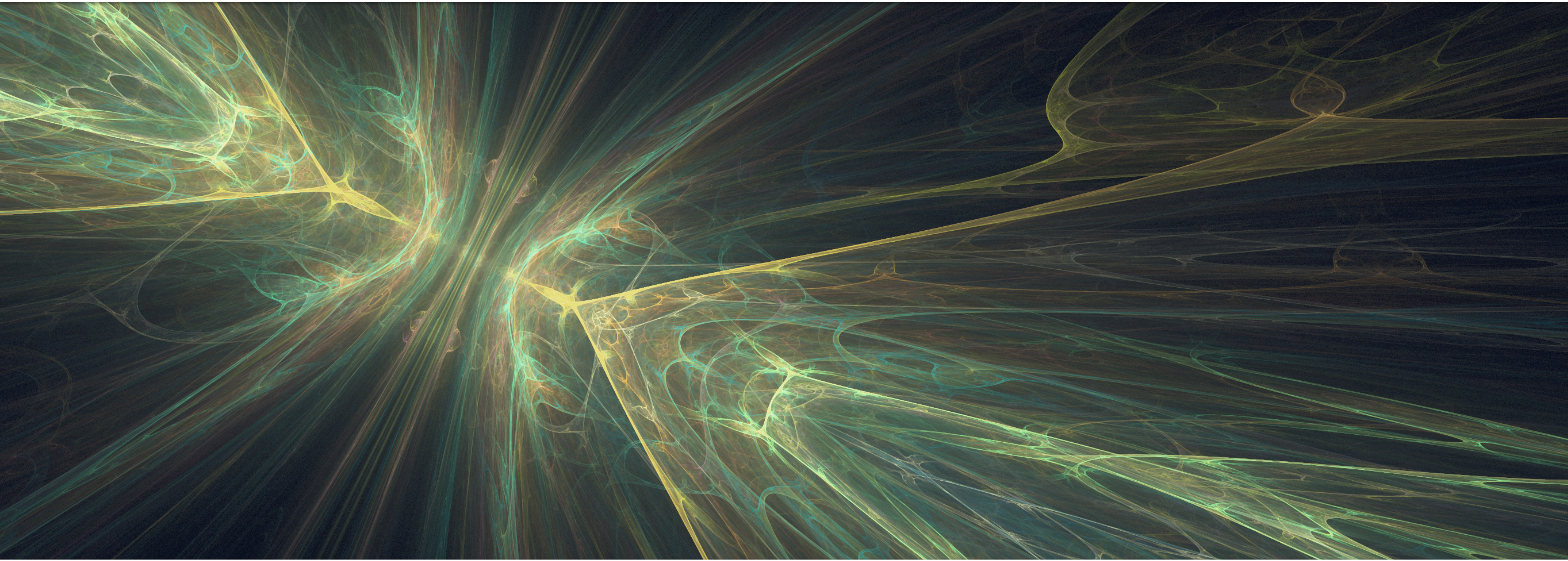
Soft QCD Review *— with some emphasis on string models, LHC, and PYTHIA*

Peter Skands — Monash University & University of Oxford



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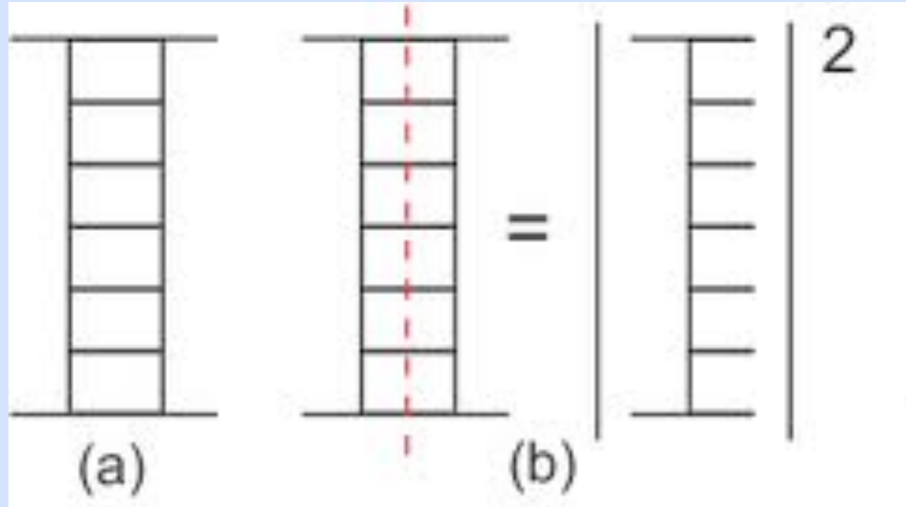
Soft QCD — Theory Models

A

Regge Theory



Optical Theorem
+ Eikonal multi-Pomeron exchanges

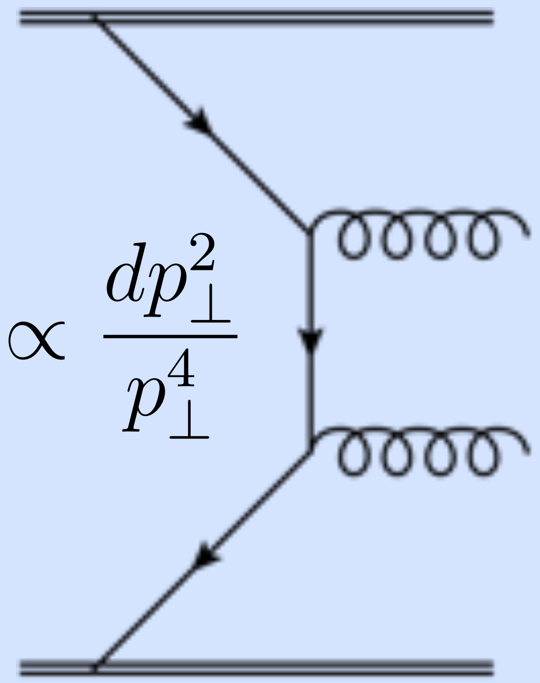
$\sigma_{\mathrm{tot,inel}} \propto s^{\varepsilon}$ or $\log^2(s)$

Cut Pomerons → Flux Tubes (strings)
Uncut Pomerons → Elastic (& eikonalization)
Cuts unify treatment of all soft processes
EL, SD, DD, … , ND

Perturbative contributions added above Q_0

B

pQCD-Based



$$d\sigma_{2\to2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \mathrm{PDFs}$$

+ Unitarity & IR Regularisation

→ Multi-parton interactions (MPI)
+ Parton Showers & Hadronization
Regulate $d\sigma$ at low p_{T0} ~ few GeV
Screening/Saturation → $\sqrt{s}$-dependent p_{T0}

Total cross sections from Regge Theory
(Donnachie-Landshoff + Parametrizations)

QGSJET

+ "Mixed"
EPOS, PHOJET

HERWIG, PYTHIA, SHERPA, SIBYLL

The Structure of an LHC pp Collision

Hard Process
- ○ Hard Interaction
- ● Resonance Decays
- 🟪 MECs, Matching & Merging

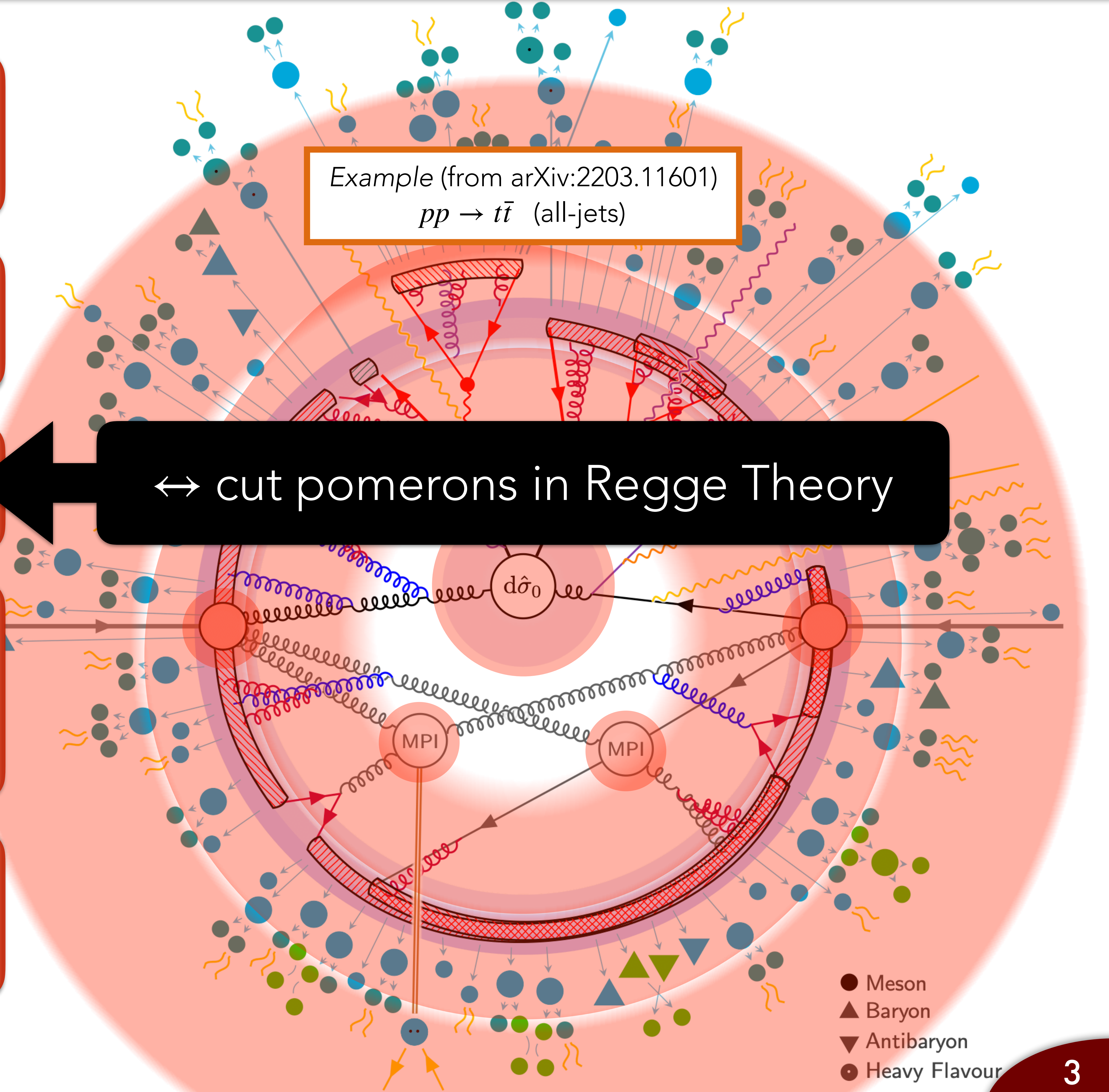
Parton Showers
- 🟥 QCD Final-State Radiation
- 🟦 QCD Initial-State Radiation*
- 🟨 Electroweak Radiation

2 **Underlying Event**
- ○ Multiparton Interactions
- ☐ Beam Remnants*

1 **Hadronization**
- ▨ Strings
- ☐ Colour Reconnections
- ☐ String Interactions
- ☐ Bose-Einstein & Fermi-Dirac

Hadron (& τ) Decays
- 🟦 Primary Hadrons
- 🟩 Secondary Hadrons
- 🟩 Hadronic Reinteractions

(: incoming lines are crossed)*



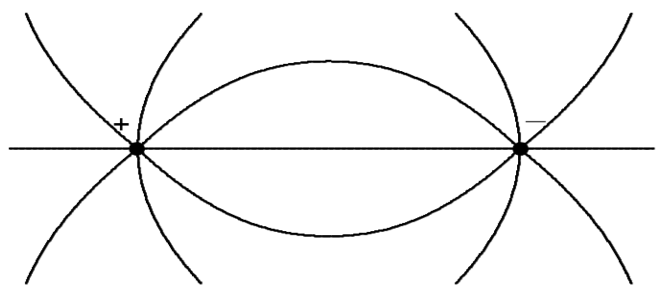
Example (from arXiv:2203.11601)
$pp \to t\bar{t}$ (all-jets)

↔ cut pomerons in Regge Theory

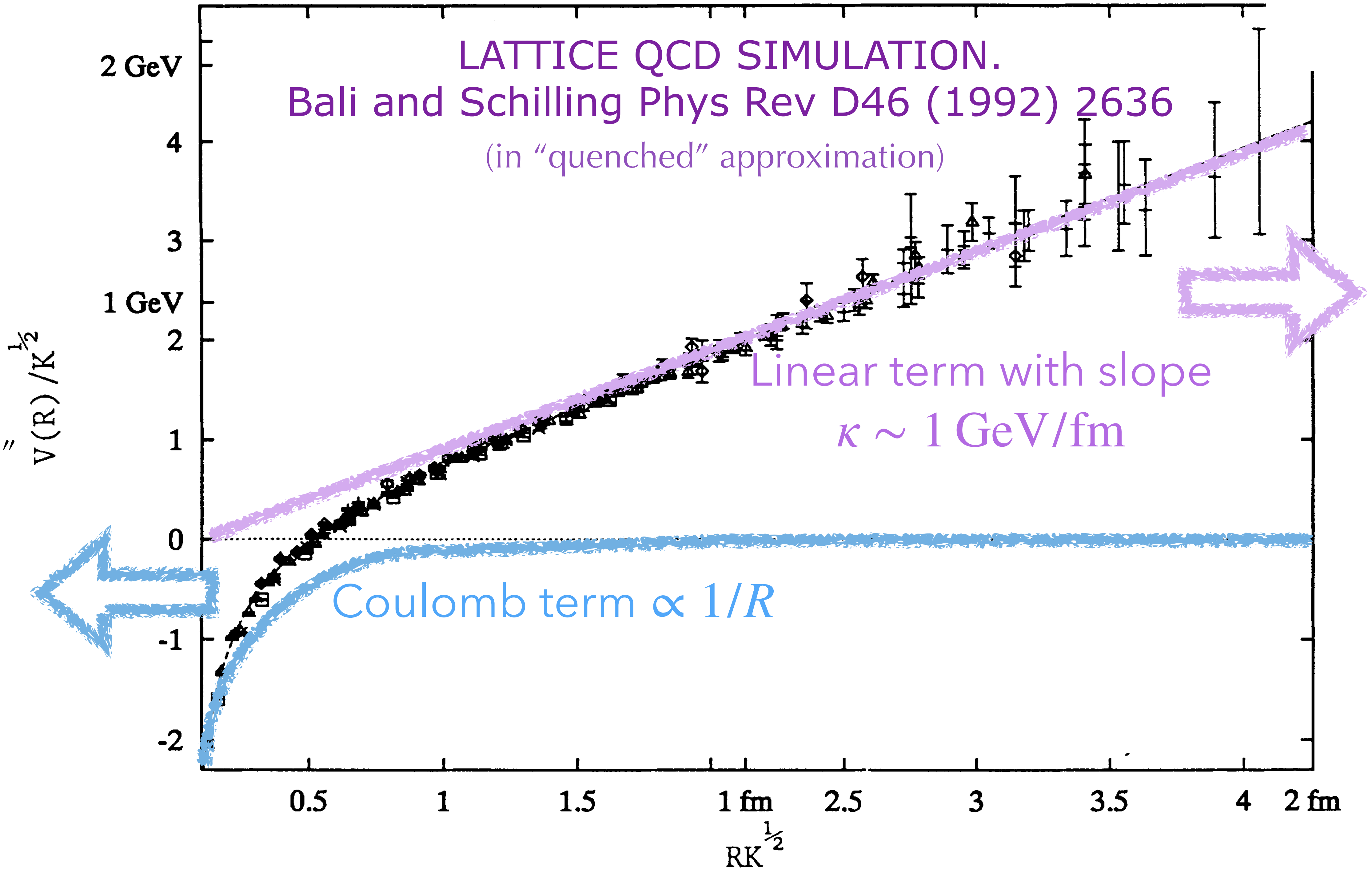
Linear Confinement

On lattice, compute potential energy 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

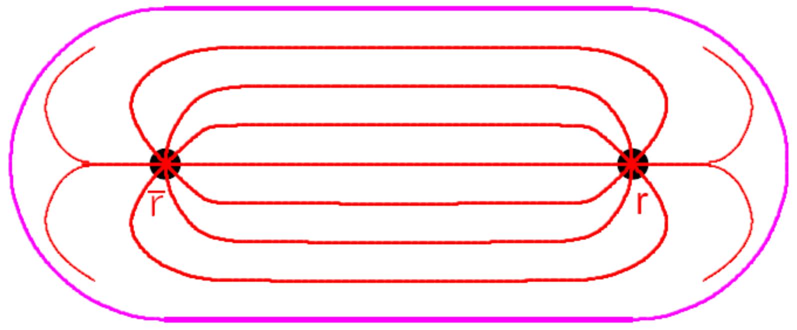


LATTICE QCD SIMULATION.
Bali and Schilling Phys Rev D46 (1992) 2636
(in "quenched" approximation)

Linear term with slope
$\kappa \sim 1\,\mathrm{GeV/fm}$

Coulomb term $\propto 1/R$

Long Distances ~ Linear Potential



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

Linear Term ➡ Model as strings (Lund Model)

String Fragmentation in One Slide

The string model provides a mapping:

Quarks ➤ String endpoints

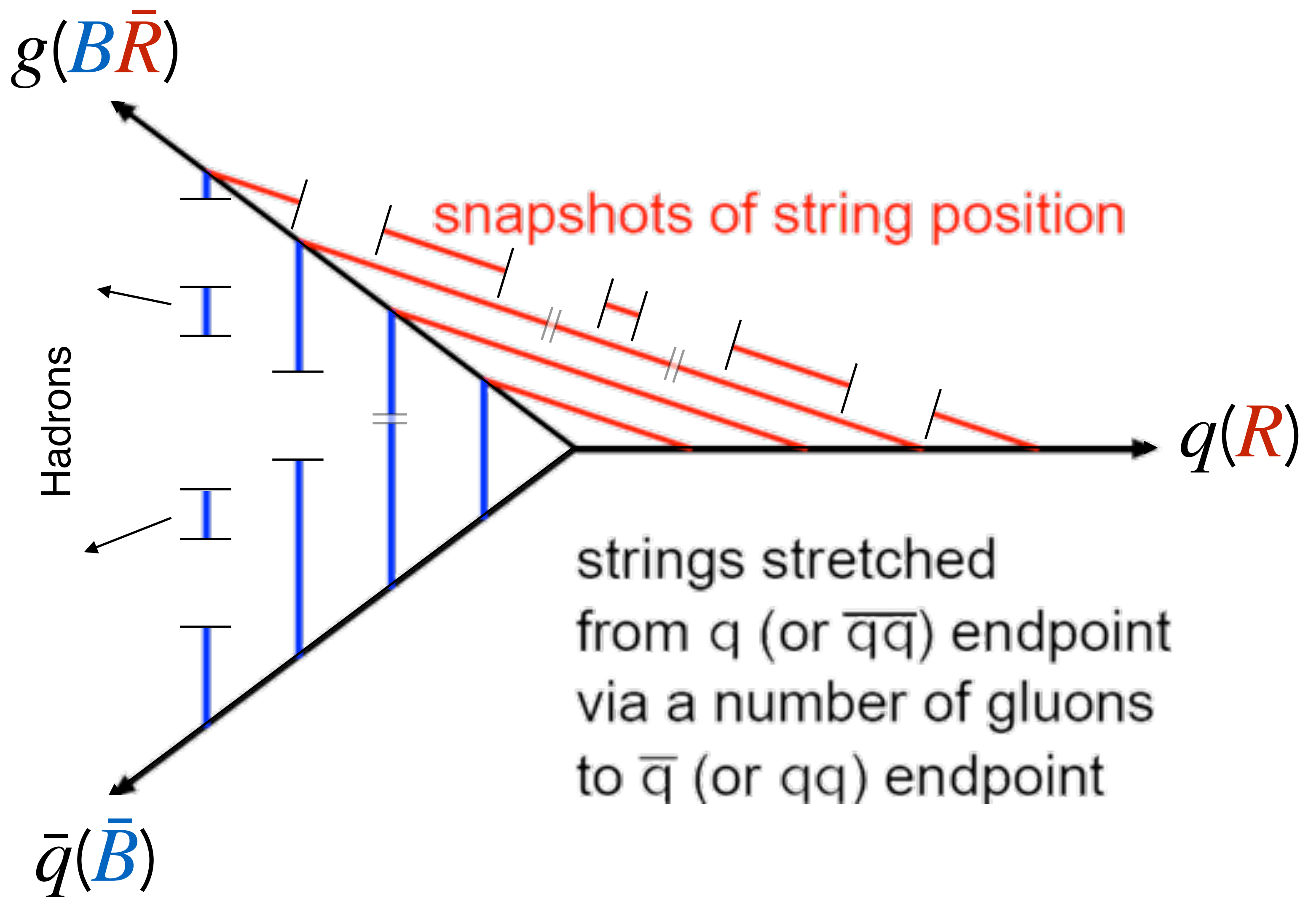
Gluons ➤ Kinks on strings

Further evolution then governed by string world sheet (area law)

+ string breaks by tunnelling

By analogy with "Schwinger mechanism" in QED (electron-positron pair production in strong electric field)

➤ (Jets of) Hadrons!



strings stretched from q (or $\overline{qq}$) endpoint via a number of gluons to $\bar{q}$ (or qq) endpoint

String breaks by quark pair production

$\Longrightarrow$ **strangeness suppression**

$$\propto \frac{\exp\left(\frac{-\pi m_s^2}{\kappa}\right)}{\exp\left(\frac{-\pi m_{u,d}^2}{\kappa}\right)}$$

