QCD Strings - junctions, strangeness, popcorn, and beyond

Javira Altmann - Monash University

- **Confinement** in High-Energy Collisions → the **Lund String Model**
- String **Hadronisation**
  - (Heavy flavour) **baryon production**
  - **Strangeness**
  - **Diquark** production

MONASH University

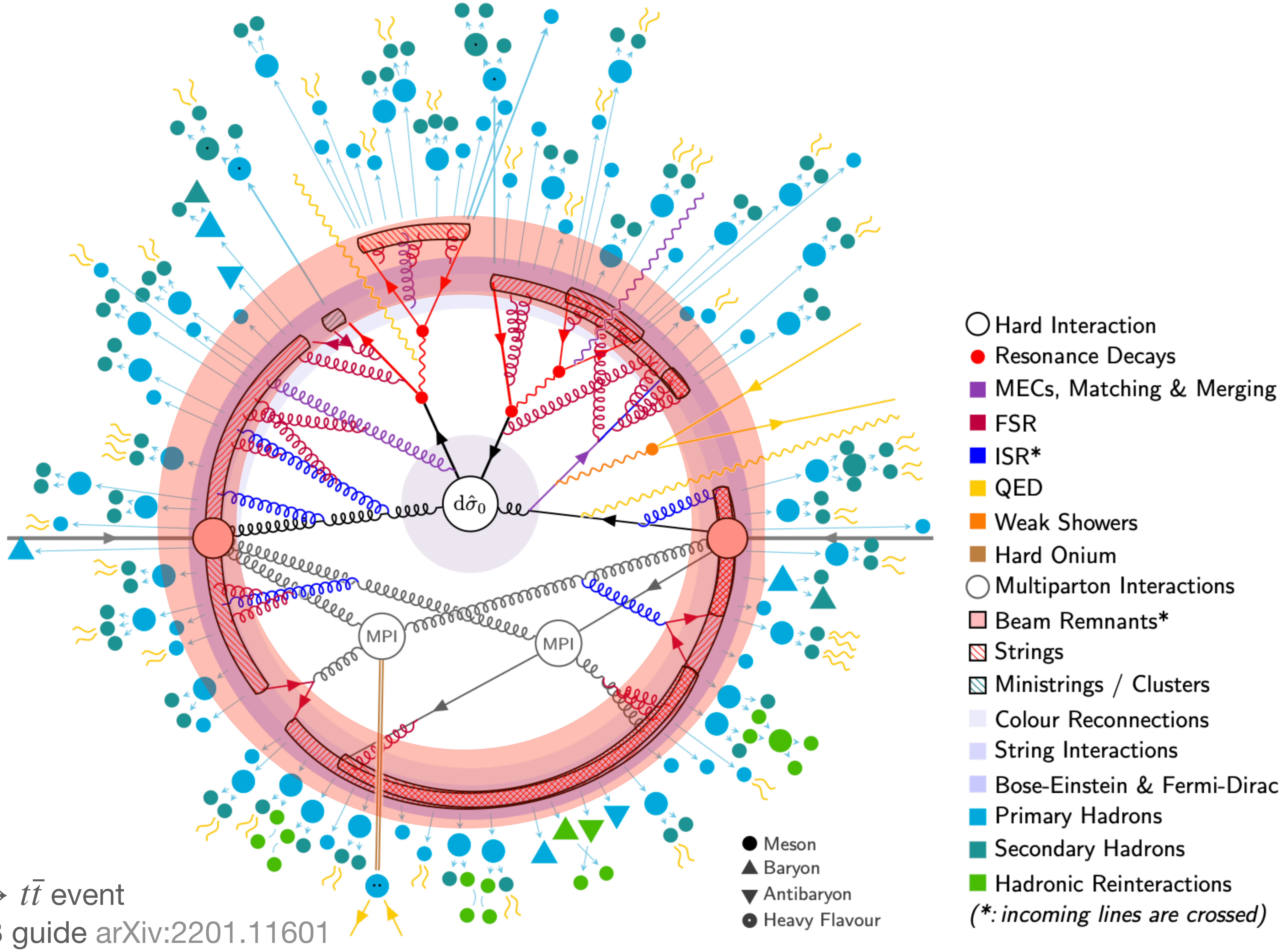
Confinement in high energy collisions

In high-energy collisions, such as proton-proton collisions at the LHC, need a dynamical process to ensure partons (**quarks and gluons**) become **confined** within hadrons

i.e. non-perturbative
parton → hadron map

Model requirements

- ➢ Colour neutralisation
- ➢ Dynamical mapping to on-shell hadrons



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

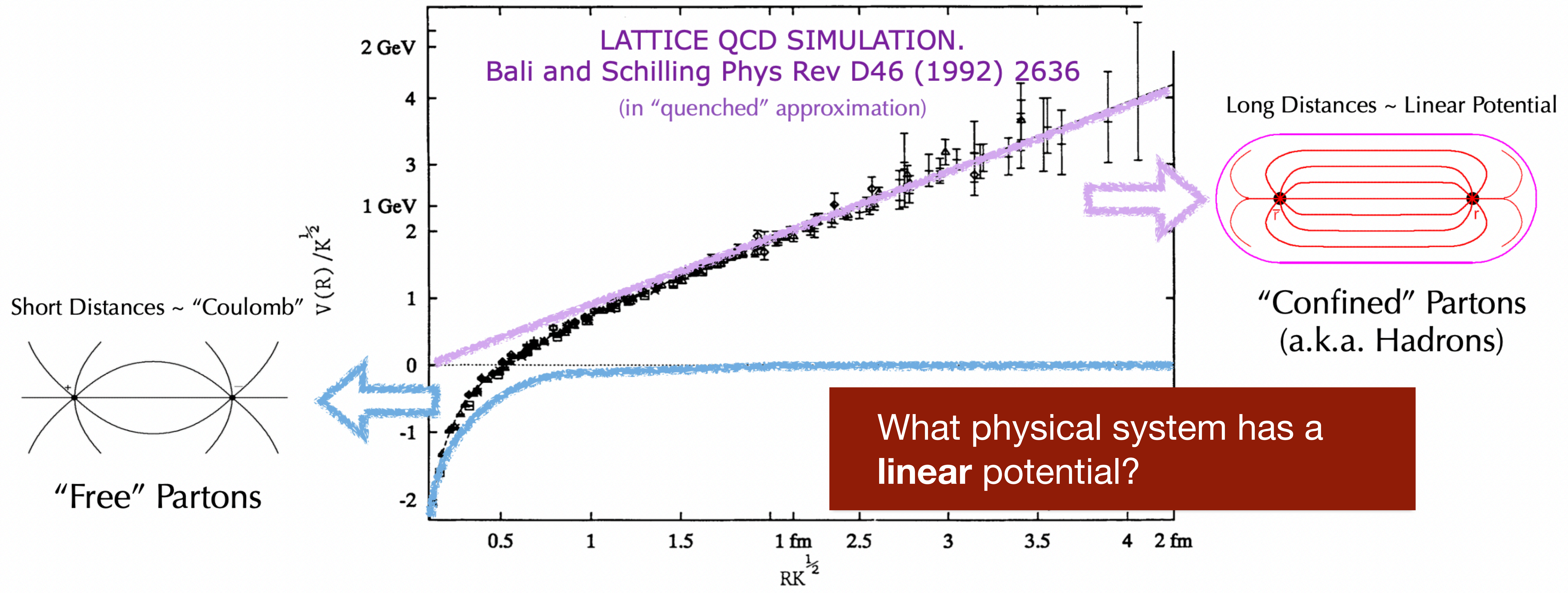
Colour neutralisation

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

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?

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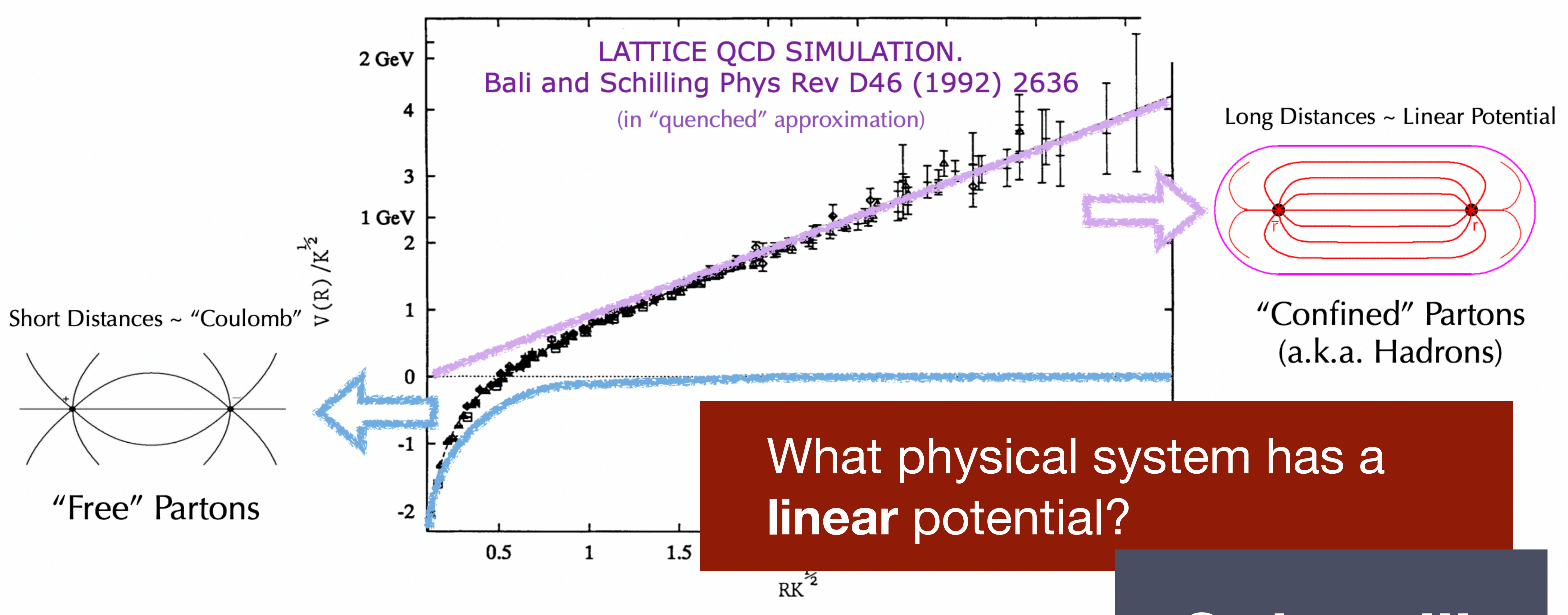

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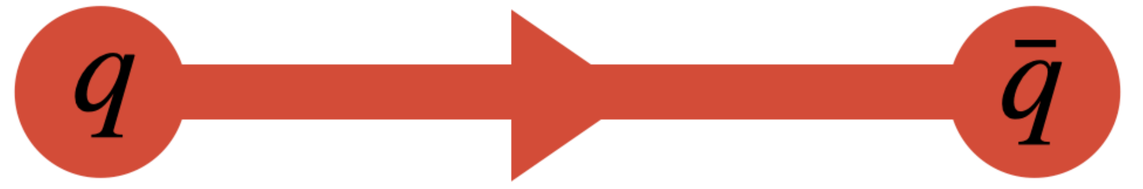
Strings !!!

Lund string model

model the **colour confinement field** as a **string**

➢ Strings form between partons that form overall **colour-singlet** states



e.g. colour-anticolour singlet combination to make a "dipole" string

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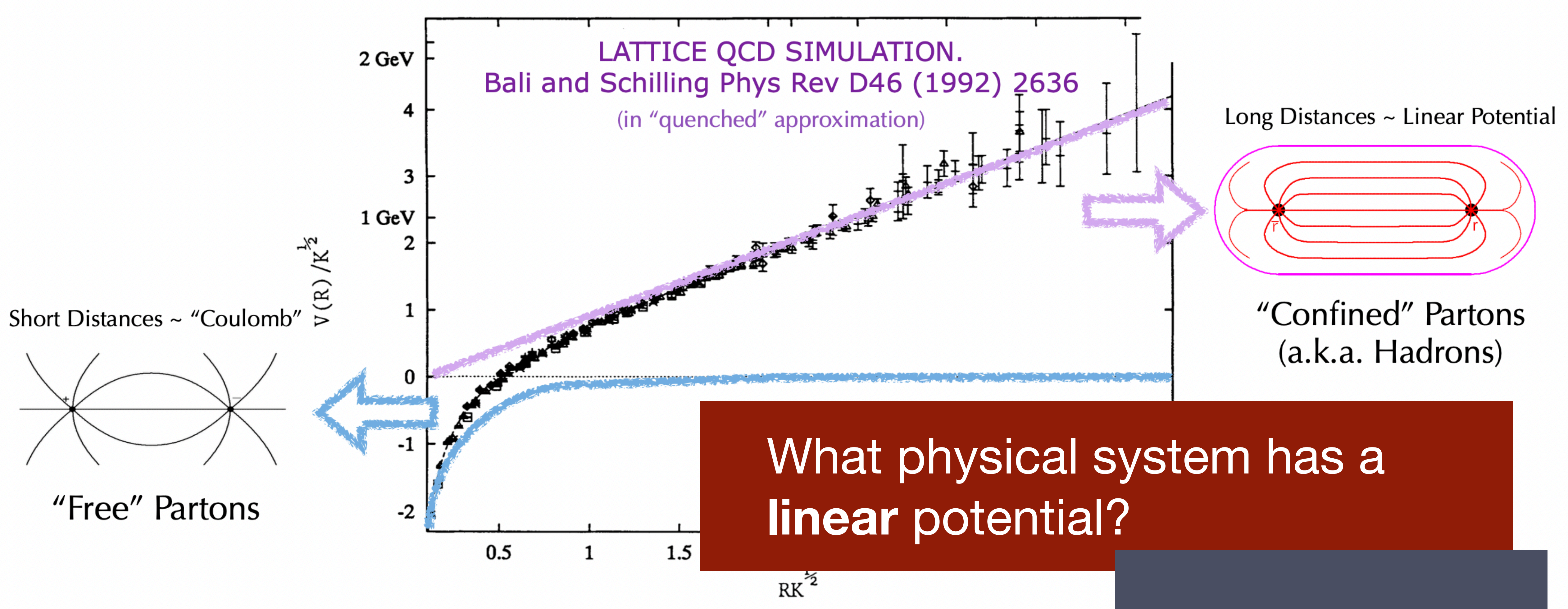

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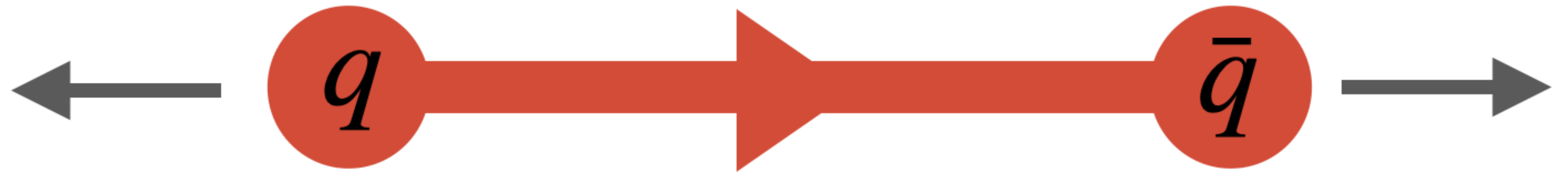

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High energy collisions → partons move apart at high energies

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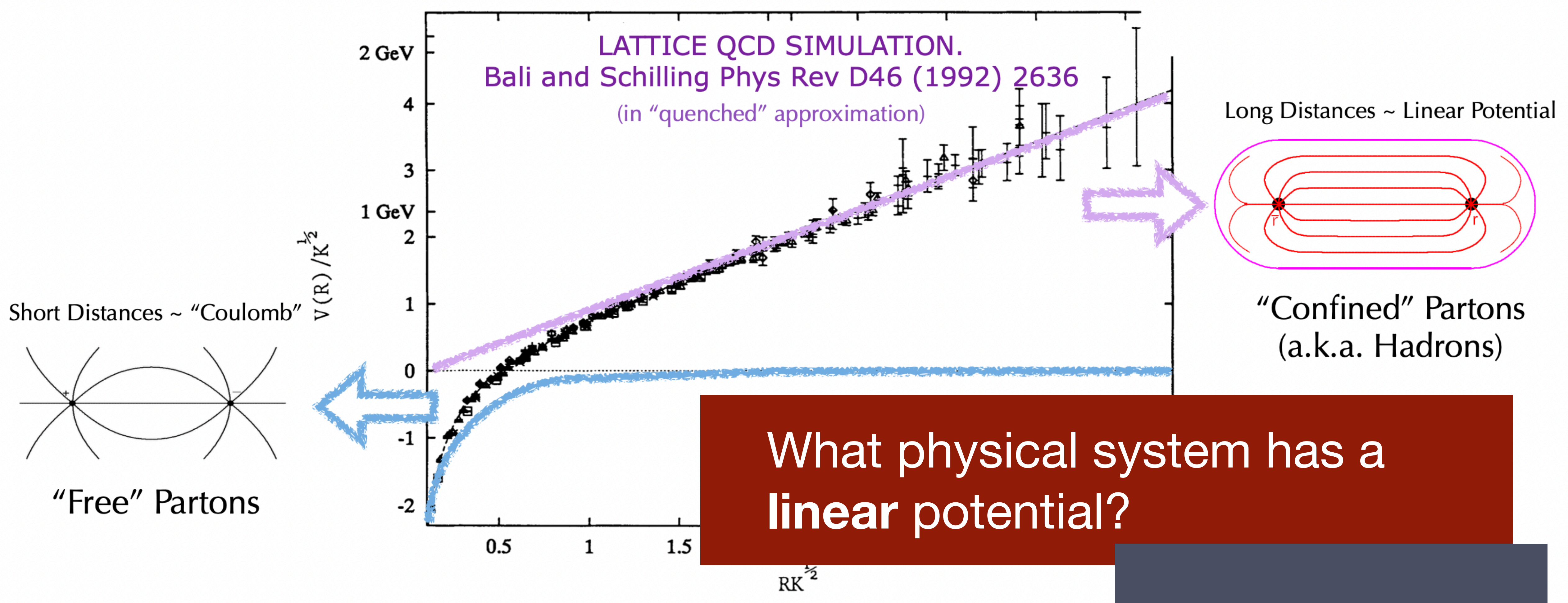

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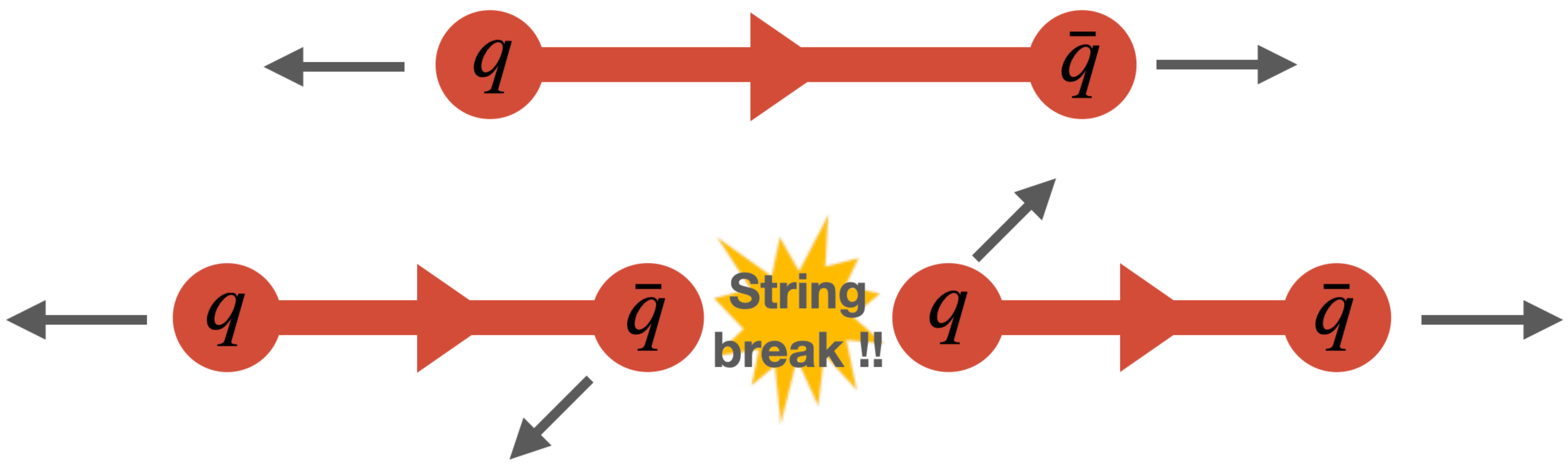
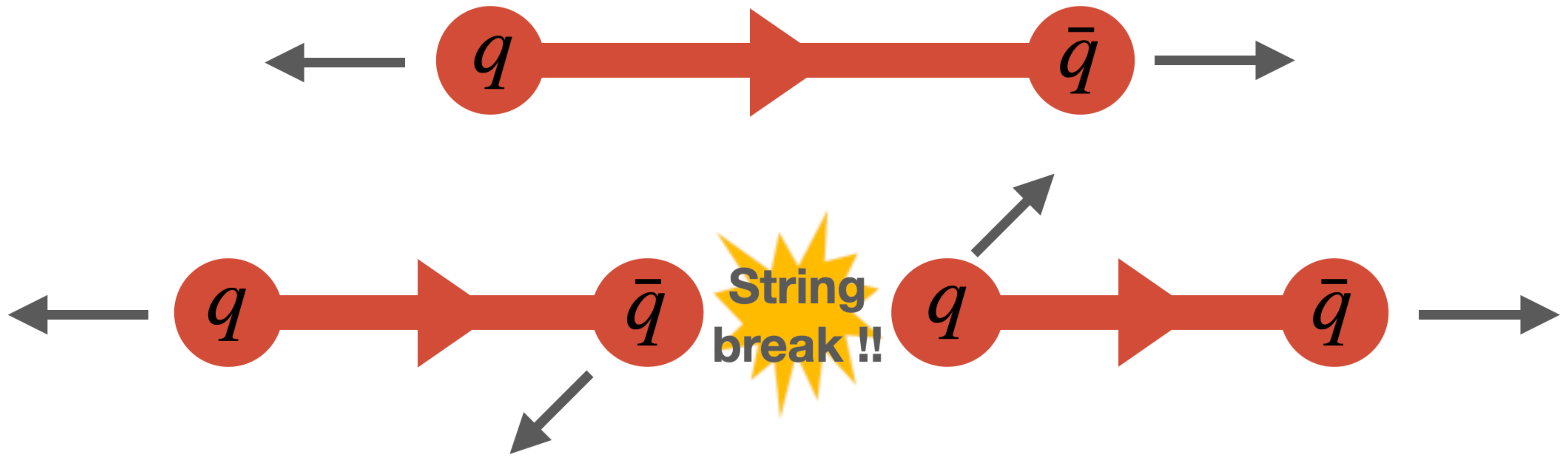


