Monte Carlo Event Generators

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Australian Government
Australian Research Council
MONASH WARWICK ALLIANCE
THE ROYAL SOCIETY
MCnet
ANCORA IMPARO

Overview

① **General Introduction:** Principles of MC Generators

Event Simulation 1

Hadronization ➤ **Dynamics of Confinement**

Hadronic (pp, pA, AA) Collisions ➤ **"Collective Phenomena"**

New Discoveries ➤ **New Ideas**

② **Event Simulation 2**

Perturbative Aspects ↔ Amplitude Calculations

Perturbative Uncertainties

The objective of science

Measure the measurable, and make the unmeasurable measurable.

It seems there is some doubt
whether Galileo actually said this.

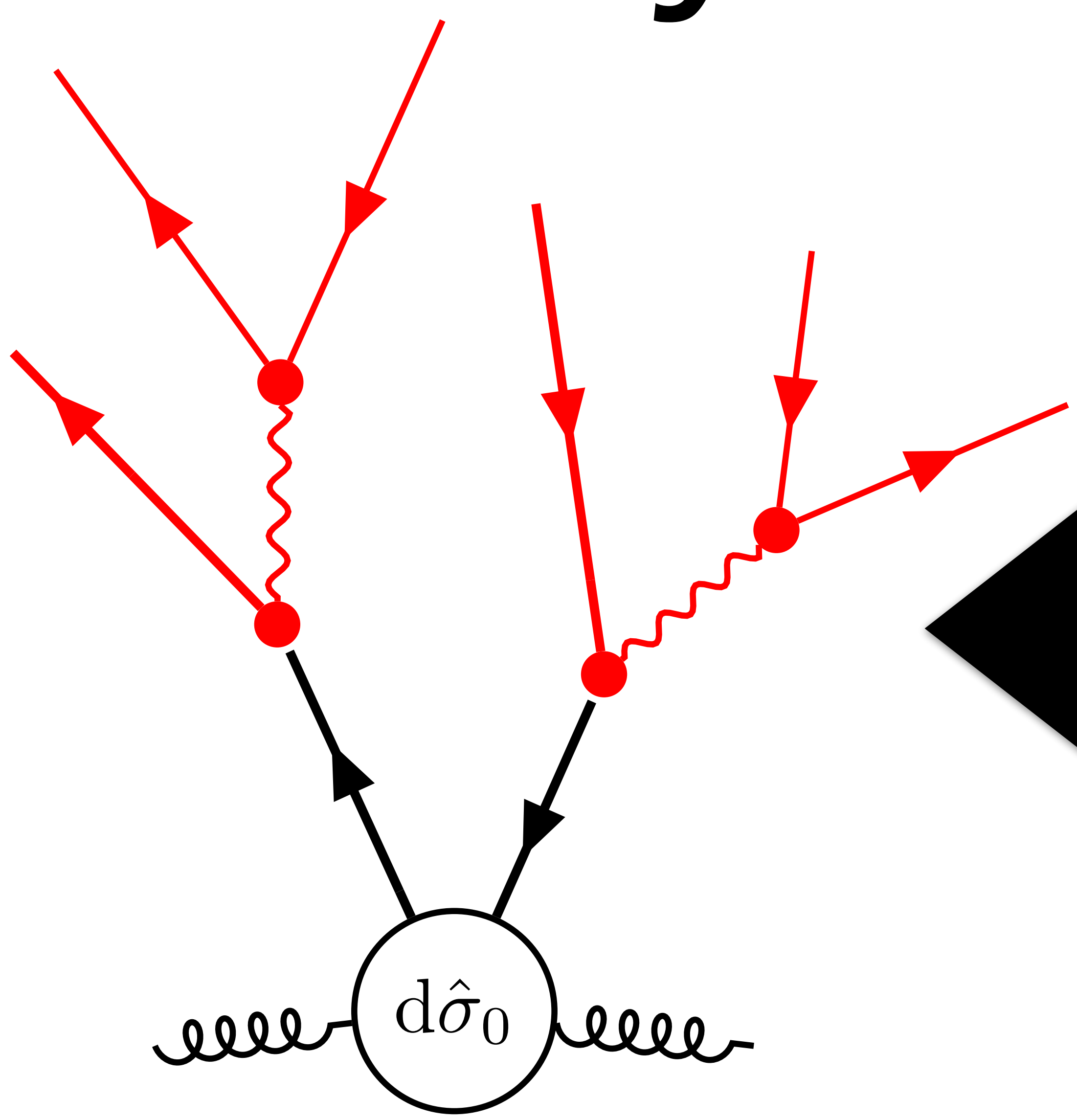
What has philosophy got to do with measuring anything?

Galileo, *Concerning the New Star* (1606)

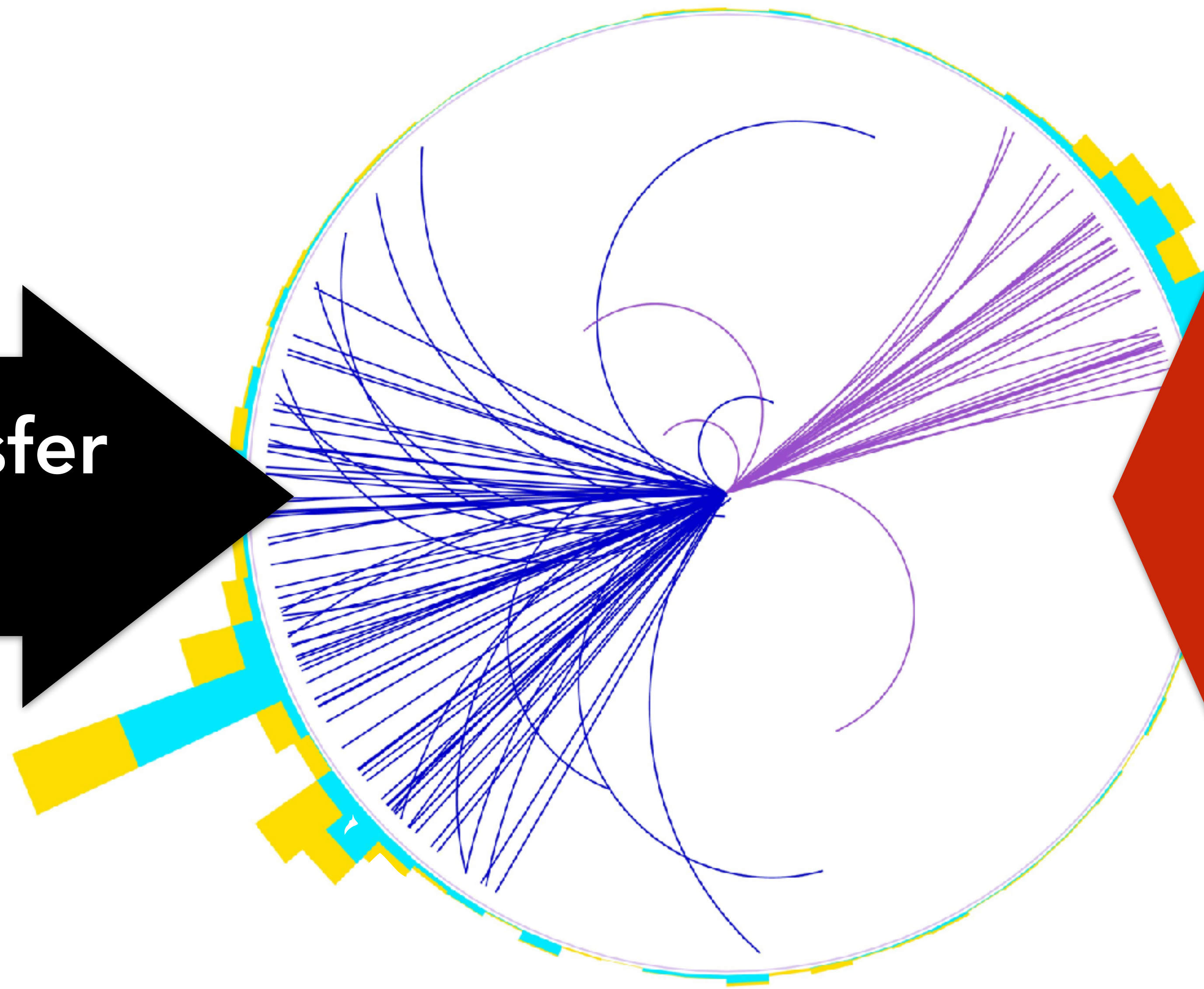
(It’s the mathematicians you have to trust, and they measure the skies like we measure a field.)

Do measurements ⇔ Learn about Nature

Theory ⟷ Experiment



Some "transfer function"



(Typically) Very Large Backgrounds

Elementary Fields & Parameters

Lagrangians & QFT

Perturbation Theory

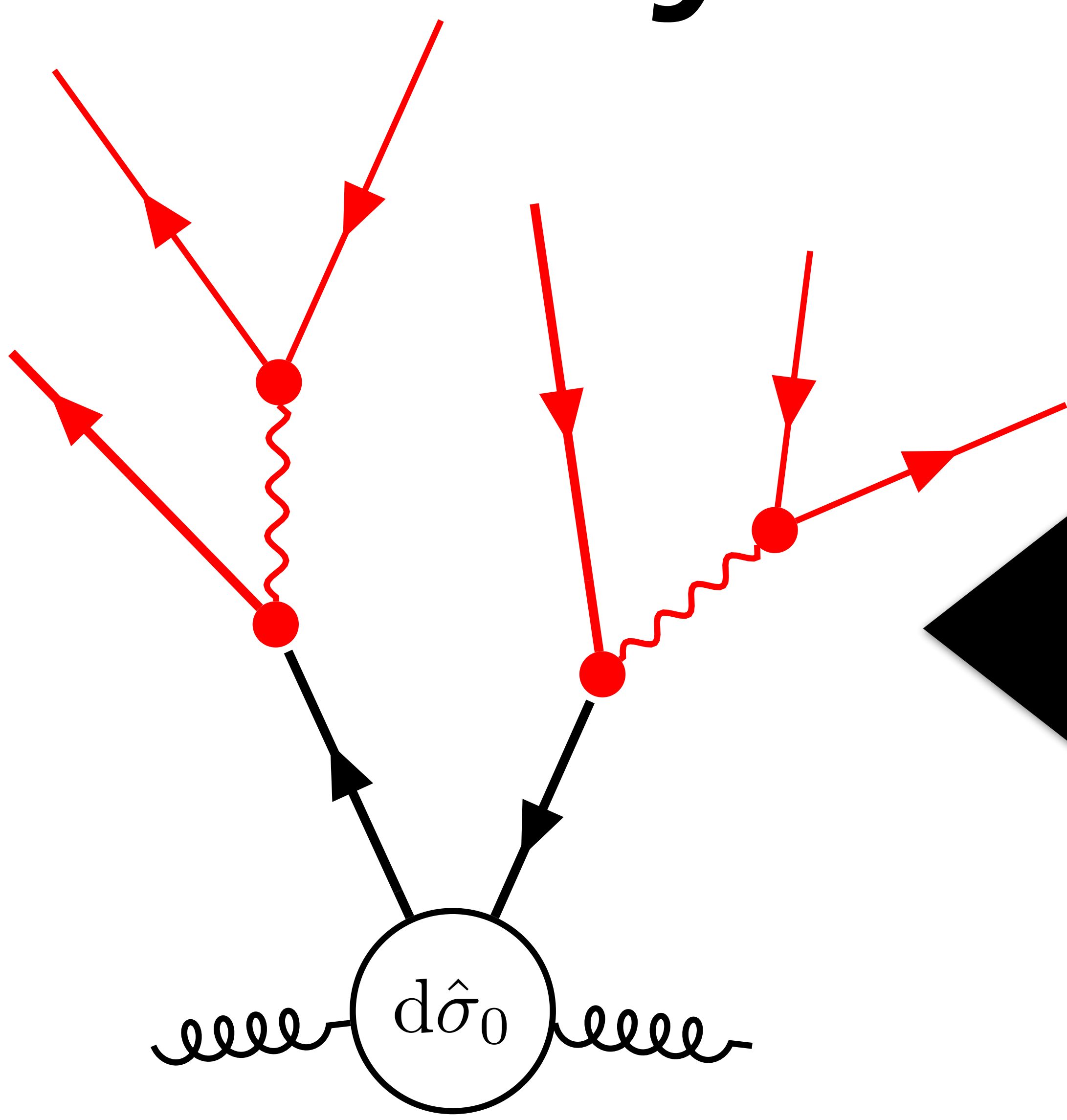
Detector Signals

Reconstructions

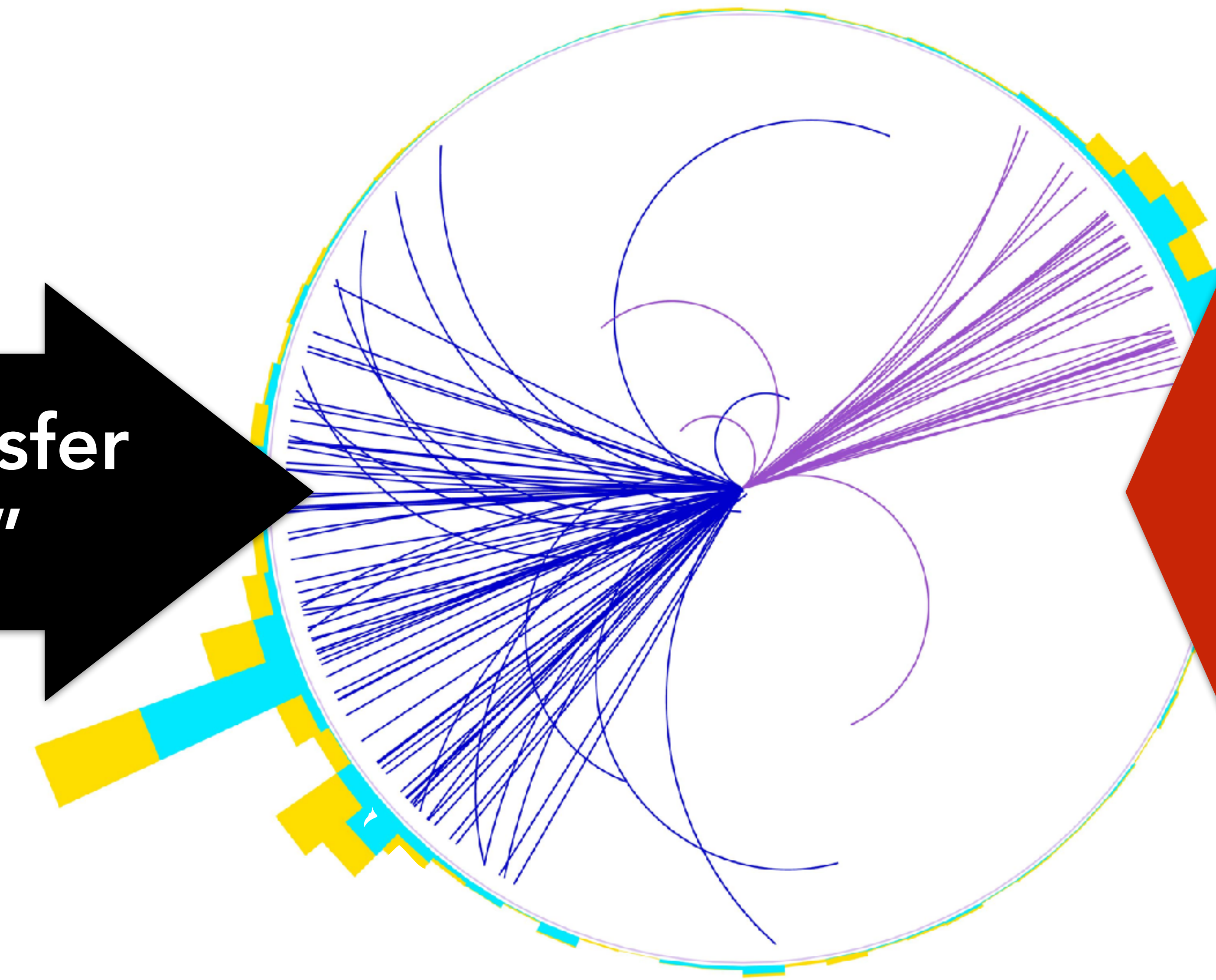
# of Observed Events

Do measurements ⇔ Learn about Nature

Theory ⟷ Experiment



Some "transfer function"

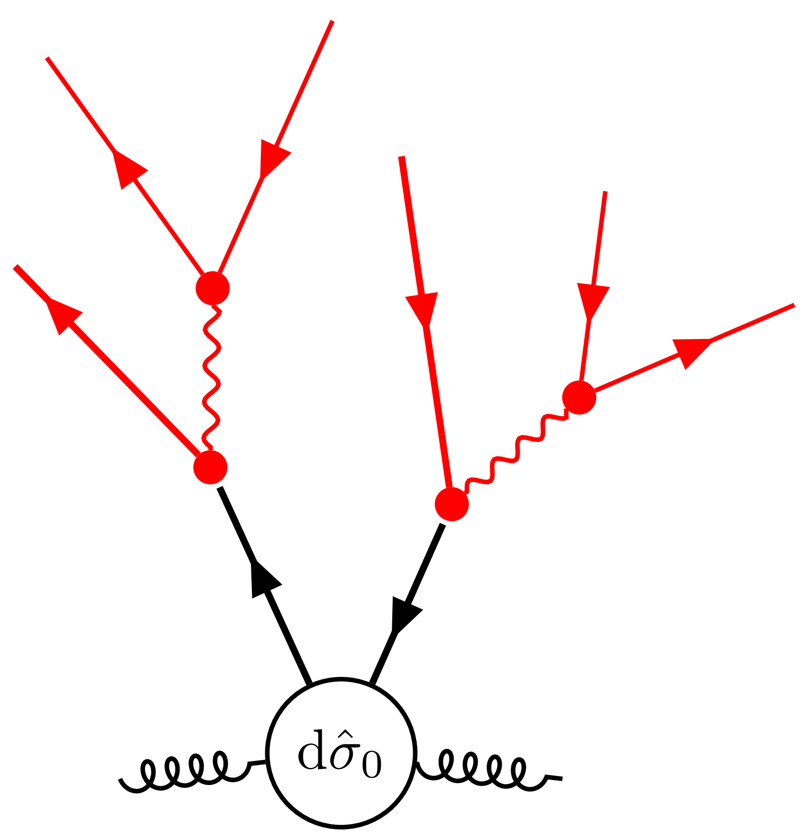


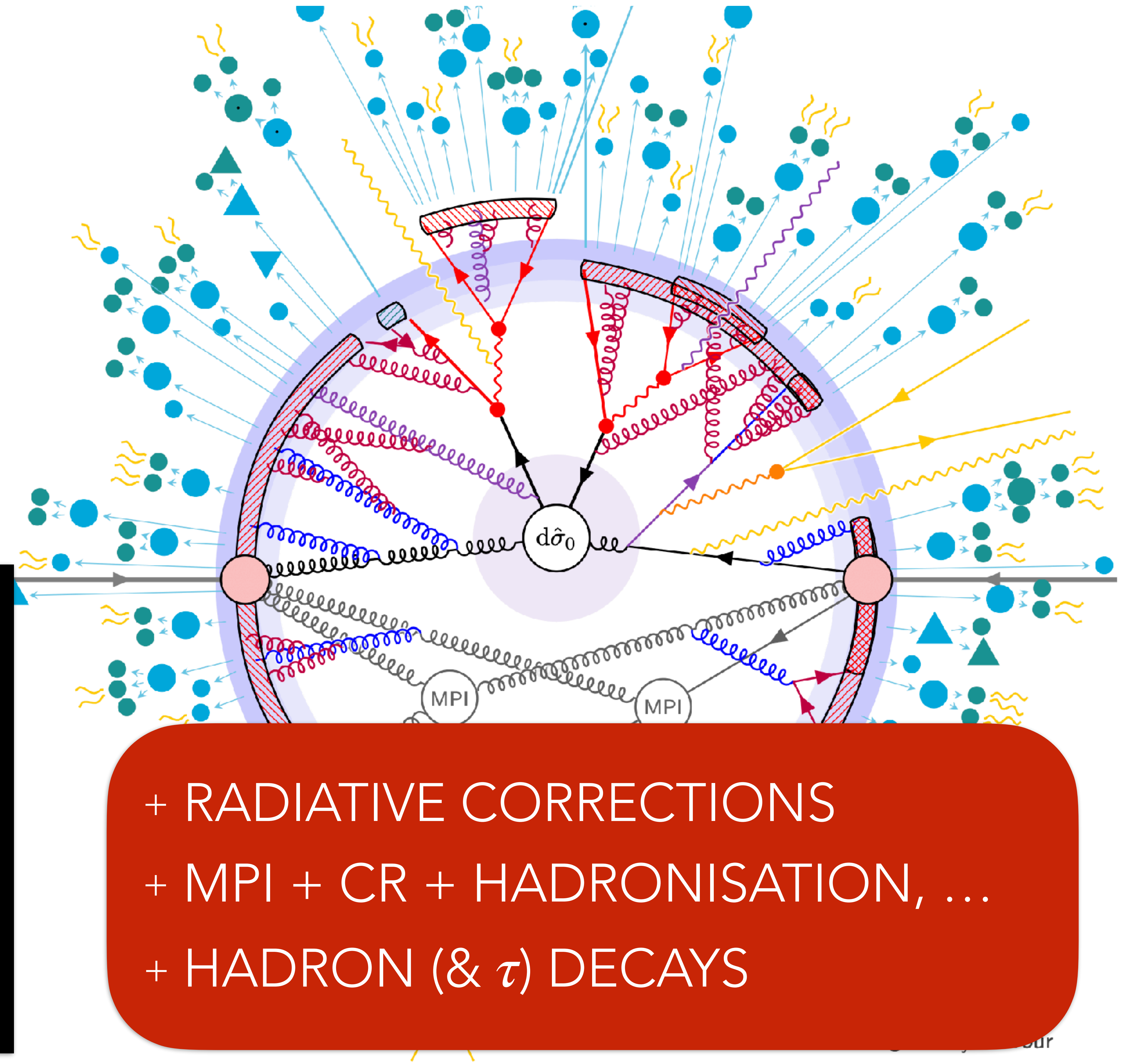
(Typically) Very Large Backgrounds

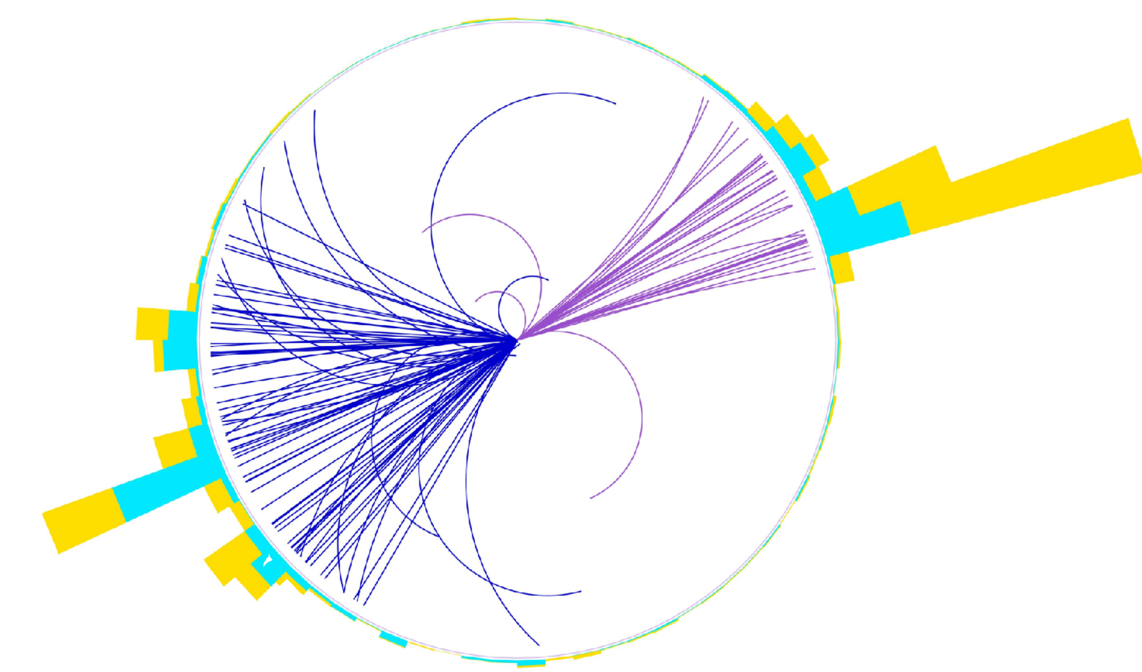
Need **precise** and **detailed** relations
+ Lots of **interesting physics** on the way

Connecting theory and experiment

MC Event Generators







HARD-PROCESS SKELETONS:

Example:

$gg \to t\bar{t}$

+ Resonance decays

+ RADIATIVE CORRECTIONS
+ MPI + CR + HADRONISATION, …
+ HADRON (& τ) DECAYS

+ DETECTOR SIMULATIONS
+ TRIGGERS
+ RECONSTRUCTION

…

⇒ **Physics Analysis**

Figure from arXiv:2203.11601

Foundational Principles of MC Event Generators

1. Divide and Conquer

Split the problem into (many) **simpler pieces**

2. Knowledge is Power

The simpler pieces are given by **Mathematical Factorisations**

+ The loss of perturbation theory in the nonperturbative regime does **not** imply a **total** loss of predictivity!

