QCD-based Colour Reconnections in Pythia - Status and Prospects

Peter Skands (Monash U)

Disclaimer: This talk is about pp

1. **Brief reminder:** Colour Flow and Colour Connections

2. **QCD-based Colour Reconnections in Pythia ➤ More Baryons** [Christiansen & PS, arXiv:1505.01681]

3. **+ (new) Close-packing model ➤ More Strangeness**

   (+ p_T broadening & further baryons)

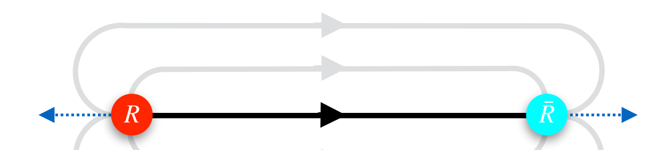
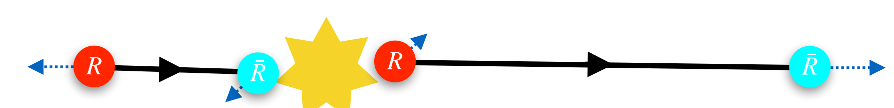
   Similar to colour ropes, with simplified (computationally fast) formulation in momentum space.

   Work started with Monash student **Javira Altmann**. Expect in Pythia during 2022 (?)

4. **Outlook**

Heavy-Ion Physics at High Energy
November 2021, Padoa

Hadronisation is the dynamic realisation of colour **confinement**

Physics	Pythia (Lund Model)
For example, a red colour charge will stretch a confinement field to nearest anti-red charge	 A (piece of) string
Given sufficient energy (separation in CM $\gg$ 1 fm $\leftrightarrow$ invariant mass $\gg$ 1 GeV), confinement field can break down by spontaneous pair creation	 String breaks

Any (QCD-based) hadronisation model therefore has to address:

1. Between which **partons** should confining potentials form? → "String topology" (dictated by Colour Connections)
2. How does spontaneous pair creation lead to (physical) **hadrons** (+ hadron spectra)? → Flavour parameters and Fragmentation Functions (longitudinal & transverse)

High-energy collisions with QCD bremsstrahlung + multi-parton interactions
➤ final states with very many coloured partons

Who gets confined with whom?

Starting point for (pQCD-based*) **MC generators = Leading Colour limit** $N_C \to \infty$

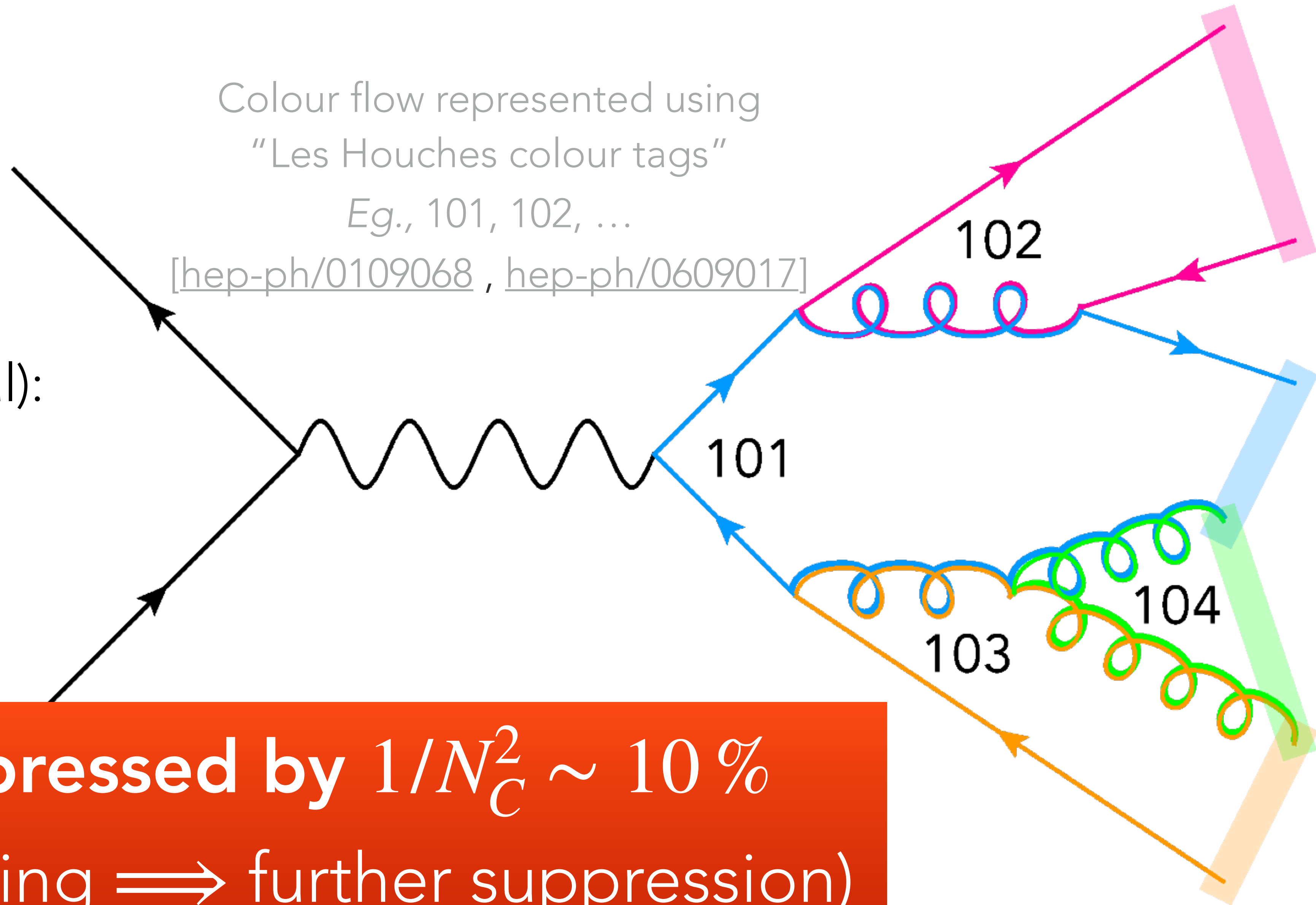
$\Longrightarrow$ Probability for any given colour charge to accidentally be same as any other $\to 0$.

$\Longrightarrow$ Each colour appears only once & is matched by a unique anticolour.

Problem solved!

Example (from upcoming big Pythia 8.3 manual):
$e^+e^- \to Z^0 \to q\bar{q}$ + parton shower

Colour flow represented using "Les Houches colour tags"
Eg., 101, 102, …
[hep-ph/0109068 , hep-ph/0609017]



Naively expect corrections to be suppressed by $1/N_C^2 \sim 10\,\%$
(+ coherence in shower $\Longrightarrow$ angular ordering $\Longrightarrow$ further suppression)

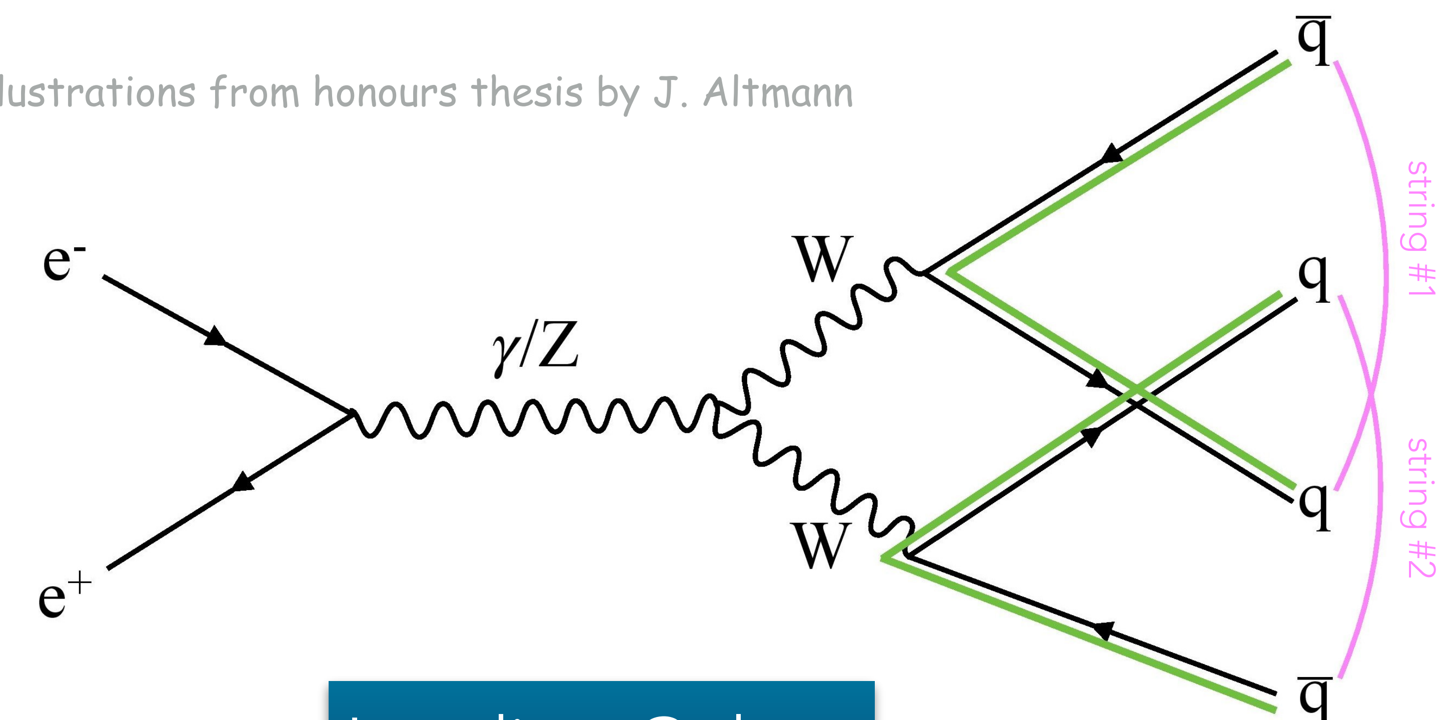
*pQCD = perturbative QCD

Colour Reconnections in Simple Systems

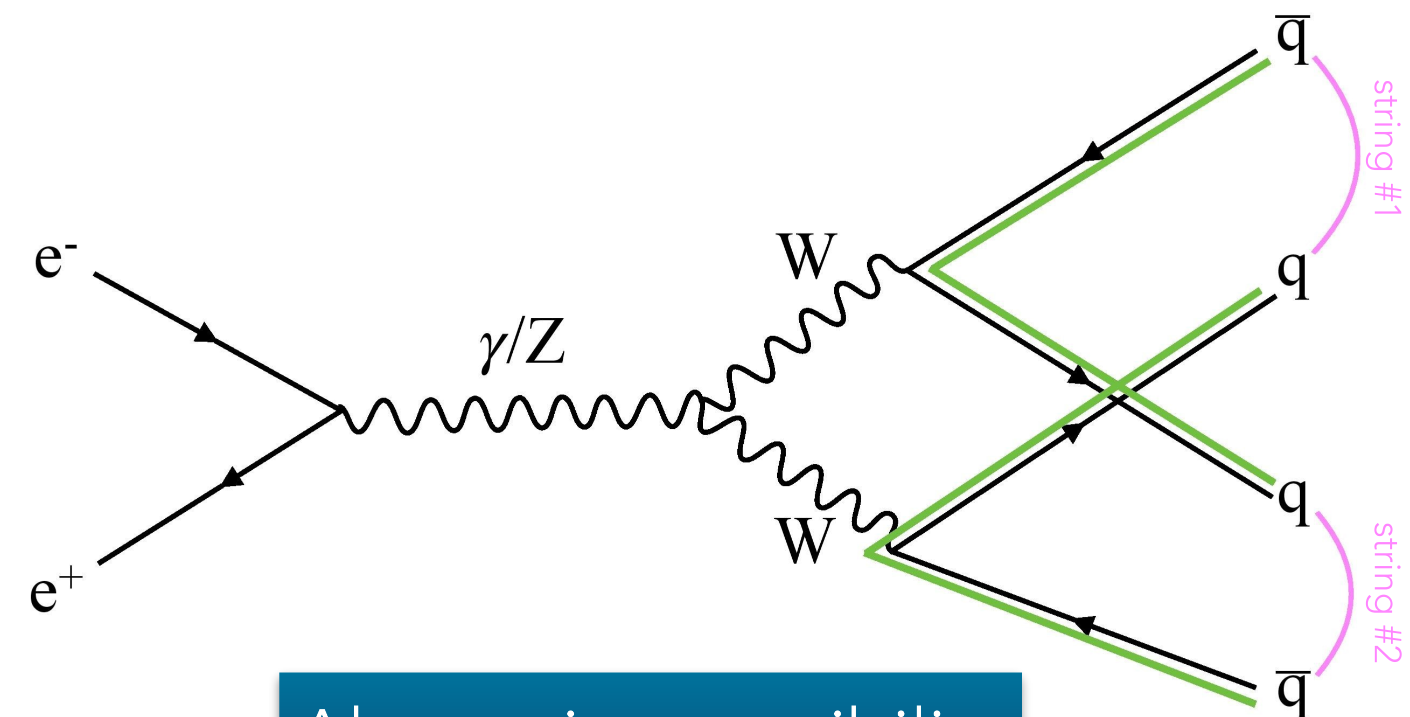
What if I have two parton systems right on top of each other?

