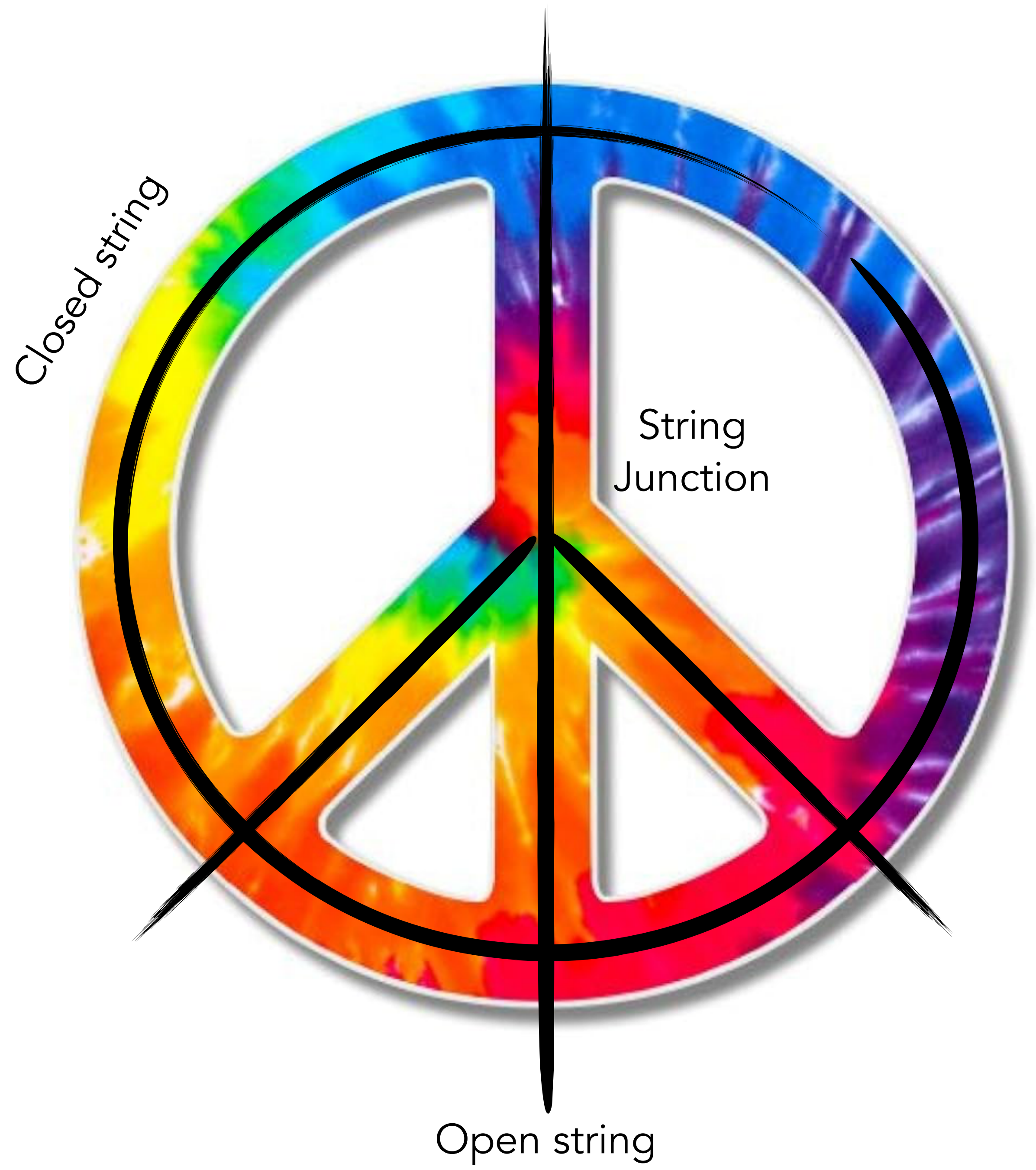
QCD strings, junctions, strangeness, and beyond

Peter Skands (Monash University)



1. **Confinement** in **High-Energy Collisions**
2. **Basics** of **String Hadronization**
3. **QCD Colour Reconnections**
4. **String Junctions**
5. **Dynamical Tension ➢ Strangeness Enhancement?**
6. **Octet Fields ➢ Diquark Suppression?**

The Problem of **Confinement** — in High-Energy Collisions

Consider a "hard" process

"Hard" = large momentum transfers

Example: $gg \to t\bar{t}$

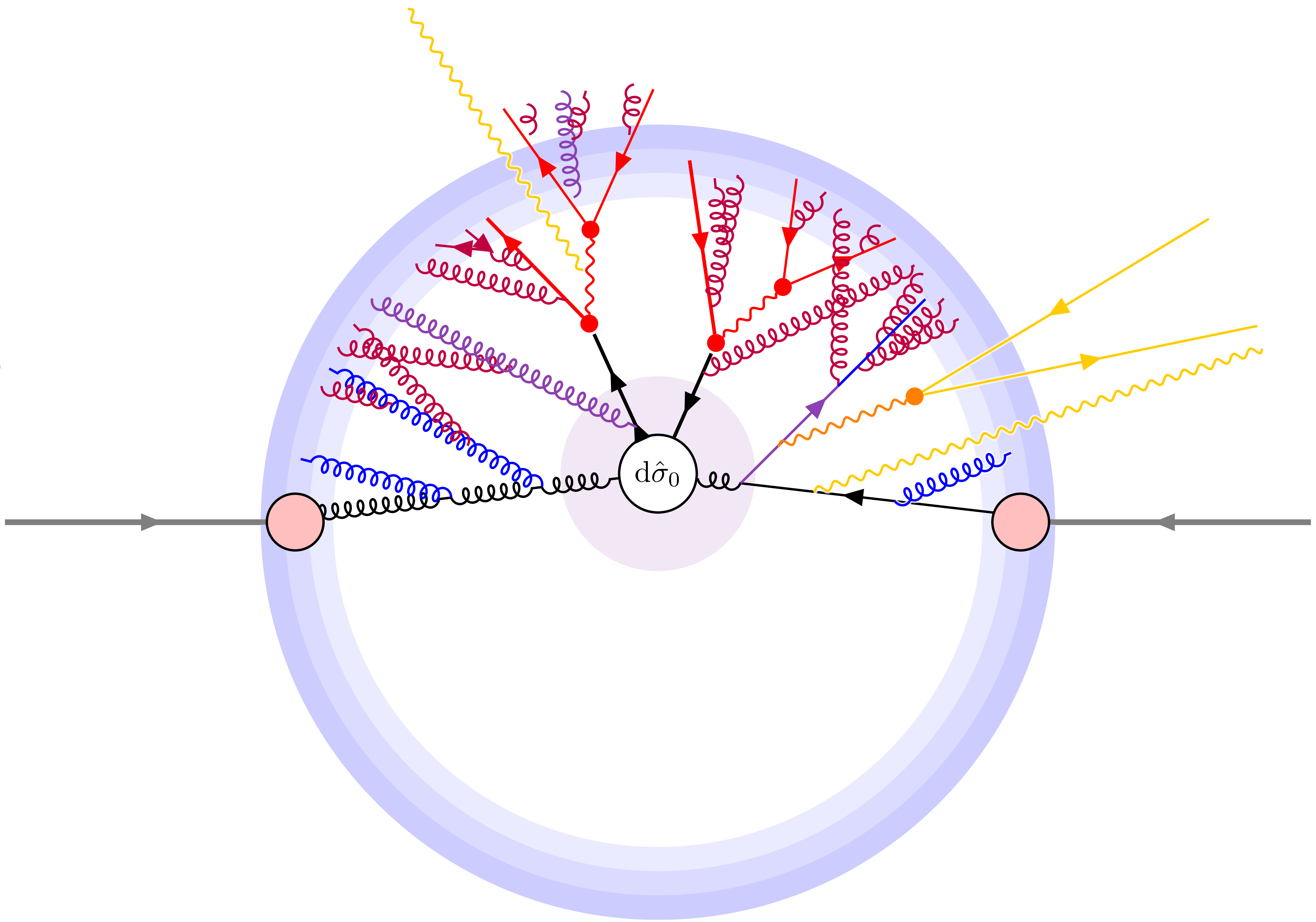
Here, $Q^2_{\mathrm{hard}} \sim m^2_{\mathrm{top}} \gg \Lambda^2_{\mathrm{QCD}}$

Accelerated charges

➜ Bremsstrahlung ➜ Parton Showers

Perturbative QCD (& QED/EW)

+ Resonance decays with $\Gamma > \Lambda_{\mathrm{QCD}}$



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Accelerated charges

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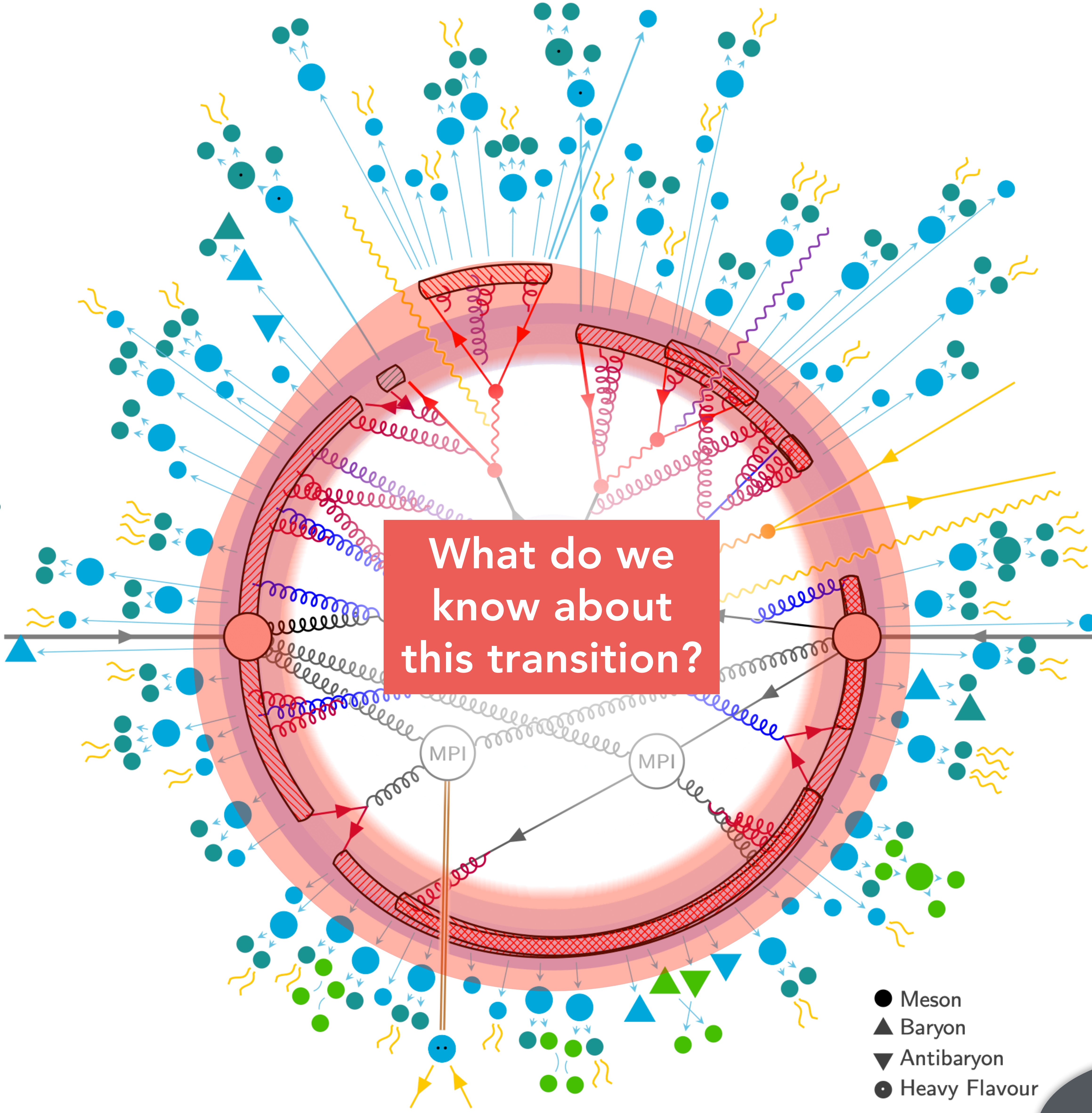
Perturbative QCD (& QED/EW)

+ Resonance decays with $\Gamma > \Lambda_{\mathrm{QCD}}$

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

Some dynamical process must force quarks and gluons to be confined inside hadrons: ***Hadronisation***



Requirement #1: Colour Neutralisation

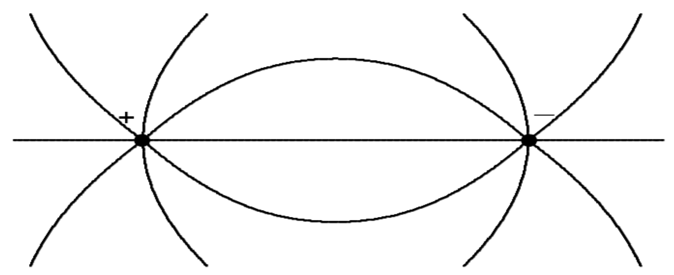
The point of confinement is that partons are coloured

A **physical** model needs two or more partons to create **colour-neutral** objects

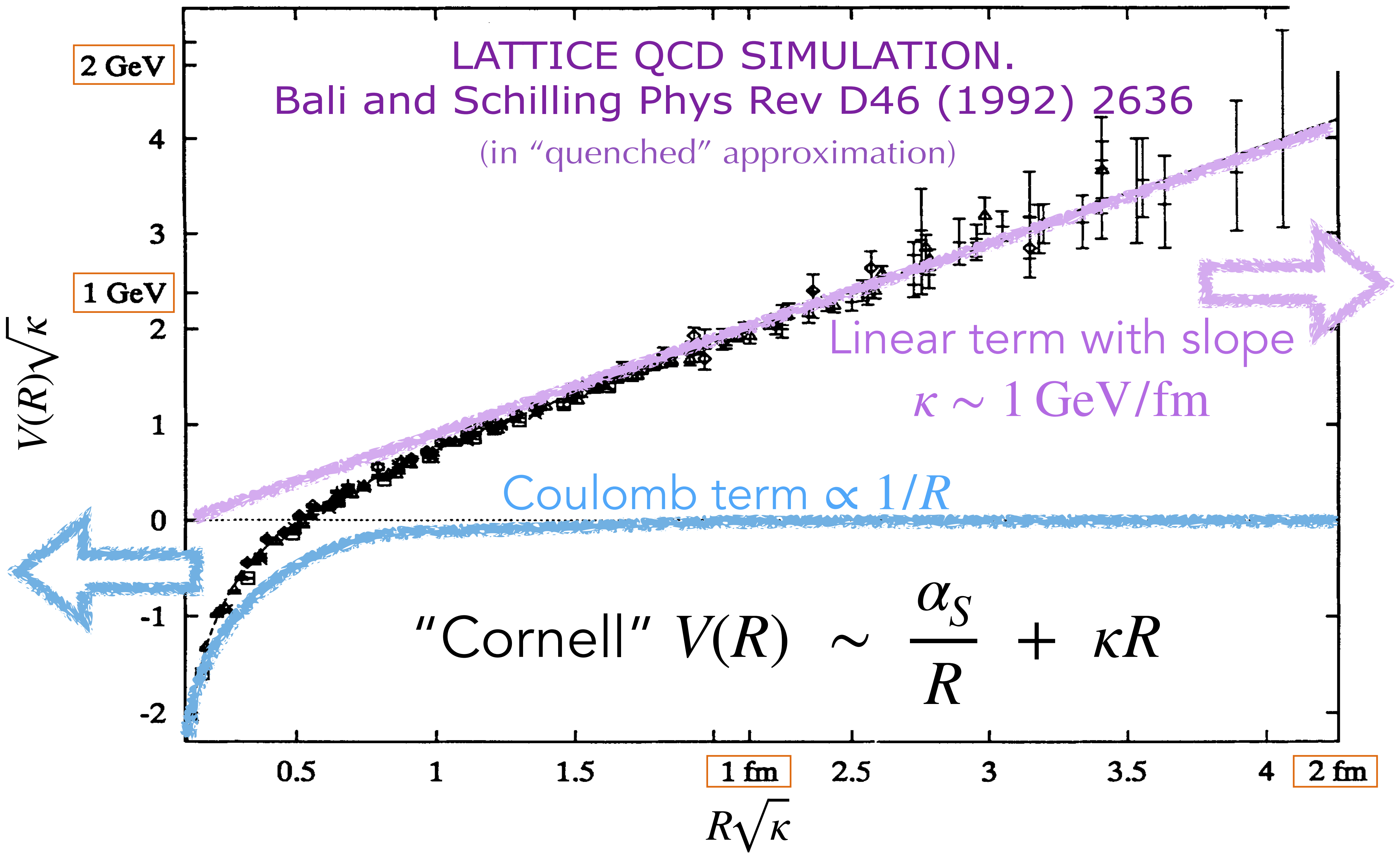
On lattice, compute potential energy $V(R)$ of a colour-singlet $q\bar{q}$ state

as function of the distance, R, between the q and $\bar{q}$:

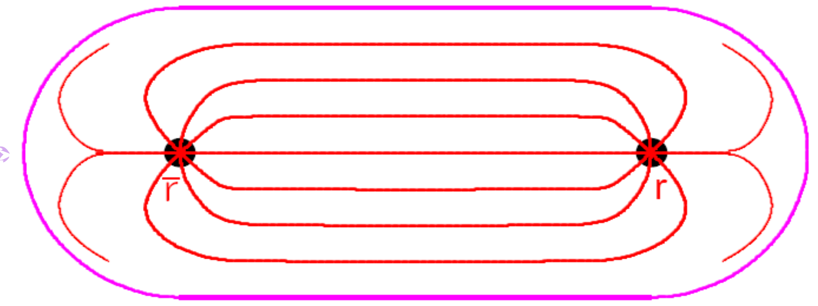
Short Distances ~ "Coulomb"



"Free" Partons

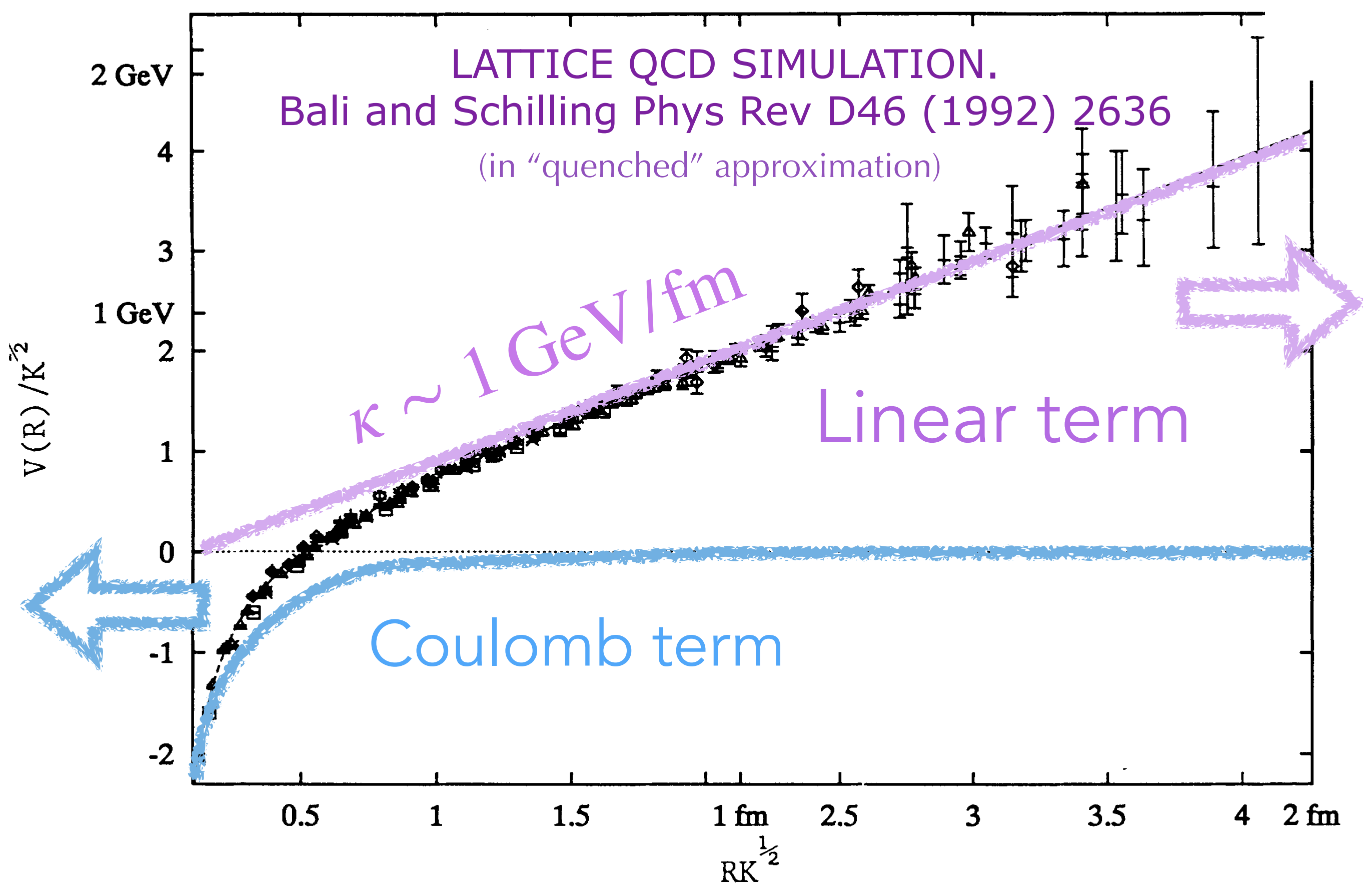


Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

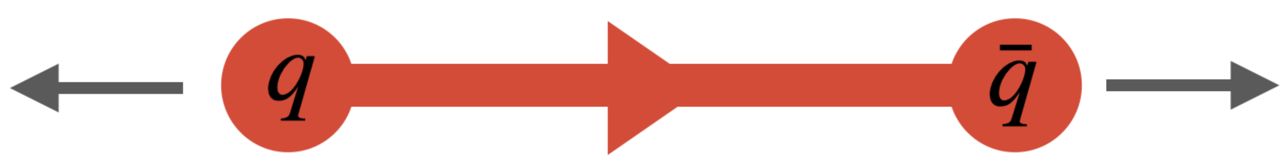
➜ Strings!!



Lund string model

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

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

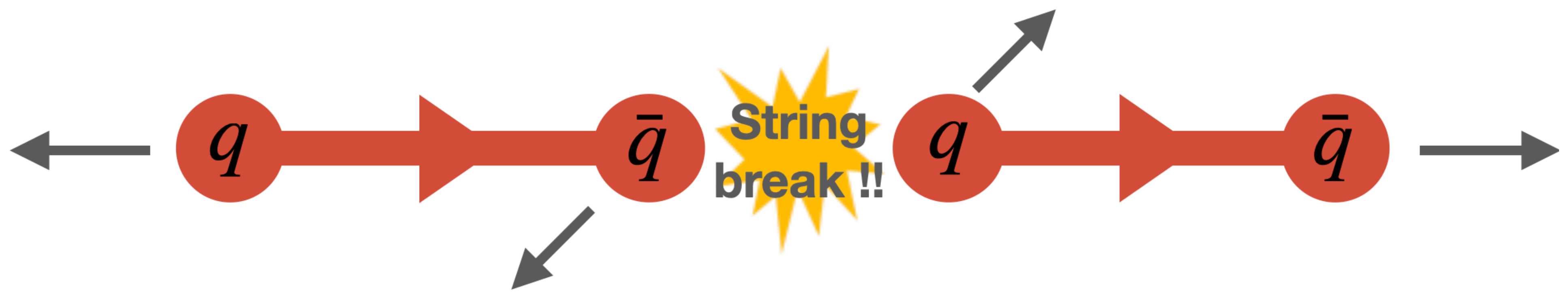


next slides

(+ Characteristic Feature of Lund Model: gluons are mapped to transverse kinks)

High separation energies $\gtrsim$ 1 GeV

$\Longrightarrow$ String Breaks (by pair creation):



Modelled by analogy with “Schwinger Mechanism” in QED

$\Longrightarrow$ **Gaussian suppression with “transverse mass”:** $\exp\left(\frac{-m_q^2 - p_{\perp q}^2}{\kappa/\pi}\right)$

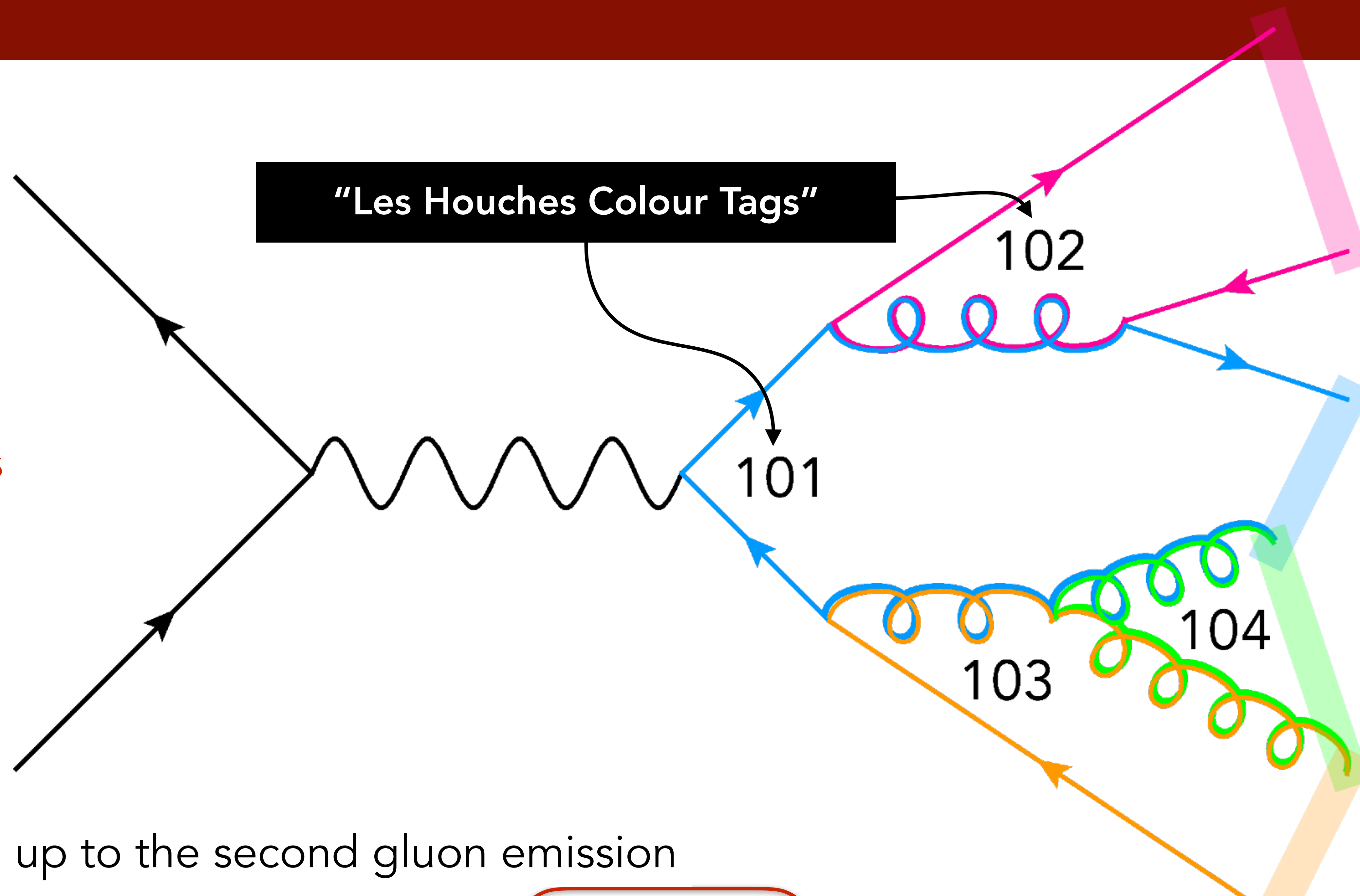
No b or c; Suppression of strange

Who gets confined with whom?