3. God plays dice

We'll do the same!

Hard LHC collisions contain **100s of particles**

Need (differential) σ_{pp} for that number of "legs"

Help! Some of them are hadrons! ← Non-perturbative

And/or have **small opening angles**

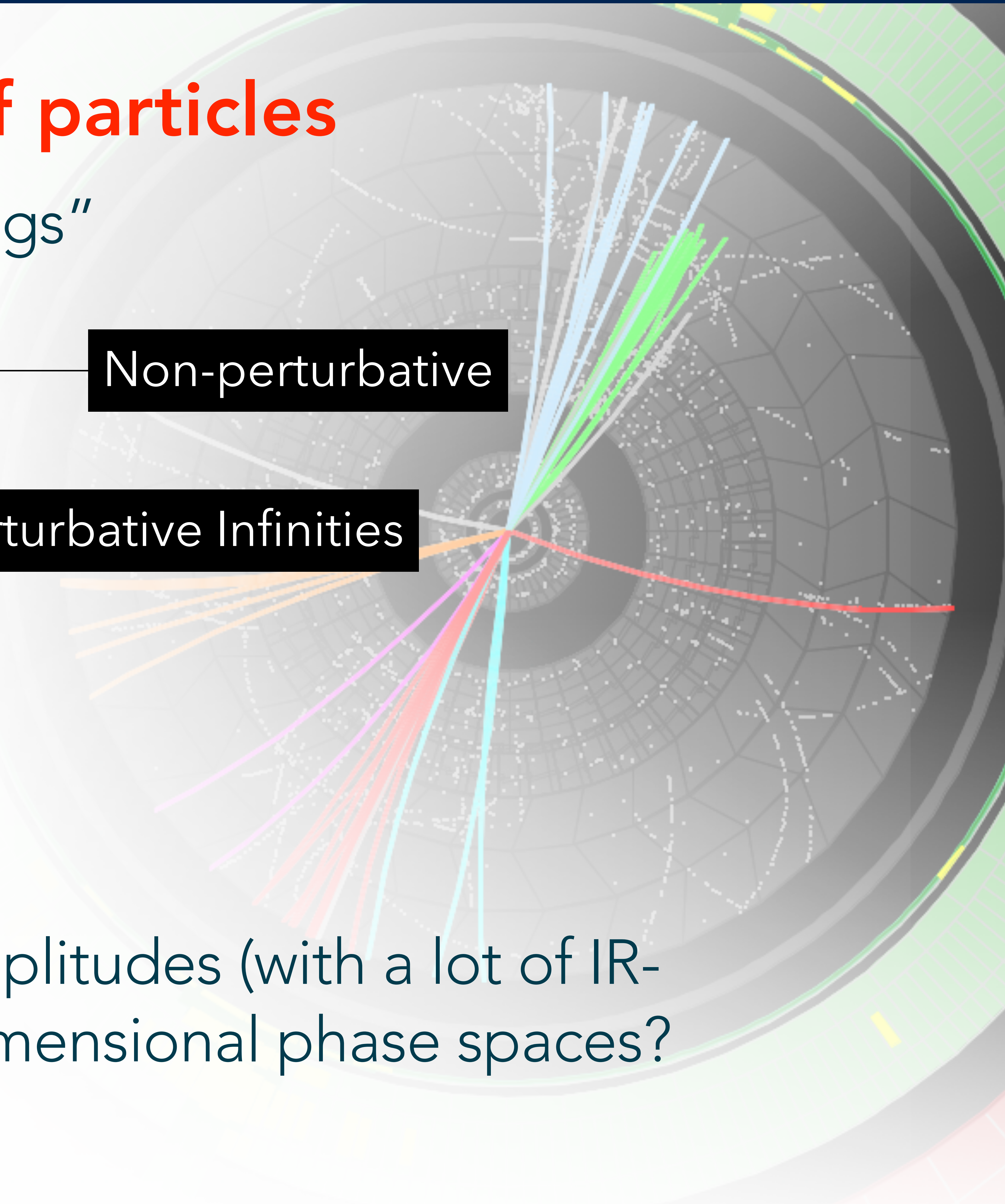
And/or are **"soft"** ← Perturbative Infinities

+ Phase Space $\propto \prod_{i=1}^{100} \frac{\mathrm{d}^3 p_i}{2E_i}$ ← Big

How would *you:*

Construct, square, and integrate 100-leg amplitudes (with a lot of IR-divergent + non-pert. structure) over 300-dimensional phase spaces?

➤ **break it down!**



Some Important Factorisations:

Factorisation of Long-Distance QCD ⟹ Can use Perturbation Theory

Narrow-Width Limit ⟹ Resonance & Hadron production and decay

Soft and Collinear Factorisation in Gauge Theories ⟹ Iterative FSR & ISR

\+ Well-Designed Observables

E.g., IR-safe & -sensitive, ratios vs yields, etc.

Give data to ML and let it work out the transfer function(s)?

If the algorithm misses any of the factorisations (or conservations laws), would you trust it?

In principle, the data contains the laws. But features differ by orders of magnitude, many are quasi-fractal, …

In MCEGs, some laws may of course also be implemented imperfectly

But physical basis can be discussed, learned from, and in principle systematically improved

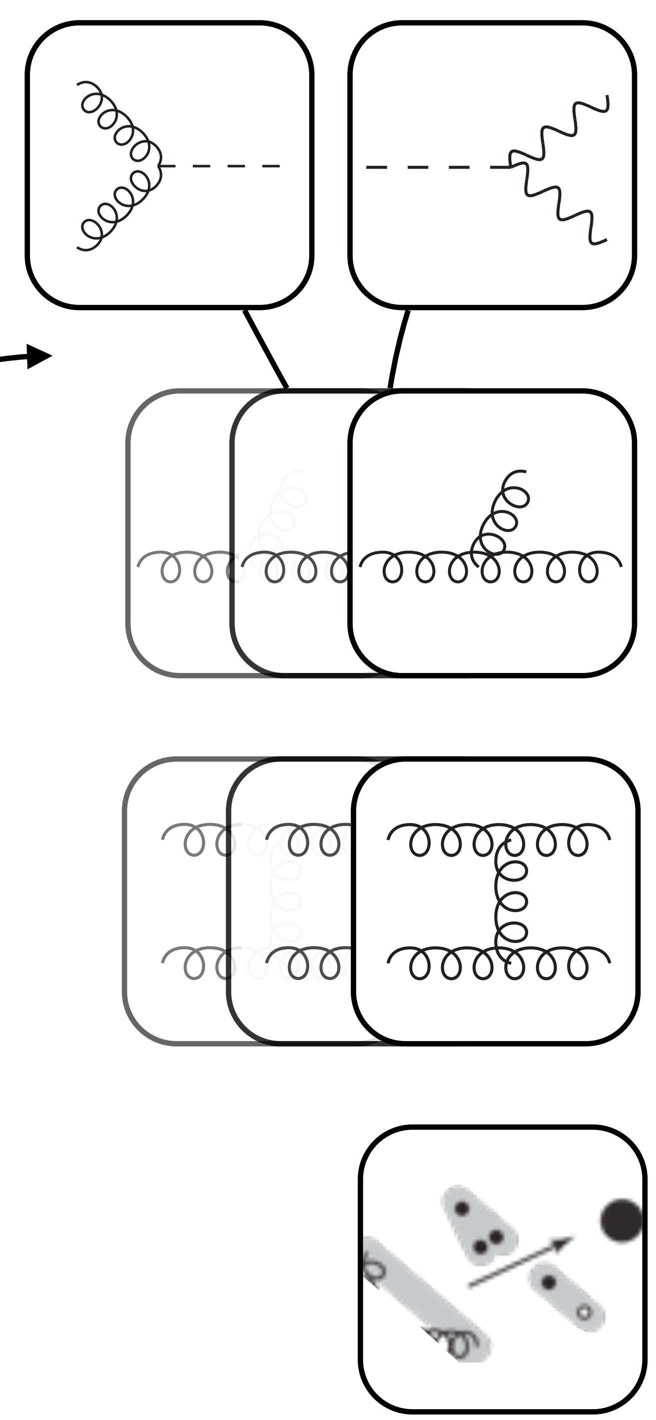
How to use ML for interpretation? For *us* to learn. *What* are we looking at?

3 — Most gods play dice; Fate plays chess. Pratchett

Physics | Separation of time scales ➤ Factorizations | Maths

➜ Can split **big** problem into many (nested) pieces + **make random choices** (MC)² ~ like in nature

$$\mathcal{P}_{\rm event} \;=\; \mathcal{P}_{\rm hard} \otimes \mathcal{P}_{\rm dec} \otimes \mathcal{P}_{\rm ISR} \otimes \mathcal{P}_{\rm FSR} \otimes \mathcal{P}_{\rm MPI} \otimes \mathcal{P}_{\rm Had} \otimes \ldots$$



Merging

Eliminate double-counting between fixed-order and shower corrections

Hard Process & Decays:

Use process-specific (N)LO matrix elements (e.g., $\mathrm{gg} \to \mathrm{H}^0 \to \gamma\gamma$)

→ Sets "hard" resolution scale for process: $Q_{\rm HARD}$

ISR & FSR (Initial- & Final-State Radiation):

Driven by differential (e.g., DGLAP) evolution equations, dP/dQ^2, as function of resolution scale; from $Q_{\rm HARD}$ to $Q_{\rm HAD}$ ~ 1 GeV

MPI (Multi-Parton Interactions)

Protons contain lots of partons → can have additional (soft) parton-parton interactions → Additional (soft) "Underlying-Event" activity

Hadronisation

Nonperturbative modeling of partons → hadrons transition

Strings or clusters; followed by hadron and τ decays

The Physics of Event Generators

- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium
- Multiparton Interactions
- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*

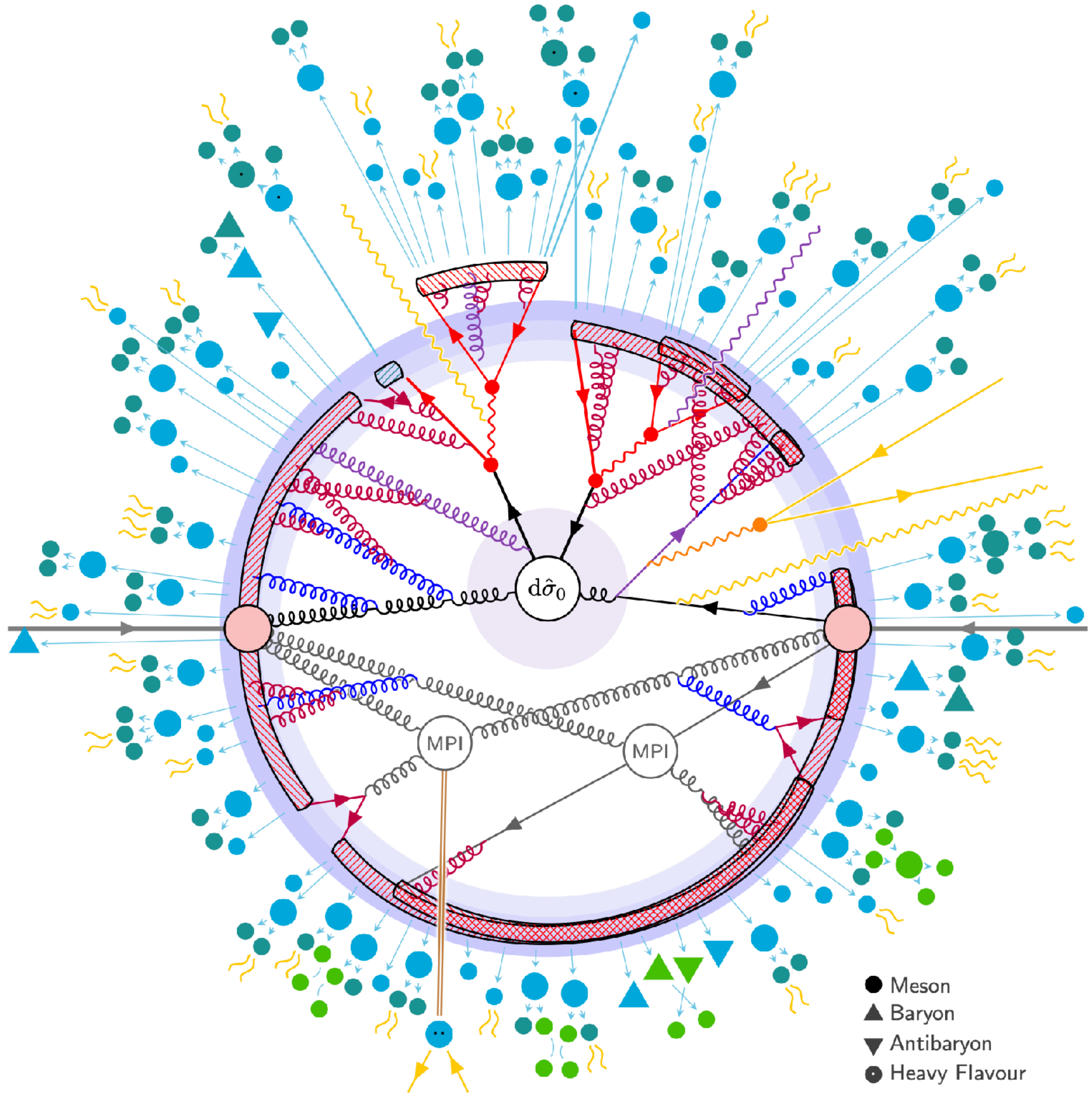


Figure from arXiv:2203.11601

The Physics of Event Generators

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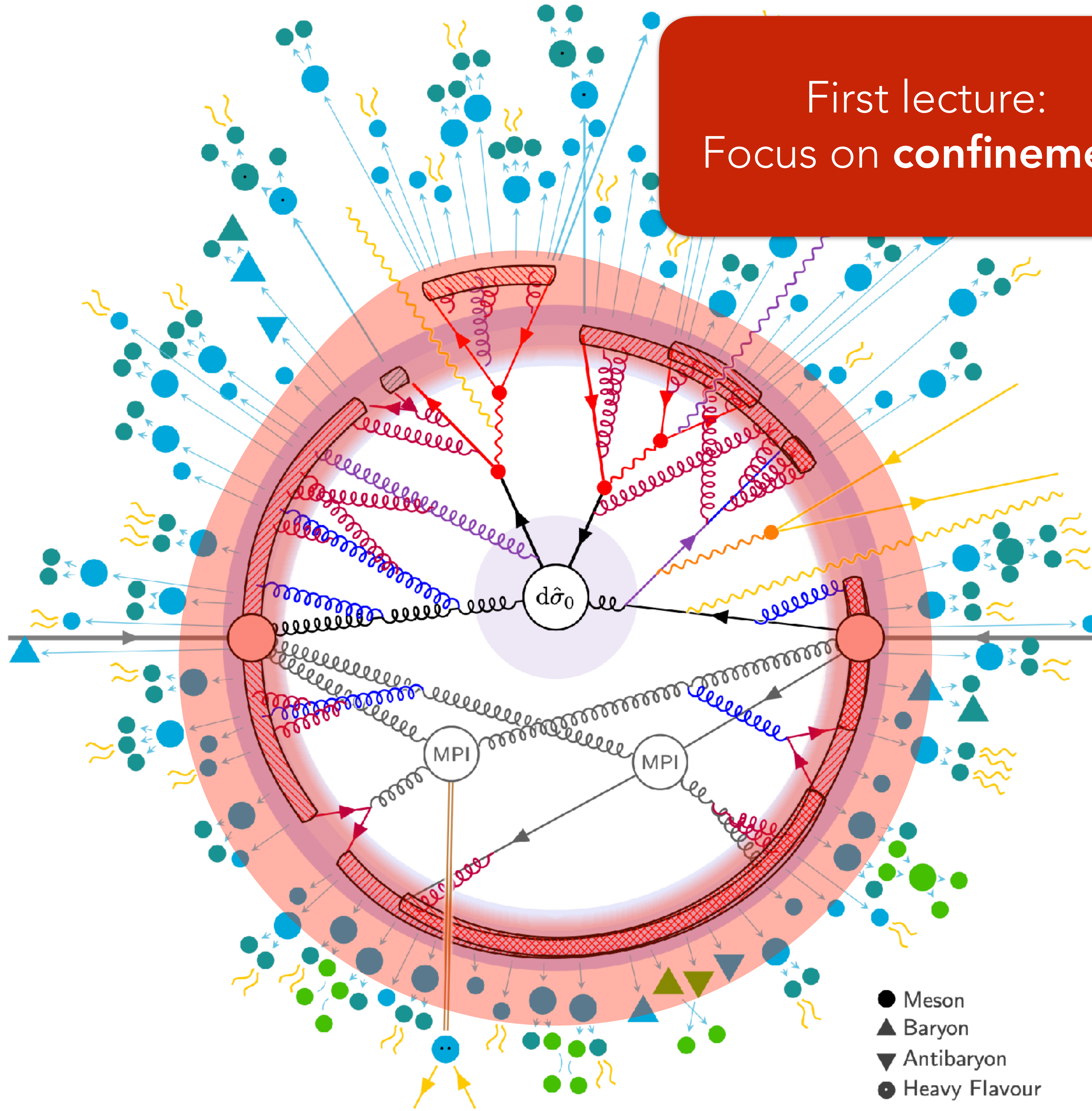


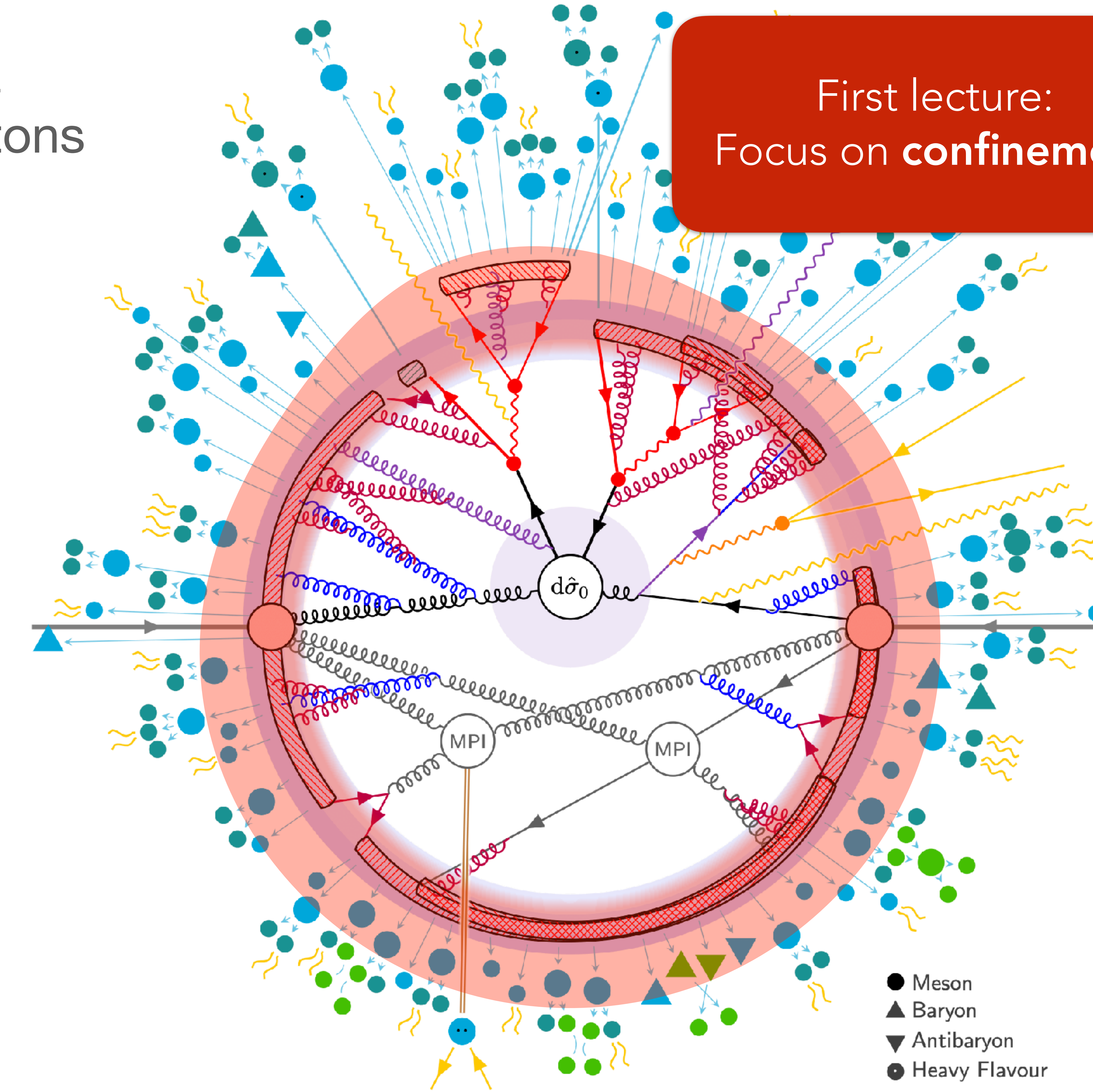
First lecture:
Focus on **confinement**

Figure from arXiv:2203.11601

In high-energy processes, need a dynamical process to ensure partons (**quarks and gluons**) become **confined** within hadrons

i.e. a non-perturbative **parton → hadron map**

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



First lecture:
Focus on **confinement**

Figure from arXiv:2203.11601

Requirement #1: Colour Neutralisation

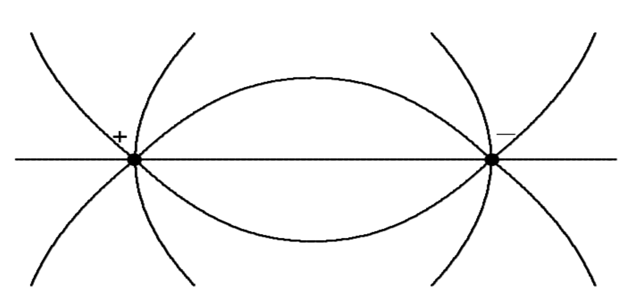
The point of confinement is that partons are **coloured**

