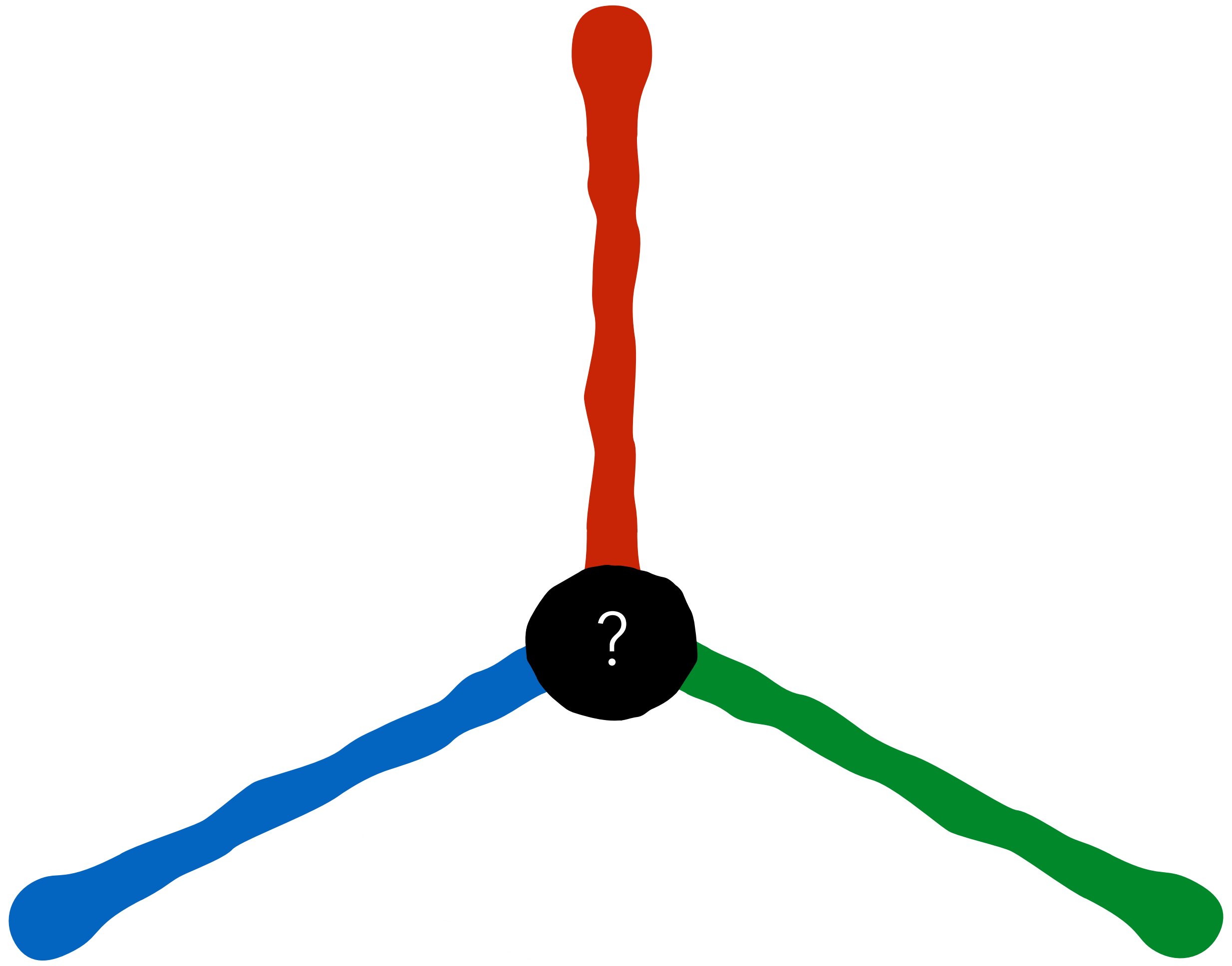
String Junctions at the Large Hadron Collider

Peter Skands (University of Oxford & Monash University)
*Work done with T. Sjöstrand, J Christiansen, and **J. Altmann***



1. **Confinement** in **High-Energy Collisions**
2. **Basics** of **String Hadronization**
3. **String Junctions**
4. **String Junctions at the LHC** (?)

Australian Government
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THE ROYAL SOCIETY
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The Problem of **Confinement** — in High-Energy Collisions

Consider a "hard" process

"Hard" = large momentum transfers

Example: $gg \to t\bar{t}$ →

Here, $Q^2 \sim m_t^2 \gg \Lambda_{\mathrm{QCD}}^2$

Accelerated charges (QED & QCD)

➜ Bremsstrahlung (QED & QCD)

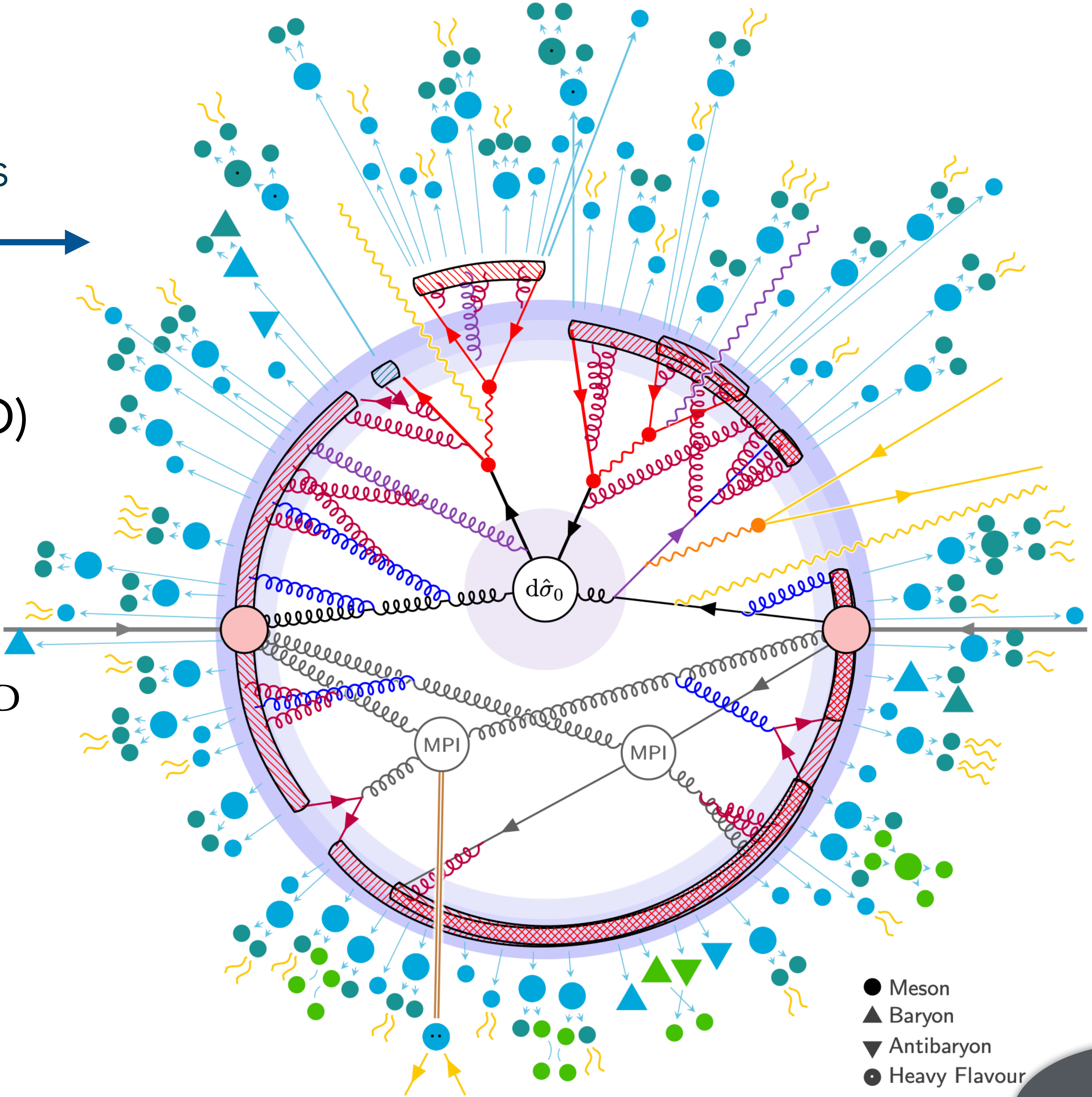
➜ Last seminar (Oct 19)

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

Some dynamical process must ensure quarks and gluons become confined inside hadrons:

Hadronization

What do we know about that?



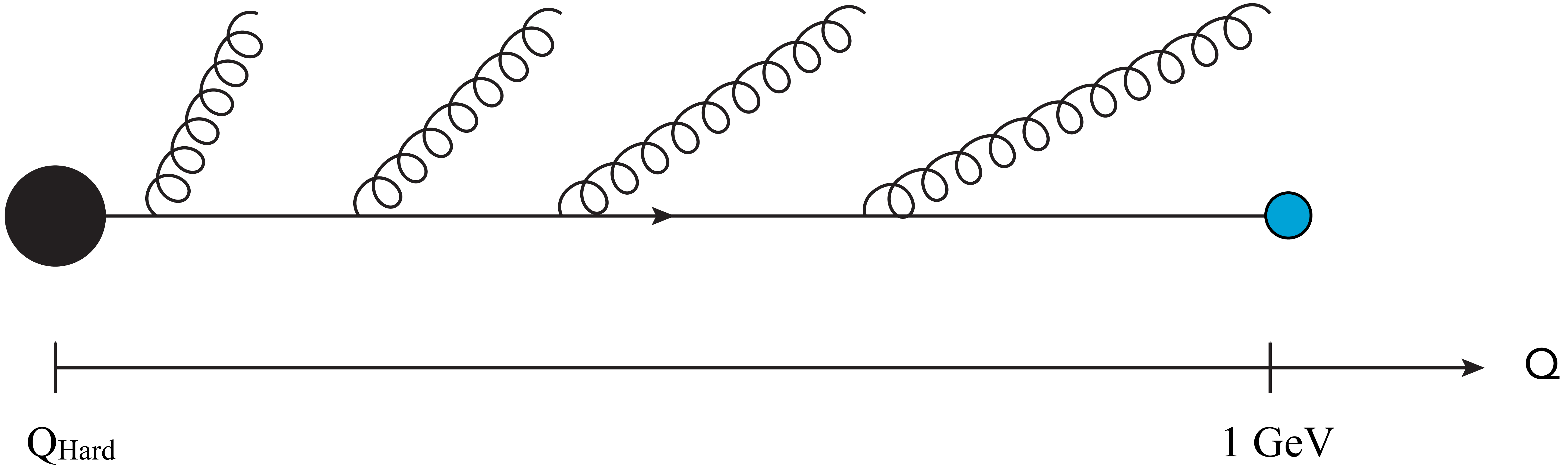
From **Partons** to **Pions**

Consider a parton emerging from a hard scattering (or decay) process

Hard:
Large momentum transfer
$Q_{\text{Hard}} \gg 1\,\text{GeV}$

It showers
(bremsstrahlung)

It ends up
at a low effective
factorization scale
$Q_{\text{Hadronization}} \sim m_\rho \sim 1\,\text{GeV}$



How about I just call it a hadron?

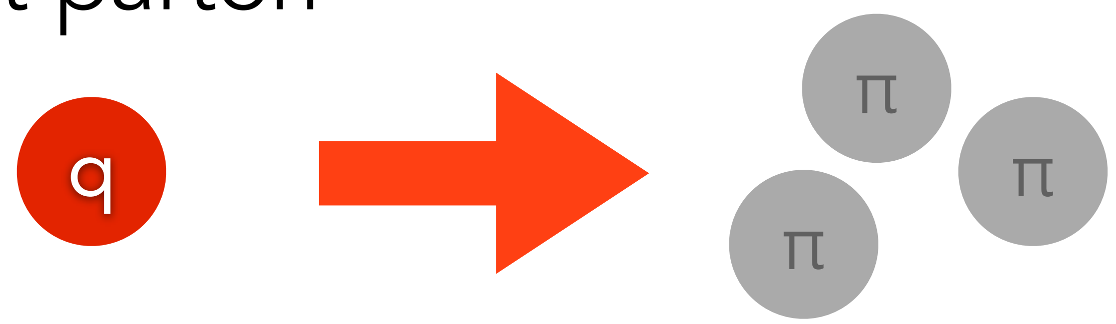
→ "Local Parton-Hadron Duality"

Local Parton Hadron Duality ↔ Independent Fragmentation

Local
Parton
Hadron
Duality

Fast parton

Hadrons



$Q_{\text{Factorization}}$

Momentum fractions $\{x\}$

$$F_{\pi/q}(Q_F, x)$$

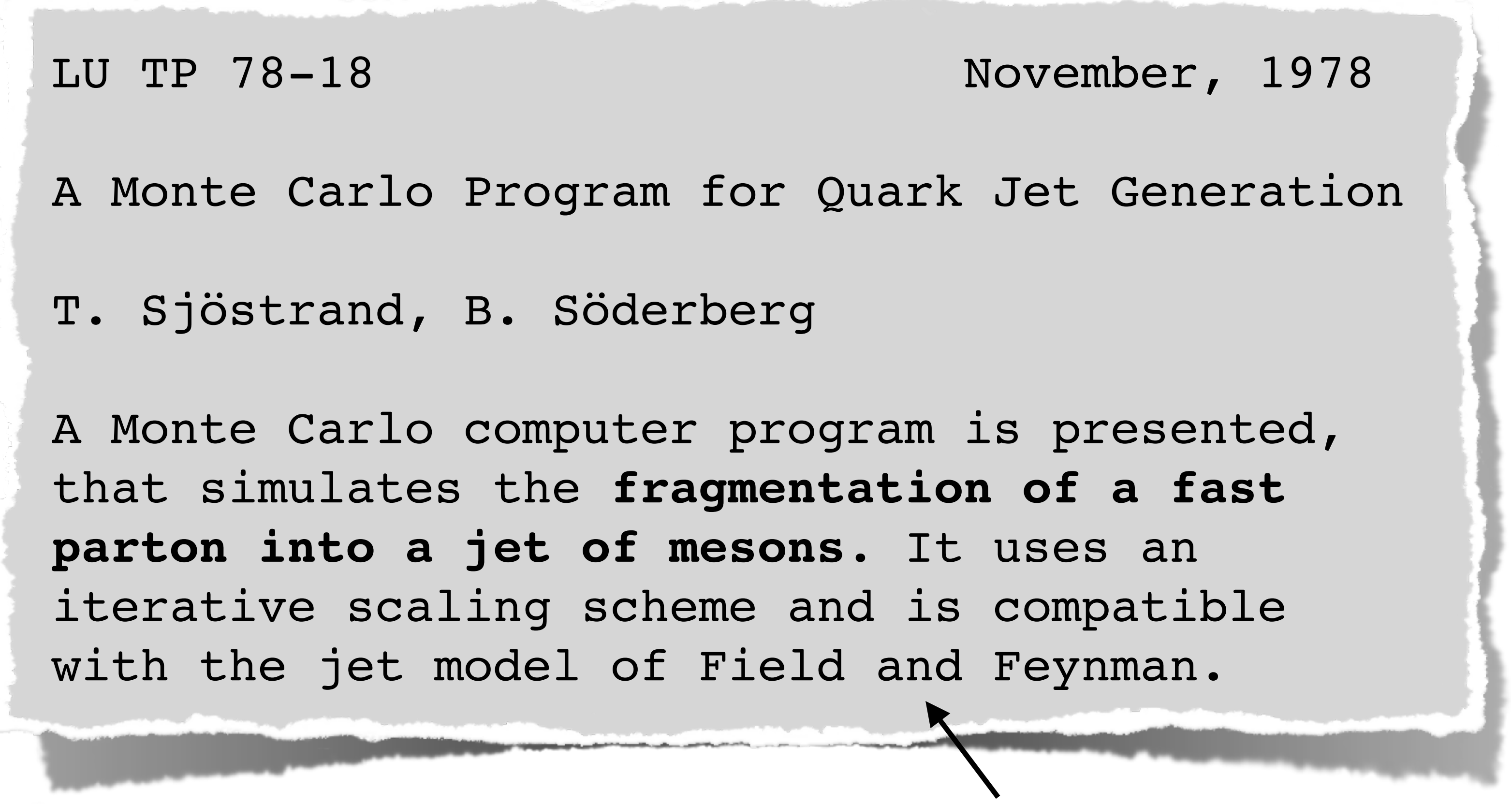
Fragmentation Function

⬍

Late 70

Late 70^{s} MC models: Independent Fragmentation

E.g., PYTHIA (then called JETSET) anno 1978



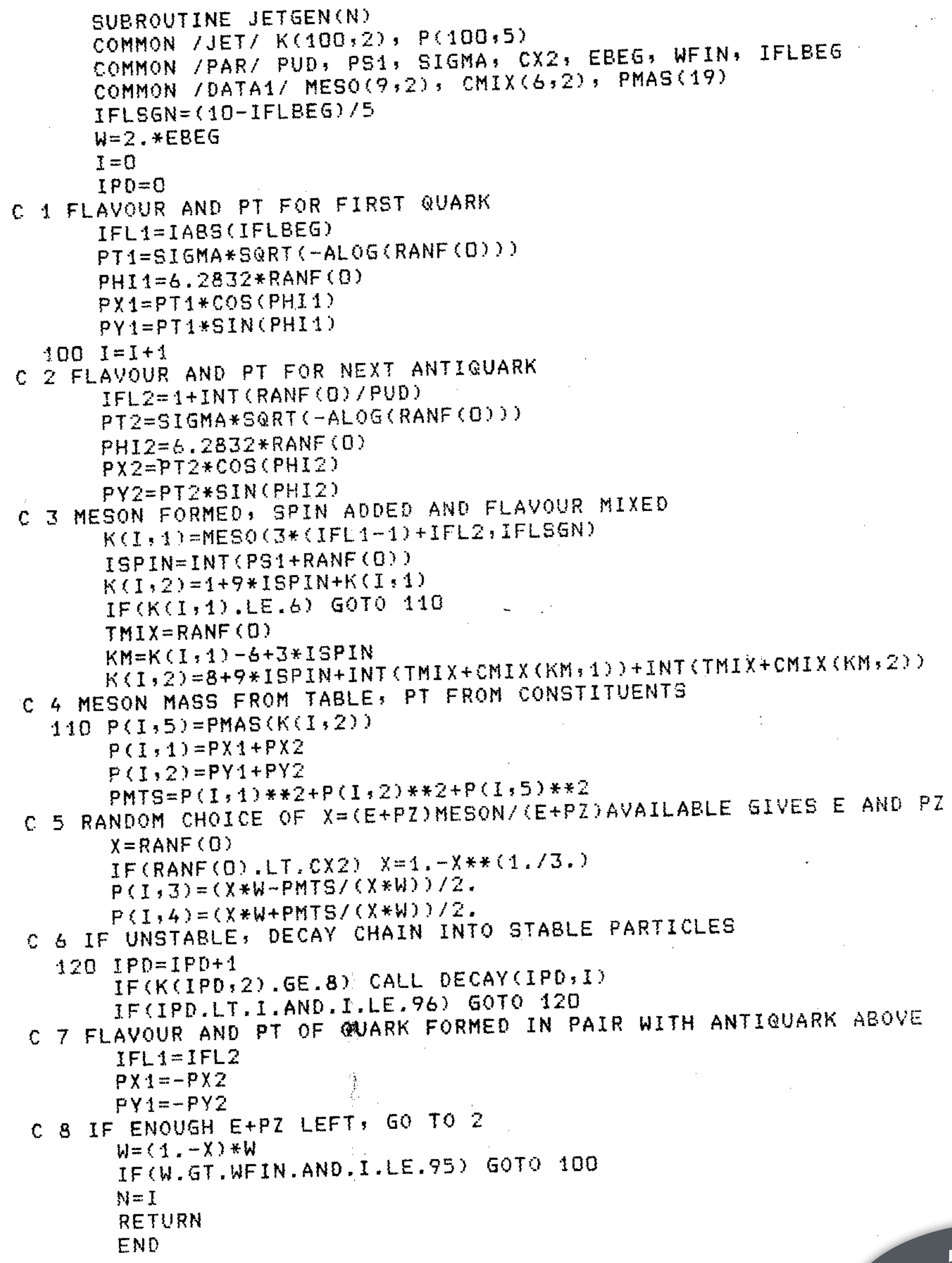
LU TP 78-18 November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the **fragmentation of a fast parton into a jet of mesons.** It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