"Leading Colour"

MCs: $N_C \to \infty$ limit formalised by letting **each "colour line"** be represented by a **unique Les Houches colour tag**† (no interference between different colour lines in this limit)

†: hep-ph/0109068; hep-ph/0609017



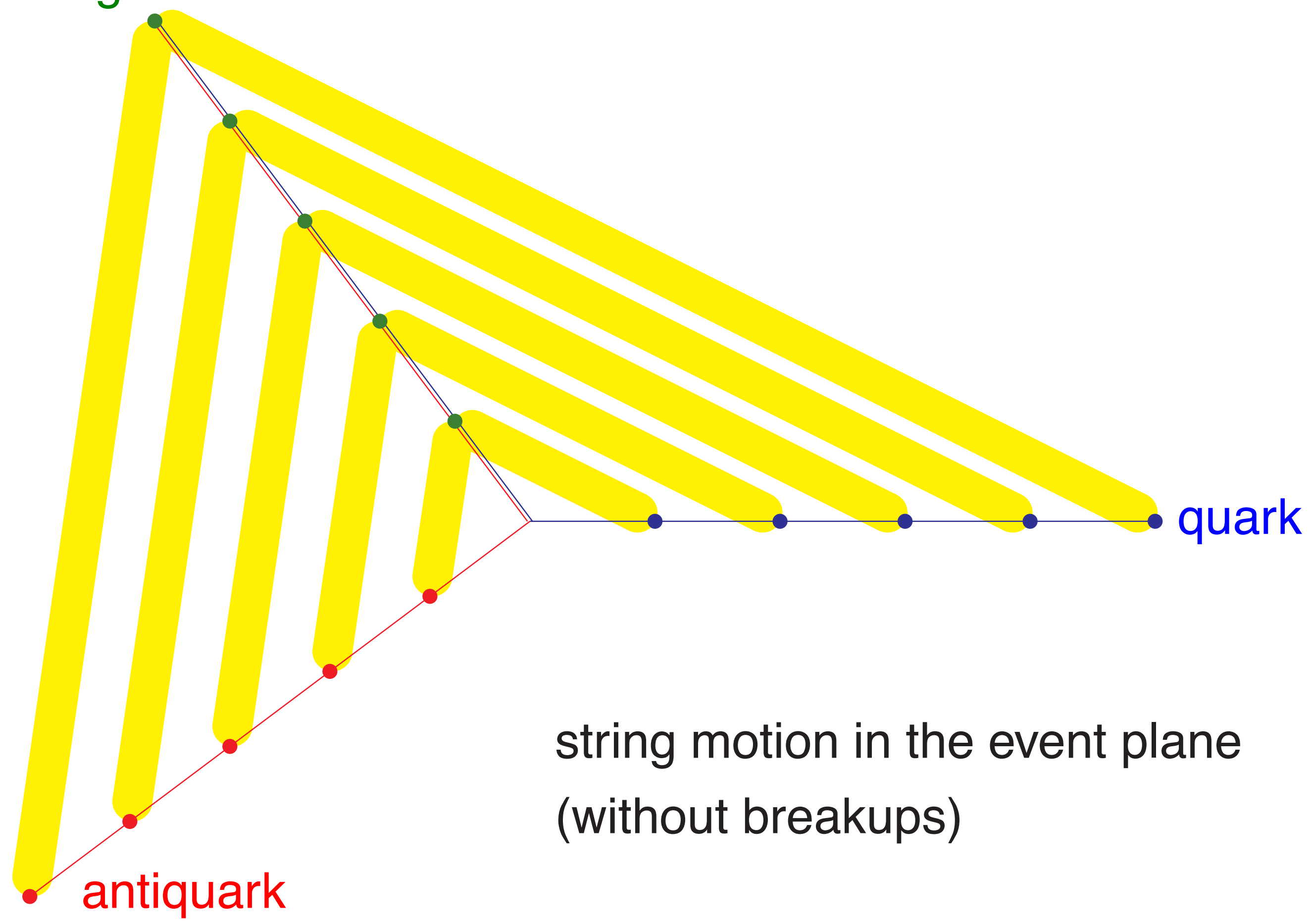
Expect accurate to $\sim 1/N_C^2 \sim 10\%$

A corresponding event record from PYTHIA, up to the second gluon emission

#	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
5	23	(Z0)	-22	3	4	6	7			0.000	0.000	0.000	91.188	91.188
6	3	(s)	-23	5	0	10	0	101	0	-12.368	16.523	40.655	45.594	0.000
7	-3	(sbar)	-23	5	0	8	9	0	101	12.368	-16.523	-40.655	45.594	0.000
8	21	(g)	-51	7	0	13	0	103	101	9.243	-9.146	-29.531	32.267	0.000
9	-3	sbar	51	7	0			0	103	3.084	-7.261	-10.973	13.514	0.000
10	3	(s)	-52	6	0	11	12	101	0	-12.327	16.406	40.505	45.406	0.000
11	21	g	-51	10	0			101	102	-2.834	-2.408	1.078	3.872	0.000
12	3	s	51	10	0			102	0	-10.246	17.034	38.106	42.979	0.000
13	21	g	52	8	0			103	101	9.996	-7.366	-28.211	30.823	0.000

Gluon Kinks: The Signature Feature of the Lund Model

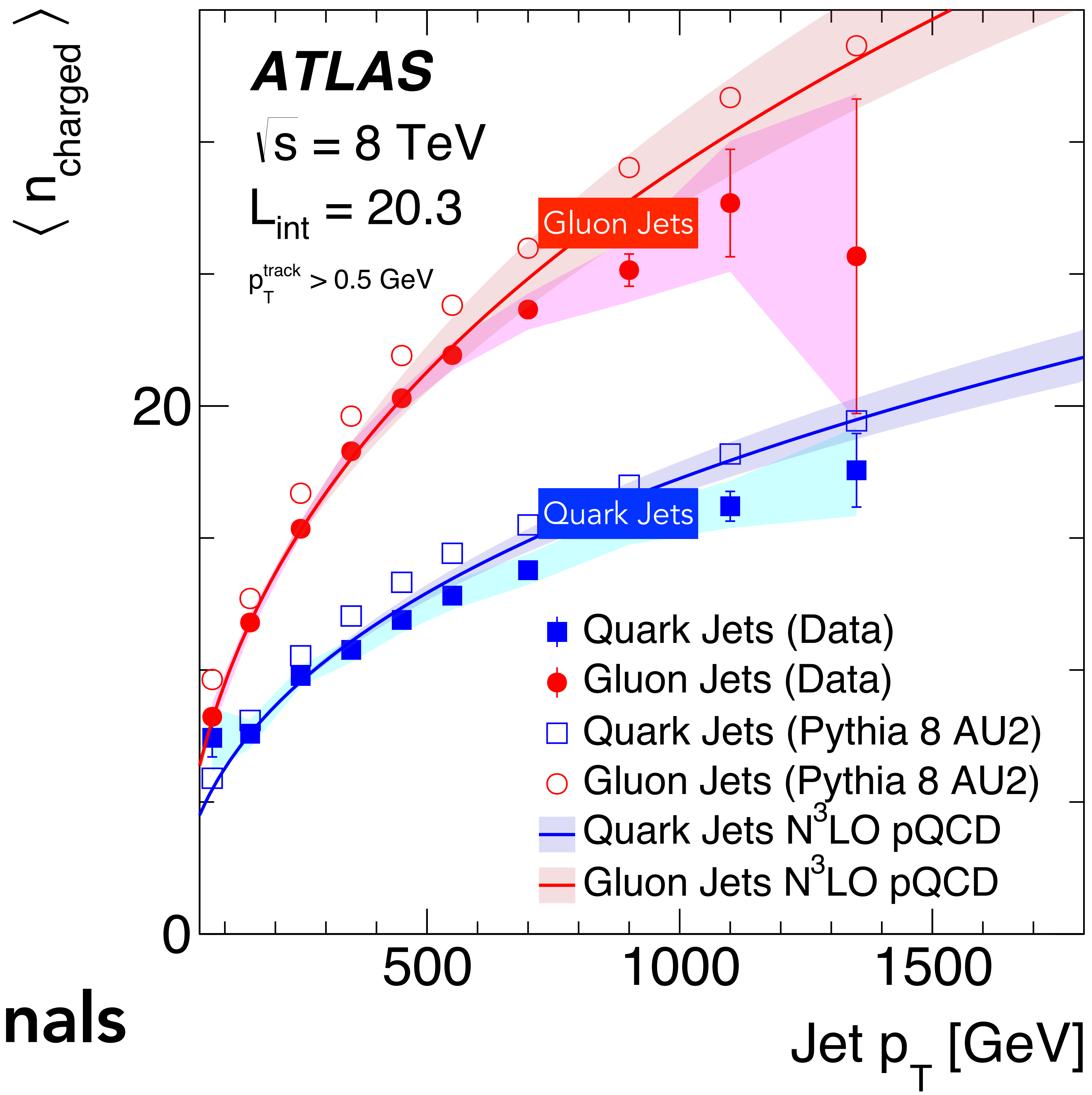
Gluons are connected to two string pieces



Each quark connected to **one** string piece

$\Longrightarrow$ Factor $C_A/C_F \sim 2$ **more particles in gluon jets**

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



Important for discriminating new-physics signals

BSM decays to **quarks** vs to **gluons**,

vs composition of **background** and **bremsstrahlung** combinatorics

Confinement in *pp* Collisions

MPI (or cut pomerons) ⇒ lots of coloured partons scattered into final state

Who gets confined with whom?

Each has a colour ambiguity $\sim 1/N_C^2 \sim 10\,\%$

E.g.: **random triplet** charge has 1/9 chance to be in **singlet** state with **random antitriplet**:

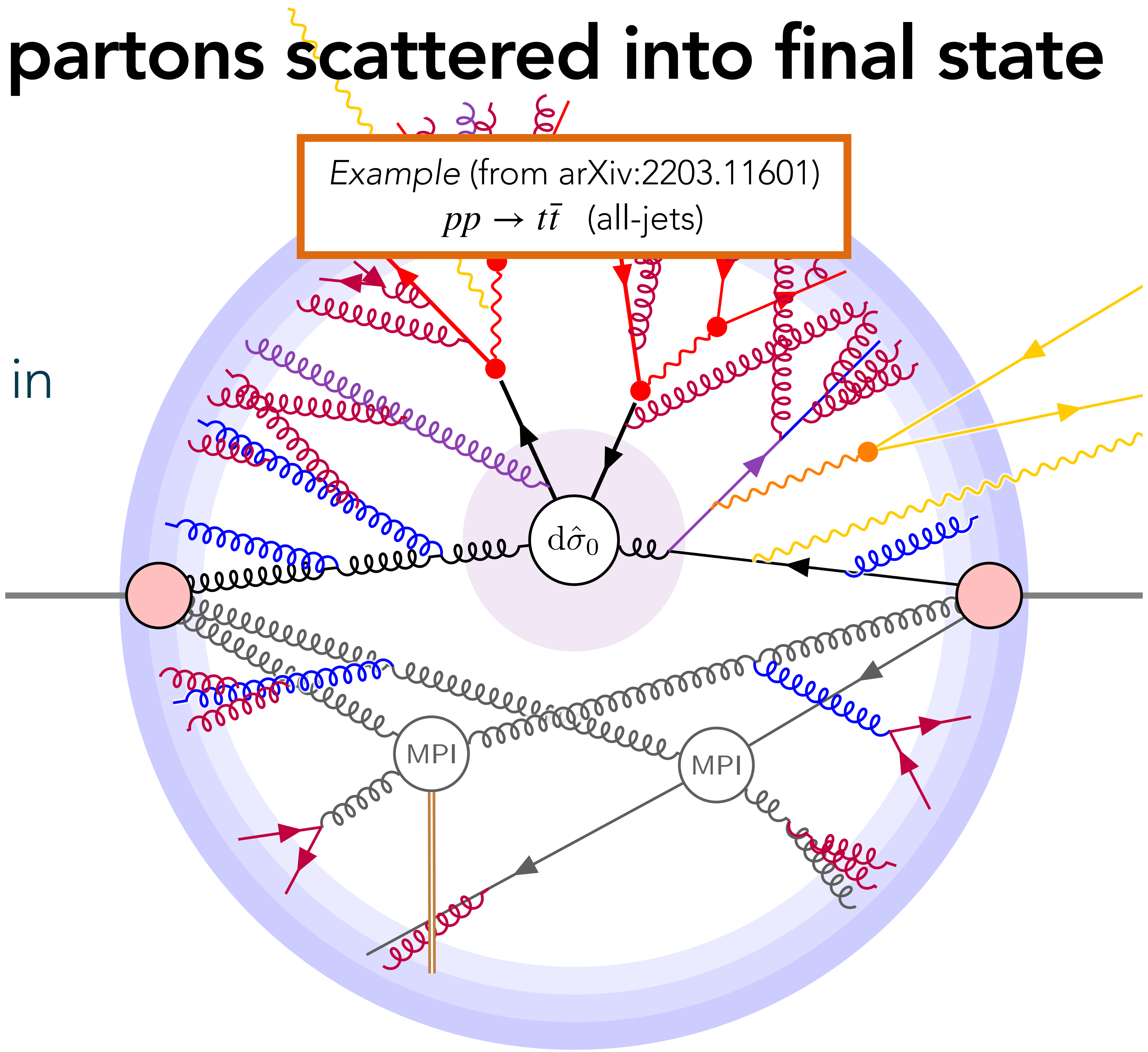
$$3 \otimes \bar{3} = 8 \oplus 1,$$

$$3 \otimes 8 = 15 + 6 + 3, \text{ etc.}$$

Many charges ➜ Colour Reconnections* (CR) more likely than not

$$\text{Expect Prob(no CR)} \propto \left(1 - \frac{1}{N_C^2}\right)^{n_{\mathrm{MPI}}}$$

(And do other things happen? Emergent dynamics?)

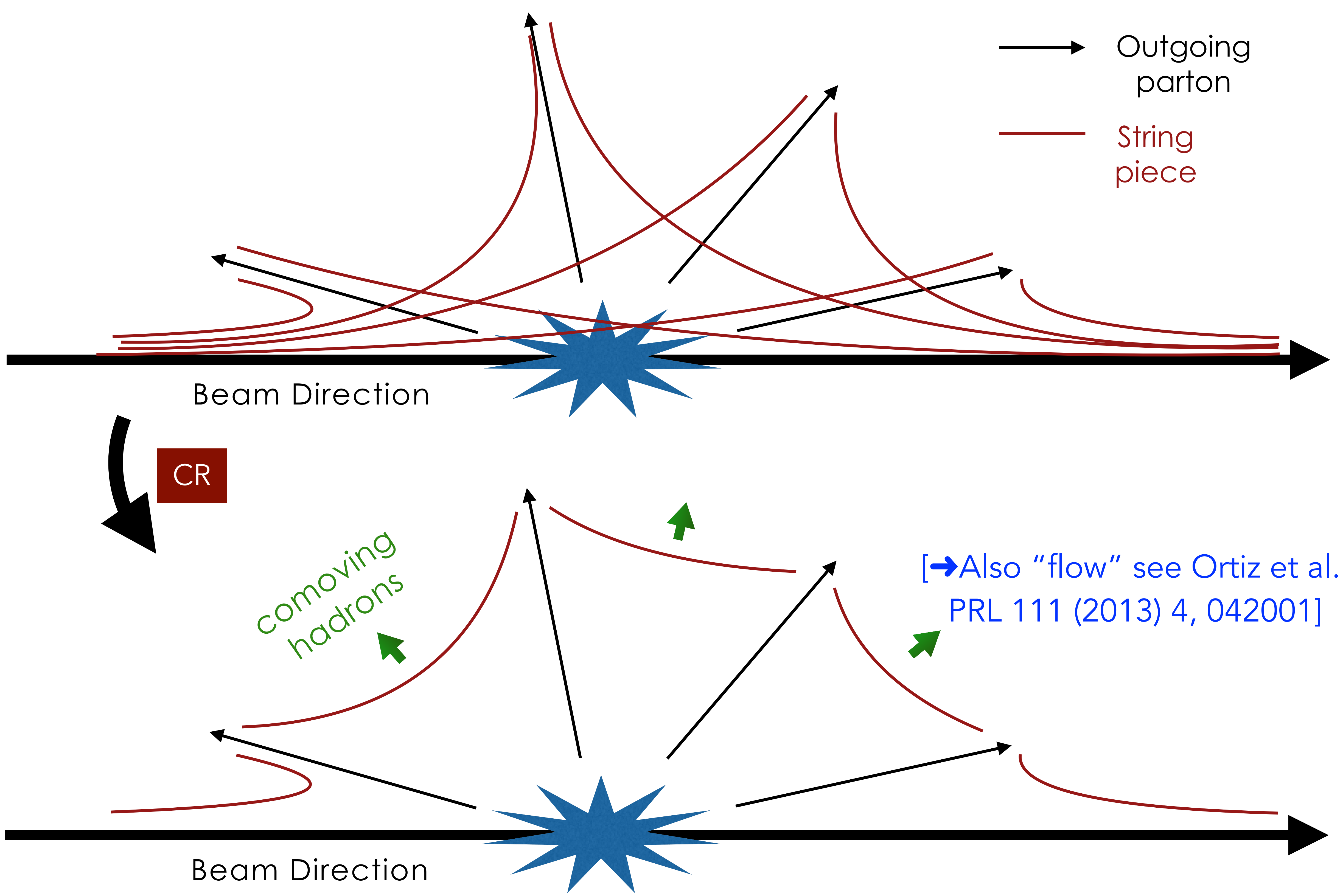


"Parton Level"
(Event structure before confinement)

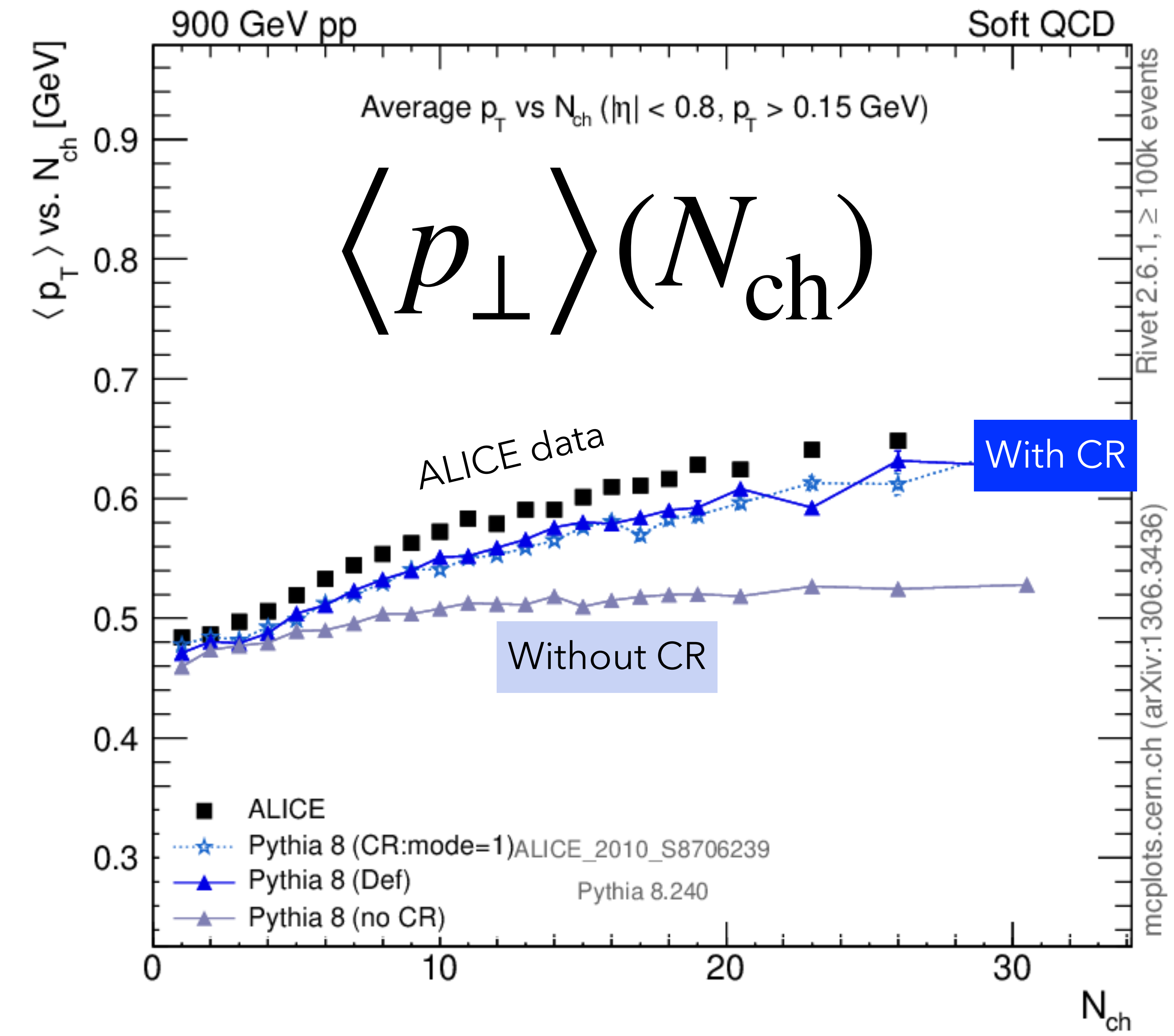
*): *in this context, QCD CR simply refers to an ambiguity beyond Leading N_C, known to exist. The term "CR" can also be used more broadly.*

String-length minimisation and <pT>(Nch)

When many string configurations are possible, assume nature picks the one with smallest potential energy ~ "string length"



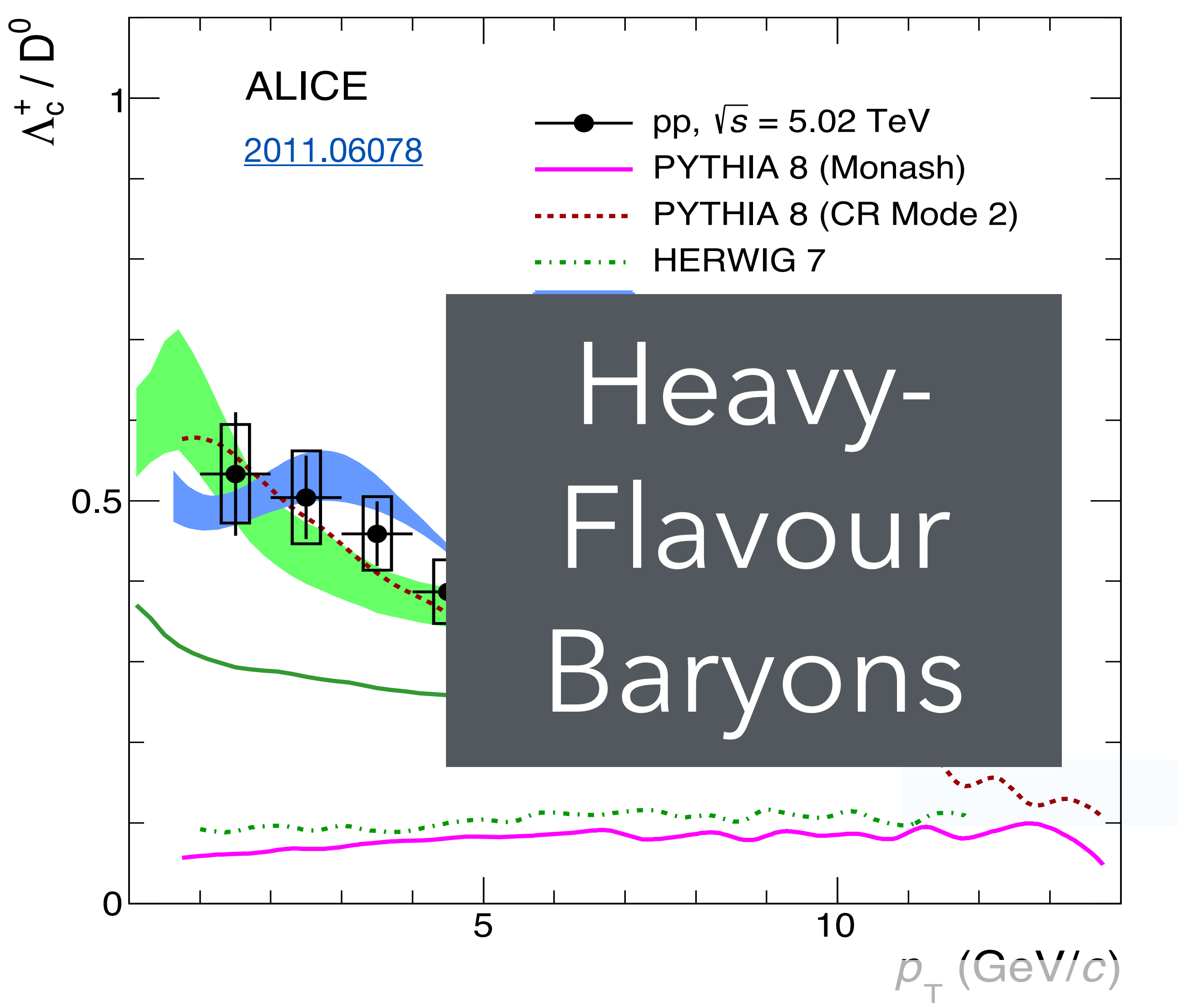
[➔Also "flow" see Ortiz et al., PRL 111 (2013) 4, 042001]

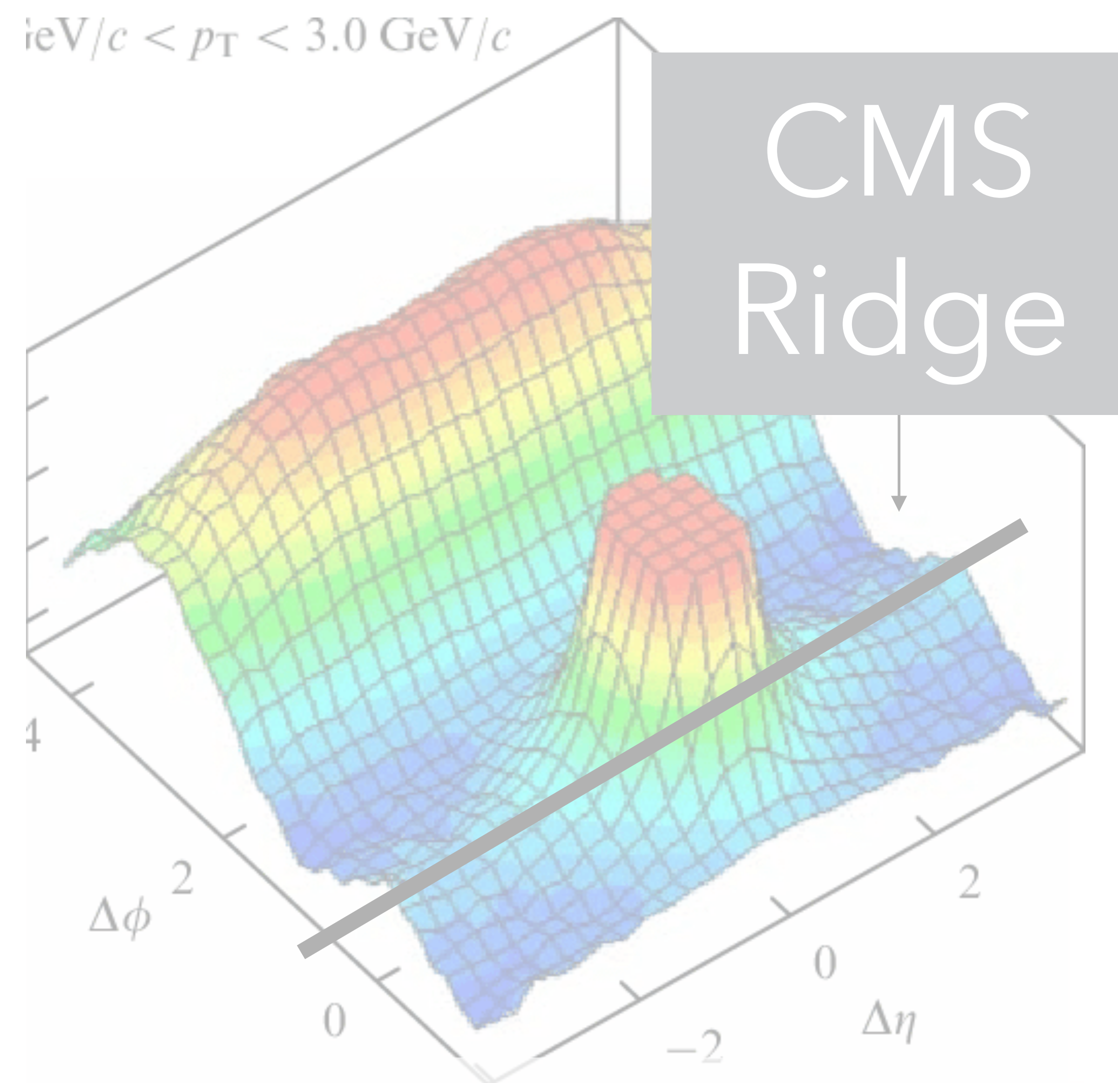


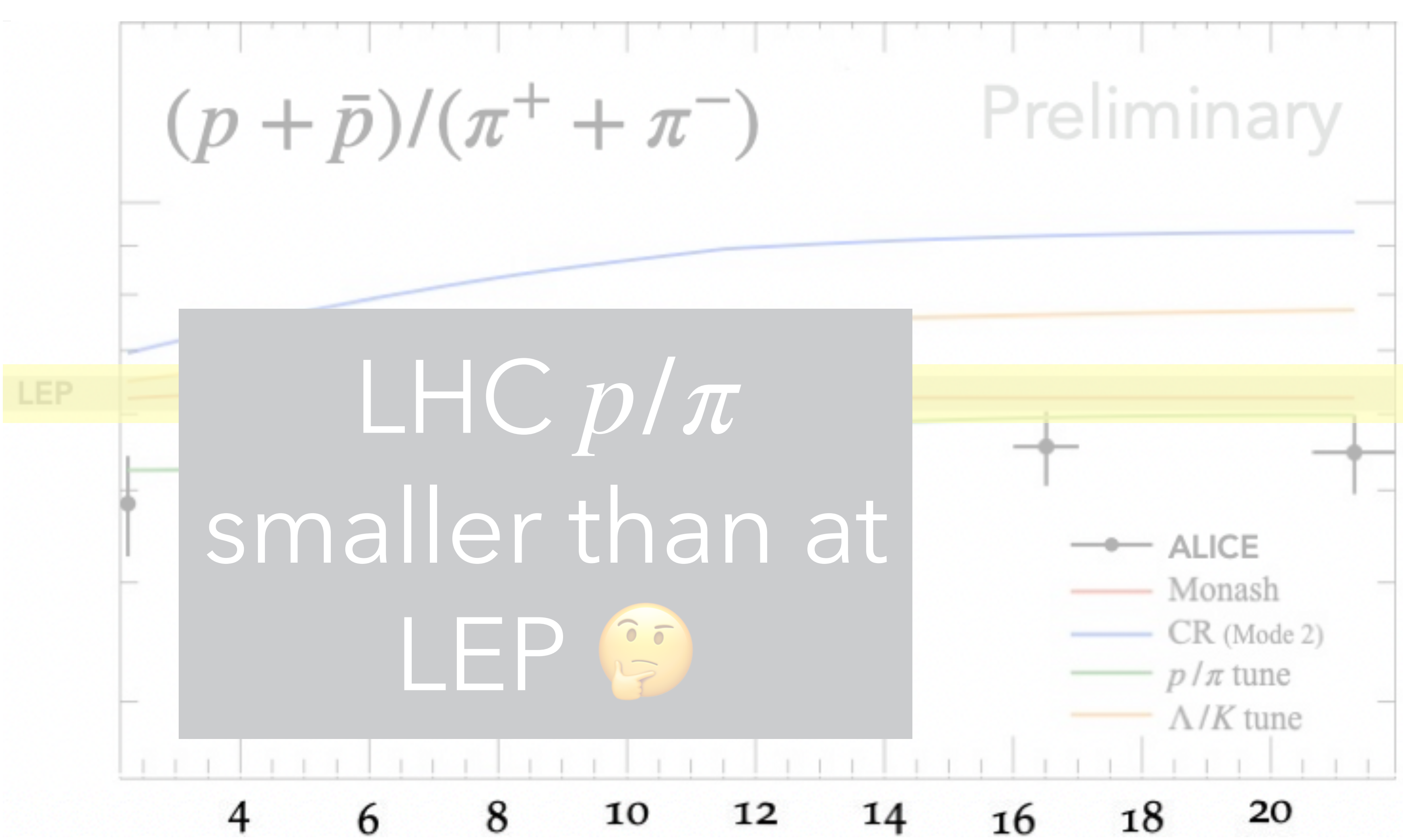
Note: <pT>(N_{ch}) already highlighted as a sensitive observable in Sjöstrand & v. Zijl, 1987

~ Status of CR pre-LHC

QCD @ LHC ➢ Lots of New Discoveries!







