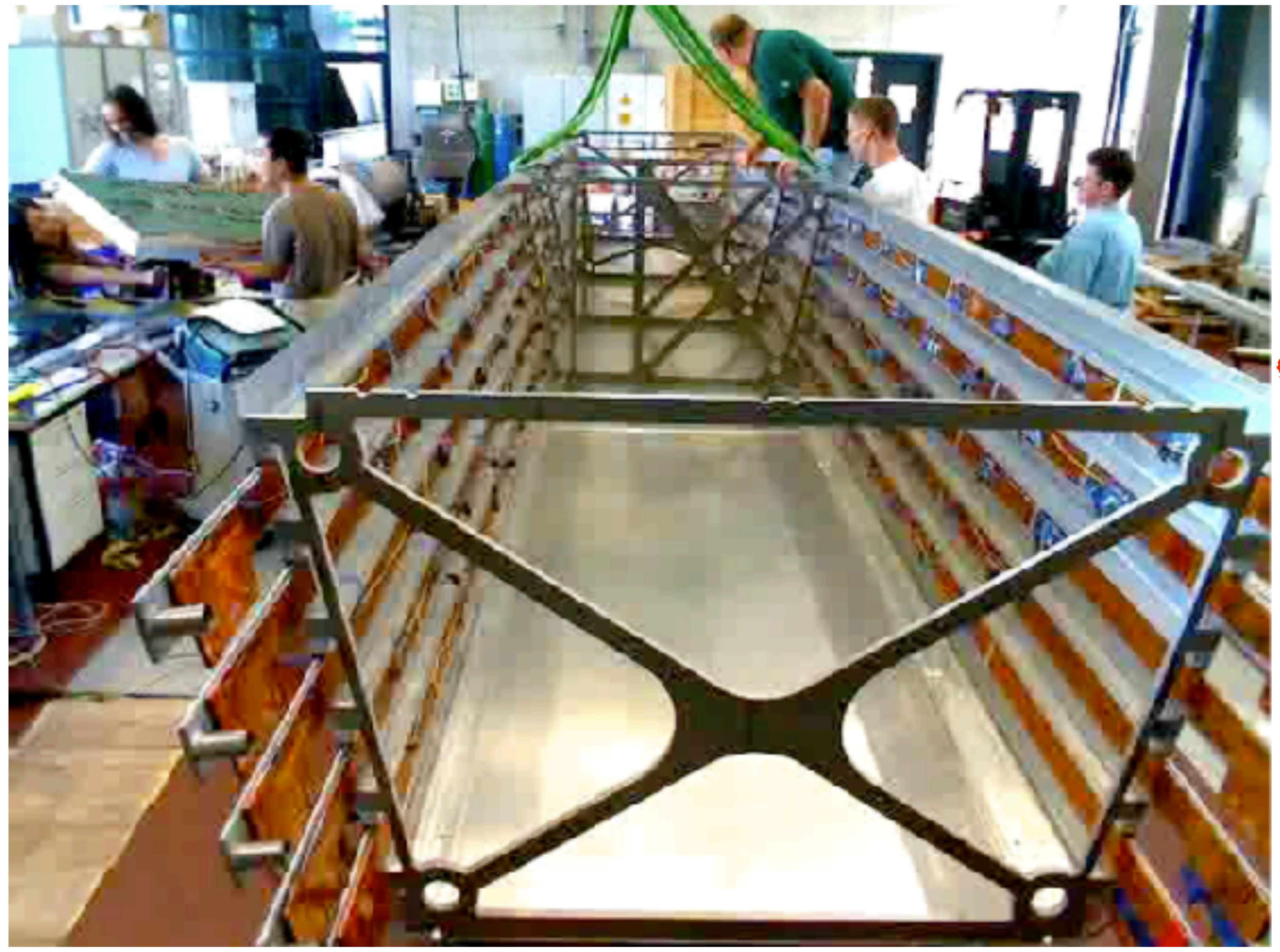
What we learned about heavy-quark hadronization in small and large collision systems

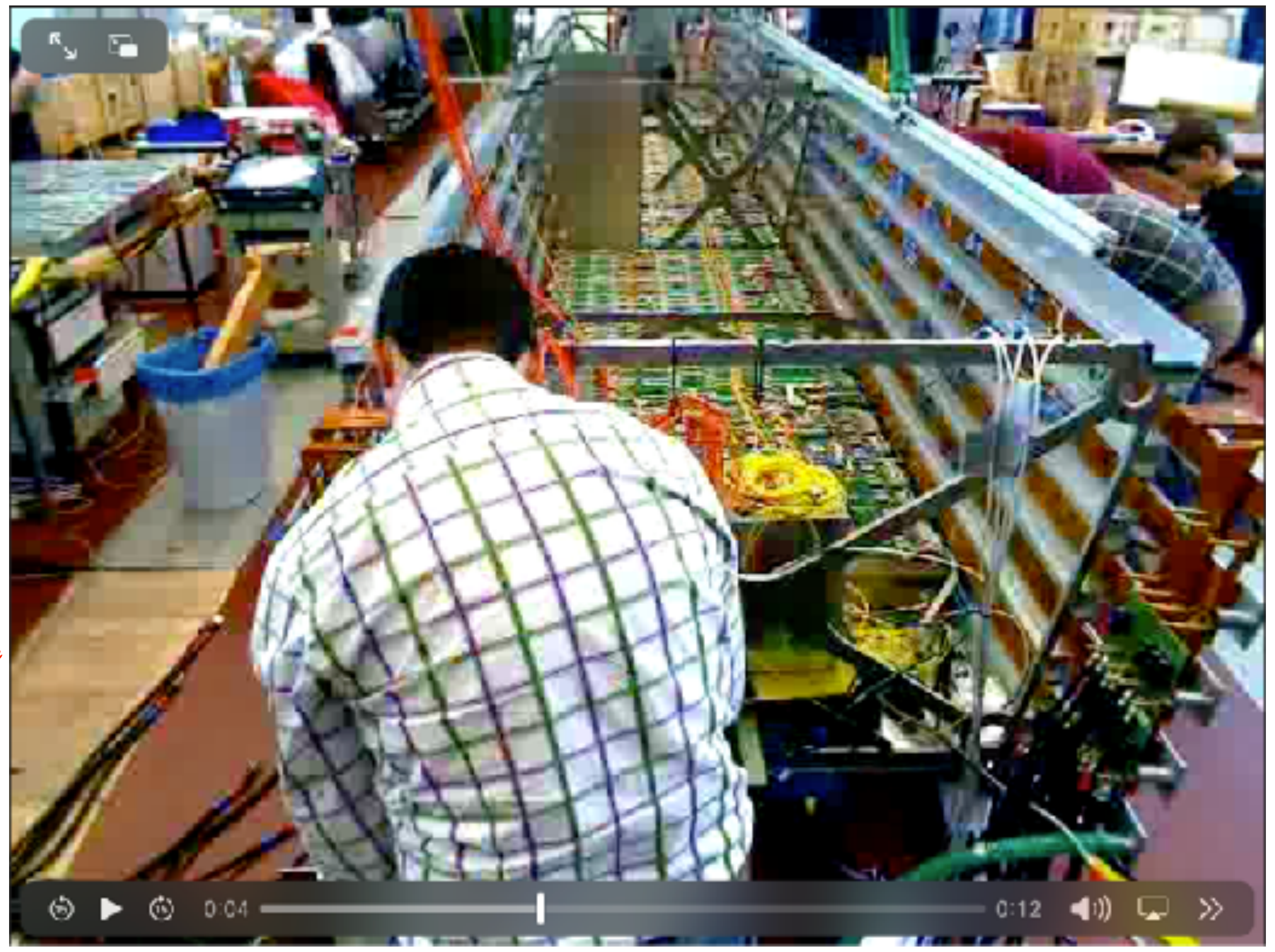
MinJung Kweon
Inha University

Never at Rest: A lifetime inquiry of QGP, 2025.2.11

Today's talk, hadronization, confining process, back then 2006

- In 2006, as a postdoc in Heidelberg, started working on confining processes





http://www-alice.gsi.de/trd/gallery/sm/sm1_fast.mpg

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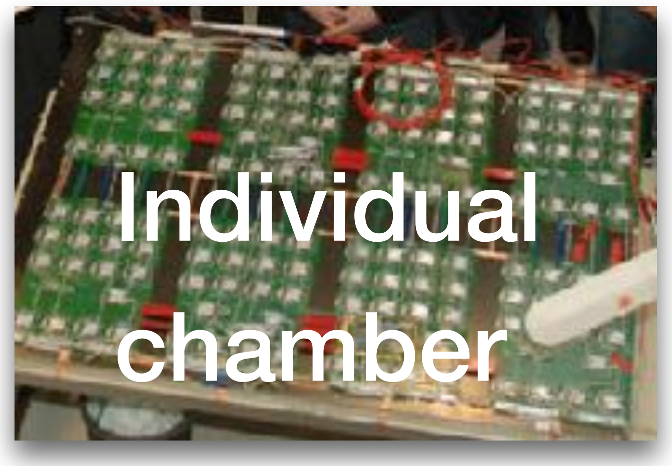

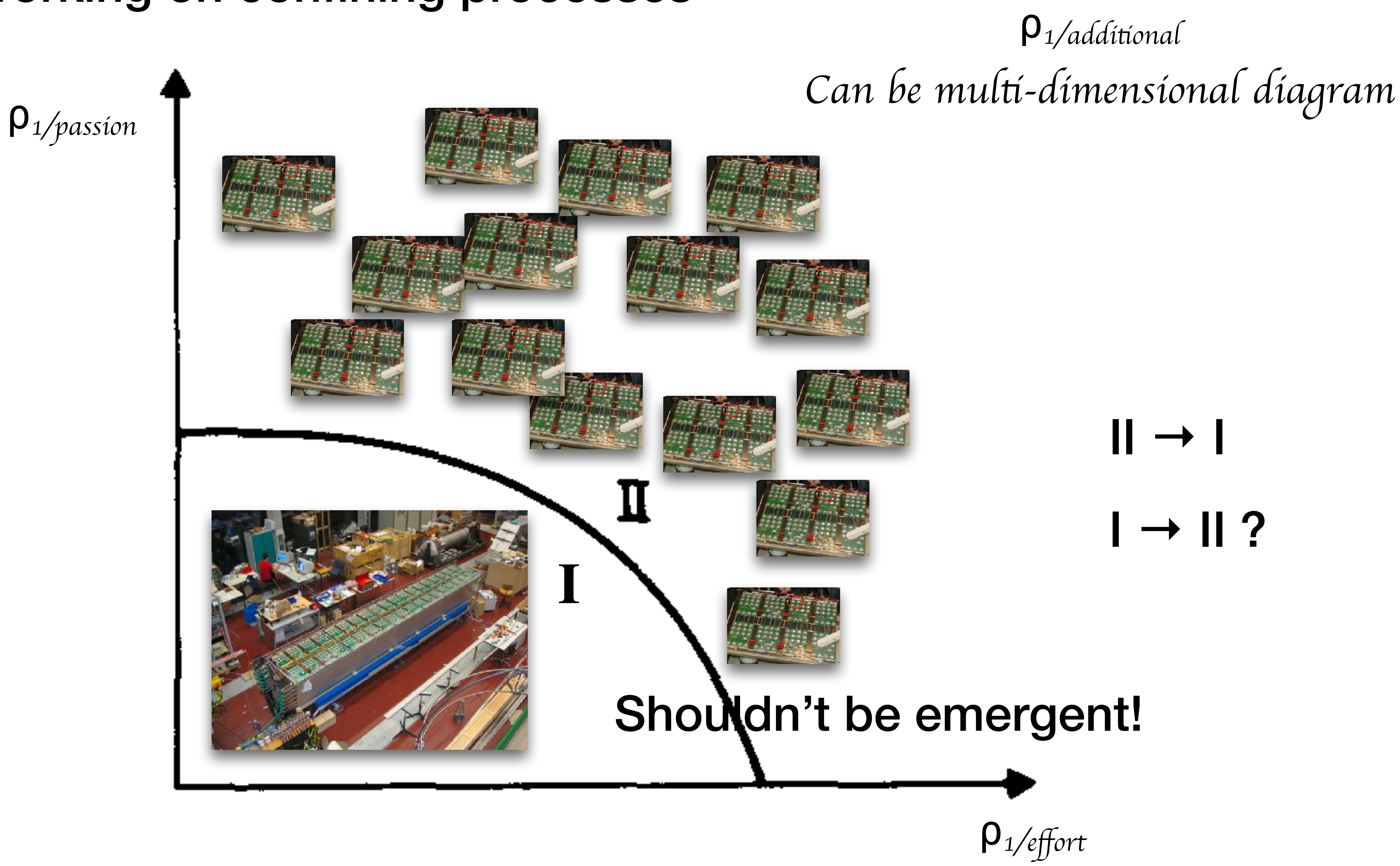

Fig. 1. Schematic phase diagram of TRD supermodel matter. $\rho_{1/effort}$ is inversely proportional to the amount of effort and also inversely proportional to passion. Chambers are confined in Phase I and unconfined in phase II.

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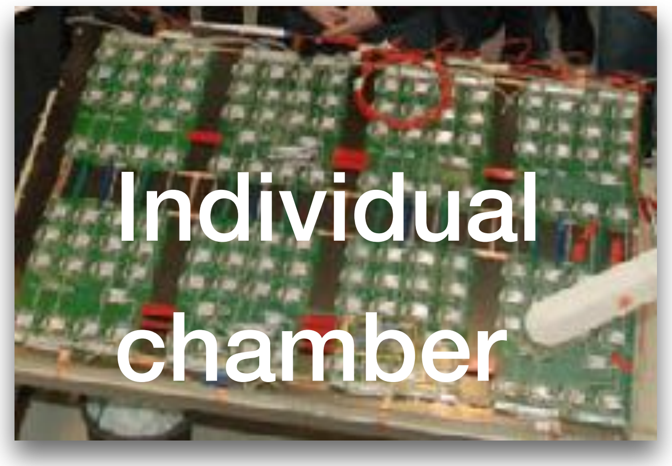
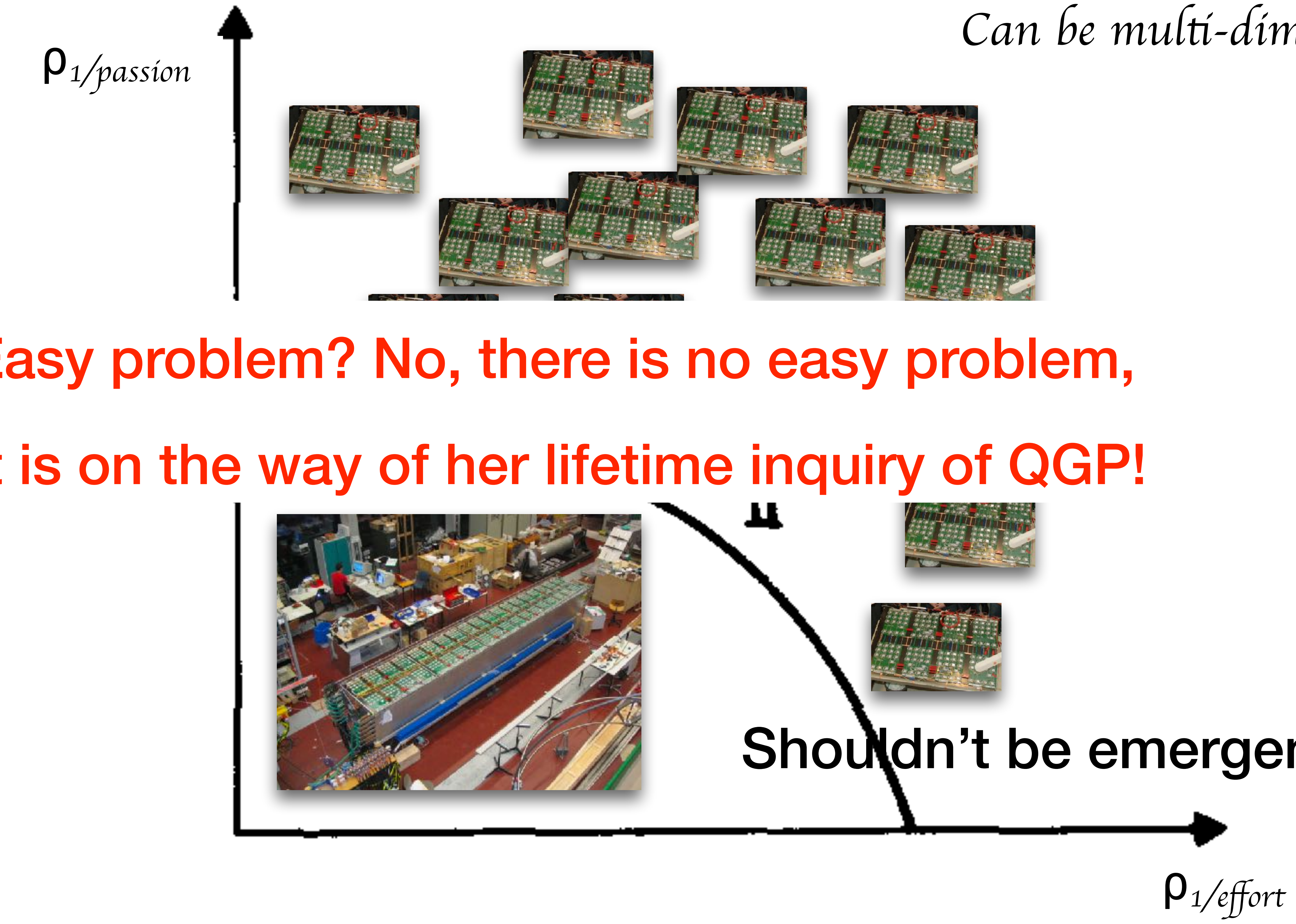


$\rho_{1/additional}$

Can be multi-dimensional diagram



Easy problem? No, there is no easy problem,

It is on the way of her lifetime inquiry of QGP!

II → I

I → II ?

Fig. 1. Schematic phase diagram of TRD supermodel matter. $\rho_{1/effort}$ is inversely proportional to the amount of effort and also inversely proportional to passion. Chambers are confined in Phase I and unconfined in phase II.

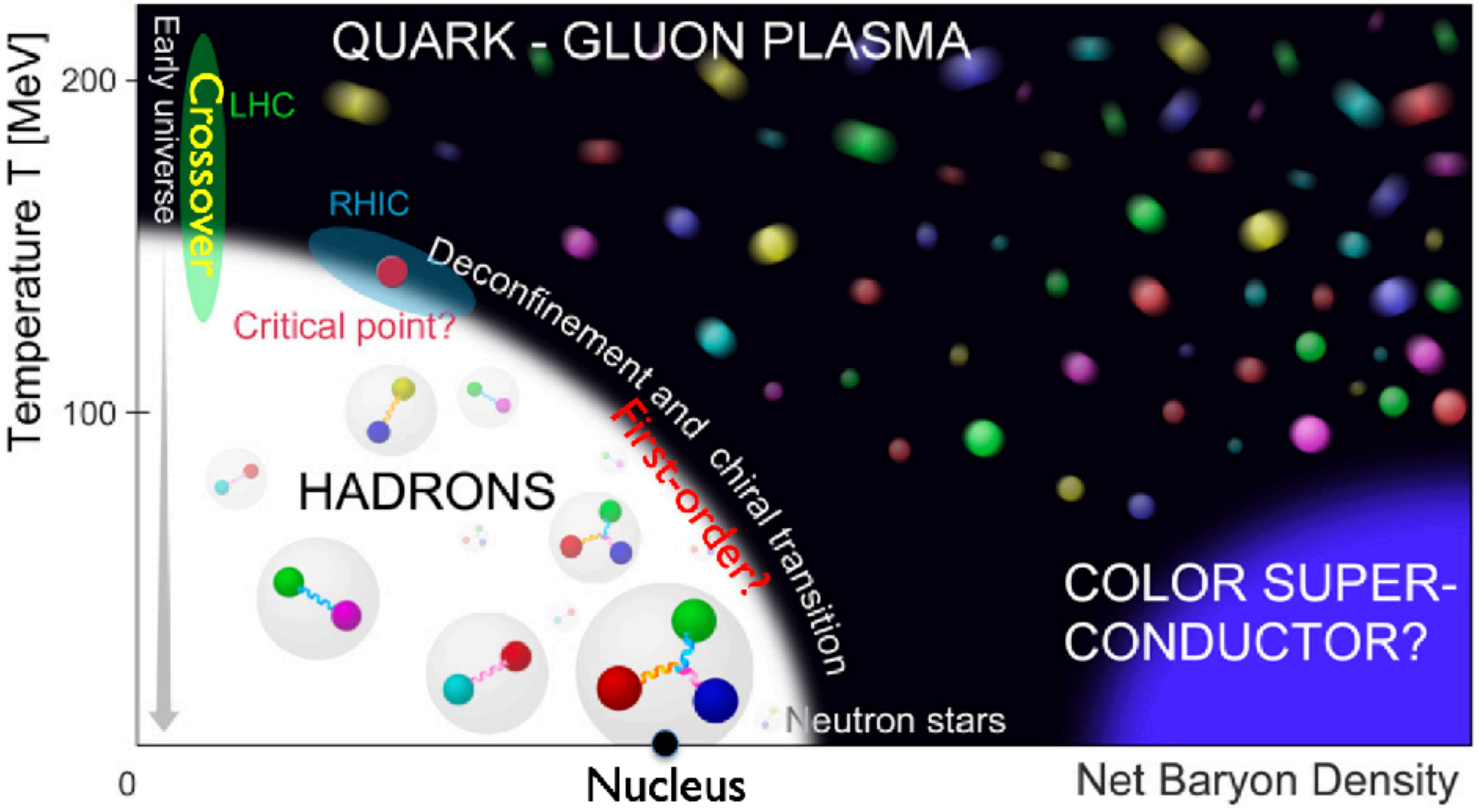
Current confining process

Minjung Kim

Heidelberg state

Jinjoo Seo

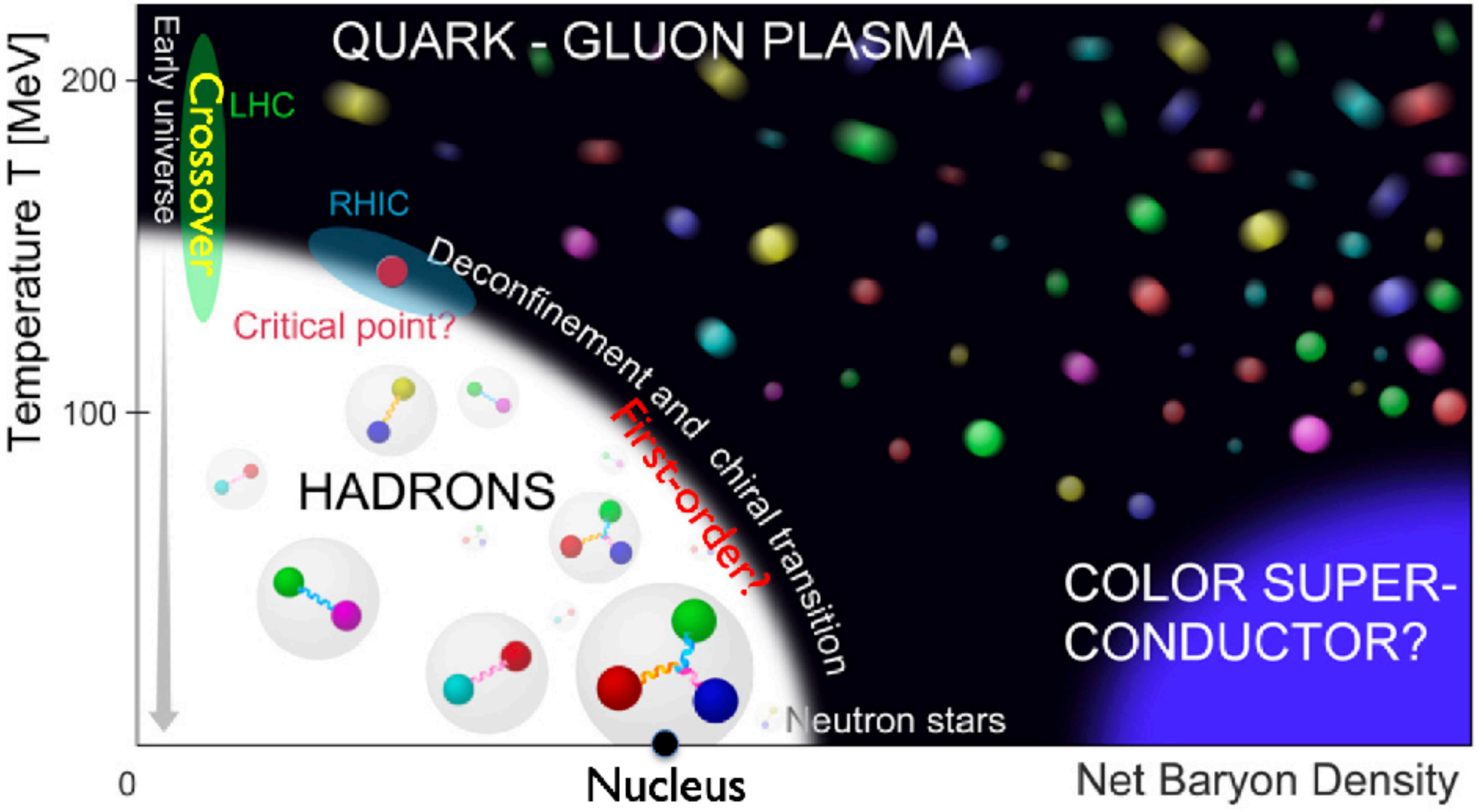
Hadronization



- Once the system reaches the crossover region with temperatures around the pseudo-critical temperature, partons constituting the QGP undergo color-neutralization into hadronic bound states

➡ a process generically denoted as hadronization.

