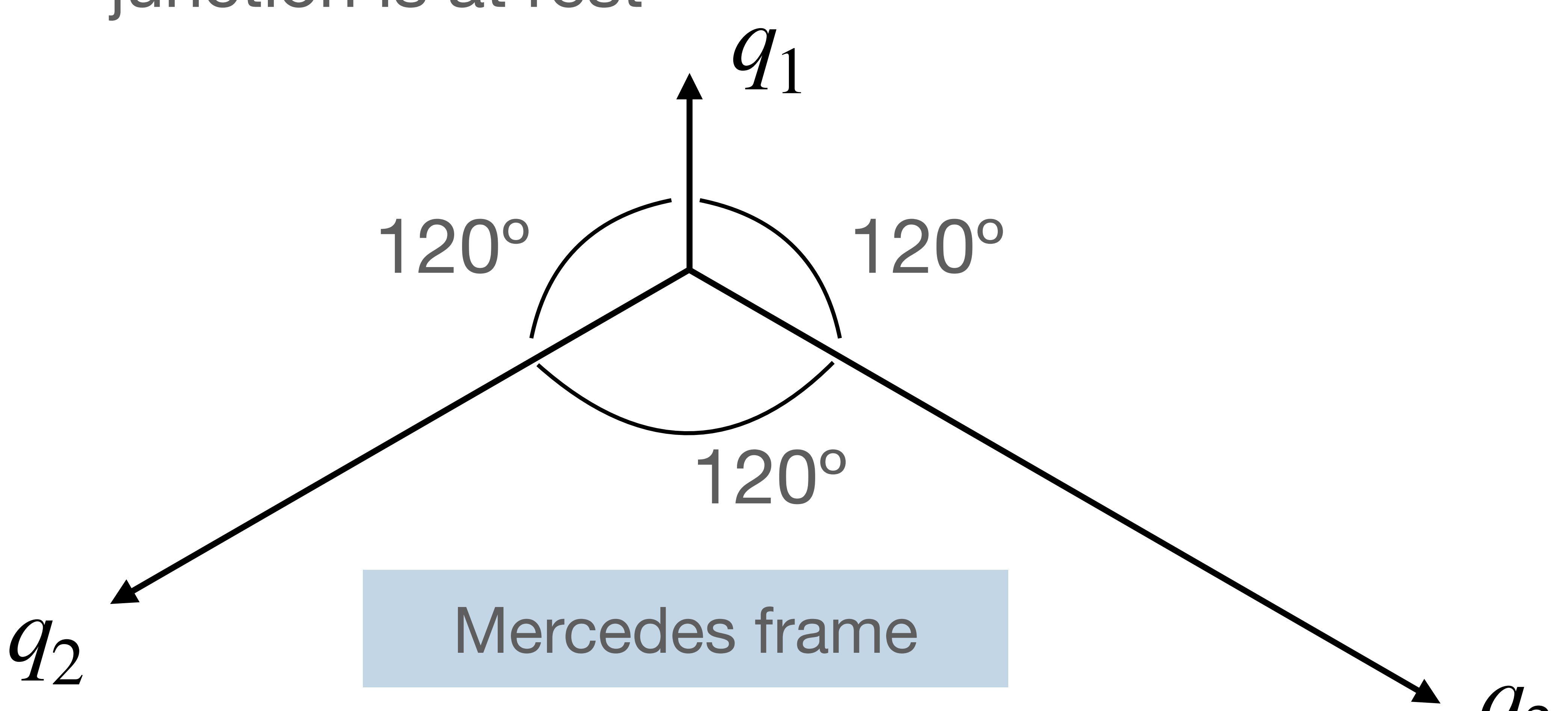


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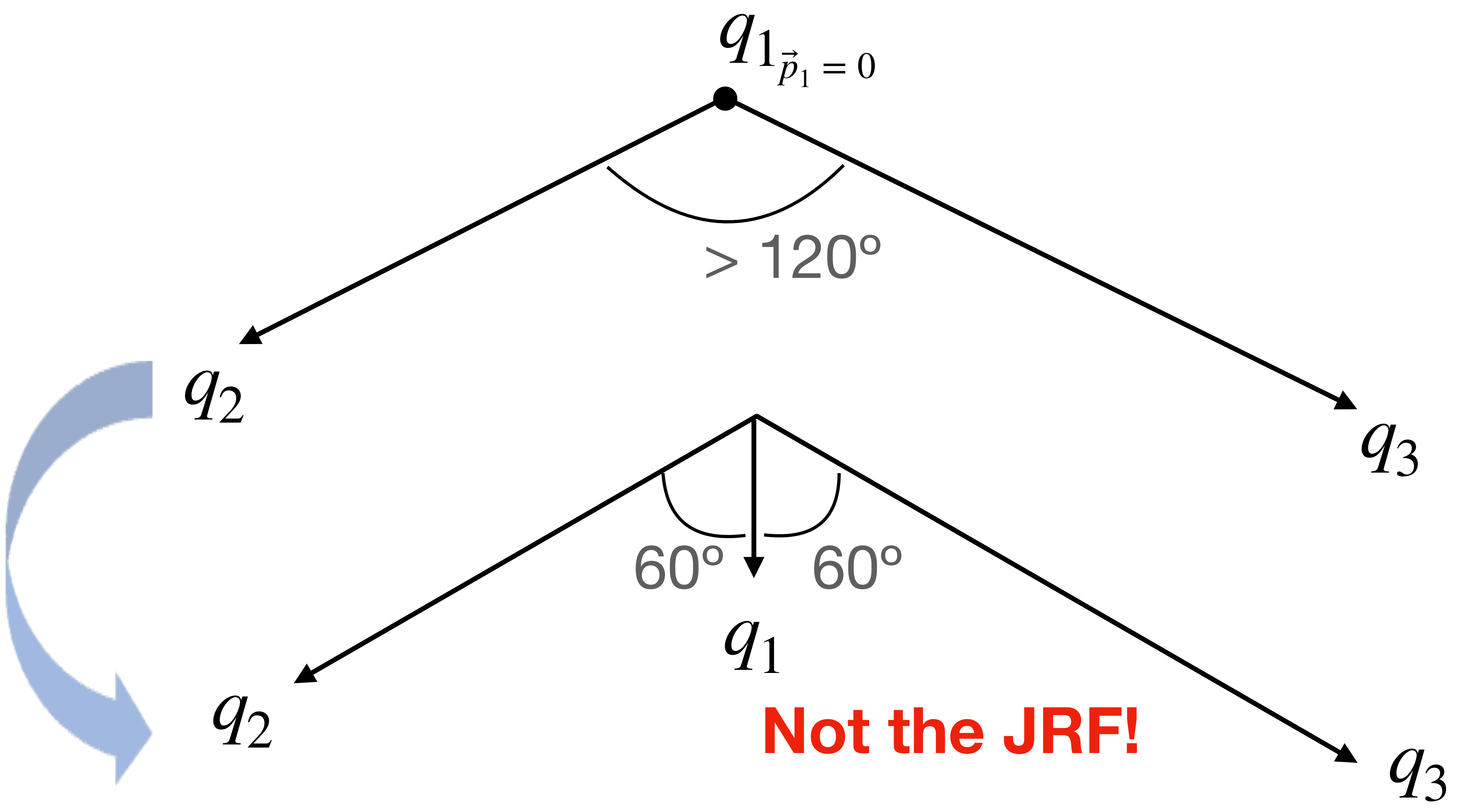
**Does a boost to the mercedes frame always exist?**

**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

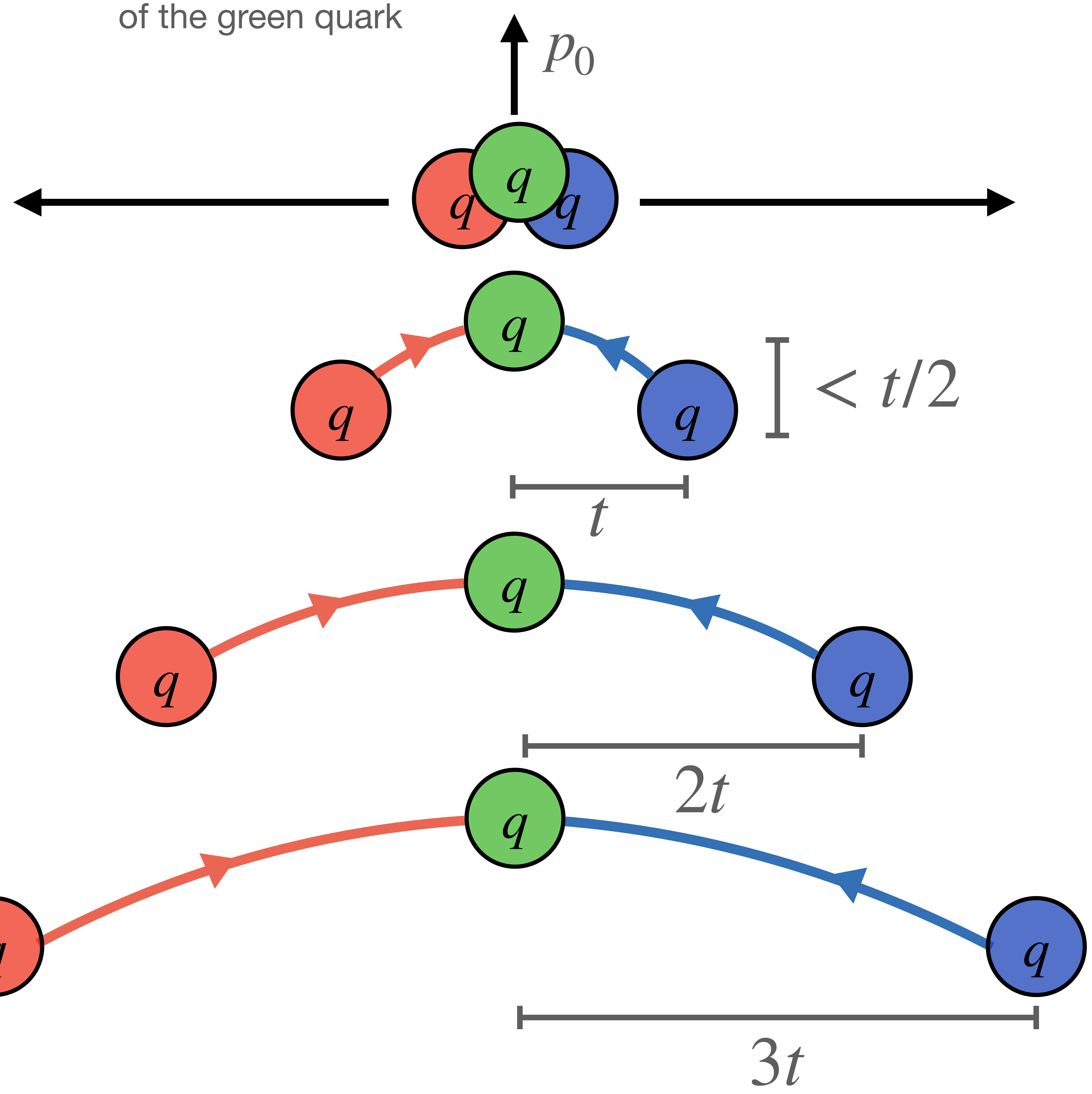


# Pearl-on-a-string

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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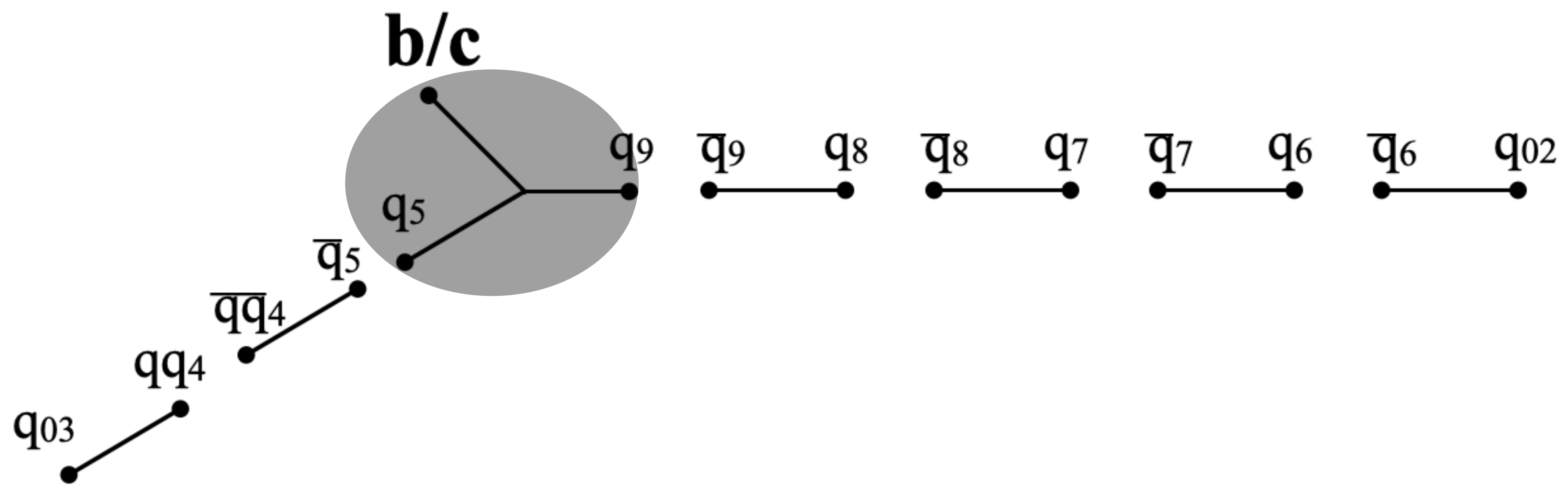


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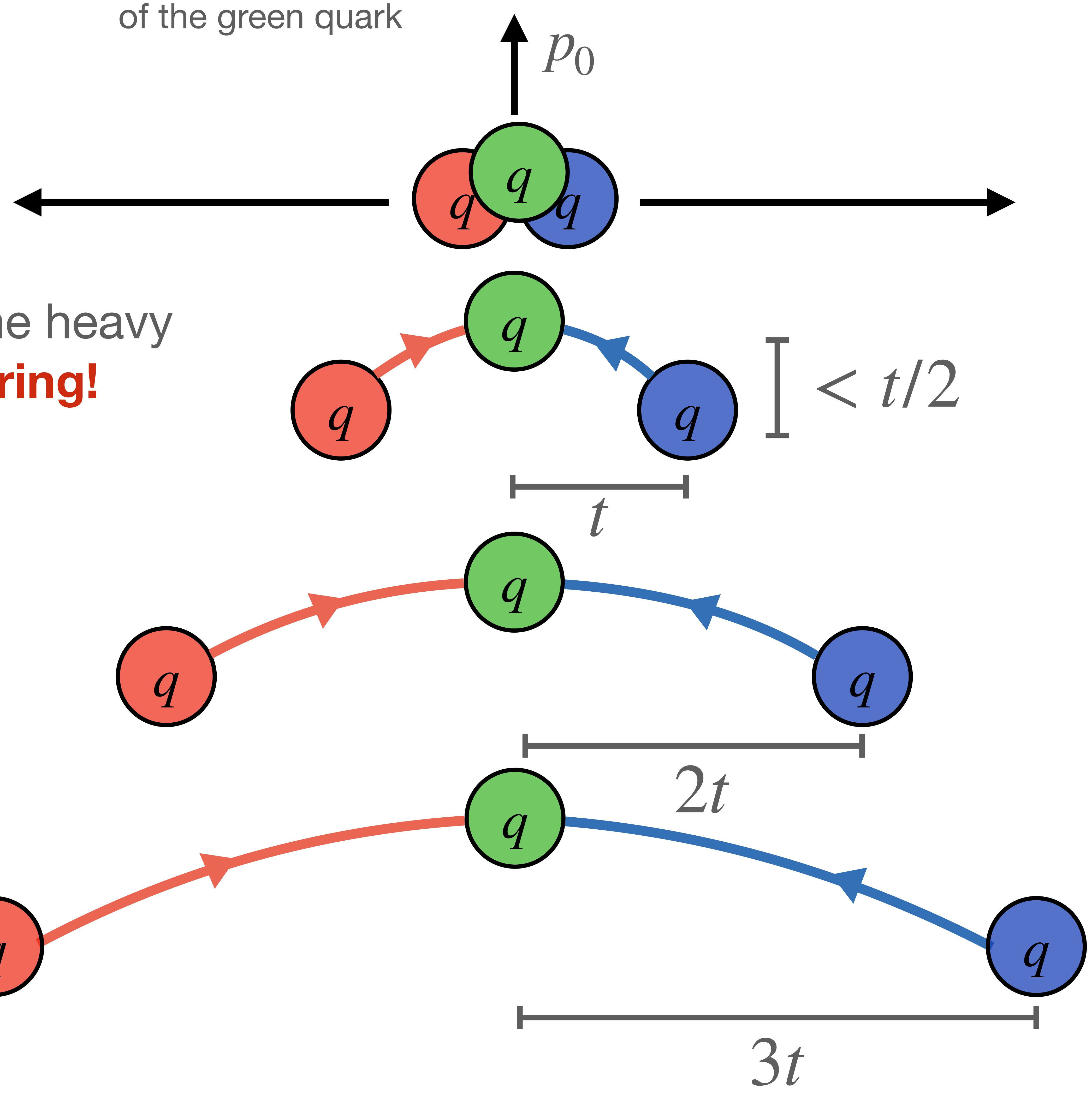

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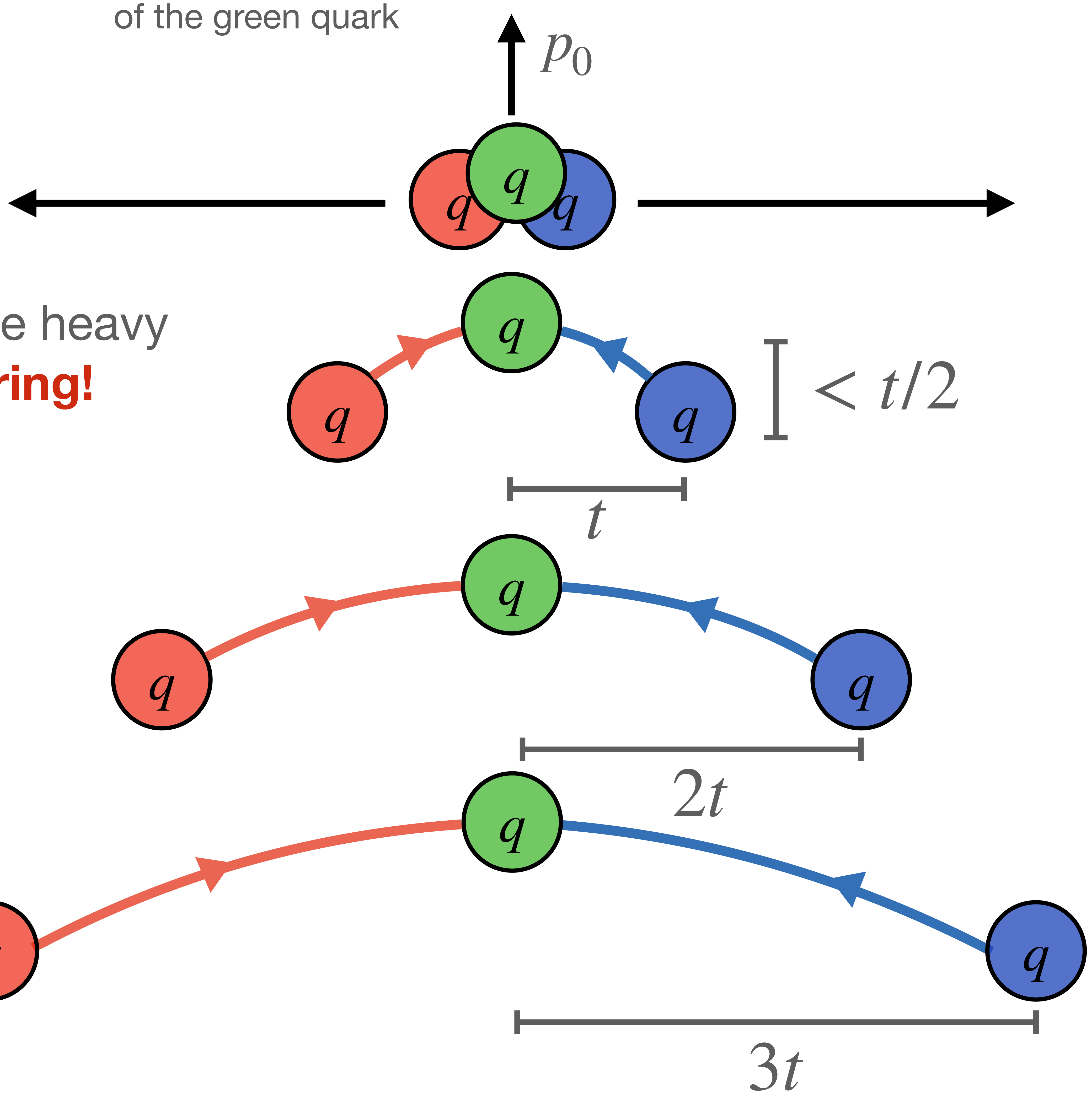