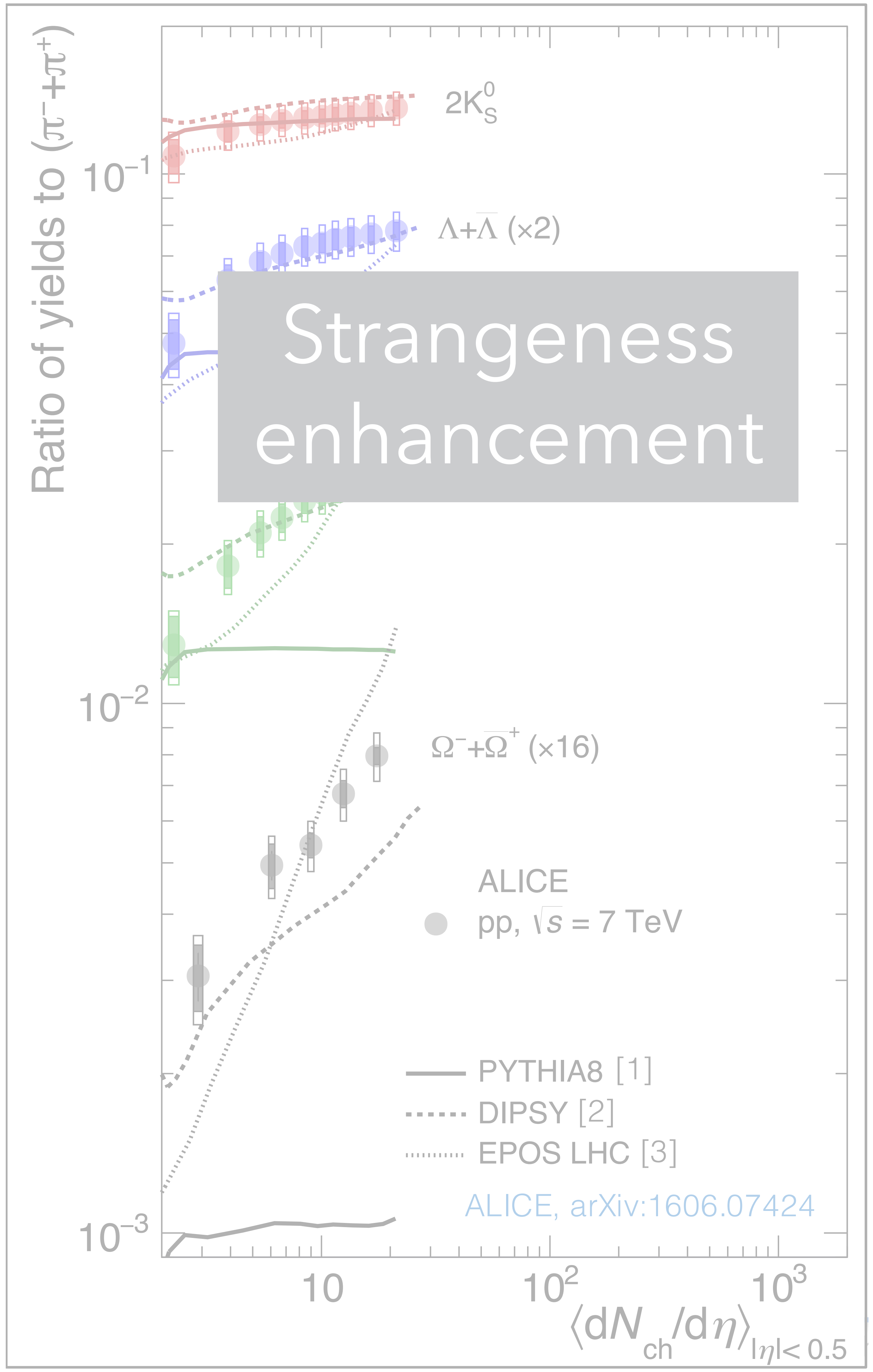
+ Many more ...

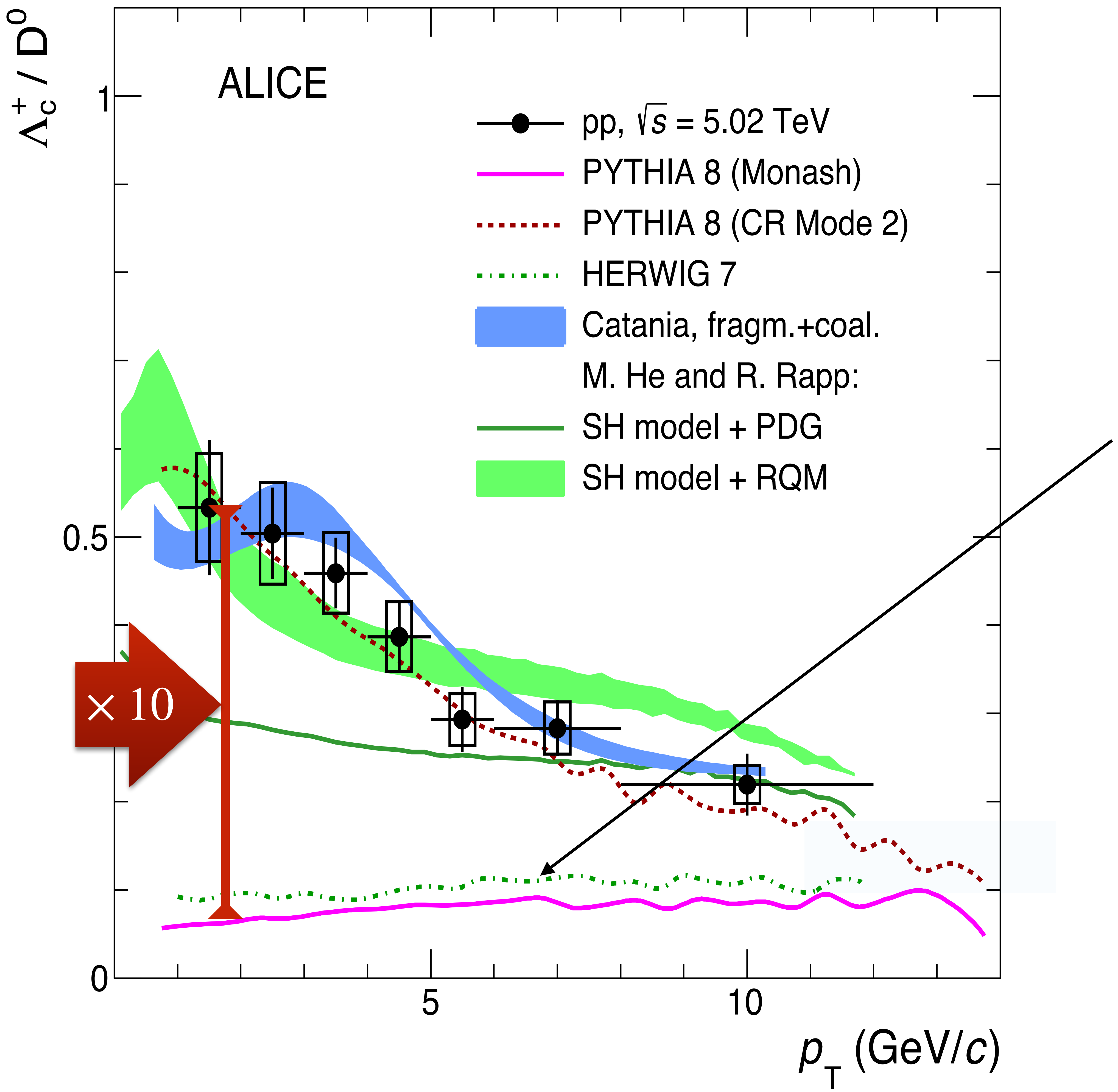
Baryon correlations

D_s asymmetries

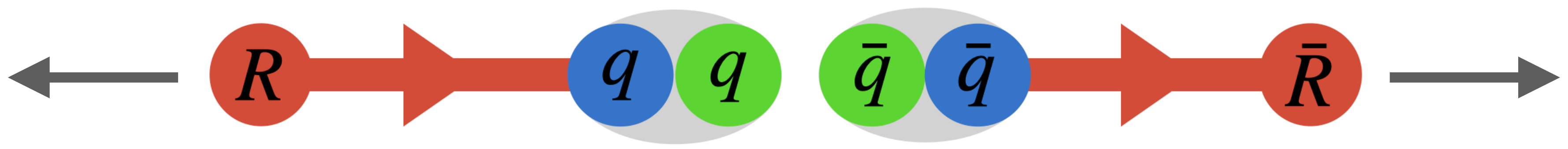
Exotica

...





Conventional Mechanism: Diquark production



In PYTHIA: constrained to agree with LEP baryon rates

⟹ baryon-to-meson ratios ~ universal

Does **not** predict factor-10 enhancement of low-pT heavy-flavour baryons

Observed at LHC (also for B baryons)

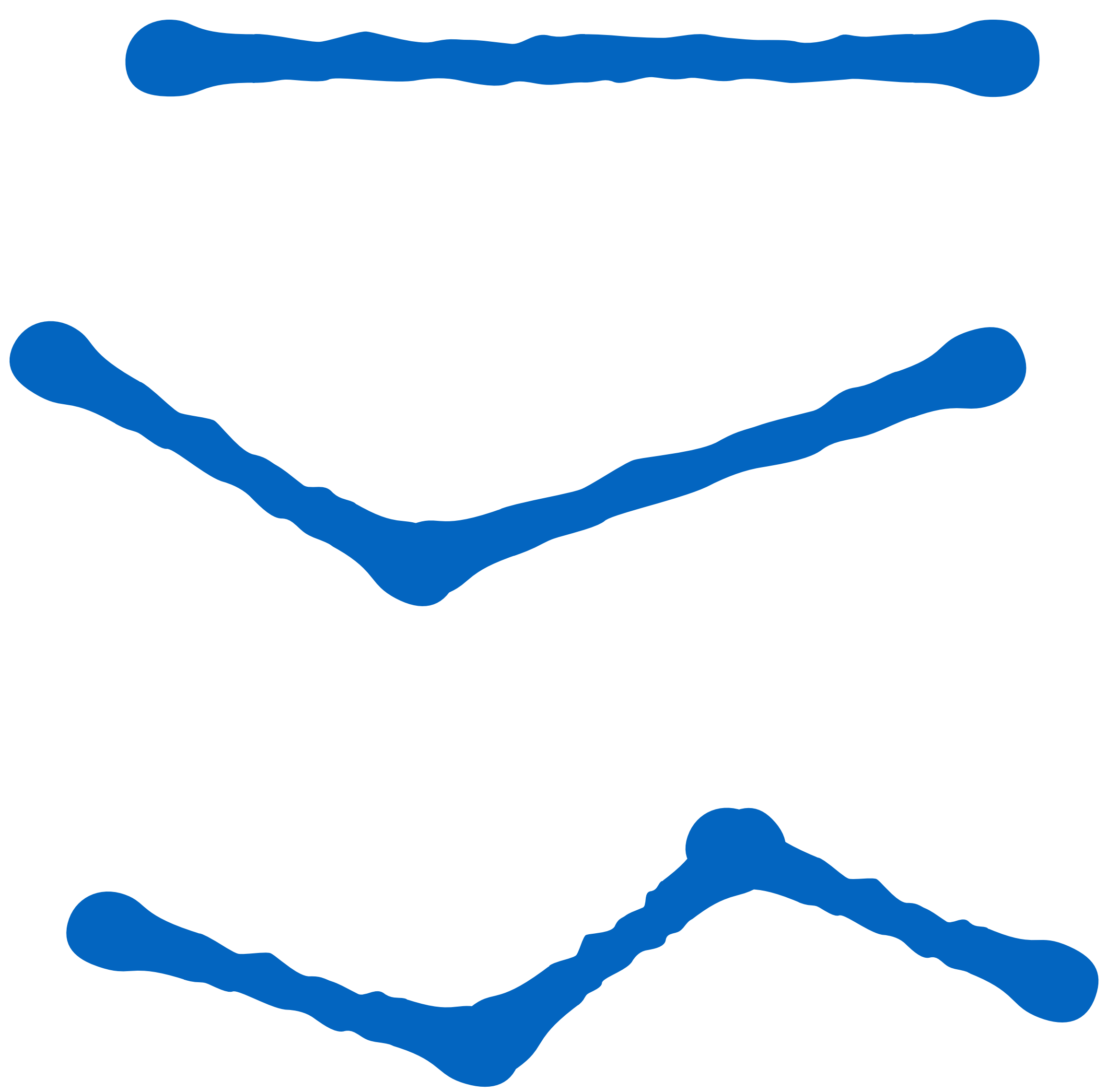
Other sources of baryon production?

Coalescence? Excited baryons? Junctions?

String Topologies

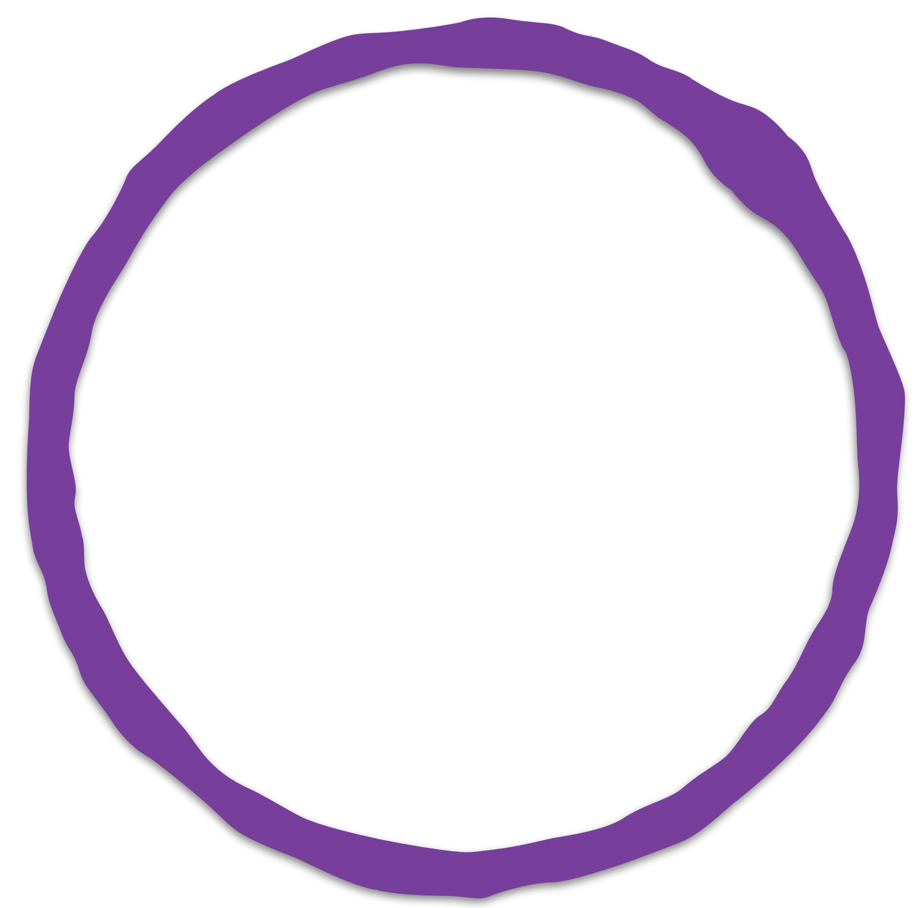
Types of string topologies:

Open Strings



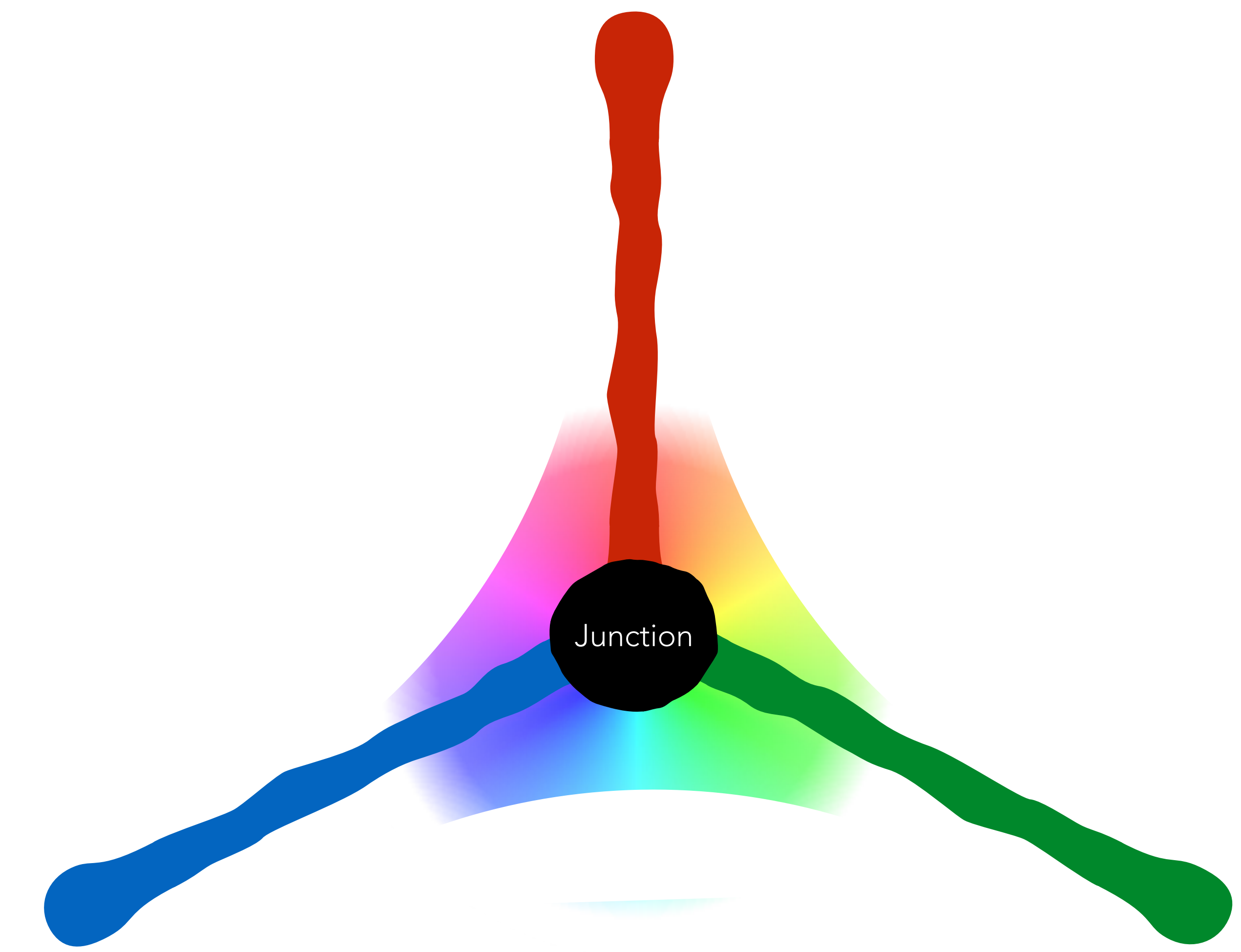
$$(3 \otimes \bar{3})_{\text{singlet}} = \frac{1}{9}$$

Closed Strings



$$(8 \otimes \bar{8})_{\text{singlet}} = \frac{1}{64}$$

SU(3) String Junction

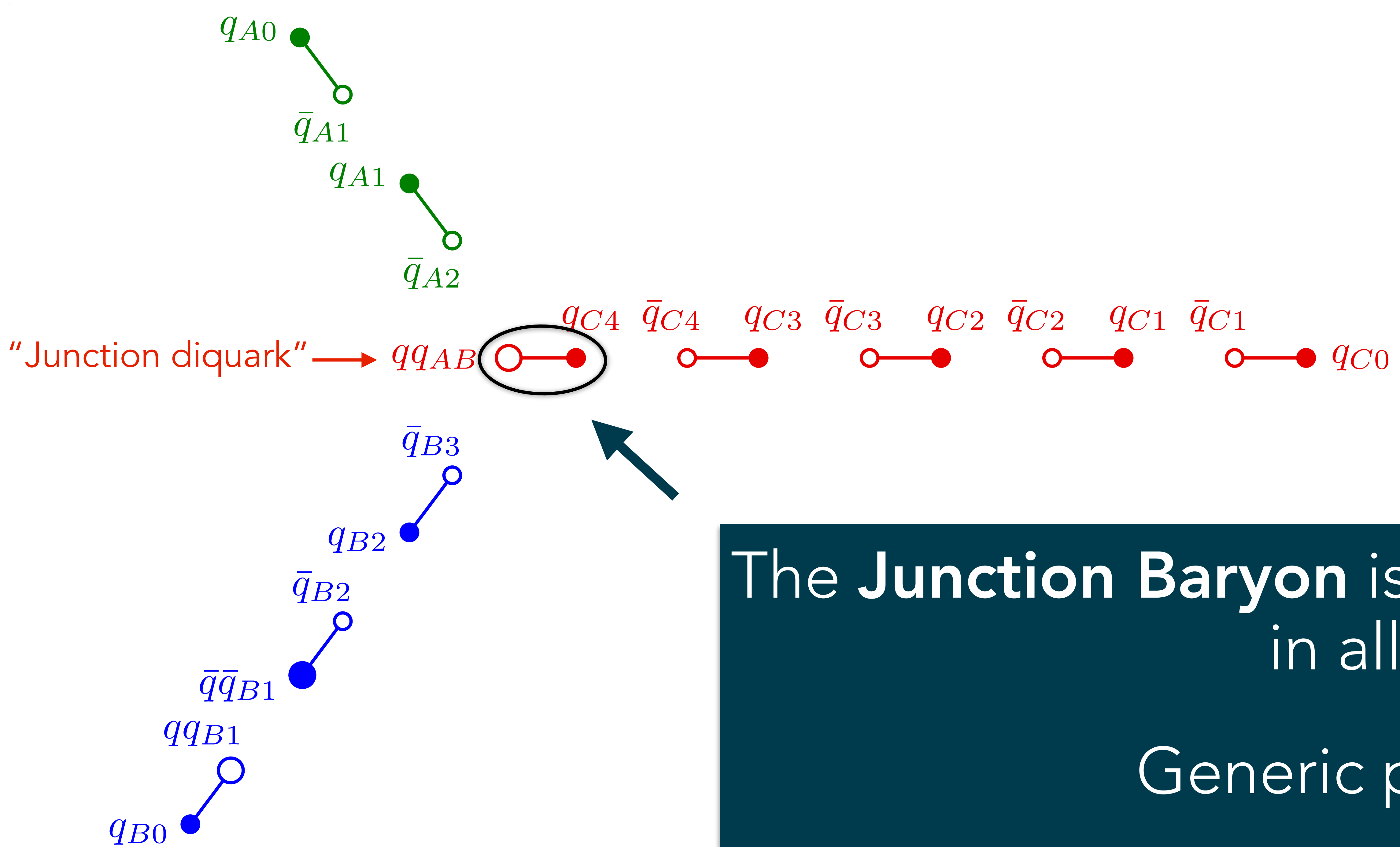


$$(3 \otimes 3 \otimes 3)_{\text{singlet}} = \frac{1}{27}$$

Could we get these at LHC?

Fragmentation of String Junctions

Assume Junction Strings have same properties as ordinary ones (u:d:s, Schwinger p_T, etc) ➤ **No new string-fragmentation parameters**



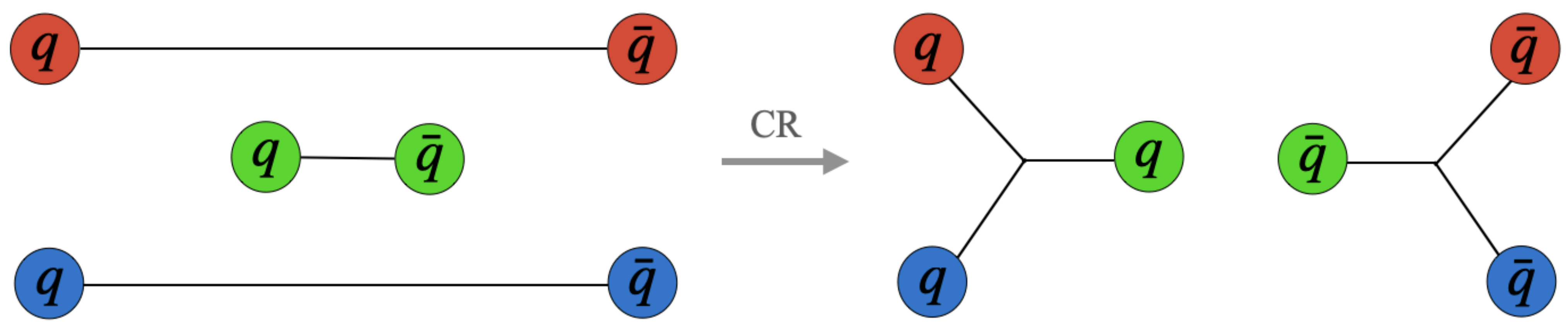
[Sjöstrand & PS, NPB 659 (2003) 243]
[+ Altmann & PS, JHEP 07 (2024) 238]

The **Junction Baryon** is the most "subleading" hadron in all three "jets".