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

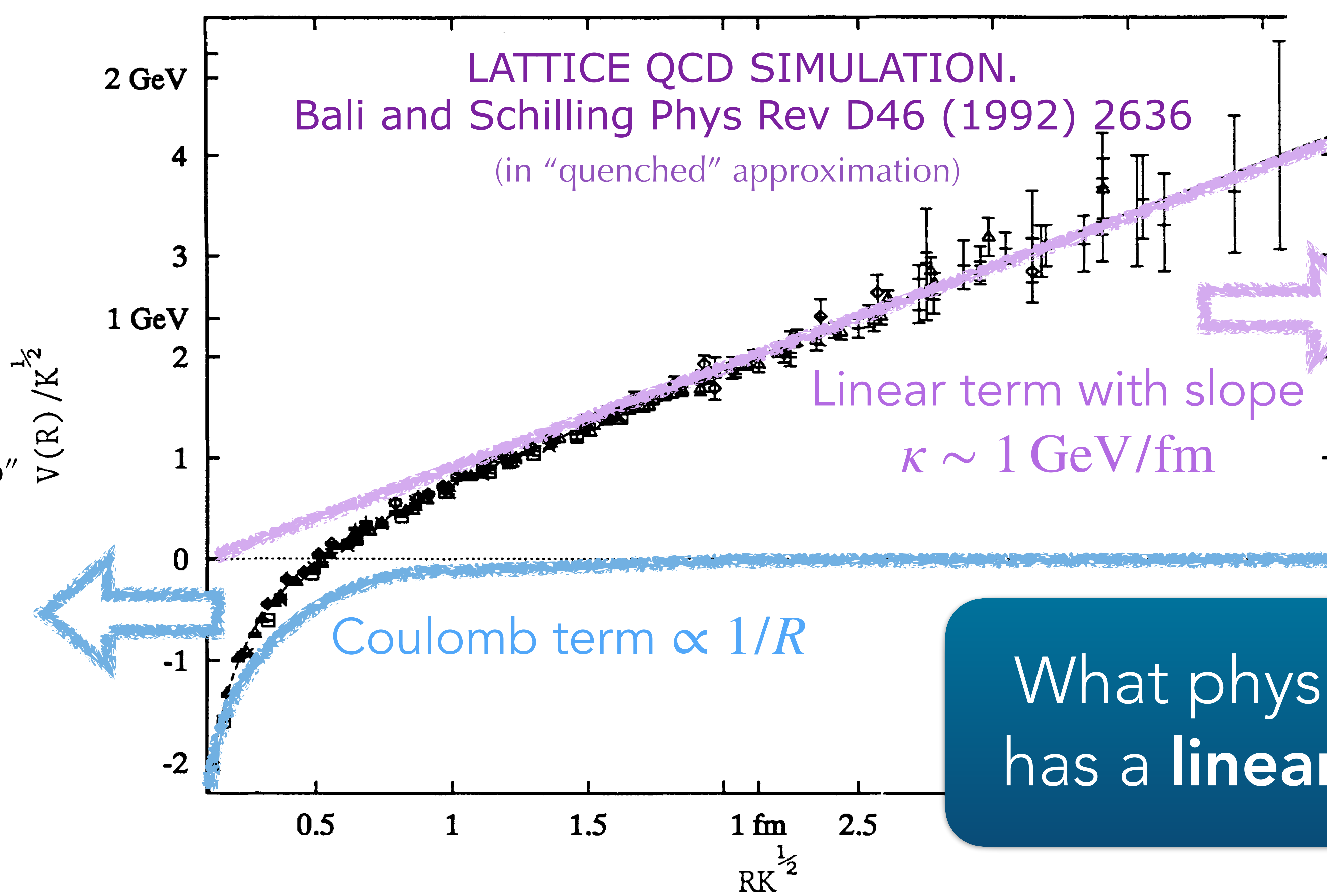
On lattice, compute **potential energy** $V(R)$ of a **colour-singlet** $q\bar{q}$ **state**

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

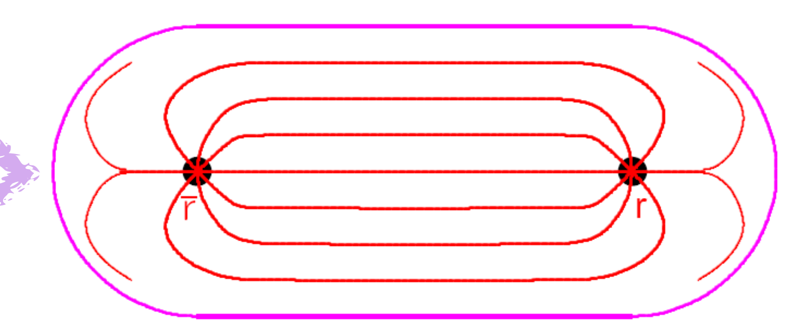
Short Distances ~ "Coulomb"



"Free" Partons



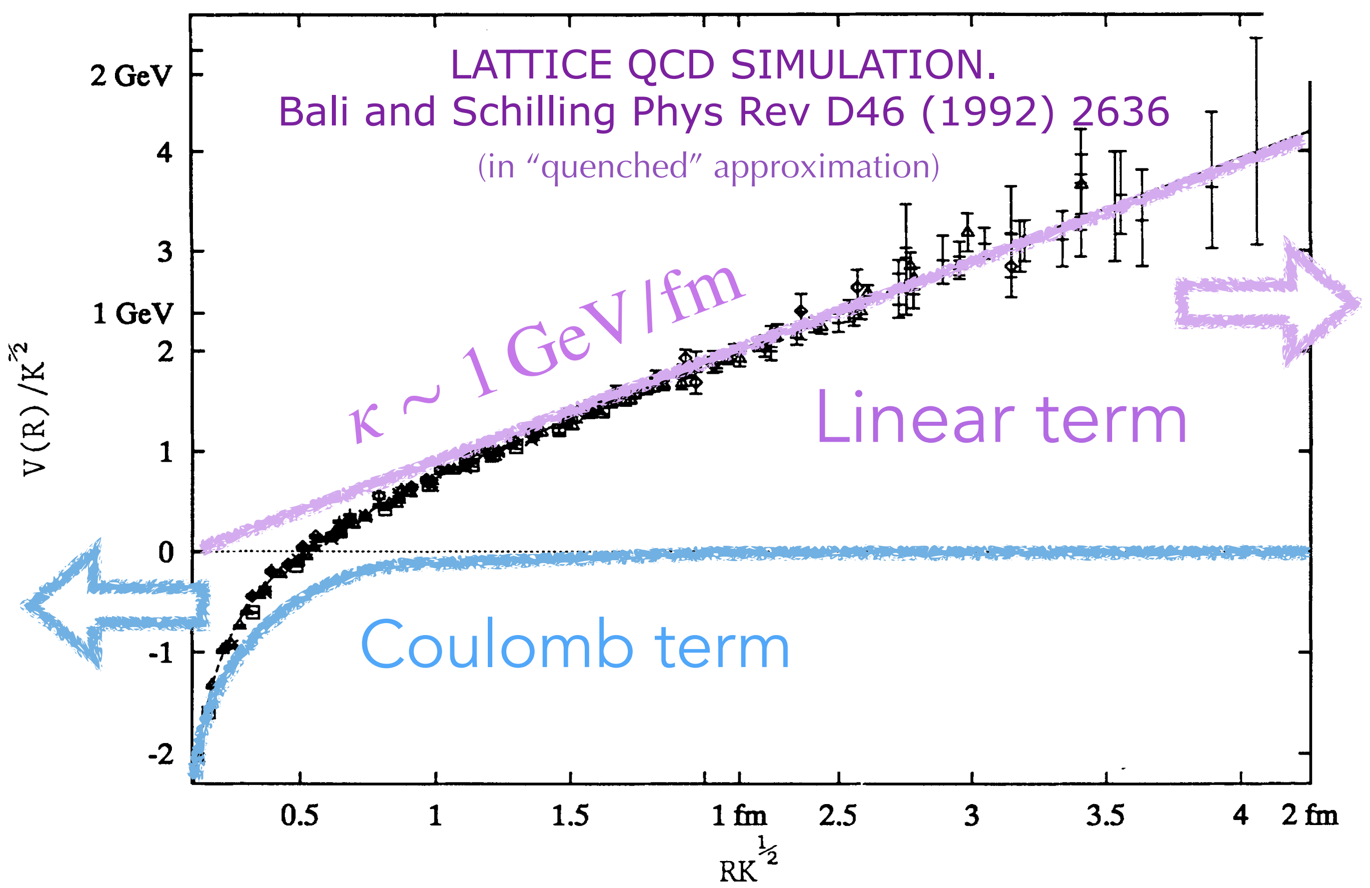
Long Distances ~ Linear Potential



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

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

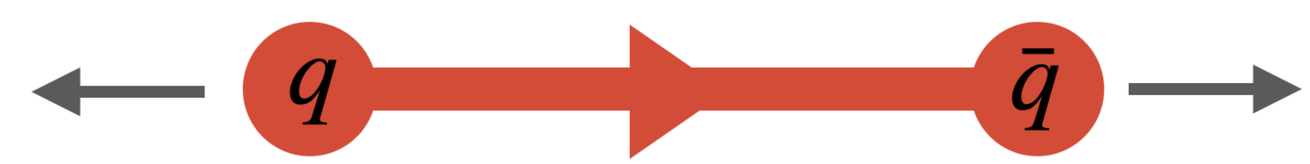
Strings!!



Lund string model

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

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

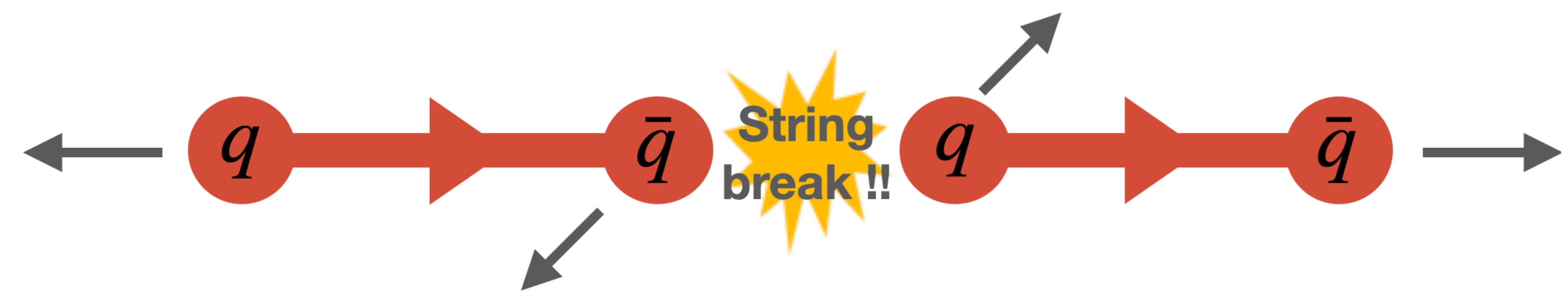


next slides

(+ 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":** $\exp\left(\frac{-m_q^2 - p_{\perp q}^2}{\kappa/\pi}\right)$

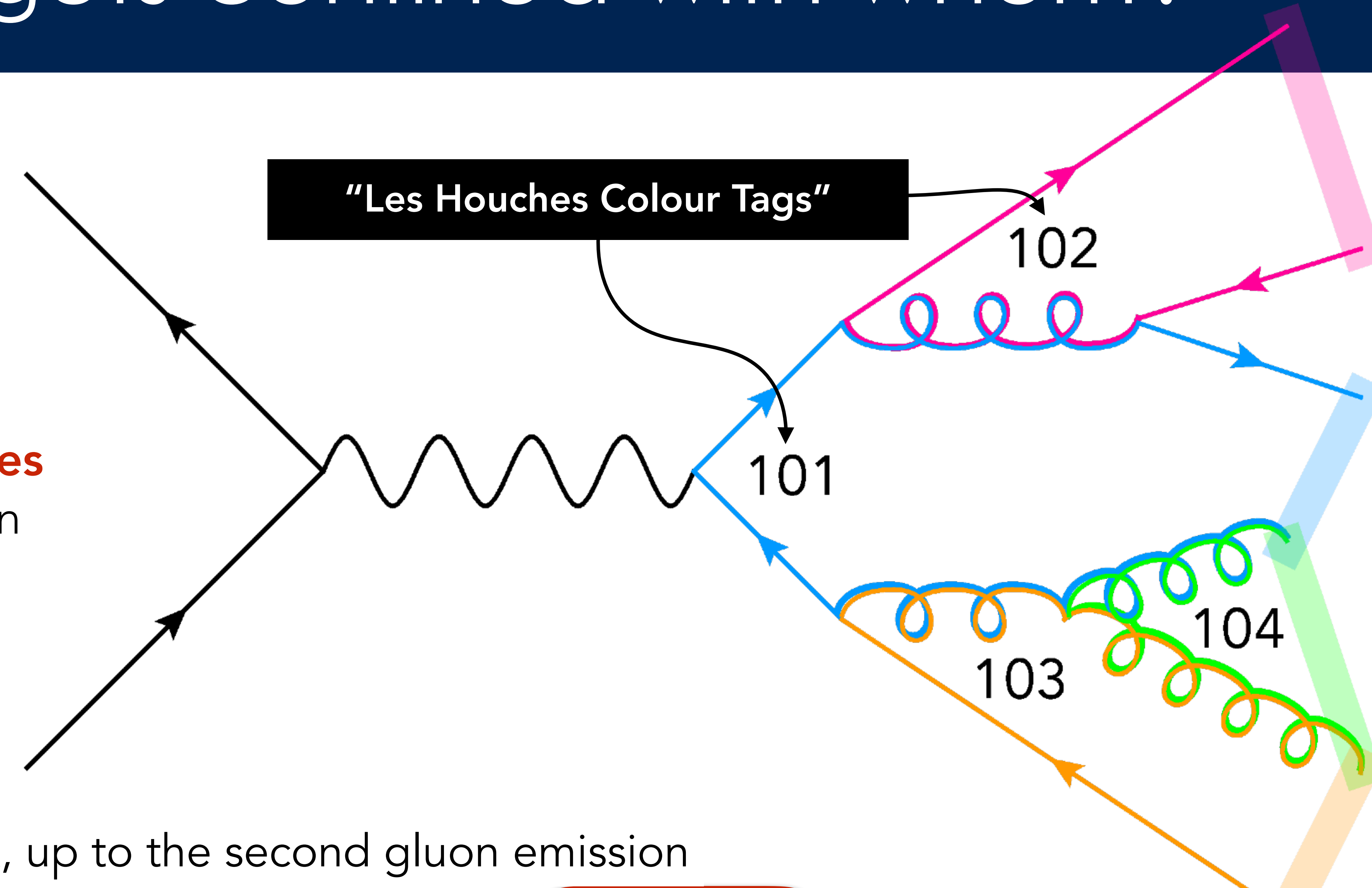
No b or c; Suppression of strange

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



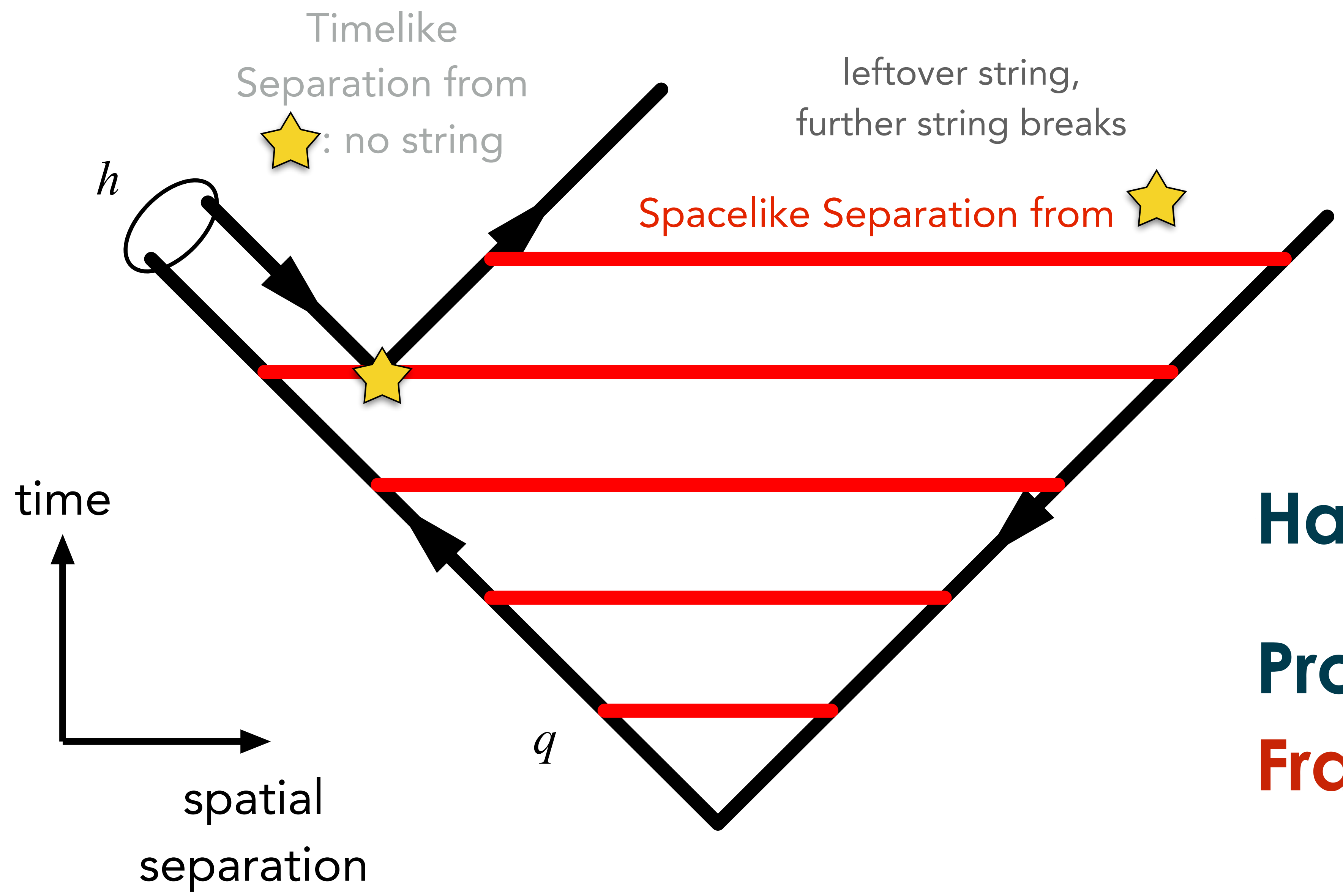
Expect accurate to ~ $1/N_C^2$ ~ 10%

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)

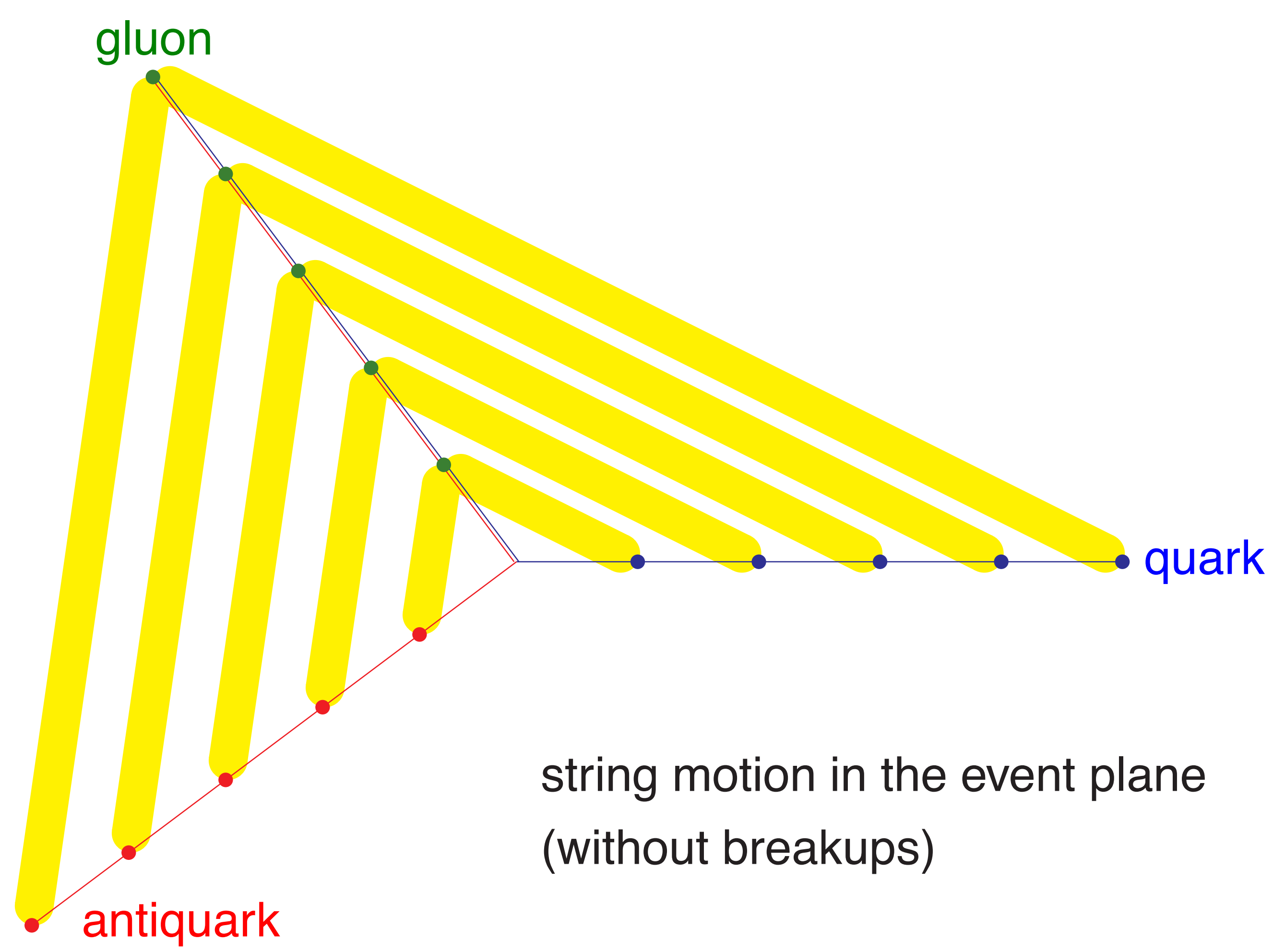
[See, e.g., Amoroso et al., JCAP 05 (2019) 007]