Partons → Hadrons

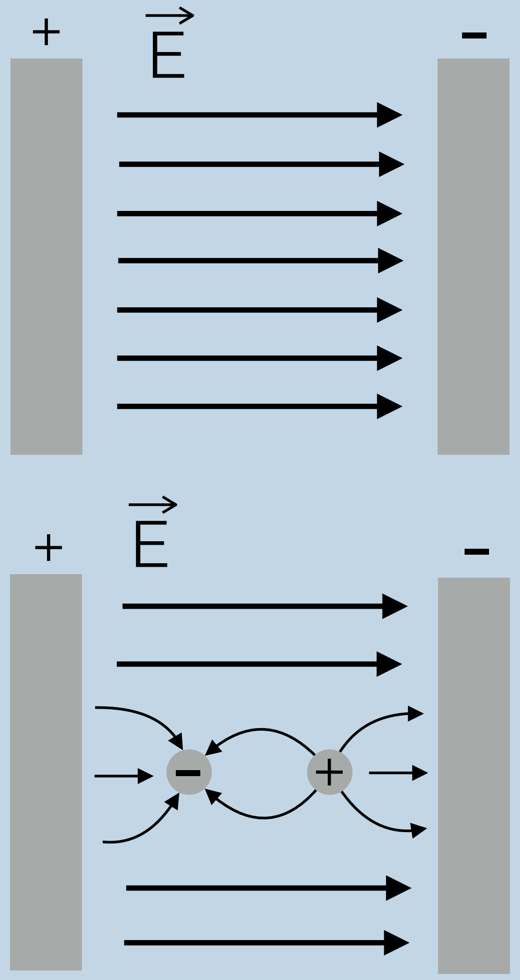
Hadronisation:

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

Instead use the **Schwinger mechanism**



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

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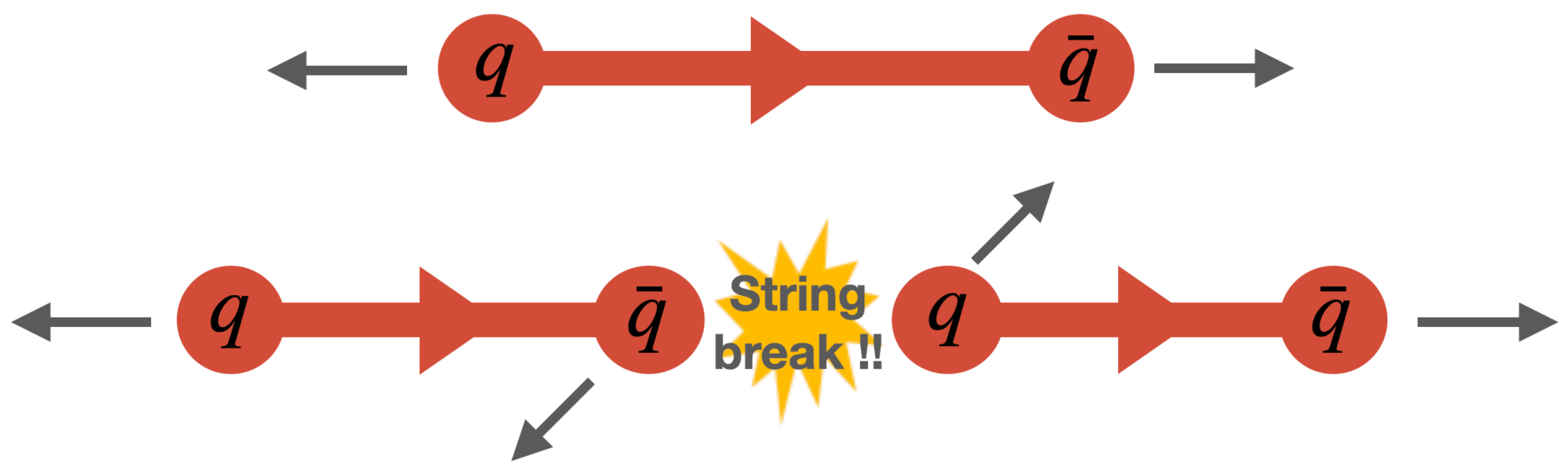

Schwinger → **Gaussian $p_\perp$ spectrum** and heavy flavour suppression **Prob(u:d:s)** $\approx$ **1 : 1 : 0.2**

Note: this is a **constant** probability along the string

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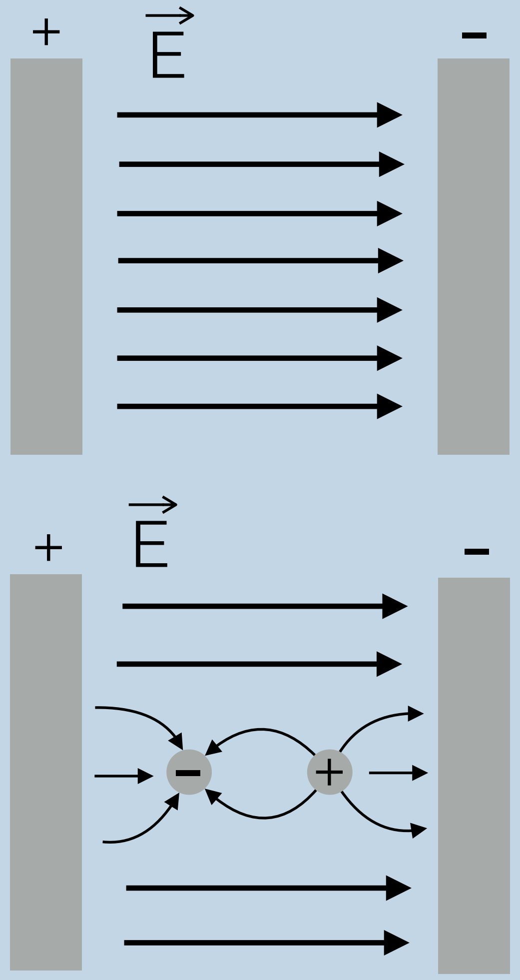

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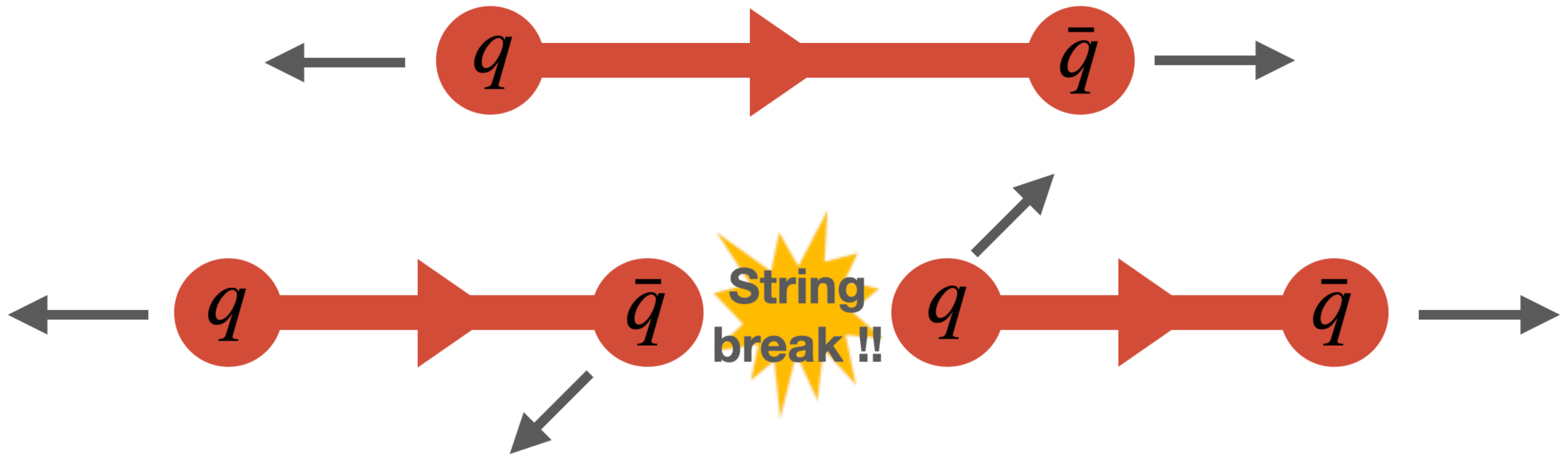

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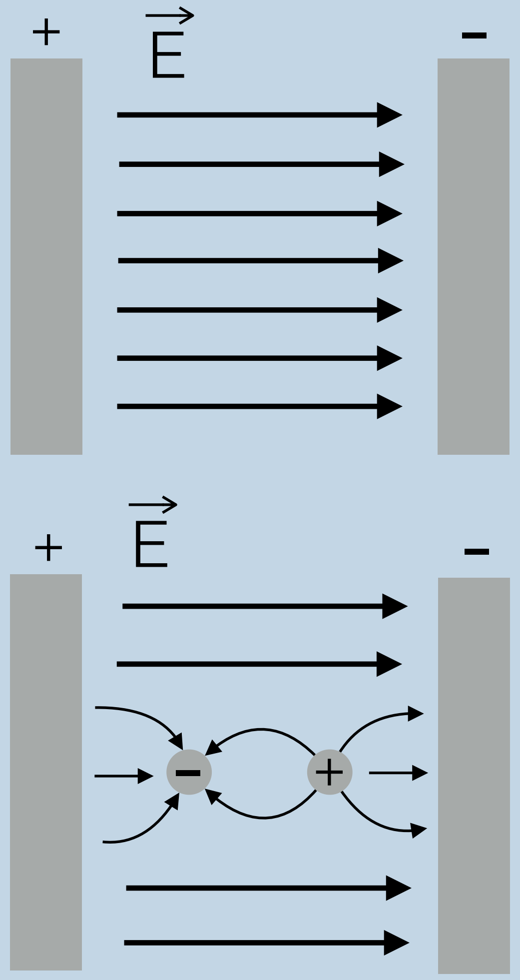

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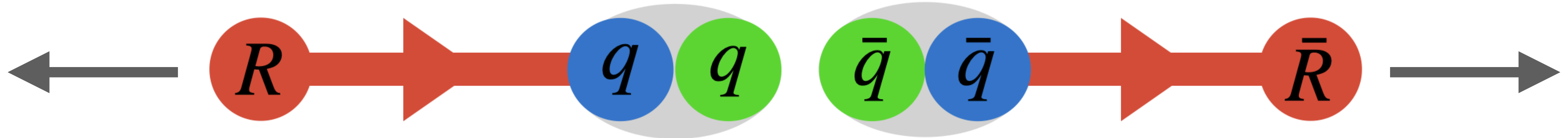
Baryon formation: **diquark-antidiquark** pair creation



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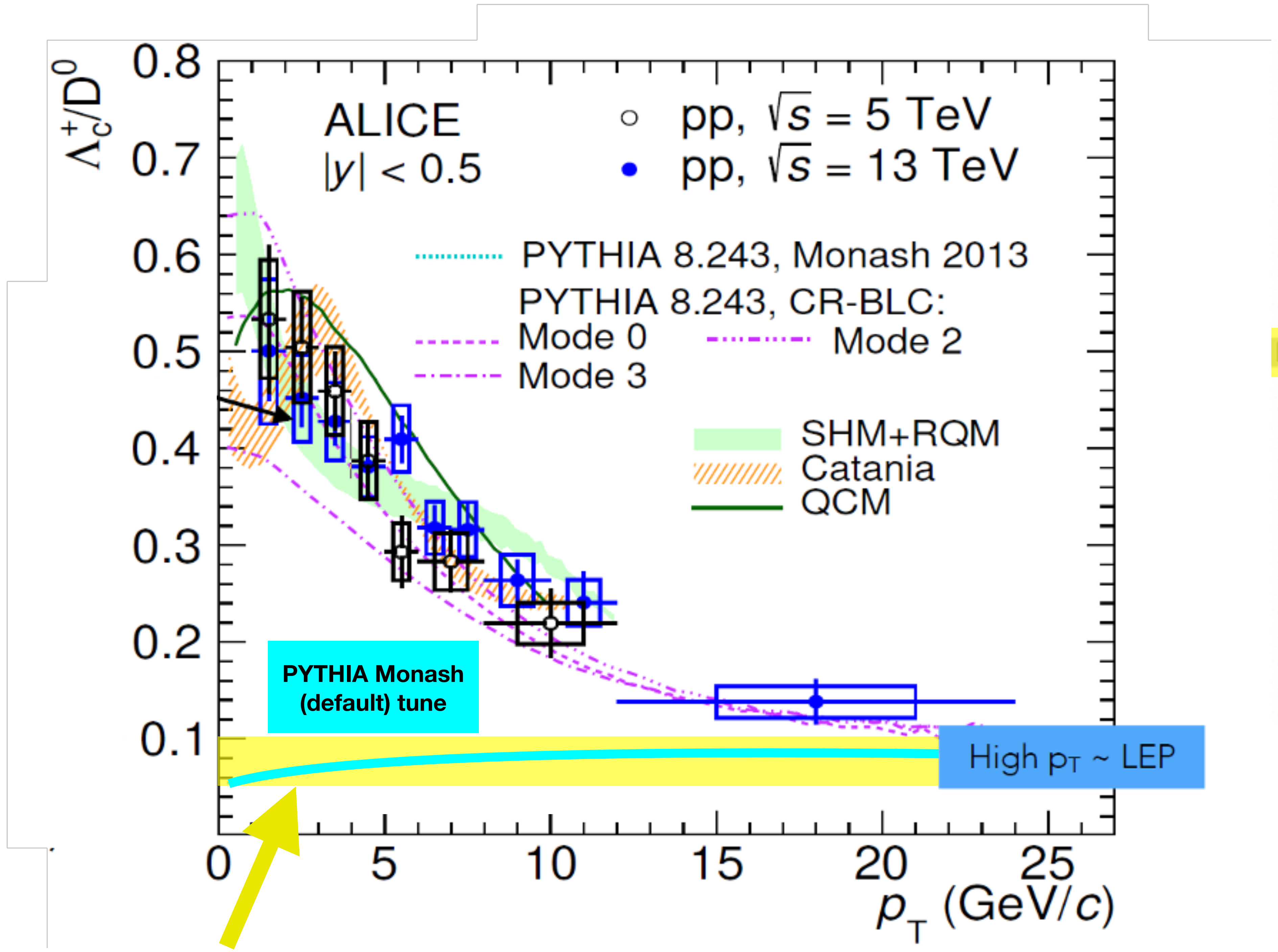
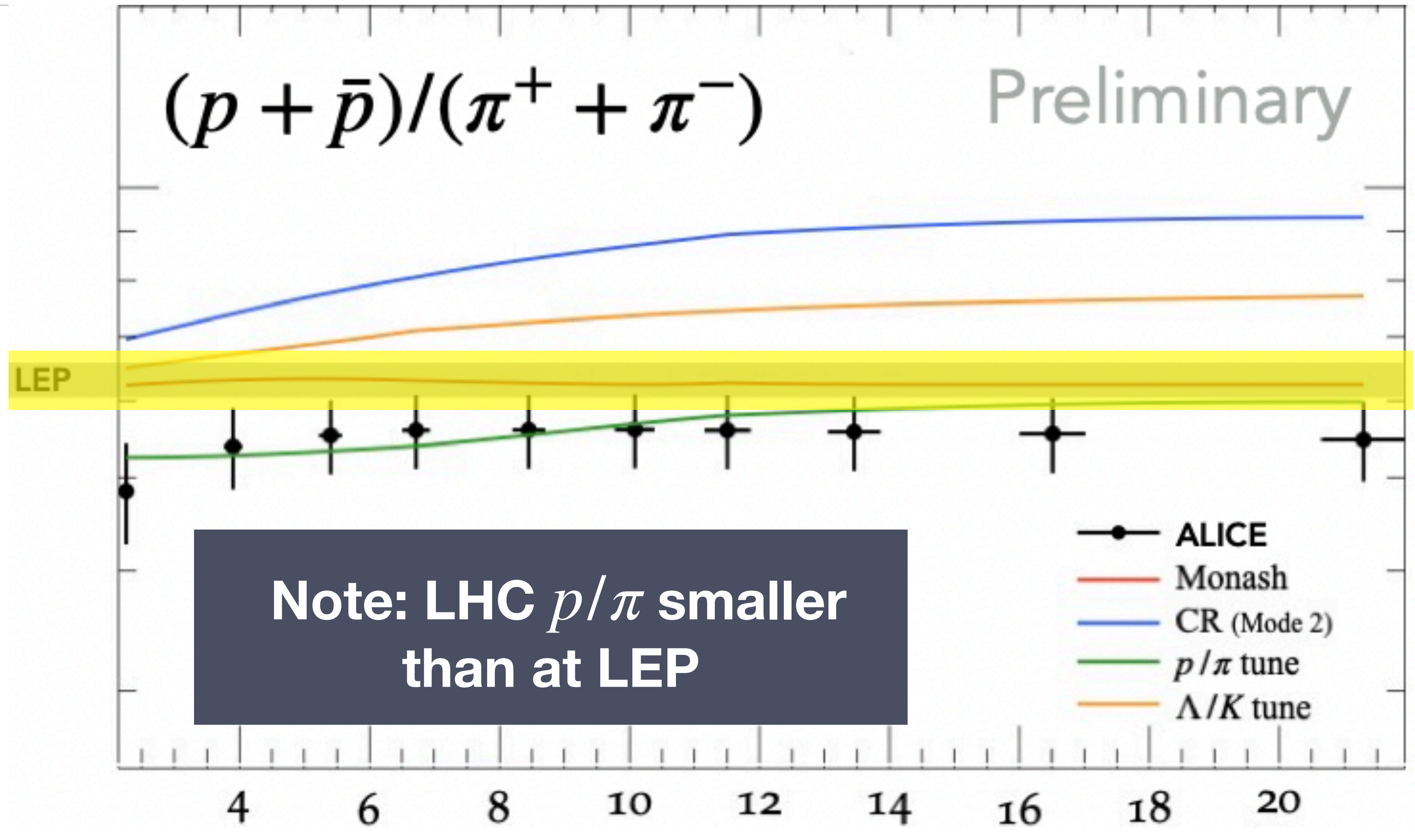
Discrepancies with LHC data

Schwinger mechanism → constant strange/diquark production along a string

But modelling of $q\bar{q}$ strings hadronizing with constant strangeness/diquark production shows discrepancies with LHC data



Heavy flavour baryon-to-meson ratios



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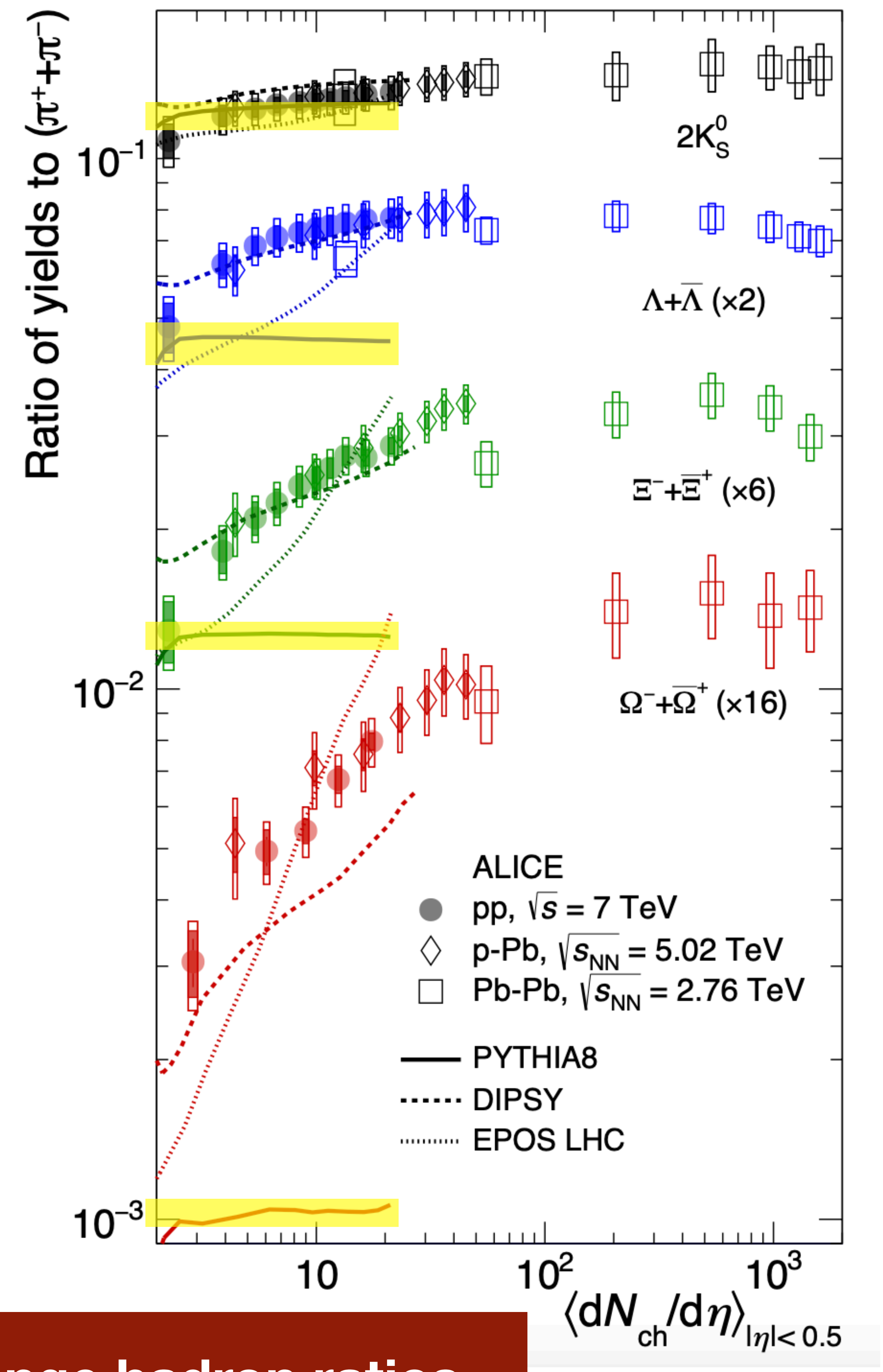

Strange to non-strange hadron ratios

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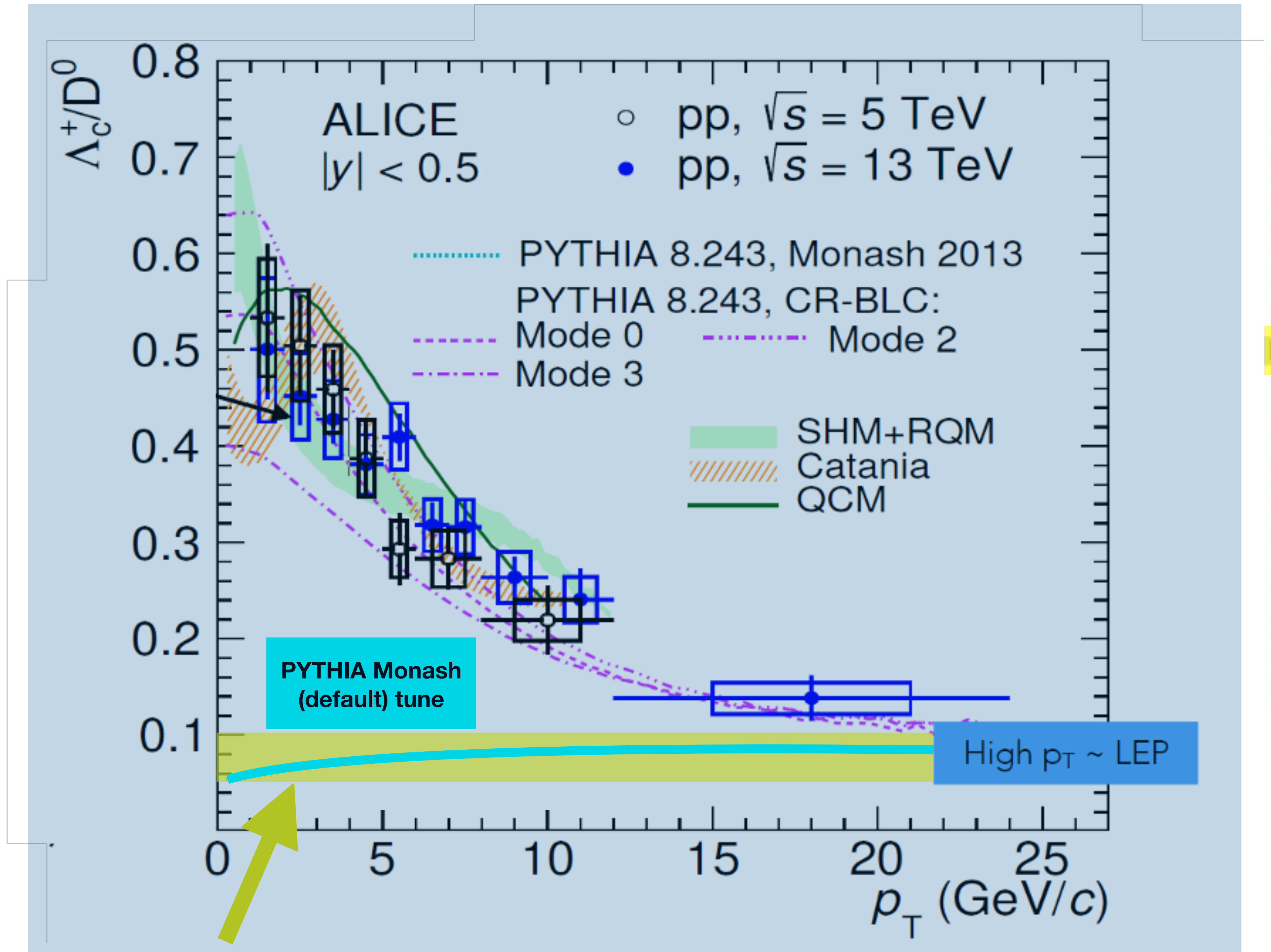