Generic prediction: **low p_T**

A Smoking Gun for String Junctions: Baryon enhancements at low p_T

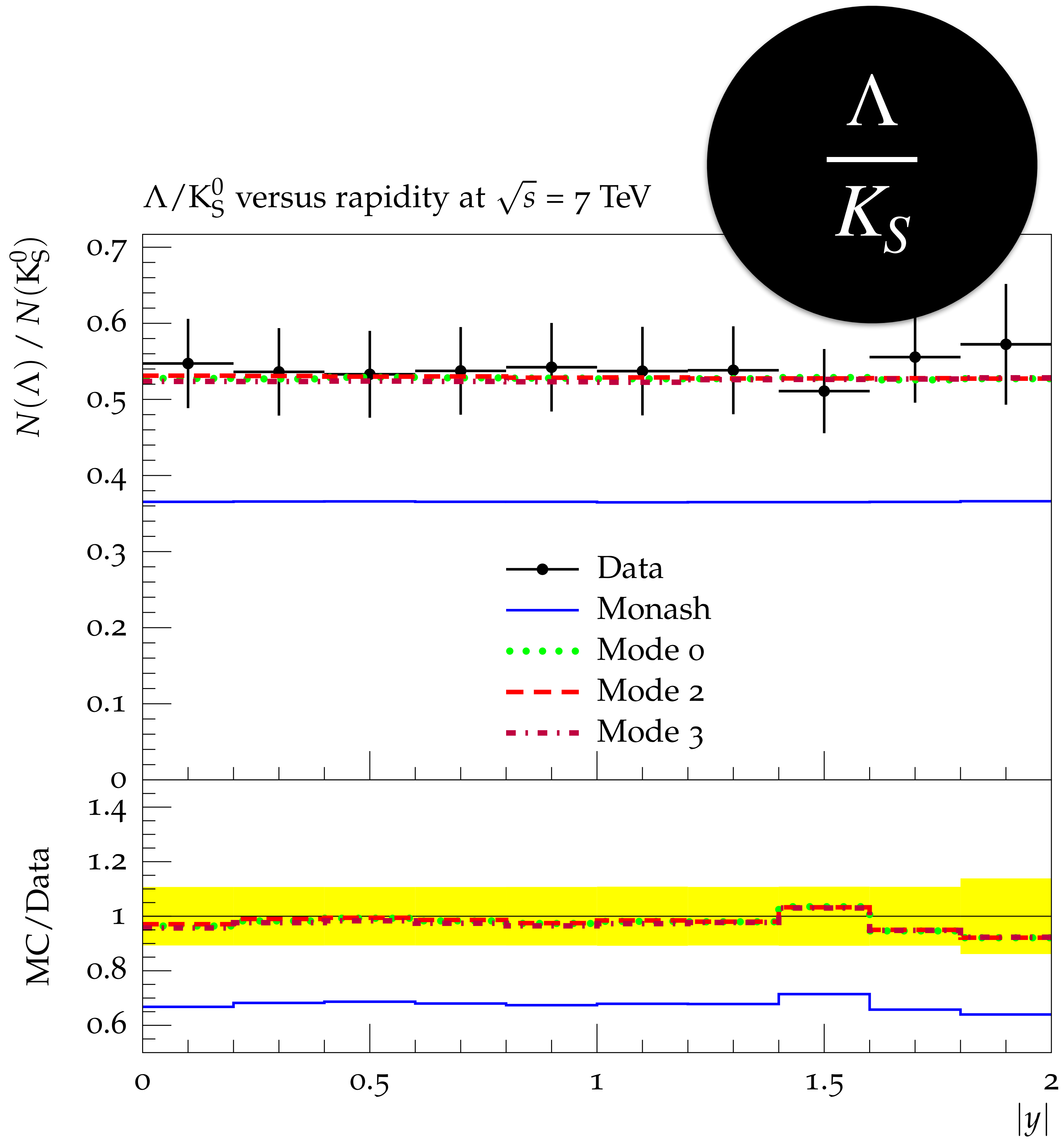
[Christiansen & PS 2015]



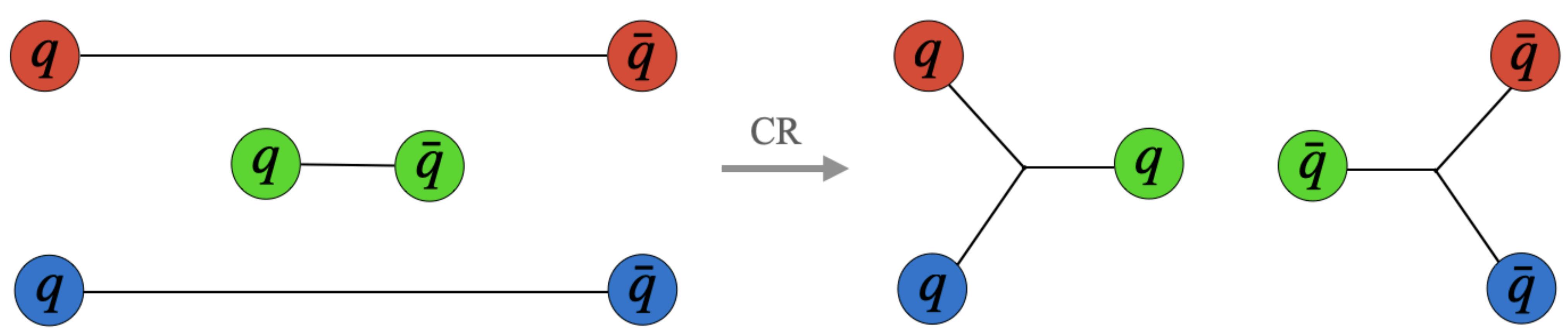
Mechanism for **baryon production**

➢ ~40% of baryons are from junctions in PYTHIA

(in pp collisions)



[ALICE 2020; Altmann & PS 2024]

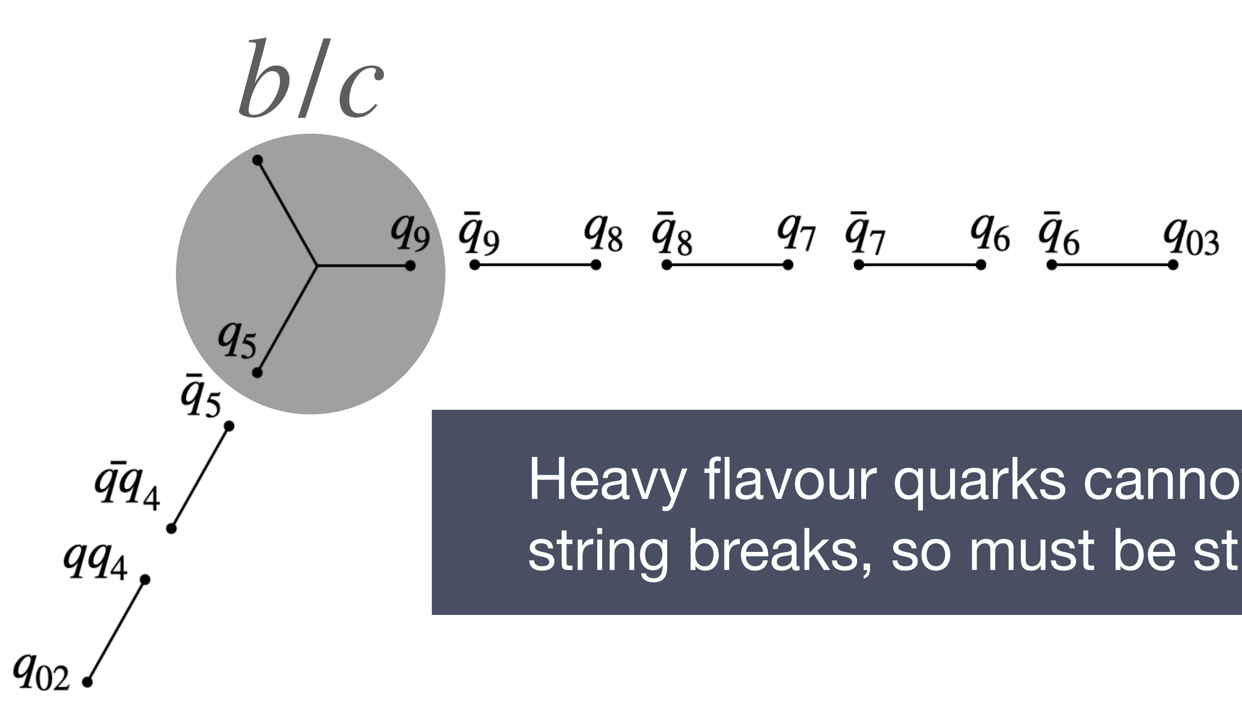


Mechanism for **baryon production**

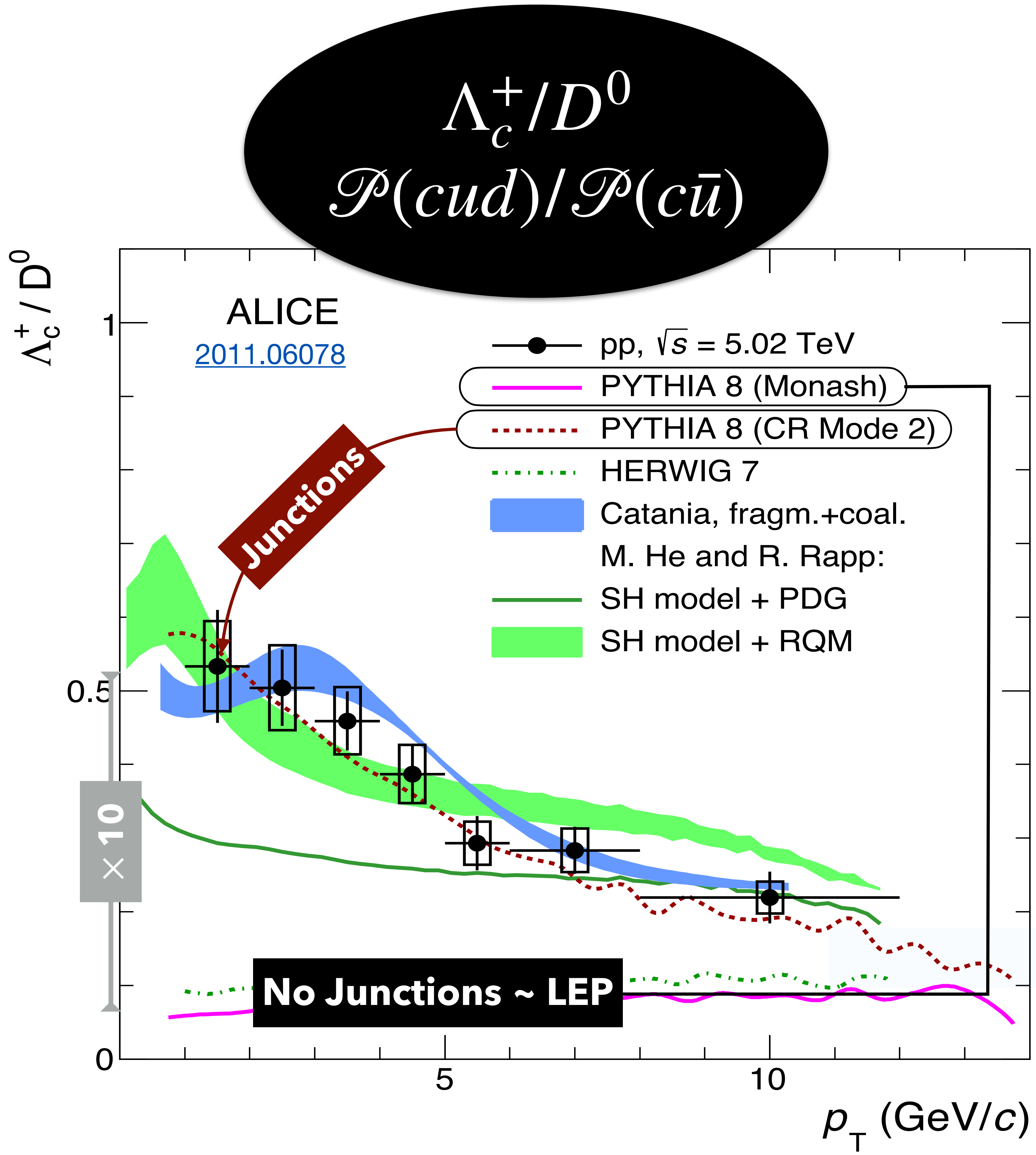
➢ ~40% of baryons are from junctions in PYTHIA

Heavy flavour baryons

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

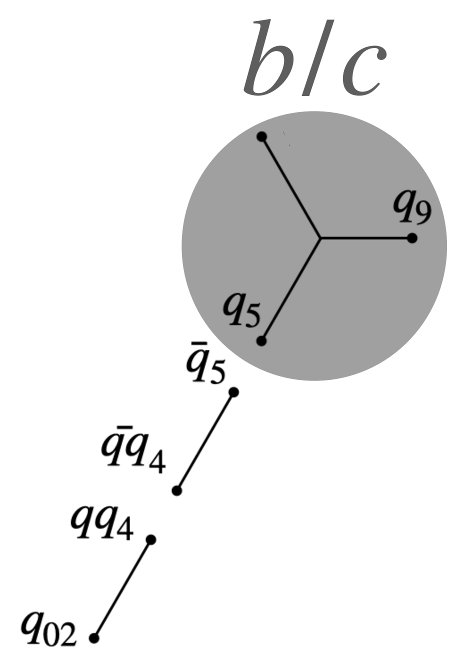


Heavy flavour quarks cannot be made from string breaks, so must be string endpoints



Spin

Σ_c/Λ_c
Sensitive to spin of "junction diquark"



Why?

More $(cq)_1$ diquarks ➜ more spin-$\frac{3}{2}$ c baryons

Spin-$\frac{3}{2}$ decay mostly to Λ_c not Σ_c

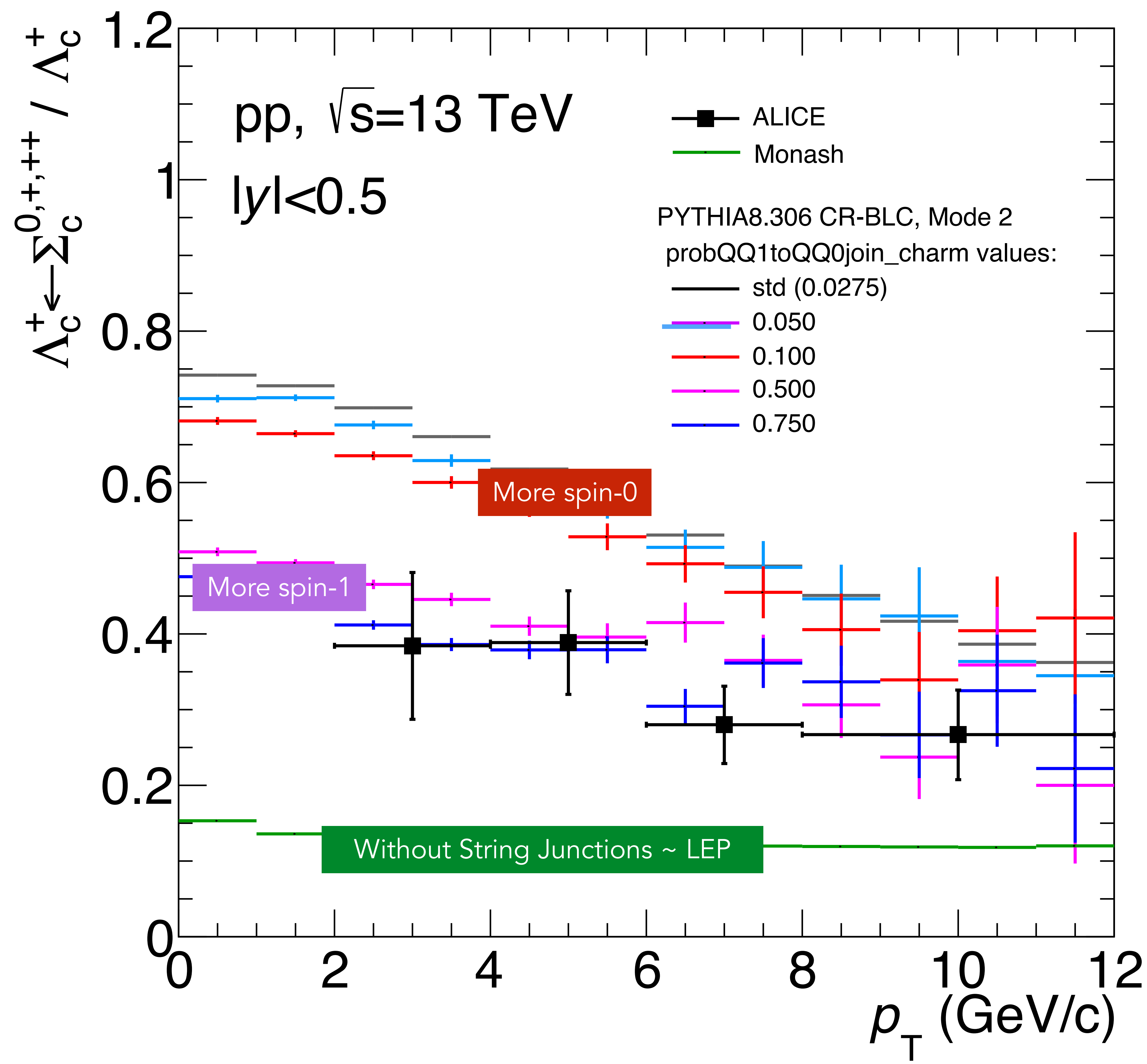
So **more** $(cq)_1$ diquarks ➜ **lower** Σ_c/Λ_c

Q: what does the heavy "junction diquark" really represent?

Physically, HQET would say heavy quark ~ "static" colour source, with light diquark cloud

Not very physical to think about intermediate heavy-light diquark?

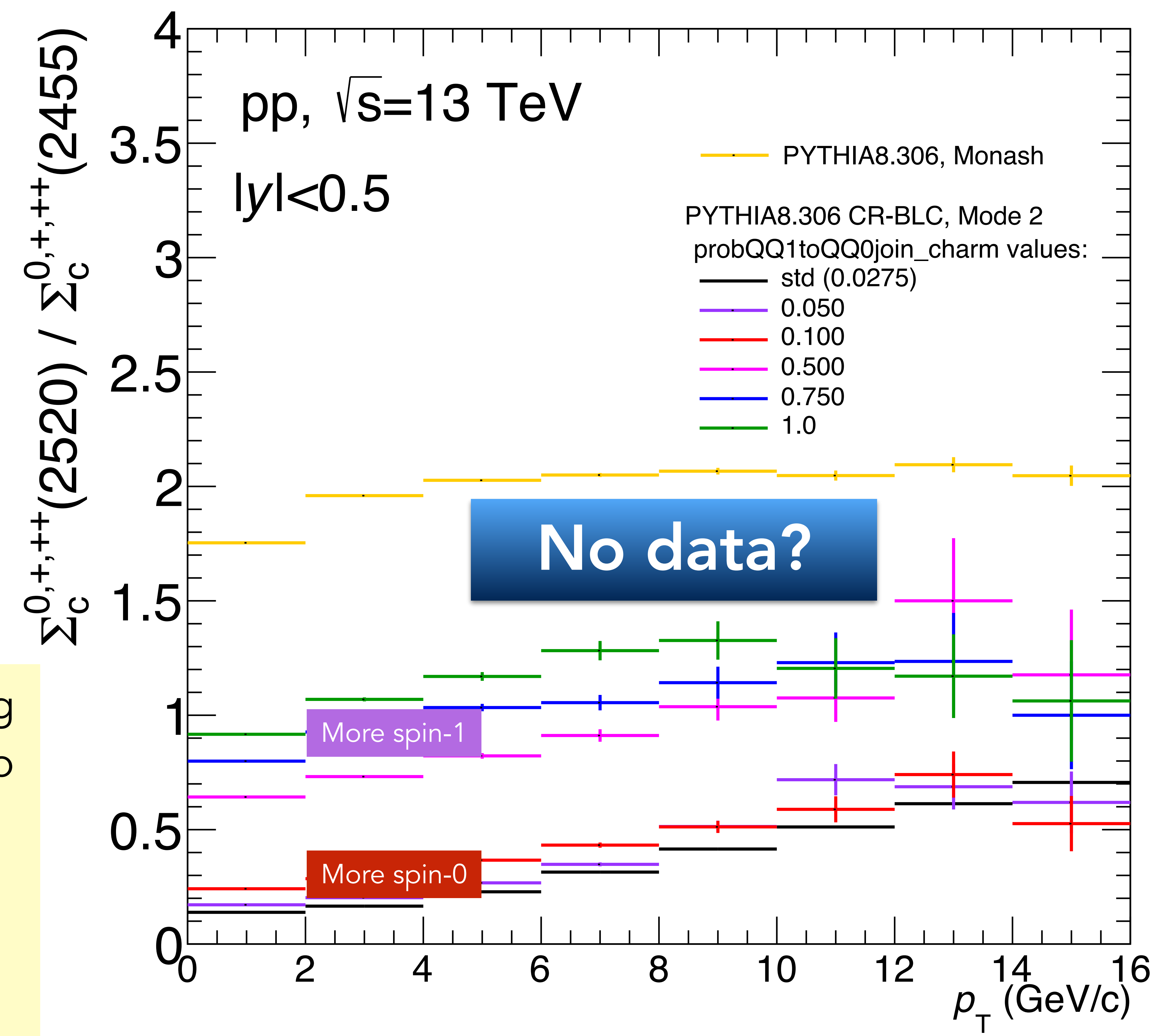
[Altmann et al. 2025]



Spin

Σ_c^*/Σ

[Altmann et al. 2025]

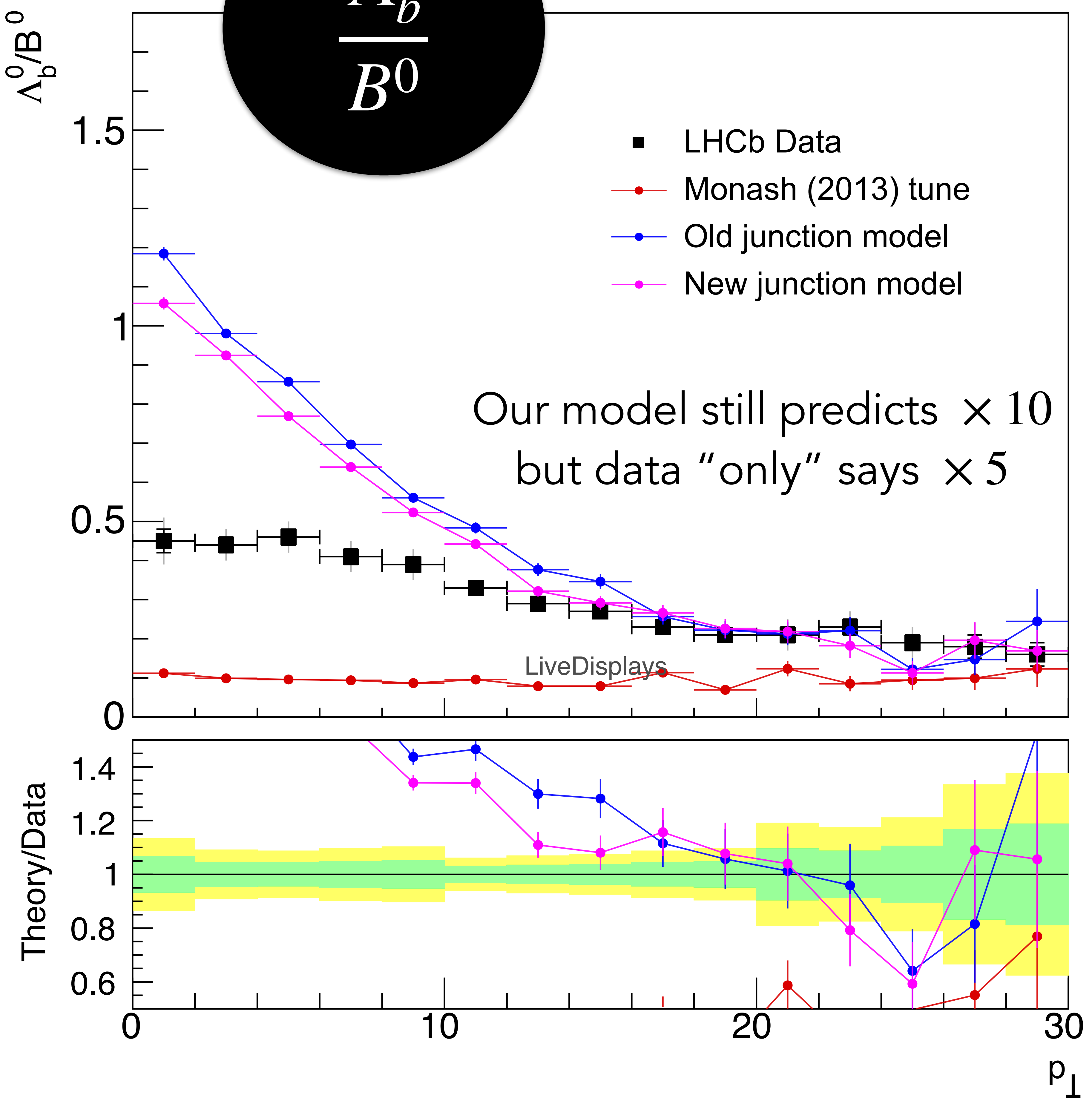


Note: in Monash baseline (yellow), you are getting much lower **total** baryon rates. No junctions → no heavy-light diquarks at all. Only the standard c + (qq) mechanism. For both Σ and Σ* this is the spin-1 iso-vector $(qq)_1$ so the overall $(qq)_1/(qq)_0$ ratio largely drops out in this ratio.

➜ Expect factor 2 ~ spin counting.