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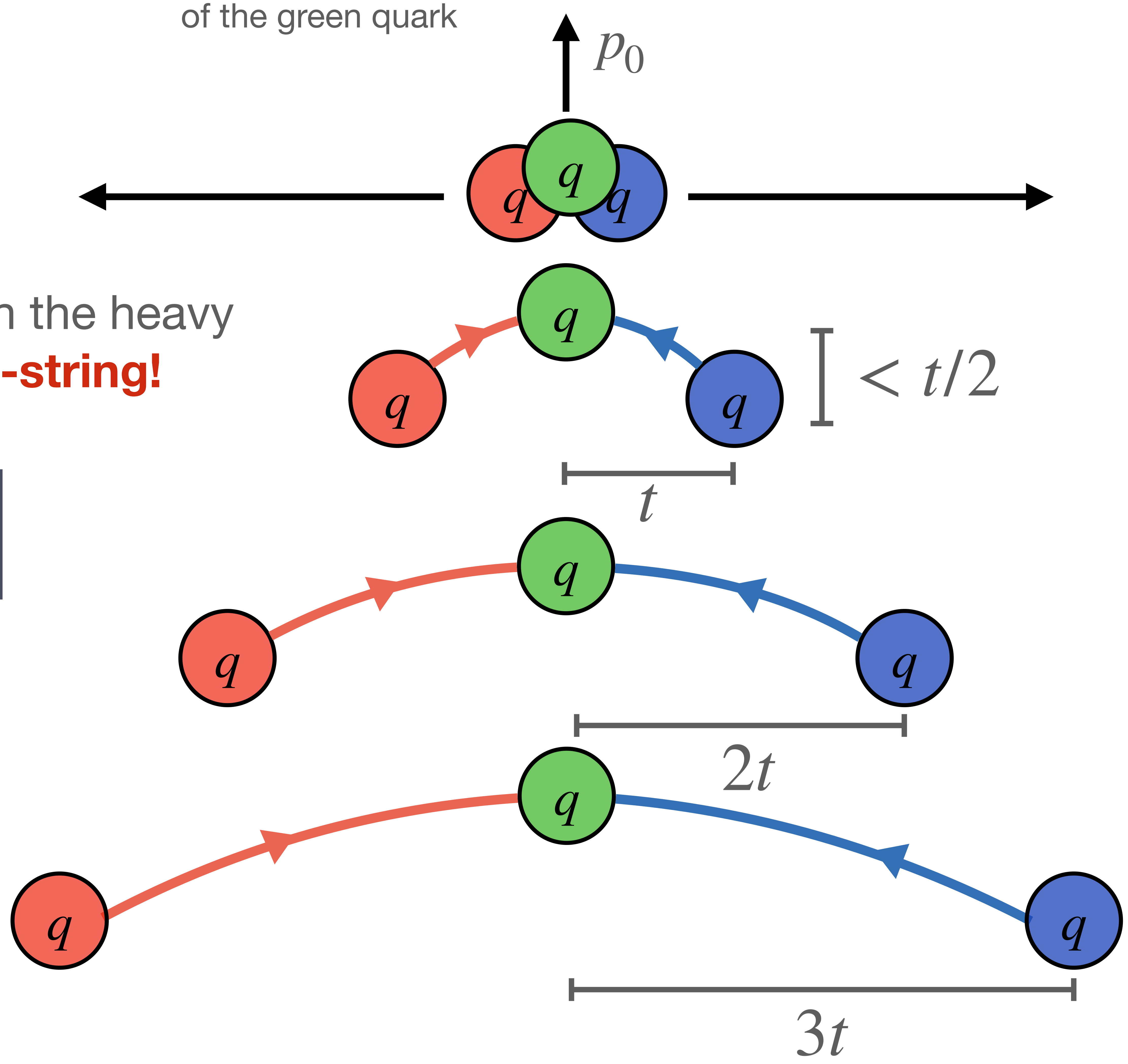
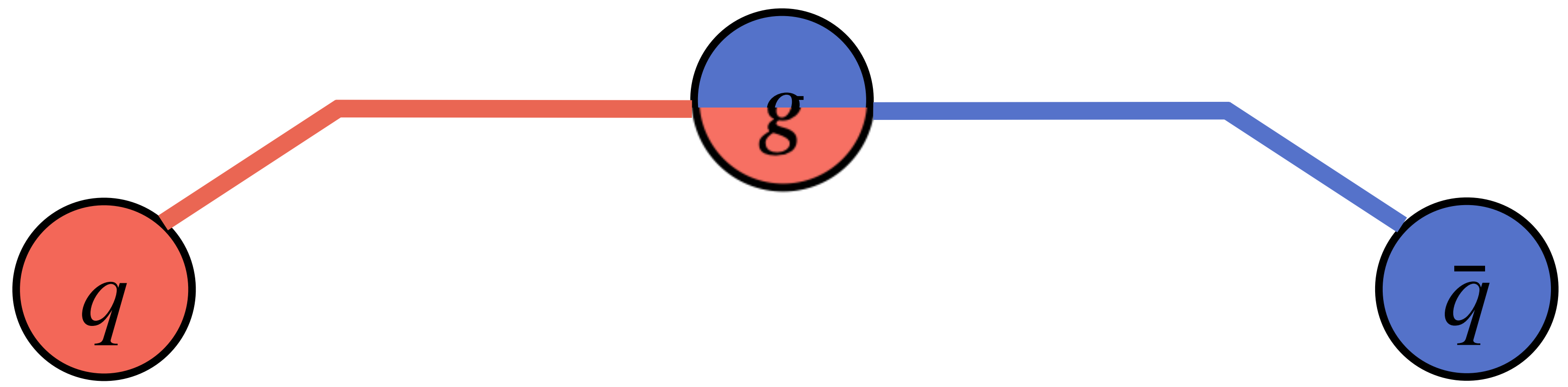
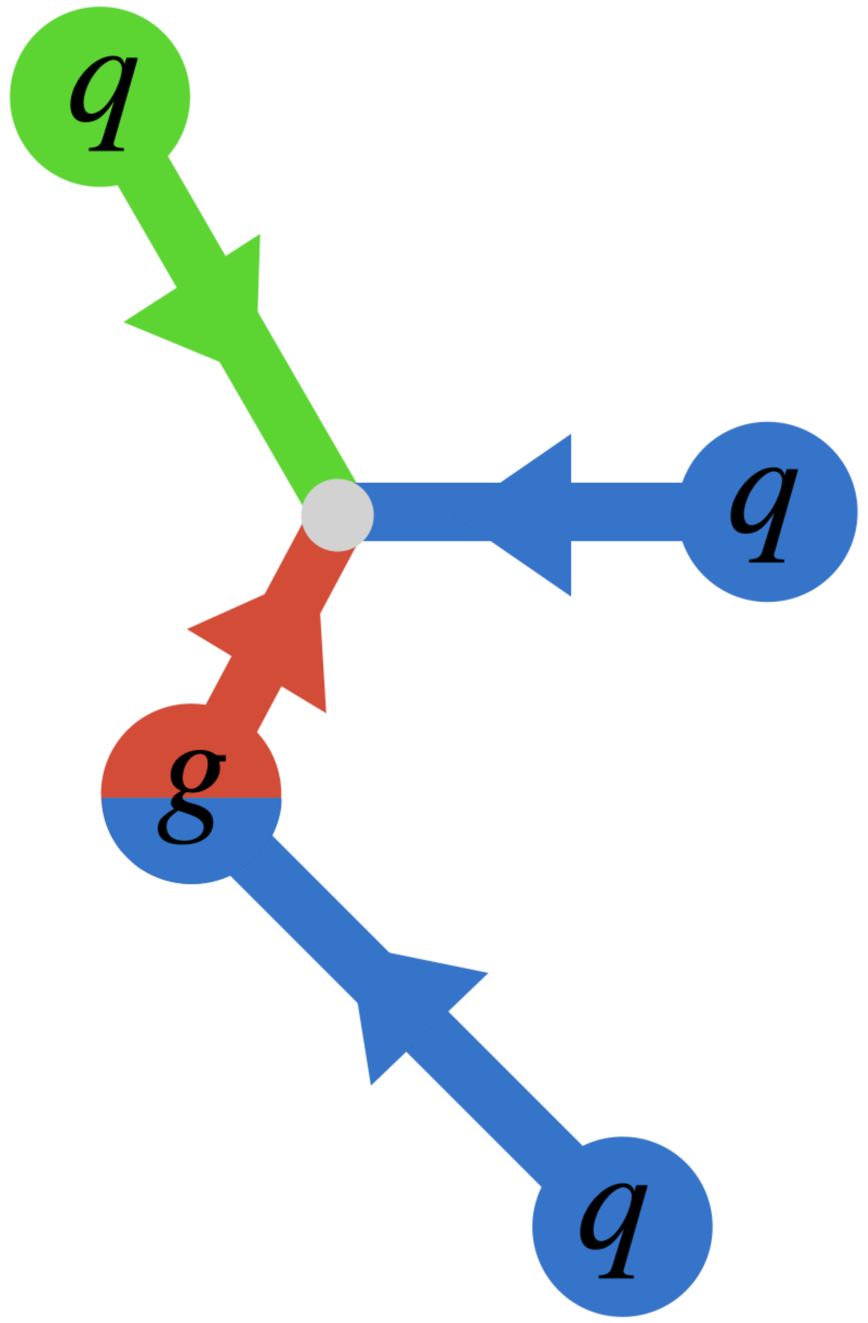



## How do we fragment pearl-on-a-string cases?

- ➢ Average over the pearl motion
- ➢ Fragment like a $q - g - \bar{q}$ string *typically only a good approximation for light quarks



# Updates to averaging

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Current procedure assumes the average is the mercedes frame

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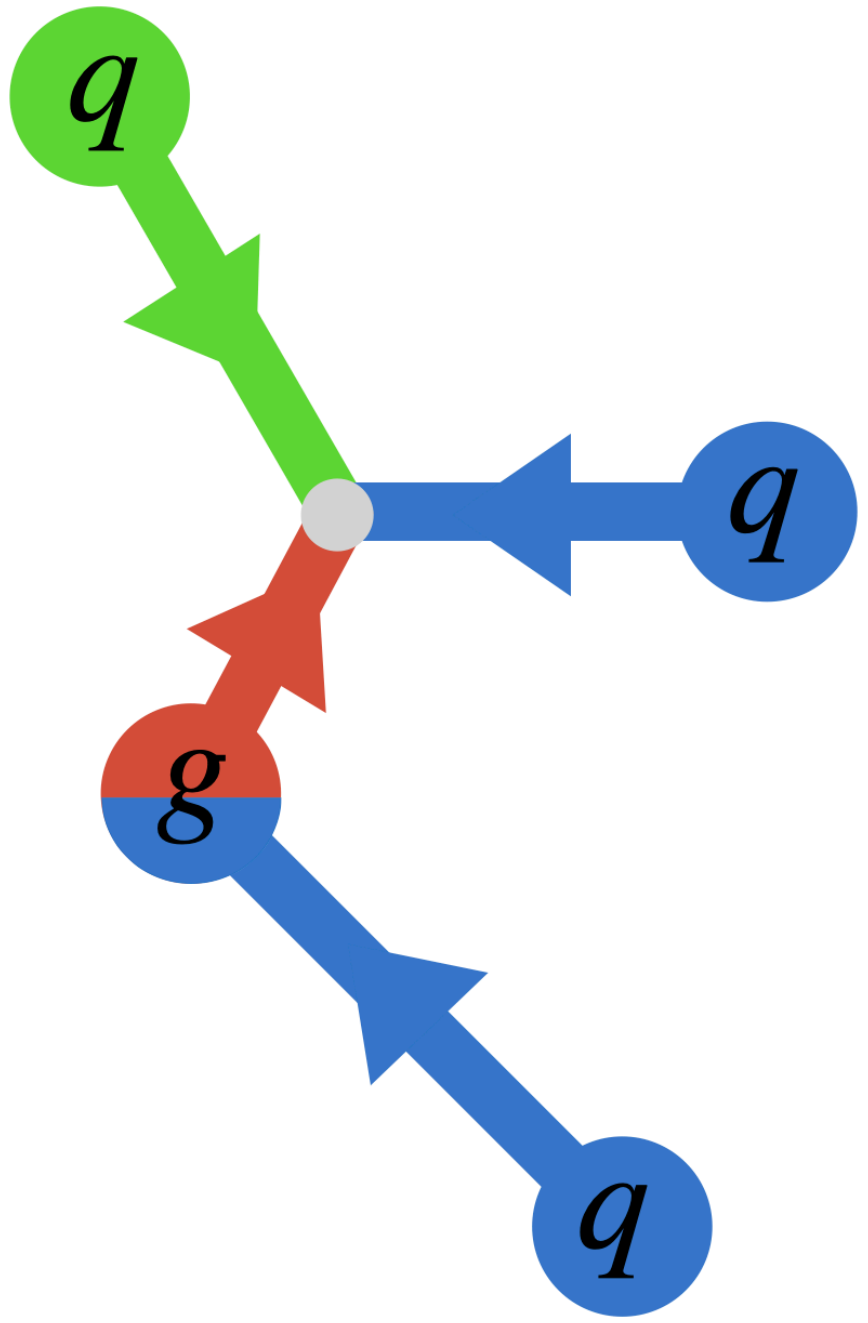


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**New treatment:**

- ➢ 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
Preliminary
ALICE pp 13 TeV
Monash
CR new
CR new with gluon-approx
CR old
WITH JUNCTIONS
NO JUNCTIONS
LiveDisplays
Theory/Data
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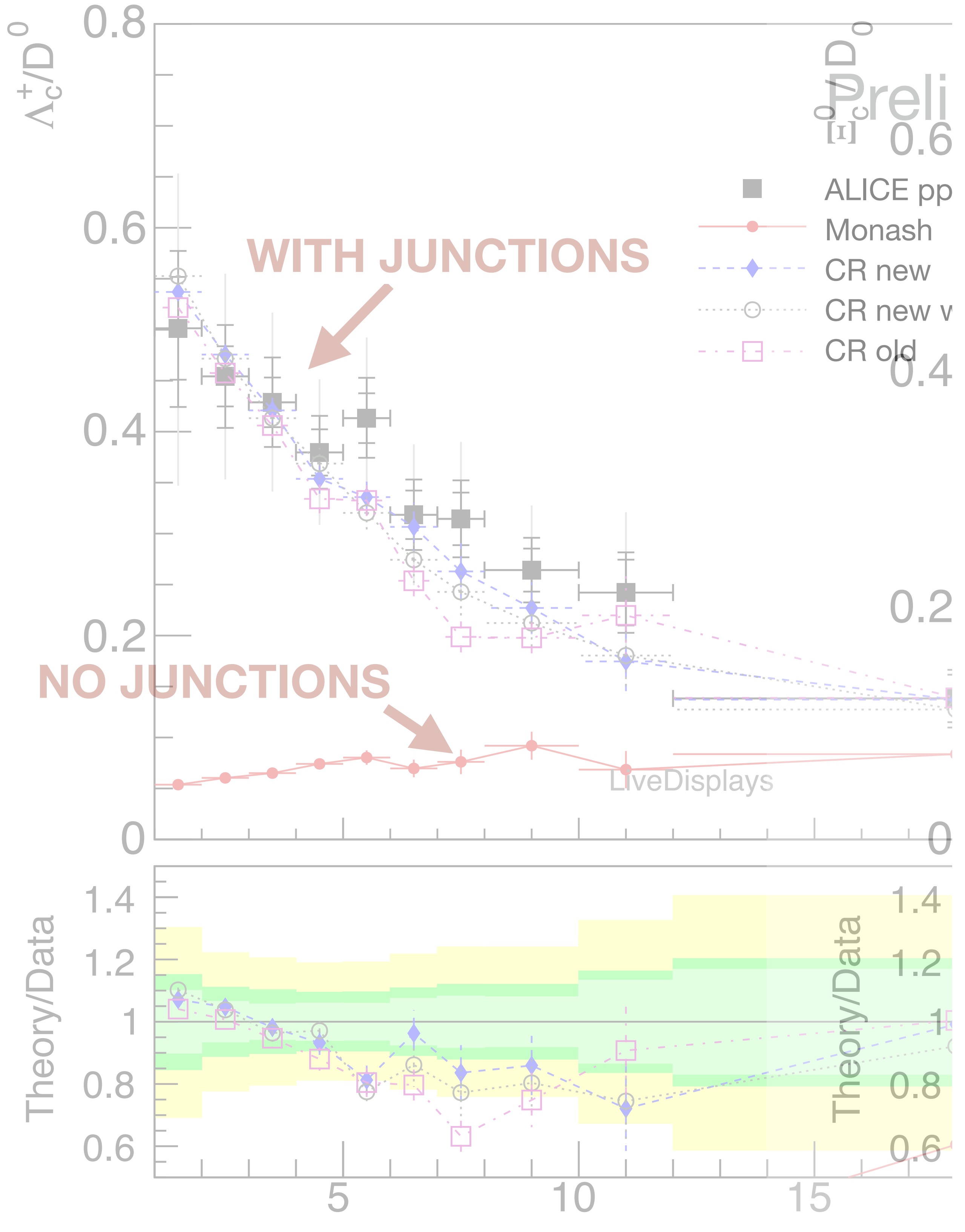
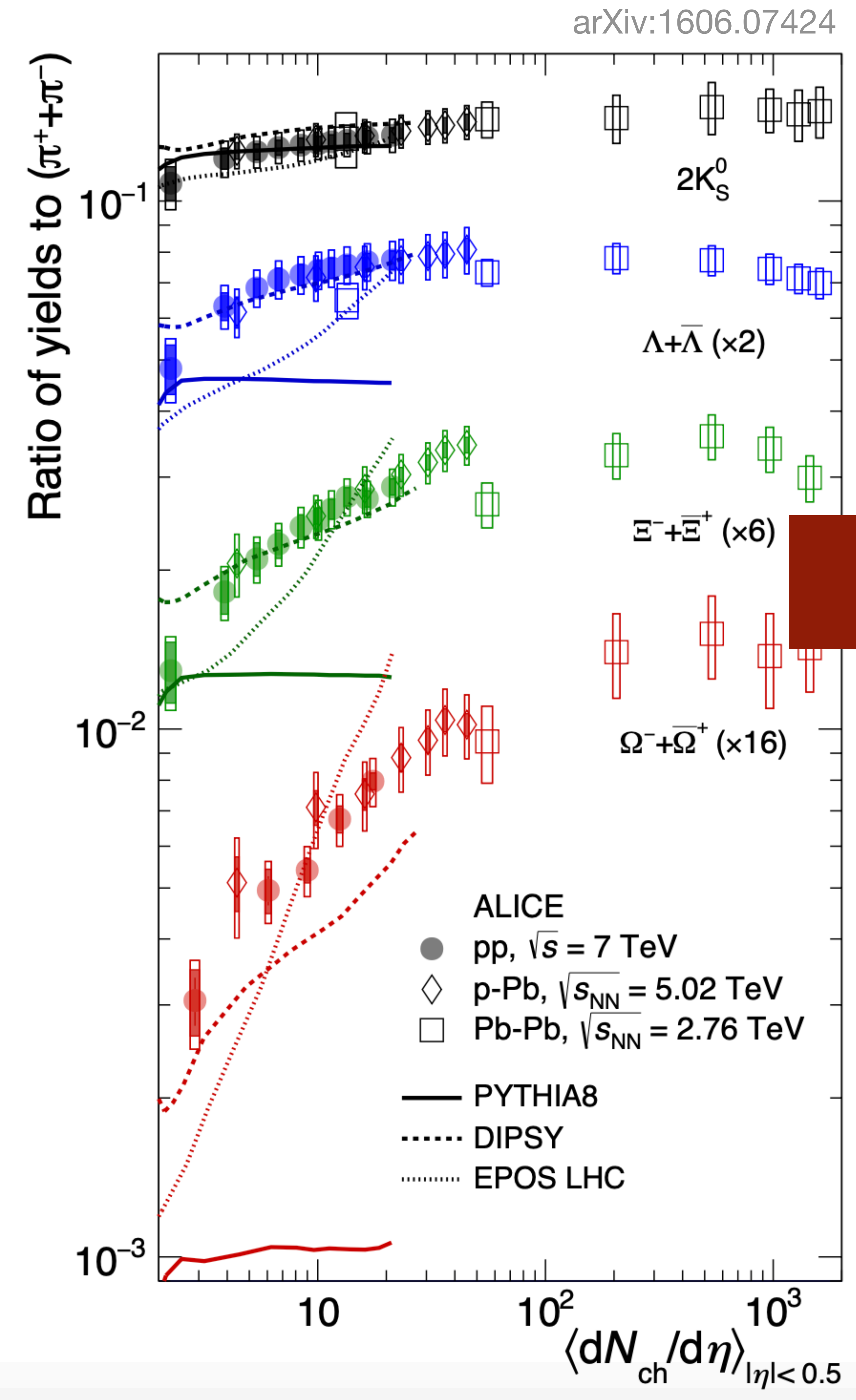
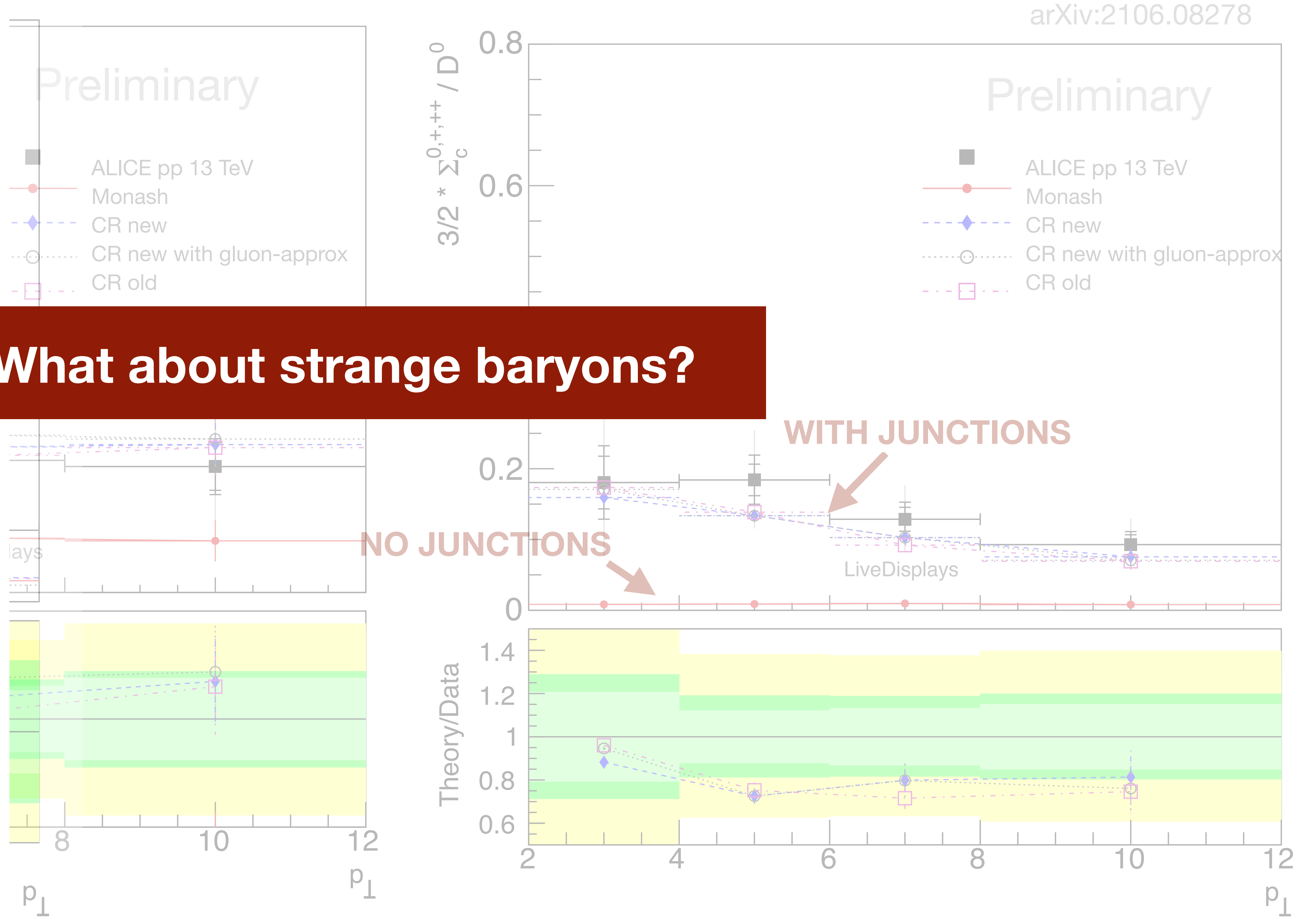