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

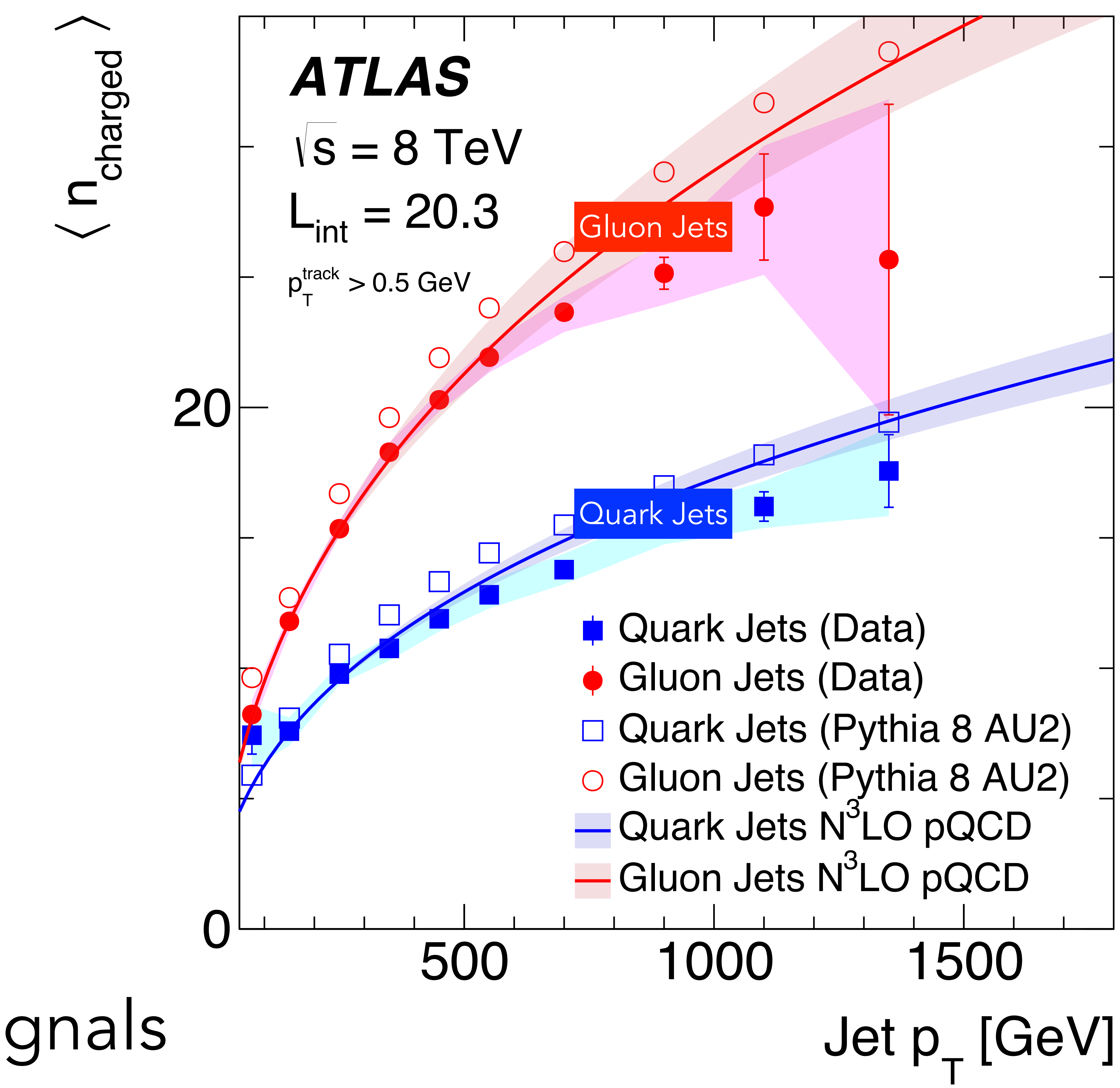
Supresses high z — Supresses low z

Gluon Kinks: The Signature Feature of the Lund Model

Gluons are connected to two string pieces



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



Each quark connected to **one** string piece

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

Important for discriminating new-physics signals

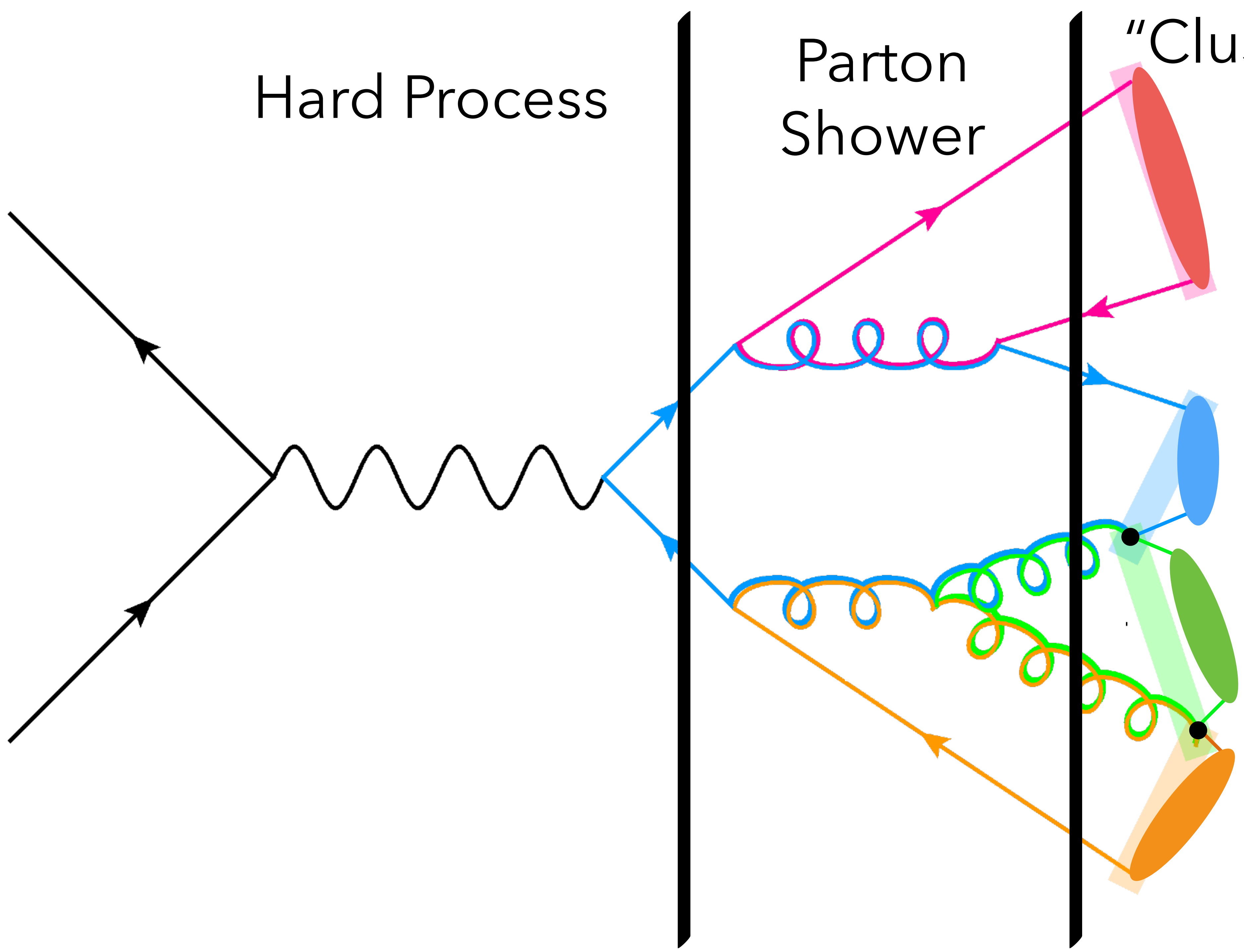
Decays to **quarks** vs decays to **gluons**,

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

Alternative: **The Cluster Model** — Used in HERWIG & SHERPA

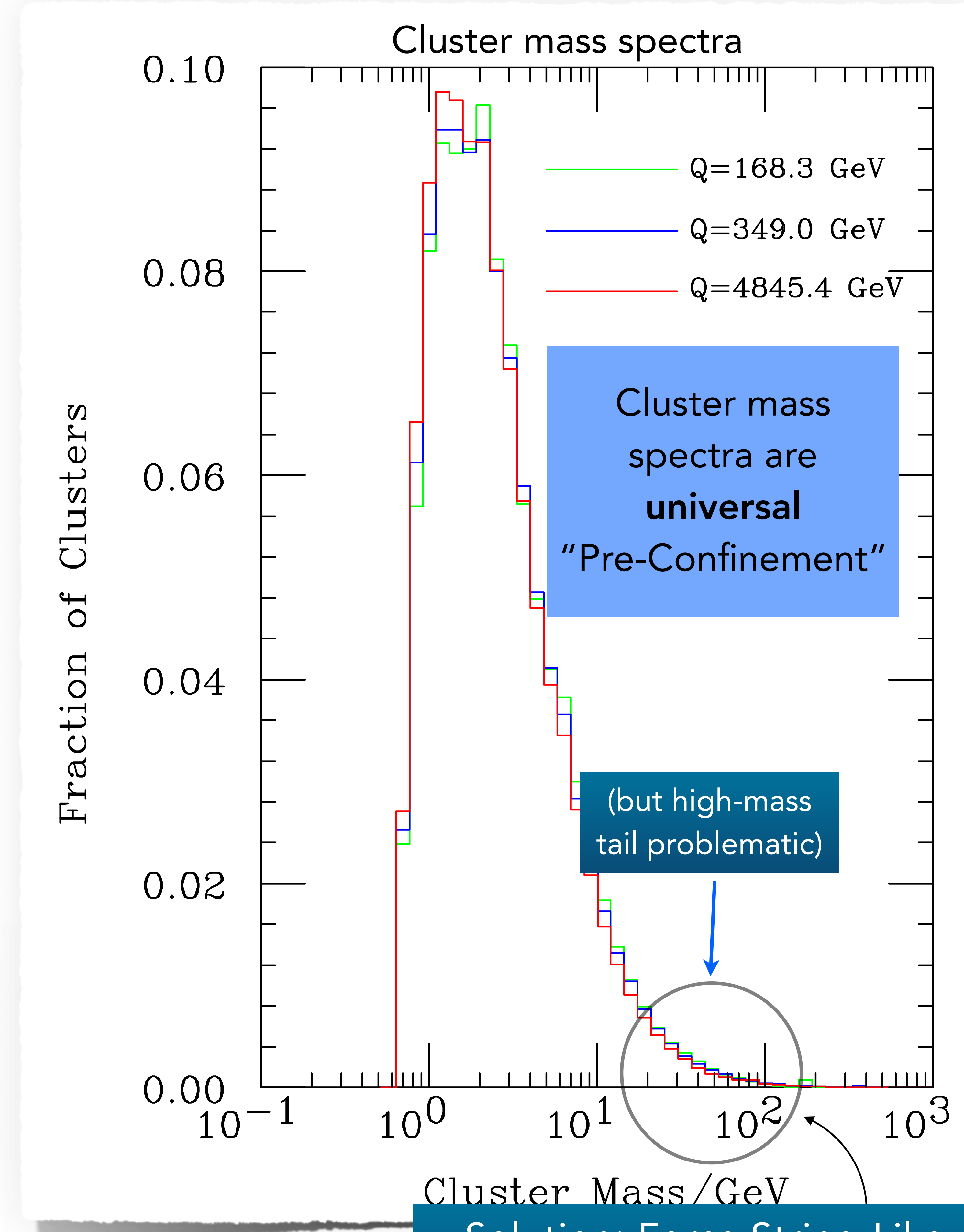
Alternative to strings:

Force $g \to q\bar{q}$ at end of shower



Isotropic 2-body decays to hadrons

According to phase space



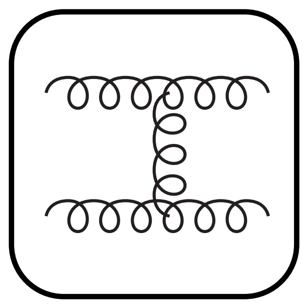
Solution: Force String-Like Splittings of Large Clusters

Hadron Collisions → Multi-Parton Interactions

Protons are composite

One proton = **beam** of partons

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

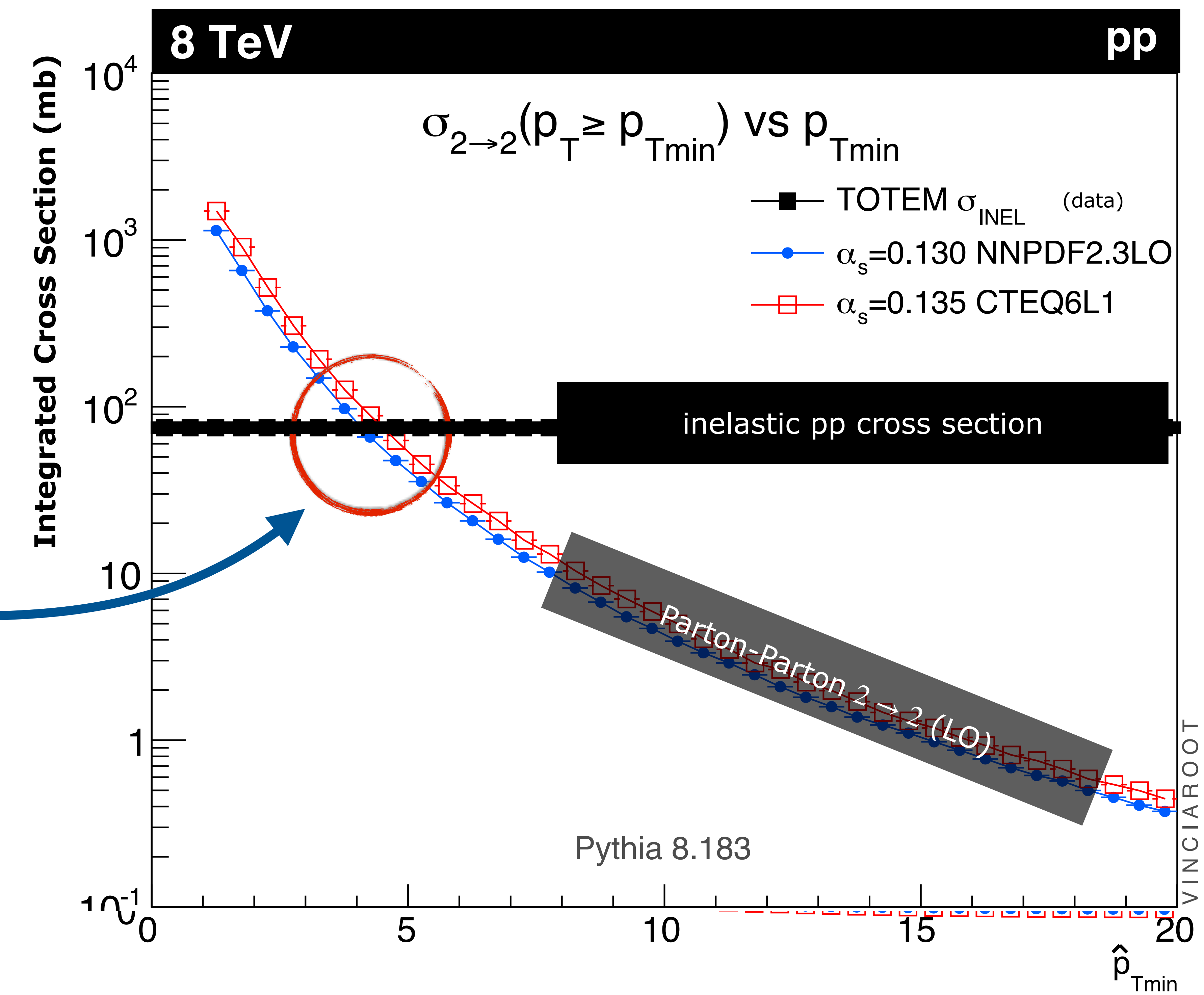
 $\propto \frac{\alpha_s(p_\perp)}{t}$

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

Interpretation: $\frac{\sigma_{\textbf{parton-parton}}(\hat{p}_\perp)}{\sigma_{\textbf{hadron-hadron}}} \sim \langle n \rangle_{\text{parton-parton}}(\hat{p}_\perp)$

(Regulated at low $\hat{p}_\perp$ by IR cutoff ~ colour screening)

➜ Multiple Parton-Parton Interactions (MPI)



≈ poor man's saturation

↔ cut pomerons in Regge Theory

A Brief History of MPI (in PYTHIA)

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

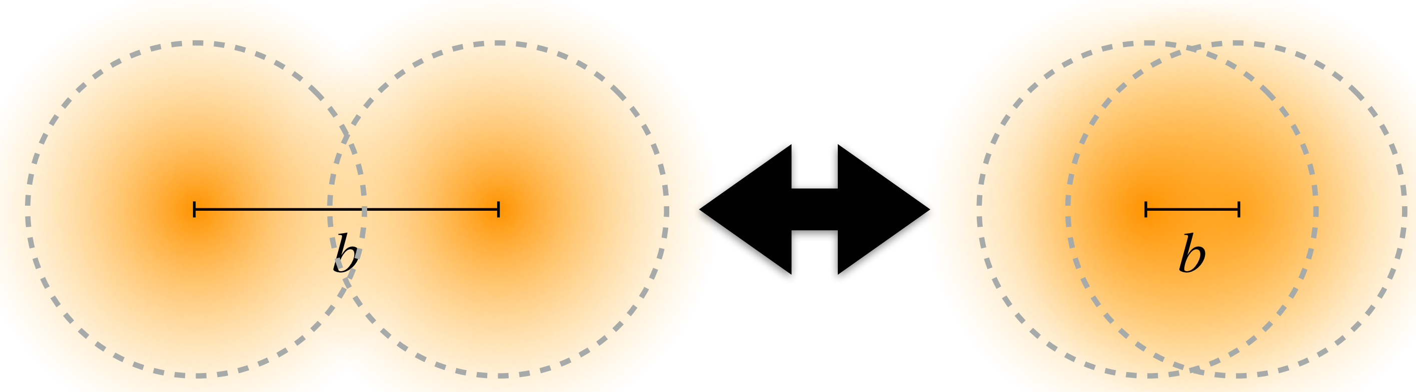
Cast MPI as Sudakov-style evolution:

Analogous to $\sigma_{X+\text{jet}}(p_\perp)/\sigma_X$ 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: $p \propto \sigma_{2\to 2}(x_T, b)/\sigma_{pp}$; $x_T = 2\hat{p}_\perp/\sqrt{s}$

with Impact-parameter dependence



Crucial to describe **"Underlying Event"**

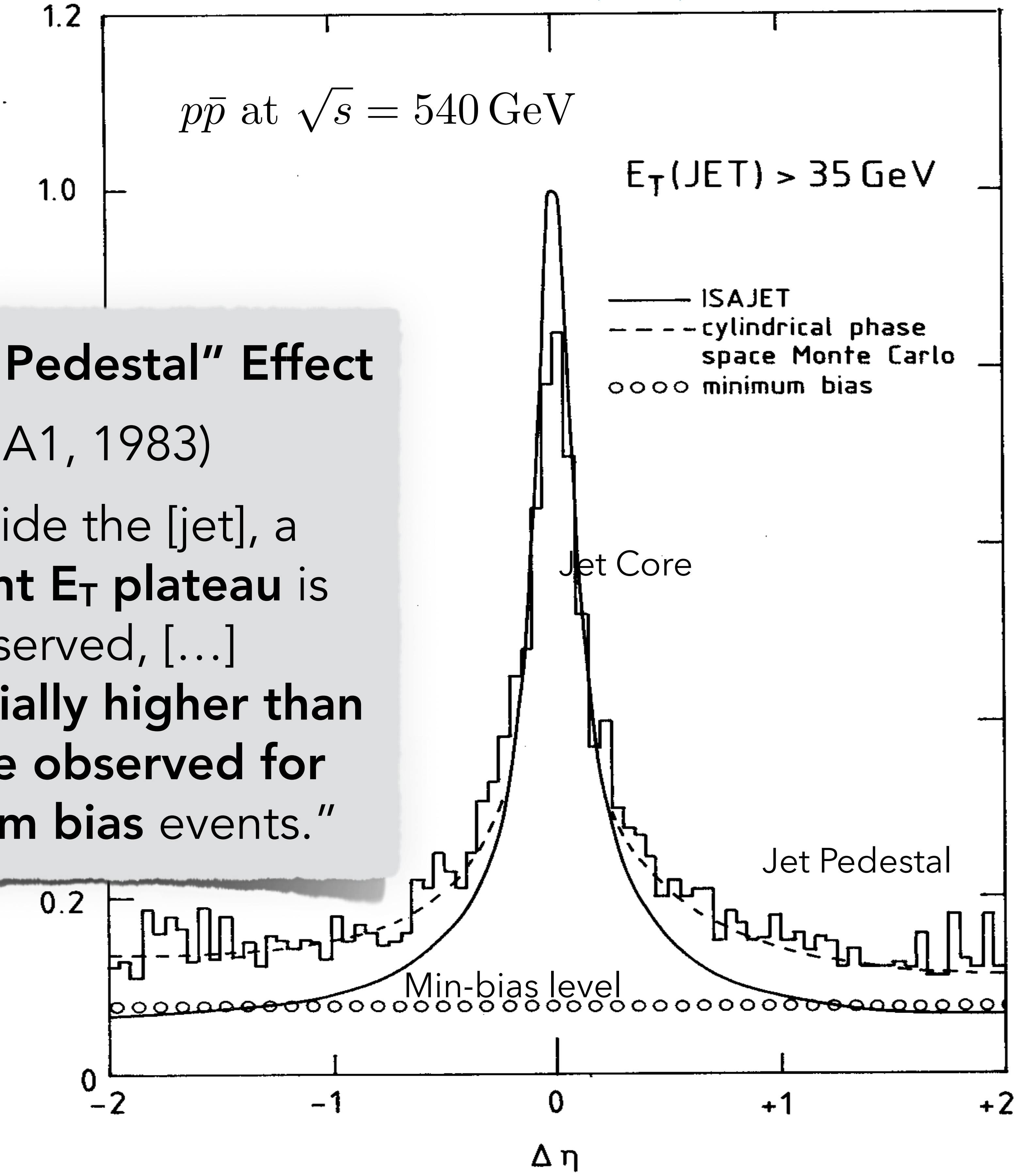
a.k.a. **"Jet Pedestal"**

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



Pythia 8 — **Interleaved** Evolution

2005 [Sjöstrand & PS, Eur.Phys.J.C 39 (2005) 129]

Interleave MPI & ISR evolutions in one common sequence of pT

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

2011 [Corke & Sjöstrand, JHEP 03 (2011) 032]

Also include **FSR** in interleaving

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

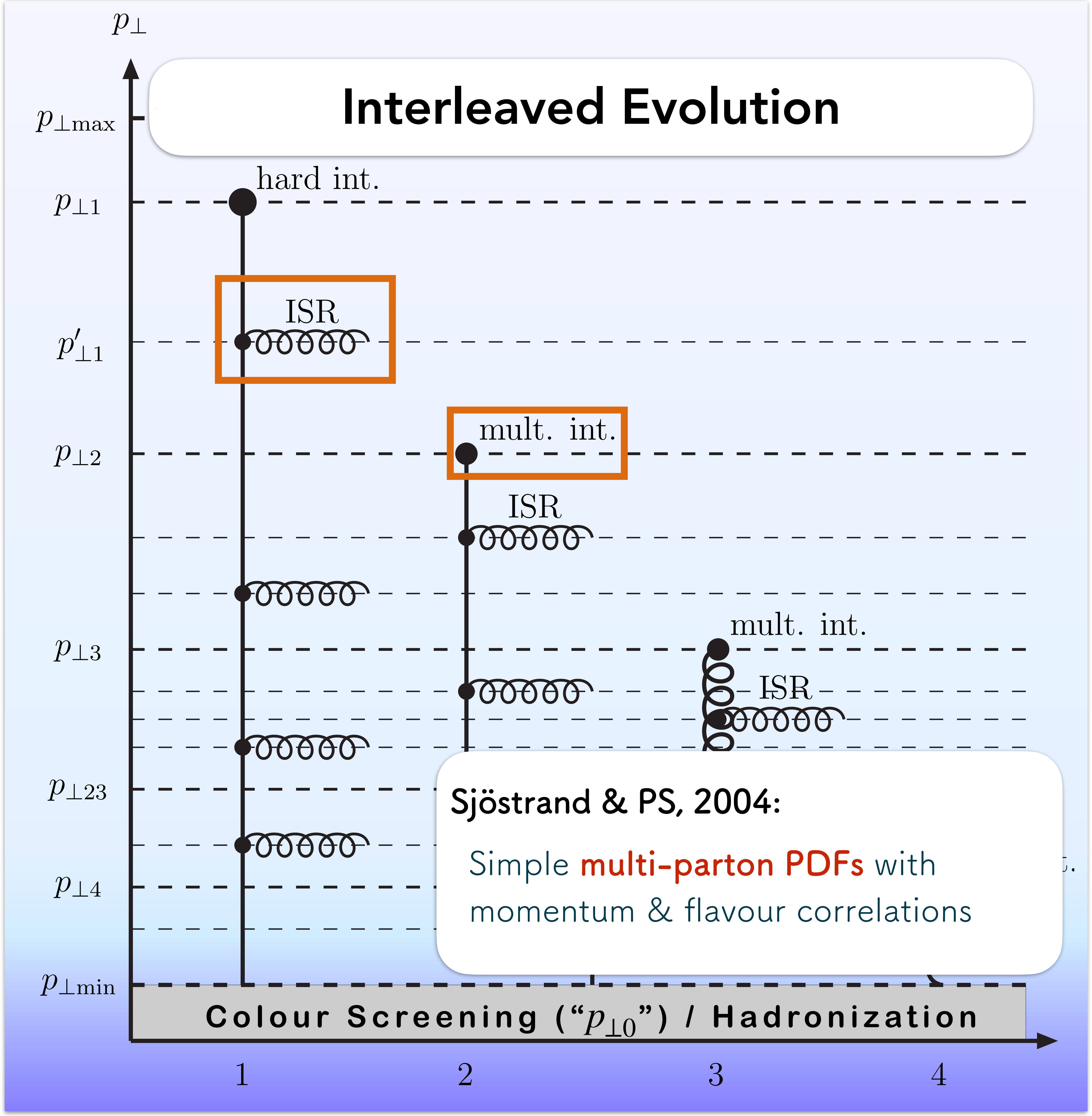


Figure from Sjöstrand & PS, 2005

Confinement in pp Collisions

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**:

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

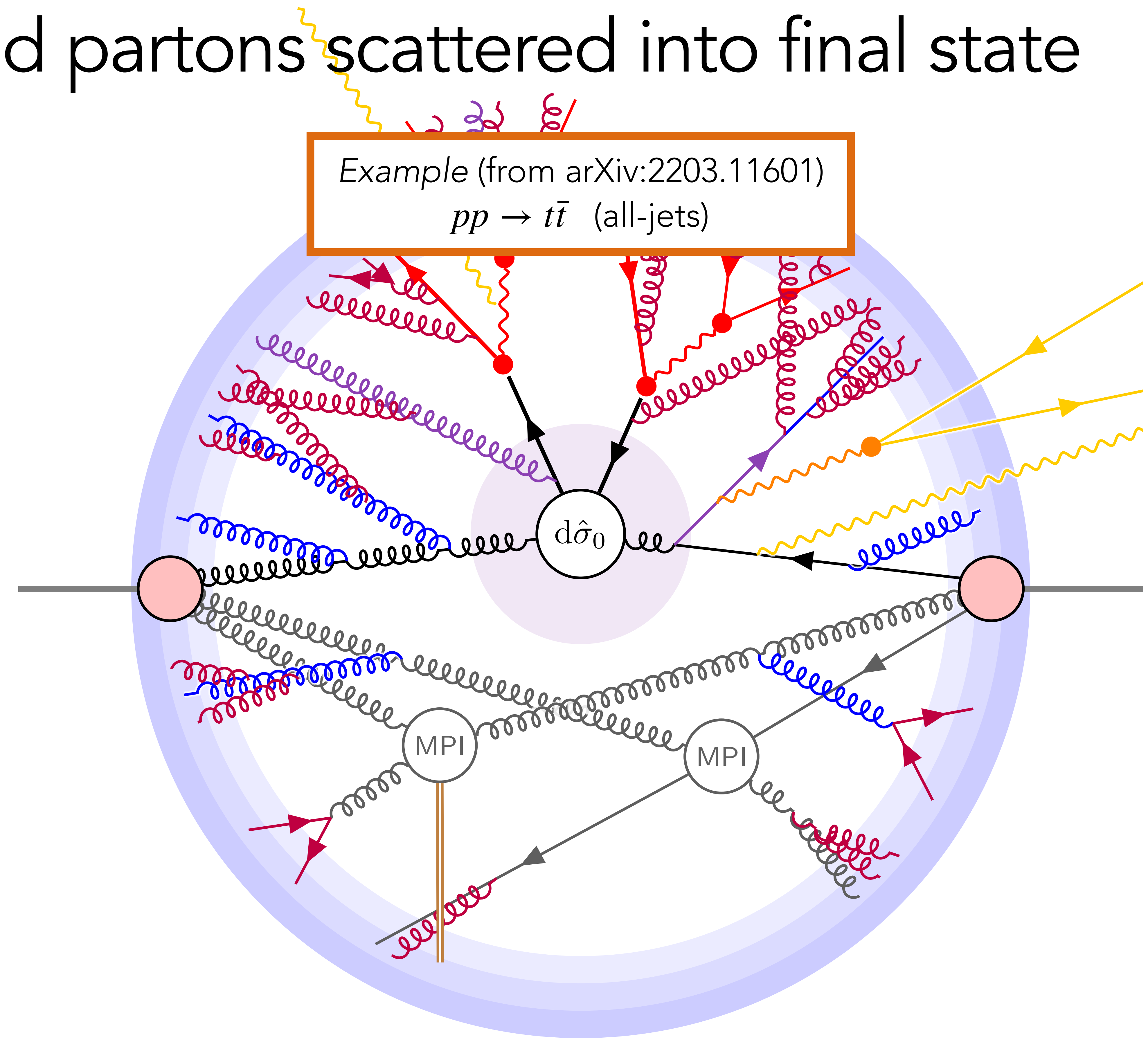
$$3 \otimes 8 = 15 + 6 + 3, \text{ etc.}$$

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?)