Hadronization



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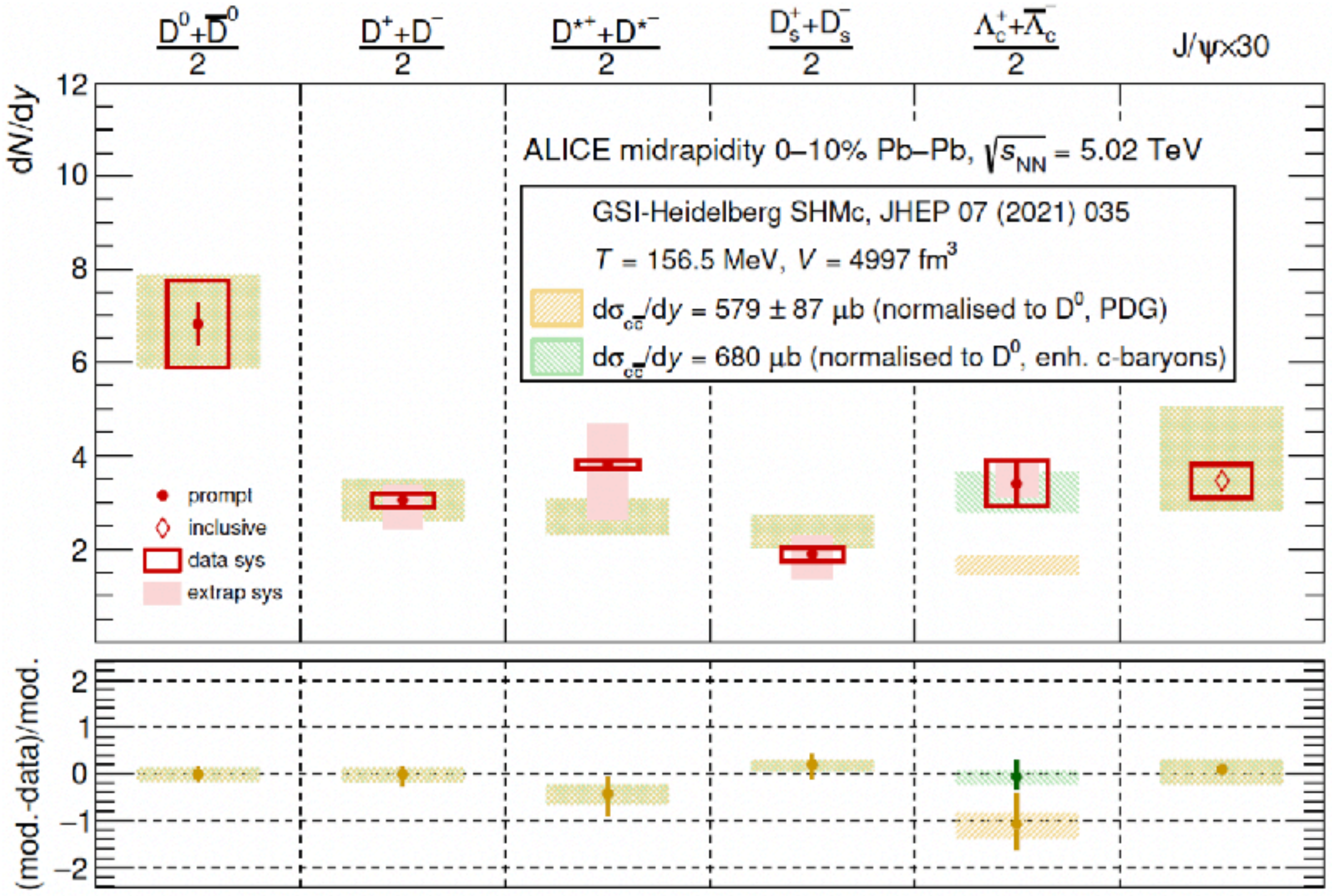
Question is… how much do we understand about hadronization in heavy-ion physics?

Hadronization

Charm data and SHMc model

A. Andronic



ALICE, EPJC 24 (2024) 813

Enh. c-baryons: *tripled* the excited charm-baryon states, *and* $d\sigma_{c\bar{c}}/dy$: +19%

RQM: He,Rapp, PLB 795 (2019) 117; LQCD, Bazavov et al., PLB 737 (2014) 210, PLB 850 (2024) 138520

leaves the mesonic sector unaffected, for the commensurately larger $\sigma_{c\bar{c}}$

Suitable probes, heavy flavour hadrons

- Heavy-quark (HQ) mass is much larger than the nonperturbative QCD scale → produced mainly in initial hard scatterings (reasonably well described by perturbative QCD)

- Determination of HQ fragmentation functions can be carried out at next-to-leading order in the production process within an HQ mass expansion using the methods of HQ effective theory (HQET)

- However, still what we measure…

  dynamics of heavy quarks from their creation at the onset of a heavy-ion collision through their evolution in the QCD medium until their detection as heavy hadrons

- We need a comprehensive description of the initial production of the heavy quarks, their interactions with the QGP, hadronization, and the interactions of heavy hadrons in the hadronic phase → rather complex to describe using first-principles QCD!

Heavy flavour production in medium: what we see

$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes \left[P(\Delta E) \otimes D_{c \to D}(z)\right]$$

Initial-state effects

"Vacuum" parton spectra

Parton interaction with the medium

(Modified) hadronization

what we wanted to probe via heavy-ion collisions

constrain models with measurements from p-Pb collisions

pp collisions

dynamics in QGP: energy loss via radiative ("gluon Bremsstrahlung") and collisional processes

- color charge (Casimir factor)
- quark mass (dead-cone effect)
- path length and medium density

Heavy flavour production in medium: what we see

$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes \left[P(\Delta E) \otimes D_{c\to D}(z)\right]$$

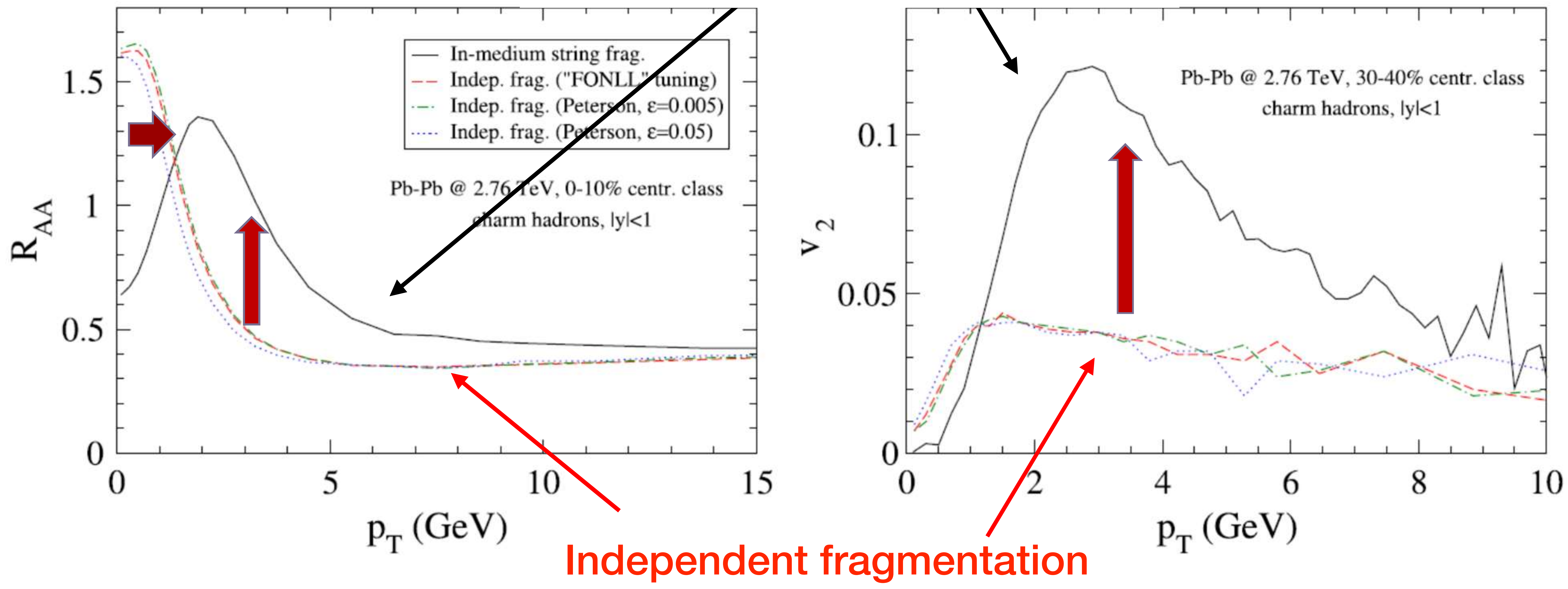
Initial-state effects

"Vacuum" parton spectra

Parton interaction with the medium

(Modified) hadronization

In-medium hadronization



Van Hees et al., PRC73 (2006) 034907

Rapp et al., NPA 979 (2018) 21

Fragmentation in vacuum

Going back to the original assumption…

Independent fragmentation of partons into hadrons is the standard way to describe hadronization in elementary collision systems (pp, e^+e^-)

$$E\frac{d\sigma_H}{d^3P_H} = E_p\frac{d\sigma_i}{d^3p_i} \otimes \mathcal{D}_{i\to H}(z) \qquad z = P_H/p$$

D(*z*) is non-perturbative quantity but it is considered to be "universal" and usually extracted from experiments such as e^+e^- collisions, BUT do not specify the hadronisation mechanism!

ex. Peterson

$$\mathcal{D}_{Q\to H}(z) \propto \frac{1}{z[1-\frac{1}{z}-\frac{\epsilon}{1-z}]^2} \qquad \epsilon = m_q^2/m_Q^2$$

ex. in PYTHIA with a modified Lund string fragmentation function

$$\mathcal{D}_{Q\to H} \propto \frac{1}{z^{1+rbm_Q^2}} z^{a_\alpha}\left(\frac{1-z}{z}\right)^{a_\beta}\exp\left(-\frac{bm_T^2}{z}\right)$$

Question on the universality

Fragmentation Issues

Fragmentation Function (FF):
provides information about the energy fraction which is transfered from quark to a given meson (the larger m_Q the harder the fragmentation function)

Questions to be answered:

▷ what's the **proper parametrization** of non-perturbative frag. function?

- Peterson: $f(z) \propto 1/[z(1 - \frac{1}{z} - \frac{\varepsilon}{(1-z)})^2]$
- Kartvelishvili: $f(z) \propto z^{\alpha}(1 - z)$
- Lund symmetric: $f(z) \propto \frac{1}{z}(1 - z)^a \exp(-\frac{bm_t^2}{z})$
- Bowler: $f(z) \propto \frac{1}{z^{1+r_b m_t^2}}(1 - z)^a \exp(-\frac{bm_t^2}{z})$

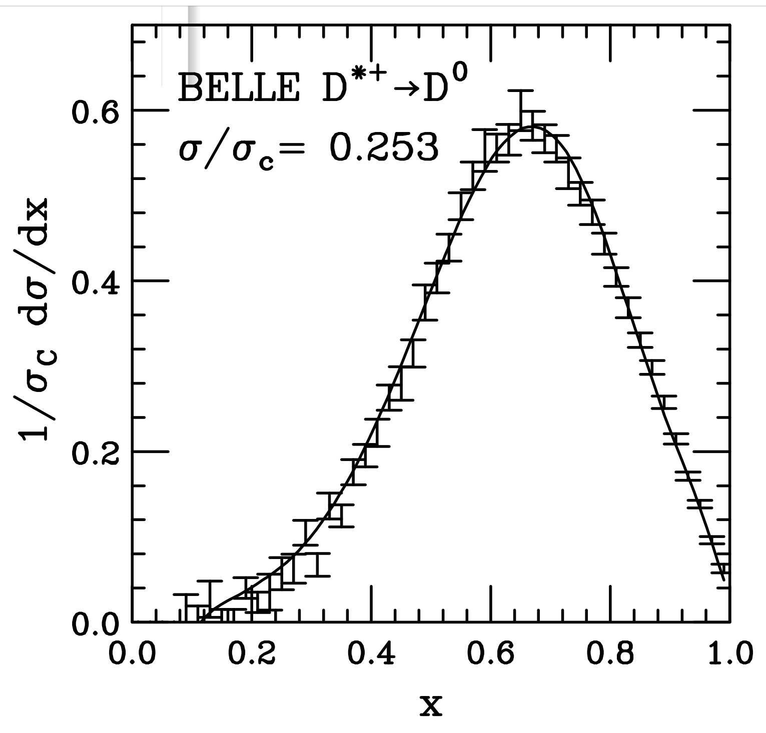
▷ is fragmentation function **universal**?
(i.e. are FF portable from e^+e^- to ep and pp?)

Zuzana Rúriková Charm Fragmentation Function – June 7, 2006

▷ different observable definitions

▷ different center of mass energies, thus different pert. components as well

$\Longrightarrow$ **Direct shape comparison impossible!**



Fit to BELLE data
(Cacciari, Nason, Oleari)

▷ **Fitted parametrization:** $f(x) \propto \delta(1 - x) + \frac{c}{N_{a,b}}(1 - x)^a x^b$

▷ **ALEPH:** a= 2.4±1.2, b=13.9±5.7, c=5.9±1.7

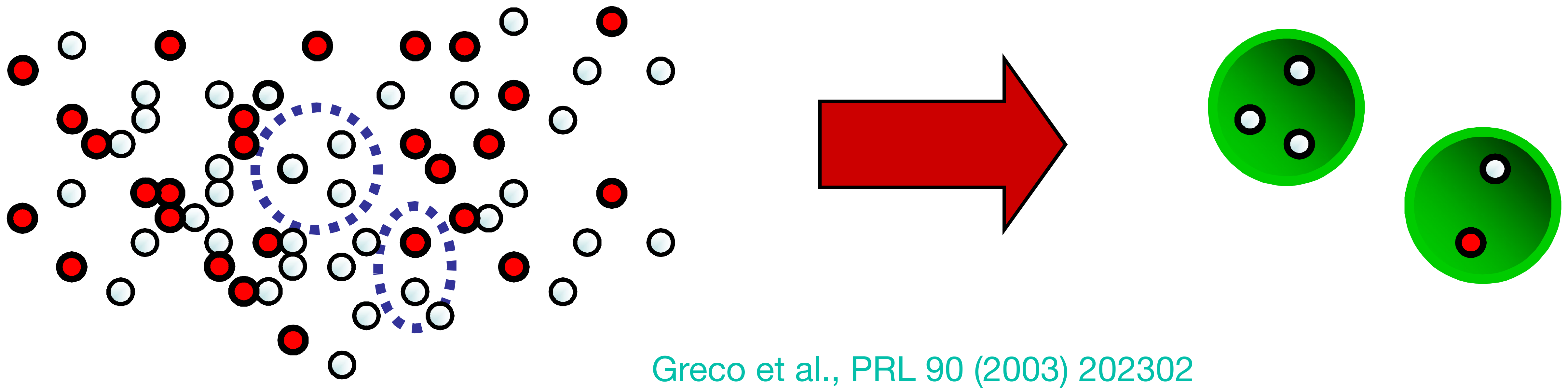
▷ **CLEO/BELLE:** a= 1.8±0.2, b=11.3±0.6, c=2.46±0.07

Fits not in agreement! Does universality of $\mathrm{FF_{np}}$ not hold?

Zuzana Rúriková Charm Fragmentation Function – June 7, 2006

Hadronization in medium

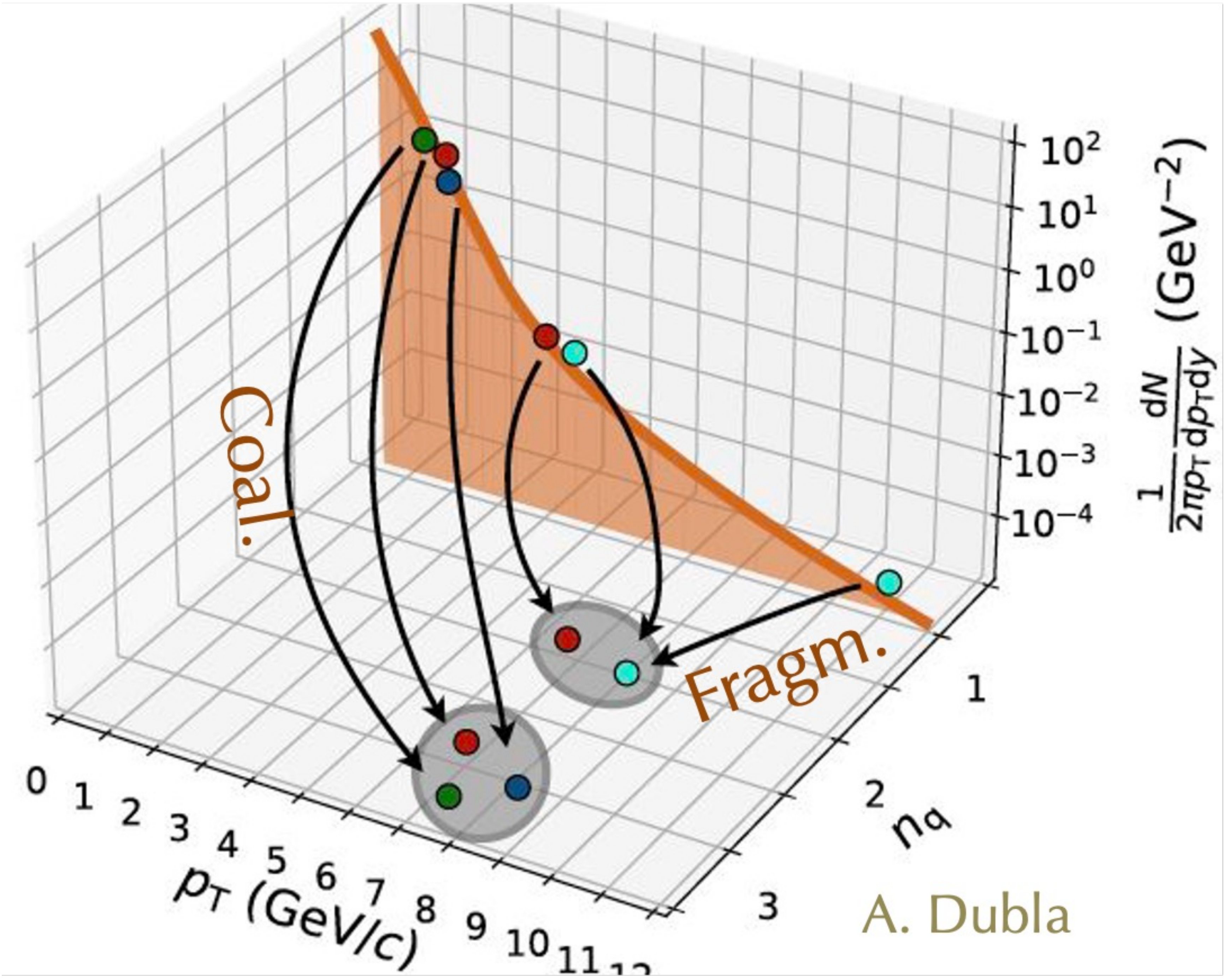
- Phase space at the hadronization is filled with partons
  - → Single parton description may not be valid anymore
  - → No need to create $q\bar{q}$ pairs via splitting / string breaking
  - → Partons that are “close” to each other in phase space (position and momentum) can simply recombine into hadrons



Greco et al., PRL 90 (2003) 202302

Fries et al., PRL 90 (2003) 202303

Hwa, Yang, PRC 67 (2003) 034902



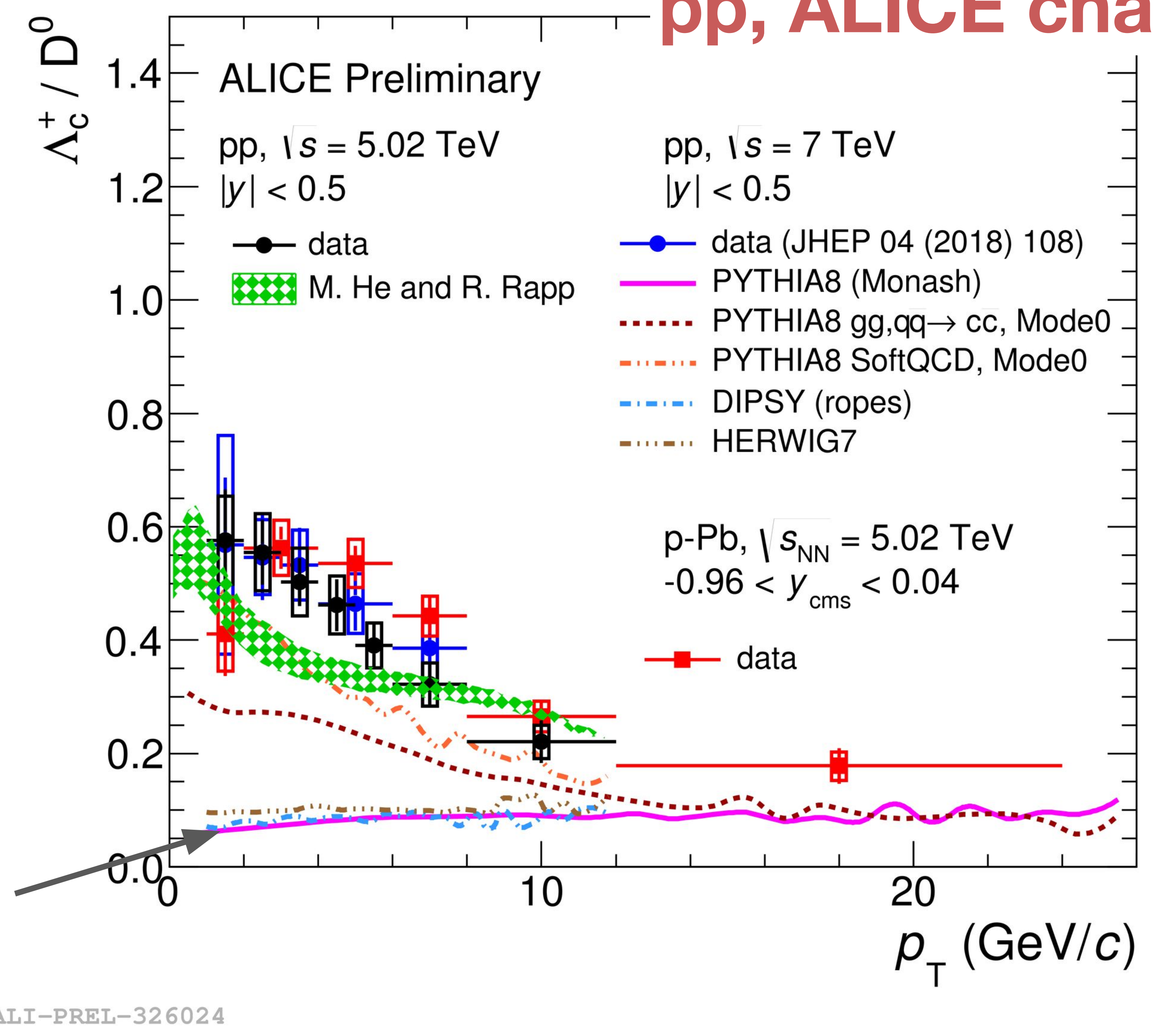
- Recombination vs. fragmentation:
  - → Competing mechanisms
  - → Recombination naturally enhances baryon/meson ratios at intermediate p_T

Hadronization in vacuum; observation

“Naive expectation: ratios of particle-species yields independent from collision system”