Textbook example: $e^+e^- \to W^+W^- \to \mathrm{hadrons}$

Illustrations from honours thesis by J. Altmann



Leading Colour



Alternative possibility

Probability for uncorrelated $q\bar{q}$ pair to **accidentally** be in colour-singlet state follows from $3 \otimes \bar{3} = 8 \oplus 1$
☛ 1 in 9 ☚
= $1/N_C^2$

With a probability of 1/9, both options are possible (remaining 8/9 allow LC only)

- Choose "lowest-energy" one (*cf* action principle) (assuming genuine quantum superpositions to be rare.)

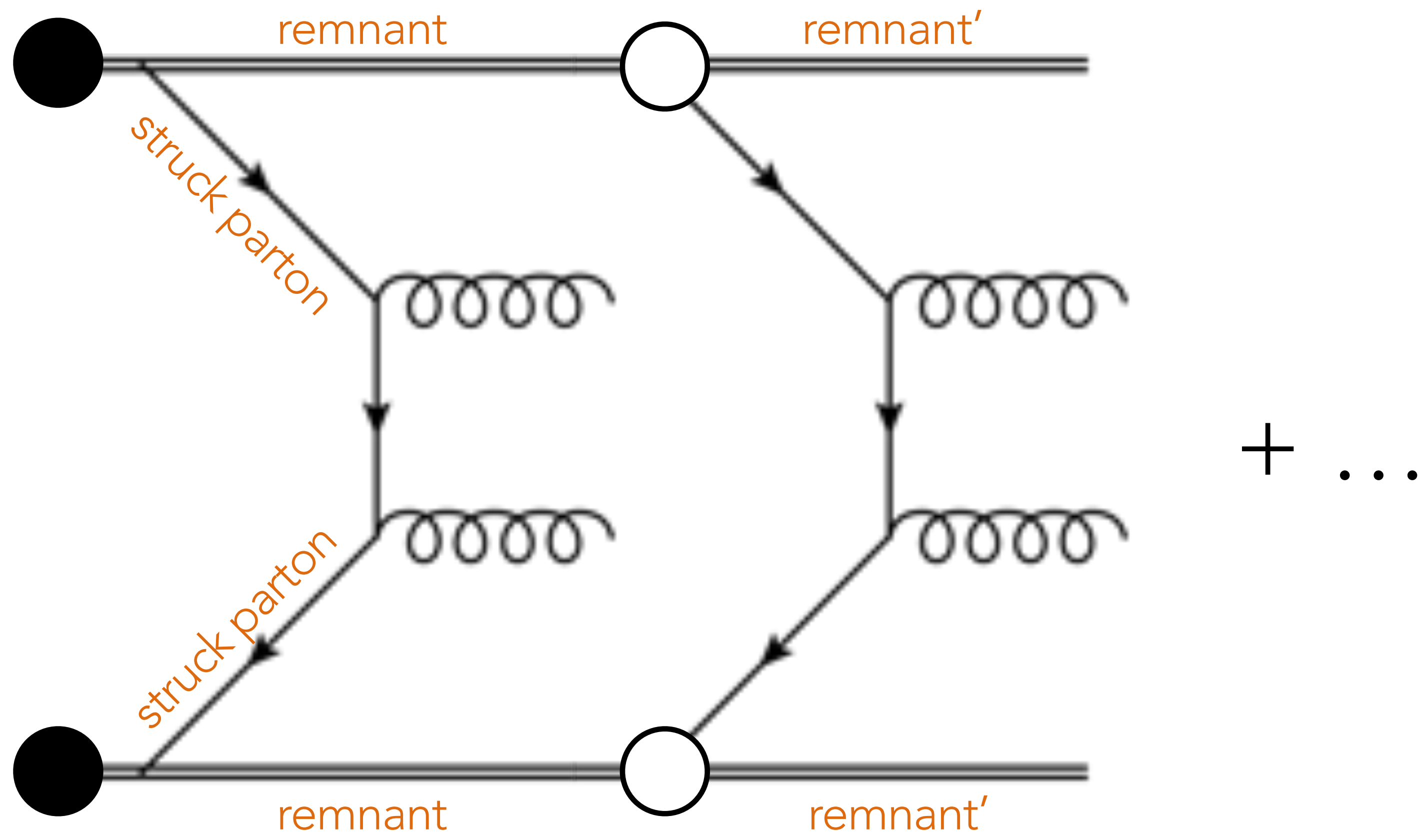
Expect small shift in W mass ("string drag")

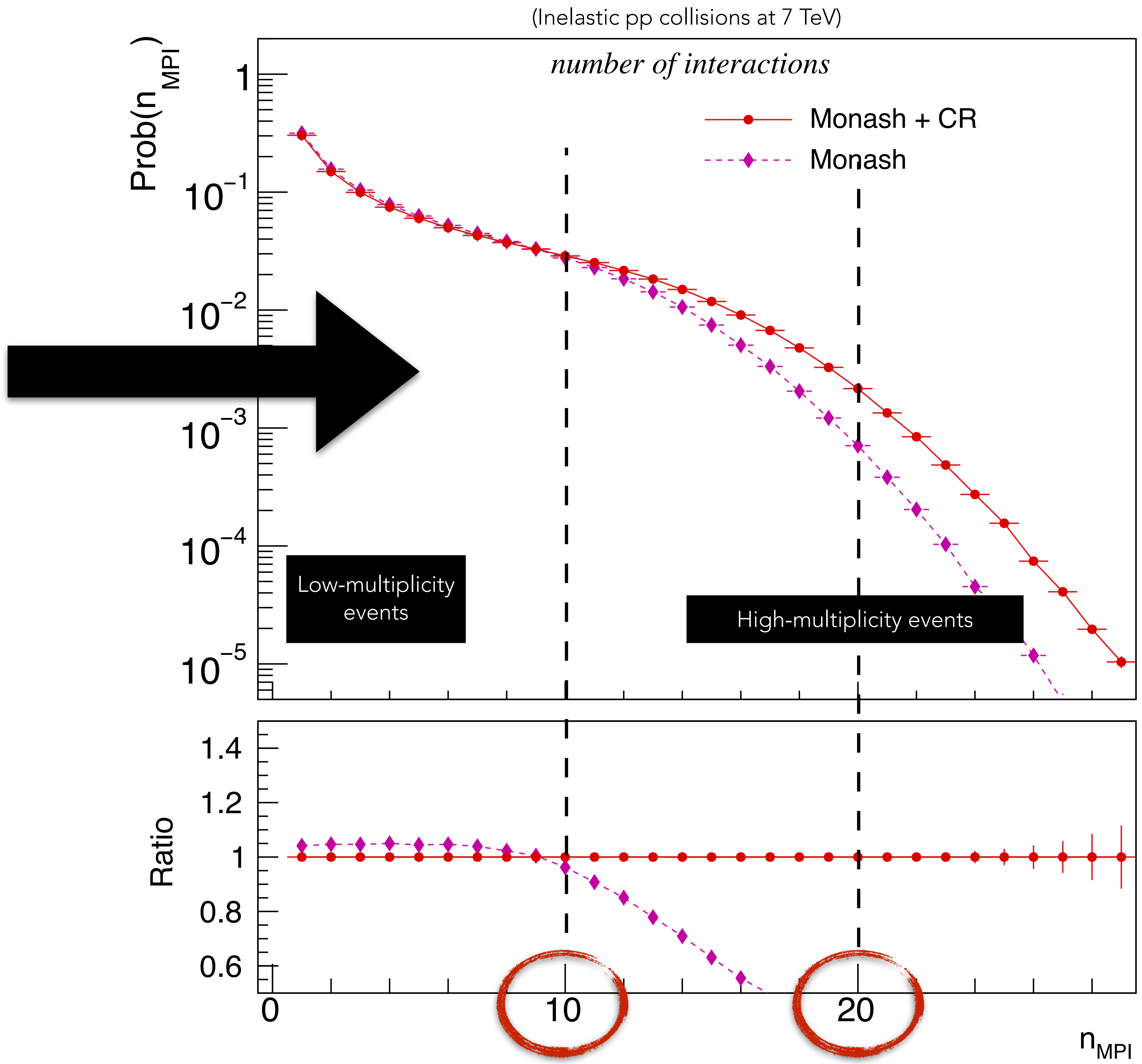
Non-zero CR effect convincingly demonstrated at LEP-2

- No-CR **excluded** at 99.5% CL [Phys.Rept. 532 (2013) 119; arXiv:1302.3415]
- Consistent with $1/N_C^2$ expectation but not much detailed information.

How many parton systems are there in pp collisions?

Multi-Parton Interactions (MPI)





⟹ can have **very** many parton systems within a single pp collision (esp. in high-multiplicity events)

All within ~ transverse size of a proton (= right on top of each other)

+ Combinatorics! Each colour has $1/N_C^2$ to be same as **any** of the others ⟹ CR galore!?

QCD-based CR Model: Rules of the Game

MPI + showers $\Longrightarrow$ partons with LC connections

Idea: restore missing ($1/N_C^2$) colour correlations stochastically. Approximate all **LC-unconnected partons** as uncorrelated and consider SU(3) rules:

(1) $3 \otimes \bar{3} = 8 \oplus 1$ for uncorrelated colour-anticolour pairs (allows "dipole CR")

(2) $3 \otimes 3 = 6 \oplus \bar{3}$ for uncorrelated colour-colour pairs (allows "junction CR")

Technically: done by assigning all partons "colour indices" from 0 to 8.

E.g., any parton given colour index 0 can be confined with any parton with anti-index 0.

- This reproduces the 1/9 stochastic probability in **eq.(1).**

Index 0 can also combine with *two* other partons (with indices 3 and 6) representing the confining (colour-neutral) combination of R, G, and B

- This gives a decent approximation to the 3/9 probability in **eq.(2)**.
- Represented by "string junctions" in Pythia [hep-ph/0212264] $\Longrightarrow$ a new source of baryons and anti-baryons.

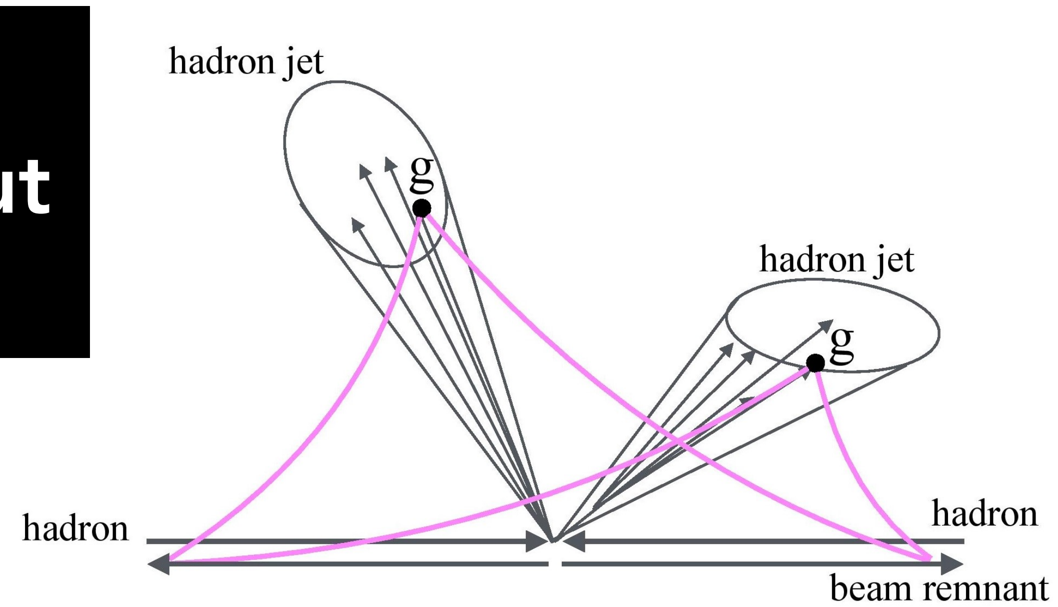
Finally, choose between which ones to actually set up confining potentials