Field-Feynman was an early fragmentation model.



```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

Colour Neutralisation

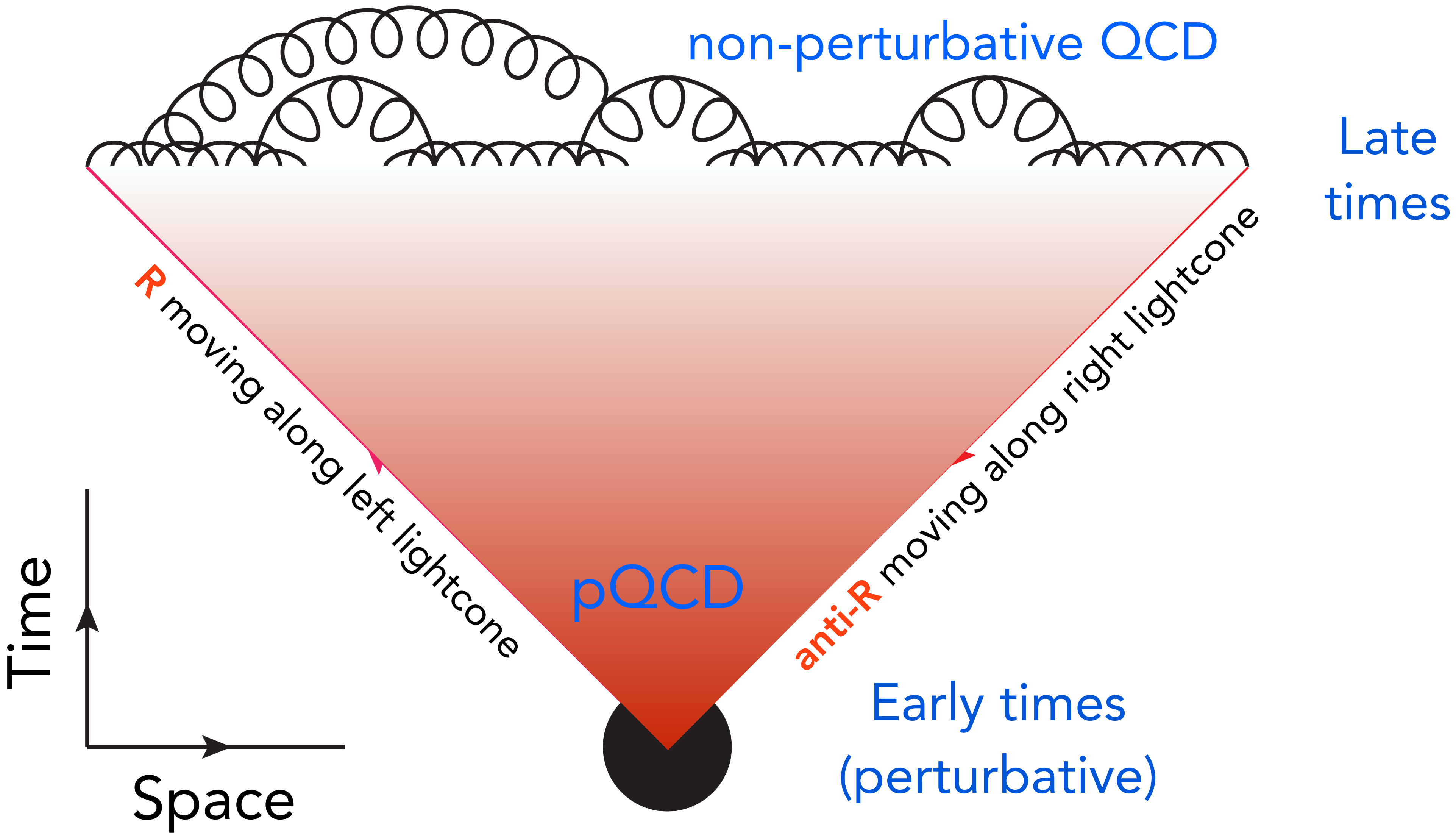
As a physical model, however, LPHD is a not a good starting point

The point of confinement is that partons are **coloured**.

A physical hadronization model

Should involve at least **two** partons, with opposite color charges

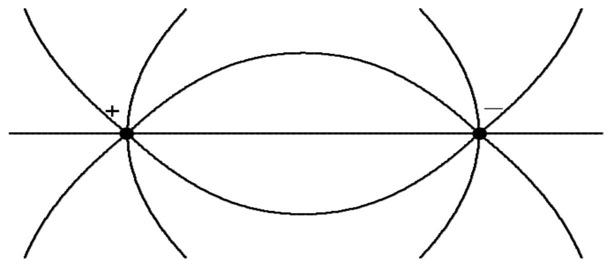
A strong **confining field** emerges between the two when their separation ≳ 1fm



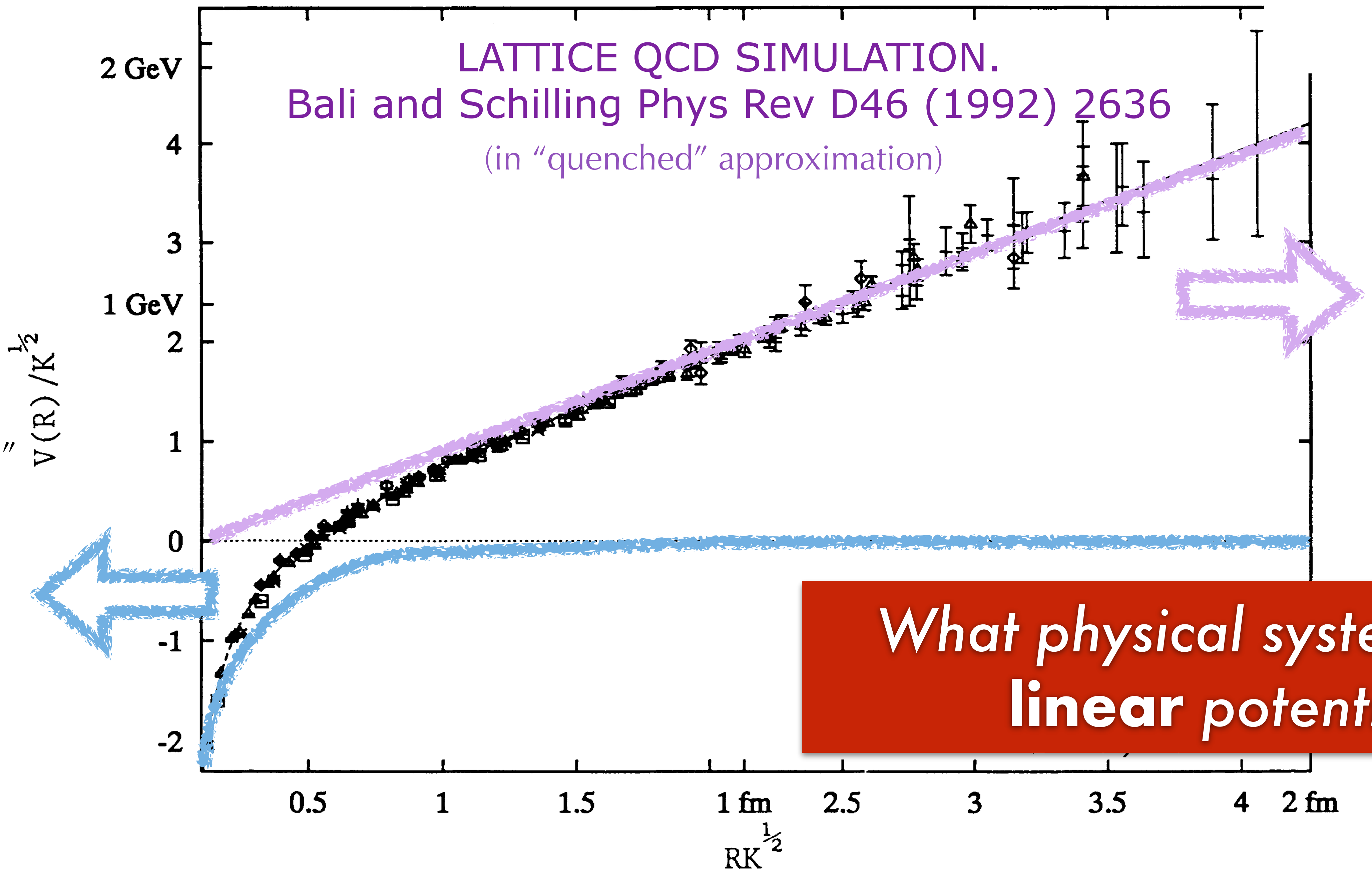
Two Partons: **Linear Confinement**

In lattice QCD, one can compute the potential energy of a colour-singlet $q\bar{q}$ state, as a function of the distance, r, between the q and $\bar{q}$

Short Distances ~ "Coulomb"

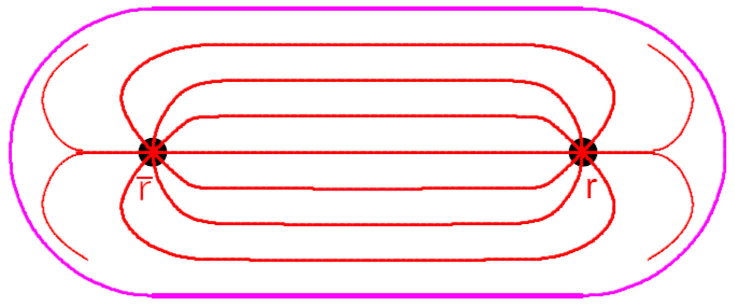


"Free" Partons



LATTICE QCD SIMULATION.
Bali and Schilling Phys Rev D46 (1992) 2636
(in "quenched" approximation)

Long Distances ~ Linear Potential



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

What physical system has a
***linear** potential?*

"Cornell Potential" fit: $V(r) = -\dfrac{a}{r} + \kappa r$ with $\kappa \sim 1\ \mathrm{GeV/fm}$ (→ could lift a 16-ton truck)

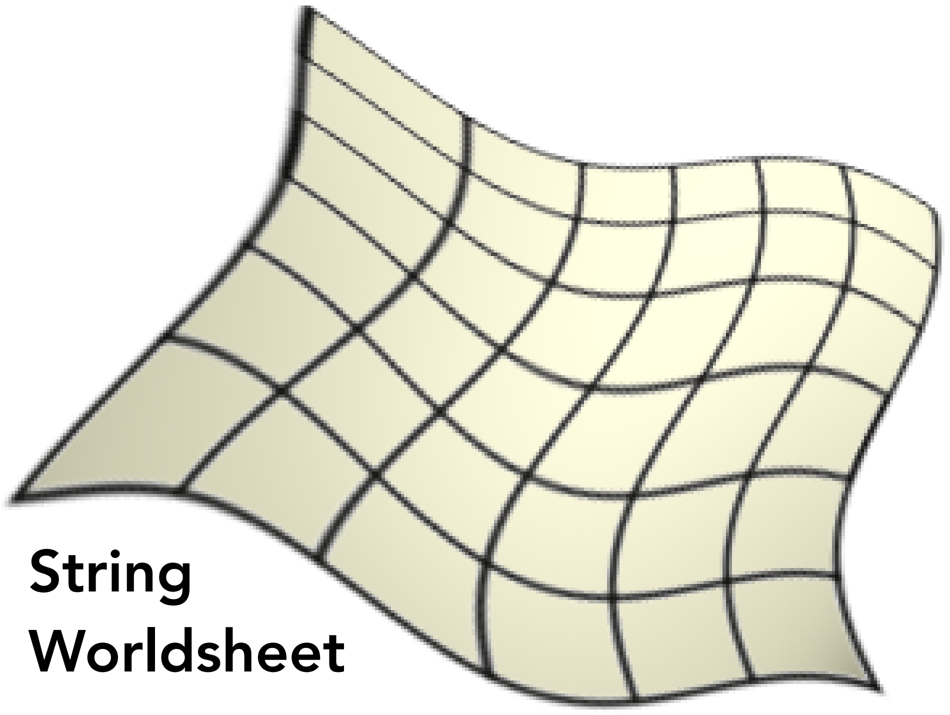
From **Partons** to **Strings**

Motivates a model:

Let colour field collapse into a narrow flux tube of uniform energy density

$\kappa \sim 1$ GeV / fm

Limit → Relativistic 1+1 dimensional worldsheet



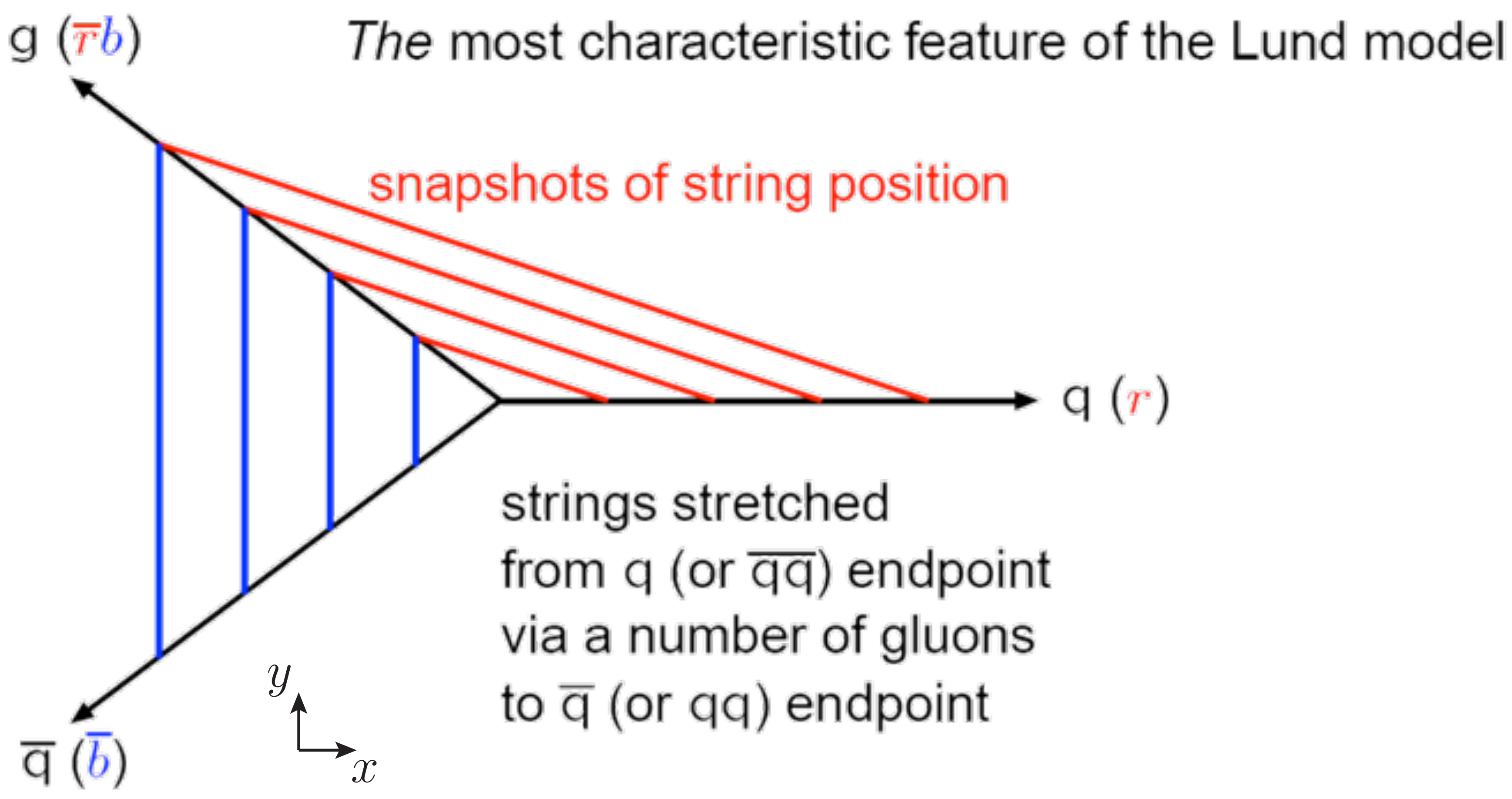
Map:

Quarks → String Endpoints

Gluons → Transverse Excitations (kinks)

Physics then in terms of string worldsheet evolving in spacetime

Nambu-Goto action $\Longrightarrow$ Area Law.



The most characteristic feature of the Lund model

Gluon = kink on string, carrying energy and momentum

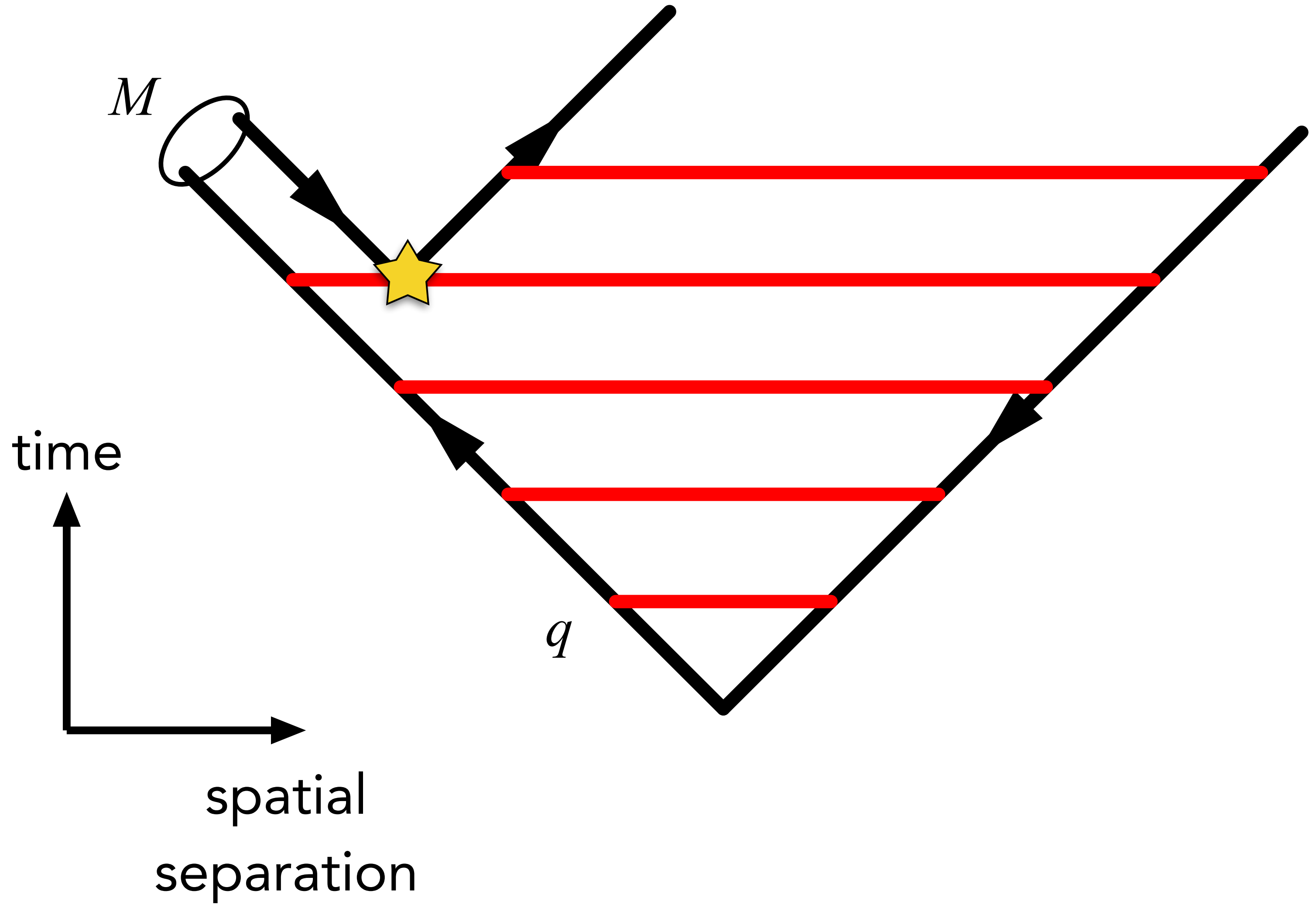
