Sector Showers & Colour Reconnections

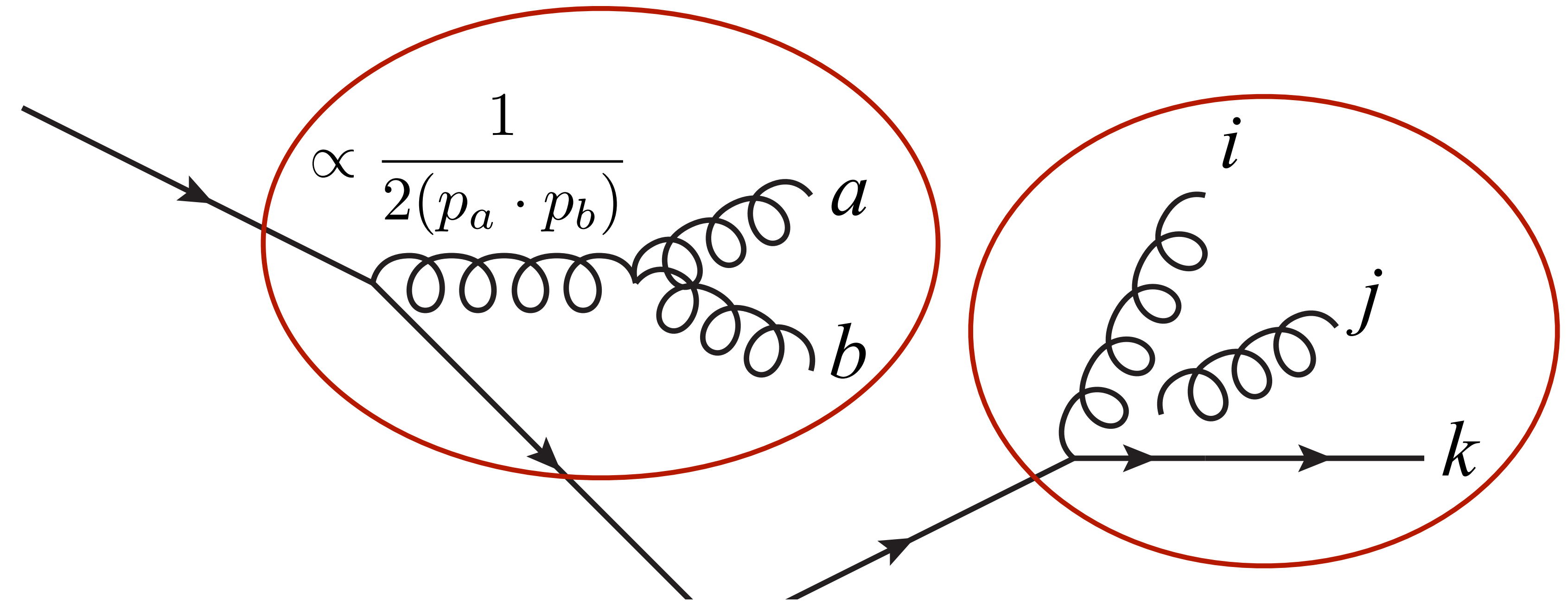
Peter Skands (Monash U)

- Antenna Showers on Sectorized Phase Spaces *Brooks, Preuss & PS 2003.00702*
- Sectorized CKKW-L Merging in Pythia 8.306 *Brooks & Preuss, 2008.09468*
- QCD-Based Colour Reconnections *Christiansen & PS 1505.01681*
- New Close-Packing Model on the Way ➤ More Strangeness *Altmann & PS, work in progress*

CMS Standard Model Workshop - Theory Session
February 2022

Parton Showers = Sums over Radiation Kernels

Most bremsstrahlung is driven by **divergent propagators** → simple universal structure, independent of process details



Amplitudes *factorise* in singular limits

In **collinear** limits, we get the DGLAP splitting kernels:

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \stackrel{a||b}{\to} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

In **soft** limits, we get the dipole (*a.k.a* eikonal) factors:

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \stackrel{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

Normal parton showers partial-fraction one or both of these.
E.g., angular ordering partial-fractions the eikonal into a left and a right half.
Dipole showers also partial-fraction collinear g→gg into a left and a right half.

Sum Over Histories

Sum over partial-fractions $\Longrightarrow$ full singularity structure ✅

Means each (n+1)-parton phase-space point receives contributions from several possible shower "histories" ~ clusterings.

Number of Histories for n Branchings (Starting from a single $q\bar{q}$ pair)

	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
CS Dipole	2	8	48	384	3840	46080	645120
Global Antenna	1	2	6	24	120	720	5040

Fewer partial-fractionings, but still factorial growth

CKKW-L style merging (incl UMEPS, NL3, UNLOPS, …)

Need to take all contributing shower histories into account.

Bottleneck at high multiplicities (+ high code complexity)

New in Pythia 8.304: Sectorized Antenna Showers in Vincia

PartonShowers:Model = 2   Brooks, Preuss & PS 2003.00702

Sector antennae: no partial-fractioning of any singularities.

Kosower, hep-ph/9710213 hep-ph/0311272; Larkoski & Peskin 0908.2450 & 1106.2182; Lopez-Villarejo & PS 1109.3608; Brooks, Preuss & PS 2003.00702

Each sector-antenna kernel contains the **full** soft-eikonal singularity and **also** the full collinear singularities for each gluon.

Double-counting avoided by dividing the *n*-gluon phase space up into *n* non-overlapping sectors, inside each of which only **one** kernel (the most singular one) is allowed to contribute.

VINCIA: Lorentz-invariant def of **most singular gluon** based on ARIADNE p_T:

$$p_{\perp j}^2 = \frac{s_{ij} s_{jk}}{s_{ijk}} \quad \text{with } s_{ij} \equiv 2(p_i \cdot p_j)$$

(+ generalisations for heavy-quark emitters)

No sum over histories!

Factorial → **constant scaling** in number of gluons.

Generalisation to $g \to q\bar{q} \Longrightarrow$ factorial in number of same-flavour quark pairs.

So What?

As a pure shower, our advert would not be that impressive

``Vincia —- not worse than any other LL* shower !"

Still, it does have better coherence properties than default Pythia showers

Especially important for VBF [2003.00702], top production and decays [2003.00702], and also just for hadron collisions in general; anything with colour flow *through* the process.

(+ No time to discuss …)

- New "interleaved" treatment of resonance decays + EW Shower [2108.10786]
- Dedicated "exact" treatment of quark mass effects [1108.6172]
- QED multipole showers with full soft interference [2002.04939]
- Reproduces eikonal point-by-point in phase space whereas angular ordering only does so at the azimuthally averaged level.

Main point: achieves LL* with a *single* history, not a factorial number.

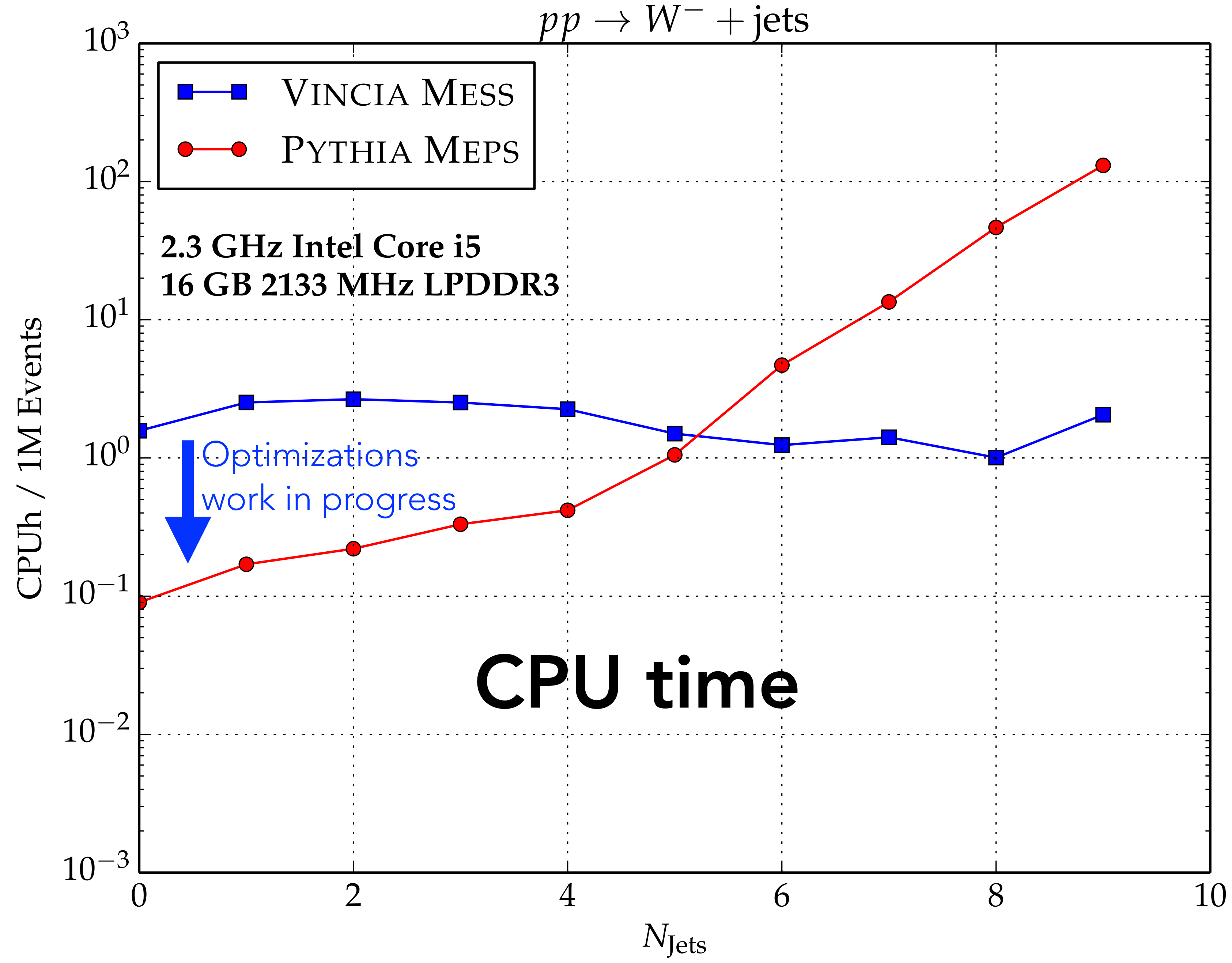
"Maximally bijective" = simple skeleton to build new things on top of.

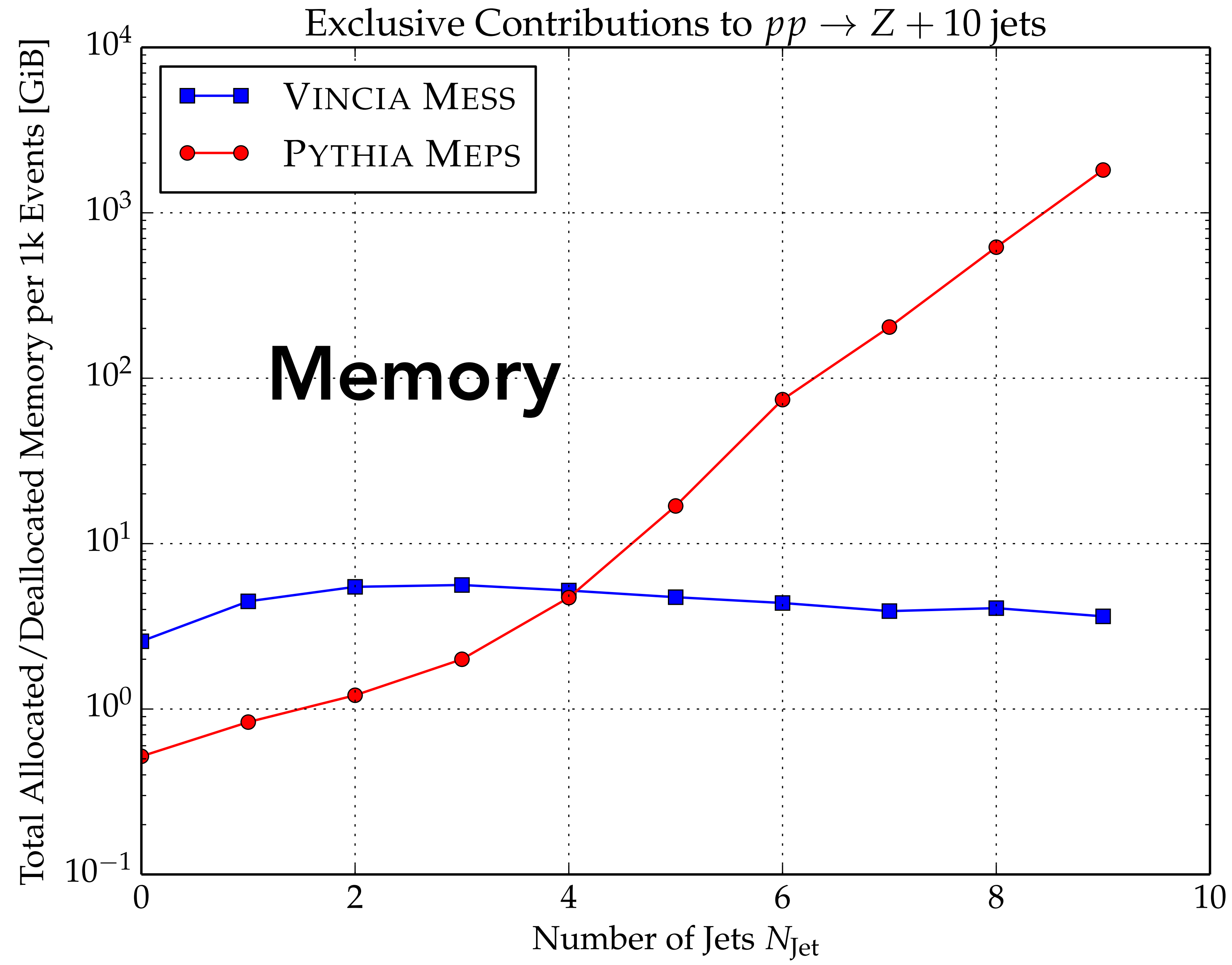
E.g., NNLO matching proof of concept [2108.07133]

LL* = NLL for a few IRC-safe observables, LL + exact (E,p) cons for most; not quite LL for some.