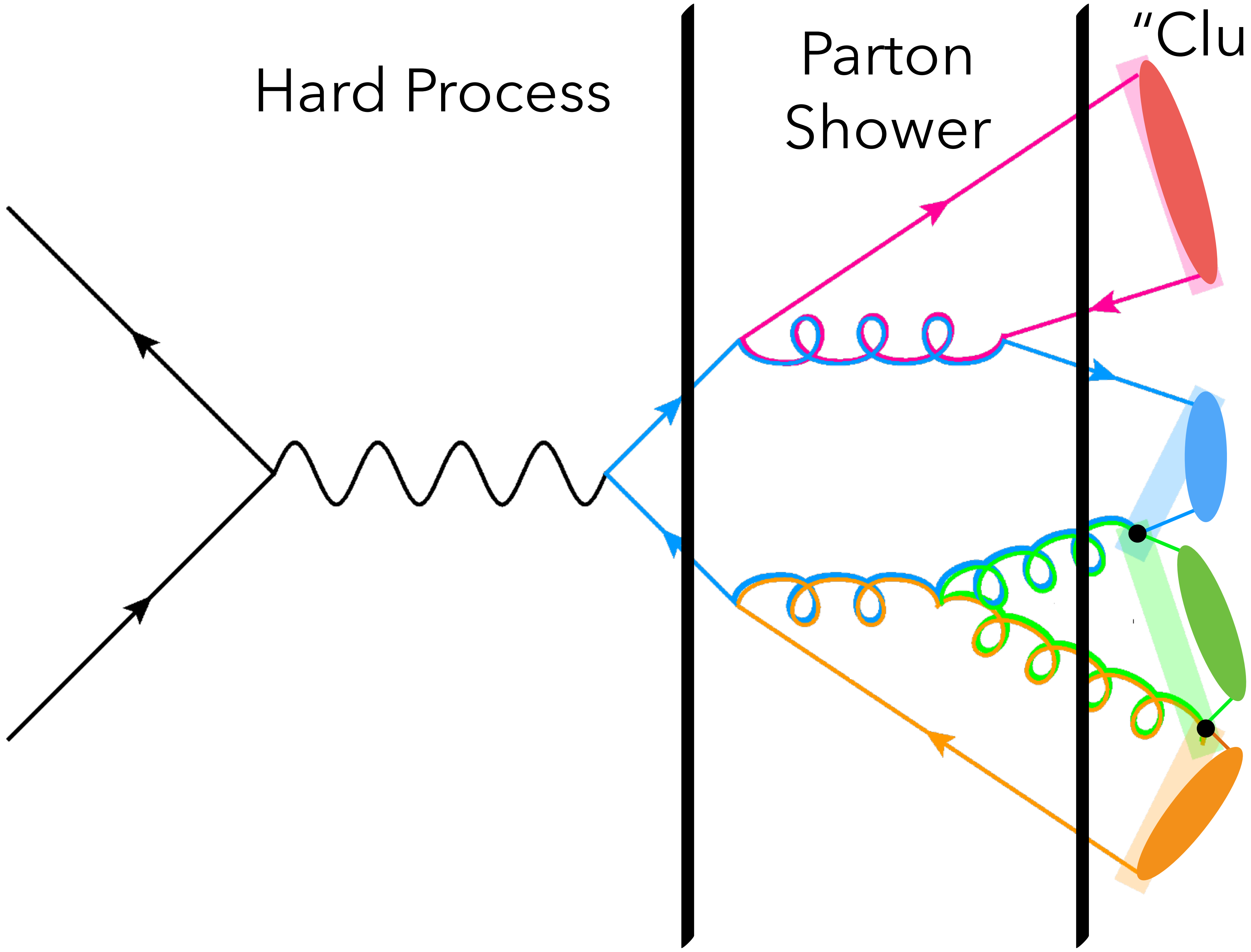
Alternative: **The Cluster Model** — Used in HERWIG & SHERPA

In “unquenched” QCD

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

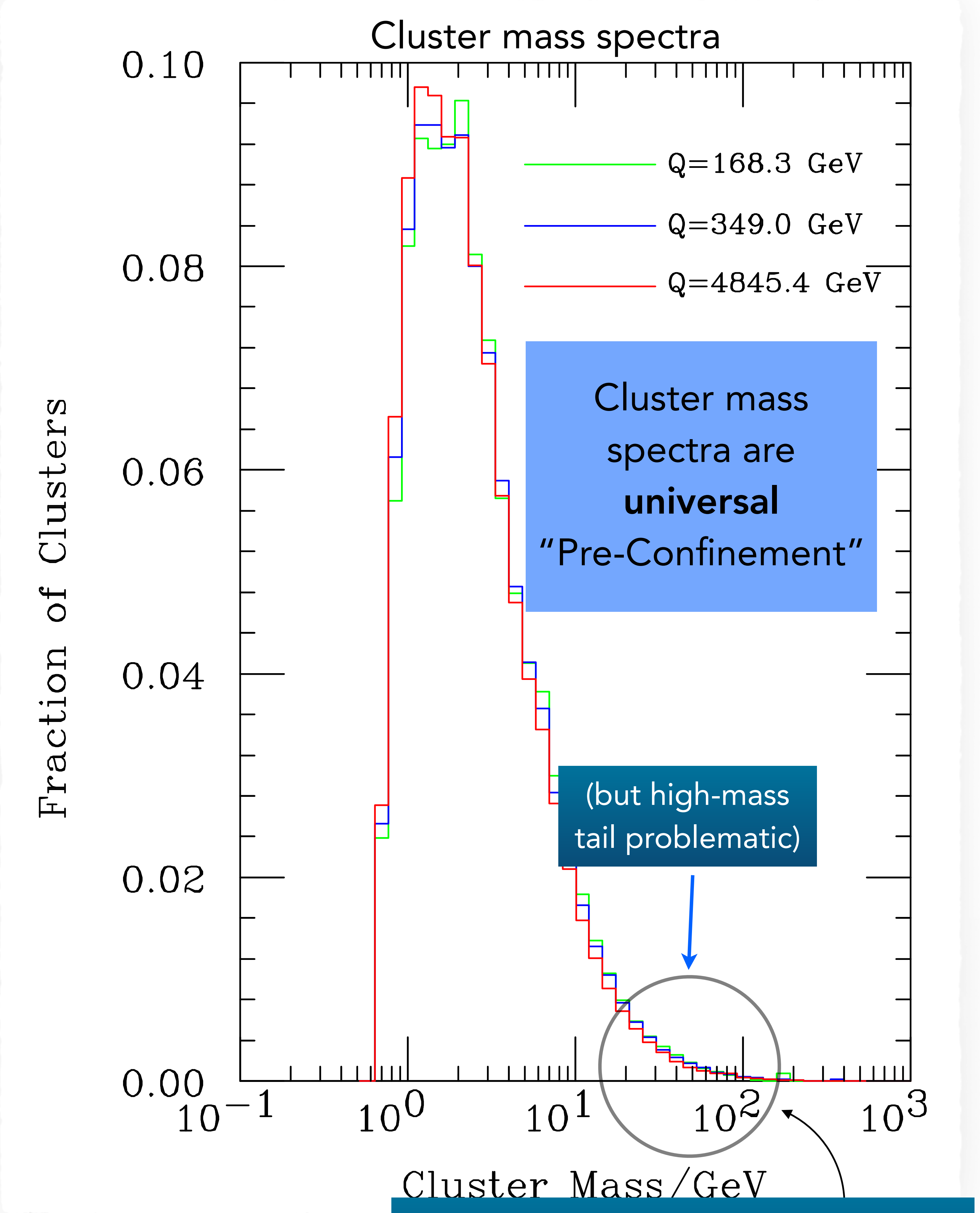
Non-perturbative so can’t use $P_{g\to q\bar{q}}(z)$

Alternative: force $g \to q\bar{q}$ at end of shower



Isotropic 2-body decays to hadrons

According to phase space



Cluster mass spectra are **universal** “Pre-Confinement”

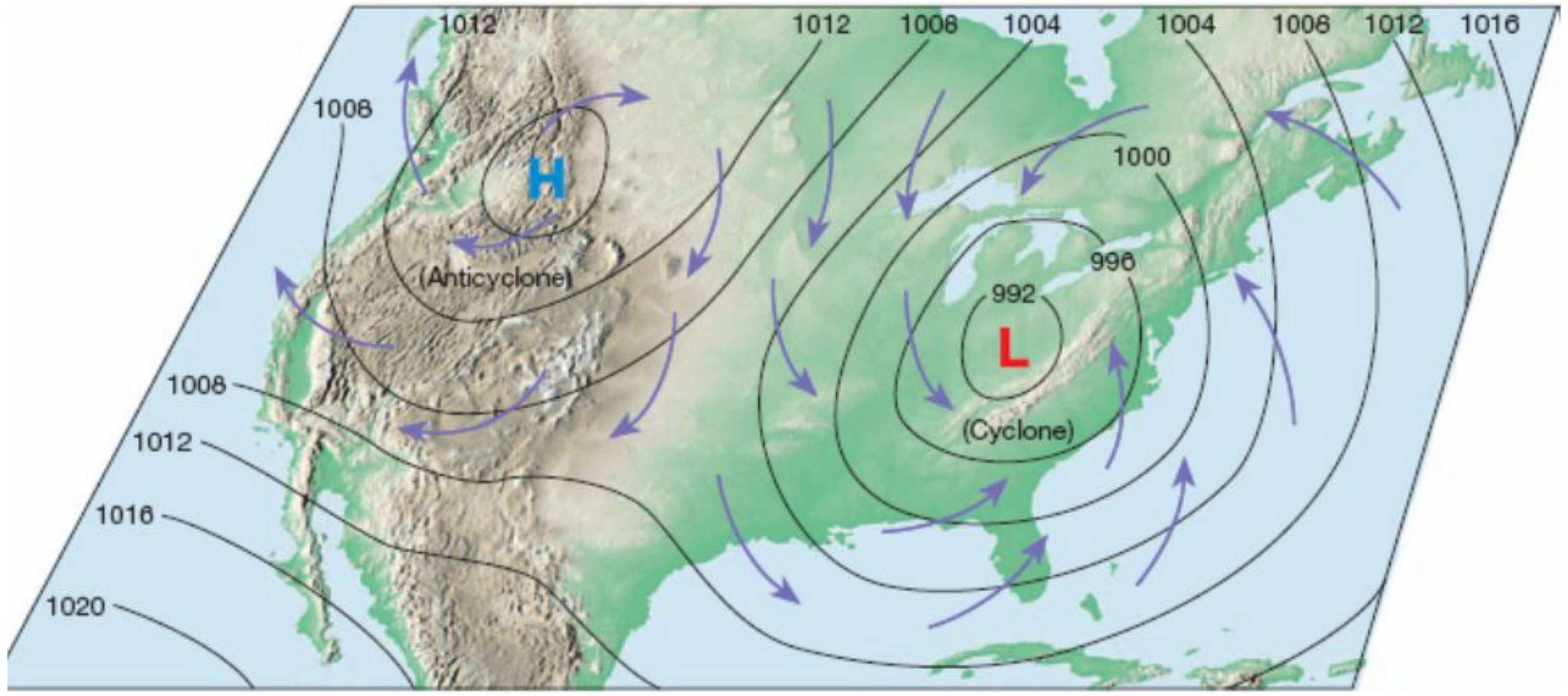
(but high-mass tail problematic)

Solution: Force String-Like Splittings of Large Clusters

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 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)

The Environment — in Hadronic Collisions

In hadronic collisions, we are not hadronizing a simple $q - g - \ldots - g - \bar{q}$ string

Coloured initial states + gluon exchanges

$\Longrightarrow$ more complicated colour flows

Also: Protons are composite

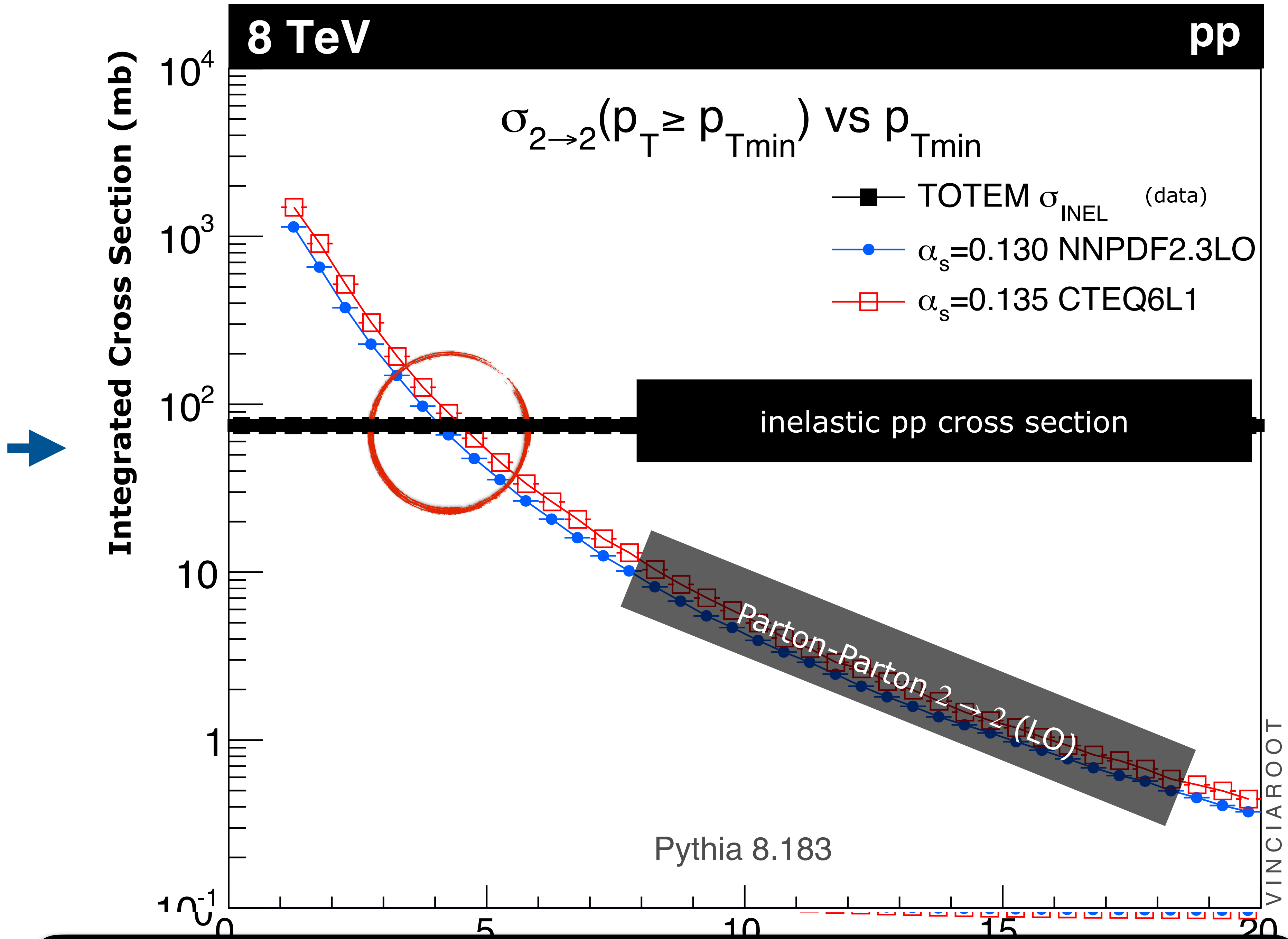
One proton = **beam** of partons

+ QCD 2 → 2 scattering diverges at low p$_T$

$\Longrightarrow \sigma_{\text{parton-parton}}(\hat{p}_\perp) > \sigma_{\text{proton-proton}}$

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

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



↔ cut pomerons in Regge Theory

Multiple Parton-Parton Interactions (MPI)

➜ **Additional colour exchanges**

MPI & Confinement

MPI / cut pomerons ⇒ lots of coloured partons scattered into final state

With significant overlaps in phase space

Who gets confined with whom?

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

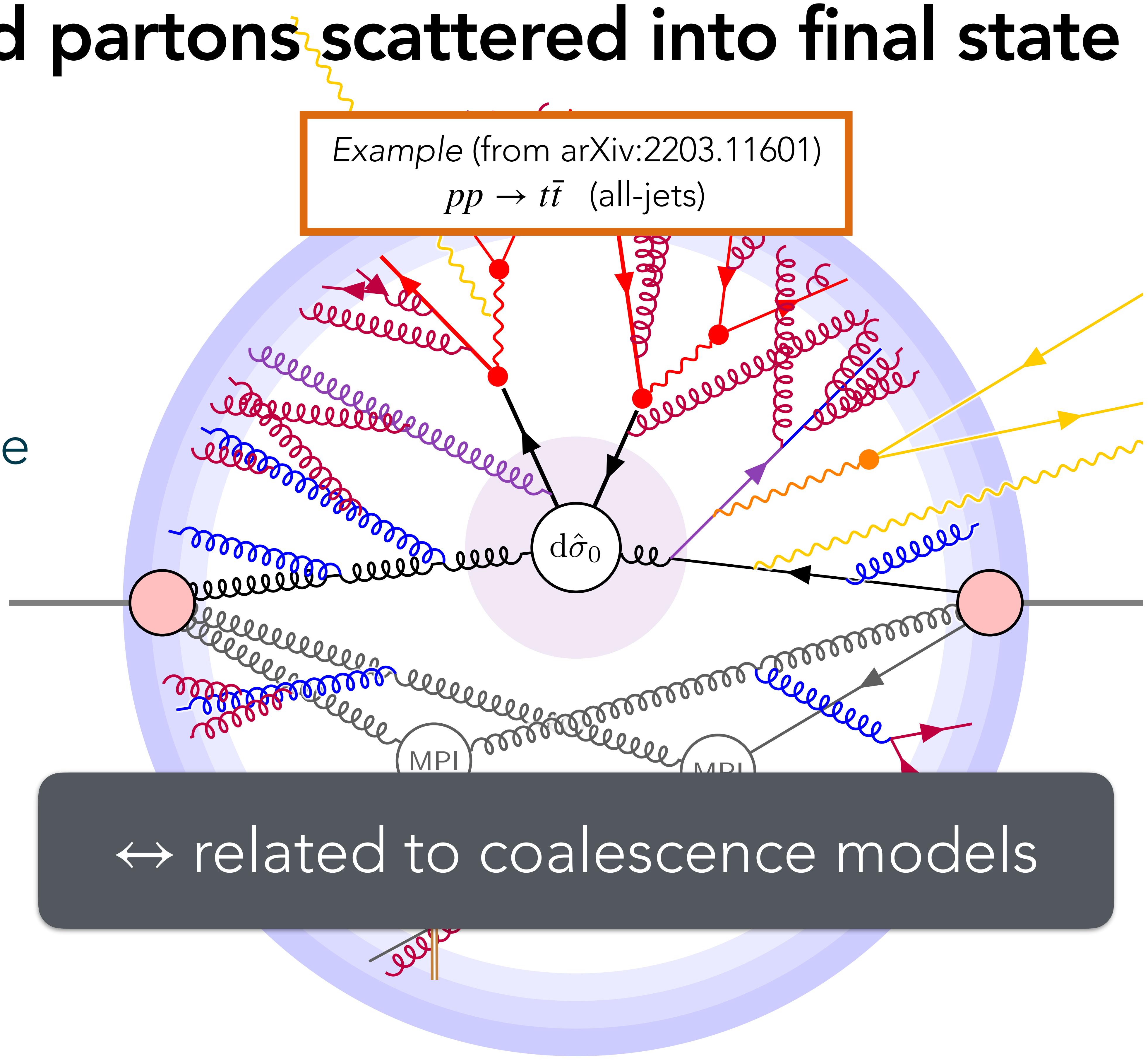
E.g.: **random triplet** charge has 1/9 chance to be in **singlet** state with **random antitriplet**:

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

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

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

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



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

↔ related to coalescence models

"Parton Level"

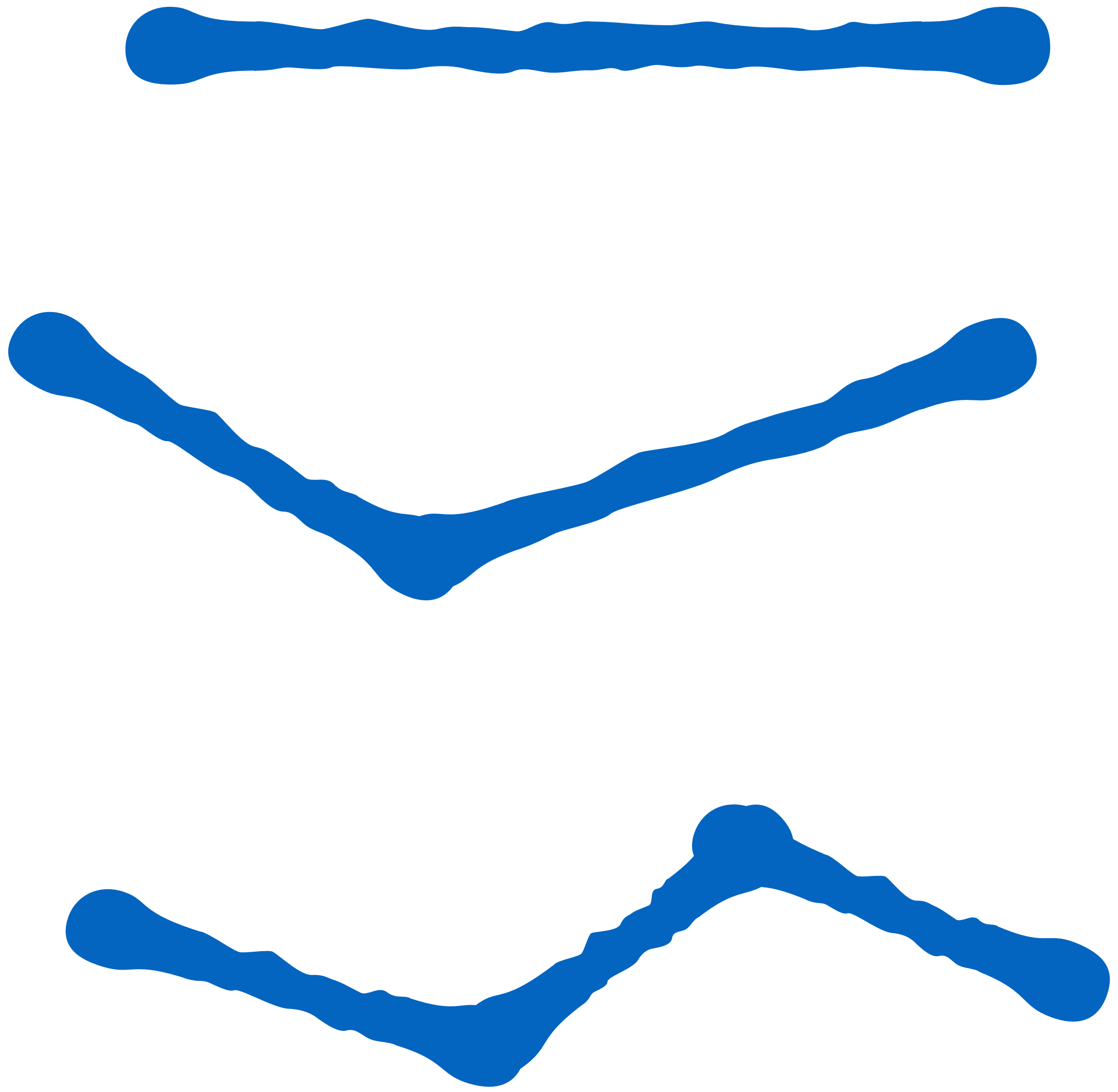
(Event structure before confinement)

**): in this context, QCD CR simply refers to an ambiguity beyond Leading N$_C$, known to exist.
Note the term "CR" can also be used more broadly to incorporate further physics concepts.*

What about Baryon Number?