Smallest measure of "invariant string length" $\propto$ number of hadrons produced ("λ measure")

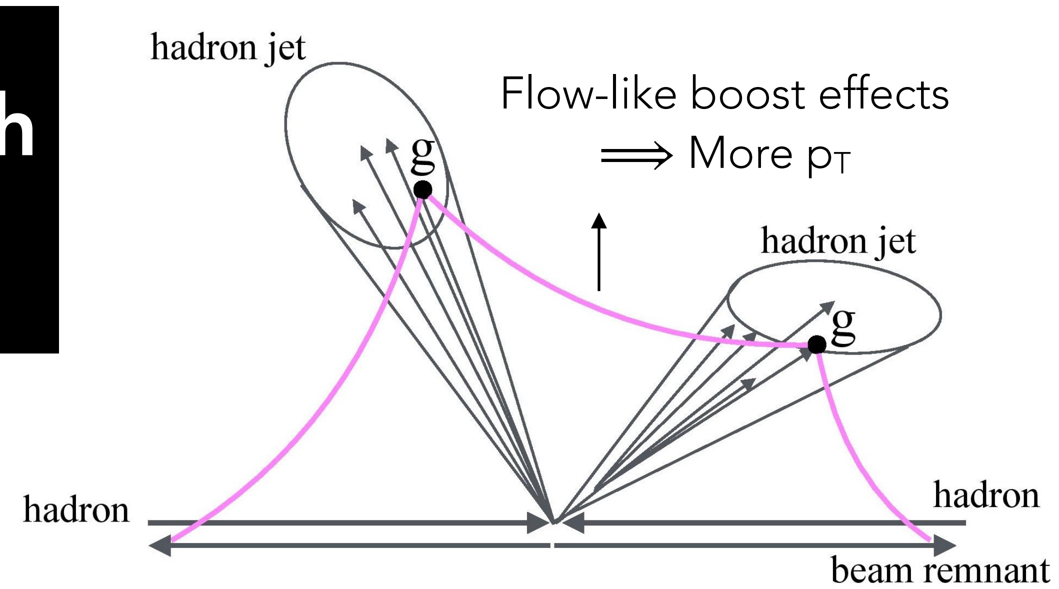
- (Subtleties include precise definition of λ measure, baryon-"junction" vs dipole λ measures, mass effects, handling of causality, …; current implementation is imperfect & definitely not final word.)

Original Goal: Provide a well-motivated theoretical underpinning for CR, capable of describing CR-sensitive observables like <p_T>(n_{ch})

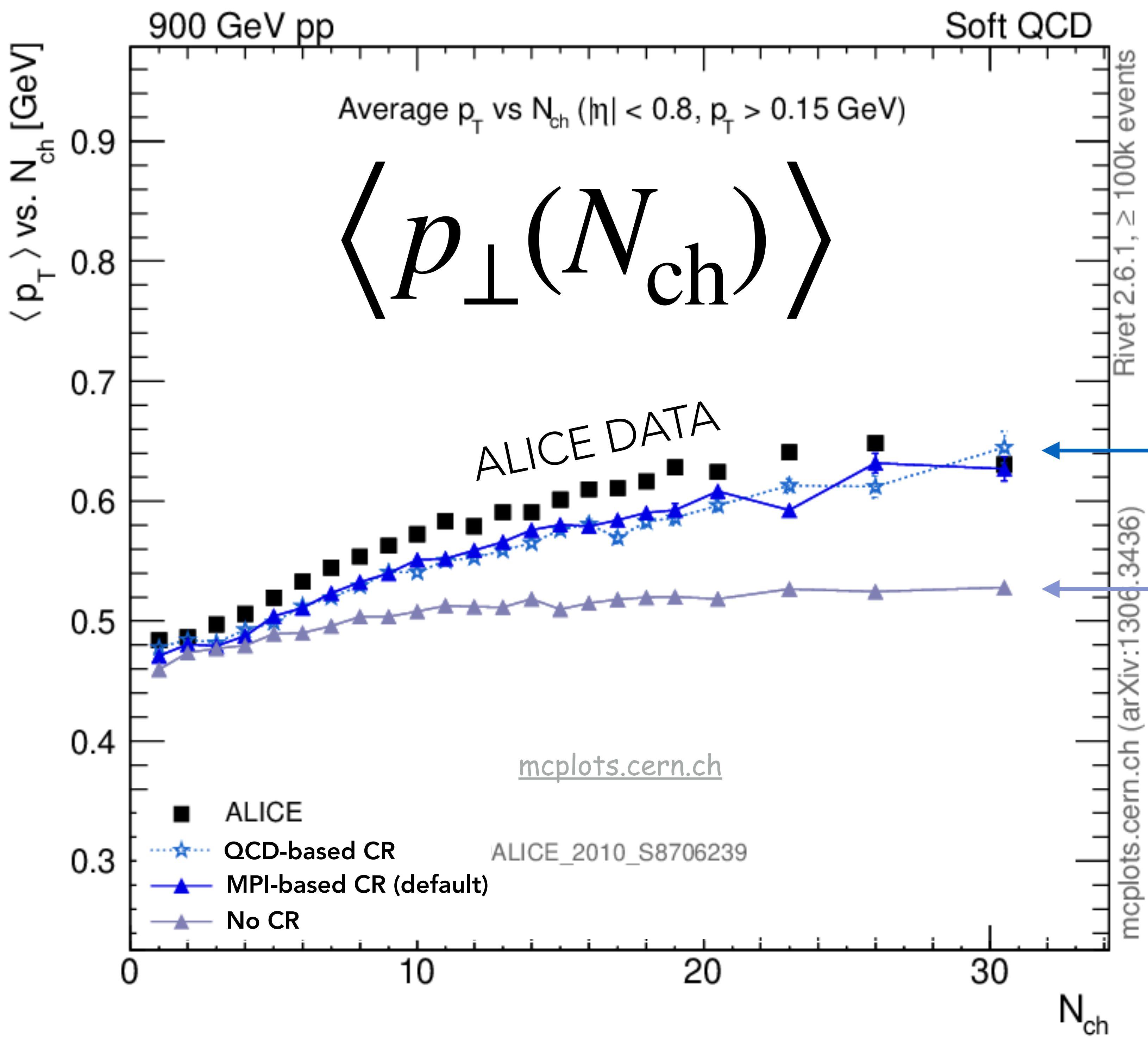
MPI without CR:



MPI with CR:



Note: for more on flow-like effects from CR, see also, e.g., Ortiz Velasquez et al. arXiv:1303.6326



Both **MPI-based** (default) and **QCD-based** CR reproduce the rising trend of <pT>(N_{ch})

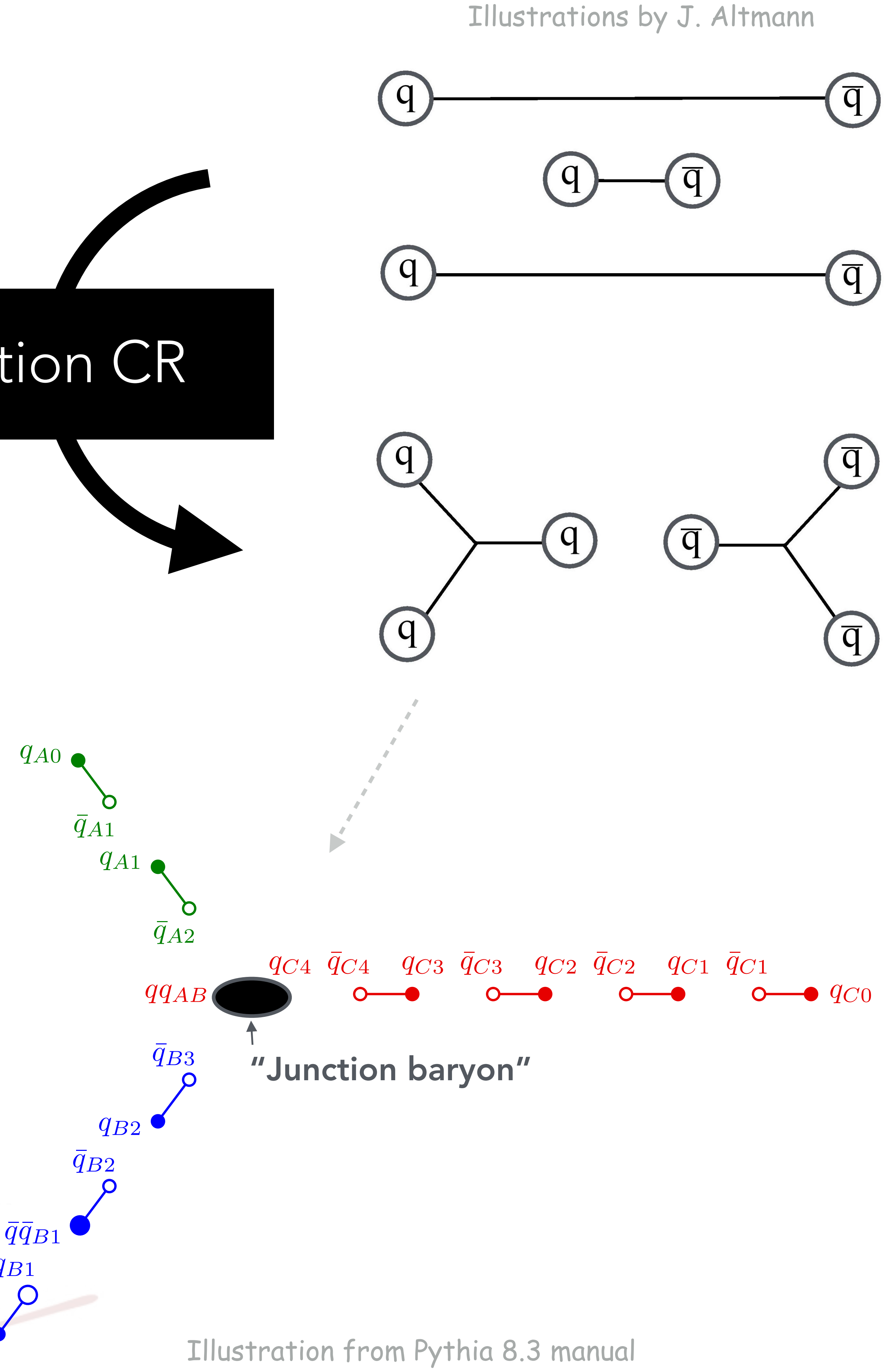
No CR ⟹ <p_T> approximately the same for all N_{ch}
(Many MPI just produce more hadrons, but with ~ same spectra)

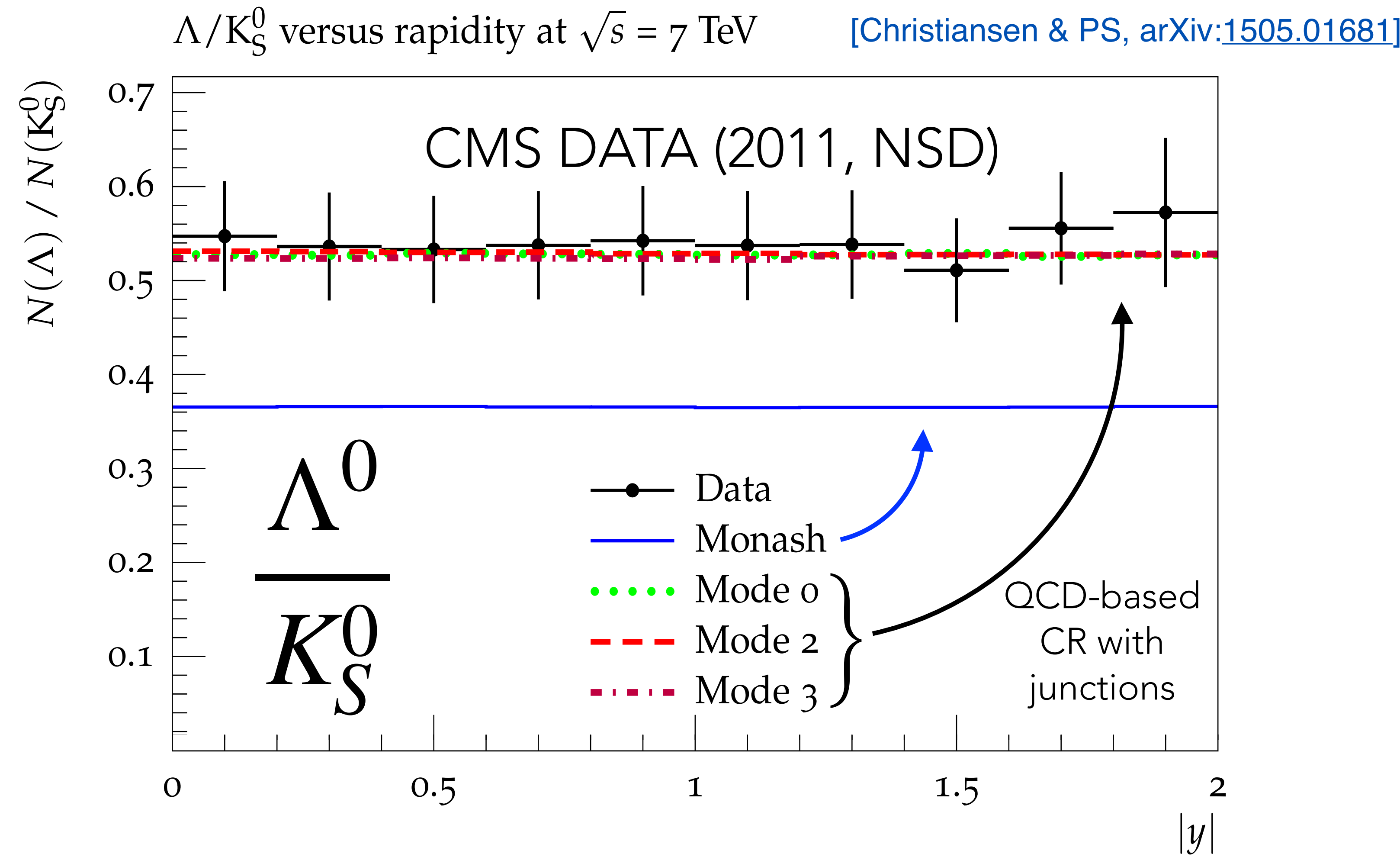
(Just one example here, that I could easily obtain from mcplots.cern.ch; with minor differences all other CM energies and fiducial cuts show same trend)