Sectorized CKKW-L Merging in Pythia 8.306

[Brooks & Preuss, 2008.09468](https://arxiv.org/abs/2008.09468)





Work ongoing to optimise baseline algorithm

Already now it is mature and ready for serious applications.

Feedback on default tuning and how sector merging works for you is valuable.

Note: Vincia also has dedicated POWHEG hooks; NLO sector merging coming in 2022.

Vincia tutorial: http://skands.physics.monash.edu/slides/files/Pythia83-VinciaTute.pdf

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

Who gets confined with whom?

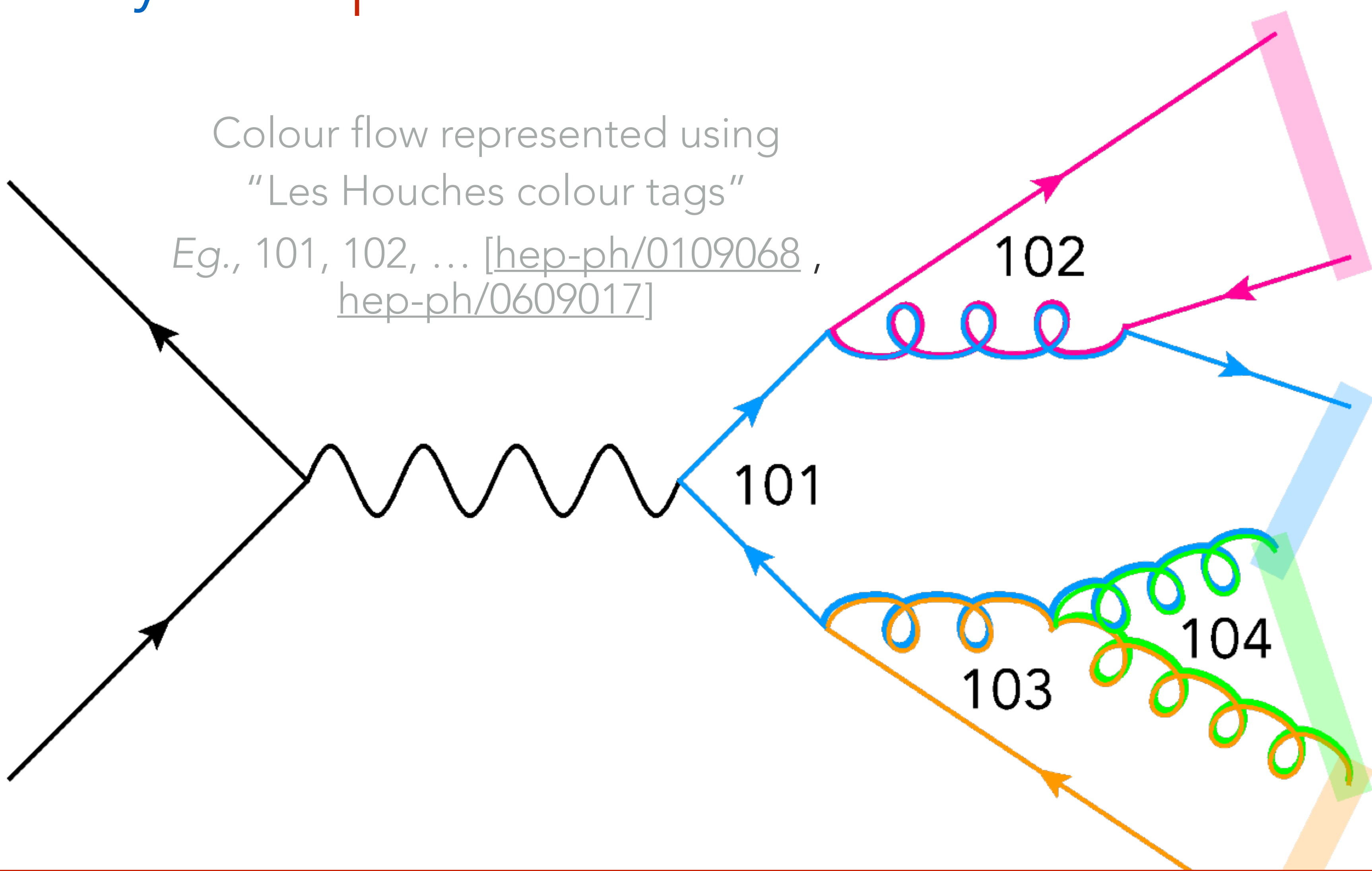
Starting point for MC generators = Leading Colour limit $N_C \to \infty$

$\Longrightarrow$ 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.

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, corrections suppressed by $1/N_C^2 \sim 10\,\%$

But in pp collisions, multi-parton interactions $\Longrightarrow$ many such systems

Each has probability ~ 10% + significant overlaps in phase space $\Longrightarrow$ CR more likely than not

QCD-based CR Model: Rules of the Game

Christiansen & PS [1505.01681]

MPI + showers $\Longrightarrow$ partons with LC connections

Idea: stochastically allow ($1/N_C^2$) colour correlations, using SU(3) rules:

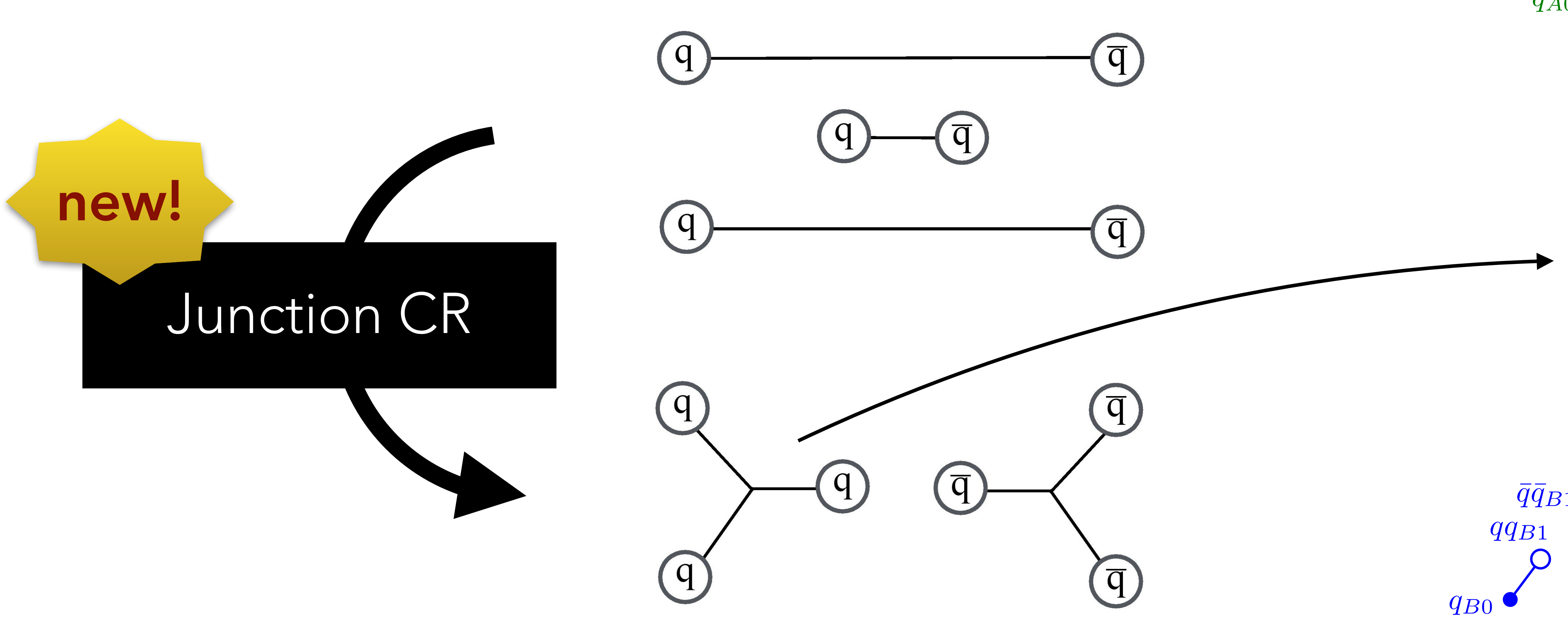
(1) $3 \otimes \bar{3} = 8 \oplus 1$ for uncorrelated colour-anticolour pairs (allows "dipole CR")

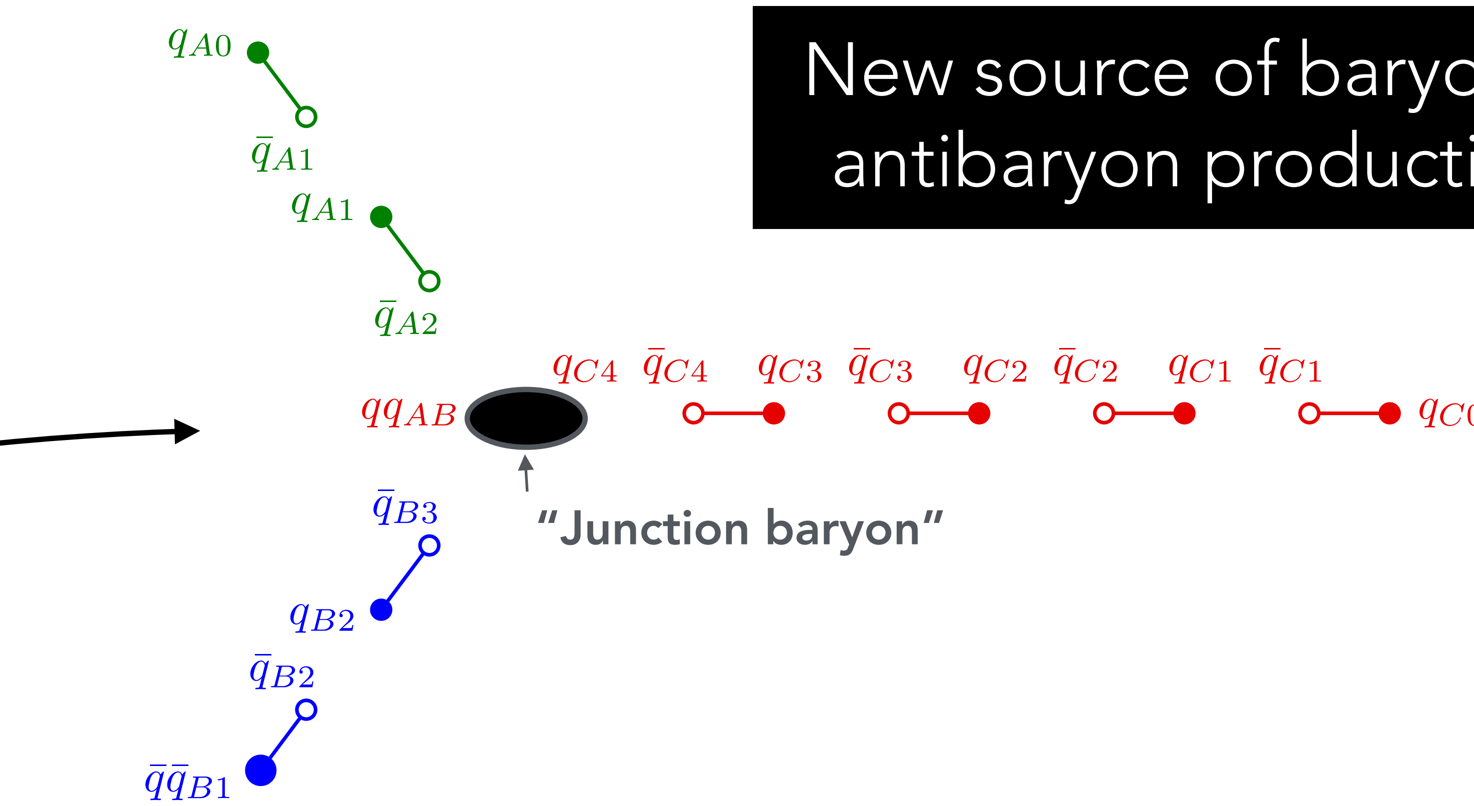
(2) $3 \otimes 3 = 6 \oplus \bar{3}$ for uncorrelated colour-colour pairs (allows "junction CR")

