# New Directions in String Fragmentation

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MONASH University

Australian Government
Australian Research Council

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# Overview

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## Old Directions

Confinement & Fragmentation

The Lund Model of String Hadronization

Multi-Parton Interactions & “Colour Reconnections”

❷

## New Directions

Experimental Directions ⟷ **New Discoveries at LHC**

Theoretical Directions ⟷ **Dynamics of Confinement**

Recent + Ongoing Work ⟷ **Next Steps?**

# Old Directions — Brief Reminder

## **60s**: Regge & S-Matrix Theory

Hadrons: $m^2 \propto J$ ~ early indicator that hadrons could be modelled as strings

## **70s**: QCD as a gauge theory + early fragmentation models

78: The "Cornell Potential" $V_{q\bar{q}}(r) = \frac{a}{r} + \kappa r + c$ (with $\kappa \sim 1\,\mathrm{GeV/fm}$)

79: Discovery of the gluon at TASSO

79: Lund String Fragmentation Model [Andersson, Gustafson, Petterson, Sjöstrand, …]

As opposed to: Independent Fragmentation ↔ Fragmentation Functions

(+ other string models: Caltech & UCLA. And Cluster model.)

## **80s**: Lattice QCD, Monte Carlos, and pQCD

80: First demonstration of linear confinement on the lattice [Creutz, (←Wilson '74)]

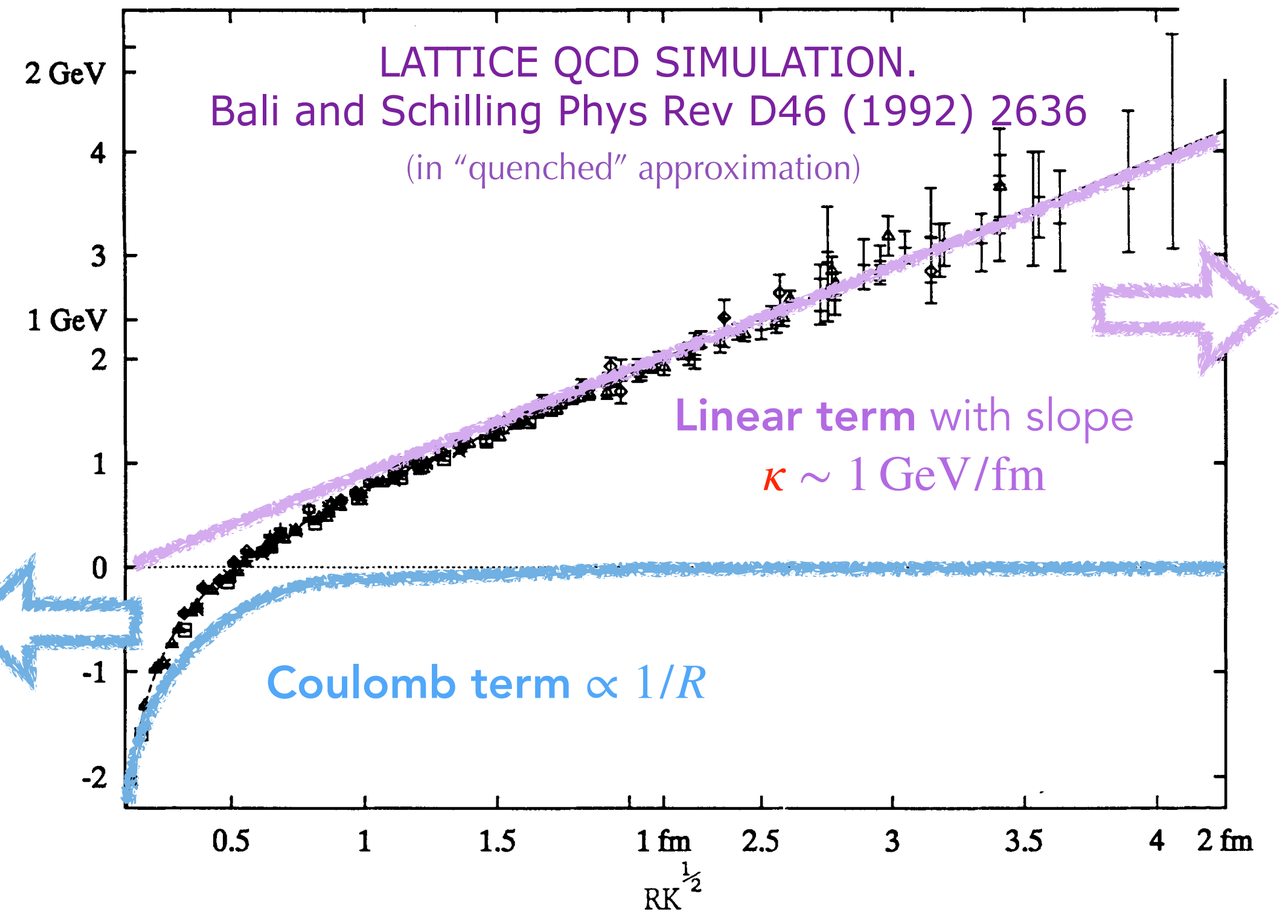
80: Discovery of the JADE (string) effect

# **Linear Confinement** — on the Lattice

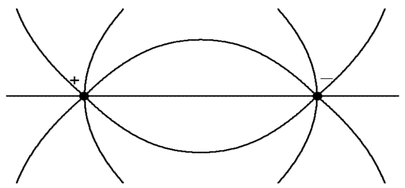
On lattice, place (fixed) $q$ and $\bar{q}$ colour sources a distance $r$ apart

Enforce that they are in a **colour-singlet state**

Compute **potential energy** $V(r)$ ⇒ **agreement** with Cornell potential $= \frac{a}{r} + \kappa r + c$

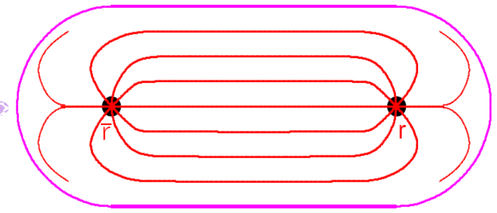



Short Distances ~ "Coulomb"



"Free" Partons

Long Distances ~ Linear Potential




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

# (Semi-classical) String Models of Fragmentation

**Linear** Confinement

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

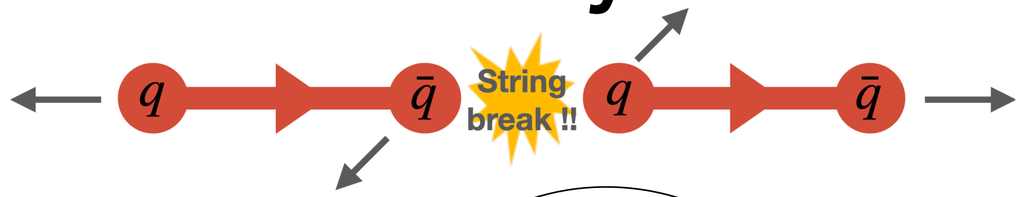



Strings **form** between partons that make overall **colour-singlet** states

Strings **obey** ~ classical equations of motion

**High** separation energies $\gg 1\,\mathrm{GeV} \Longrightarrow$ **Not Steady State**

⇒ **String breaks** (by **pair creation**):




Analogy with "Schwinger Mechanism" in QED:

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

$u\bar{u}$ & $d\bar{d}$ more likely than $s\bar{s}$; No $b\bar{b}$ or $c\bar{c}$;

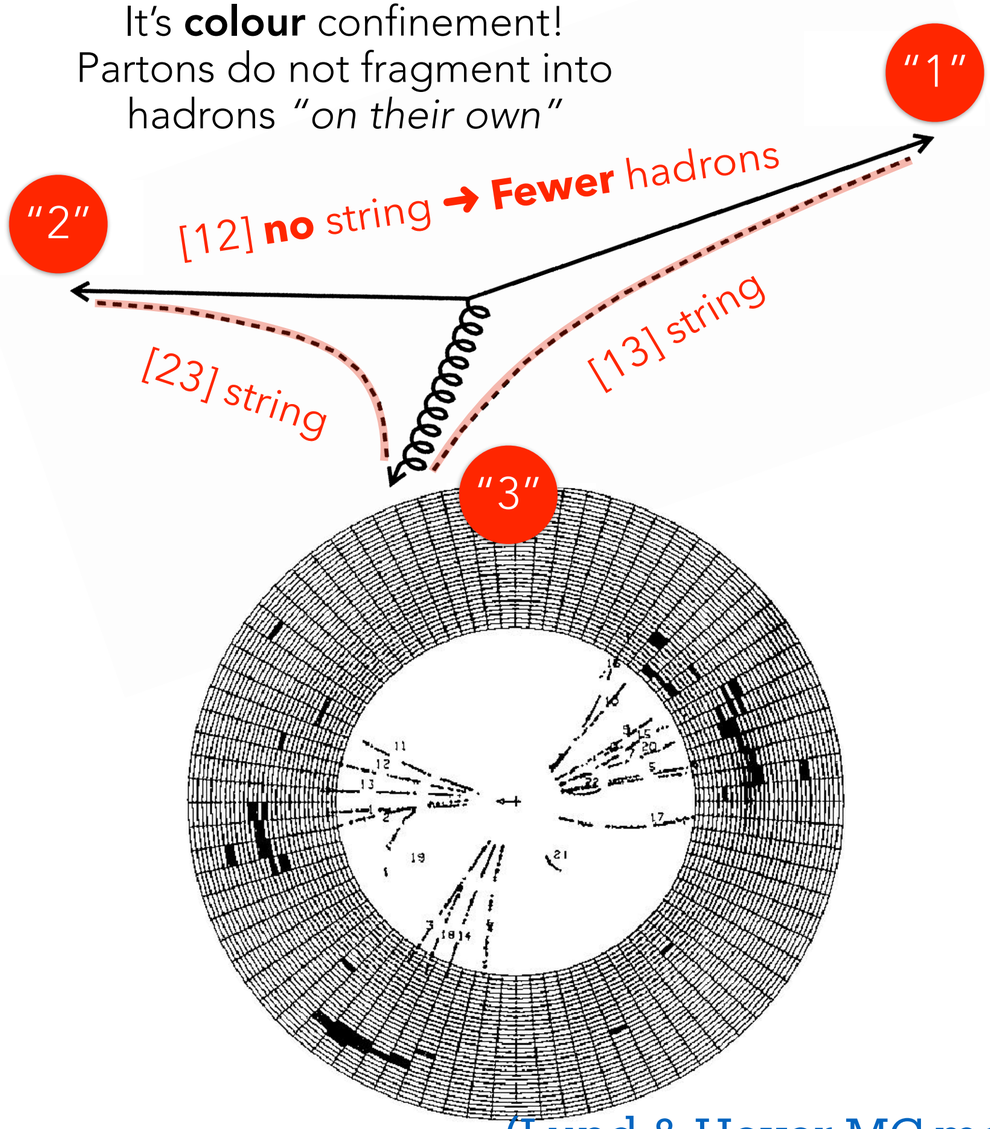
**Signature feature** of Lund Model: **gluons ↔ transverse kinks**

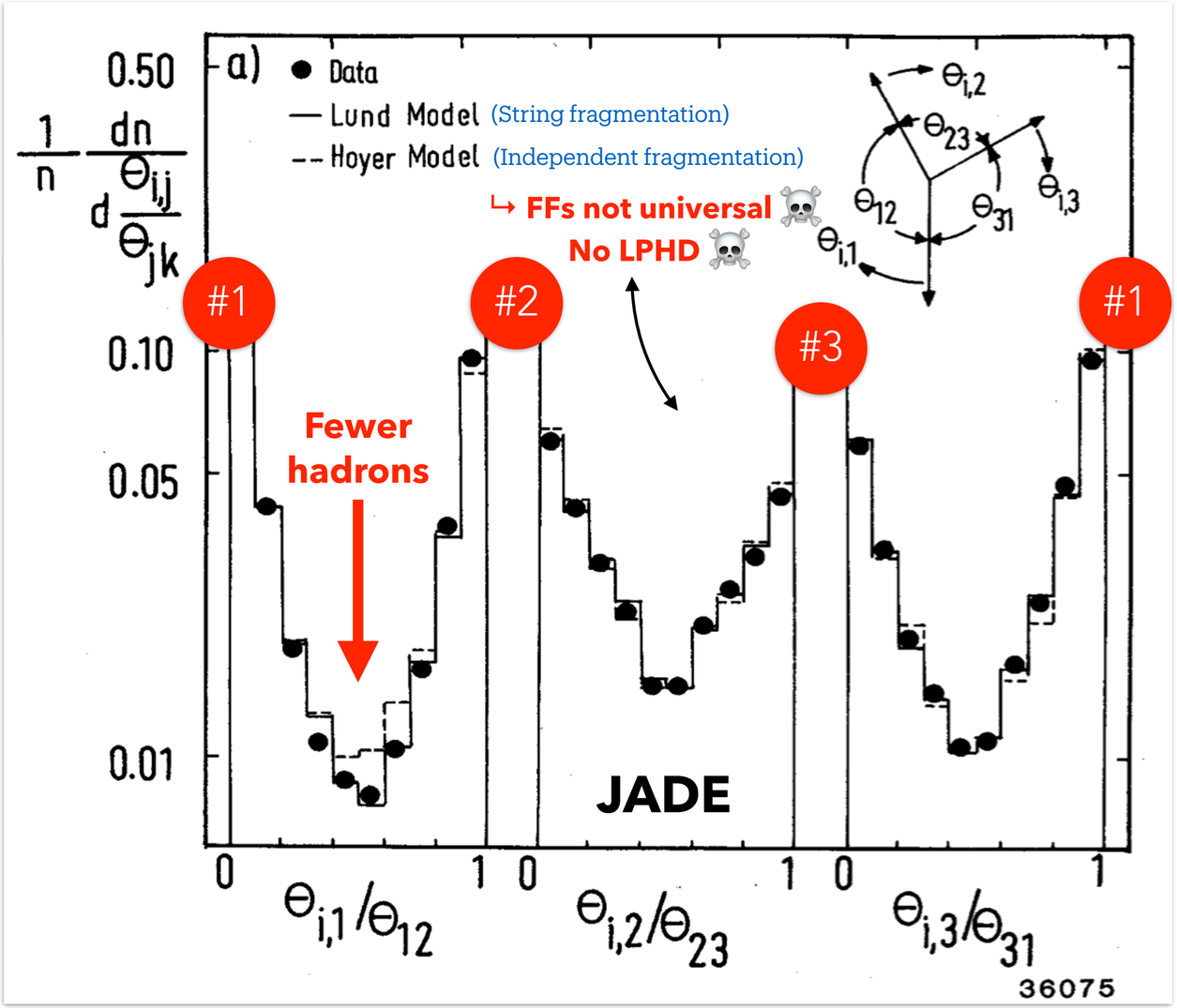
# The JADE/string effect (1980)

Nice historical review of JADE:
S. Bethke [*Eur.Phys.J.H* 47 (2022) 16]

$e^+e^- \to$ **3 jets** @ $\sqrt{s} = 33$ GeV (at PETRA), ordered with $E_1 > E_2 > E_3$

It's **colour** confinement!
Partons do not fragment into hadrons *"on their own"*




(Lund & Hoyer MC models crucial for theory comparisons)

# Some Properties of Strings

Constant tension $\kappa$

$\Longleftrightarrow$ String is everywhere the same (away from endpoints)

Invariant under Longitudinal Boosts

$\Longleftrightarrow$ **Constant hadron density in rapidity** (measured longitudinally along string)

Fragmentation function expressed in scale-less variables: **"lightcone scaling"**

& same average **"hadrochemistry"** (same relative fractions of each hadron species)

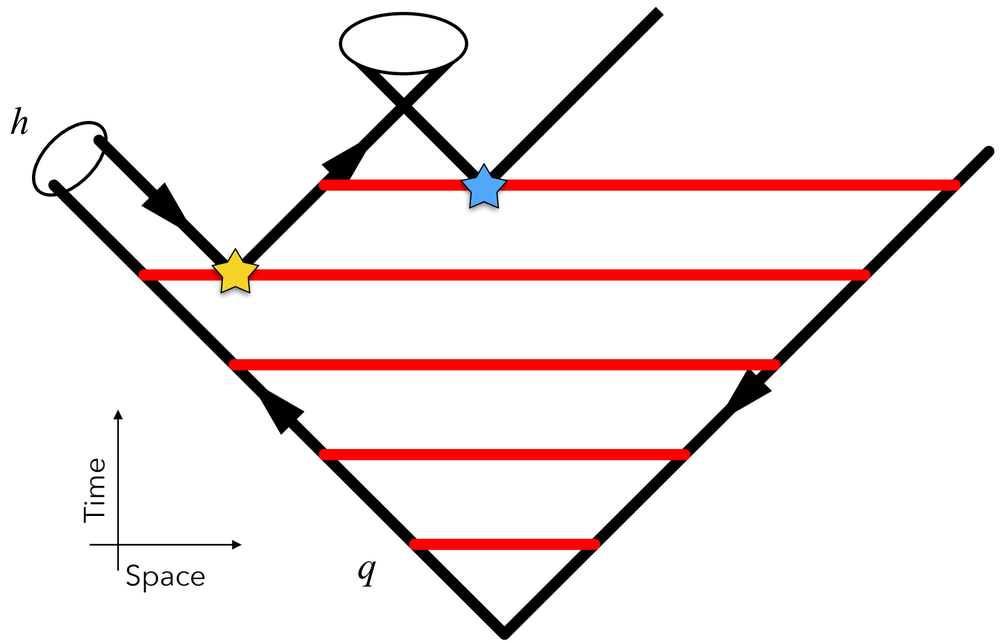
String breaks are *causally disconnected*