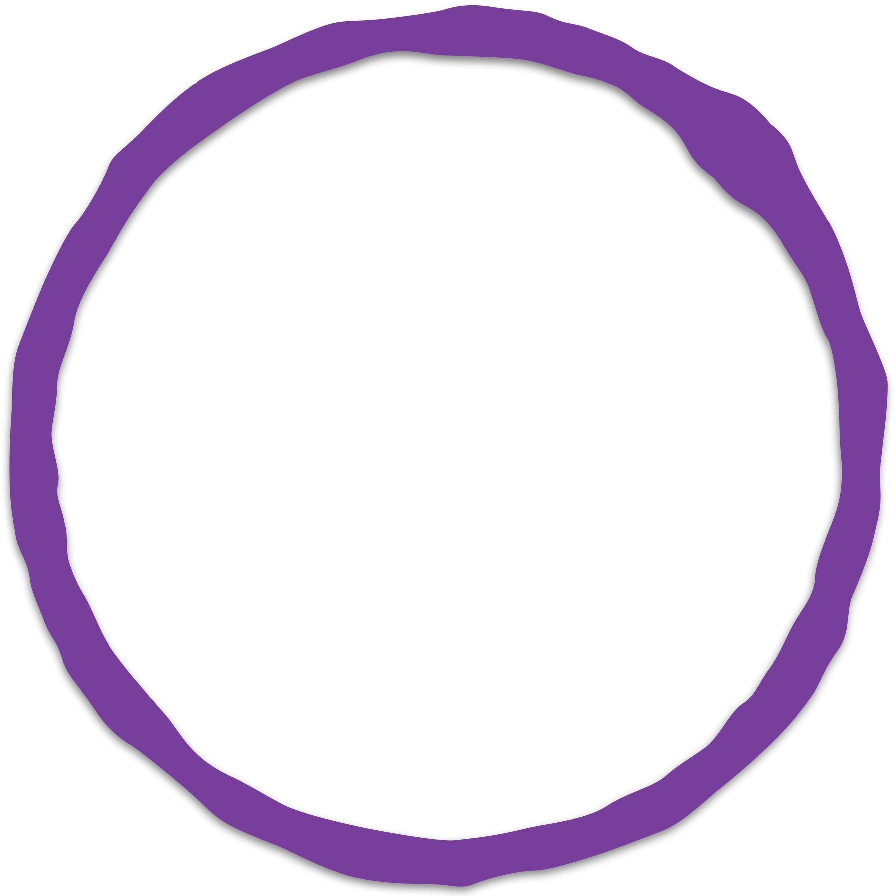
Types of string topologies:

Open Strings



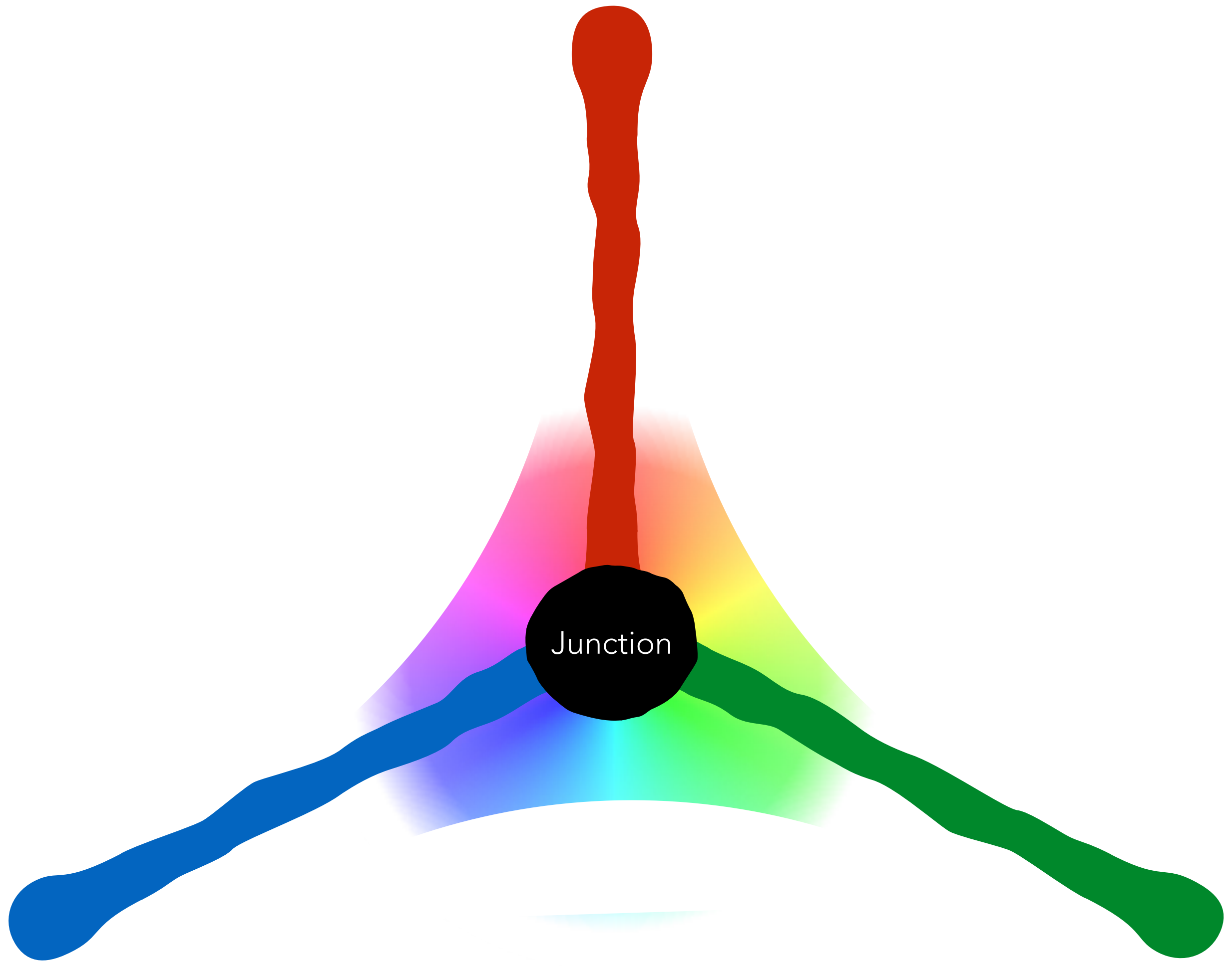
$$(3 \otimes \bar{3})_{\text{singlet}} = \frac{1}{9}$$

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?

String Formation Beyond Leading Colour
Christiansen & PS, 1505.01681

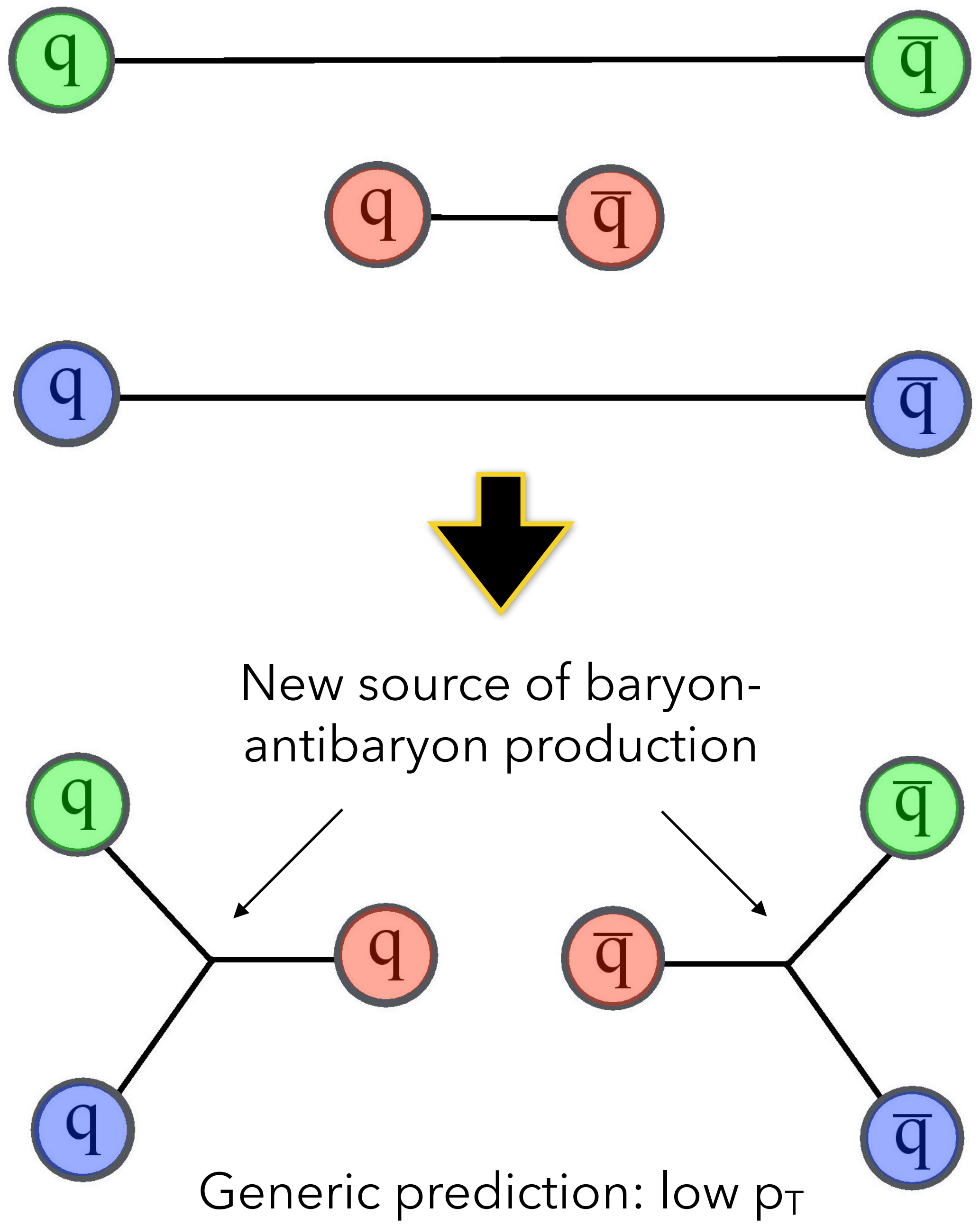
String Junctions at LHC ?

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

Stochastic sampling of SU(3) group probabilities (e.g., $3 \otimes 3 = 6 \oplus \bar{3}$)

⟹ Random **(re)connections in colour space** (weighted by group weights)

"QCD Colour Reconnections"



Example of possible colour configuration

Choose this string configuration instead if "string length" ~ total potential energy is lower

New source of baryon-antibaryon production

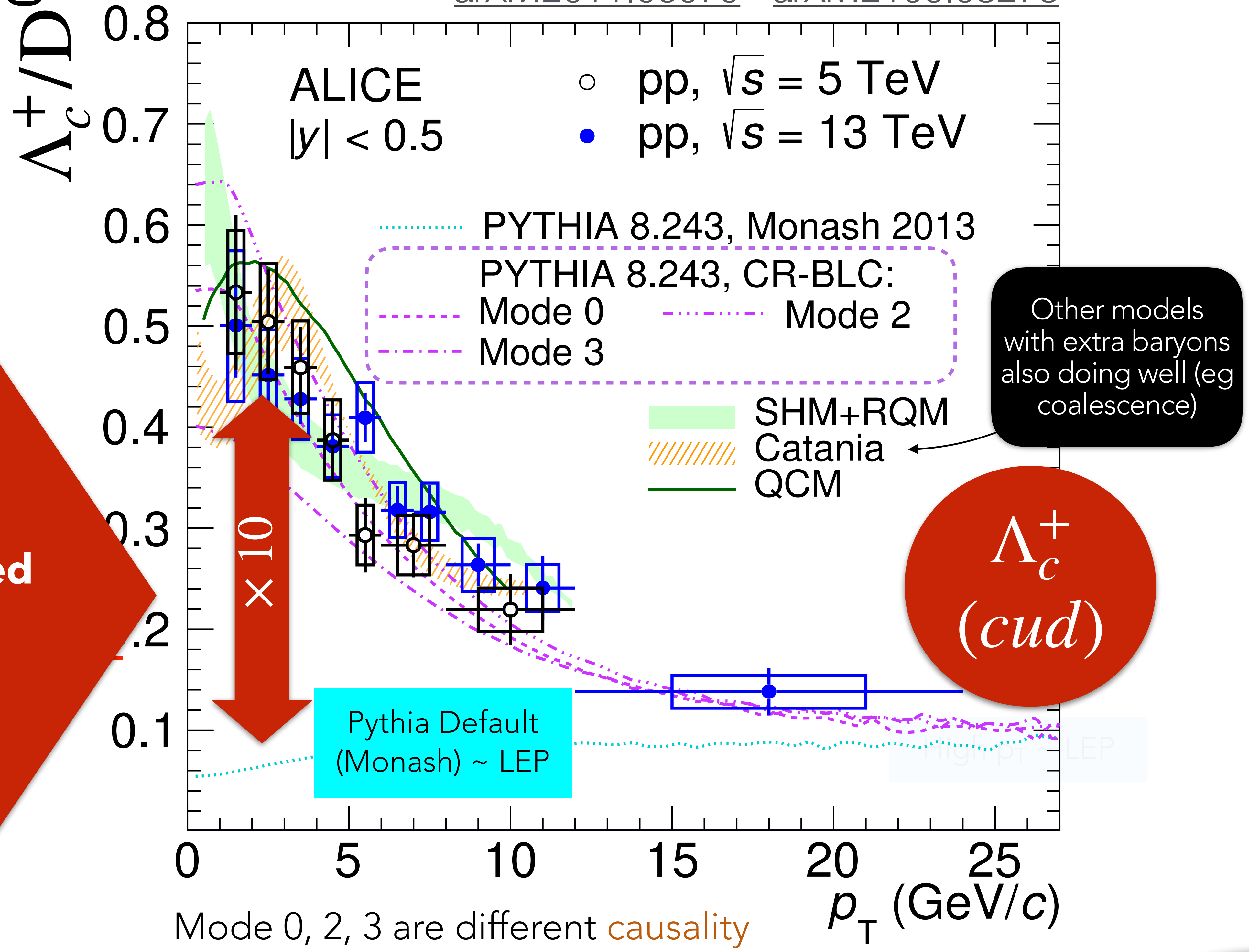
Generic prediction: low p_T

Illustration by J. Altmann

Predicted this

ALICE 2021

arXiv:2011.06079 arXiv:2106.08278



Other models with extra baryons also doing well (eg coalescence)

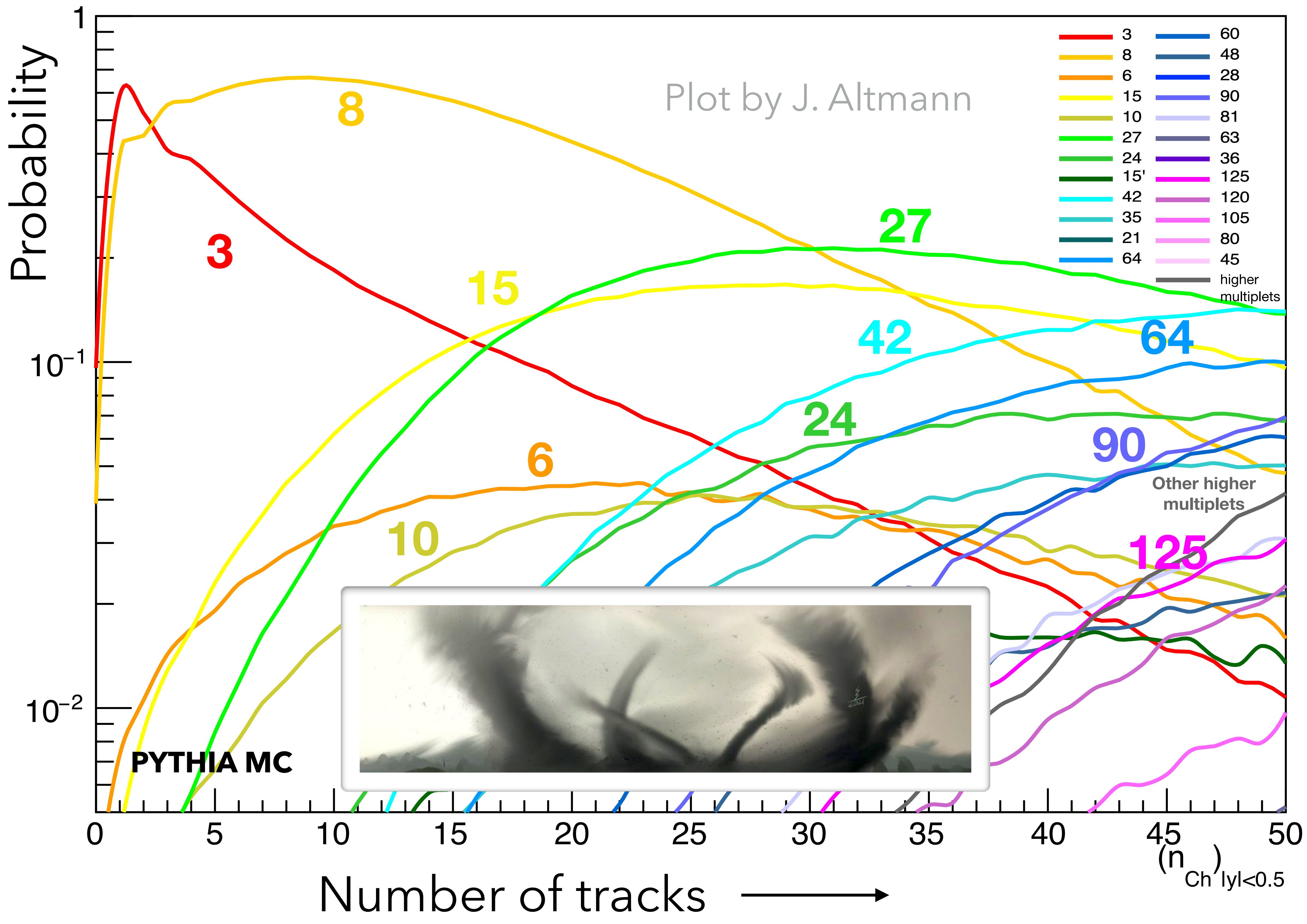
Pythia Default (Monash) ~ LEP

Mode 0, 2, 3 are different causality restrictions (0 = none)

Non-Linear String Dynamics?