Then choose between which ones to realise confining potentials

Smallest measure of "invariant string length" $\propto$ number of hadrons

Illustrations by J. Altmann





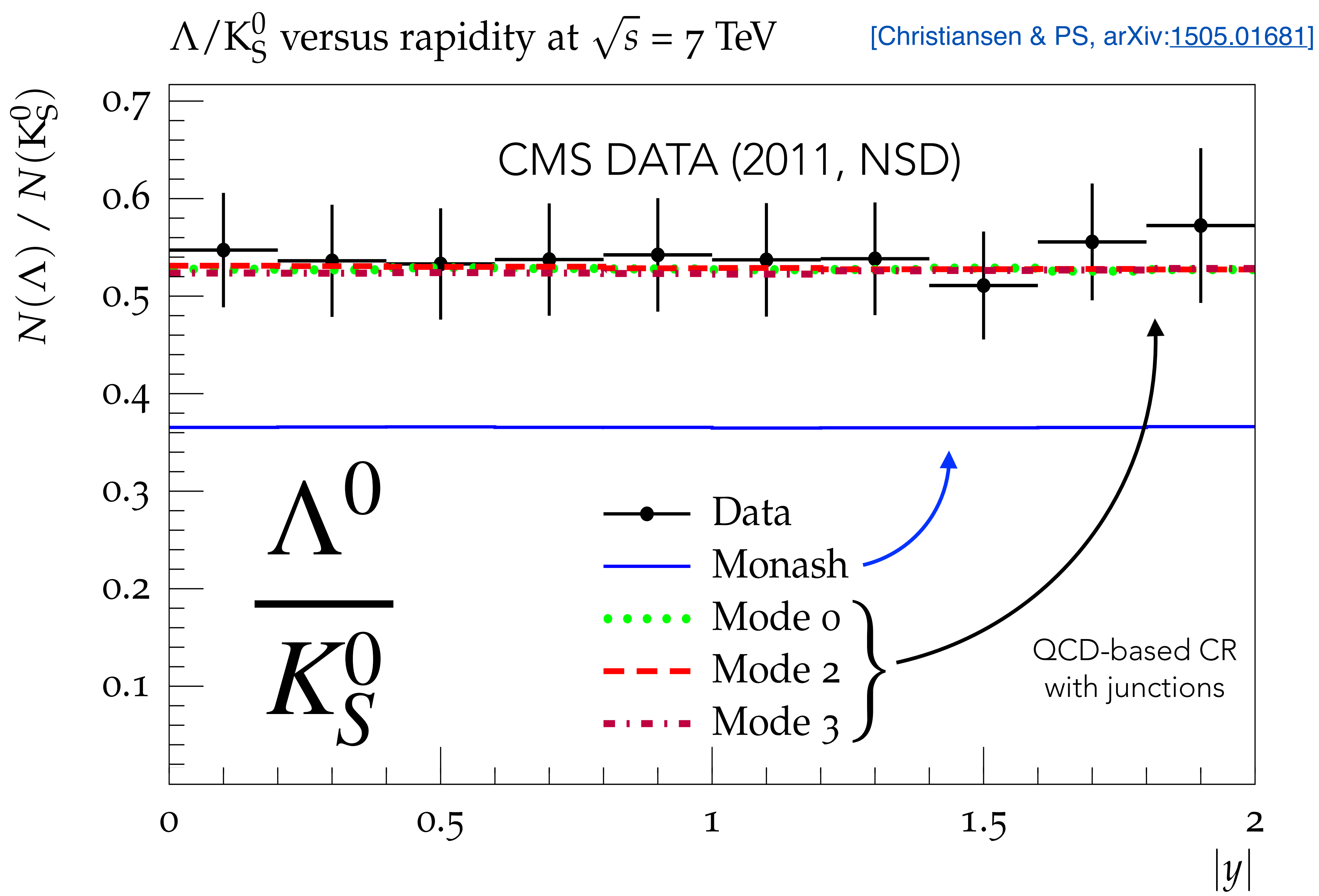
New source of baryon + antibaryon production

Sjöstrand & PS [hep-ph/0212264]

Illustration from Pythia 8.3 manual

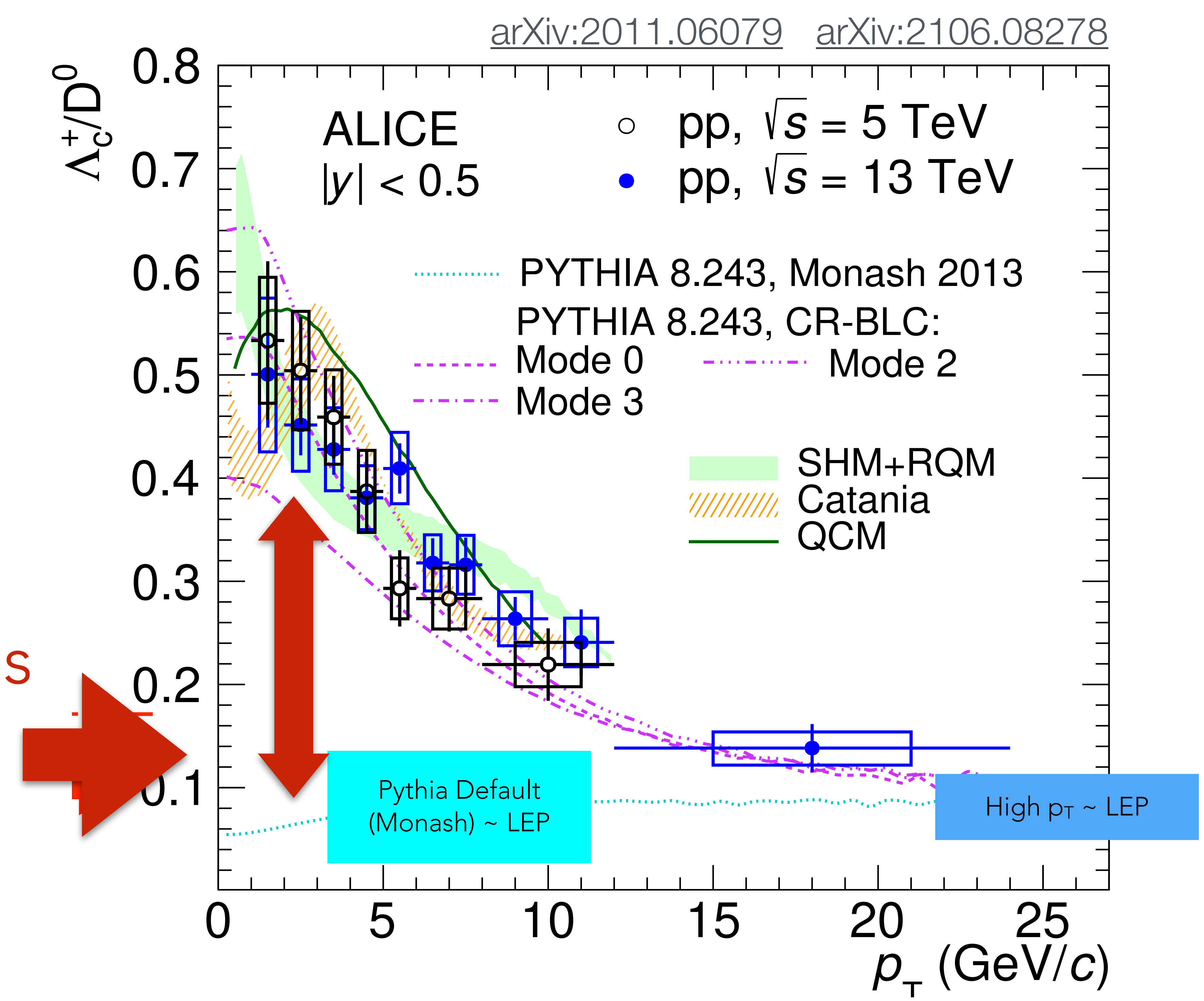
+ New junction-type CR ⟹ Increased Baryon-to-Meson ratios

Original main goal / constraint: Λ/K



QCD CR model(s): Junctions drive order-of-magnitude increase in Λ_c/D^0 at low $p_\perp$