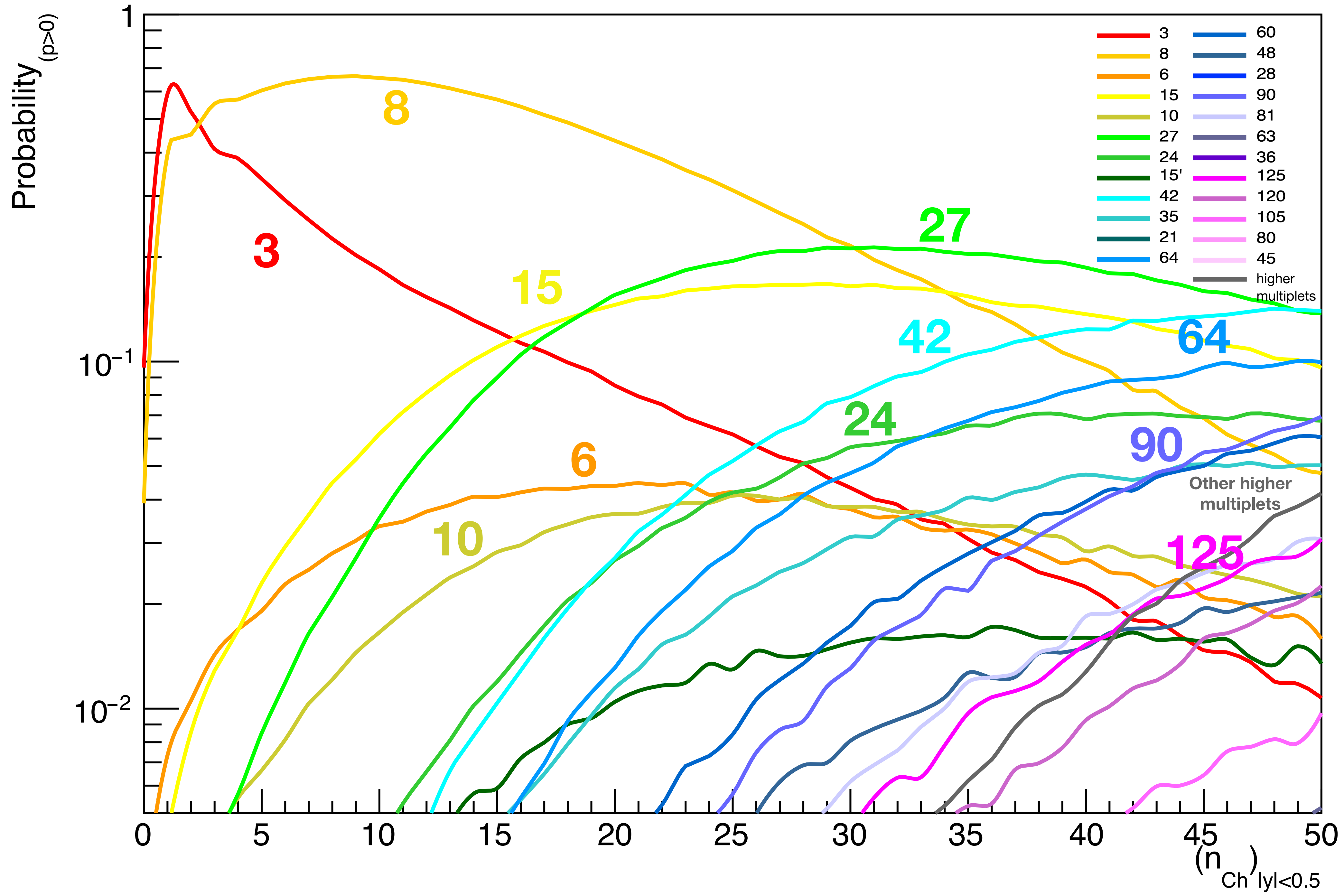




**What about strange baryons?**

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

# Strangeness Enhancement

## Multiplets (y=0, pp 7 TeV)

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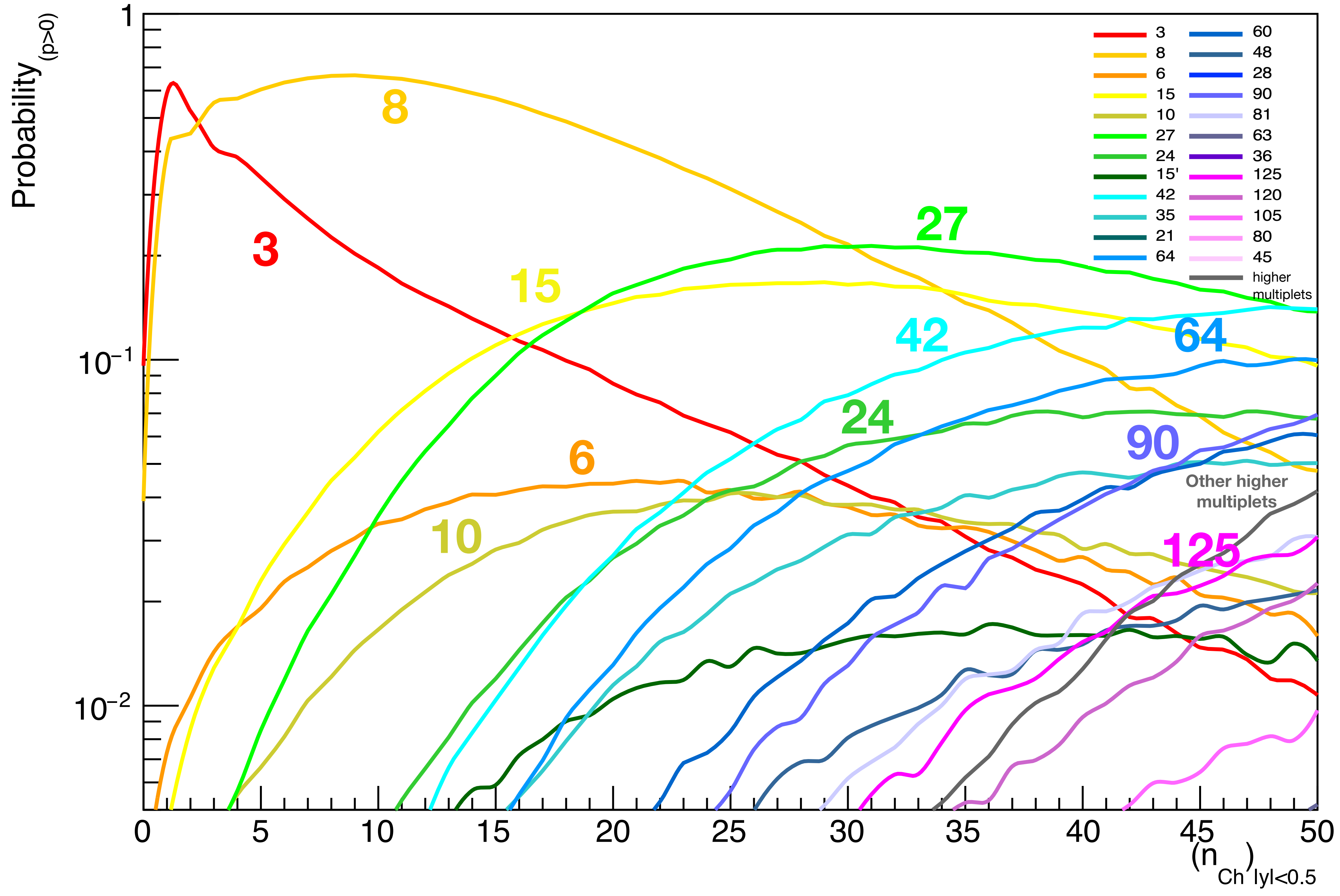


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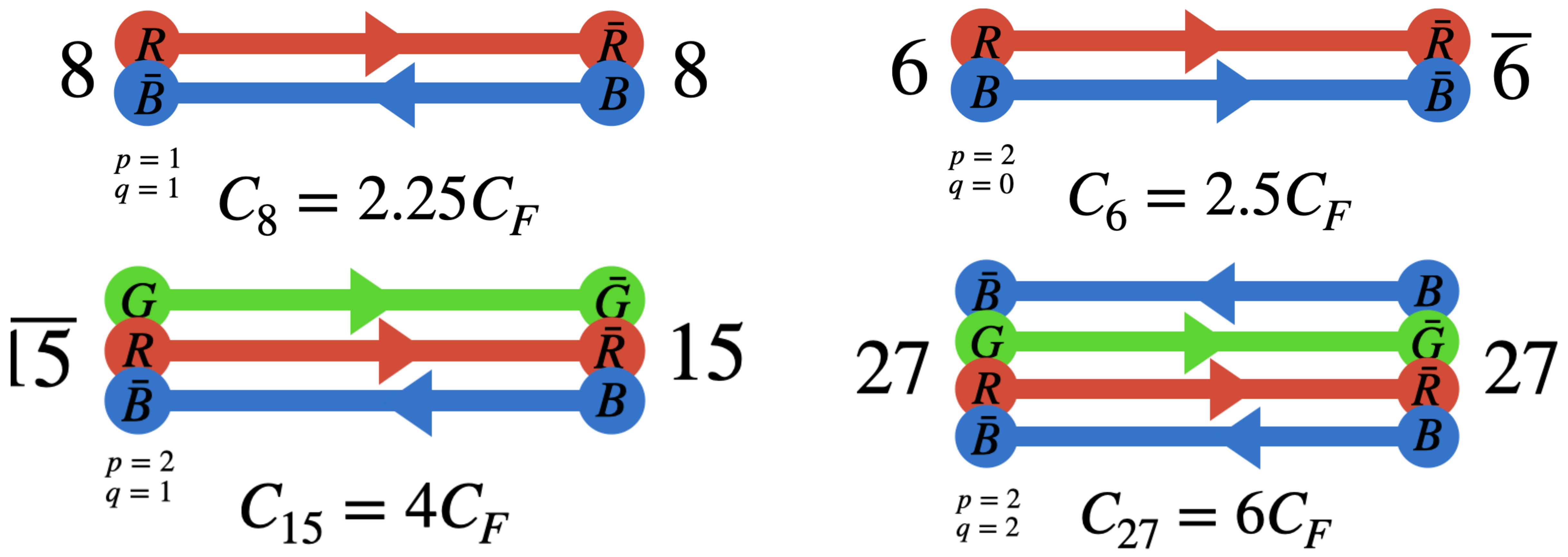


Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

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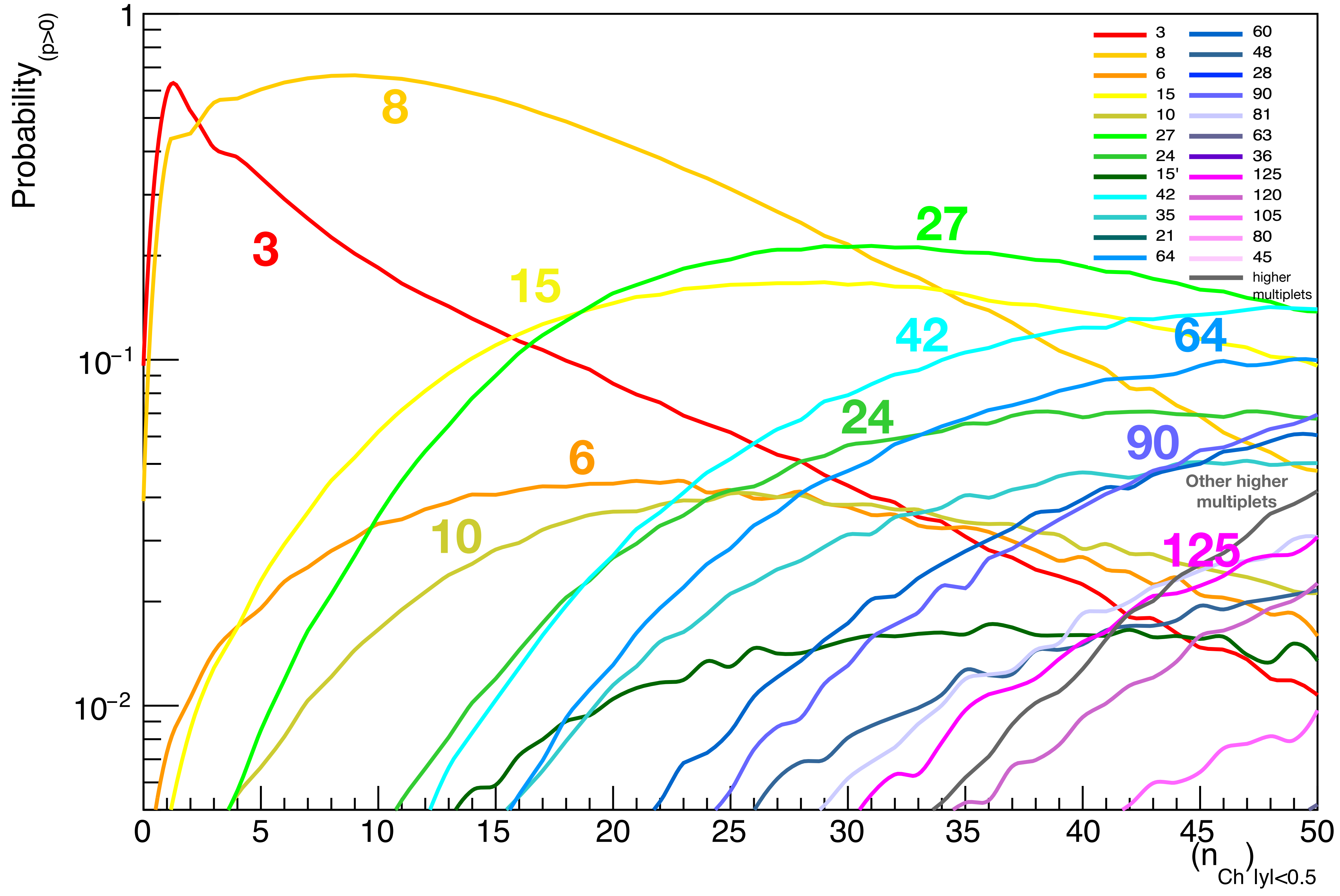


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## Close-packing


$p = 1$, $q = 1$ $\quad C_8 = 2.25 C_F$

$p = 2$, $q = 0$ $\quad C_6 = 2.5 C_F$

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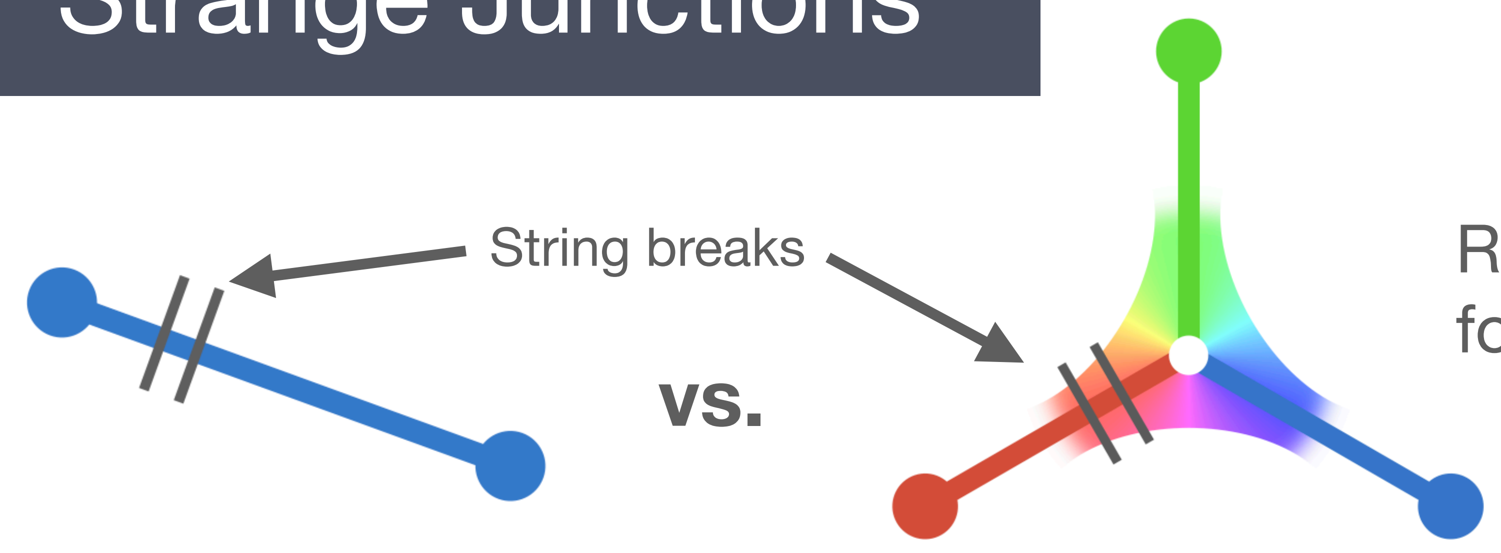
## Strange Junctions




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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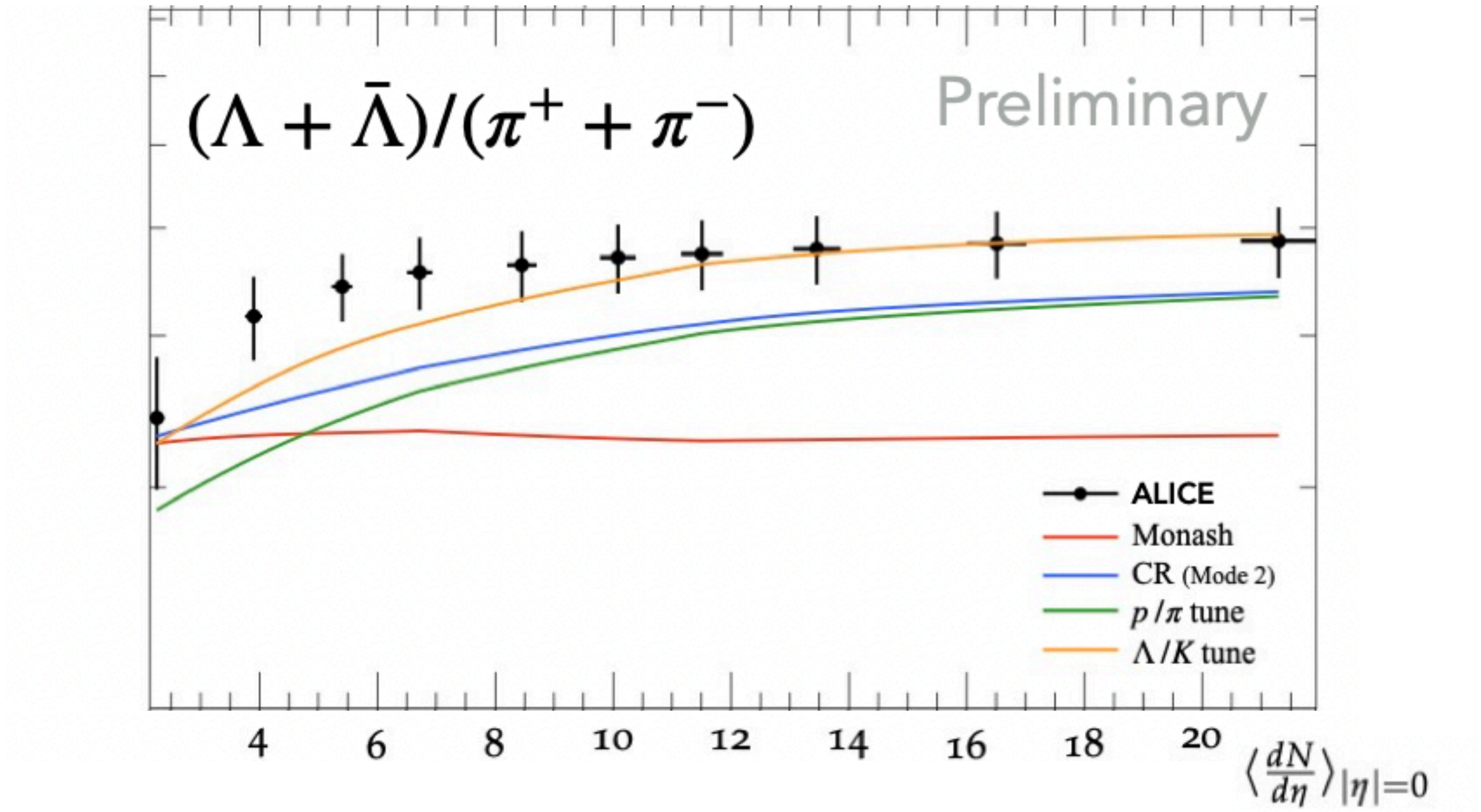


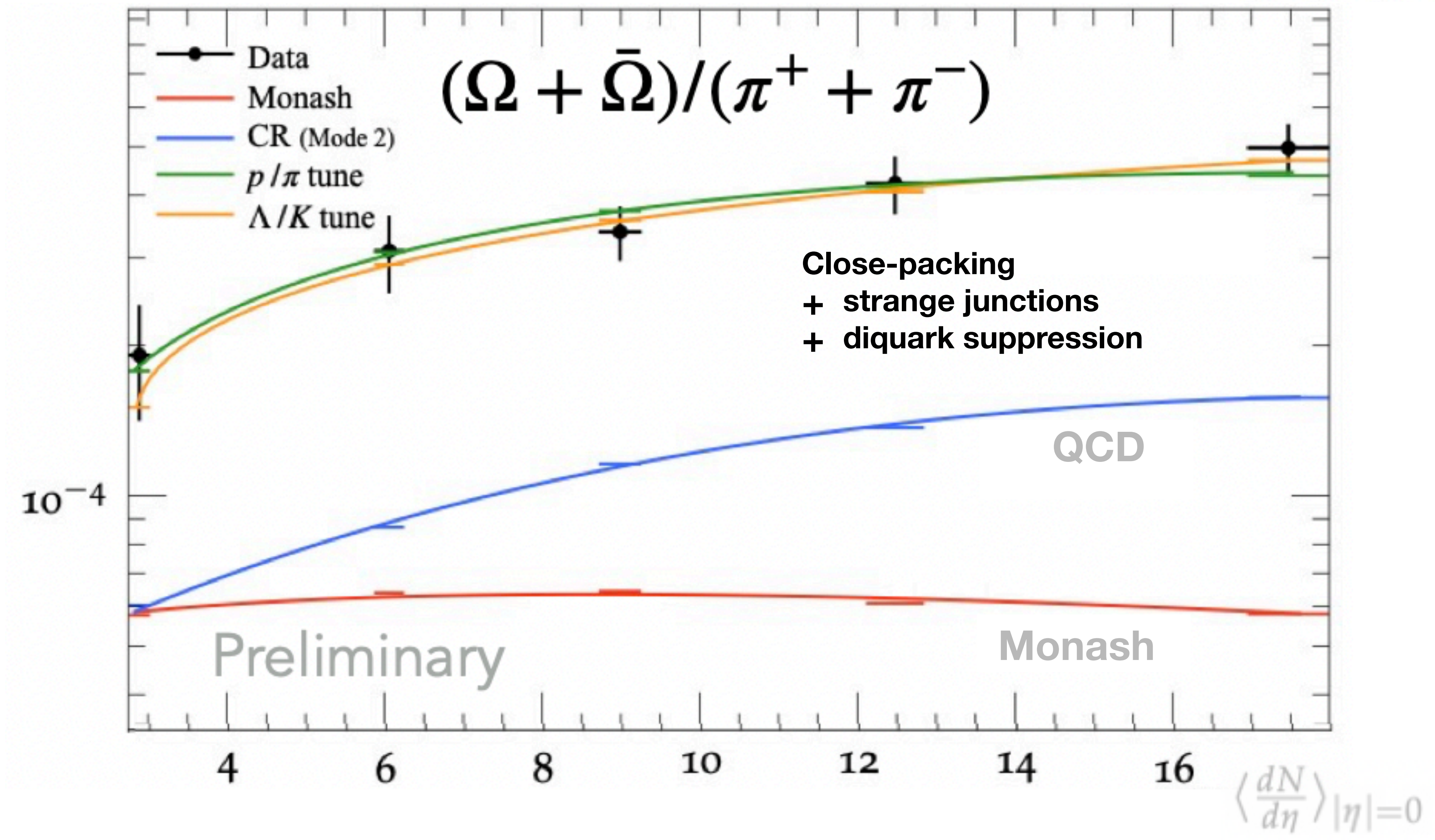


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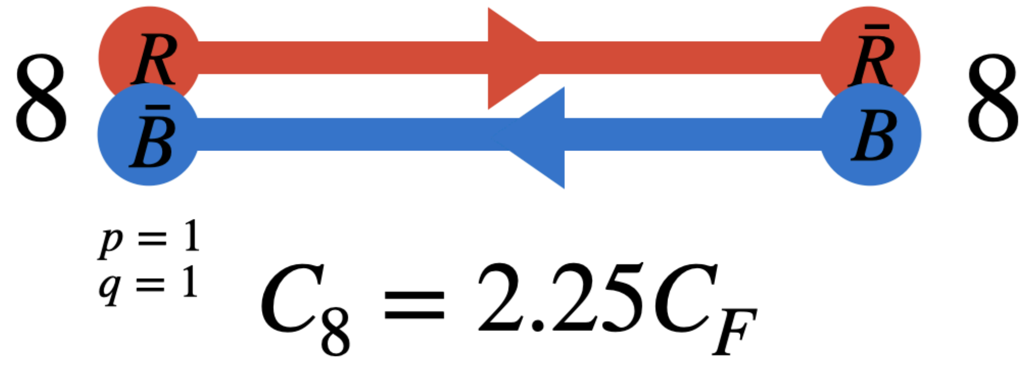