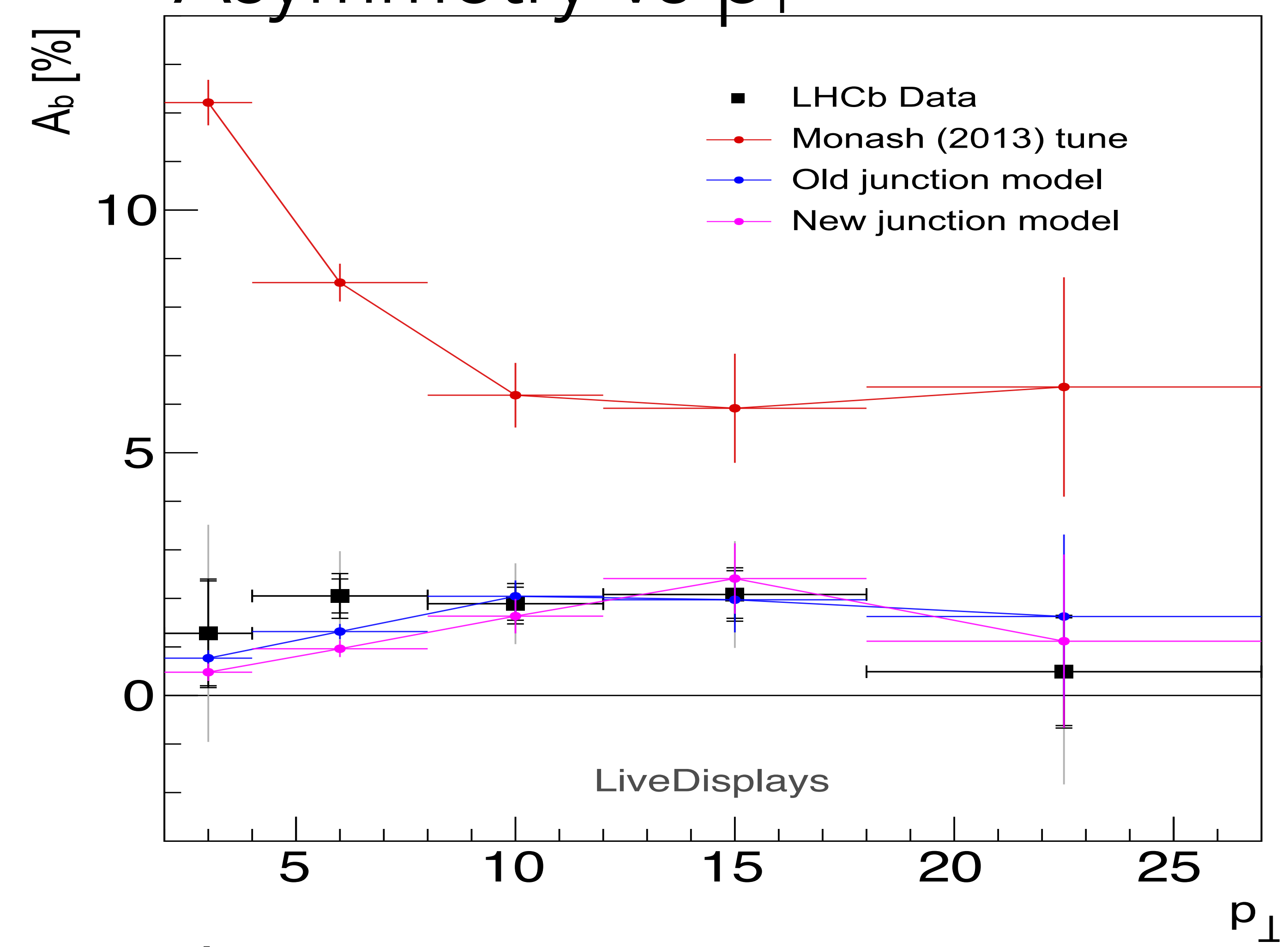
Beauty

$$\frac{\Lambda_b^0}{B^0}$$

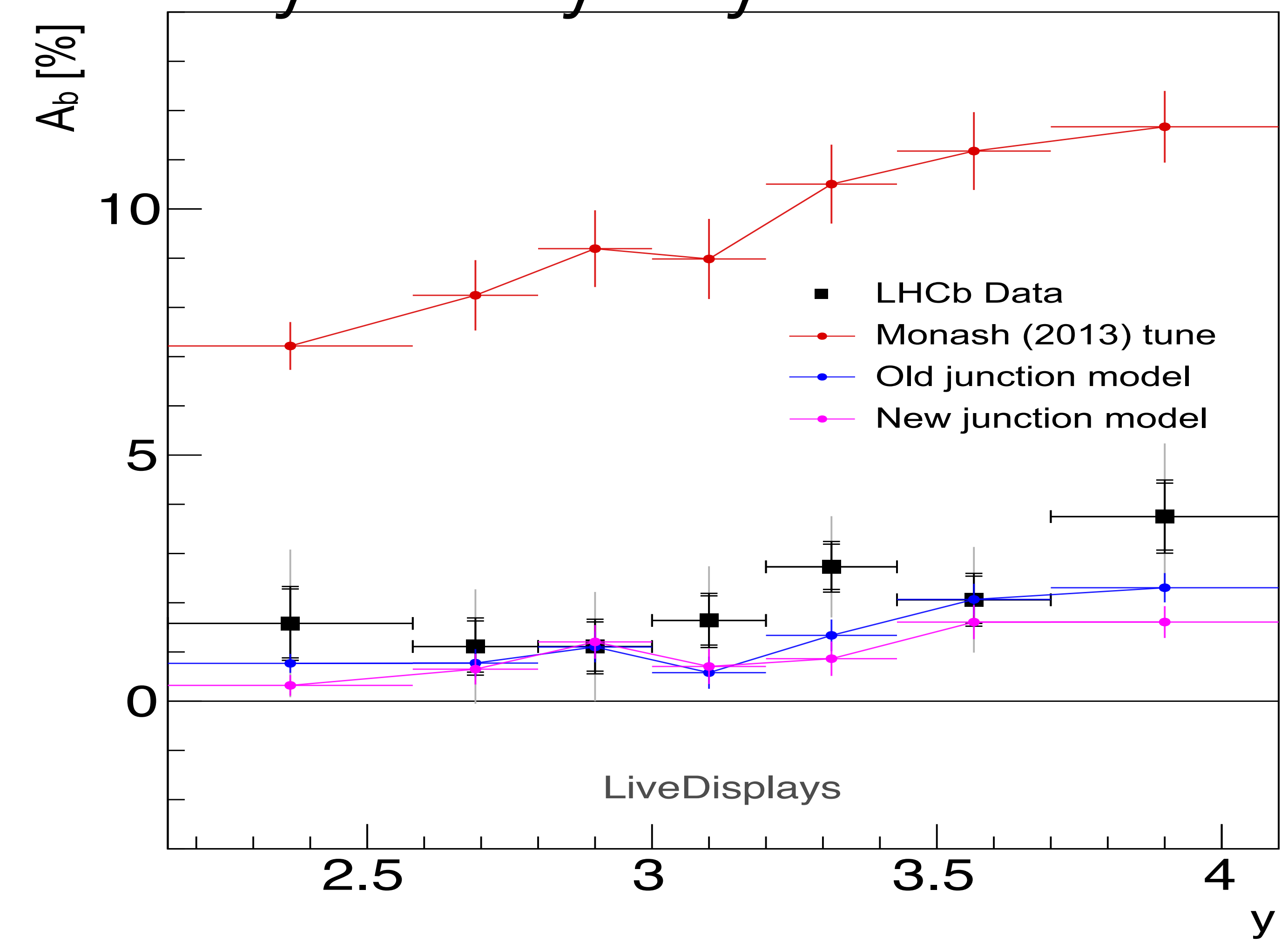


Our model still predicts $\times 10$
but data "only" says $\times 5$

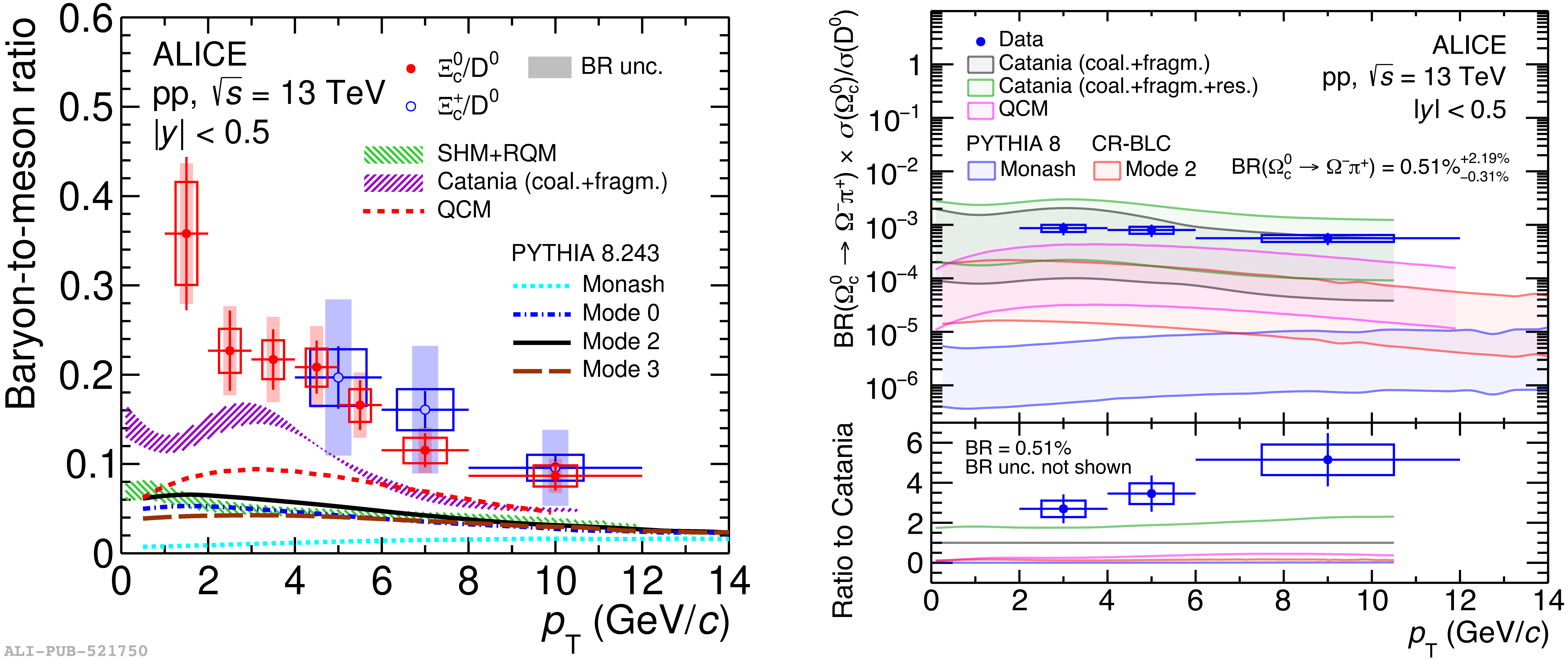
Asymmetry vs p_T



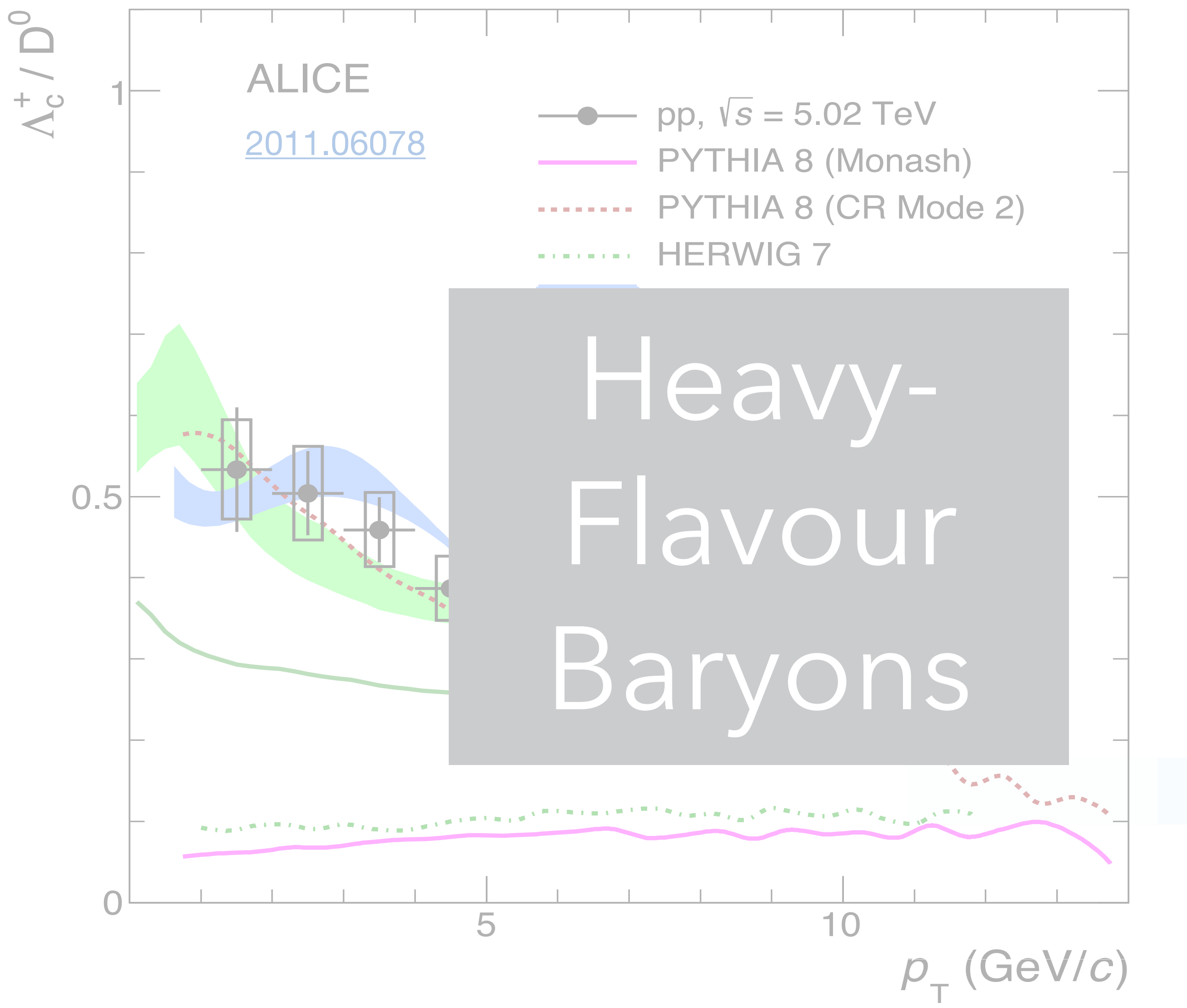
Asymmetry vs y

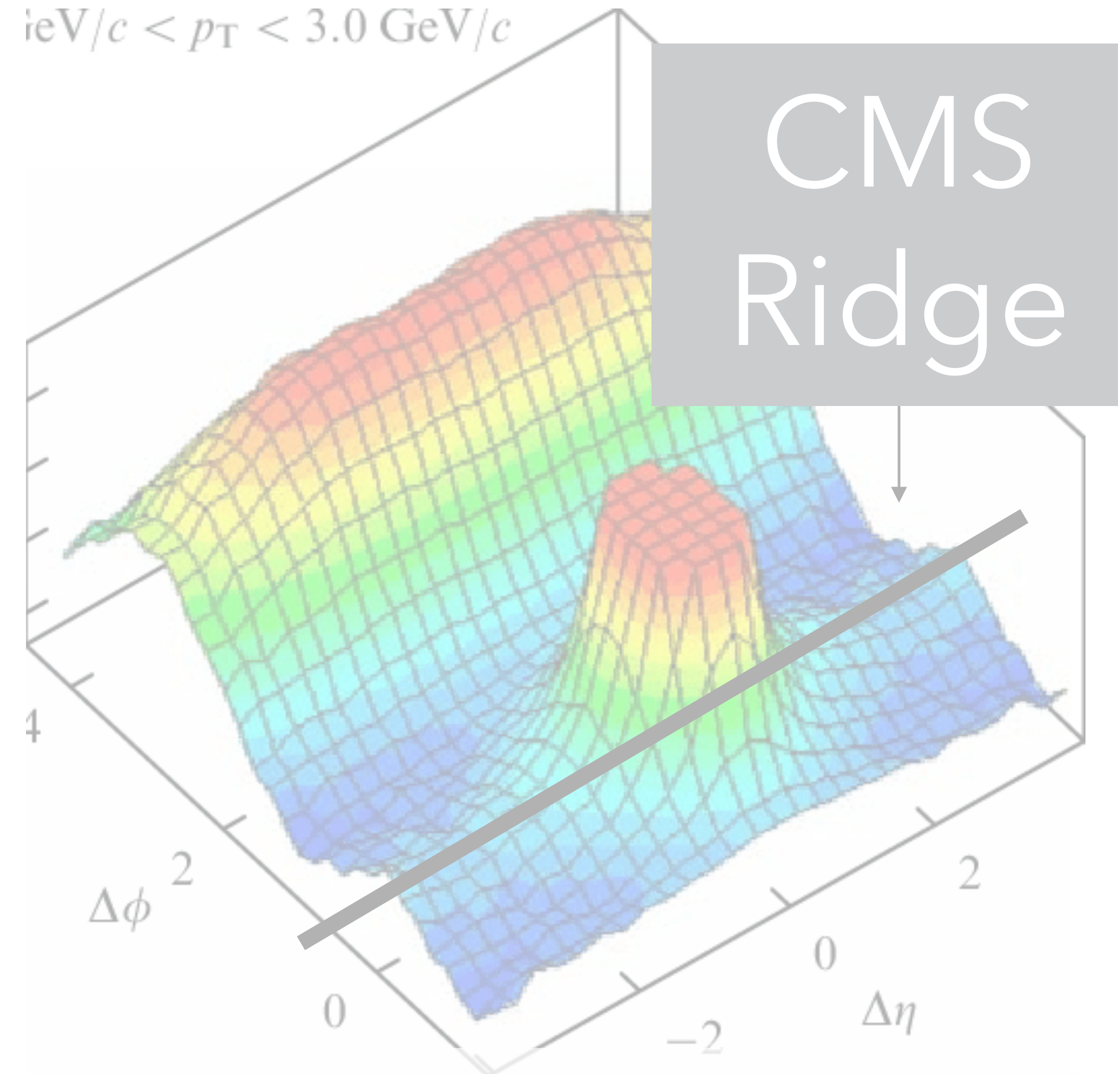


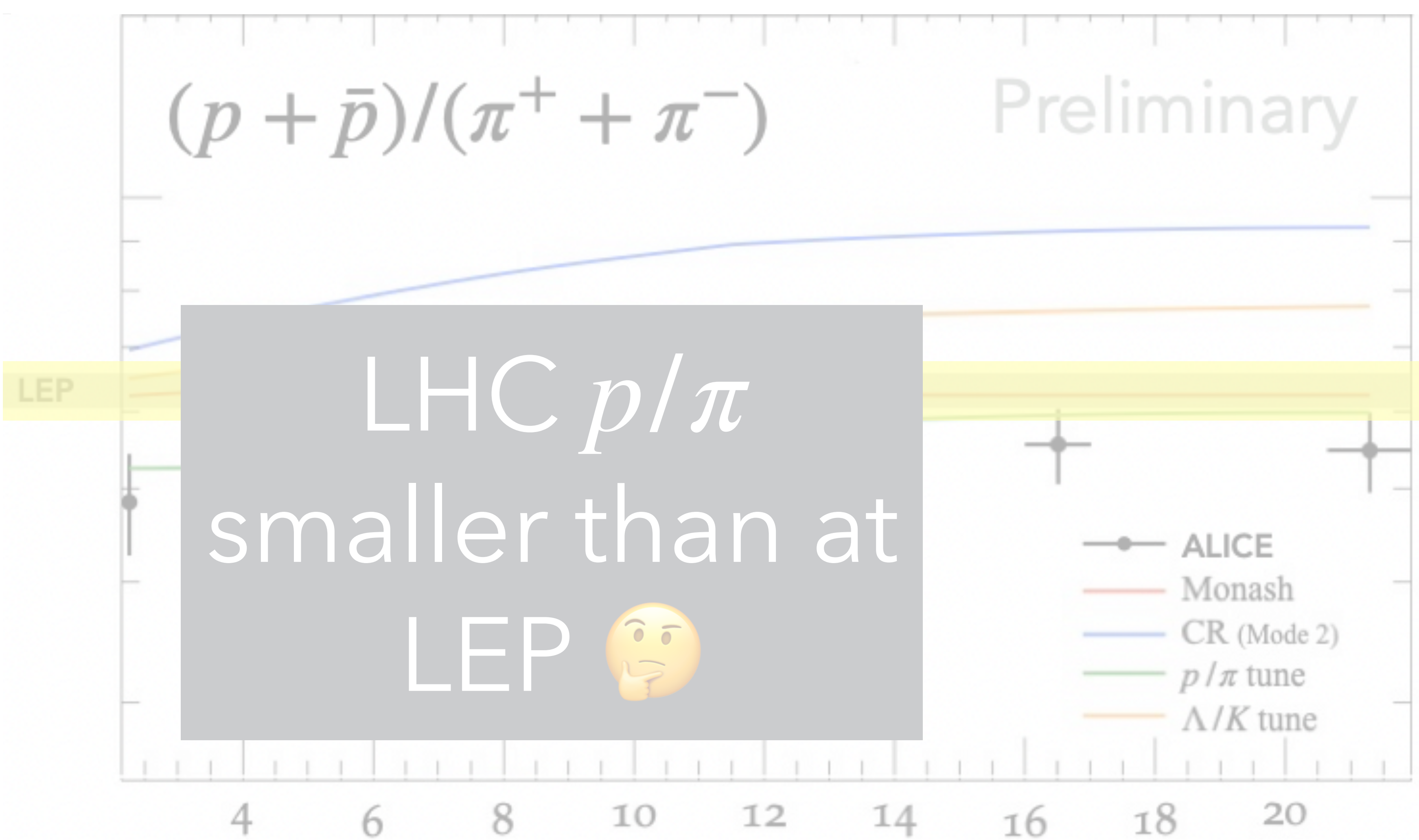
(still in context of heavy-flavour Baryon sector)



QCD @ LHC ➢ Lots of New Discoveries!







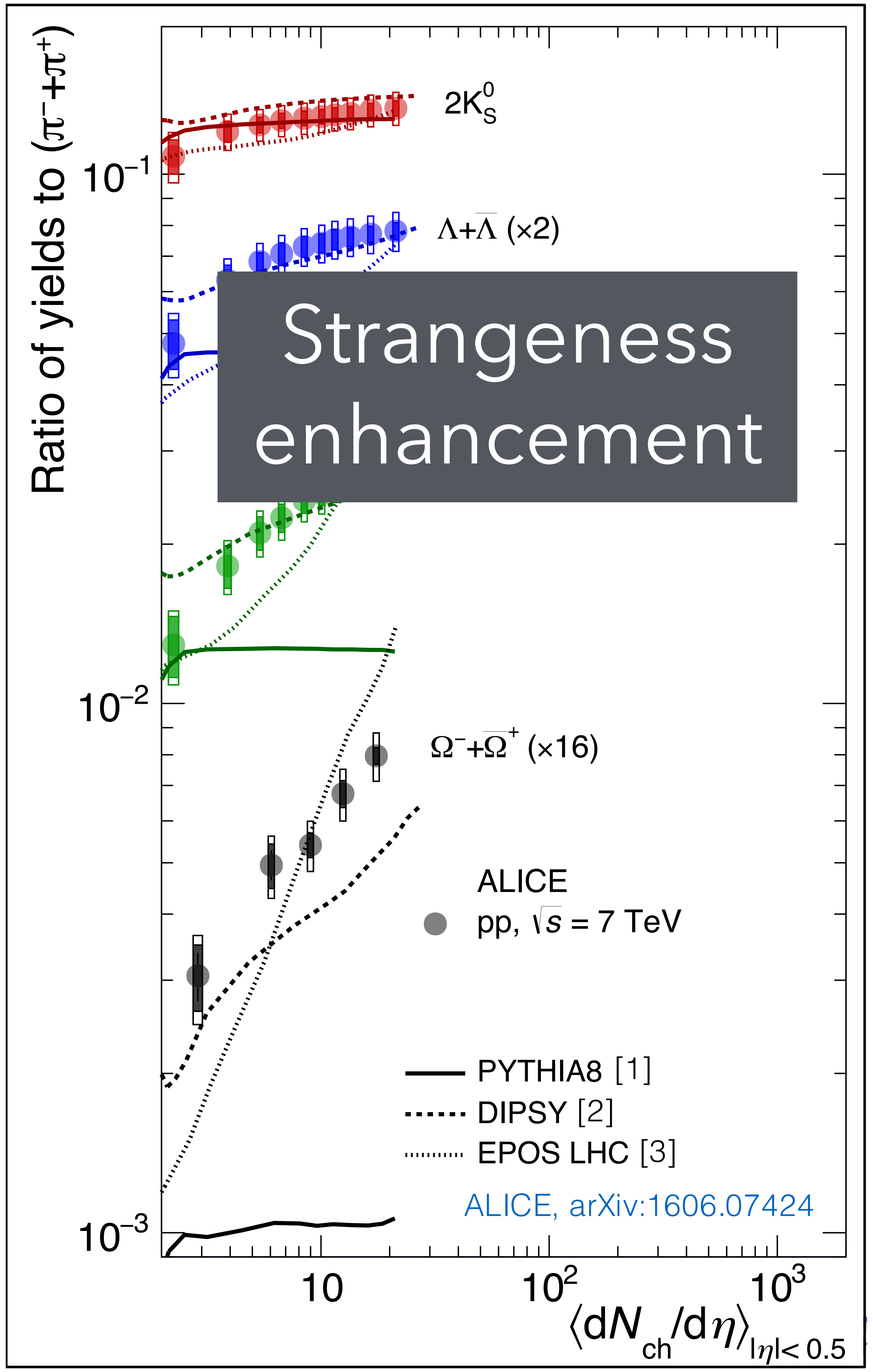
+ Many more …

Baryon correlations

D_s asymmetries

Exotica

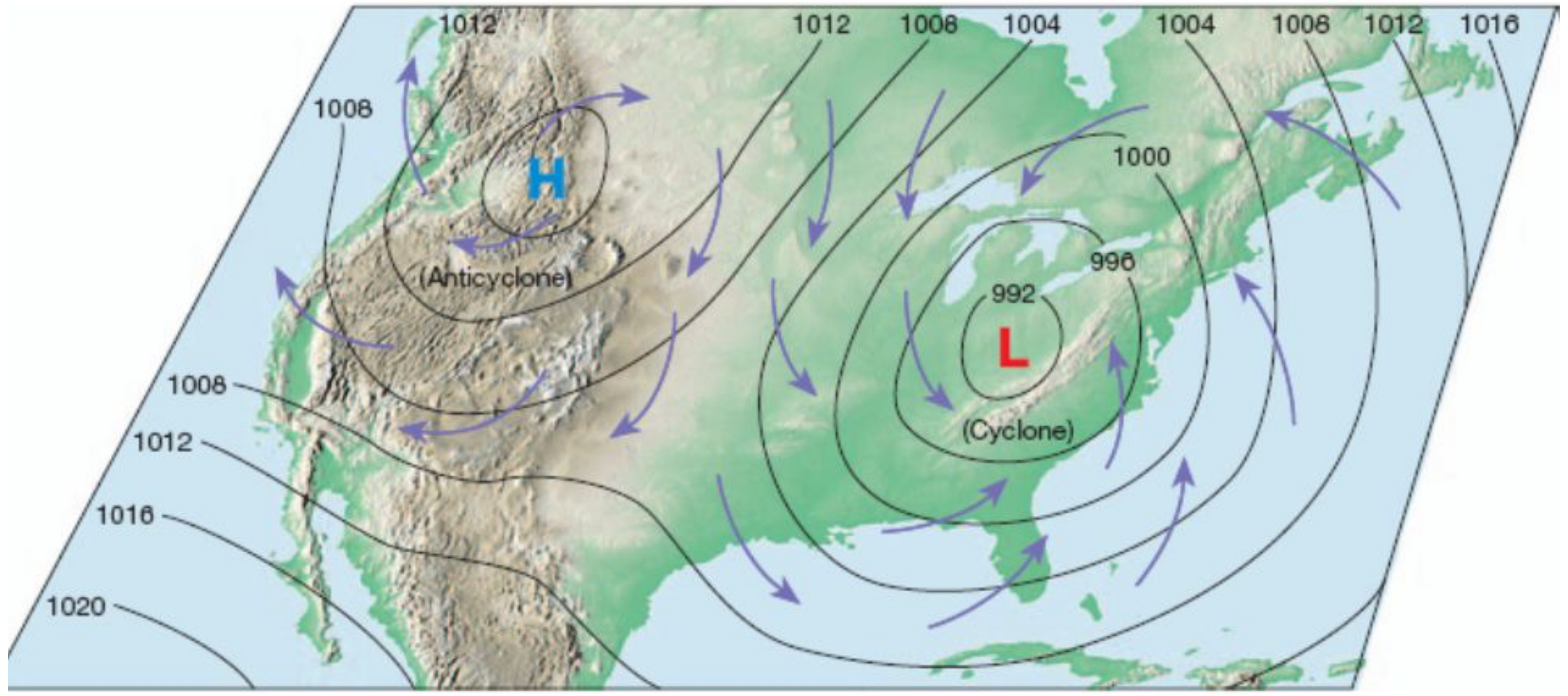
…



New Directions in String Fragmentation

→ Regard tension κ as an emergent quantity (not fundamental strings)

Cyclonic and Anticyclonic Winds



May depend on (invariant) time τ?

E.g., **hot** strings which cool down

[Hunt-Smith & PZS EPJ C 80 (2020) 11]

May depend on spatial coordinate σ?

Ideas of "fluctuating string tension": Bialasz 1997; Pirner, Kopeliovich & Reygers 2018

+ New work in progress with Altmann (Monash), and Carragher & March-Russell (Oxford).

May depend on environment? (e.g., other strings nearby)

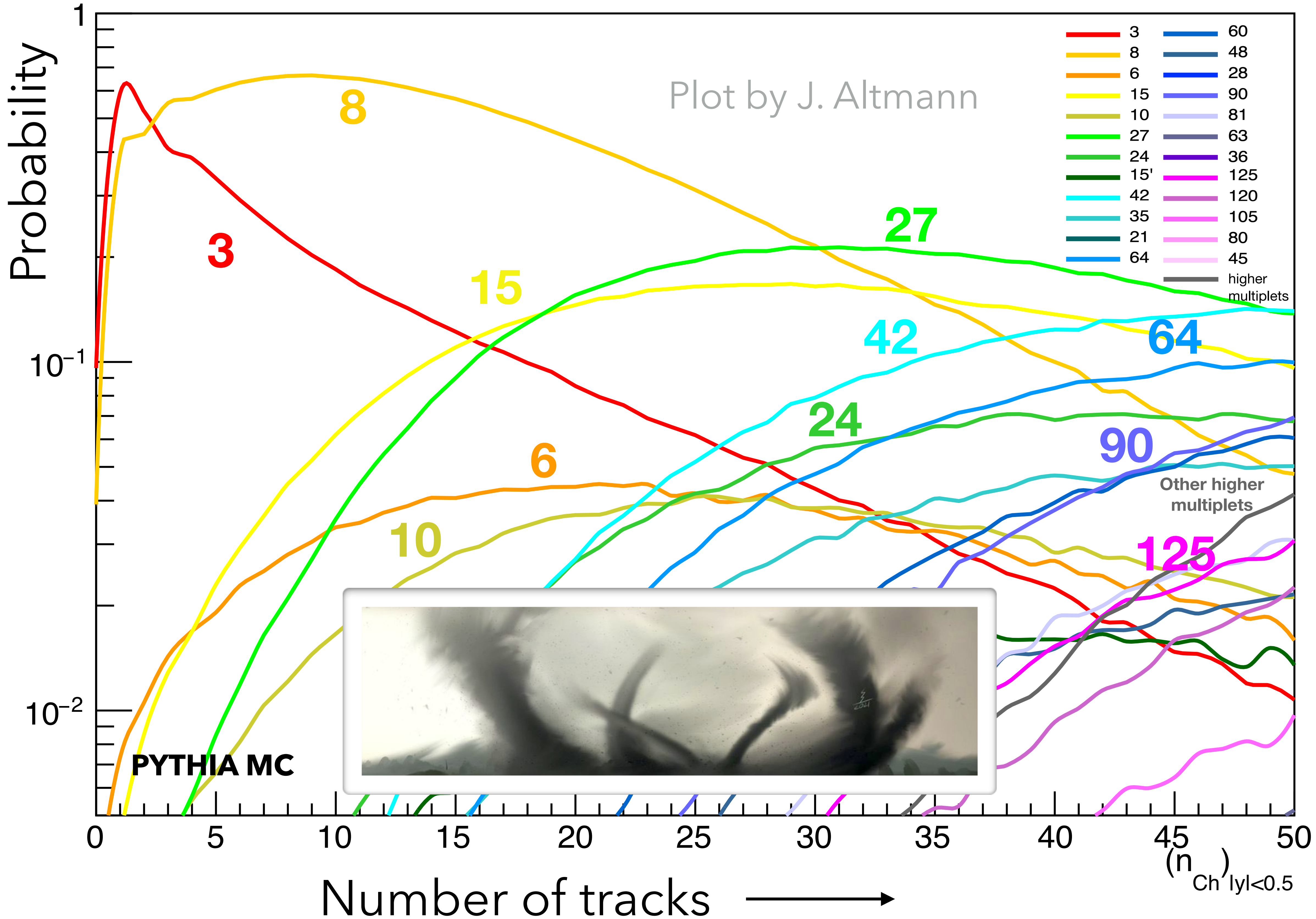
Two approaches (so far) within Lund string-model context:

Colour Ropes [Bierlich et al. 2015] + several more recent

Close-Packing [Fischer & Sjöstrand 2017] + Work in progress with L. Bernardinis & V. Zaccolo (Trieste)

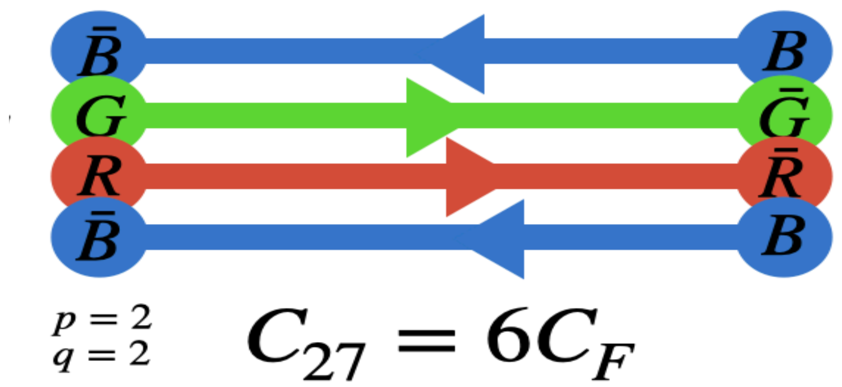
Count # of (oriented) flux lines crossing $y = 0$ in pp collisions at LHC

(according to PYTHIA) — And classify by SU(3) multiplet:



Confining fields may be reaching **higher effective representations** than simple $q\bar{q}$ (3) ones.