ALICE 2021: also in charm



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

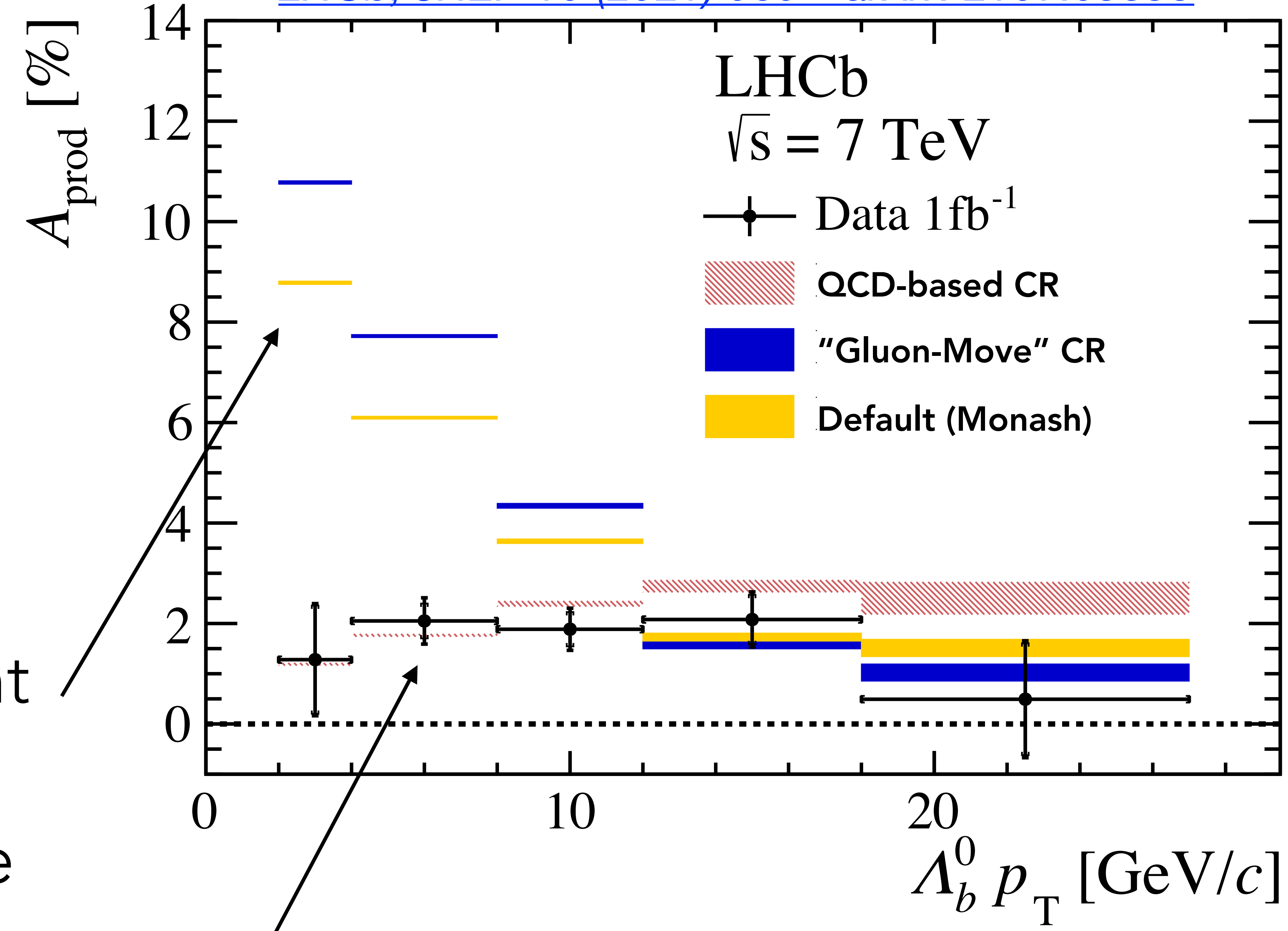
Λ_b asymmetry

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

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

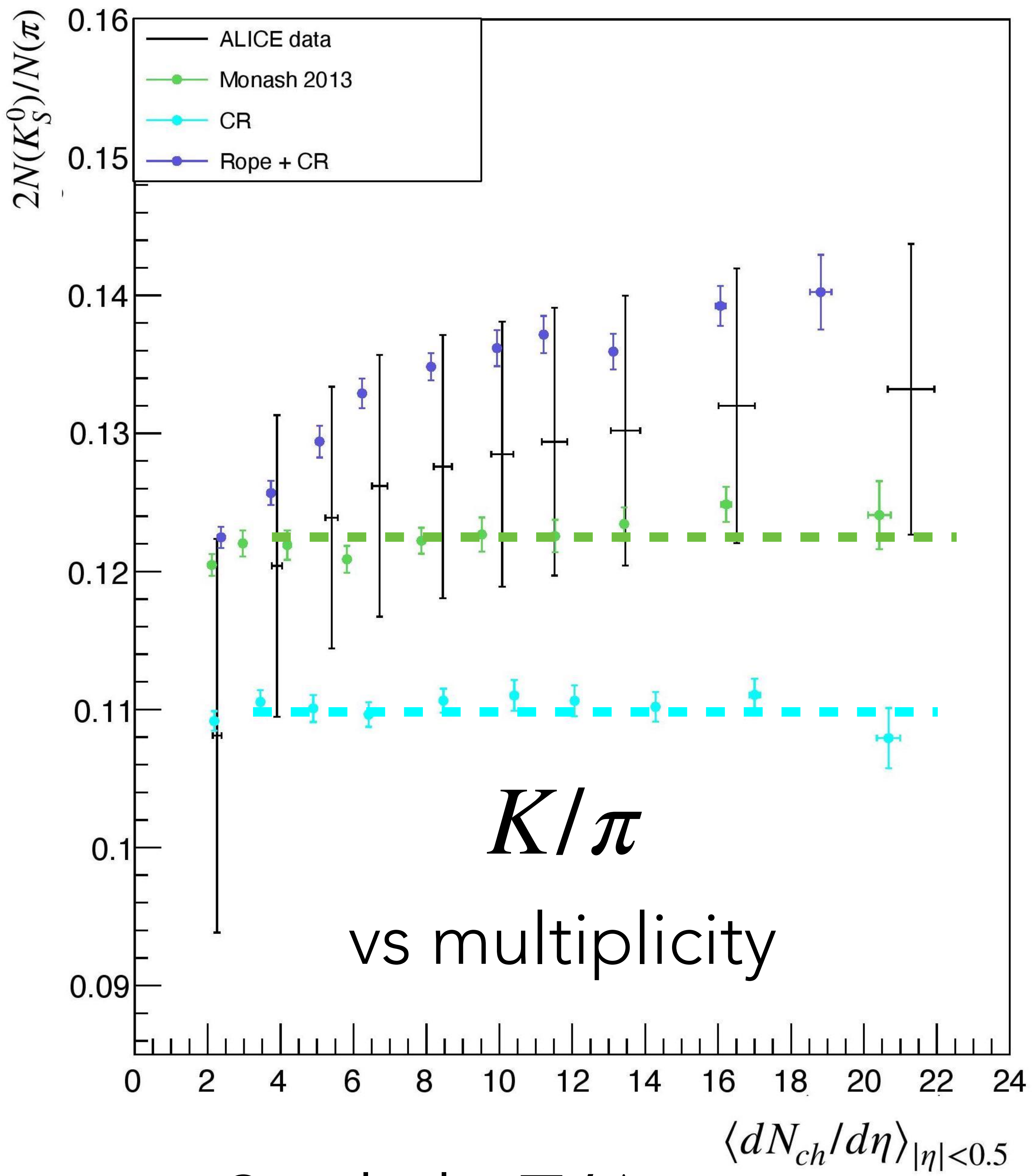


QCD CR adds large amount of low-p_T junction Λ_b and $\bar{\Lambda}_b$, in equal amounts. Dilutes asymmetry!

QCD-CR is not a mechanism for strangeness enhancement

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

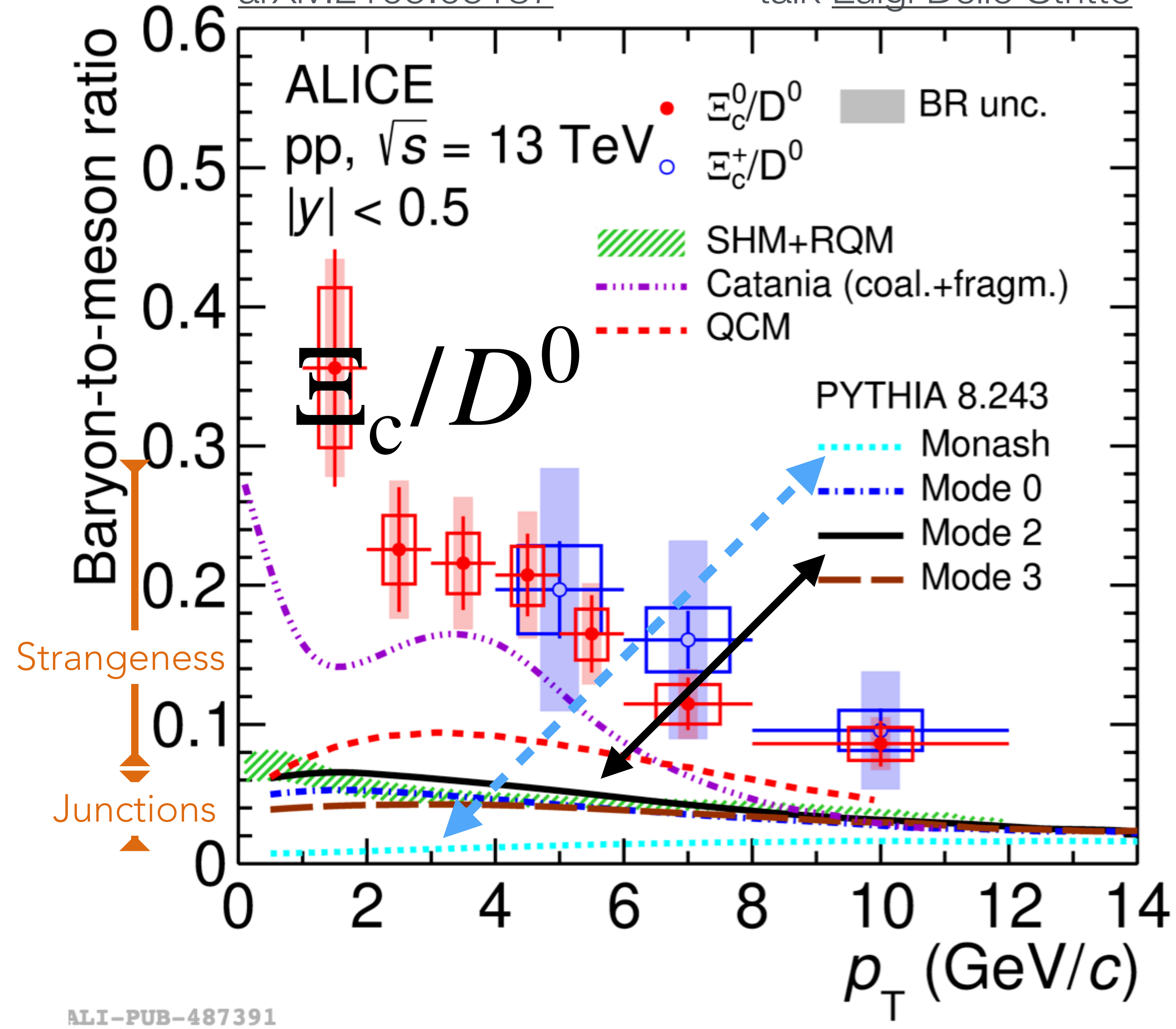
Ratio of yields of K_S to π vs charged multiplicity



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

ALICE 2021: also in charm

arXiv:2105.05187 talk Luigi Dello Stritto



Enter: Close-Packing

"Close Packing" of strings   Fischer & Sjöstrand, 1610.09818

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>)

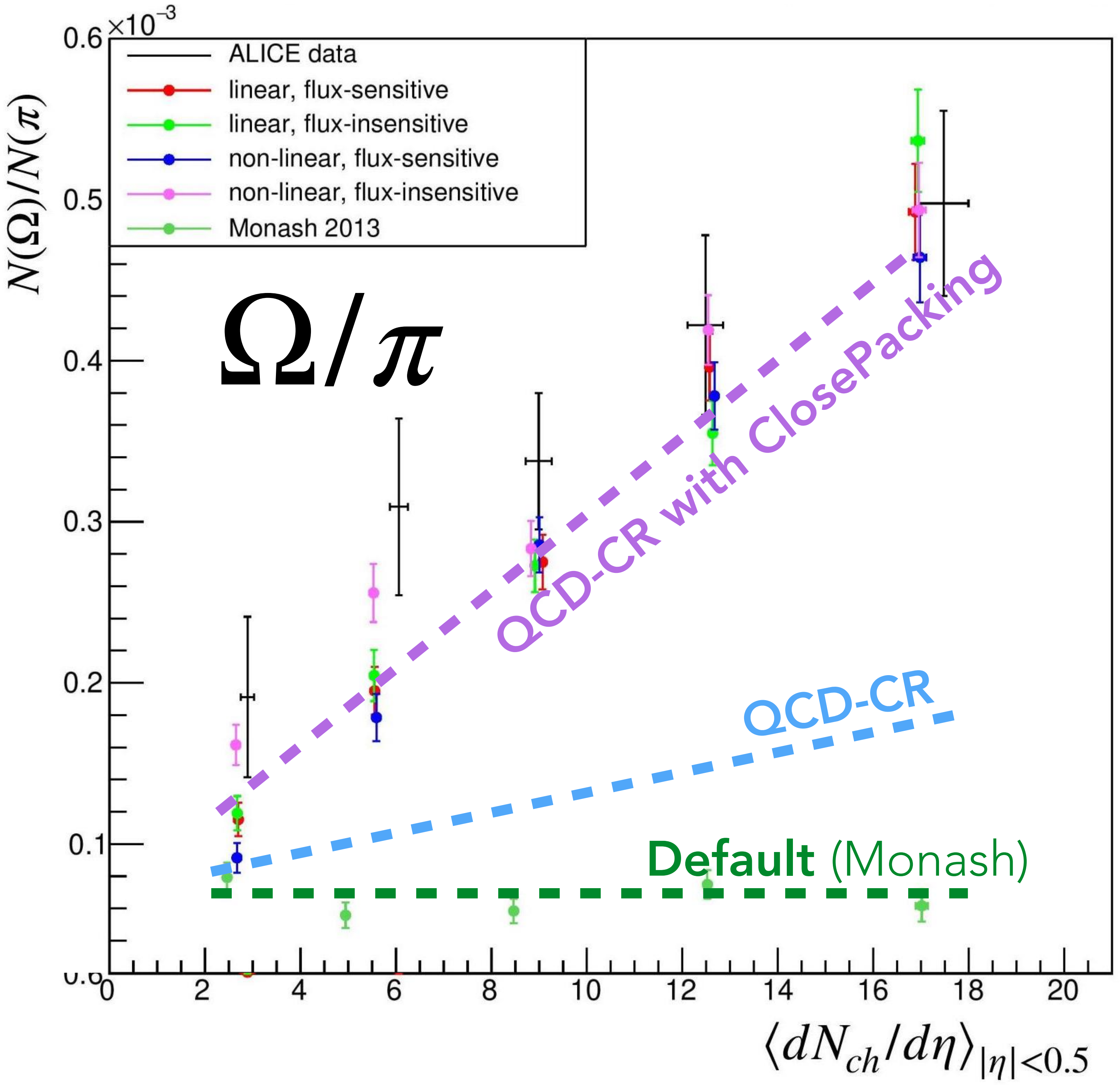
Current close-packing model in Pythia only for "thermal" string-breaking model

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!**

Intended as a simple alternative to rope model.

Preliminary results (J. Altmann)



Summary

The QCD-CR model in Pythia [Christiansen & PS, 1505.01681](#) `(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?

Originally was "just" a 6-month studentship project (cf laundry list). Impressive new LHC results (esp heavy flavour) ➤ Renewed interest in tying up loose ends.

Extra Slides 1
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.

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** ($J/\psi, \Upsilon$)?

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.

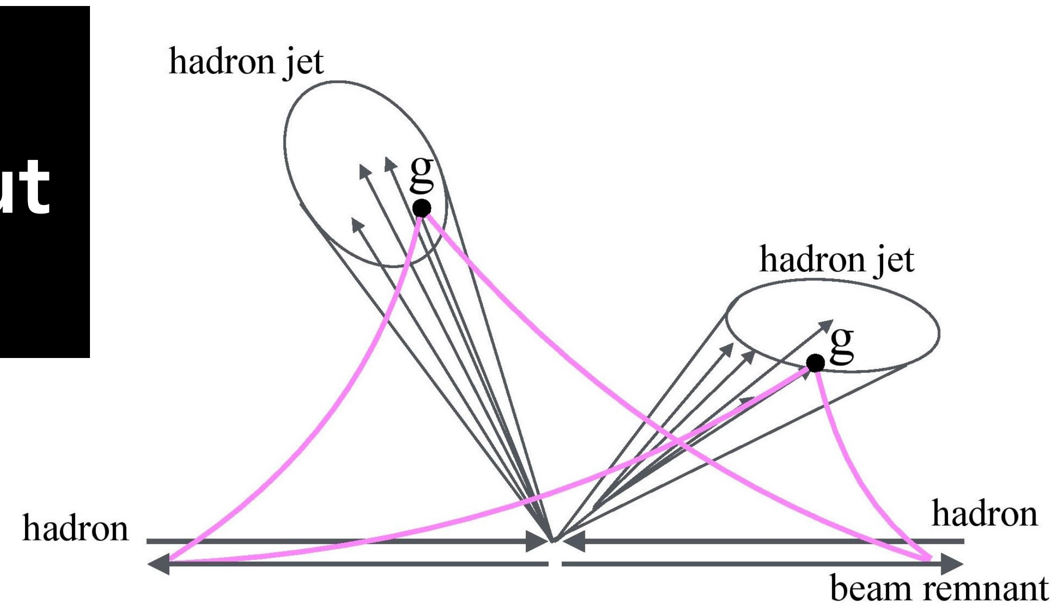
(So not enough to just constrain existing options by measurements.)

Needs further thought & theoretical work.