$\Longrightarrow$ Can be considered in any order

String breaks nevertheless *entangled*

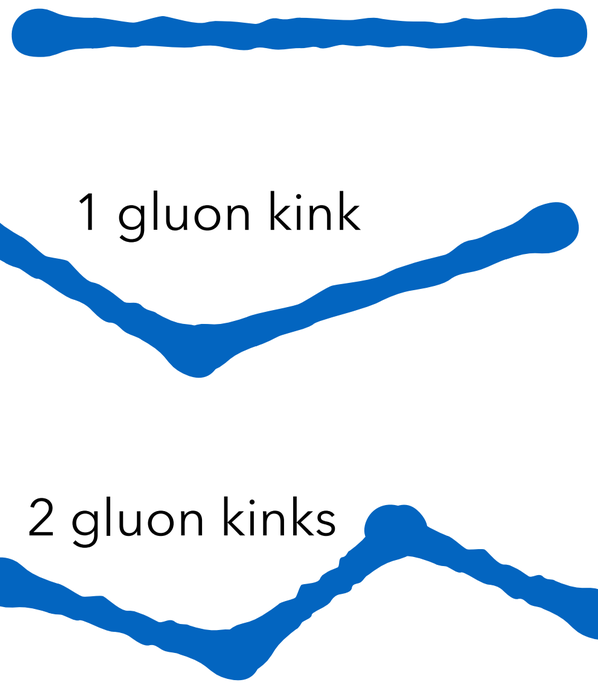
Common production point

Total energy and momentum conservation



# String Topologies

## Open Strings

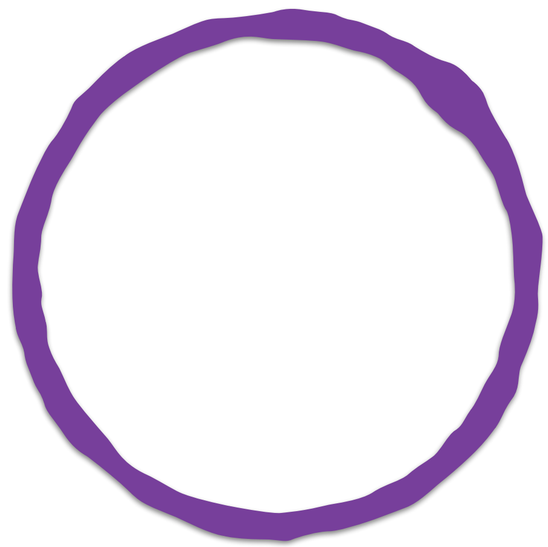



$q\bar{q}$ strings

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

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

## Closed Strings

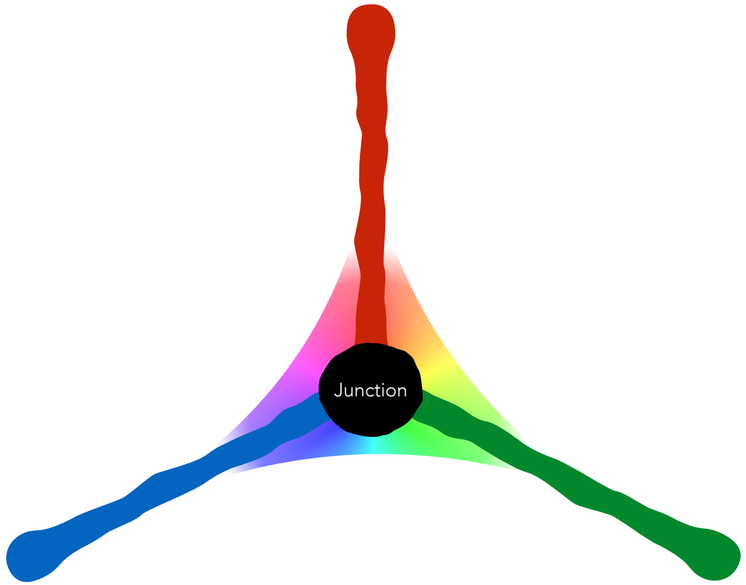


Gluon rings

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

$\Upsilon \to ggg$ + shower

## SU(3) String Junction




Could we get these at LHC?

Junction Fragmentation: Sjöstrand & PS, 2003

With heavy quarks: Altmann & PS 2024

With Closepacking & Strange Junctions: Altmann, Bernardinis, PS, Zaccolo 2025

# Enter *pp* Collisions

*pp* collisions

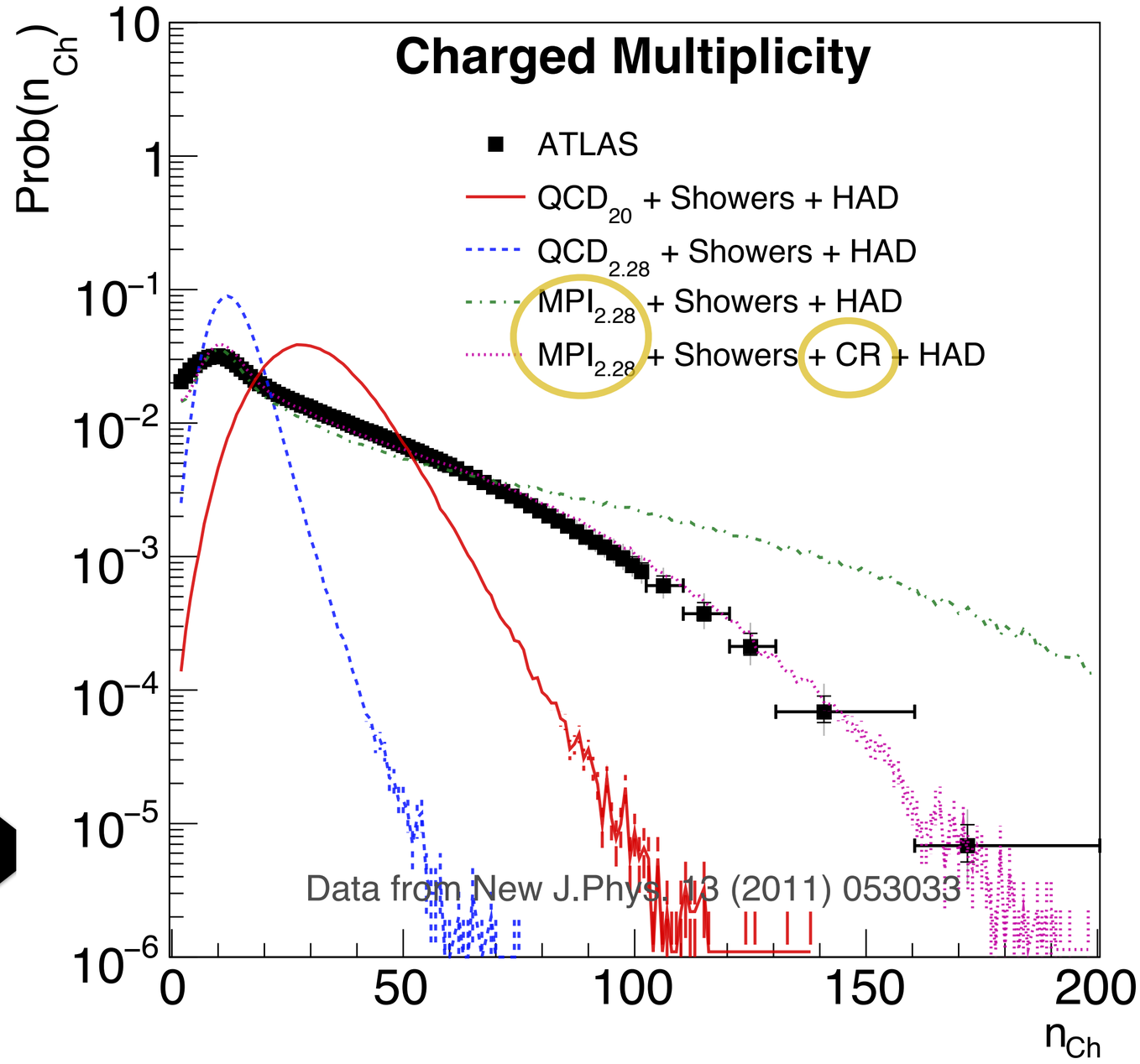
7 TeV

"Minimum Bias"*

Count # of tracks

+ unfold ! 


**Make histogram of probabilities**



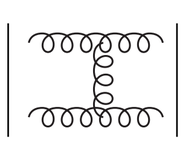

*MB definition here: $n_{\mathrm{ch}} \geq 2$ inside $|\eta| \leq 2.5$, with $p_{\perp} \geq 0.1\,\mathrm{GeV}$

# Hadron Collisions → Multi-Parton Interactions

## Protons are composite

**One** proton = **beam** of partons

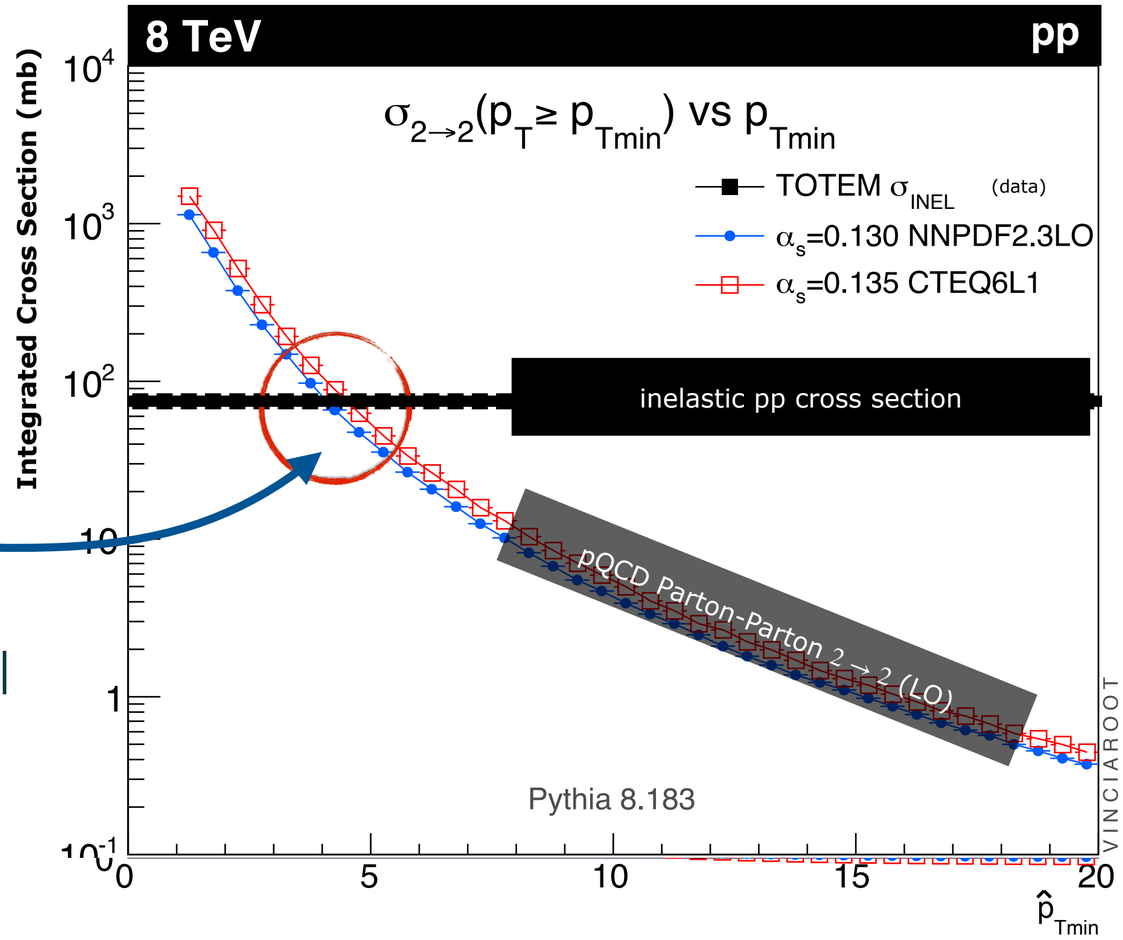
+ $\mathrm{d}\sigma_{\mathrm{parton-parton}}$ is dominated by $t$-channel gluon exchange: **diverges for** $\hat{p}_\perp \to 0$ GeV



$$\propto \frac{\alpha_s^2(p_\perp)}{t^2} \approx \frac{\alpha_s^2(p_\perp)}{p_\perp^4}$$

$\Longrightarrow$ For sufficiently low $p_\perp$(~ 5 GeV at LHC), we will have $\sigma_{\mathrm{parton-parton}}(p_\perp) \gtrsim \sigma_{\mathrm{proton-proton}}$

Interpretation: $\dfrac{\sigma_{\textbf{parton-parton}}(p_\perp)}{\sigma_{\textbf{hadron-hadron}}} \sim \langle n \rangle_{\mathrm{parton-parton}}(p_\perp)$




Regulated at low $p_\perp$ by IR cutoff ~ colour screening = main "tuning" parameter; determines $\langle n \rangle_{\mathrm{parton-parton}}$

➜ **Multiple Parton-Parton Interactions (MPI)** [$\langle n \rangle_{\mathrm{parton-parton}} > 1$ per pp collision]

# A Brief History of MPI (in PYTHIA)

**1987** [Sjöstrand & van Zijl, Phys.Rev.D 36 (1987) 2019]

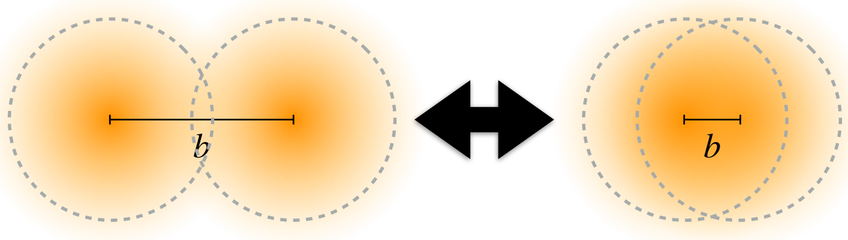
Cast MPI as Sudakov-style evolution:

Analogous to $\sigma_{\mathrm{X+jet}}(p_\perp)/\sigma_{\mathrm{X}}$ for parton showers

$$\frac{dP_{\text{hardest}}}{d^2b\ dx_{T1}} = p(x_{T1},b)\ \exp\left\{-\int_{x_{T1}}^{1} p(x'_T,b)\ dx'_T\right\}$$

with: $\mathrm{p} \propto \sigma_{2\to2}(x_T,b)/\sigma_{pp}$ ; $x_T = 2\hat{p}_\perp/\sqrt{s}$

with Impact-parameter dependence




Crucial to describe **"Underlying Event"**

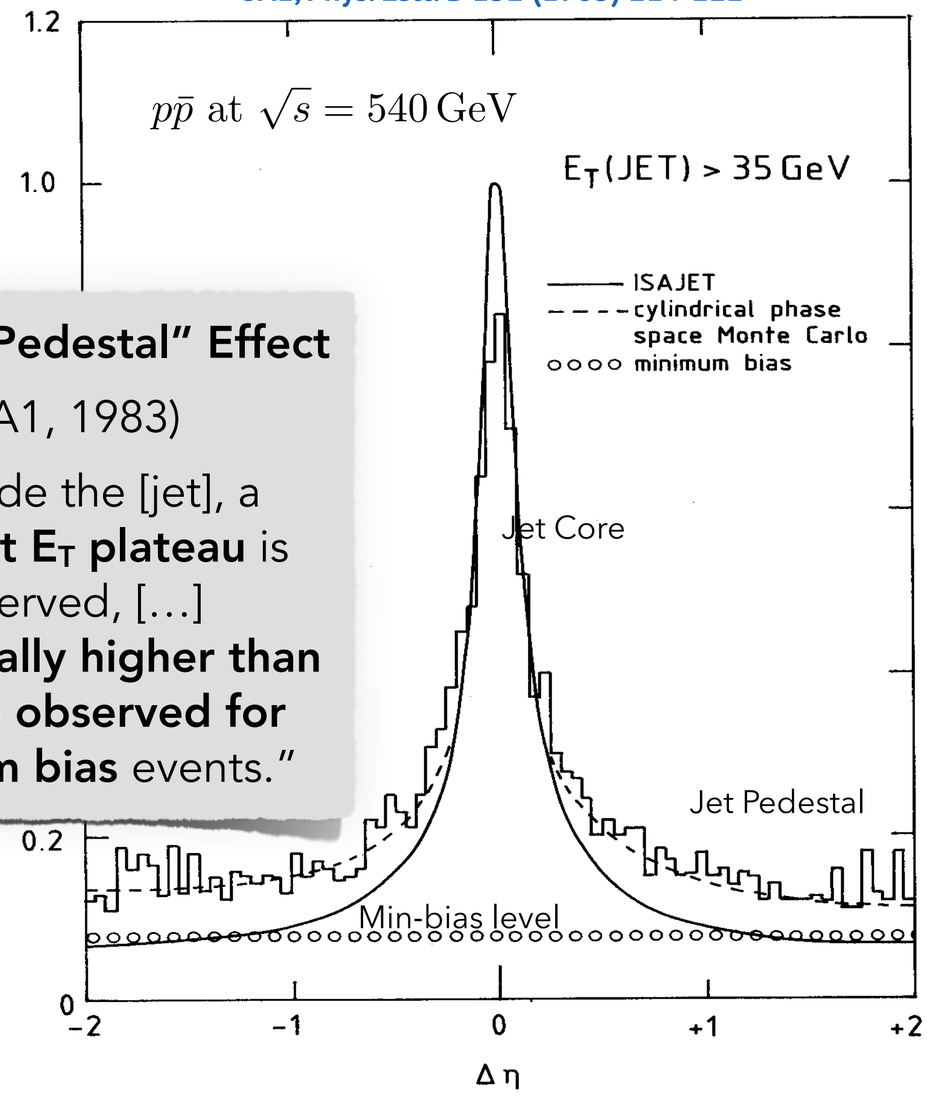
a.k.a. **"Jet Pedestal"**

**The "Jet Pedestal" Effect**

(UA1, 1983)

"Outside the [jet], a **constant $E_T$ plateau** is observed, […] **substantially higher than the one observed for minimum bias** events."