+ New junction-type CR ⟹ Increased Baryon-to-Meson ratios

new!

Junction CR



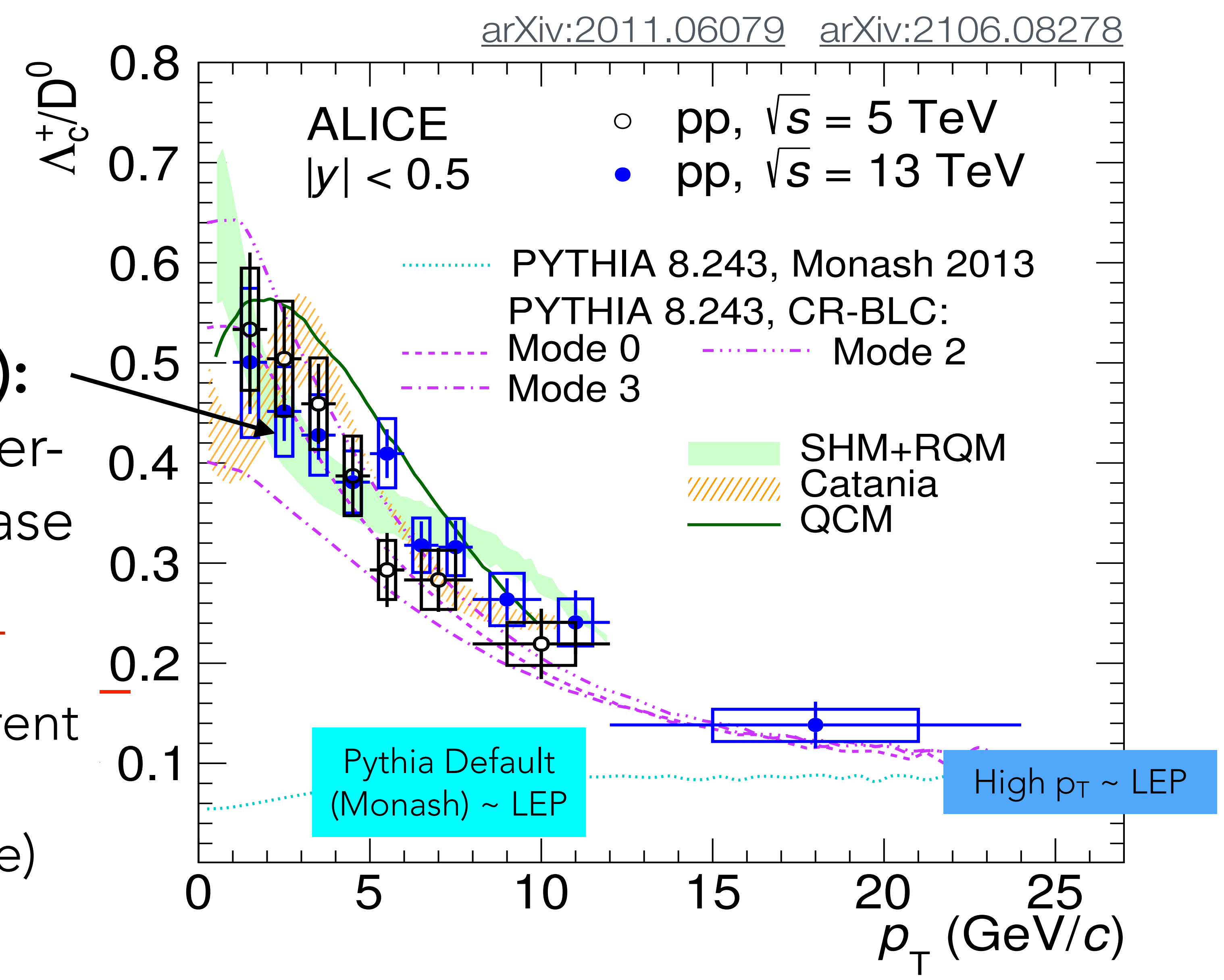


ALICE 2021: also in charm

QCD CR model(s):

Junctions drive order-of-magnitude increase in Λ_c/D^0 at low $p_\perp$

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



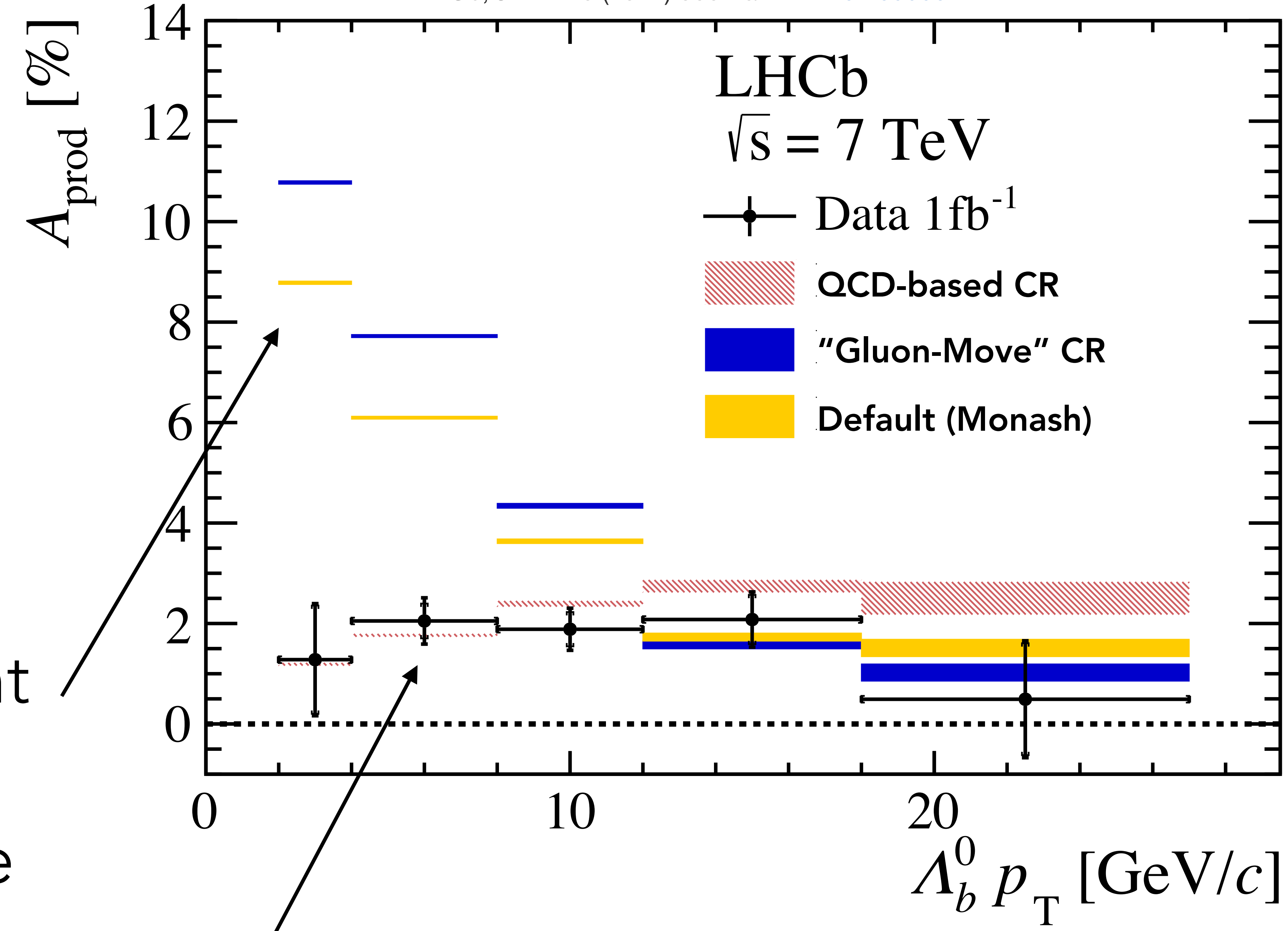
Λ_b asymmetry

$$A = \frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)}$$

Without junction CR, an important source of low-p_T Λ_b production is when a b quark combines with the proton beam remnant.

Not possible for $\bar{\Lambda}_b$ (no $\bar{p}$ remnant at LHC)

LHCb, *JHEP* 10 (2021) 060 • arXiv: 2107.09593

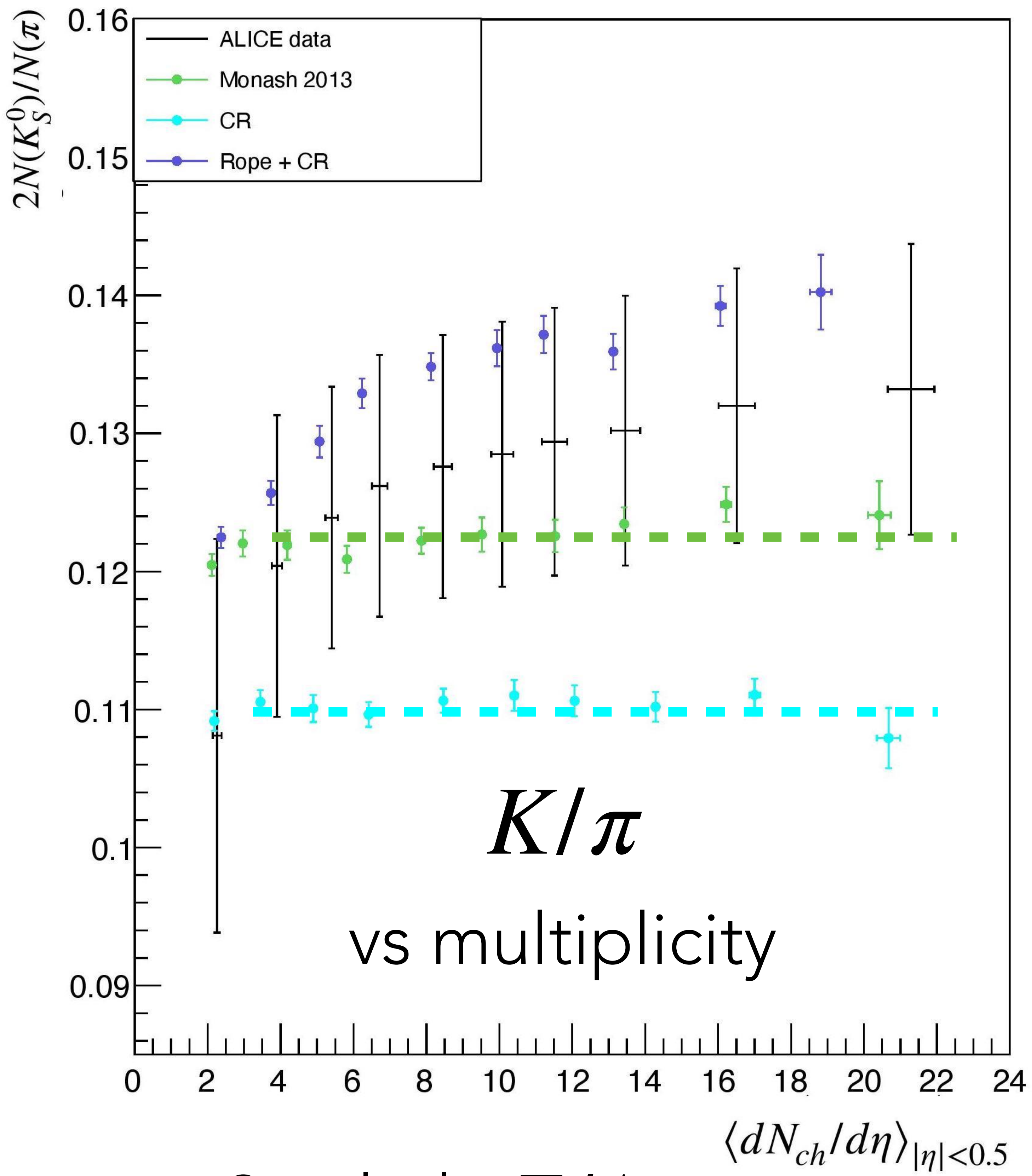


QCD CR adds large amount of low-p_T junction Λ_b and $\bar{\Lambda}_b$, in equal amounts. Dilutes asymmetry!