E.g.: 27



27

$C_{27} = 6C_F$

➜ Is "emergent tension" driving strangeness enhancement in pp?

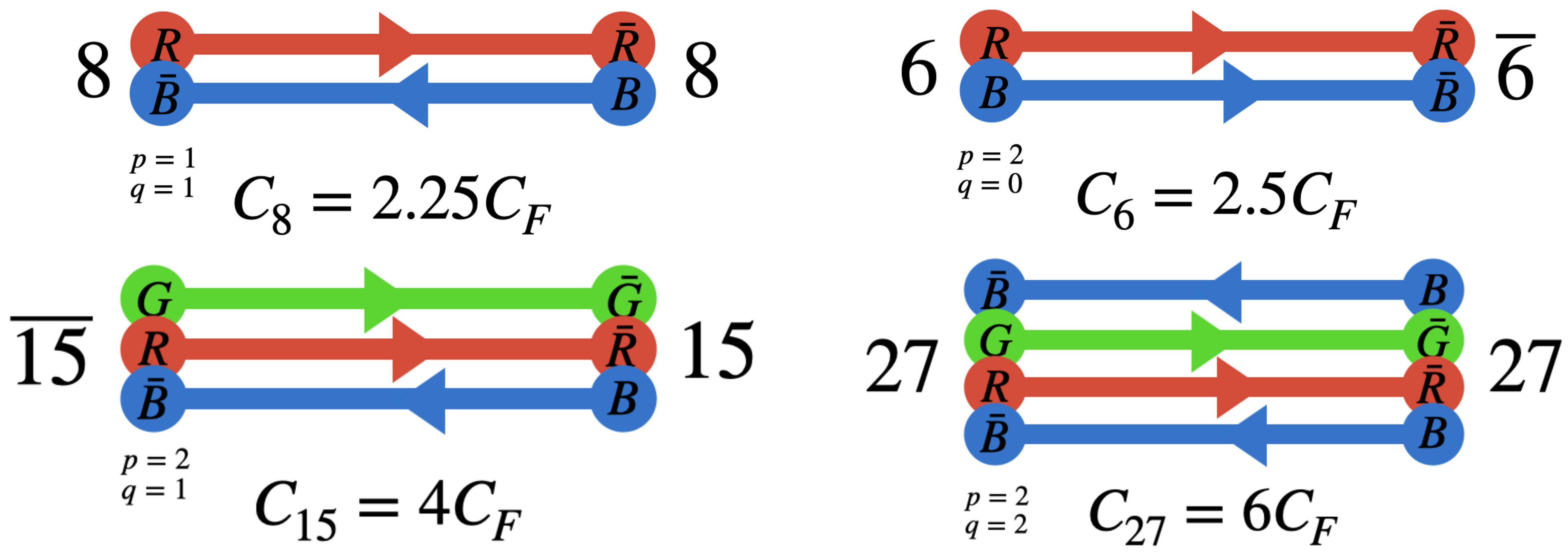
Colour Ropes (Bierlich et al.),

+ Close-Packing: Altmann, Bernardinis, Jueid, Kreps, **PS**, Zaccolo (in progress)

Strangeness enhancement with strings

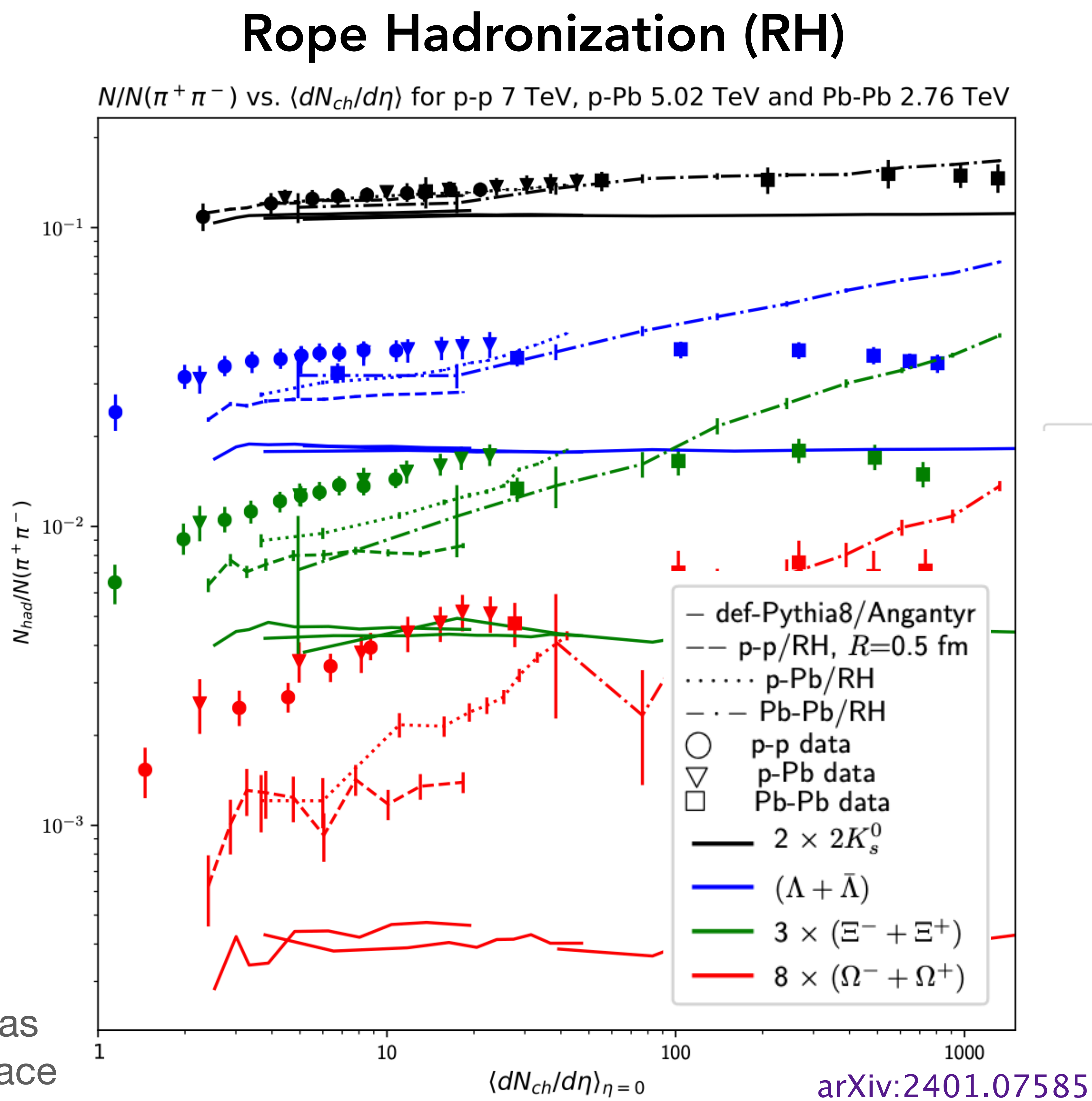
Rope hadronisation / Closepacking

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

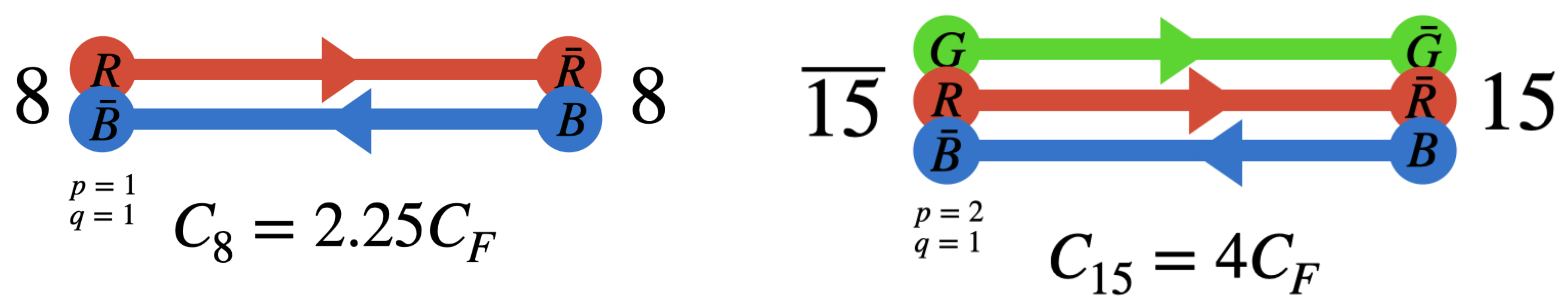


arXiv:2401.07585

Close-Packing Model in PYTHIA

Rope hadronisation / Closepacking

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



Close-Packing:

- High-density string systems → increased string tension → depends on parallel and anti-parallel strings

$$\tilde{\kappa} = \left[1 + \boldsymbol{k_p}\left(\frac{p + (k_a/k_p)q}{1 + p_{\perp,\text{had}}^2/p_{\perp 0}^2}\right)\right]^{2r} \kappa$$

- k_p = `ClosePacking:tension`

So far only measured as function of rapidity along z axis

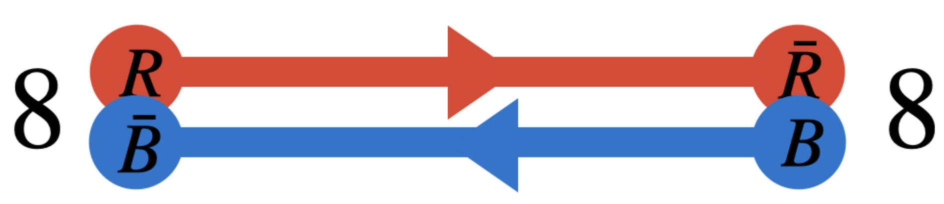
↓

Monash Honours Project 2025: Claire Bergman: Echidna Model

Strangeness Enhancement: Close-Packing

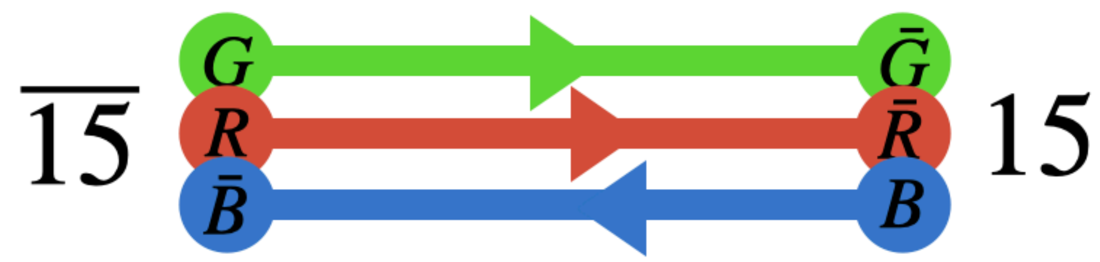
Rope hadronisation / Closepacking

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



$p = 1$, $q = 1$

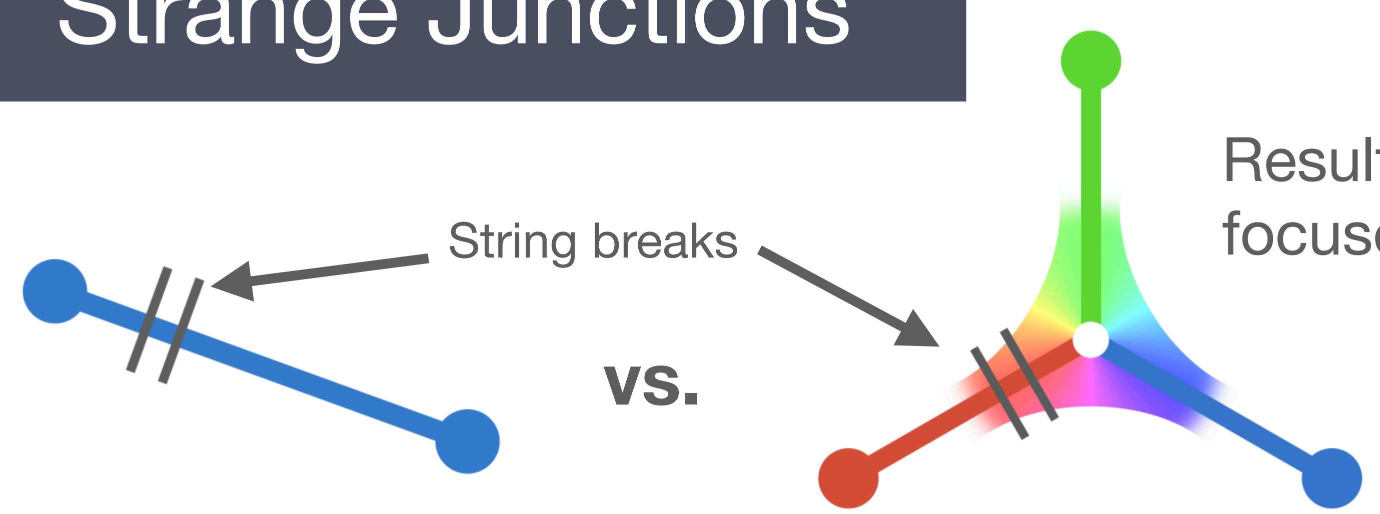
$C_8 = 2.25 C_F$



$p = 2$, $q = 1$

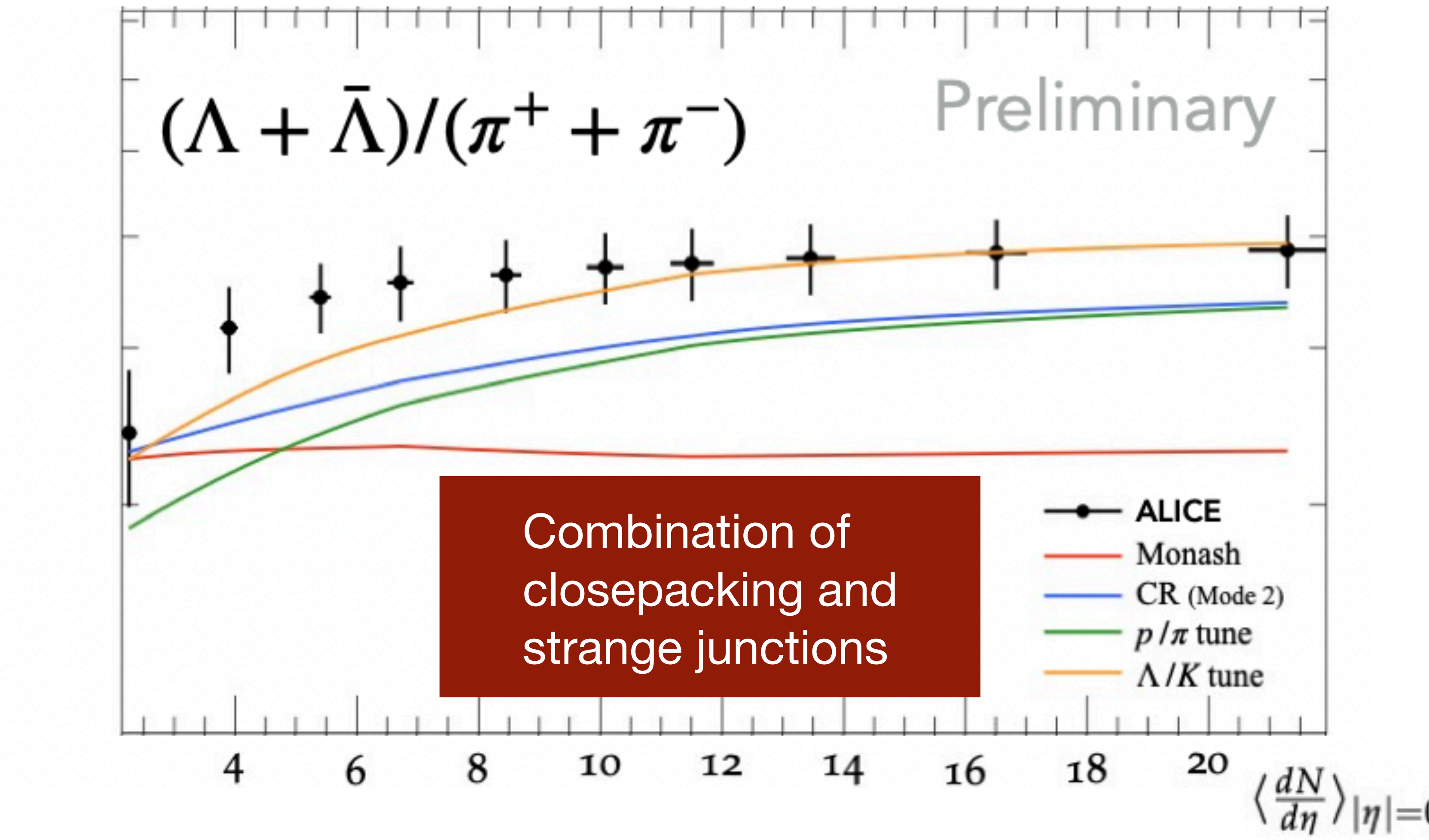
$C_{15} = 4 C_F$

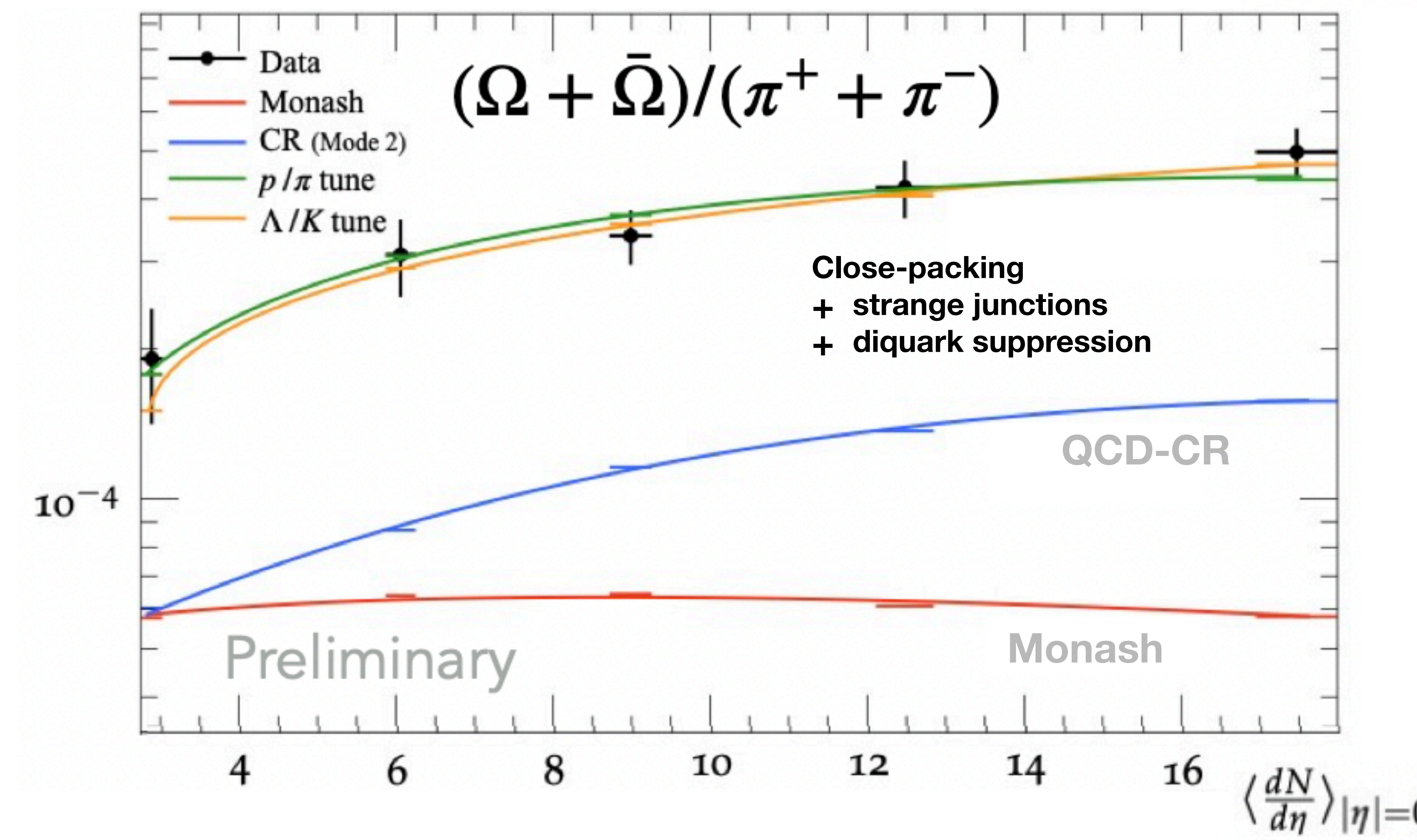
Strange Junctions



Results in strangeness enhancement focused in baryon sector

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



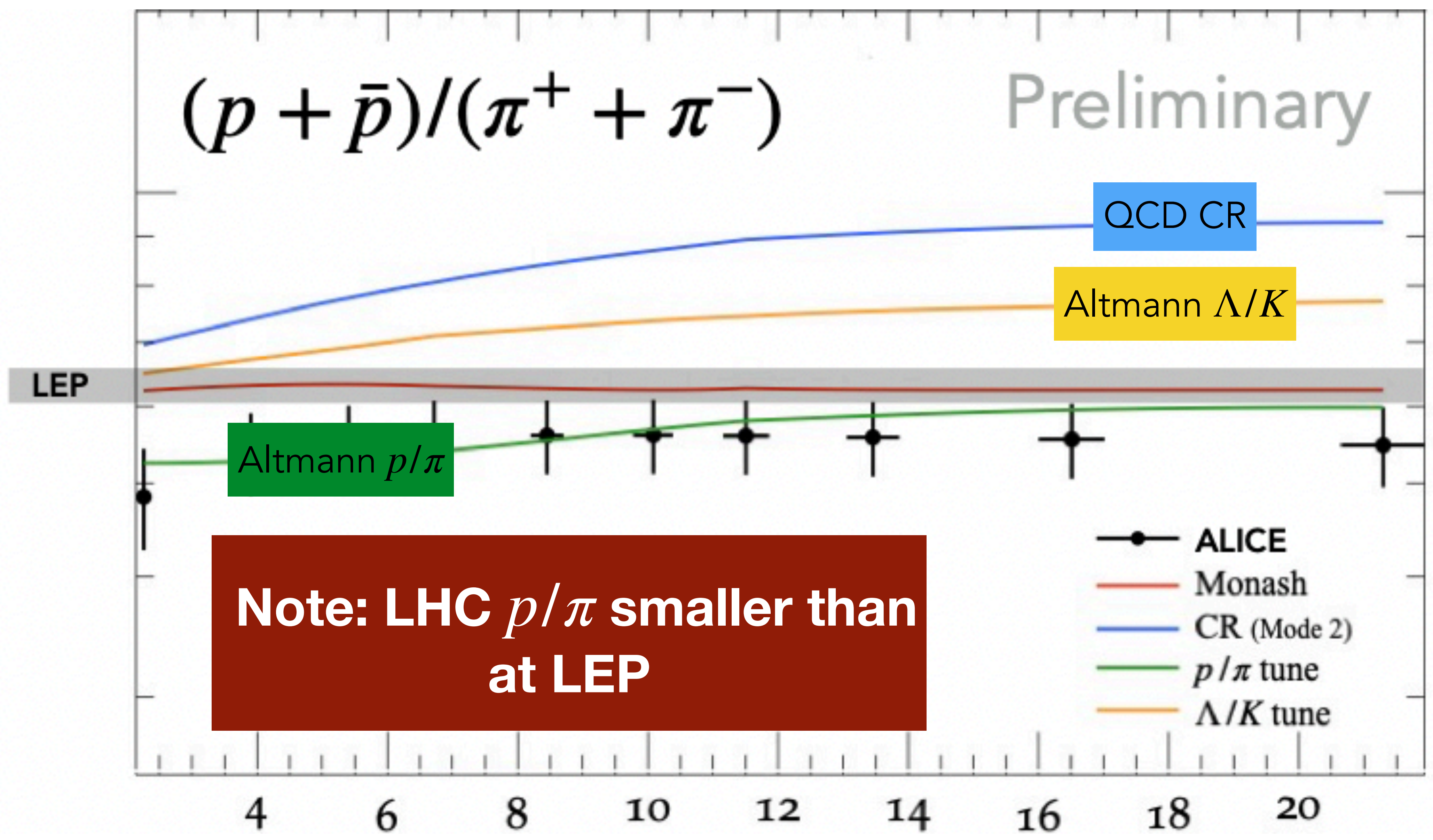


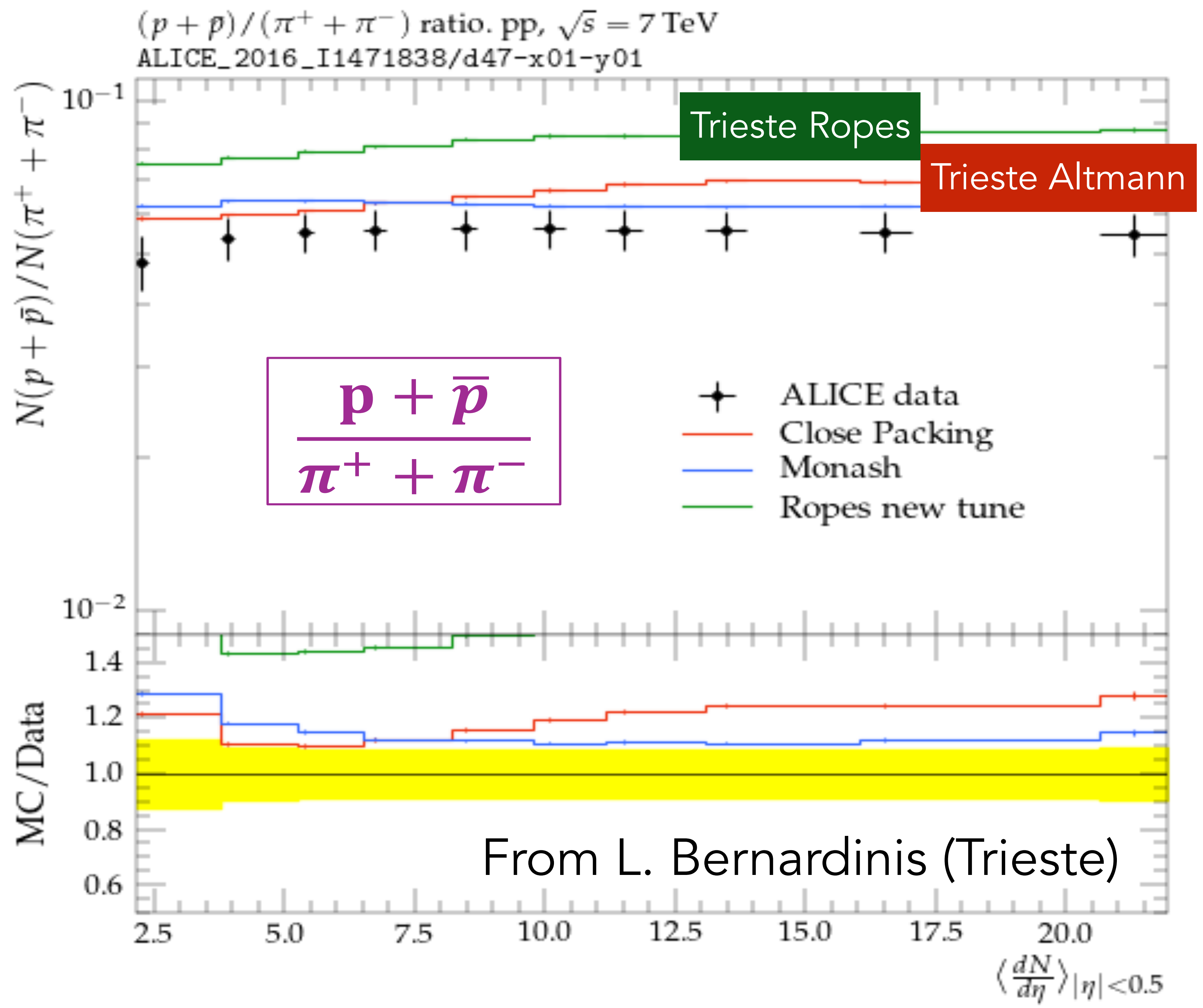
Thorny Issue ⚠️ The Proton-to-Pion Ratio

Observed p/π in pp collisions at LHC ~ ***lower*** than in e^+e^- ones (LEP).