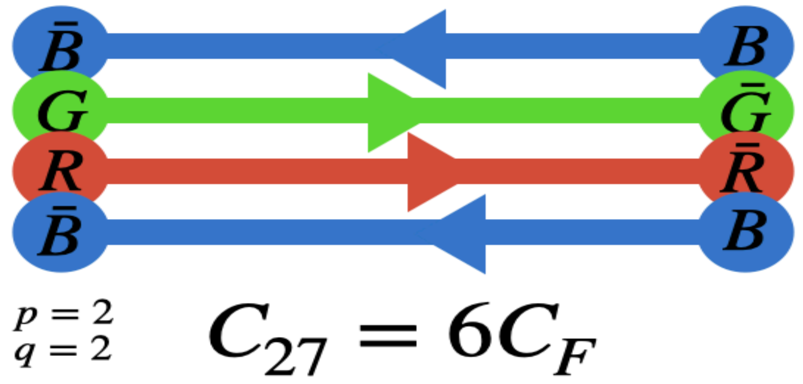
Count # of (oriented) flux lines crossing $y = 0$ in pp collisions at LHC

(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.: 27



27

$C_{27} = 6C_F$

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

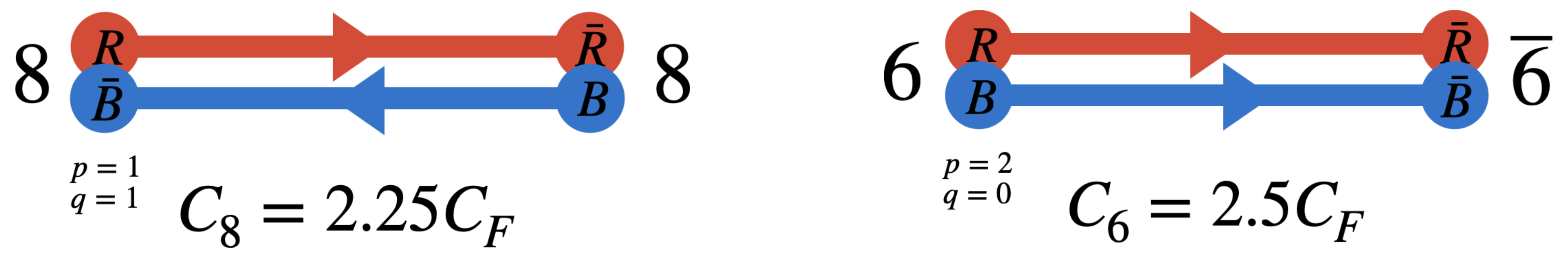
Colour Ropes (Bierlich et al.),

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

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

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

Close-packing

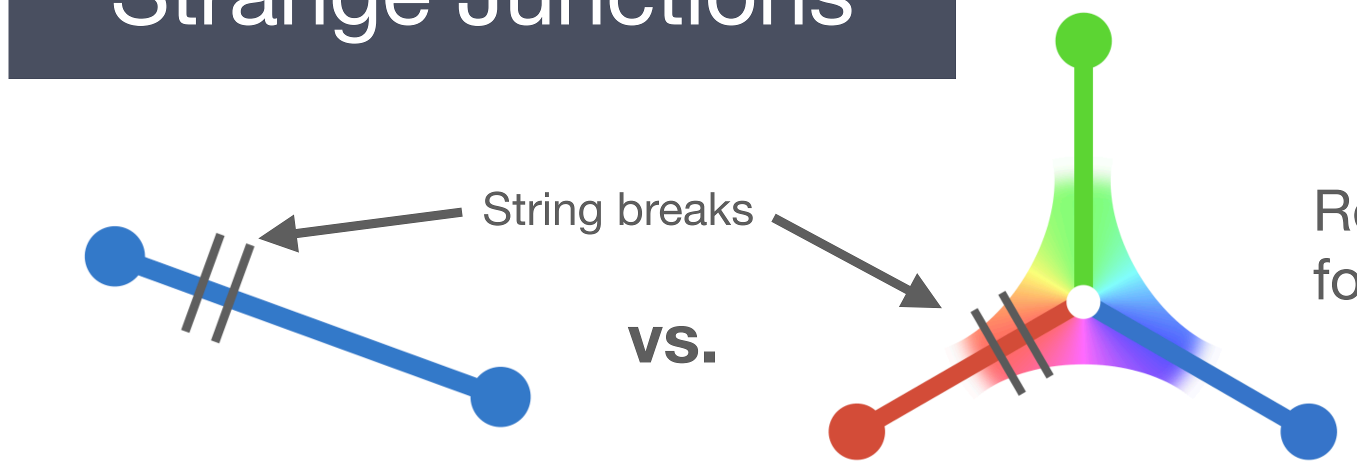


Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

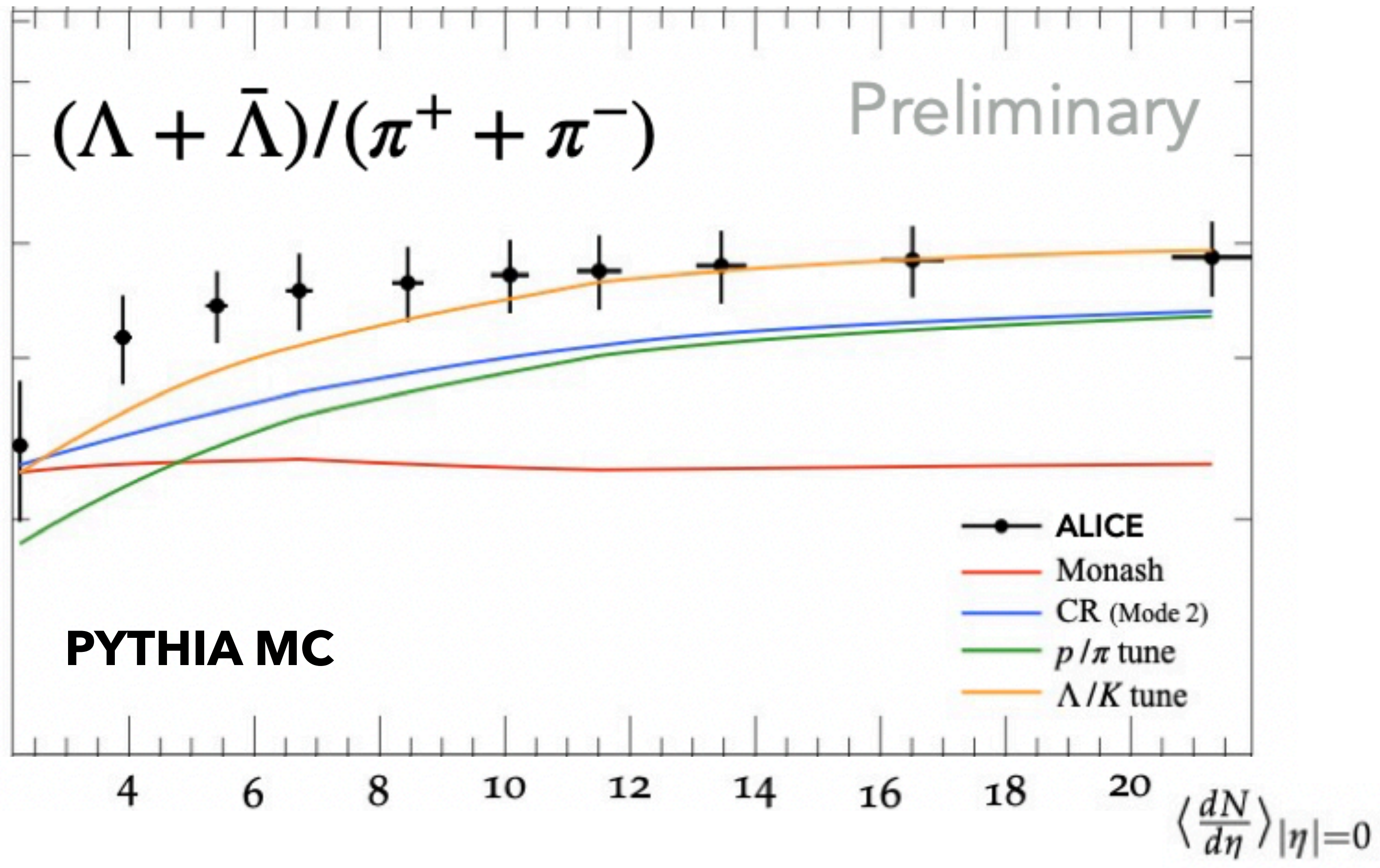
Strange Junctions

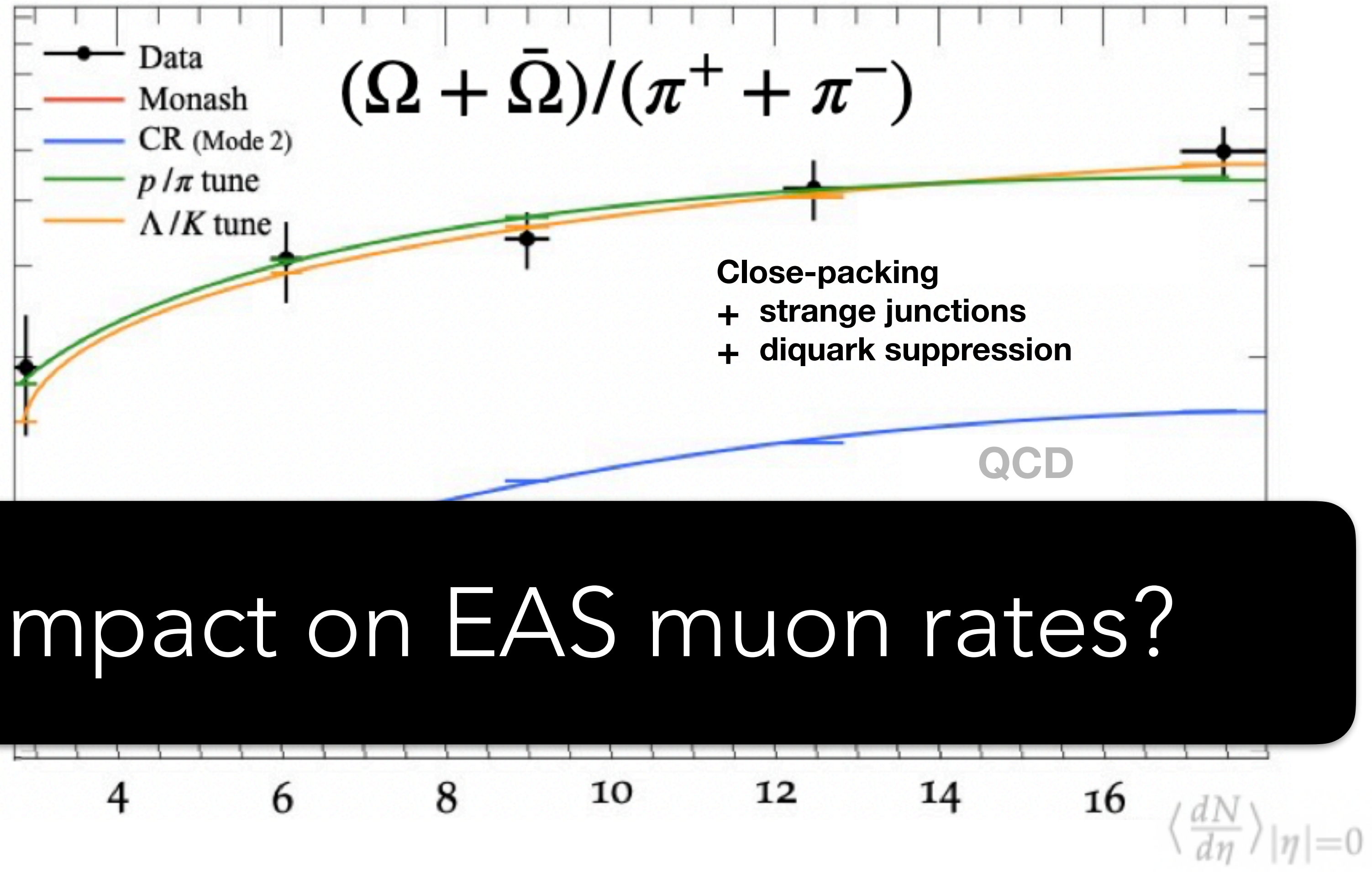


Results in strangeness enhancement focused in baryon sector

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

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





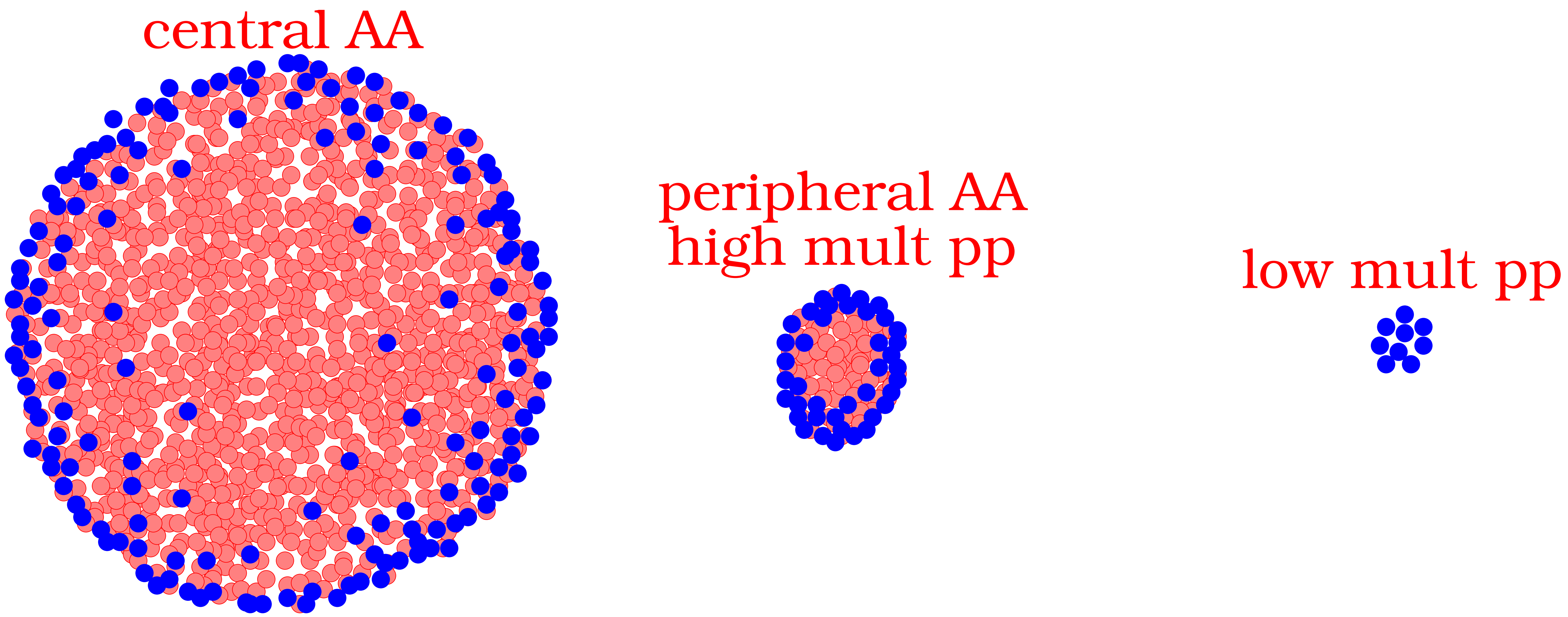
↔ Impact on EAS muon rates?

Slide adapted from J. Altmann

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?)

Slide adapted from T. Sjöstrand

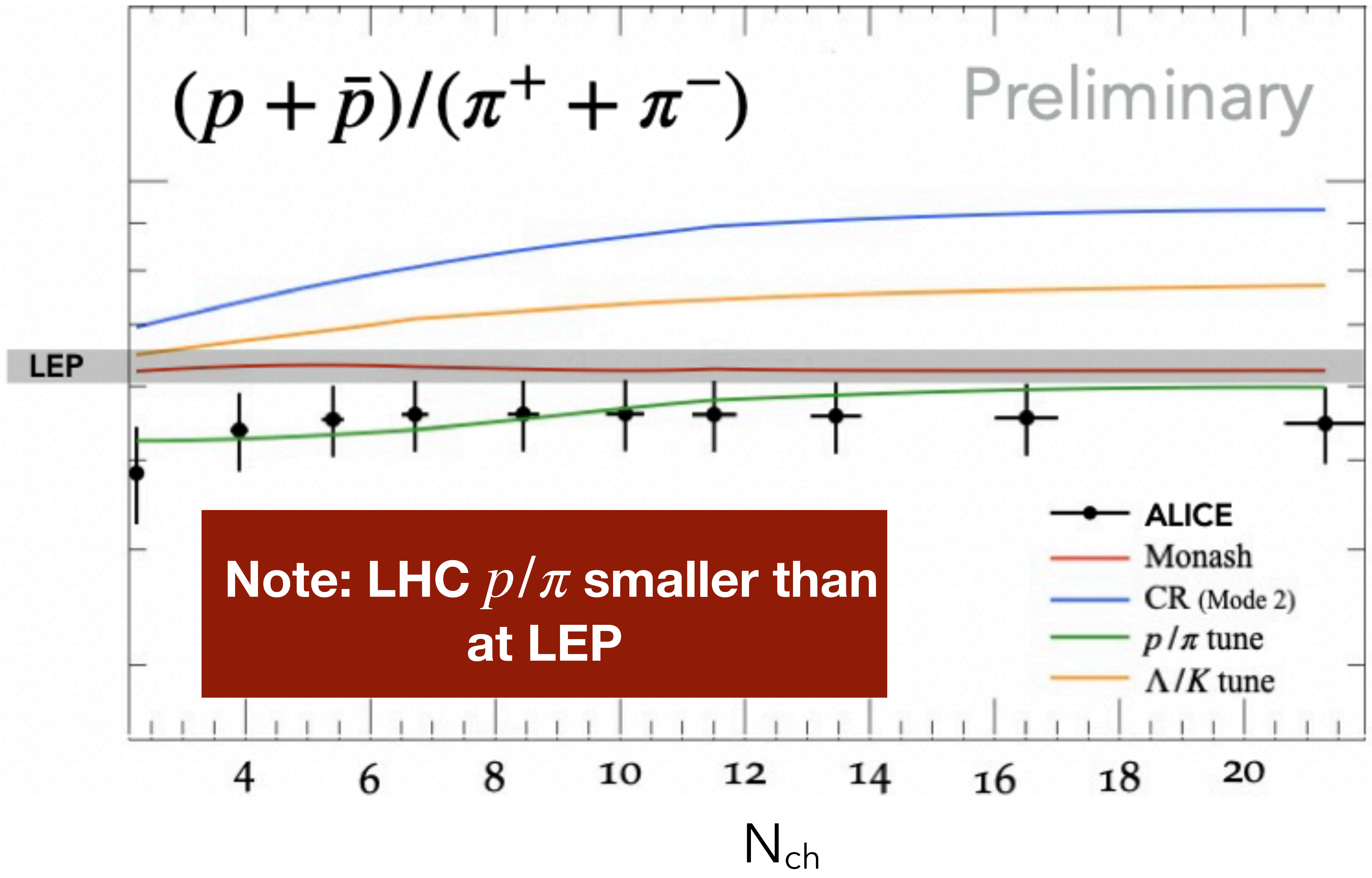
Thorny Issue ⚠️ The **Proton-to-Pion** Ratio

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

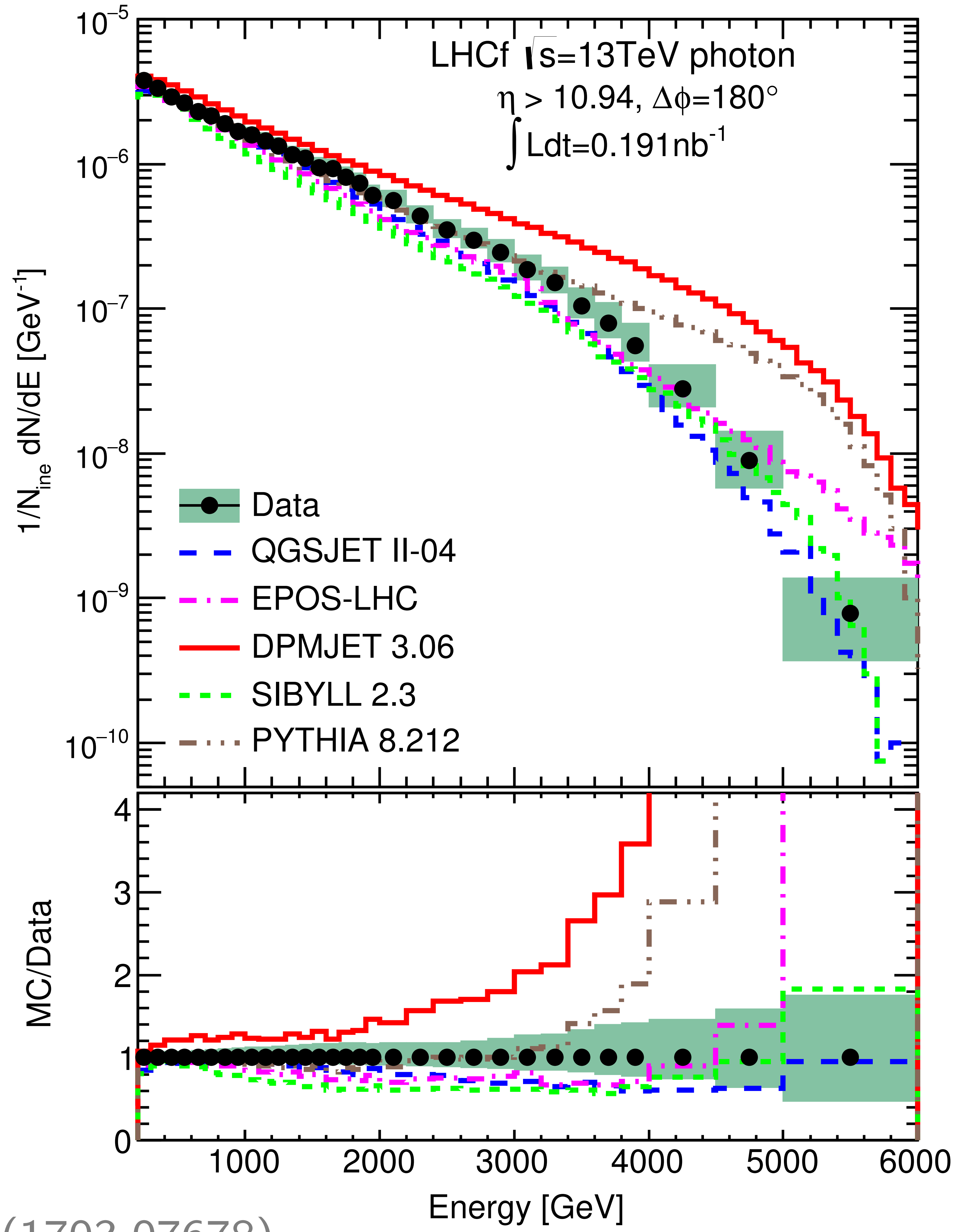
Interactions? Upscattering/Annihilation? Octet vs Triplet fragmentation? …?



Note: LHC p/π smaller than at LEP

Slide adapted from J. Altmann

Forward Physics



(1703.07678)

Forward region important for cosmic-ray physics ⇒ LHCf.

Also for FASER/. . . and the Forward Physics Facility.

Wide spread of predictions; no generator perfect.

PYTHIA: π^0 too hard, n too soft.

May require improved modelling of

- beam remnant,
- diffraction, and
- $\mathrm{c}/\mathrm{b}/\tau$ production.