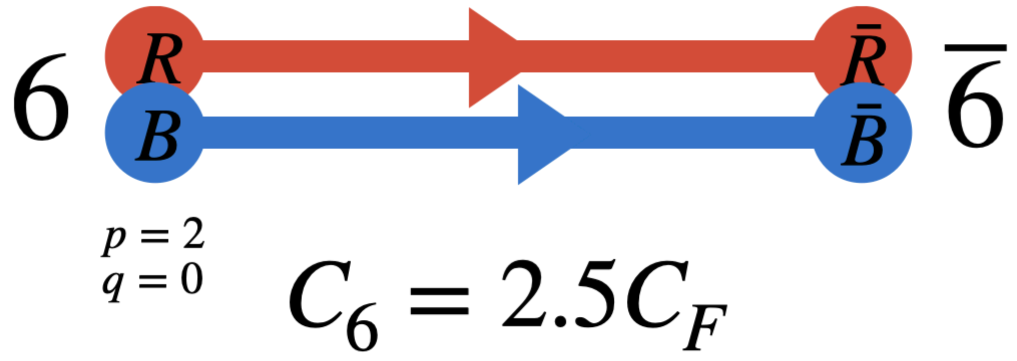


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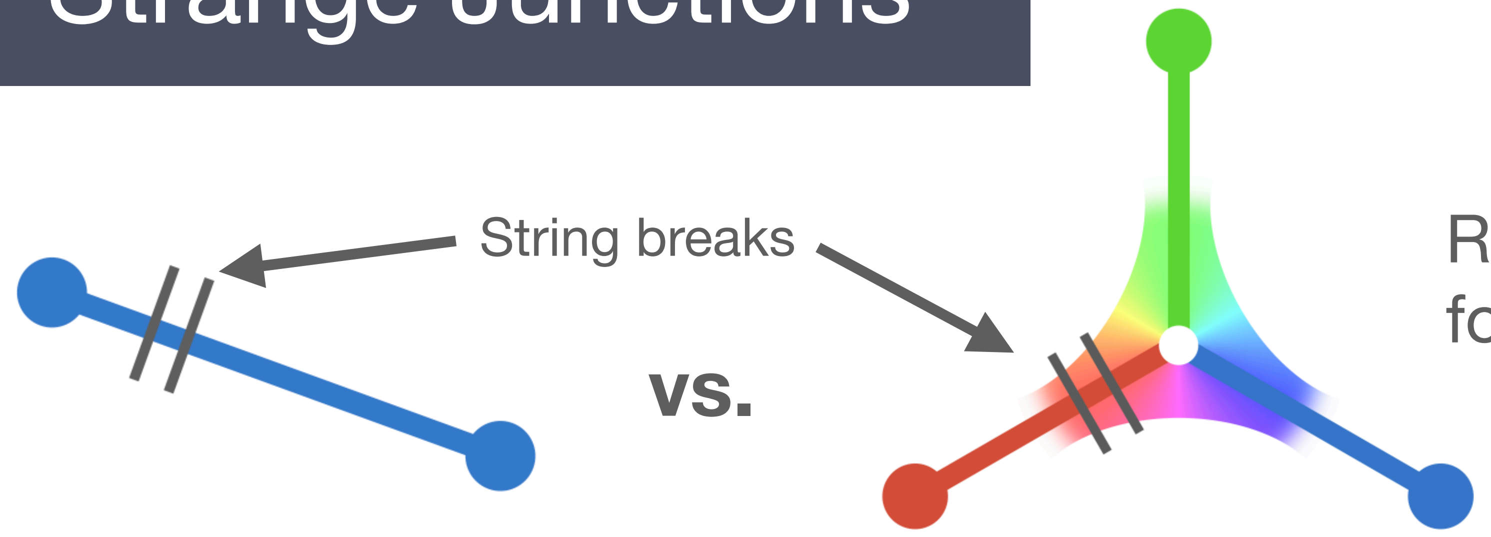


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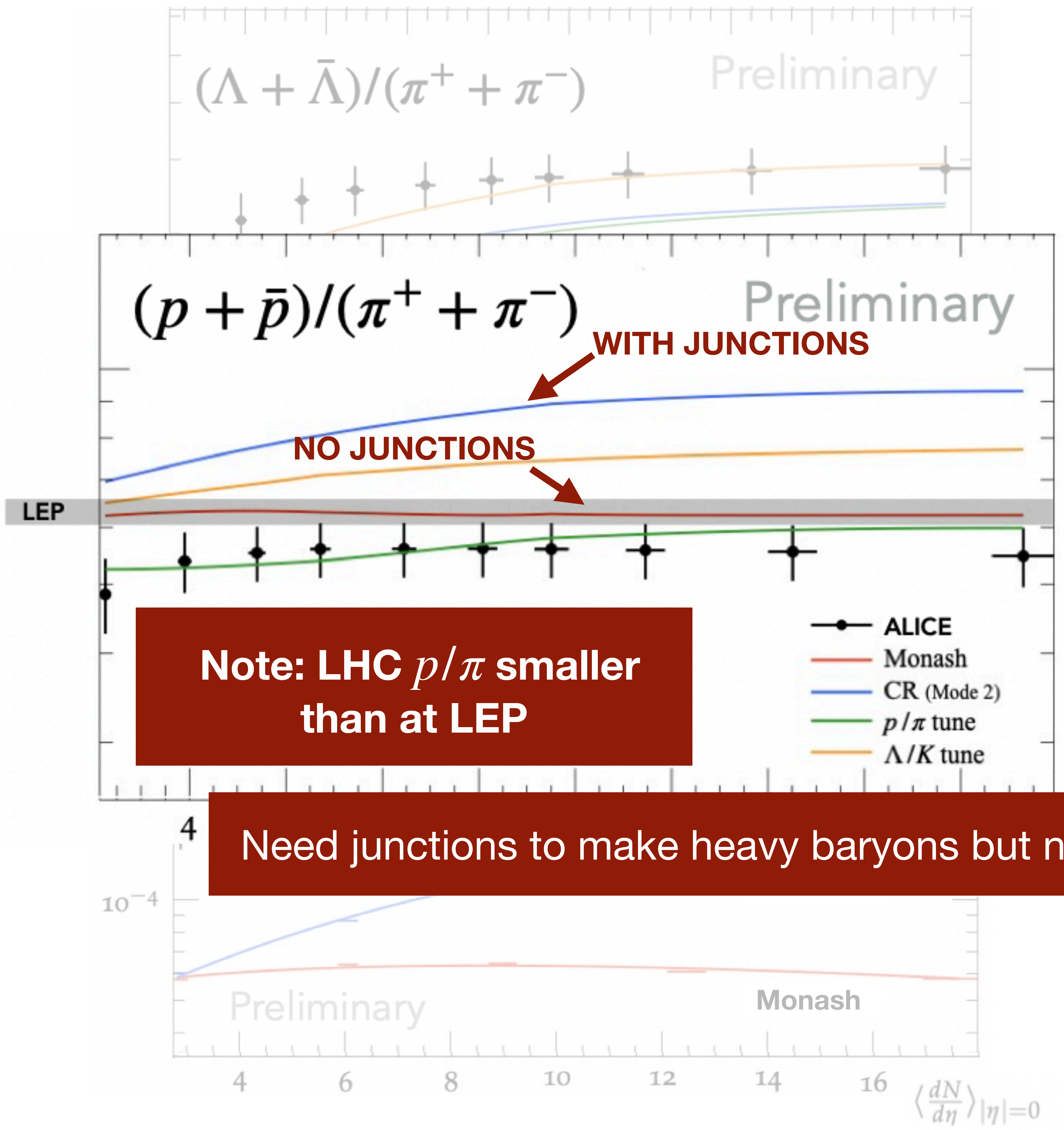


**Note: LHC $p/\pi$ smaller than at LEP**

Need junctions to make heavy baryons but need less protons?

## Close-packing


Dense string environments

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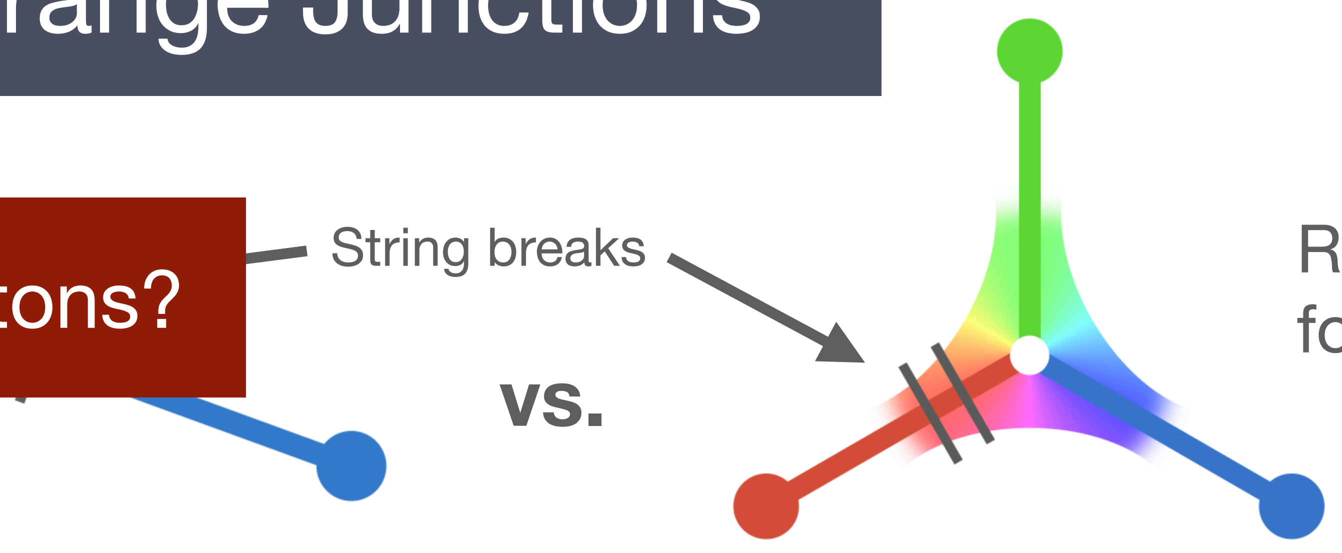
## Strange Junctions

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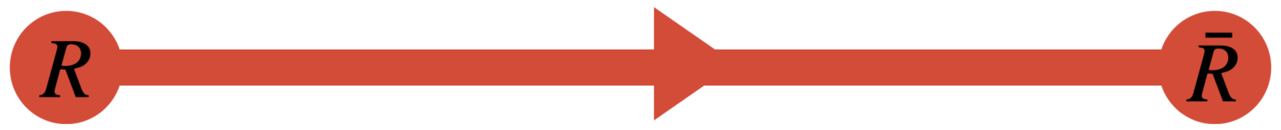
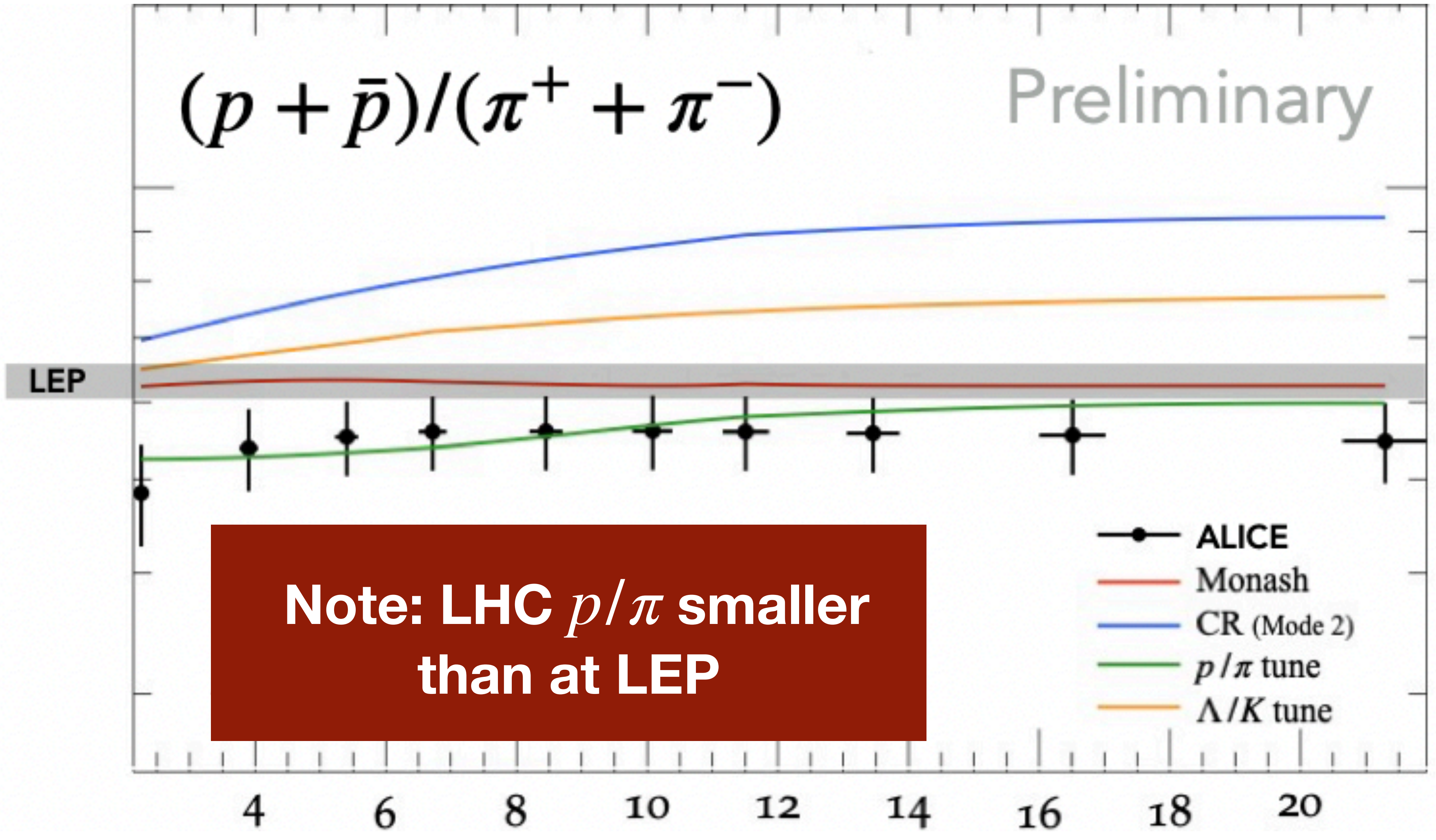
# Diquark Suppression

## Popcorn Mechanism

Diquark formation via **successive colour fluctuations**



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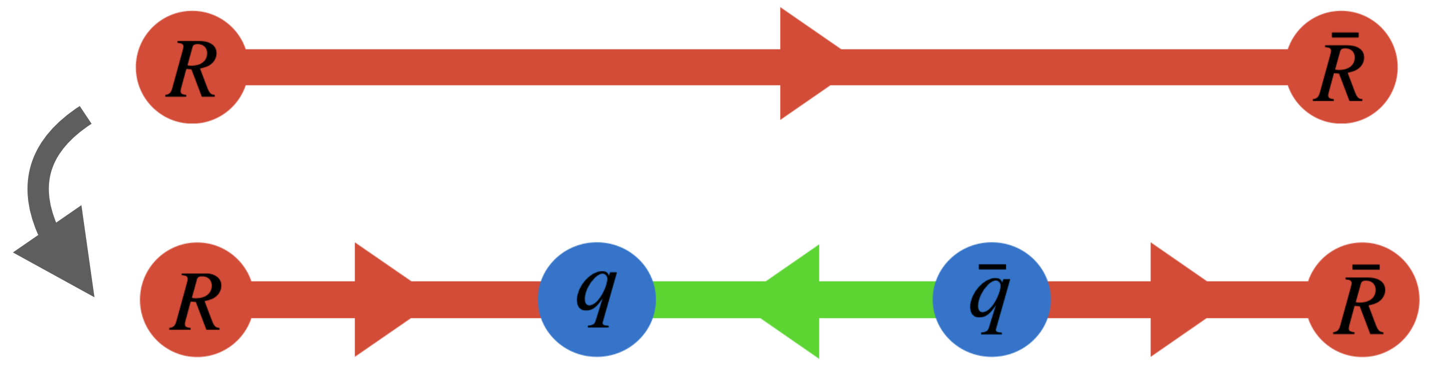
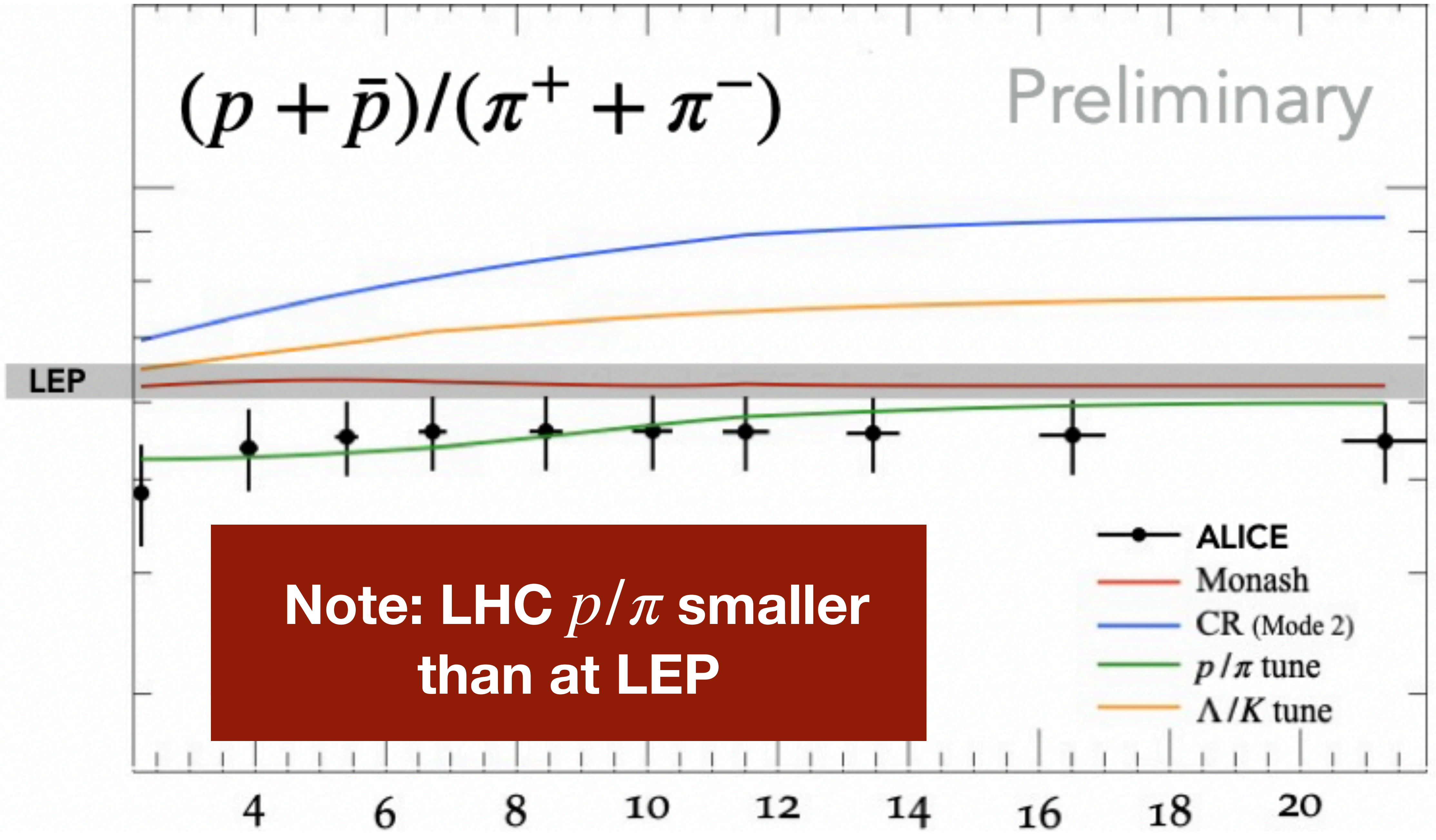



blue $q\bar{q}$ fluctuation on the string

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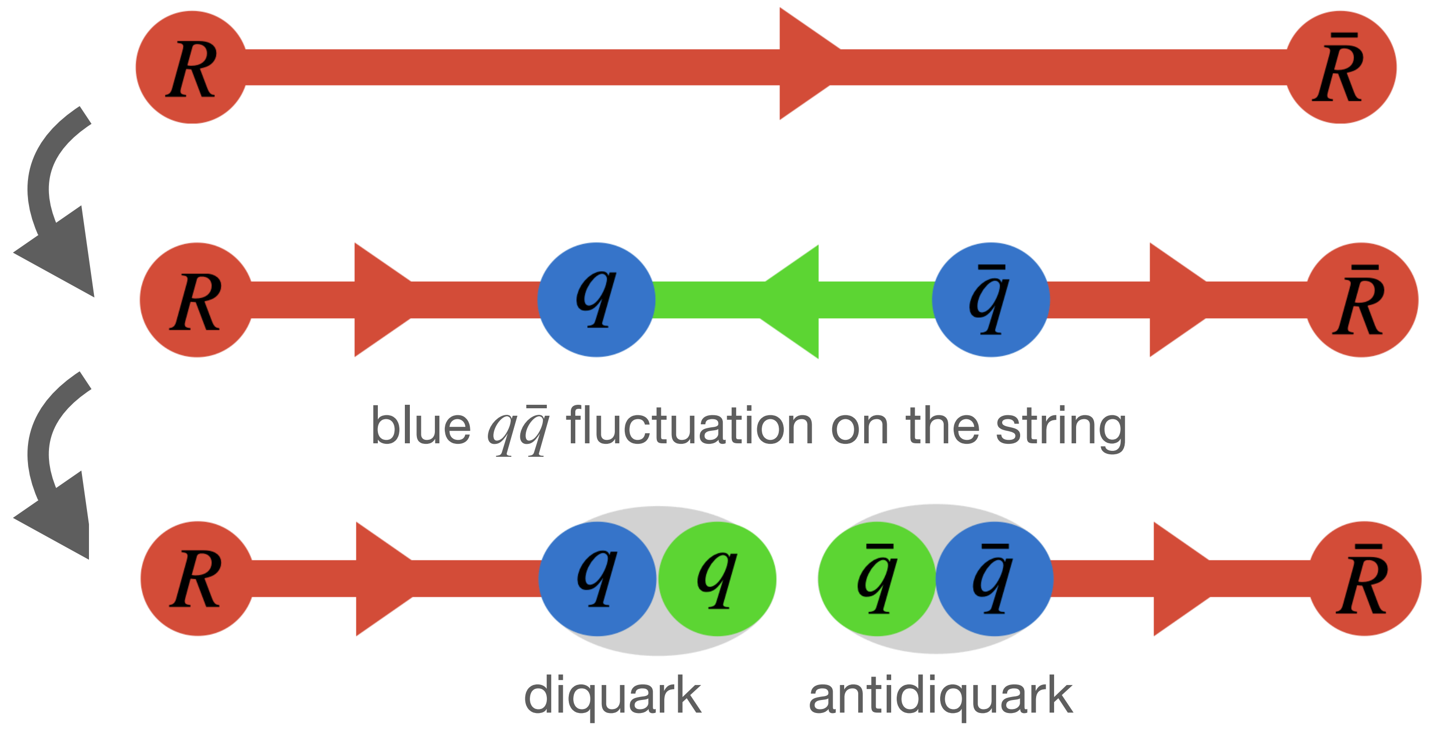