I think this is now the **main challenge** for strangeness-enhancement models

Interactions? Upscattering/Annihilation? Octet vs Triplet fragmentation? …?

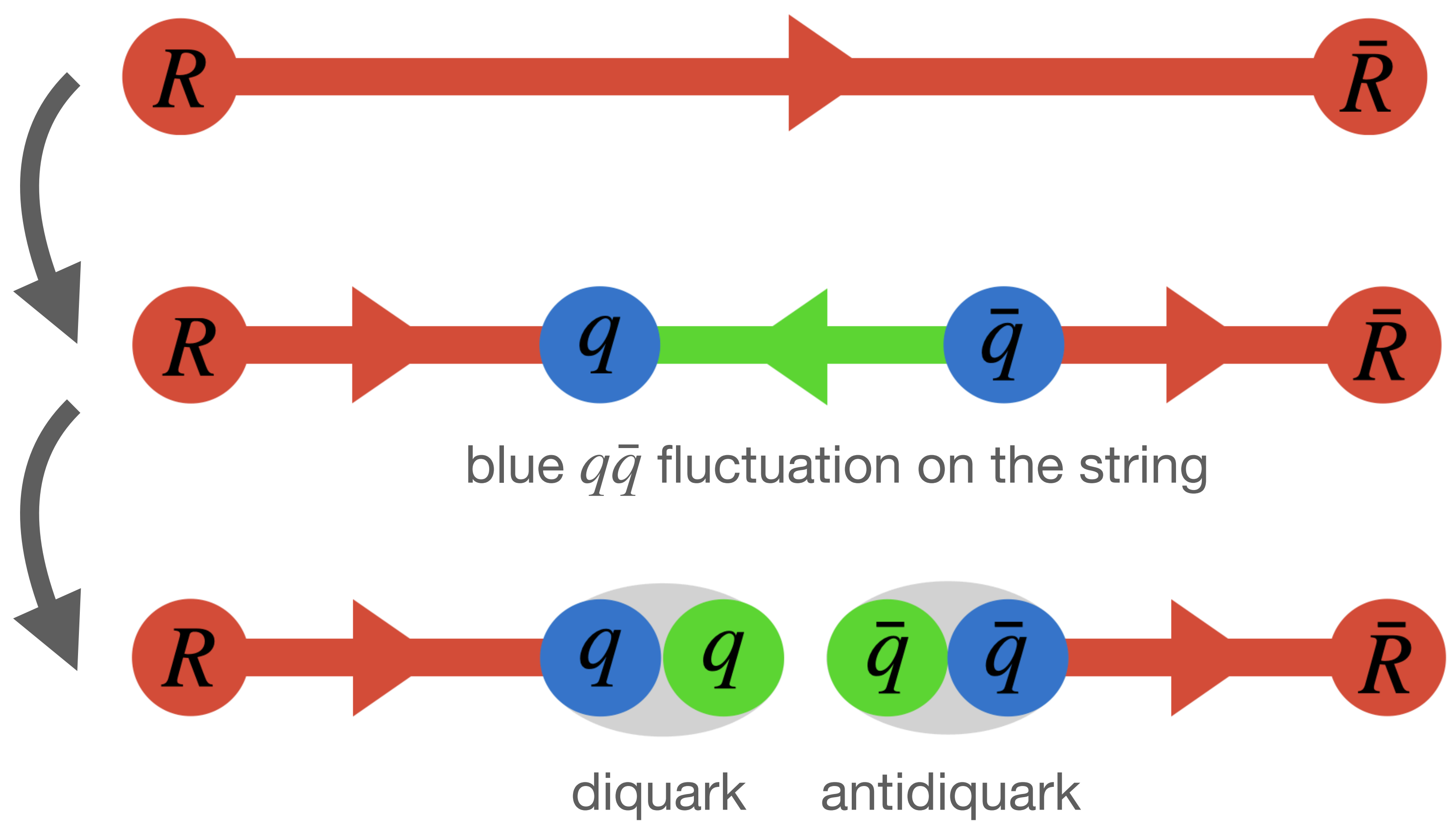




Reexamine baryon formation via diquark production

Popcorn mechanism for diquark production

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



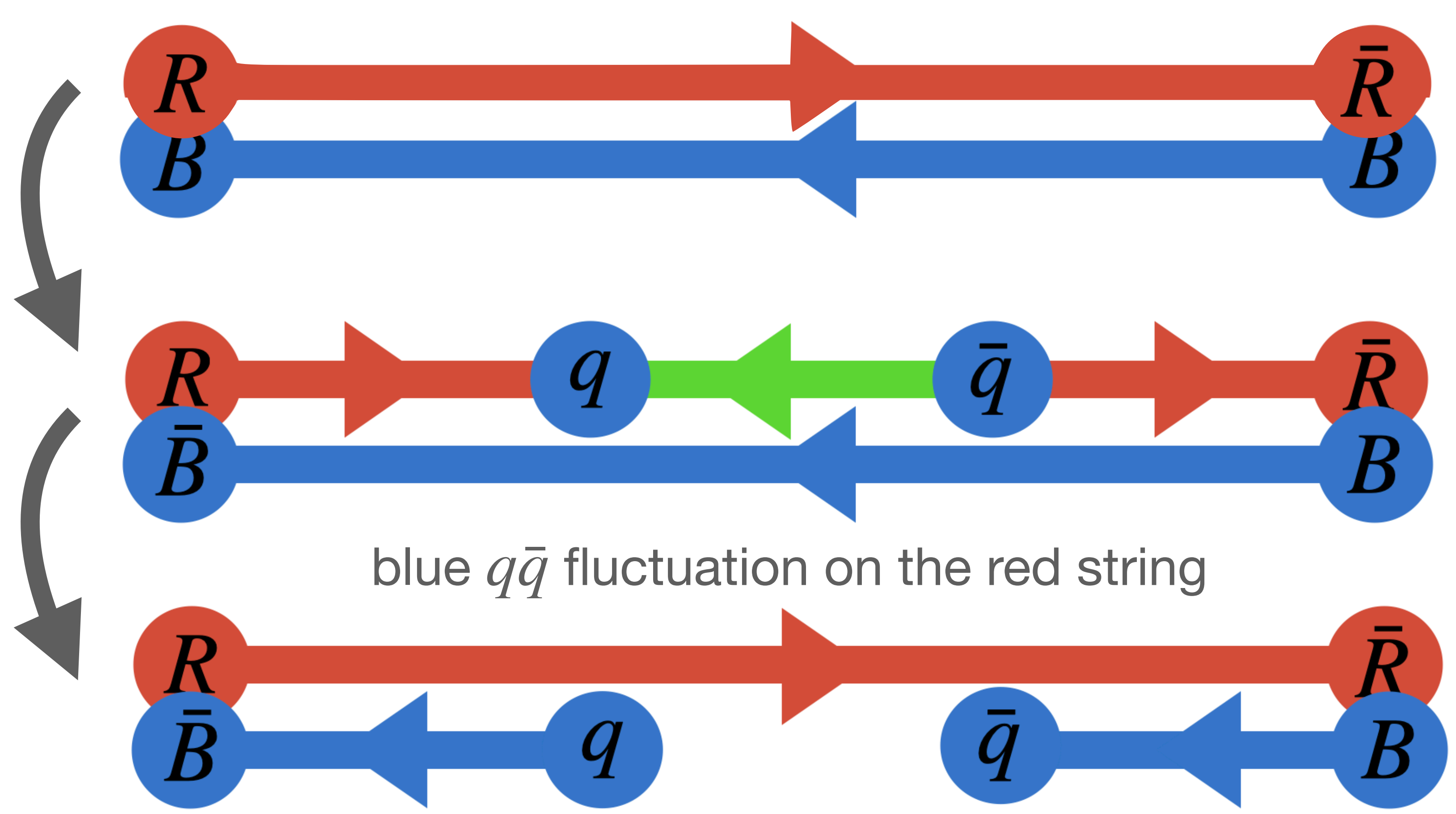
What would happen if we put this **red string** next to another string? e.g. a **blue string**

Diquark Disruption in Octet Fields? (The Altmann Mechanism)

Reexamine baryon formation via diquark production

Popcorn mechanism for diquark production

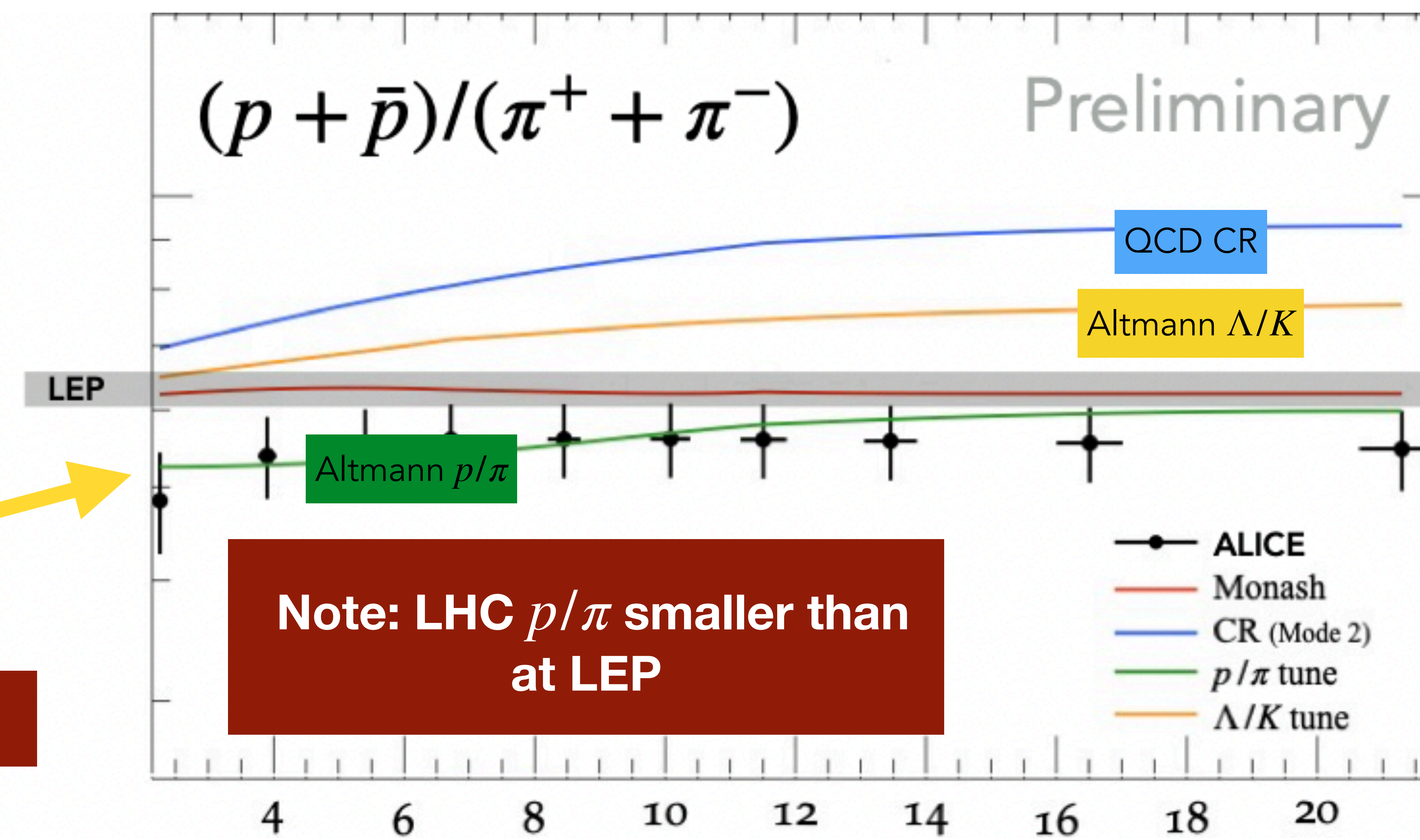
Diquark formation via **successive colour fluctuations** — popcorn mechanism



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

NEW

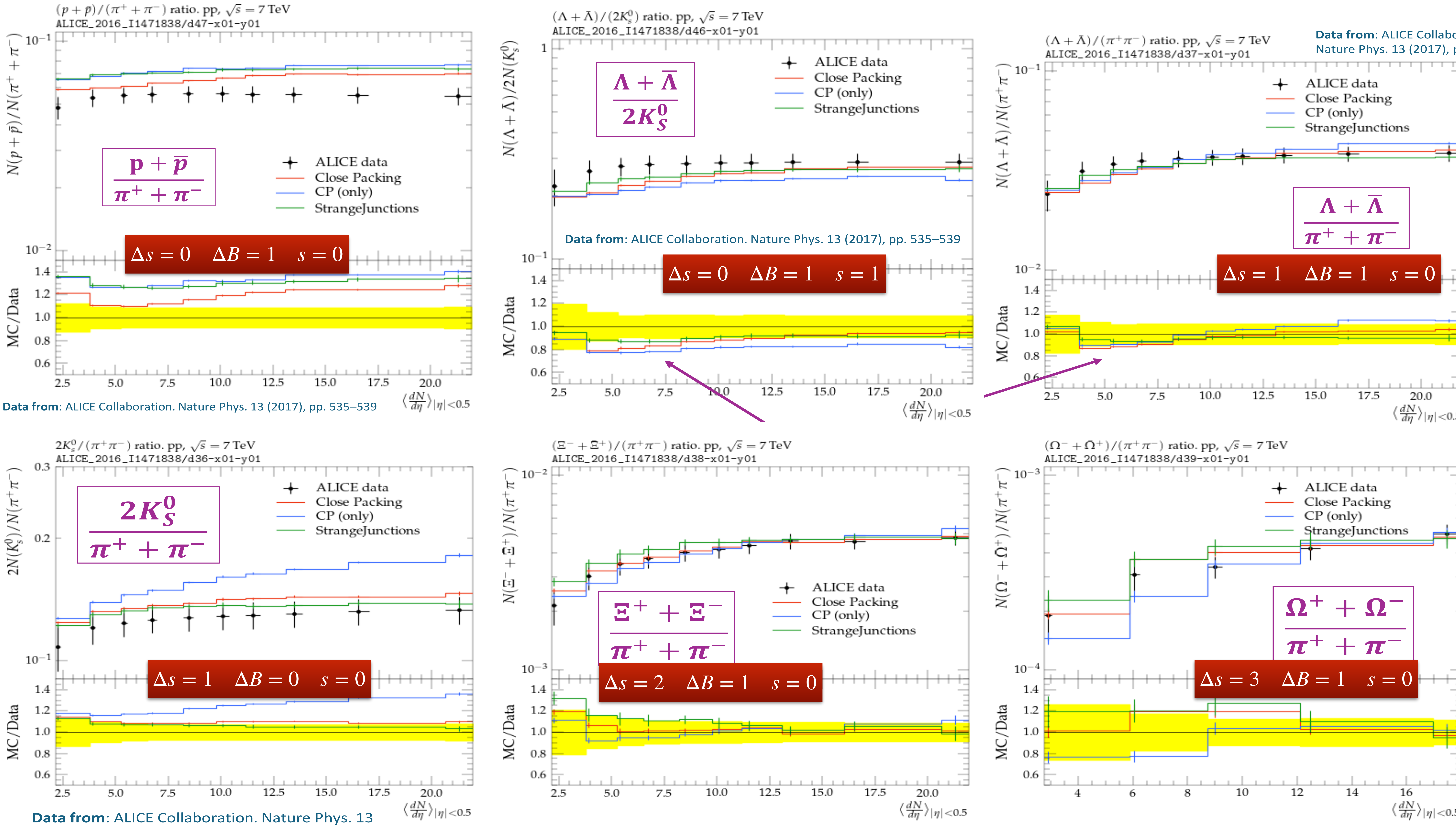
Popcorn destructive interference



Q: could one see this also in (at tips of) gluon jets?

Preliminary Trieste Tunes by L. Bernardinis (& V. Zaccolo)

Data from: ALICE Collaboration. Nature Phys. 13 (2017), pp. 535–539



Data from: ALICE Collaboration. Nature Phys. 13 (2017), pp. 535–539

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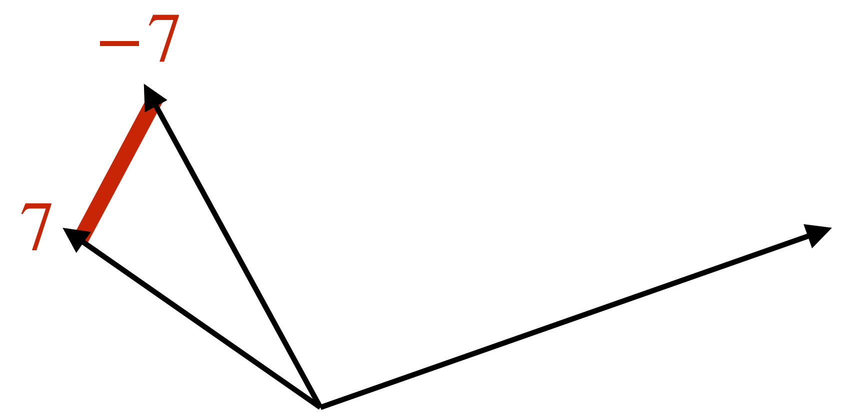
New directions: QCD CR Sequential-Recombination model?

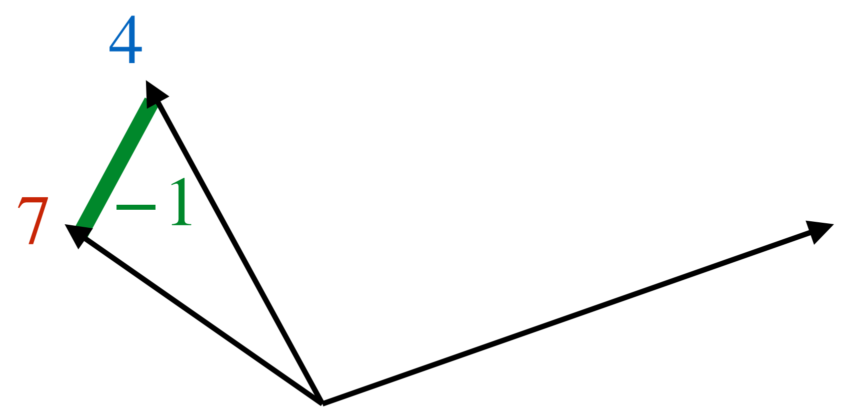
The stochastic SU(3) model:

Assign "Colour indices" $\in [1,9]$ to each parton



Dipole type screening: $i \oplus -i = 0$**:**

Partons with matching (anti)indices can screen each other



Junction type screening : $i \oplus (i+3) = -(i+6)$**:**

Partons with indices in modulo-3 groups can screen each other

New QCD CR by sequential recombination under development:

Combine nearby partons (by λ measure) if at least partially screening

$\Longrightarrow$ Can build larger reps (p, q) with p indices and q anti-indices.

E.g., we already use $(p, q) = (1,1)$ to represent QCD octets (**8**)

But also, e.g., a state with $(p, q) = (3,2) =$ **42** could be represented by: (1 3 2);(-4 -8)

Screening implies additional rules. E.g., for octet, the p and q index cannot be the same (or it would be singlet)

For higher multiplets, we also check for degeneracies modulo 3 among the p or q indices respectively.

Outlook

Works underway

Close-packing + tuning with Altmann, Bernardinis, Kreps, Zaccolo

Excited Strings with Altmann, Carragher, March-Russell

QCD CR by sequential recombination with Altmann, El-Menoufi, Scyboz, Smith

CP Echidna Model with Bergmann

Lightcone Scaling & follow-ups with Abidi

Stay "tuned" !

LEP tuning with Jueid + others

LEP studies with Hansen + others?

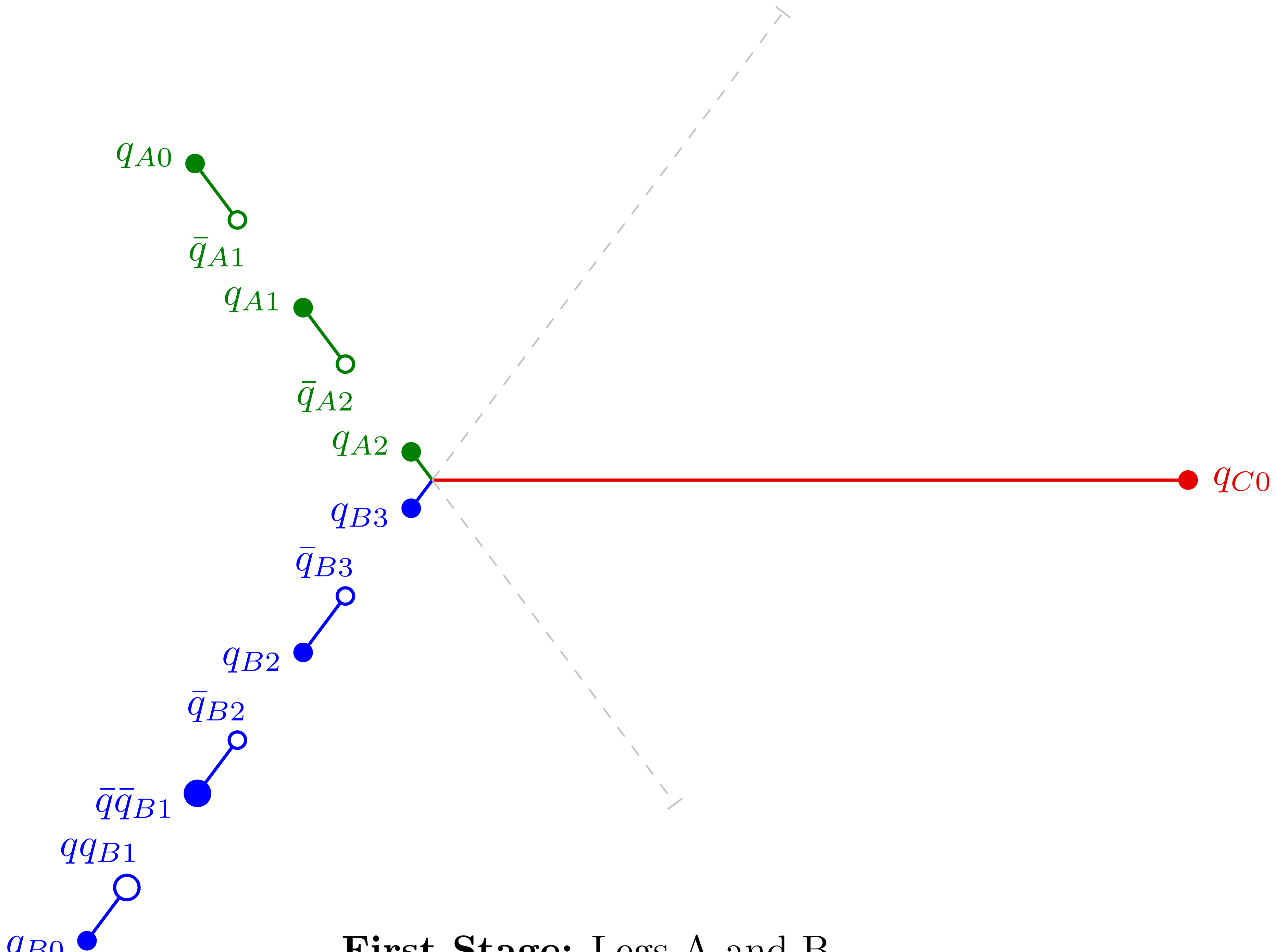
+ Renewed PYTHIA 8.3 general tuning effort

Backup Slides

Fragmentation of String Junctions

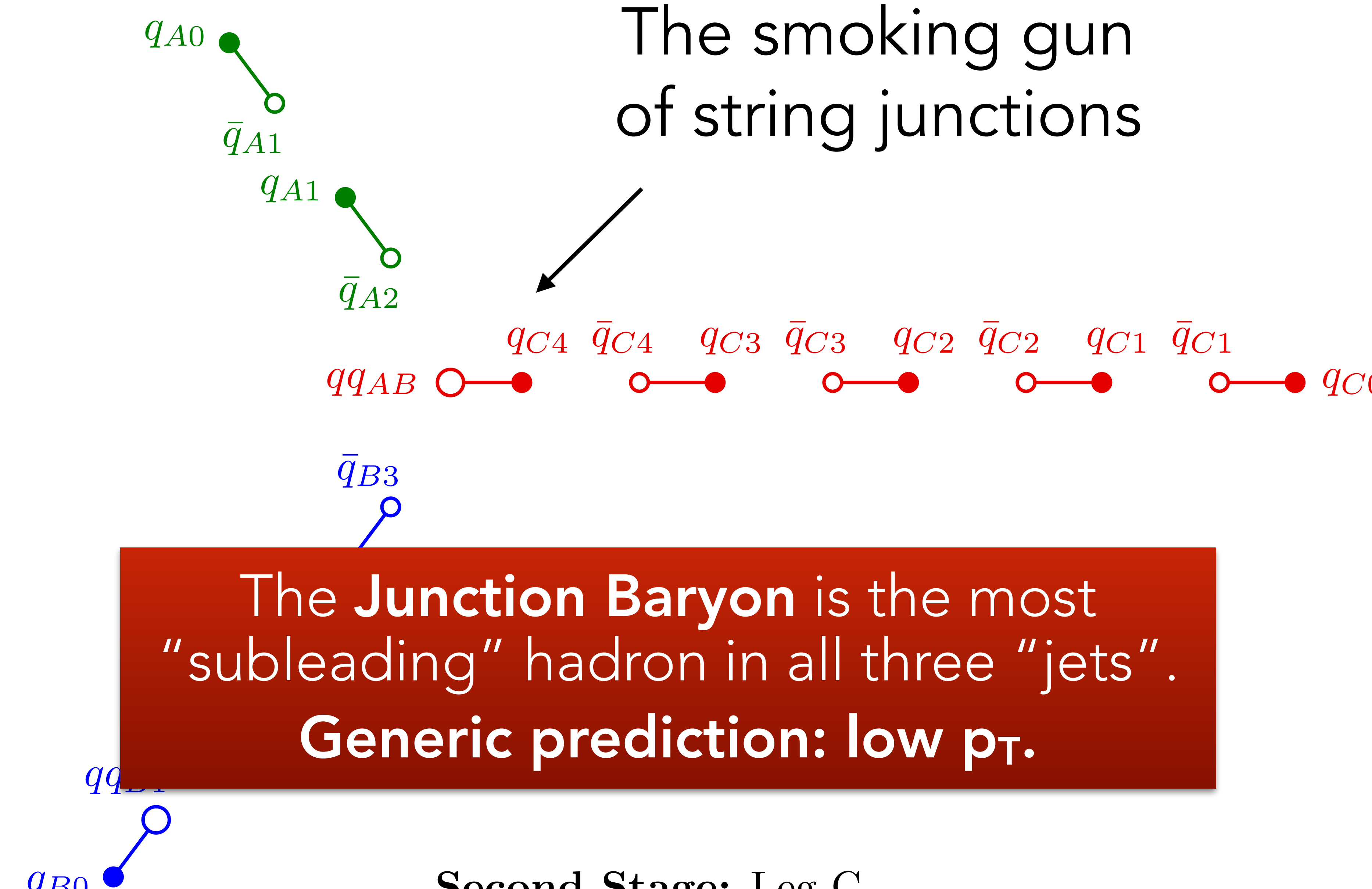
Assume Junction Strings have same properties as ordinary ones (u:d:s, Schwinger p_T, etc)

- Exploit causality again to fragment outwards-in, from endpoints towards junction
- **First Stage:** 2 least energetic legs (q_{A0}, q_{B0}) fragmented first
- When little energy left, remains (q_{A2}, q_{B3}) collapsed to "diquark" (qq_{AB})
- **Second Stage:** Remaining qq_{AB}—q_{C0} string fragmented as usual. Leading hadron on qq_{AB} end = **junction baryon**.



First Stage: Legs A and B

The smoking gun of string junctions



The **Junction Baryon** is the most "subleading" hadron in all three "jets".
Generic prediction: low p_T.

Second Stage: Leg C

Predicting the Junction Baryon Spectrum

The Junction Baryon = smoking gun of String Junctions

Predicting the movement of the string junction is crucial!