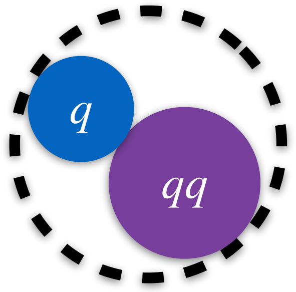
Slide adapted from T. Sjöstrand

Improved Beam-Remnant Modelling & New Forward Tune in PYTHIA

[Fieg, Kling, Schulz, Sjöstrand, 2309.08604]

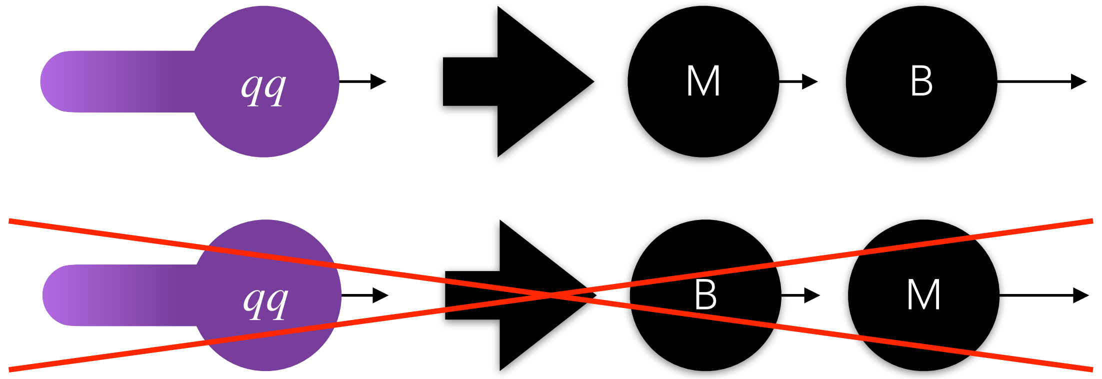
Some possible actions for harder baryons and softer mesons:

- Use QCDCR for better central baryon production. [Christiansen & PS, 1505.01681]
- Make diquark remnant take more than twice quark ditto: (already default) helps some.



Remnant:
$\langle x \rangle_{qq} > 2 \langle x \rangle_{q}$

- In string diquark picture B and $\overline{\mathrm{B}}$ are nearest neighbours, but with popcorn allow intermediate meson: $\ldots\mathrm{BM}\overline{\mathrm{B}}\ldots$ Thus leading diquark either $\mathrm{BMM}\ldots$ or $\mathrm{MBM}\ldots$. New: forbid latter possibility (or only suppress it).



- Normal fragmentation function

$$f(z) \propto \frac{1}{z}\,(1-z)^{a}\,\exp\left(-\frac{b m_{\perp}^{2}}{z}\right)\;, \quad z = \frac{(E+p_z)_{\mathrm{hadron}}}{(E+p_z)_{\mathrm{left\ in\ string}}}$$

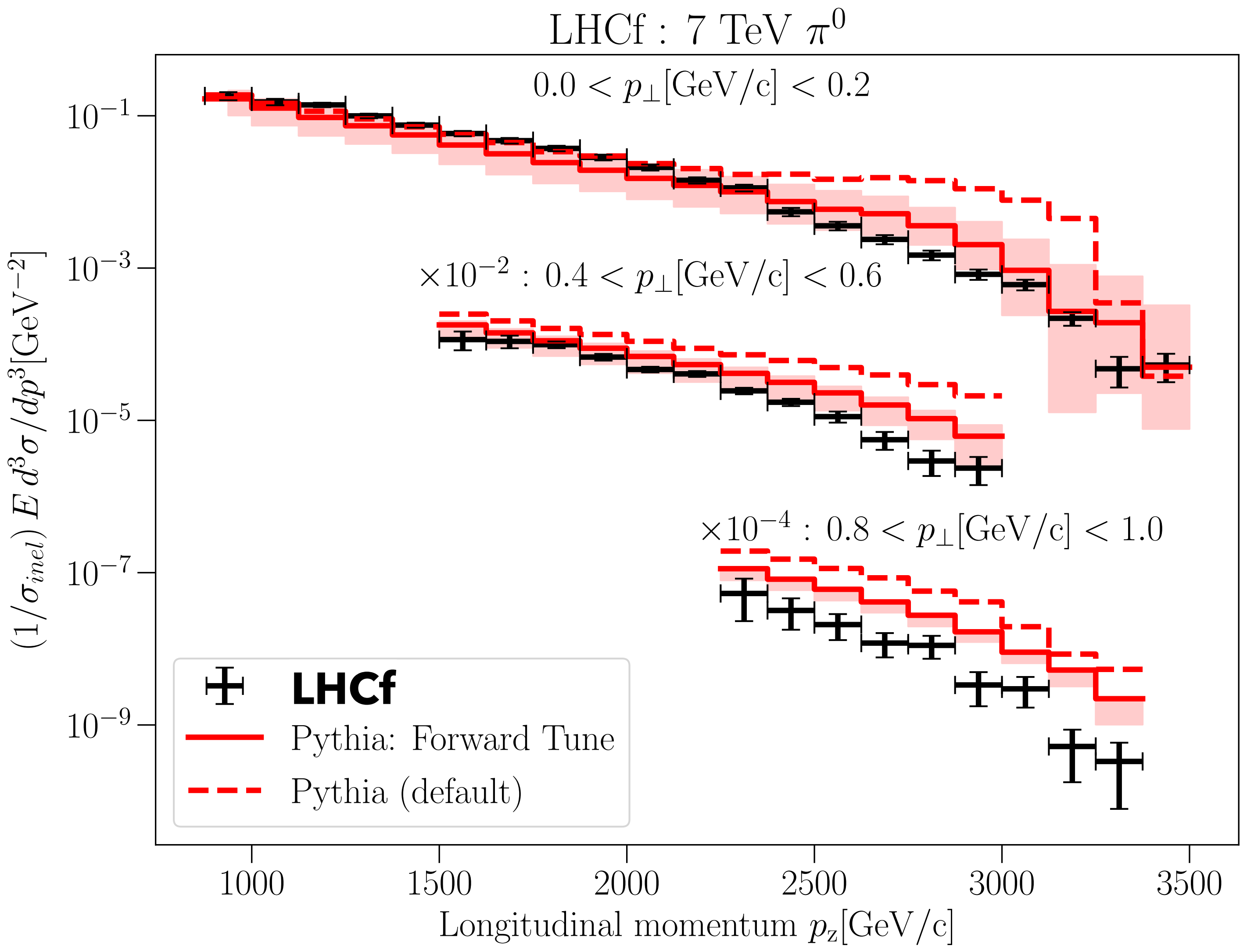
  modified with separately tuned (a and) b for leading diquark.
- Reduce primordial $k_{\perp}$ in remnant for soft collisions.

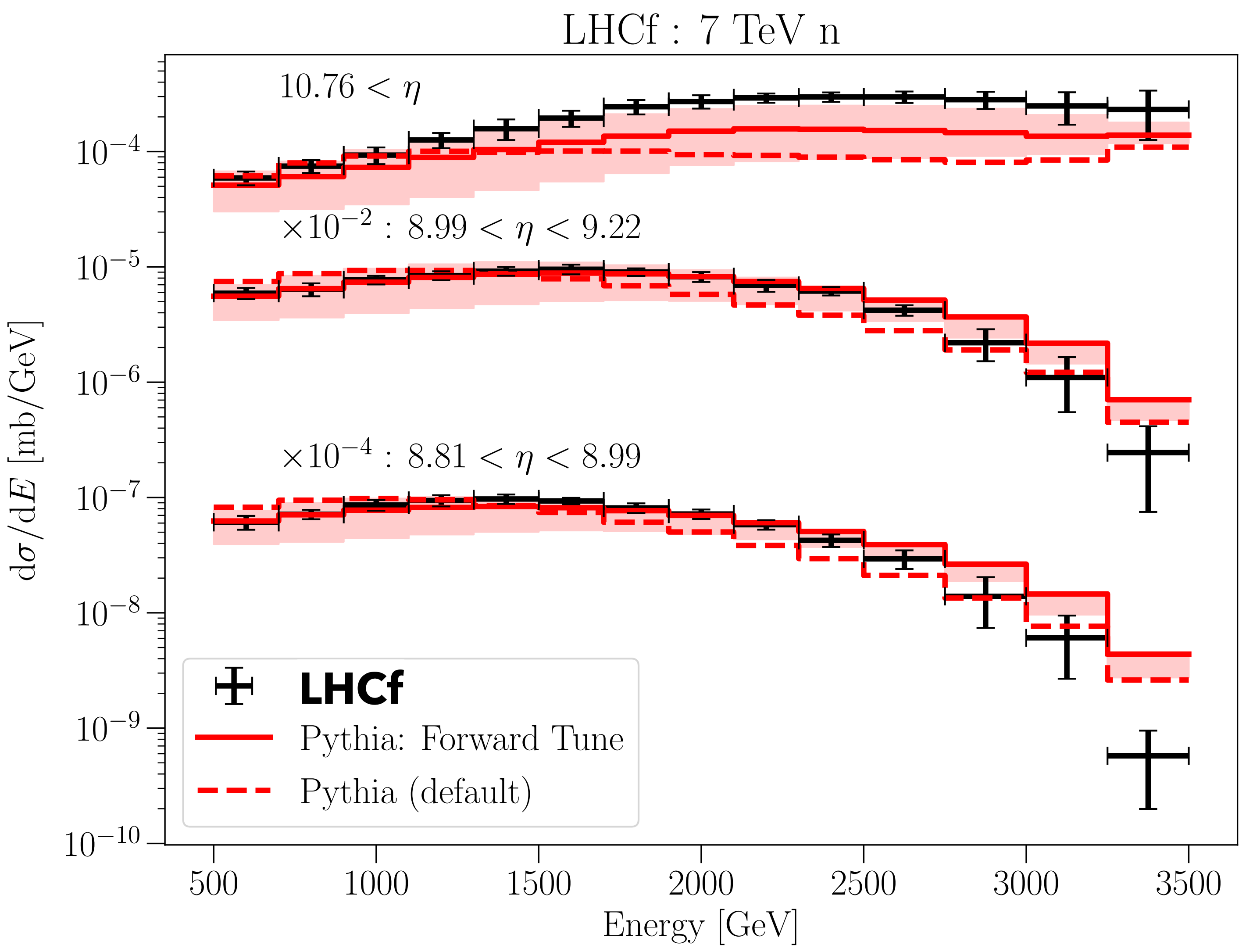
Slide adapted from T. Sjöstrand

New Forward Results [Fieg, Kling, Schulz, Sjöstrand, 2309.08604]

π^0

7 TeV


LHCf : 7 TeV π^0


LHCf : 7 TeV n

n

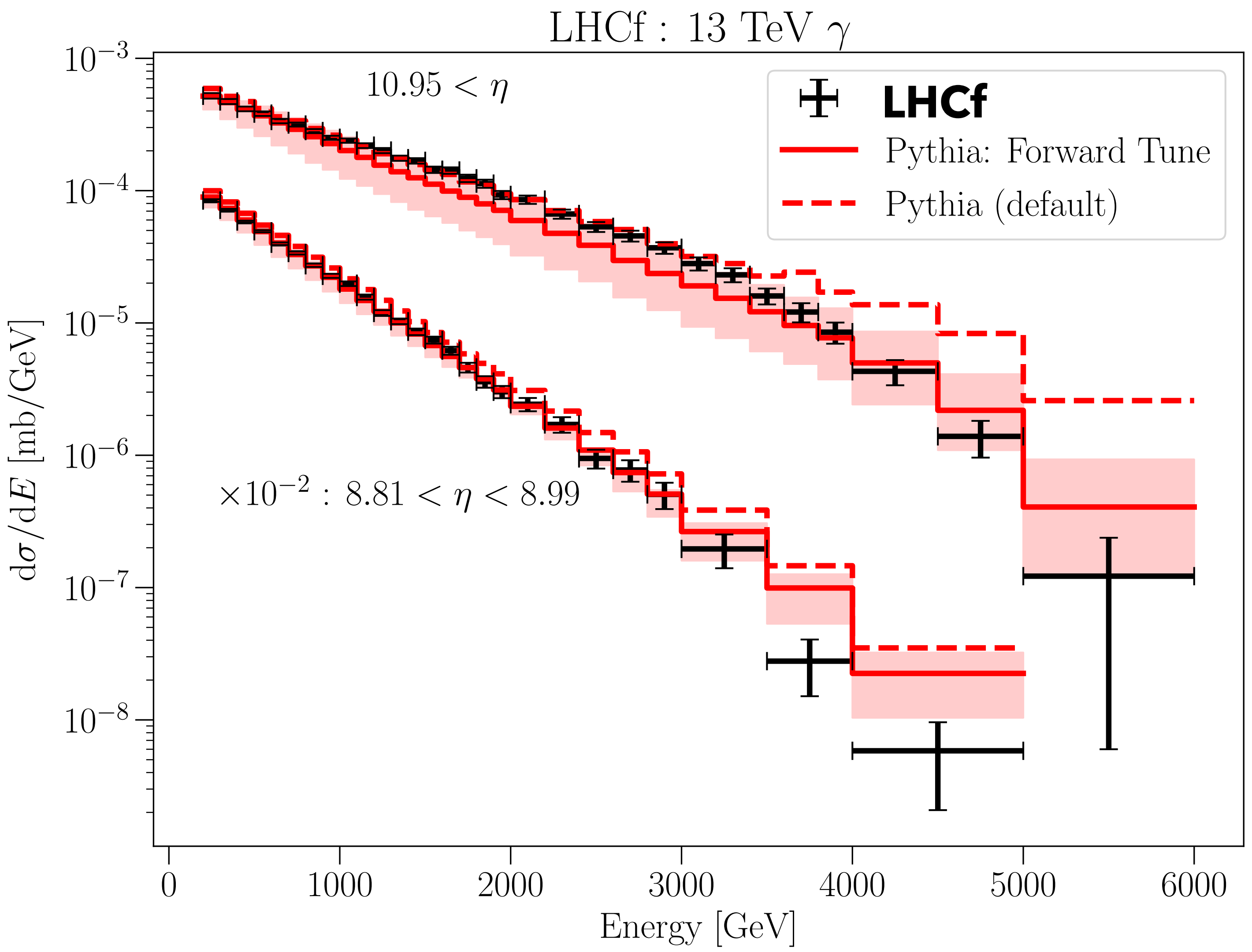
7 TeV

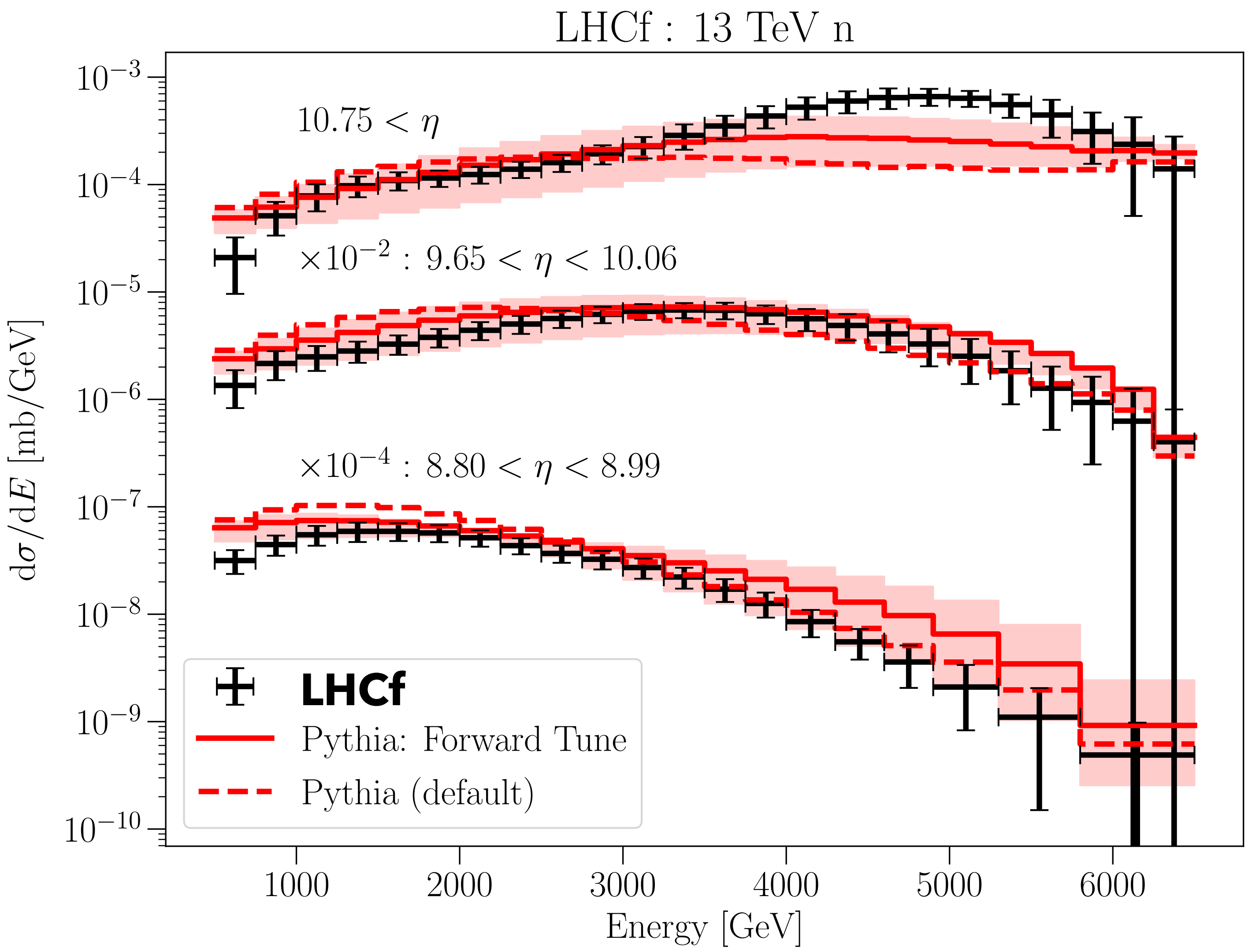
Recall:

Default was overshooting the pions and undershooting the neutrons

γ

7 TeV


LHCf : 13 TeV γ


LHCf : 13 TeV n

n

13 TeV

Conclusion:

Not perfect but significantly improved

Slide adapted from T. Sjöstrand

A New Framework for Hadronic Collisions (→ Cosmic Rays)

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

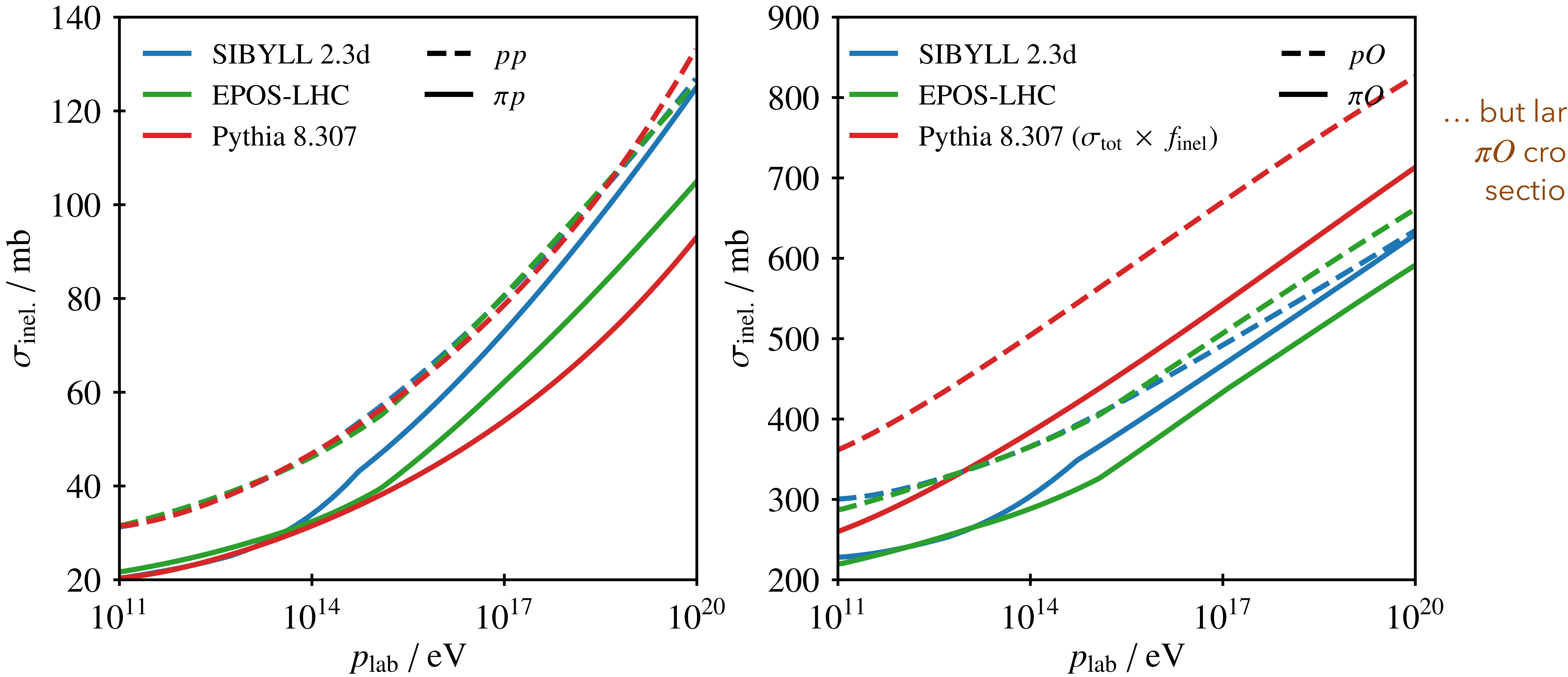
- Models arbitrary hadron–hadron collisions at low energies.
- Models arbitrary hadron-p/n collisions at any energy.
- Initialization slow, $\sim$ 15 minutes,
  $\star$ but thereafter works for any hadron–p/n at any energy, and
  $\star$ initialization data can be saved, so only need to do once.
- The 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.