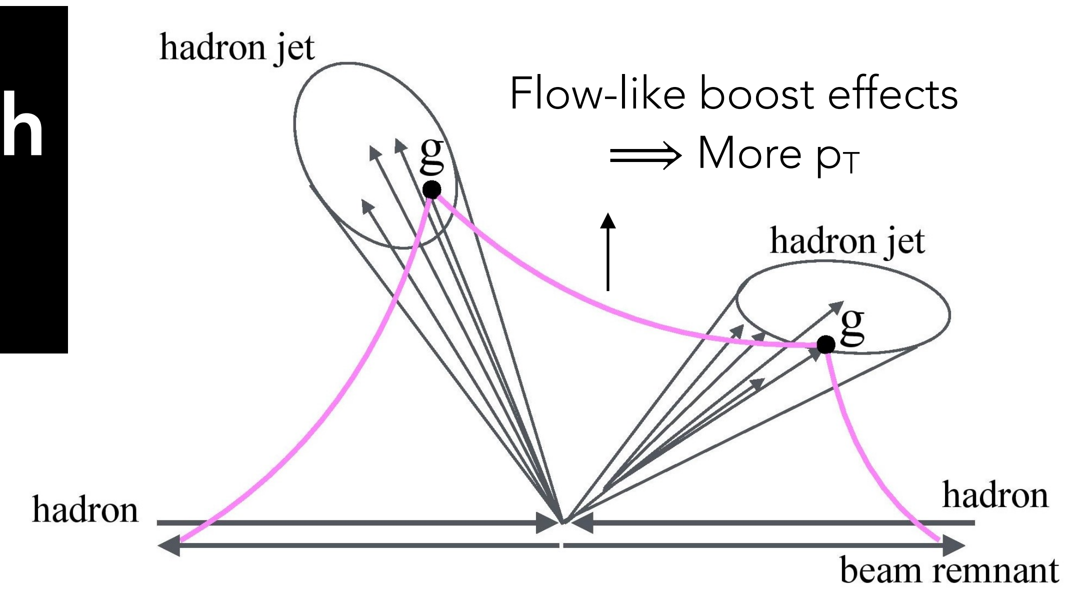
Extra Slides 2

Colour Reconnections Original Goal: describe observables like $<p_T>(n_{ch})$

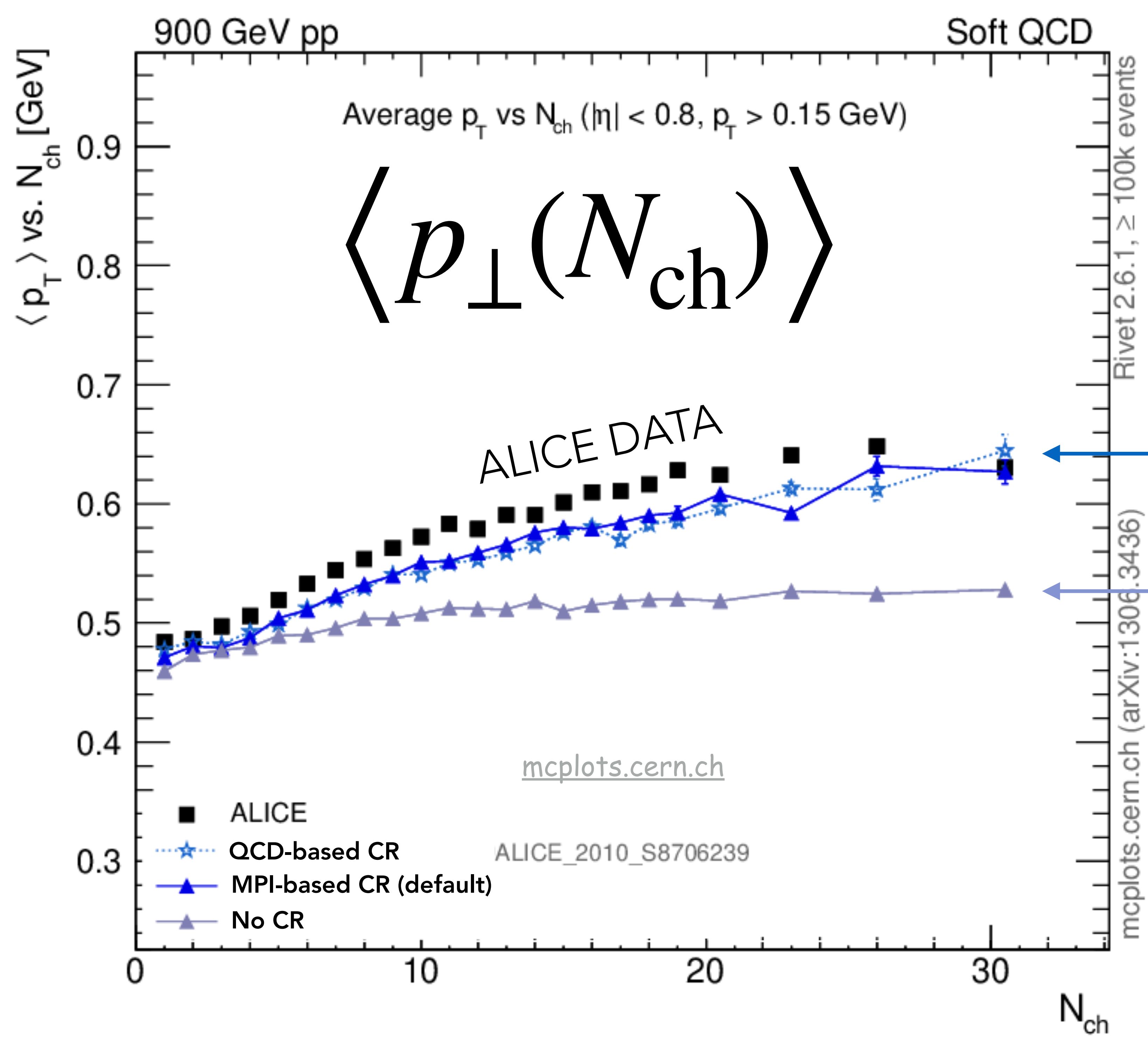
MPI **without** CR:



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 [1505.01681] reproduce the rising trend of $<pT>(N_{ch})$

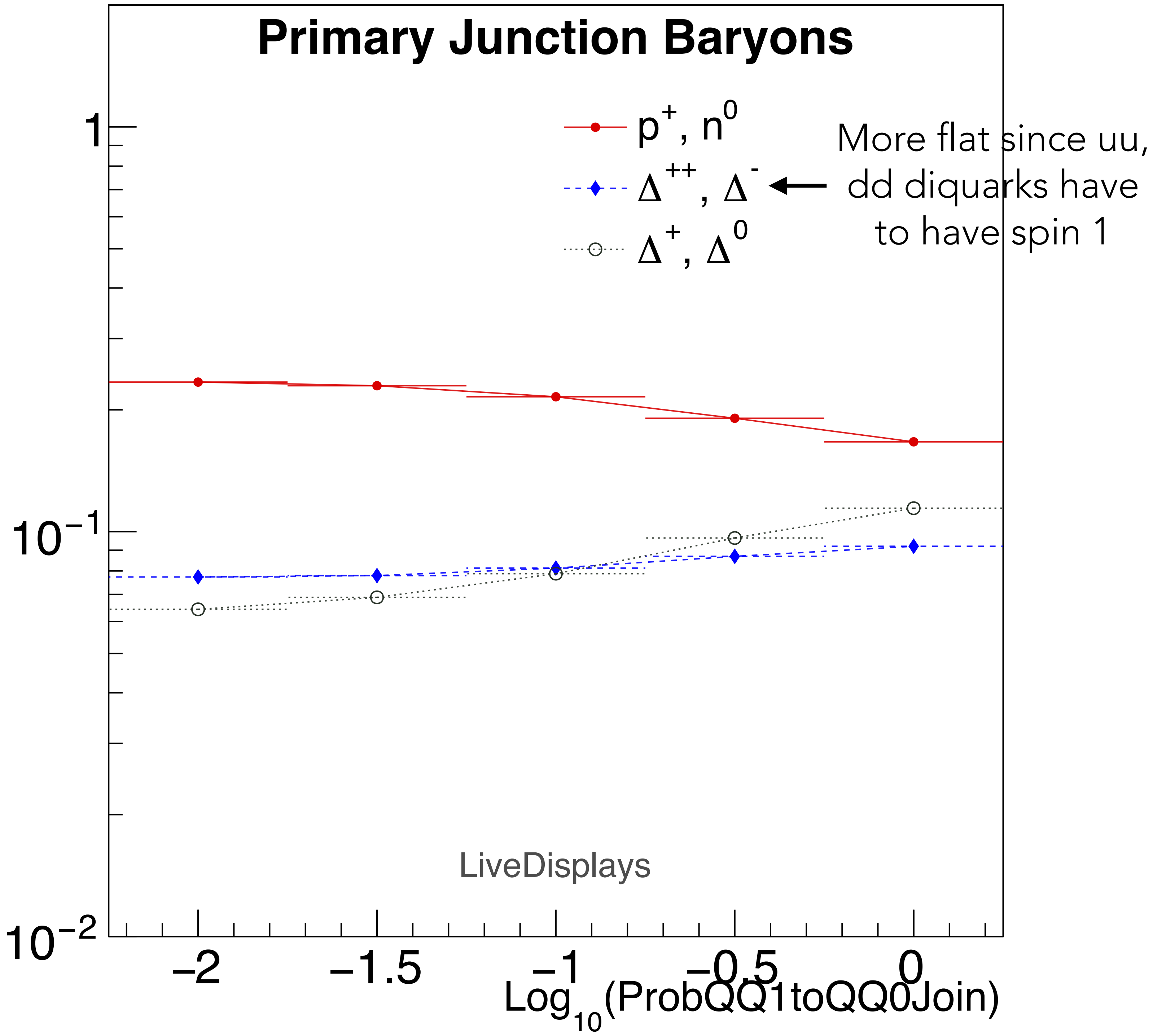
No CR ⟹ $<p_T>$ approximately the same for all N_{ch} (Many MPI just produce more hadrons, but with ~ same spectra)

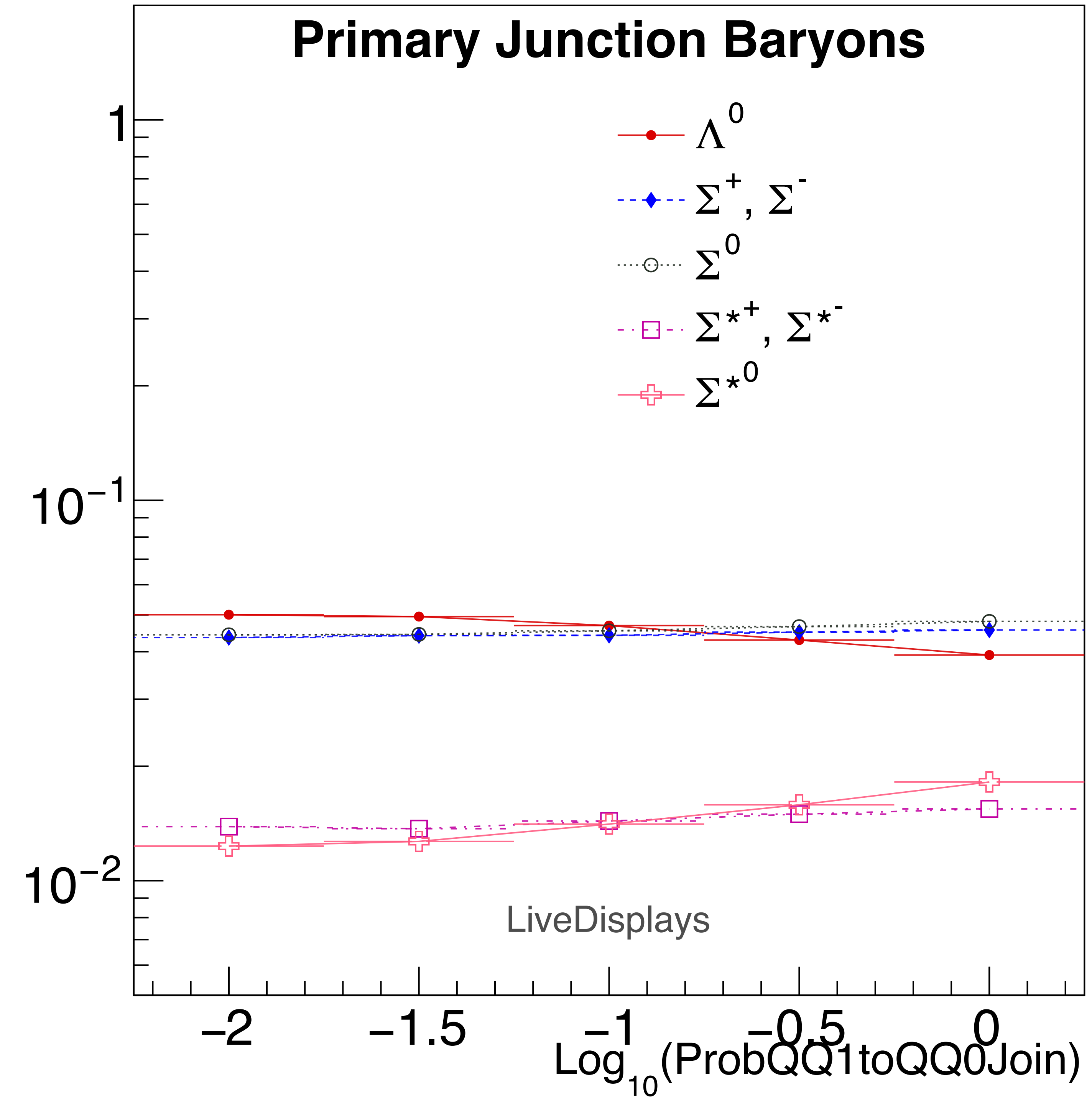
(Just one example here, that I could easily obtain from mcplots.cern.ch; with minor differences all other CM energies and fiducial cuts show same trend)

