Heavy Flavour Hadronisation in Pythia

Peter Skands (Monash University)

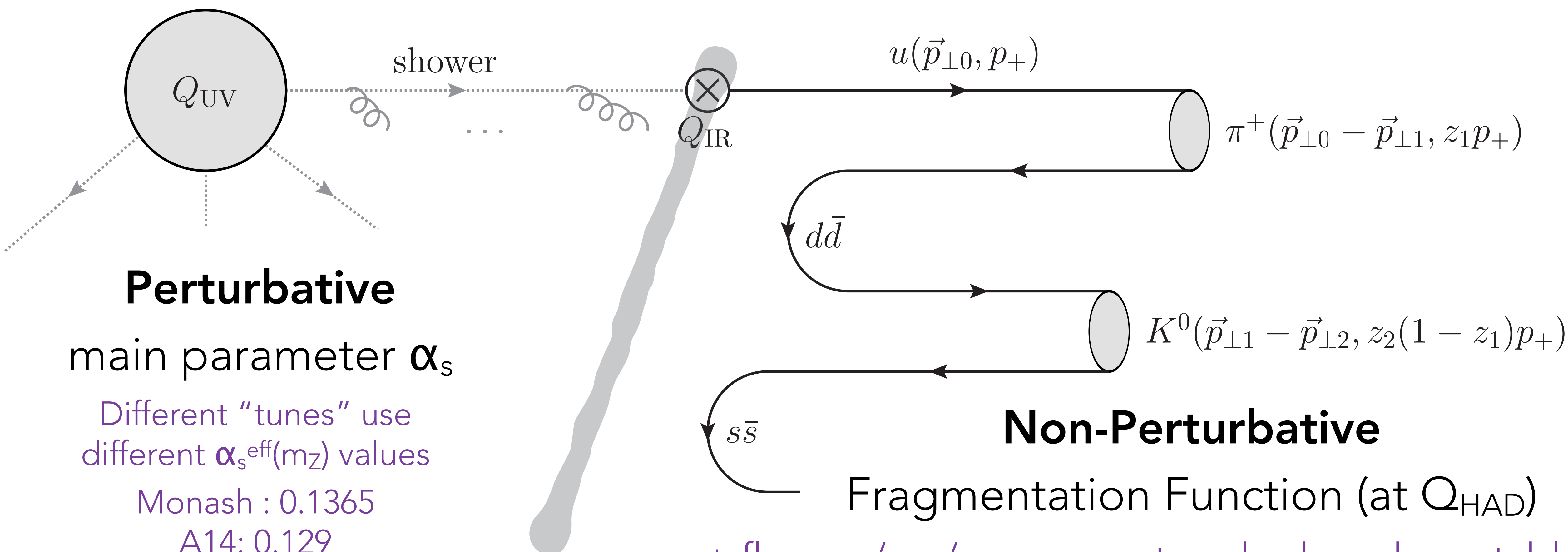
1. Heavy-Flavour Hadronisation in the Lund Model
2. Constraints
3. From ee to pp
4. New Theory Models in Pythia
5. Some Suggestions for New Measurements
6. Multiply heavy hadrons?

Reminder: Fragmentation Models

Hard process (e.g., dijets) ➤ hard factorisation scale Q_{UV} ~ p_{Tjet}

Parton Showers: perturbative bremsstrahlung down to Q_{IR} ~ 1 GeV

Hadronisation: confinement (+ hadron decays) at Q_{HAD} ~ Q_{IR}



Perturbative

main parameter α_s

Different "tunes" use different $\alpha_s^{eff}(m_Z)$ values

Monash : 0.1365

A14: 0.129

Non-Perturbative

Fragmentation Function (at Q_{HAD})

+ flavour / p_T / … parameters, hadron decay tables

Spectrum = combination of α_s choice & non-perturbative parameters

Flavour Composition in the Lund Model

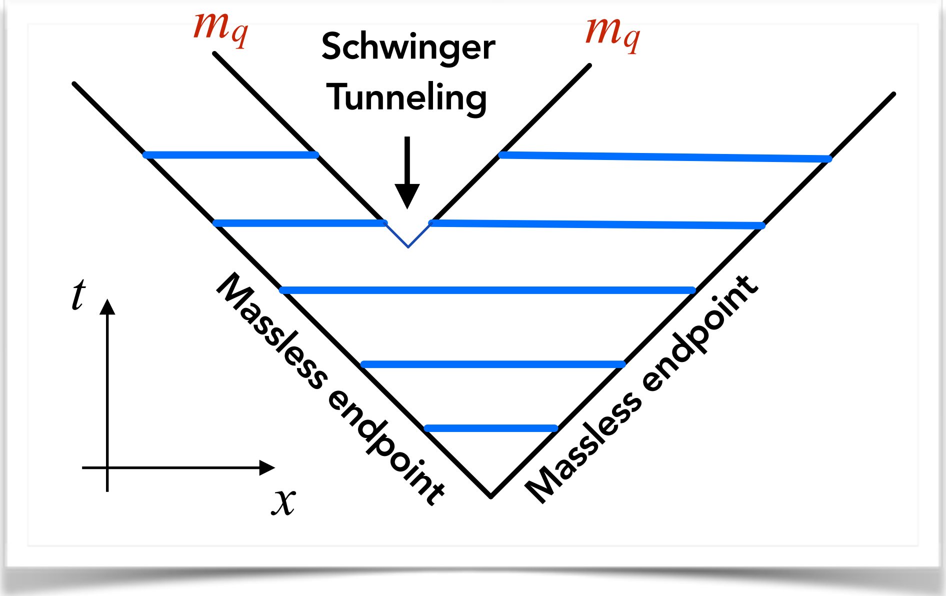
Starting point: **isolated** string in 1+1 dimensions

Tension κ ~ 1 GeV/fm ~ 0.2 GeV^2

String breaks by Schwinger mechanism

➜ **Suppression** of strange quarks (and diquarks) $\exp\left(-\frac{m_q^2+p_\perp^2}{\kappa}\right)$

➜ StringFlav:probStoUD = 0.217



+ Spin-splitting in hadron multiplets V/P ≠ 3

ρ/π StringFlav:mesonUDvector = 0.50

K*/K StringFlav:mesonSvector = 0.55

D*/D StringFlav:mesonCvector = 0.88

B*/B StringFlav:mesonBvector = 2.2

Note: model parameters are for **primary** hadrons ≠ measured ratios (feed-down)

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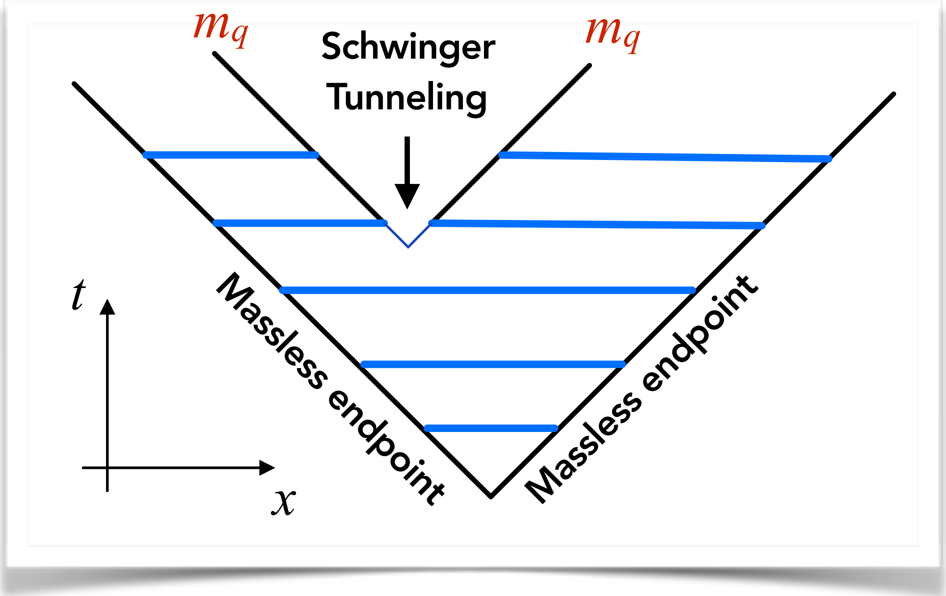

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Rookie Mistake: for D*/D in the Monash tune

arXiv:1404.5630

I took the D and D* rates from separate sources ➤ wrong ratio
Should be higher ~ 1.25 - 1.5 to agree with measured values

Thanks to D. Bardhan for pointing to this

Heavy-Flavour Endpoint Quarks

Same starting point as for massless endpoints

Tension κ ~ 1 GeV/fm ~ 0.2 GeV^2

String breaks by Schwinger mechanism

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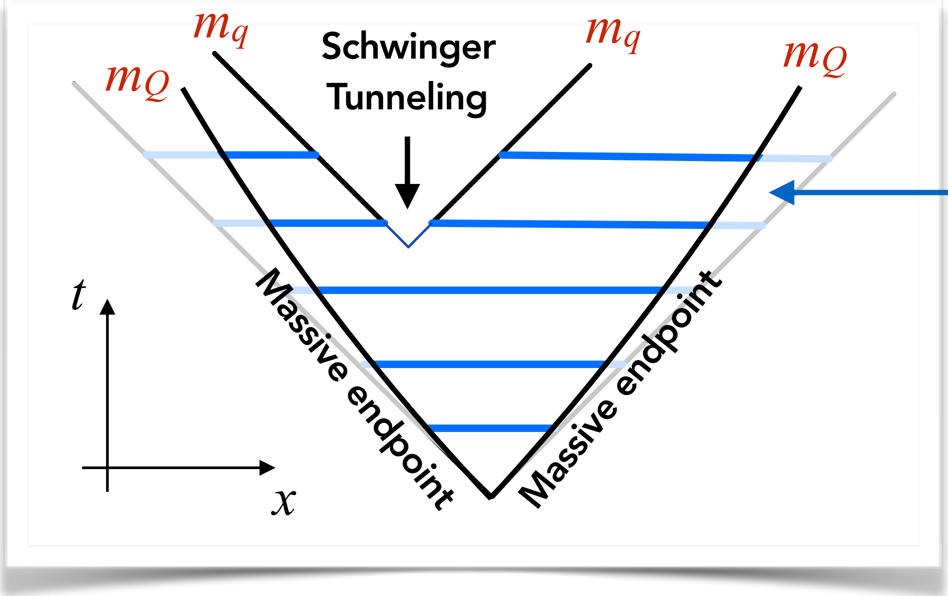


! Same parameters govern **D$_s$/D, B$_s$/B, Λ$_c$/D, Λ$_b$/B** ➜ Interesting to check if D$_s$/D, B$_s$/B affected in same way in same environments where we see *strangeness enhancements* in light-quark sector: **multiplicity** dependence