String **Breaking**

In “unquenched” QCD

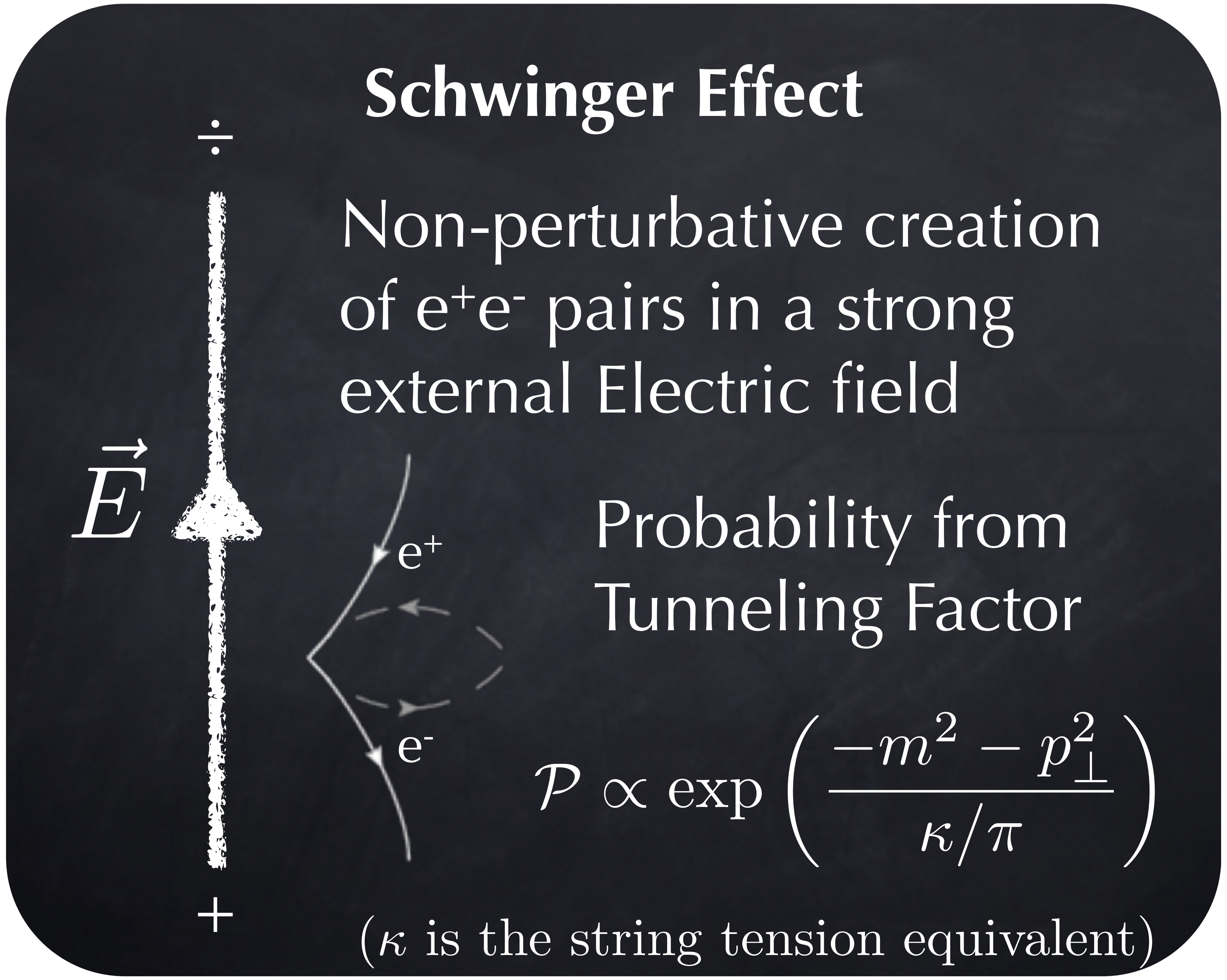
$g \to q\bar{q} \implies$ The strings will “break”

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

Model: Schwinger mechanism →



J. Schwinger, Phys. Rev. **82** (1951) 664



Schwinger Effect

Non-perturbative creation of e+e- pairs in a strong external Electric field

Probability from Tunneling Factor

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

(κ is the string tension equivalent)

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

Assume probability of string break constant per unit world-sheet area

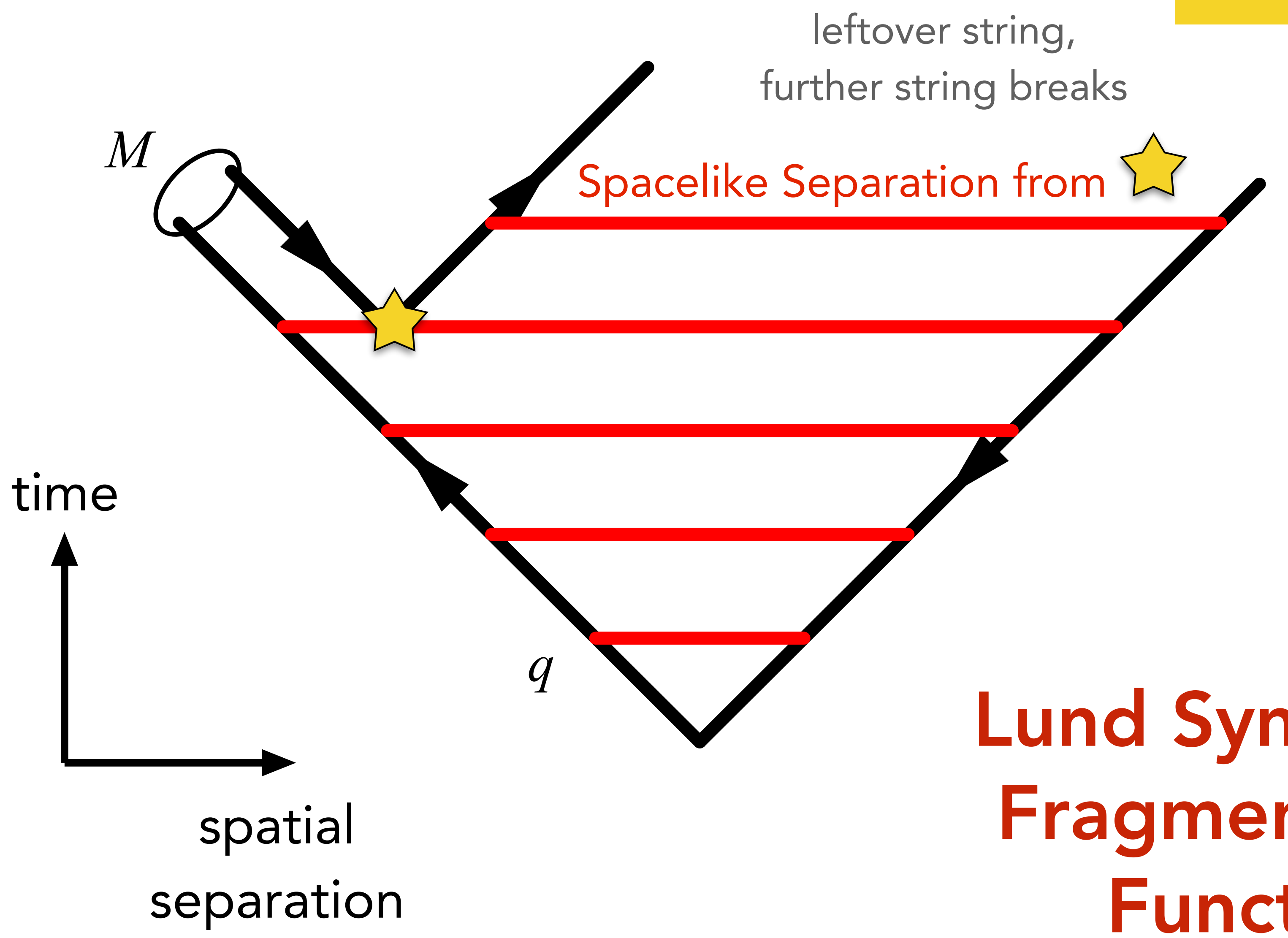
Schwinger Case: **the String Fragmentation Function**

Schwinger $\Longrightarrow$ Gaussian $p_\perp$ spectrum (transverse to string axis) **& Prob(d:u:s) ≈ 1 : 1 : 0.2**

The meson M takes a fraction z of the quark momentum,

Probability distribution in $z \in [0,1]$, is parametrised by the **Fragmentation Function**, $f(z, Q^2_{\mathrm{HAD}})$

Observation: All string breaks are **causally disconnected**



Lorentz invariance $\Longrightarrow$ string breaks can be considered in *any order*. Imposes "left-right symmetry" on the **FF**

$\Longrightarrow$ **FF** constrained to a form with **two free parameters**, a & b: constrained by fits to measured hadron spectra

Lund Symmetric Fragmentation Function

$$f(z) \propto \frac{1}{z}\underset{\uparrow}{(1-z)^a}\exp\left(\underset{\uparrow}{-}\frac{b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

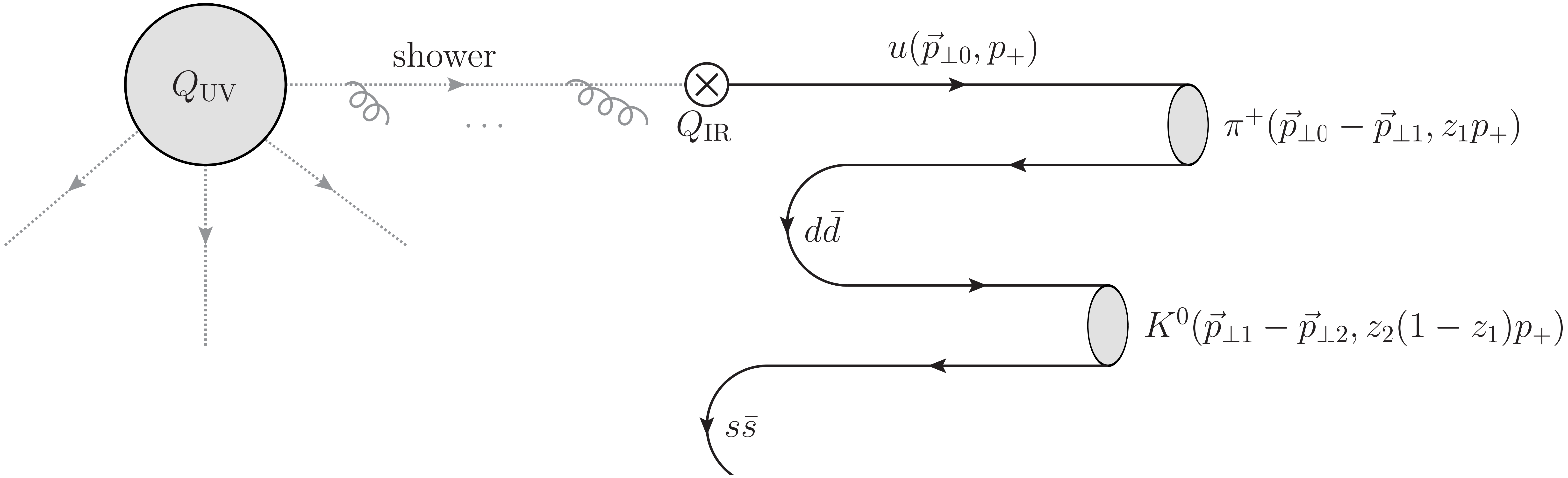
Supresses high-z hadrons

Supresses low-z hadrons

Iterative String Breaks

Causality → May iterate from outside-in

Note: using light-cone coordinates: $p_+ = E + p_z$



On average, expect energy of nth "rank" hadron ~ E_n ~ $<z>^n E_0$