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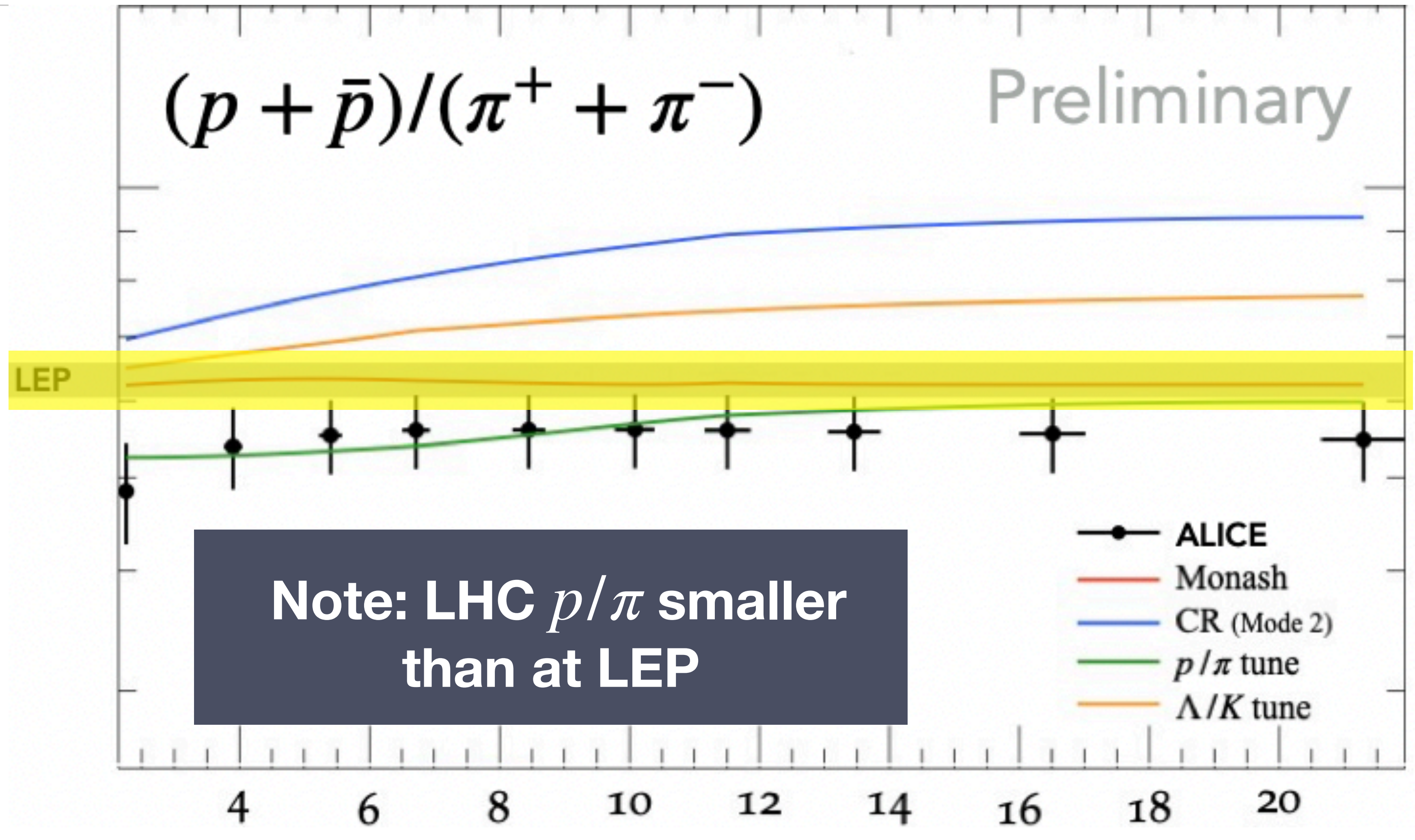

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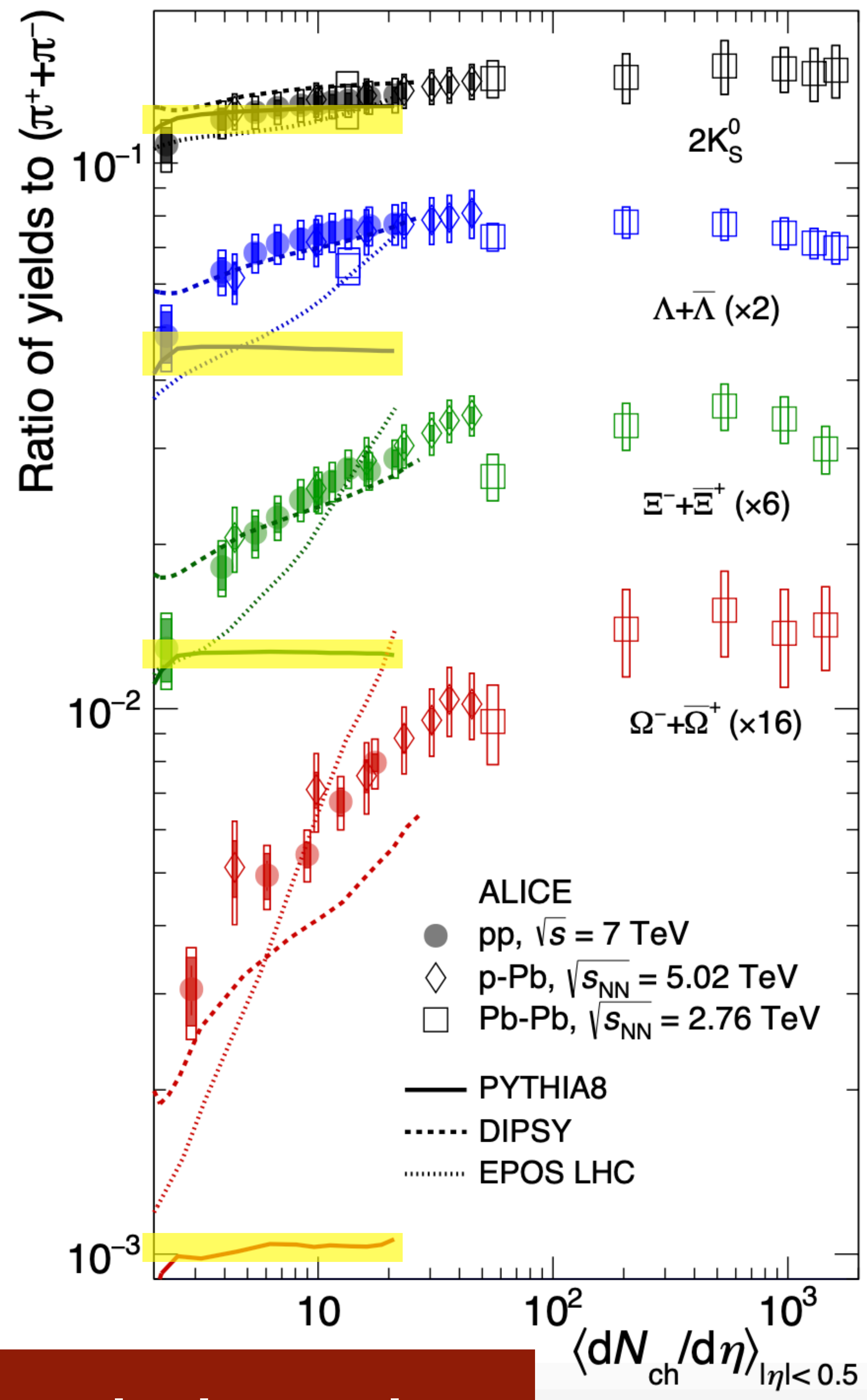

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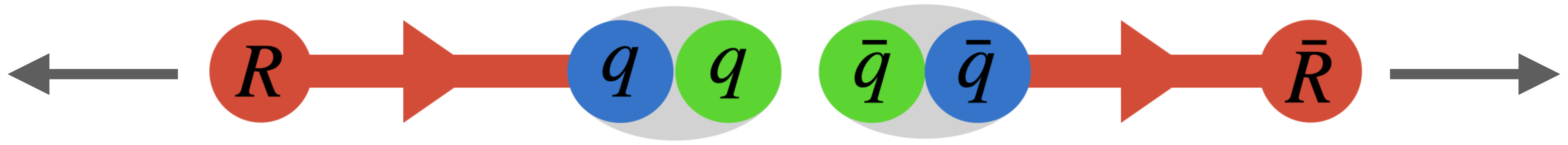
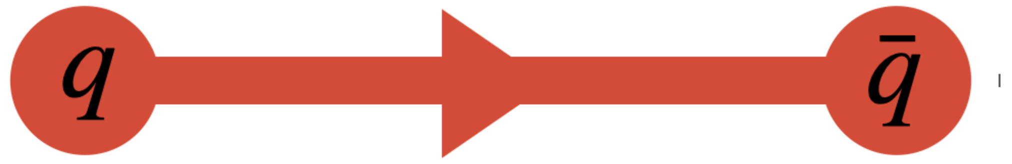
Baryon formation: **diquark-antidiquark** pair creation





e.g. a **dipole** string using the red-antired colour singlet combination

Shown **dipole strings** formed due to the **colour-anticolour singlet** state

QCD is decribed by **SU(3)**, so there should exist a **red-green-blue** colour singlet state

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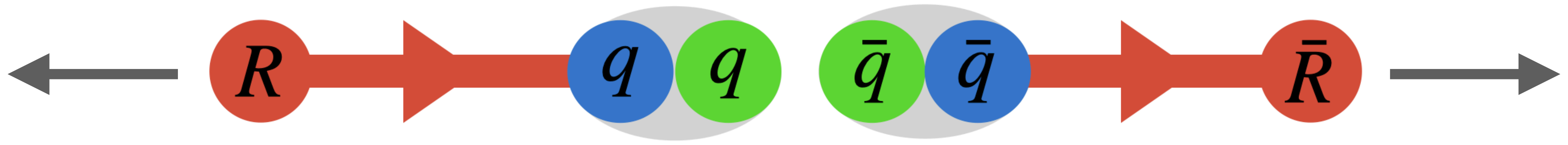

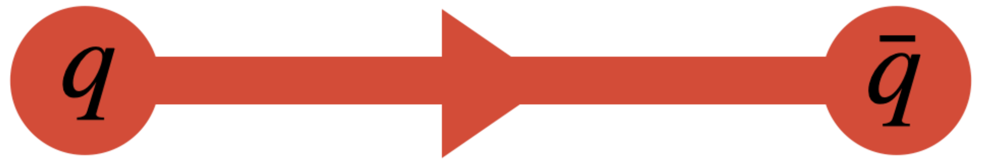

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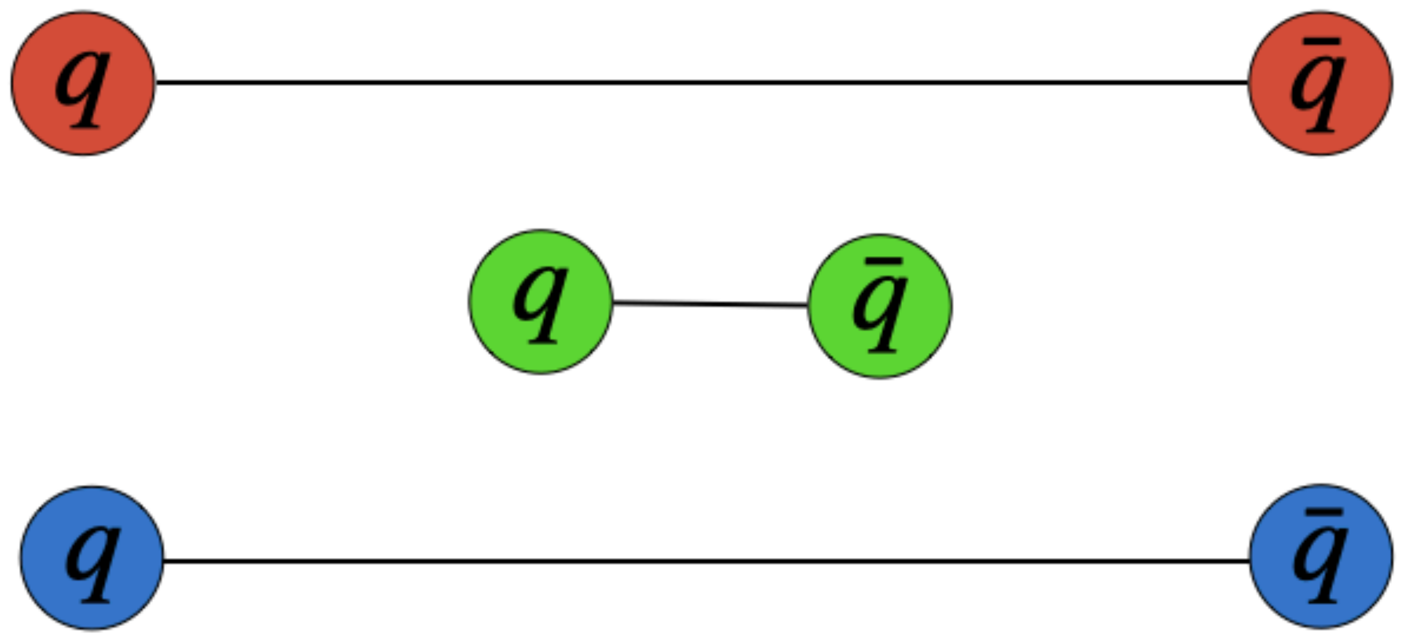

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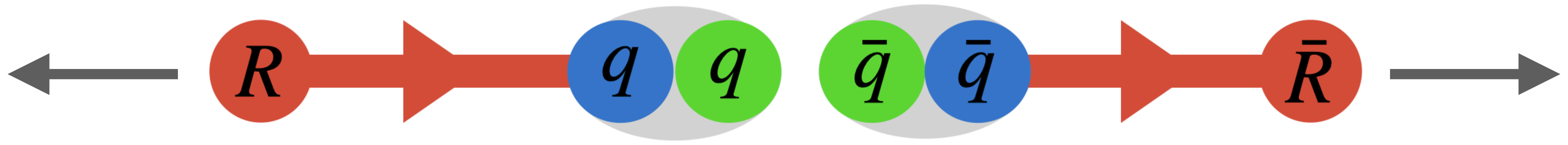

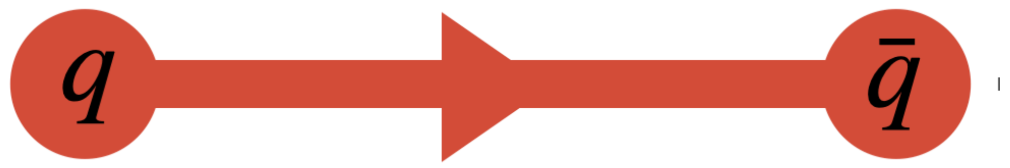

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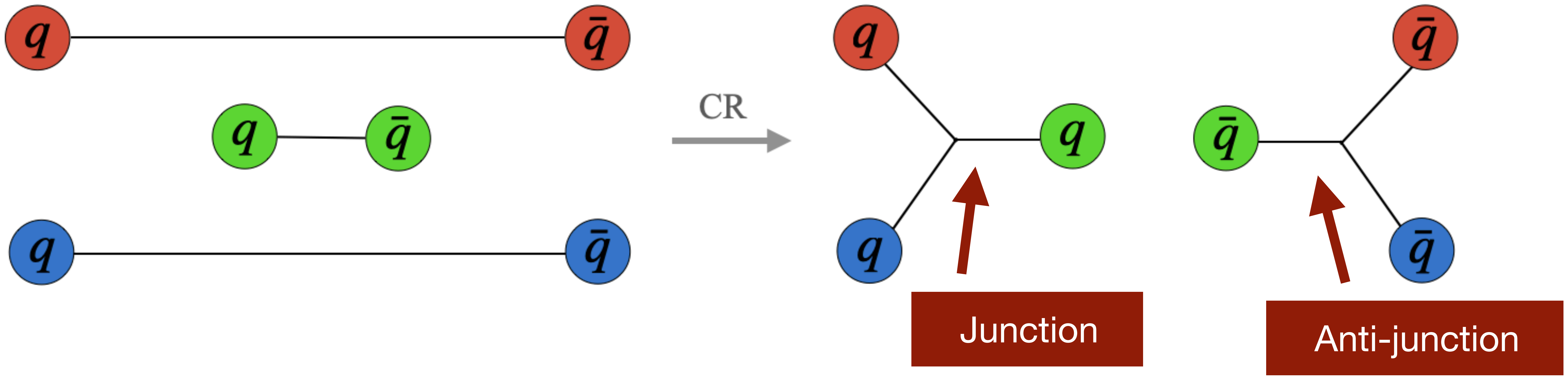
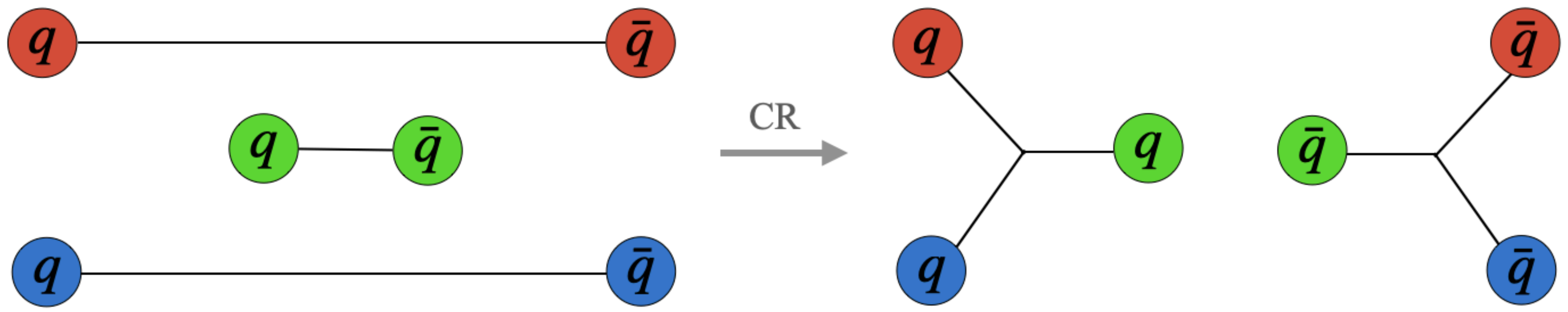


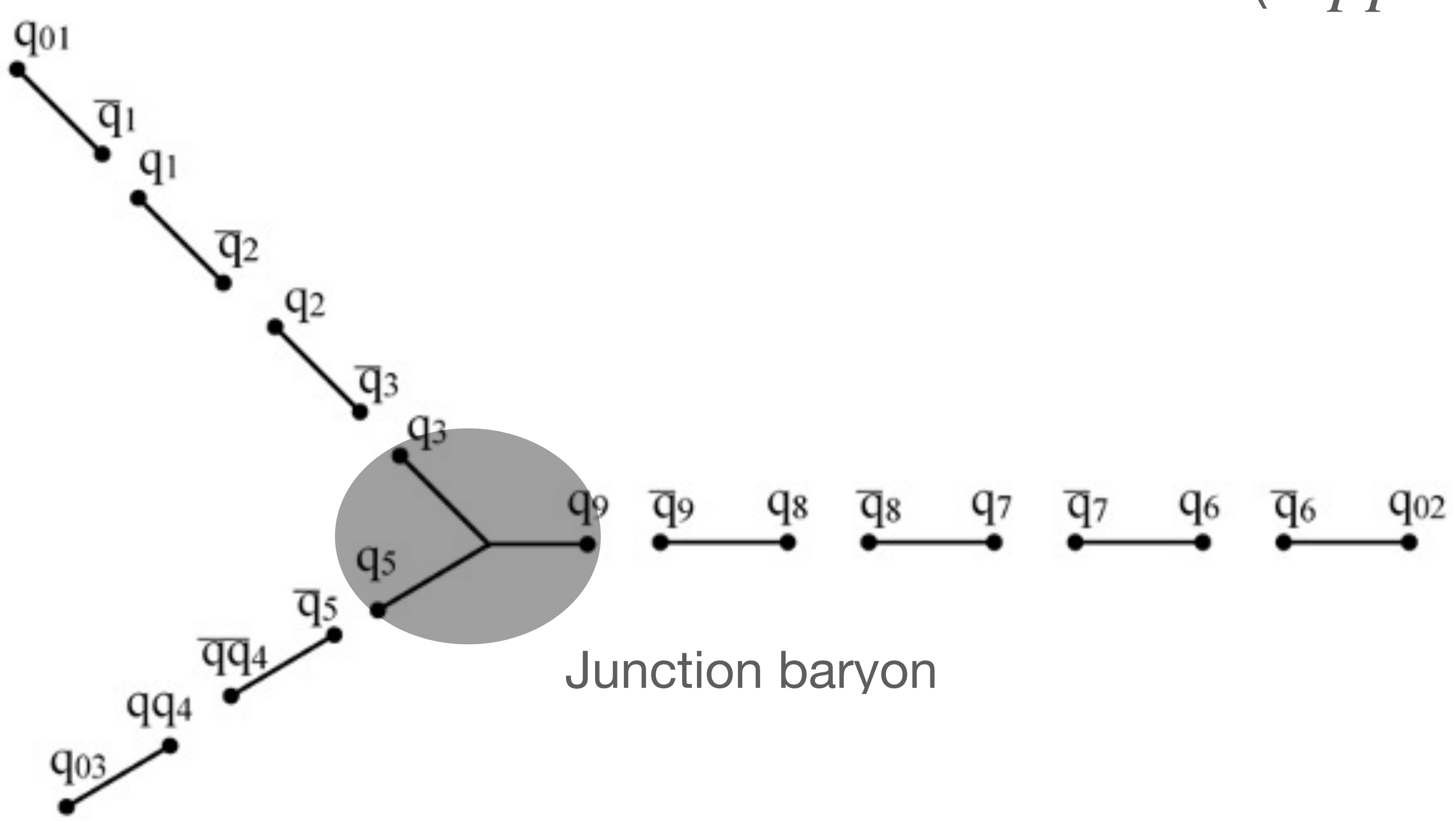
Including Junctions

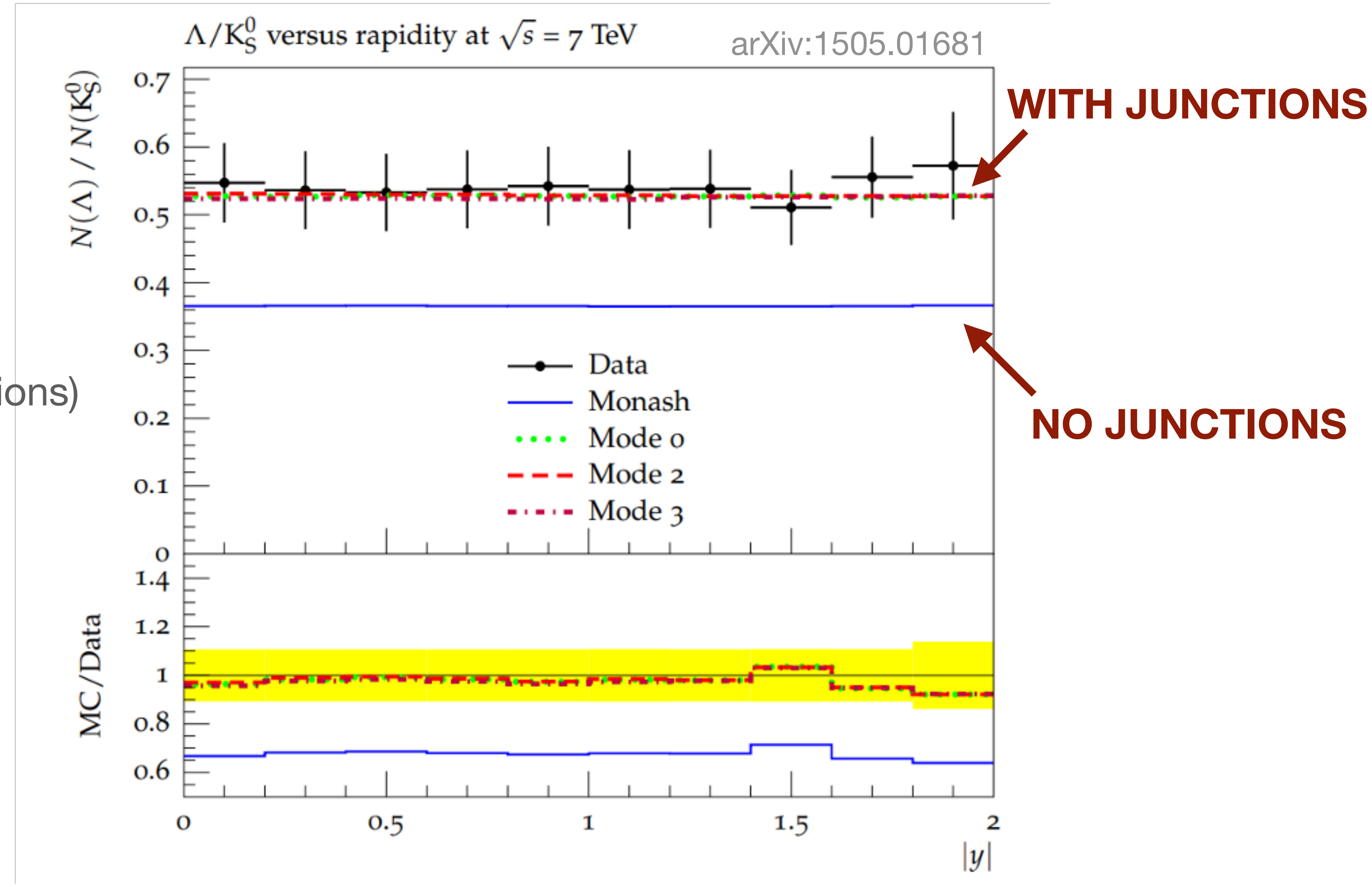


Mechanism for **baryon production**

➢ ~40% of baryons are from junctions in PYTHIA

(in *pp* collisions)