Massive endpoints have v < c ➜ **smaller string space-time area:**

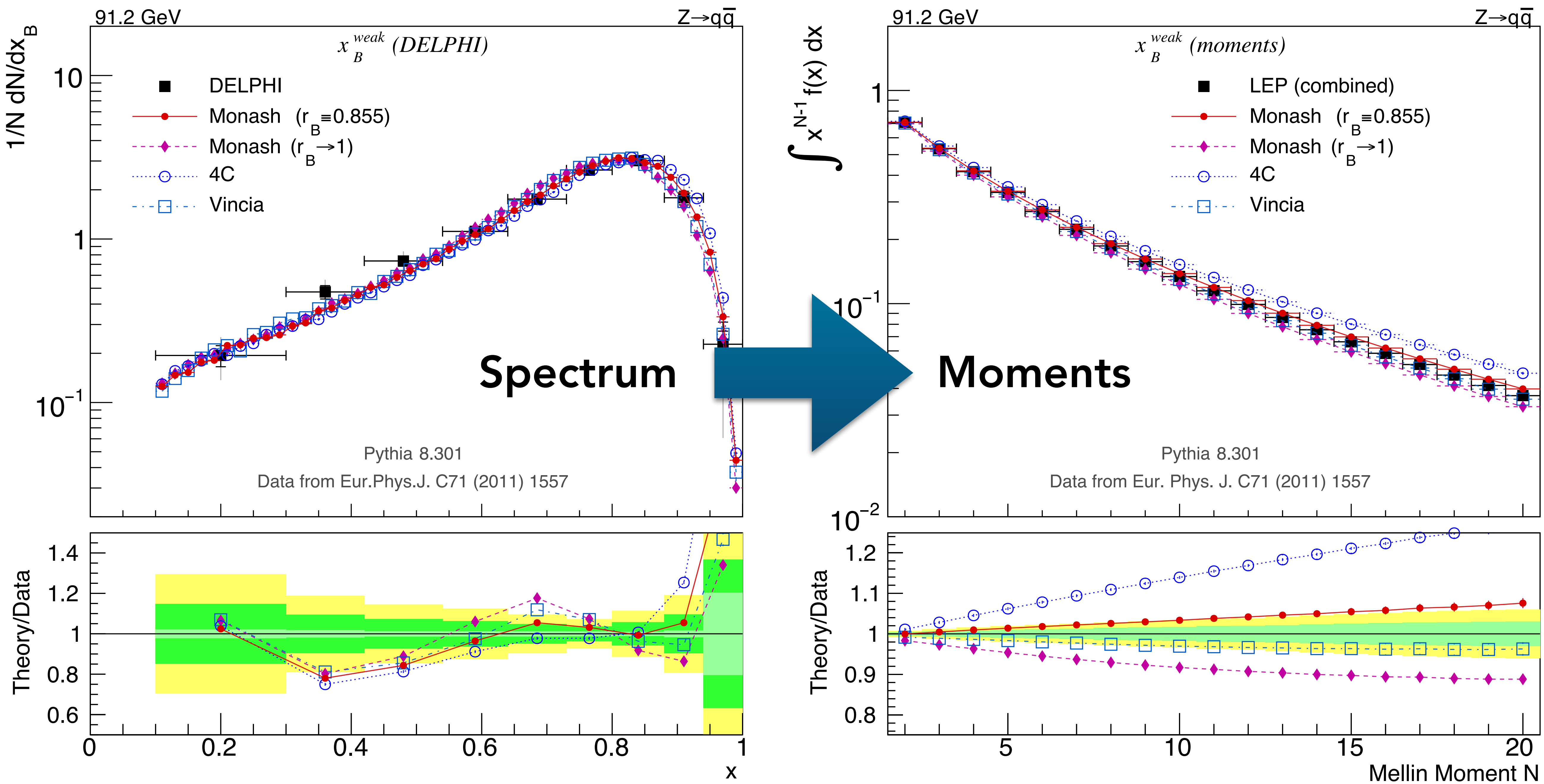
➜ Modified ("Lund-Bowler") FF: $$\frac{(1-z)^a}{z^{1+r_Q\, b\, m_Q^2}} \exp\left(\frac{-b\, m_{\perp,h}^2}{z}\right)$$ with $r_b \sim r_c \sim 1$

(Note: Peterson etc strictly speaking incompatible with causality in string picture)

StringZ:rFactB = 0.855

Constraints : B Spectra

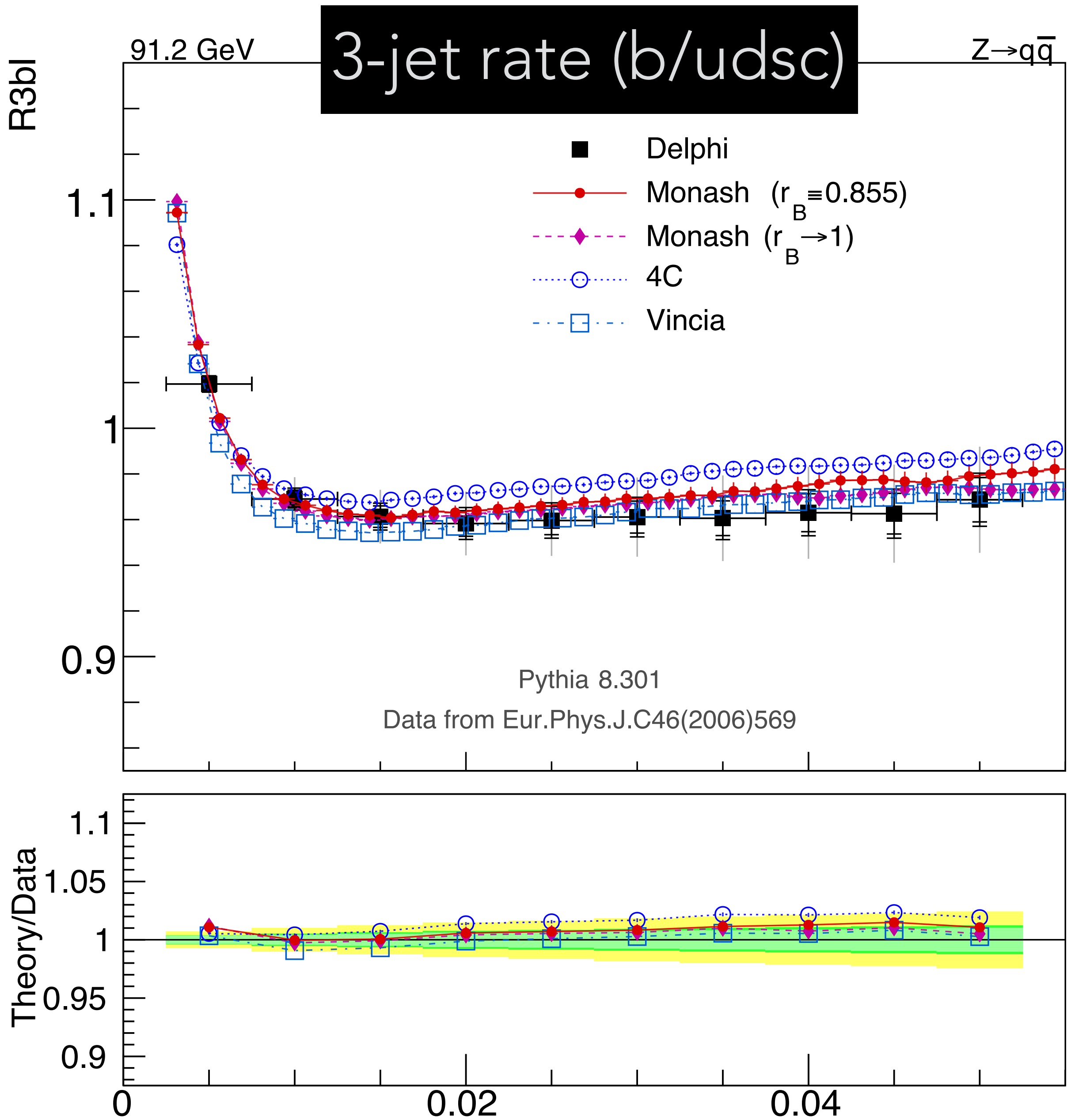
Main constraint: x_B spectra of weakly decaying B hadrons in Z decays



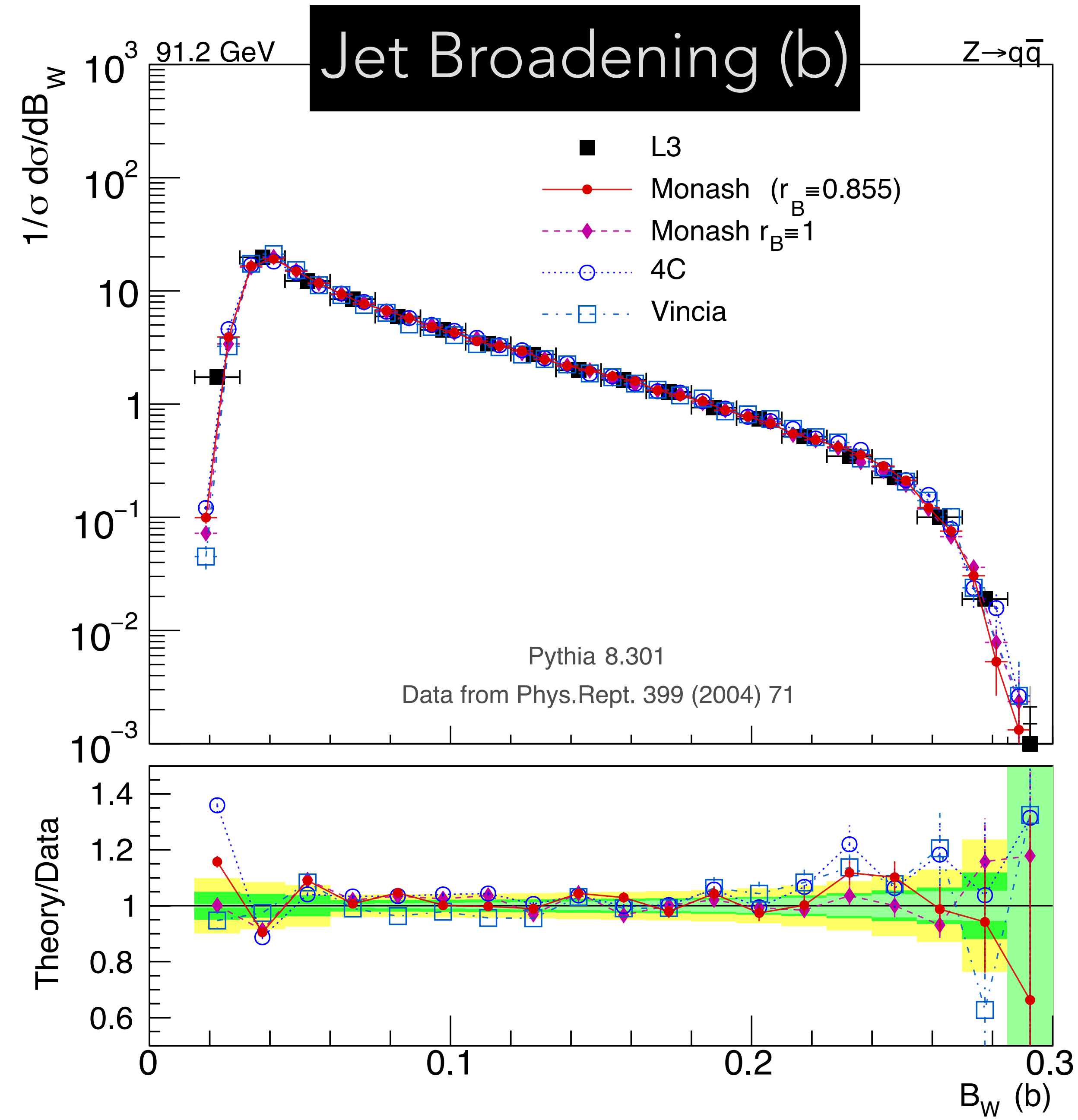
for details see arXiv:1404.5630 (section 2.3)