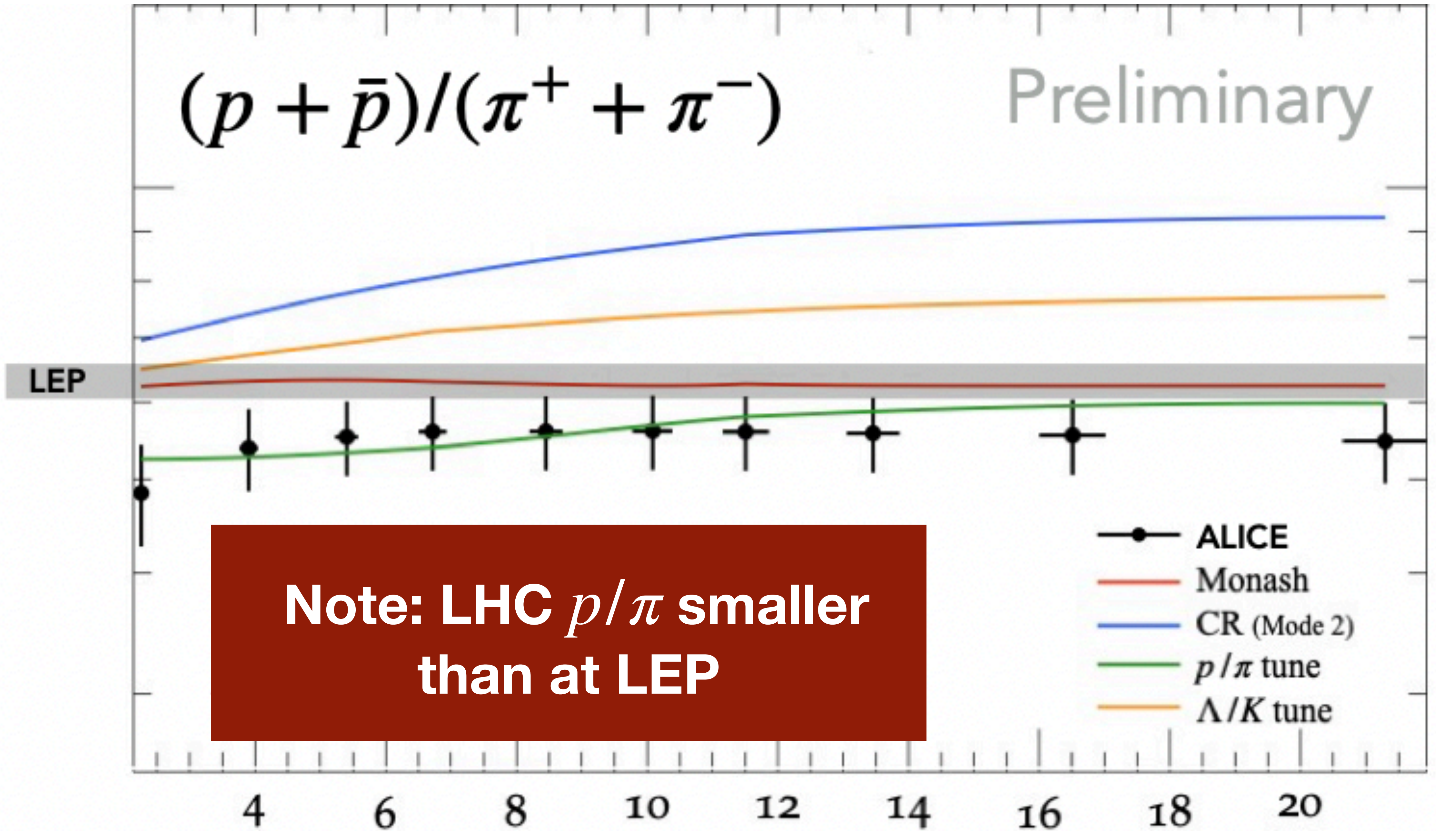

# Diquark Suppression

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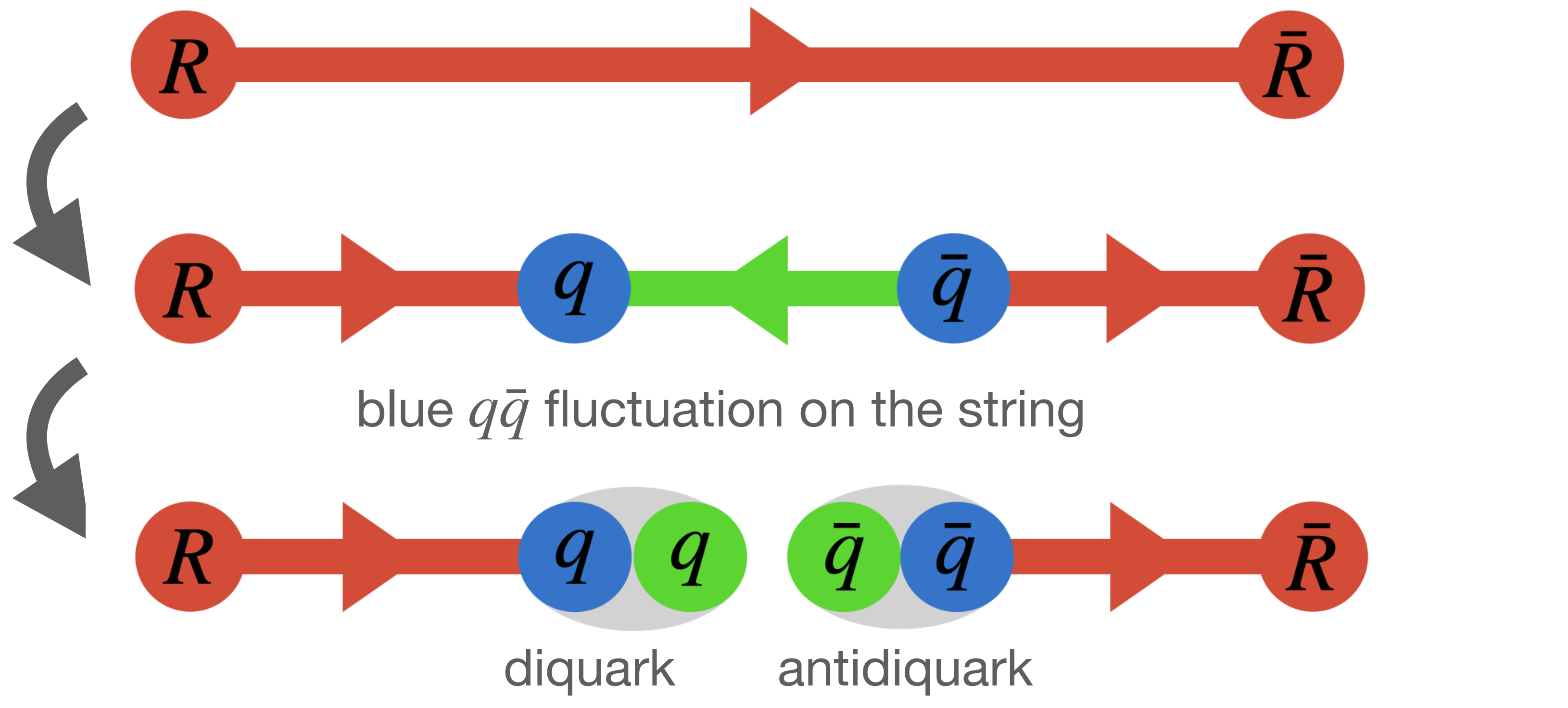
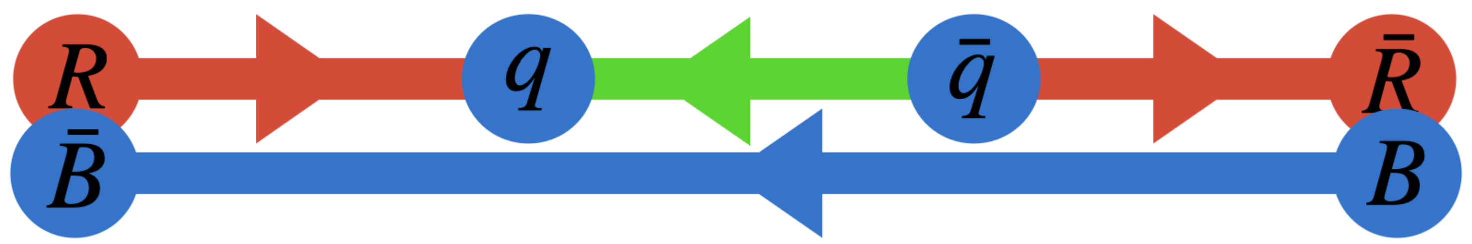
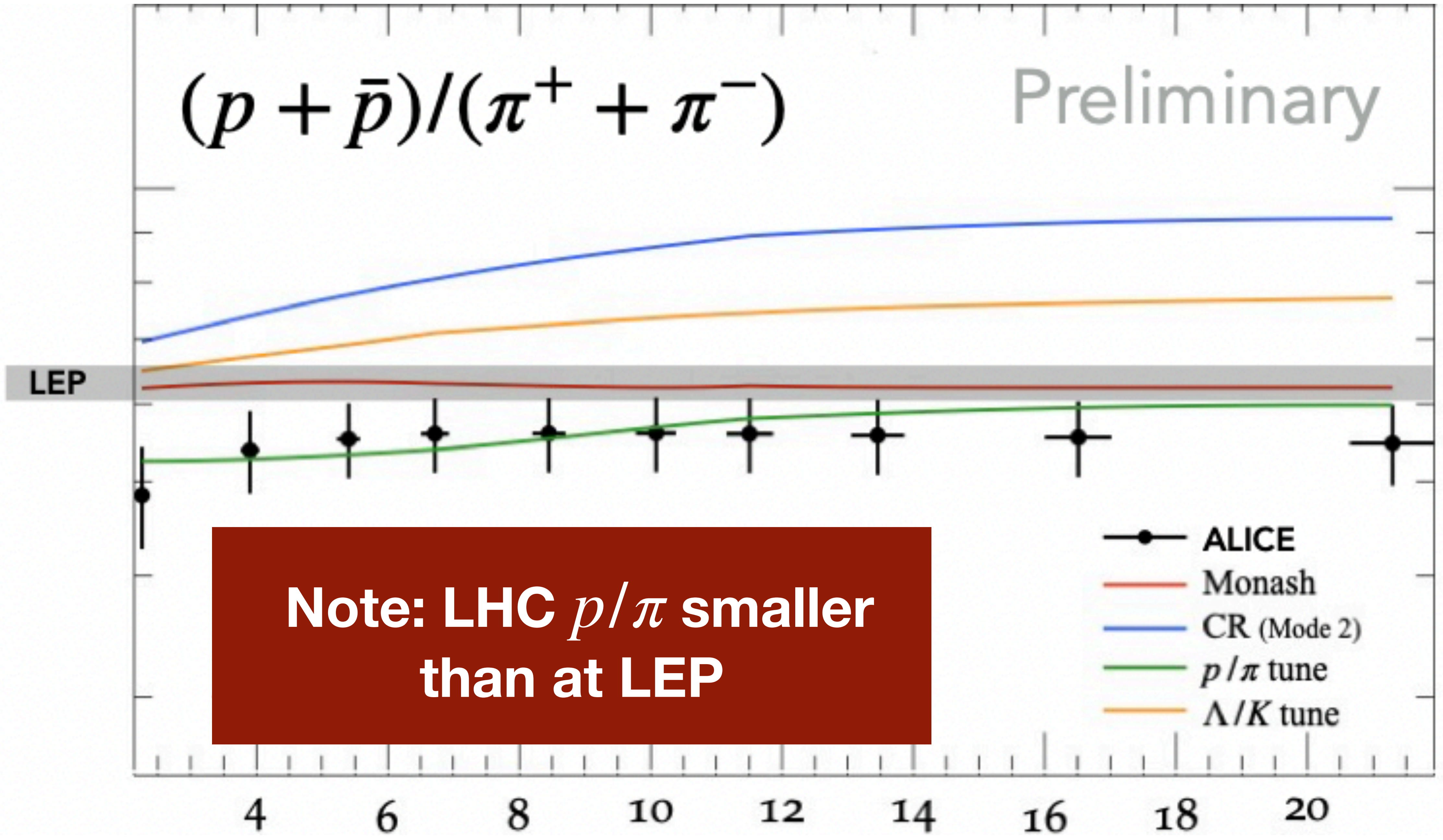



What if there's a blue string nearby?



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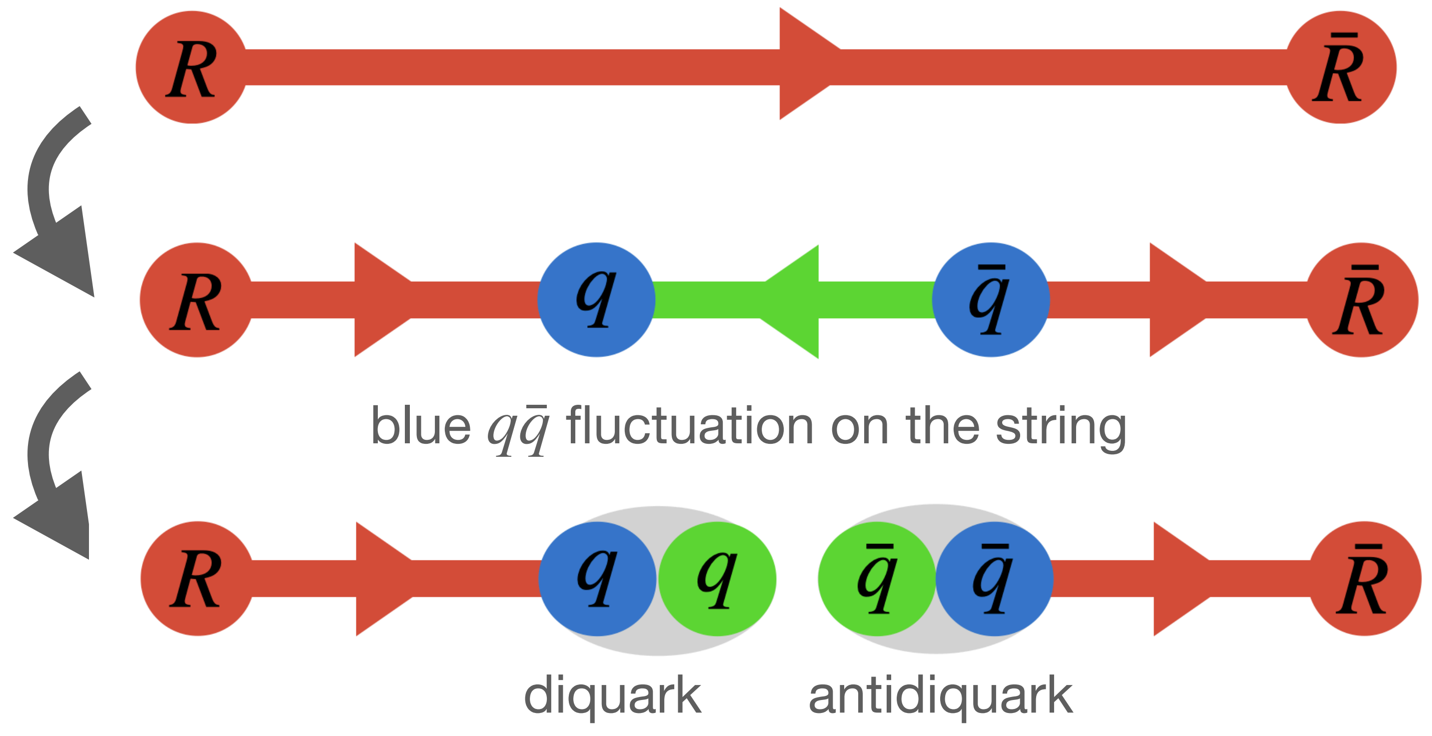


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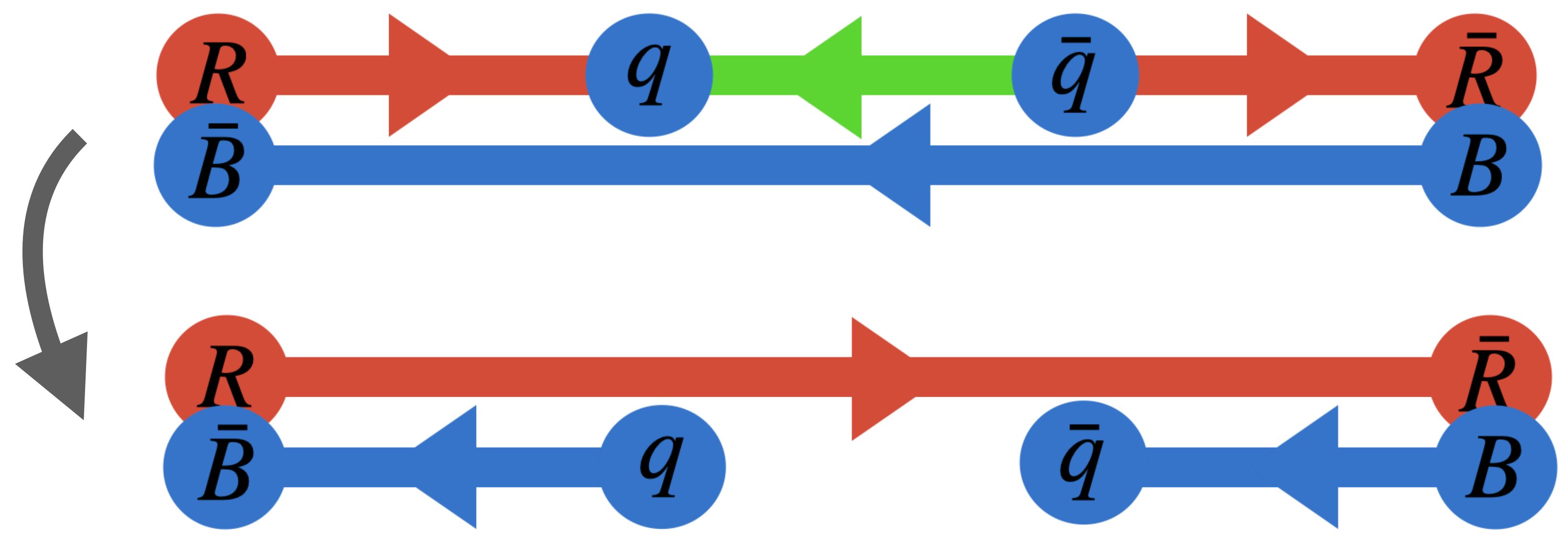
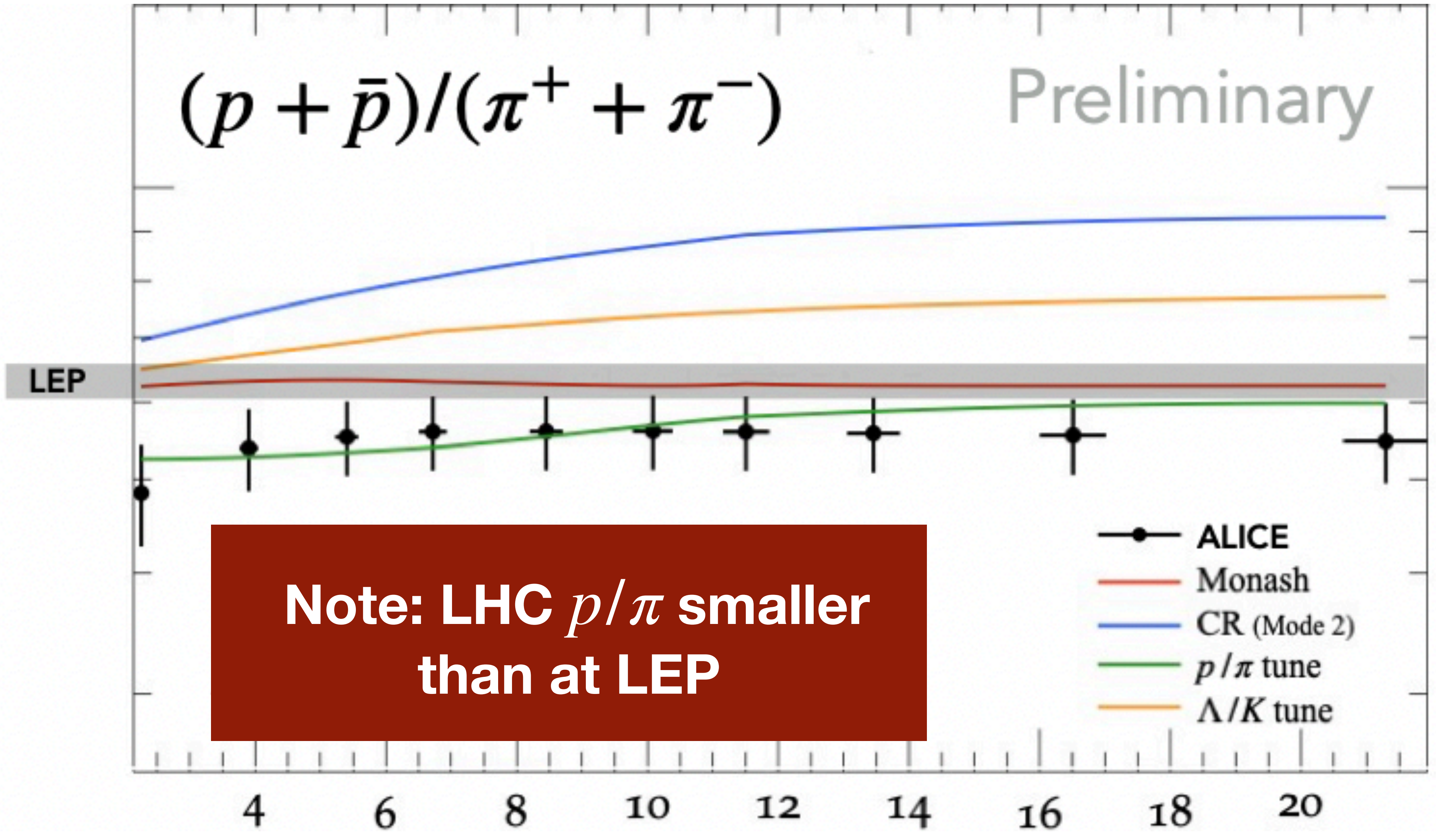



blue $q\bar{q}$ fluctuation breaks nearby blue string, preventing diquark formation



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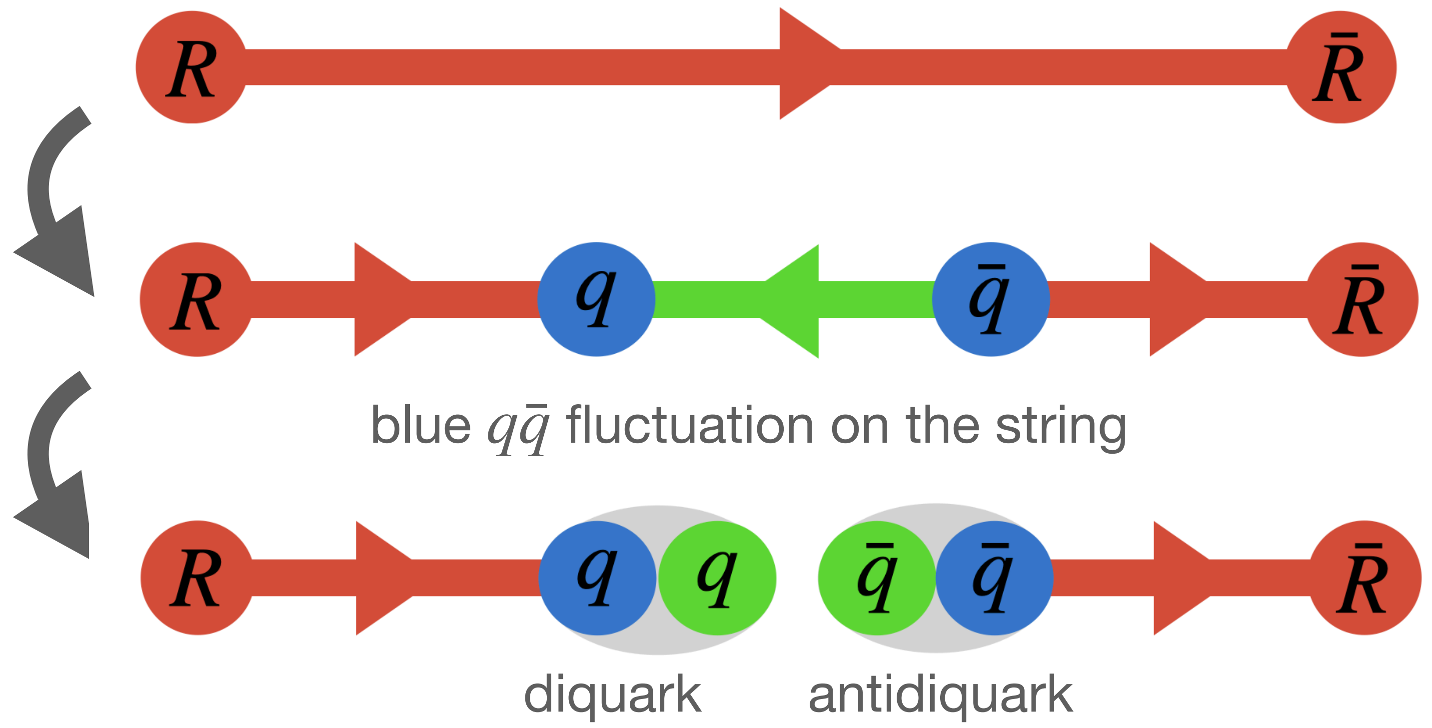