Slide adapted from T. Sjöstrand

Comparison to Other Models — 1

Maximilian Reininghaus, TS, M. Utheim, arXiv:2303:02792

PYTHIA has smallest πp cross section



… but largest πO cross section

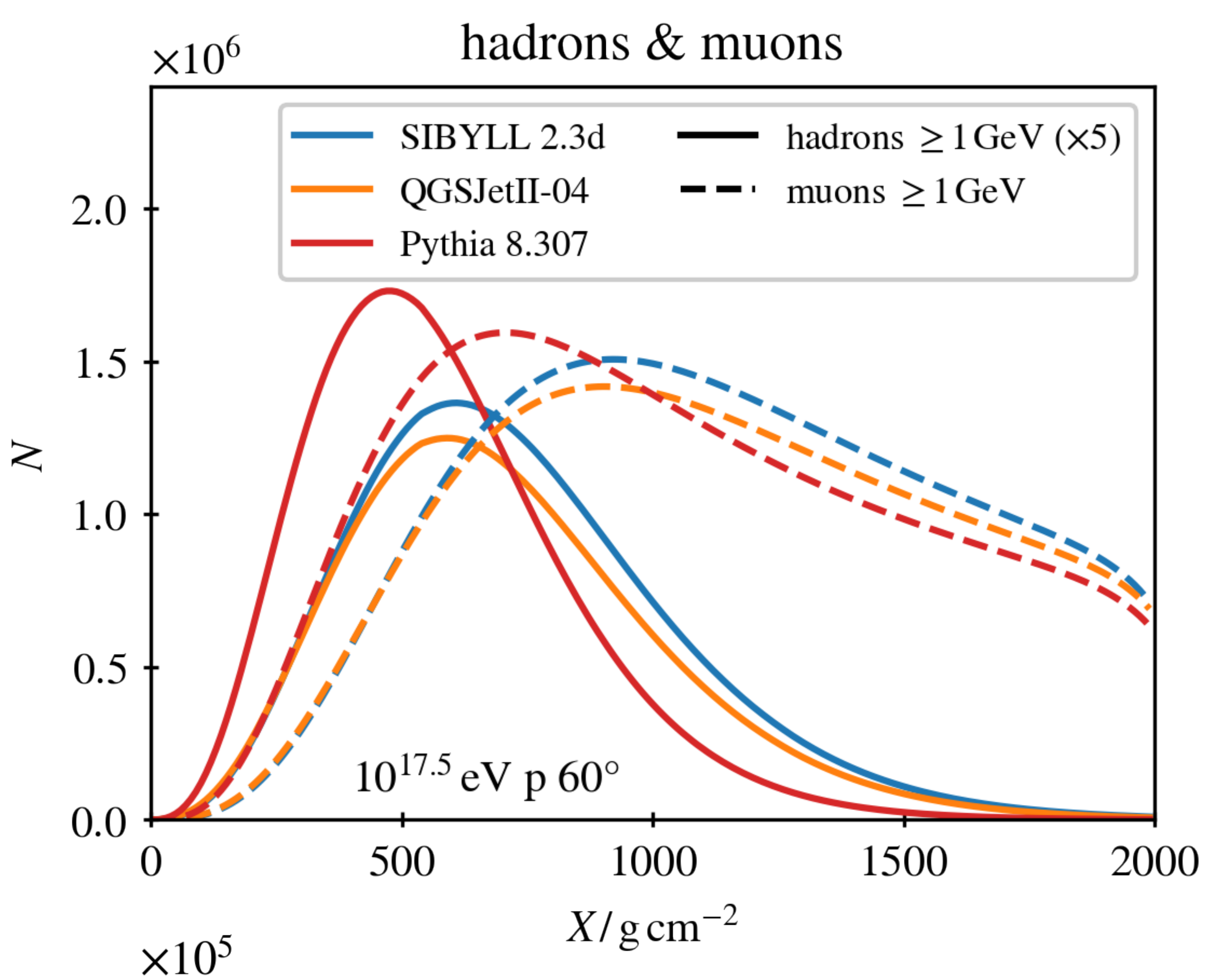
Additive quark rule $\sigma_{\pi\text{p}} \approx (2/3)\sigma_{\text{pp}}$ at high energies.

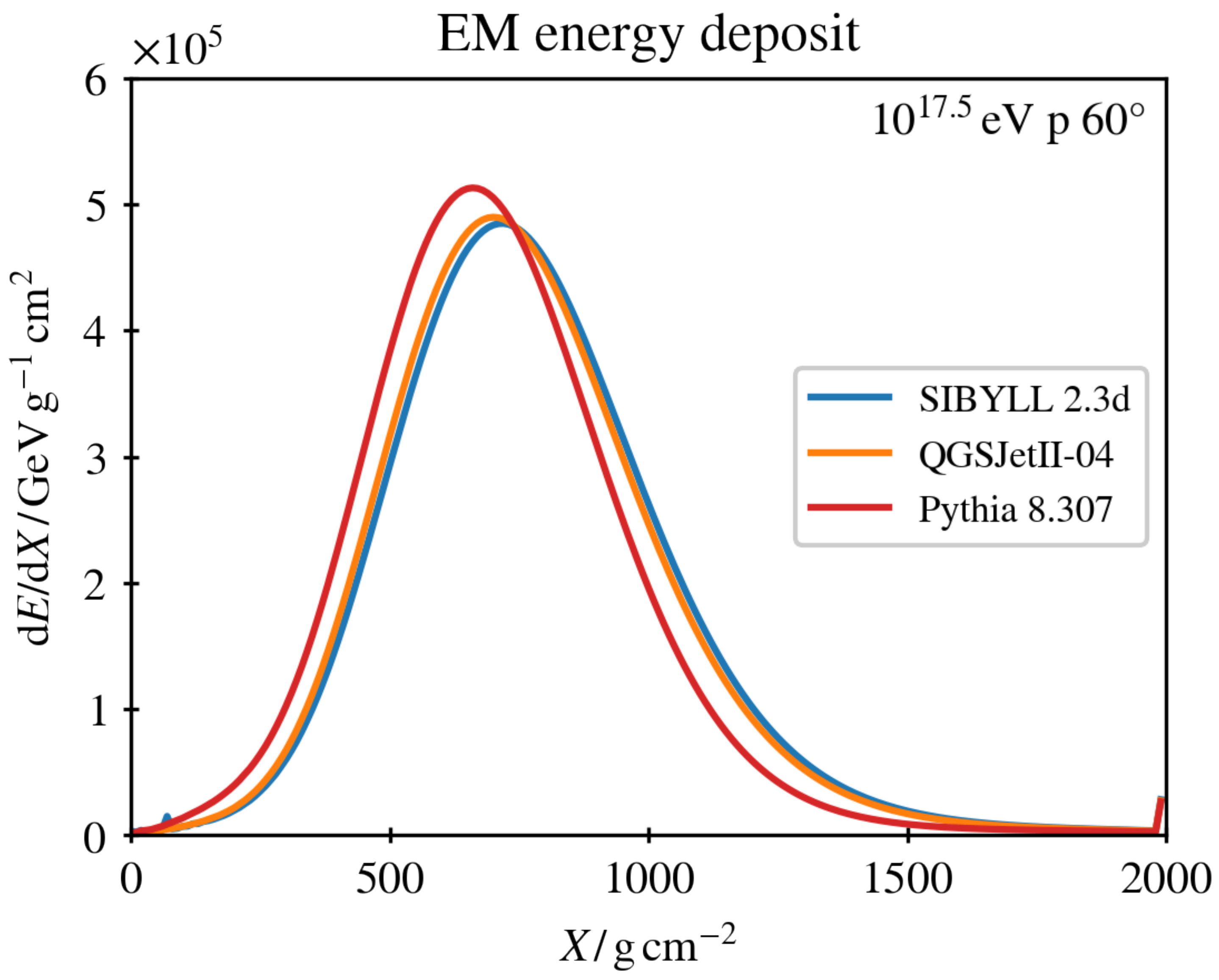
Simple extension to pA: $\sigma_{hA} = \dfrac{A}{\langle n_{\text{coll}} \rangle} \sigma_{h\text{p}}$ where $\langle n_{\text{coll}} \rangle$ comes from Angantyr

Slide adapted from T. Sjöstrand

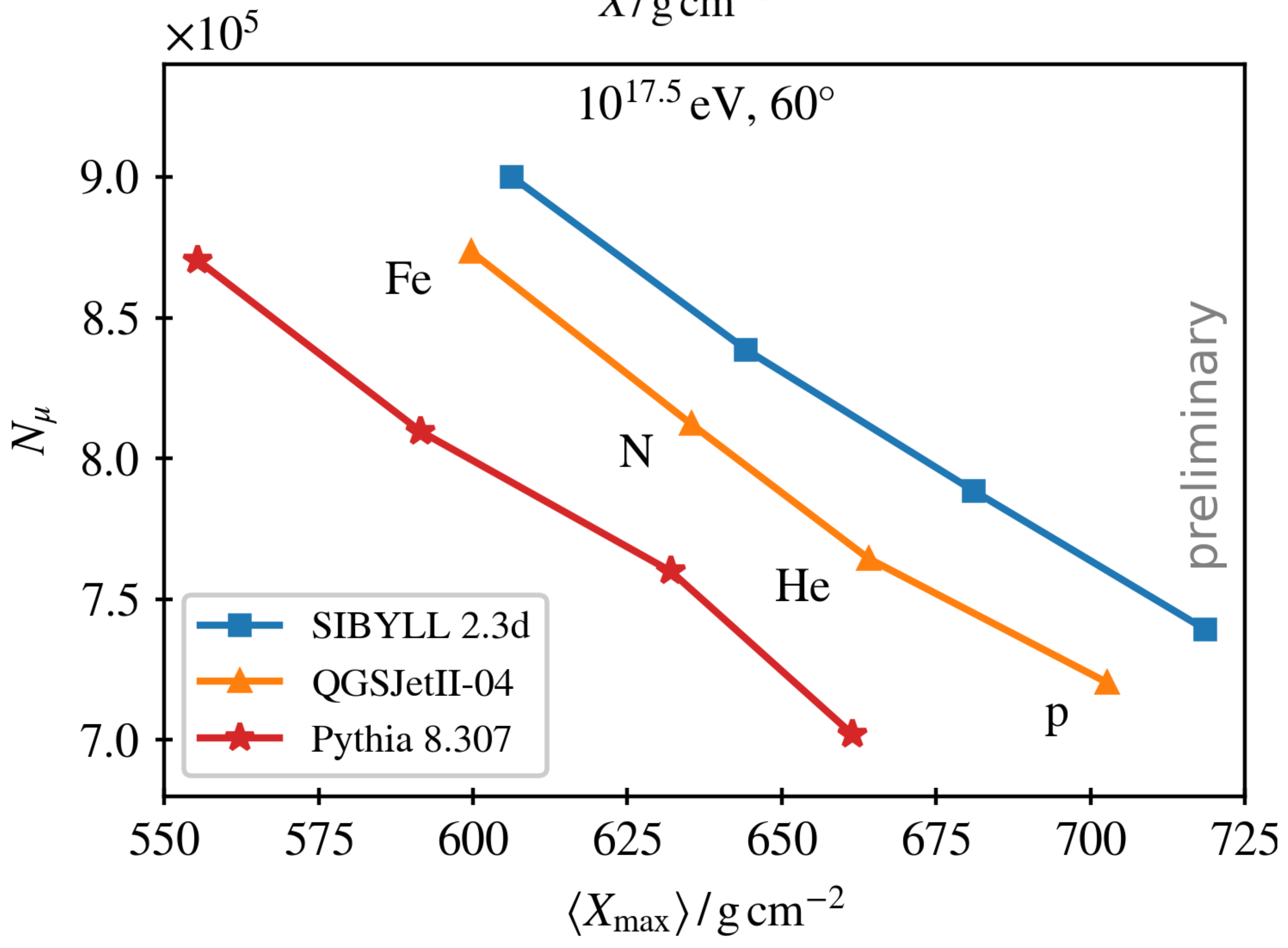
Comparison to Other Models — 2

Hadronic cascades quite different





EM cascades quickly decouple from hadronic ones



Some Further PYTHIA aspects:

Includes charm and bottom (and jets)

Native C++ → multithreading

Users can do tunings themselves
→ study air-shower / accelerator interplay

Slide adapted from T. Sjöstrand

Thank you

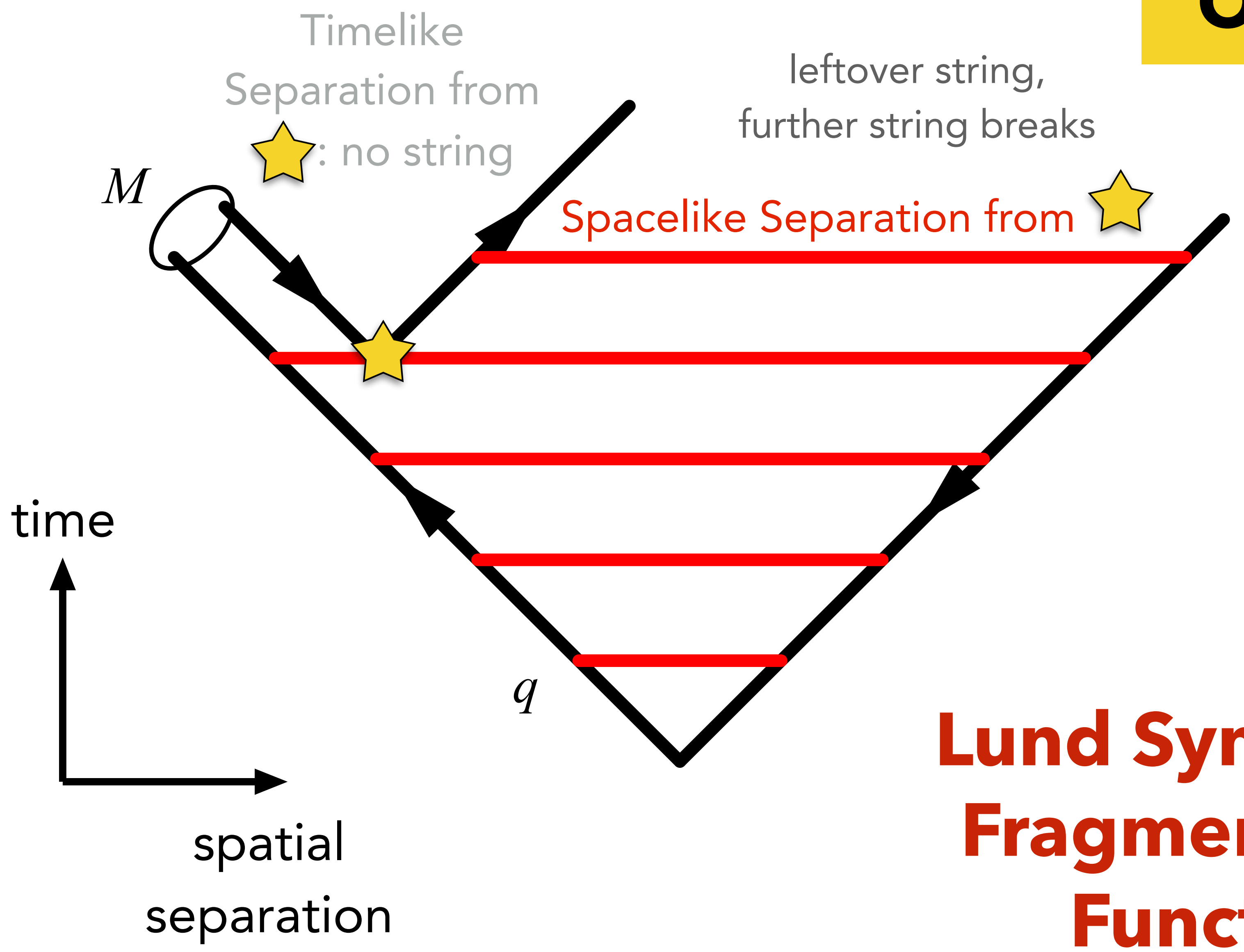
Extra Slides

Returning to **Strings**: 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 $z \in [0,1]$ parametrised by **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

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

Supresses high-z hadrons

Supresses low-z hadrons

(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

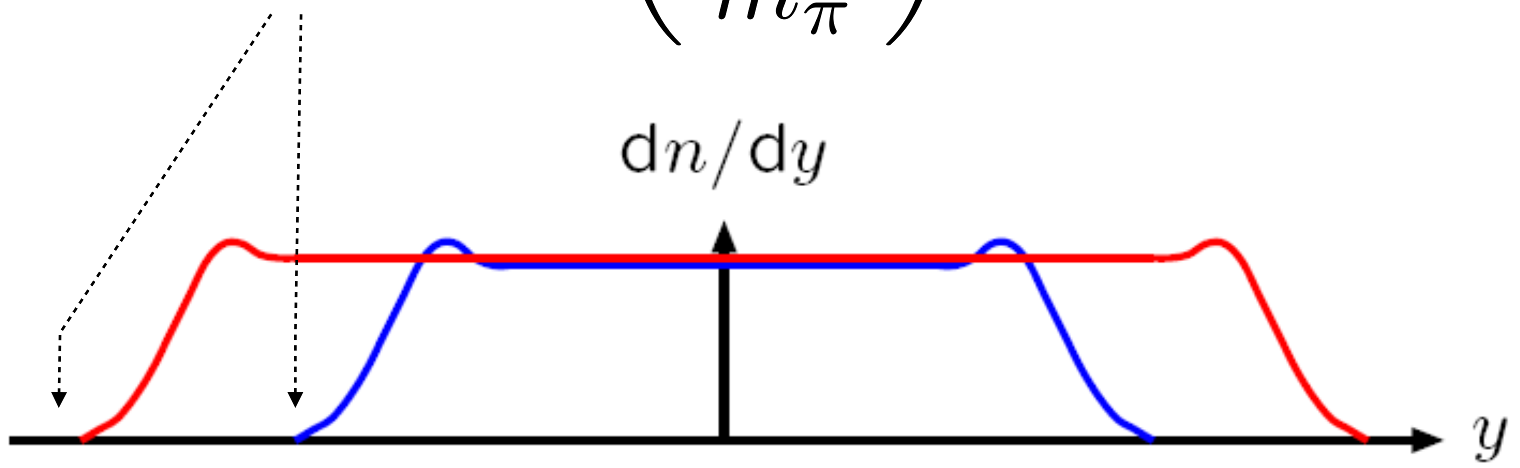
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$$

➡

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

A Brief History of MPI (in PYTHIA)

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

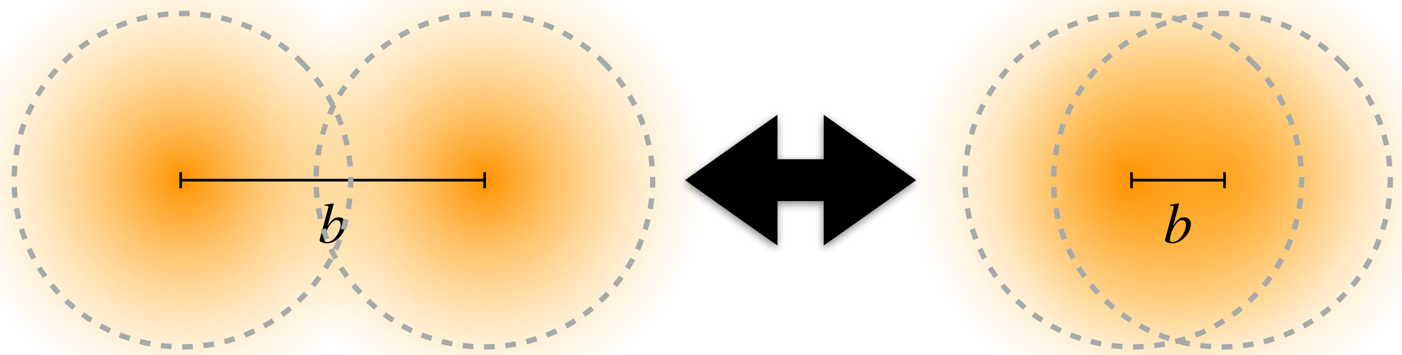
Cast MPI as Sudakov-style evolution equation

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

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

$$p \propto \sigma_{2\to 2}(x_T,b)/\sigma_{pp} \quad ; \quad x_T = 2\hat{p}_\perp/\sqrt{s}$$

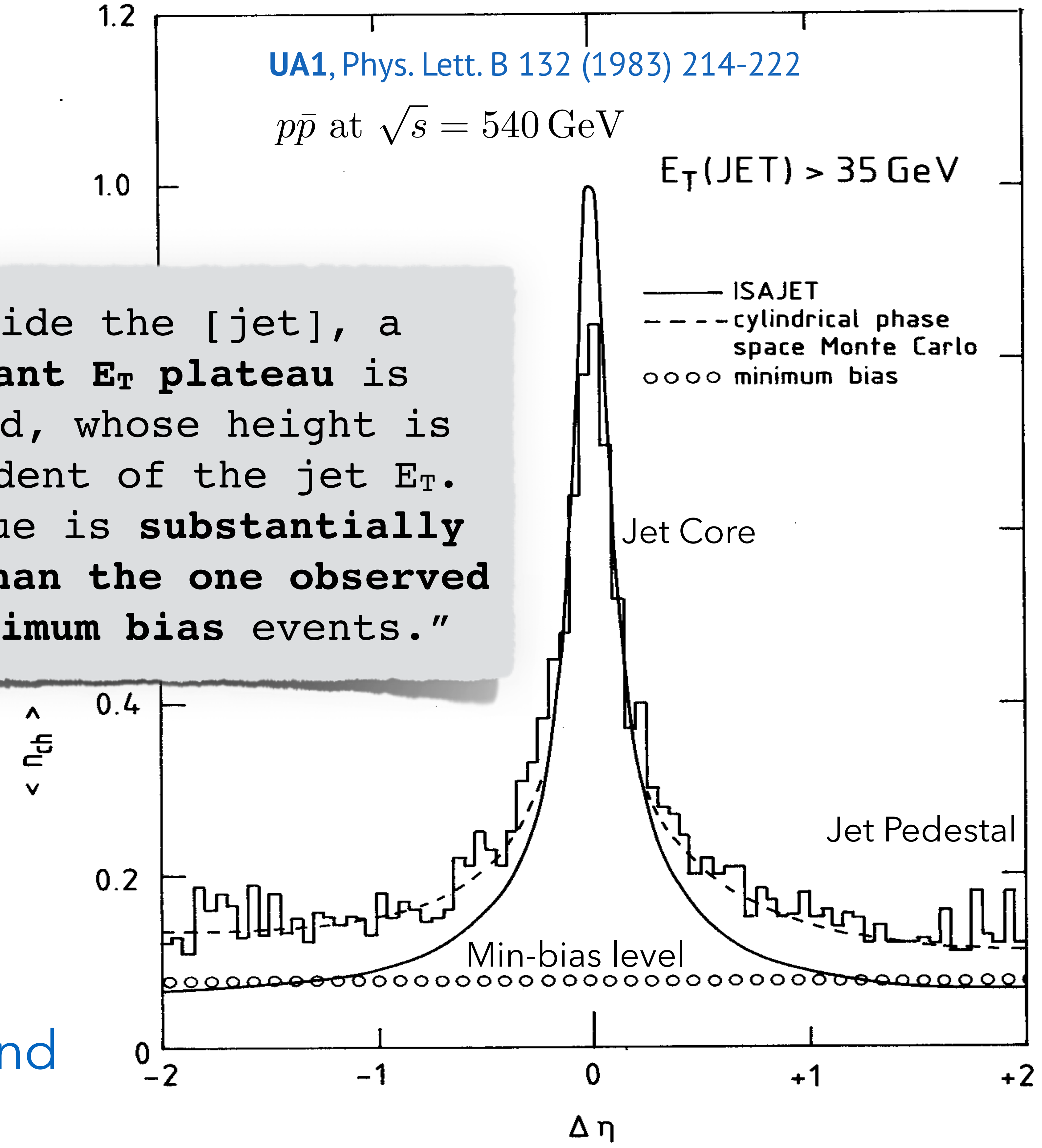
with Impact-parameter dependence



Crucial to describe **"Underlying Event"**

a.k.a. **"Jet Pedestal"**: hard jets are accompanied by — and sit on top of — higher-than average particle densities *(compared with the average = minimum-bias pp collision)*

> "Outside the [jet], a **constant E_T plateau** is observed, whose height is independent of the jet E_T. Its value is **substantially higher than the one observed for minimum bias** events."