QCD-CR is not a mechanism for strangeness enhancement

When we look at "steps in strangeness", we see disagreements

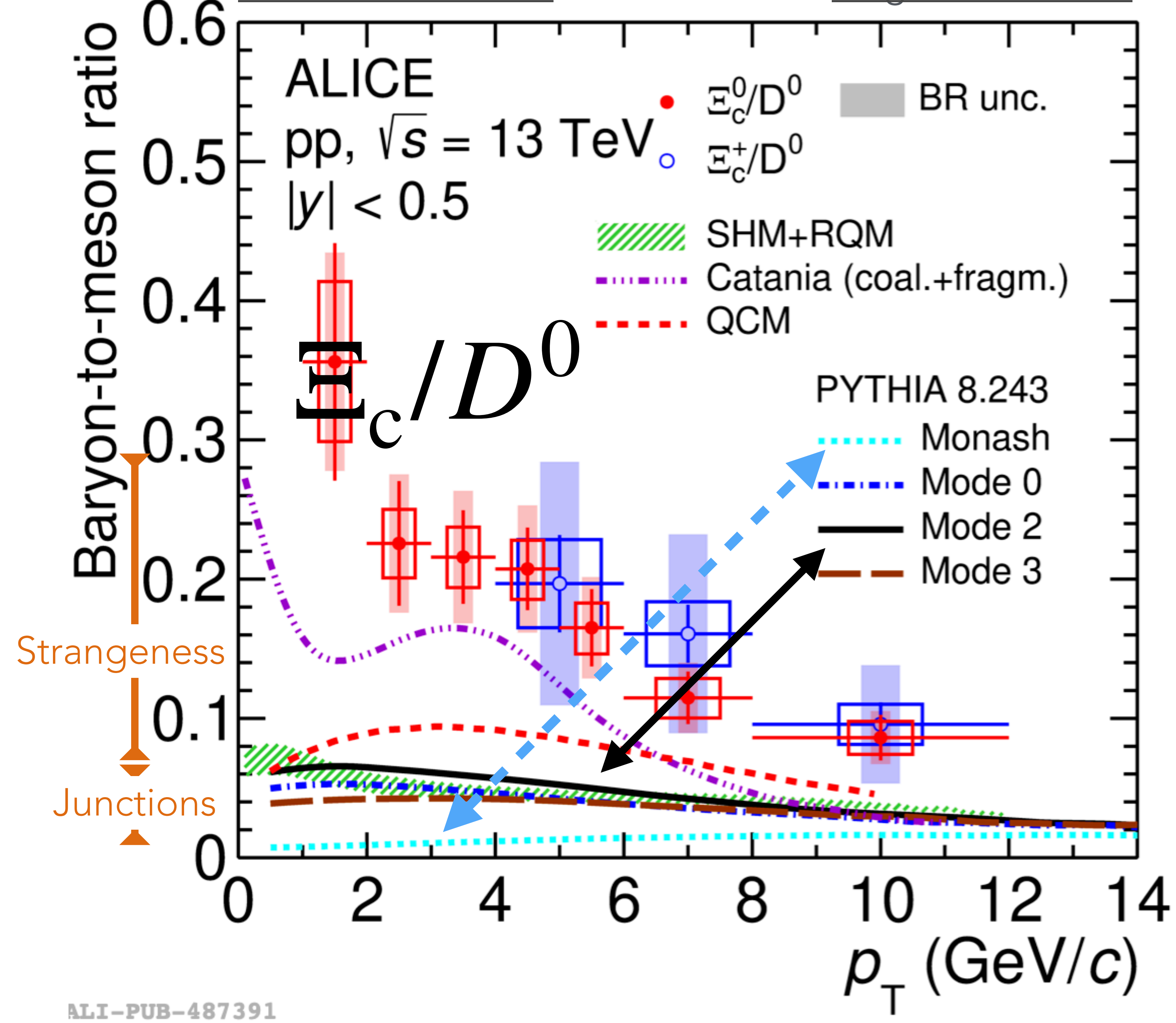
Ratio of yields of K_S to π vs charged multiplicity



Similarly, $\Xi/\Lambda, \ldots$

ALICE 2021: also in charm

arXiv:2105.05187 talk Luigi Dello Stritto



"Close Packing" of strings

Even with CR, high-multiplicity events still expected to involve multiple overlapping strings.

Interaction energy $\Longrightarrow$ higher effective string tension (similar to Colour Ropes)

$\Longrightarrow$ strangeness (& baryons & <p_T>)

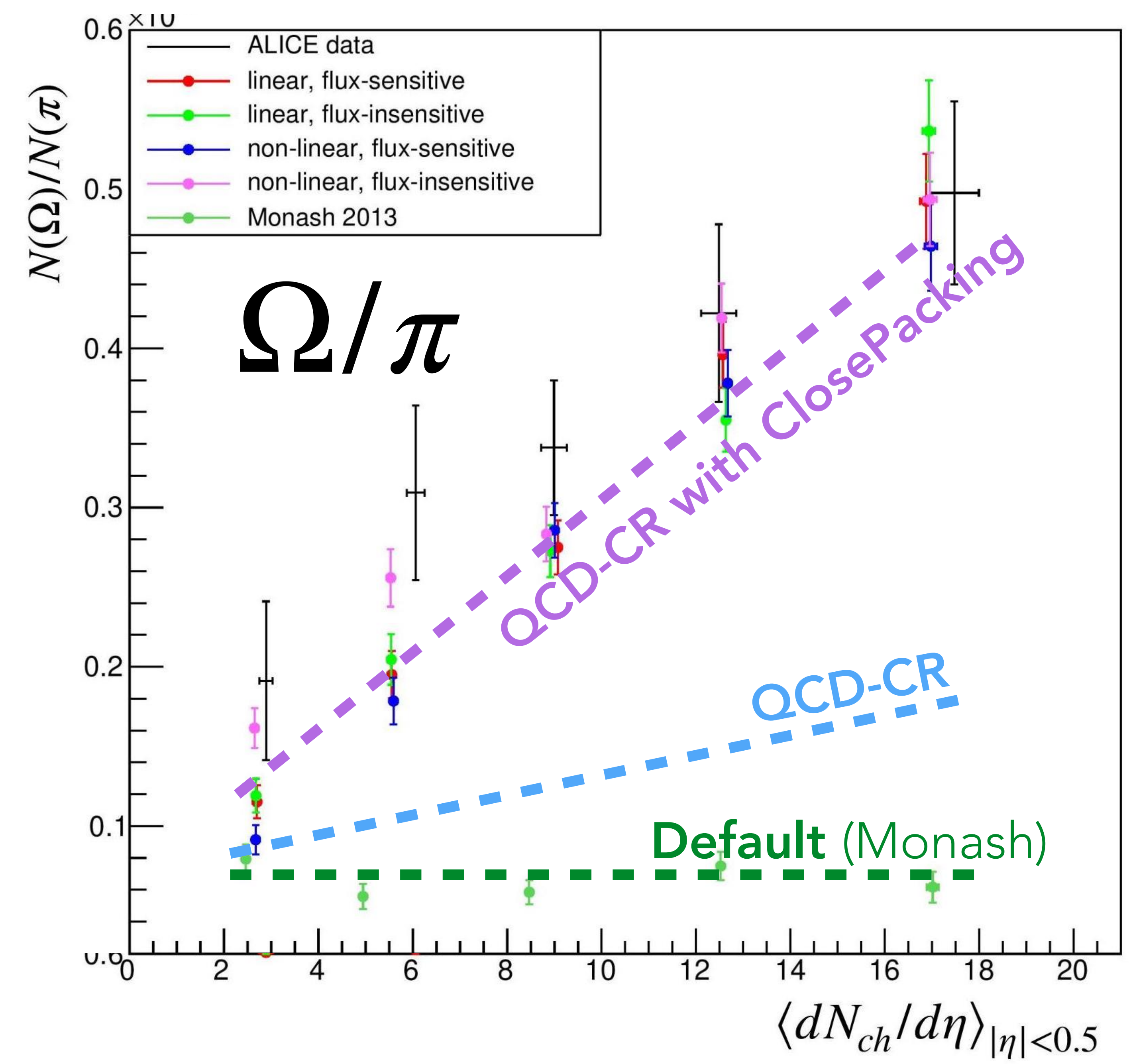
Current close-packing model in Pythia only for "thermal" string-breaking model

[Fischer & Sjöstrand, *JHEP*01(2017)140,arXiv:1610.09818]

Interesting in its own right!

2021: Monash student J. Altmann extended it to conventional string-breaking model and began the (complicated) work to extend to junction topologies. Work in progress!

Preliminary result from Javira's honours thesis



Summary

[Christiansen & PS, JHEP08(2015)003, arXiv:1505.01681]

The QCD-CR model in Pythia (ColourReconnection:mode = 1)

Physically well-motivated paradigm for CR. Based on stochastic sampling in $SU(3)_C$.

New aspect: Junction Baryons

➤ Increased **baryon-to-meson ratios**, especially at low p_T

➤ Dilution of **baryon asymmetries** (junctions always come with anti junctions)

Also expect junction baryons to exhibit quite different baryon-antibaryon **correlations** : experimental tests? (+ these baryons are probably ***not* in jets**?)

Too many protons: could they annihilate by rescattering?

It produces some flow (via boosted strings) but not enough / not right kind? Supplement by shoving / repulsion / rescattering ?

It does *not* increase strangeness: Supplement by ropes / close-packing?

"Just" a single MCnet student project (cf laundry list). Impressive new LHC results (esp heavy flavour) ➤ Renewed interest in tying up loose ends.

Loose Ends: Interplay with Measurements

QCD-CR $\Longrightarrow$ too many protons already at low N$_{ch}$

Can Pythia's new **hadronic rescattering** model help by annihilating away the excess?

Sjöstrand & Utheim, arXiv:2005.05658

Junction Diquarks: need better **constraints** (& more physics?)

`ProbQQ1toQQ0join` = { ? , ? , ? , ? } affects eg spin-3/2 vs spin-1/2 baryons.

Measurement constraints?

+ *Multiply-heavy* baryons (Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, …): **only** made by junctions.

Updated QCD-CR tuning would be timely.

(Monash tune was made in 2013, QCD-CR baseline ones in 2015.)

Should include new LHC data and modern PDFs with more strangeness.

Have been procrastinating until close-packing could be included… → 2023 ?

String rescattering (repulsion / shoving) $\Longrightarrow$ Flow, p_T spectra.

A close-packing version of **shoving**? Proof of concept: Duncan & PS arXiv:1912.09639

+ Heavy Ions?

Momentum-space formulation assumes everything starts in a point. Not enough for HI.

Increasing efforts to add space-time information - but so far not used in CR / CP models.

MCnet

Loose Ends: Technical

Diffraction

Current QCD-CR implementation breaks for **diffractive events (errors)**.

$\Longrightarrow$ Probably unreliable for low-N_{ch} INEL. Needs work.

Heavy Quarks

Neither CR nor junction fragmentation were specifically designed/optimised for heavy quarks. E.g.: problems finding "junction rest frame" often worse for heavy quarks.

Measurements at LHC ➤ **Dedicated theoretical consideration would be timely.**

+ CR effects in **onia** (J/ψ, Υ)?

Causality

`ColourReconnection:timeDilationMode = 0, 2, 3`: different options for restrictions on CR between systems with relative boosts.

Current options are very crude, probably all are "wrong", to some extent.