UA1, Phys. Lett. B 132 (1983) 214-222



# **Interleaved** Evolution

**Interleave MPI + ISR + FSR** evolutions in one **common** sequence of $p_T$

➜ ISR & MPI "compete" for the available $x$ in the proton

[**MPI** & **ISR**: Sjöstrand & PS, 2004]

[+ **FSR**: Corke & Sjöstrand, 2010]

[**+ Res Dec**: Brooks, PS, Verheyen 2021]

**~ Fine-graining of all event structure above hadronization scale in one common sequence of quantum mechanical resolution $\propto p_\perp$**

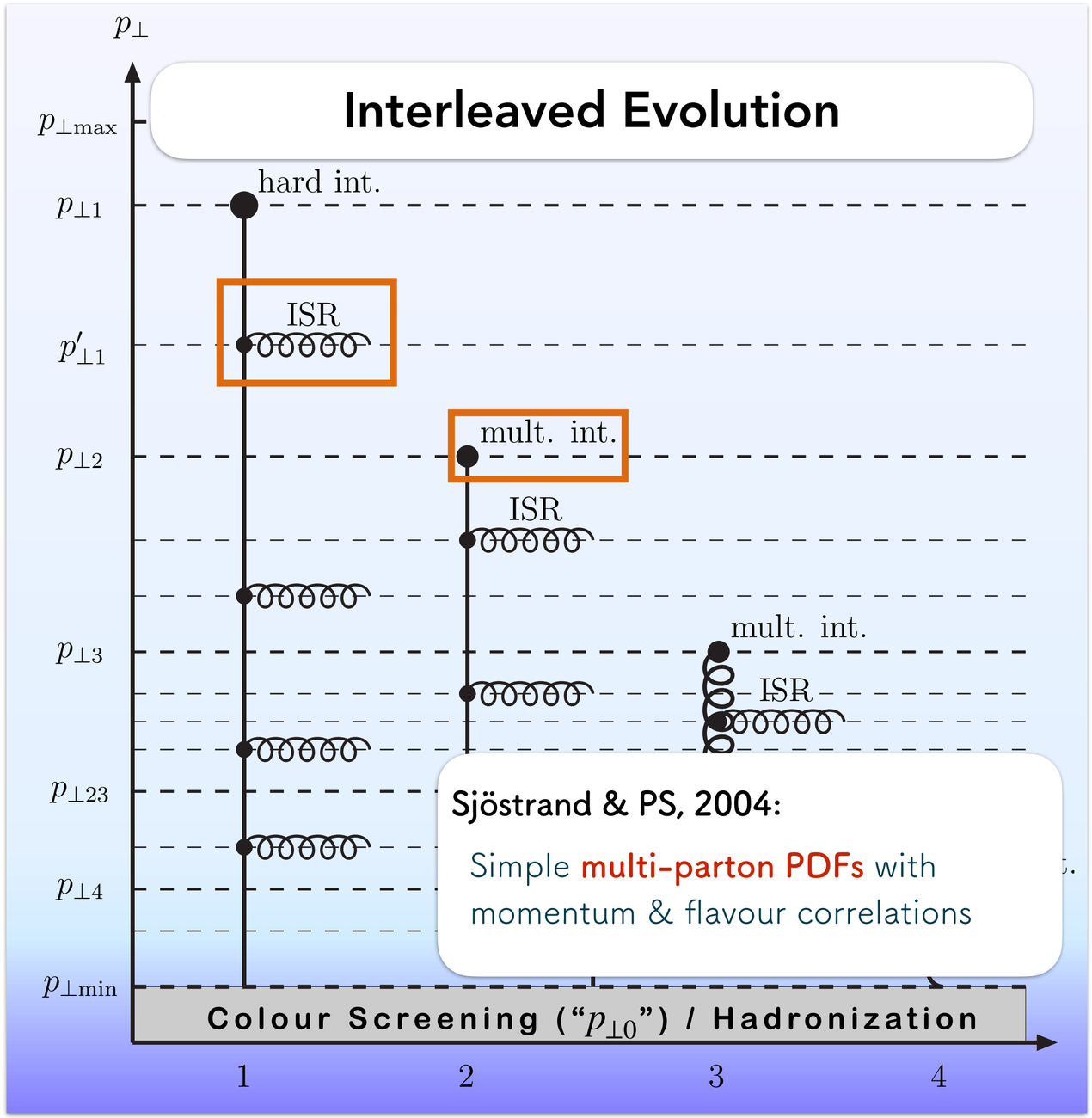



Figure from Sjöstrand & PS, 2005

# Confinement in $pp$ Collisions: "Colour Reconnections"

MPI ⇒ 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**:

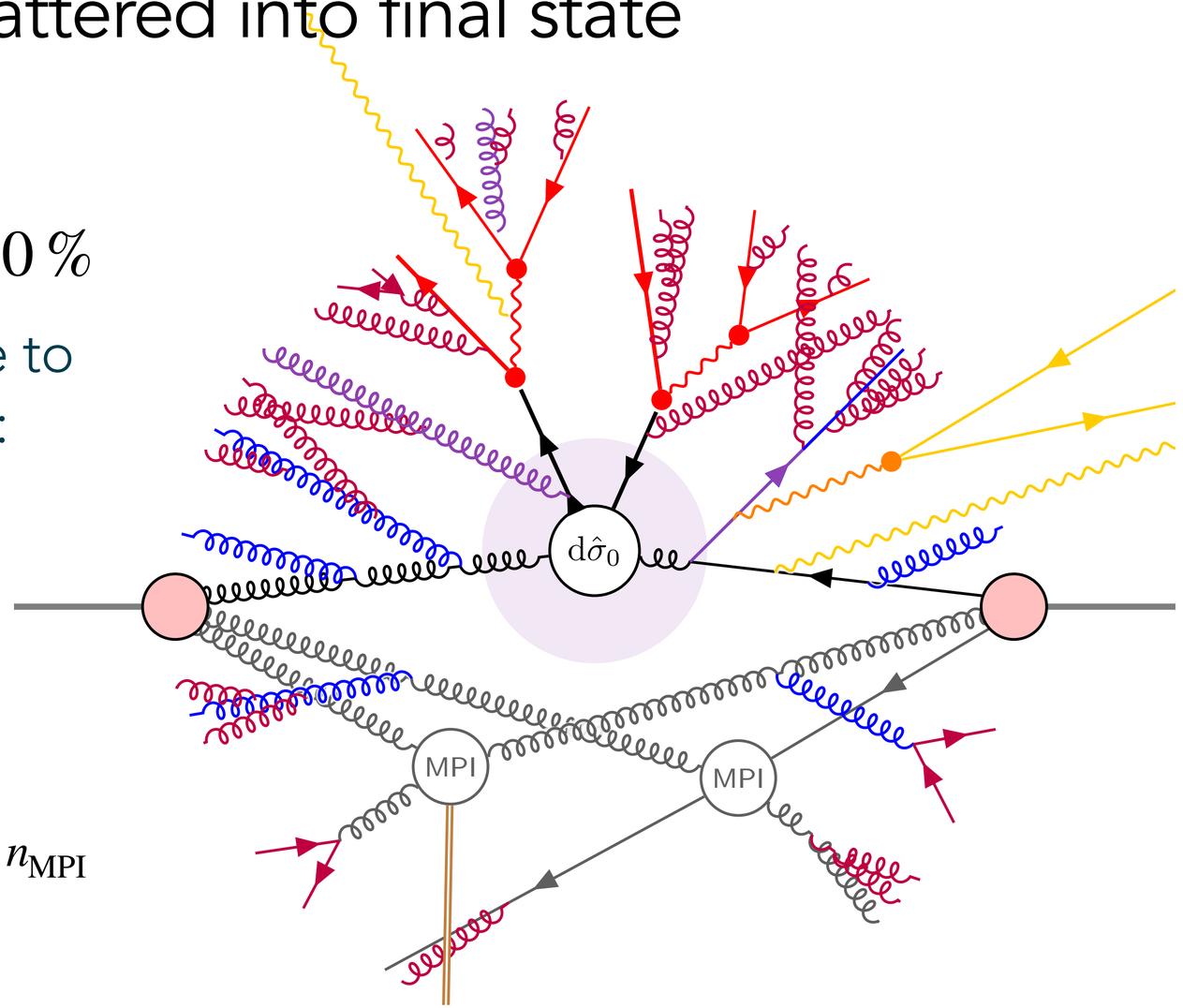
$3 \otimes \bar{3} = 8 \oplus 1,$

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

***Many* charges ➜ Colour Reconnections***

**(CR)** more likely than not

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

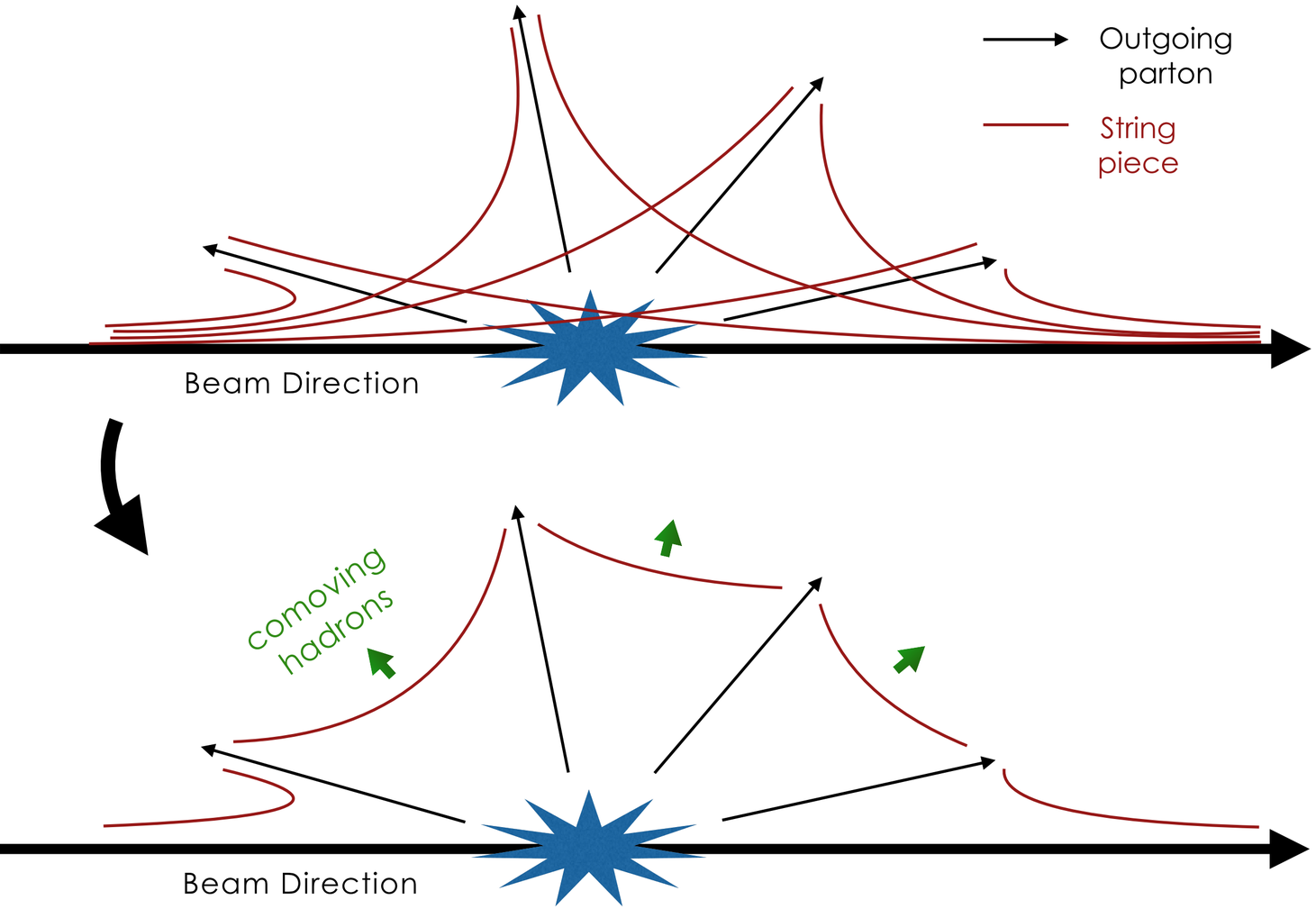


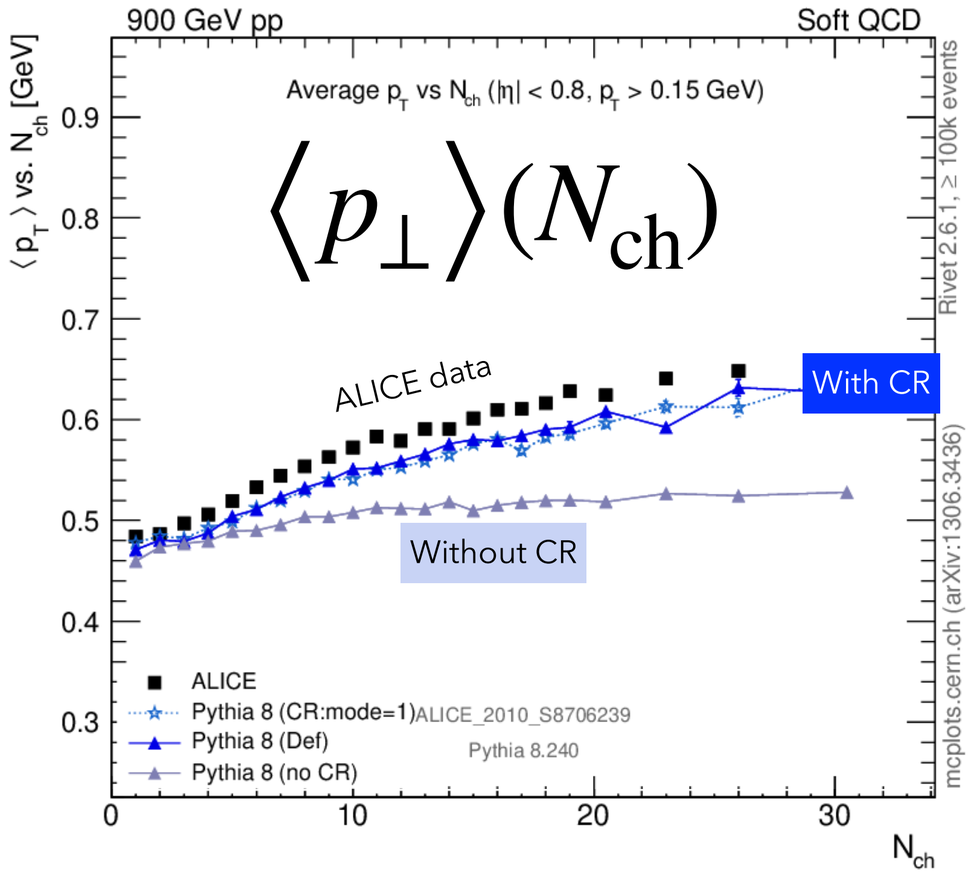

*Example* (from arXiv:2203.11601)
$pp \to t\bar{t}$ (all-jets)