Interleaved Evolution in PYTHIA

Interleaved Evolution

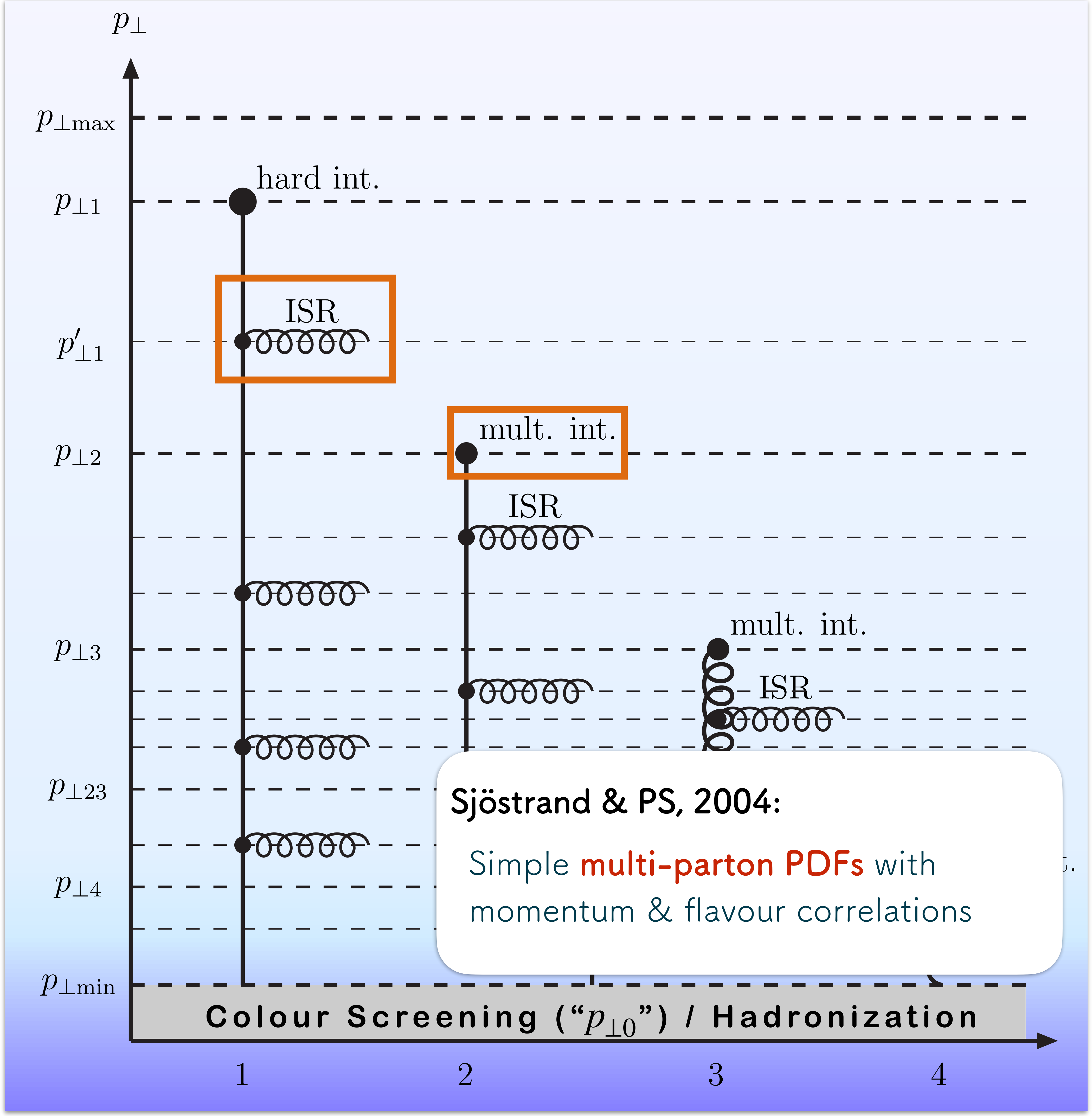
2005 [Sjöstrand & **PS**, Eur.Phys.J.C 39 (2005) 129]

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



Sjöstrand & PS, 2004:

Simple **multi-parton PDFs** with momentum & flavour correlations

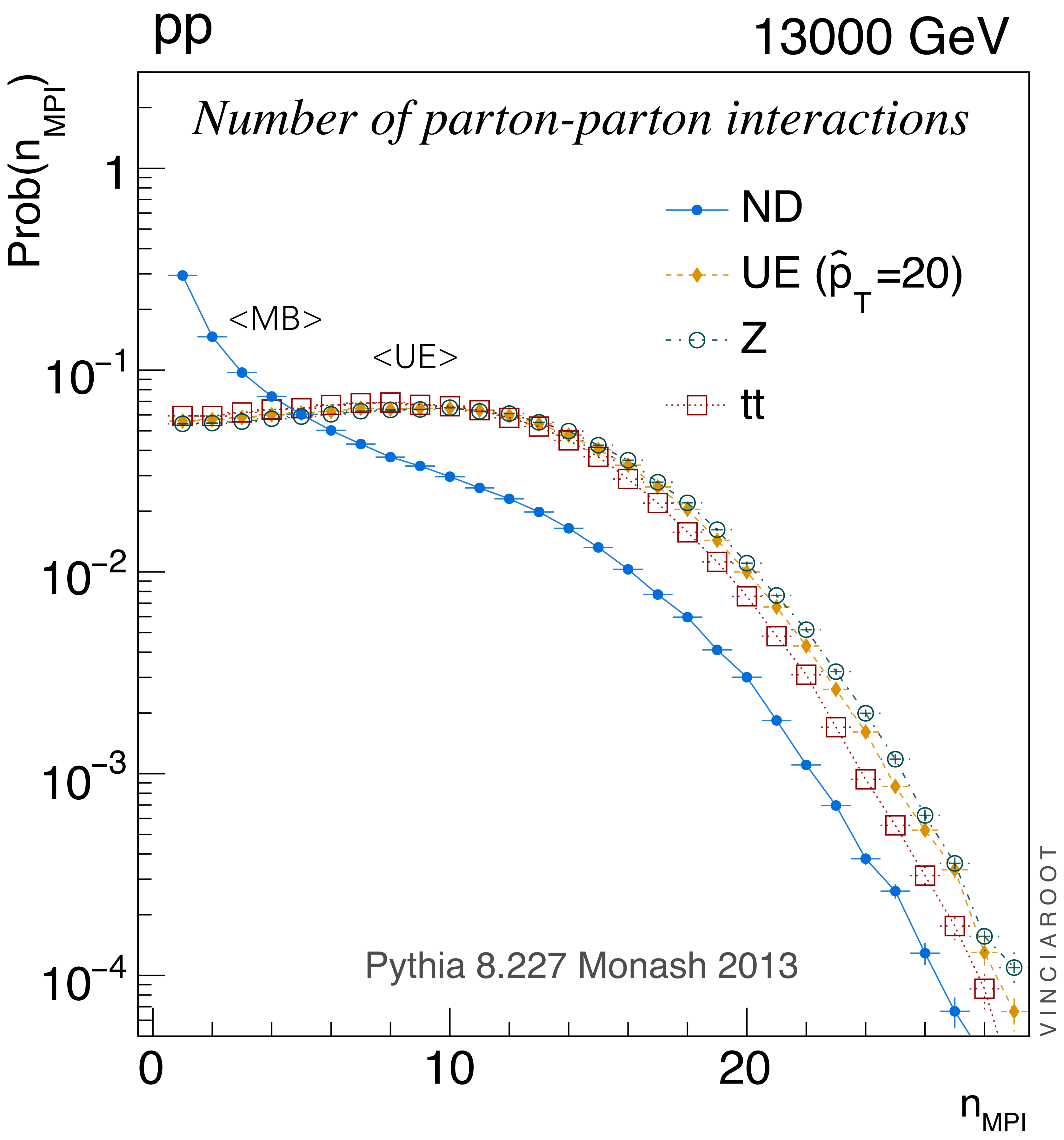
Figure from Sjöstrand & PS, 2005

How many MPI are there? *

Example for pp collisions at 13 TeV — PYTHIA's default MPI model

Averaged over all pp impact parameters

(Really: averaged over all pp overlap enhancement factors)



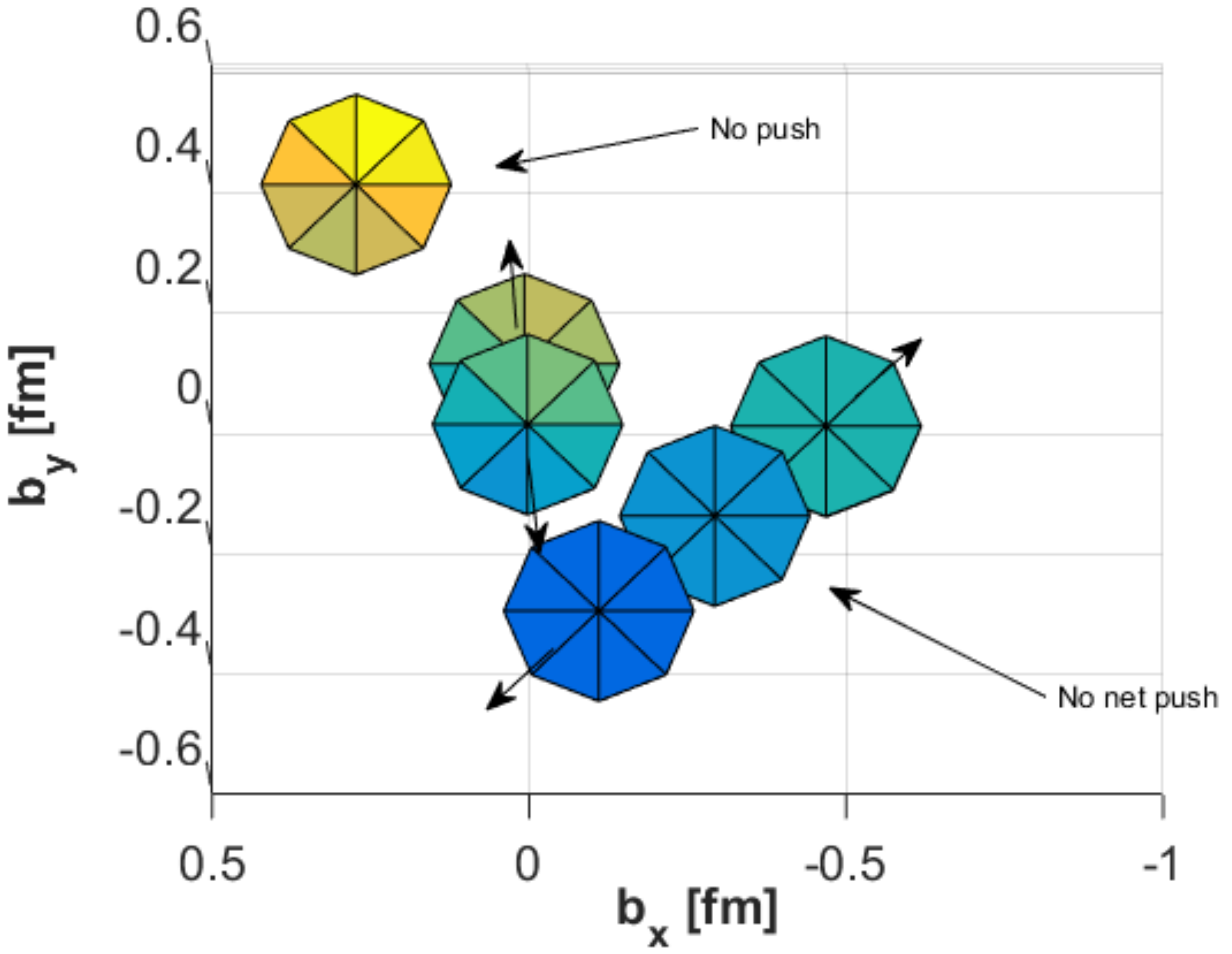
*note: can be arbitrarily soft

Collective Flow in PYTHIA: *String Shoving*

Bierlich, Chakraborty, Gustafson, Lönnblad, arXiv:1710.09725, 2010.07595

Strings should push each other transversely

Colour-electric fields ➜ Classical force



Model string radial shape & shoving physics

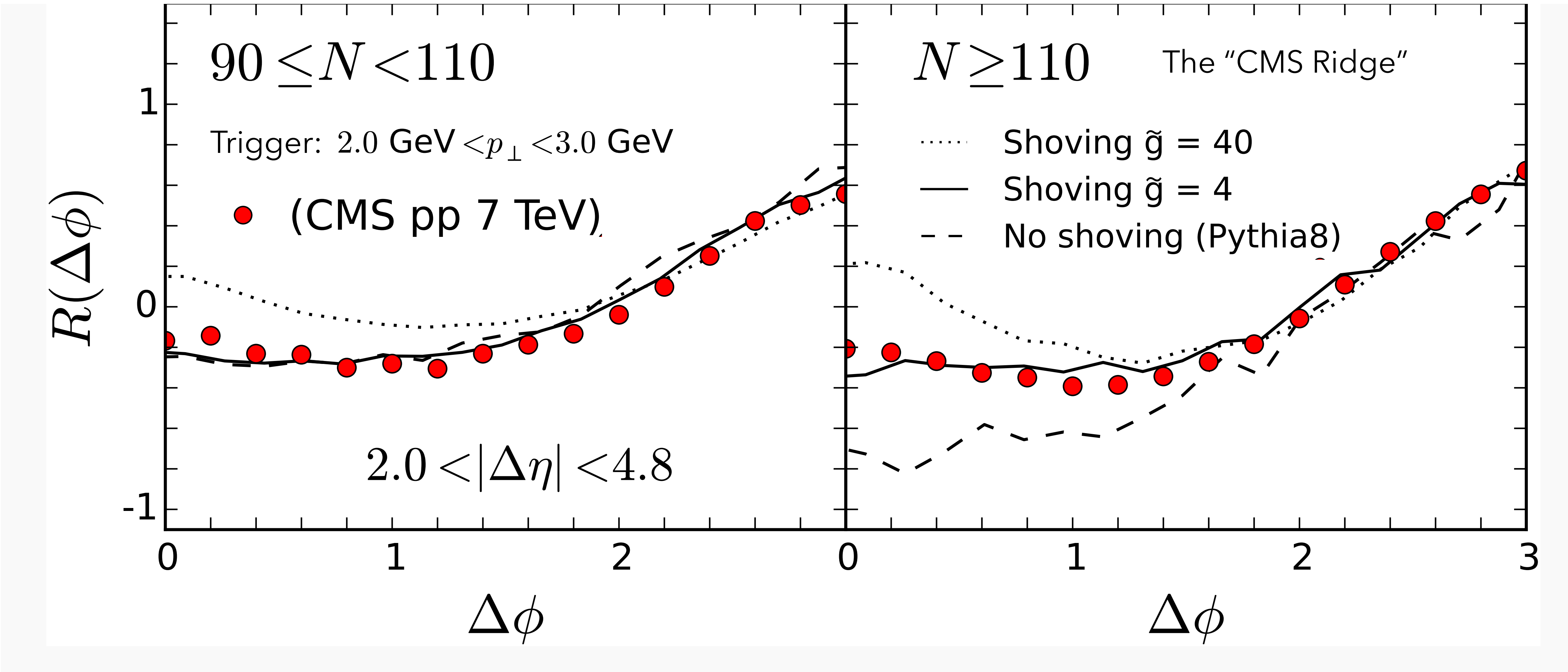
$\Longrightarrow$ force $$f(d_\perp) = \frac{g\kappa d_\perp}{R^2} \exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

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

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

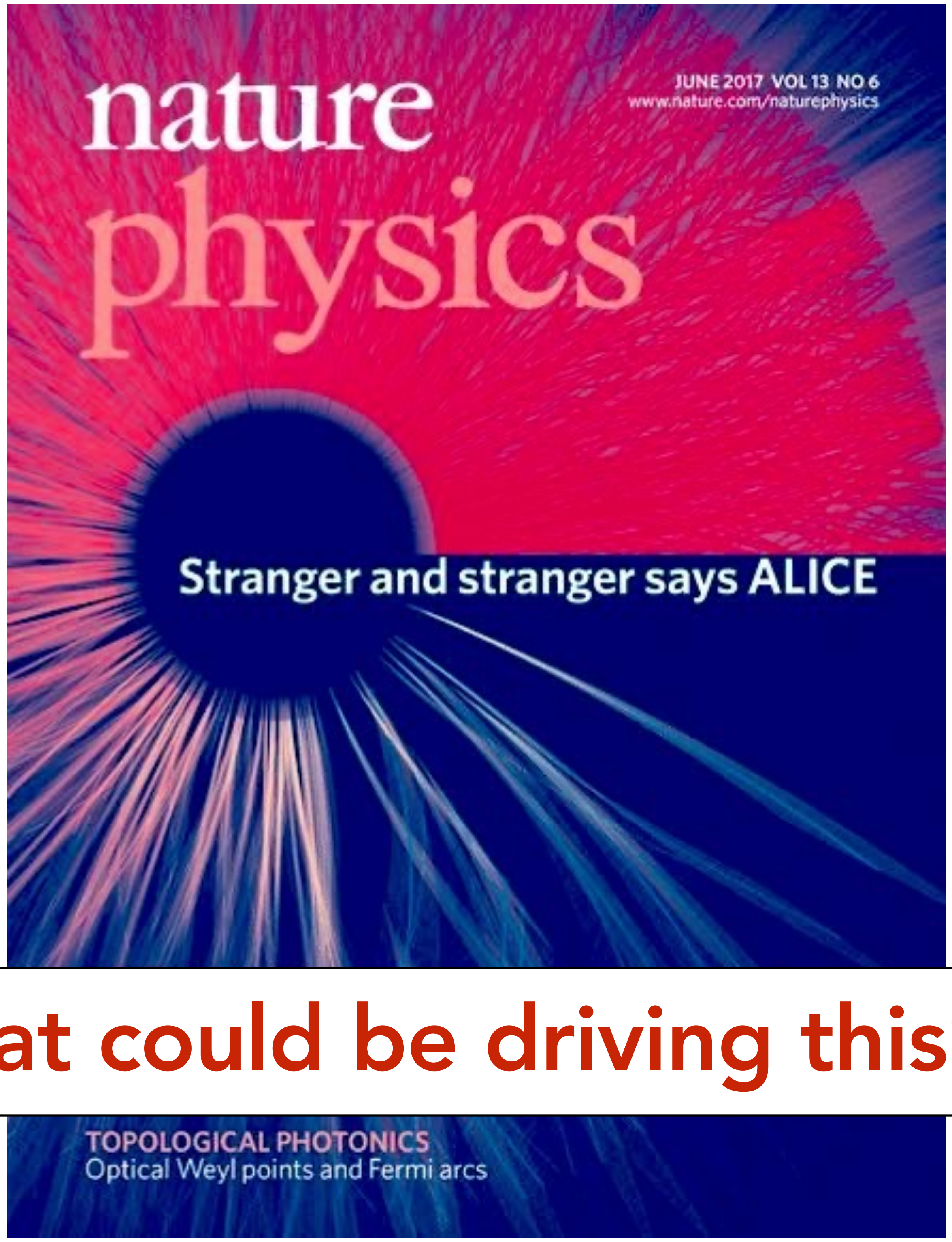


CMS 1009.4122. Also: ATLAS 1906.08290, ALICE 2101.03110

What a **strange** world we live in, said Alice

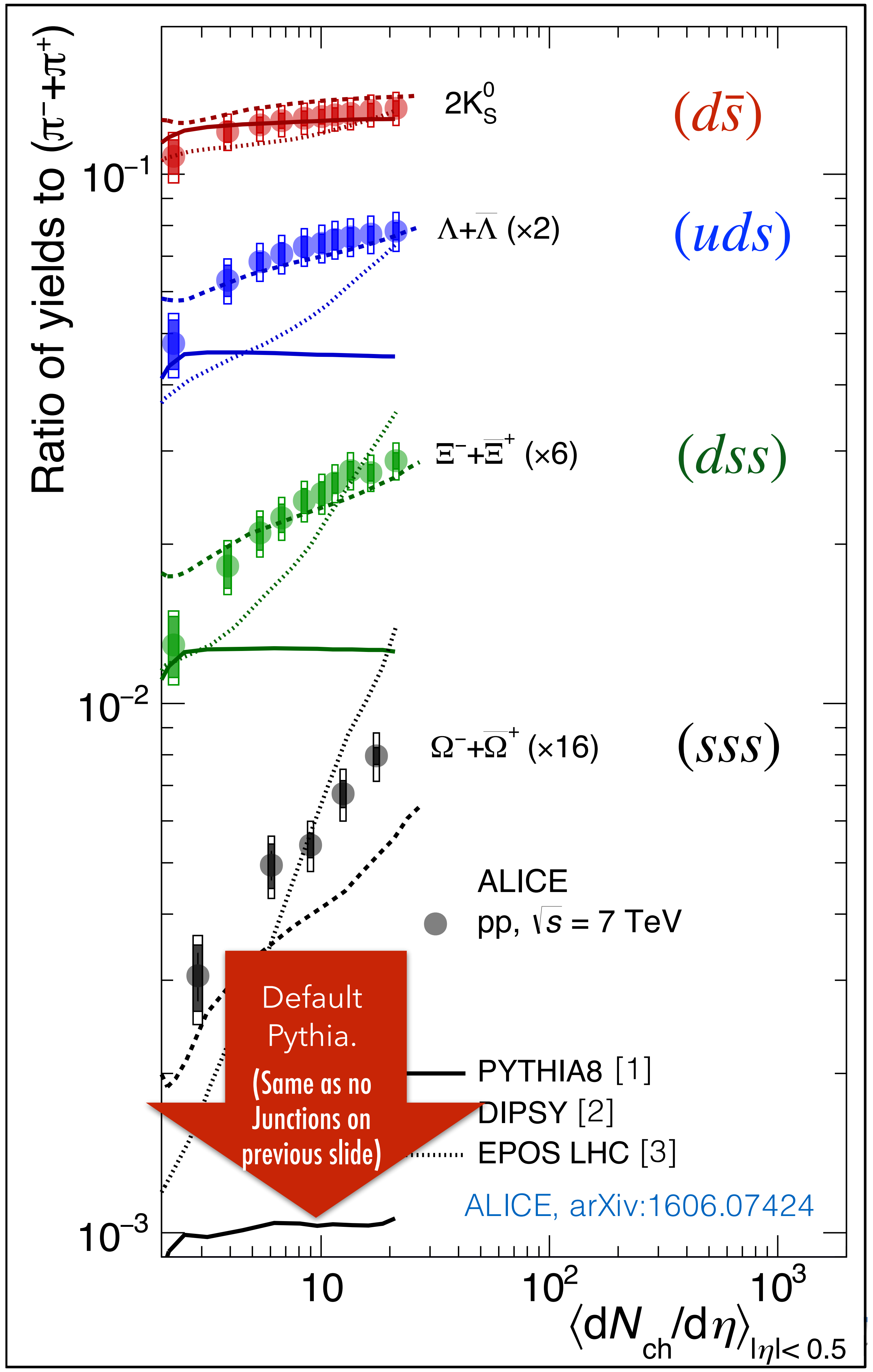
We know ratios of strange hadrons to pions strongly increase with event activity

Landmark measurement by ALICE (2017)



June 2017

What could be driving this?