(So not enough to just constrain existing options by measurements.)

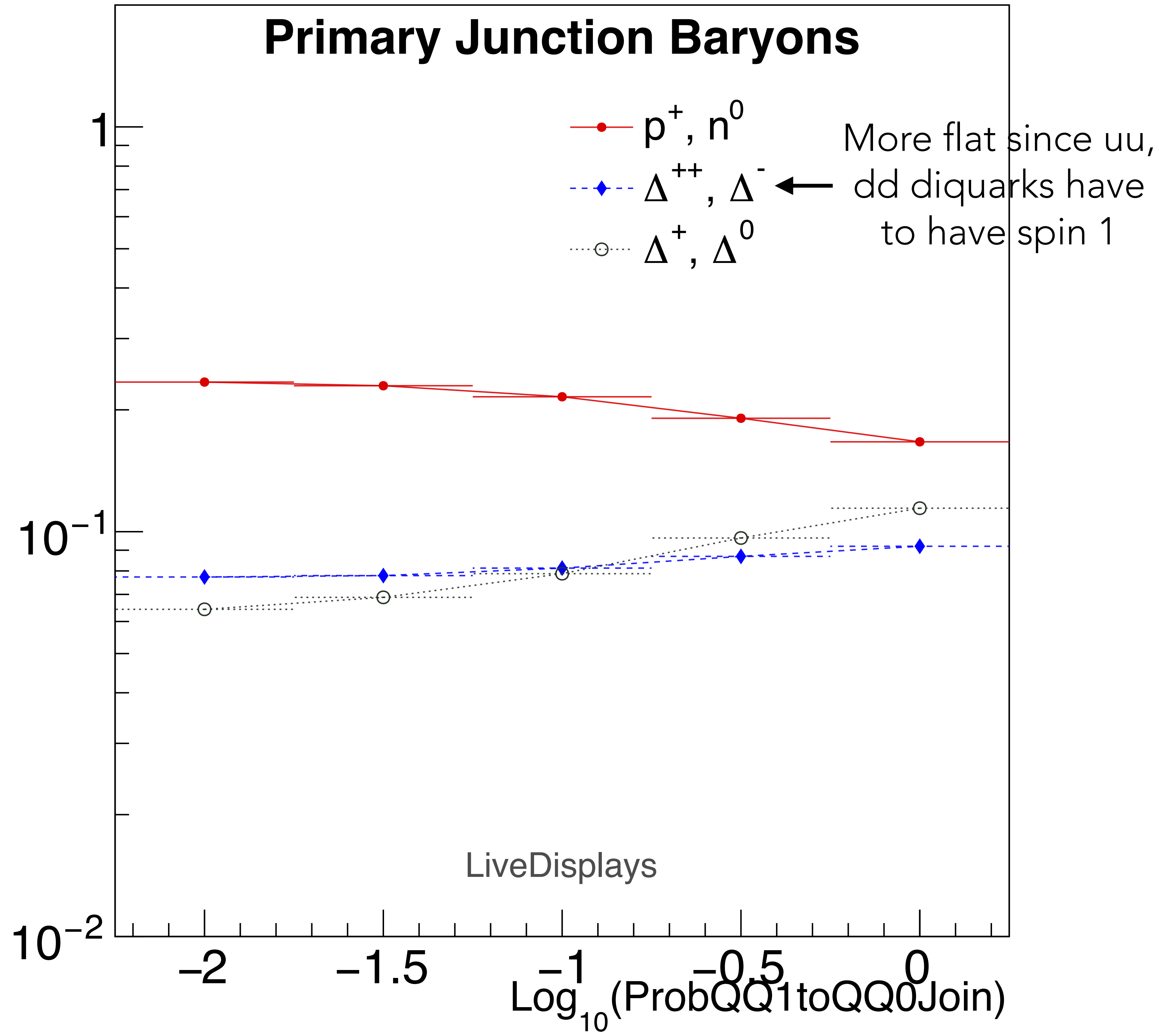
Needs further thought & theoretical work.

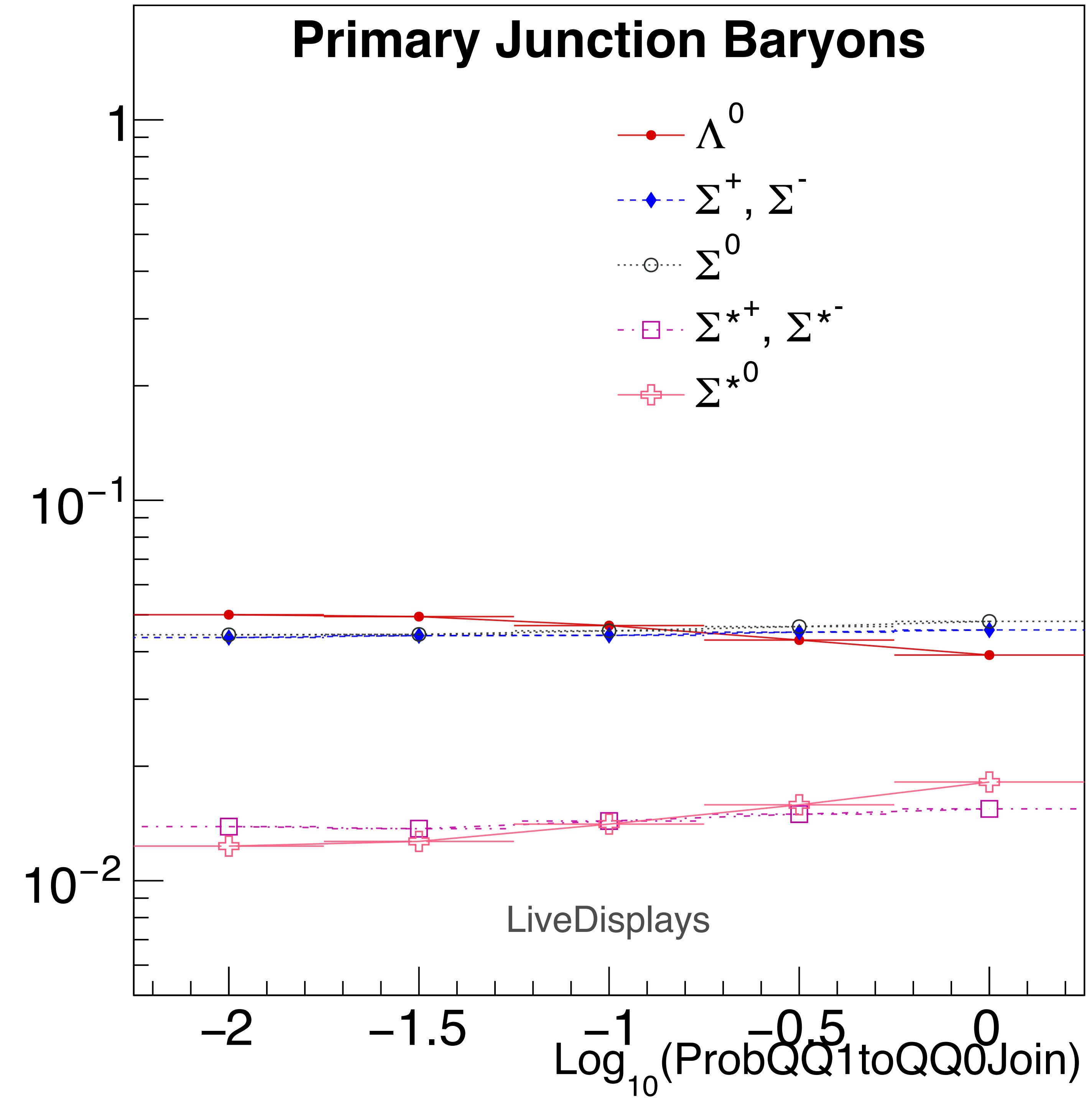
Extra Slides

Effects of ProbQQ0toQQ1Join

`ProbQQ1toQQ0join` = { **?** , 0.1 , 0.1 , 0.1 } (Note: keeping the others at 0.1 was arbitrary, for illustration)

First entry = spin-1 diquark suppression for ud diquarks (uu & dd have to be spin-1)





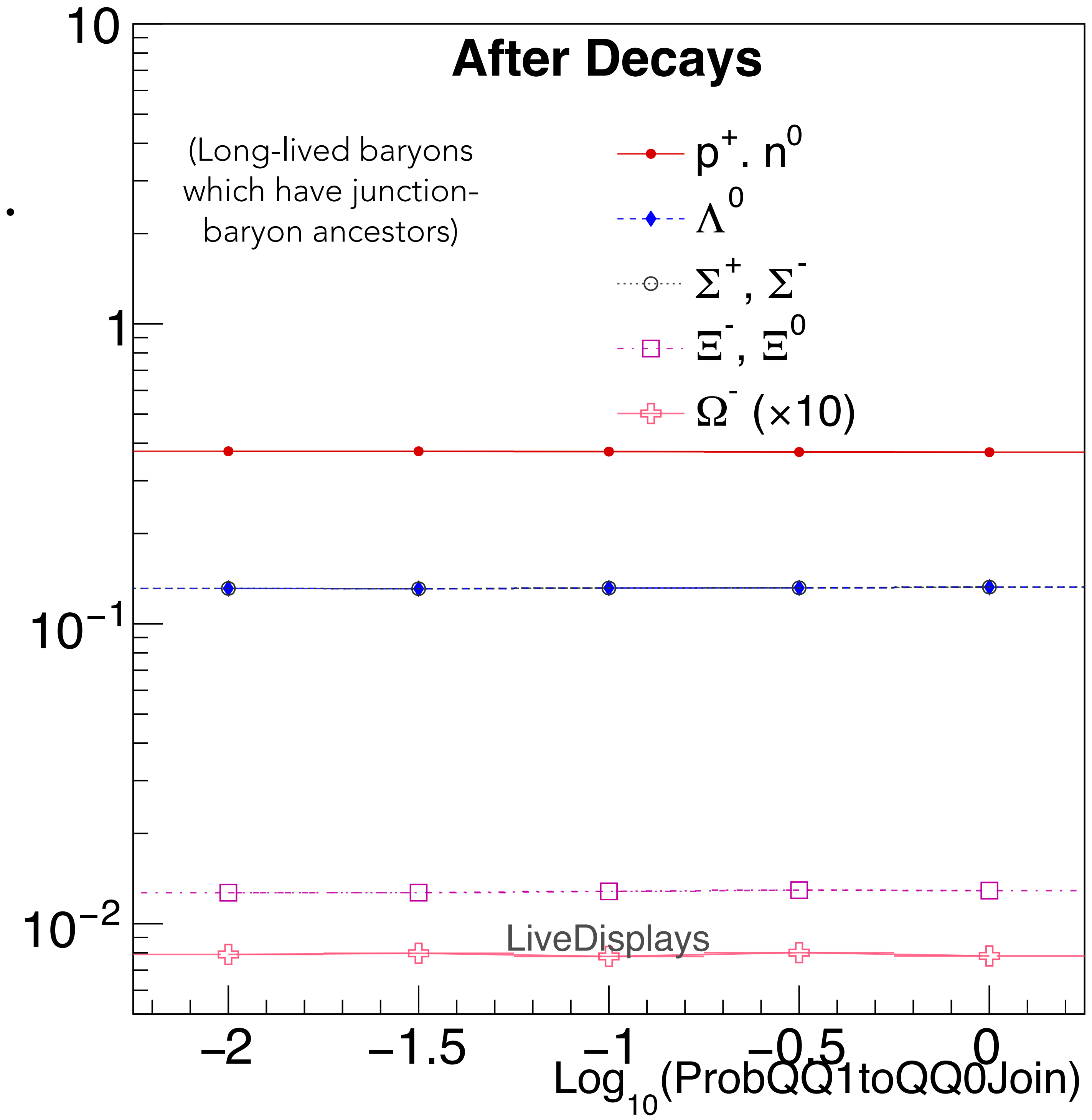
Higher values => more spin-3/2 baryons

Effects of ProbQQ0toQQ1Join

`ProbQQ1toQQ0join` = { **?** , 0.1 , 0.1 , 0.1 }   (Note: keeping the others at 0.1 was arbitrary, for illustration)

First entry = spin-1 diquark suppression for ud diquarks (uu & dd have to be spin-1)