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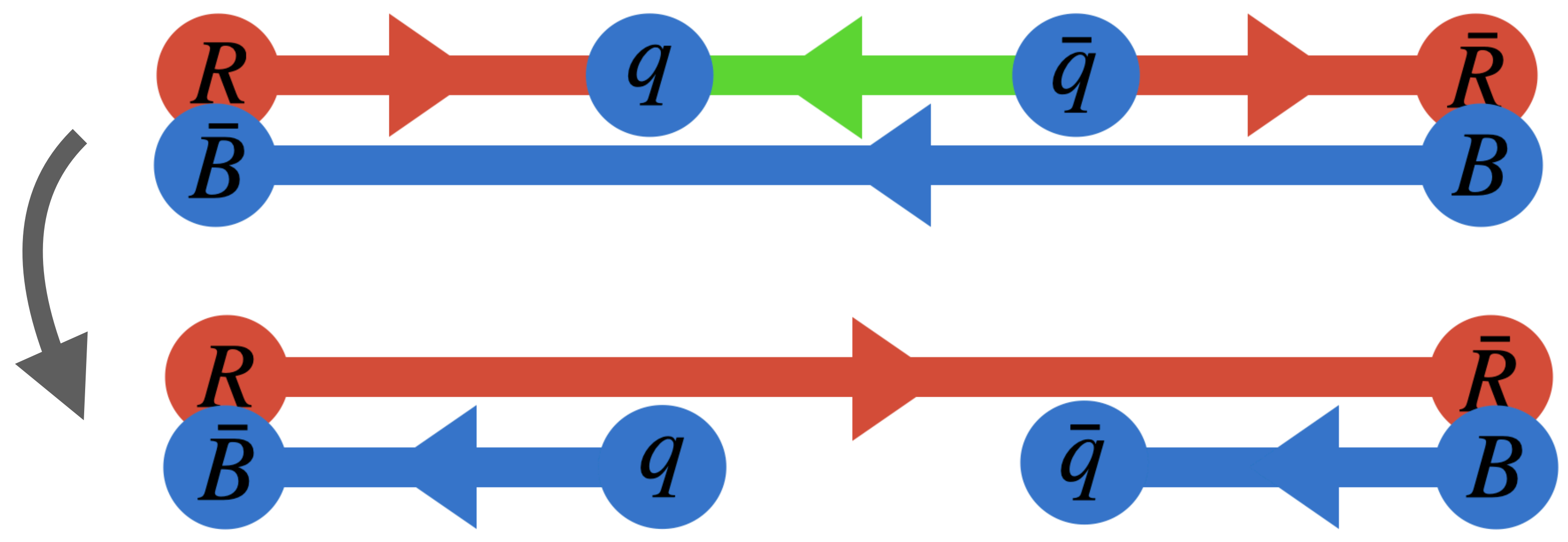


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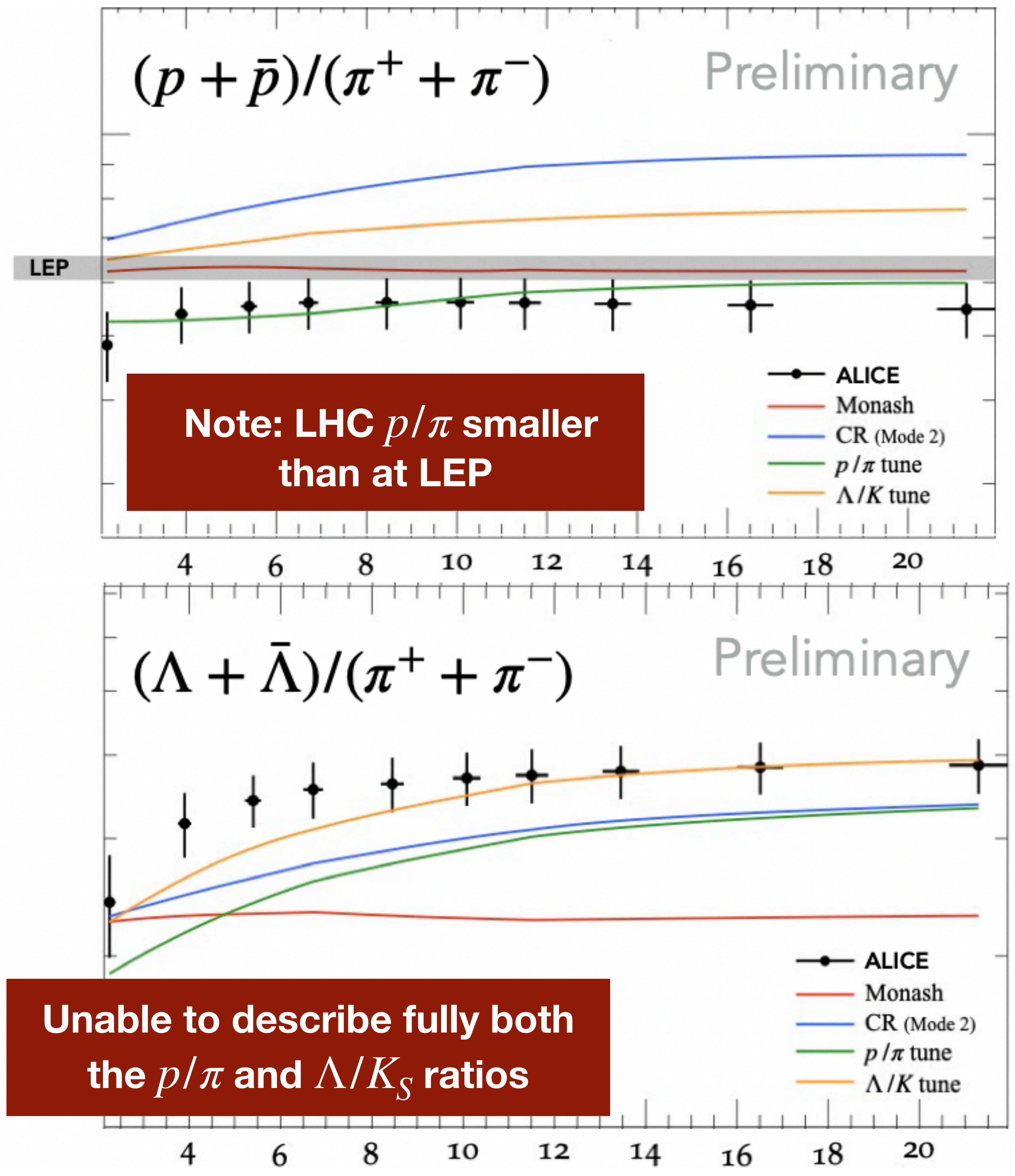

# Thank you for listening!

# Backup Slides

# Junction Rest Frame

What is the **junction rest frame**?

The standard JRF for a 3-parton configuration is defined as when the angle between each legs 3-momentum is 120º

## Finding the 120º JRF:

- Fix the angle between the 3-momenta to 120º and calculate the invariants:

$$a_{ij} = p_i' p_j' = E_i' E_j' - |\vec{p}'_i||\vec{p}'_j| \cos\frac{2\pi}{3} = E_i' E_j' + \frac{1}{2}|\vec{p}'_i||\vec{p}'_j|$$

Where dashed values are energy and momentum in the 120º JRF

- Therefore we can make equation

$$f_{ij} = f(|\vec{p}'_i|, |\vec{p}'_j|; m_i, m_j, a_{ij}) = \sqrt{|\vec{p}'_i|^2 + m_i^2}\sqrt{|\vec{p}'_j|^2 + m_j^2} + \frac{1}{2}|\vec{p}'_i||\vec{p}'_j| - a_{ij}$$

with solutions when $f_{ij} = 0$

- Set $f_{13} = f_{12} = 0$, and solving for $|\vec{p}'_j|$ in terms of $|\vec{p}'_1|$ we get

$$|\vec{p}'_j|(\vec{p}'_1) = \frac{2E_1'\sqrt{4a_{1j}^2 - m_j^2(4E_1'^2 - |\vec{p}'_1|^2)} - 2|\vec{p}'_1|a_{ij}}{4E_1'^2 - |\vec{p}'_1|^2}$$

**Then what if the JRF is no solution to $f_{23} = 0$?**

- Set $f_{23} = 0$, sub in the above equations for $|\vec{p}'_2|$ and $|\vec{p}'_3|$, and solve for $|\vec{p}'_1|$

# Junction Rest Frame

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

Consider a basic case:

➢ Two massless legs and one massive soft leg in the Ariadne frame with respect to the massive parton

$$p(t) = p_0 - 2\kappa x(t) = \frac{mv(t)}{\sqrt{1 - v(t)^2}}$$

$$\frac{dx}{dt} = \frac{1}{\sqrt{1 + \frac{m^2}{(p_0 - 2\kappa x)^2}}}$$

$$x_{max} = p_0/2\kappa$$

The differential equation is
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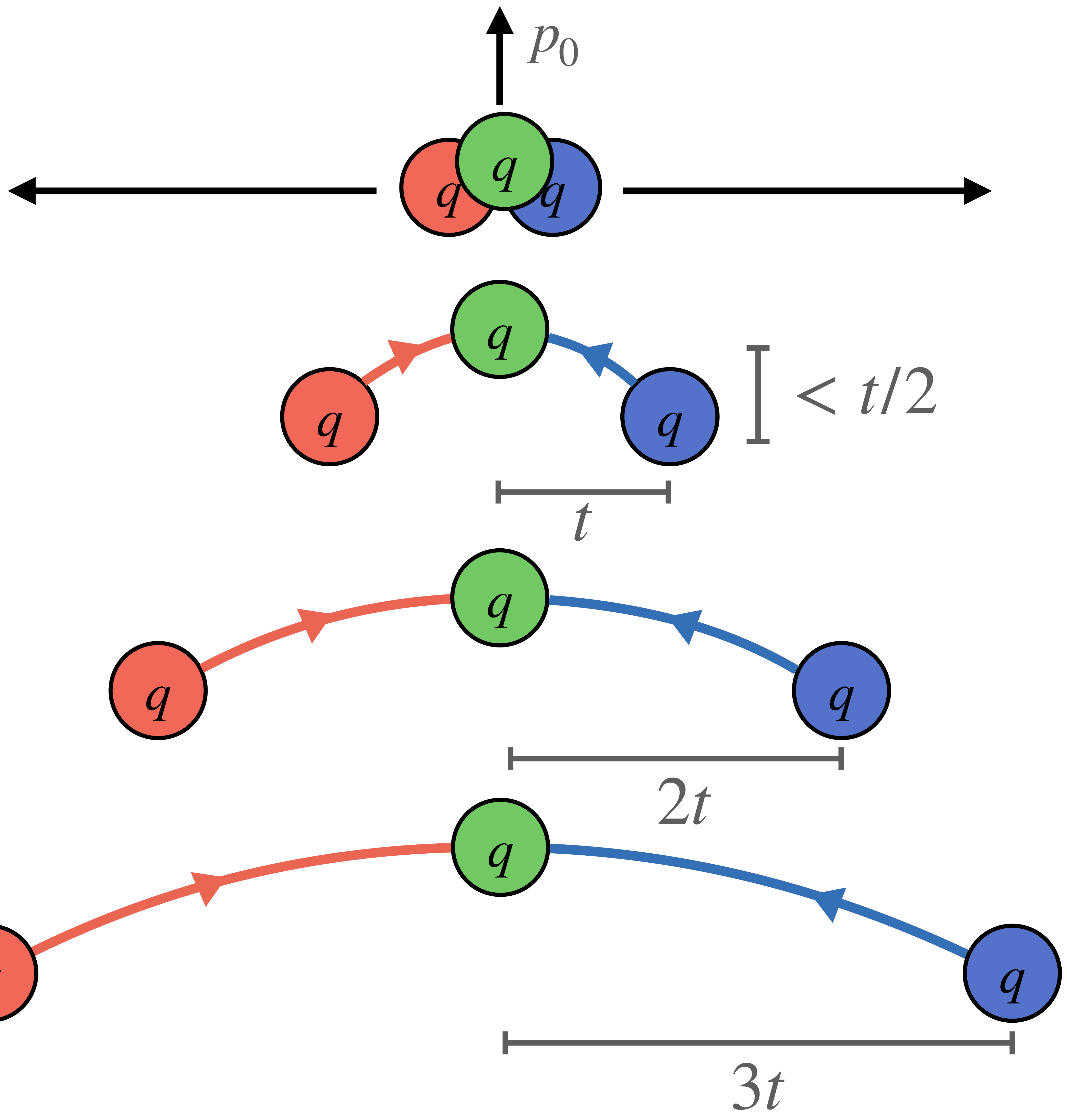


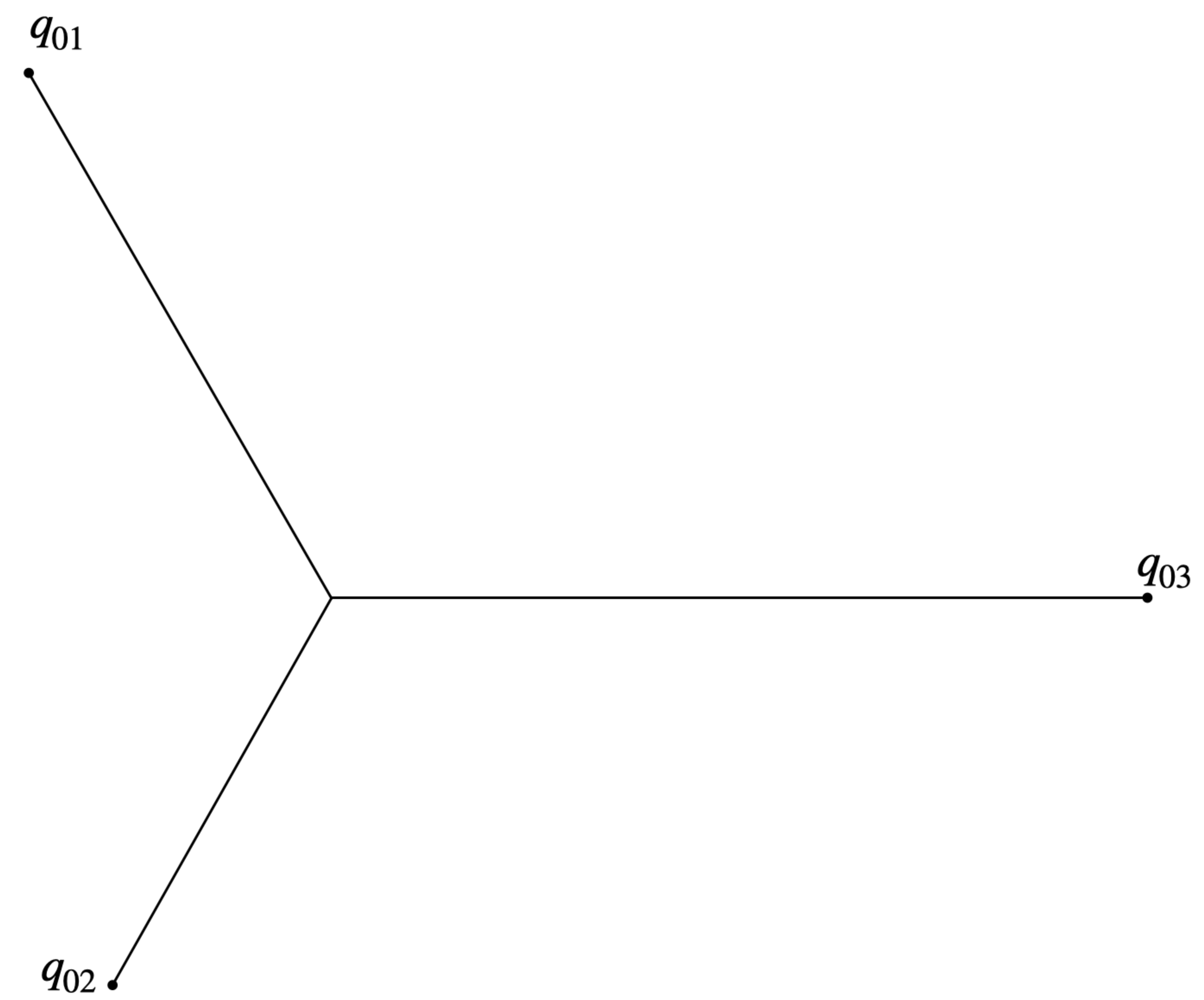
# Junction Fragmentation

How do we fragment these junction systems? How do we get the junction baryon?

Use similar fragmentation method as with dipole strings, fragmenting off on-shell hadrons from **each junction-leg string end.** Treat each **junction leg as half a dipole string.**

**Standard Procedure:**

- ➢ Go to junction rest frame (JRF)



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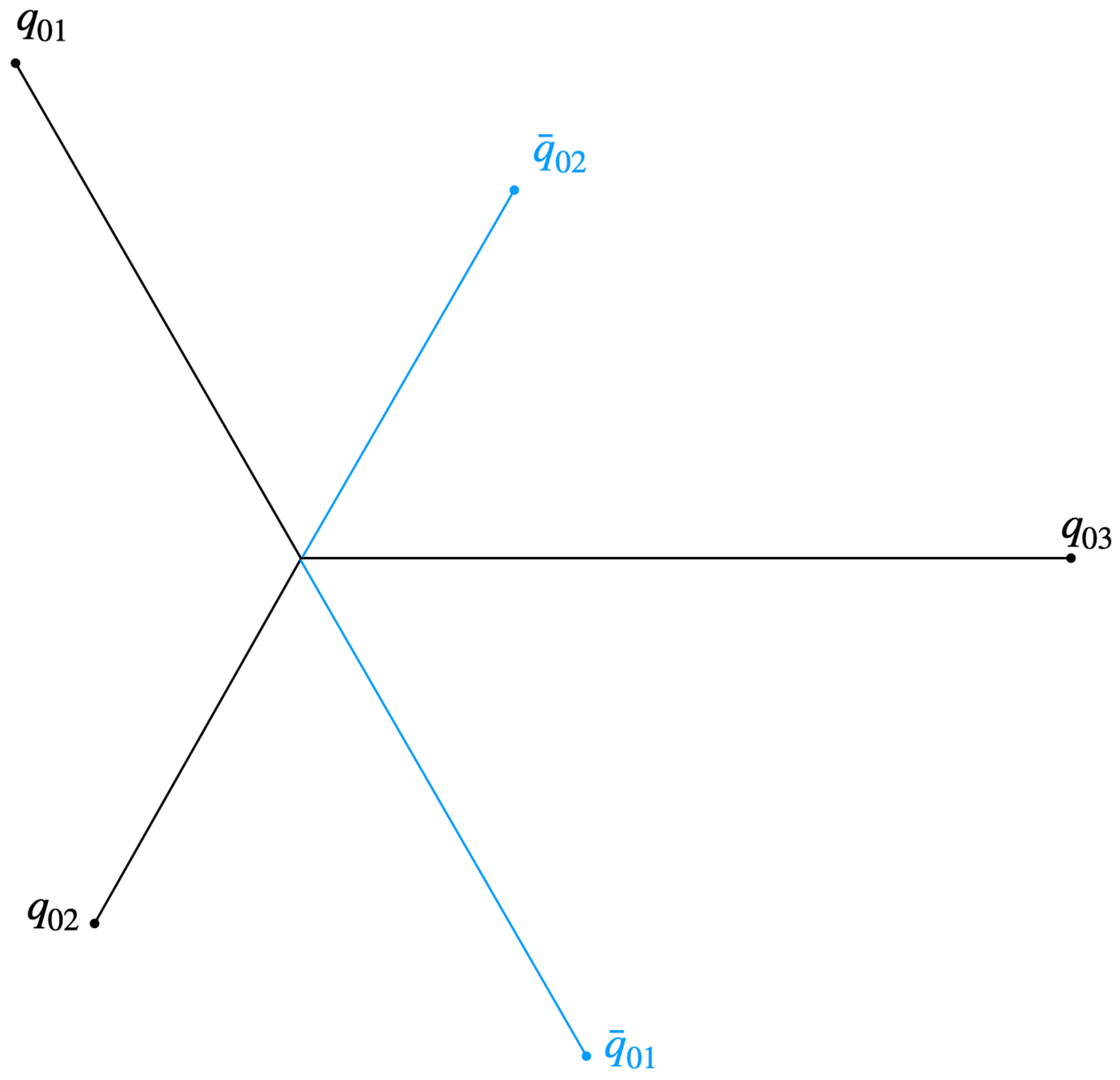

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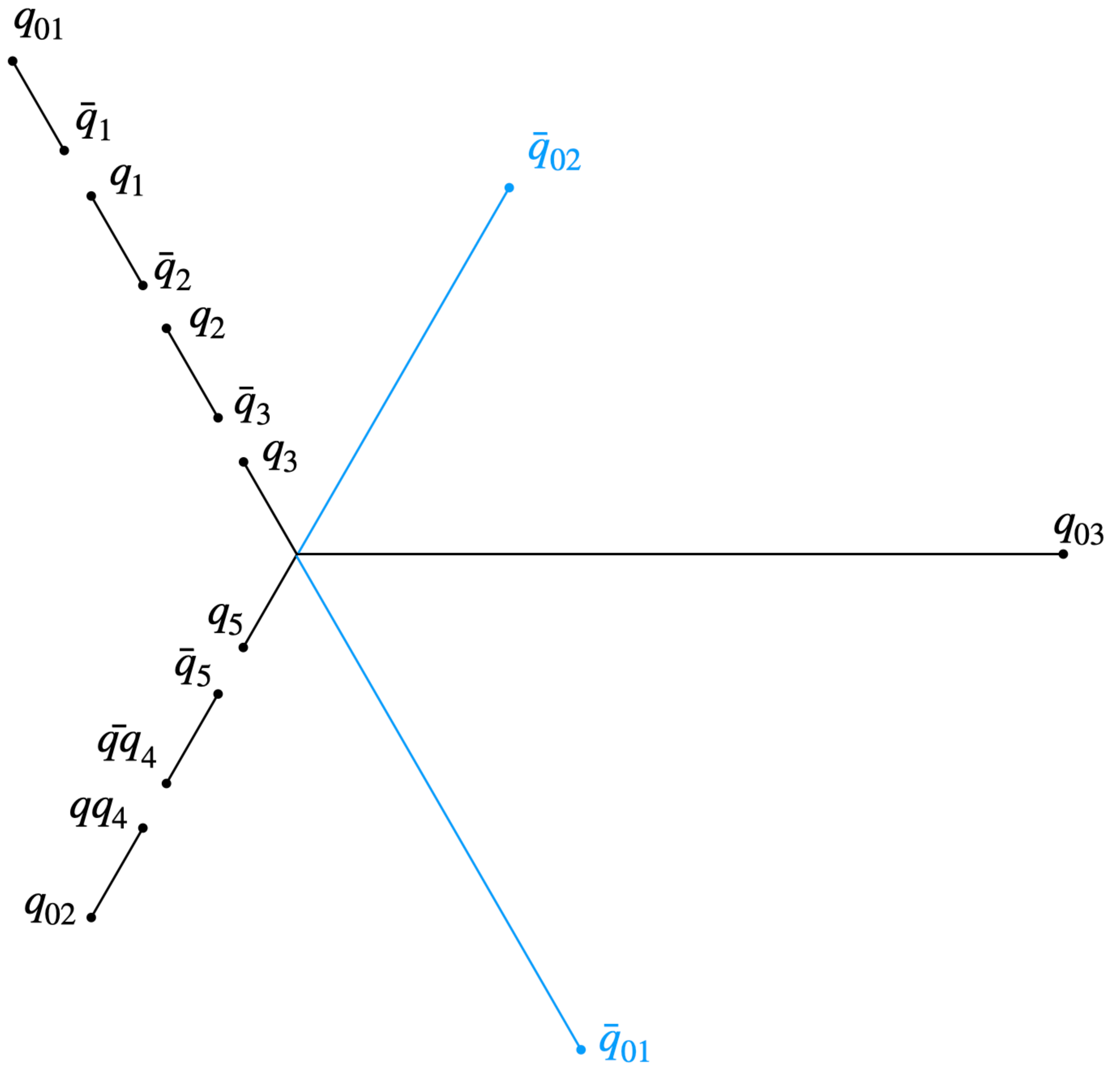