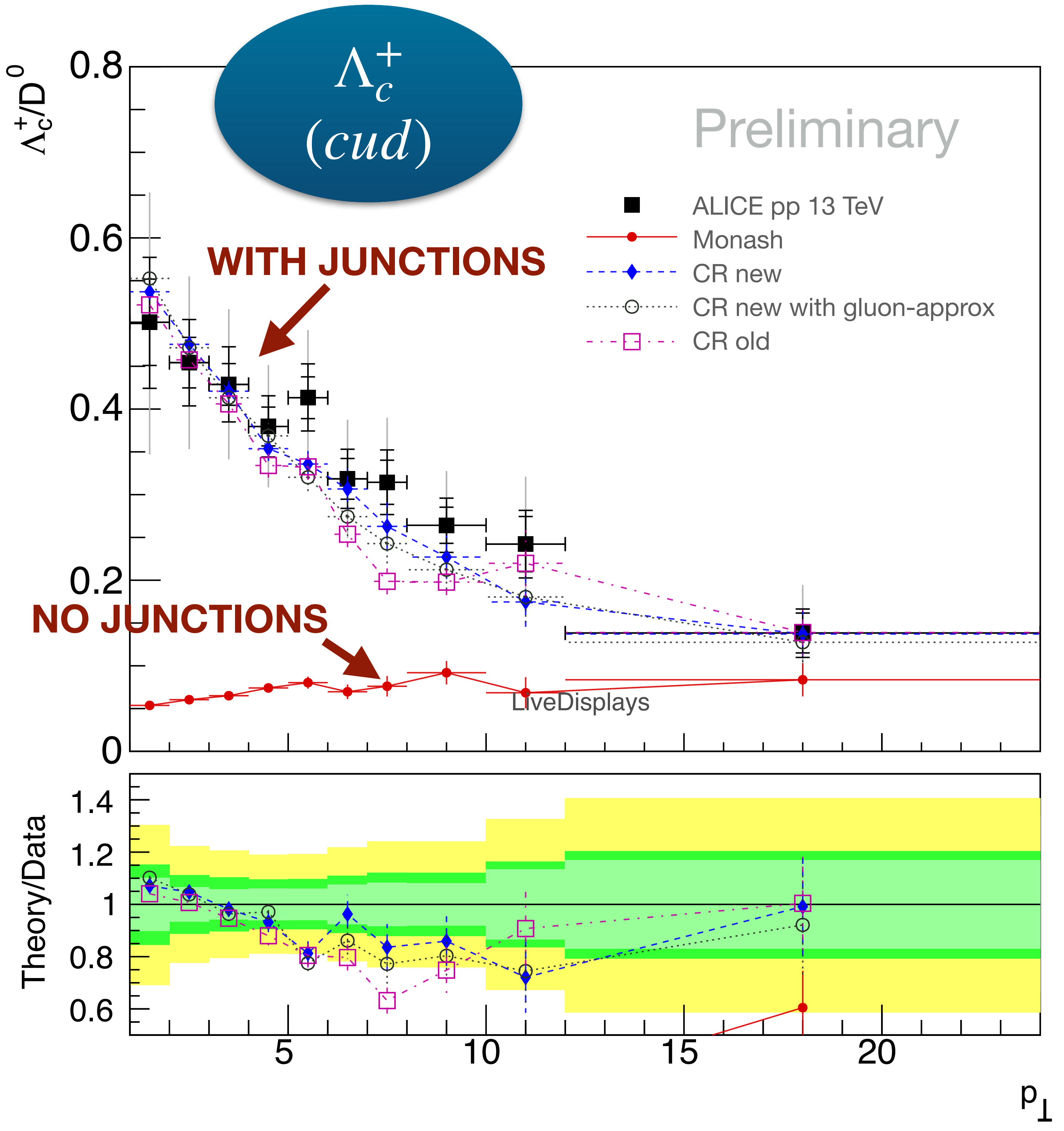
ALICE, arXiv:1606.07424

Default Pythia.
(Same as no Junctions on previous slide)

NEW

Confront with Measurements

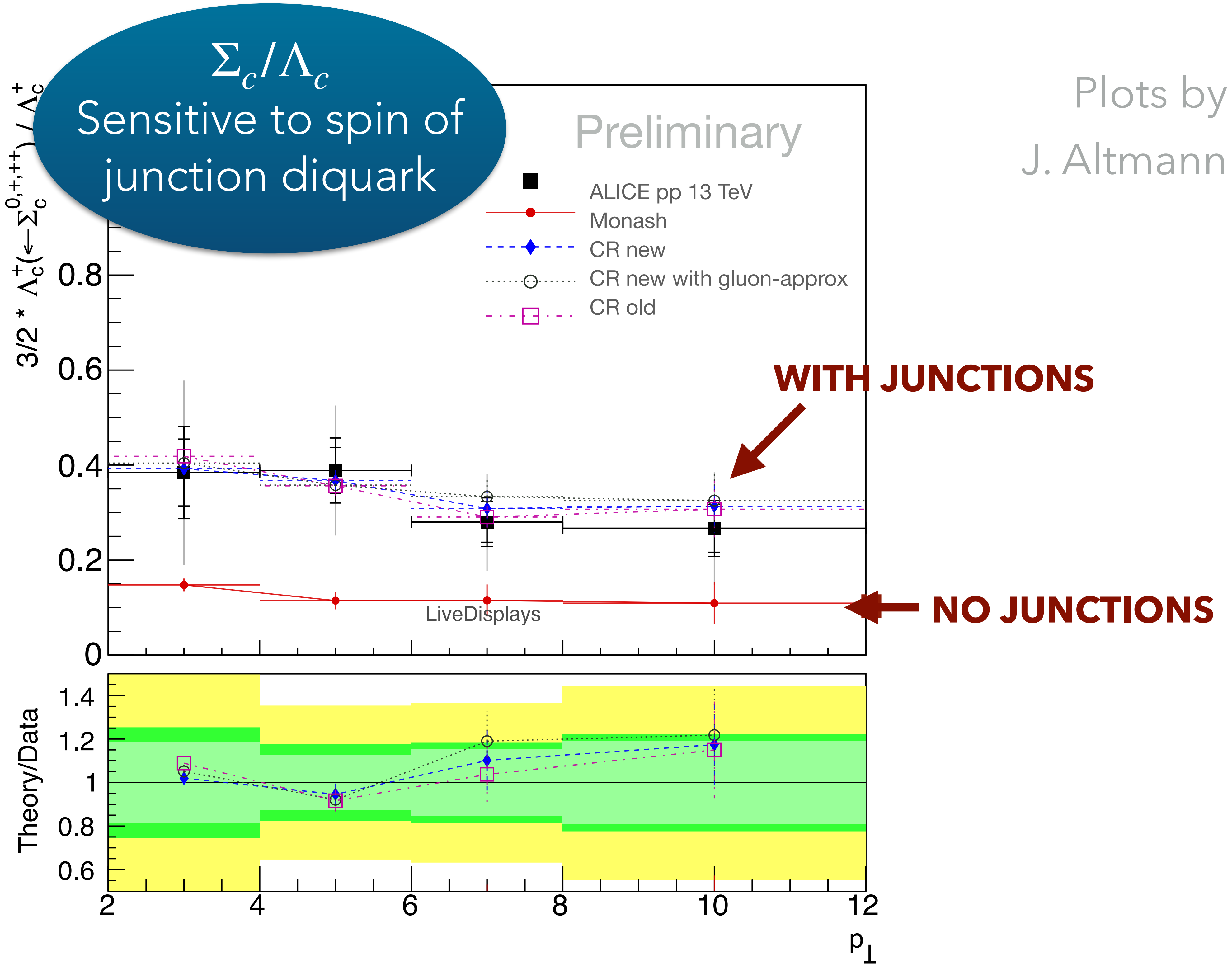
LHC experiments report very large (factor-10) enhancements in heavy-flavour baryon-to-meson ratios at low p_T!



Λ_c^+ (cud)

WITH JUNCTIONS

NO JUNCTIONS



Σ_c/Λ_c
Sensitive to spin of junction diquark

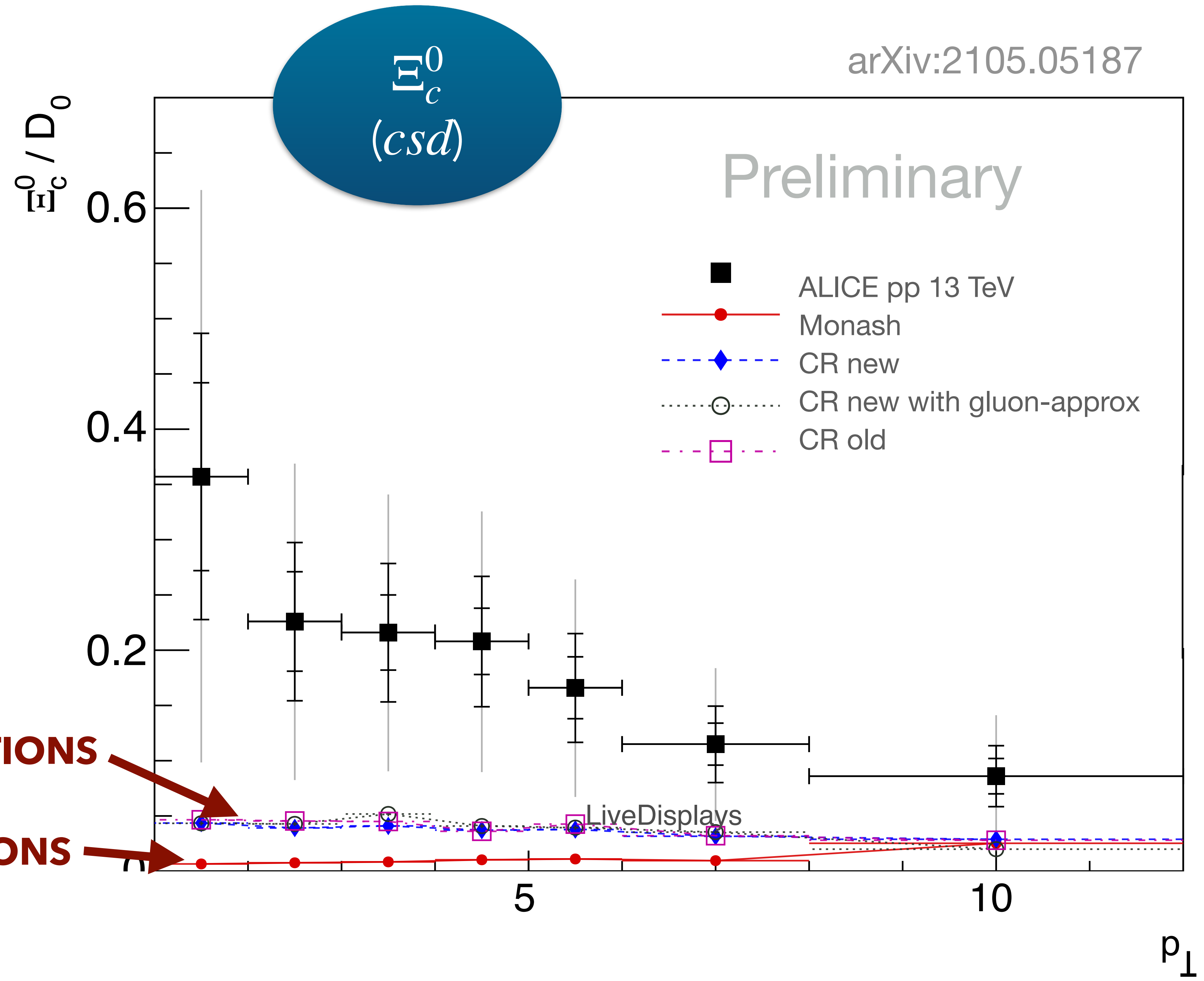
WITH JUNCTIONS

NO JUNCTIONS

Plots by
J. Altmann

Confront with Measurements: **Strangeness**

What about Strange heavy-flavour baryons ?



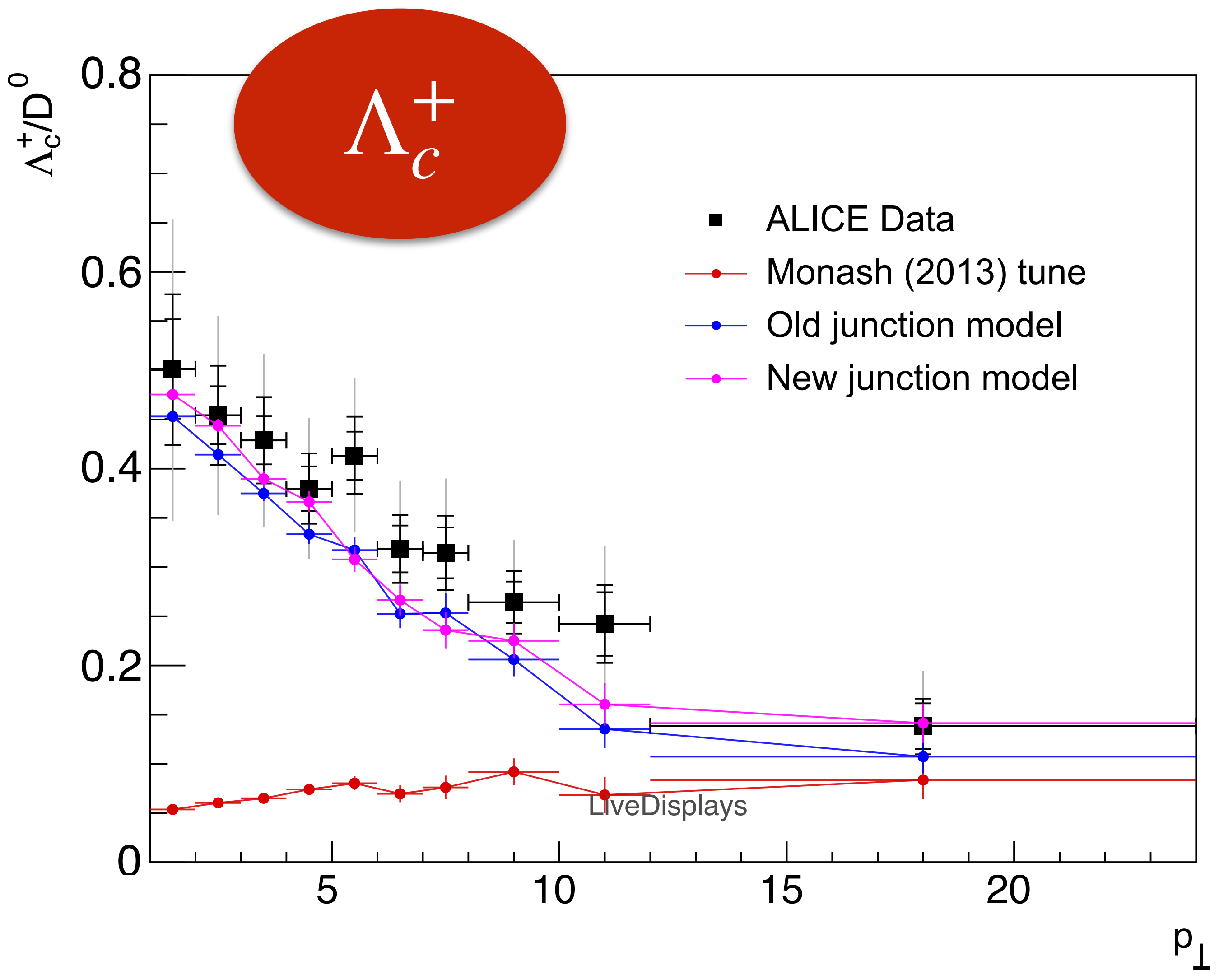
arXiv:2105.05187

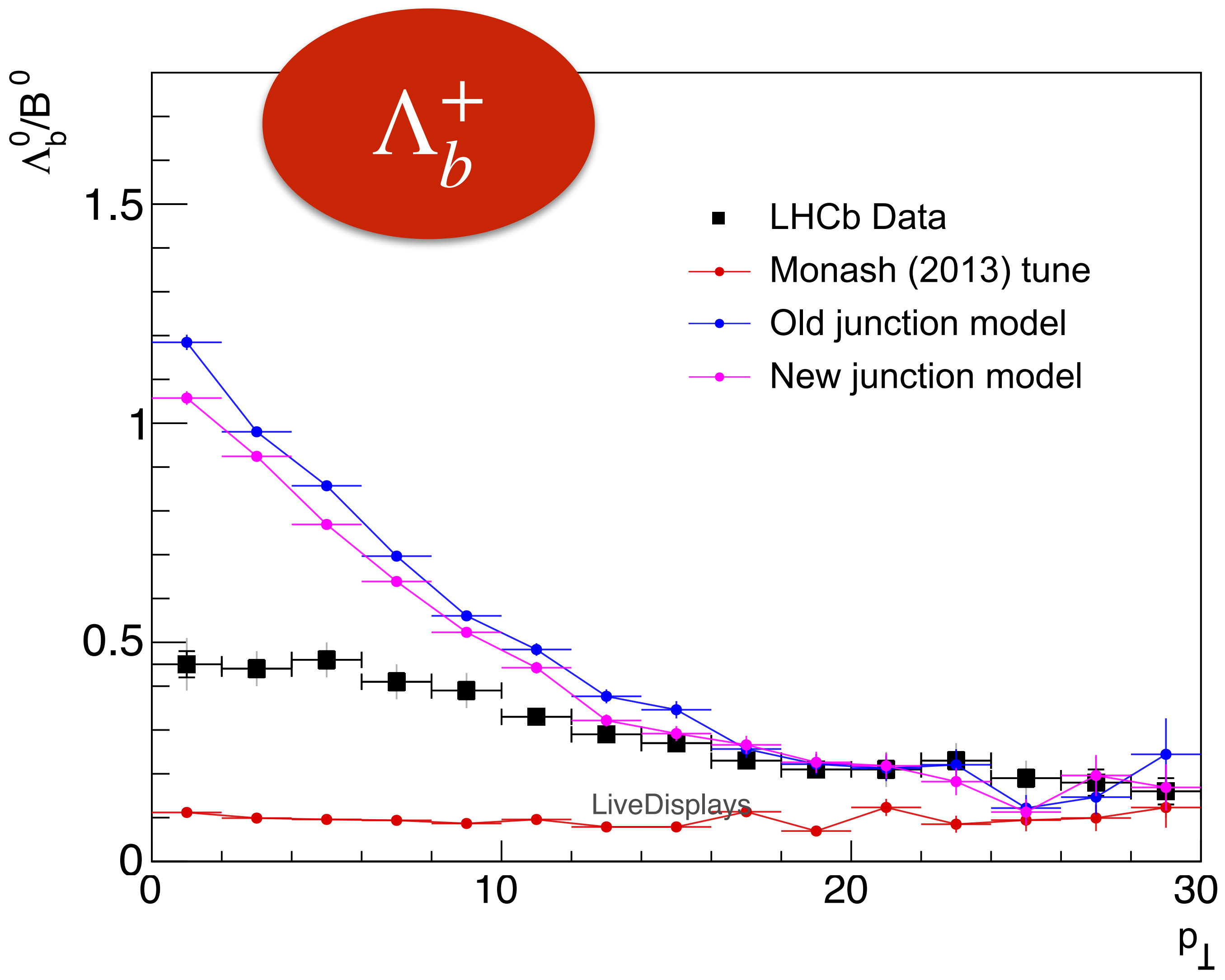
WITH JUNCTIONS

NO JUNCTIONS

Slide adapted from J. Altmann

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