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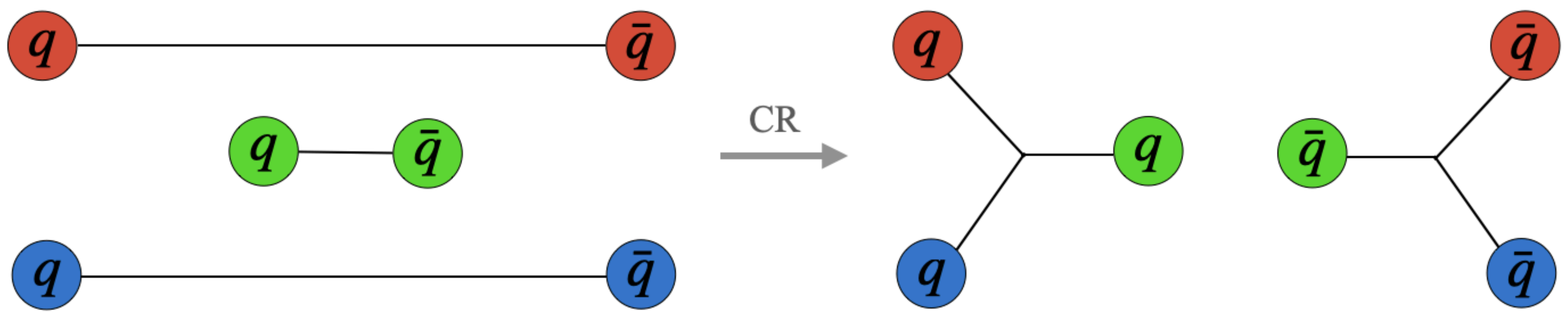

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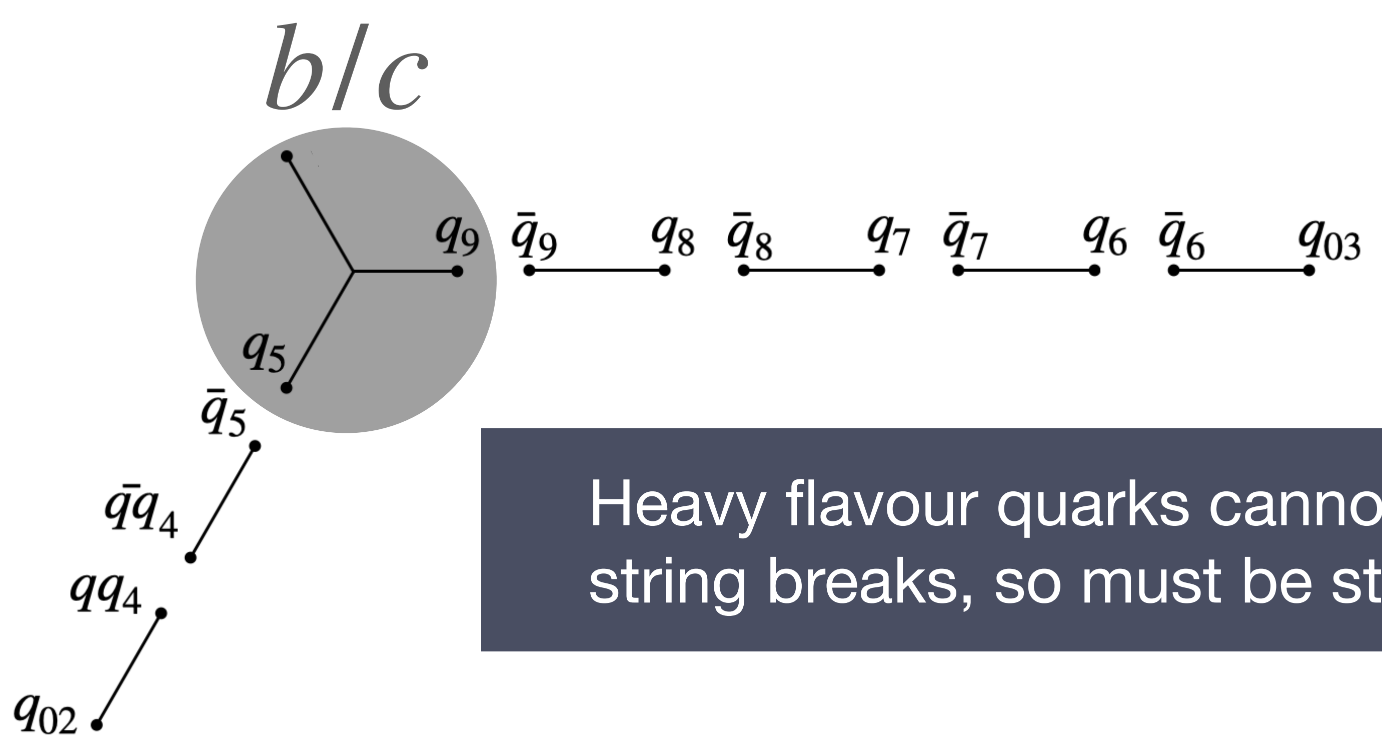
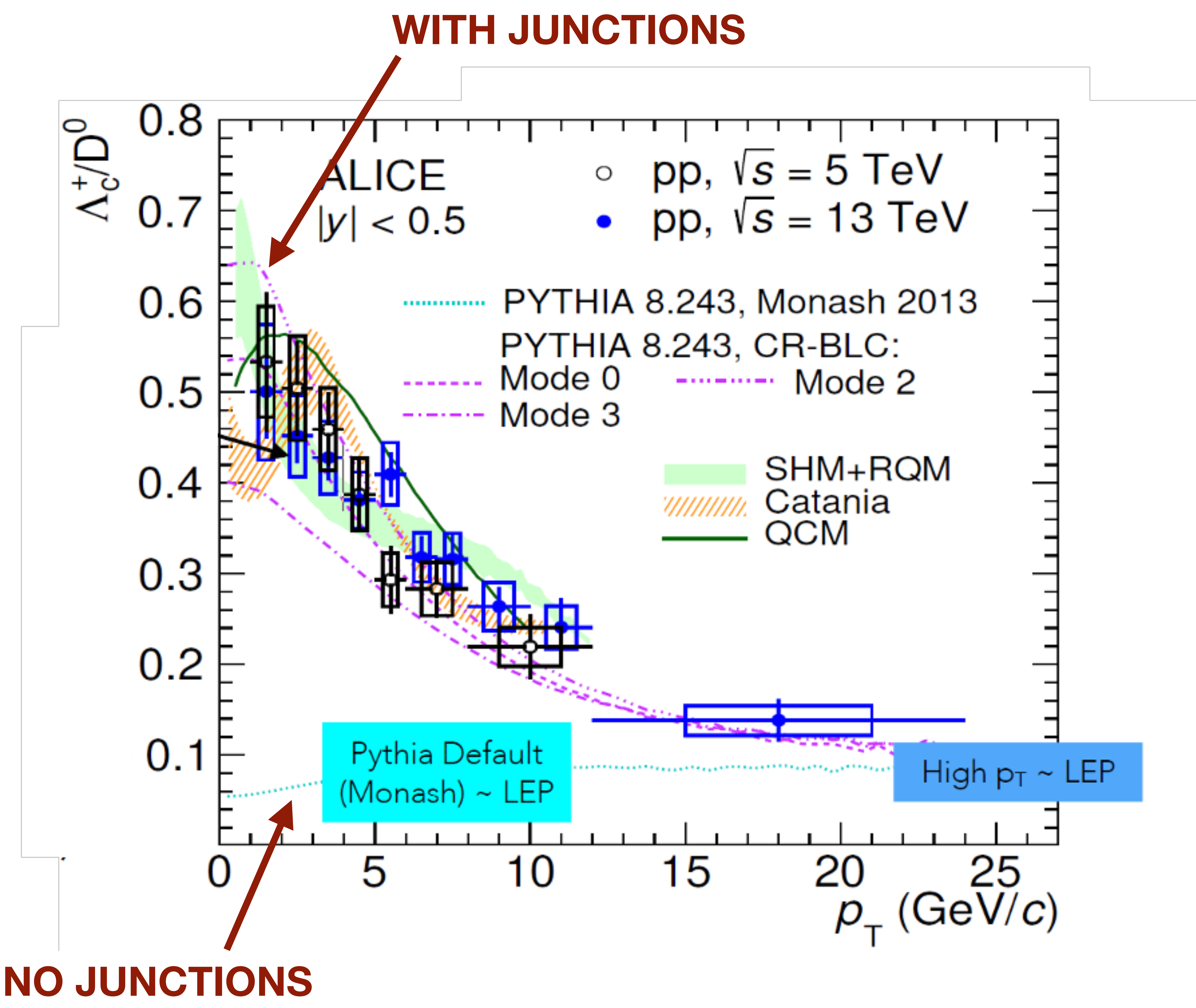
Heavy flavour baryons

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



Heavy flavour quarks cannot be made from string breaks, so must be string endpoints



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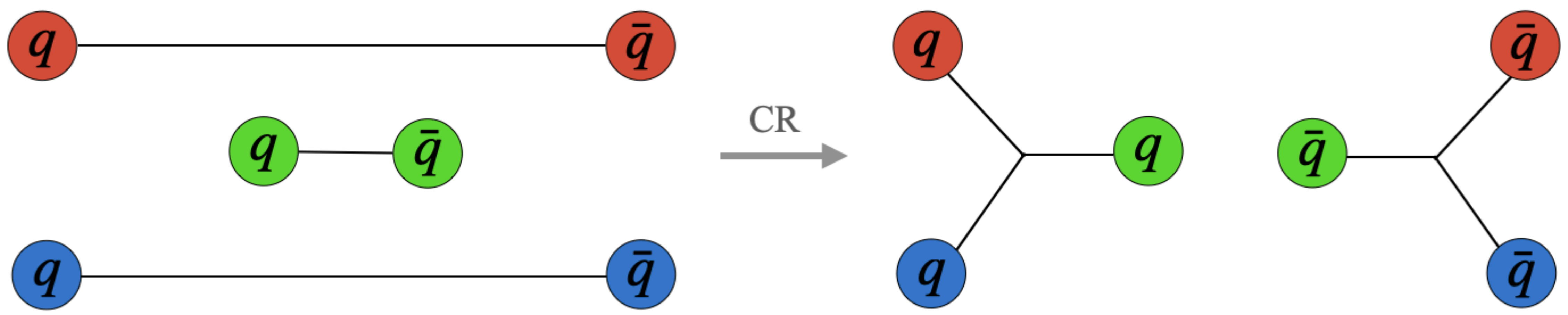

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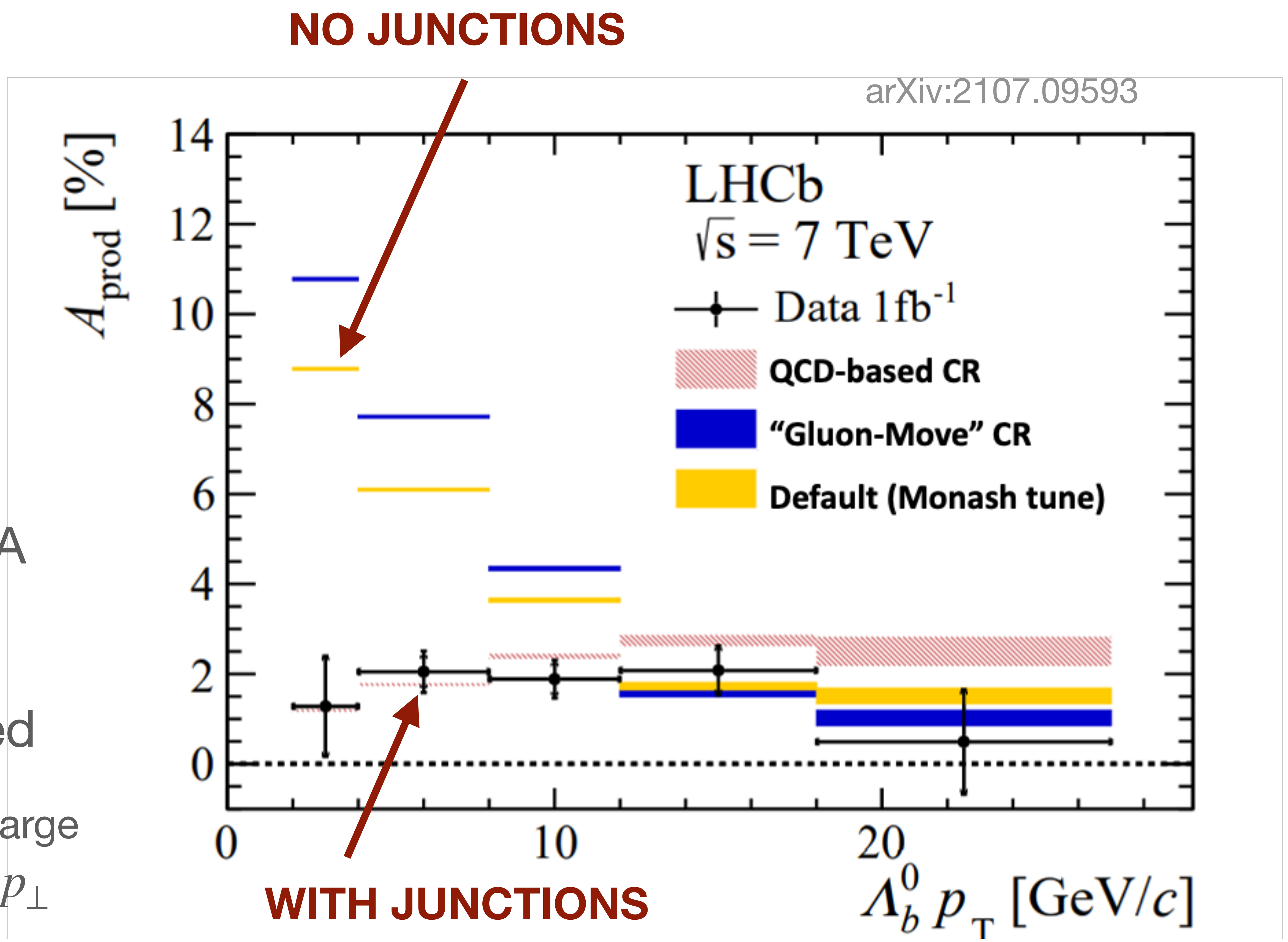
Asymmetries

- ➢ Equal amount of junctions and antijunctions 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** $p_\perp$



Discrepancies with LHC data

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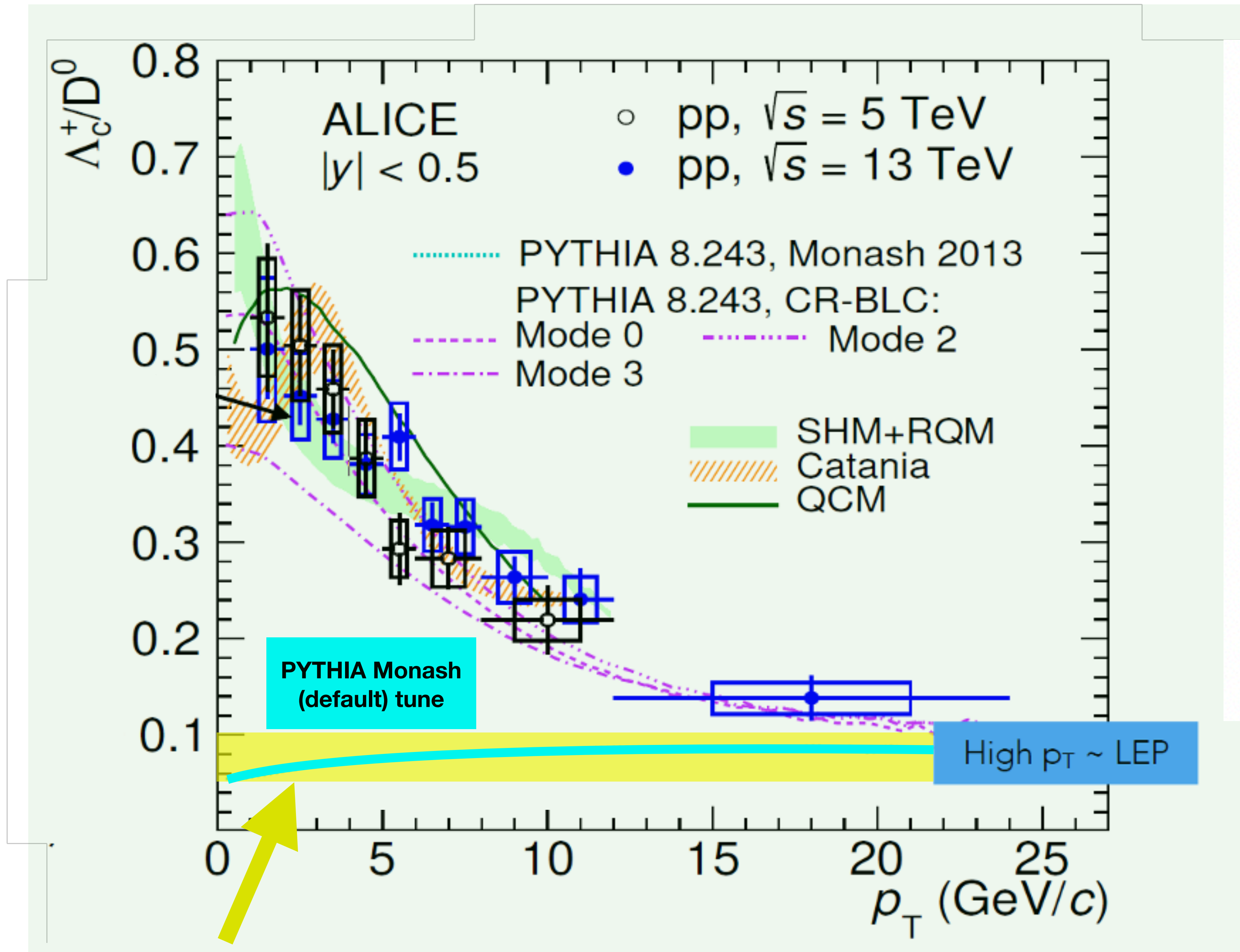
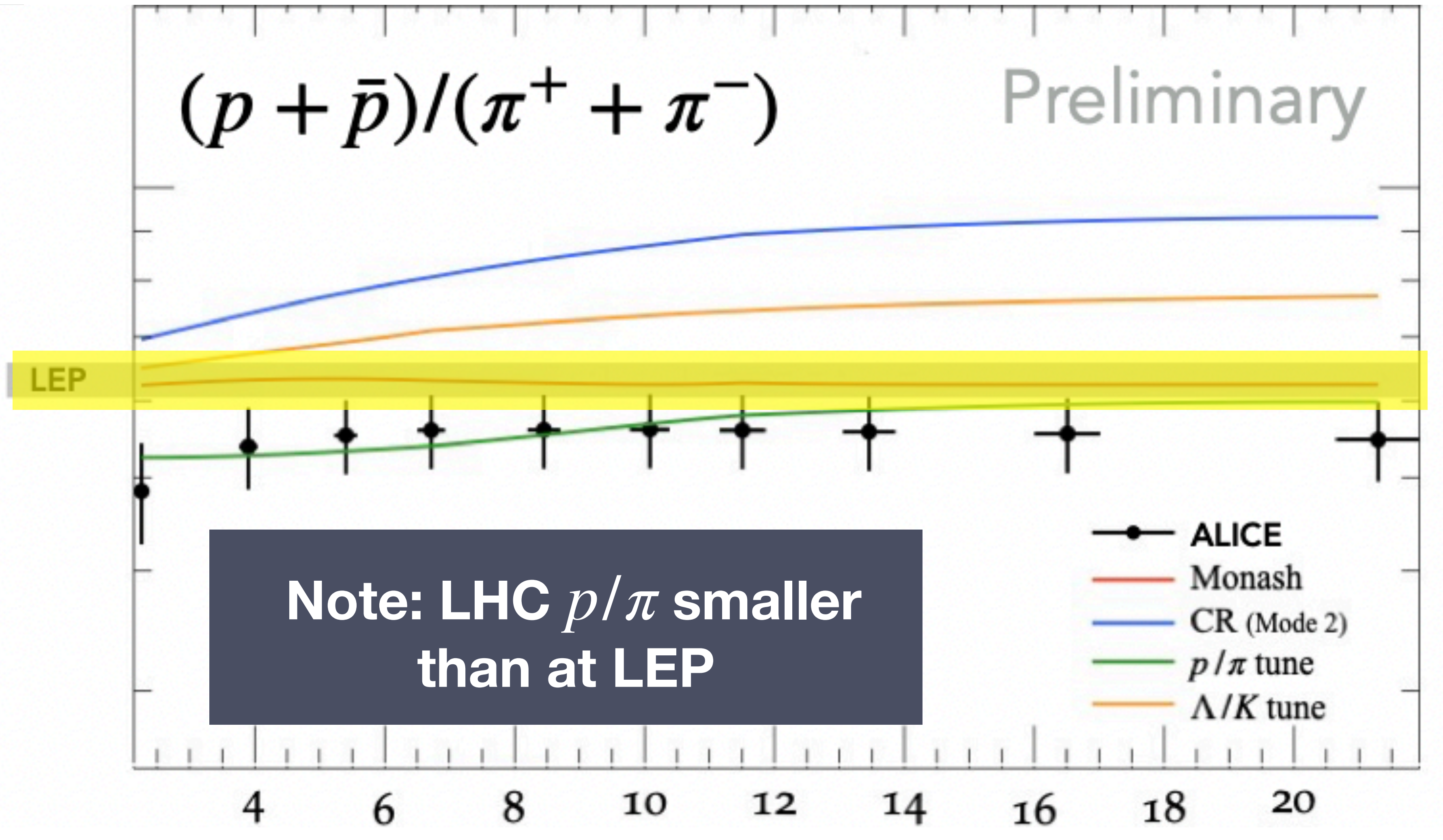
But modelling of $q\bar{q}$ strings hadronizing with constant strangeness/diquark production shows discrepancies with LHC data