To make solid predictions for Junction Baryon spectra, we use a trick: Sjöstrand & **PS**, *Nucl.Phys.B* 659 (2003) 243

Find the Lorentz frame in which the string **junction is at rest (JRF)**

Inverse boost (+ $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ kicks) $\Longrightarrow$ junction baryon spectrum

Junction = Topological Feature of Confinement Field

$$V(r) = \kappa r$$

$\Longrightarrow$ each "leg" (string piece) acts on the other two with **constant force**

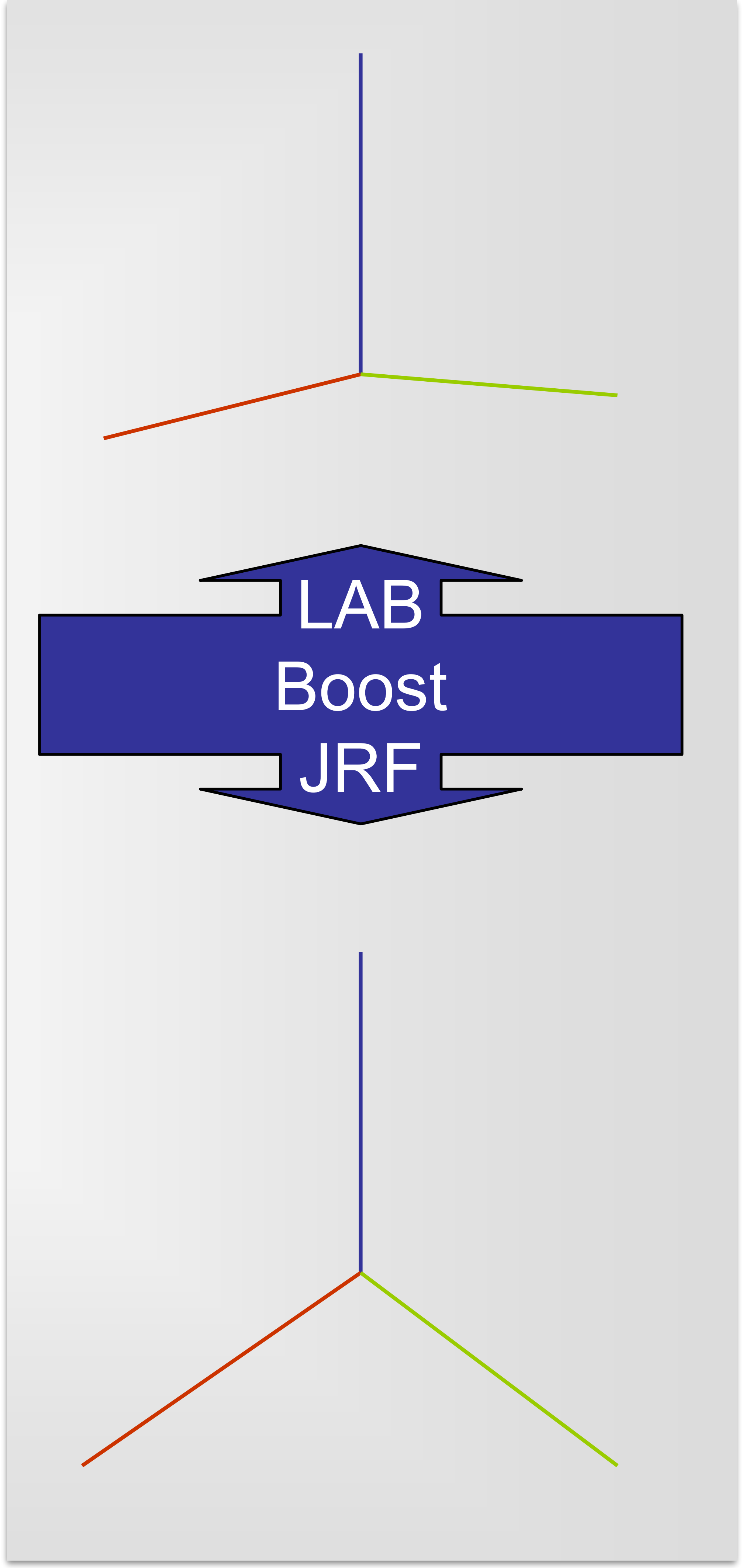
$$\vec{F} = \kappa\,\vec{e}_r.$$

$\Longrightarrow$ In "Mercedes Frame", the angle is $120°$ between the legs

Massless legs: exact solution. **Mercedes Frame = Junction Rest Frame (JRF).**

Massive legs (eg heavy flavours or ones with lots of kinks!) => Iterative algorithm.

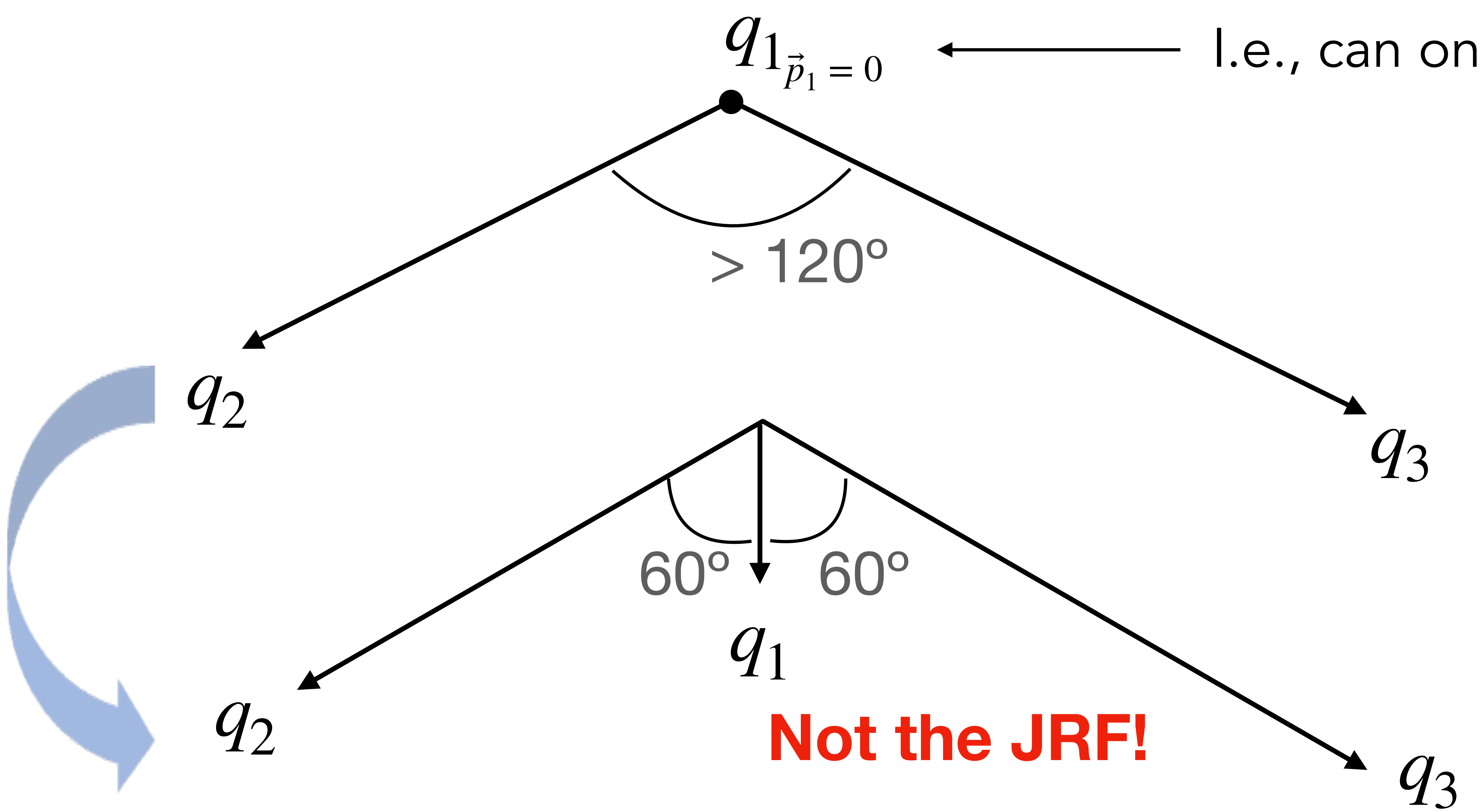
But org algorithm often broke down (failed to converge) for "soft legs"



Does a Boost to the Mercedes Frame Always Exist?

Consider the following kinematic case

In the **rest frame of one of the partons**, and the angle between the other two is **greater than 120 degrees** (not considered in org algorithmic implementation)



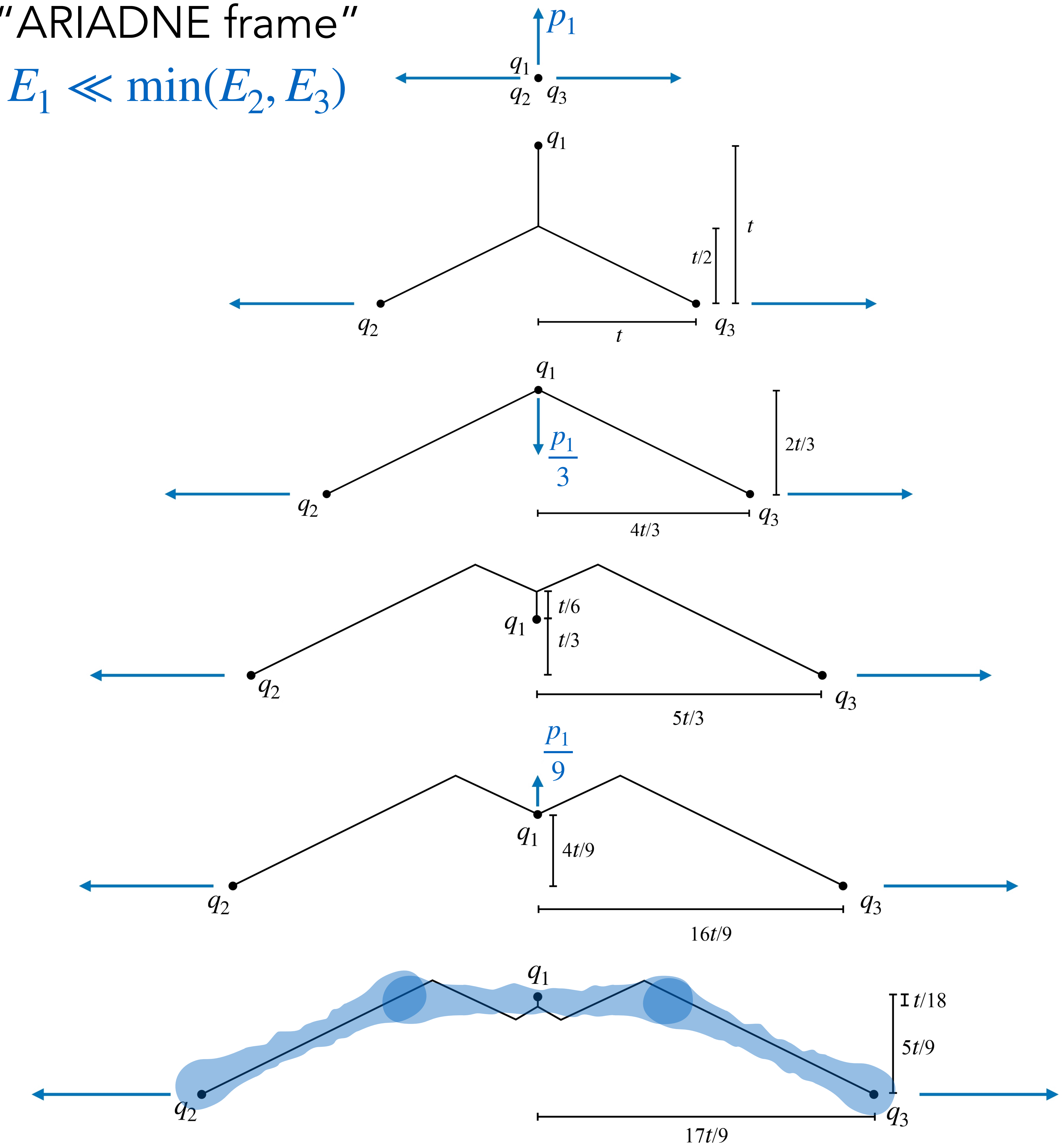
Org algorithm failed to converge

The case of a **heavy slow endpoint**: Pearl on a String

String Motion: Soft Massless Case

"ARIADNE frame"

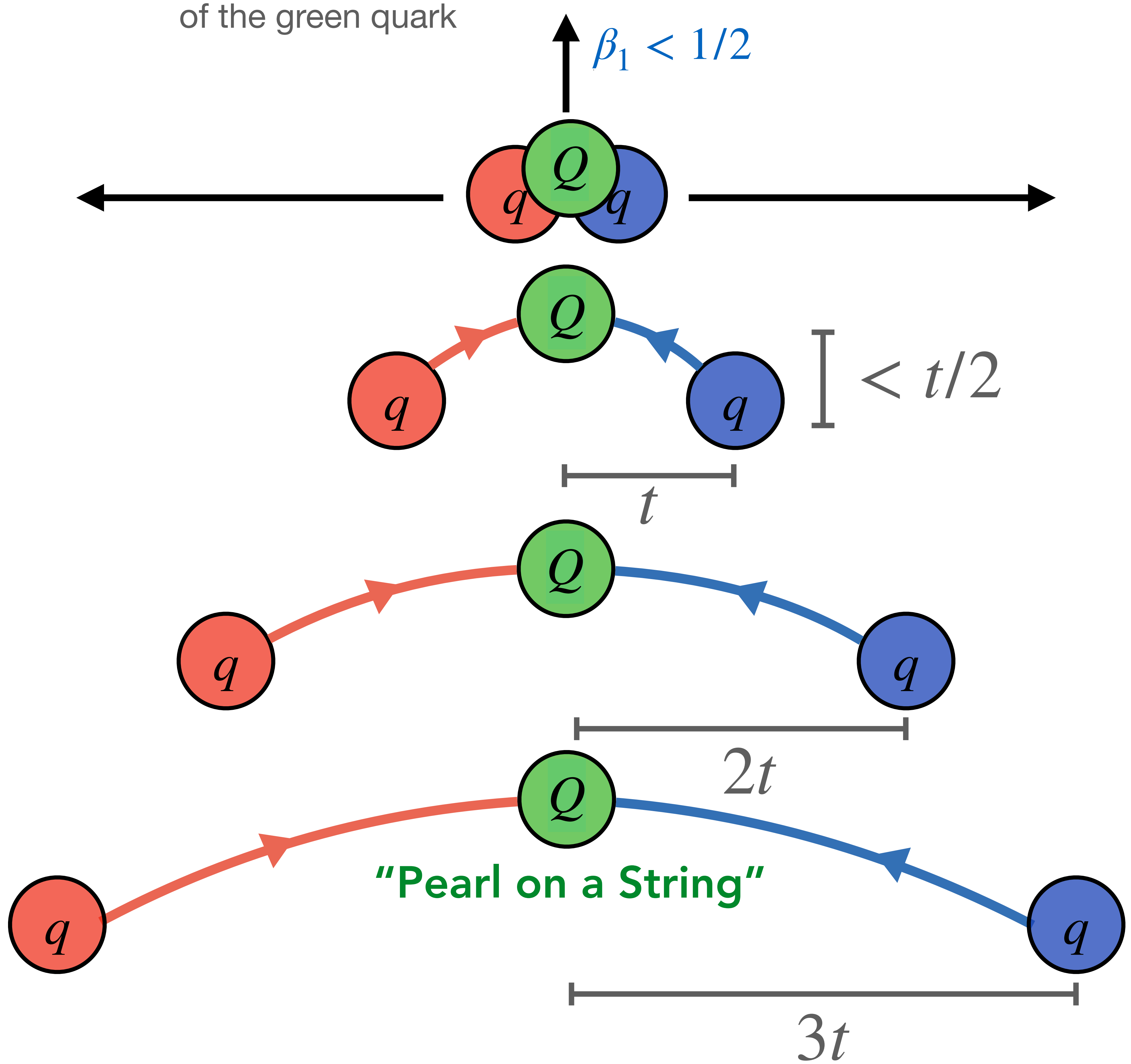
$E_1 \ll \min(E_2, E_3)$



Similar to a mesonic string with a gluon kink

String Motion: Slow Massive Case

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

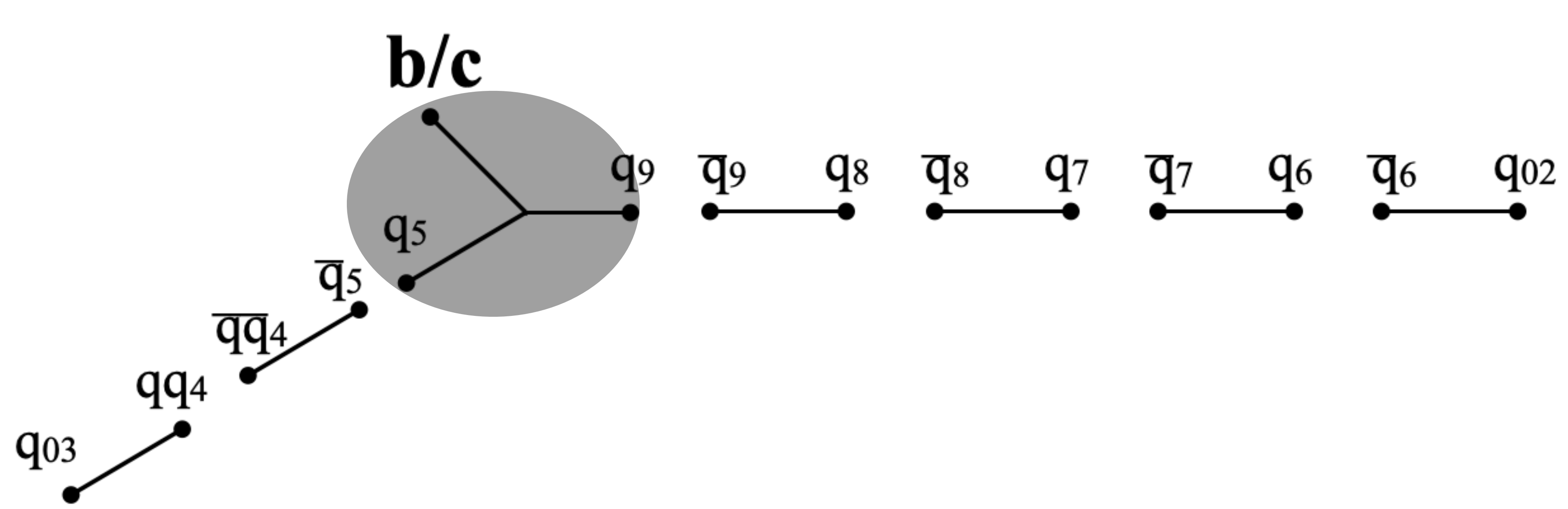


The case of a **heavy slow endpoint**: Pearl on a String

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



String Motion: Slow Massive Case

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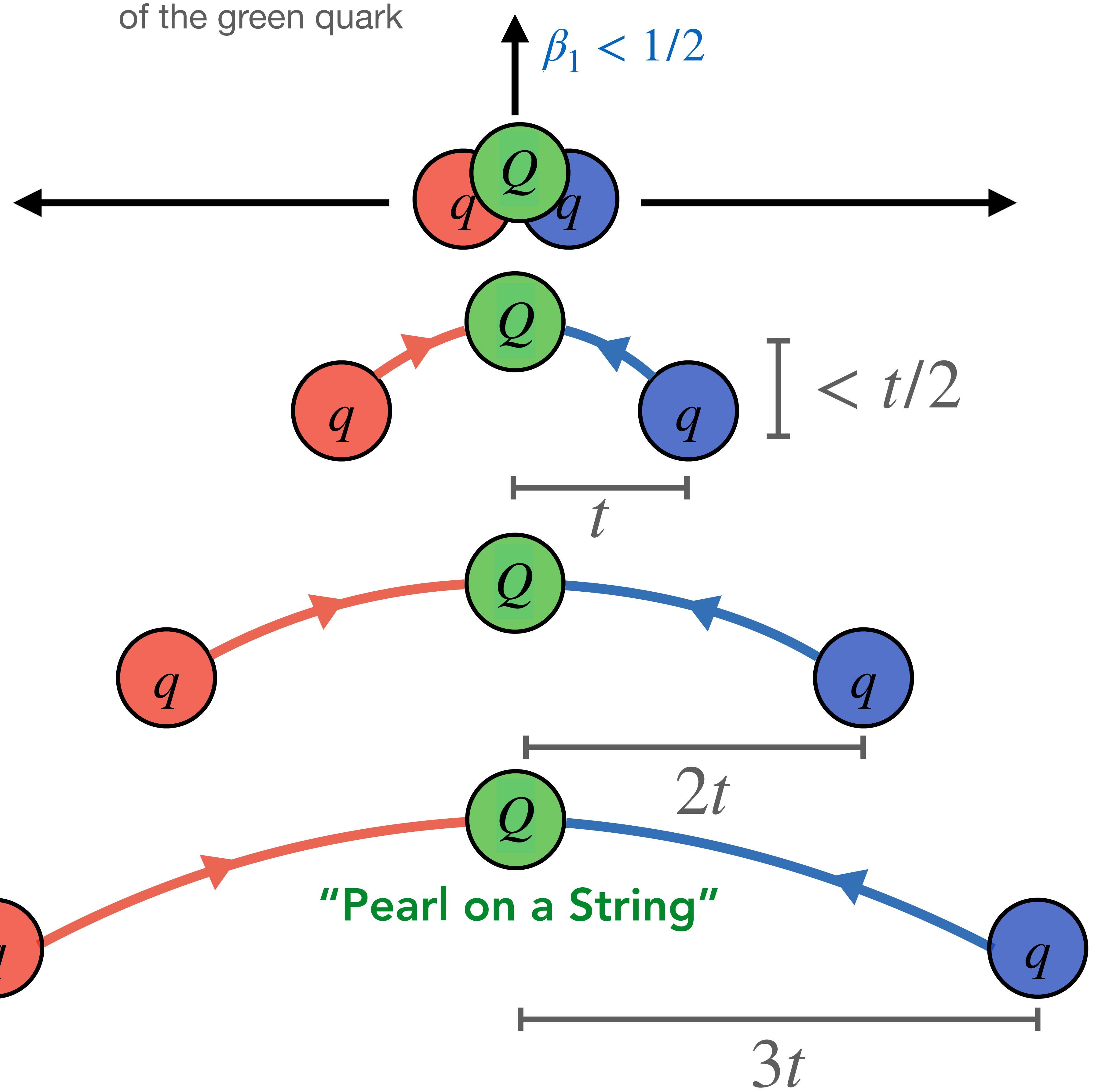


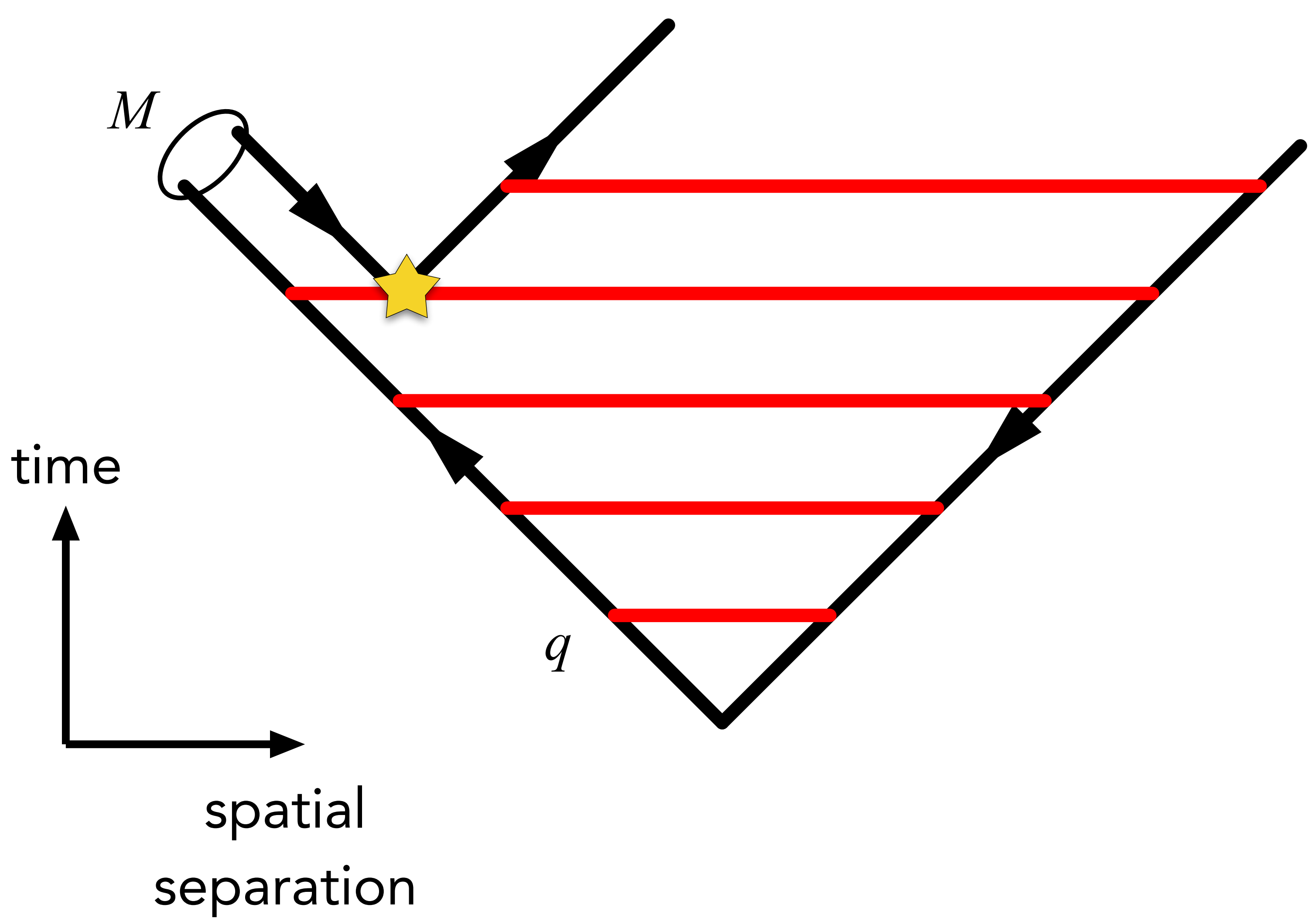
(Could it be Thermal?)

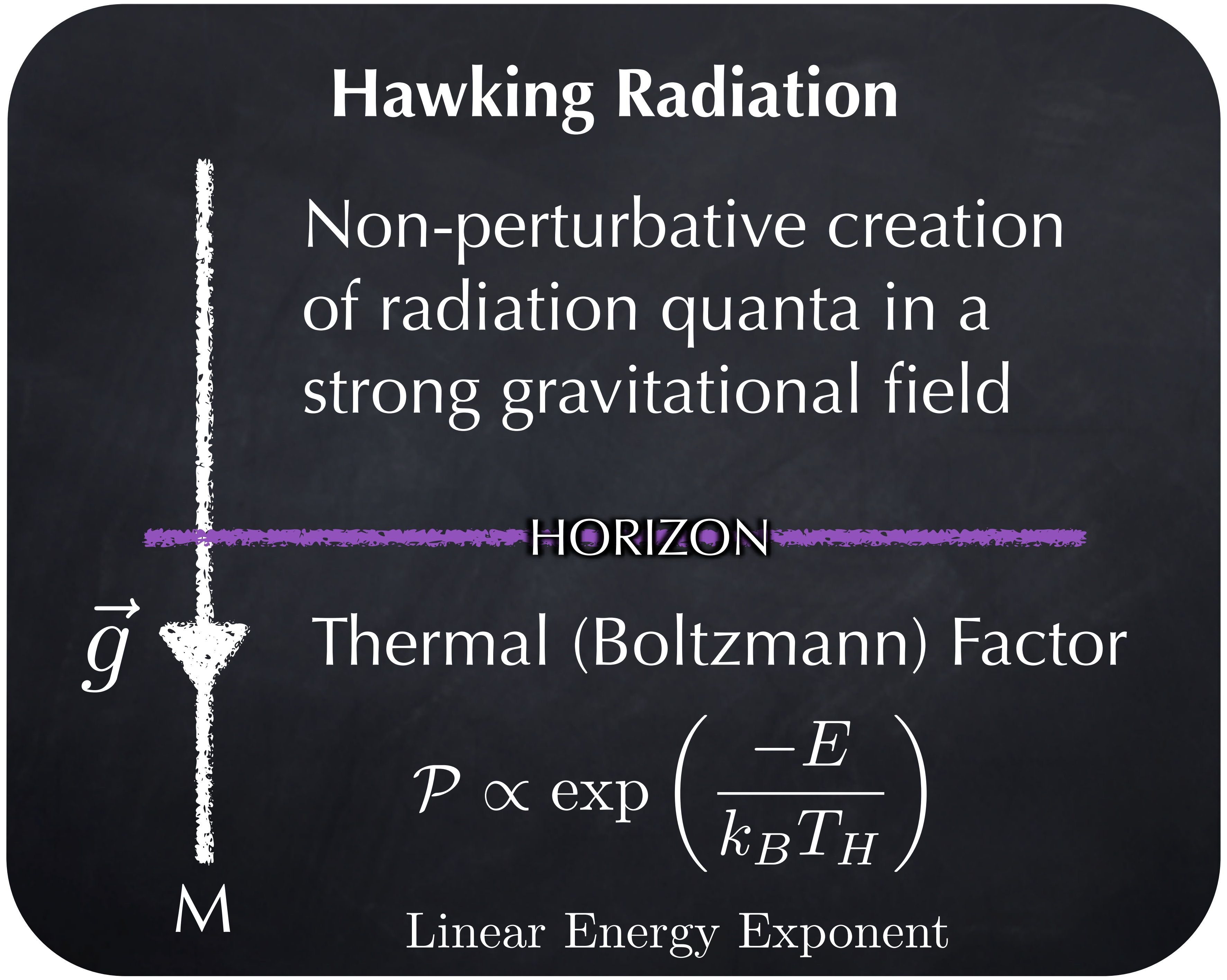
An Alternative Analogy … ?

$g \to q\bar{q} \implies$ The strings will "break"

Non-perturbative so can't use $P_{g\to q\bar{q}}(z)$

Pair creation near a black hole? →





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

Fischer & Sjöstrand JHEP 01 (2017) 140

Or a "hot string" that cools down?

*Hunt-Smith & **PS**, Eur.Phys.J.C 80 (2020) 11*