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

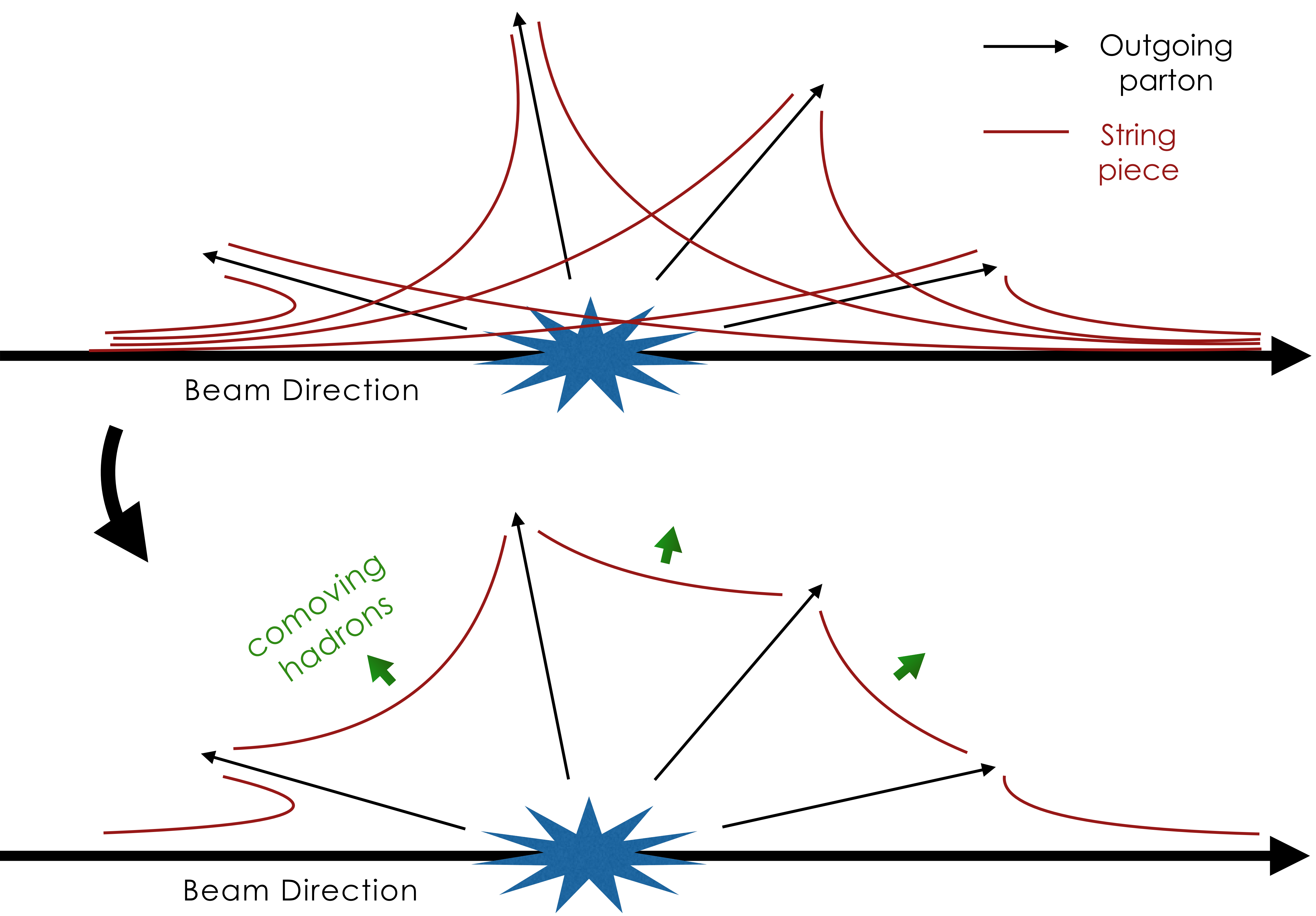


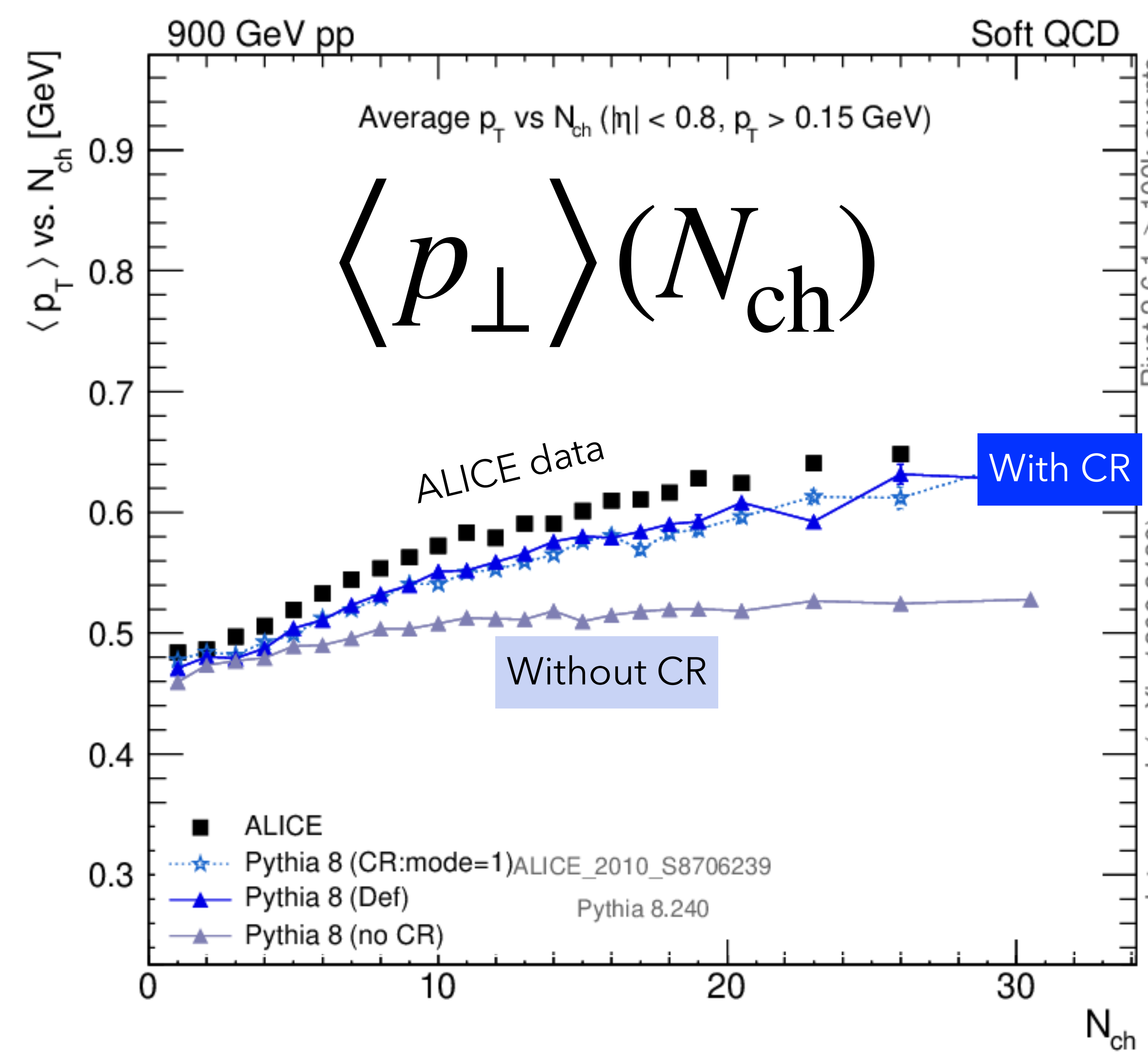
"Parton Level"
(Event structure before confinement)

**): 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>(N_{ch})

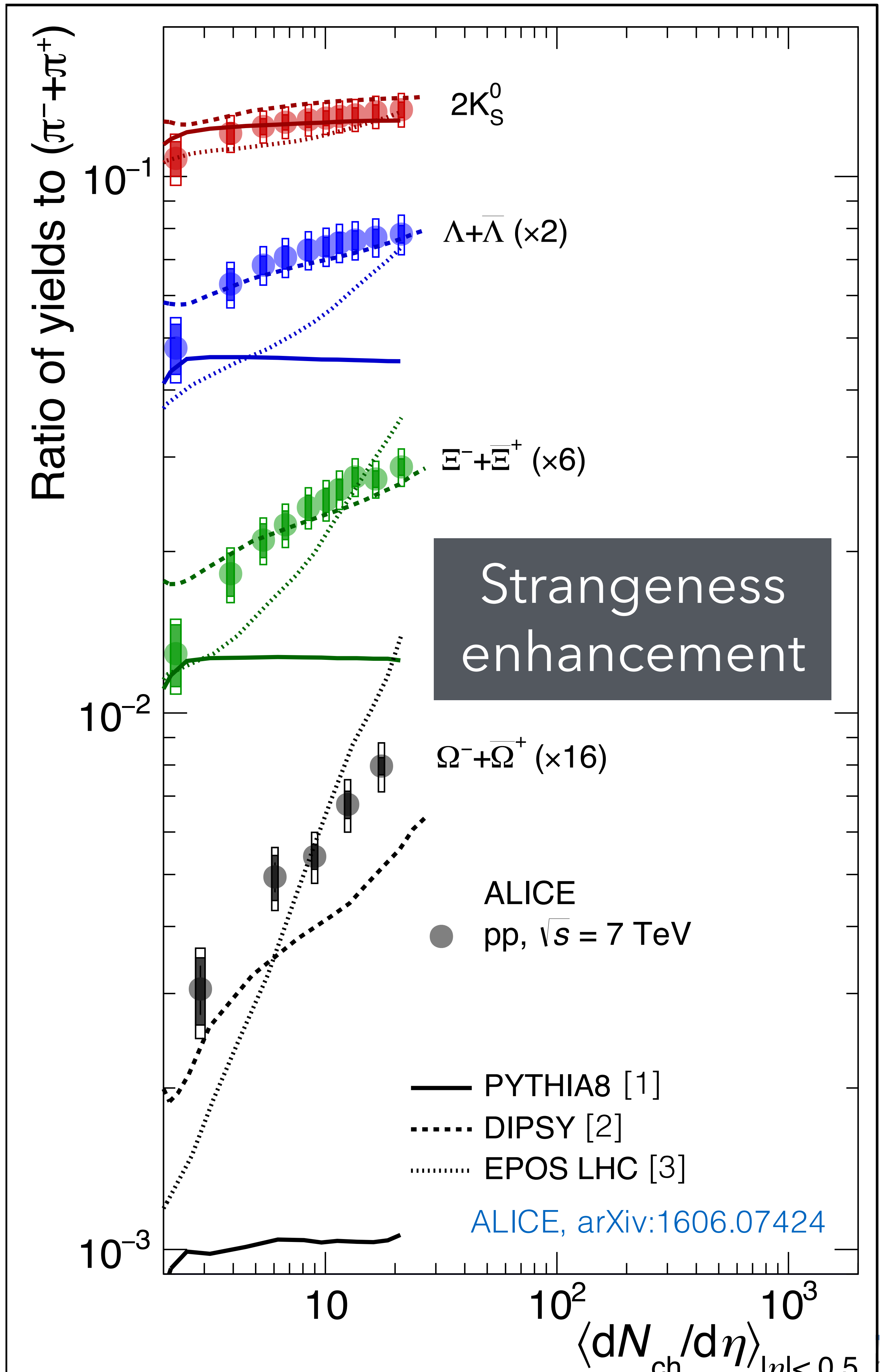
When many string configurations are possible, assume nature picks the one with smallest potential energy ~ "string length"

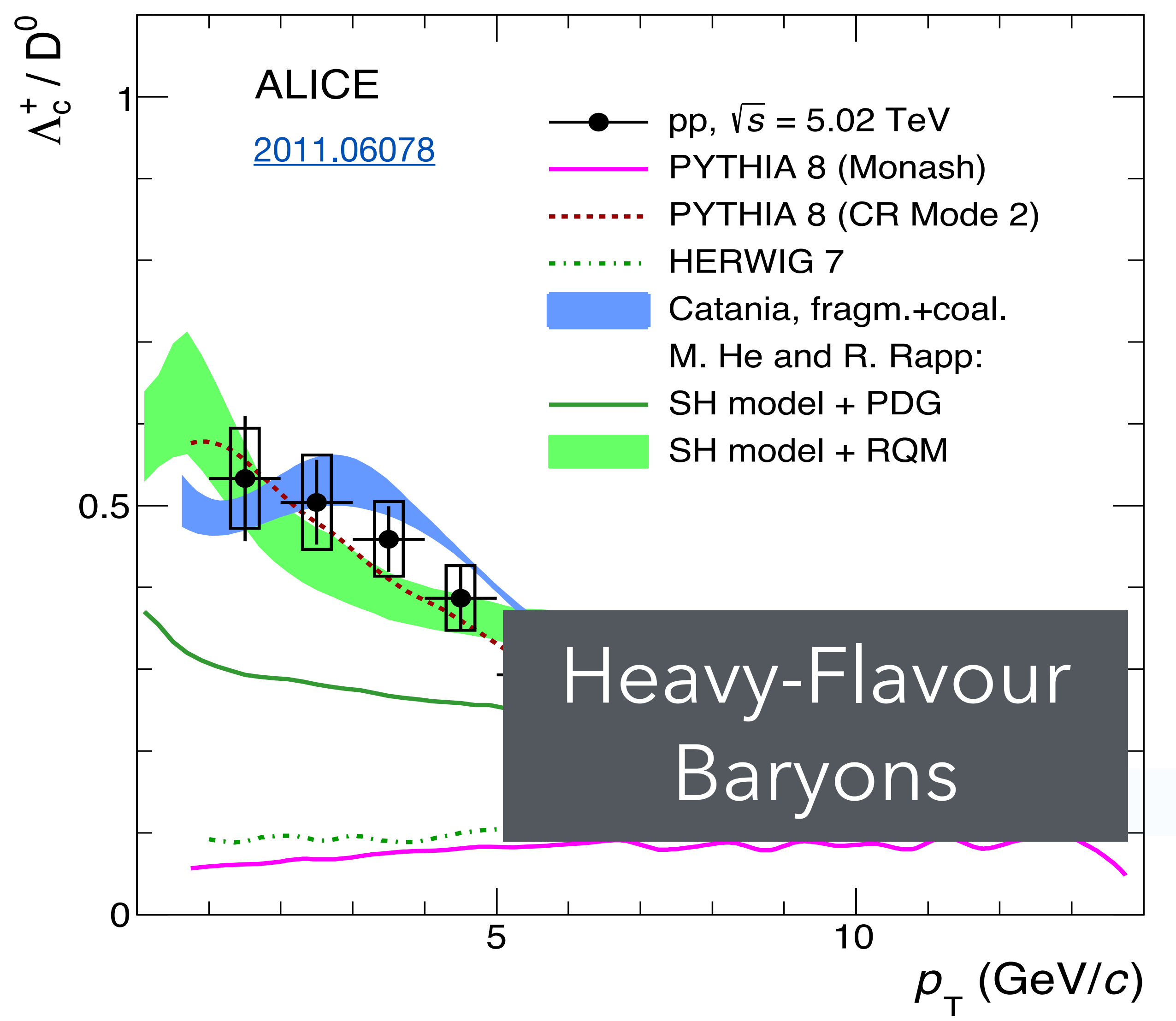


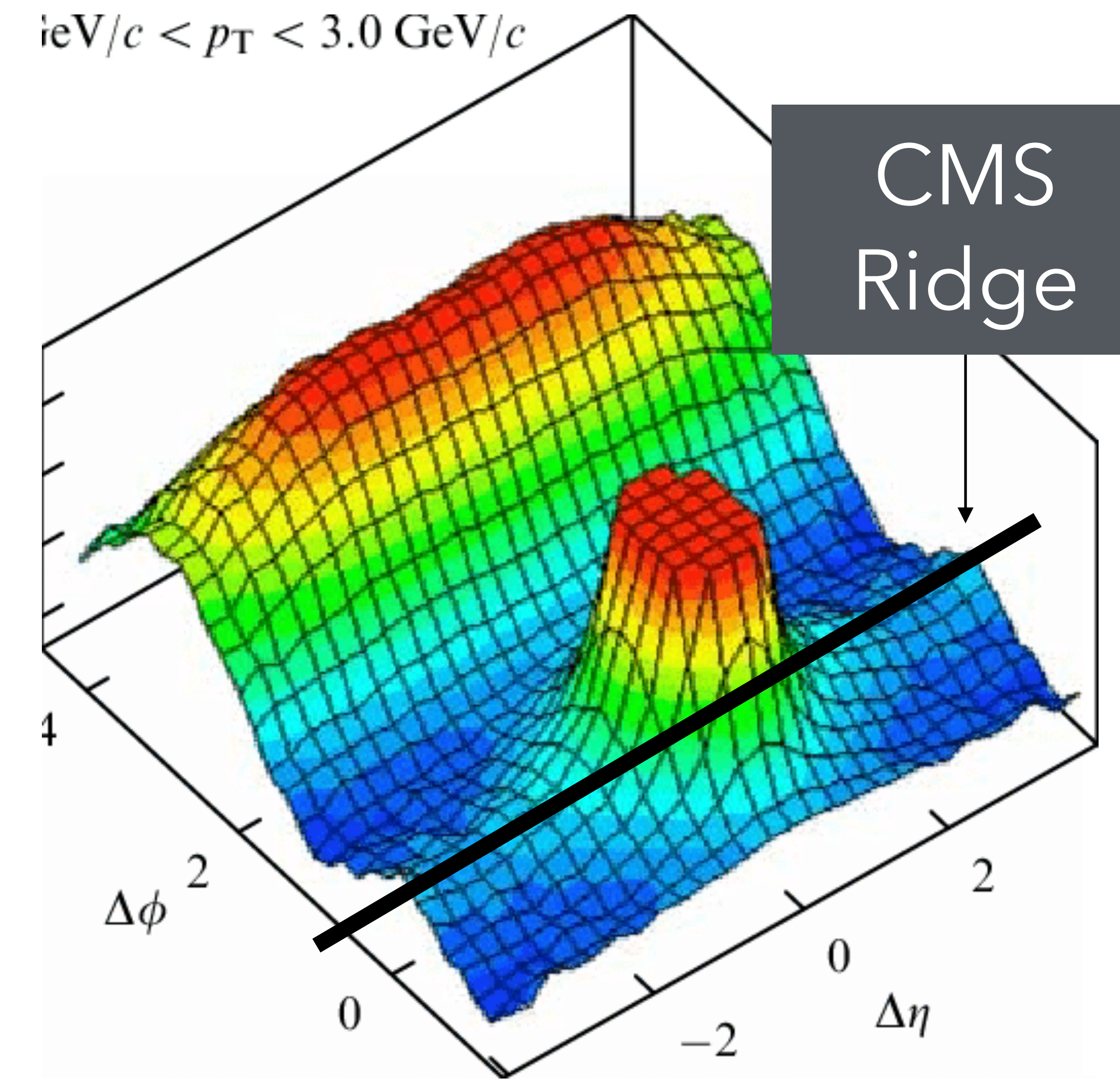


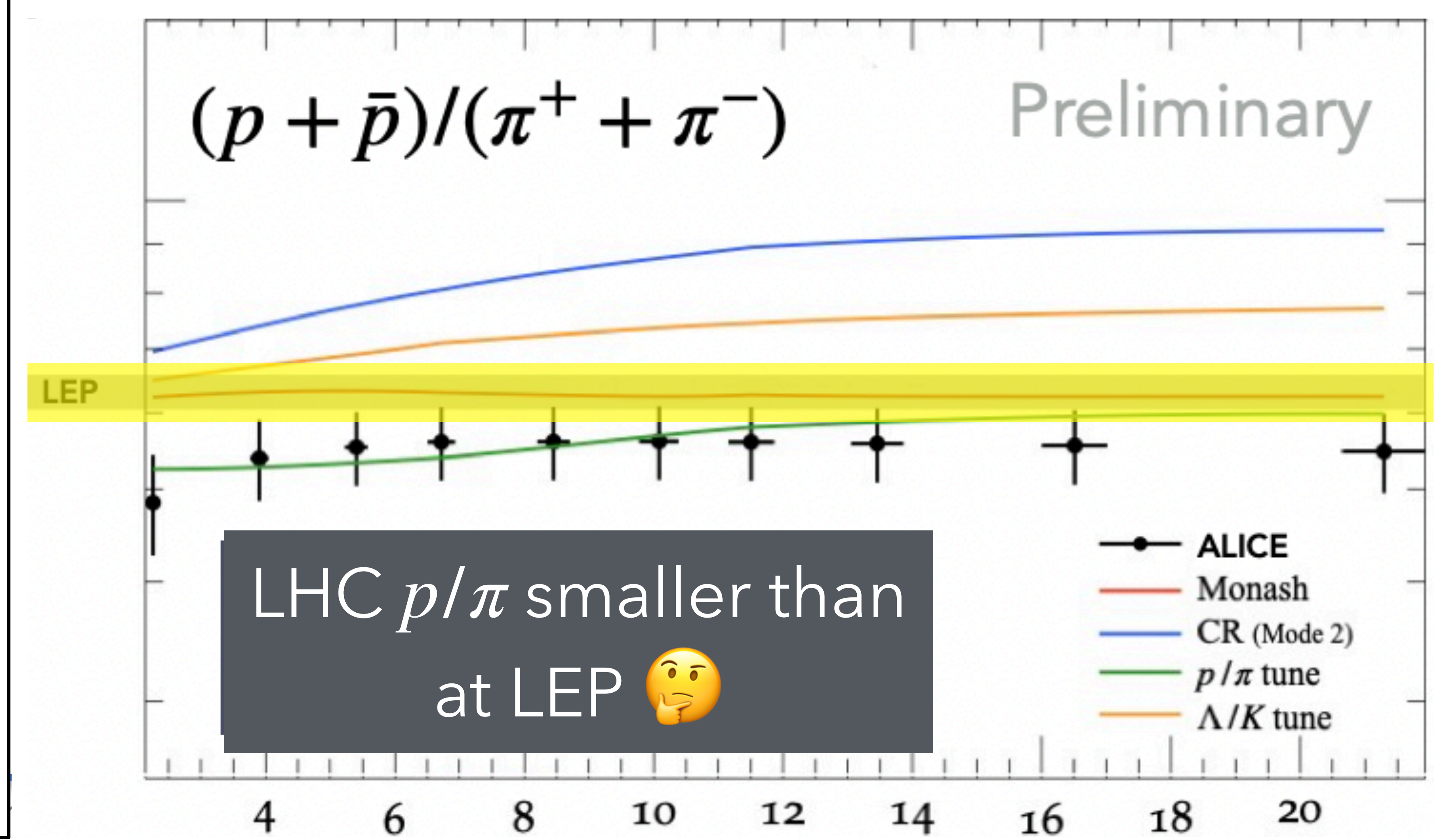
[See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001]

QCD @ LHC ➢ Lots of New Discoveries!









