Experimental overview on the open heavy flavor measurement in relativistic heavy-ion collisions

ATHIC 2025

KoALICE

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ATHIC 2025, 2025. 1.14

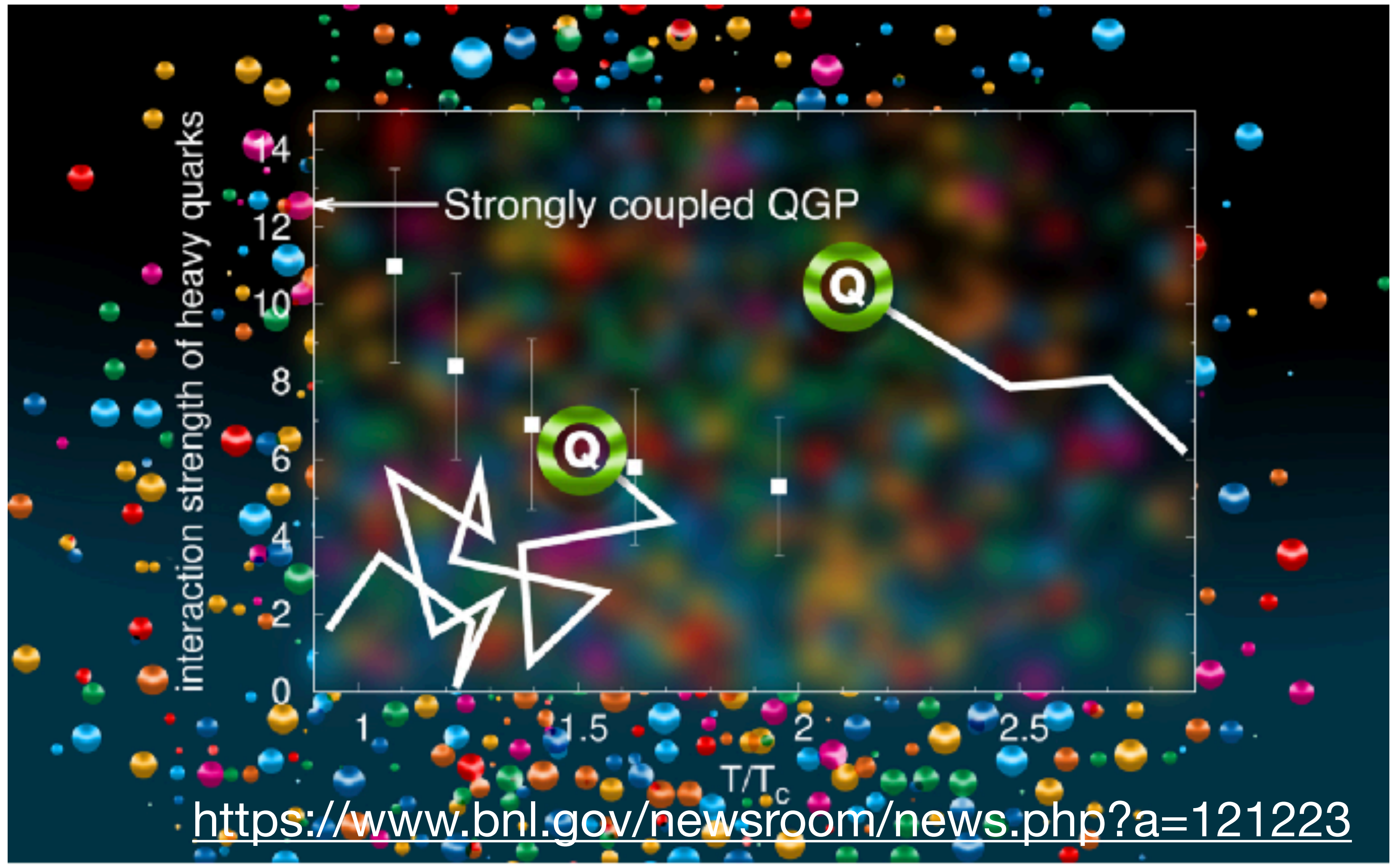
Suitable probes to understand QCD medium, heavy quarks