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

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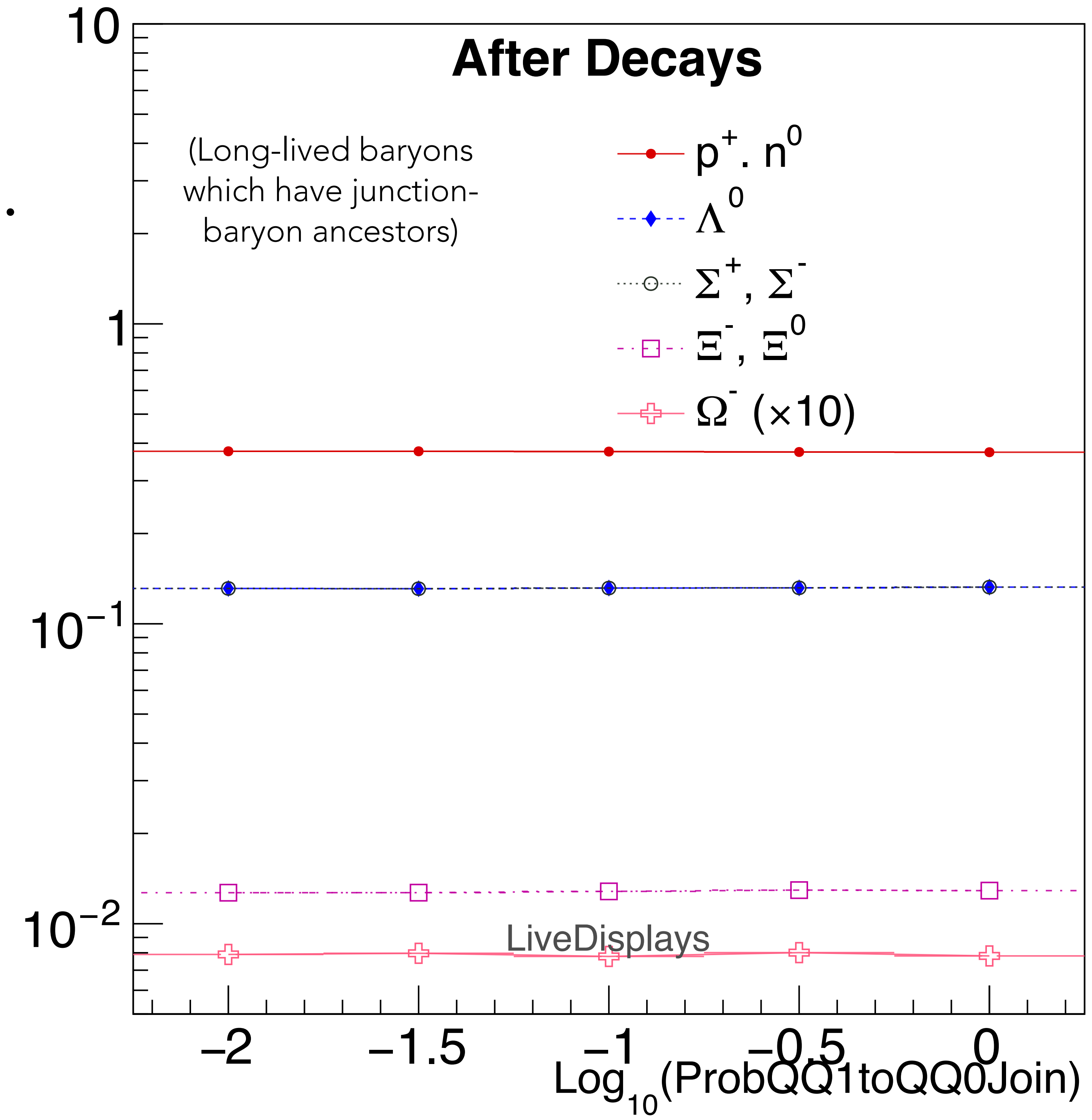
Everything must decay …



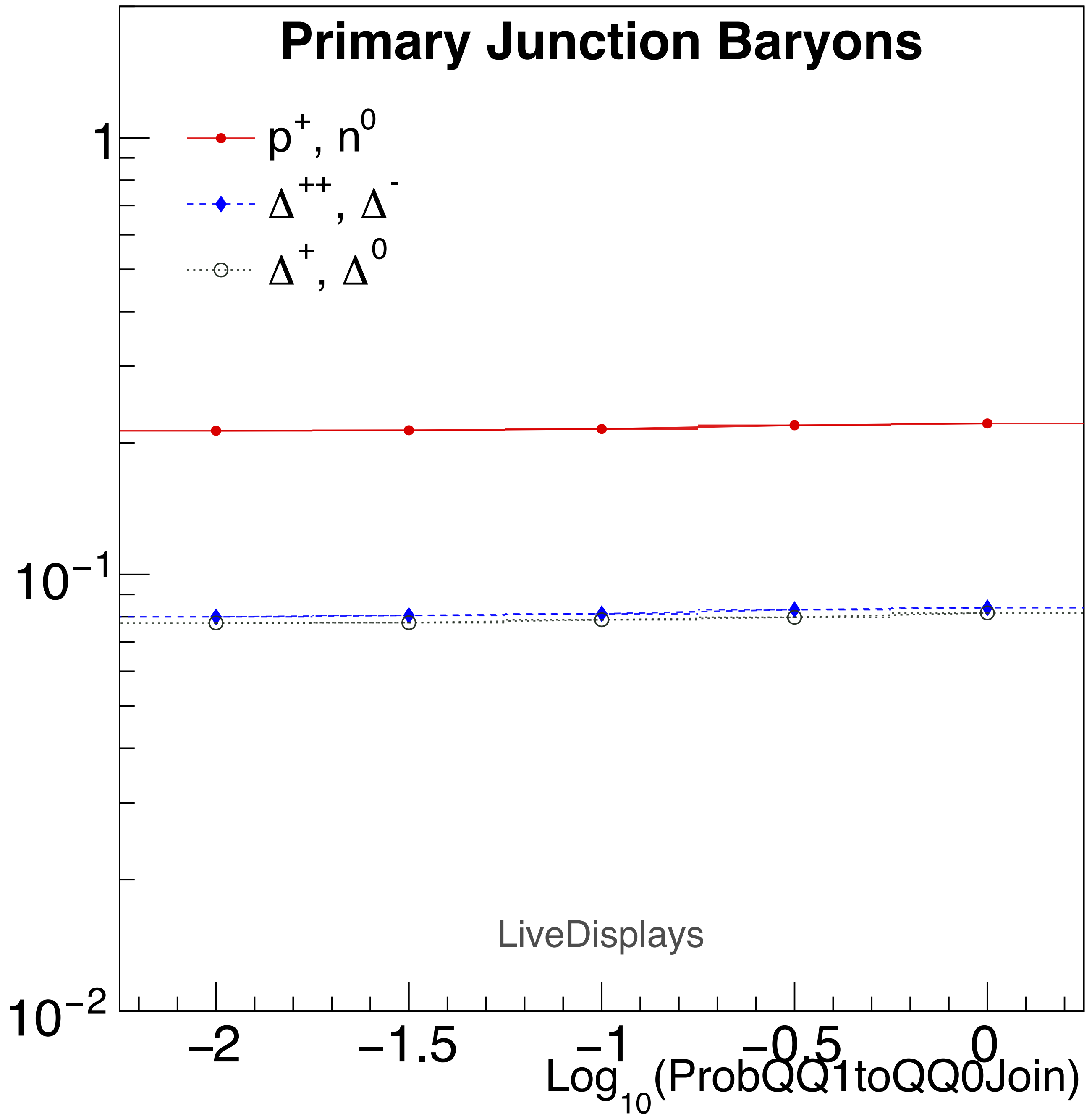
Not much difference in rates of final long-lived baryons

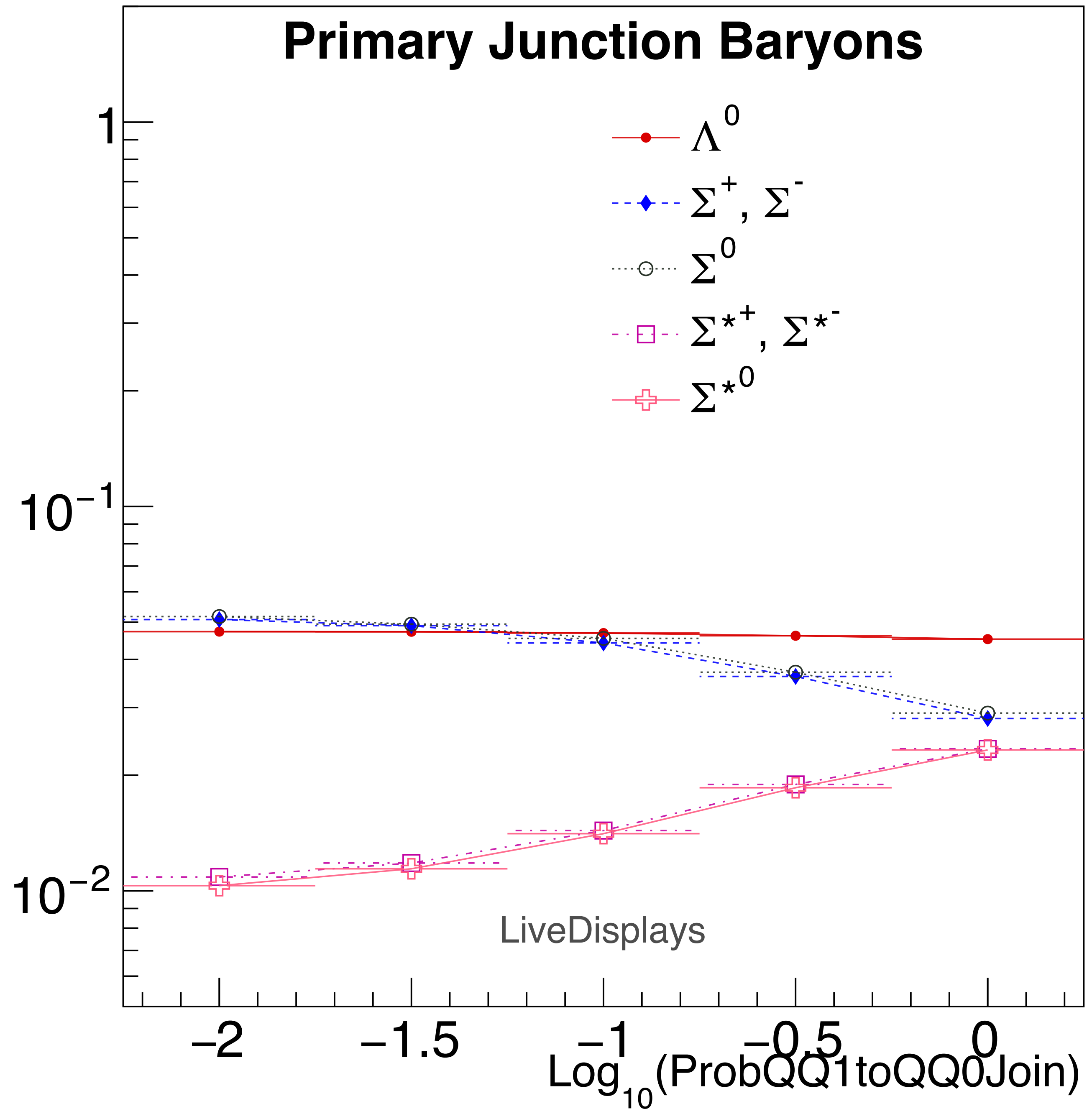
So, important to reconstruct primaries when possible: **more information!**