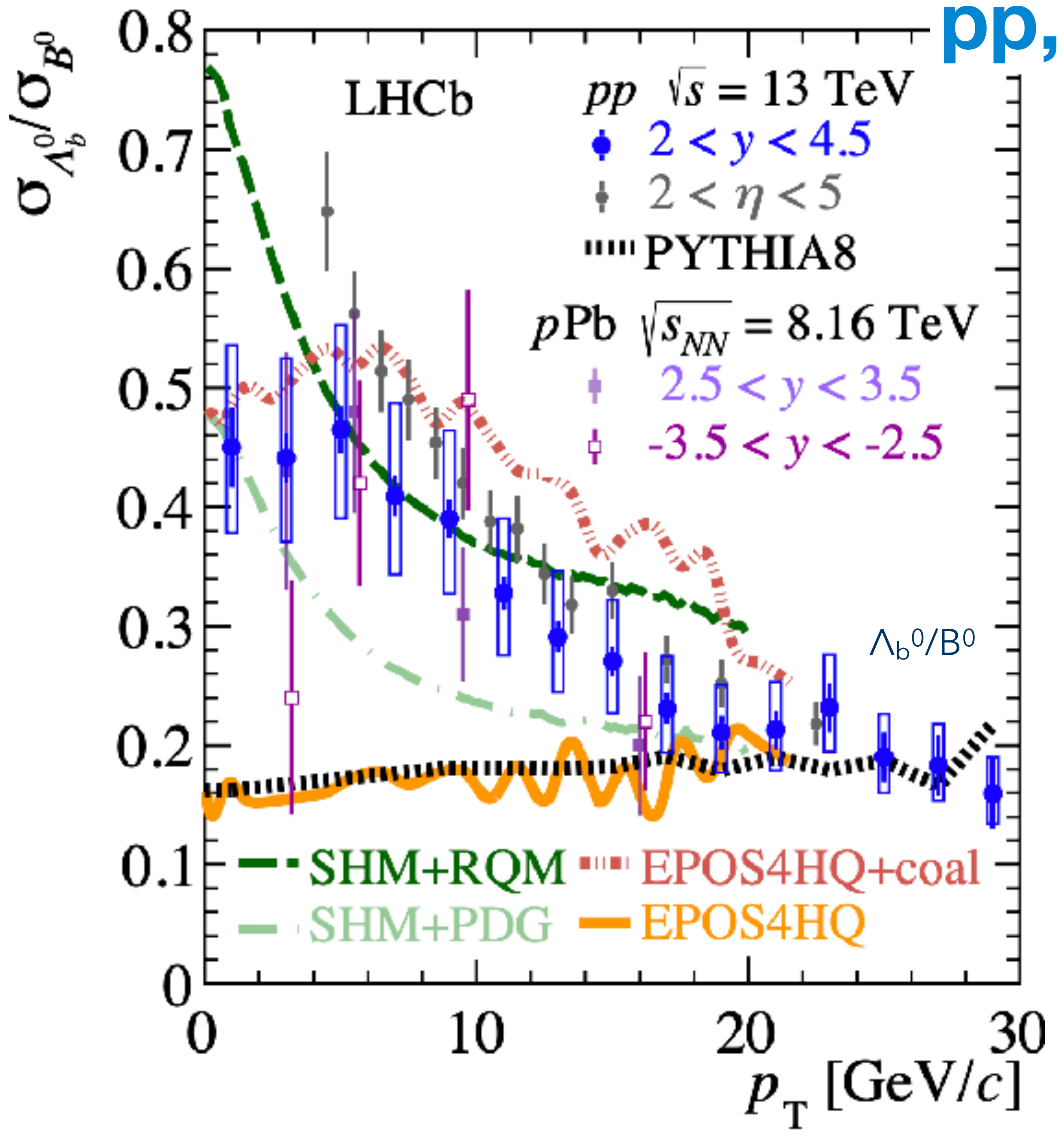
Surprises: Λ_c/D^0 ~0.5 (at intermediate p_T) not only in AA but even in pp → strong enhancement wrt e^+e^-

pp, ALICE charm



e^+e^-

pp, LHCb beauty



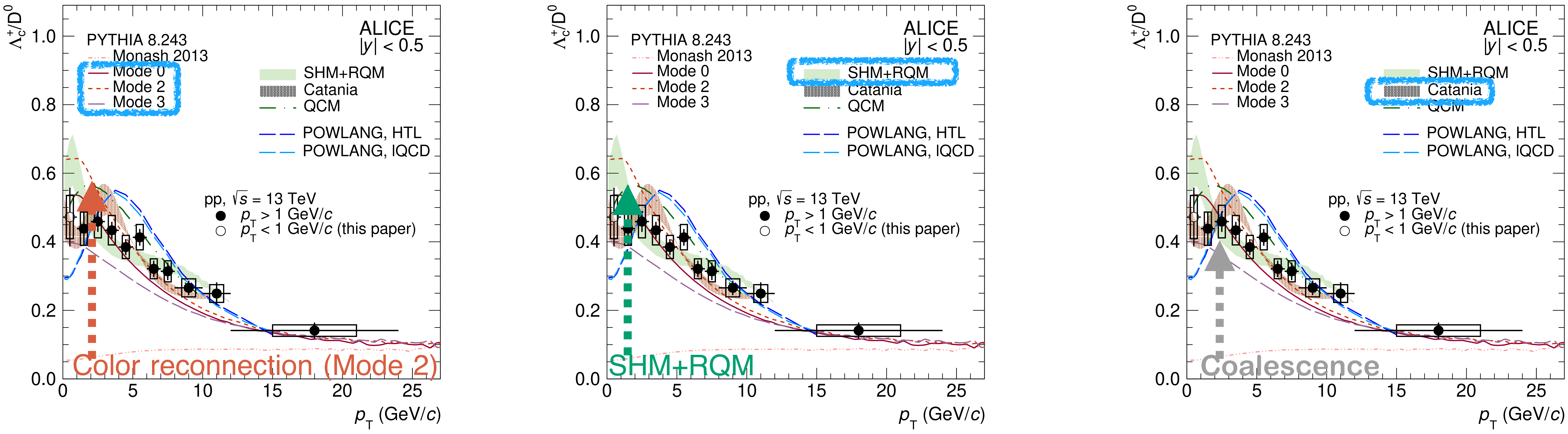
PRL 132, 081901 (2024)

Λ_b/B^0 → Similar trend in charm and beauty sectors!

OK, how do we explain? Heavy flavour baryon enhancement impact…

- Heavy-flavour hadronization stimulated the model developments
  - PYTHIA with Color Reconnection (CR) beyond Leading Color (LC) in pp
  - SHM+RQM: combine SHM and Relativistic Quark Model
  - Catania: Coalescence+Fragmentation approach applied to pp
  - Local color recombination: POWLANG in AA and in pp
  - Inclusion of heavy-flavour Coalescence+Fragmentation in EPOS (pp & AA)

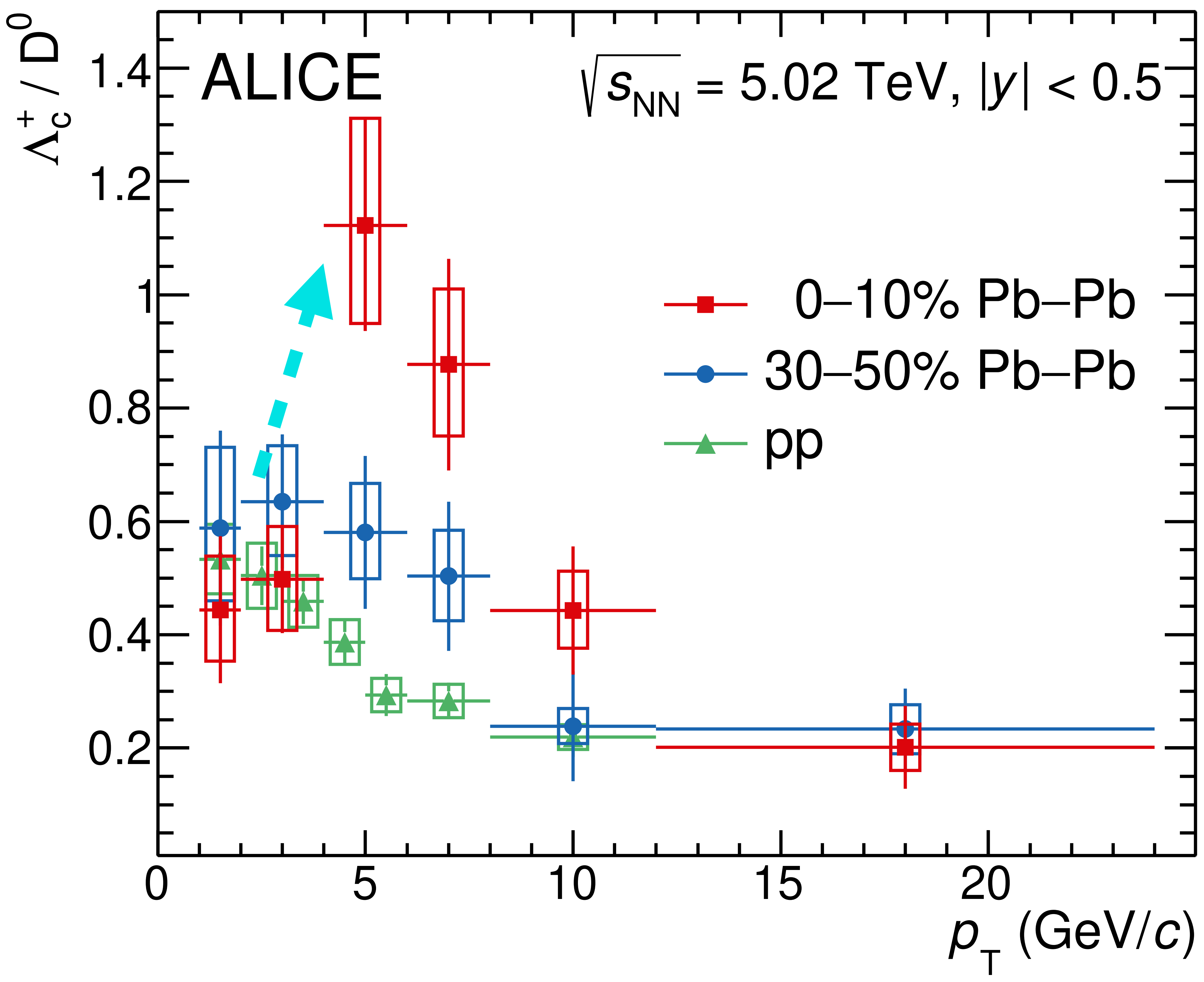
ALICE JHEP 12 (2023) 086

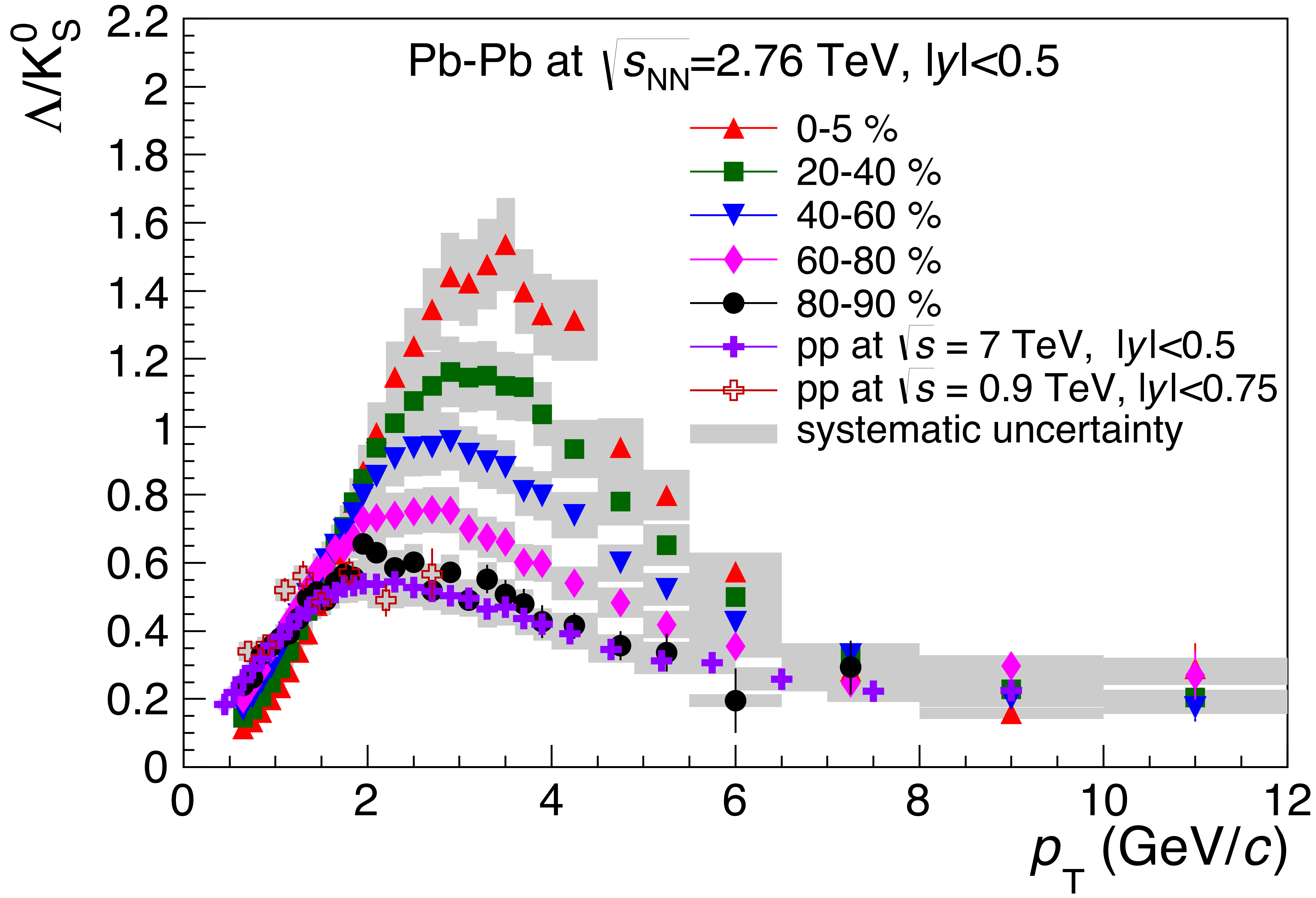


- Different hadronization mechanisms proposed!

How about in Pb–Pb?

Phys. Lett. B 839 (2023) 137796

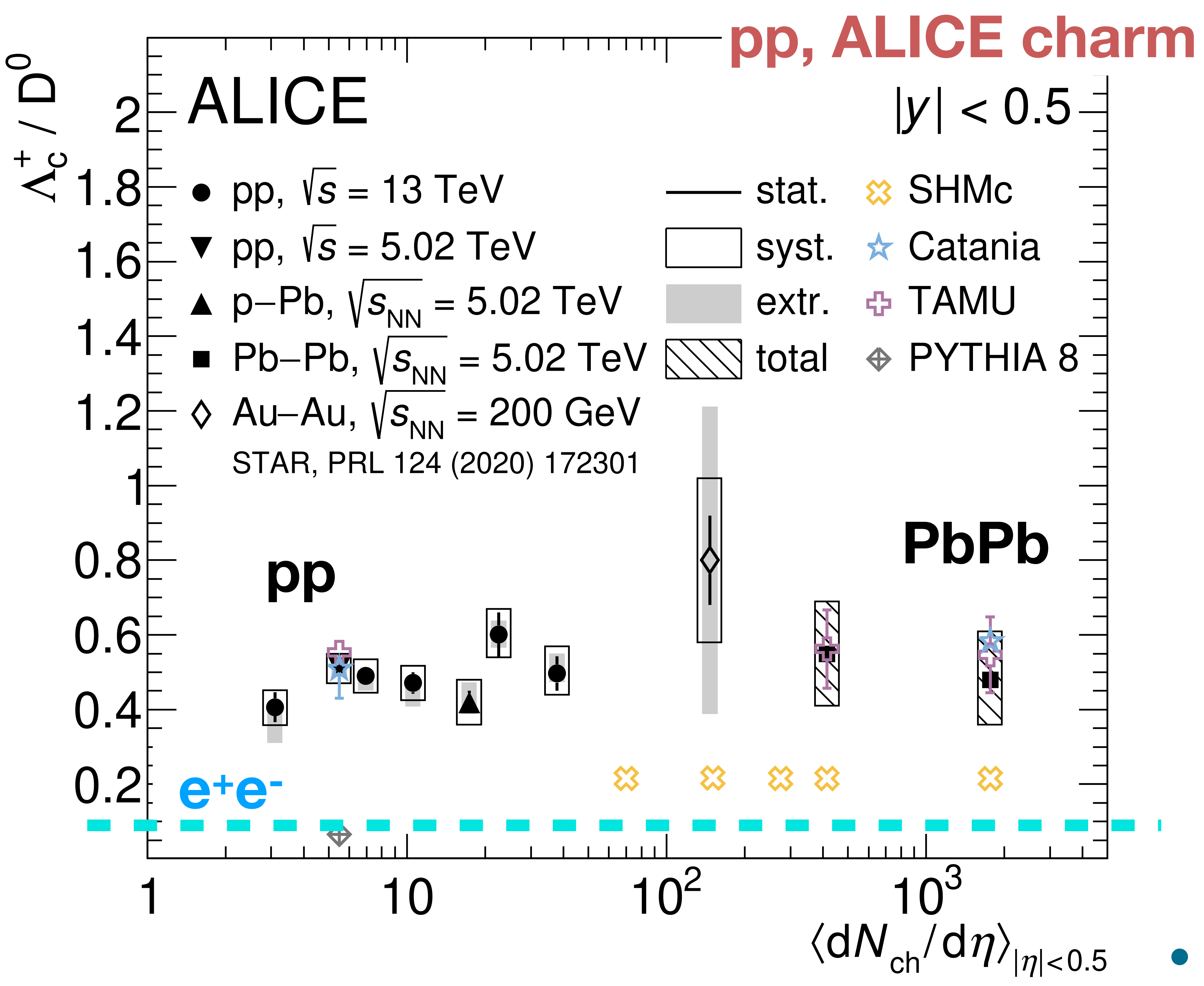




- Ratio increases from pp to mid-central and central Pb-Pb at intermediate p_T
- Trend qualitatively similar to what is observed for Λ/K_s^0 ratios

p_T–Integrated yield ratio

p_T-integrated Λ_c^+/D^0 ratios



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p_T-integrated Λ_b^+/B^0 ratios

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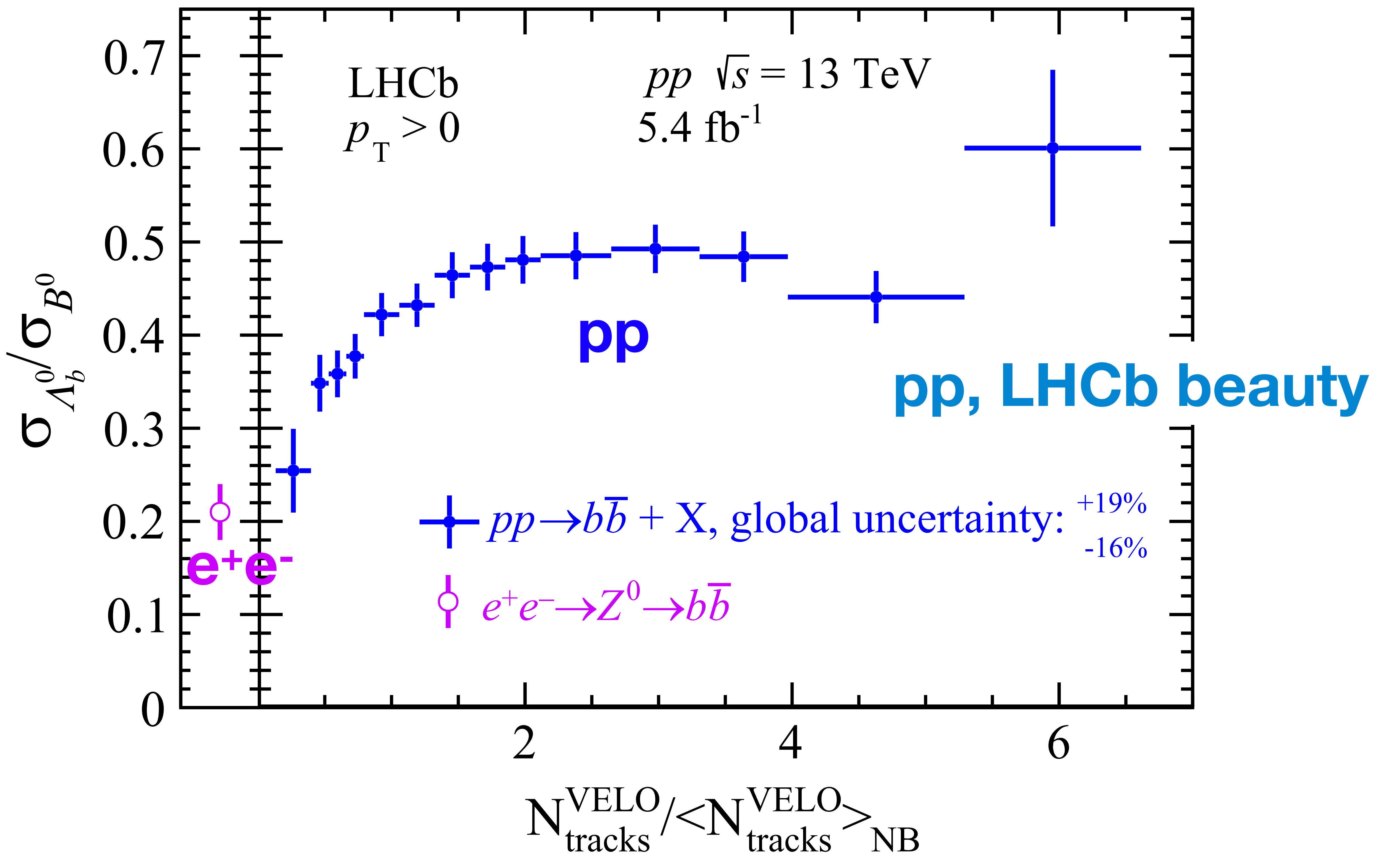
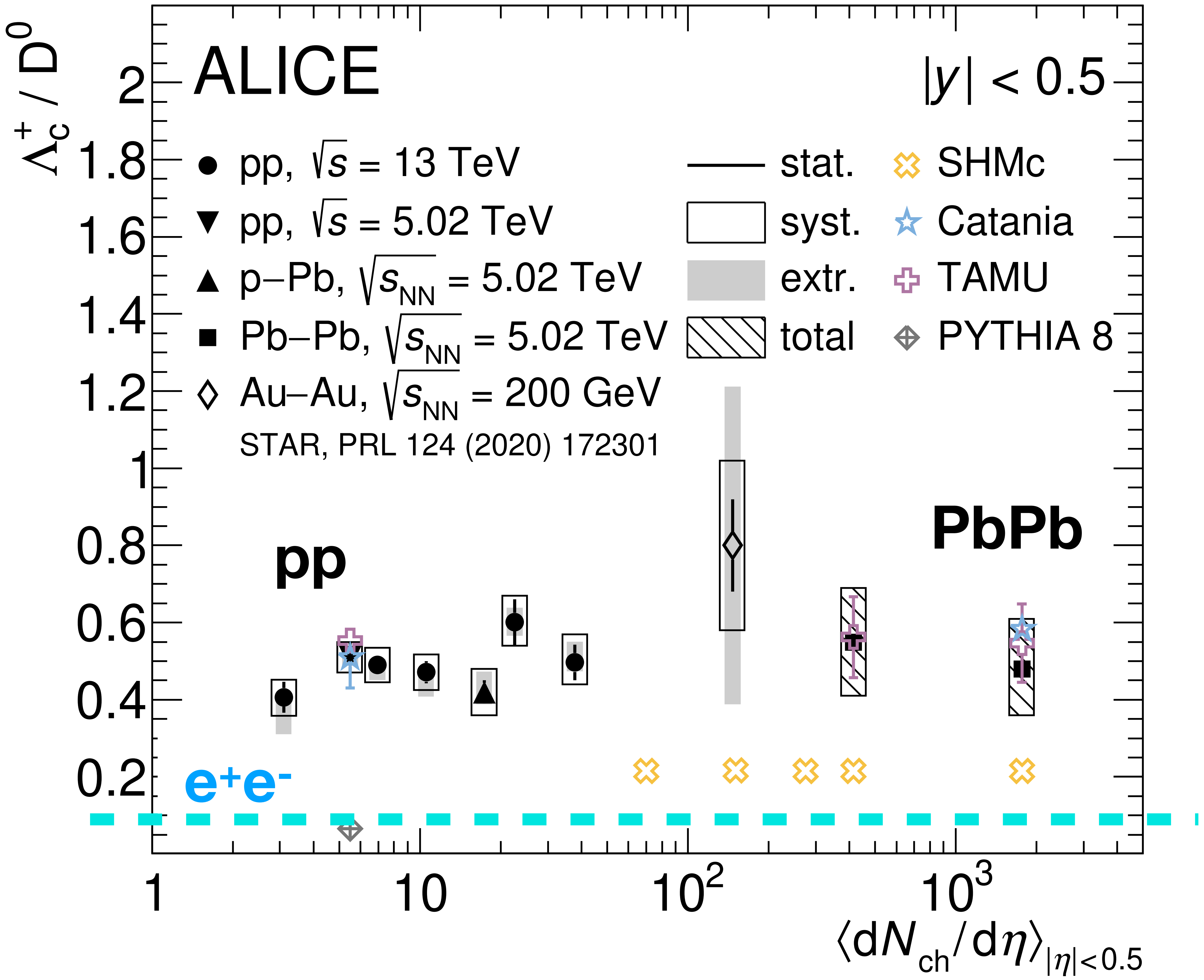