Everything must decay …



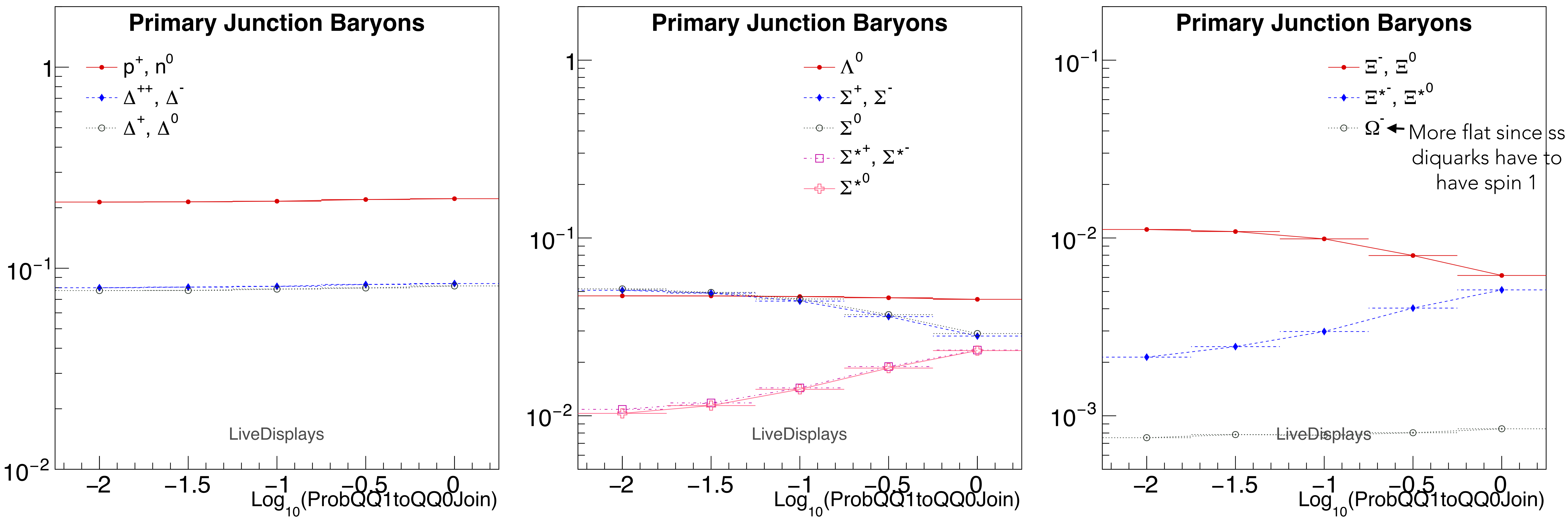
Not much difference in rates of final long-lived baryons

So, important to reconstruct primaries when possible: **more information!**

Effects of ProbQQ0toQQ1Join: Strange

`ProbQQ1toQQ0join` = { 0.1 , **?** , 0.1 , 0.1 } (Note: keeping the others at 0.1 was arbitrary, for illustration)

Second entry = spin-1 diquark suppression for su & sd diquarks (ss have to be spin 1)



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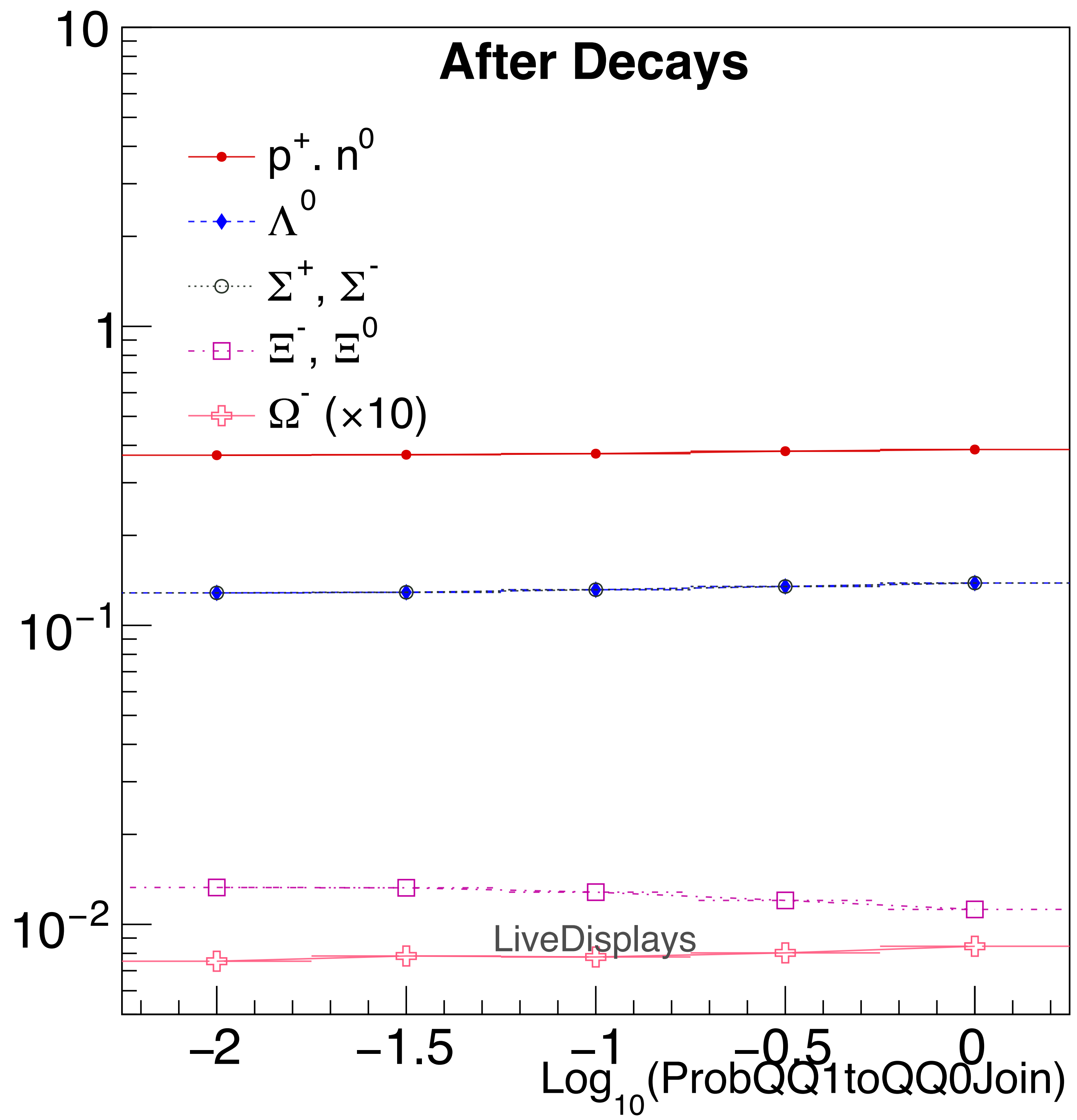
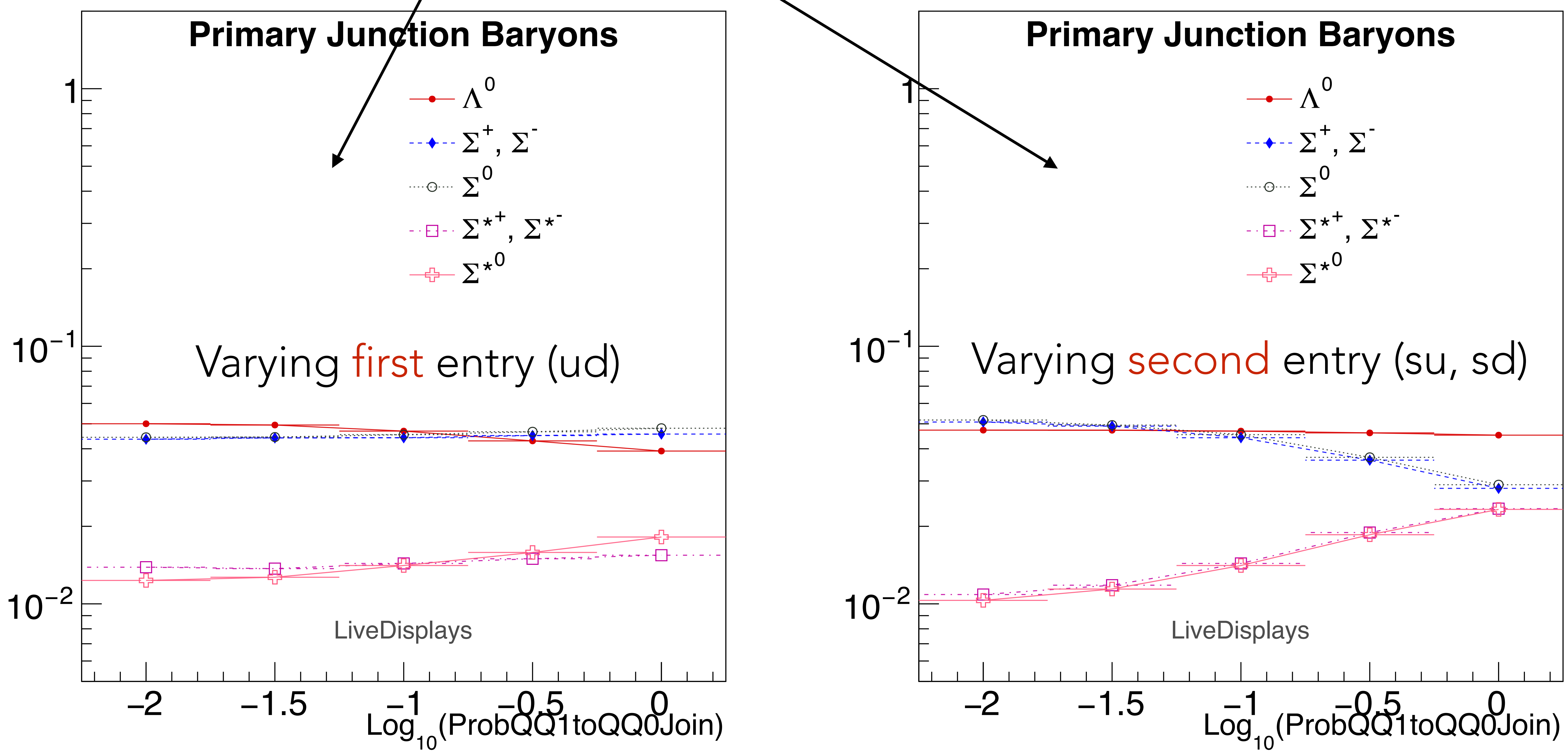