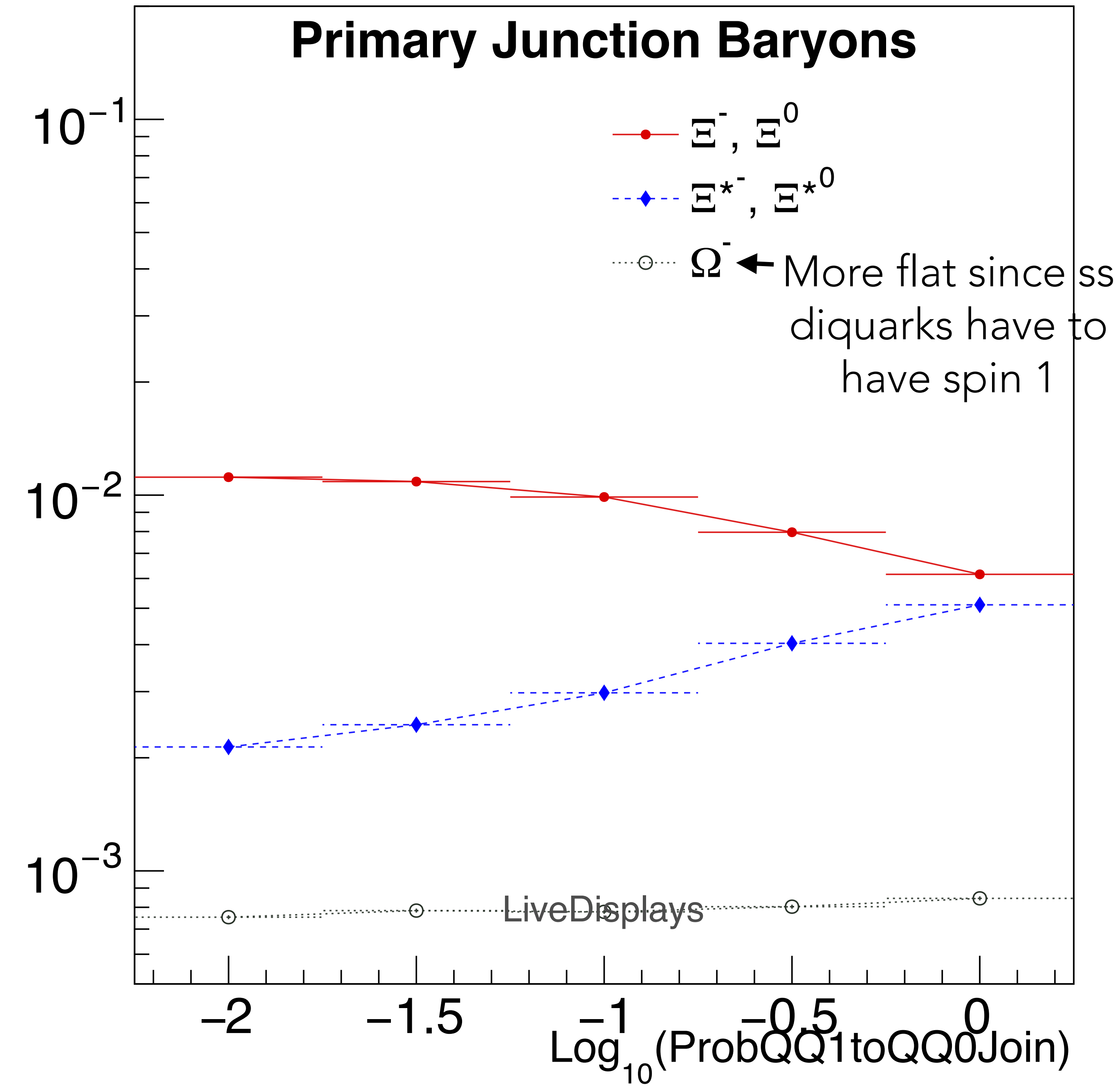
Effects of ProbQQ0toQQ1Join: Strange

`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)







Effects of ProbQQ0toQQ1Join: Strange

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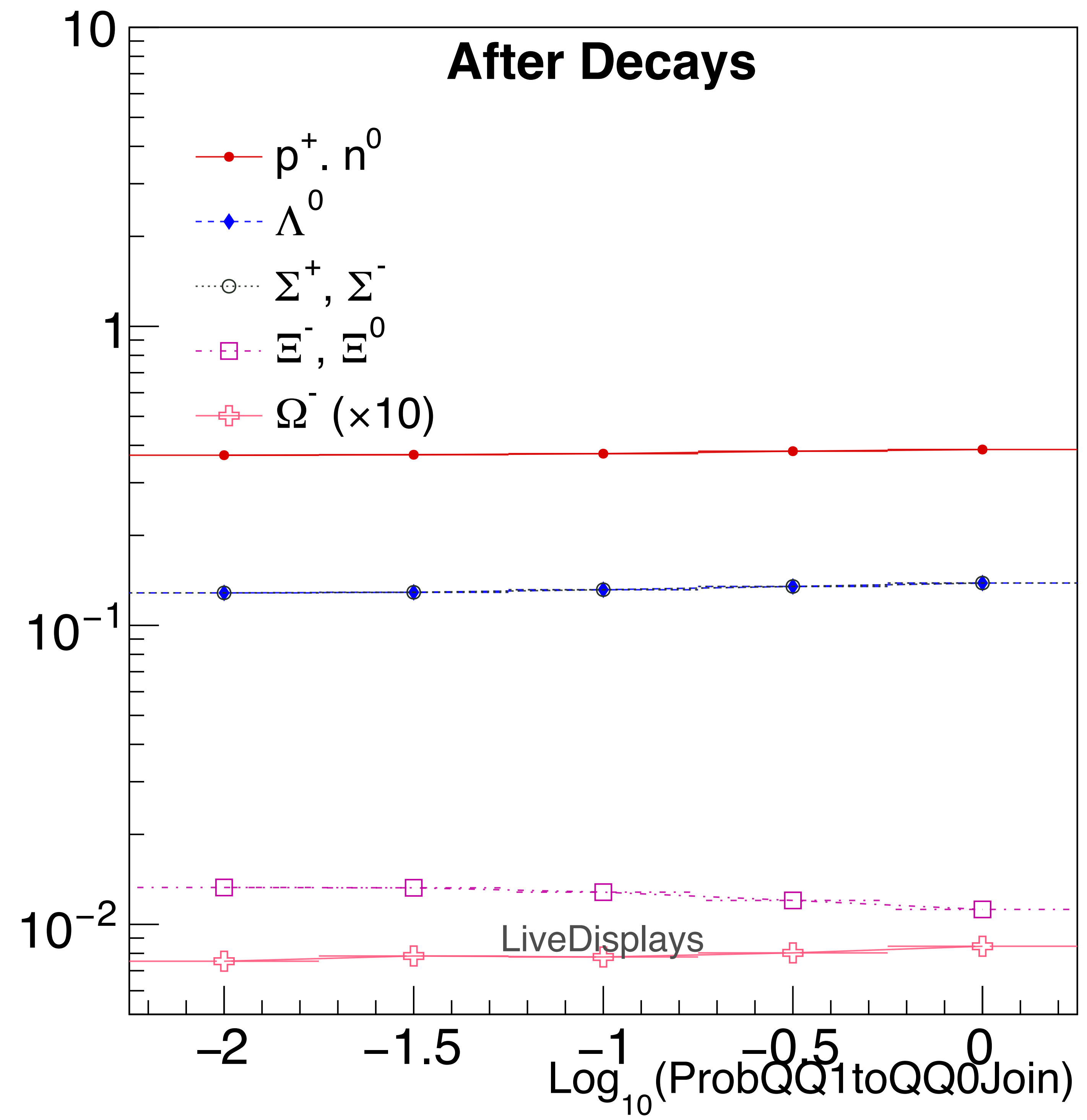
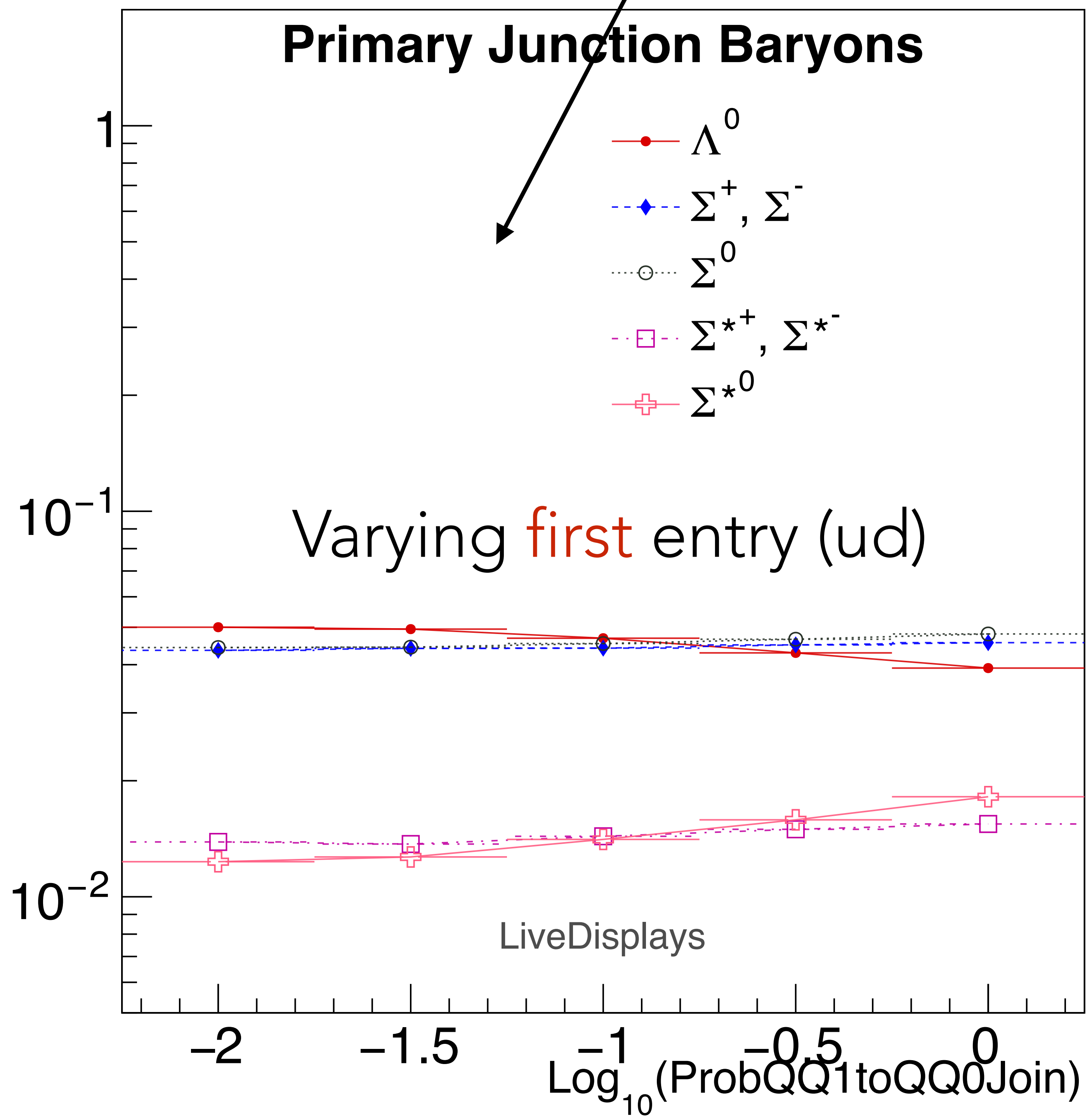
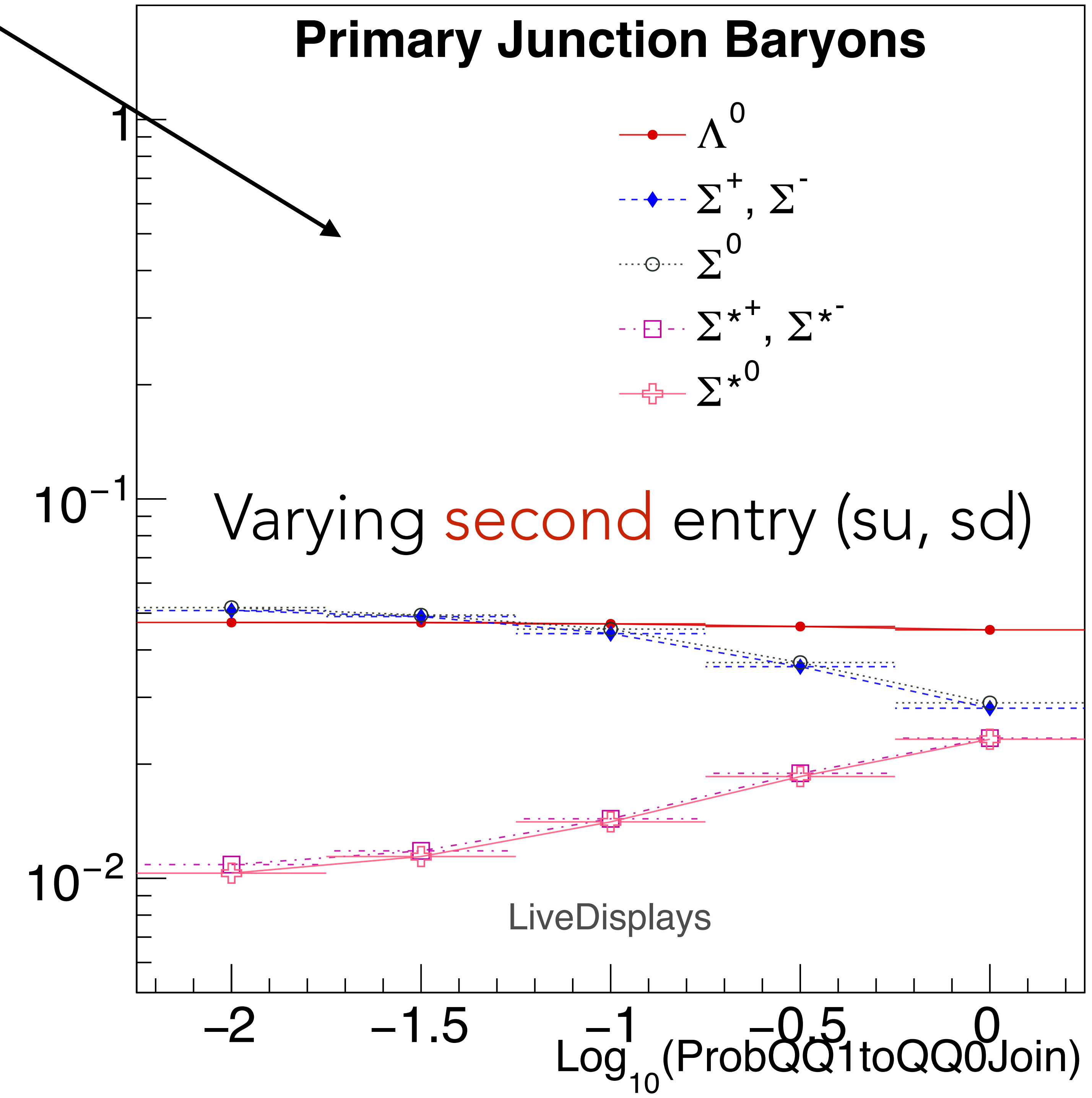