Heavy flavour baryon-to-meson ratios



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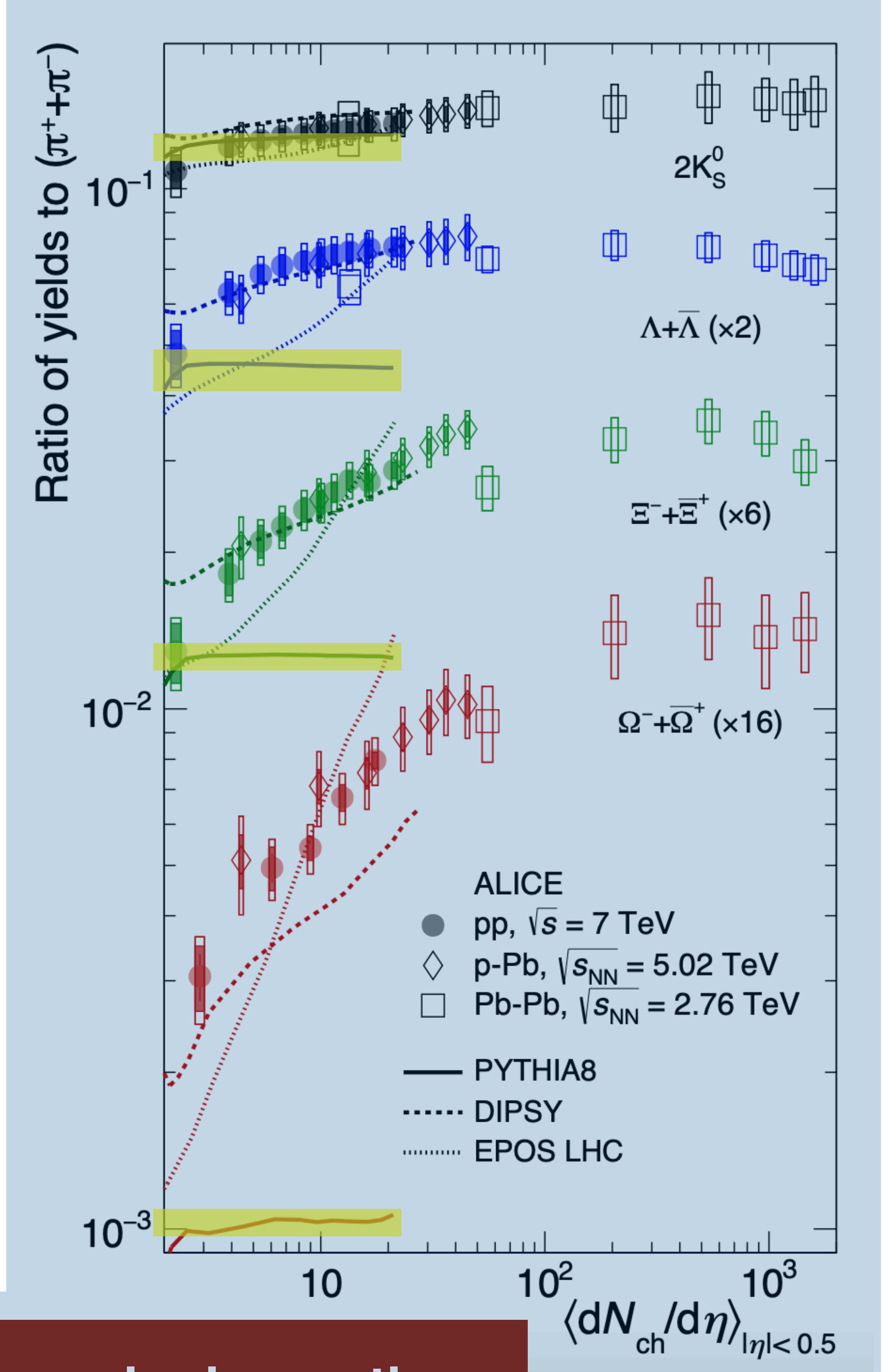
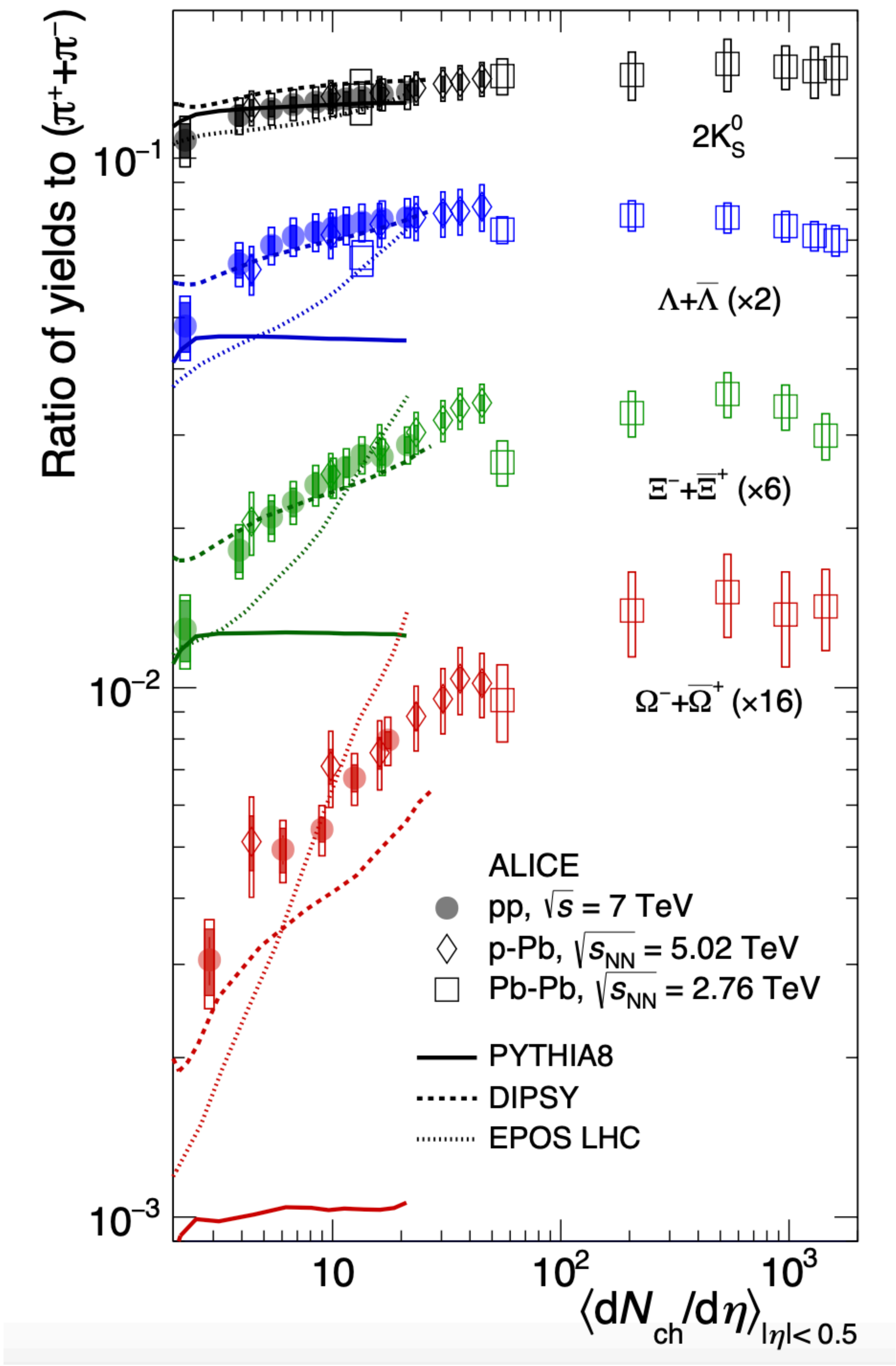


Strange to non-strange hadron ratios

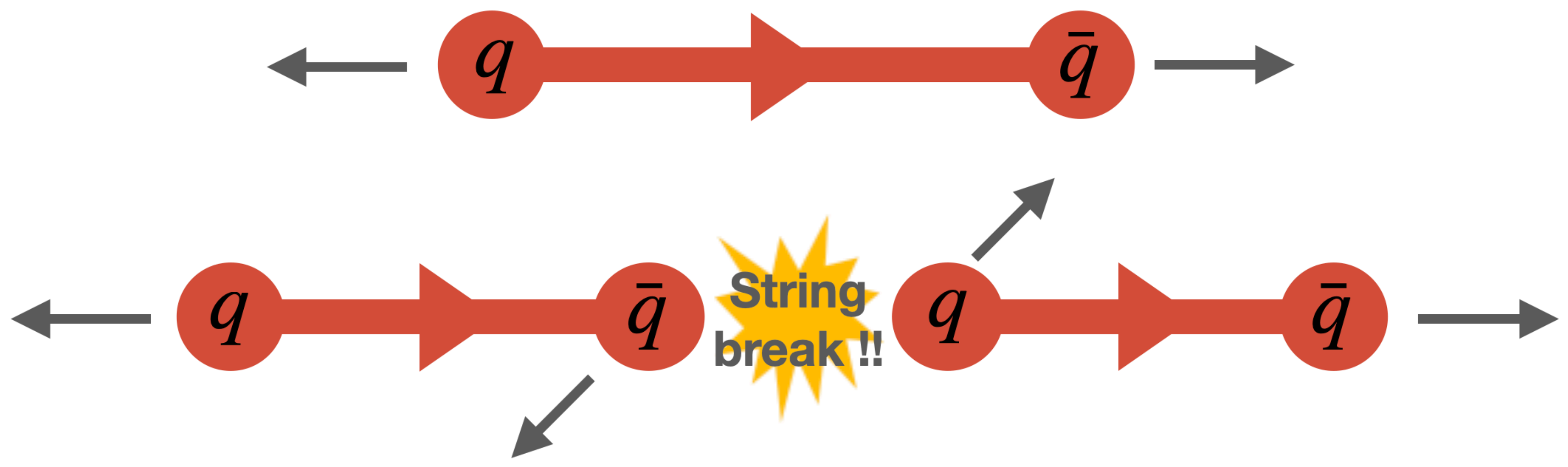
*remains an issue with the Λ_b/B^0 ratio

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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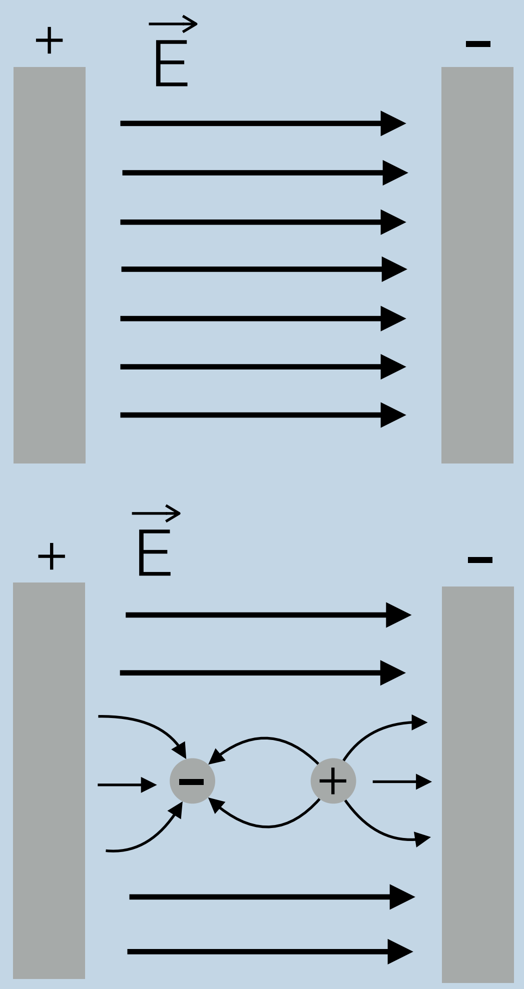


Non-perturbative creation of e^+e^- pairs in a string electric field

Probability from tunnelling factor

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

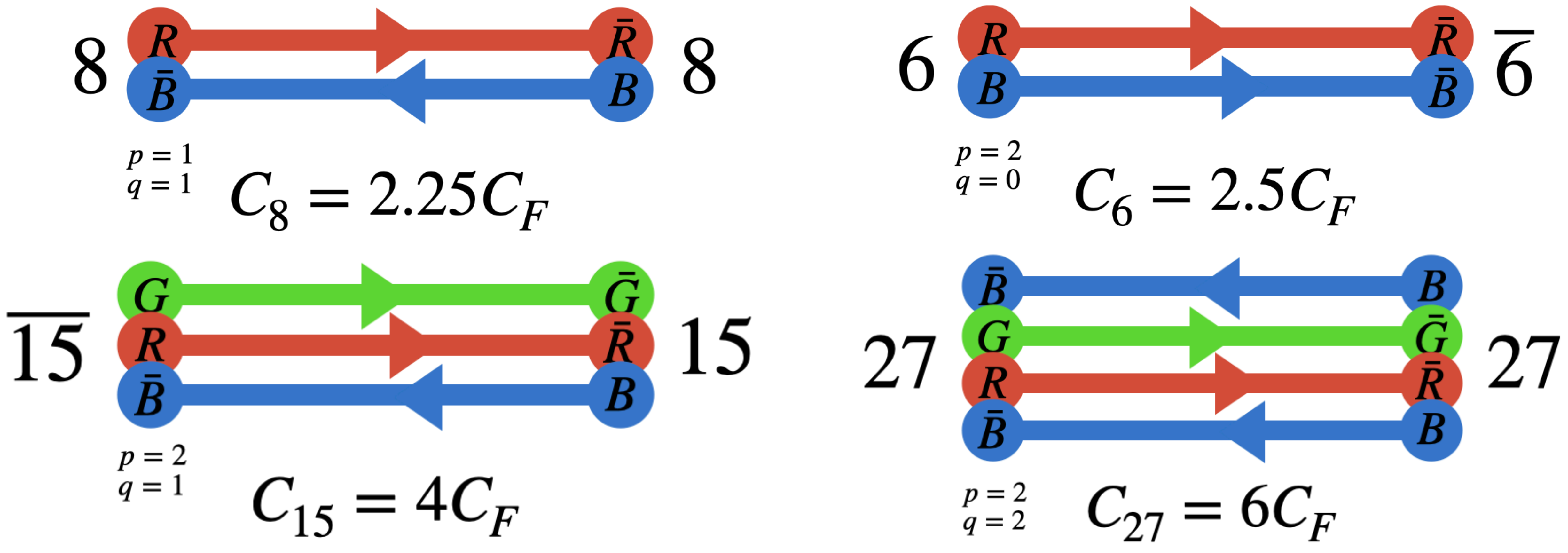
κ = string tension

increasing string tension → reducing mass suppression → more strange quarks

Strangeness Enhancement

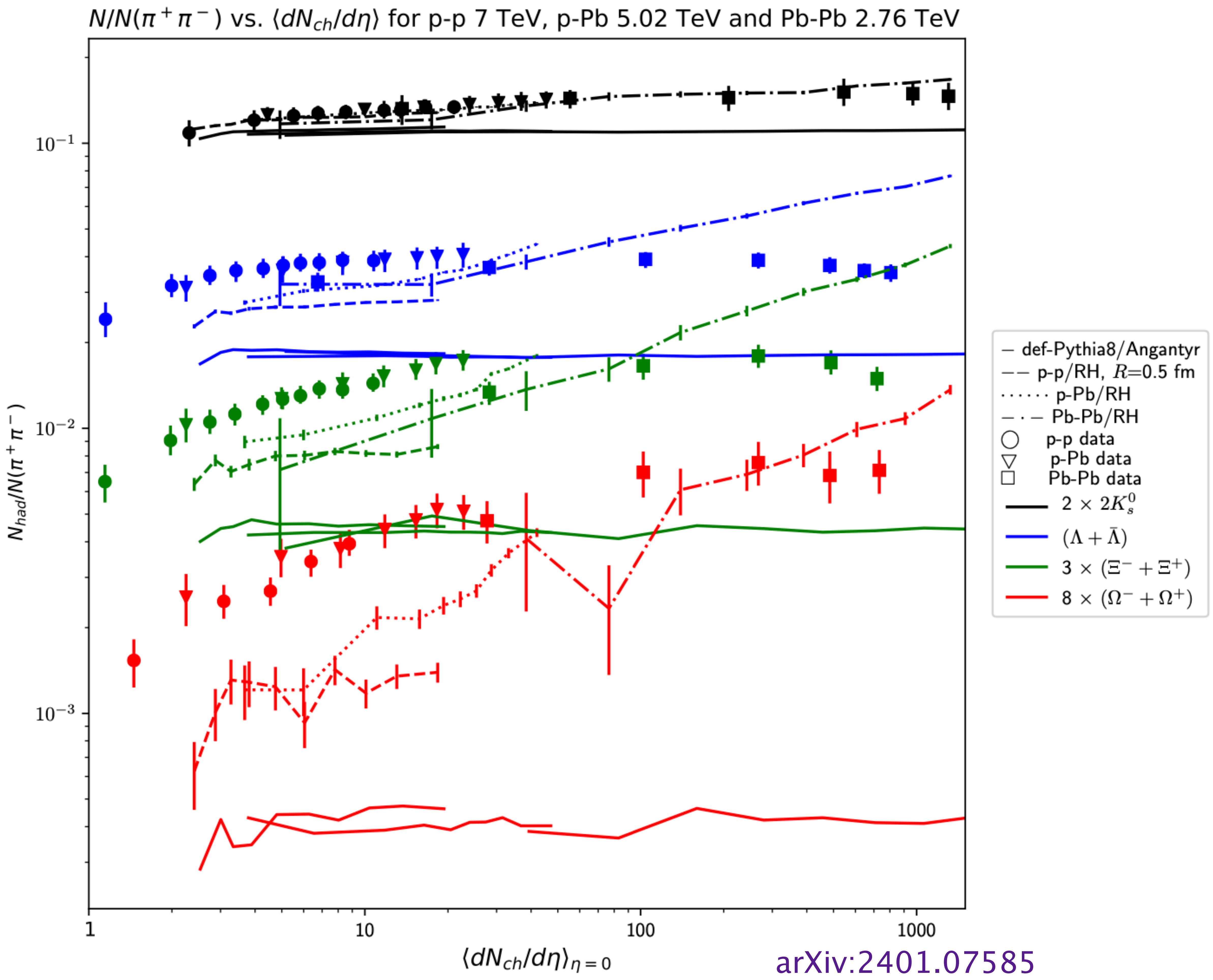
Rope hadronisation / Closepacking

Enhance string tension for higher multiplets according to **Casimir scaling**



High multiplicity is correlated with more partons
→ more dense string environments

**Rope hadronization and closepacking are very similar, with rope hadronization using space-time information of string breaks, whereas closepacking is intended as a simpler model fully in momentum space



arXiv:2401.07585

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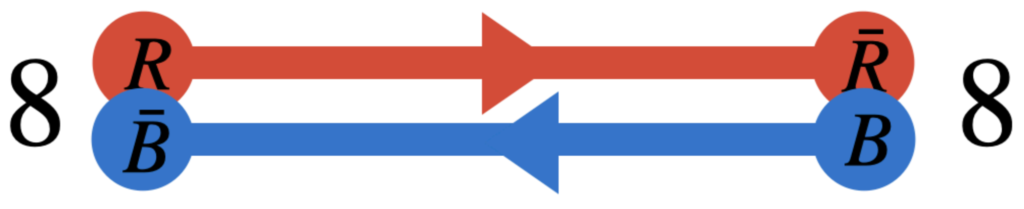
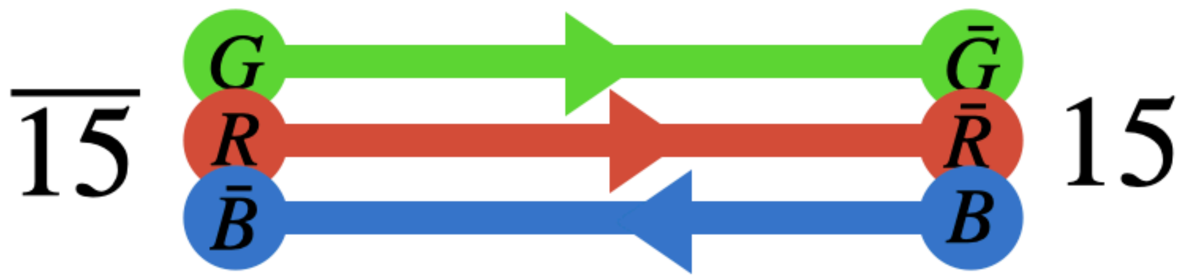