(Note on the Length of Strings)

In Spacetime:

String tension ≈ 1 GeV/fm → a 10-GeV quark can travel 10 fm before all its kinetic energy is transformed to potential energy in the string. Then it must start moving the other way.

(→ “yo-yo” model of mesons. Note: string breaks → several mesons)

The MC implementation is formulated in momentum space

Lightcone momenta $p_\pm = E \pm p_z$ along string axis

Rapidity (along string axis) and $p_\perp$ transverse to it

If the quark gives all its energy to a single pion traveling along the z axis

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$$

→

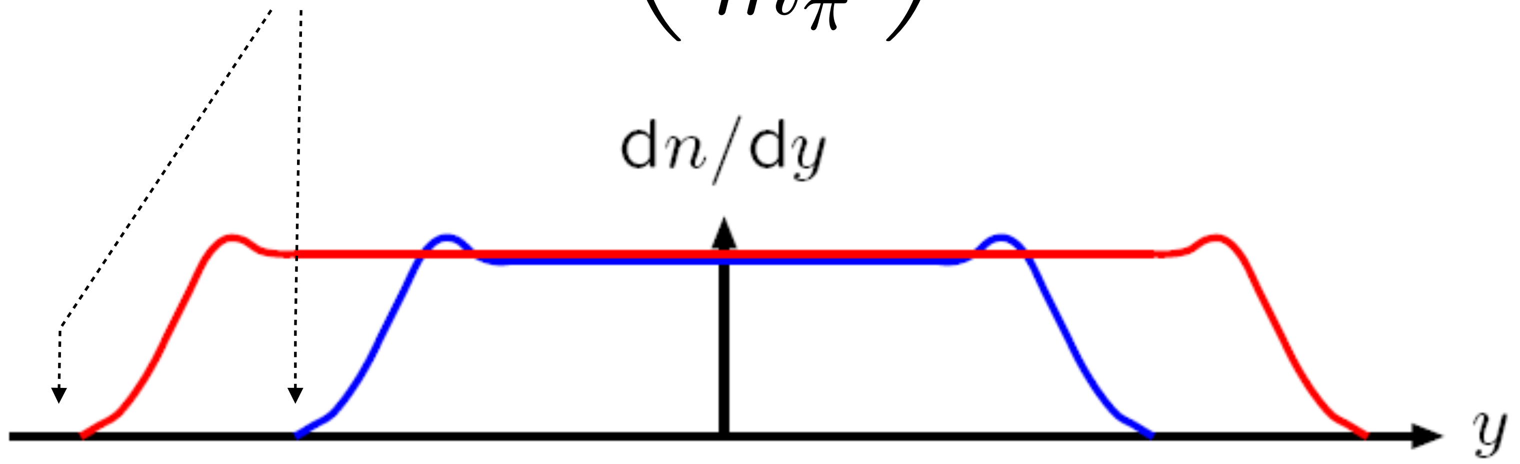
$$y_{\max} \sim \ln\left(\frac{2E_q}{m_\pi}\right)$$

Increasing E_q → logarithmic growth in rapidity range

Particle Production:

Scaling in $z \Longrightarrow$ flat in rapidity (long. boost invariance)

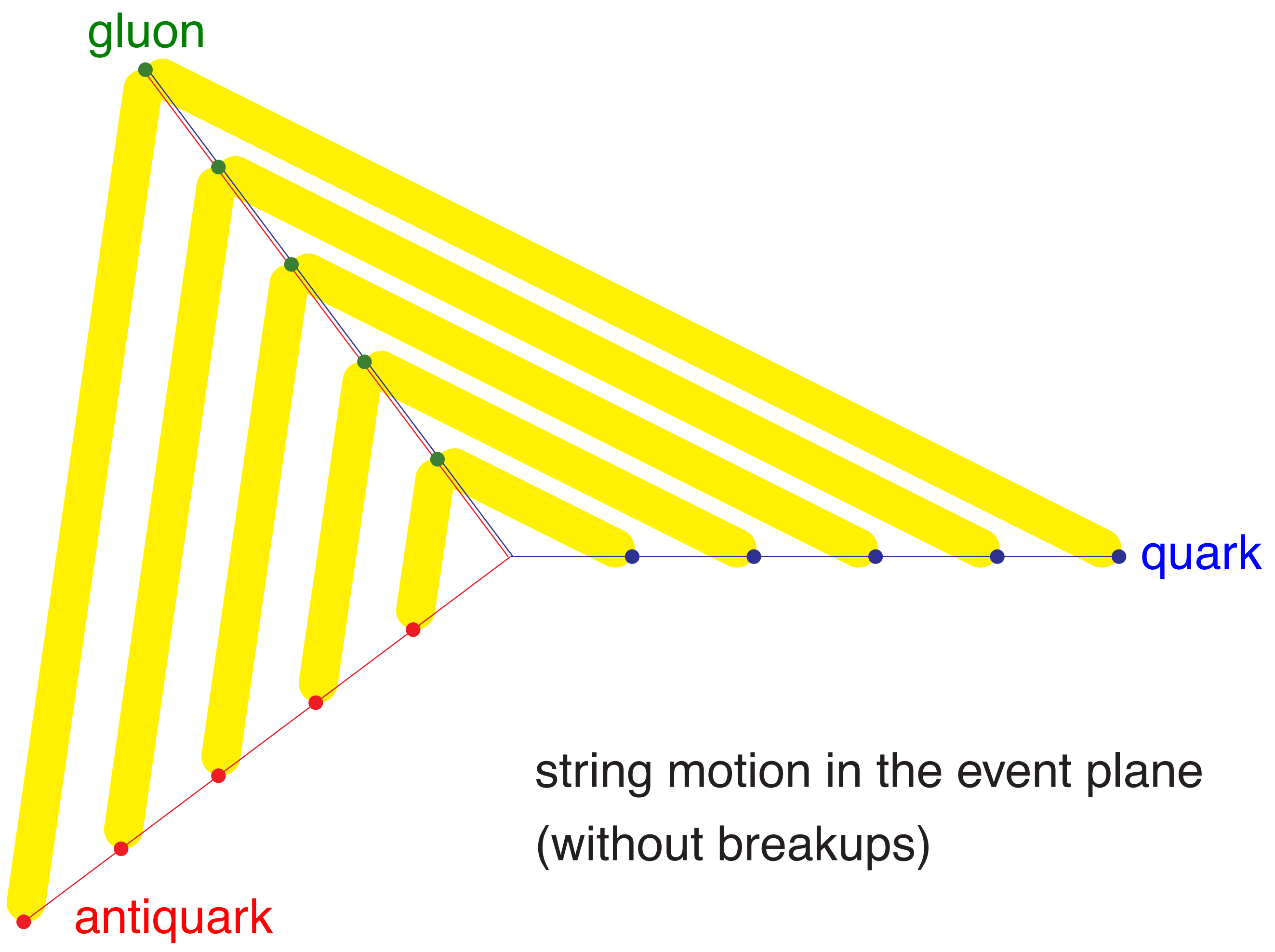
"Lightcone scaling"



$\langle n_{\mathrm{ch}}\rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, ∼ Poissonian multiplicity distribution

Gluon Kinks: The Signature Feature of the Lund Model

Gluons are connected to two string pieces

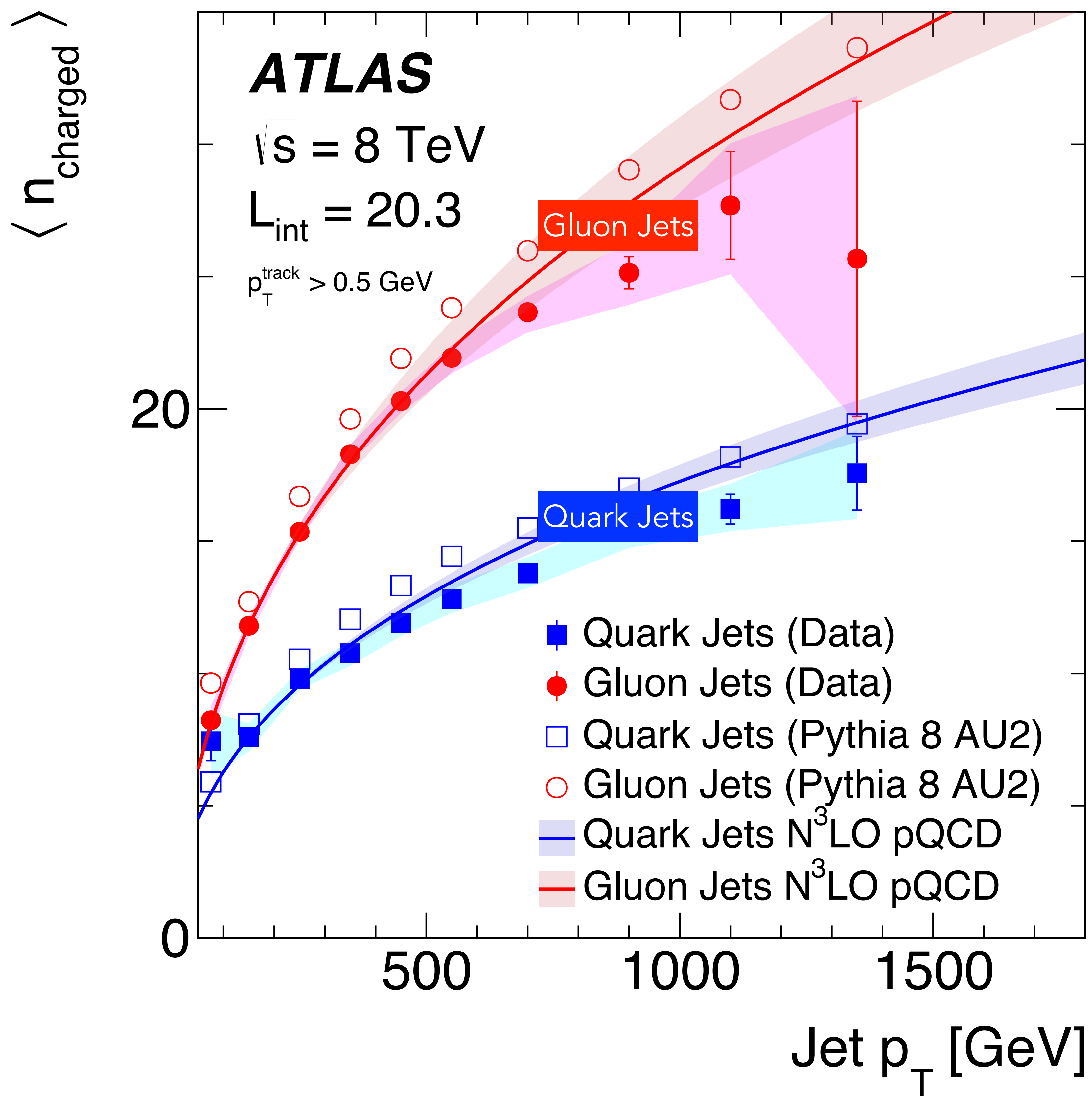


string motion in the event plane
(without breakups)

Each quark connected to **one** string piece

Expect factor ~ 2 ~ C_A/C_F more particles in gluon jets

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



Important for discriminating new-physics signals

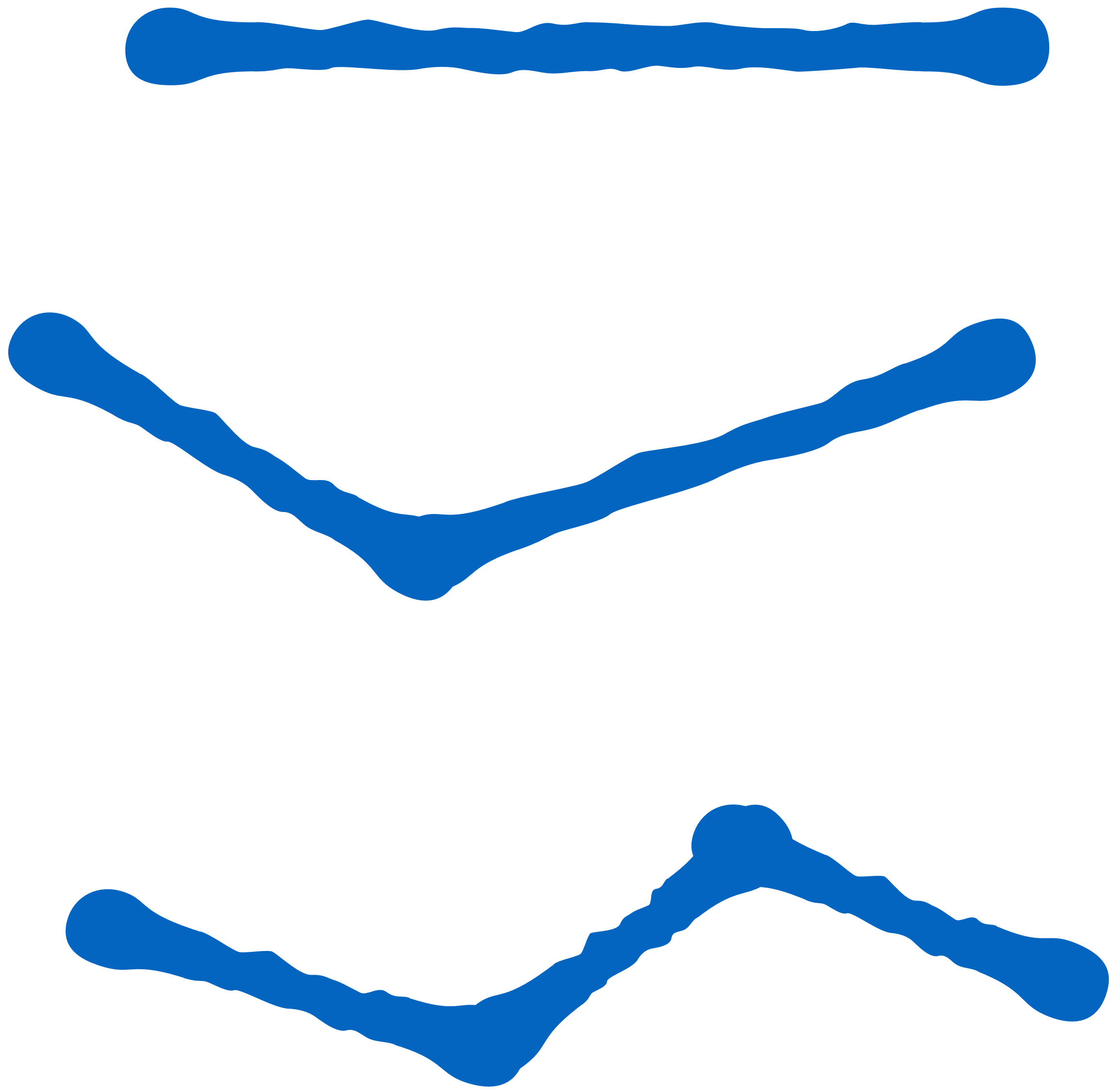
Decays to **quarks** vs decays to **gluons**,

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

See also
Larkoski et al., JHEP 1411 (2014) 129
Thaler et al., Les Houches, arXiv:1605.04692

Other String Topologies

Open Strings

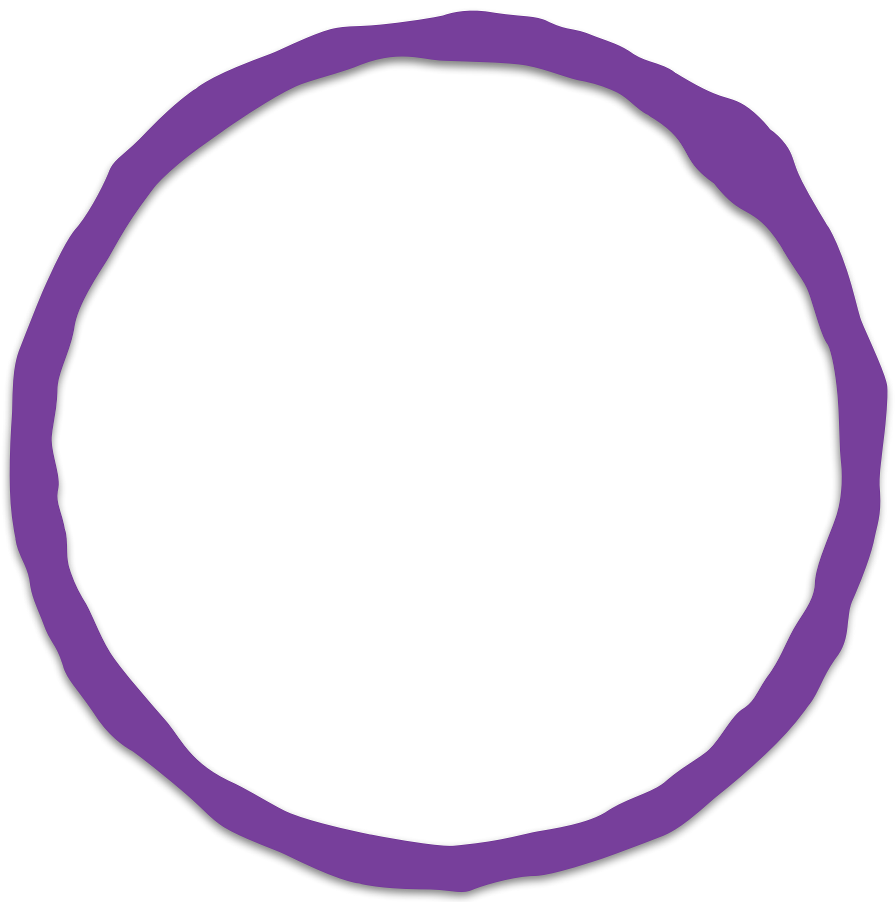


$q\bar{q}$ strings (with gluon kinks)

E.g., $Z \to q\bar{q}$ + shower