***):** 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>($N_{ch}$)

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




[See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001]

# Current picture of, e.g., a $gg \to t\bar{t}$ event @ LHC

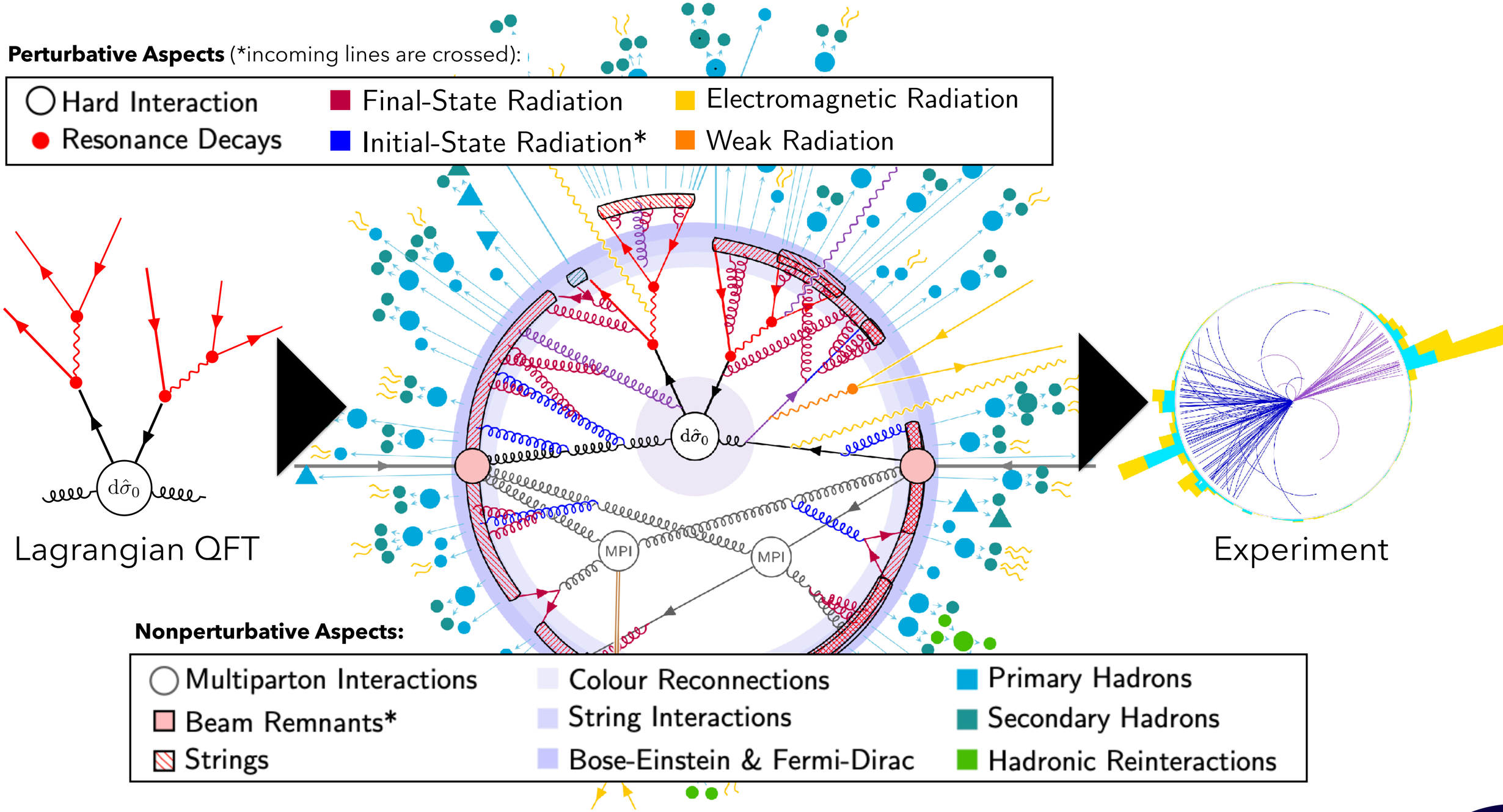



Figure from arXiv:2203.11601

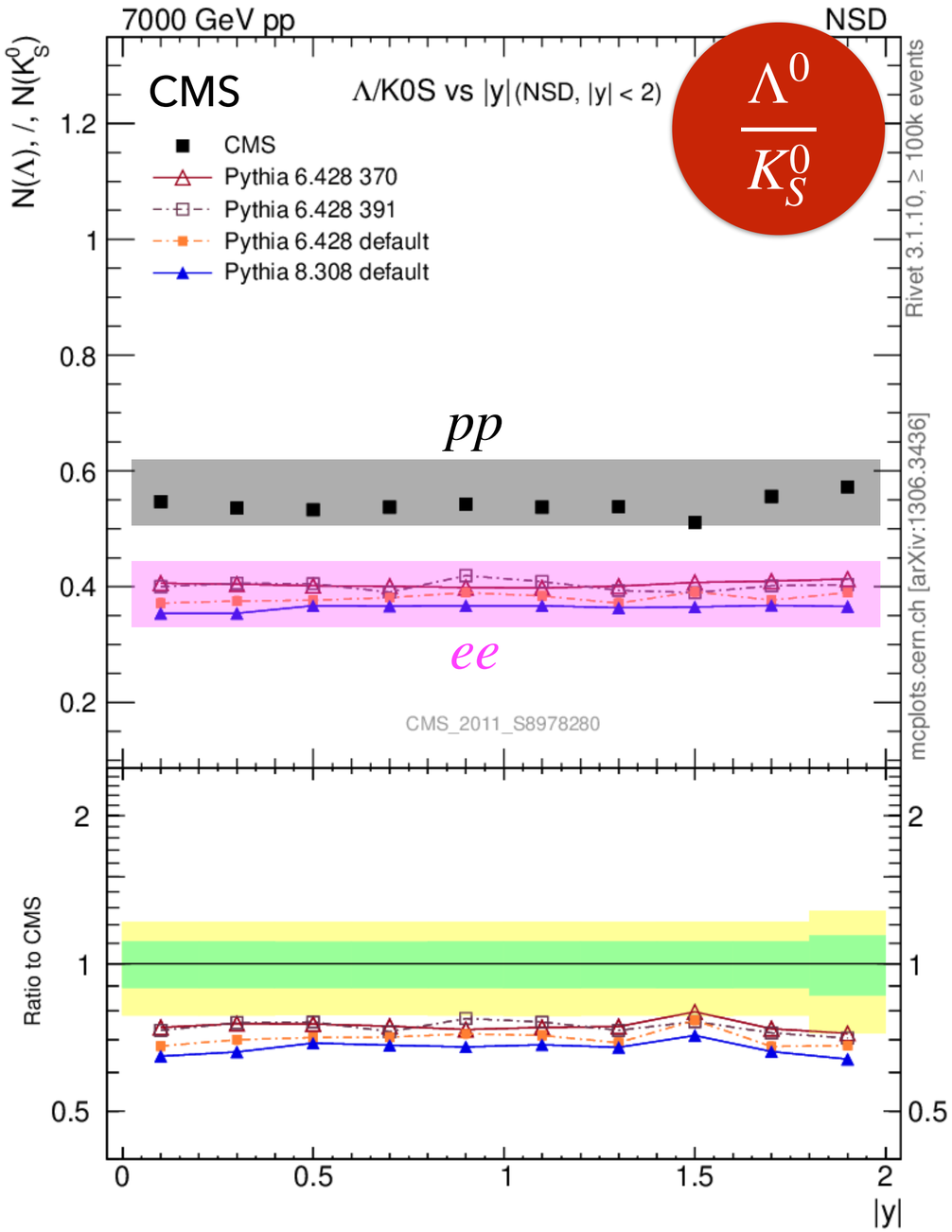
I will first highlight the **measurements**
**then** discuss theory

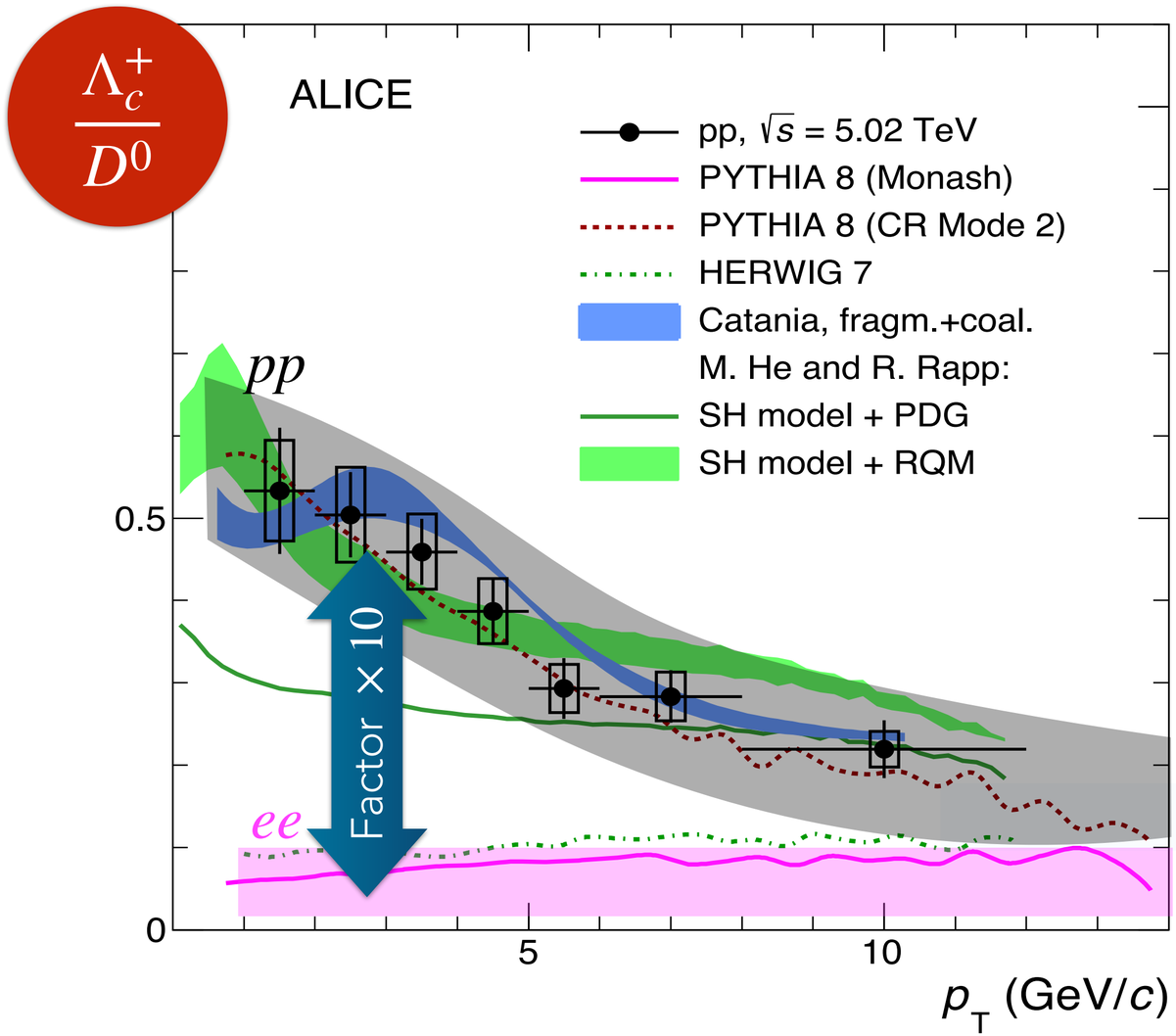
# What has philosophy got to do with measuring anything?

Galileo, *Concerning the New Star (1606)*

*Note: I will just highlight one or two measurements of each effect.*
*But all of them have been measured in multiple ways, by multiple experiments.*

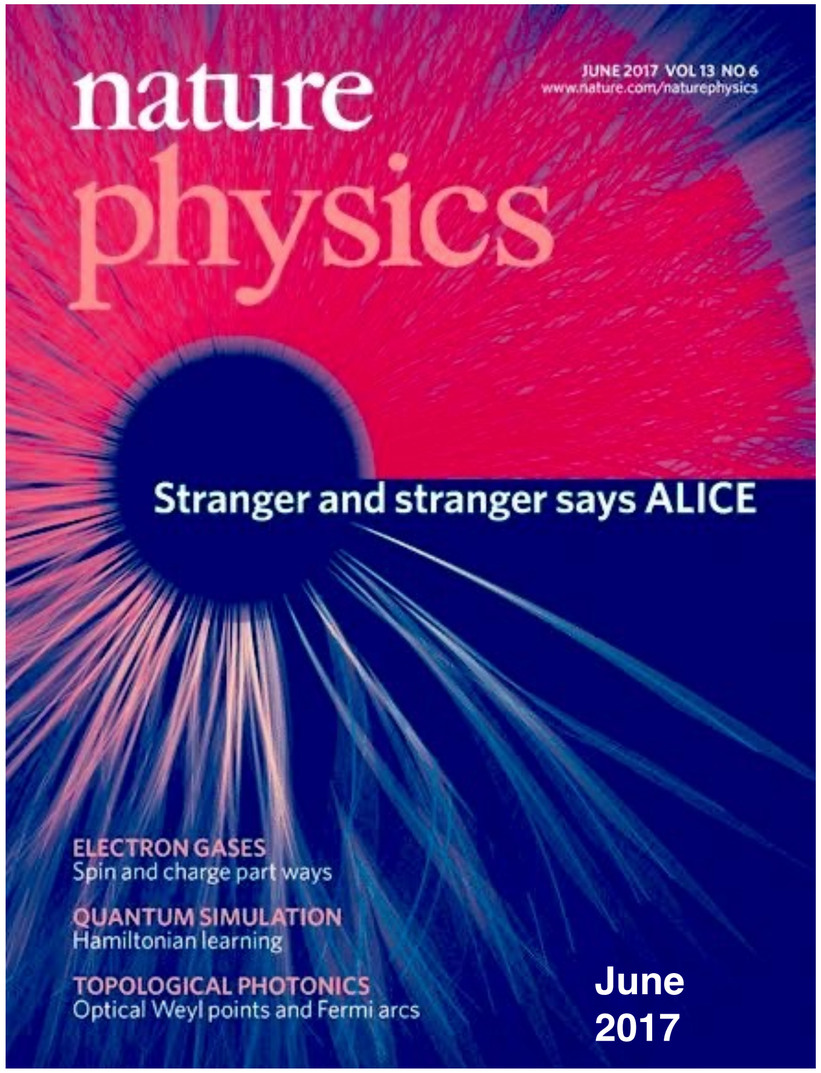
# More Strange & Heavy $(c, b)$ **Baryons** at LHC