- p_T-integrated yield ratio is saturated in all hadronic collision systems
- Then, enhancement is due to p_T redistributions?
- Similar to b sector

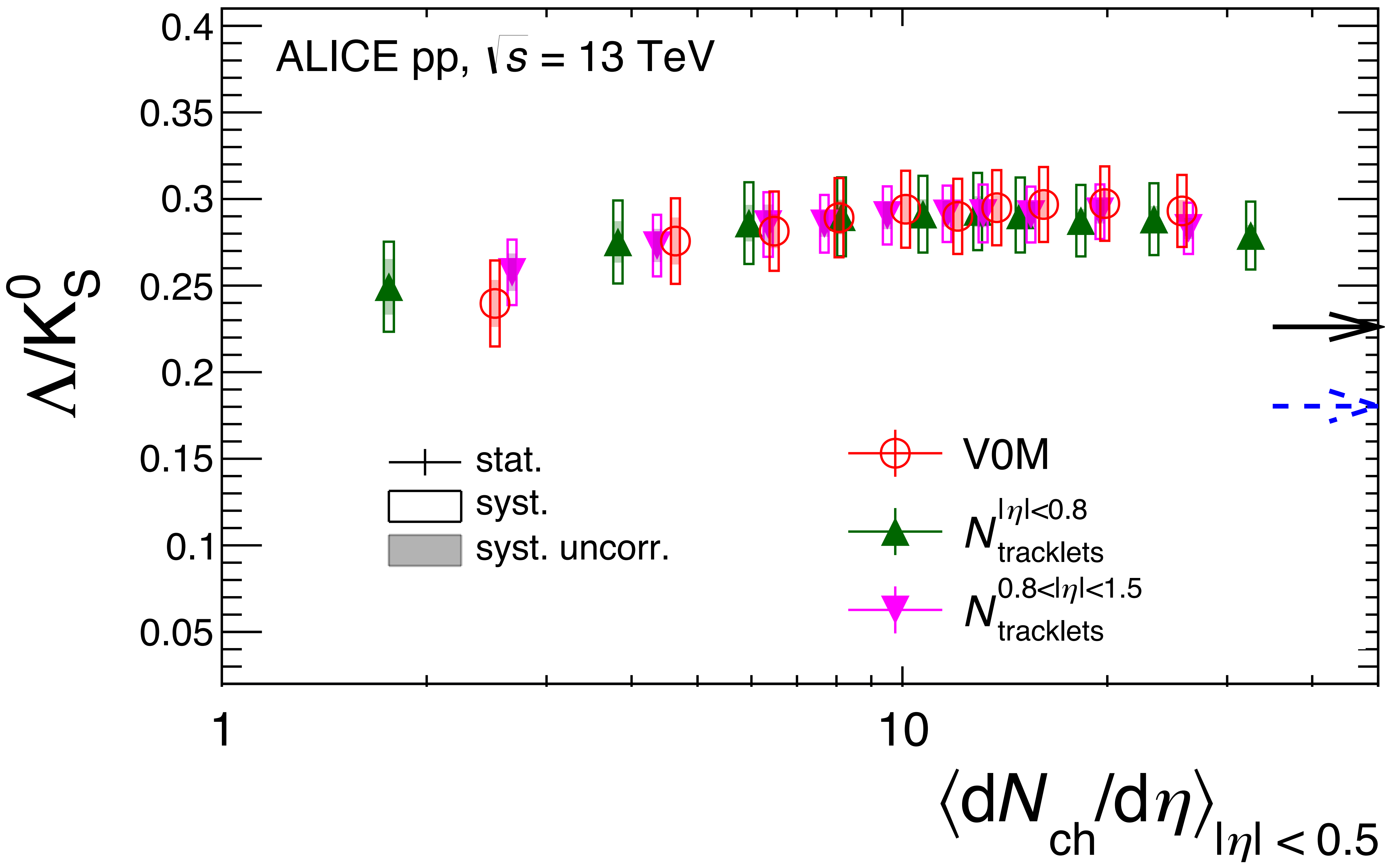
Where does the p_T differential enhancement come from?

p_T-integrated Λ_c^+/D^0 ratios

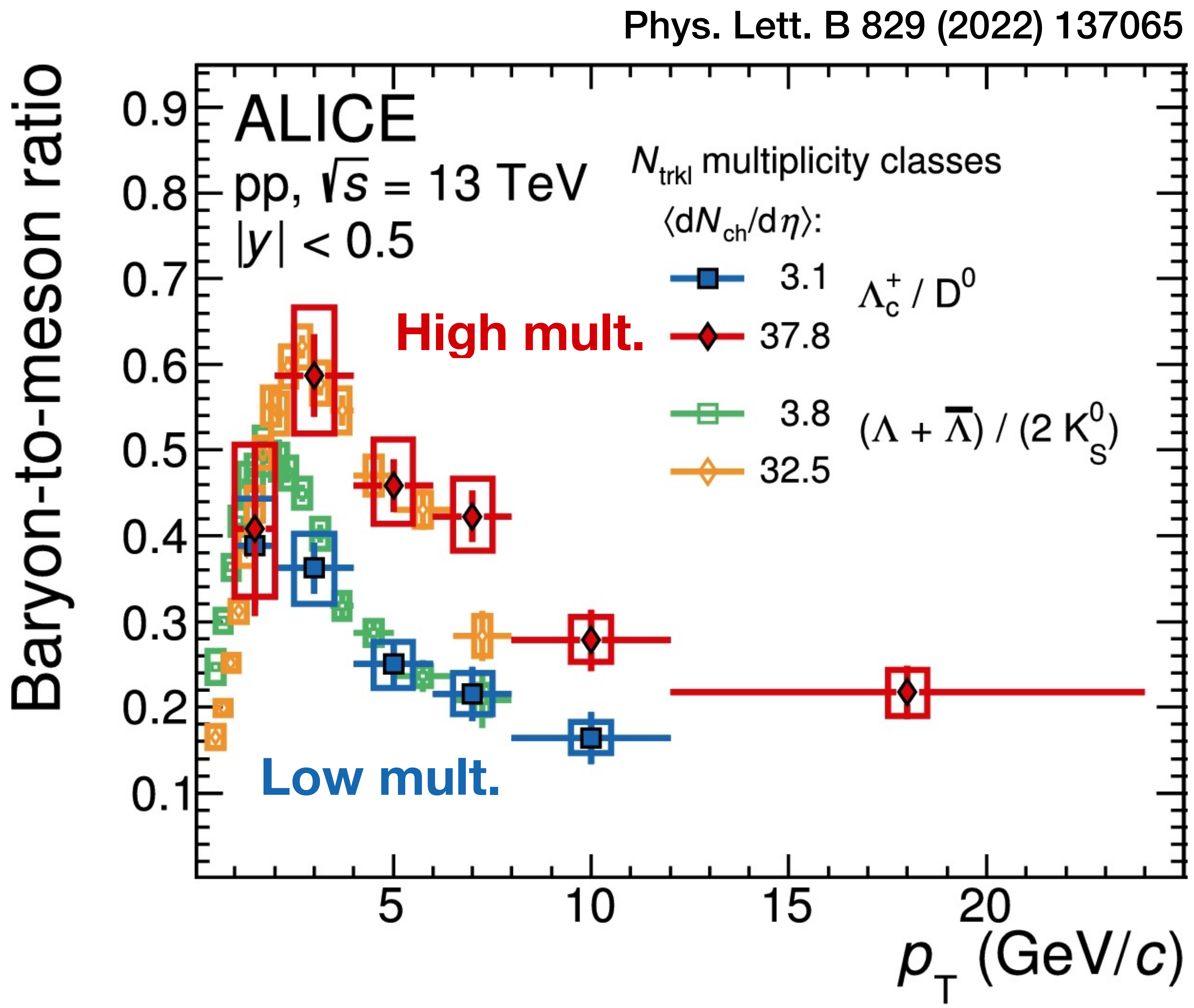


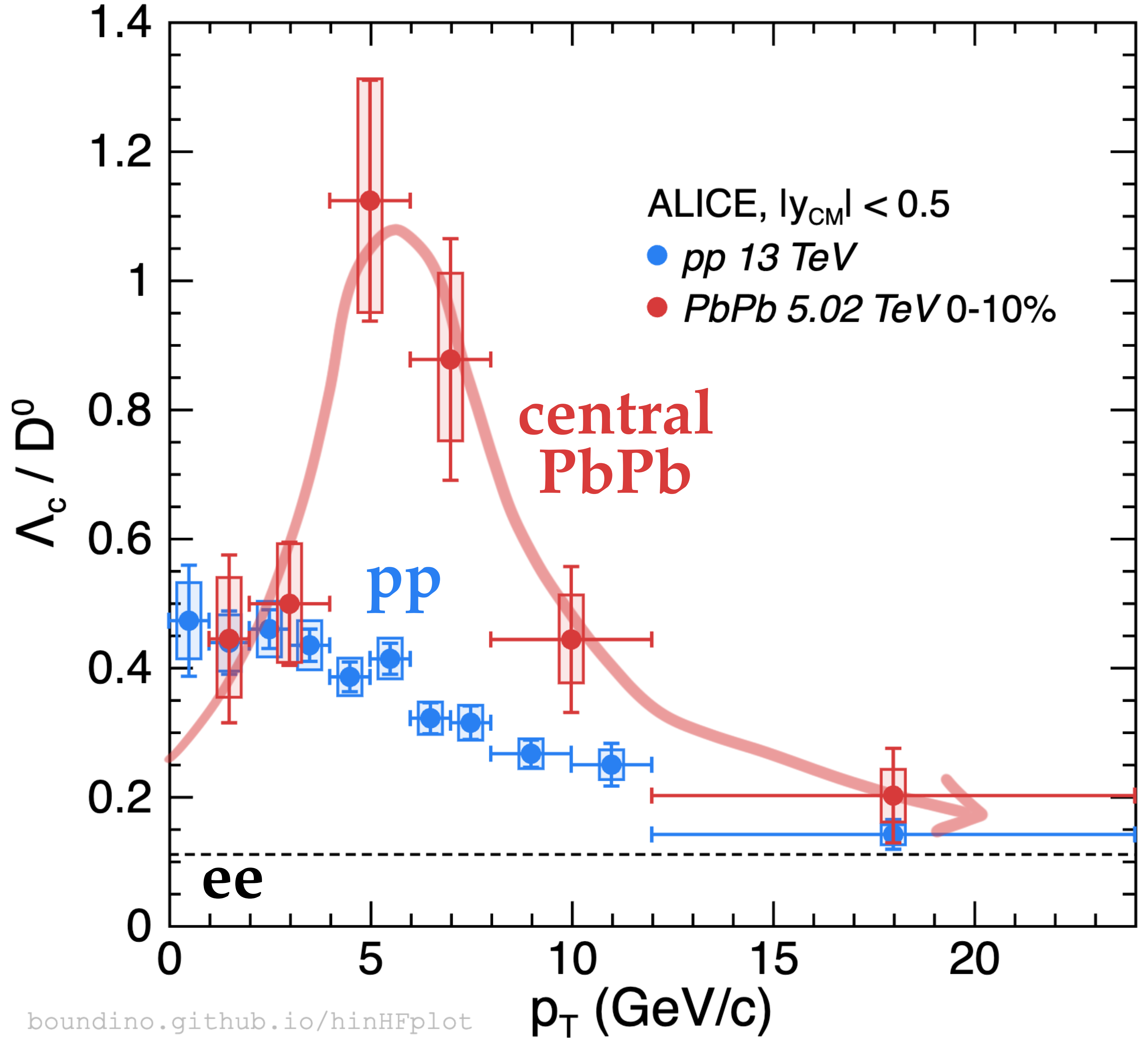
Phys. Lett. B 839 (2023) 137796

- Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?
- Modified mechanism of hadronization in all hadronic collision systems with respect to charm fragmentation tuned on e^+e^- and e^-p measurements?



p_T redistribution?

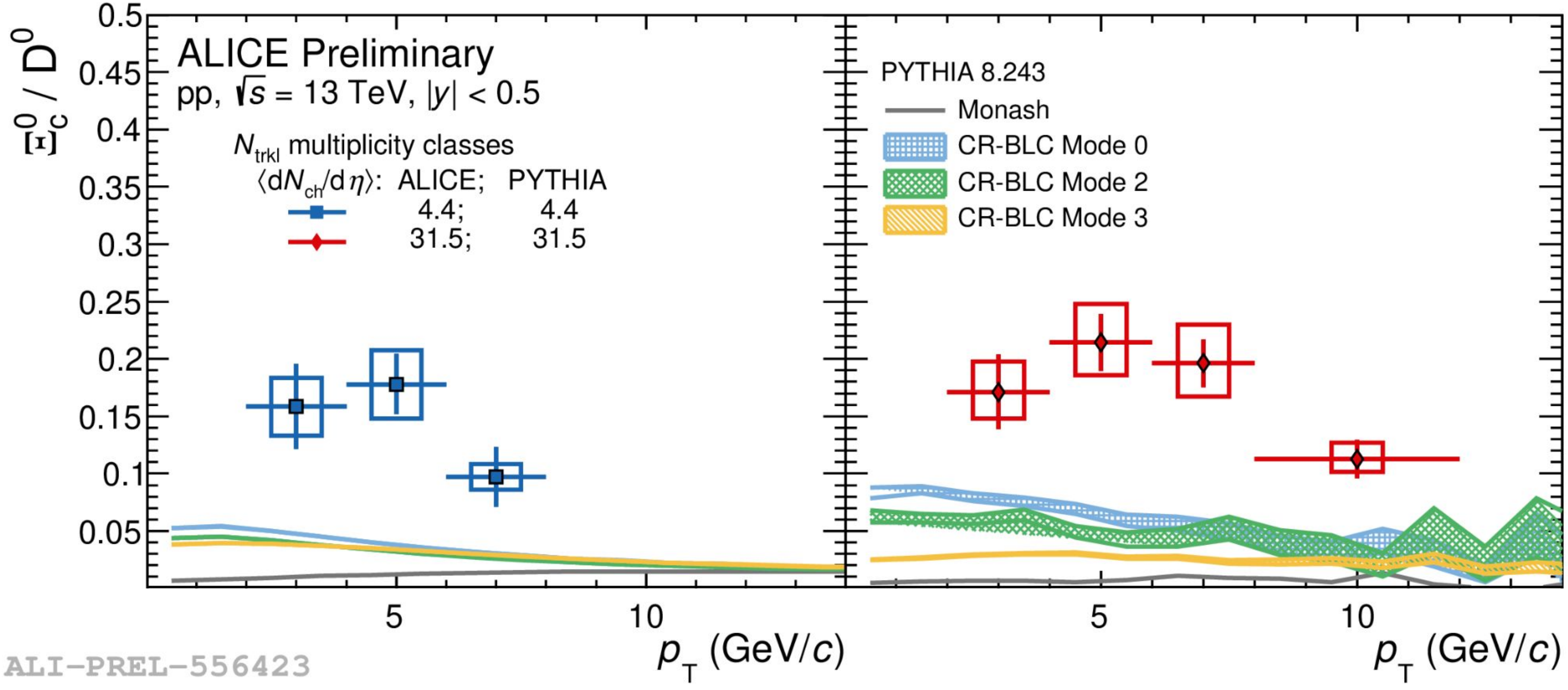


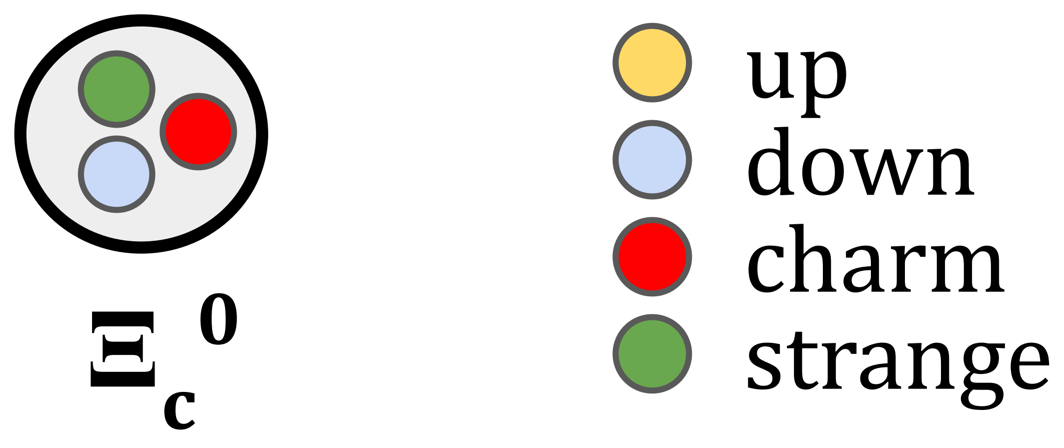


- Charm baryons/meson like for strangeness!
- Common mechanism for light- and charm-baryon formation in hadronic collisions? (unlikely) or coincidence in a redistribution?
- Shape changes dramatically in central PbPb → Strongest radial flow?

What about strangeness charm baryon?

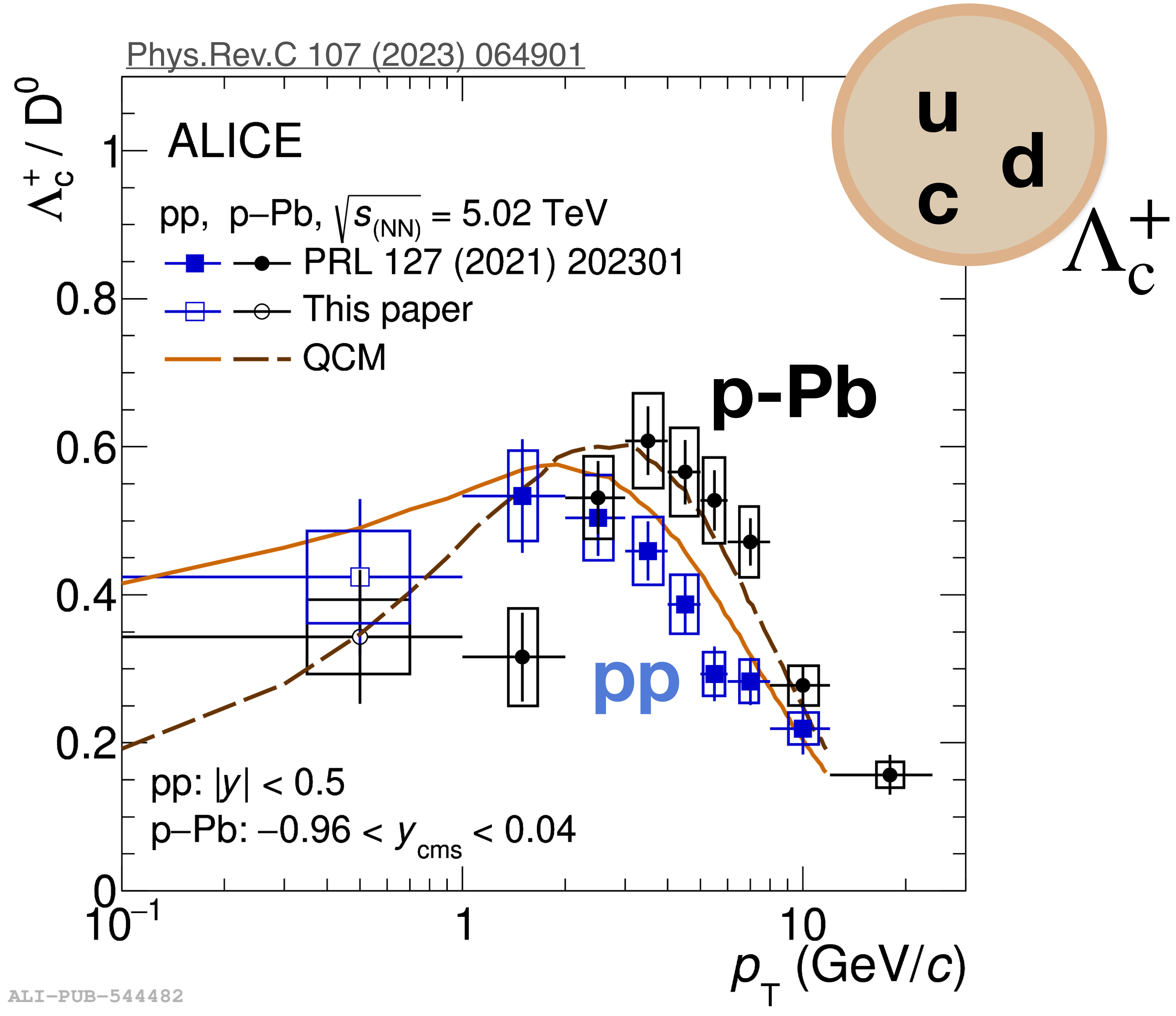
More challenges!