+ B-tagged Event Shapes & Jet Rates

IR safe: sensitive to α_s and b mass effects in shower + hadronisation



Durham k_T 3-jet resolution y_{23}



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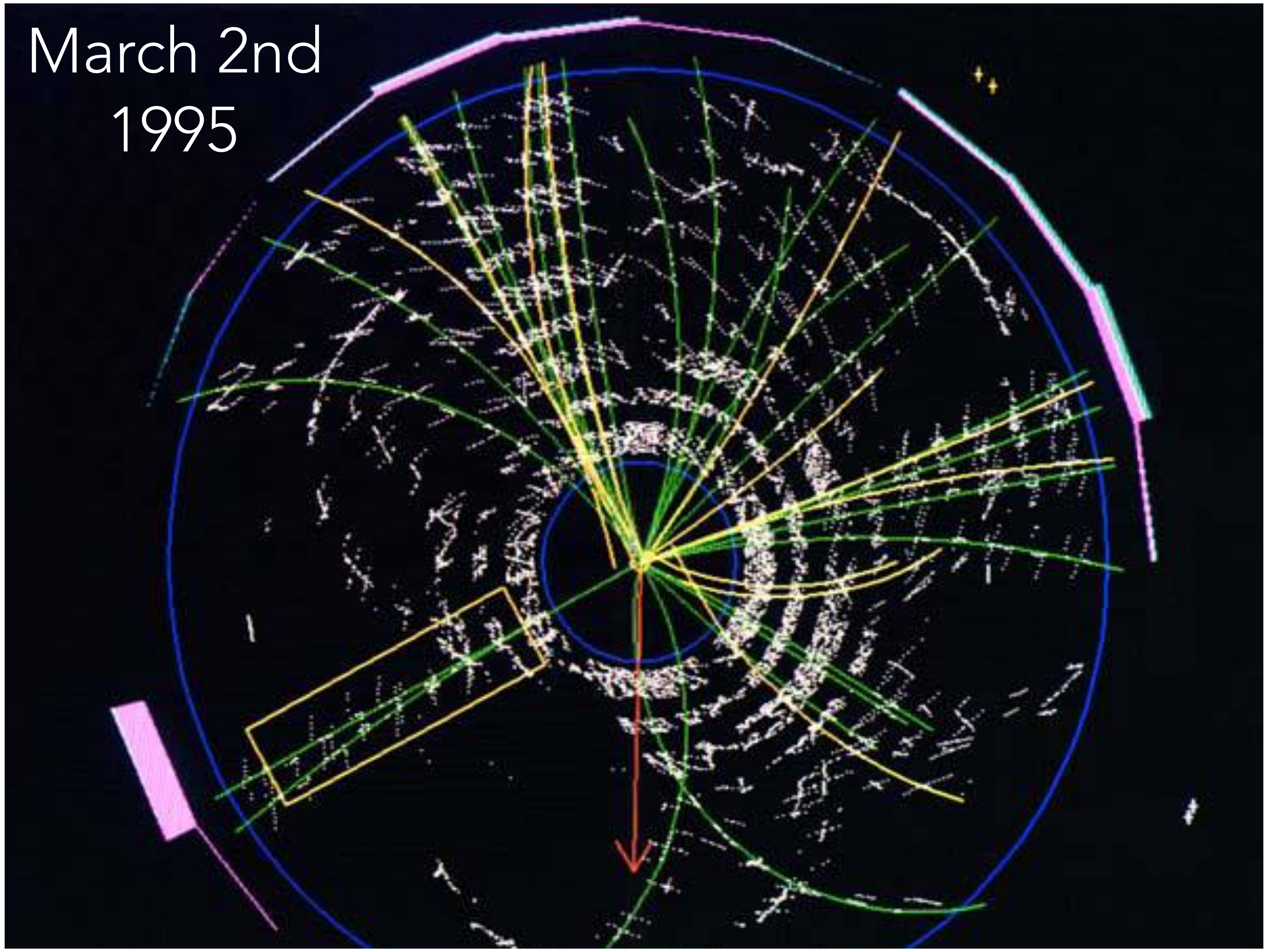
LHC: Top Decays ➤ In-situ controlled B-Jet Sample?

Yesterday: **25th anniversary of the top quark discovery**



t→bW provides a clean high-statistics reference sample, with a well-defined initial b-quark energy (in top CM) very similar to Z → bb.

Compare B FF(x) and B hadron flavour ratios to those for inclusive b-jets, incl. any dependence on UE level (measured away from the top jets)

Note: finite top width ➜ "collective effects" may be suppressed in top

("early" vs "late" resonance decays)

Some Comments on b fragmentation "tuning"

Note: Monash uses "large" TimeShower:alphaSvalue = 0.1365

Regarded at least in part as making up for **NLO** K-factor for **ee→3 jets** (baseline Pythia only accurate to LO for 3 jets).

Consistent with 3-flavour Λ_{QCD} ~ 0.35 GeV (since we use 1-loop running)

Not guaranteed to be universal.

LHC studies tend to prefer lower effective values of α_s

E.g., A14 uses TimeShower:alphaSvalue = 0.129 (could be reinterpreted via CMW to MSbar alphaS(mZ) ~ 0.12 so consistent with world average.)

(but I would then also change to 2-loop running to preserve Λ_{QCD} value)

E.g., a lower α_s ➜ less perturbative radiation ➜ harder $x_b(Q_{IR})$

➜ Would need to retune non-perturbative parameters (e.g., r_b) at LEP

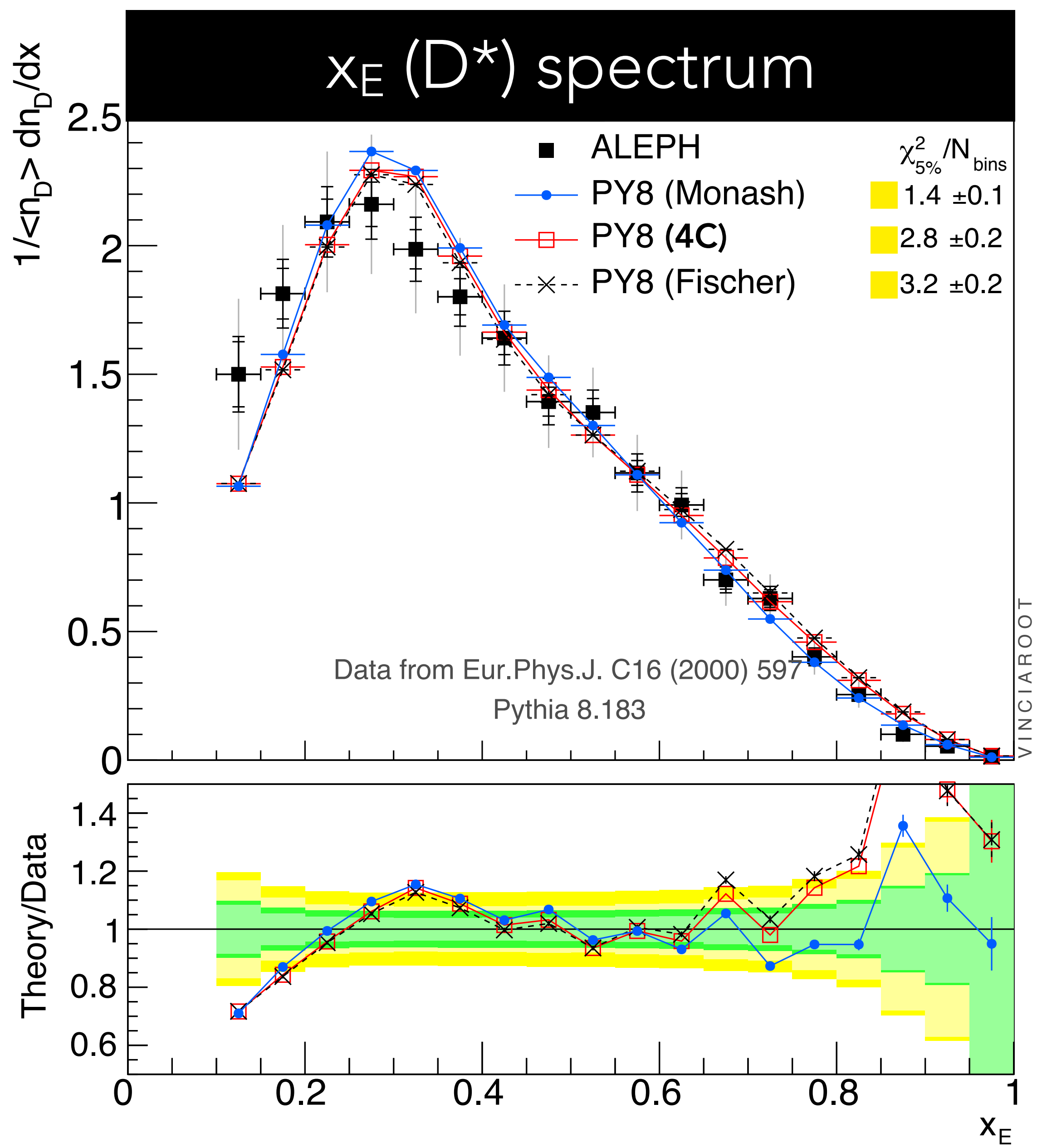
Problem: most LEP measurements are inclusive (including 3-jet events)

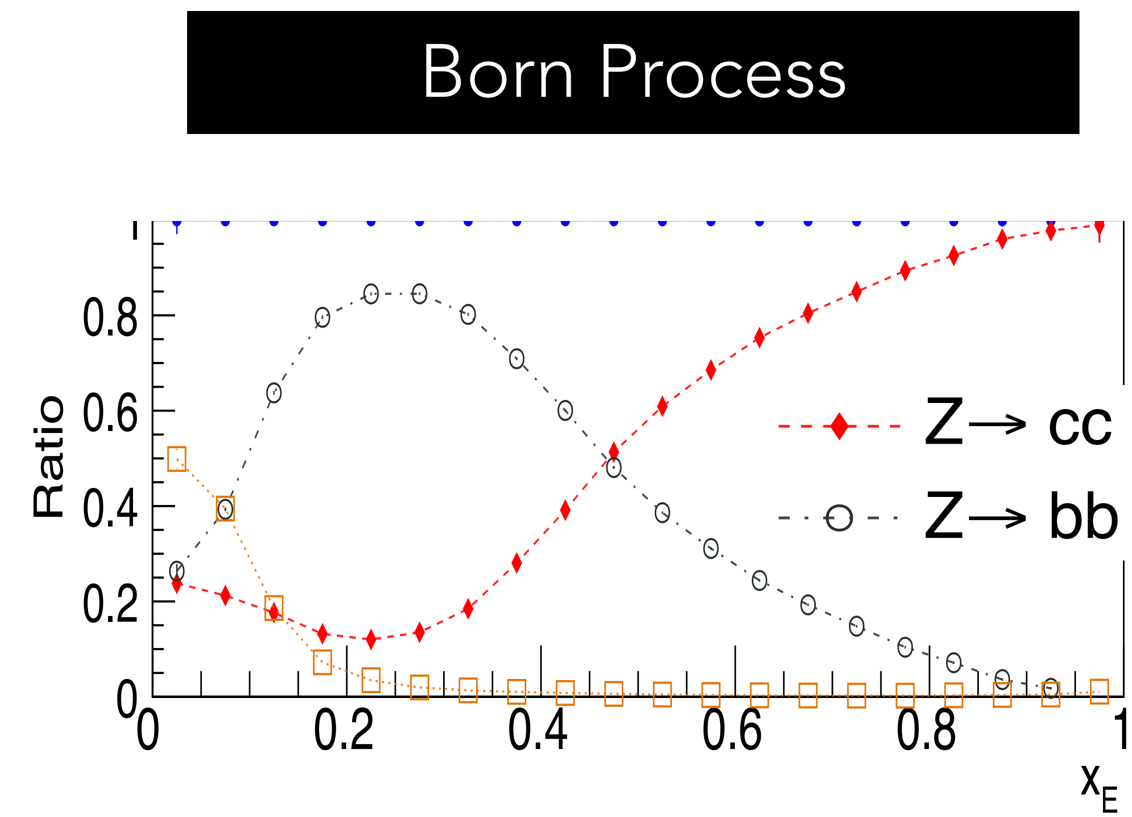
➜ Would need 3-jet NLO merging to ensure correct 3-jet admixture.

Constraints : Charm

No "C-tagged" data from LEP (that I am aware of)