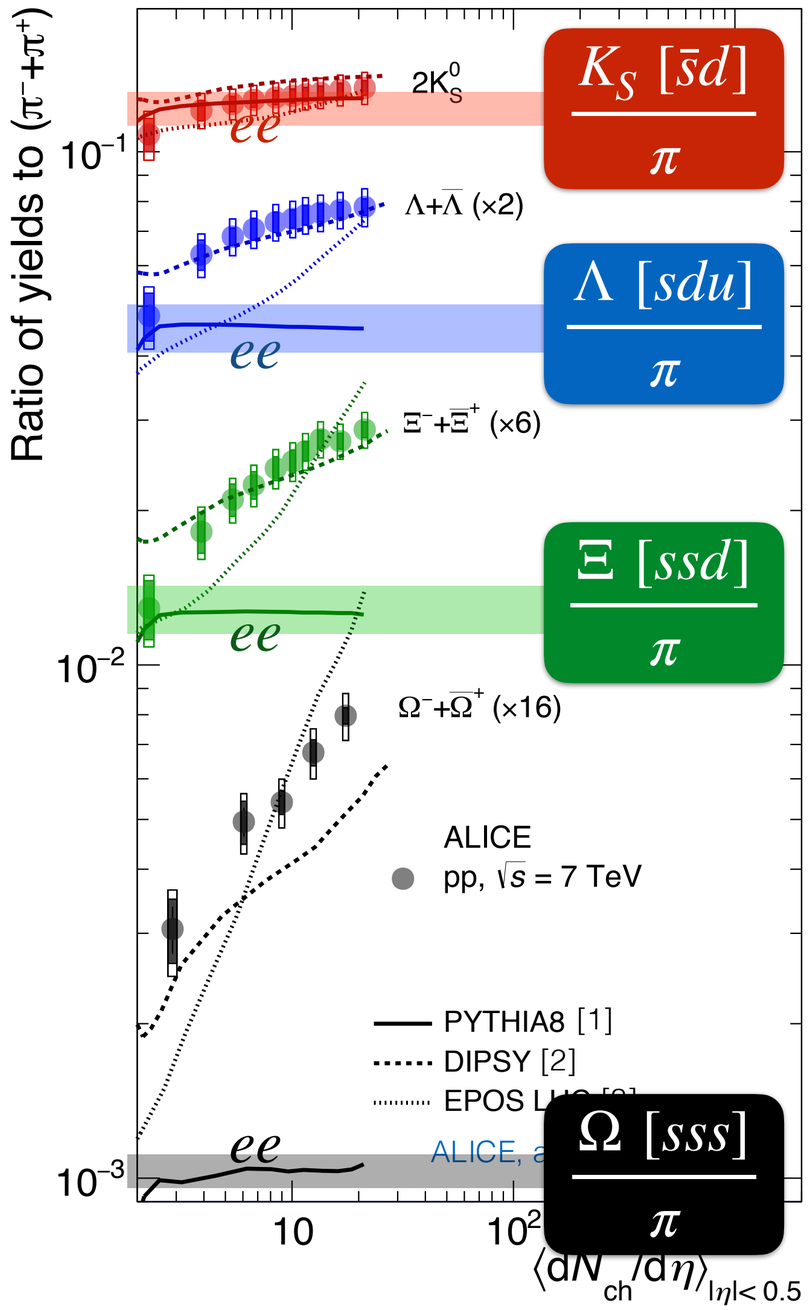



☠ Fragmentation Universality is Dead

# *"What a **Strange** World We Live In", said ALICE*




**Shaded bands** indicate universality ~ LEP

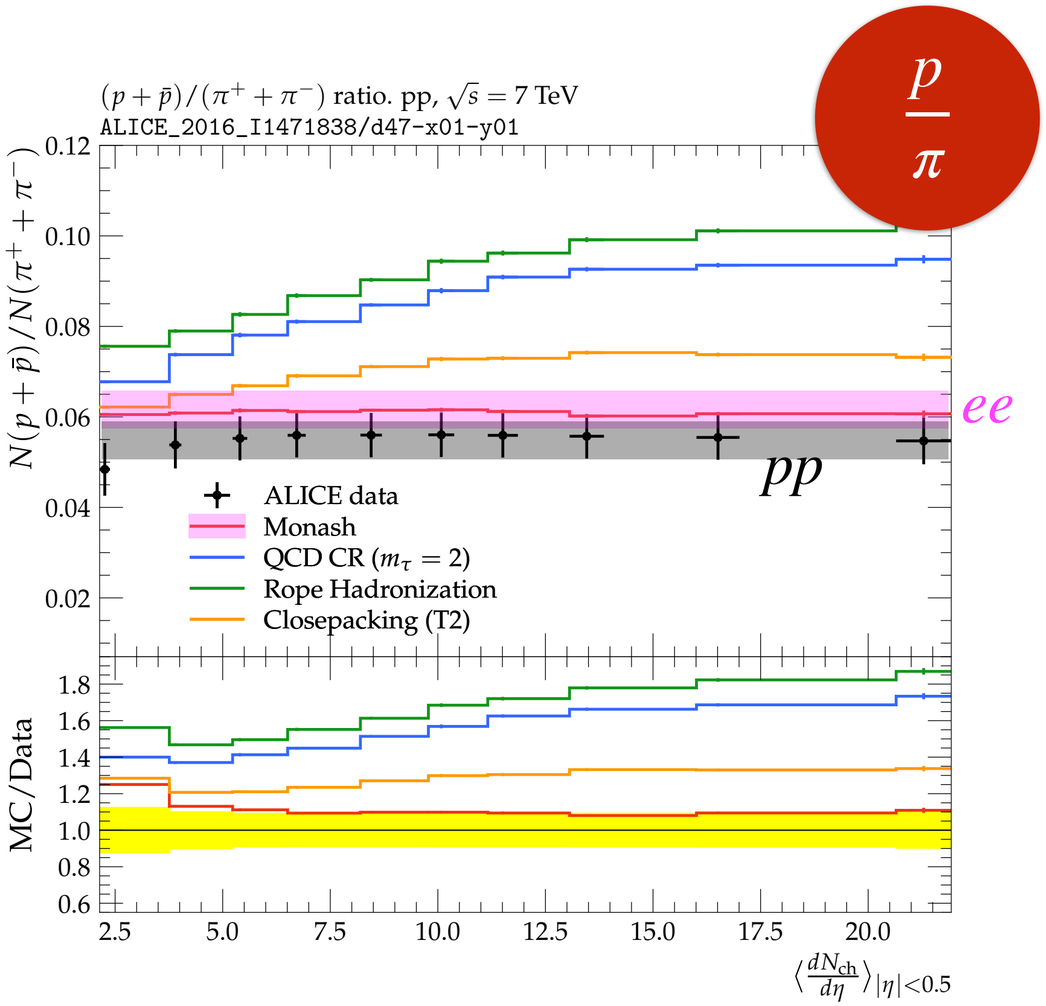
**Solid lines** = Universal flavour ratios in string breaks (default PYTHIA)

(**Dashed / dotted** lines = "Ropes" / QGP-inspired models; will return to these)

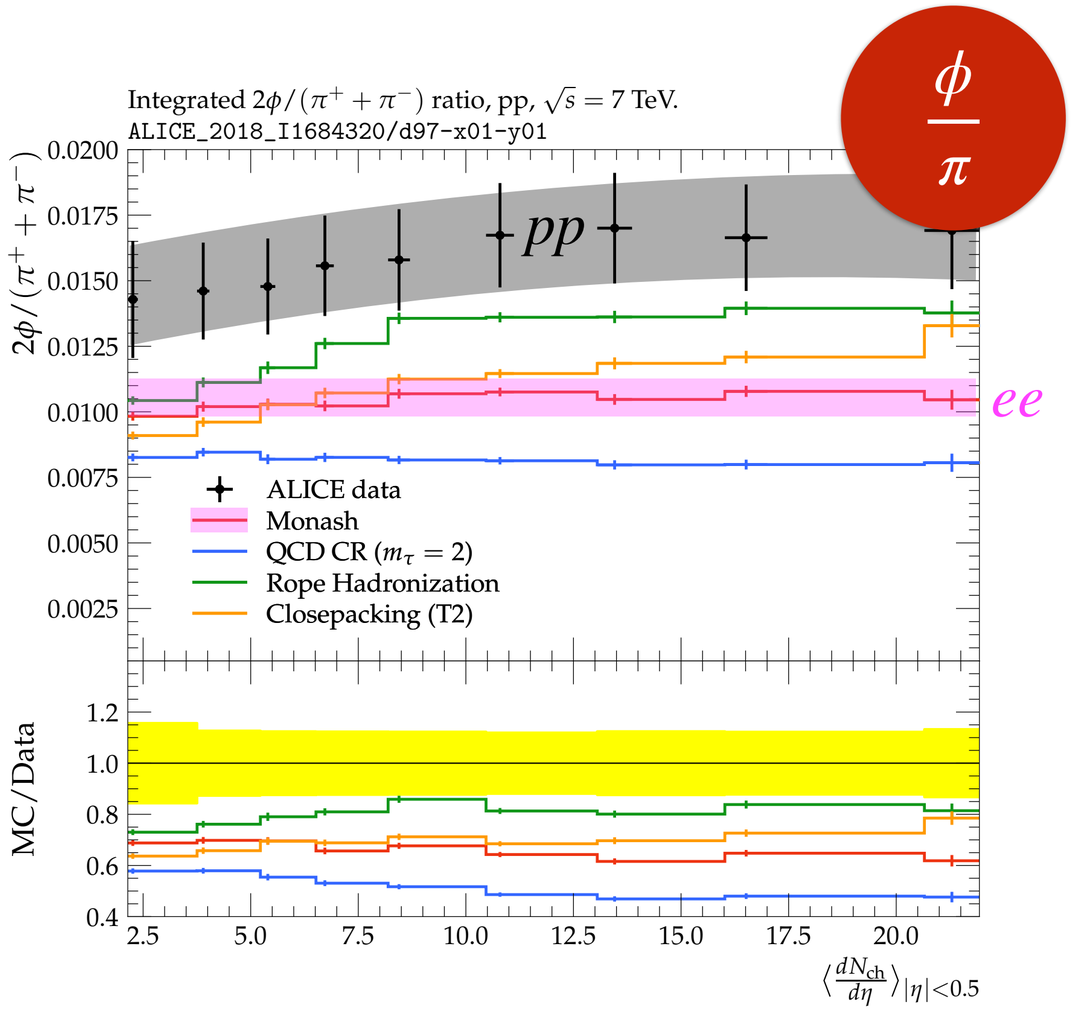
☠️ **Universal flavour ratios are dead**

Strangeness suppression exhibits strong dependence on "overall event activity"

# It truly is **strange** — $(p/\pi)$ and $(\phi/\pi)$




Need ~ **same** $p/\pi$ as in ee




Need **more** phi

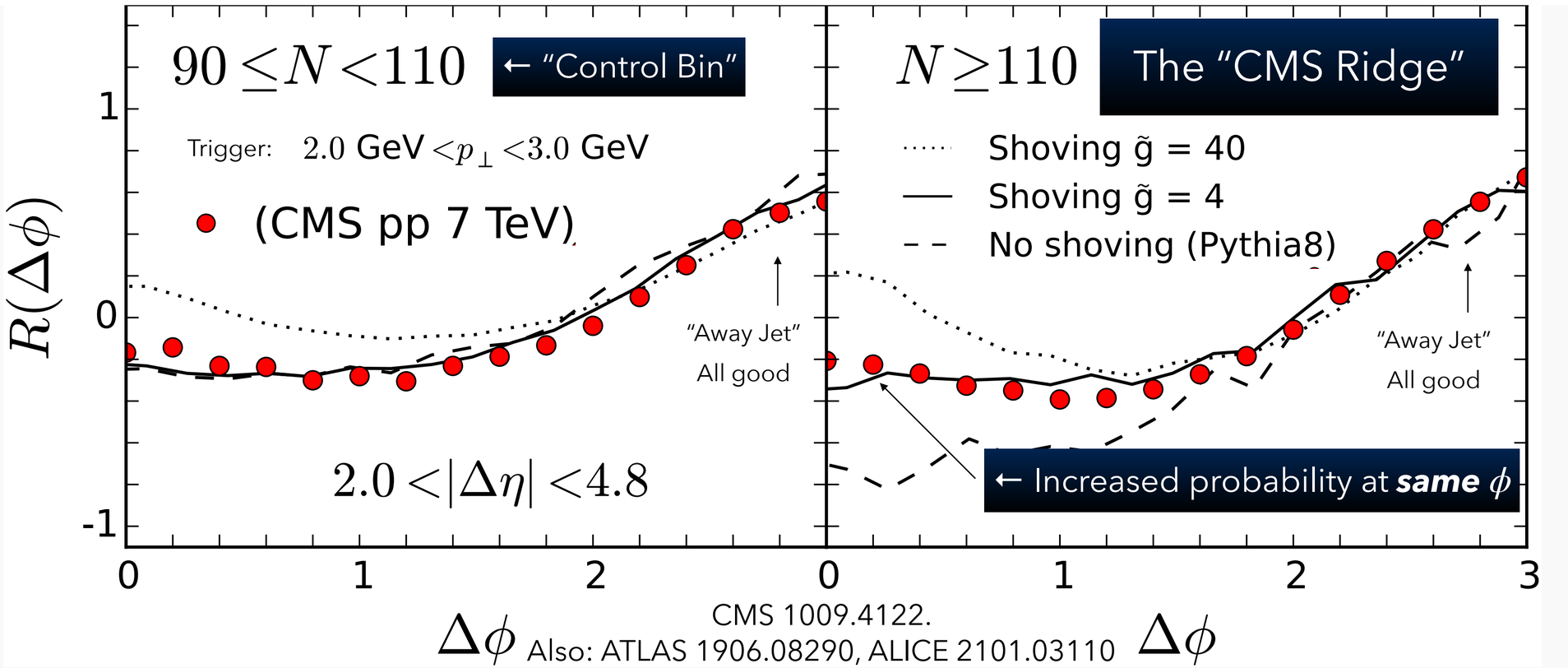
**not** *just* **baryon** enhancement

# Collective **Flow** (in pp)

**2-particle correlations** in **high-multiplicity** minimum-bias events

Strong **short-distance correlations expected** (perturbative excitations)

Look at probability to find a particle **far away in rapidity**, as function of $\phi$




CMS 1009.4122.
Also: ATLAS 1906.08290, ALICE 2101.03110

# New Directions: **Theory**

In **QCD:** strings and string tension $\kappa$ are **emergent** phenomena

**Dynamical Strings?** ⇒ **Effective** $\kappa$ may depend on:

Invariant worldsheet time $\tau$ ; Spatial coordinate $\sigma$ ; Environment

e.g., PYTHIA

**String Breakdowns?** ("Quenching" above a critical field?)

⇒ Droplets of QGP ⇒ $\kappa$ replaced by temperature, $T$ ?

e.g., EPOS

# Explorations of the Worldsheet

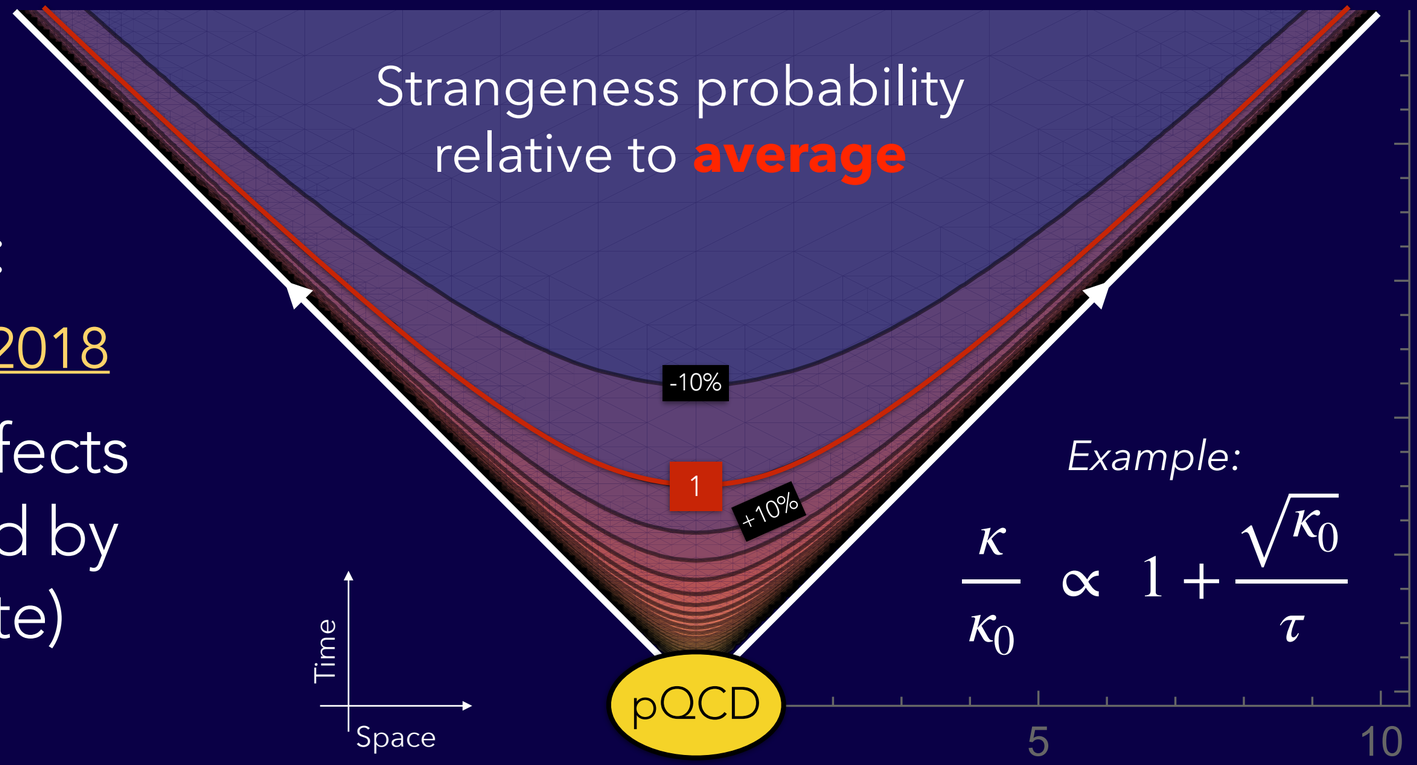
## **Pilot Study:** $\tau$ dependence

Hunt-Smith & PS 2020

E.g., Hot strings that cool down:

Berges, Floerchinger, Venugopalan 2018

Note also: out-of-equilibrium effects (e.g., at early times) not captured by standard lattice limit (steady state)




*Example:*

$$\frac{\kappa}{\kappa_0} \propto 1 + \frac{\sqrt{\kappa_0}}{\tau}$$

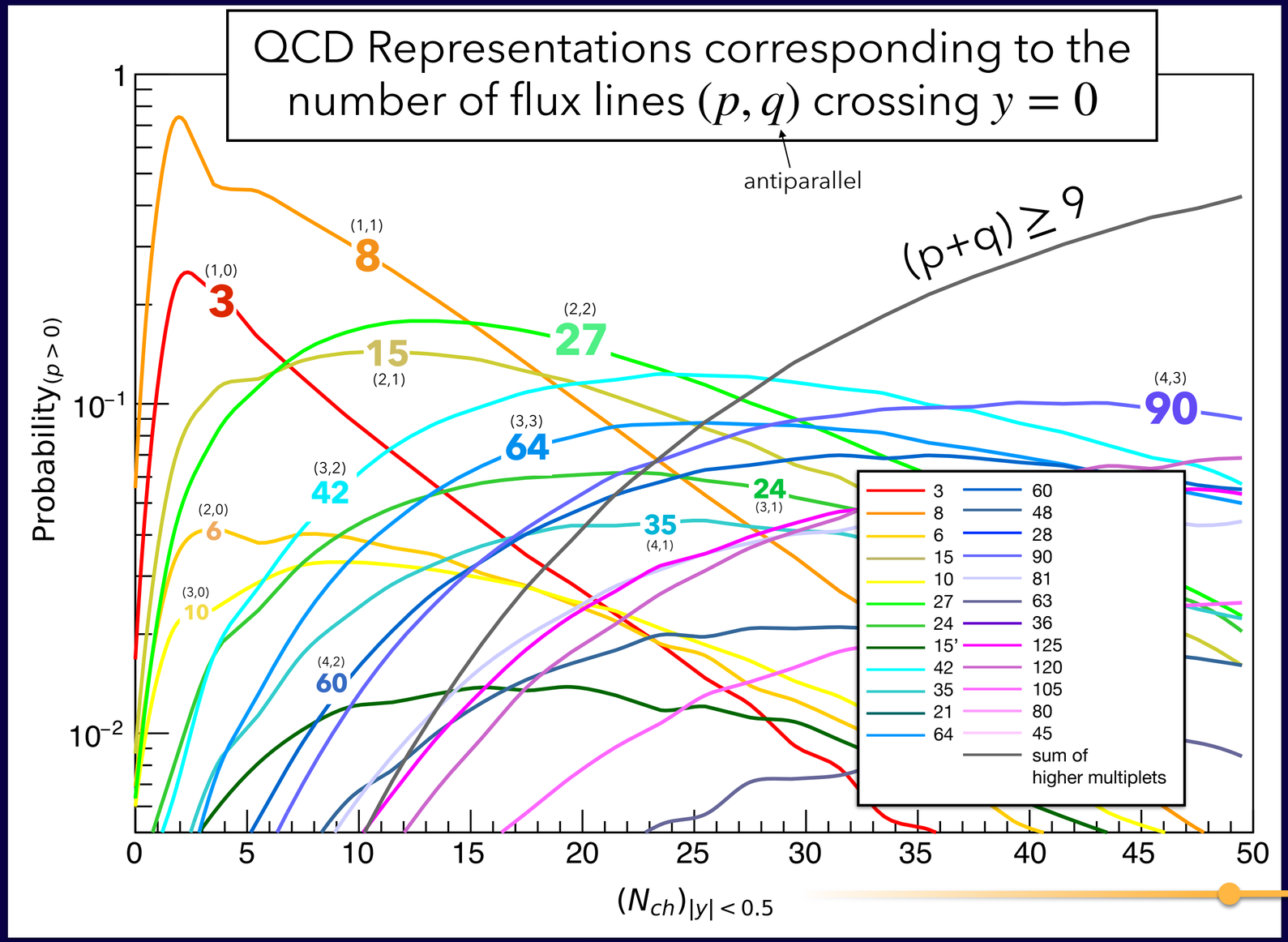
## **Work in progress:**

Altmann, Carragher, March-Russell, PS

Fragmentation of a world sheet with a general ($\sigma$,$\tau$) tension (Altmann, PhD)

From a string theory with an explicit spectrum of excitations (Carragher, PhD)

# $pp$: **how many strings** are we talking about?




Pythia with MPI

(educated guess)

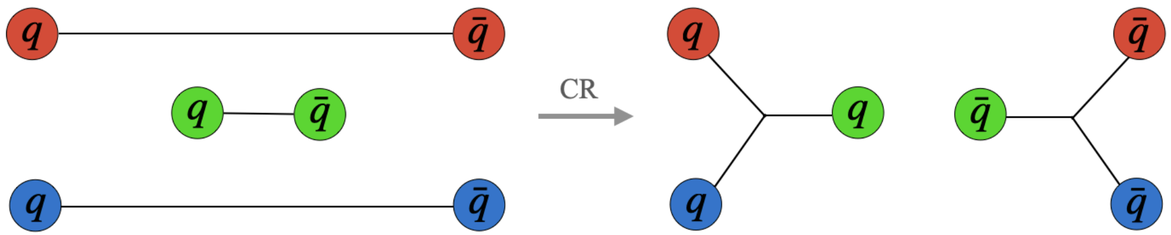
Each MPI = a "colour spark" between the beams

Large $N_{ch}$

⇒ Lots of colour exchanged between the beams

So many strings, so little room

# Colour Reconnections ➢ **String Junctions**

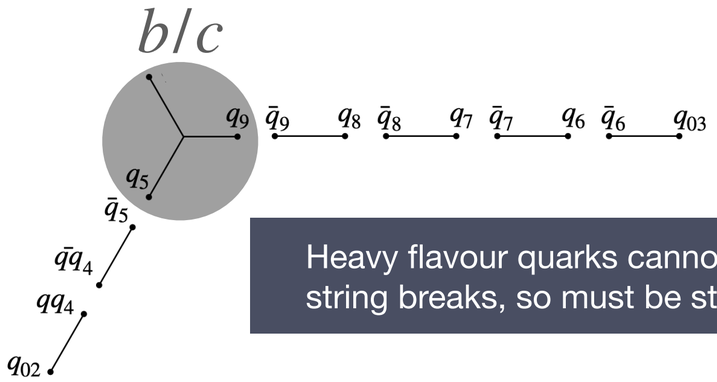



Mechanism for **baryon production**

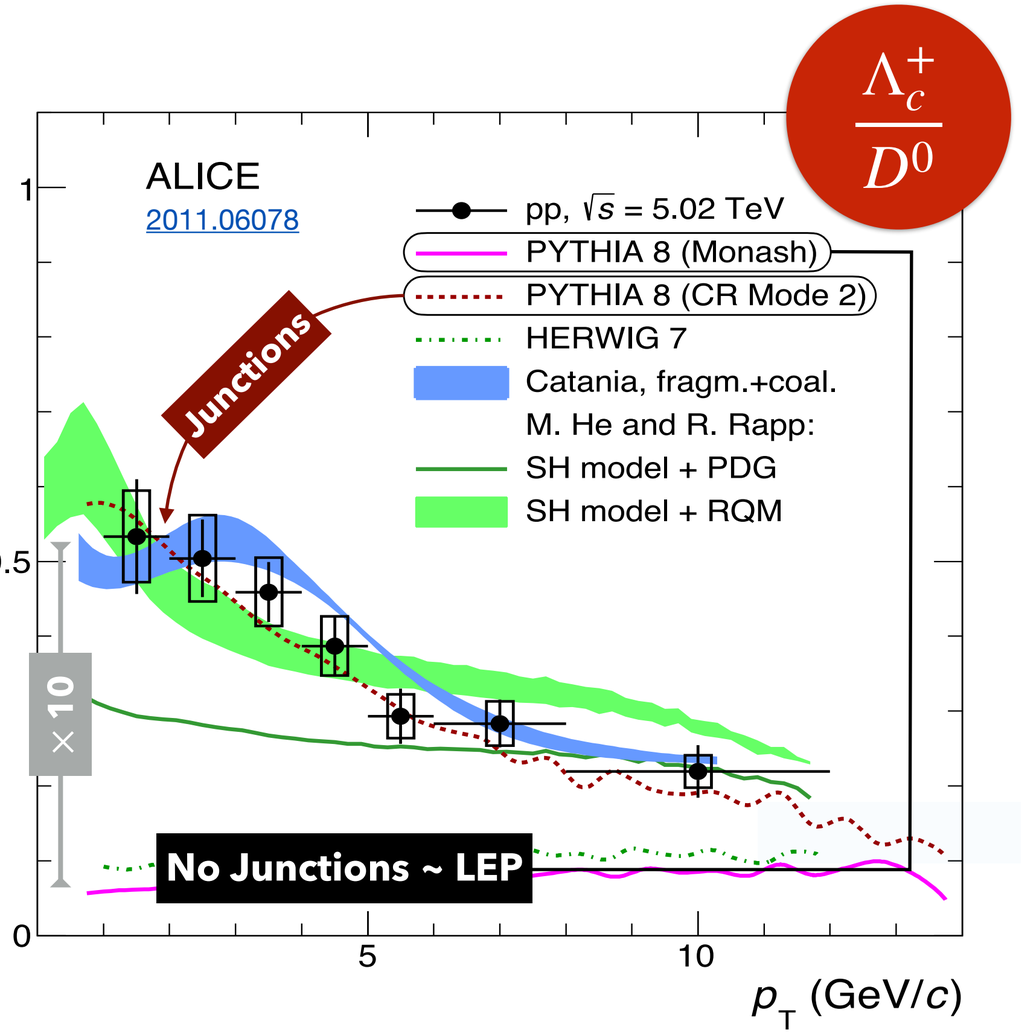
➢ ~40% of baryons are from junctions in PYTHIA

**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




Christiansen & PS 2015: light flavours

Altmann & PS 2024: heavy flavours

# Diquark Suppression & Strange Junctions ?

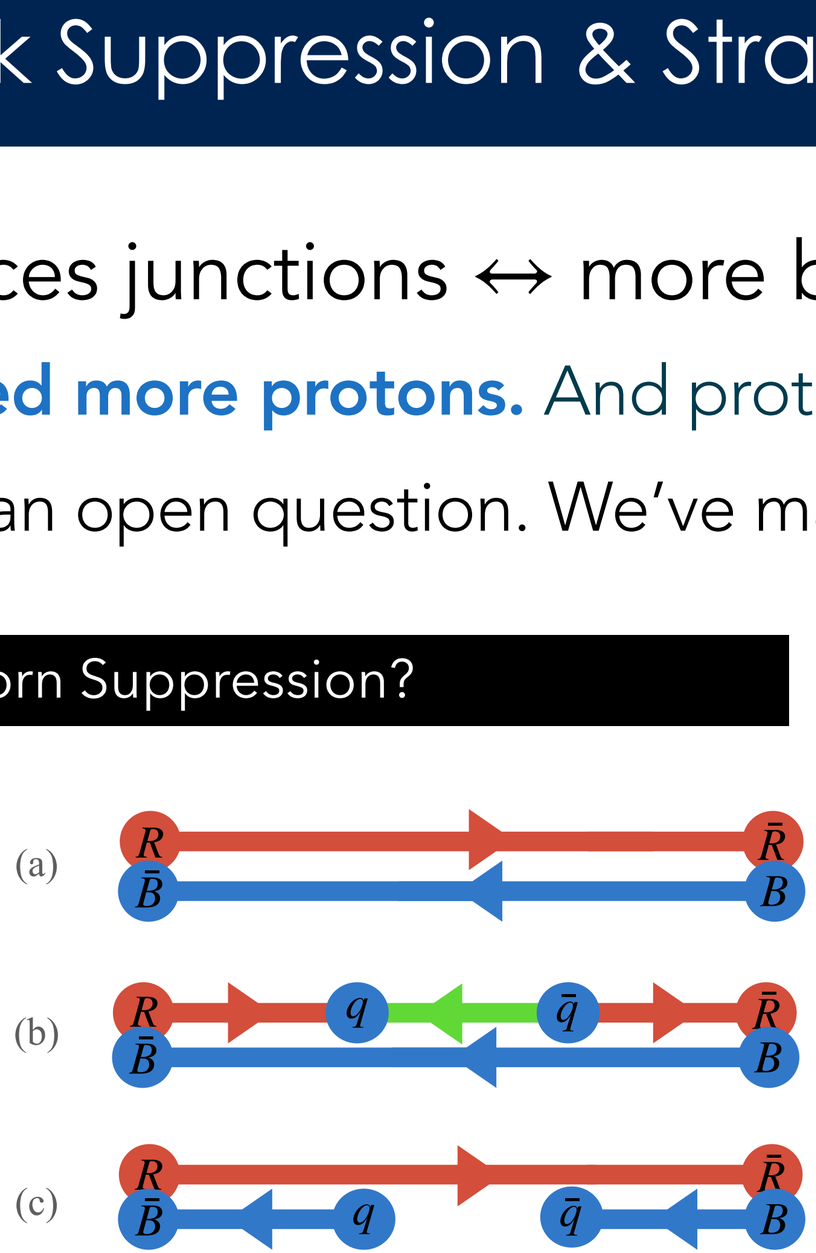
QCD CR produces junctions ↔ more baryons in general

But we **didn't need more protons.** And protons **cannot be neglected!**

Small $p/\pi$ ratio is an open question. We've made 2 speculations:

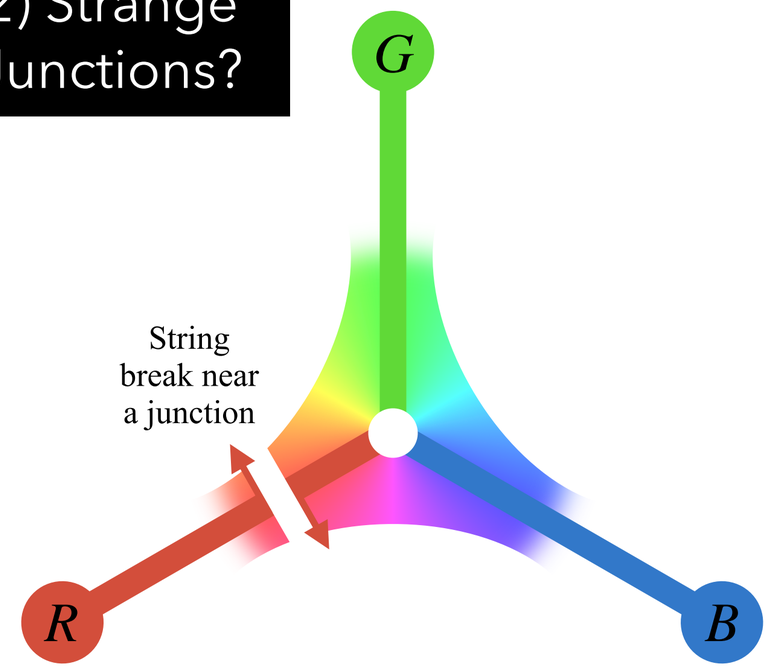
## 1) Popcorn Suppression?