+ Many more …

Baryon correlations

D_s asymmetries

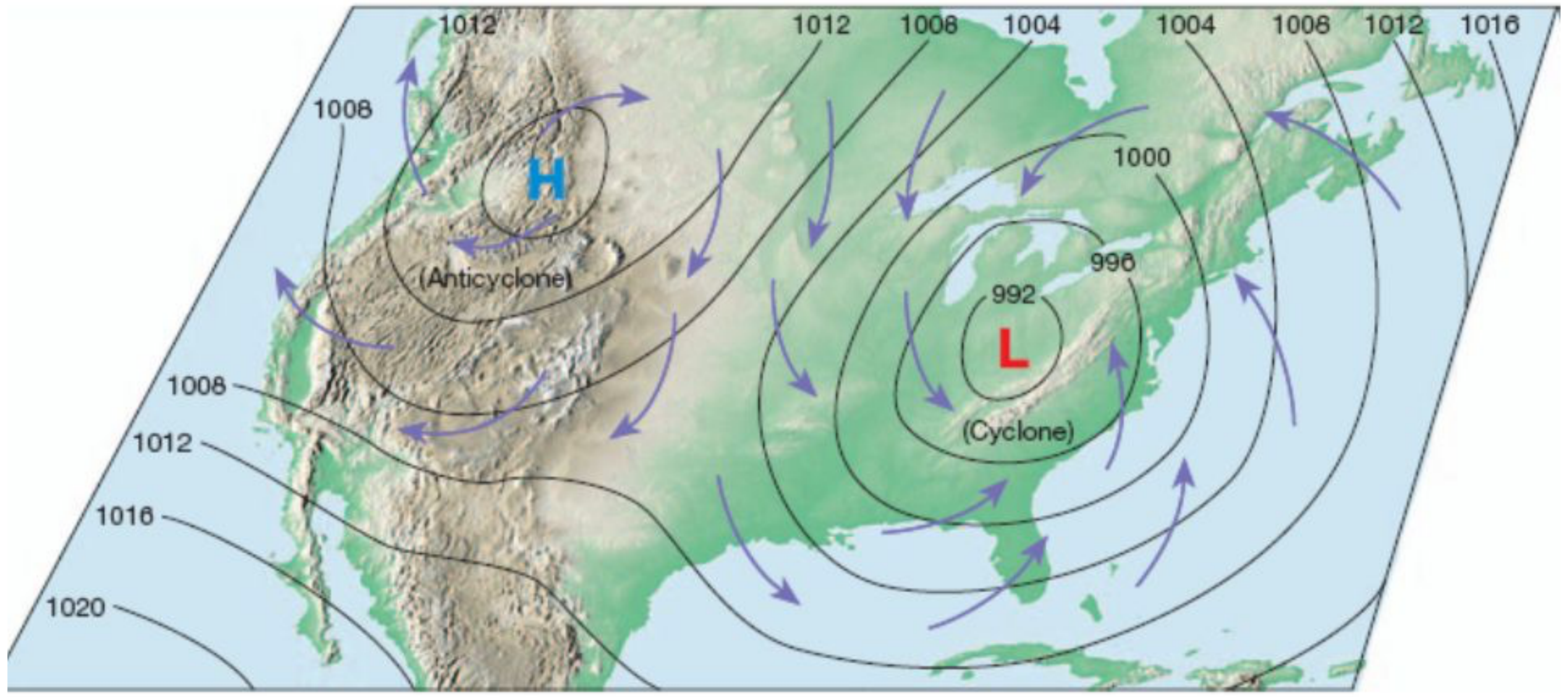
Exotica

…

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?

Work in progress with J. Altmann (Monash), and E. Carragher & J. March-Russell (Oxford).

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

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

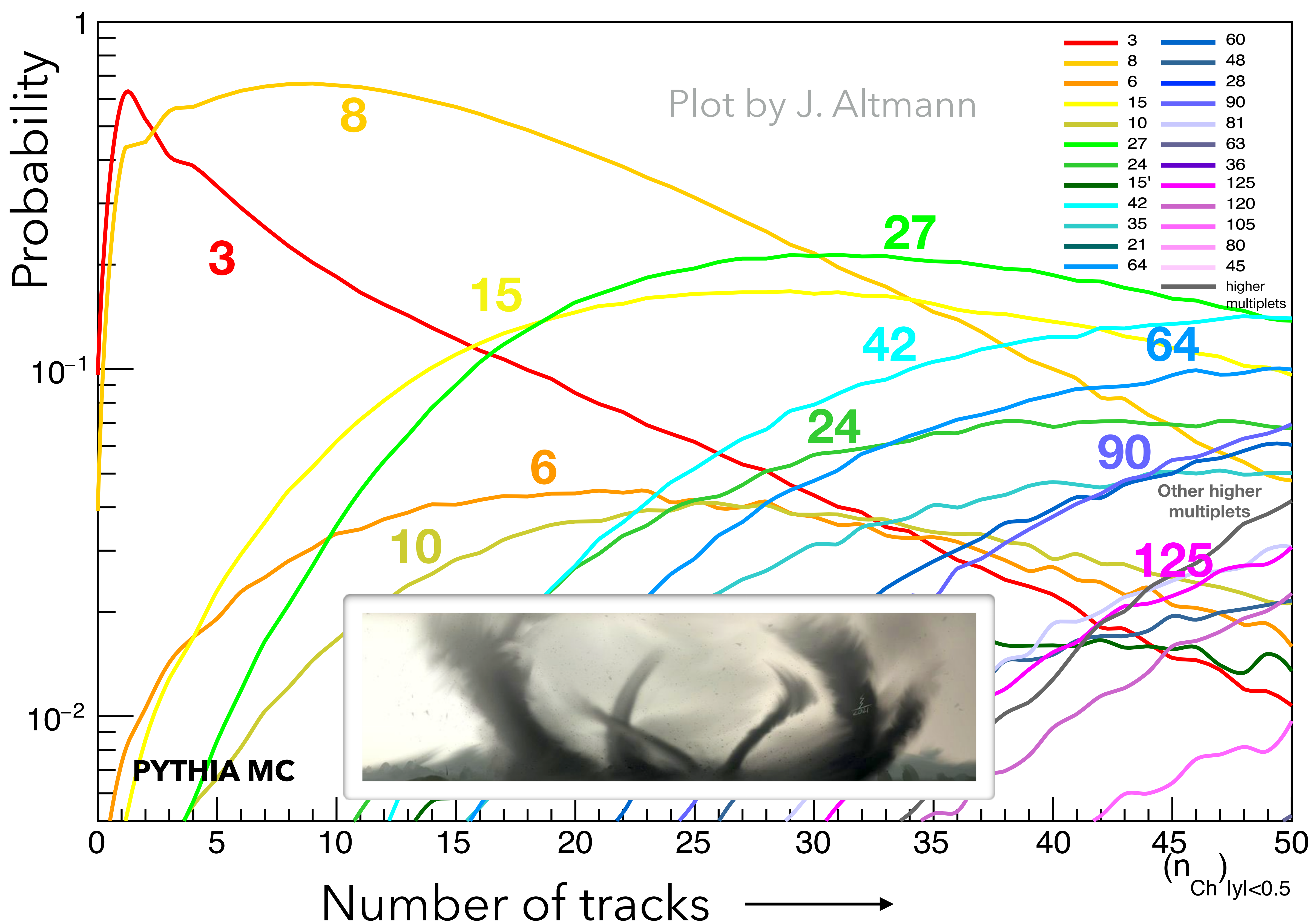
Colour Ropes [Bierlich et al. 2015] + several more recent

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

Non-Linear String Dynamics?

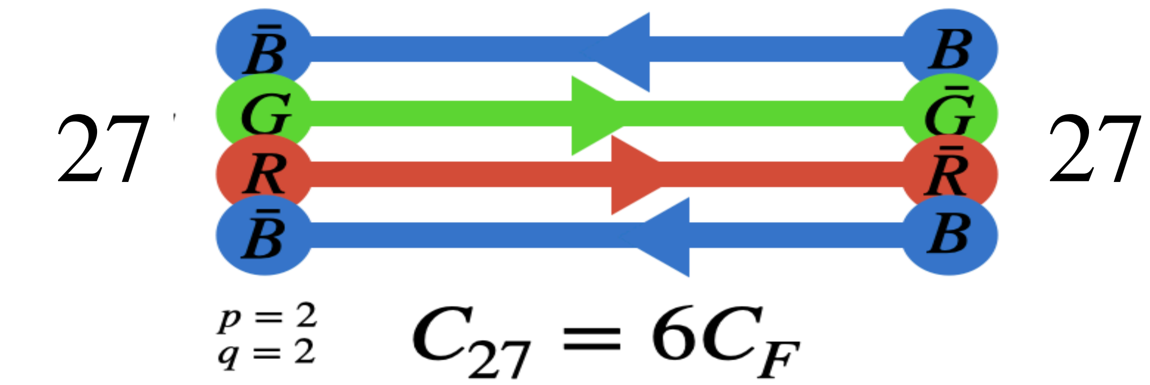
Count # of (oriented) flux lines crossing $y = 0$ in pp collisions at LHC

(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.:



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

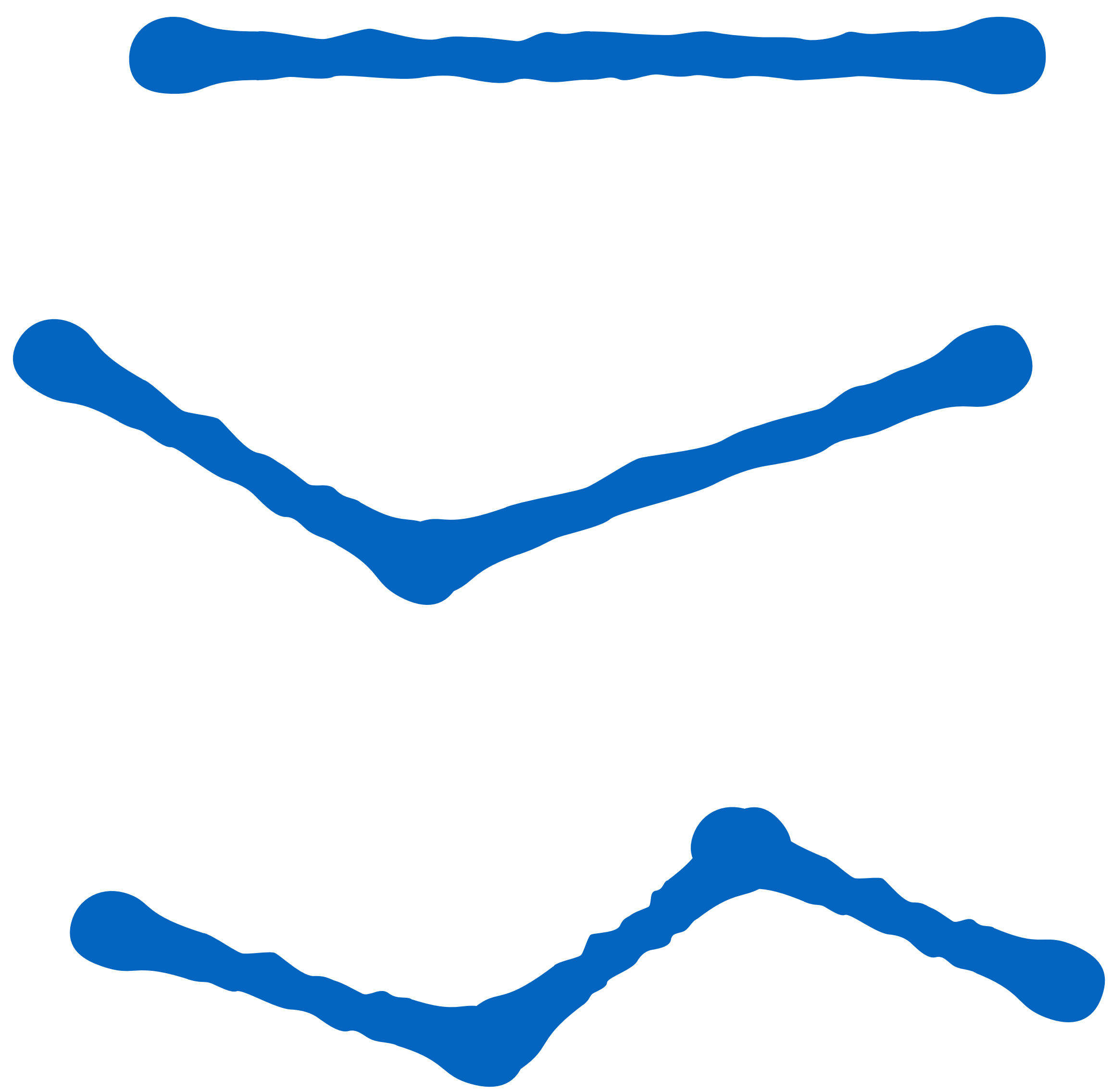
Colour Ropes (Bierlich et al.),

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

What about Baryon Number?

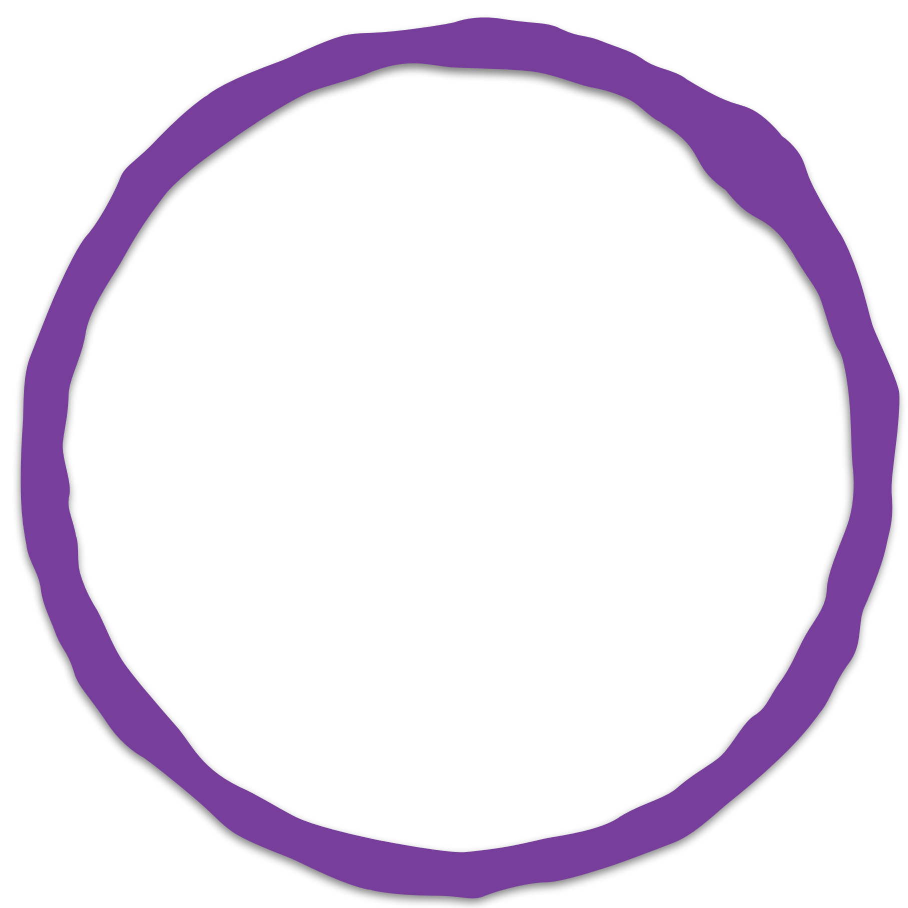
Types of string topologies:

Open Strings



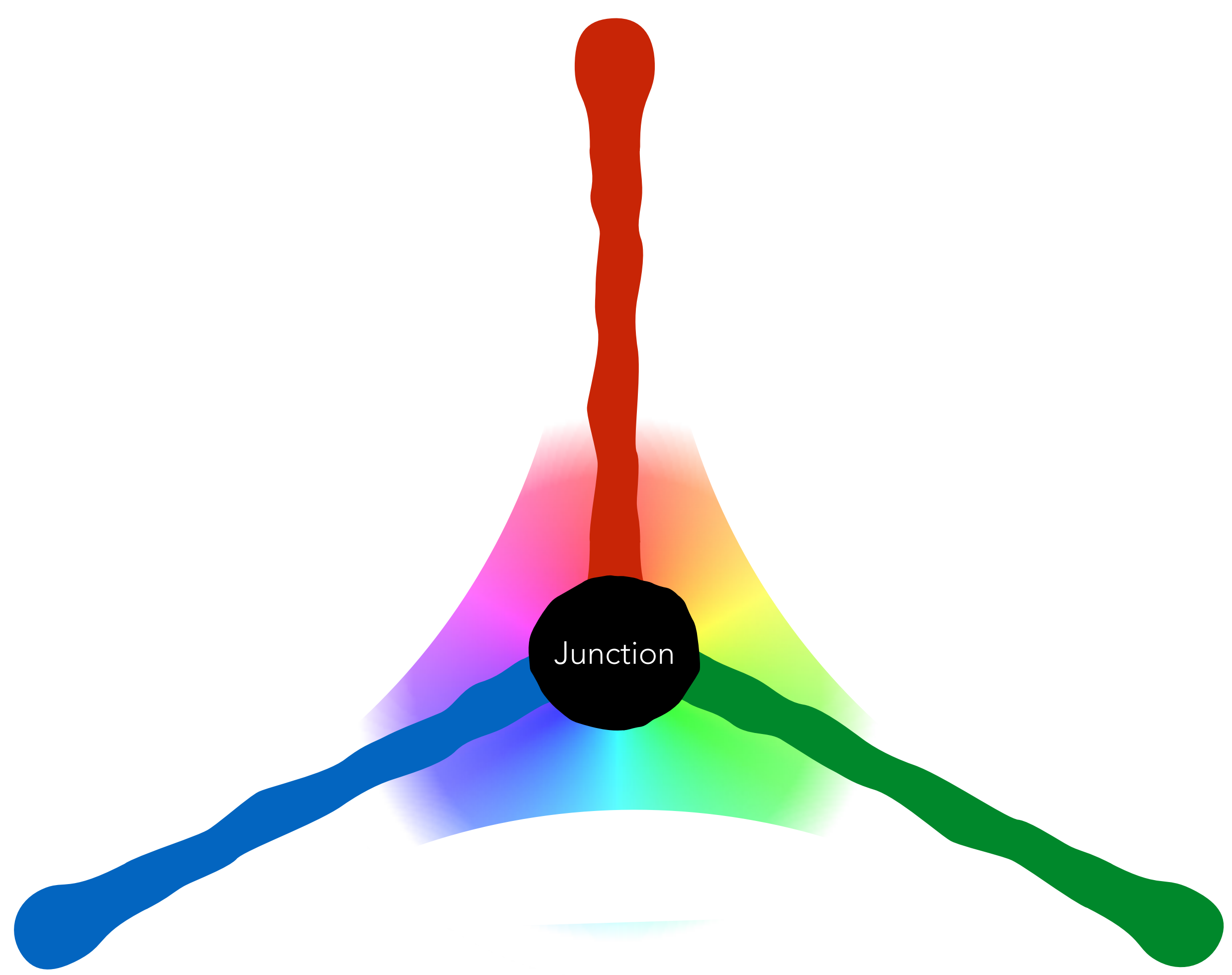
$$(3 \otimes \bar{3})_{\text{singlet}} = \frac{1}{9}$$

Closed Strings



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

SU(3) String Junction

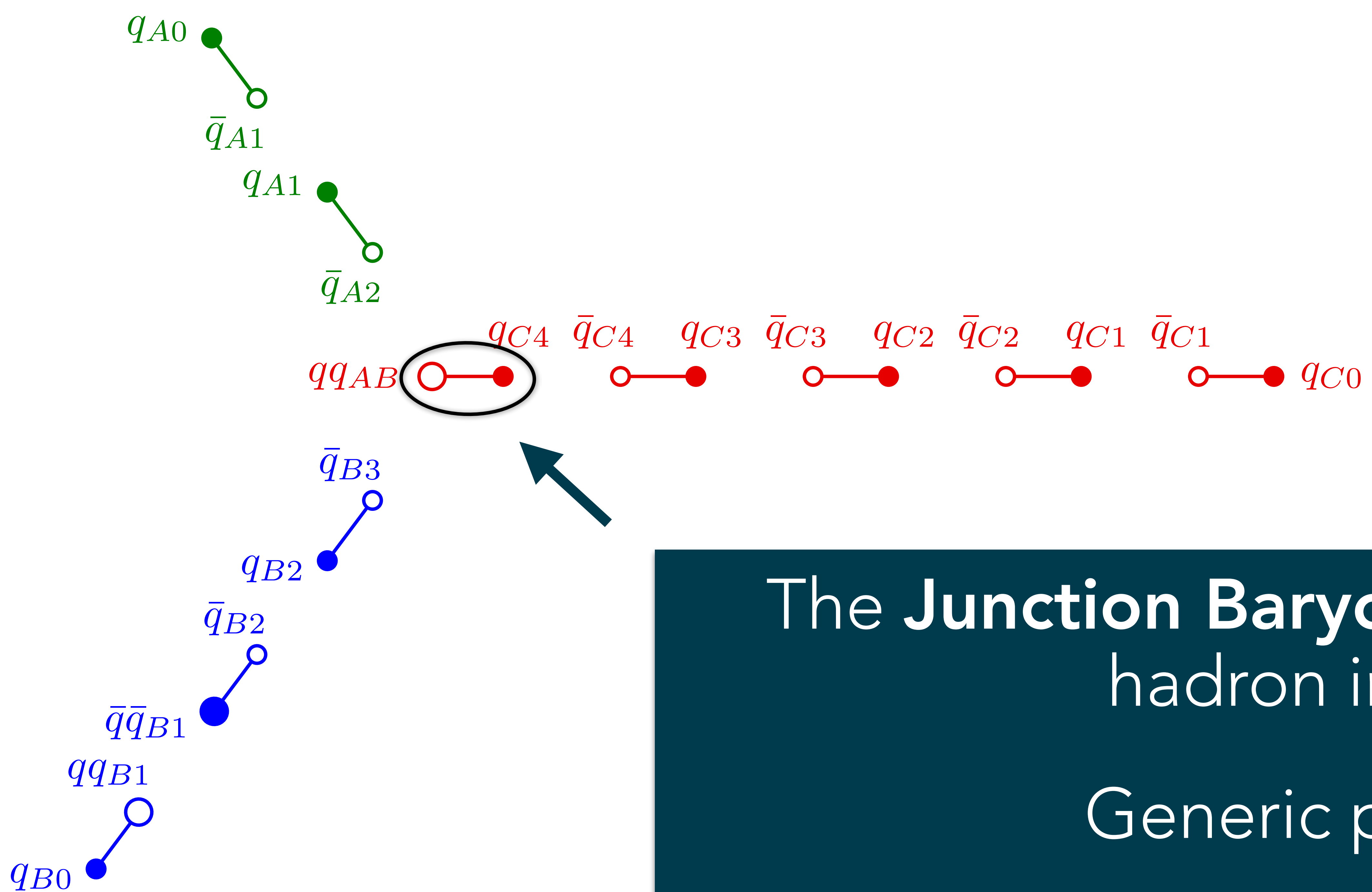


$$(3 \otimes 3 \otimes 3)_{\text{singlet}} = \frac{1}{27}$$

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]

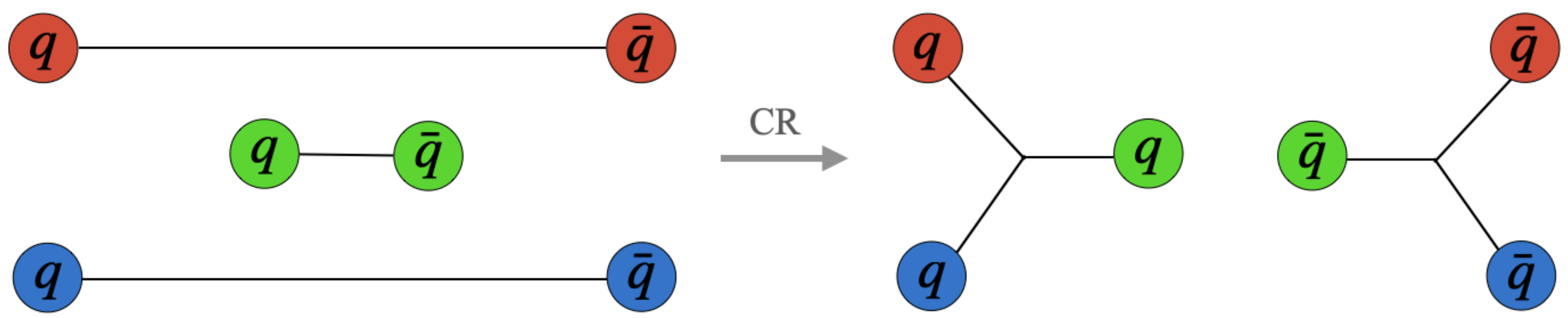
The **Junction Baryon** is the most "subleading" hadron in all three "jets".