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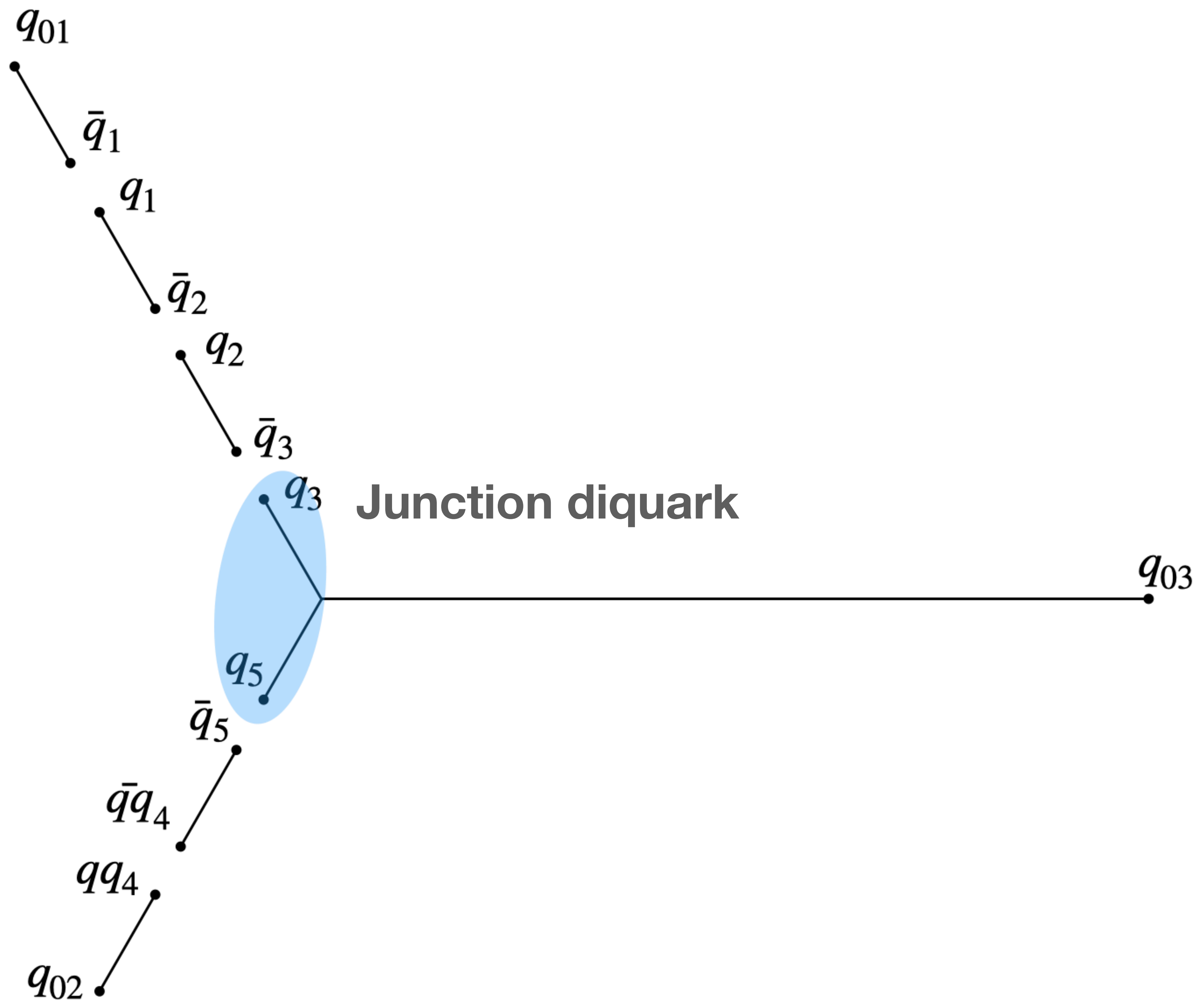

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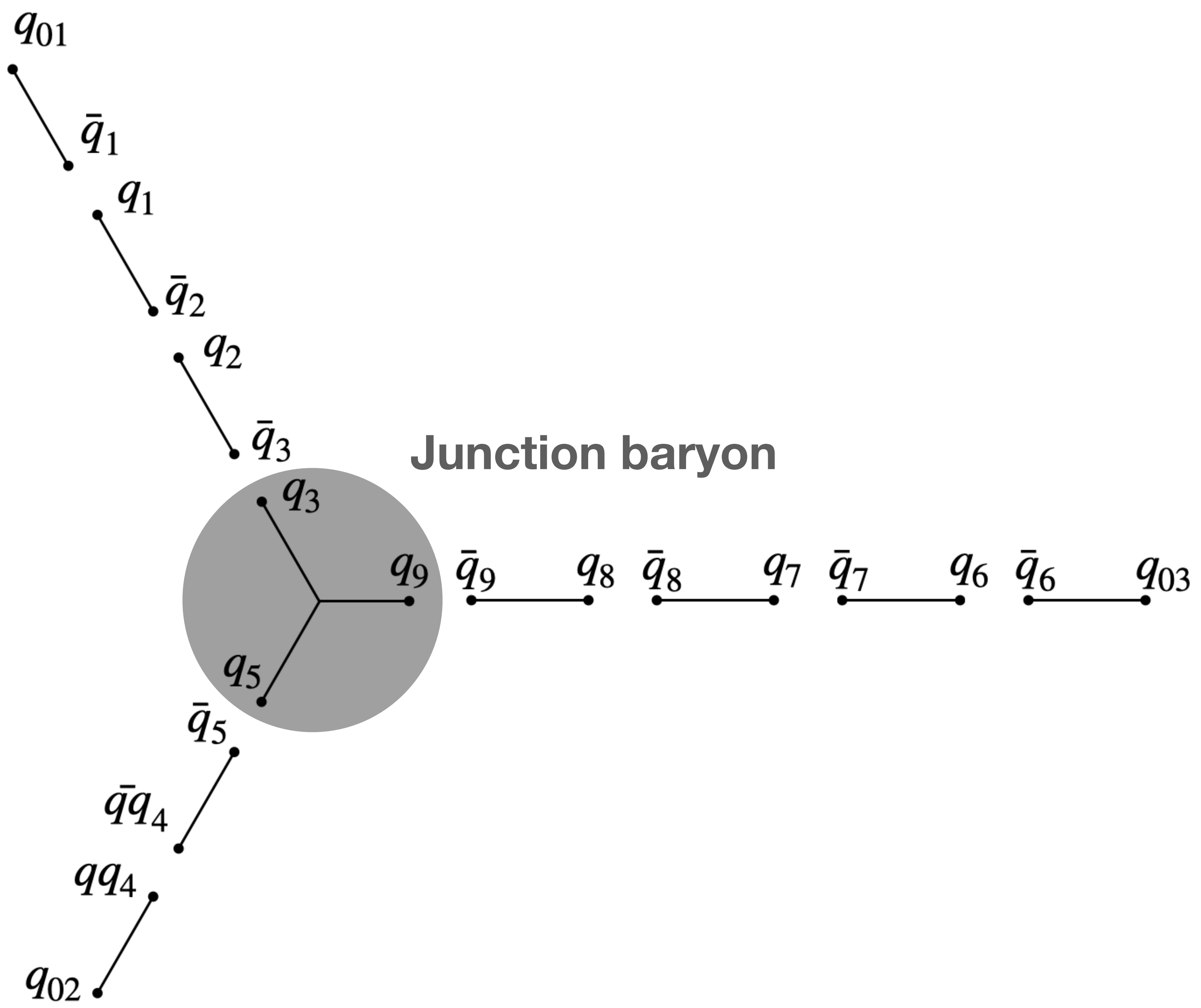
- ➢ Fragment the last junction leg as dipole with endpoints $q_3q_5$ - $q_{03}$



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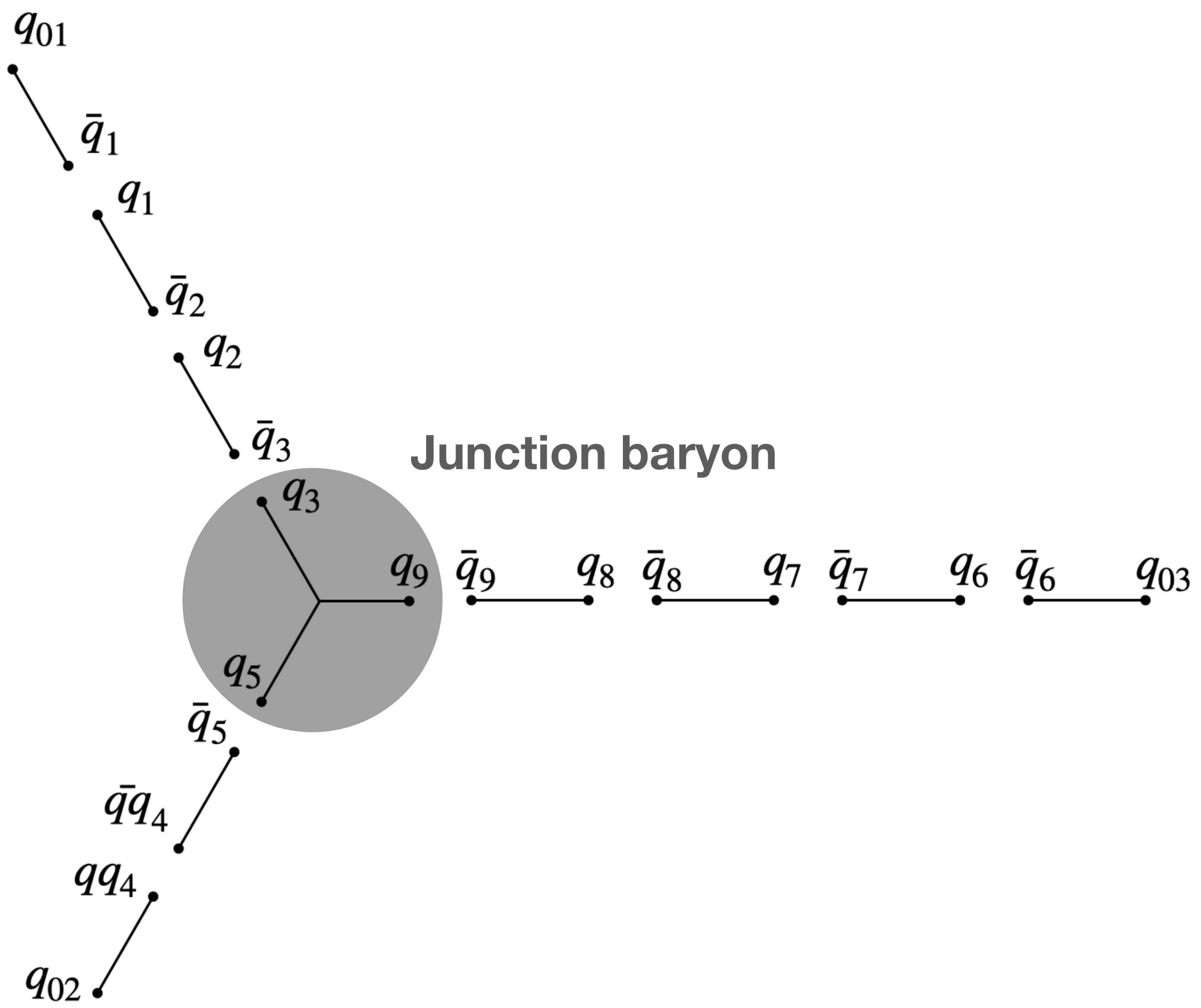

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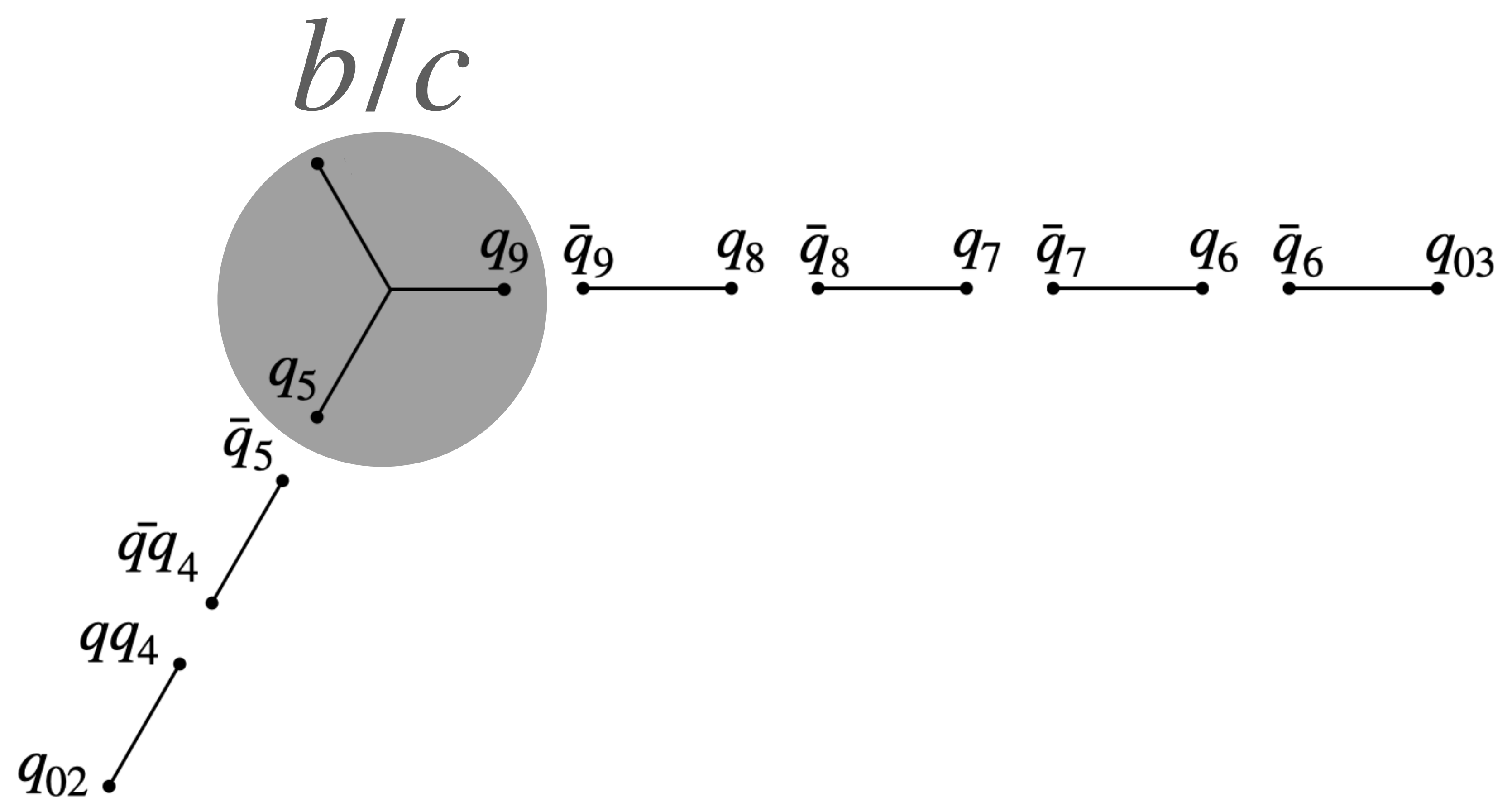
Modelling particularly important for **heavy flavour baryons** as they are more sensitive to junction motion



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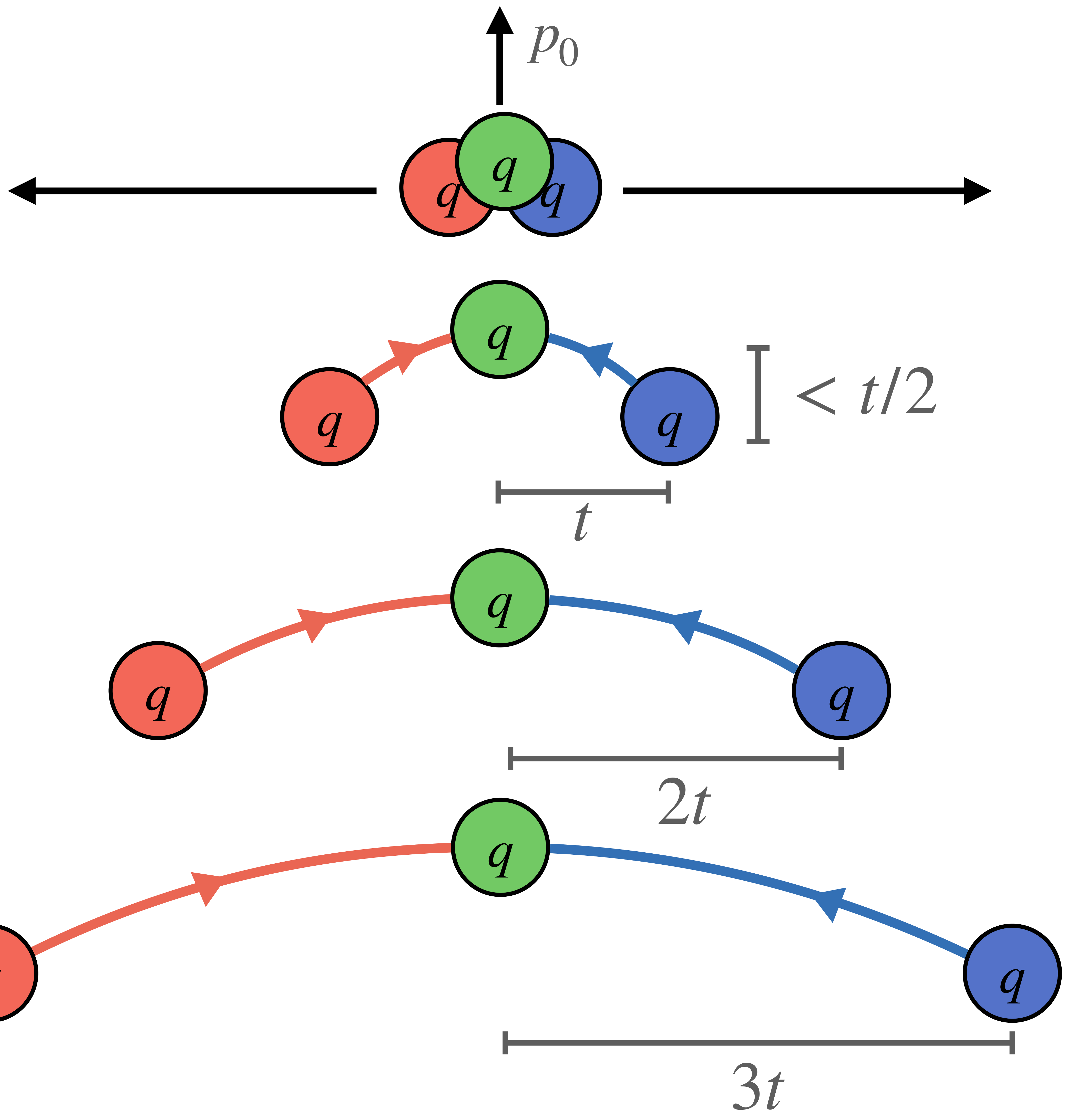
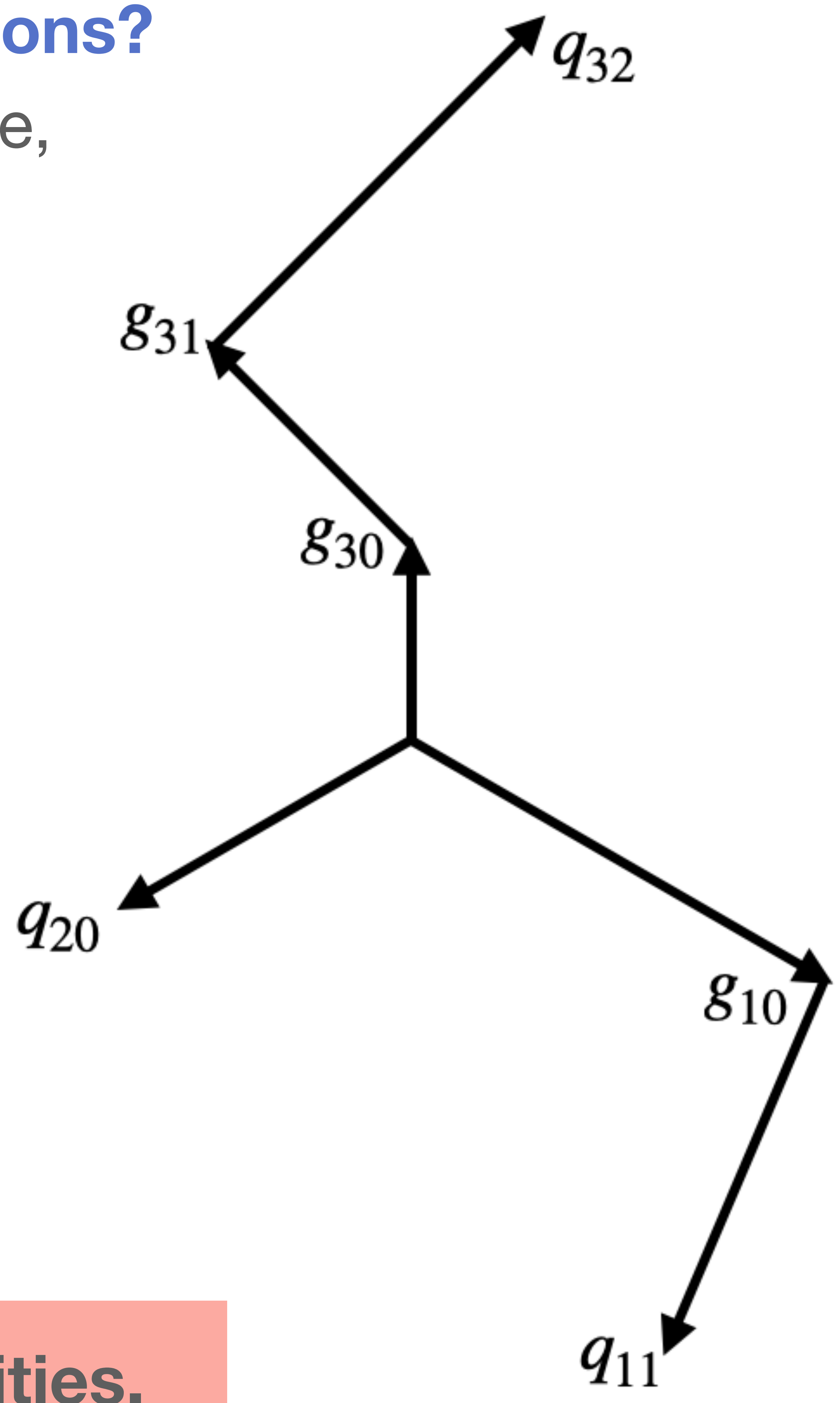


# Implementation

Know JRF given 3-parton configuration, however **what about junctions with gluons?** Do not want to map the junction motion and fragmentation in a space-time picture, so instead need some **“average JRF”** to describe the junction motion.