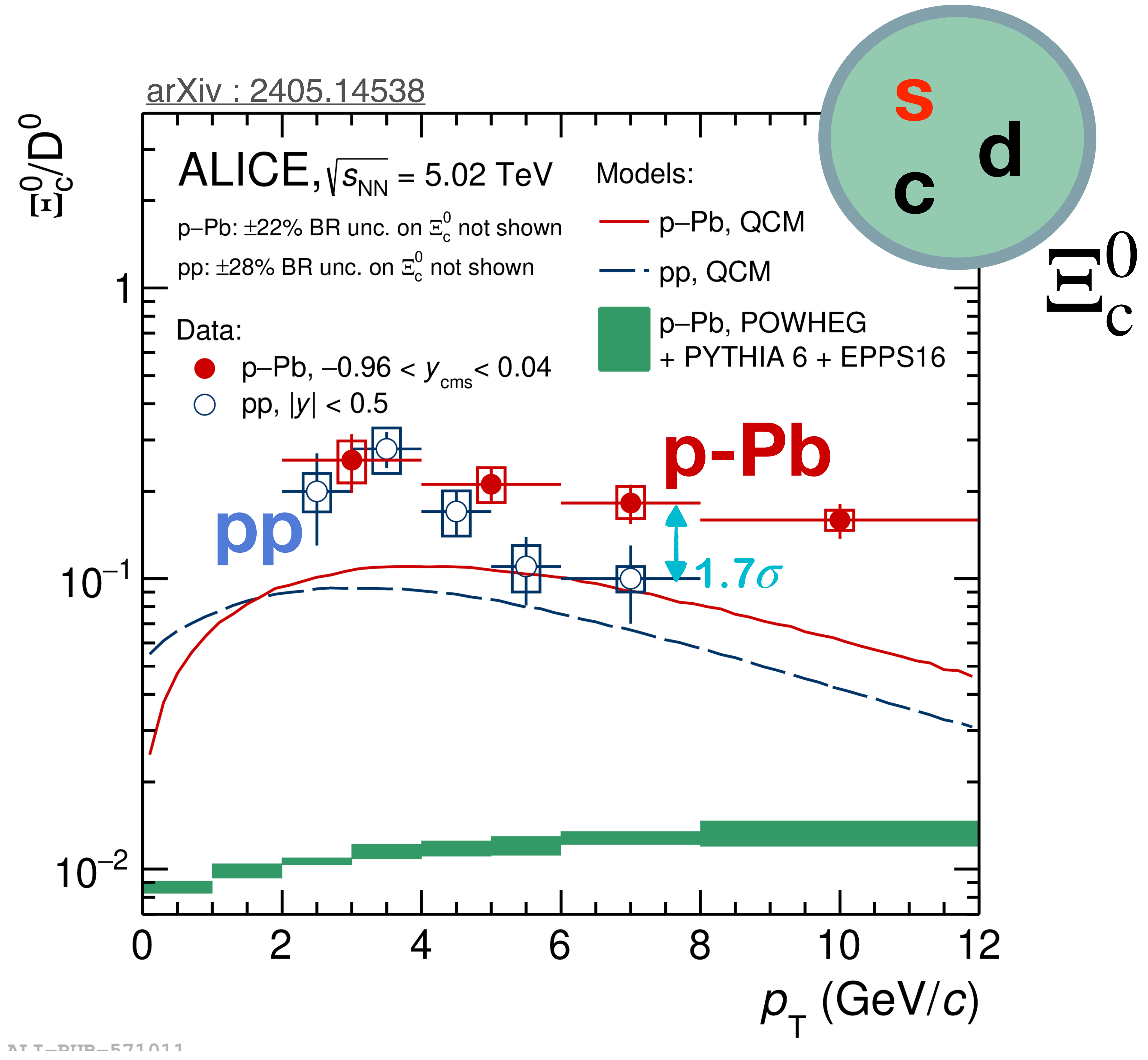




- Strong p_T dependence
- Enhancement compared to the measurement in e^+e^- and e^-p collisions

Challenging models

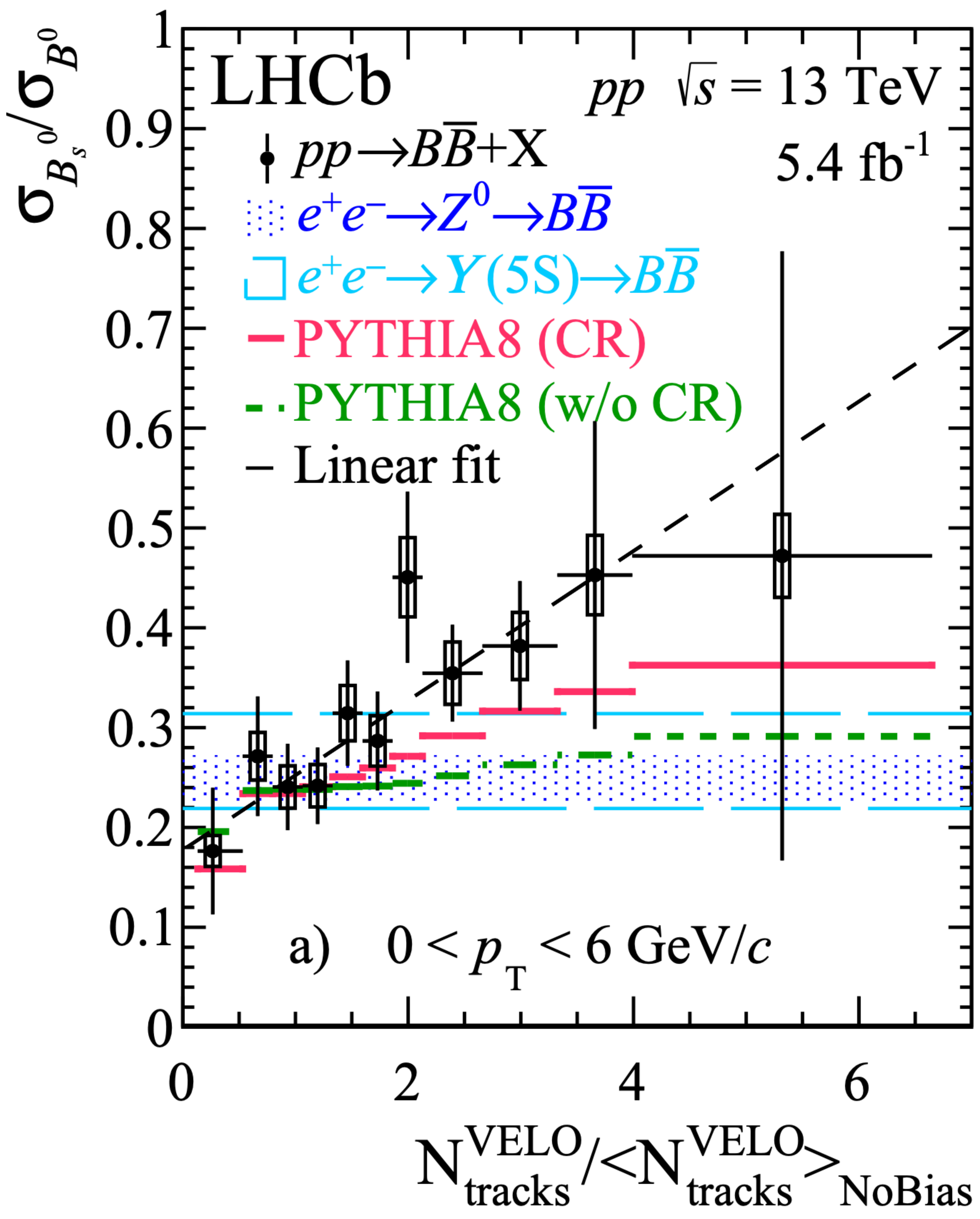




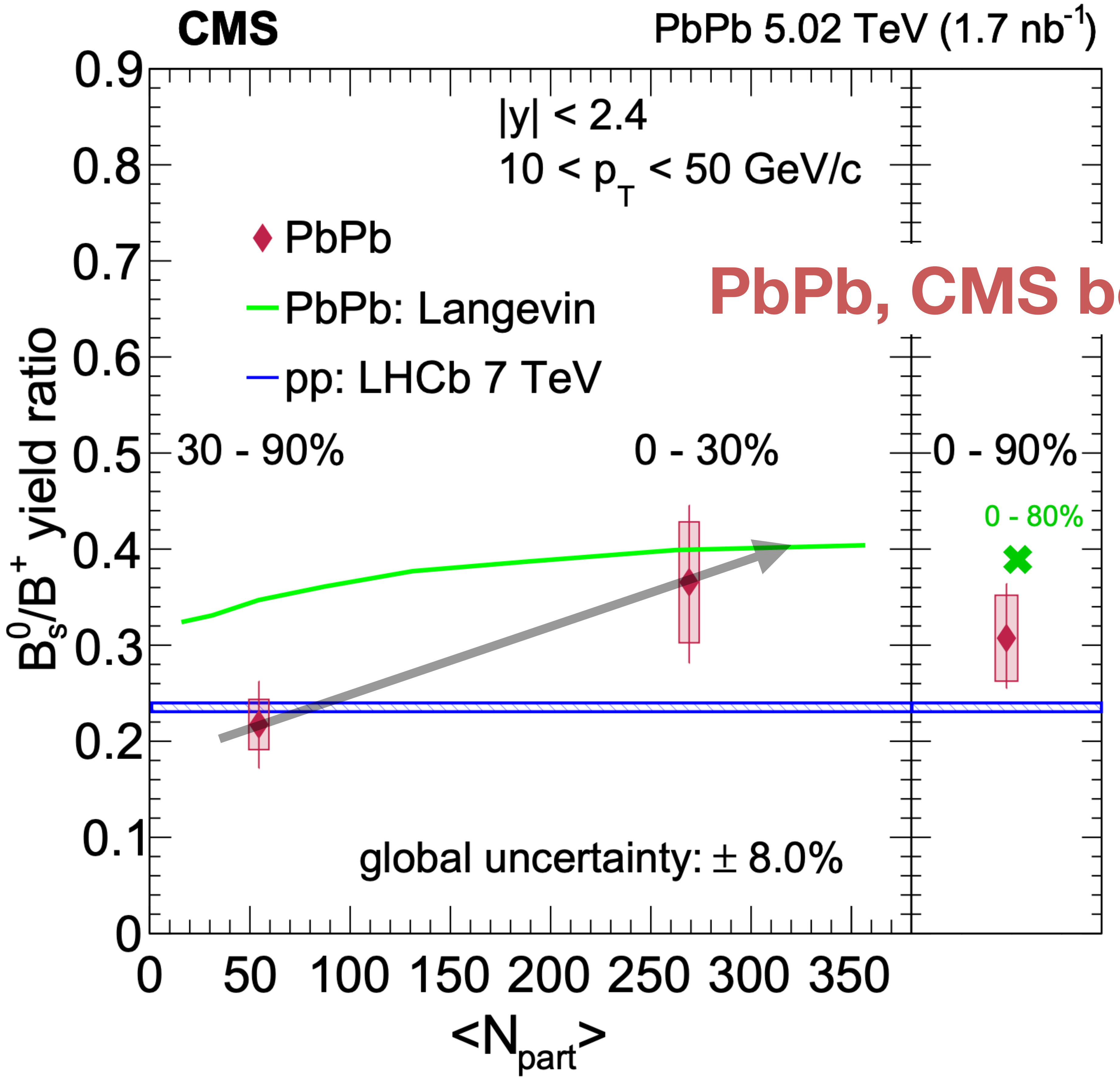
- Shift of distribution peak towards higher p_T could be attributed to radial flow
- QCM describes the magnitude of the ratio for Λ_c^+/D^0, but underestimate for Ξ_c^0

Is beauty different?

pp, LHCb beauty



B0s/B+

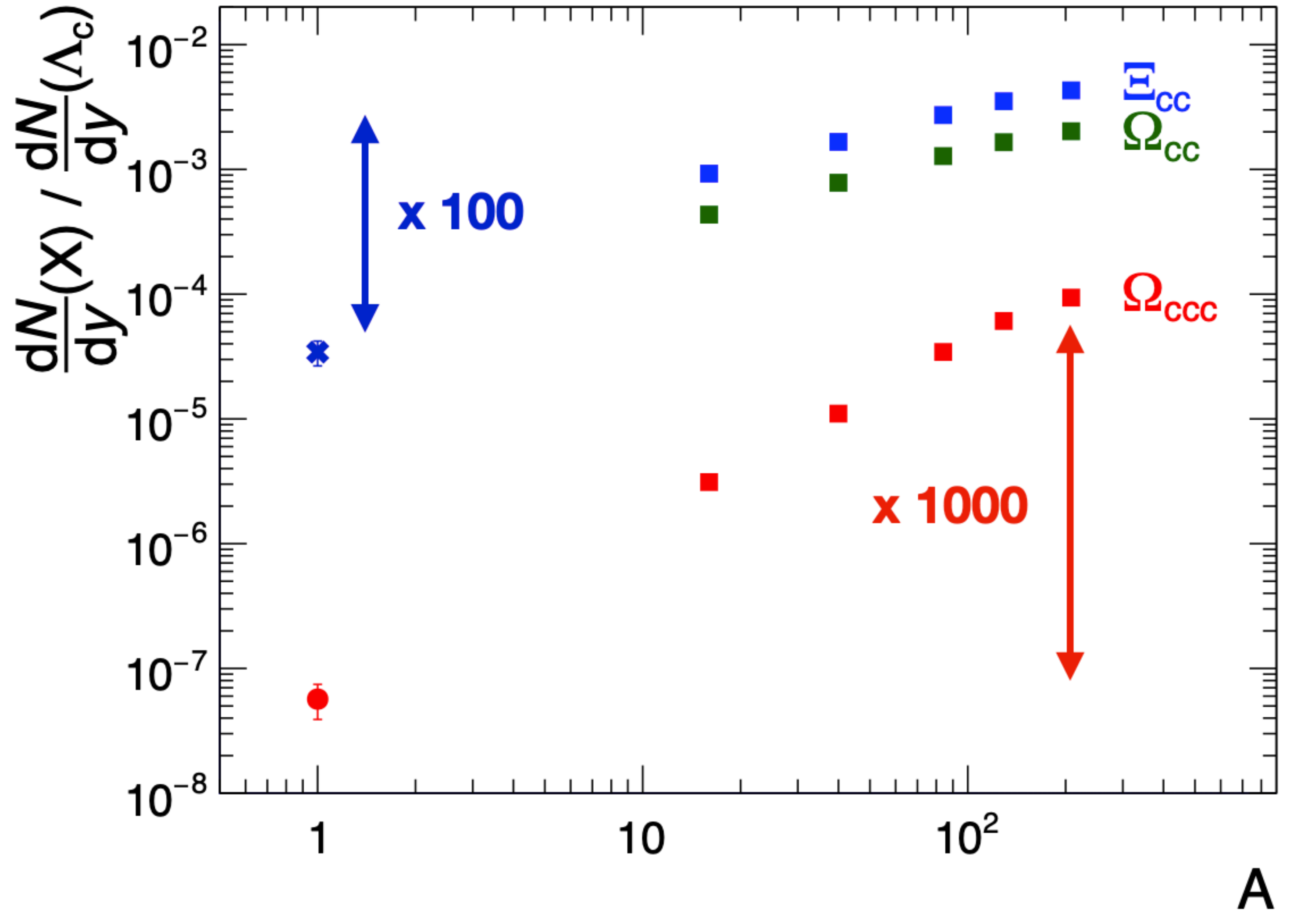


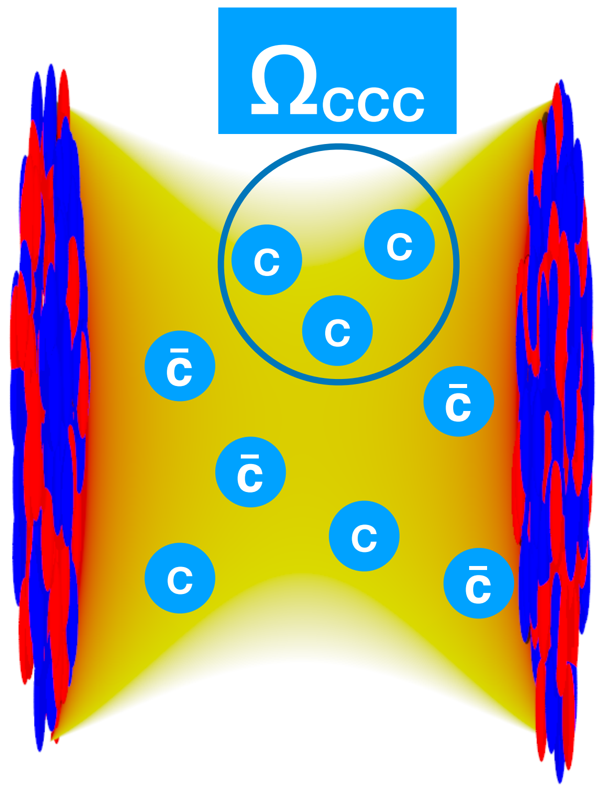
PbPb, CMS beauty

- Hint of different behavior of beauty
- Need precision measurement

What is obvious?, what is vague, what is unknown, …

- Enhancement due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?
- At least in the market, coalescence → a common framework for heavy-flavor hadronization from pp to AA?
- Other approaches such as PYTHIA-CR, POWLANG-LCN, … point also to
  - In medium local recombination
  - Large evolution from e^+e^- to pp while reshuffling in p_T from pp to AA



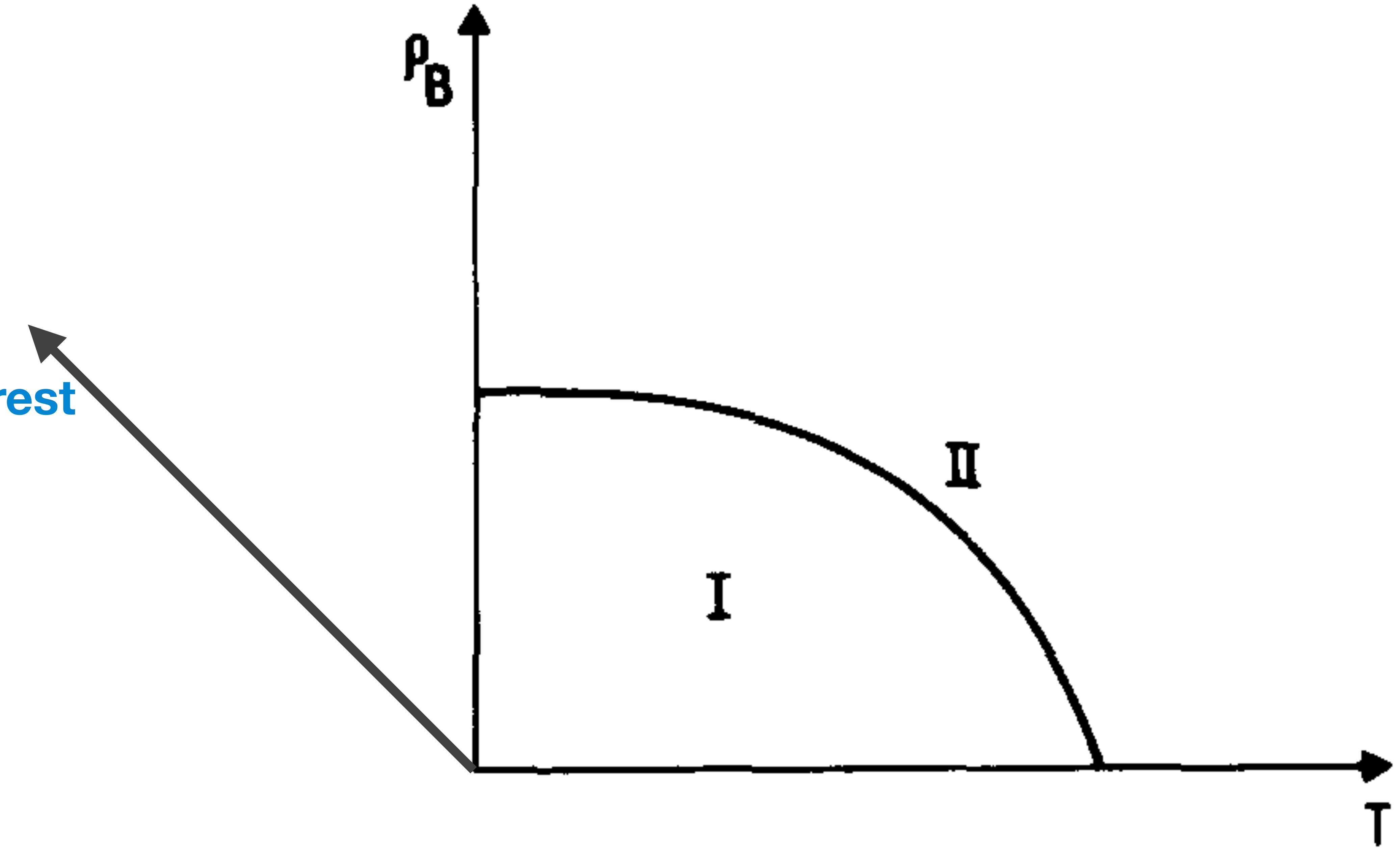


- Need more differential observables and precision measurement
  - Rapidity evolution
  - Extend to bottom
  - Effect on the other observables (ex. v_2)
  - ....

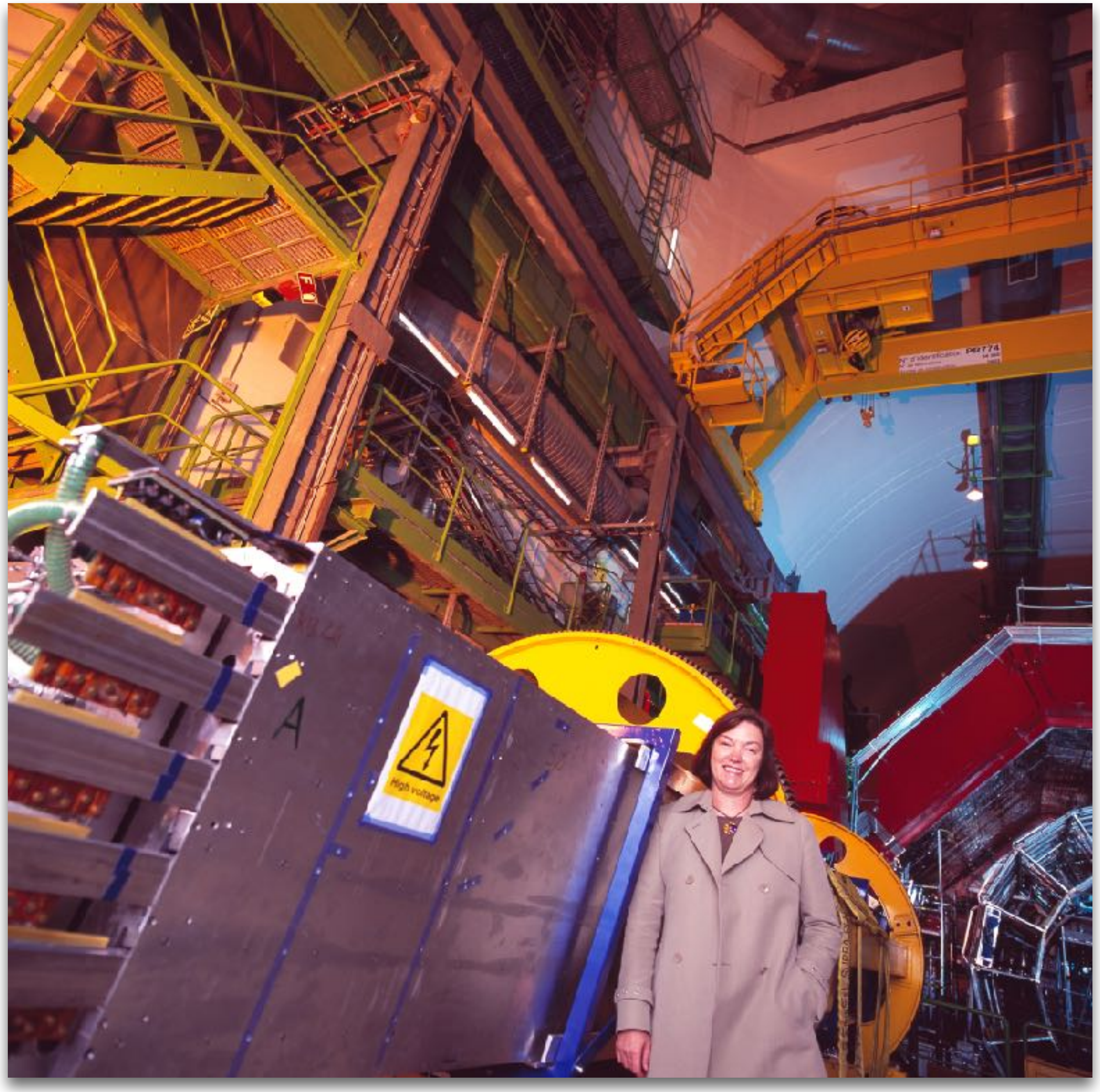
→ Very large enhancement predicted by Statistical hadronization model in Pb-Pb

⇨ Require new detector ALICE 3!

Including another axis allows for…



ρ never at rest



Thank you!

Extra Slides

Way of heavy-flavour hadronization, also in small systems?