Effects of ProbQQ0toQQ1Join: Strange

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

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

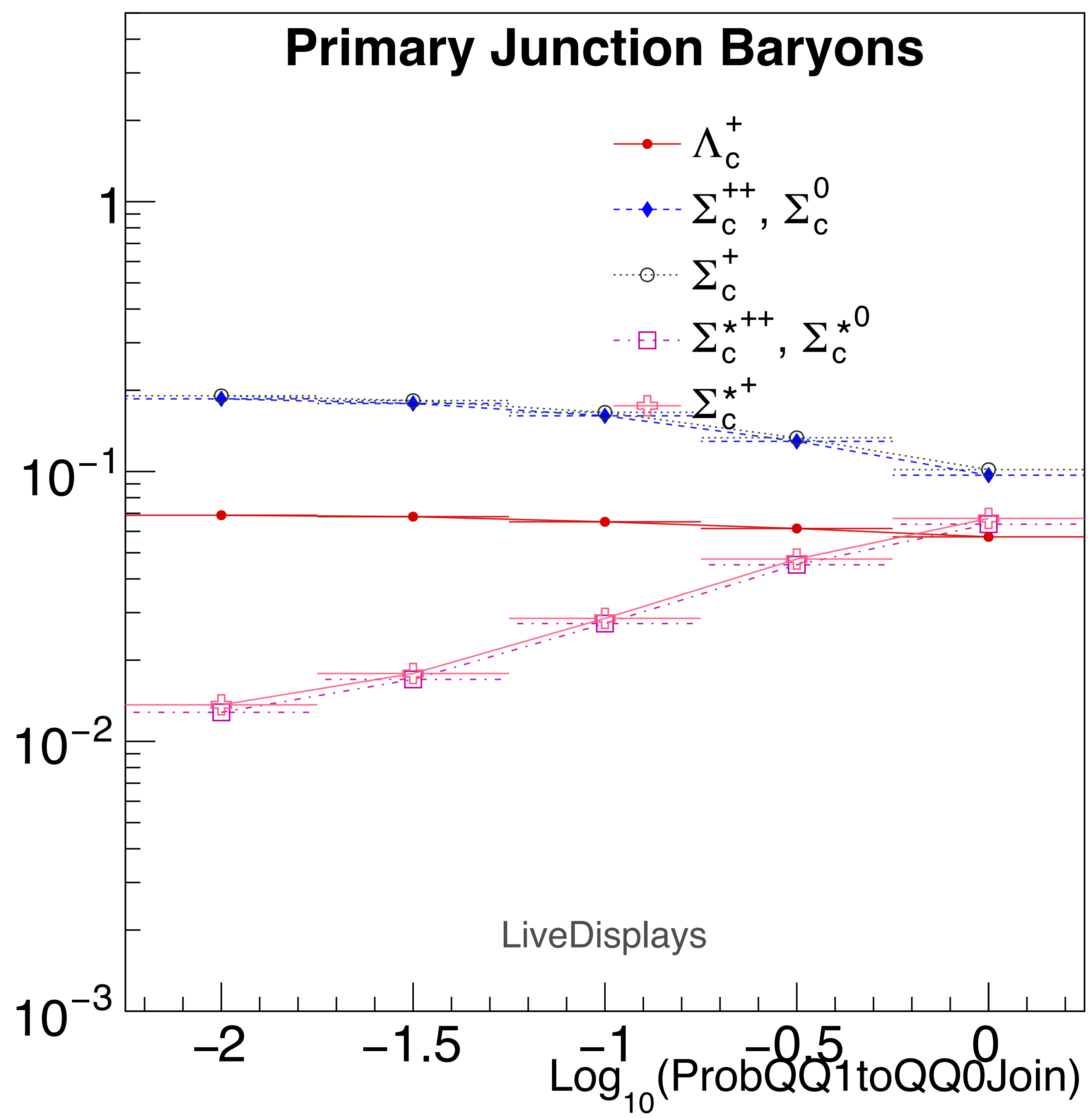


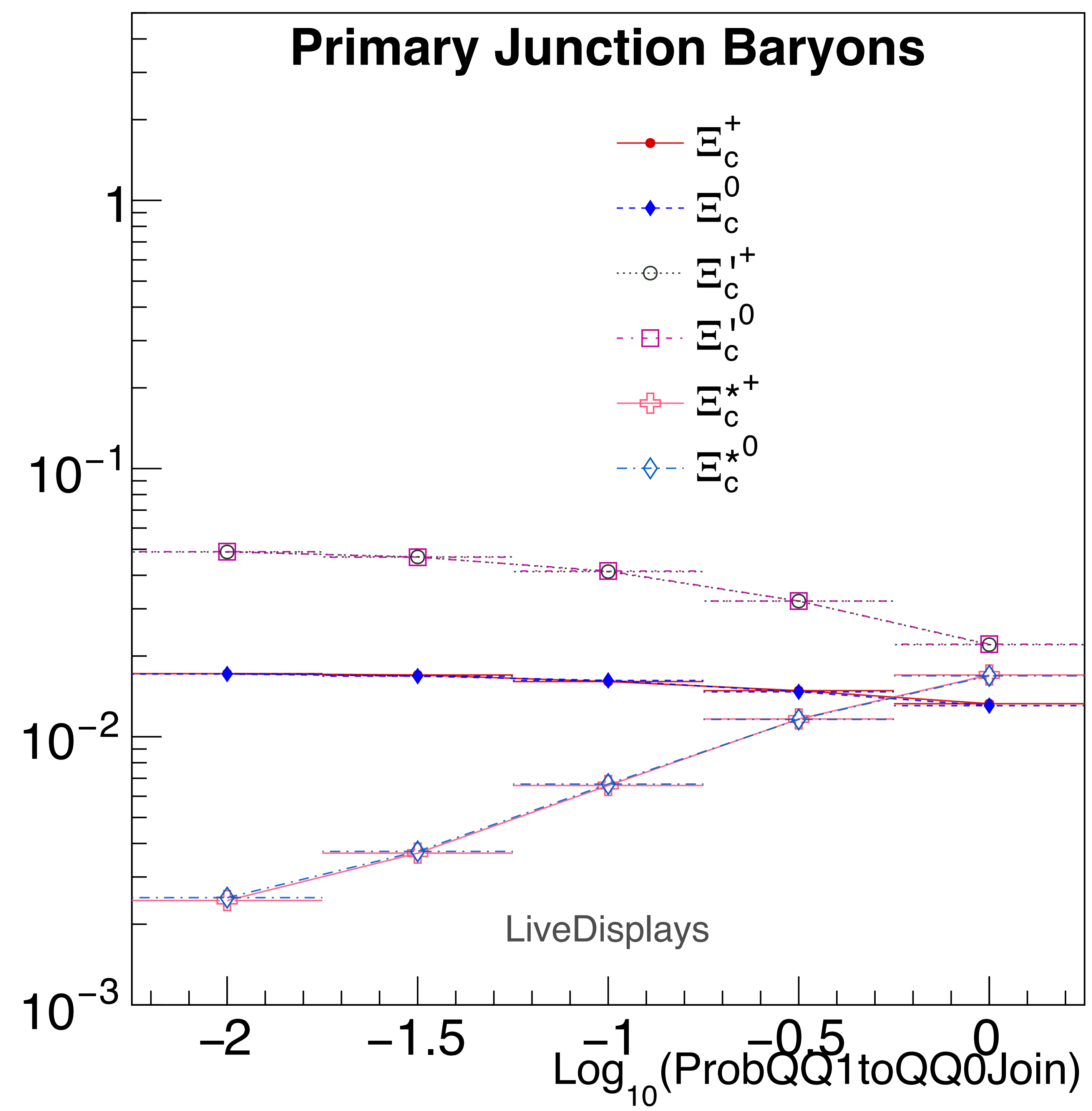


Note: primaries = before decays

`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

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)

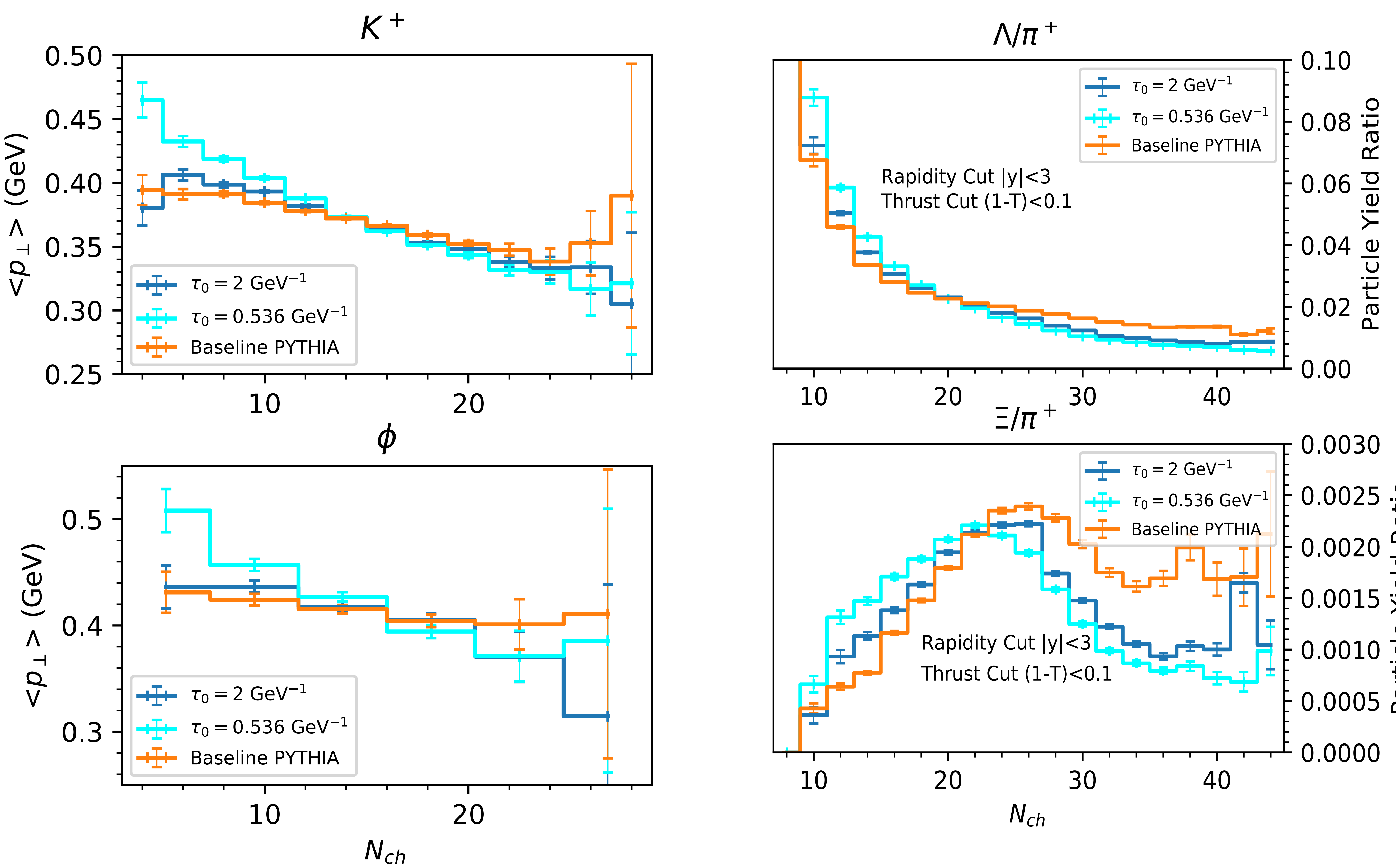
Toy Model with Time-Dependent String Tension

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}.

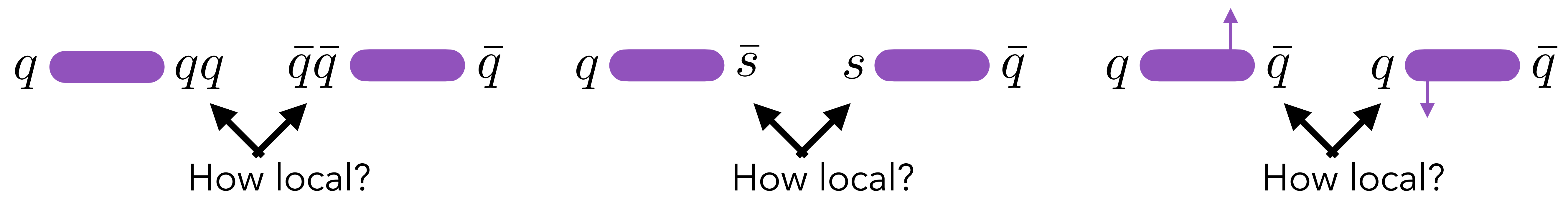


- ➤ Want to study (suppressed) tails with very low and very high N_{ch}.
- ➤ These plots are for LEP-like statistics.
- ➤ Would be crystal clear at CEPC/ FCC-ee

Thermal string breaks?

Detailed modelling of hyperfine splitting? (New work!)

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