Monash tune only used a single D* spectrum (ALEPH) ➜ r_c





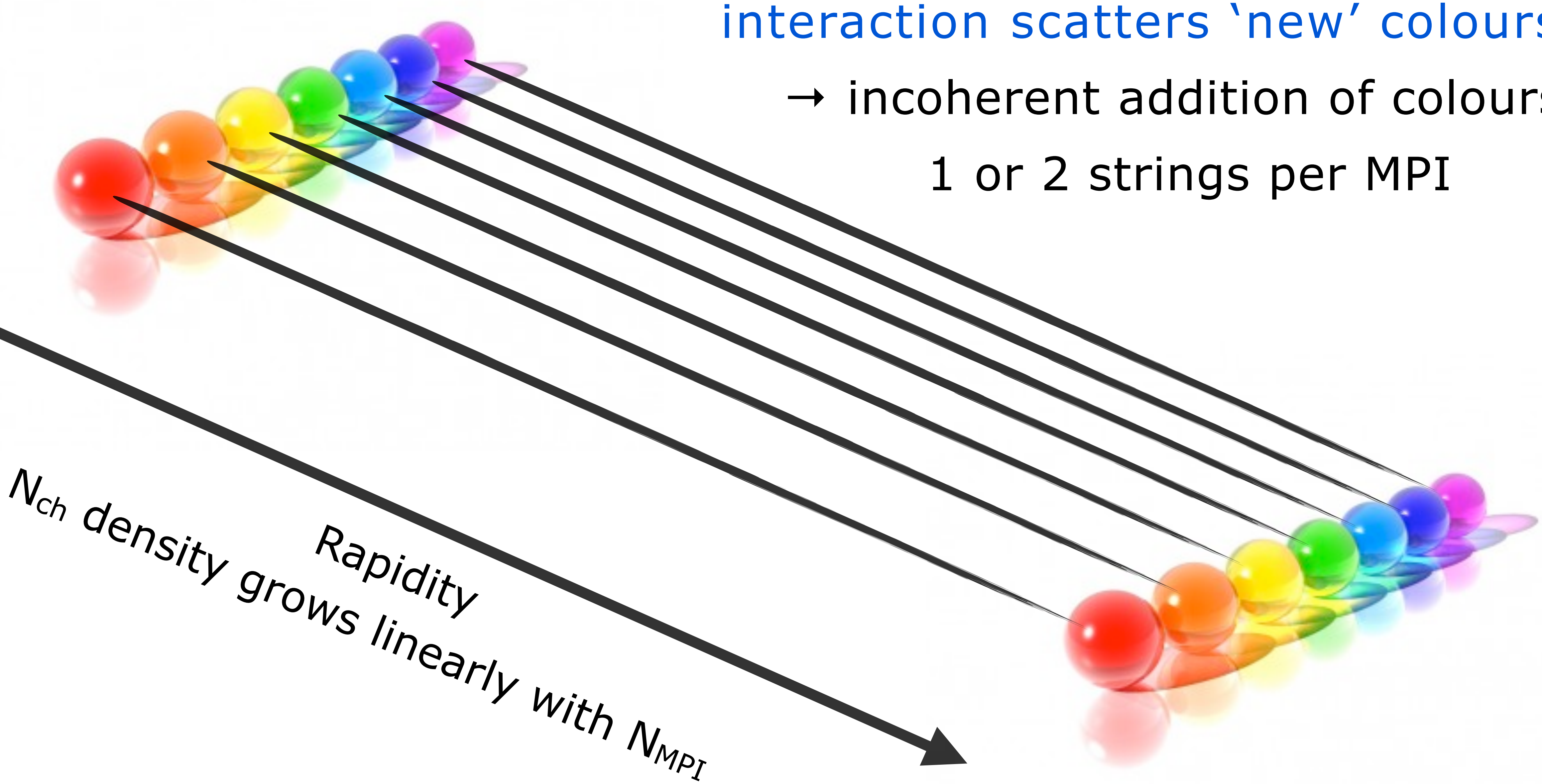
Actual charm fragmentation not seen very clearly. For x<0.5, the inclusive D* spectrum is dominated by B decays

From ee to pp: multiple parton interactions (MPI)

Leading N_C: each parton-parton interaction scatters 'new' colours

→ incoherent addition of colours

1 or 2 strings per MPI

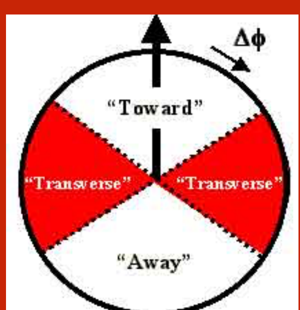


Simple, clean, factorized picture …

WRONG!

Anticipated already in first Pythia MPI model ***(Sjöstrand & van Zijl, 1987)***

"CR" parameter = probability for MPI to just generate "kinks" on hard-process colour structure, rather than new strings of their own



Tevatron $<N_{ch}>$ and $<\Sigma p_T>$ in "Transverse" UE region
Required ~ 100% CR ***(Rick Field, "Tune A", 2002)***

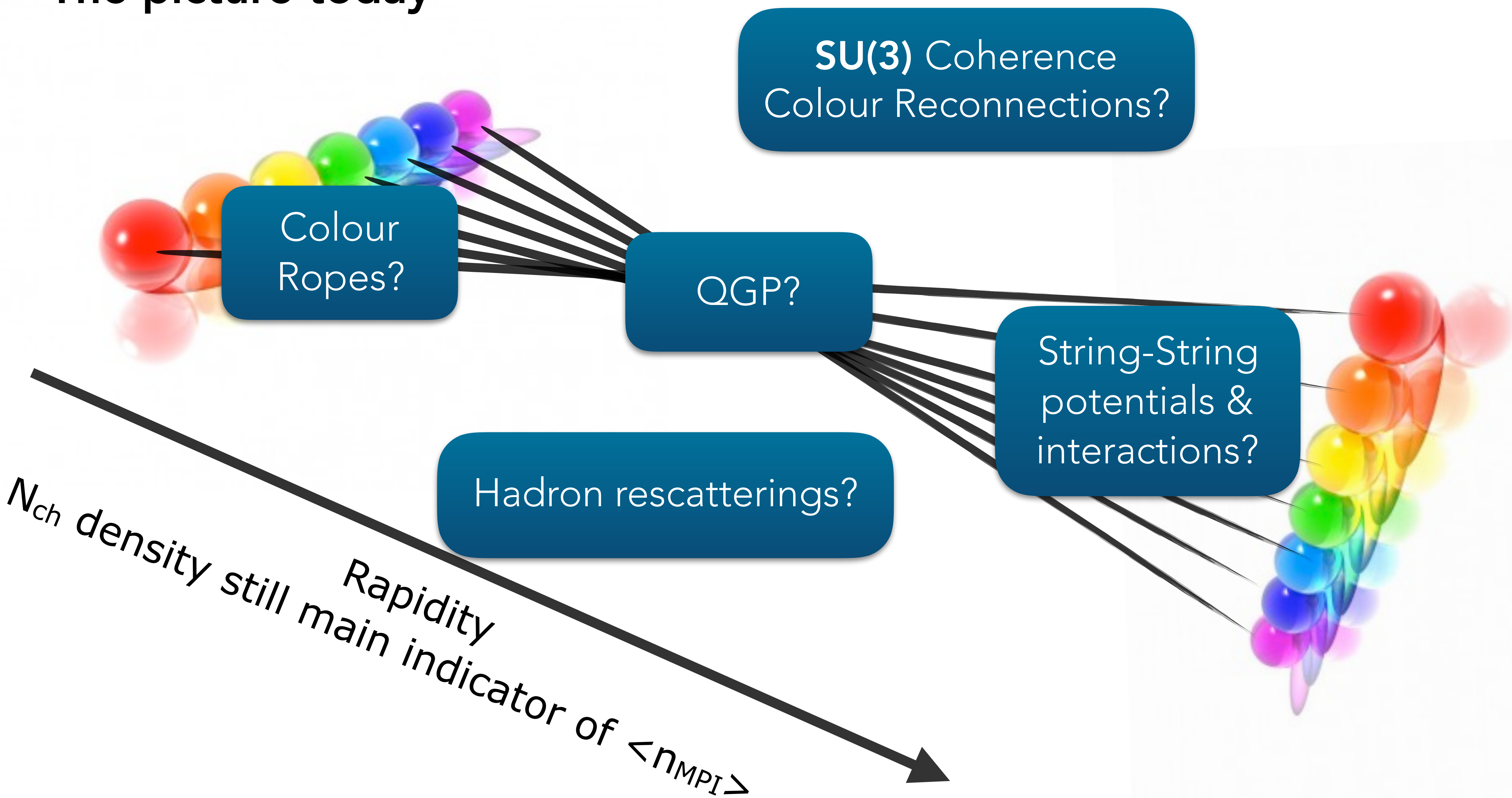
➤ Not a small effect, then …

+ Many new measurements and discoveries from LHC (& RHIC)

(e.g., CMS ridge, ALICE strangeness vs N_{ch}, …)

The MPI are all within a proton radius of each other (in pp)

The picture today



Fertile ground for model building

Brief Summary of "New" Theory Models in Pythia

QCD-inspired CR `ColourReconnection:mode = 1` Christiansen, Skands, JHEP 1508 (2015) 003

Stochastically sample subleading-N_C connections according to **SU(3) weights** and choose among possibilities (incl colour-ϵ ones) based on **string-length minimisation**.

➤ **some flow effects** & **additional baryons** (incl multiply-heavy); no extra strangeness

Ropes & Shoving

Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503 (2015) 148
Bierlich, Gustafson, Lönnblad, PLB 779 (2018) 58

Ropes: allow QCD charges to combine into higher representations: 6, 10, 15, 21, 28, … with **higher string tensions** (Casimir scaling) ➤ **more strangeness & more baryons**

Shoving: explicit dynamical model of repulsion between different strings/ropes ➤ **flow**

Thermodynamical String fragmentation Fischer, Sjöstrand, JHEP 1701 (2017) 140

+ Much ongoing work …

Hadronic Rescattering (Sjöstrand+Utheim)

HI extensions (Angantyr, PISTA) & extensions with **UrQMD** (Bierlich et al.)

Interacting Strings: momentum-space alternative to ropes+shoving (Duncan+Skands)

Back to basics: fragmentation of a single string: early / out-of-equilibrium, and thermal effects. **Time-varying string tension** out soon. + other variants? E.g., **UCLA model**?

Some Suggestions for New Measurements

Want to disentangle <p_T>, <strangeness>, <baryons>, <N_{ch}>

$\langle \varsigma \rangle$ *(\varsigma)* $\langle \mathscr{B} \rangle$

E.g., CR and "flow" increase <p_T> without (directly) affecting $\langle \varsigma \rangle$

"Baryonic" CR can increase $\langle \mathscr{B} \rangle$

Higher tensions/temperatures: correlated <p_T>, $\langle \varsigma \rangle$, and $\langle \mathscr{B} \rangle$

Some Simple Questions:

How **local** are the $\langle \varsigma \rangle$ and $\langle \mathscr{B} \rangle$ enhancement mechanisms?

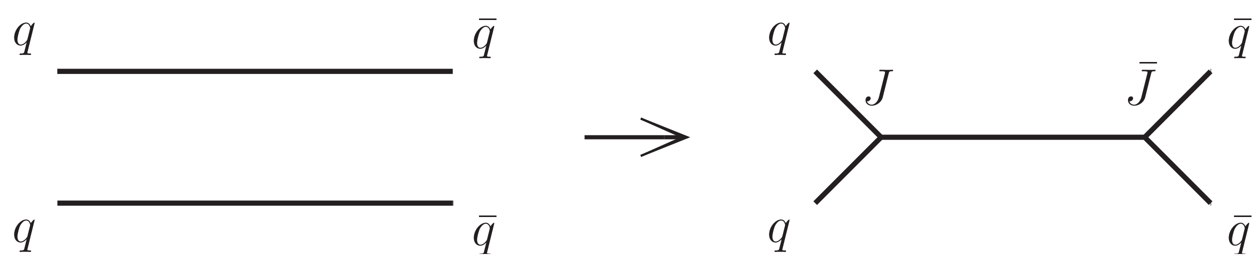
- **How far** in phase space **is nearest anti-strange / anti-baryon?**
- **For different values of** N_{ch} density, p_{TB} or p_T(b-jet), and ς density
- E.g., heavy-flavour tag, say B_s ➤ know the endpoint flavour ➤ look for nearest anti-strange quark.
- What is the distance in p_T? in rapidity (along z / along b-jet)? in ΔR?