$p = 1$
$q = 1$

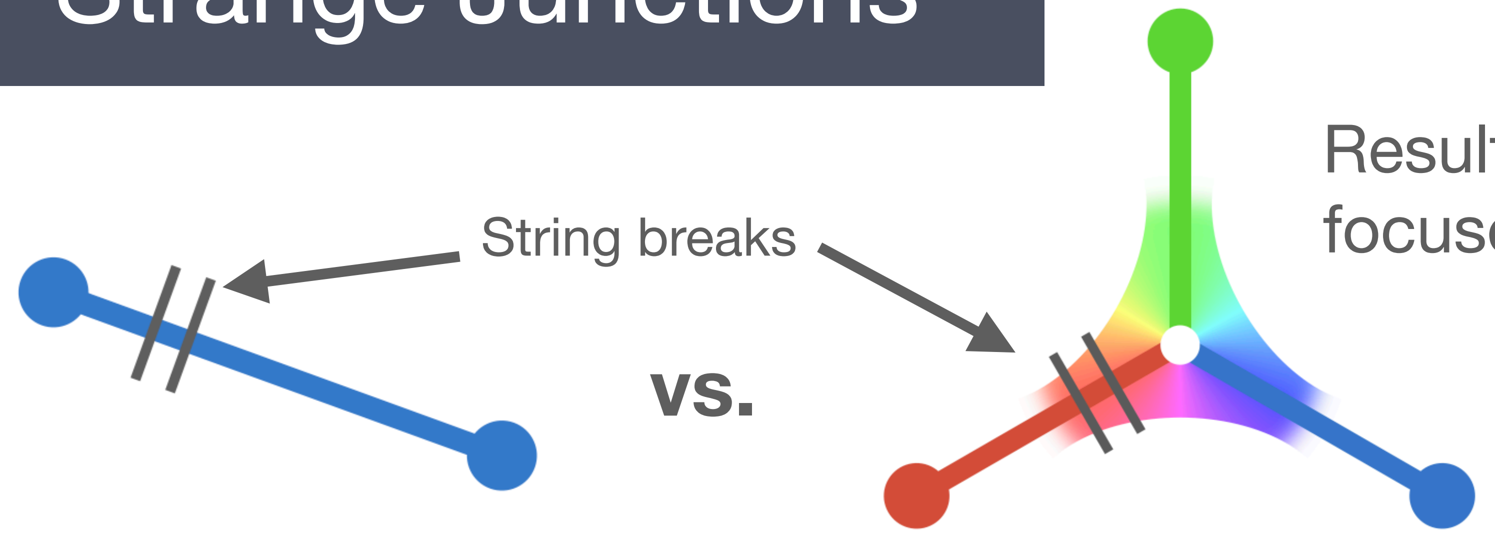
$C_8 = 2.25 C_F$



$p = 2$
$q = 1$

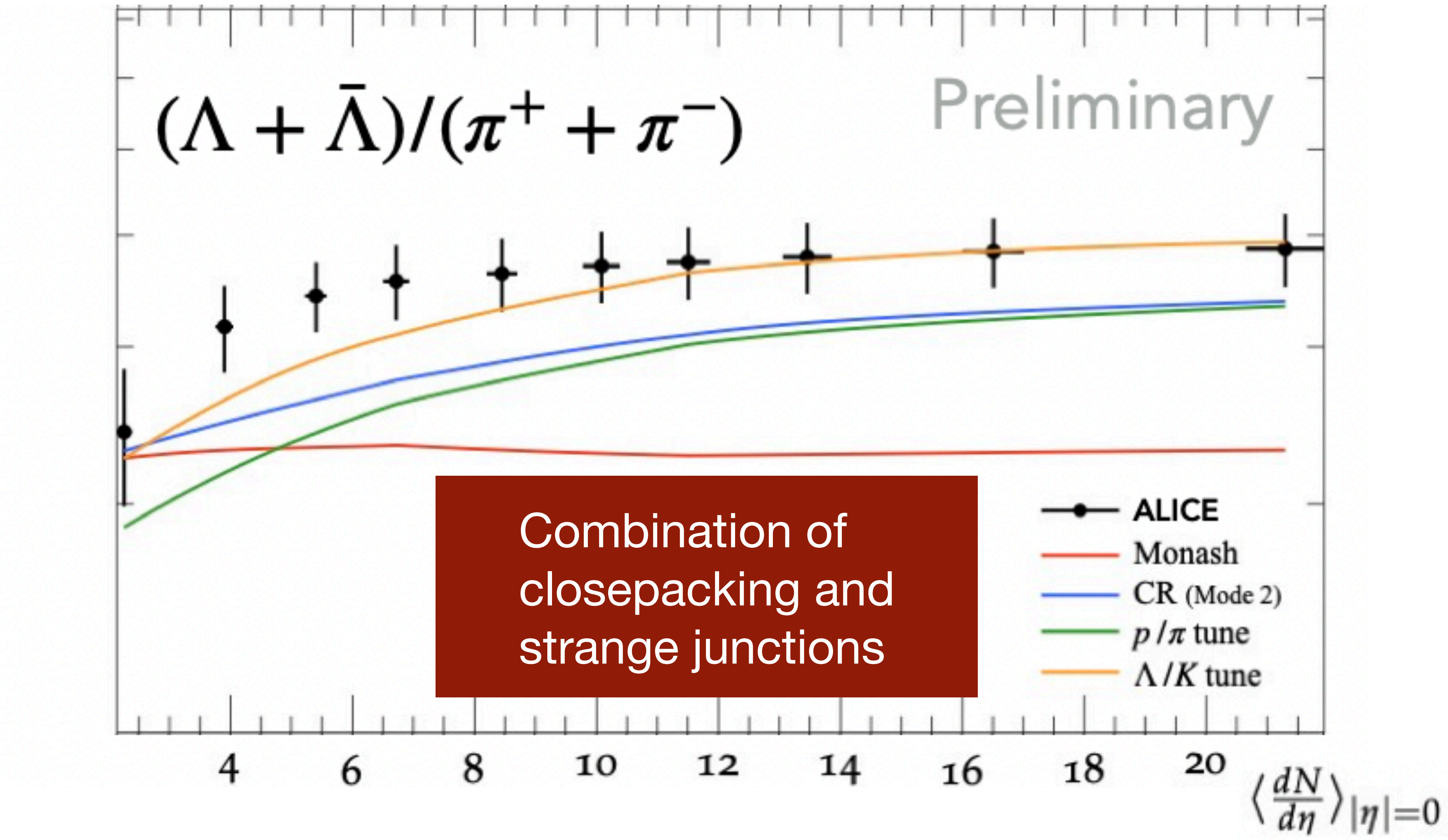
$C_{15} = 4 C_F$

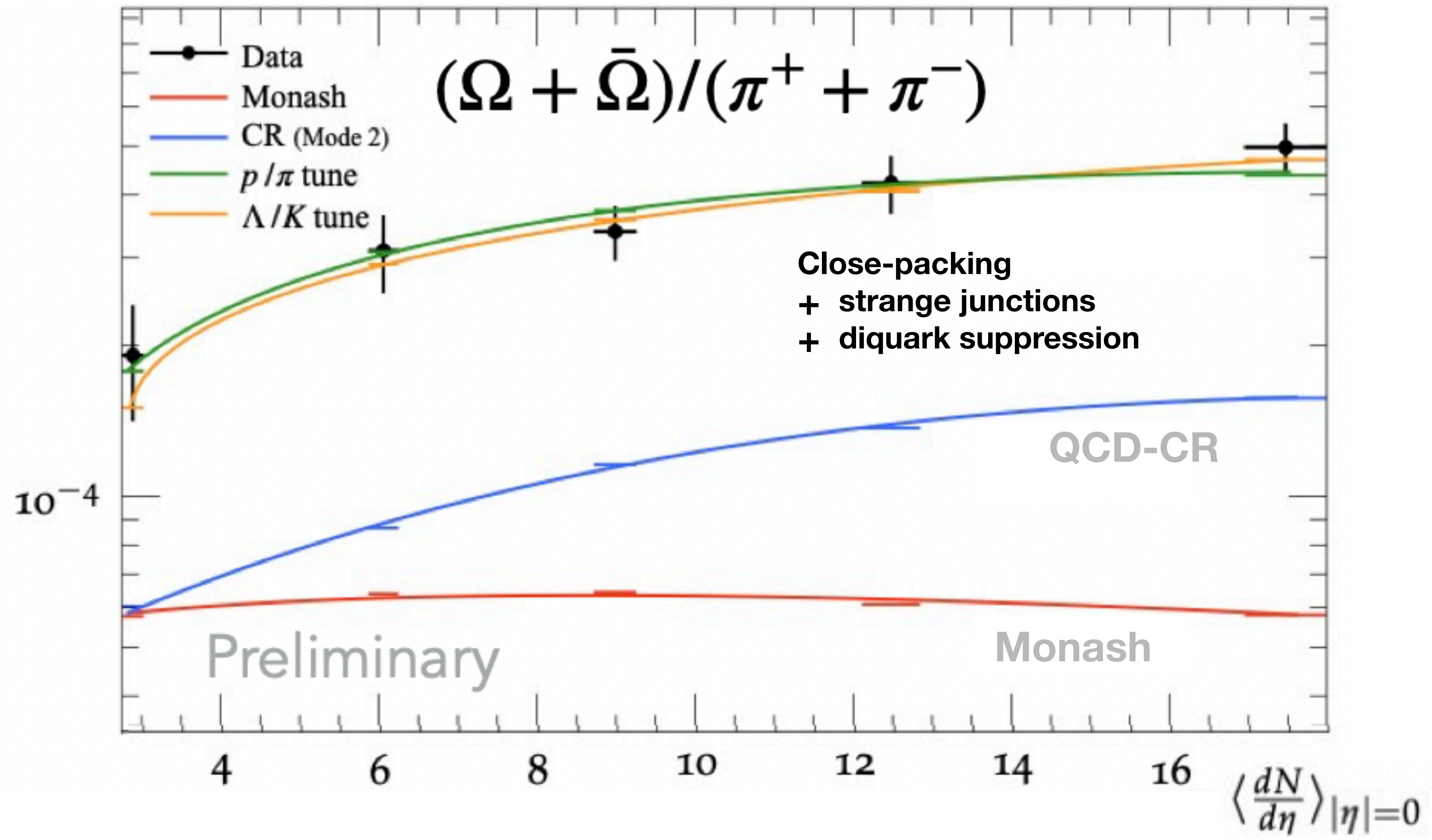
Strange Junctions



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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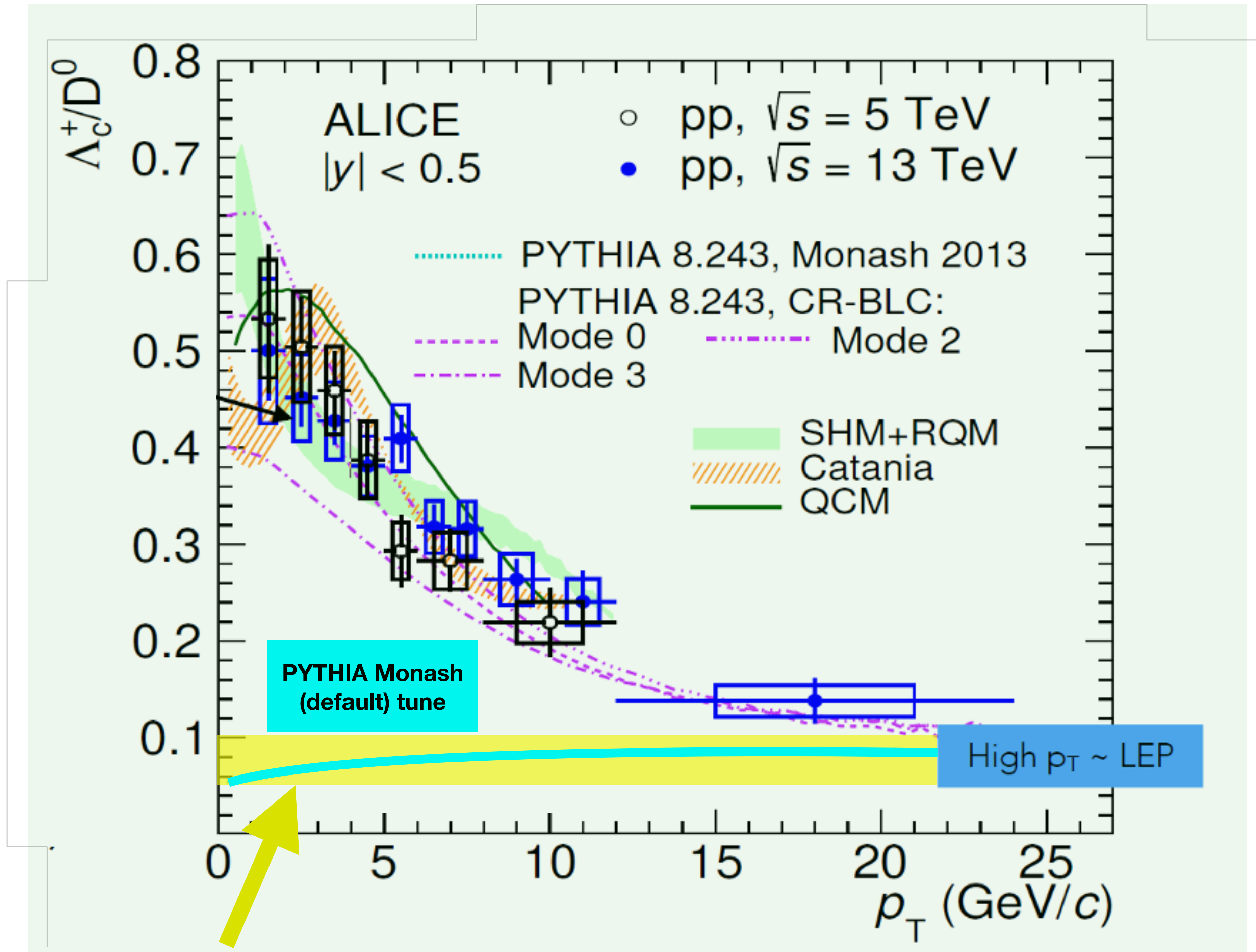

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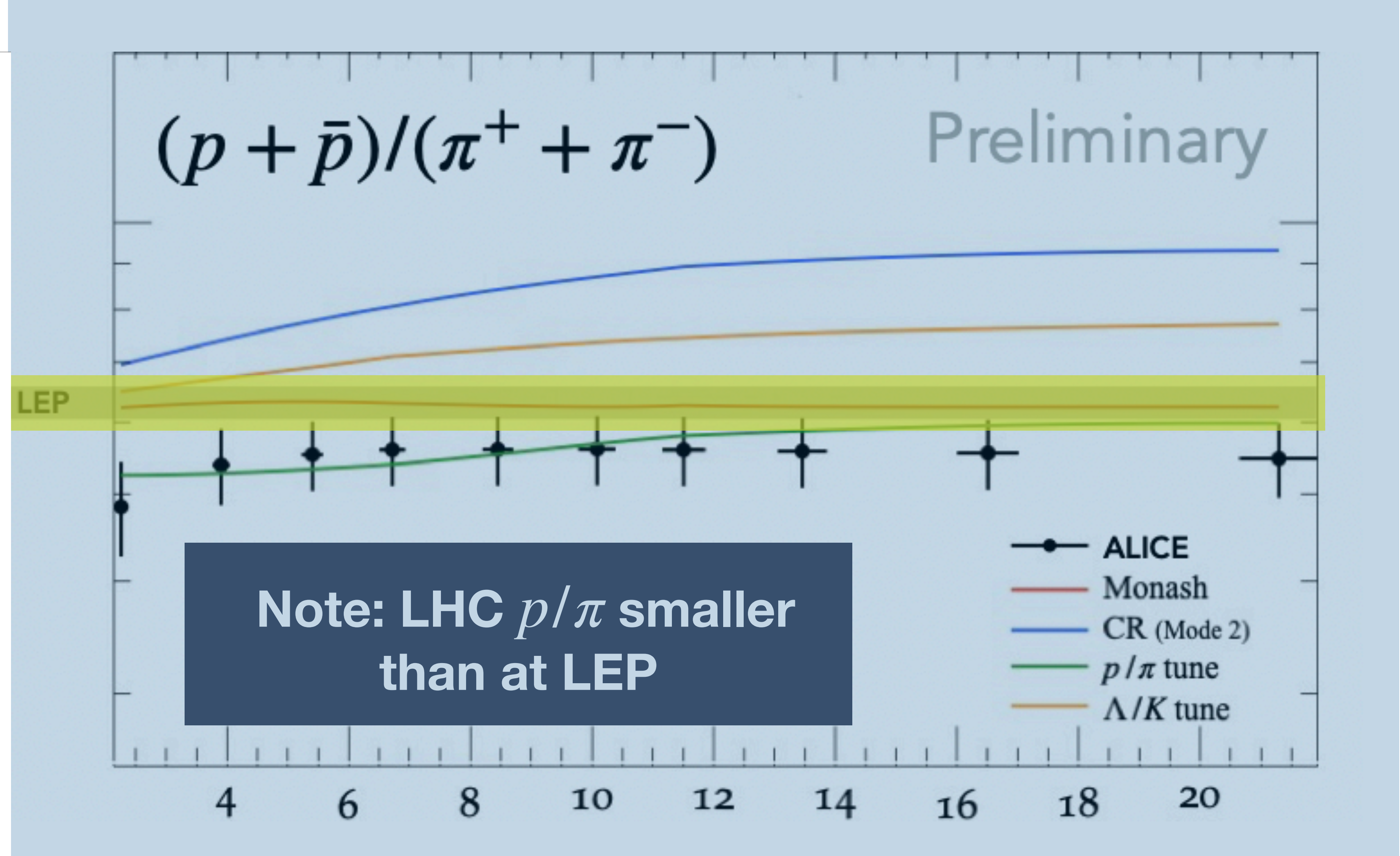
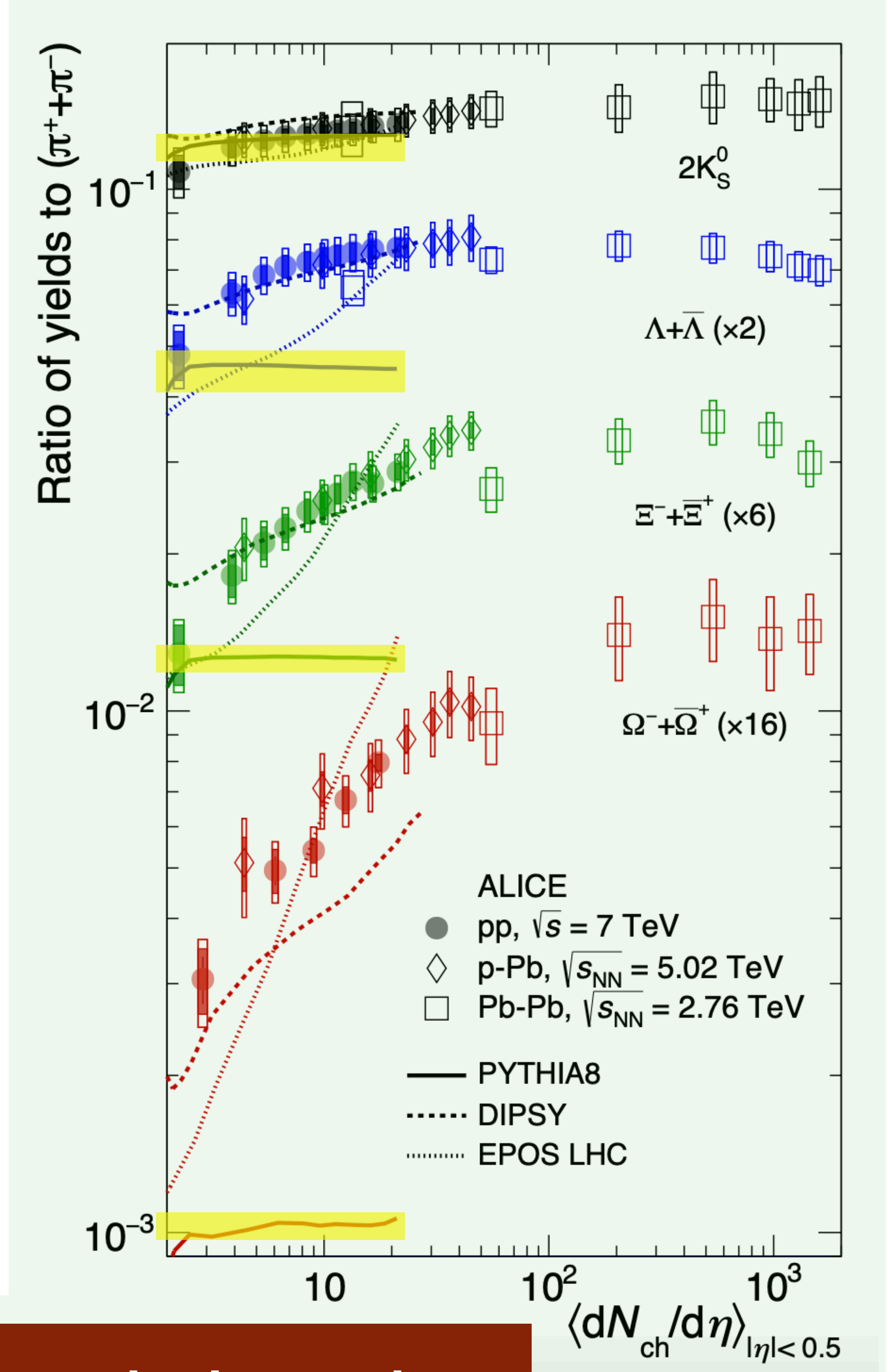


Overprediction of proton-to-pion ratio



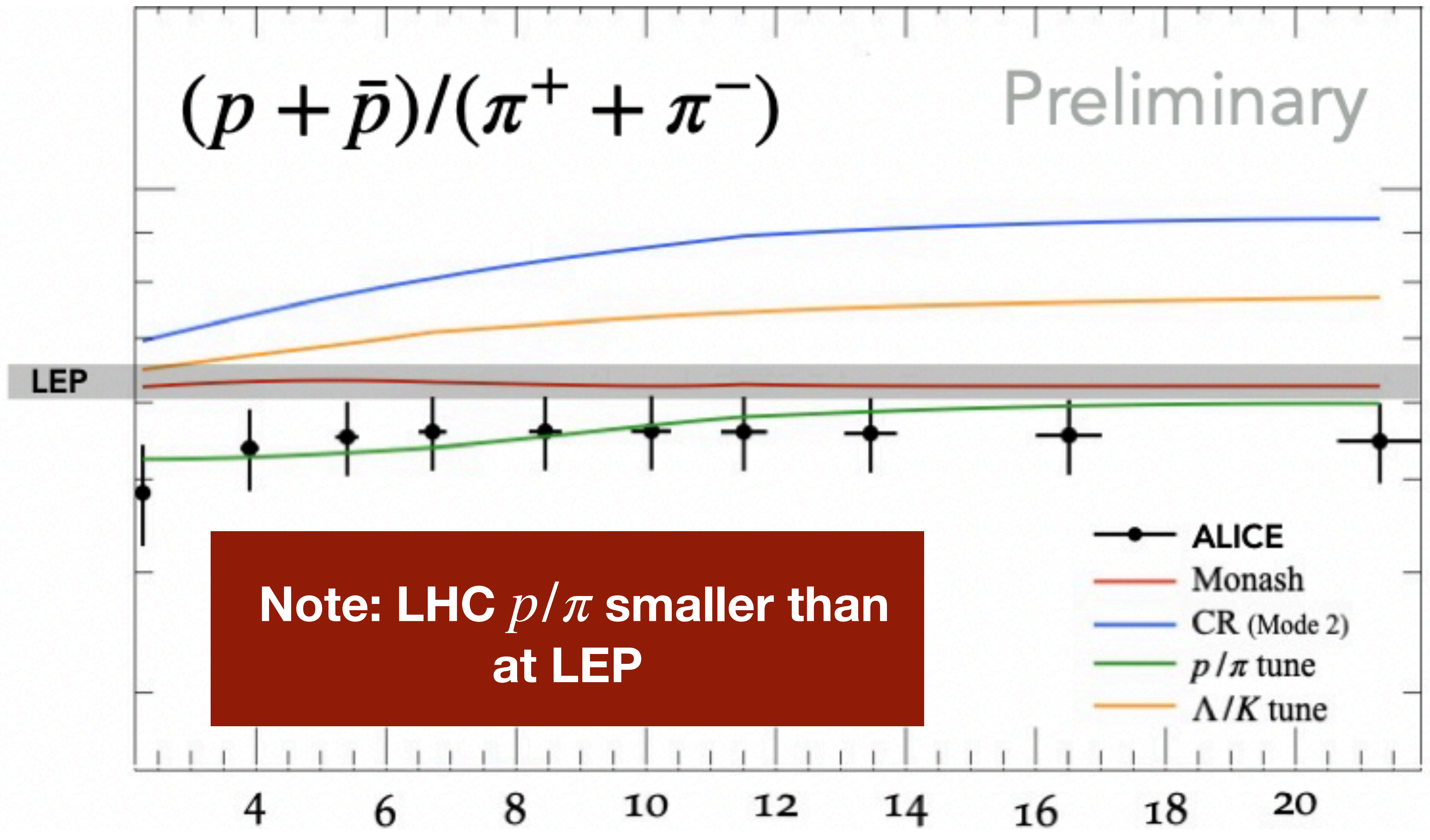
Strange to non-strange hadron ratios

*remains an issue with the Λ_b/B^0 ratio

Proton problem

As seen before, **junction baryon production** is important for **heavy flavour baryon production** and for the Λ/K_S ratio