Generic prediction: **low p_T**

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

Colour Reconnections ➢ String Junctions

[Christiansen & PS 2015, Altmann & PS 2024]

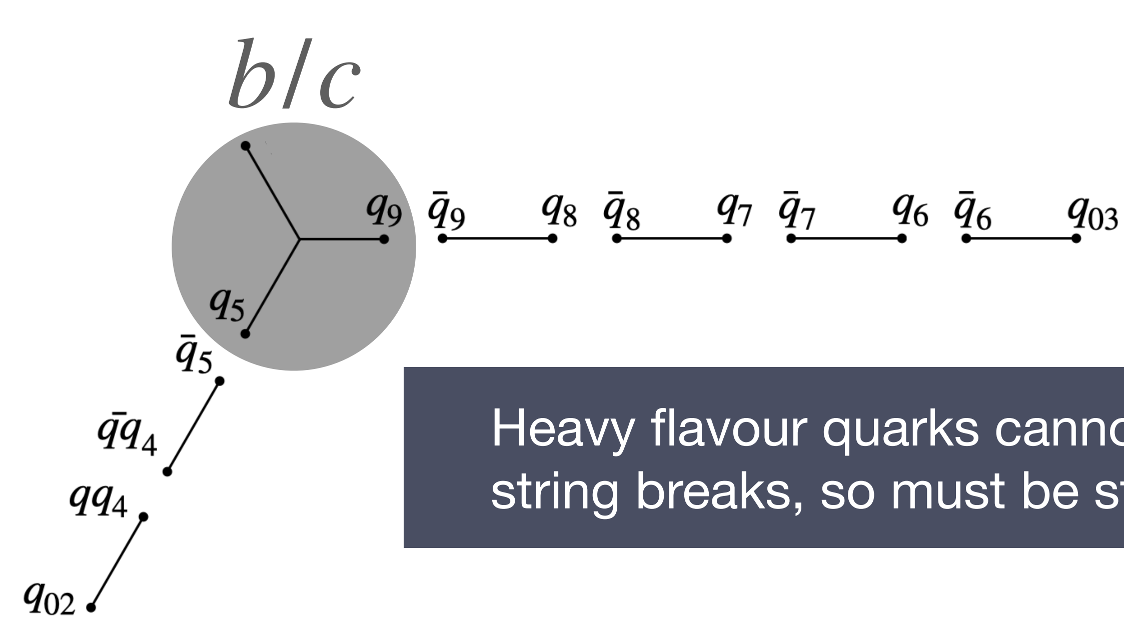


Mechanism for **baryon production**

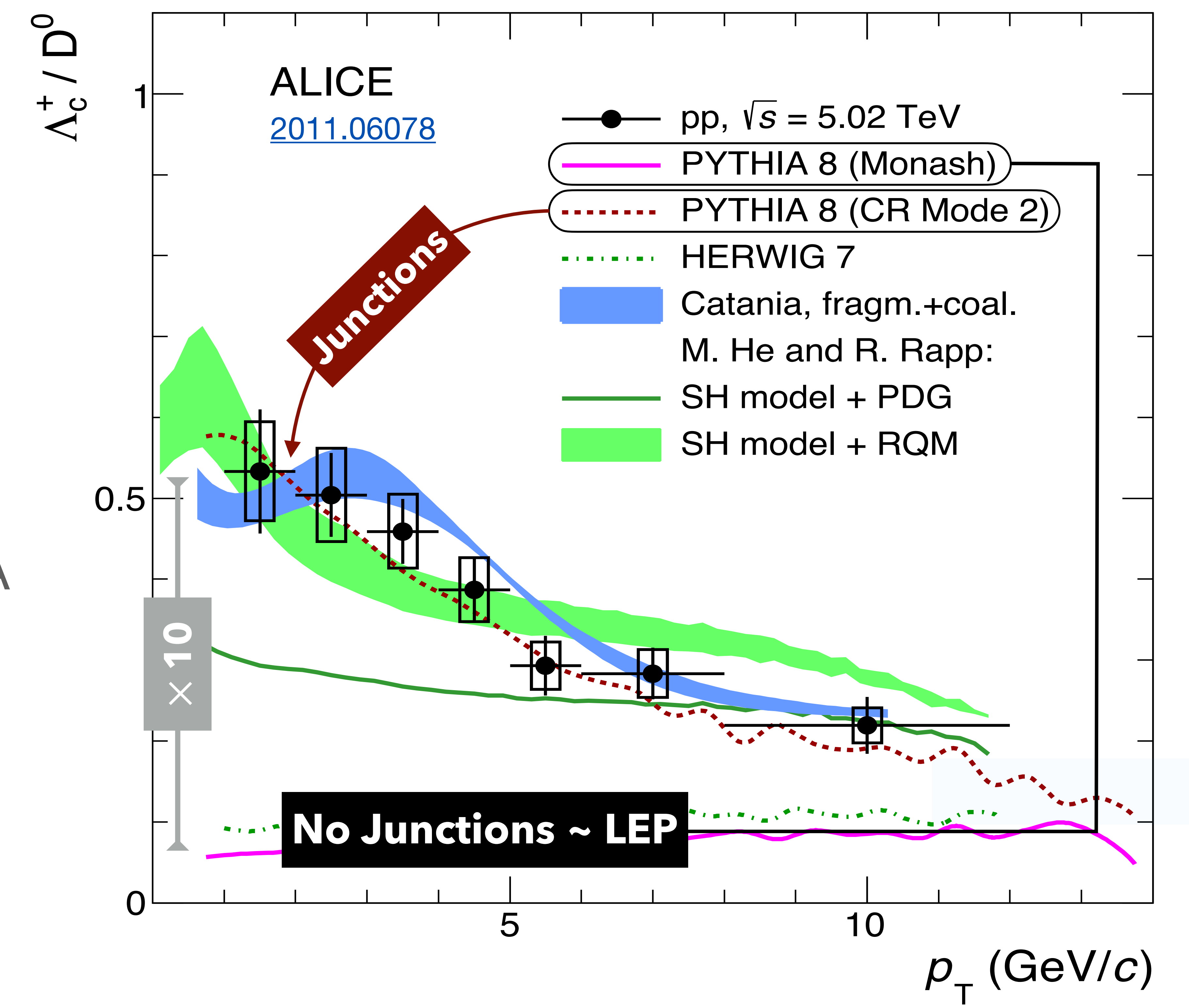
➢ ~40% of baryons are from junctions in PYTHIA

Heavy flavour baryons

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



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



Next Steps: put it all together *(+ "Altmann mechanism" for diquark disruption in octet fields)*

See how close we can get to describing light, strange, and heavy-flavour mesons + baryons in *pp*

+ Lund group developing extensions/applications to heavy-ion collisions!

Heavy-Ion Physics

Disclaimer: I am not an expert

Also for HI, there are of course **event generators** ←

- E.g., ANGANTYR, EPOS, HIJING, JEWEL, QGSJET, SIBYLL, …

> Lots of recent activity **!**
> Also in PYTHIA
> Led by **Jyväskylä** & **Lund**

Another big class of models: **statistical hadronization**

Differ in **how much detail** you aim for, how multi-differential and/or event-by-event you want to be able to go …

- You may **want** to focus on macroscopic properties, not the microphysics
- Or you may **want** to pursue a microscopic description, without all macroscopic aspects

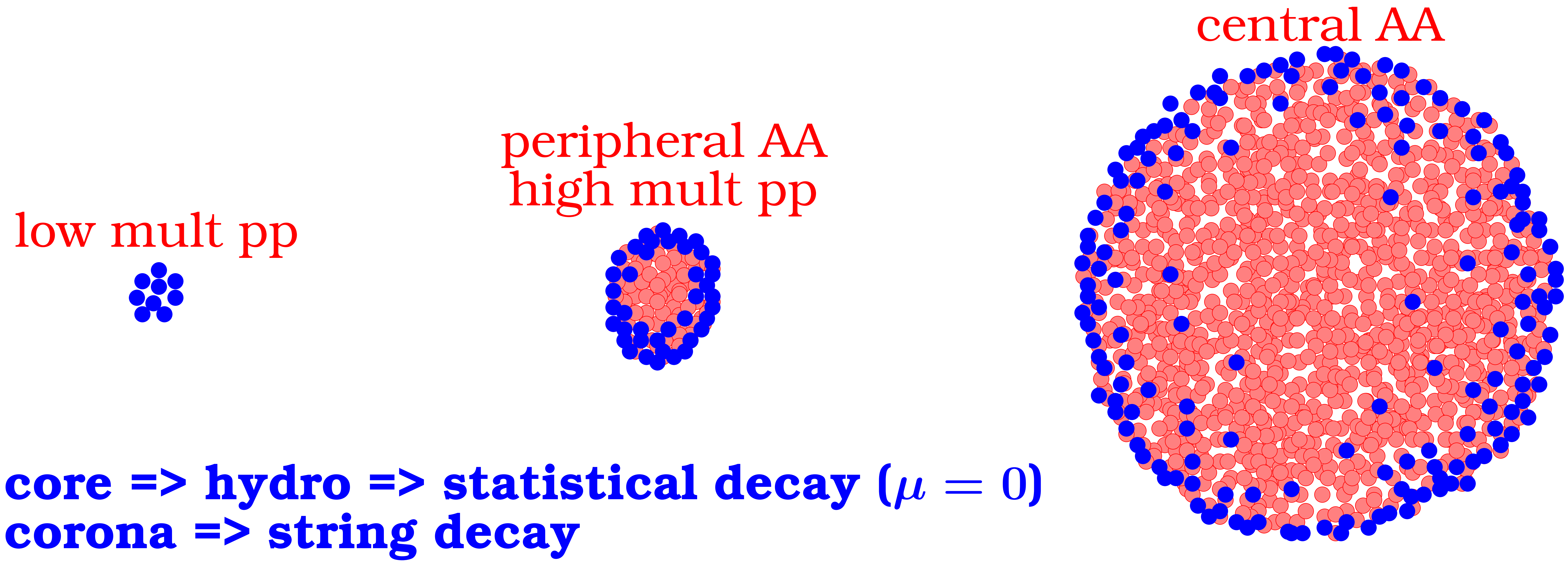
Most of us specialise, but I don't think the point is to pick a winner

- As a physicist, I'd like to understand ***both:*** what are the **macroscopic** properties? what is the **microphysics**? **How** do the former **emerge** from the latter?
- Which paradigms are compatible / incompatible? How to form **clear** conclusions from **data?**

Beyond Strings — QGP?

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

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



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

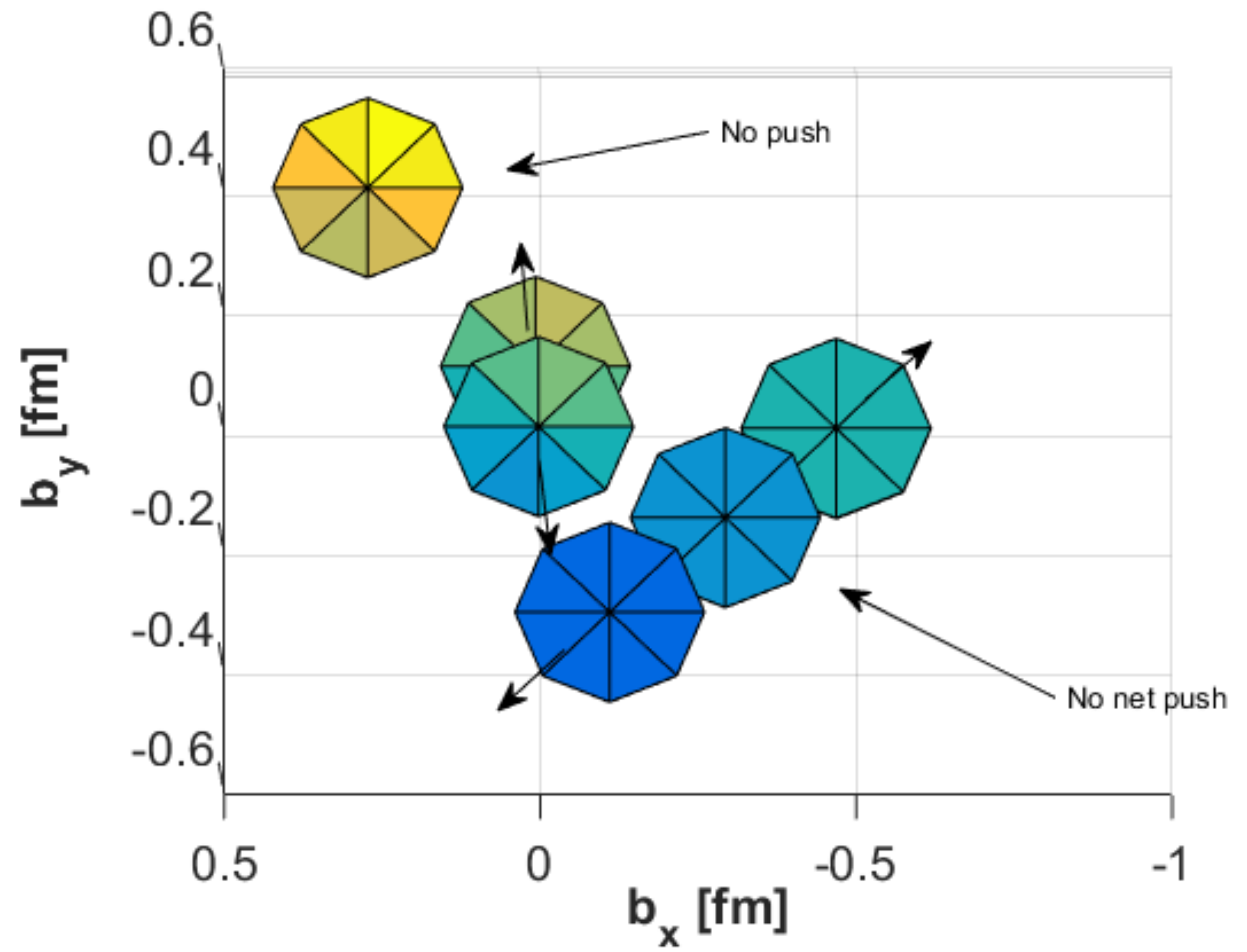
$$\Longrightarrow \text{force} \quad f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

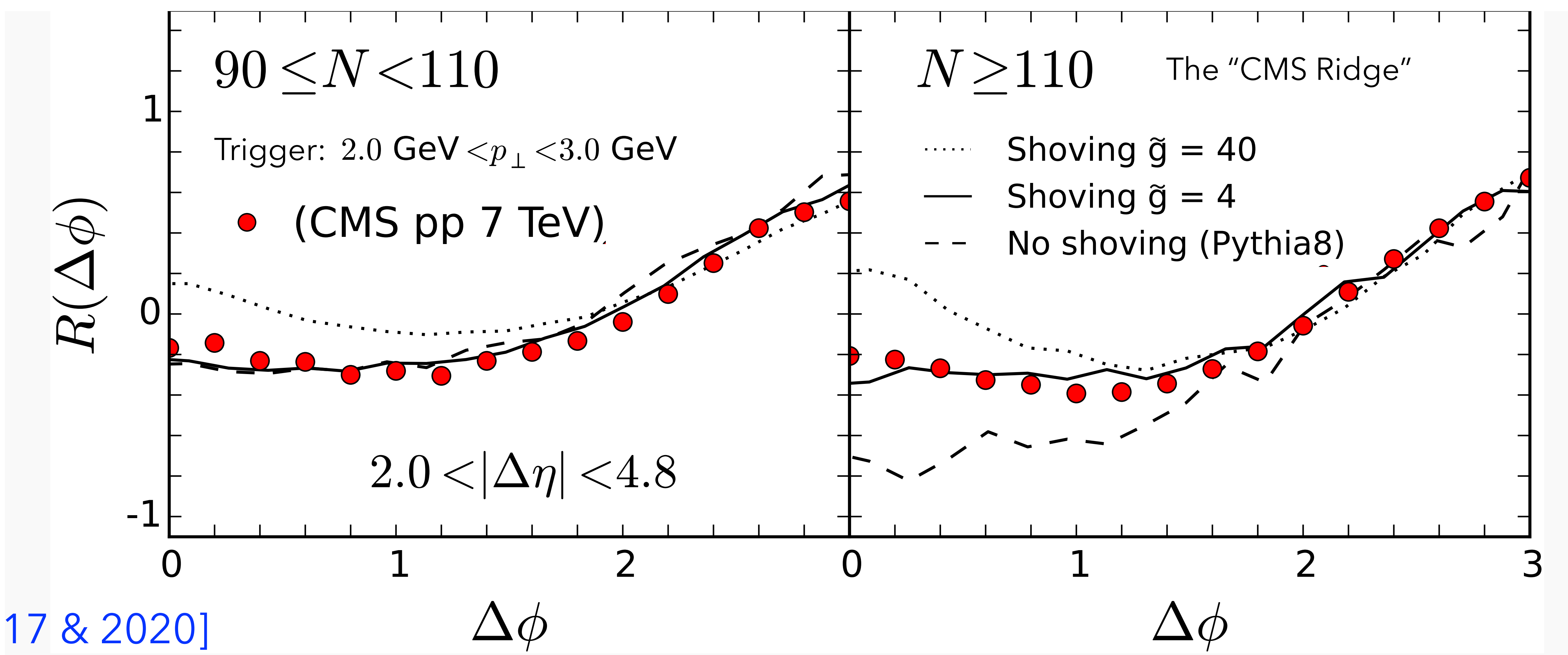
g: fraction of energy in chromo-electric field (as opposed to in condensate or magnetic flux)

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

R: string radius

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





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

CMS 1009.4122. Also: ATLAS 1906.08290, ALICE 2101.03110

Pythia for Cosmic Rays ↔ Corsika 8

Based on 2 articles by **Marius Utheim** & TS:
"A Framework for Hadronic Rescattering in pp Collisions",
Eur. Phys. J. C80 (2020) 907, arXiv:2005.05658
"Hadron Interactions for Arbitrary Energies and Species,
with Applications to Cosmic Rays",
Eur. Phys. J. C82 (2022) 21, arXiv:2108.03481

- Models arbitrary hadron–hadron collisions at low energies.
- Models arbitrary hadron-p/n collisions at any energy.
- Initialization slow, $\sim$ 15 minutes,
  ⋆ but thereafter works for any hadron–p/n at any energy, and
  ⋆ initialization data can be saved, so only need to do once.
- The ANGANTYR nuclear geometry part used to extend to hadron-nucleus at any energy.
- Native C++ simplifies interfacing PYTHIA 8 ↔ CORSIKA 8.
- So far limited comparisons with data.

+ Extension with ANGANTYR (→incoming nuclei) ➢ **PYTHIA 8.313**

Extra Slides

(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

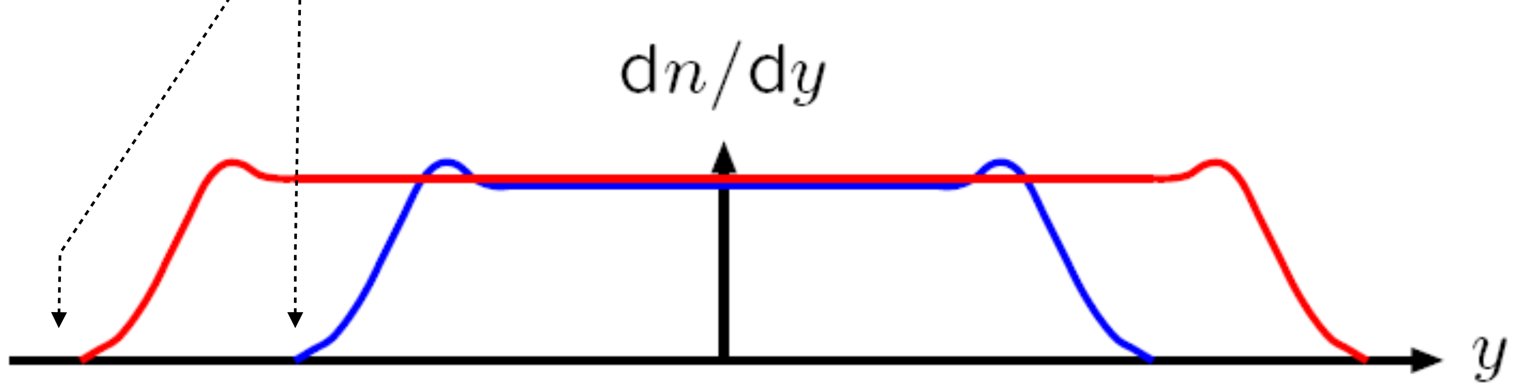
→ Rapidity (along string axis) and $p_\perp$ transverse to it

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

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"

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

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!