$H \to b\bar{b}$ + shower

Closed Strings

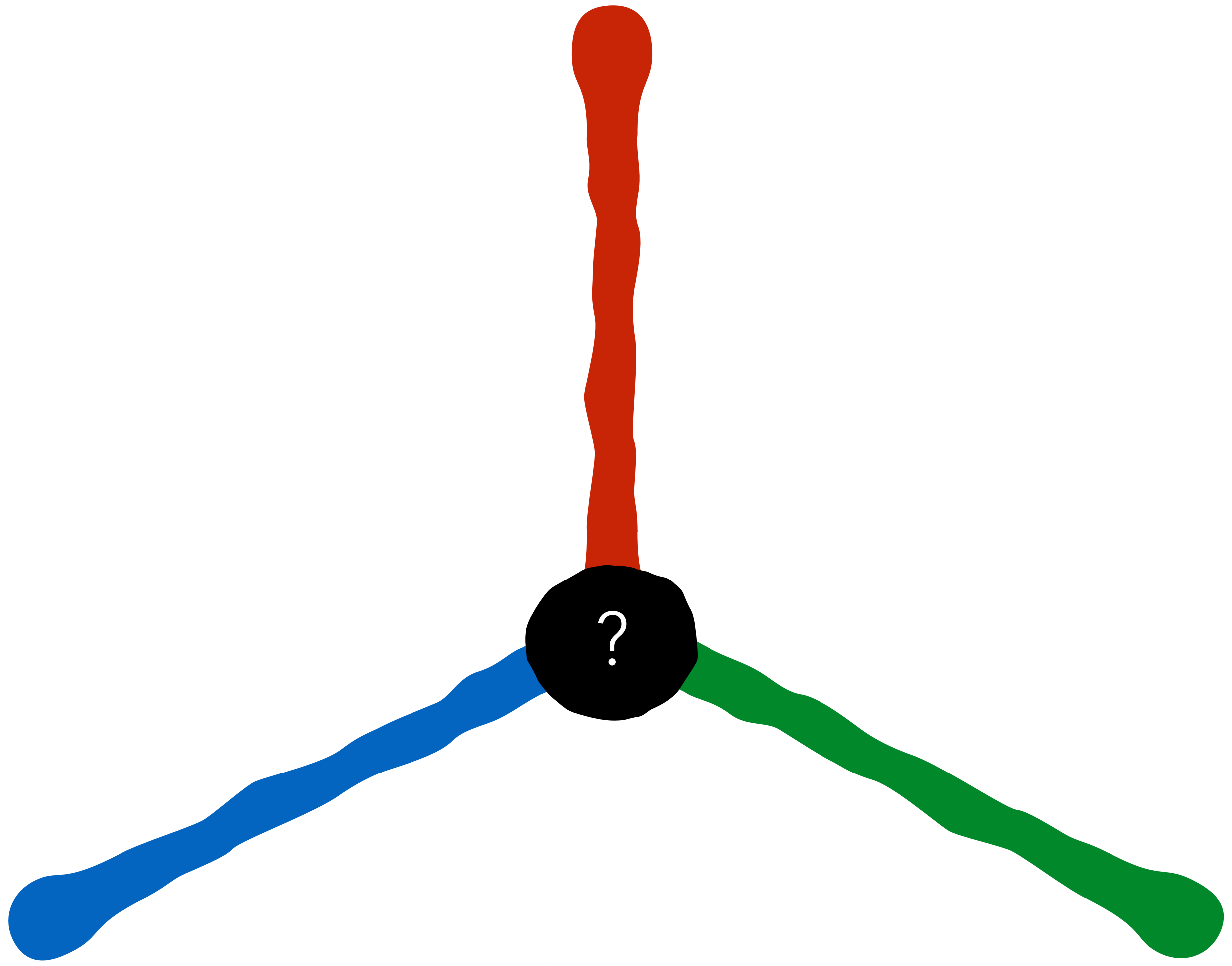


Gluon rings

E.g., $H \to gg$ + shower

$\Upsilon \to ggg$ + shower

SU(3) String Junction



Open strings with N endpoints

E.g., Baryon-Number violating

neutralino decay $\chi^0 \to qqq$ + shower

Fragmentation of String Junction Systems

Assume vortex-line string picture still OK

Which topology? Y, Δ, V, T, …?

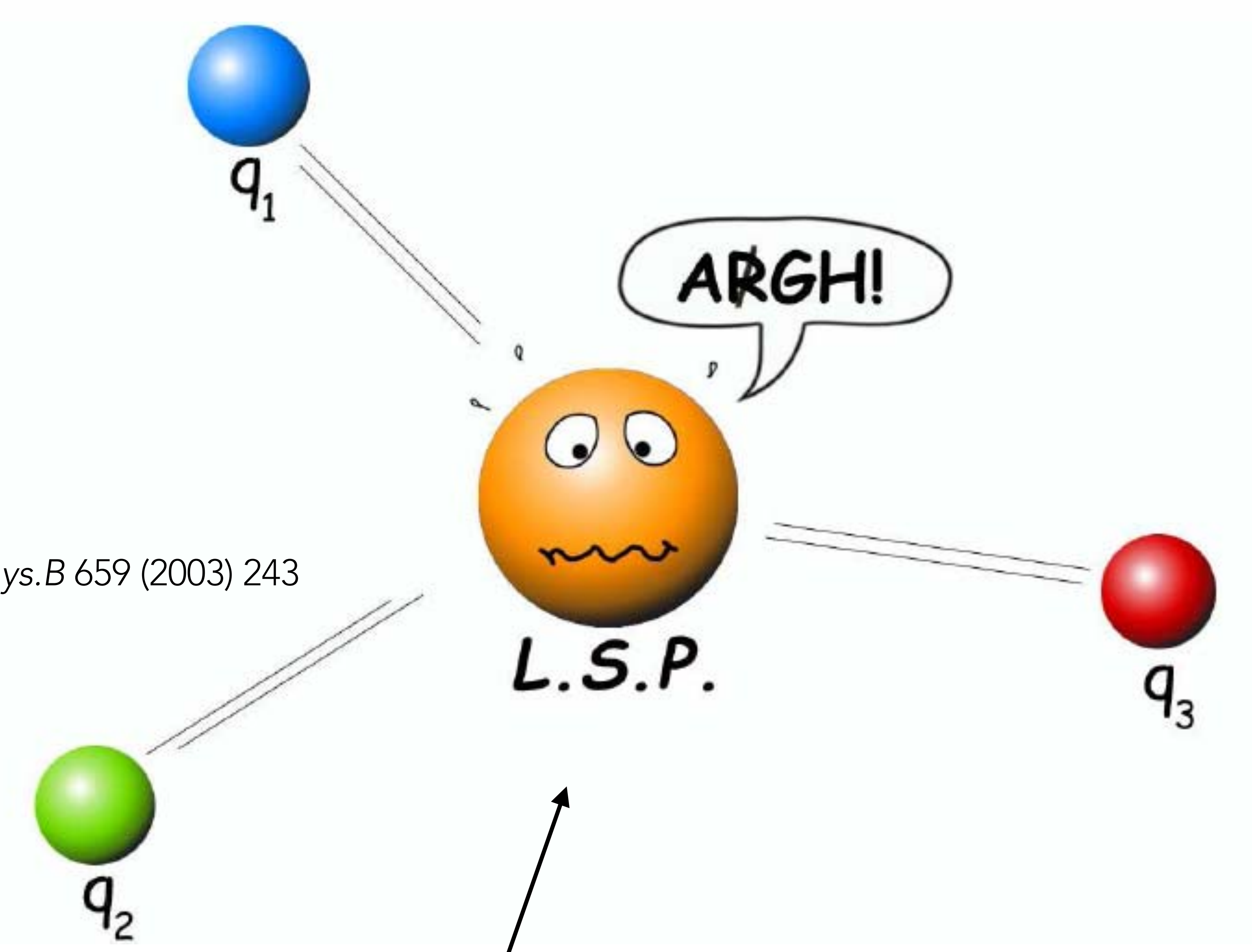
Baryon wave functions & minimal string length

⟹ Picture of Y-shaped topology with "string junction"

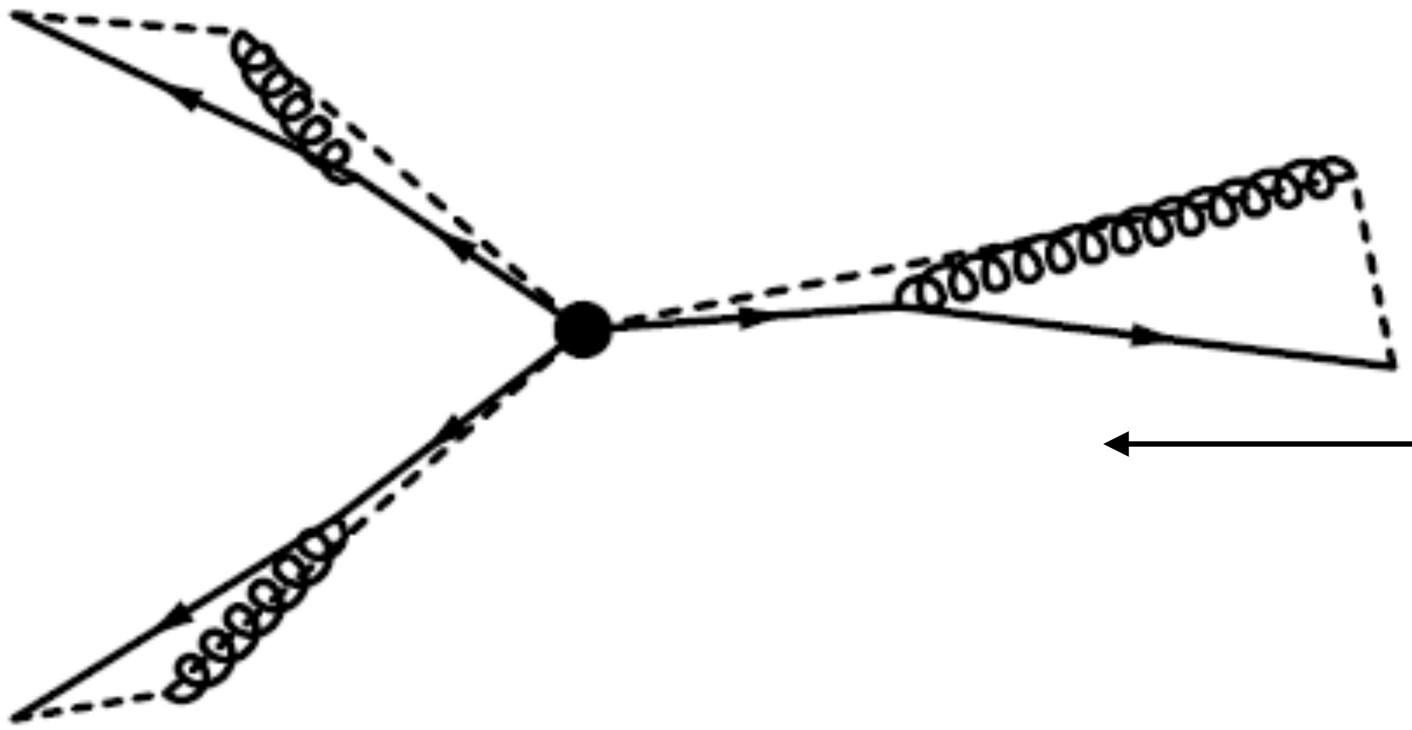
1st String-Junction Fragmentation Model Sjöstrand & **PS**, *Nucl.Phys.B* 659 (2003) 243

Focused on hard BNV processes: $\tilde{\chi} \to q_i q_j q_k$, $\tilde{t}_i^* \to q_j q_k$, …

Fun (but a bit of a long shot …)



(Junction strings can also have kinks):



Would love to tell you ***this*** has been seen at LHC

But then you probably wouldn't be hearing about it from me

However, **string junctions** *may* have been seen!

Fragmentation of String Junctions

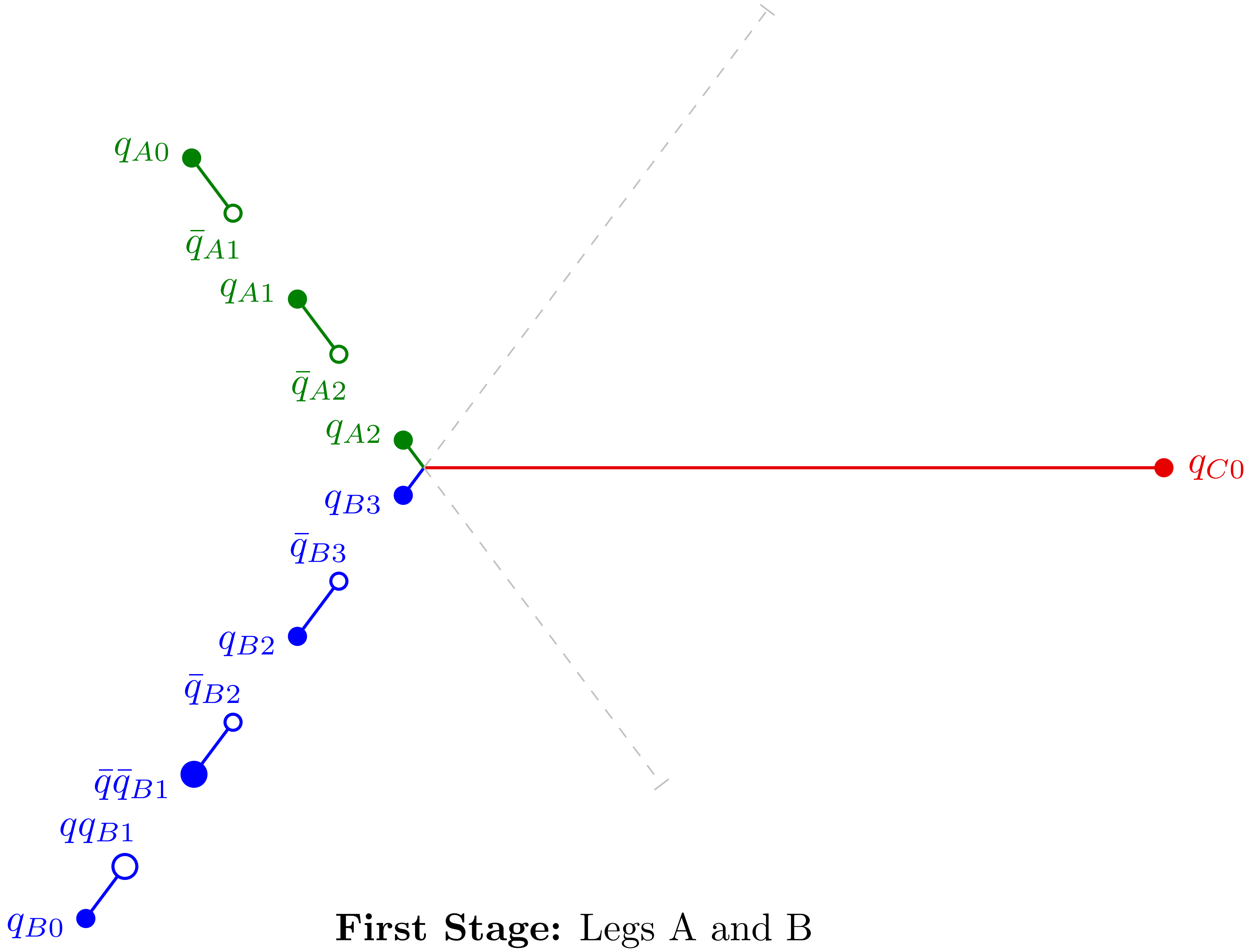
Assume Junction Strings have same properties as ordinary ones (u:d:s, Schwinger p_T, etc)

Exploit causality again to fragment outwards-in, from endpoints towards junction

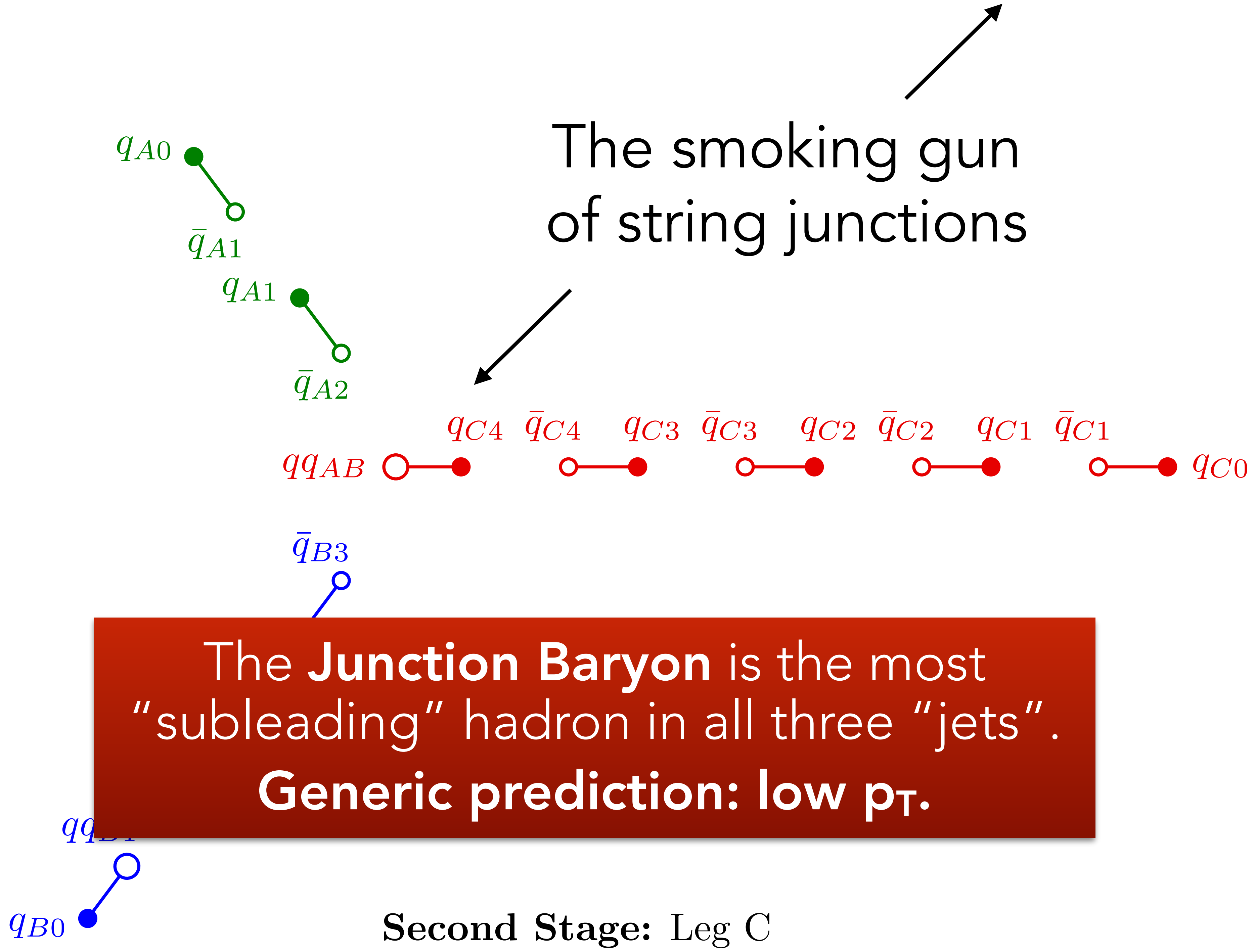
First Stage: 2 least energetic legs (q_{A0}, q_{B0}) fragmented first

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**

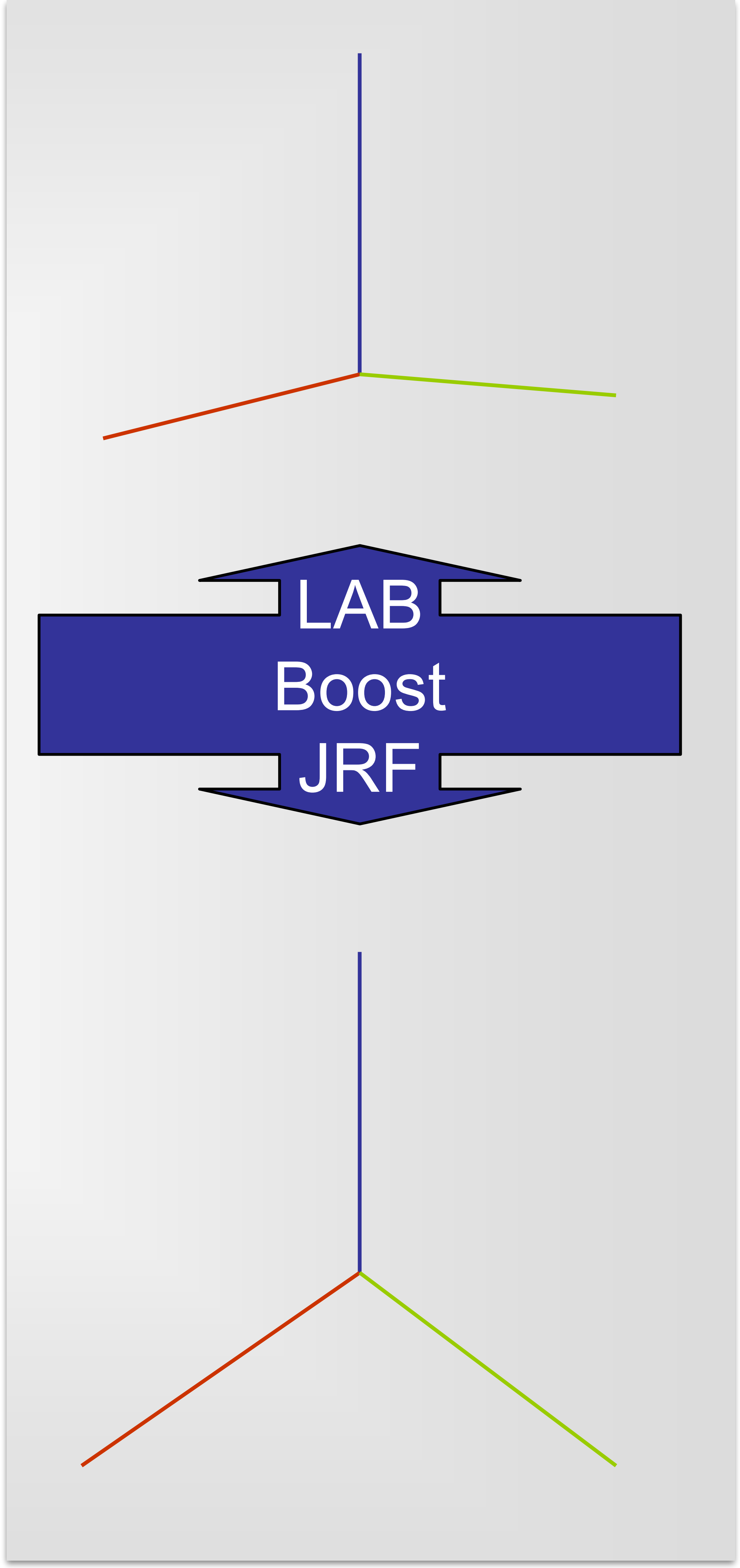
$$\vec{F} = \kappa \vec{e}_r.$$

$\Longrightarrow$ 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.

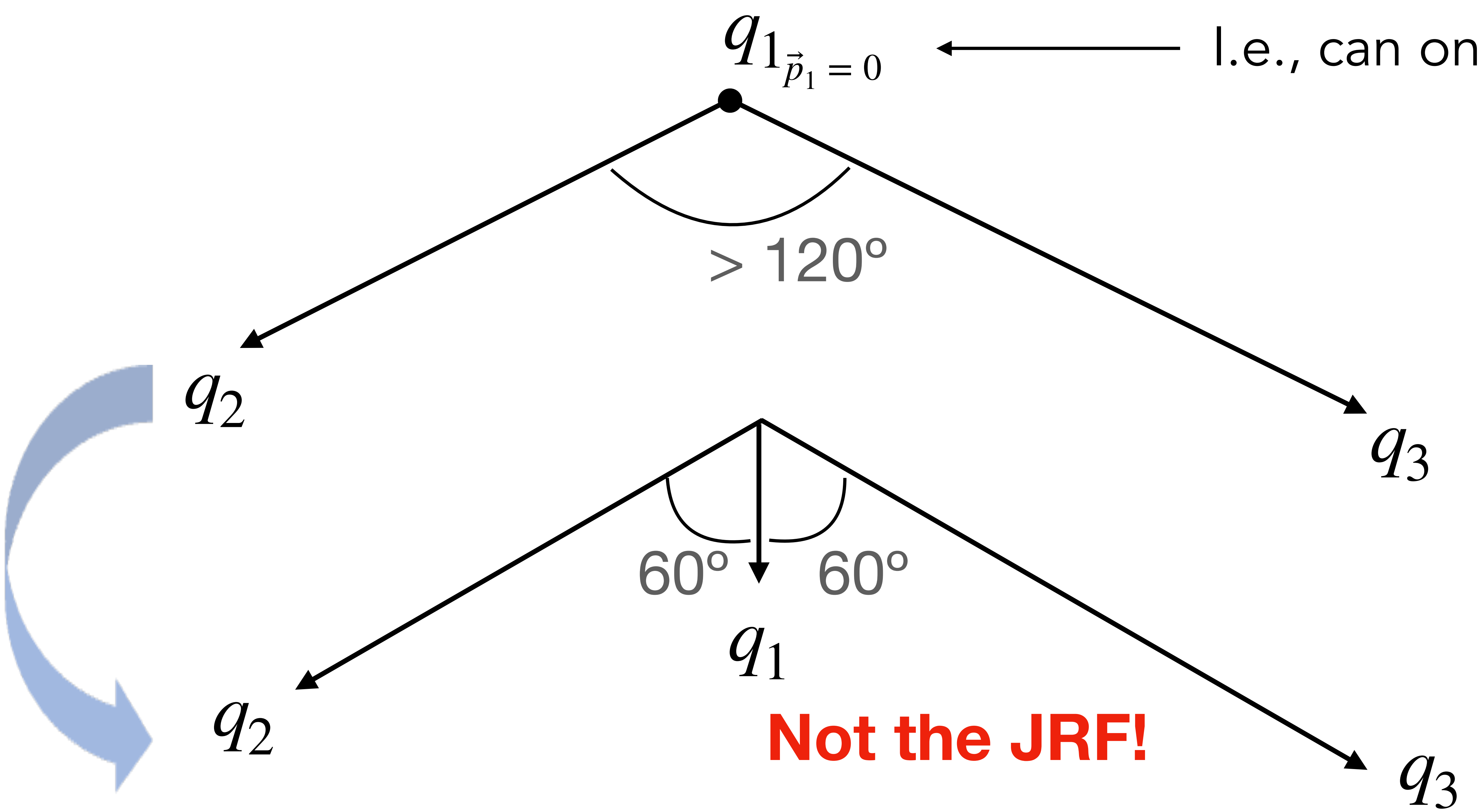
But org algorithm often broke down (failed to converge) for "soft legs"



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)



I.e., can only happen for massive partons

Not the JRF!