Reexamine baryon formation via **diquark production**



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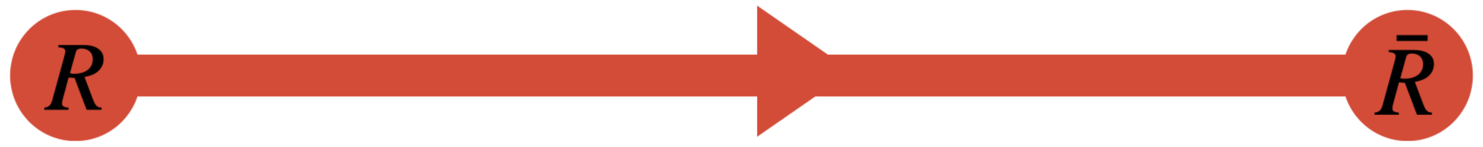
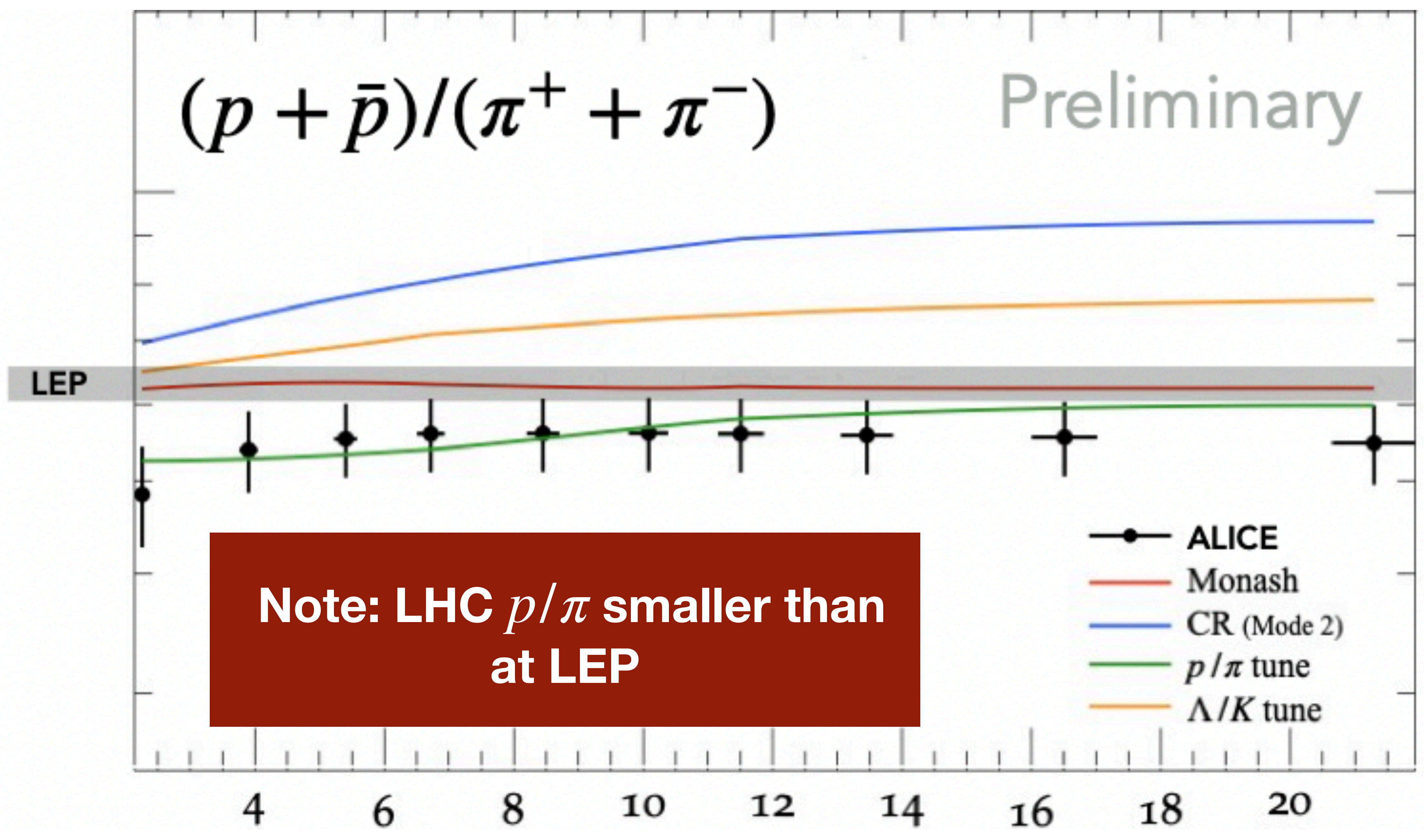
Popcorn mechanism for diquark production

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





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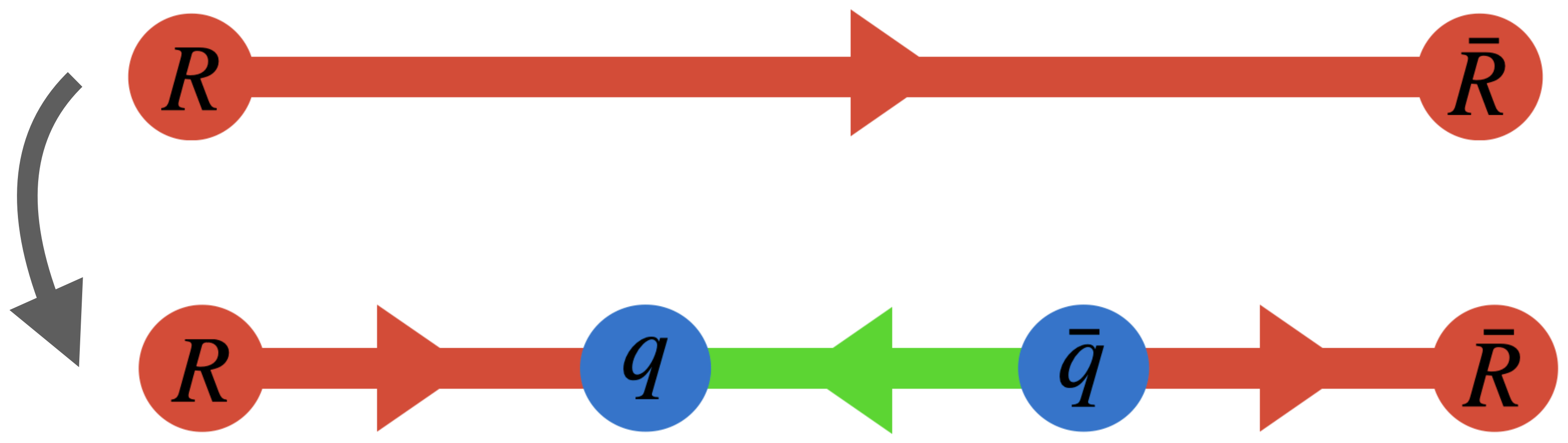
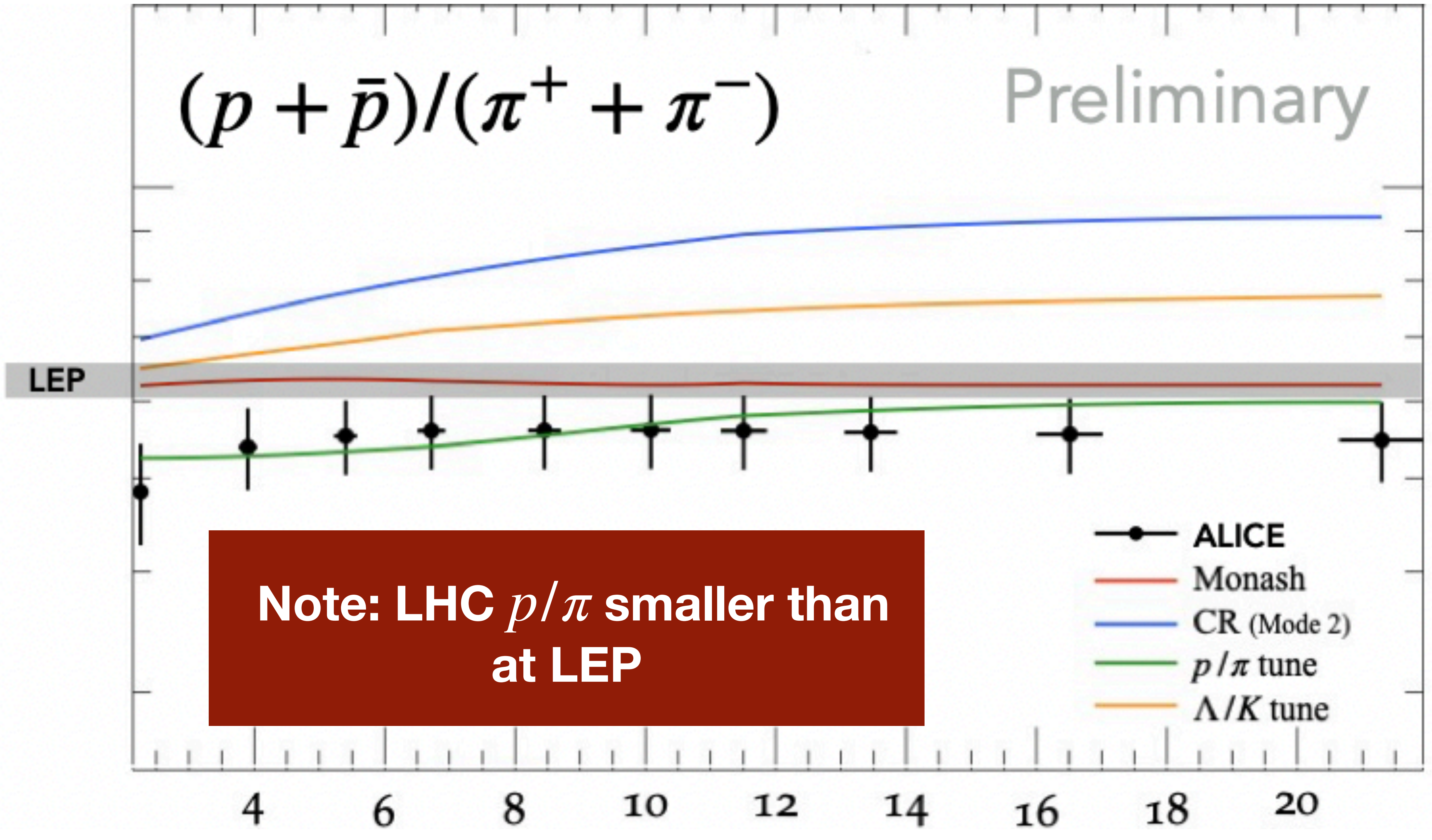


blue $q\bar{q}$ fluctuation on the string



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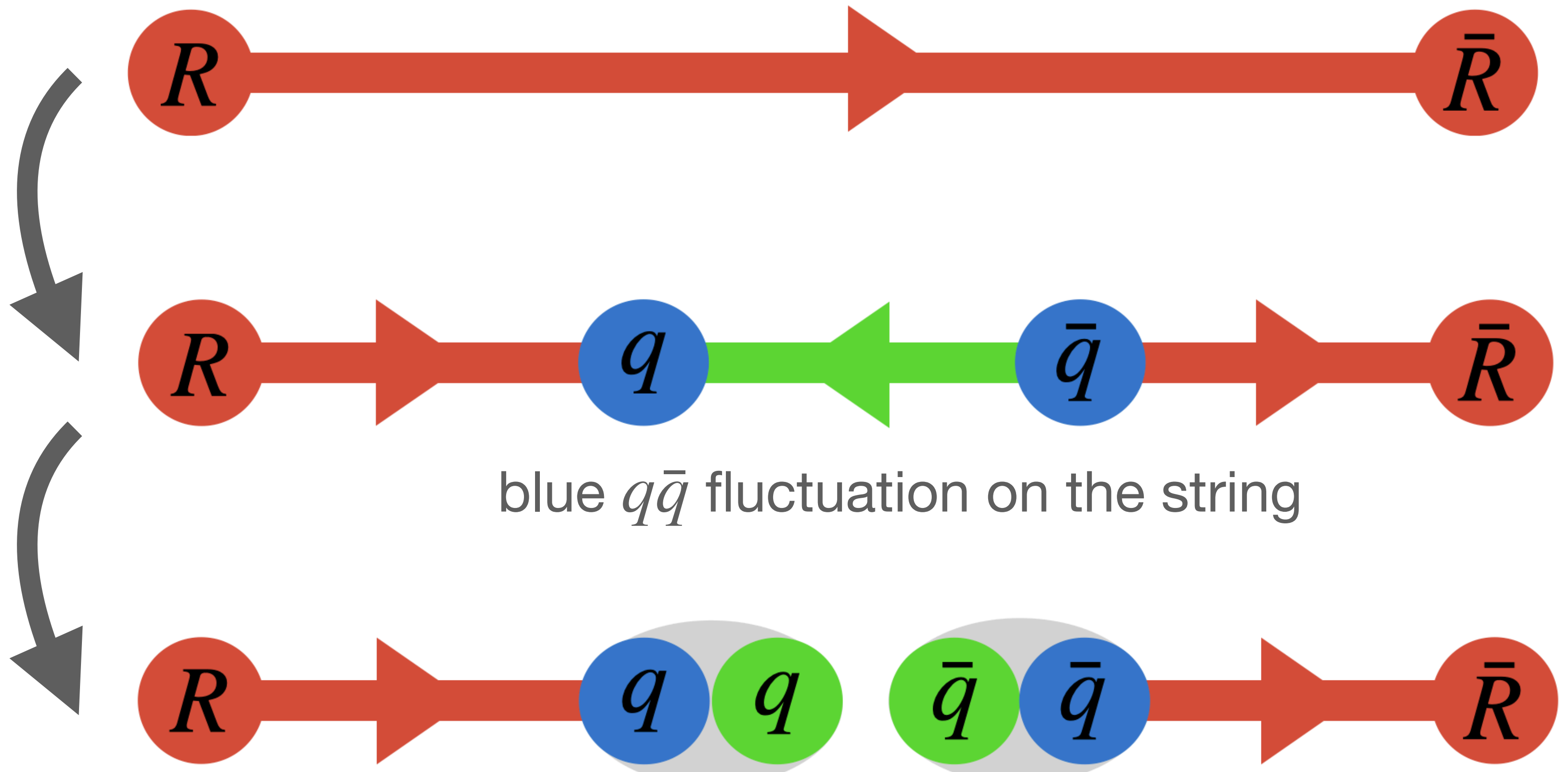
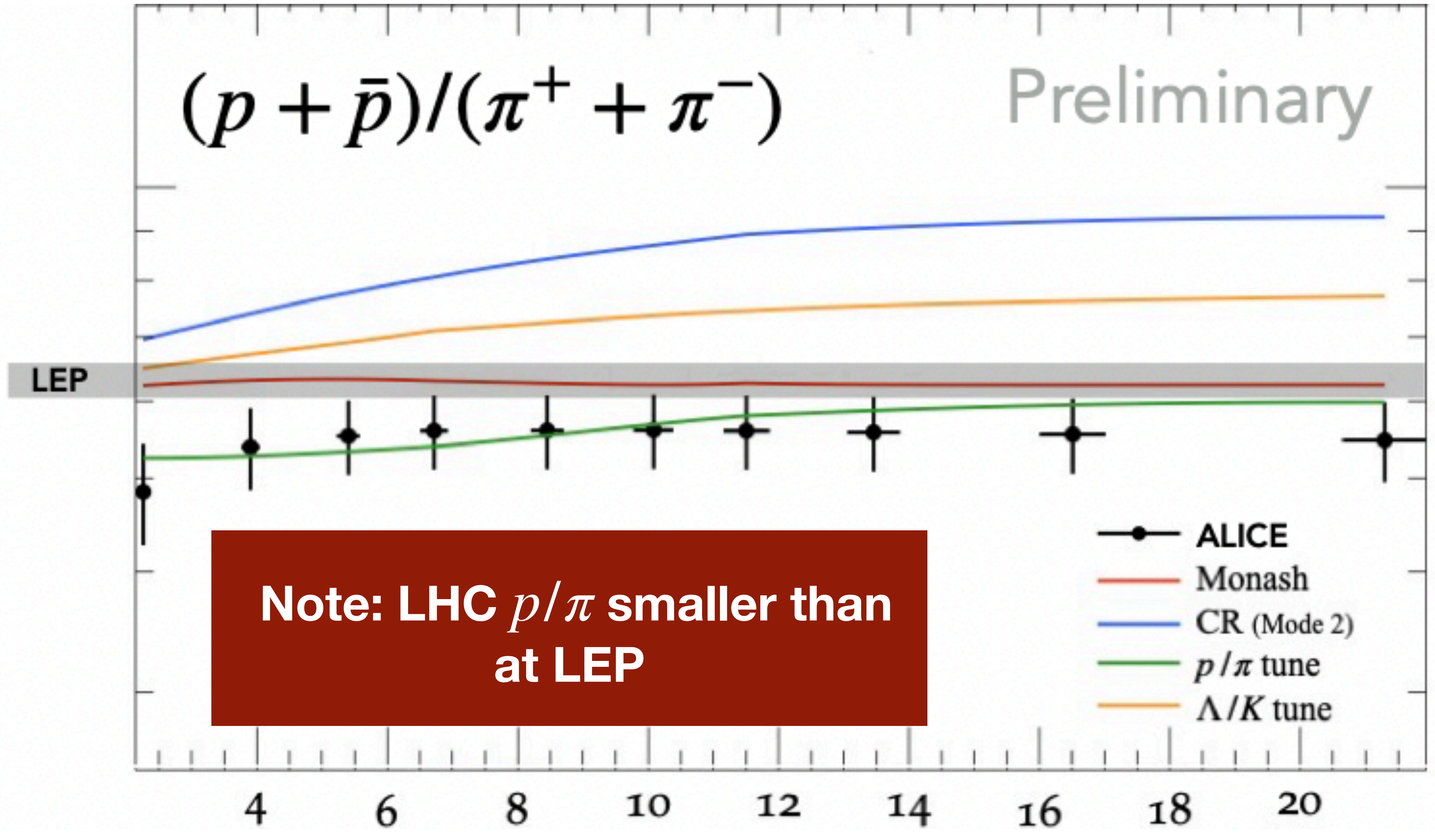


What would happen if we put this **red string** next to another string? e.g. a **blue string**



Note: LHC p/π smaller than at LEP

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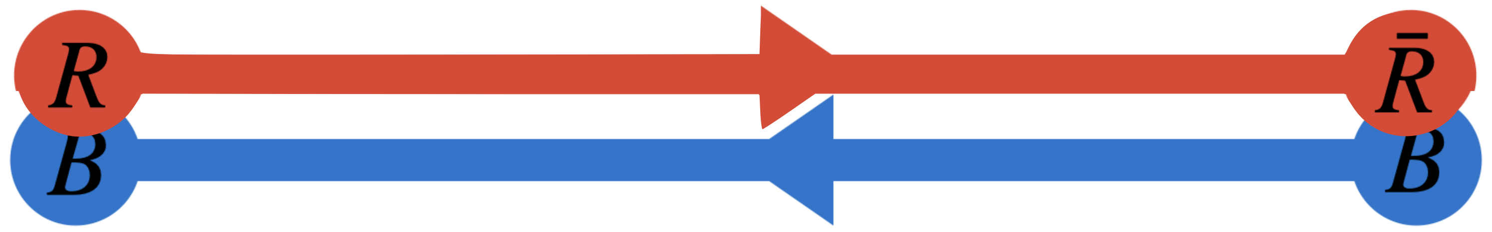

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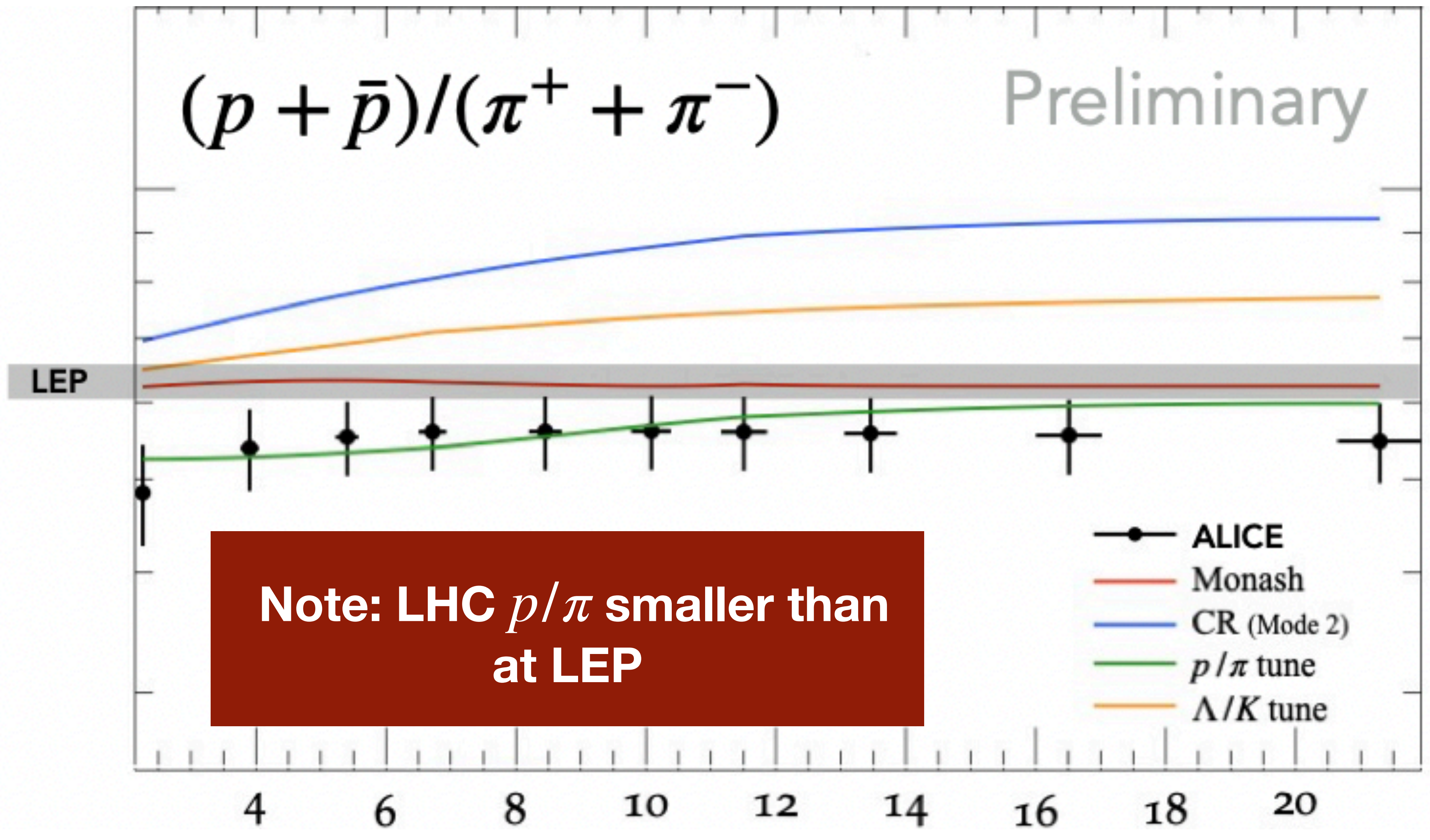