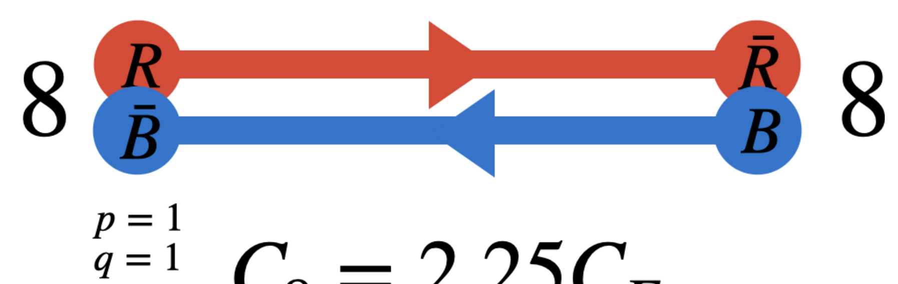
Motivates Careful Models & Careful Constraints

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

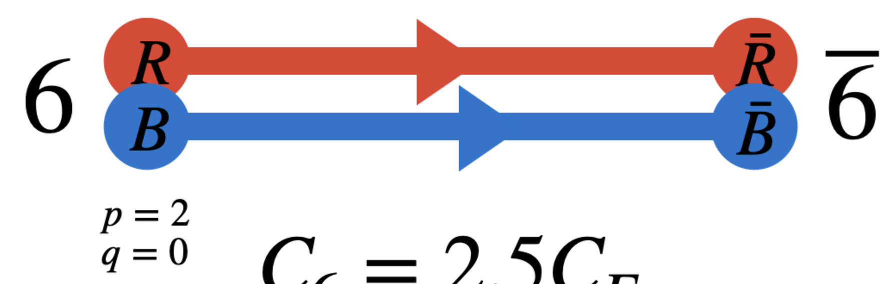
Work in Progress: **Strangeness Enhancement from Close-Packing**

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

Close-packing



$C_8 = 2.25 C_F$

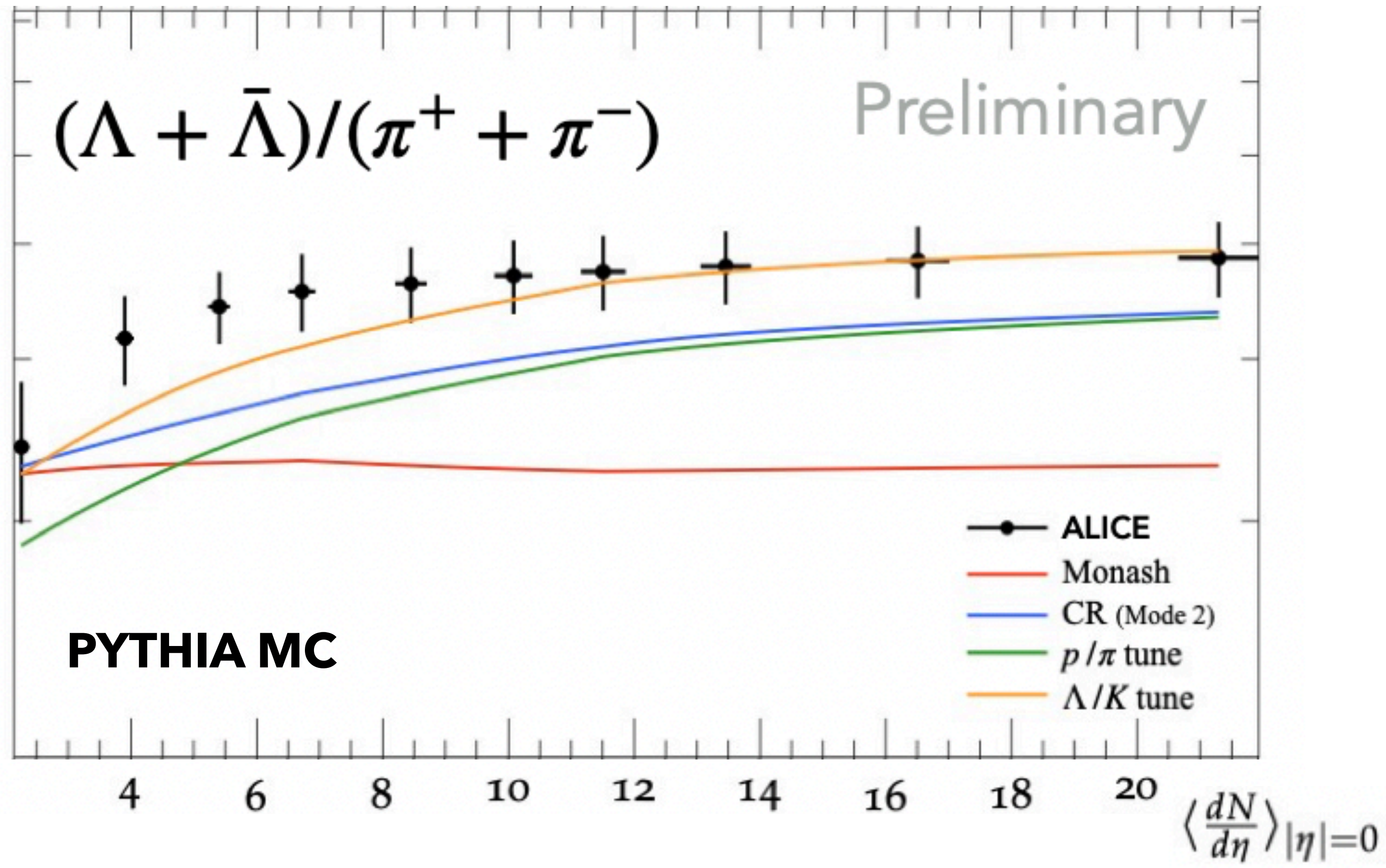


$C_6 = 2.5 C_F$

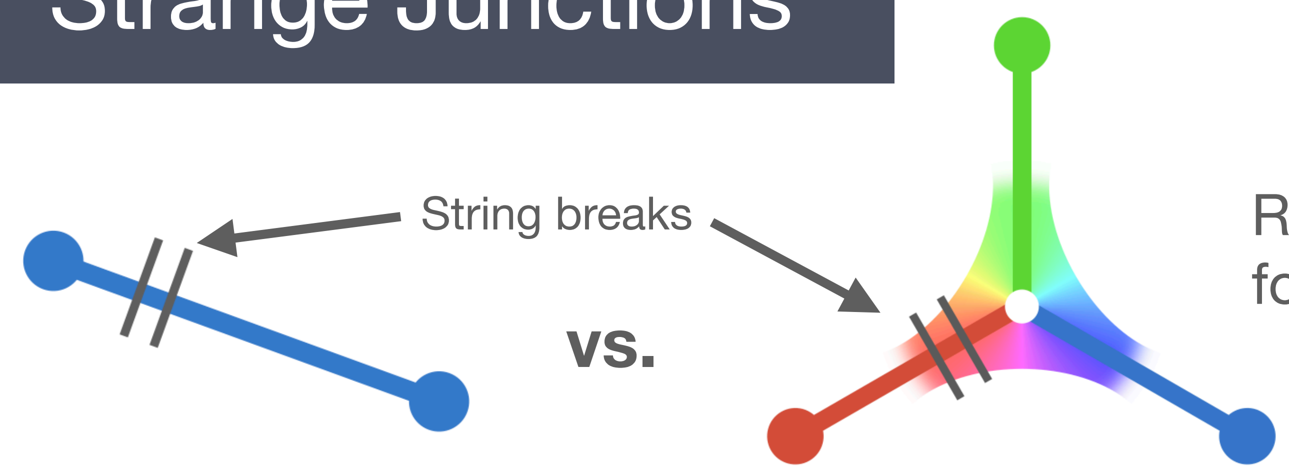
Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks



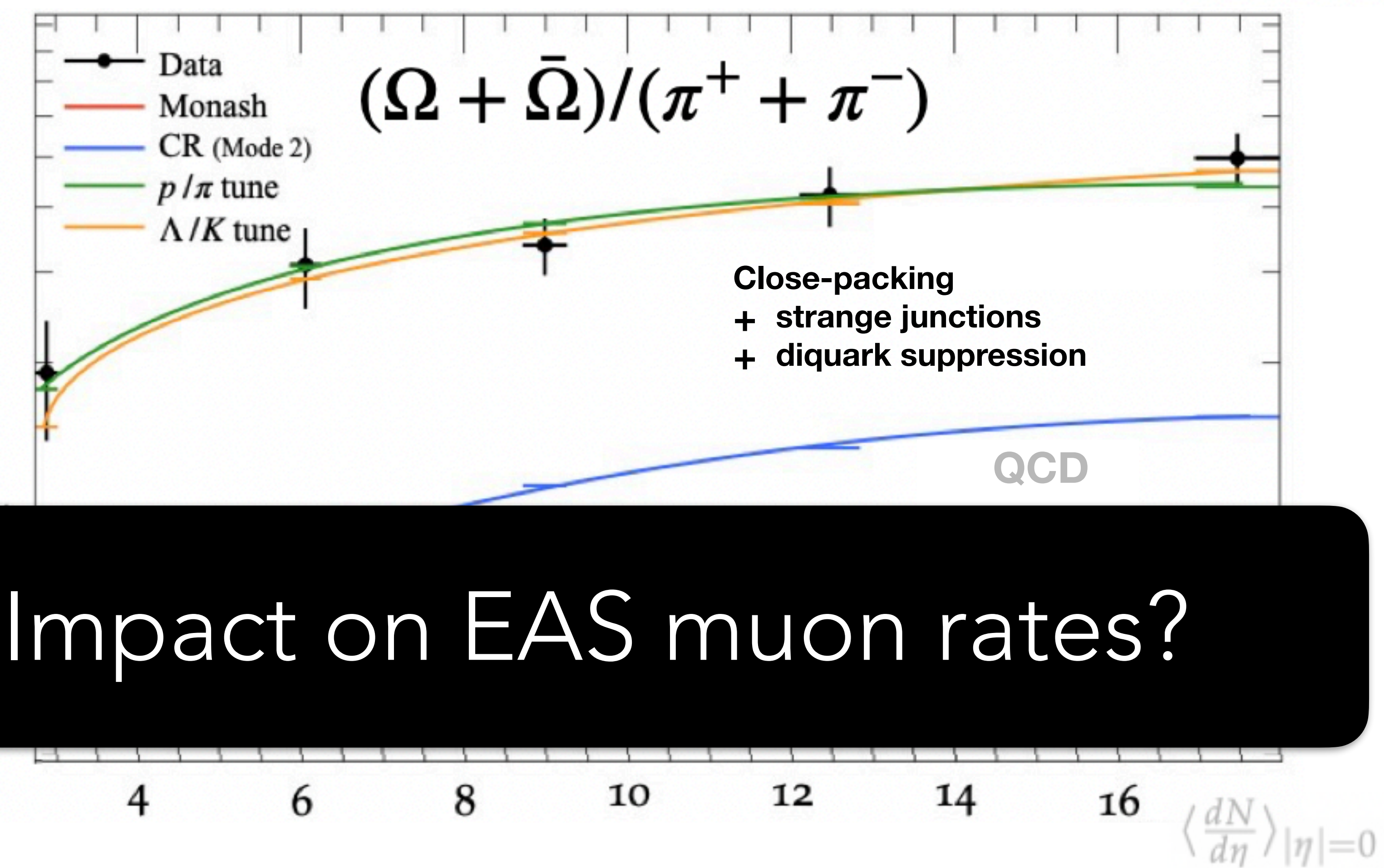
Strange Junctions



Results in strangeness enhancement focused in baryon sector

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

Altmann, Bernardinis, Jueid, PS, Zaccolo (in progress)



↔ Impact on EAS muon rates?

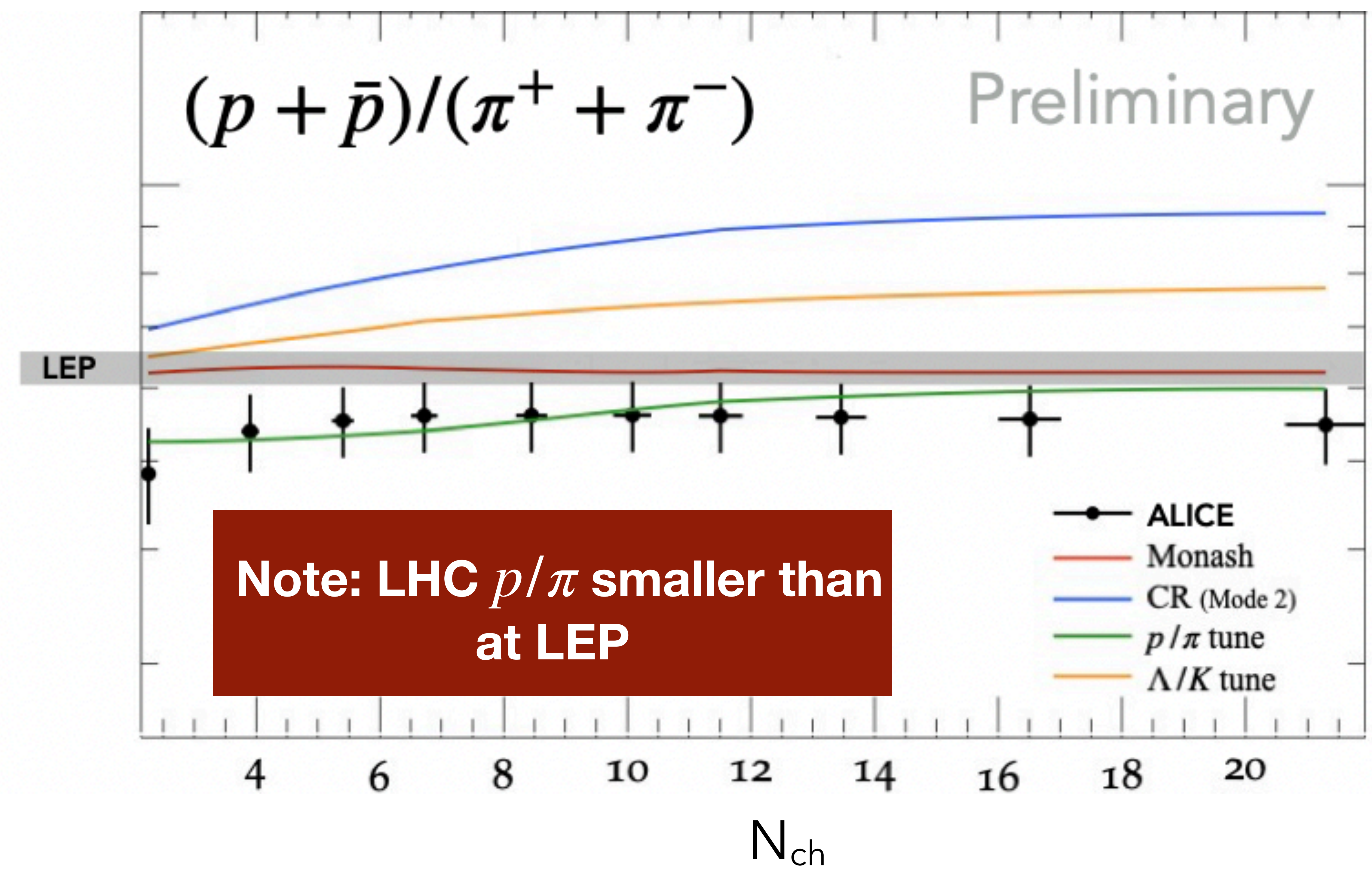
Thorny Issue ⚠️ The **Proton-to-Pion** Ratio

Note:

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

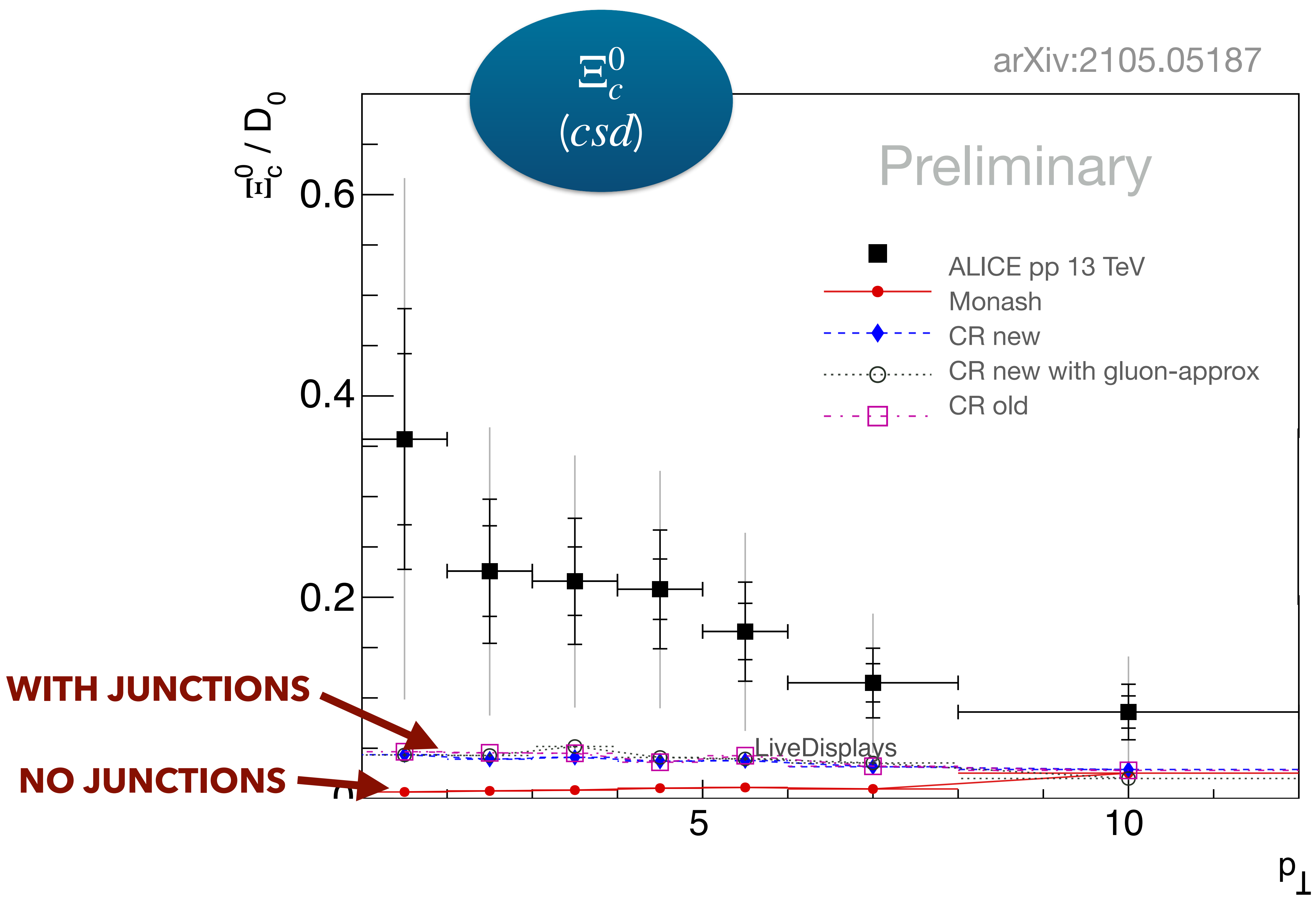
I think this is now the **main challenge** for strangeness-enhancement models

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

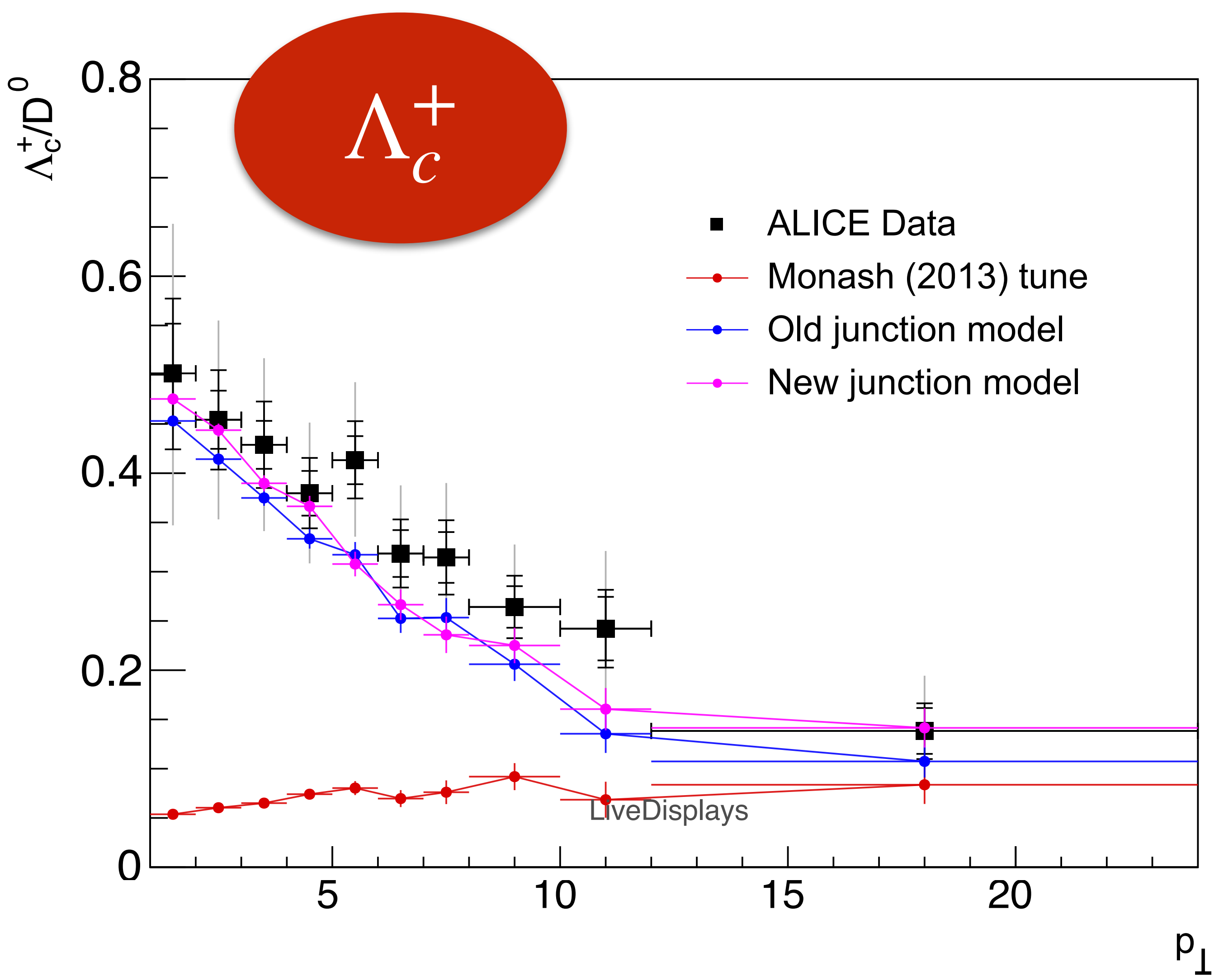


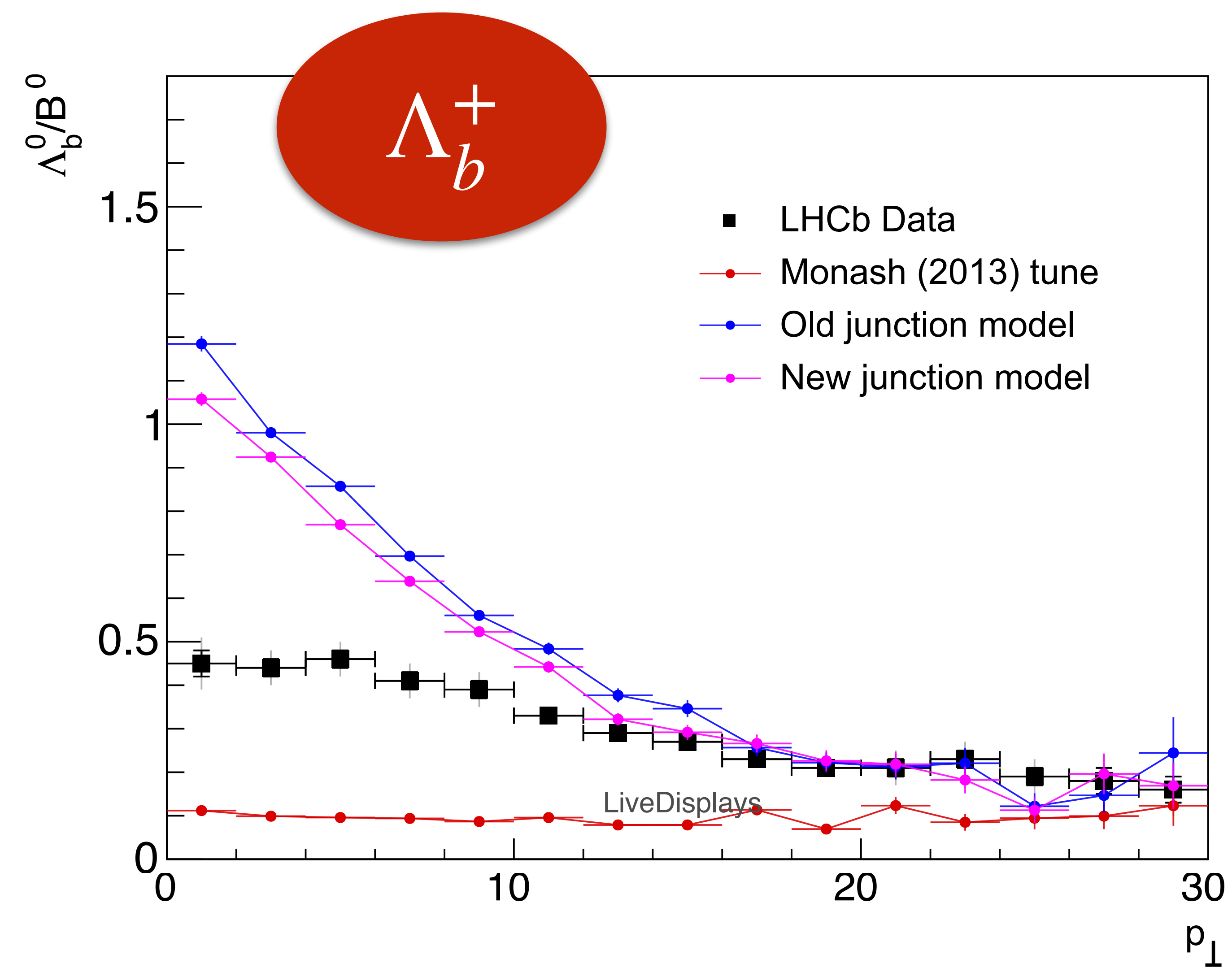
Confront with Measurements: **Strangeness**

What about Strange heavy-flavour baryons ?



LambdaB





***String Formation Beyond Leading Colour,* Christiansen & PZS, 1505.01681**

New: *String Junctions Revisited,* Altmann & PZS, 2404.12040

Also: baryon asymmetry diluted by extra baryon pairs