The normal "popcorn" mechanism for baryon production invokes "zero-energy wrong-colour fluctuations", but if there is a string with that colour nearby, that could break instead




The "Altmann" mechanism, suppressing popcorn diquarks in the presence of another string

## 2) Strange Junctions?



# Colour Ropes & Closepacking

In QCD, effective charge scales nonlinearly with # of indices

Potential ∝ quadratic Casimir $C_2(p,q) = (p+1)(q+1)(p+q+2)/2$

p = number of fundamental indices; q = number of antifundamental indices

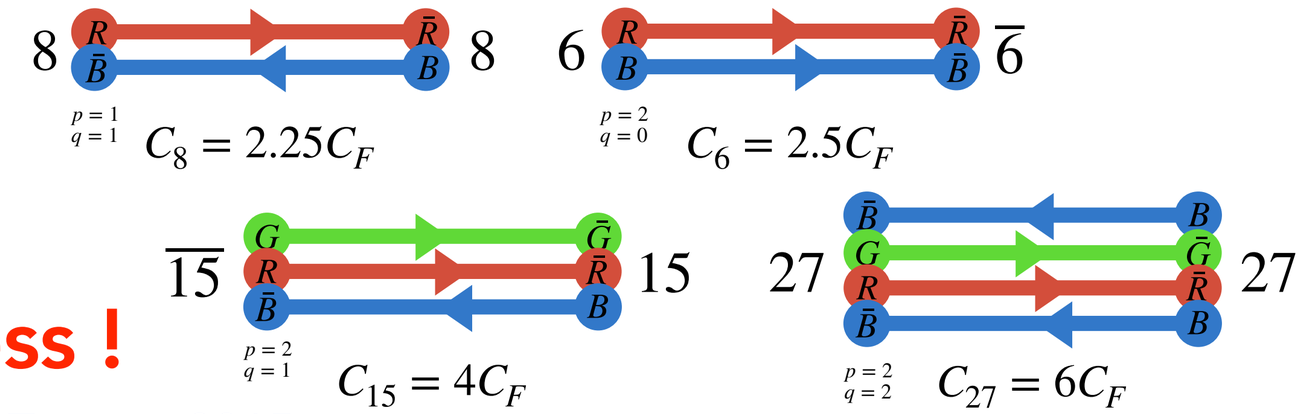
Lattice supports that $\kappa$ scales in the same way ("Casimir scaling"): Bali 2000

E.g., a single string has tension ∝ $C_2(1,0) = C_3 = 4/3 = C_F$

Two strings acting coherently

$C_8 = C_2(1,1) = C_A = 3 = 2.25\, C_F$

$C_6 = C_2(2,0) = 10/3 = 2.5\, C_F$




**Larger $\kappa \Rightarrow$ more strangeness !**

**Rope Model:** Bierlich, Gustafson, Lönnblad, Tarasov 2015

**Closepacking:** Fischer & Sjöstrand 2017; Altmann, Bernardinis, PS, Zaccolo 2025

Altmann, Bernardinis, PS, Zaccolo 2025

# Summary of $\chi^2_{5\%}$ values ($\equiv \chi^2$ with flat 5% "theory uncertainty")

| **Light Hadrons** | $\frac{dN_{ch}}{d\eta}$ vs $\eta$ | $\langle p_\perp \rangle$ vs $n_{ch}$ | $K^0_S/\pi^\pm$ | $\Lambda/\pi^\pm$ | $\Xi^\pm/\pi^\pm$ | $\Omega^\pm/\pi^\pm$ | $\Lambda/K^0_S$ | $(p+\bar{p})/\pi^\pm$ |
|---|---|---|---|---|---|---|---|---|
| Monash | 0.02 | 0.95 | 0.12 | 14.18 | 20.11 | 31.83 | 12.32 | 1.17 |
| QCD CR ($m_\tau = 2$) | 0.24 | 0.24 | 1.91 | 1.98 | 12.22 | 18.92 | 0.58 | 20.97 |
| Rope Hadronization | 0.05 | 1.19 | 0.58 | 2.40 | 0.70 | 0.92 | 1.11 | 28.42 |
| Closepacking (T1) | 0.05 | 0.66 | 2.14 | 0.75 | 0.32 | 1.98 | 2.58 | 1.65 |
| Closepacking (T2) | 0.02 | 0.24 | 0.24 | 0.31 | 0.11 | 0.94 | 0.50 | 6.37 |
| (no diquark suppression) Closepacking (simple) | 0.11 | 0.31 | 2.41 | 0.76 | 0.80 | 2.08 | 1.07 | 14.67 |
| Strange Junctions | 0.02 | 0.23 | 0.04 | 0.64 | 0.15 | 0.54 | 0.57 | 7.72 |

| **Charm Hadrons** | $\frac{\Lambda_c^+}{D^0}$ | $\frac{\Sigma_c}{D^0}$ | $\frac{\Lambda_c^+(\leftarrow\Sigma_c)}{\Lambda_c^+}$ | $\frac{\Xi_c^0}{D^0}$ | $\frac{\Xi_c^+}{D^0}$ | $\frac{\Xi_c^0}{\Lambda_c^+}$ | $\frac{\Xi_c^{0,+}}{\Sigma_c}$ |
|---|---|---|---|---|---|---|---|
| Monash | 41.53 | 19.83 | 7.72 | 8.67 | 3.14 | 3.19 | 0.40 |
| QCD CR ($m_\tau = 2$) | 1.69 | 0.50 | 0.64 | 6.06 | 2.19 | 5.43 | 4.00 |
| Rope Hadronization | 1.46 | 0.16 | 0.42 | 5.40 | 2.20 | 5.11 | 3.86 |
| Closepacking (T1) | 1.66 | 0.97 | 0.13 | 4.54 | 2.07 | 4.01 | 2.67 |
| Closepacking (T2) | 1.75 | 0.54 | 0.16 | 5.18 | 2.22 | 4.97 | 3.65 |
| Closepacking (simple) | 2.67 | 0.70 | 0.40 | 5.31 | 2.84 | 4.36 | 3.72 |
| Strange Junctions | 11.26 | 6.11 | 0.79 | 6.79 | 3.05 | 3.87 | 2.58 |
| Strange Junctions (max.) | 12.21 | 3.67 | 0.36 | 6.15 | 2.60 | 3.35 | 2.49 |

## Conclusions:

Both **Ropes** and **Closepacking** are in agreement with strangeness ratios

$p/\pi$ is important!

$\Xi_c$ still challenging

# (Particle Composition: Impact on Jet Energy Scale)

**ATLAS PUB Note**

ATL-PHYS-PUB-2022-021

29th April 2022

**Dependence of the Jet Energy Scale on the Particle Content of Hadronic Jets in the ATLAS Detector Simulation**

The dependence of the ATLAS jet energy measurement on the modelling in Monte Carlo simulations of the particle types and spectra within jets is investigated. **It is found that the hadronic jet response, i.e. the ratio of the reconstructed jet energy to the true jet energy, varies by ~ 1–2% depending on the hadronisation model used in the simulation. This effect is mainly due to differences in the average energy carried by kaons and baryons in the jet.** Model differences observed for jets initiated by *quarks* or *gluons* produced in the hard scattering process are dominated by the differences in these hadron energy fractions indicating that **measurements of the hadron content of jets and improved tuning of hadronization models can result in an improvement in the precision of the knowledge of the ATLAS jet energy scale.**

Variation largest for gluon jets

- For $E_T$ = **[30, 100, 200] GeV**
- Max JES variation = **[3%, 2%, 1.2%]**

Fraction of jet $E_T$ carried by baryons (and kaons) varies significantly

- Reweighting to force similar baryon and kaon fractions
- Max variation ➜ **[1.2%, 0.8%, 0.5%]**
- Significant potential for improved Jet Energy Scale uncertainties!

Motivates Careful Models & Careful Constraints

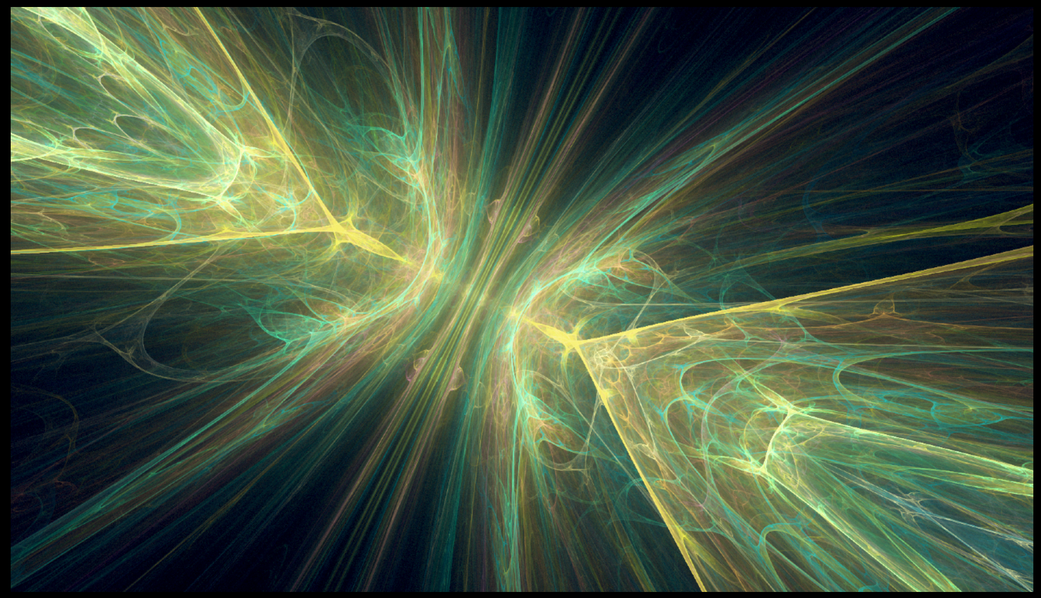
- Interplay with advanced UE models
- In-situ constraints from LHC data
- Revisit comparisons to LEP data

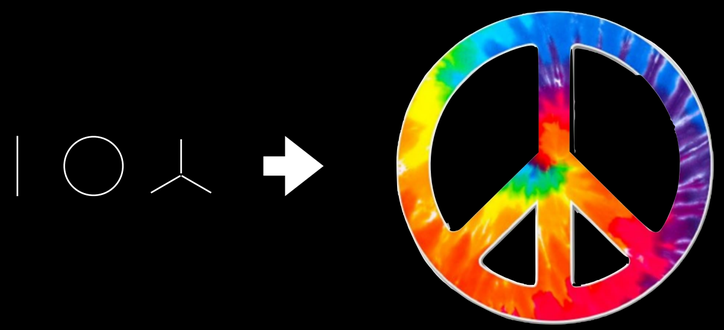
# Summary

Increasingly viewing (QCD) strings as emergent, dynamically generated objects

In particle collisions, confinement is imposed **dynamically**

New studies of worldsheet dynamics, string-theory connections, string interactions & Rings, Strings, and Junctions





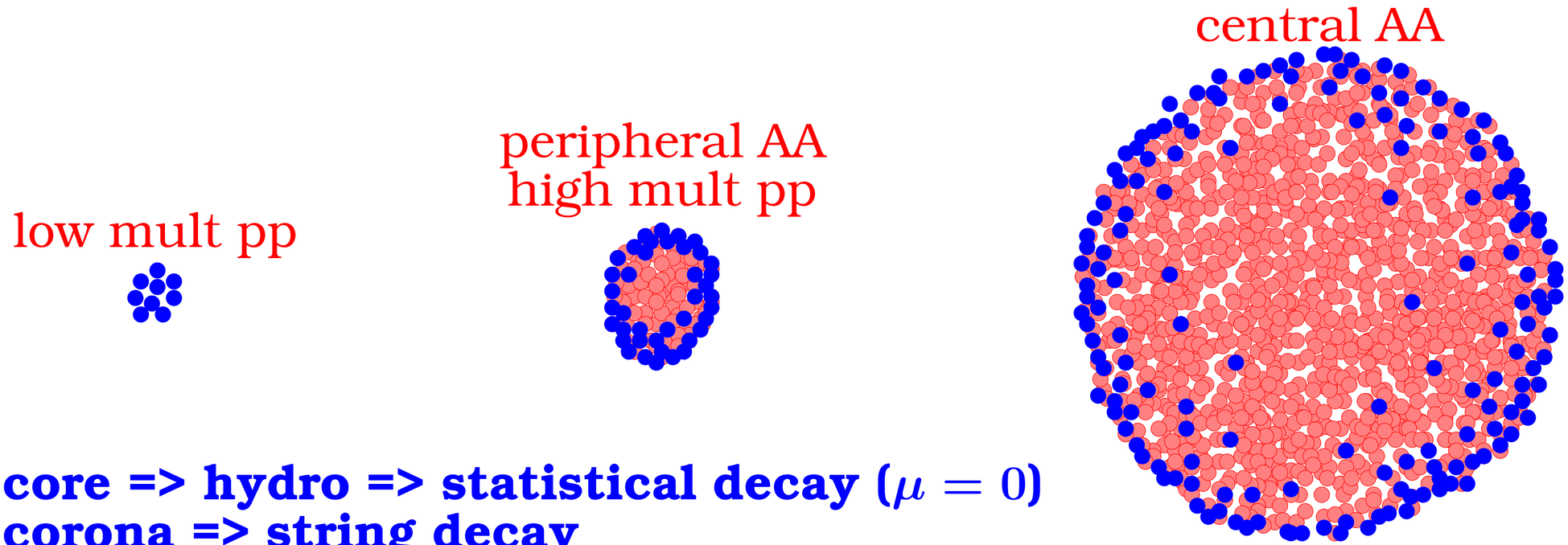
**Make Dynamics, Not Statics !**

# Extra Slides

# Beyond Strings — QGP?

Currently most realistic complete approach for pp ↔ pA ↔ AA?

The core-corona solution [Werner 2007]: **mix** discrete **strings** with continuous **QGP**




**core => hydro => statistical decay ($\mu = 0$)**
**corona => string decay**

Allows smooth transition between string and hydro descriptions. Implemented in **EPOS MC**
Qualitatively agrees with ALICE strangeness data (but too steep rise with multiplicity?)

# **Conversely:** Collective flow from strings? (without QGP)

**Strings should push each other transversely**

Colour-electric fields ➜ Classical force

**Model string radial shape & shoving physics**

$\Longrightarrow$ force $$f(d_\perp) = \frac{g\kappa d_\perp}{R^2}\exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

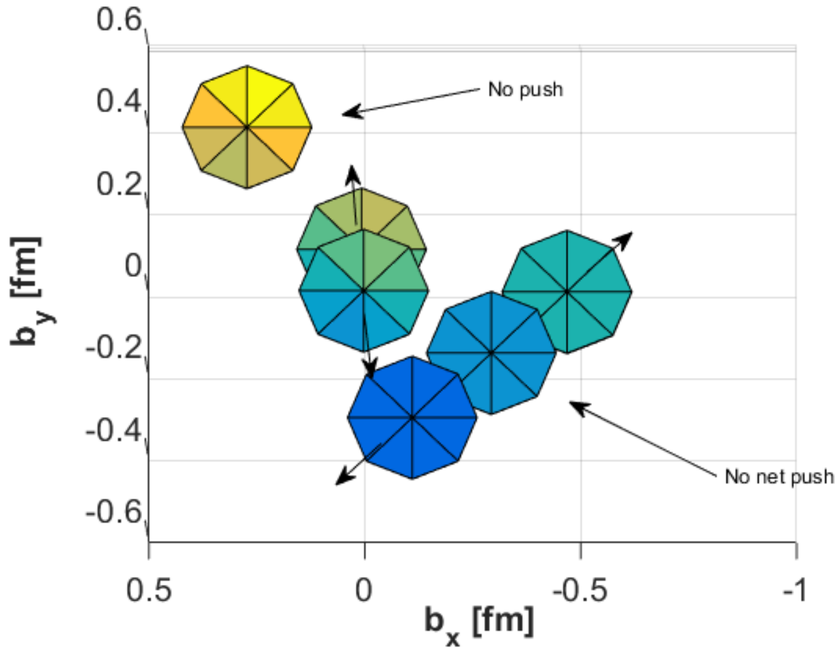
$g$: fraction of energy in chromo-electric field (as opposed to in condensate or magnetic flux)

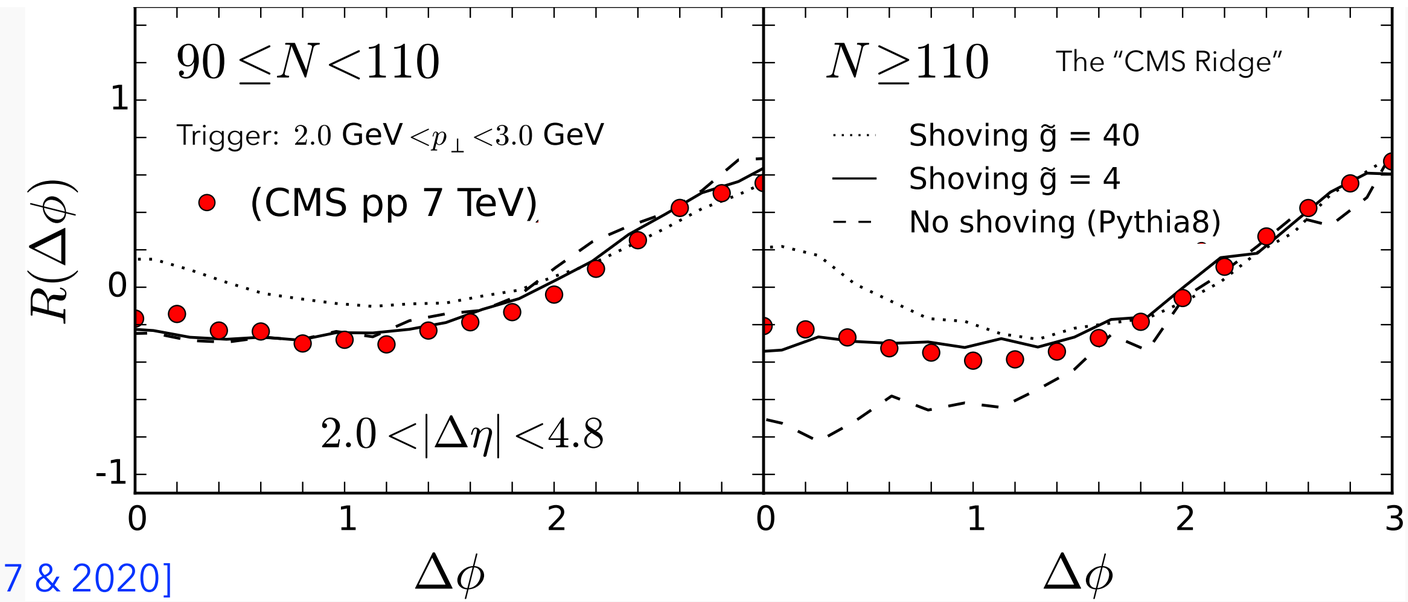
$d_\perp$: transverse distance (in string-string "shoving frame")