- **Fragmentation**
  - → production from hard-scattering processes (PDF+pQCD)
  - → fragmentation functions: data parametrization, assumed universal

$$\sigma_{pp\to h} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

Parton shower: String fragmentation (Lund model - PYTHIA) + color reconnection (interaction from different scattering), Cluster decay (HERWIG)

- **Coalescence:**
  - → recombination of partons in QGP close in phase space

$$\frac{dN_{Hadron}}{d^2 p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3} \; f_q(x_i, p_i) \; f_W(x_1, \dots, x_n; p_1, \dots, p_n) \; \delta(p_T - \sum_i p_{iT})$$

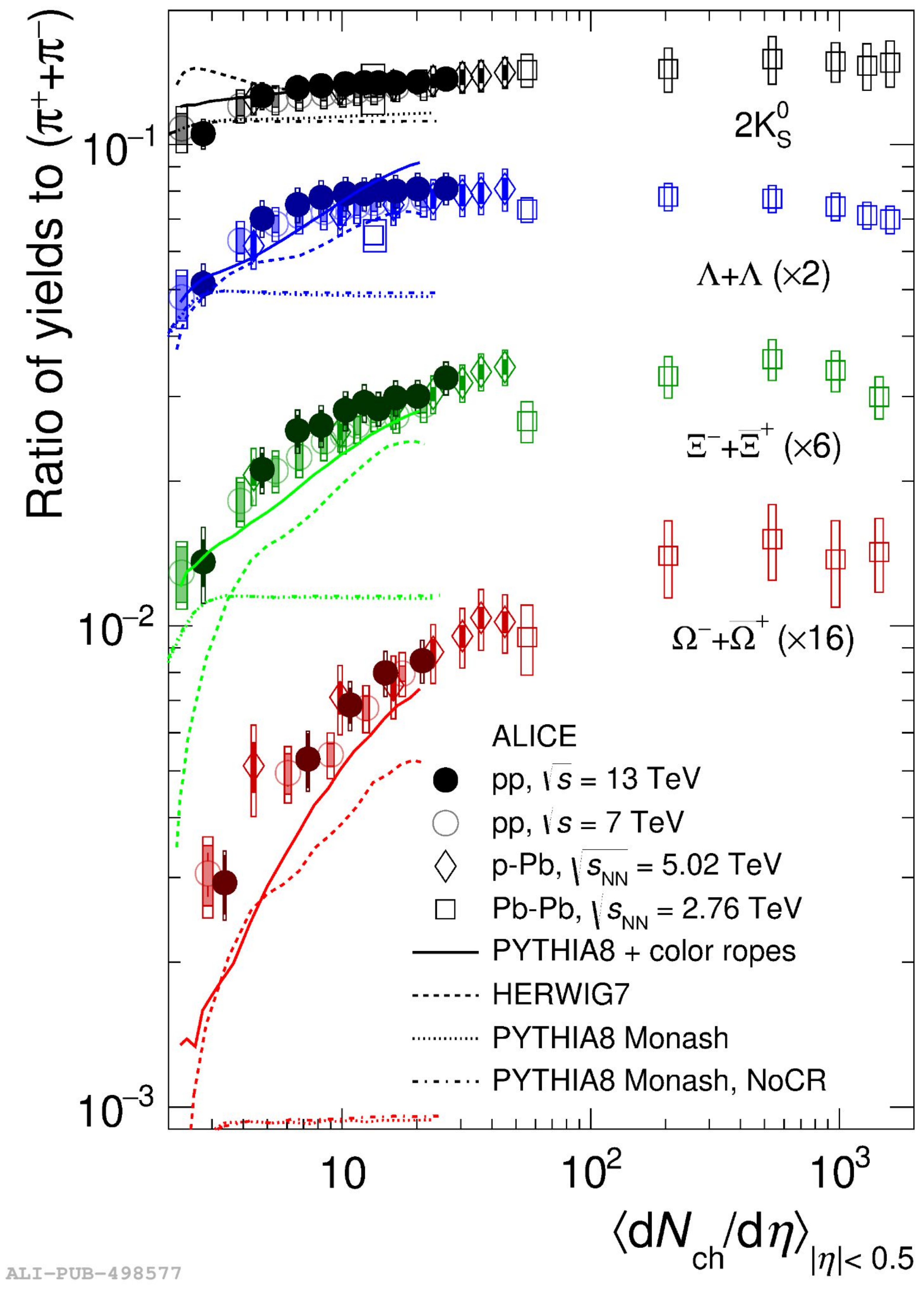
Have described first AA observations in light sector for the enhanced baryon/meson ratio and elliptic flow splitting

Support need of abandoning independent hadronisation of different MPI
A hadronic environment matters

- **Statistical hadronization**
  - → equilibrium + hadron-resonance gas + freeze-out temperature
  - → production depends on hadron masses and degeneracy, and on system properties require total charm cross section

Role of strangeness in heavy-quark hadronization

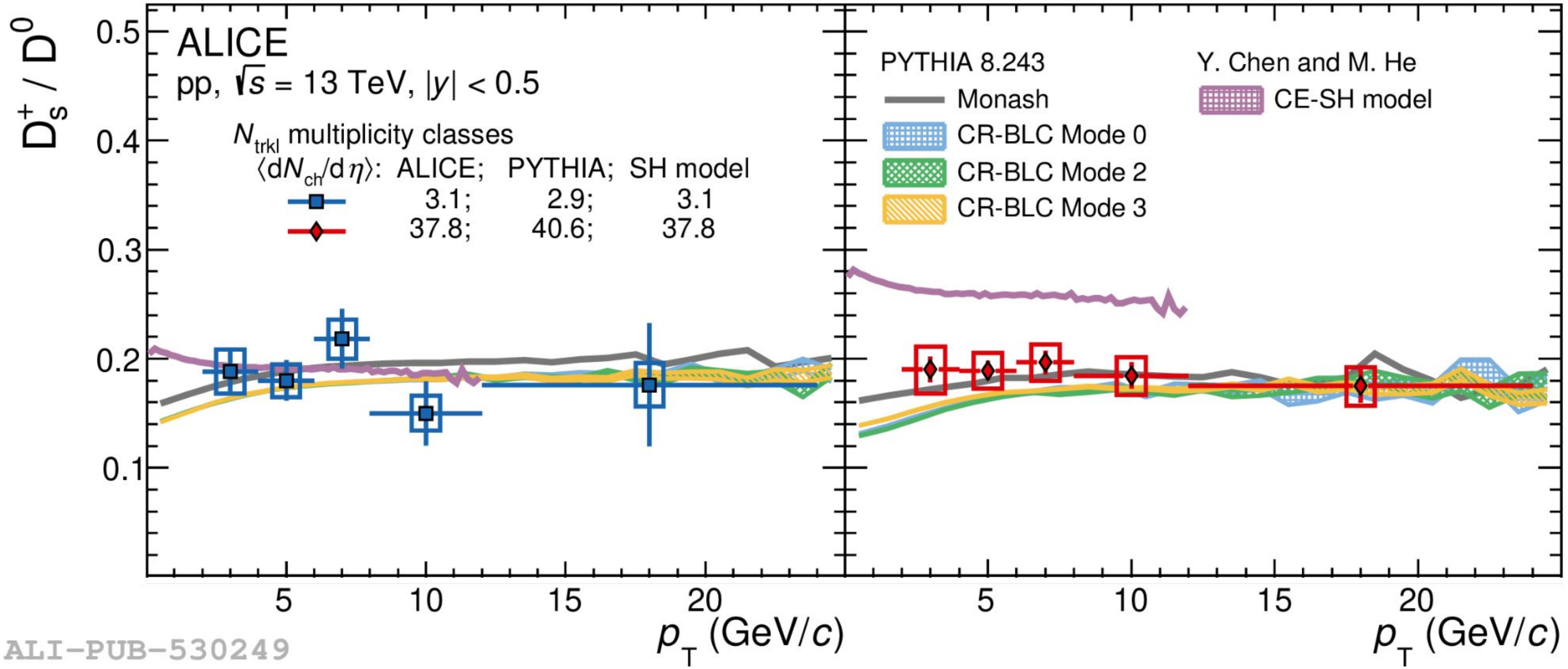
Eur. Phys. J. C 80 (2020) 693

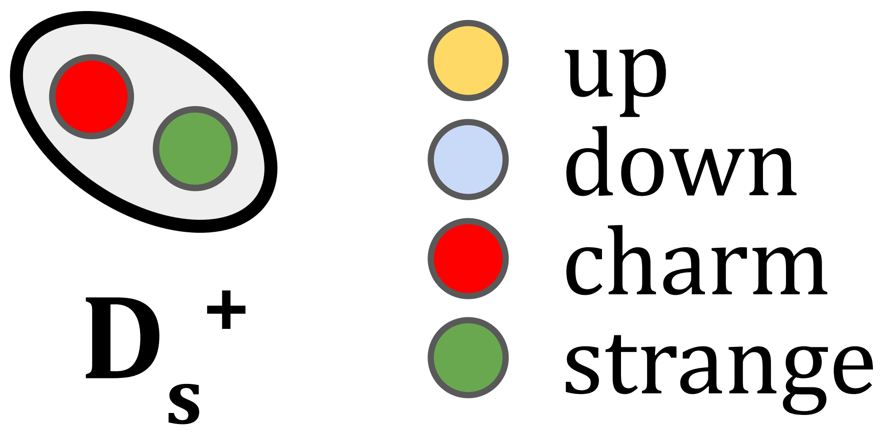


- Strangeness enhancement: yield-ratio between (multi)strange hadrons and pion larger in heavy-ion collisions than minimum-bias pp collisions
- Smooth increase vs. event multiplicity, without a clear collision-system dependence
- What do we learn from strange heavy hadron (D^0, Λ_c^+, Ξ_c^0,…) production about heavy-quark hadronization
  - ➡ evolve vs. event multiplicity?
  - ➡ sensitive to QGP-induced effects (e.g. strangeness enhancement, coalescence, *E*-loss, flow, …)?

D_s^+: strange charm meson

Phys. Lett. B 829 (2022) 137065

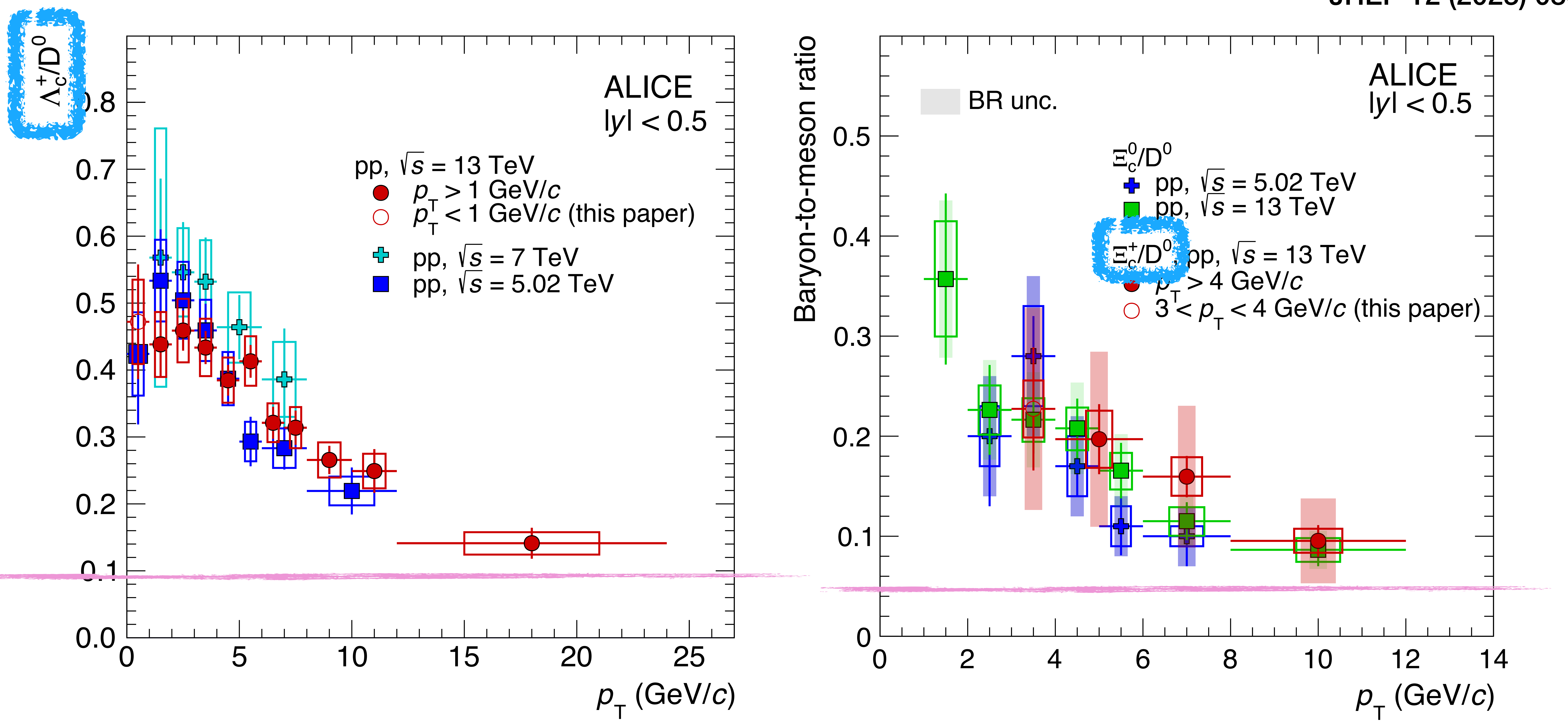




- D_s^+/D^0 ratio are independent of p_T
- No strong multiplicity dependency
- Comparable with measurement at e^+e^- and e^-p collisions

Charm baryon production in pp at a glance

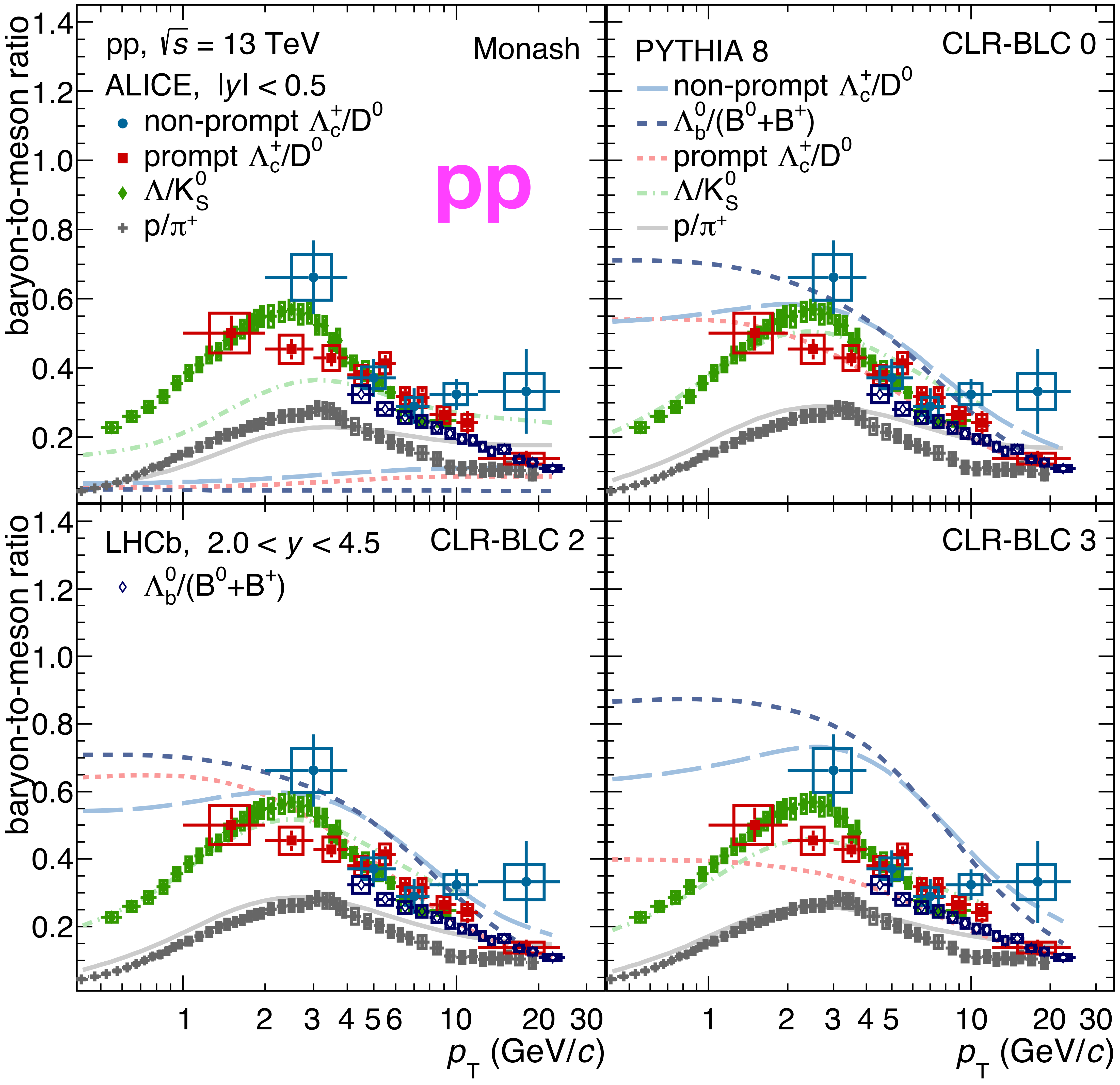
JHEP 12 (2023) 086



Significantly larger fraction of charm quarks hadronising to baryons is found compared to e^+e^-, ep collisions.

Baryon to meson ratios of different flavors

Phys. Rev. D 108, 112003 (2023)



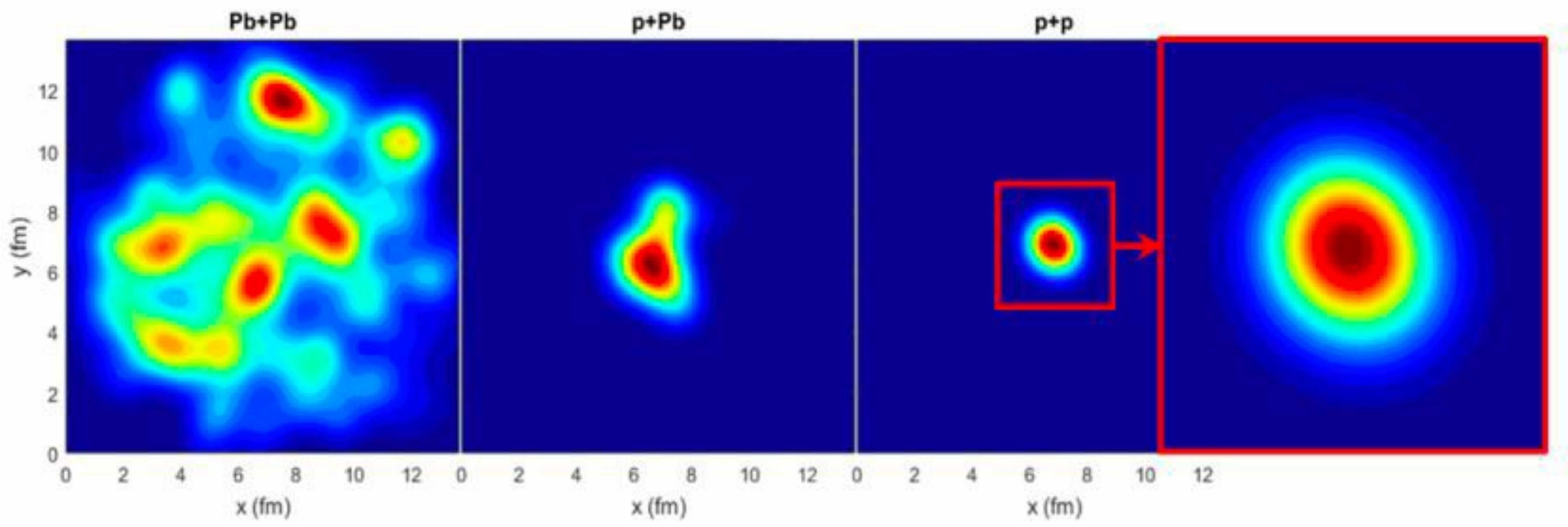
- All the measurements for beauty, charm, and strange hadrons show a similar trend as a function of p_T and are compatible within the uncertainties

→ Similar baryon-formation mechanism among light, strange, charm and beauty hadrons?

- non-prompt Λ_c^+/D^0
- prompt Λ_c^+/D^0
- Λ/K^0_S
- p/π^+
- $\Lambda_b^0/(B^0+B^+)$

Note: for LHCb, different normalization & should consider decay kinematics (for the other case)
* These three tunes are characterized by different constraints on the time dilation and causality

As an example, in Catania, coalescence + fragmentation in pp



R. D. Weller, P. Romatschke, PLB 774 (2017) 351-356

Vincenzo Greco's expression in his SQM talk!

Daring to assume a small fireball according **viscous hydro** applied to pp as in AA, but **size,time, flow given by hydro for pp**

p+p @ 5 TeV

- t_{pp}=1.7 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm³

+ $f_c(p)$ from **FONNL distribution**

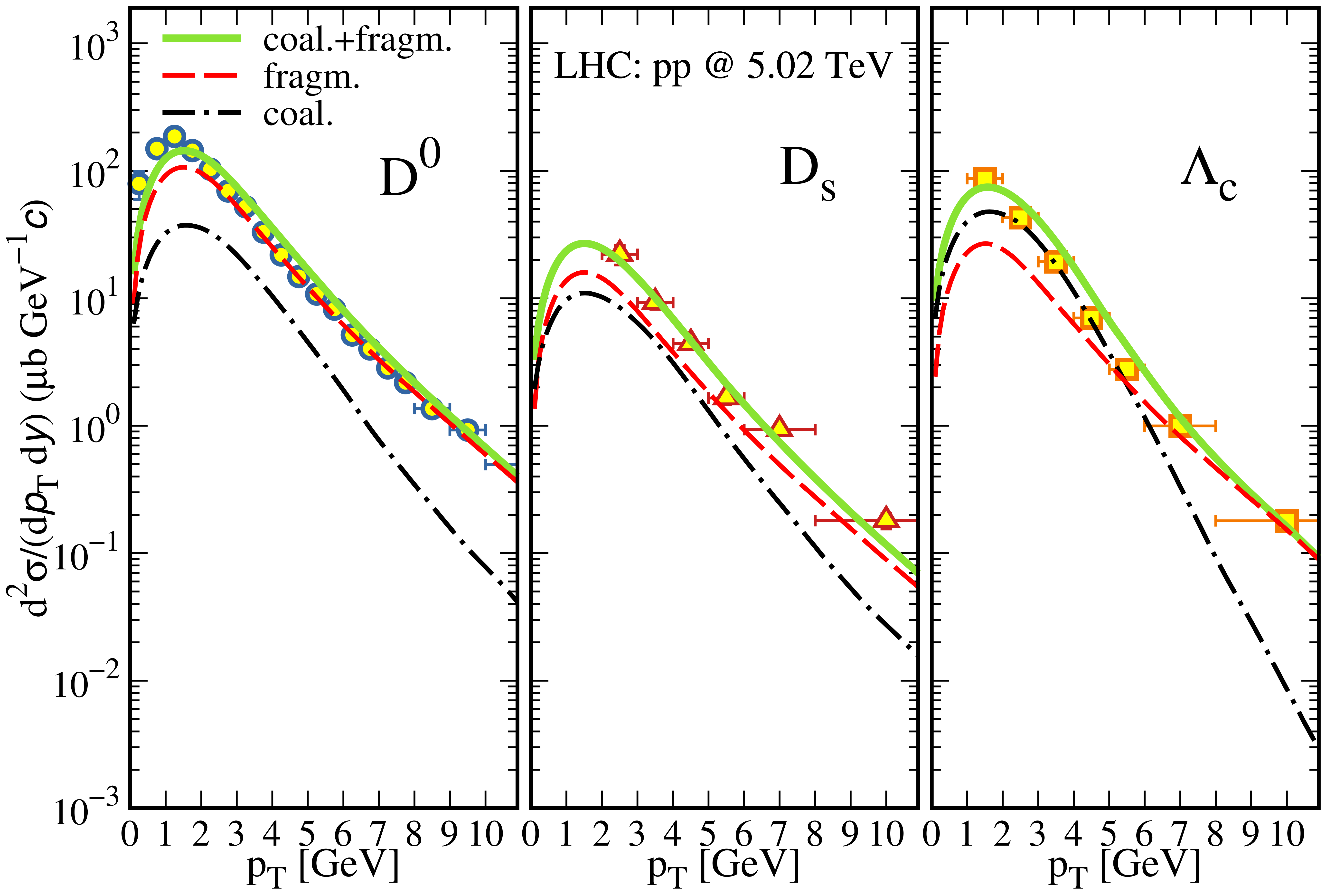
$$f_q(p) \sim \frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma_T\left(m_T - p_T \cdot \beta_T \mp \mu_q\right)}{T}\right)$$

+ same Wigner function widths $\sigma_{r,i}$ of hadrons in AA

$$f_H(x_{\mathrm{i}},; p_i) = \prod_{i=1}^{N_q-1} 8 \exp\left(-\frac{x_{r,i}^2}{\sigma_{r,i}^2} - p_{r,i}^2\sigma_{r,i}^2\right)$$