How do the HF fractions depend on **event multiplicity?**

Heavy-Flavour Baryons

Example: QCD-inspired CR

Allows "junction reconnections", e.g.:



(b) Type II: junction-style reconnection

For the parameters used in that study,

Λ_c/D^+ increased by factor 2

Λ_b/B^+ by factor 3

+ potentially larger changes for $\Sigma_{c,b}^{(*)}$

Christiansen, Skands, JHEP 1508 (2015) 003

Particle	`ColourReconnection:mode = 1`	`= 0`
	$N_{\rm par}/N_{\rm events}$	
D^+	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^+	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^0	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$
Σ_c^{*++}	$2.2 \cdot 10^{-3}$	$9.5 \cdot 10^{-4}$
Σ_c^{*+}	$2.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-4}$
Σ_c^{*0}	$2.2 \cdot 10^{-3}$	$9.1 \cdot 10^{-4}$
ccq^7	$2.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-7}$
B^+	$1.6 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
Λ_b^0	$8.2 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
Σ_b^+	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$
Σ_b^0	$1.0 \cdot 10^{-3}$	$3.7 \cdot 10^{-5}$
Σ_b^-	$9.4 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$
Σ_b^{*+}	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$
Σ_b^{*0}	$1.0 \cdot 10^{-3}$	$3.7 \cdot 10^{-5}$
Σ_b^{*-}	$9.4 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$
bcq^7	$1.8 \cdot 10^{-5}$	0
bbq^7	$1.1 \cdot 10^{-6}$	0

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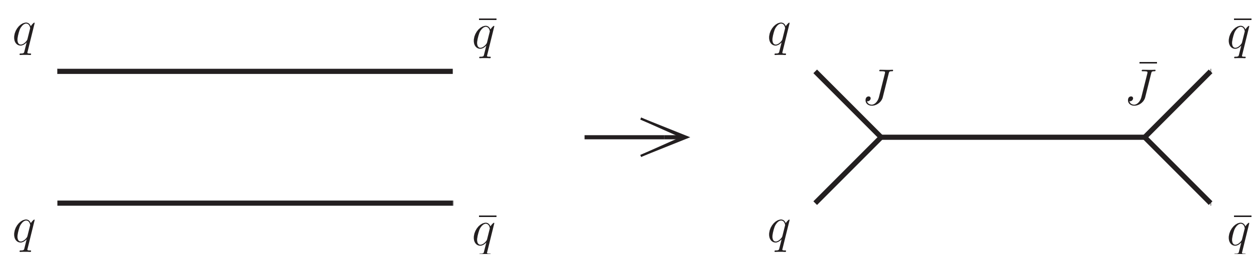

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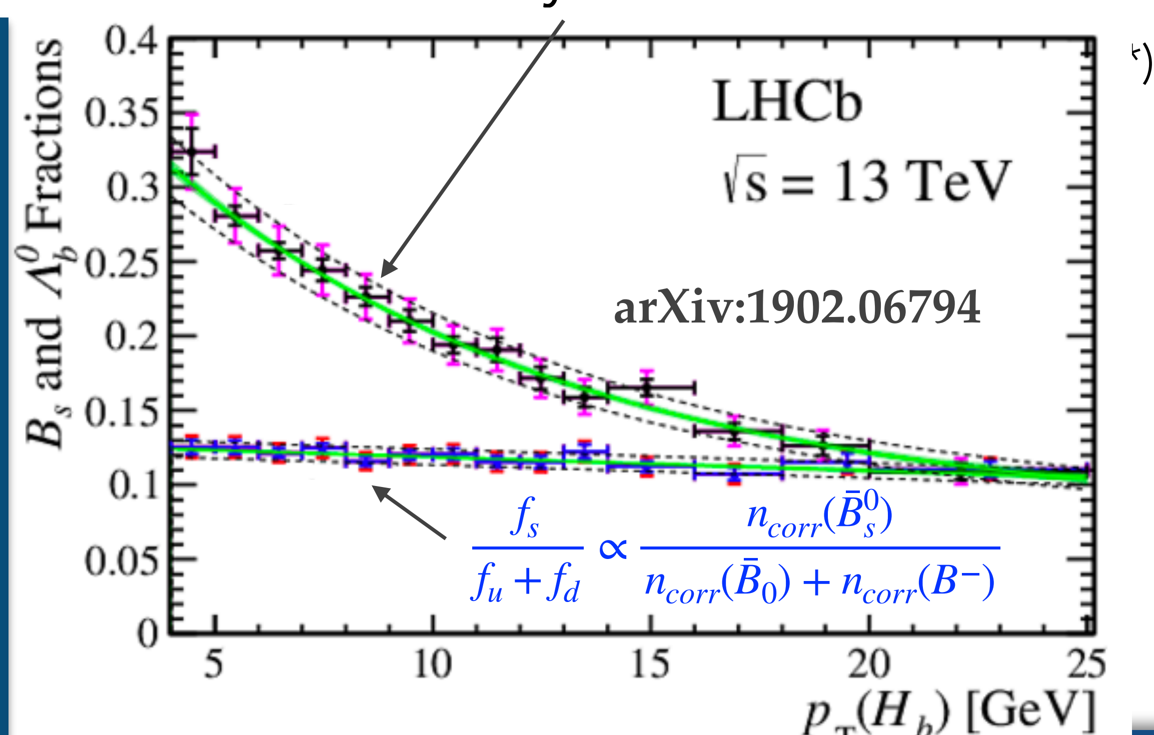
For the parameters used in that study,

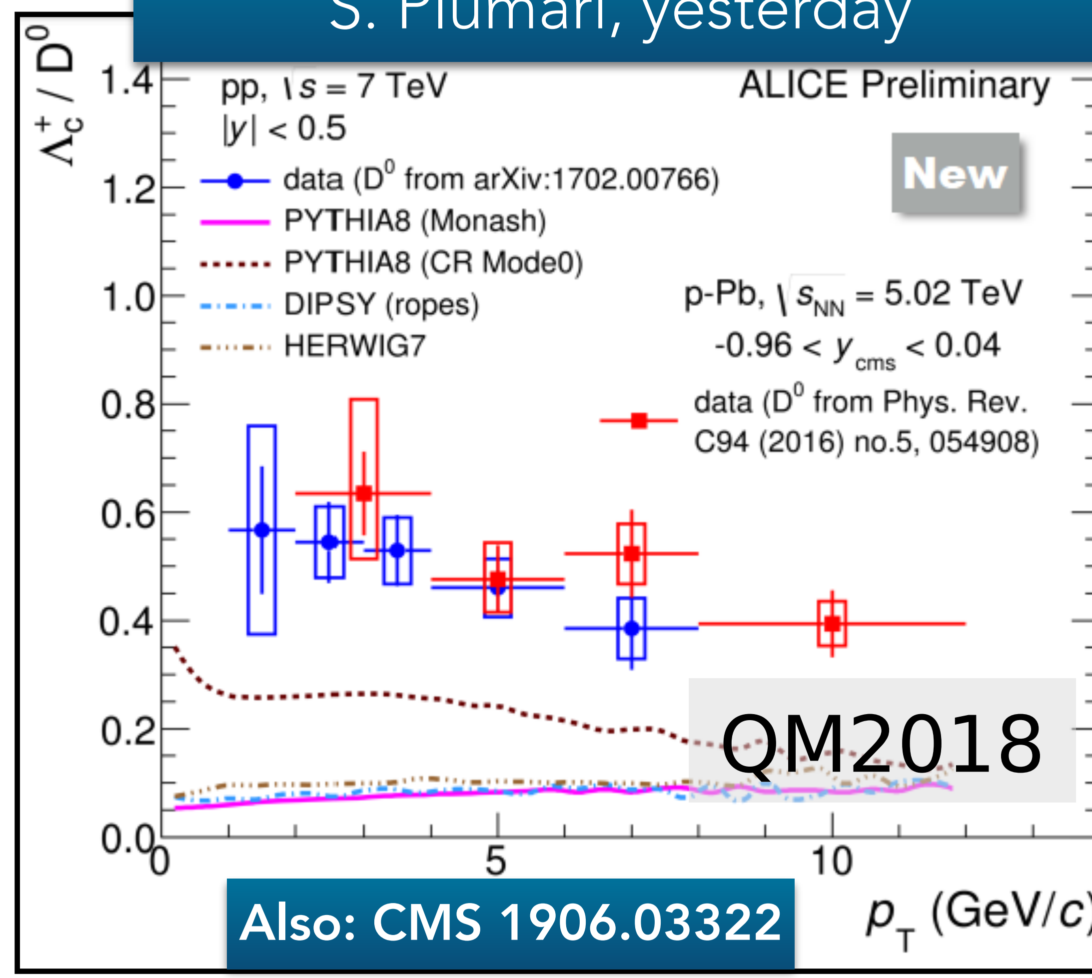
Λ_c/D^+ increased by factor 2

Λ_b/B^+ by factor 3

B. Audurier, yesterday



S. Plumari, yesterday



Also: CMS 1906.03322

Heavy-Flavour Baryons

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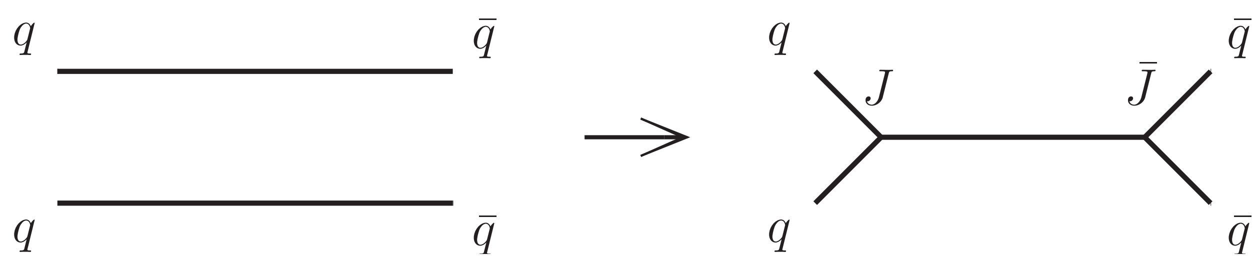

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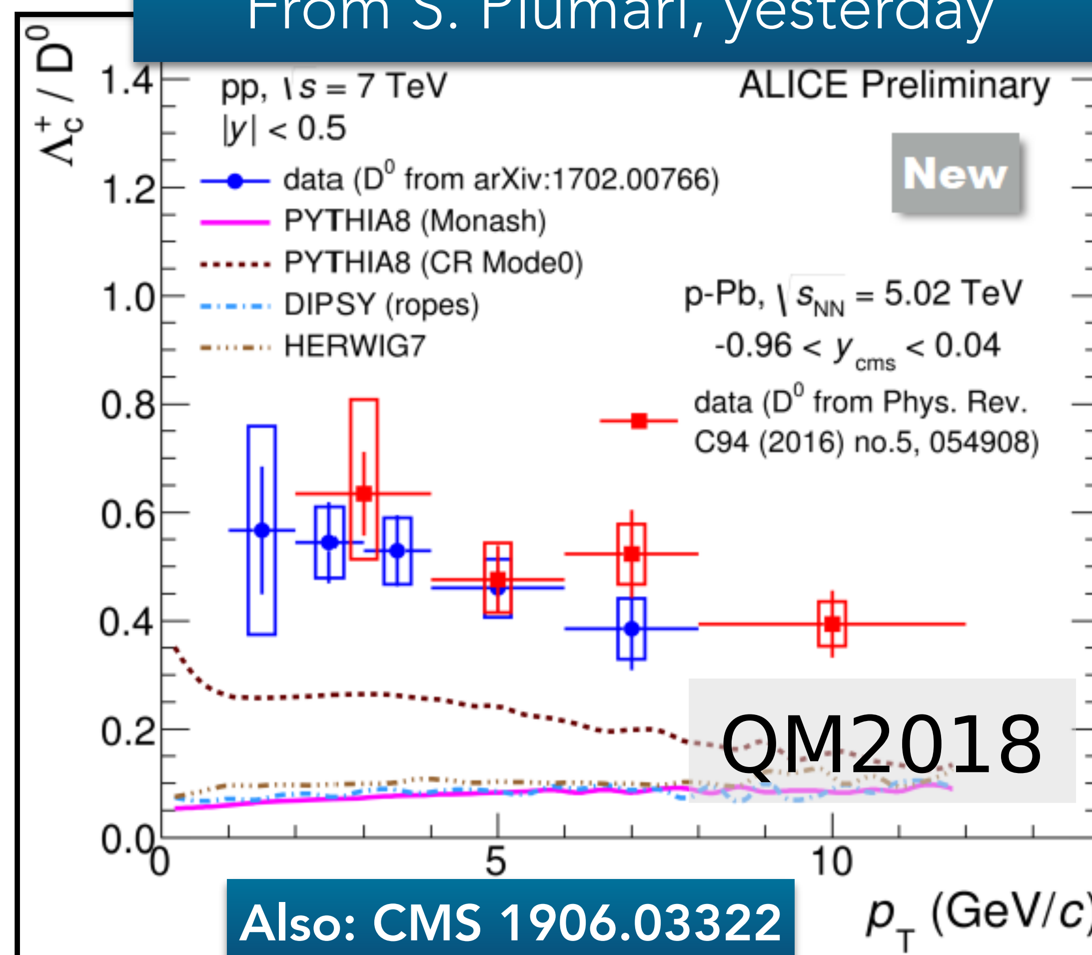
From S. Plumari, yesterday



Also: CMS 1906.03322

Generically expect **dependence on multiplicity** ➤ Measure <B/M>(N_{ch}) ?

(Should be true for ropes, hydro, … too)

+ **baryon-antibaryon** rapidity dependence?