Effects of ProbQQ0toQQ1Join: Strange

`ProbQQ1toQQ0join` = { **?** , **?** , 0.1 , 0.1 }

Note: **Single-strange particles are affected by both first and second entries**

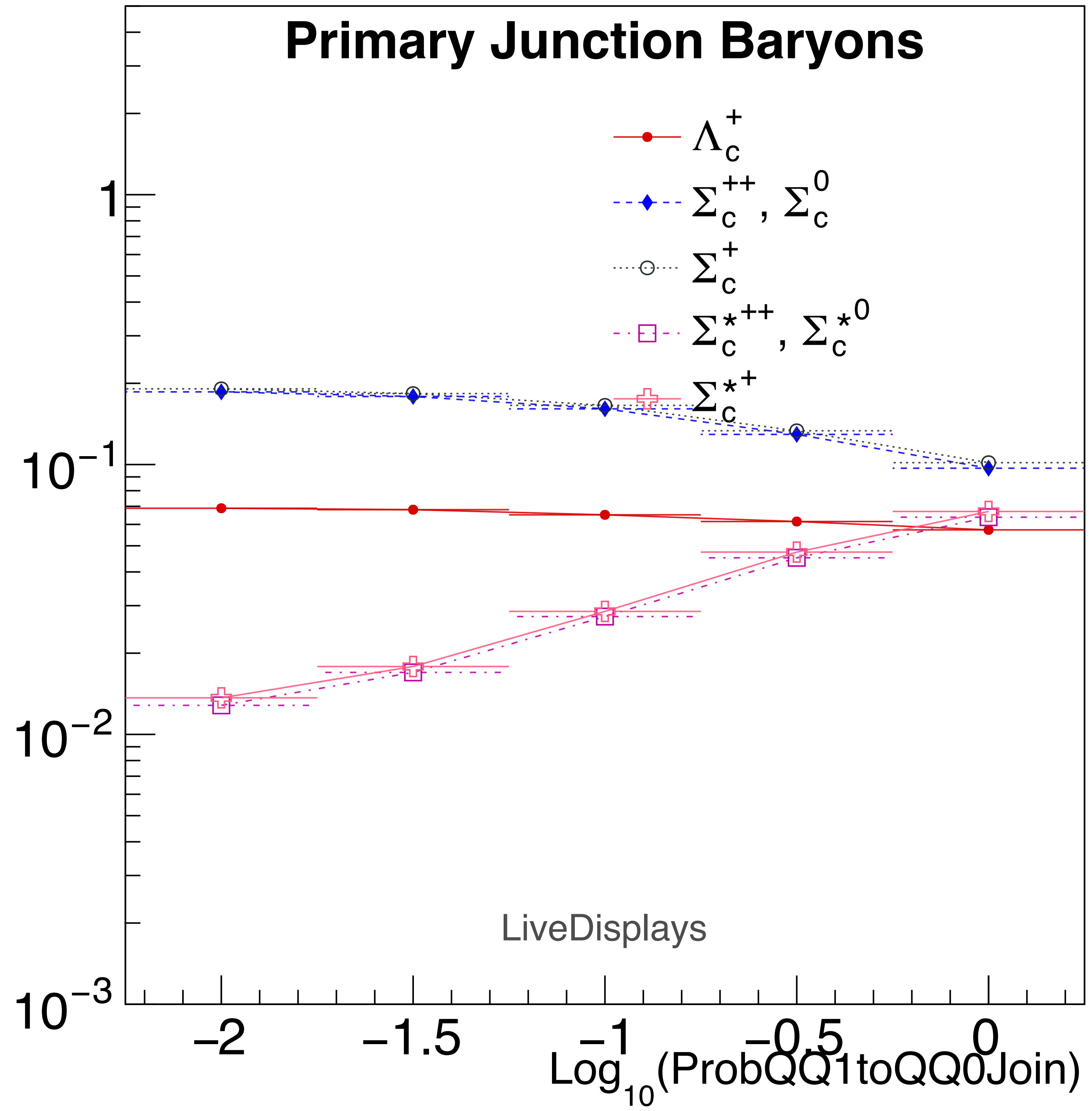


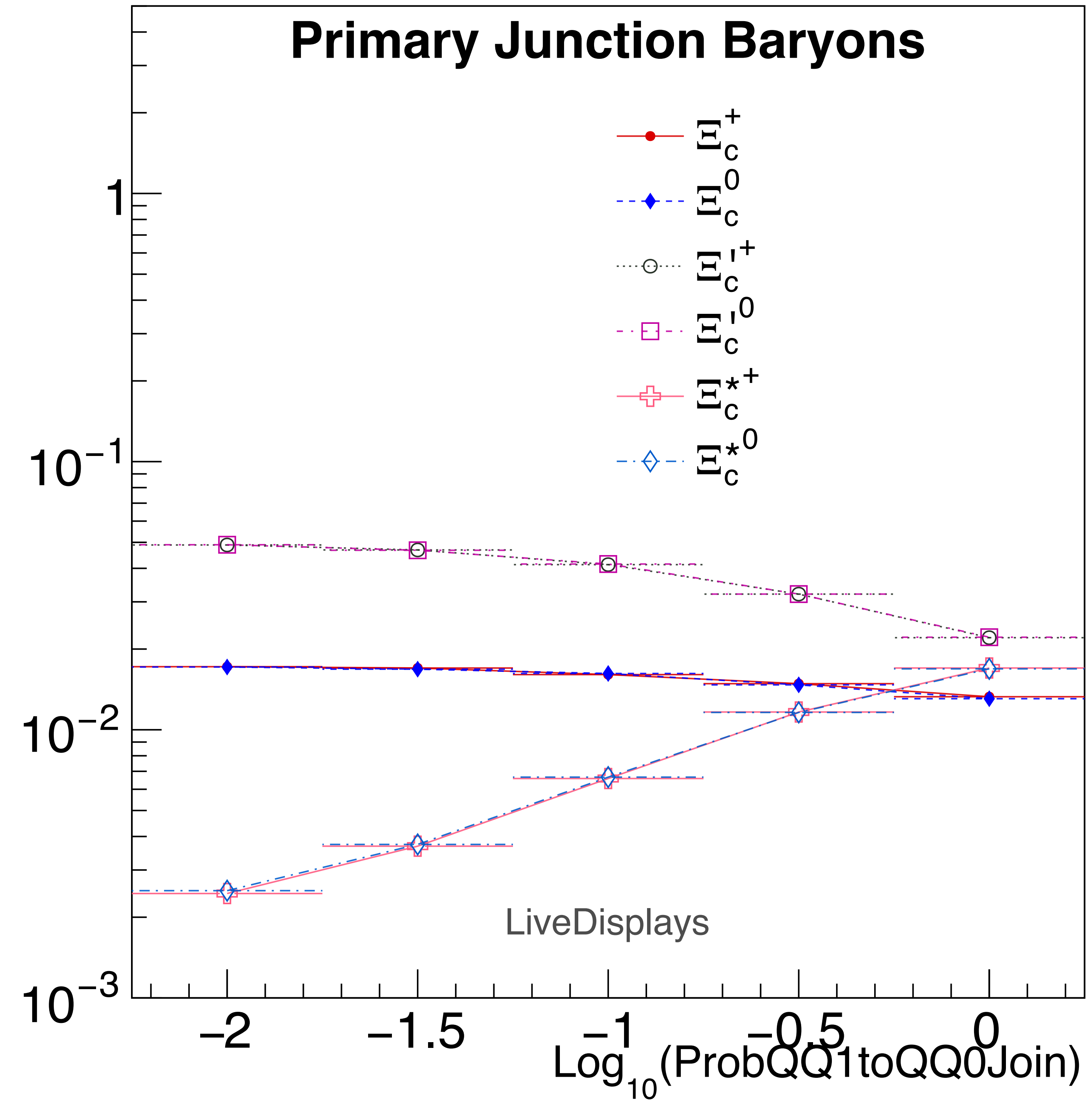
Note: primaries = before decays

Effects of ProbQQ1toQQ0join: Charm Sector

`ProbQQ1toQQ0join` = { 0.1 , 0.1 , **?** , 0.1 } (Note: keeping the others at 0.1 was arbitrary, for illustration)

Third entry = spin-1 diquark suppression for (cd, cu, cs) diquarks





Note: primaries = before decays

Example of recent reexamination of String Basics

Cornell potential

Potential V(r) between **static** (lattice) and/or **steady-state** (hadron spectroscopy) colour-anticolour charges:

$$V(r) = -\frac{a}{r} + \kappa r$$

Coulomb part

String part
Dominates for $r \gtrsim 0.2\,\mathrm{fm}$

Lund string model built on the asymptotic large-*r* linear behaviour

But intrinsically only a statement about the late-time / long-distance / steady-state situation. Deviations at early times?

Coulomb effects in the grey area between shower and hadronization?
Low-*r* slope > κ favours "early" production of quark-antiquark pairs?

+ Pre-steady-state thermal effects from a (rapidly) **expanding string?**

Berges, Floerchinger, and Venugopalan JHEP 04(2018)145)

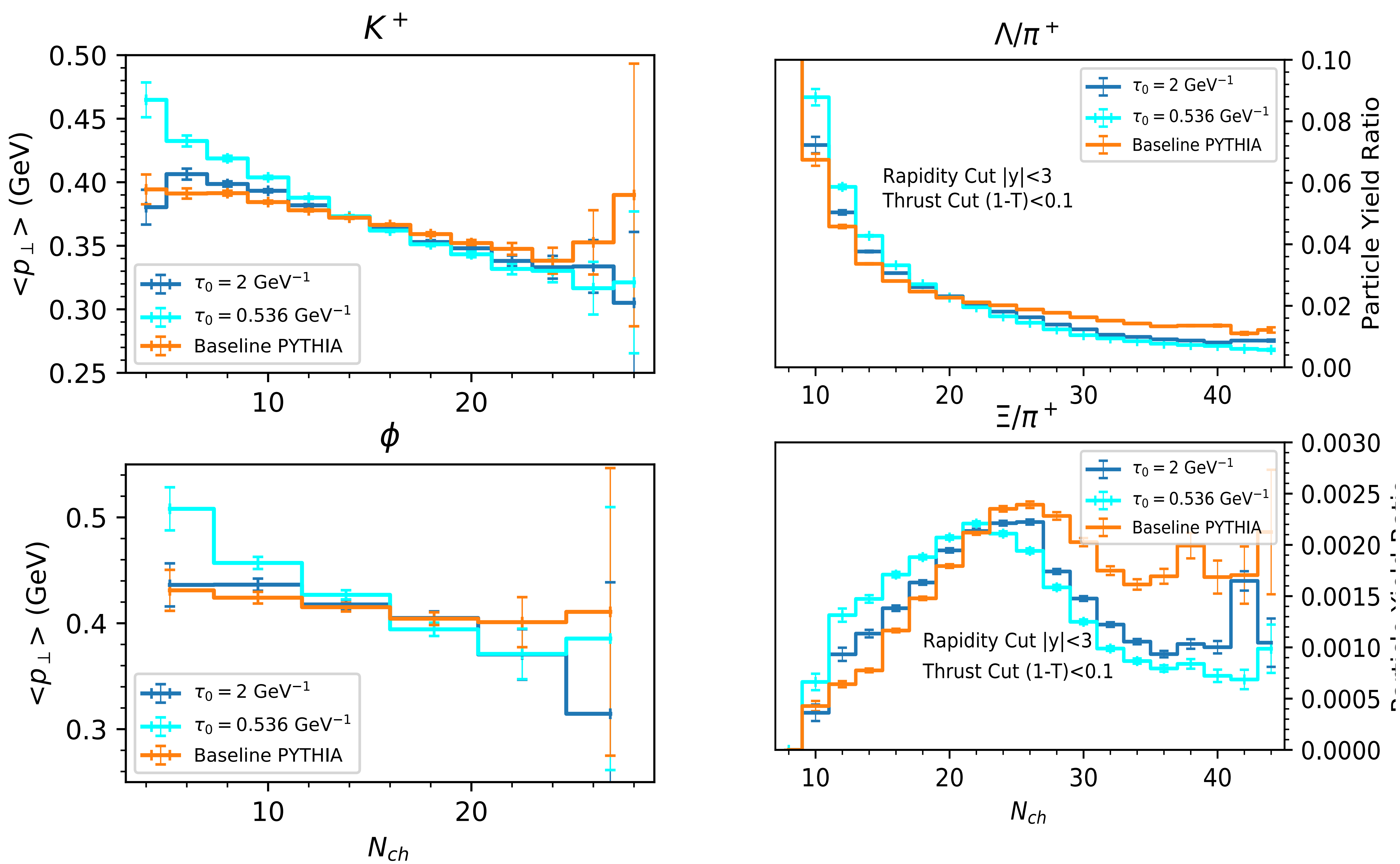
Toy Model with Time-Dependent String Tension

N. Hunt-Smith & PS arxiv:2005.06219

Model constrained to have same average tension as Pythia's default "Monash Tune"

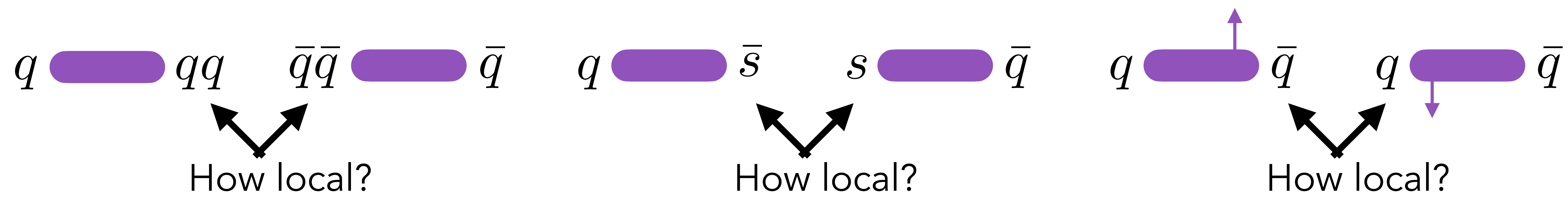
➤ same average N_{ch} etc ➤ main LEP constraints basically unchanged.

But expect different fluctuations / correlations, e.g. with multiplicity N_{ch}.



- ➤ Want to study (suppressed) tails with very low and very high N_{ch}.
- ➤ These plots are for LEP-like statistics.
- ➤ Would be crystal clear at CEPC/ FCC-ee

The point of MC generators: address more than one hadron at a time!



Further precision non-perturbative aspects: How local is hadronisation?

Baryon-Antibaryon correlations — both OPAL measurements were statistics-limited

+ Strangeness correlations, p_T, spin/helicity correlations ("screwiness"?)

+ Bose-Einstein Correlations & Fermi-Dirac Correlations

Identical baryons (pp, ΛΛ) **highly** non-local in string picture — puzzle from LEP; correlations across multiple exps & for both pp and ΛΛ → Fermi-Dirac radius ~ 0.1 fm ≪ r_p

Octet neutralisation? (zero-charge gluon jet with rapidity gaps) → **neutrals**
Colour reconnections, glueballs, …

Leading baryons in g jets?
(discriminates between string/cluster models)
High-x baryons