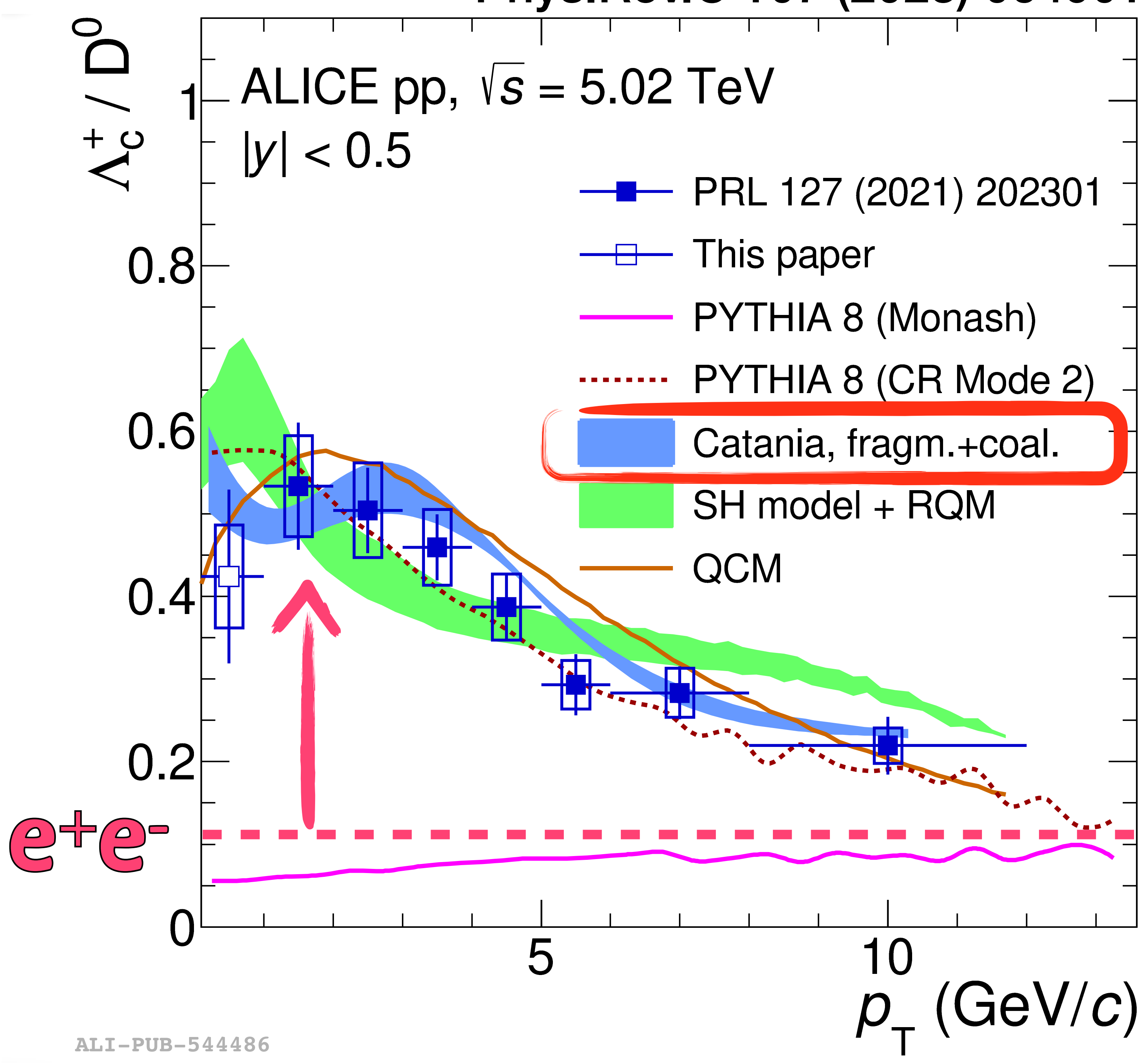
Coalescence in pp vs p_T in Catania

Phys. Lett. B 821 (2021) 136622



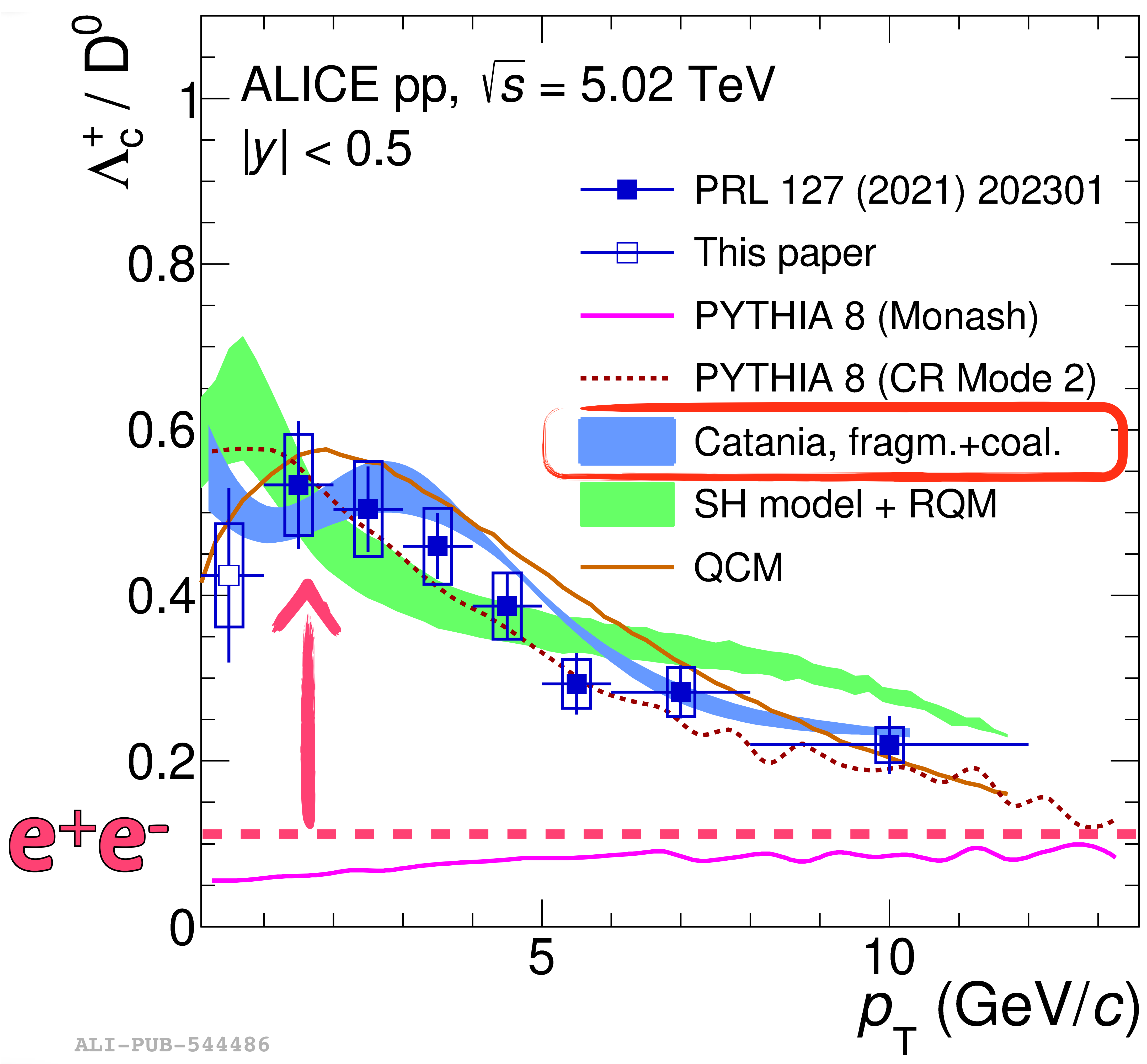
- All the coalescence does not affect significantly D^0, but is dominant for baryons Λ_c and Ξ_c

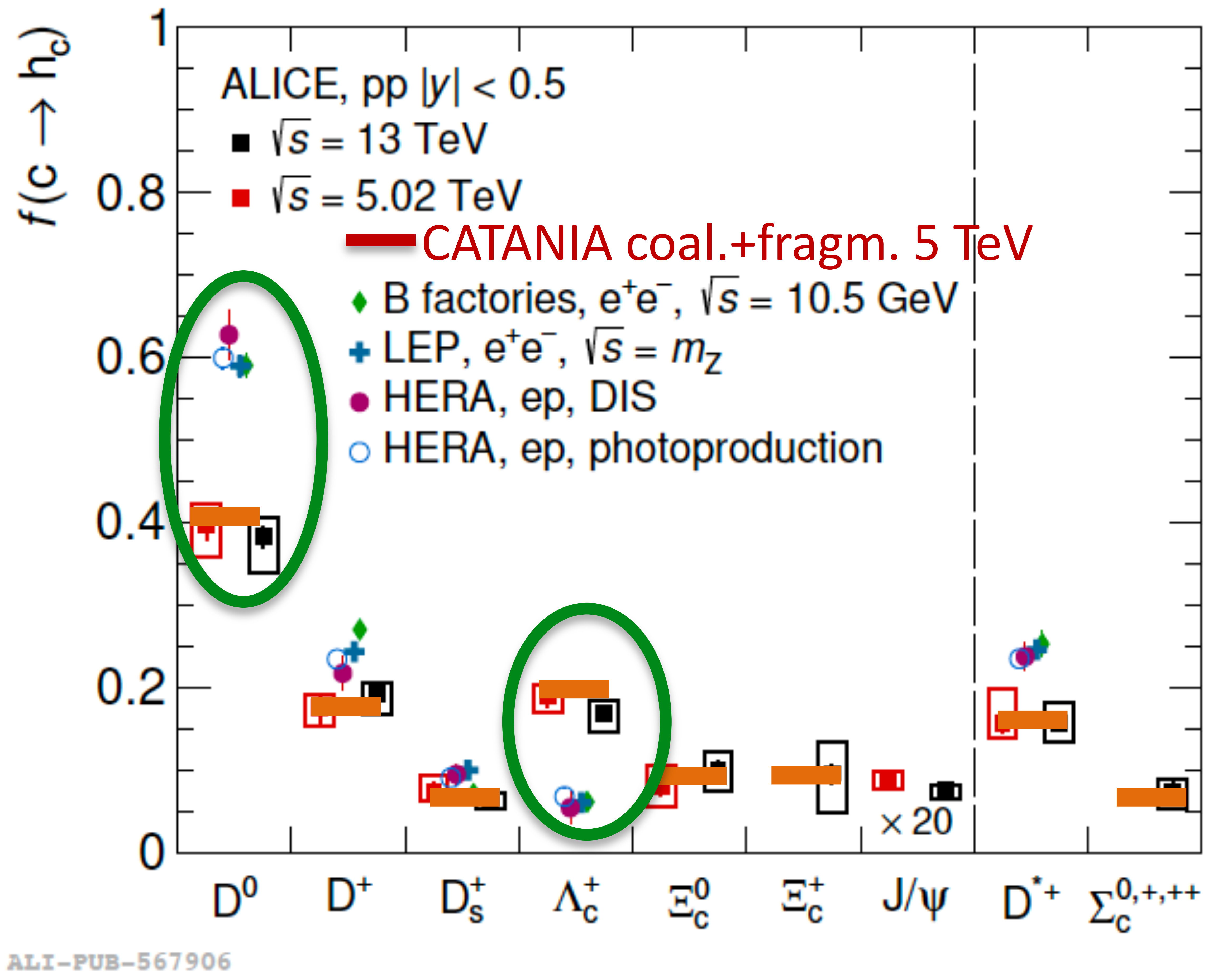
Phys.Rev.C 107 (2023) 064901



Catania baryon to meson ratio

Phys.Rev.C 107 (2023) 064901

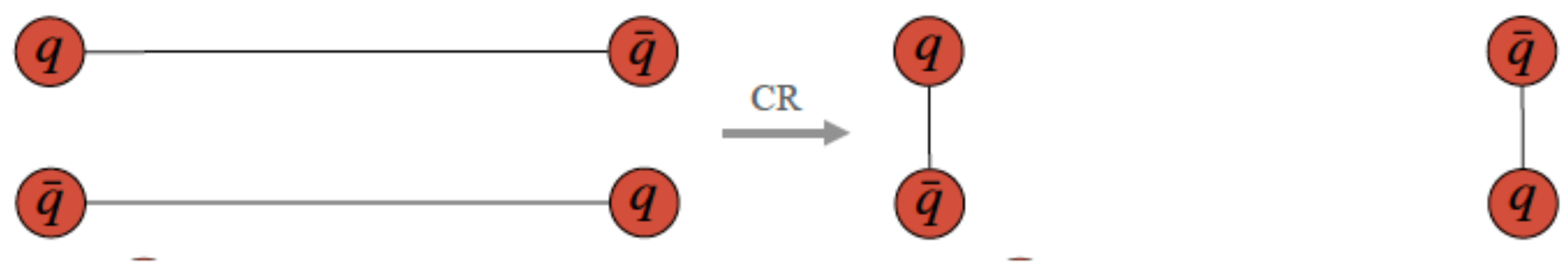




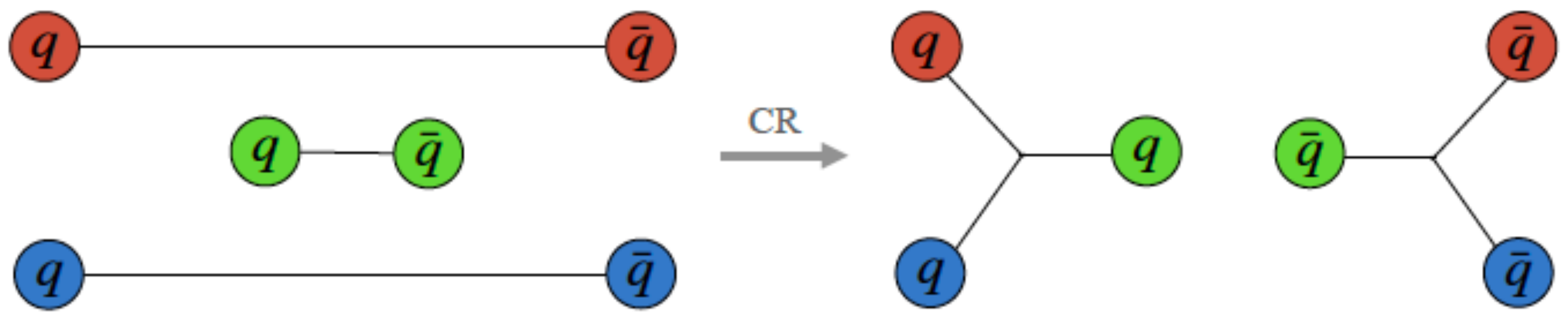
- Catania Coal+Fragm. very close to pp FF

PYTHIA Color Reconnection

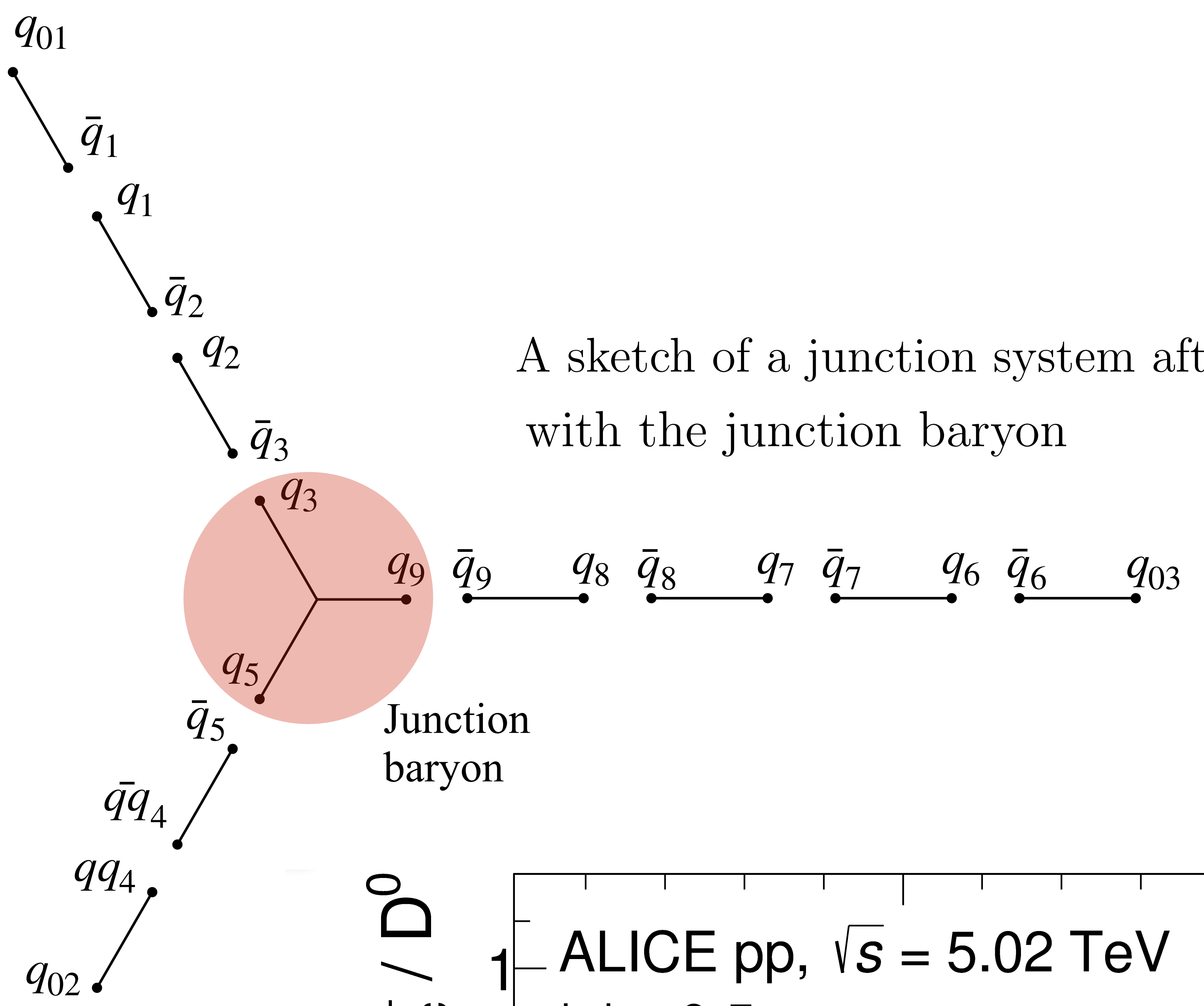
Altmann et al., arXiv 2405.19137



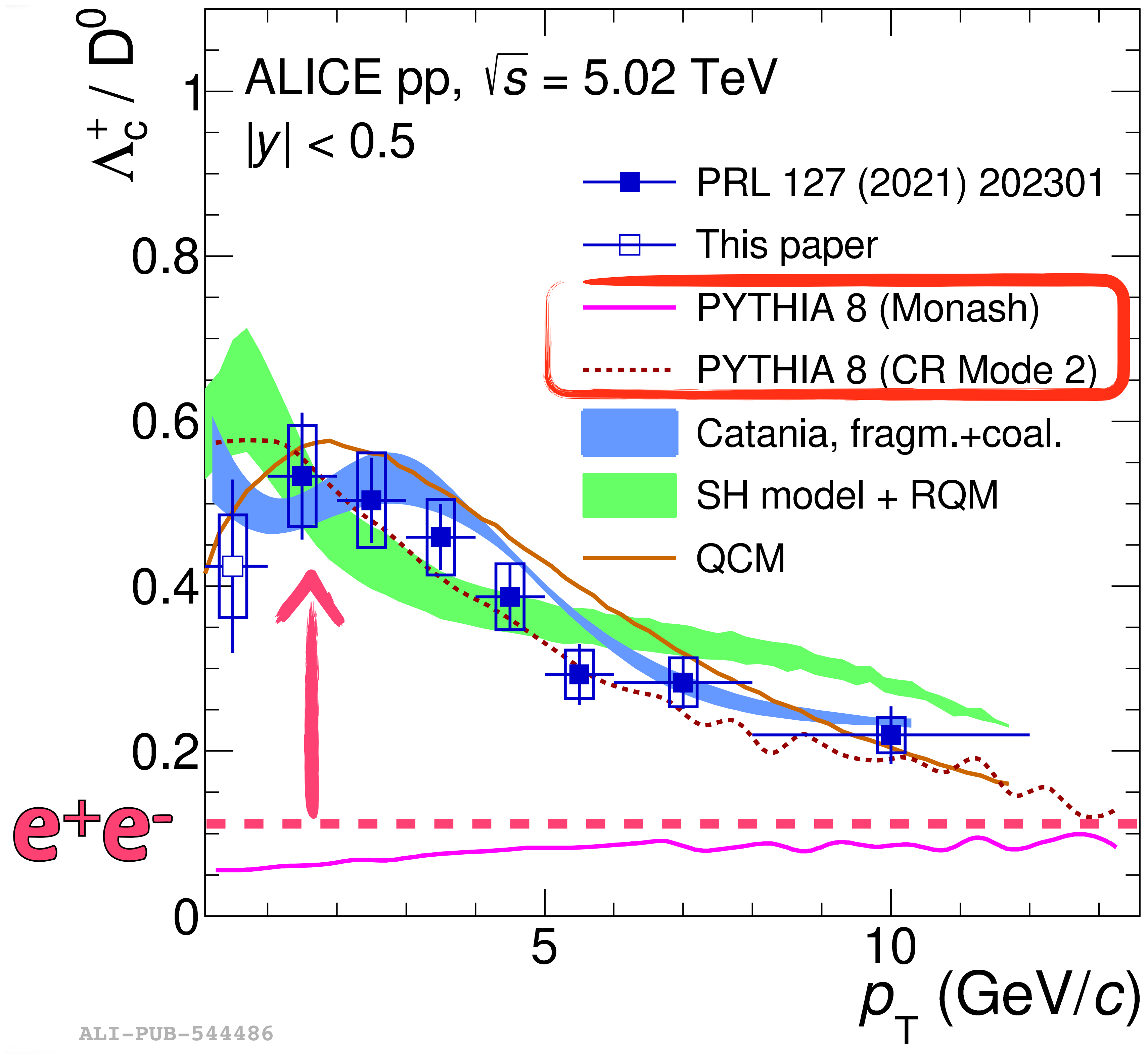
(a) Dipole-type reconnection.



(b) Junction reconnection.



A sketch of a junction system after fragmentation, with the junction baryon



- When string color reconnection is switched-on in pp:
  - → Very large baryon Λ_c enhancement
  - → not that relevant for D

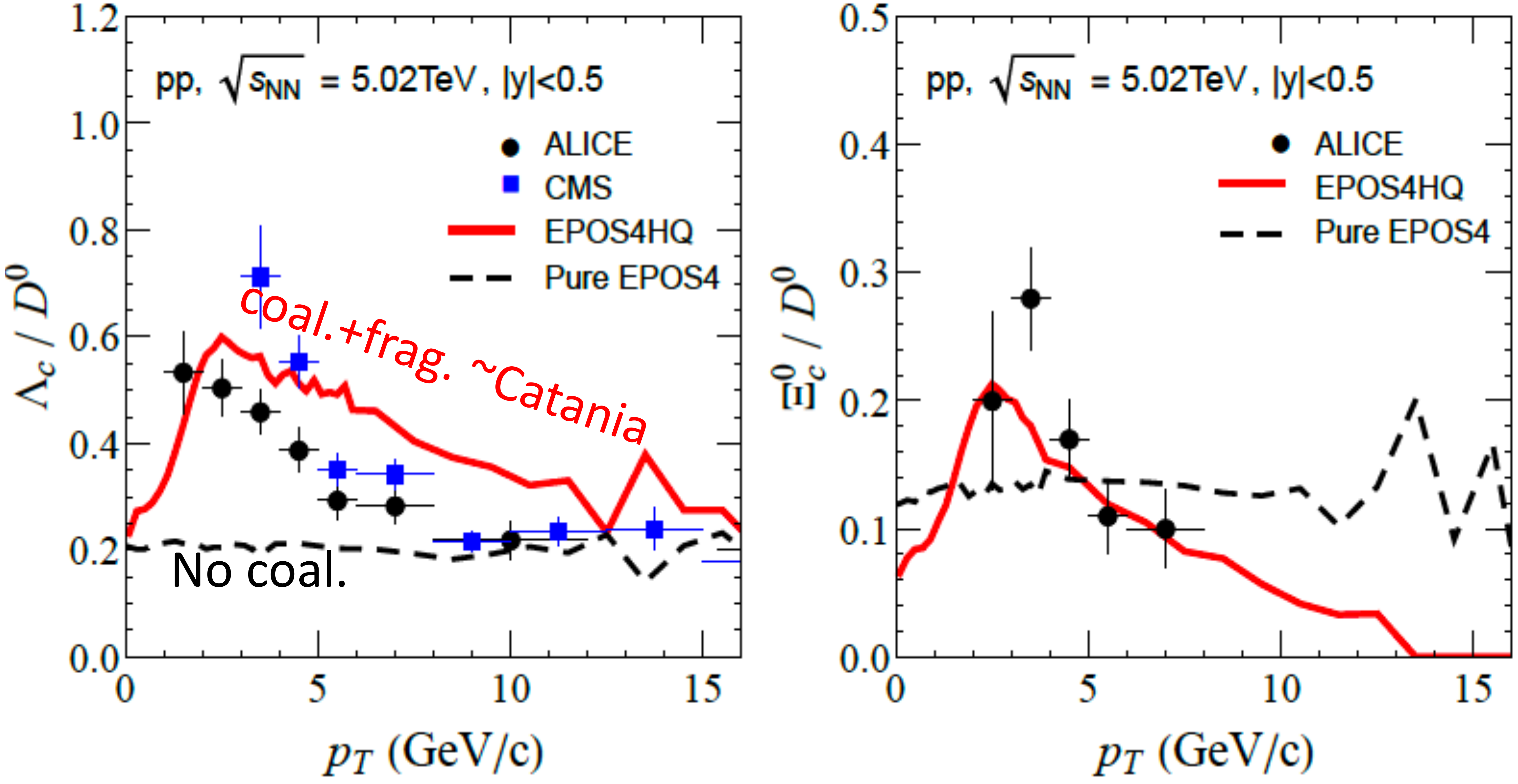
Not so different qualitatively wrt Coalescence and POWLANG Local color recombination

Many models in market enhancing baryon production

- Coalescence [+Fragmentations] model:

  → Catania, Coal-TAMU(KO), Ko-Cao, CCNU-Duke, [QCM], PHSD, RRM-TAMU, Nantes-EPOS4HQ,...