Current procedure finds average “pull” on junction of each leg and looks for 120° frame given the average pulls. **Problems in current procedure in PYTHIA:**

- ➢ Convergence failure of iterative procedure for about 10% of junction systems
- ➢ Only considers 120° JRF
  - ➢ No special handling if there is no 120° frame
- ➢ Weightings used in averaging procedure not most physically logical

Need more rigorous handling in order to be able to draw solid physics conclusions from the results

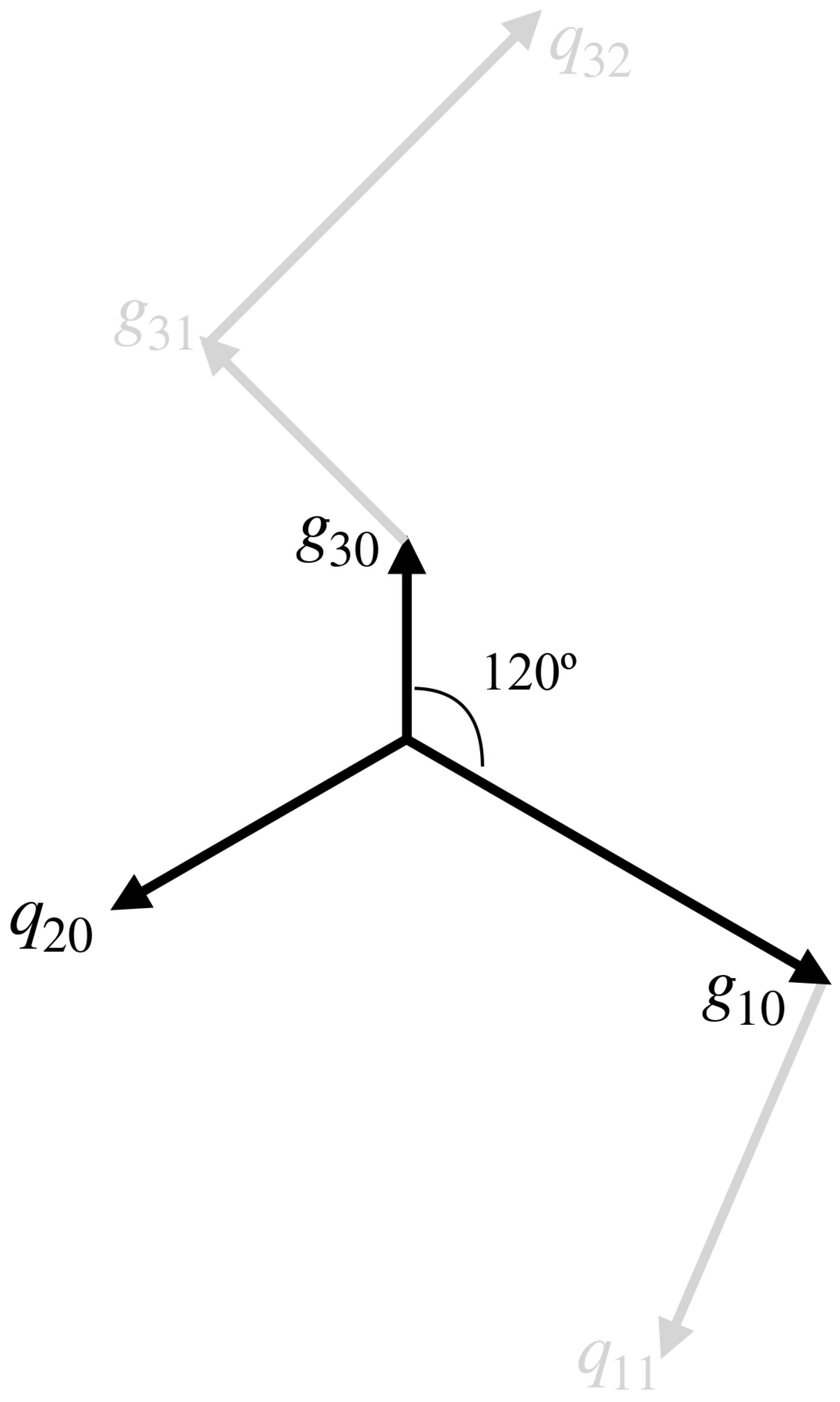
**Look at JRFs at different time steps and average over junction velocities.**

# Implementation

**New iterative procedure:**

1. Find JRF using the first parton on each junction leg, store the associated velocity, and boost to this frame.
   A. If 120º frame does not exist, use rest frame of soft quark as an approximation of the pearl-on-a-string treatment

(should only occur for massive endpoints)



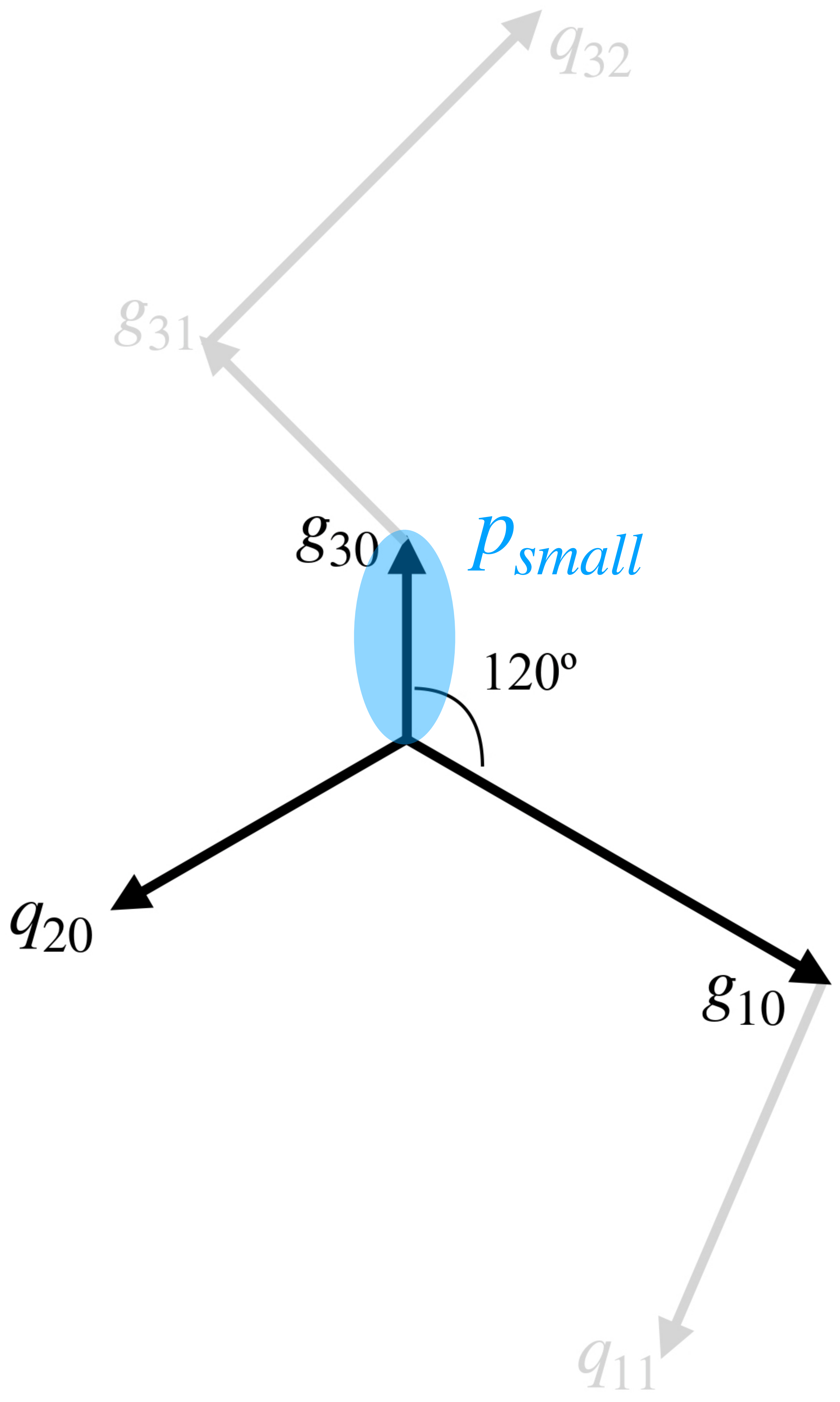
# Implementation

**New iterative procedure:**

1. Find JRF using the first parton on each junction leg, store the associated velocity, and boost to this frame.
2. **Time associated with JRF:** $p_{small}$ = smallest absolute 3-momentum

   A. If the smallest 3-momentum is zero, let $p_{small}$ be the next lowest 3-momentum

$$\frac{dp}{dt} = -\kappa$$
$$\therefore t \propto |\vec{p}|$$



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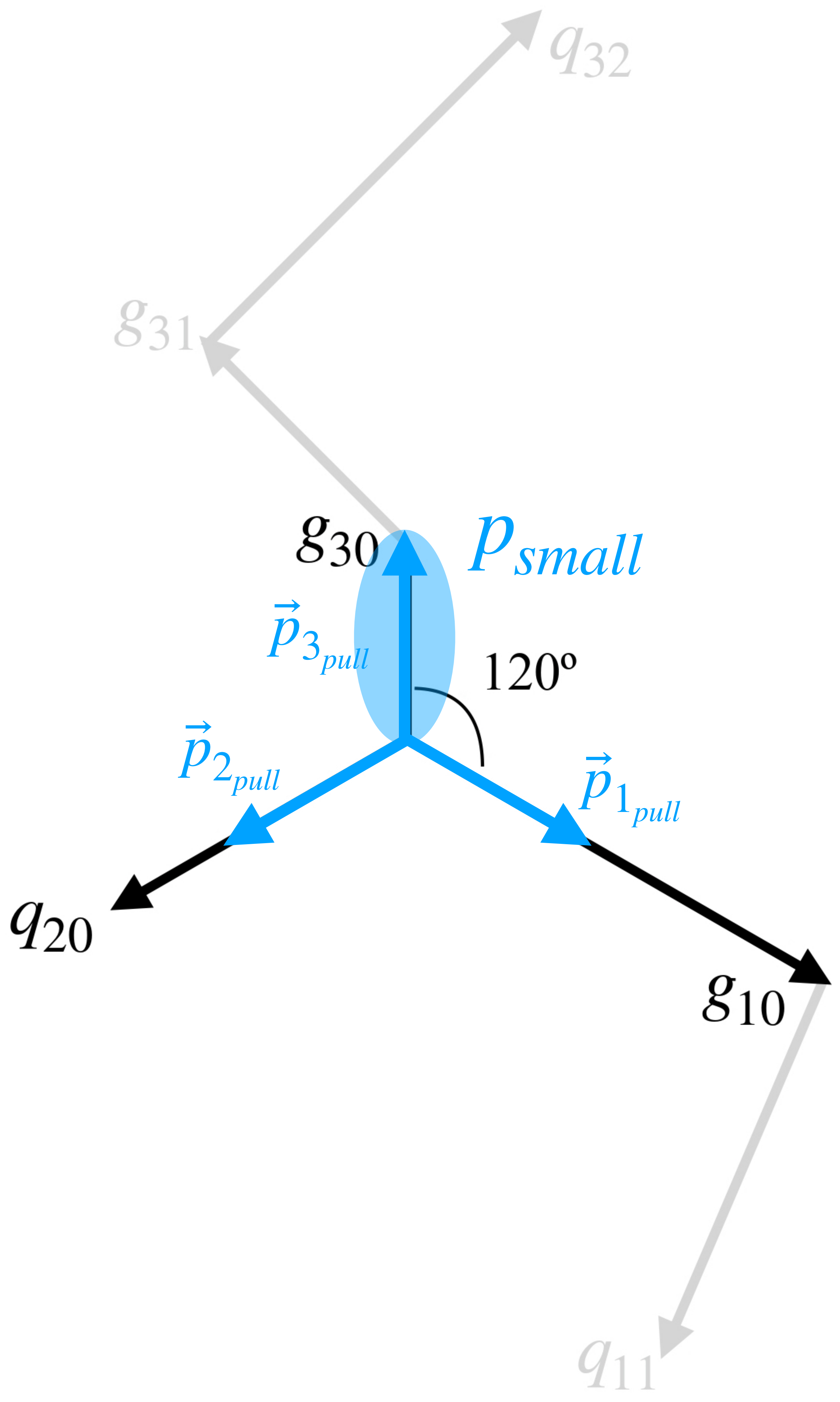
   A. If the smallest 3-momentum is zero, let $p_{small}$ be the next lowest 3-momentum
3. **Pull vectors:** Store 4-momenta scaled down (conserving mass) to have 3-momentum magnitude of $p_{small}$.
   A. If at rest, store the rest frame momentum.



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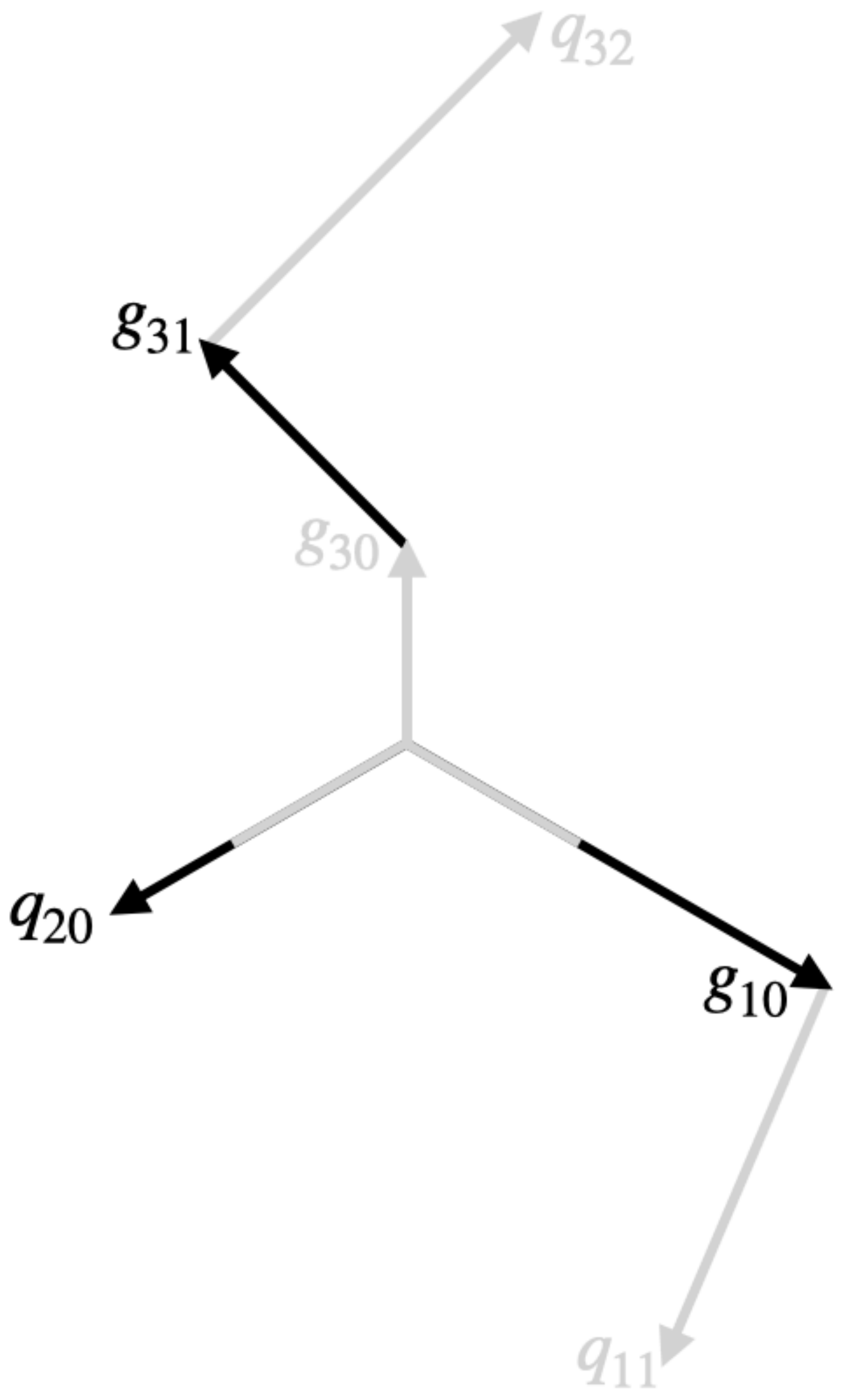
3. **Pull vectors:** Store 4-momenta scaled down (conserving mass) to have 3-momentum magnitude of $p_{small}$.
4. **Update momenta:**
   A. For small leg
      i. Step to next parton on leg if possible.
      ii. If massive endpoint, reduce the endpoint to at rest.
      iii. If massless endpoint, make this final iteration.
   B. Reduce the momentum of the other partons by $p_{small}$.



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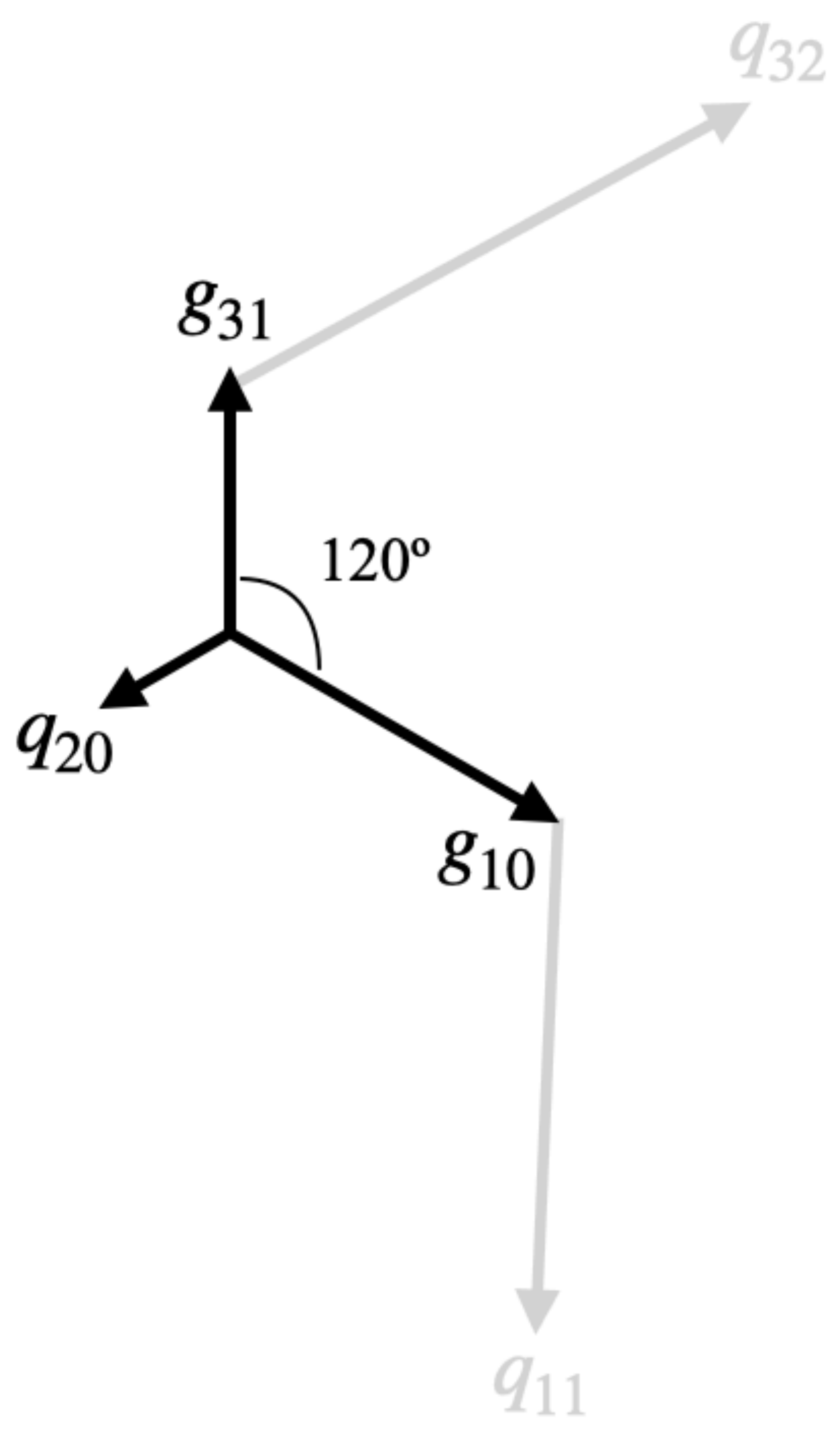
3. **Pull vectors:** Store 4-momenta scaled down (conserving mass) to have 3-momentum magnitude of $p_{small}$.
4. **Update momenta**
5. Find **JRF with new 3-parton configuration** and iterate: Repeat steps 2 - 4 till either:
   A. the sum of all $p_{small}$ exceeds 10 GeV
   B. two endpoints are reached
   C. parton associated with $p_{small}$ is a massless endpoint.



# Average JRF

**Averaging procedure:**

Concerned with the junction motion in the time-frame of the hadronisation process

→ introduce **normalisation parameter** $p_{norm} = 2$ GeV by default

Expect early time pulls to more heavily influence junction motion

→ use **exponential weighting** to model time dependence

$$v_{jun} = \frac{\sum_{i=1}^{i_{max}} v_i (e^{-p_{i-1}/p'_{norm}} - e^{-p_i/p'_{norm}})}{1 - e^{-p_{i_{max}}/p'_{norm}}}$$

Mathematical subtleties:

- ➢ Each $p_{small}$ is measured in the successive JRFs, therefore transform by $\gamma$-factor to lab frame
- ➢ $p_{norm}$ is recalculated to consider $\gamma$-factors

$$p'_{norm} = \sum_{i=1}^{N} \gamma_i p_{small_i} + \gamma_{N+1}(p_{norm} - \sum_{i=1}^{N} p_{small_i})$$

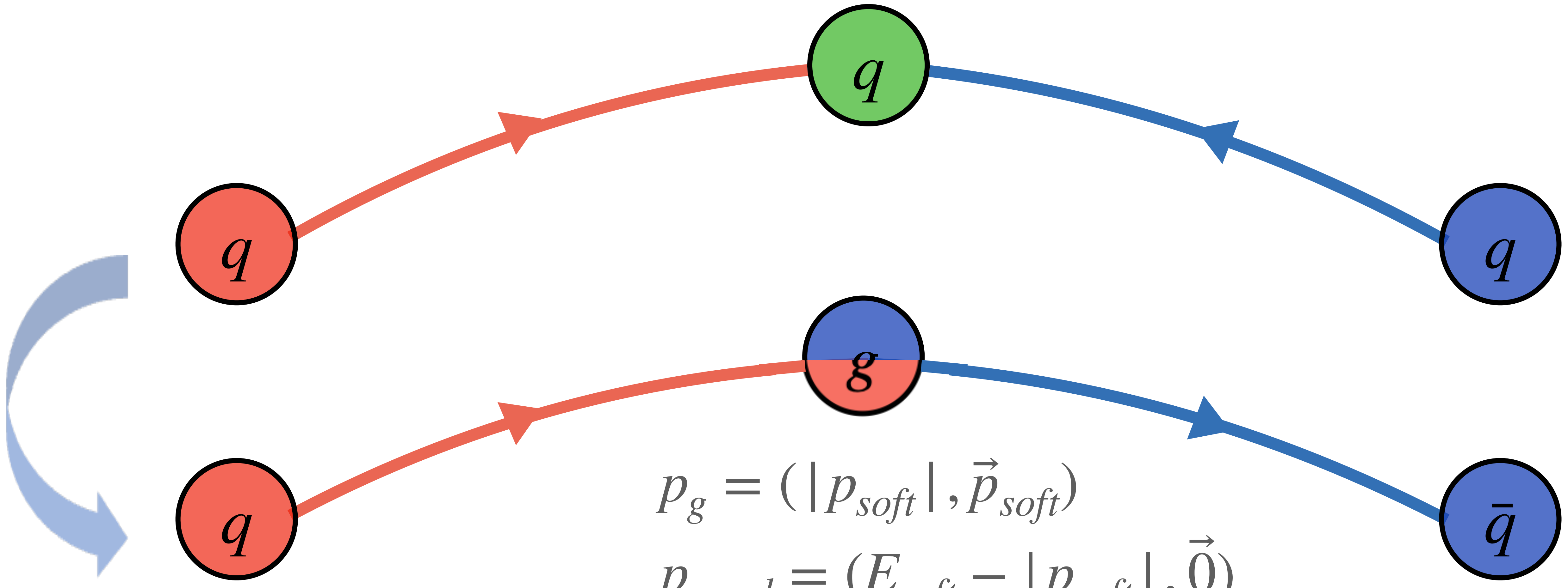
The same averaging procedure is used to calculate the average pull on the junction by each leg

→ used to construct **fictitious endpoints** for fragmentation

# Pearl-on-a-string

How do we implement pearl-on-a-string model? What is the **Ariadne frame** if we have gluons the junction legs? Instead, we model the **soft quark as a gluon** with momentum determined by the average JRF.

Fragment $q - q_{pearl} - q$ string as a $q - g - \bar{q}$ string **using existing fragmentation mechanism in PYTHIA**




$$p_g = (|p_{soft}|, \vec{p}_{soft})$$

$$p_{pearl} = (E_{soft} - |p_{soft}|, \vec{0})$$

➢ Fragment the $q - g_{pearl} - \bar{q}$ string system from the $\bar{q}$ end, reversing the hadron IDs

➢ Pick up quark and energy from $p_{pearl}$ for “free” when stepping over junction