$R$: string radius

$\kappa$: string tension ~ $1\,\mathrm{GeV/fm}$

[Bierlich, Chakraborty, Gustafson, Lönnblad, 2017 & 2020]



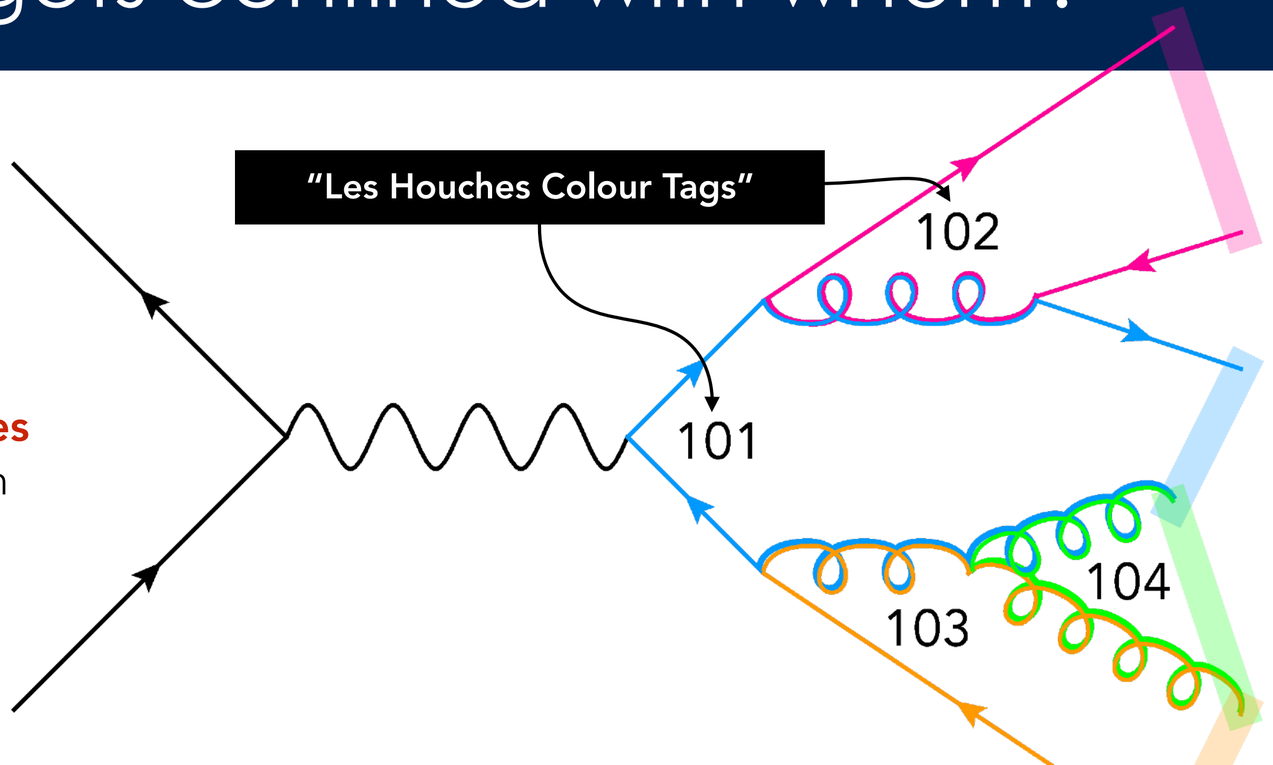

CMS 1009.4122. Also: ATLAS 1906.08290, ALICE 2101.03110

# 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 ~ $1/N_C^2$ ~ 10%

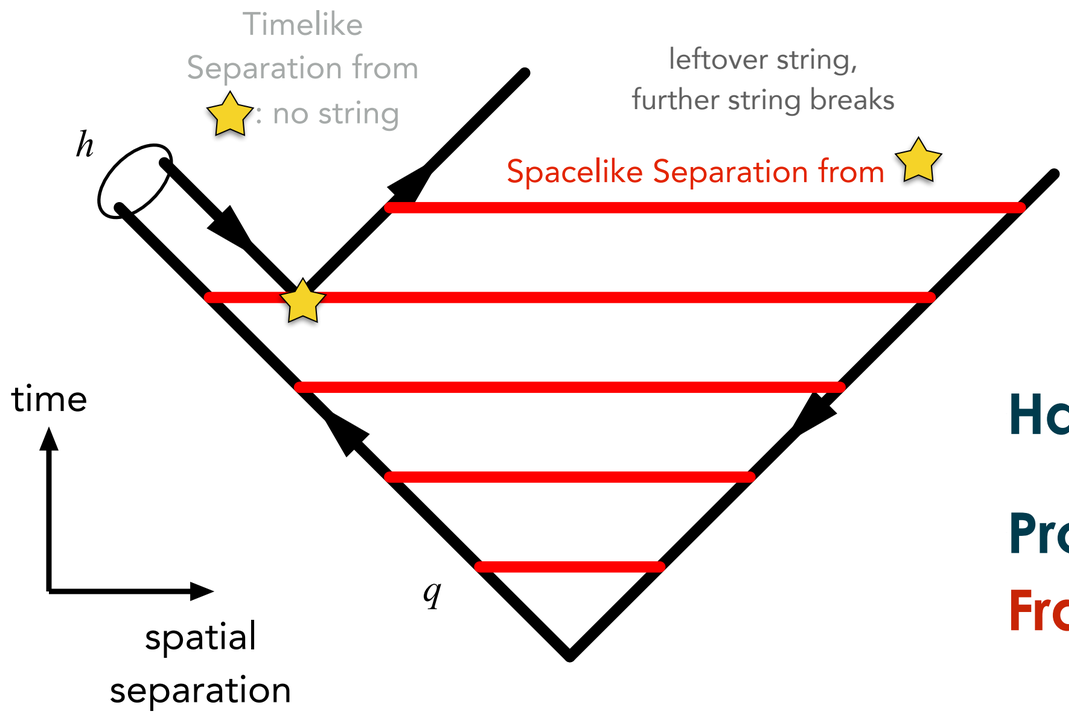
A corresponding event record from PYTHIA, up to the second gluon emission

| # | 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 |

# Requirement #2: on-shell hadrons

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

(➢ independent modulo entanglement from common origin)




Lorentz invariance $\Longrightarrow$ string breaks can be considered in *any order*.

Exploit this to split off "outermost" hadron either from left or right (randomly) — **iteratively!**

**Hadron** $h$ takes a fraction $z$ of the **quark** momentum

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

**"Left-right symmetry"** $\Longrightarrow$ **FF** constrained to a form with **two free parameters**, $a$ & $b$
*(constrained by fits to measured hadron spectra)*

[See, e.g., Amoroso et al., JCAP 05 (2019) 007]

$$f_{\mathrm{Lund}}(z) \propto \frac{1}{z}(1-z)^{a}\exp\left(-\frac{b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

$a$: Supresses high $z$; $b$: Supresses low $z$

# (Note on the Length of Strings)

In Spacetime:

String tension ≈ 1 GeV/fm → a 50-GeV quark can travel 50 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

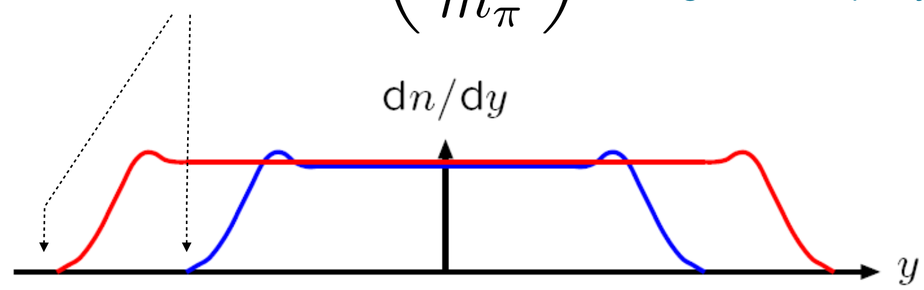
➜ Rapidity (along string axis) and $p_\perp$ transverse to it

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

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

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

Increasing $E_q$ → logarithmic growth in rapidity range




## Particle Production:

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

**"Lightcone scaling"**

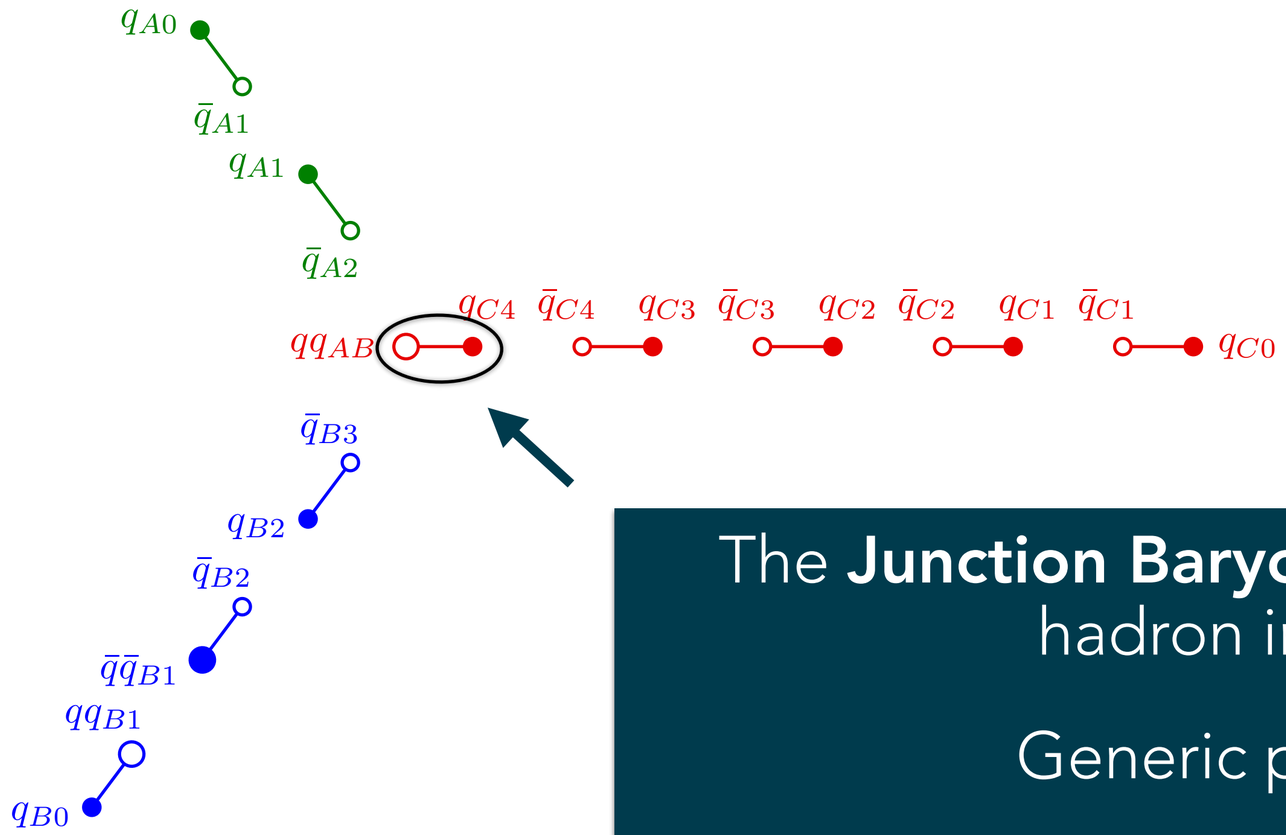
$\langle n_{\text{ch}} \rangle \approx c_0 + c_1 \ln E_{\text{cm}}$, ~ Poissonian multiplicity distribution

# Fundamental Laws

Jade's project

# 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 $p_T$**

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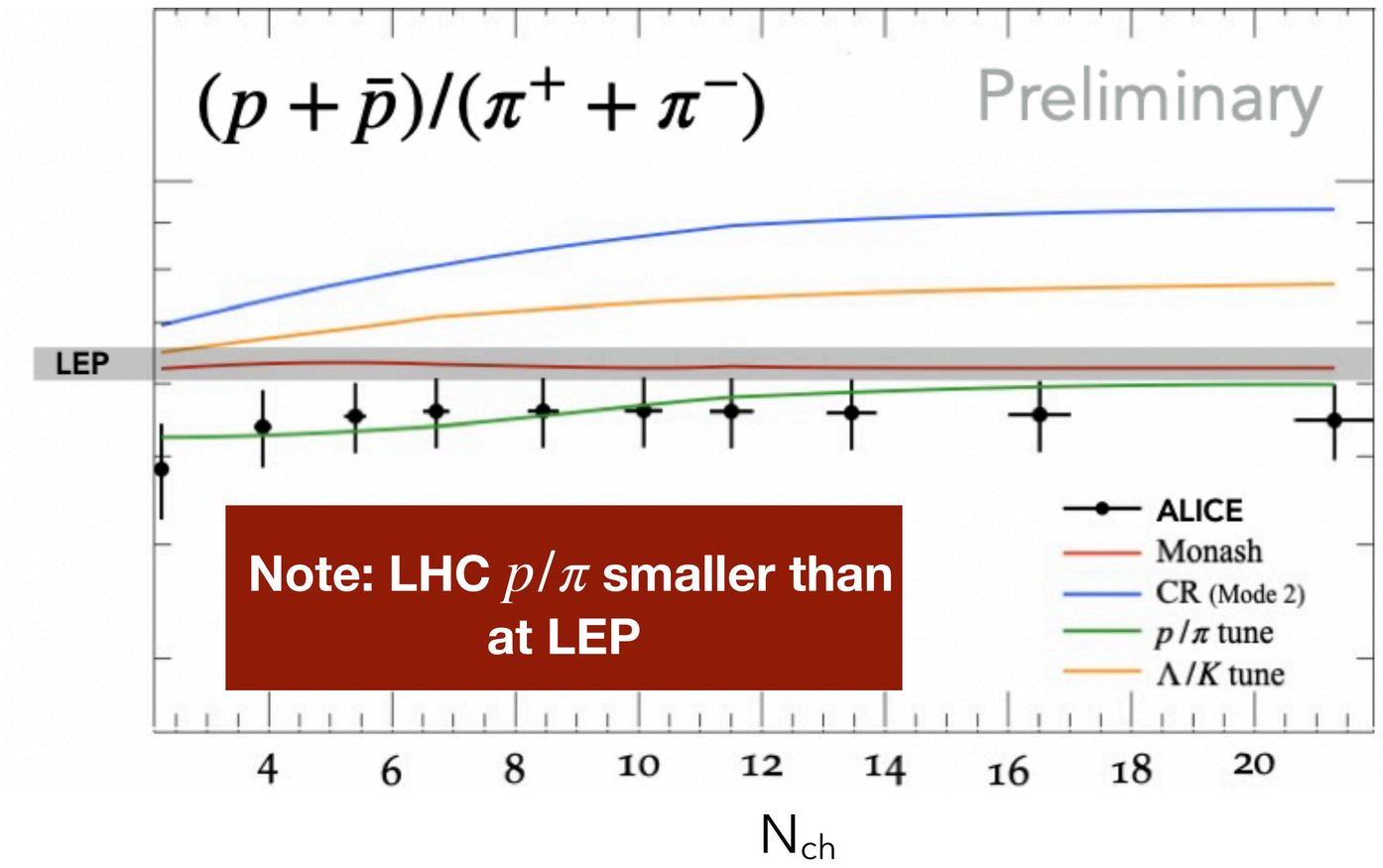
# Thorny Issue ⚠️ The **Proton-to-Pion** Ratio

**Note:**

Observed $p/\pi$ in pp collisions at LHC is ***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? …?*






*Slide adapted from J. Altmann*