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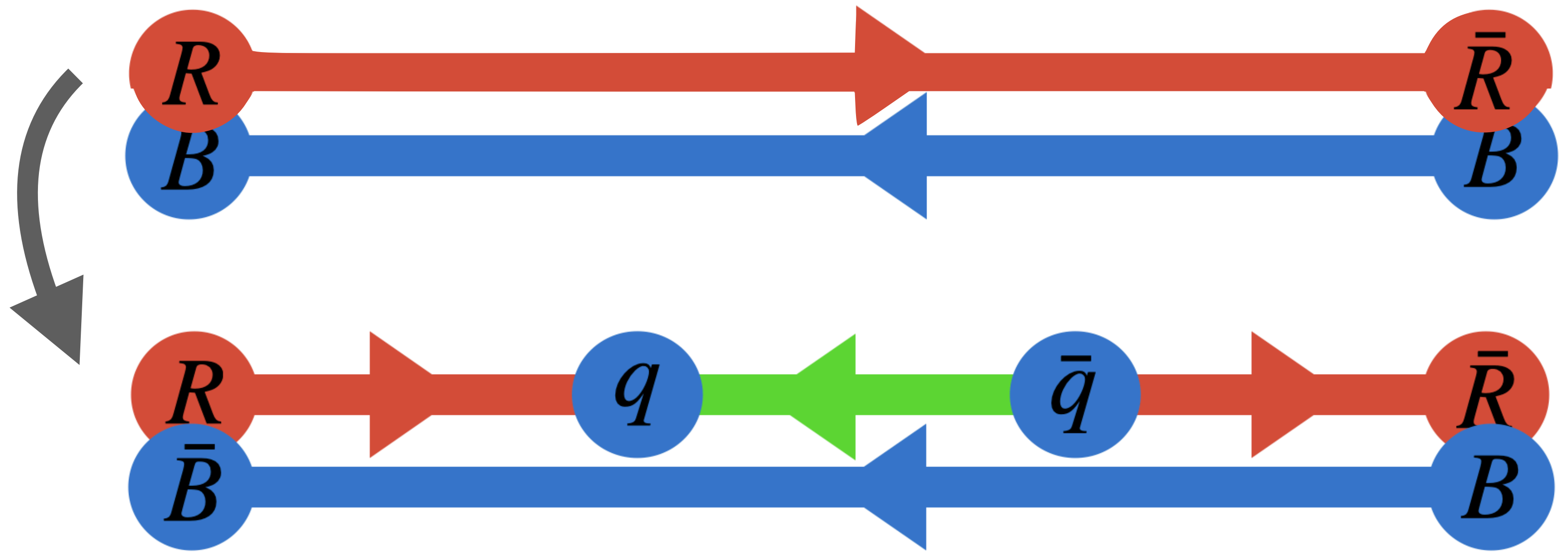

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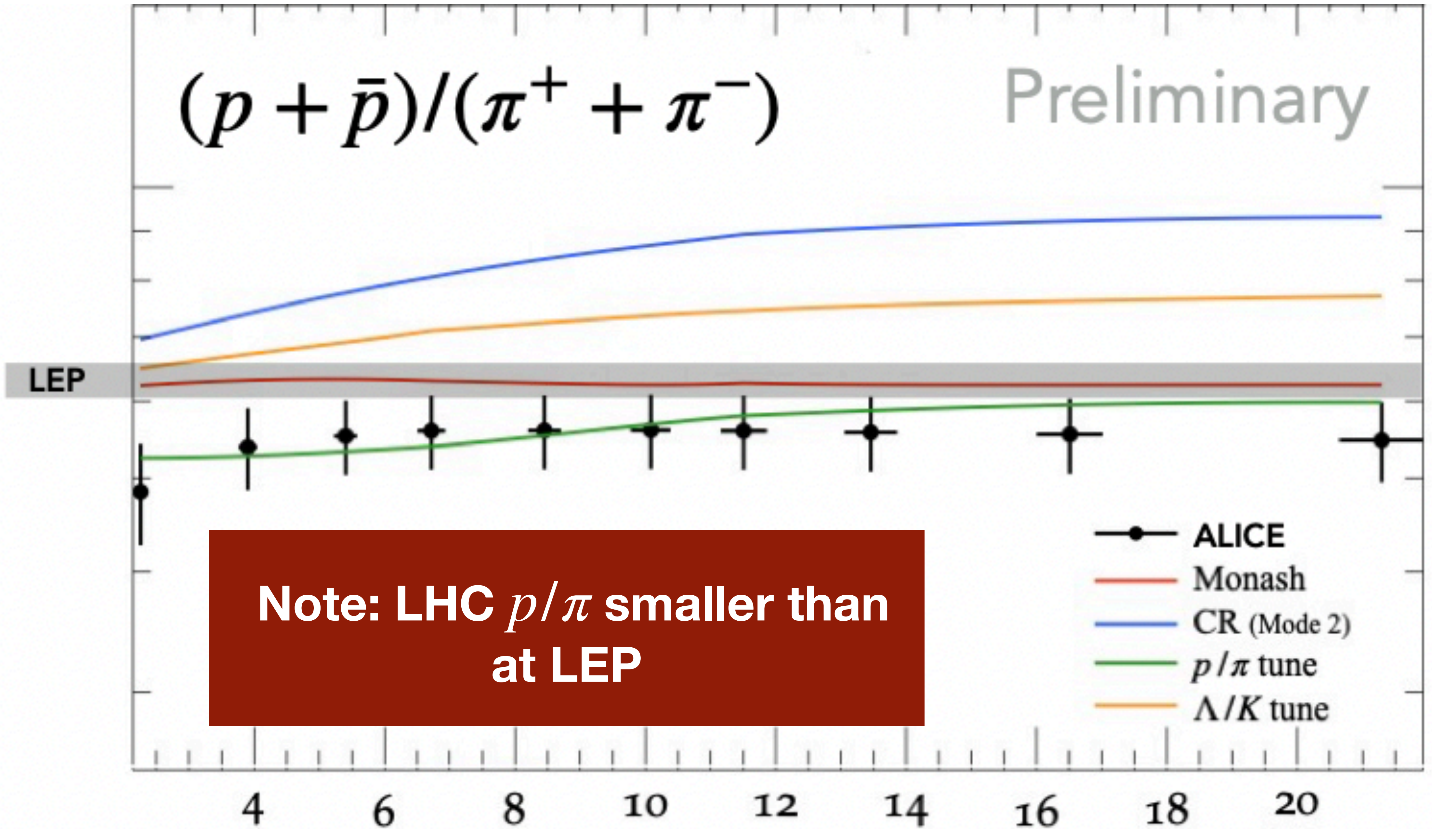

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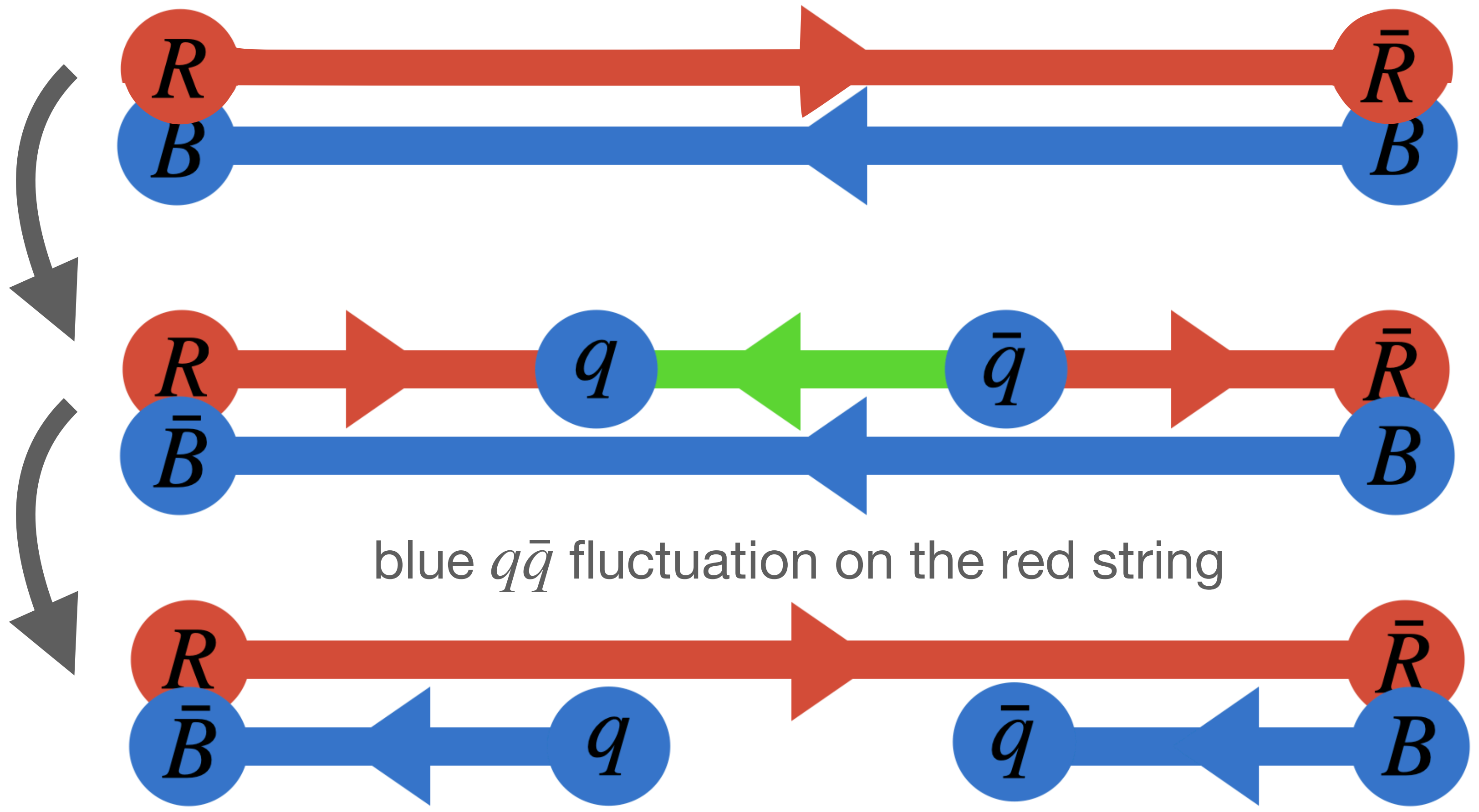
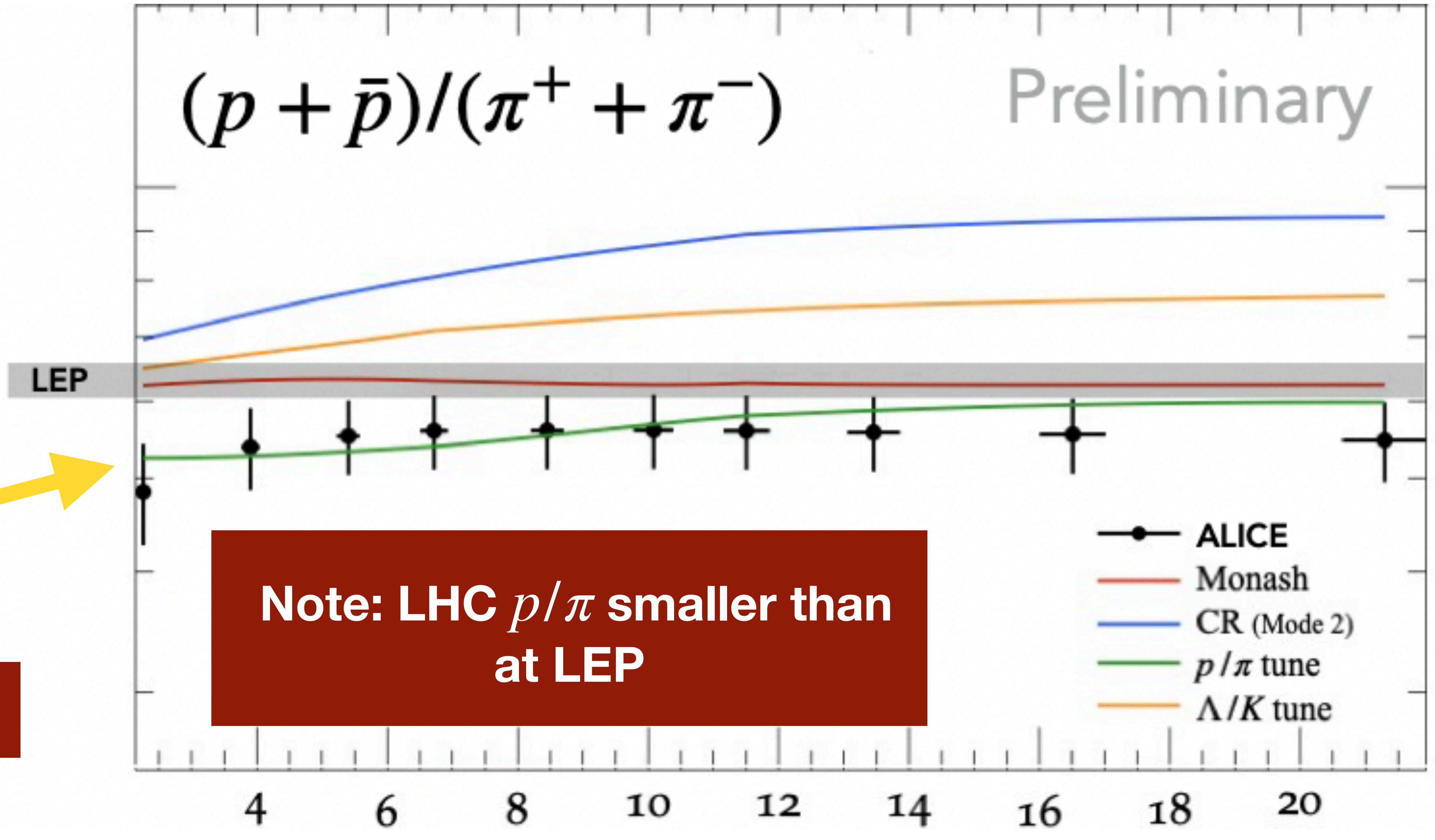


NEW

Popcorn destructive interference



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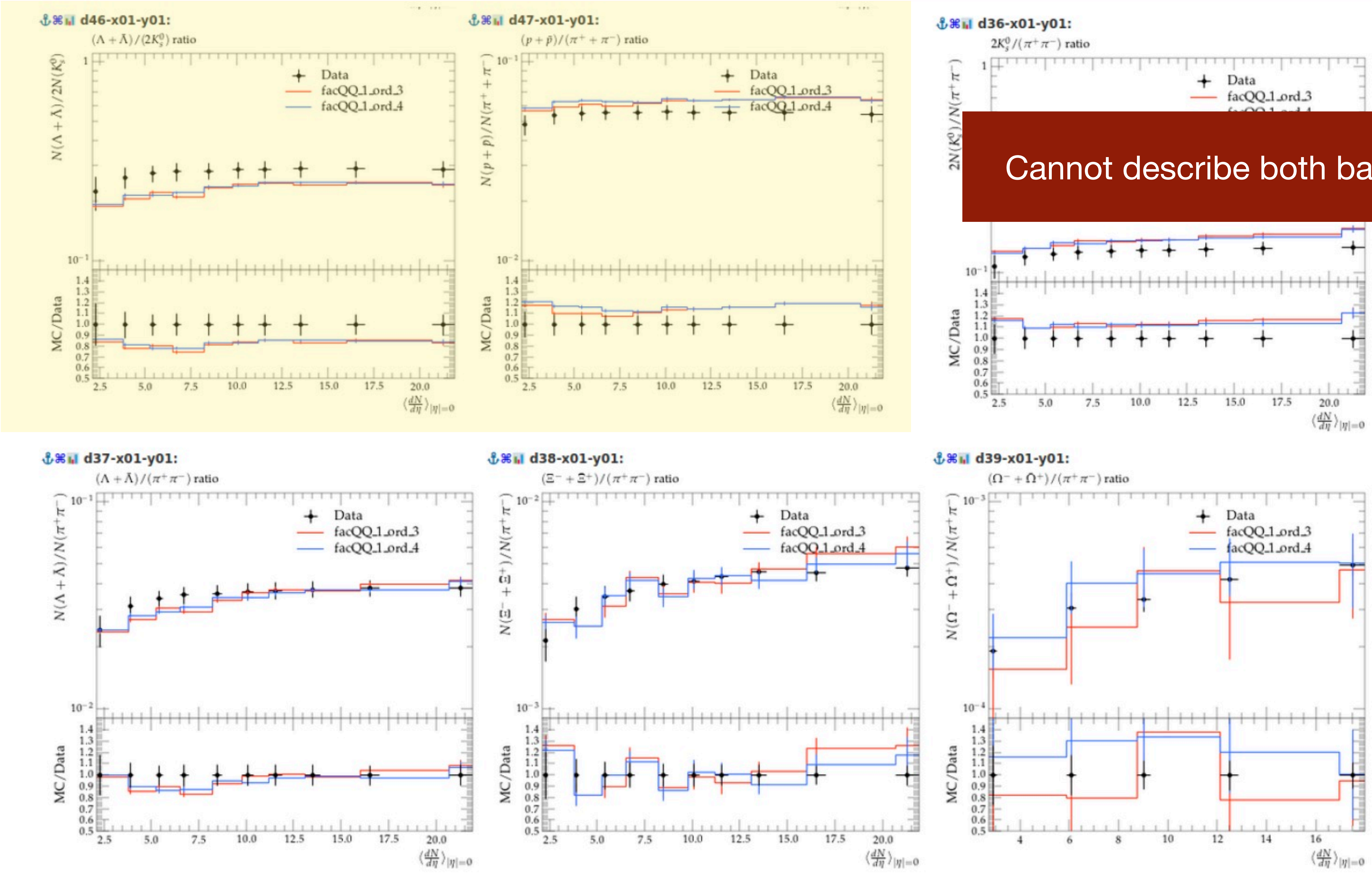
Results — ongoing



Cannot describe both baryon-to-meson ratios simultaneously

Taken from slide by Lorenzo Bernadinis: PhD student currently in Trieste undertaking tuning project with the model

Future prospects

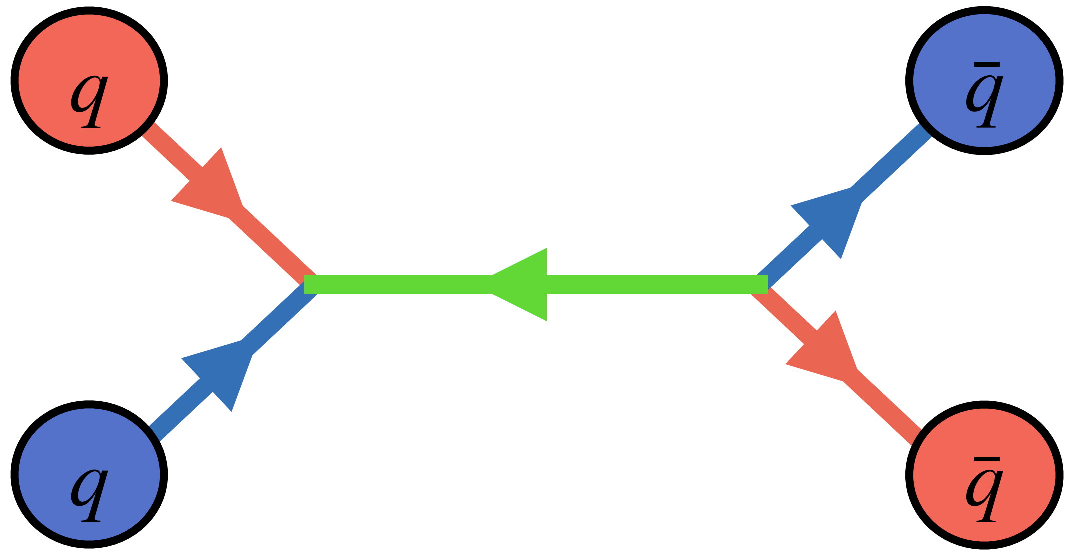
There of course remains a lot of remaining work and exciting future prospects for the string model, some of which are listed below

Beyond Lund strings

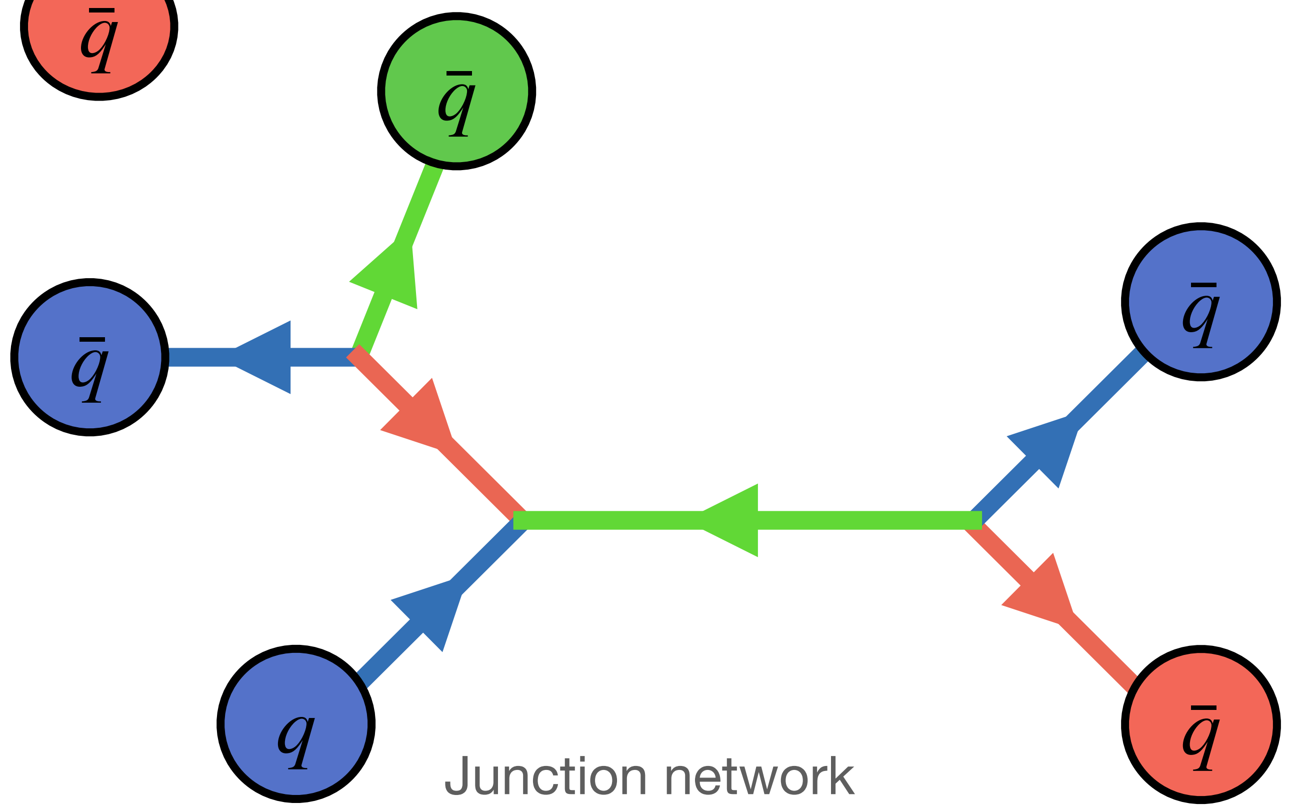
- ➢ Non-constant tensions e.g. time dependent string tensions, string excitations, and their effect on correlations

Baryon production

- ➢ Strange heavy baryon descriptions e.g. Ξ_c/Λ_c
- ➢ Λ_b/B^0 overprediction
- ➢ Λ/K simultaneously with p/π



Junction-antijunction system
Possible tetraquark?



Junction network
Possible pentaquark?

Extending strings to **heavy ion collisions**

Using **junction networks** to describe **exotica**

Return to examining e^+e^- **collision** data

- ➢ is there multiplicity dependence for strangeness?
- ➢ Useful for triplet vs octet string studies, a useful probe for rope hadronization/closepacking

Thank you for listening!