Org algorithm failed to converge

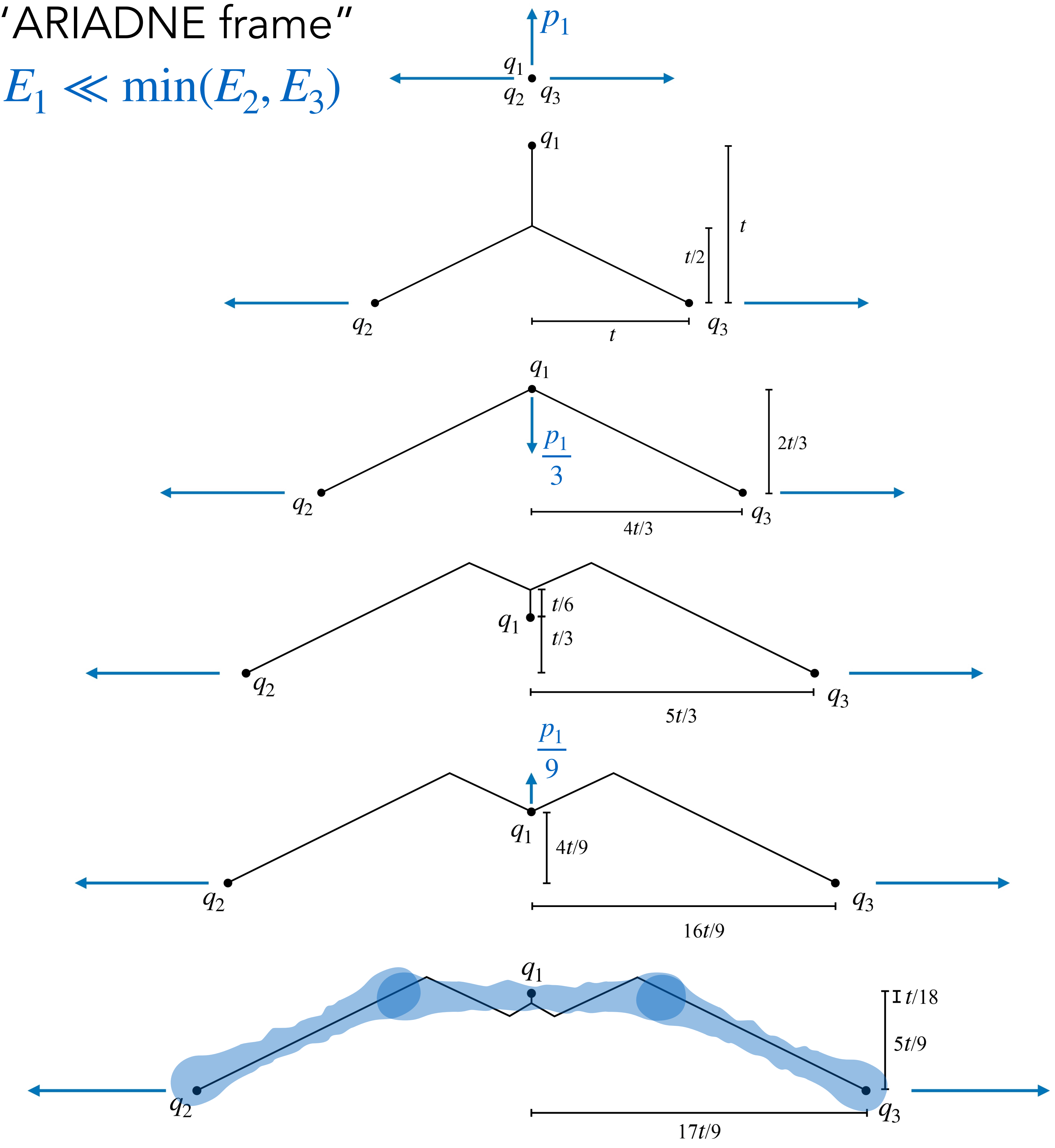
Slide adapted from J. Altmann

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

String Motion: Soft Massless Case

"ARIADNE frame"

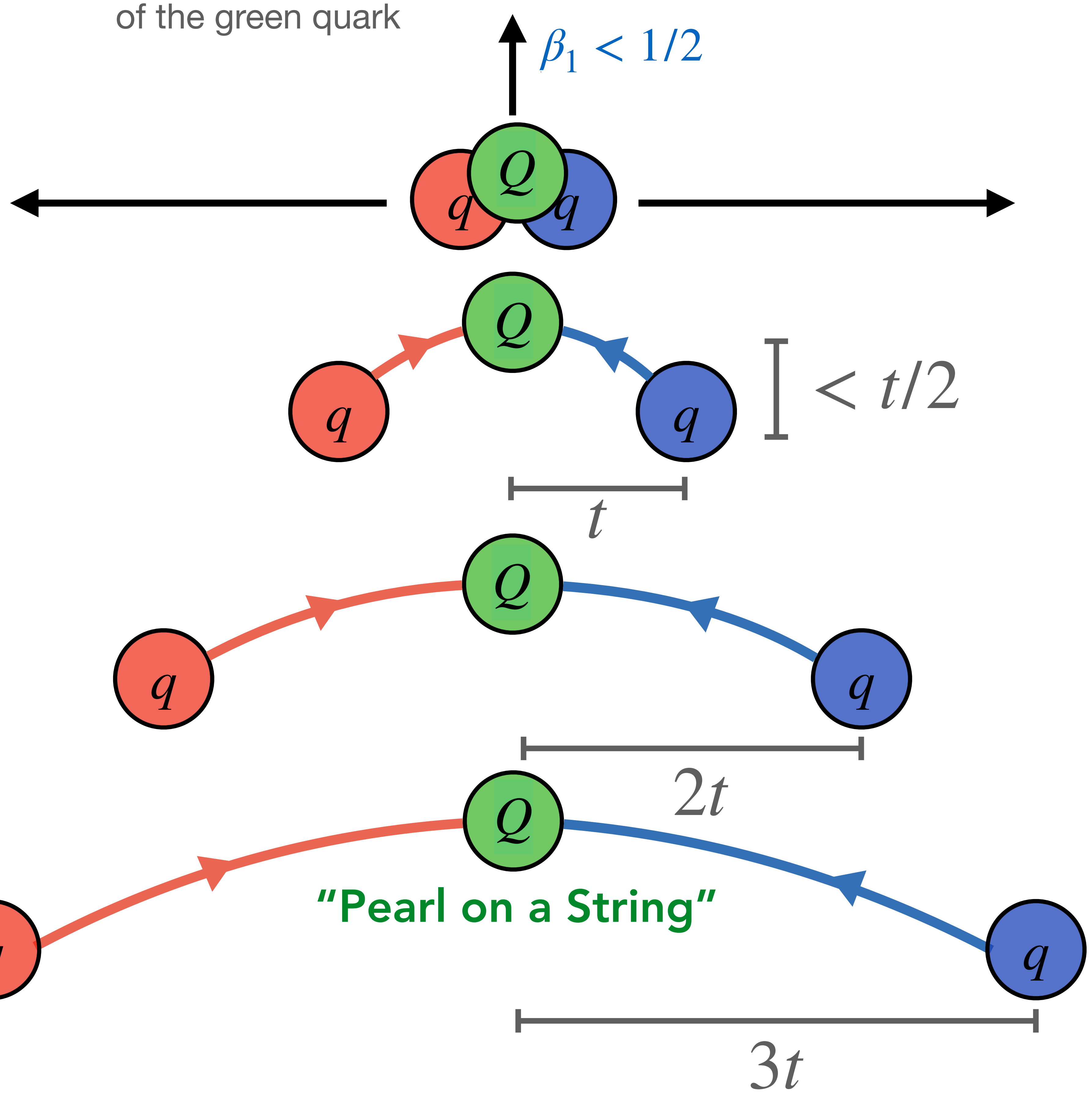
$E_1 \ll \min(E_2, E_3)$



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



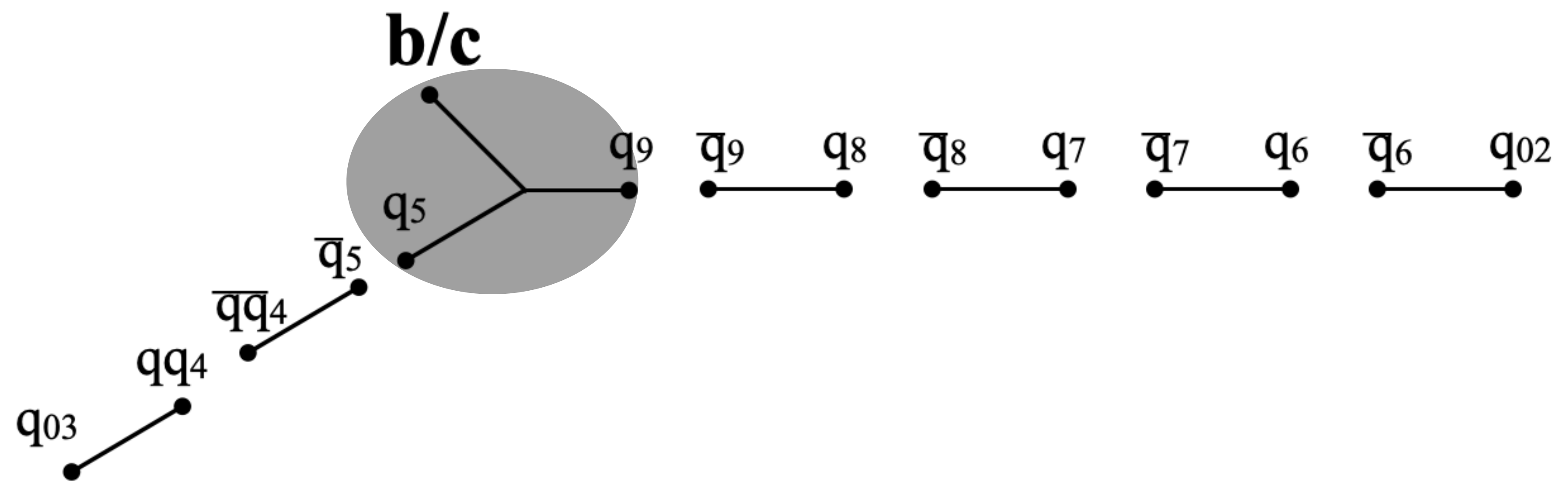
With thanks to G. Gustafson. Slide adapted from J. Altmann

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**

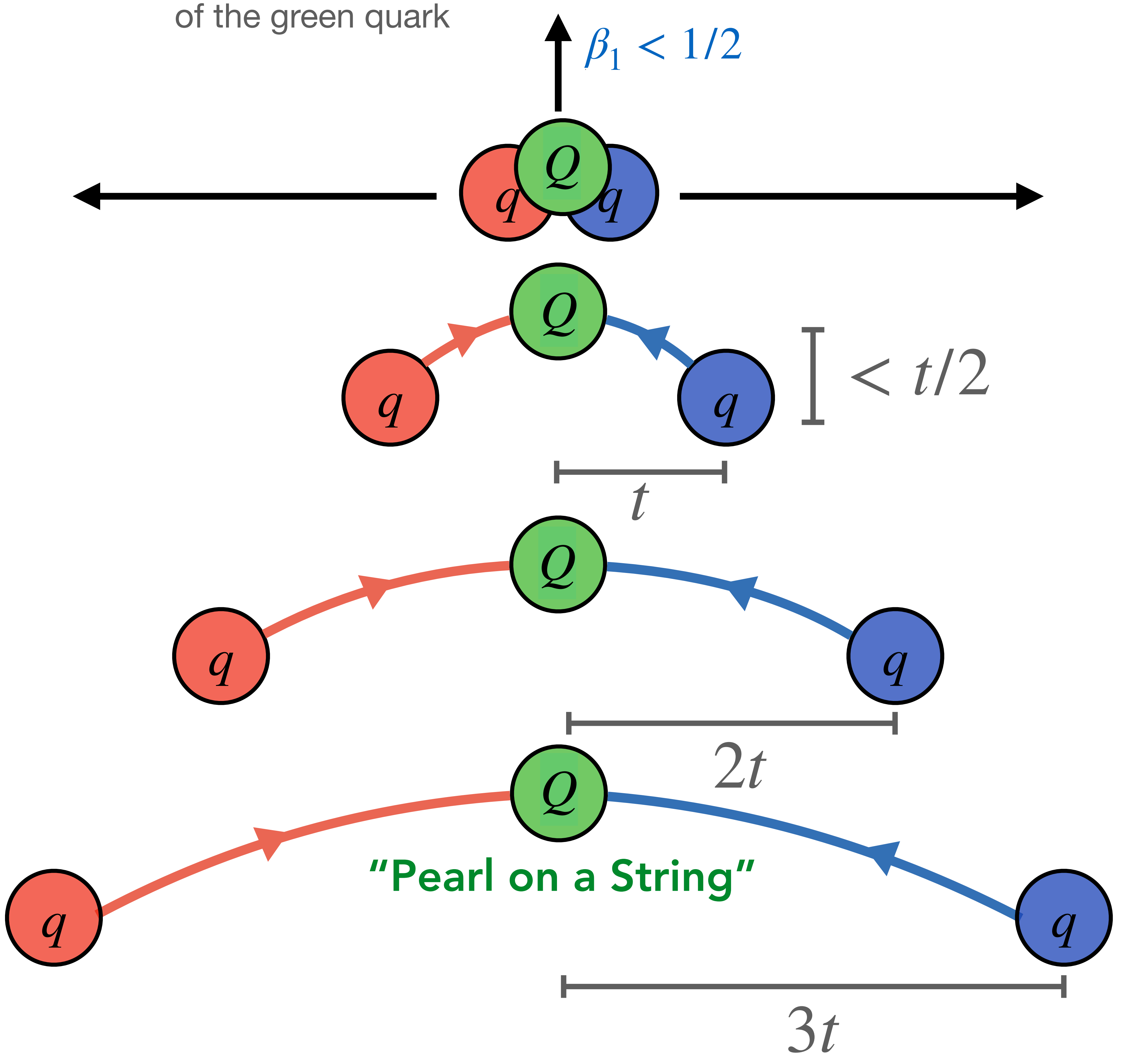
More likely to occur for junctions with heavy flavour endpoints

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

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



Slide adapted from J. Altmann

Confront with Measurements

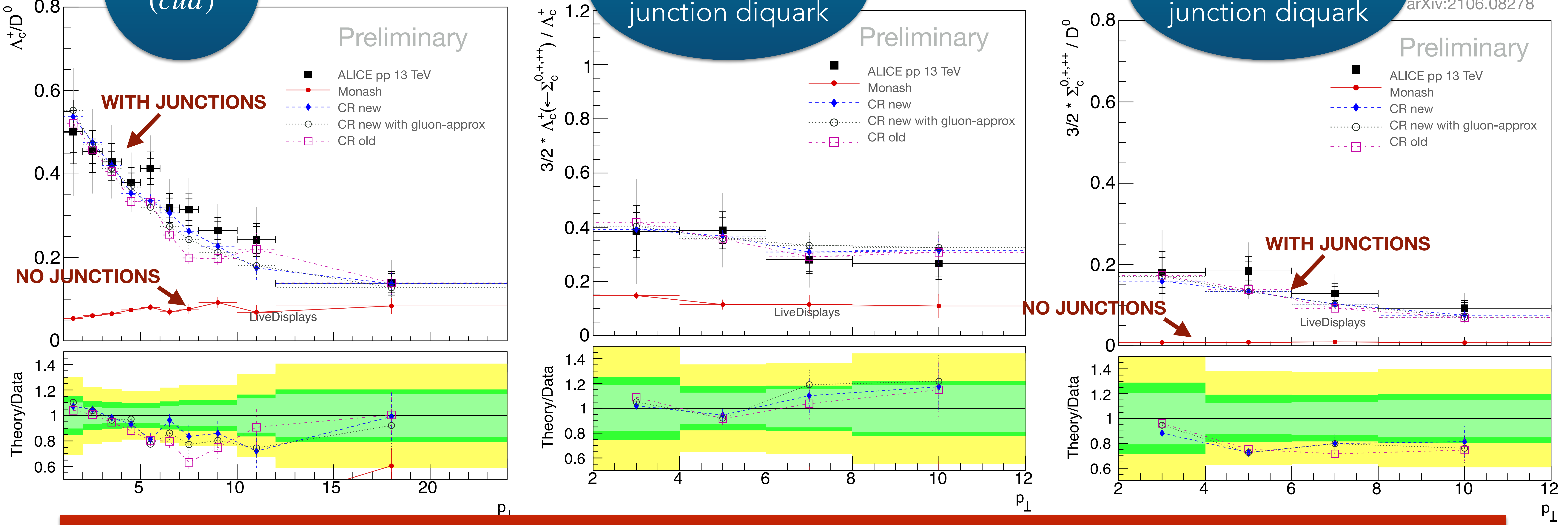
Since 2020, ALICE (and LHCb) **have been reporting large (factor-10) enhancements in heavy-flavour baryon-to-meson ratios** **at low p_T!**

Λ_c^+
(cud)

Σ_c/Λ_c
Sensitive to spin of junction diquark

Σ_c/D
Sensitive to spin of junction diquark

arXiv:2106.08278



WITH JUNCTIONS

NO JUNCTIONS

WITH JUNCTIONS

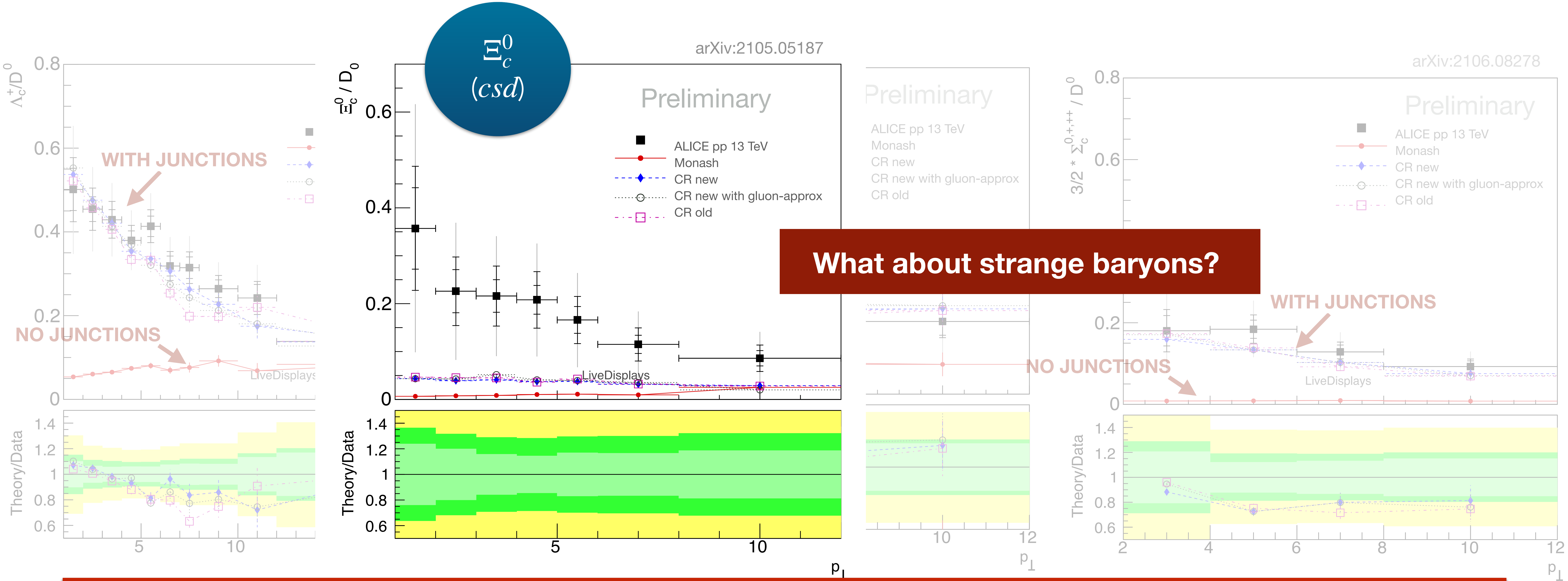
NO JUNCTIONS

Very exciting!

Slide adapted from J. Altmann

Confront with Measurements: **Strangeness**

Since 2020, ALICE (and LHCb) **have been reporting large (factor-10) enhancements in heavy-flavour baryon-to-meson ratios** at low p_T!



What about strange baryons?

Even more exciting!

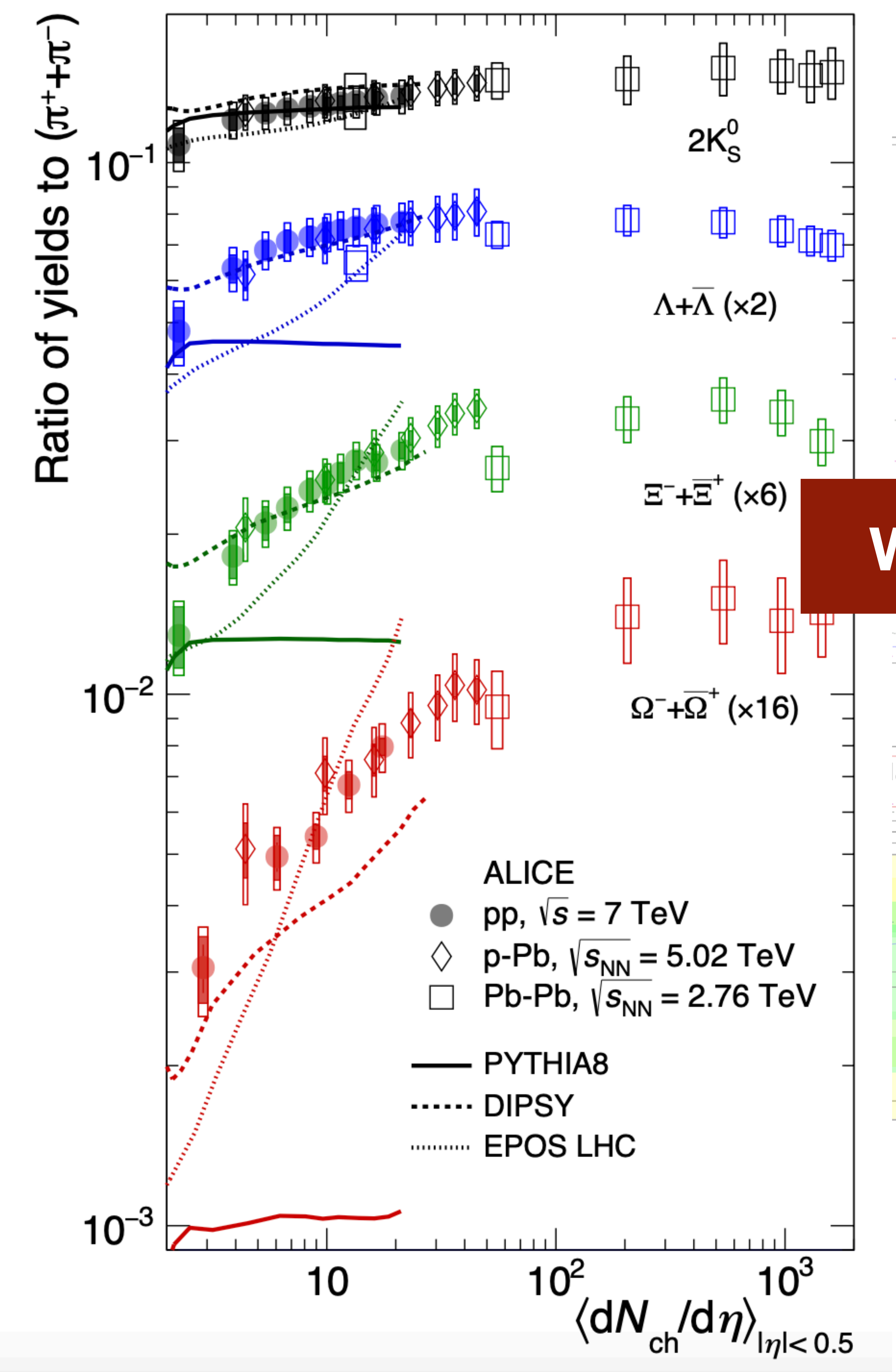
Slide adapted from J. Altmann

Strangeness Enhancement

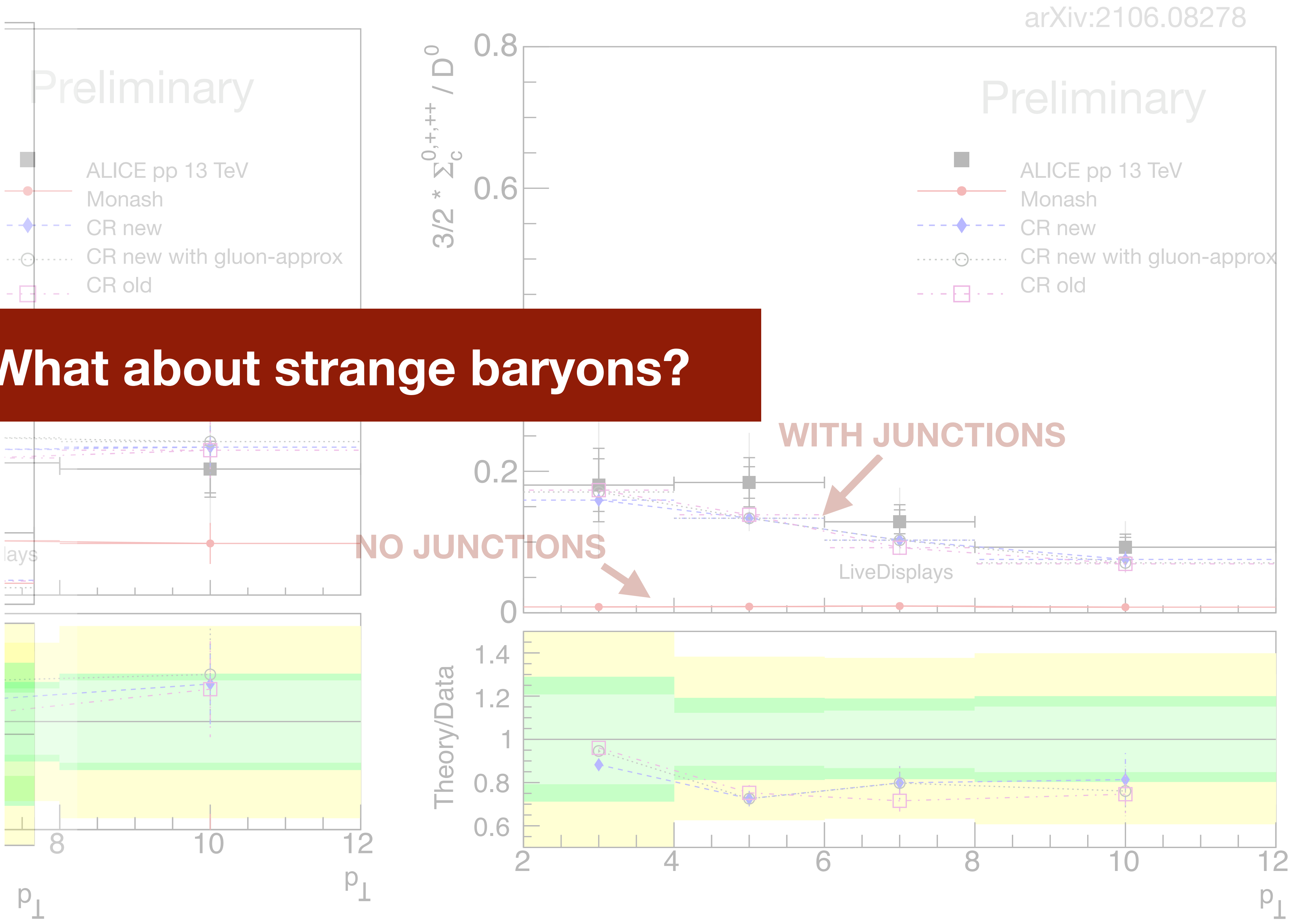
Clear observations of enhancements of strange baryons with multiplicity

Also among **light-flavour hadrons**

arXiv:1606.07424



arXiv:2106.08278



What about strange baryons?

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