J.Zhao et al., PRD109 (2024)



Ex) EPOS4HQ

→ To describe HF spectra & ratios needs Coalescence in phase space ~Catania

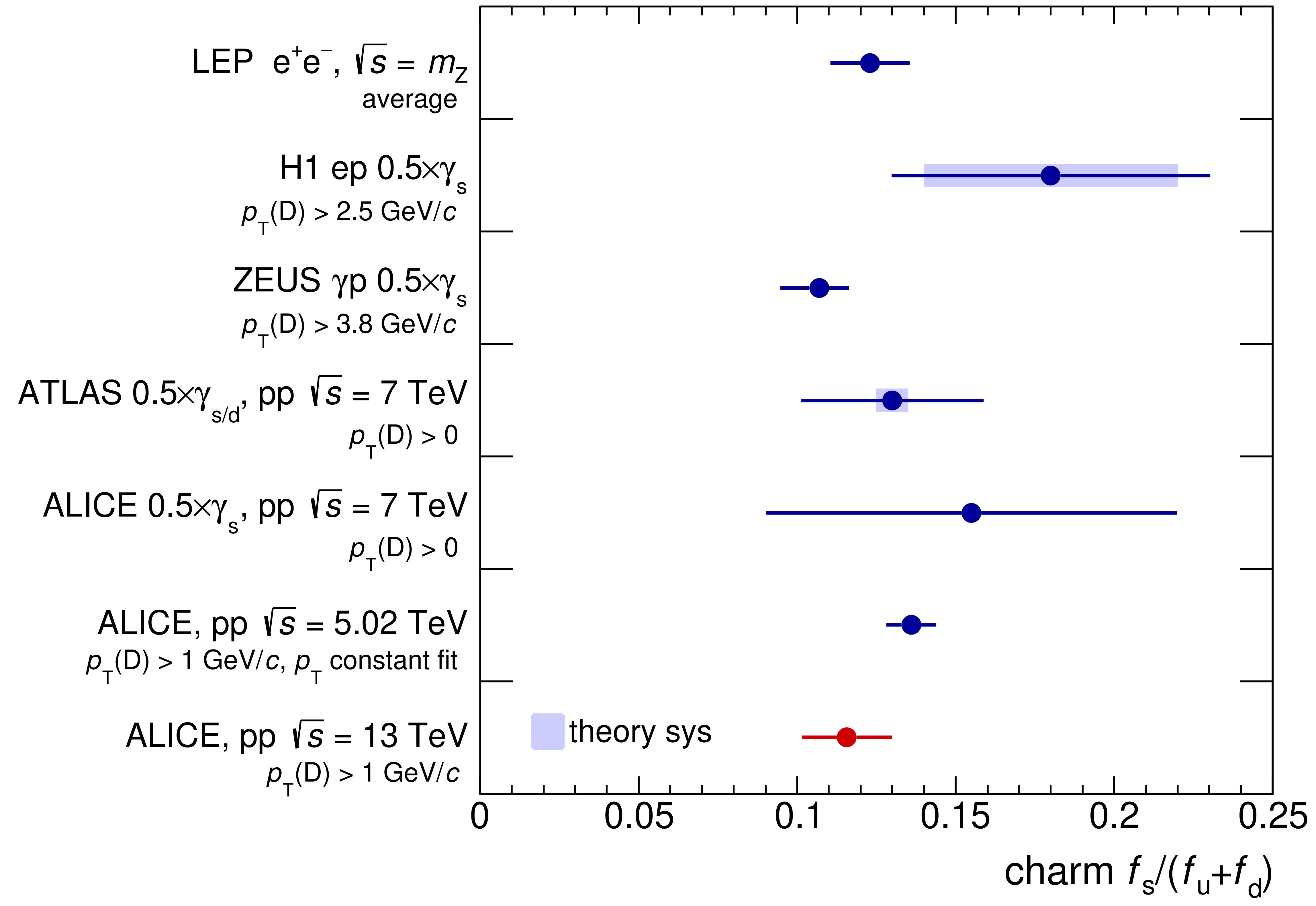
Only difference wrt Catania:

- Assume RQM states like in SHM

Charm-quark fragmentation-fraction ratio

arXiv:2308.04877

Strange to non-strange charm-meson production ratio

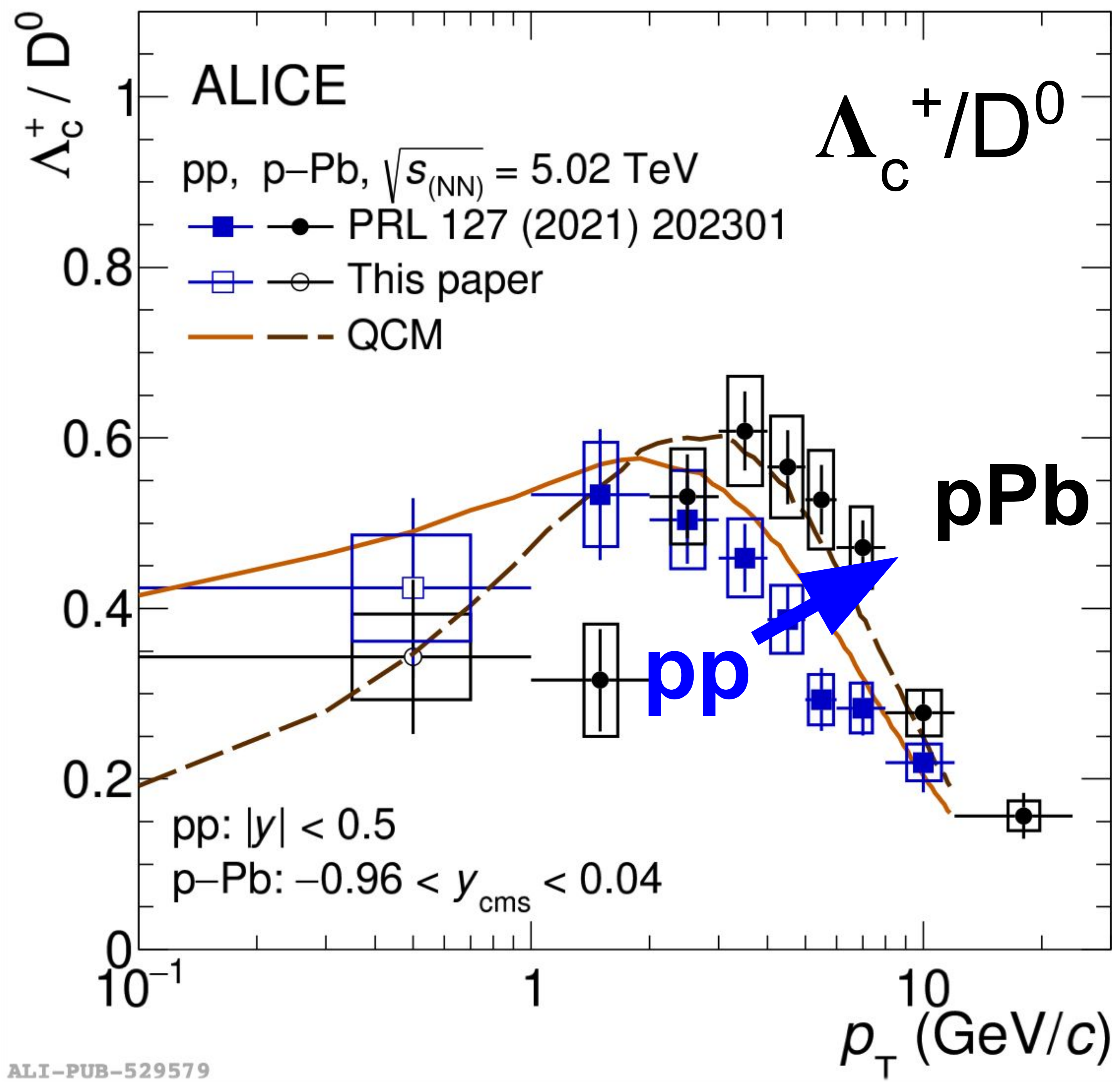


	$d\sigma/dy\|_{\|y\|<0.5}$ (μb), $p_T > 0$
D^0	749 ± 27 (stat.) $^{+48}_{-50}$ (syst.) $\pm$ 12 (lumi.) $\pm$ 6 (BR)
D^+	375 ± 32 (stat.) $^{+35}_{-35}$ (syst.) $\pm$ 6 (lumi.) $\pm$ 6 (BR)
D_s^+	120 ± 11 (stat.) $^{+12}_{-13}$ (syst.) $^{+25}_{-10}$ (extrap.) $\pm$ 2 (lumi.) $\pm$ 3 (BR)
Λ_c^+	329 ± 15 (stat.) $^{+28}_{-29}$ (syst.) ±5 (lumi.) ±15 (BR)
Ξ_c^0 [52]	194 ± 27 (stat.) $^{+46}_{-46}$ (syst.) $^{+18}_{-12}$ (extrap.) $\pm$ 3 (lumi.)
Ξ_c^+	187 ± 25 (stat.) $^{+19}_{-19}$ (syst.) $^{+13}_{-59}$ (extrap.) $\pm$ 3 (lumi.) $\pm$ 82 (BR)
J/ψ [84]	7.29 ± 0.27 (stat.) $^{+0.52}_{-0.52}$ (syst.) $^{+0.04}_{-0.01}$ (extrap.)
D^{*+}	306 ± 26 (stat.) $^{+33}_{-34}$ (syst.) $^{+48}_{-17}$ (extrap.) $\pm$ 5 (lumi.) $\pm$ 3 (BR)
$\Sigma_c^{0,+,++}$	142 ± 22 (stat.) $^{+24}_{-24}$ (syst.) $^{+24}_{-32}$ (extrap.) $\pm$ 2 (lumi.) $\pm$ 6 (BR)

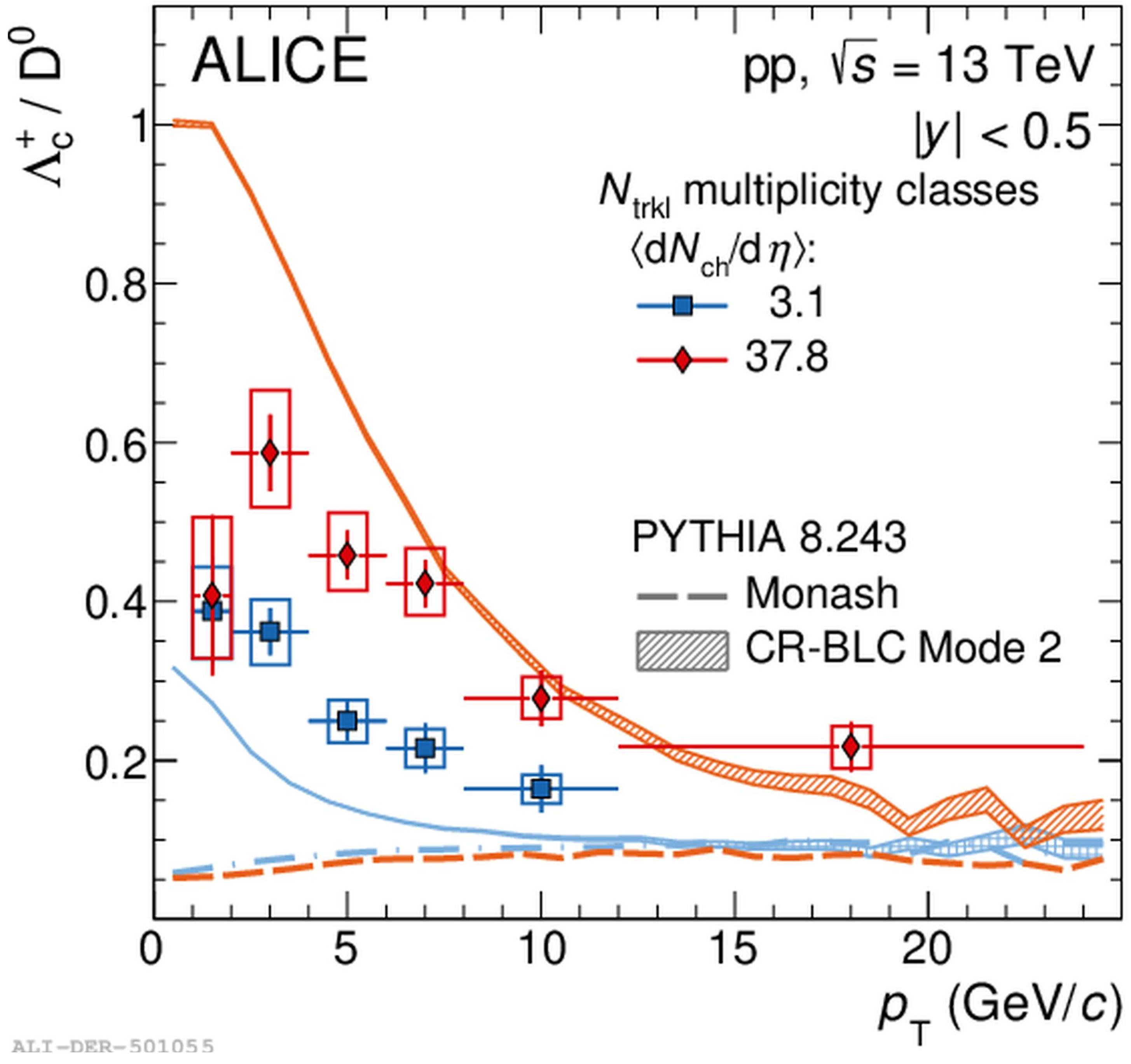
f_x: probability for a charm quark to hadronize with another quark of flavour x
⇨ D_s^+/D^0+D^+

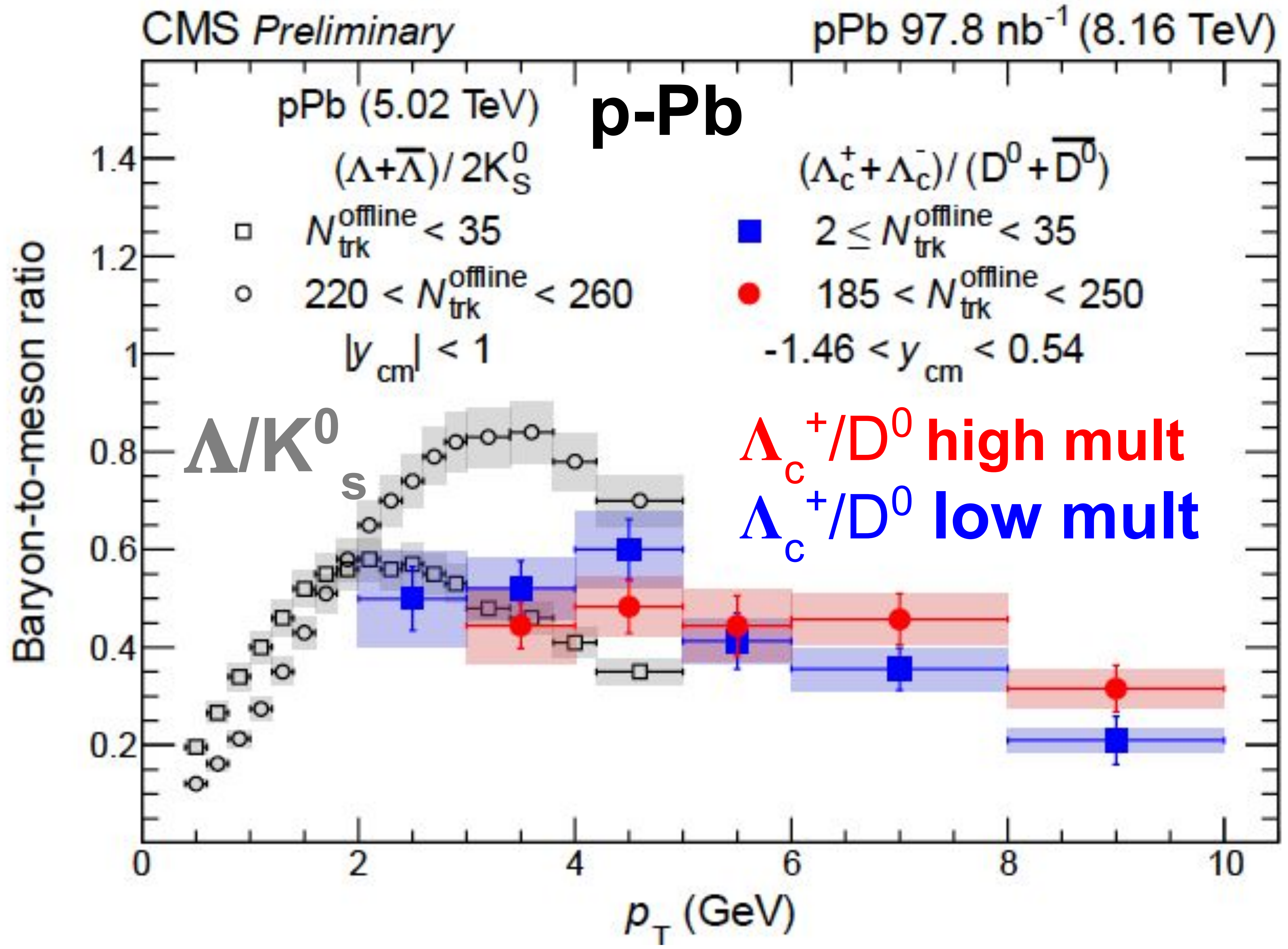
Production of prompt strange D mesons / prompt non-strange D mesons in e^+e^-, ep and pp collisions doesn't show any significant dependence of the collision system & energy!

PRC 104 054905 (2021)



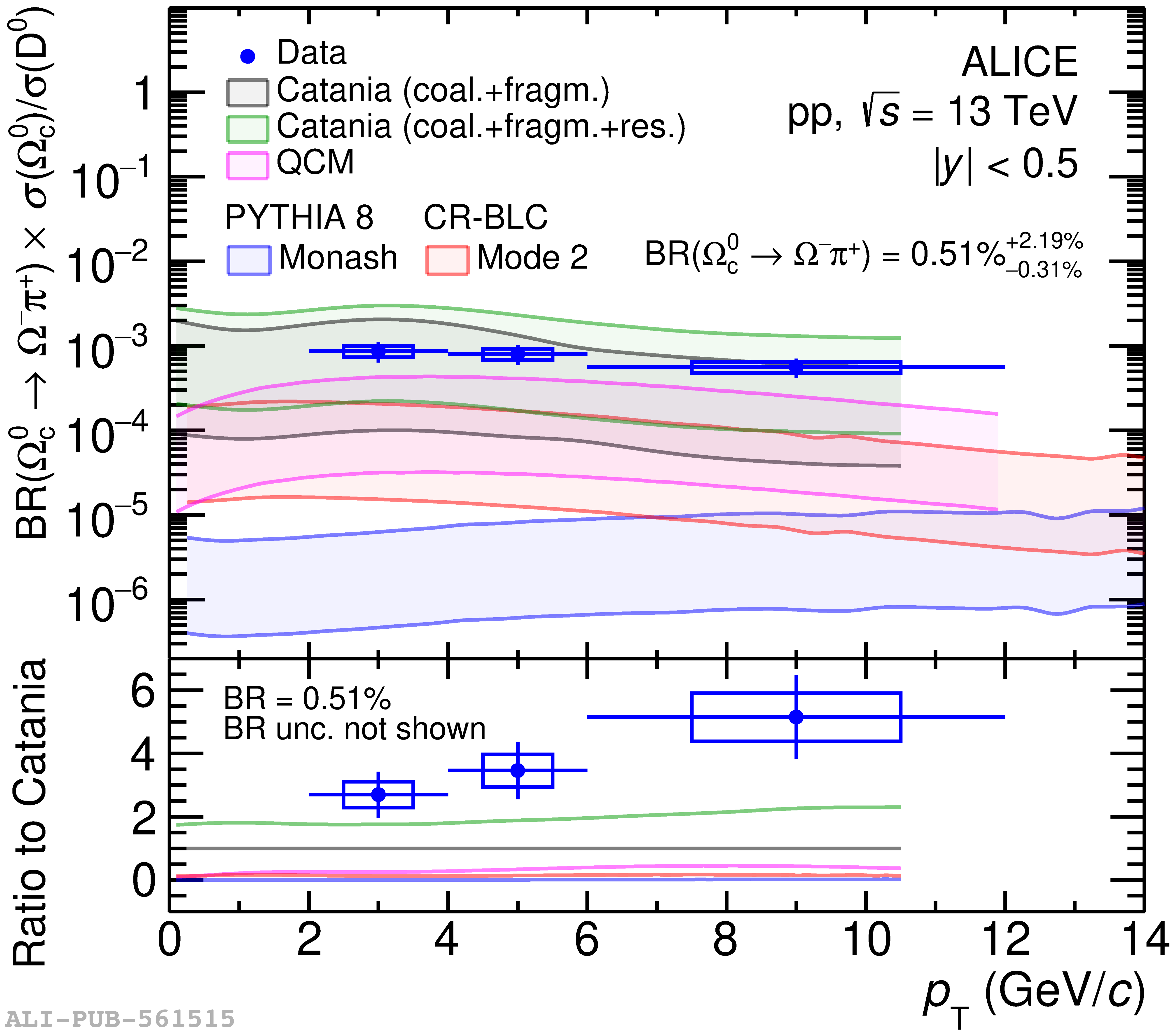
PLB 829 (2022) 137065





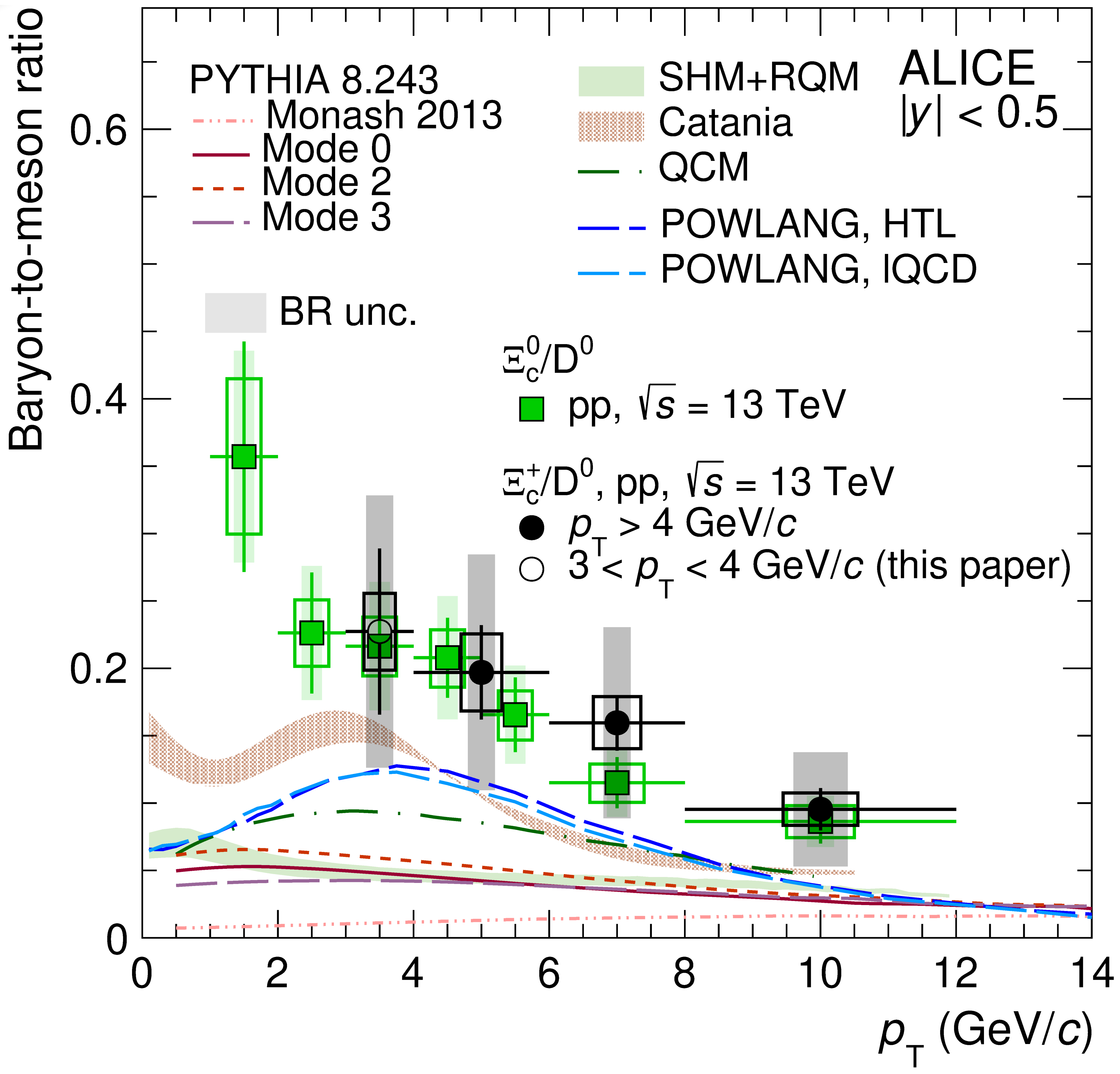
With 2 strangeness

Phys.Lett.B 846 (2023) 137625



ALI-PUB-561515

JHEP 12 (2023) 086



ALI-PUB-567881

Back then 2006,