First step, e.g., ALICE D meson associated track multiplicities in arXiv:1910.14403

(Some) LHCb measurements

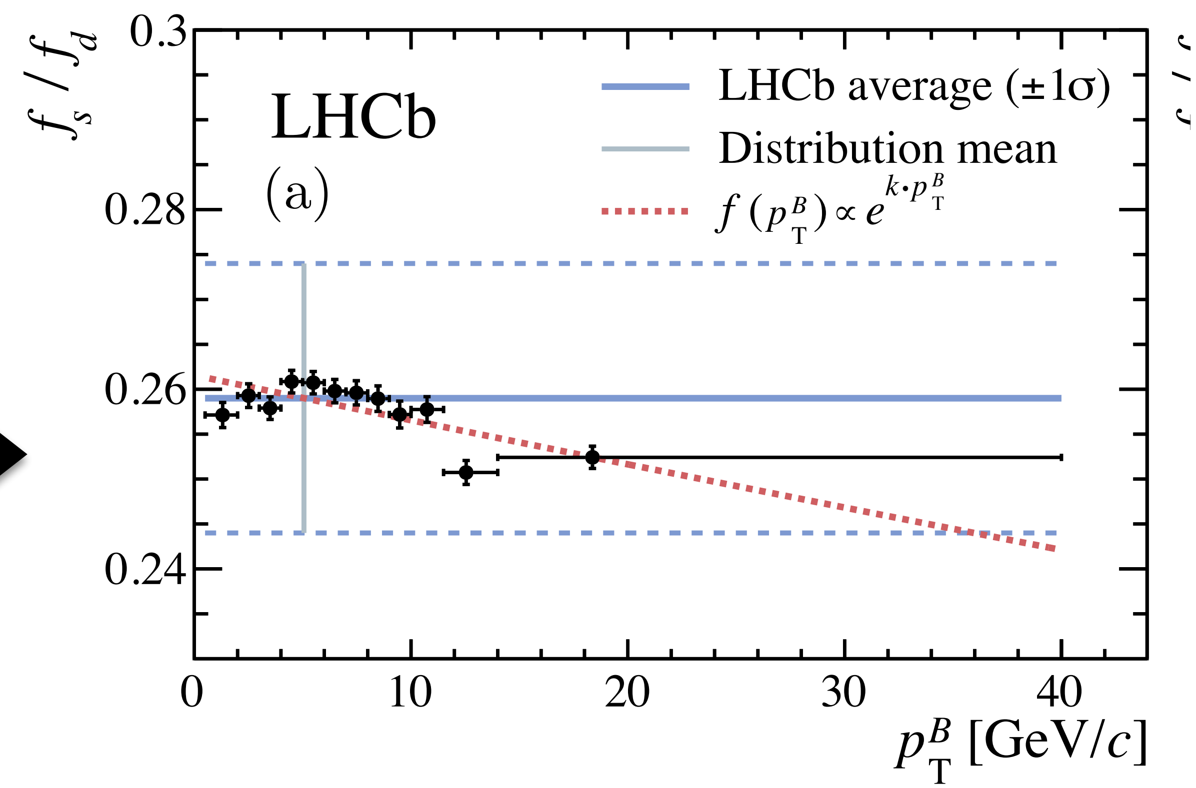
B_s/B^+ vs event kinematics

From $B_s \to J/\psi\ \varphi$ & $B^+ \to J/\psi\ K^+$

No dependence on p_{LB}, η_B

Decreasing trend with p_{TB} →

Would be highly interesting to see vs event multiplicity / associated track multiplicity

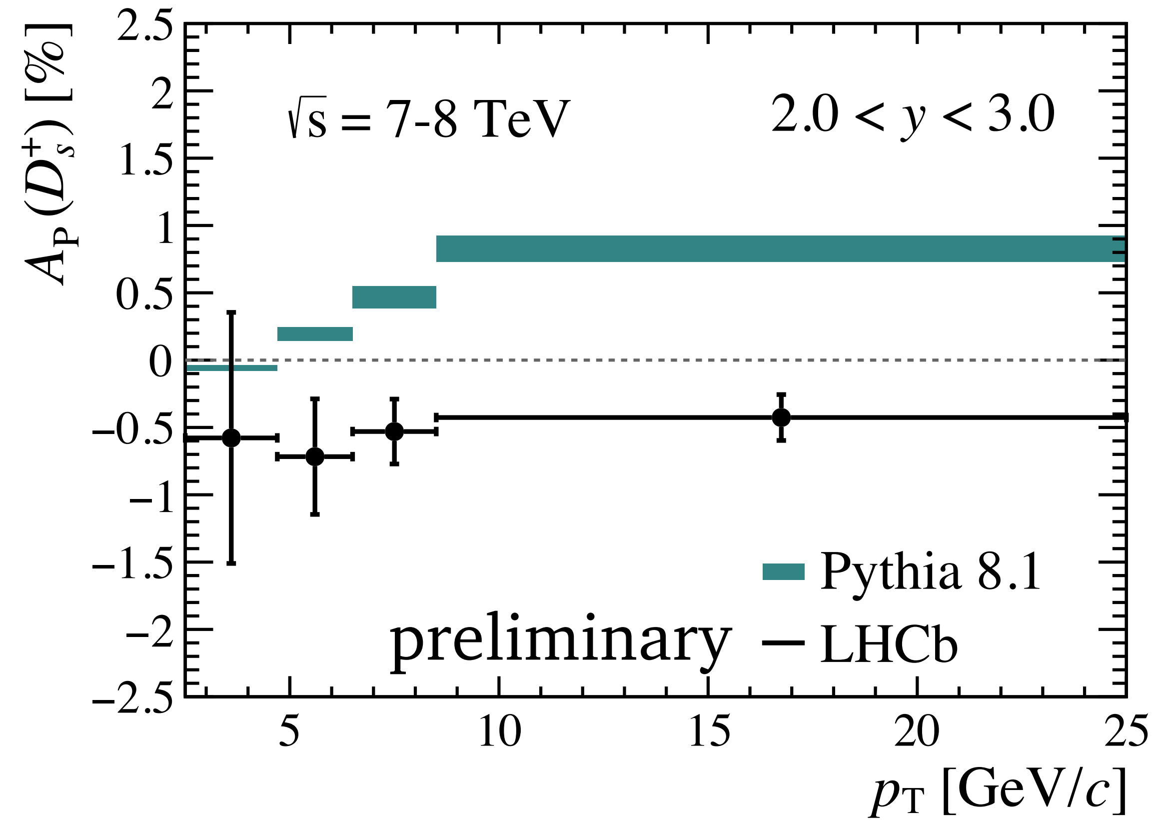


D_s asymmetry (S. Klaver, Moriond 2018)

$$\frac{\sigma(pp \to D_s^+) - \sigma(pp \to D_s^-)}{\sigma(pp \to D_s^+) + \sigma(pp \to D_s^-)}$$

Strong p_T dependence in Pythia, not seen in data

High p_T ➤ Coherence effect?



Multiply Heavy Hadrons?

Heavy flavours produced perturbatively, not in string/cluster breakups;

So why would multiply heavy hadrons be interesting as soft probes?

Because they also **probe the confinement field** in unique ways (colour-ϵ_{ijk})

E.g., the Ξ_{cc} has been measured LHCb-PAPER-2019-037

Does its rate vary with associated track density?

Christiansen, Skands, JHEP 1508 (2015) 003

Particle	ColourReconnection:mode = 1 New CR model (N_{par}/N_{events}) string	junction	all	= 0 Old CR model N_{par}/N_{events} (all)
D^+	$5.3 \cdot 10^{-2}$	0	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$4.0 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$2.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^+	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^0	$2.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$
Σ_c^{*++}	$5.1 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$9.5 \cdot 10^{-4}$
Σ_c^{*+}	$4.9 \cdot 10^{-4}$	$1.9 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-4}$
Σ_c^{*0}	$4.8 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$9.1 \cdot 10^{-4}$
ccq^7	0	$2.1 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-7}$
B^+	$1.6 \cdot 10^{-3}$	0	$1.6 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
Λ_b^0	$1.9 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$	$8.2 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
Σ_b^+	$1.1 \cdot 10^{-5}$	$9.3 \cdot 10^{-4}$	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$
Σ_b^0	$1.2 \cdot 10^{-5}$	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$3.7 \cdot 10^{-5}$
Σ_b^-	$1.1 \cdot 10^{-5}$	$9.3 \cdot 10^{-4}$	$9.4 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$
Σ_b^{*+}	$1.1 \cdot 10^{-5}$	$9.3 \cdot 10^{-4}$	$9.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$
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Σ_b^{*-}	$1.1 \cdot 10^{-5}$	$9.3 \cdot 10^{-4}$	$9.4 \cdot 10^{-4}$	$3.2 \cdot 10^{-5}$
bcq^7	0	$1.8 \cdot 10^{-5}$	$1.8 \cdot 10^{-5}$	0
bbq^7	0	$1.1 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$	0

Note: the baryon "predictions" depend on poorly constrained model parameters; highlight measurement sensitivity

To discuss: observables to tell apart …

CR: longitudinal (1D) strings + transverse boosts: flow-like effects

No <ς> enhancement; low velocity dispersions relative to common boosts

Additional tracers: multiply heavy baryons (will at least ➤ constraints!)

Ropes etc: longitudinal (1D) strings with higher effective tensions

Strangeness enhancement + higher <p_T>, but still "1D"

➤ rank ordering, const dN/dy?

Shoving etc.: Longitudinal strings with transverse repulsions

1D "rank" still relevant for <$\mathscr{B}$>, <ς>, and (local) p_T conservation ➤ correlations?

+ higher tensions? Is <p_T> correlated or anti-correlated with <ς>, <$\mathscr{B}$> ?

Thermal/Statistical systems: 3D systems with higher effective T

Very high dispersions, 3D.

Quantum number and p_T conservation not ordered in "rank" at all?

Extra Slides

We wanted to know if "violent" collision events produced higher-strength fields.

Smoking gun would be a higher fraction of strange particles being produced

(higher-strength fields $\Longrightarrow$ more energy per "space-time volume" $\Longrightarrow$ easier to produce higher-mass quark-antiquark pairs)

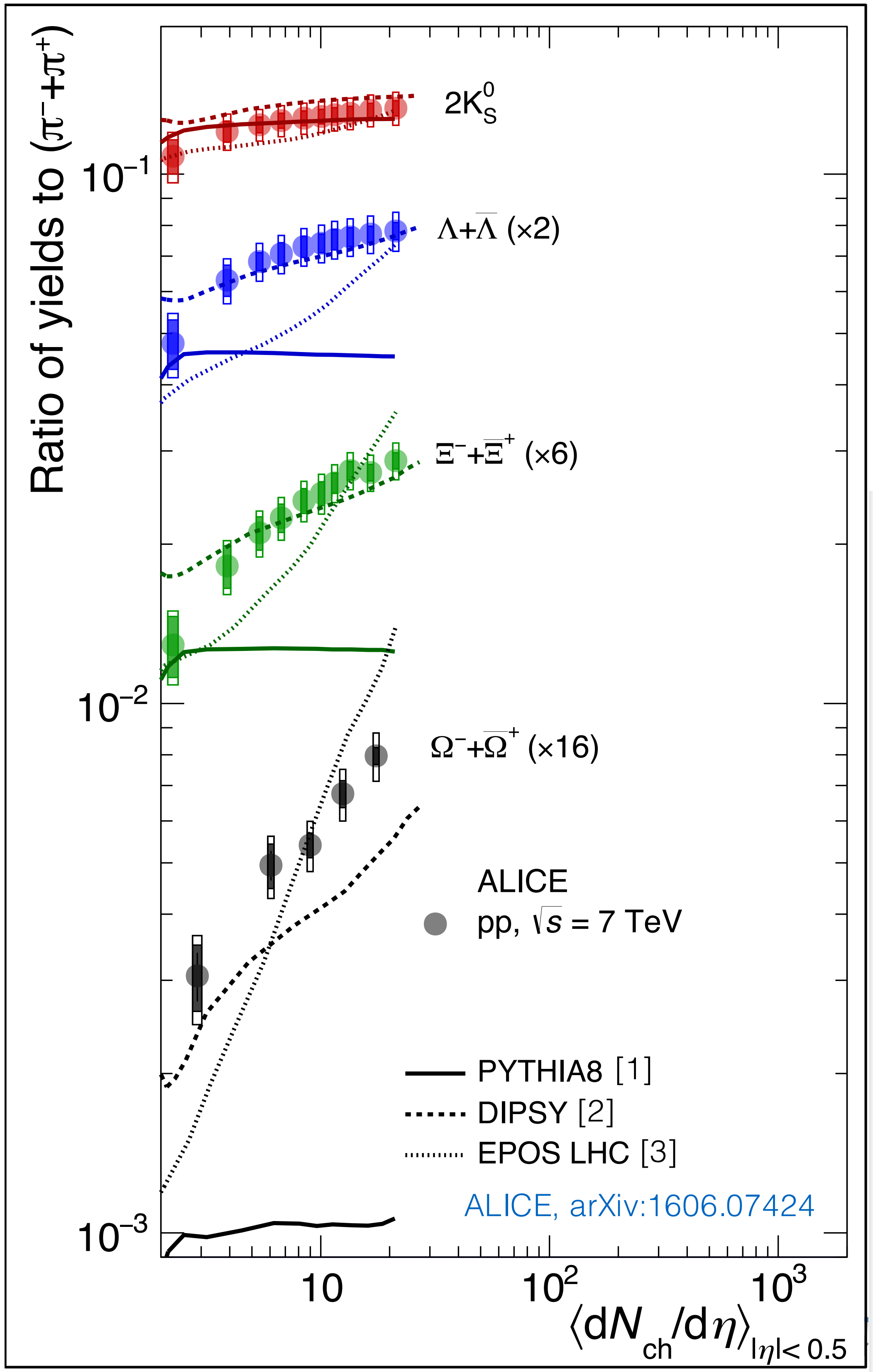
Jackpot!