Slide adapted from J. Altmann

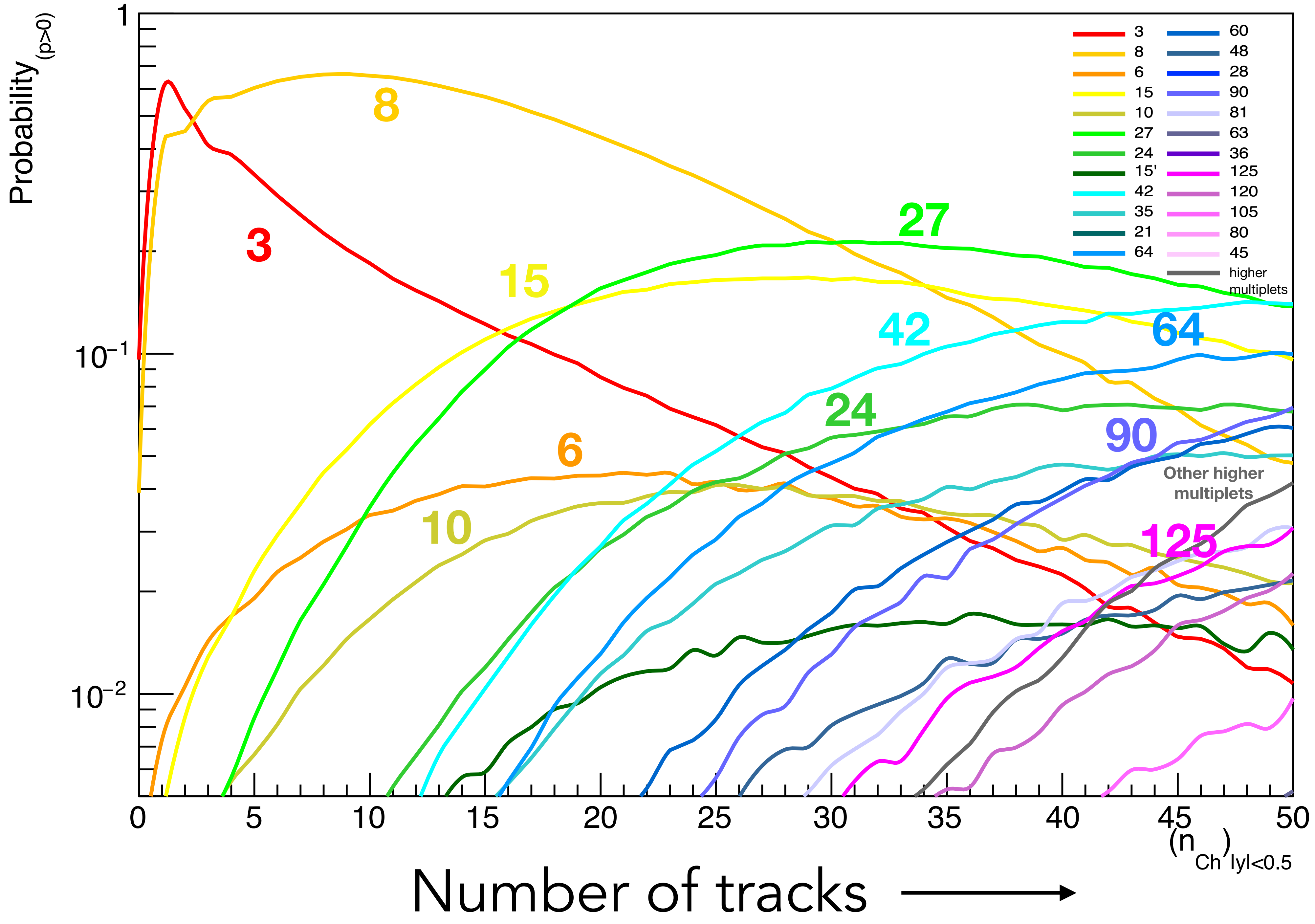
What we **think** is driving this: **Multiple Parton-Parton Interactions**

Beam particles at LHC = protons: composite; lots of quarks and gluons inside

As they pass through each other, they present a **beam** of partons to each other

➤ **Multiple parton-parton interactions. Explicit MC models around since 80s**

Lots of colour exchanges ⟹ lots of coloured partons scattered into the final states



Counting number of fundamental and anti-fundamental flux lines at central rapidity in pp collisions (according to PYTHIA)

Confining fields may be reaching much **higher effective representations** than simple quark-antiquark (3) ones.

Two approaches in PYTHIA:

1) Colour Ropes (Lund)

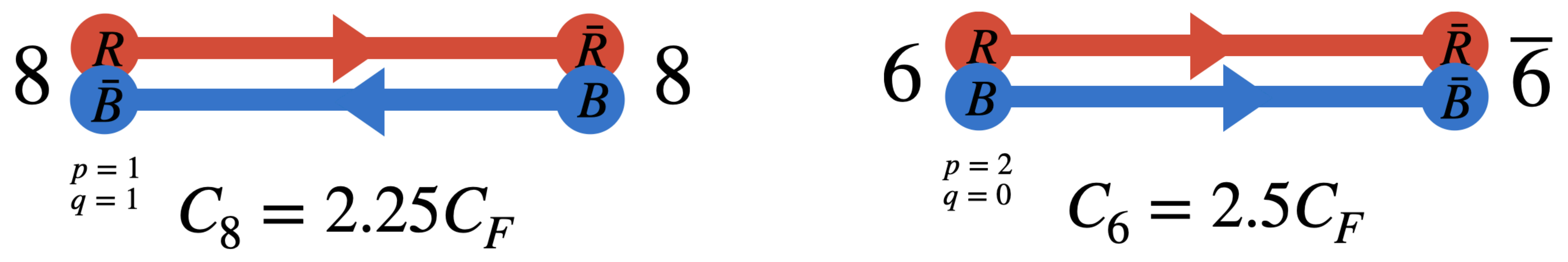
2) Close-Packing (Monash/Oxford)

Plot produced by J. Altmann

Work in Progress: Strangeness Enhancement from Close-Packing

Idea: each string exists in an effective background produced by the others

Close-packing



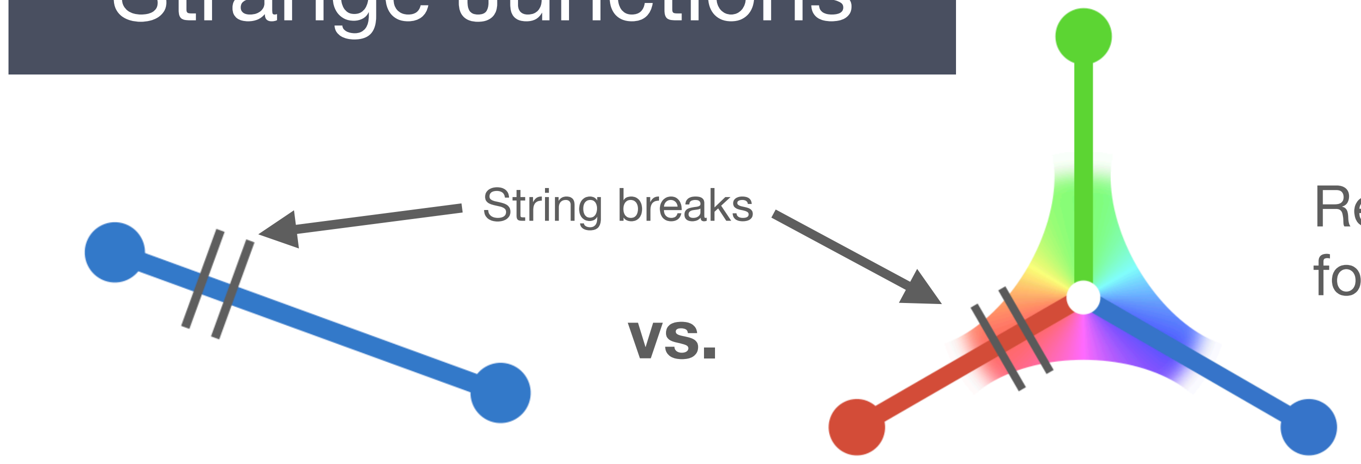
$C_8 = 2.25C_F$ $C_6 = 2.5C_F$

Dense string environments

→ Casimir scaling of **effective string tension**

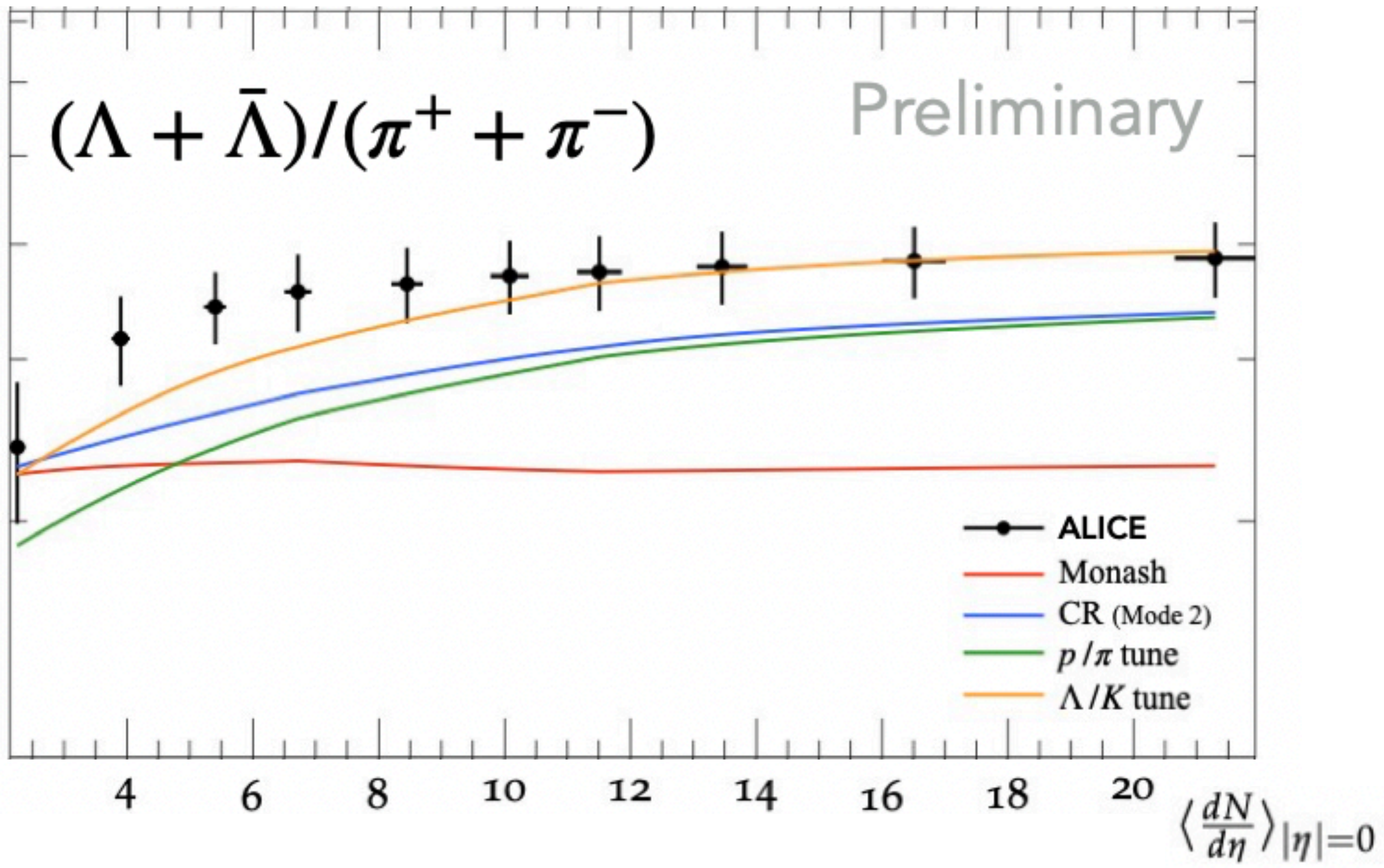
→ Higher probability of strange quarks

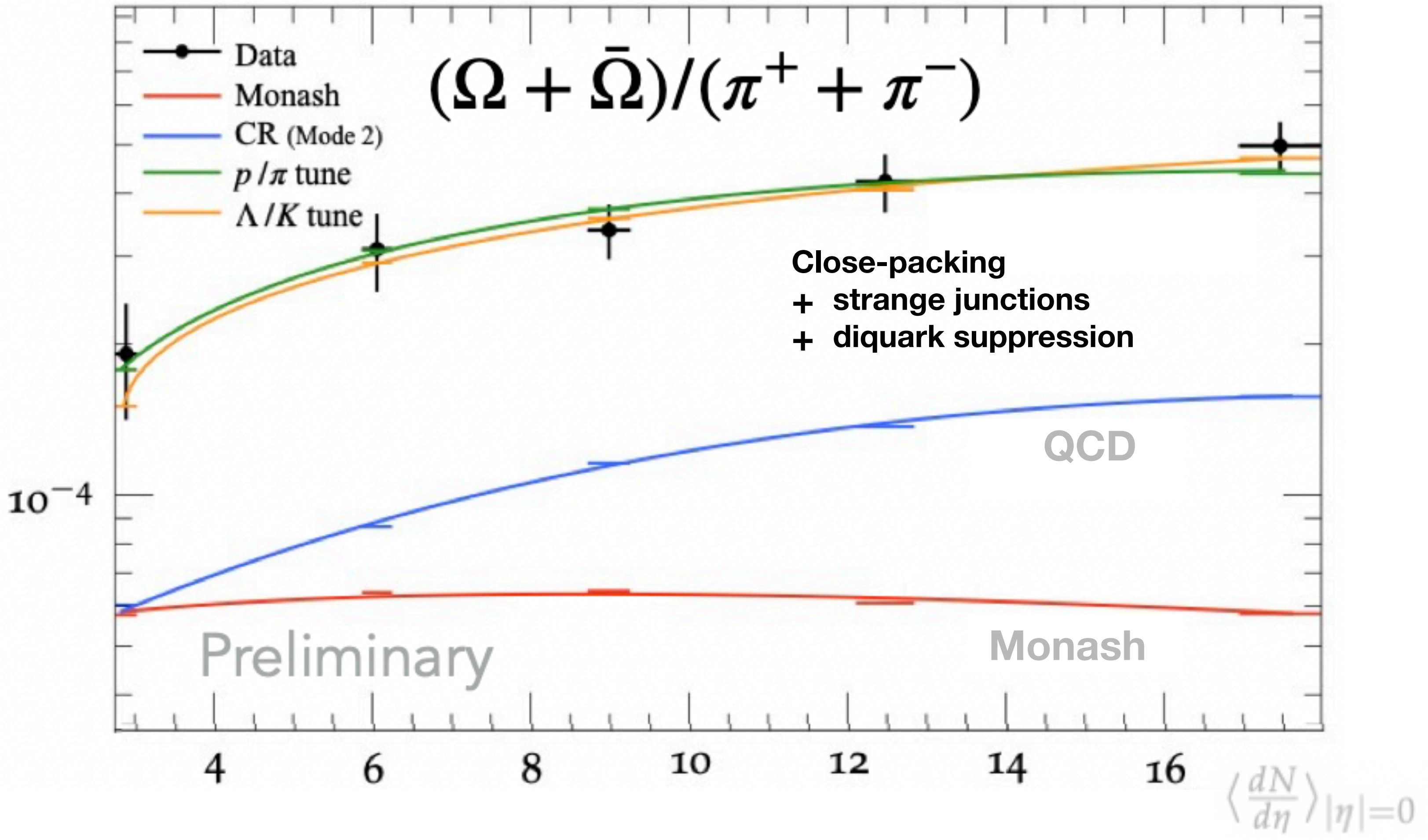
Strange Junctions



Results in strangeness enhancemen
focused in baryon sector

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





Slide adapted from J. Altmann

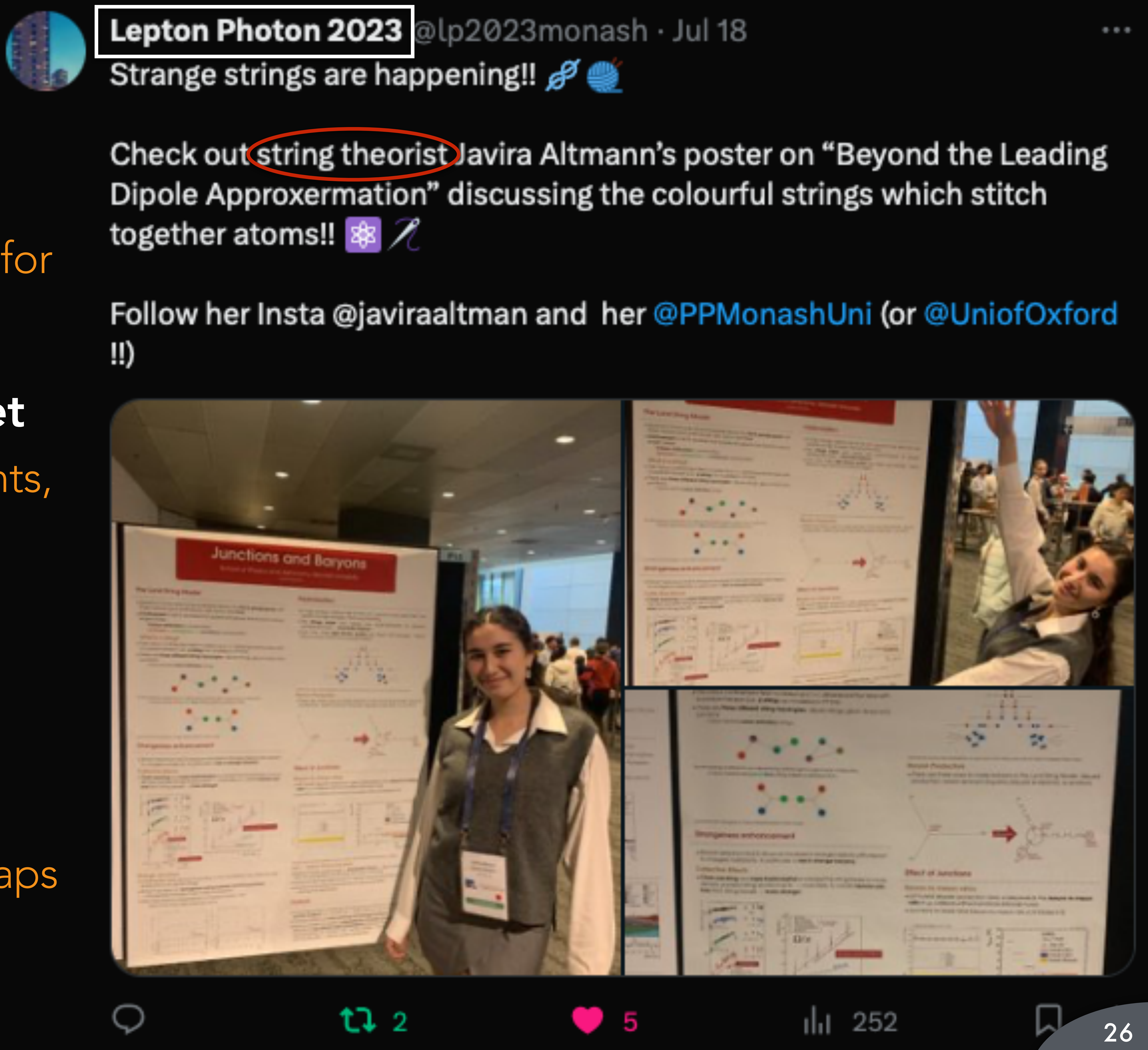
Summary / Outlook

Perturbative QCD has been revolutionised from 80s

- Culminating now/soon in NNLO+NNLL matched MC models for colliders

Non-perturbative QCD more quiet

- (Apart from lattice), few developments, driven by a few research groups
  - *String Junctions*
  - *Colour Ropes/Close-Packing*
  - *String Shoving/Repulsion*
  - *Thermal Effects*
  - *Interplay with pQCD calculations?*
- Scope for input and new ideas perhaps from unexpected areas?



Lepton Photon 2023 @lp2023monash · Jul 18

Strange strings are happening!! 🧬 🧶

Check out string theorist Javira Altmann's poster on "Beyond the Leading Dipole Approxermation" discussing the colourful strings which stitch together atoms!! ⚛️ 🪡

Follow her Insta @javiraaltman and her @PPMonashUni (or @UniofOxford !!)

Extra Slides

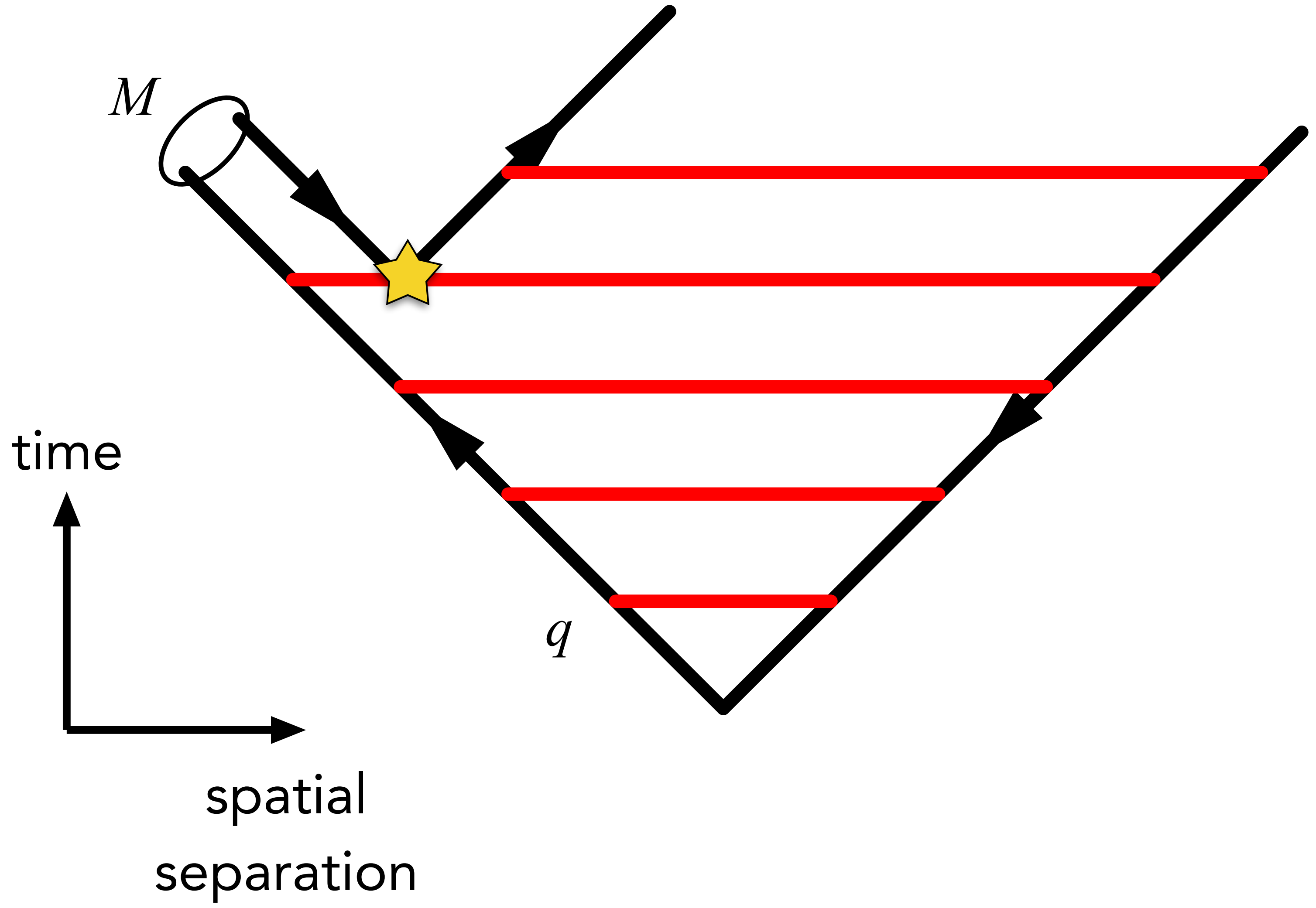
(Or could it be Thermal?)

An Alternative Analogy … ?

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

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

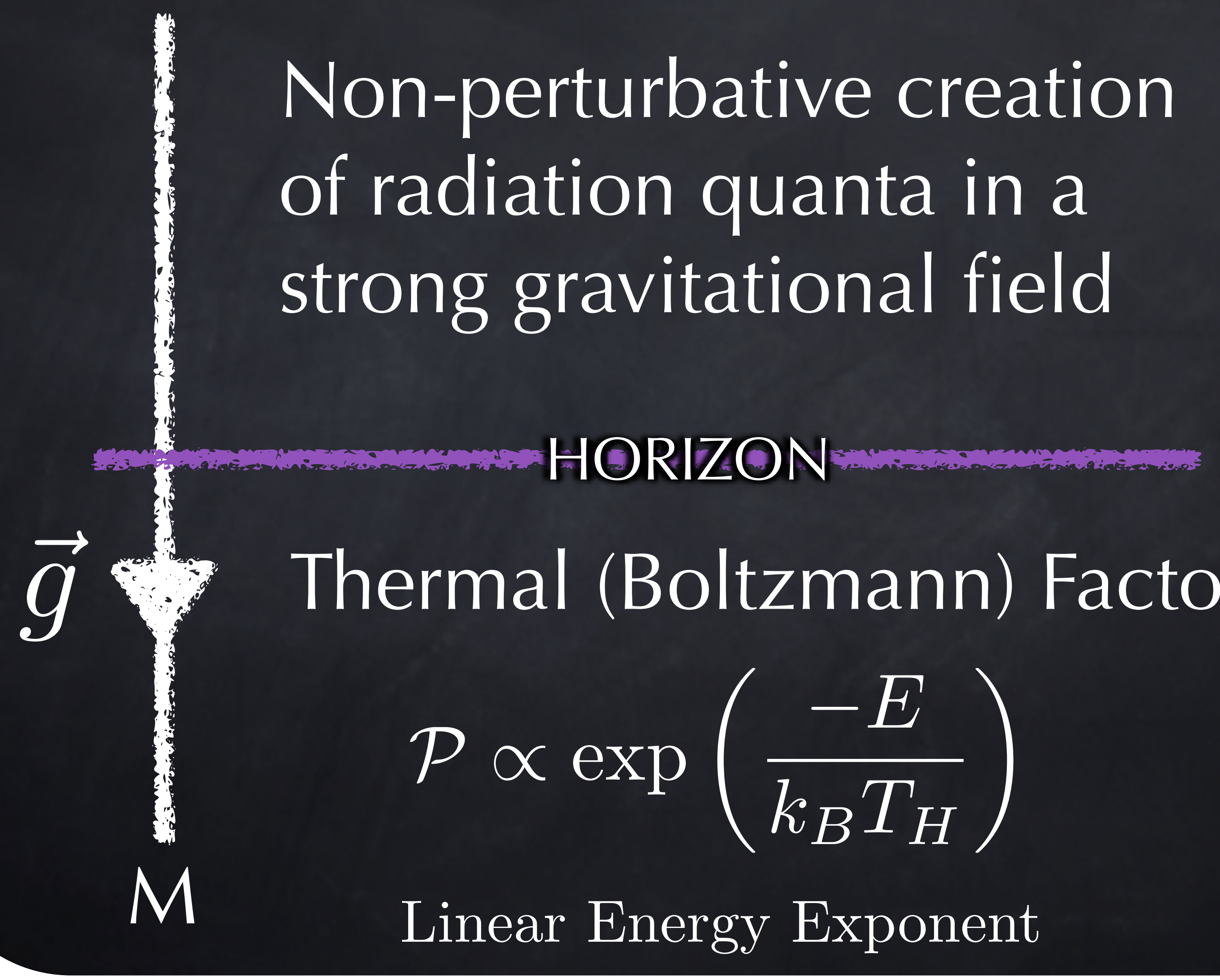
Pair creation near a black hole? →



Or a "hot string" that cools down?

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

Hawking Radiation



Non-perturbative creation of radiation quanta in a strong gravitational field

Thermal (Boltzmann) Factor

$$\mathcal{P} \propto \exp\left(\frac{-E}{k_B T_H}\right)$$

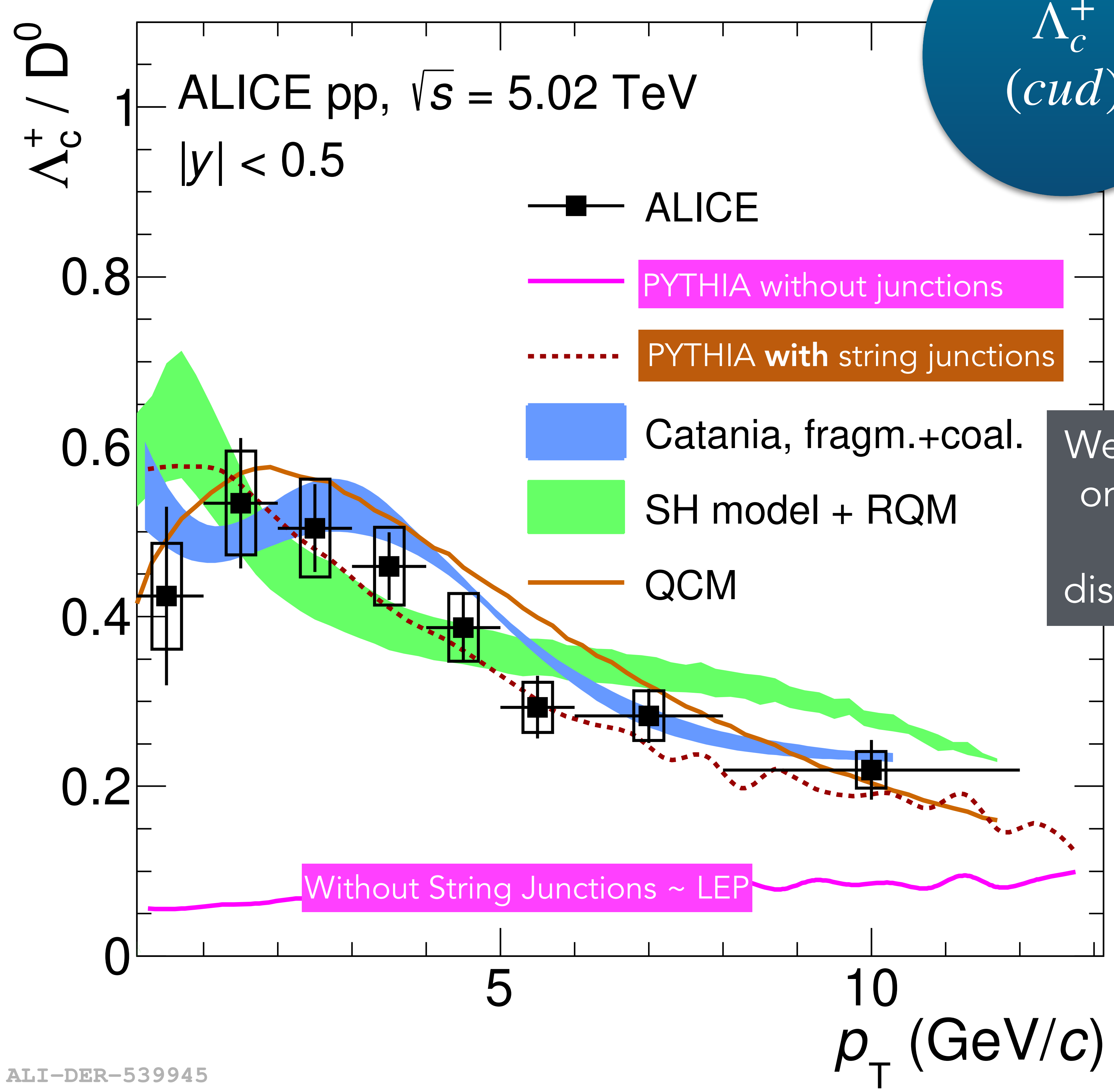
Linear Energy Exponent

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

Fischer & Sjöstrand JHEP 01 (2017) 140

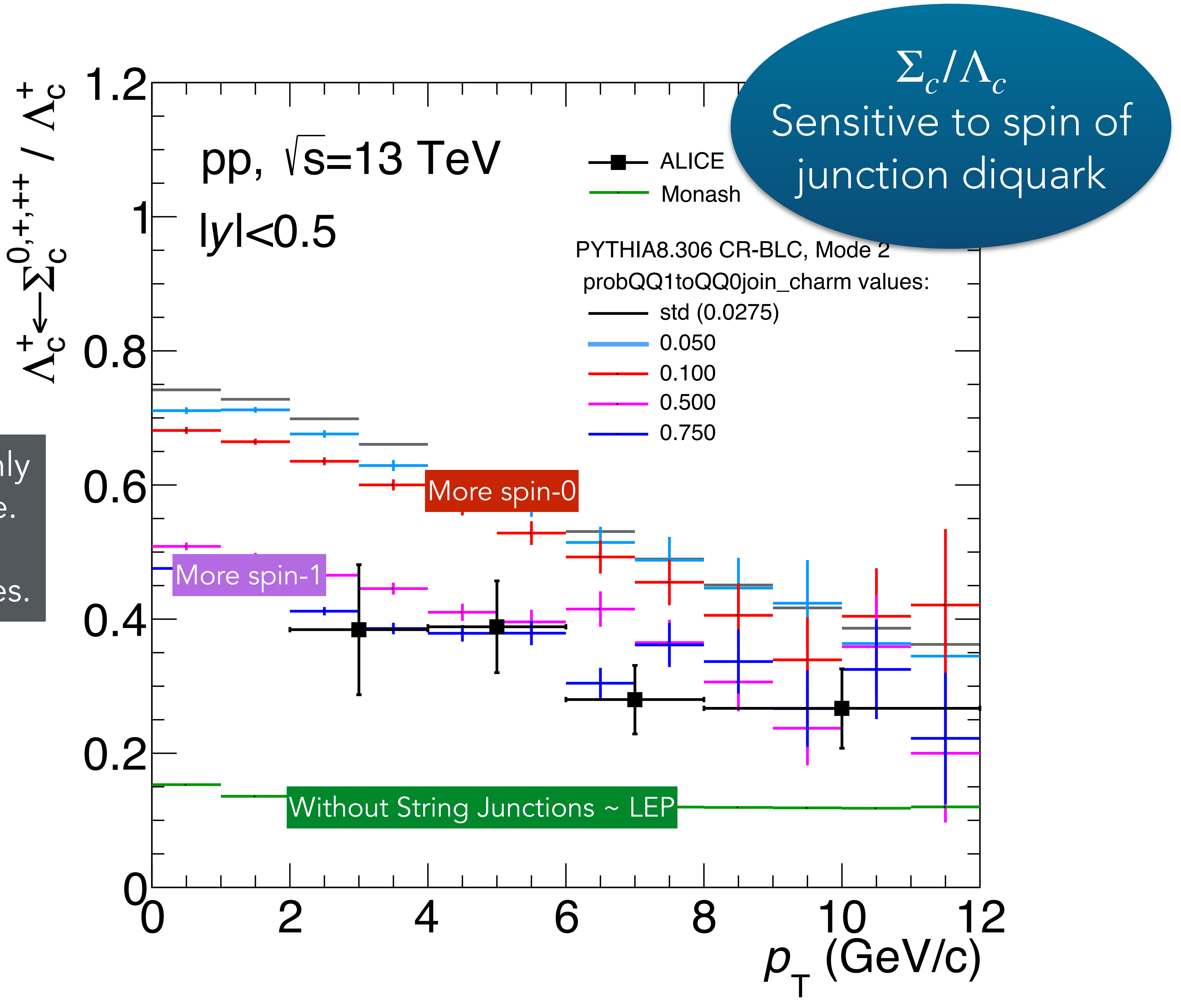
Charm Baryons

Since 2020, ALICE (and LHCb) **have been reporting large (factor-10) enhancements in heavy-flavour baryon-to-meson ratios** **at low p_T!**



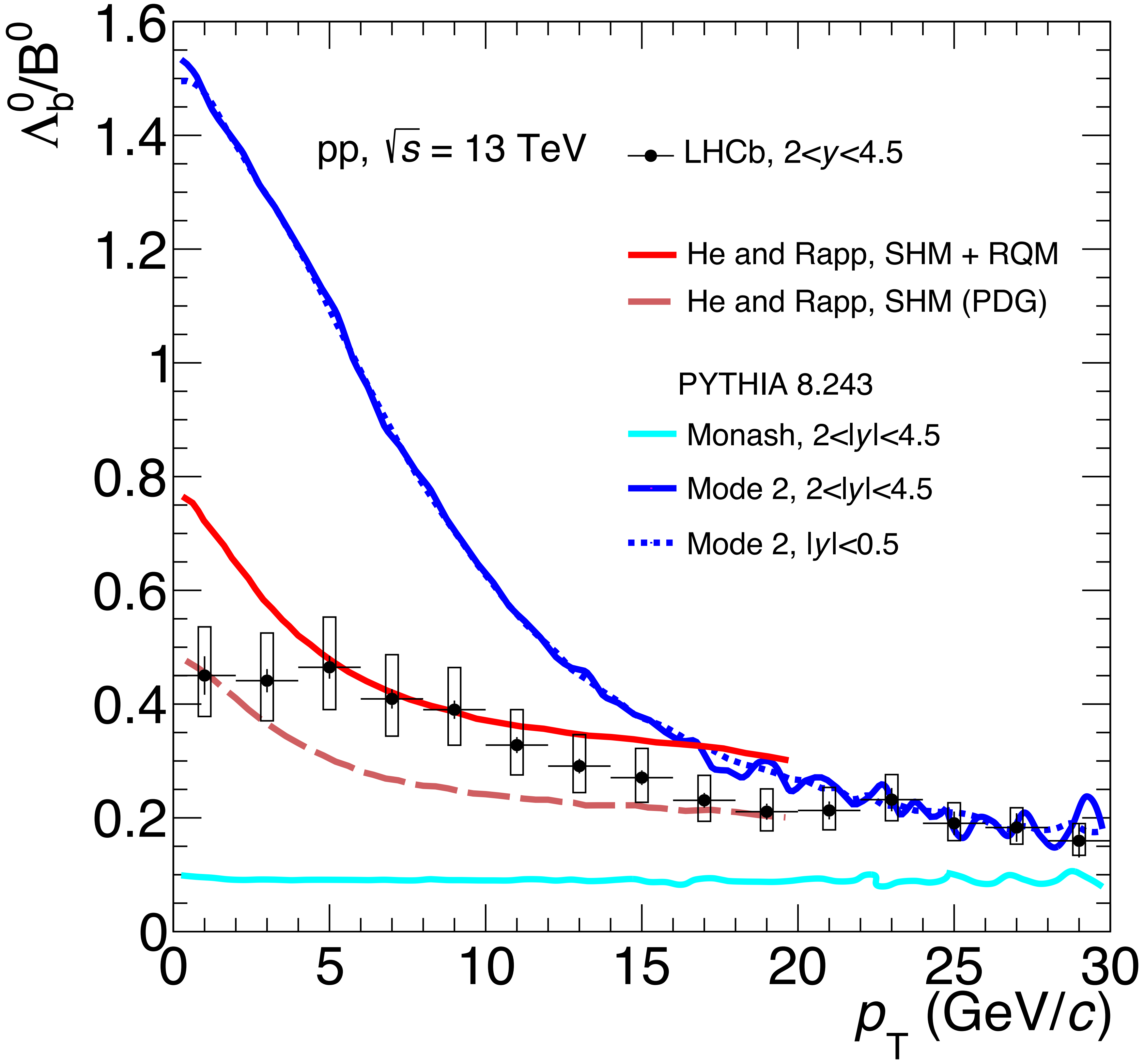
Λ_c^+
(cud)

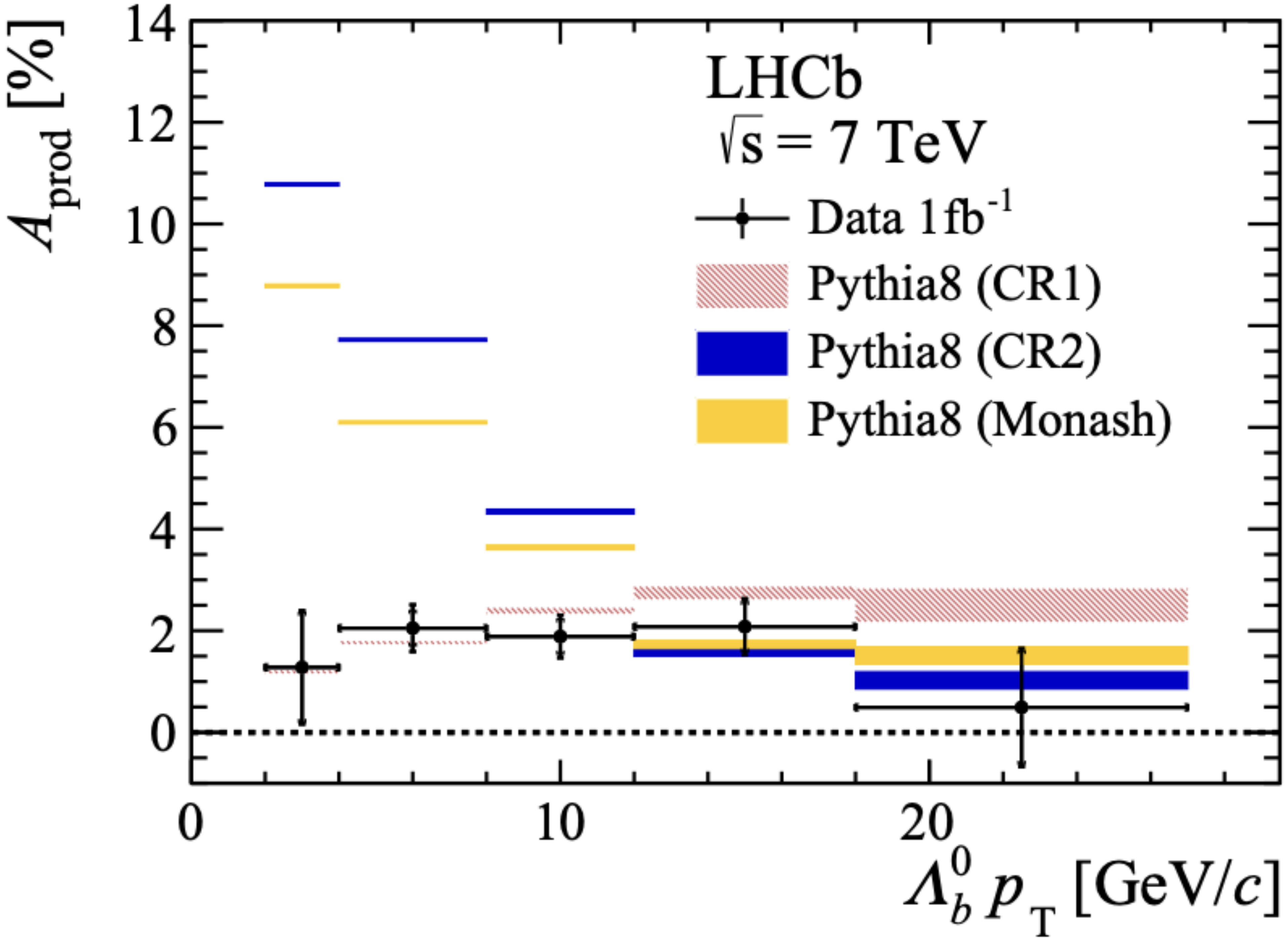
We are not the only ones in the game. But no time to discuss alternatives.



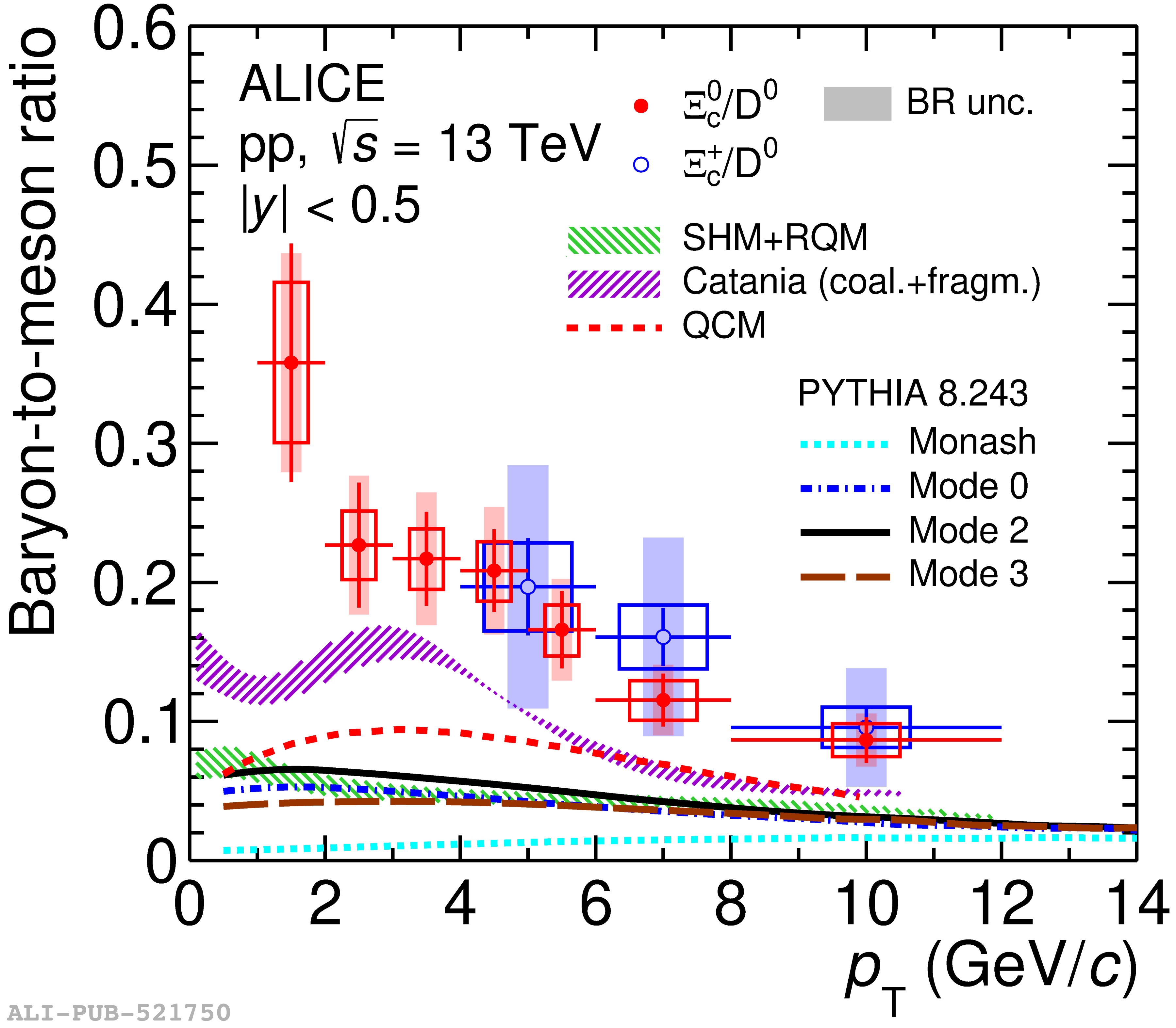
Σ_c/Λ_c
Sensitive to spin of junction diquark

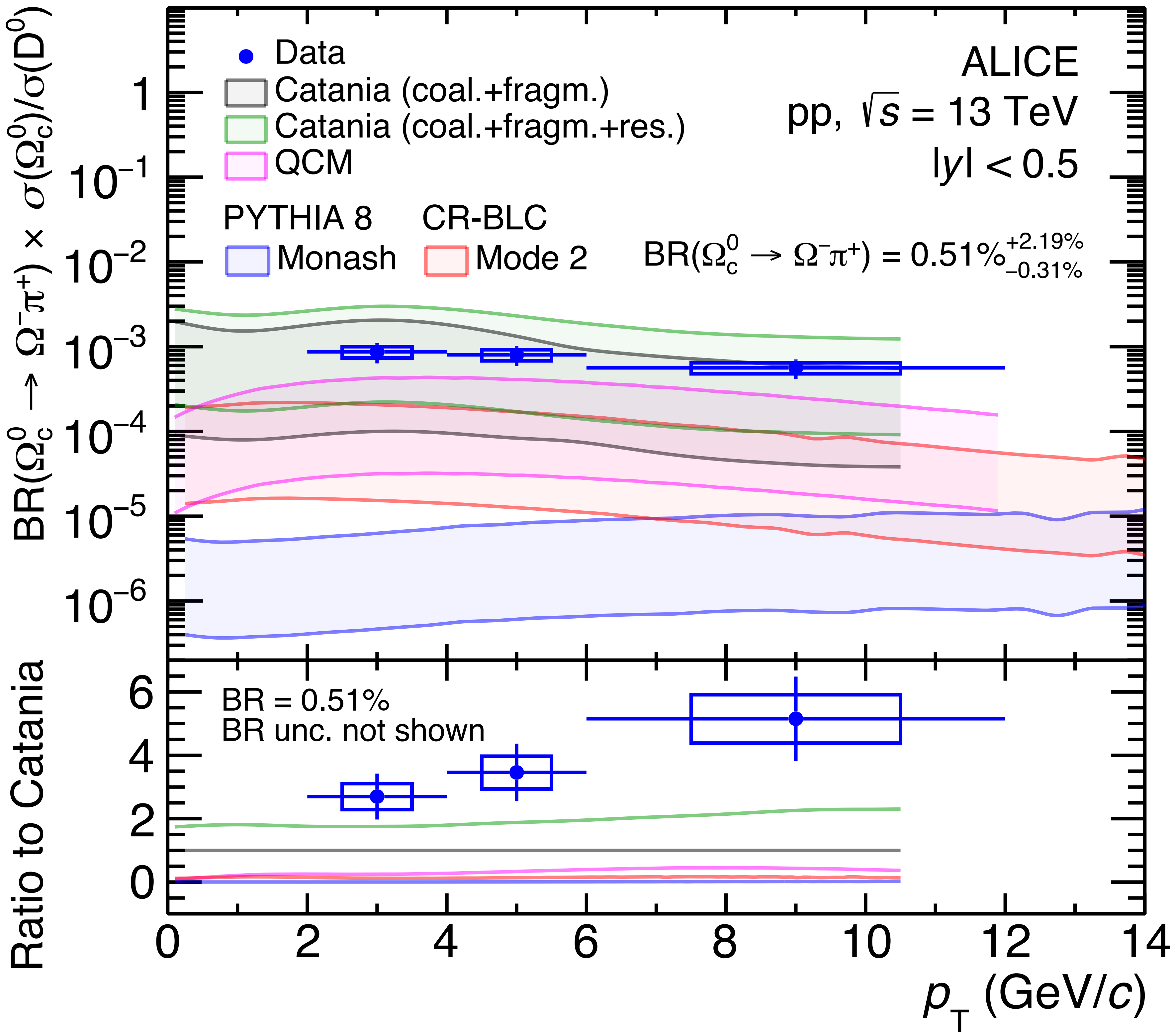
Beauty Baryons





The Charmed Strange Baryons





What we **think** is driving this: **MPI + QCD CR**

2) QCD Colour Reconnections