Now working on models in which nearby fragmenting fields interact with each other.

Interactions between QCD strings!

Higher tensions + repulsion effects ➤ modifications in high-density environments

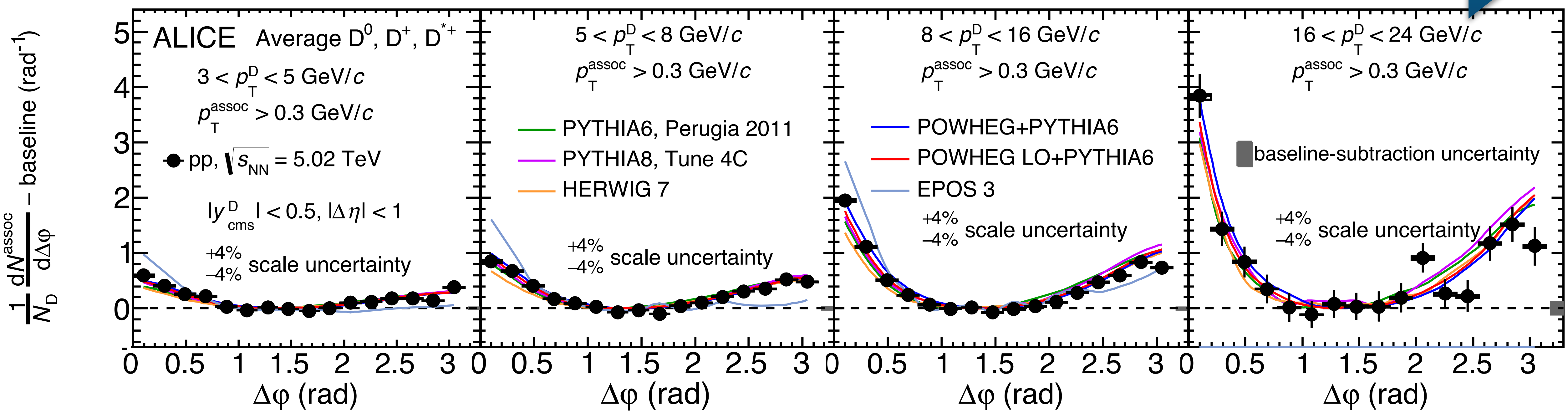
(Competing idea: the whole thing turns into a near-perfect liquid which gets heated up.)

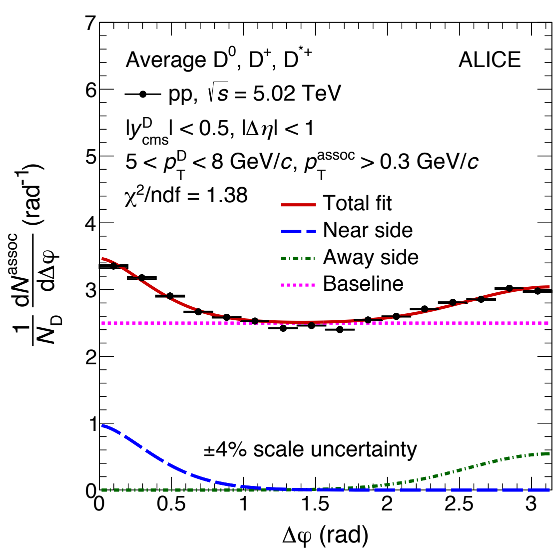


D.D. Chinellato – 38th International Conference on High Energy Physics

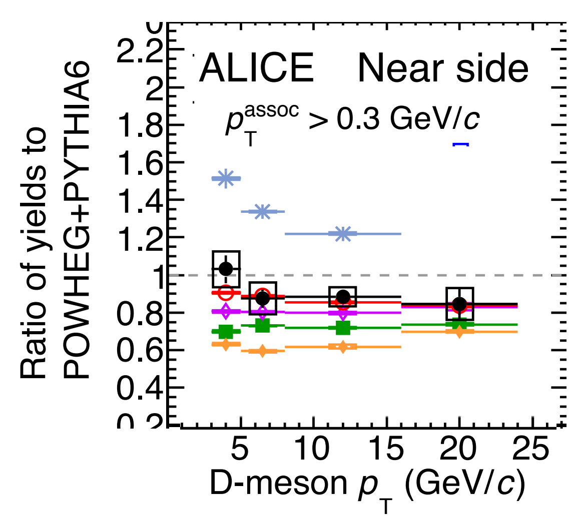
D meson associated tracks (ALICE)

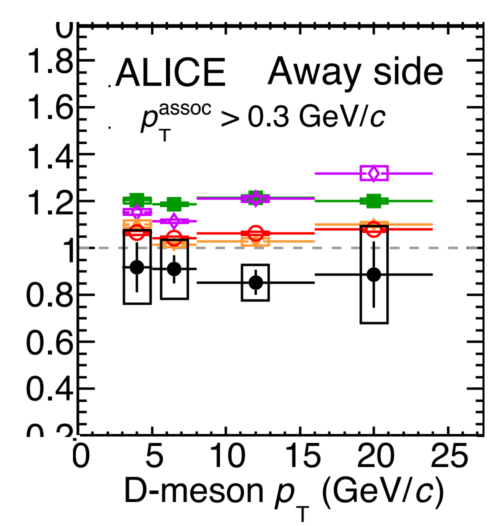
Soft — D meson pT — Hard

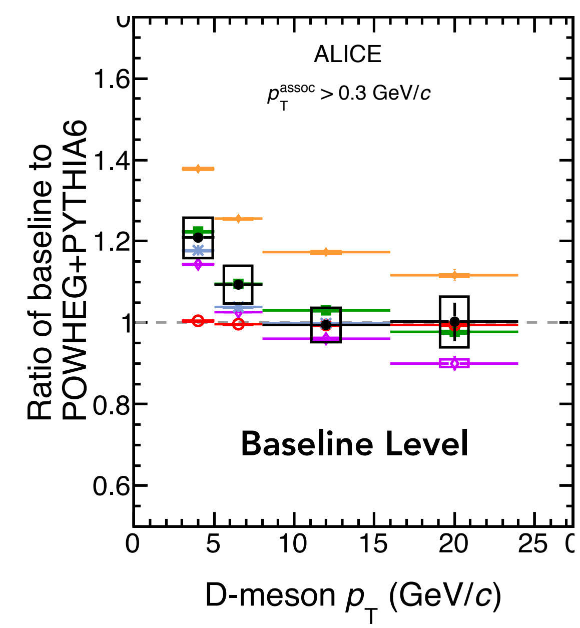




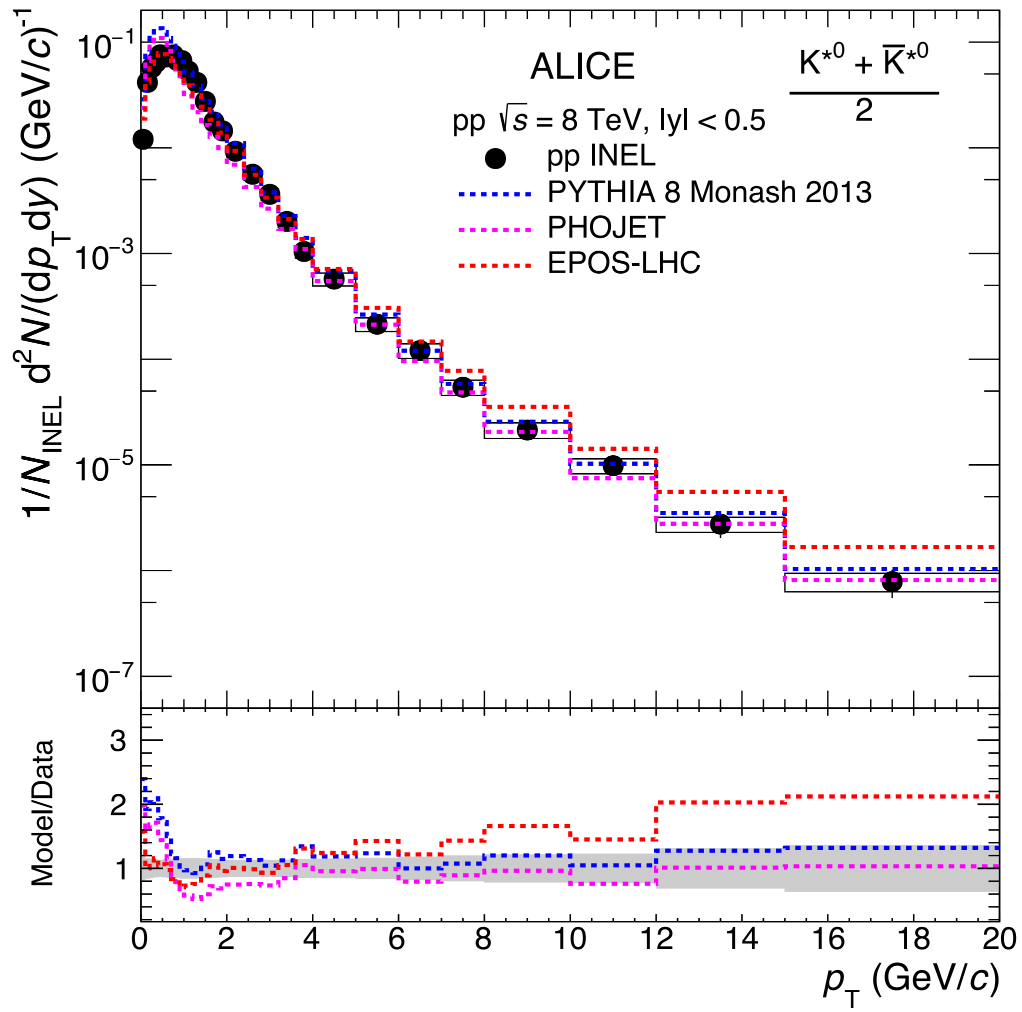
Fit

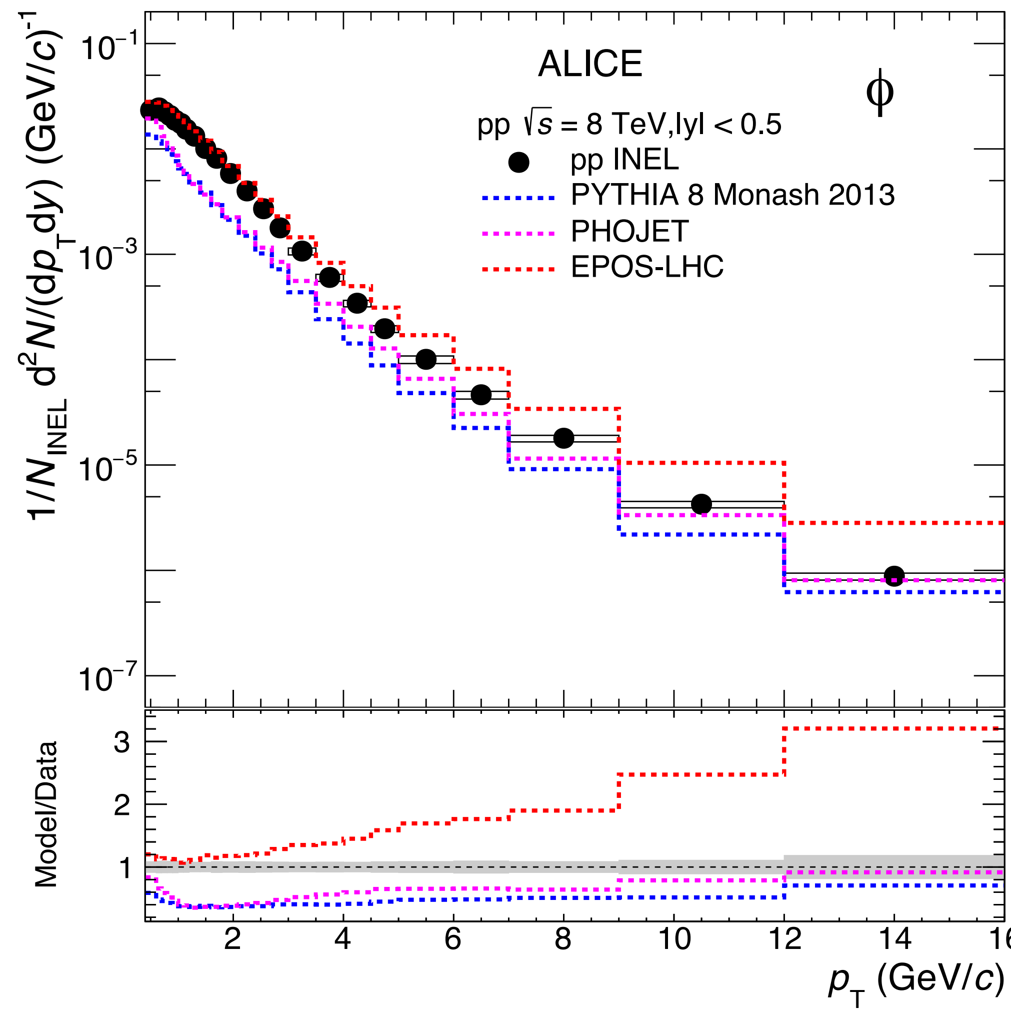


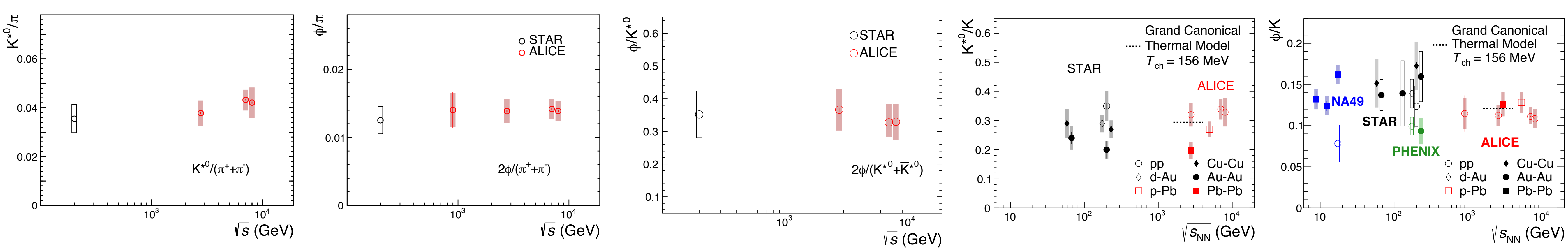




K* and φ (ALICE)

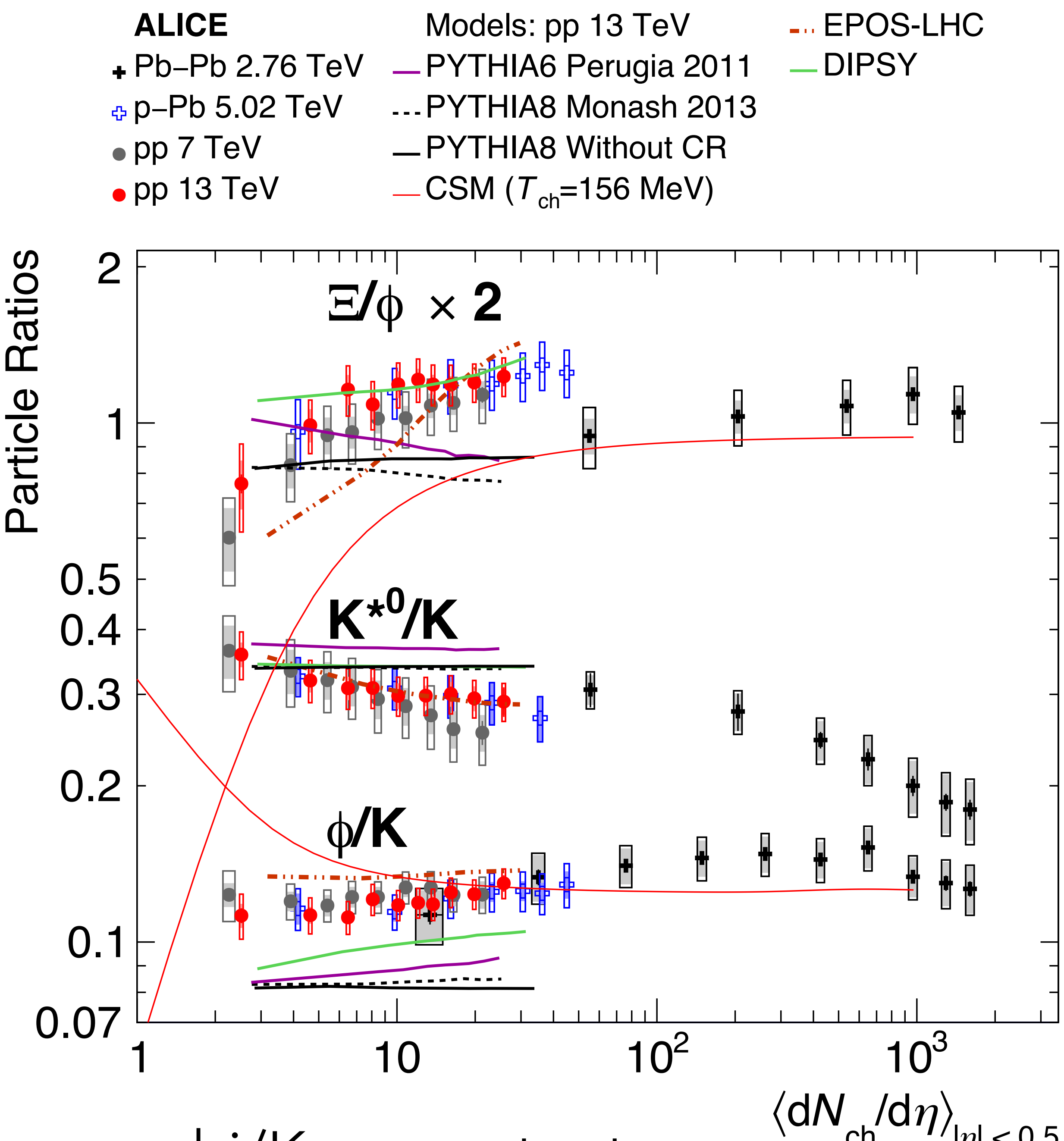


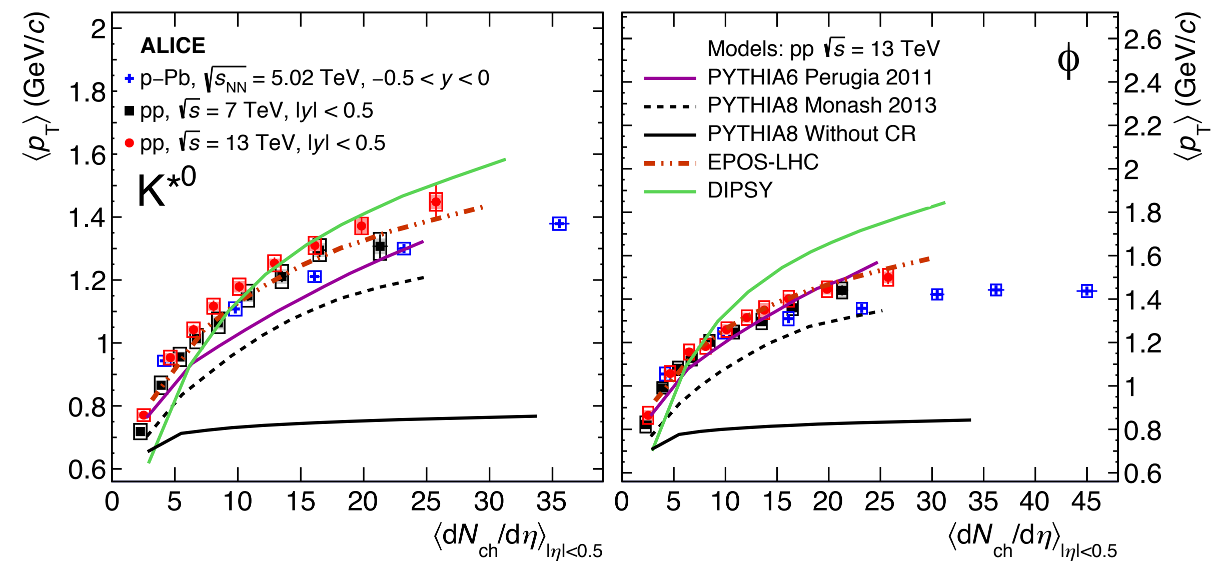


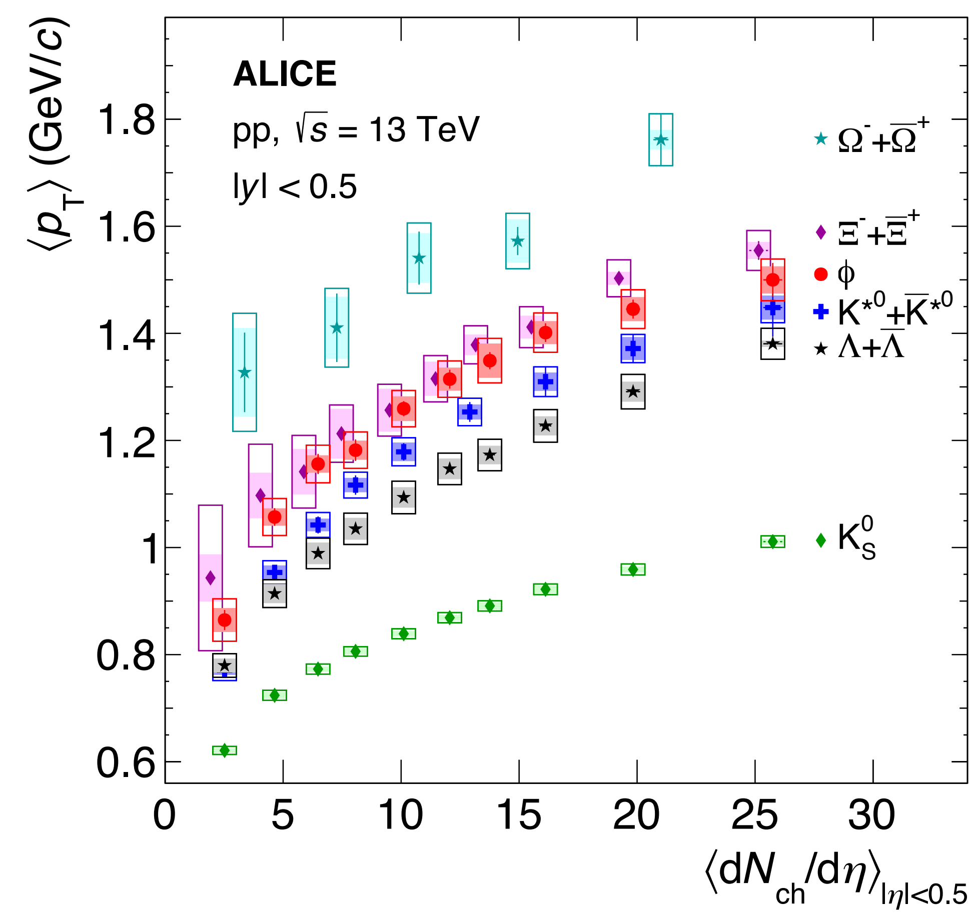


NB: n_{ch} dependence measured separately, in arXiv:1910.14397

K* and φ multiplicity dependence (ALICE)







phi/K ~ constant

K*/K decreasing

Xi/phi increasing