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

- However, the story is not easy since what we measure is …

  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 measure

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

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

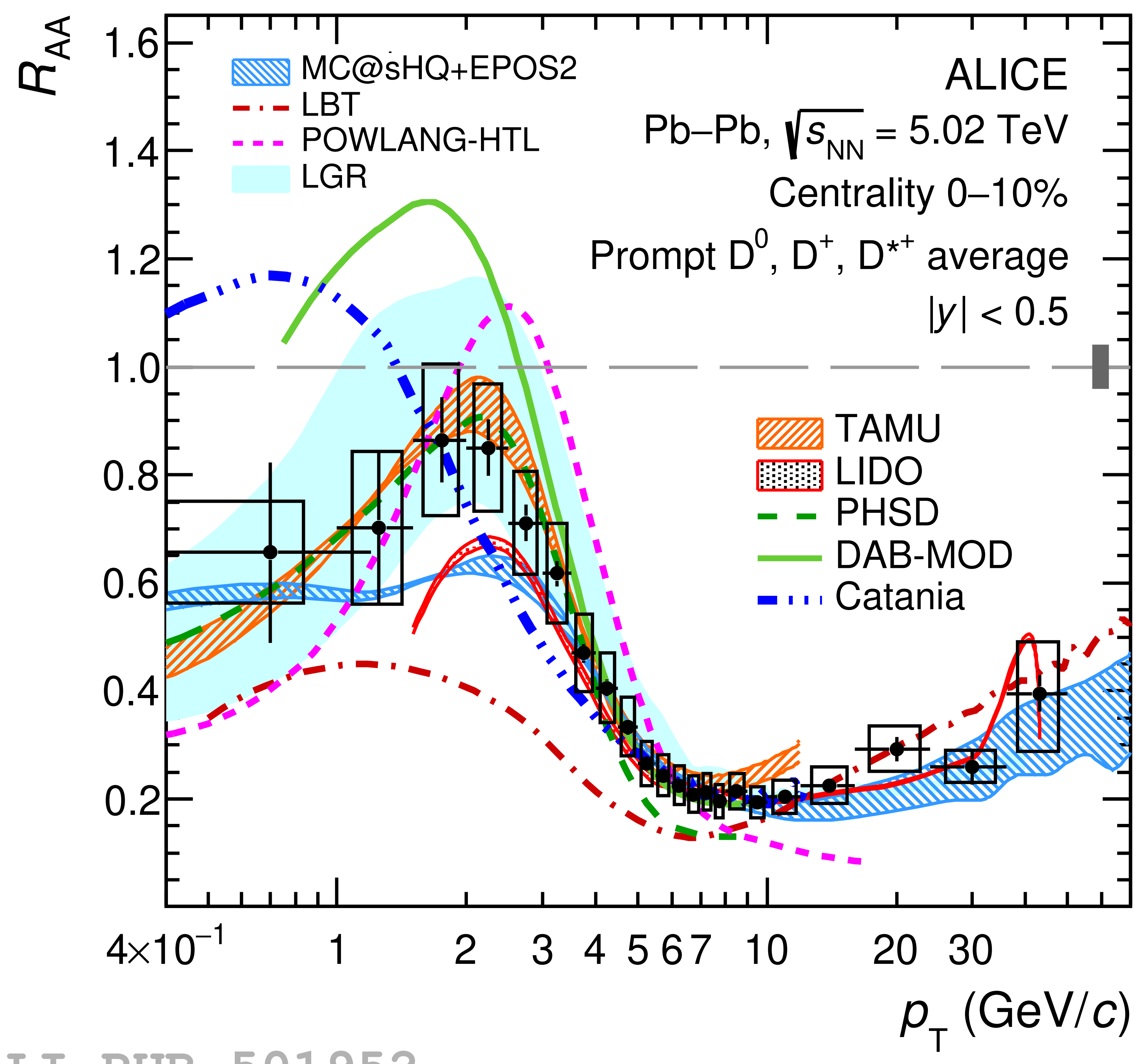
pp collisions

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: where to see, what we see

D meson R_{AA}



ALI-PUB-501952

collective flow, hadronisation, nuclear PDF

collisional E loss

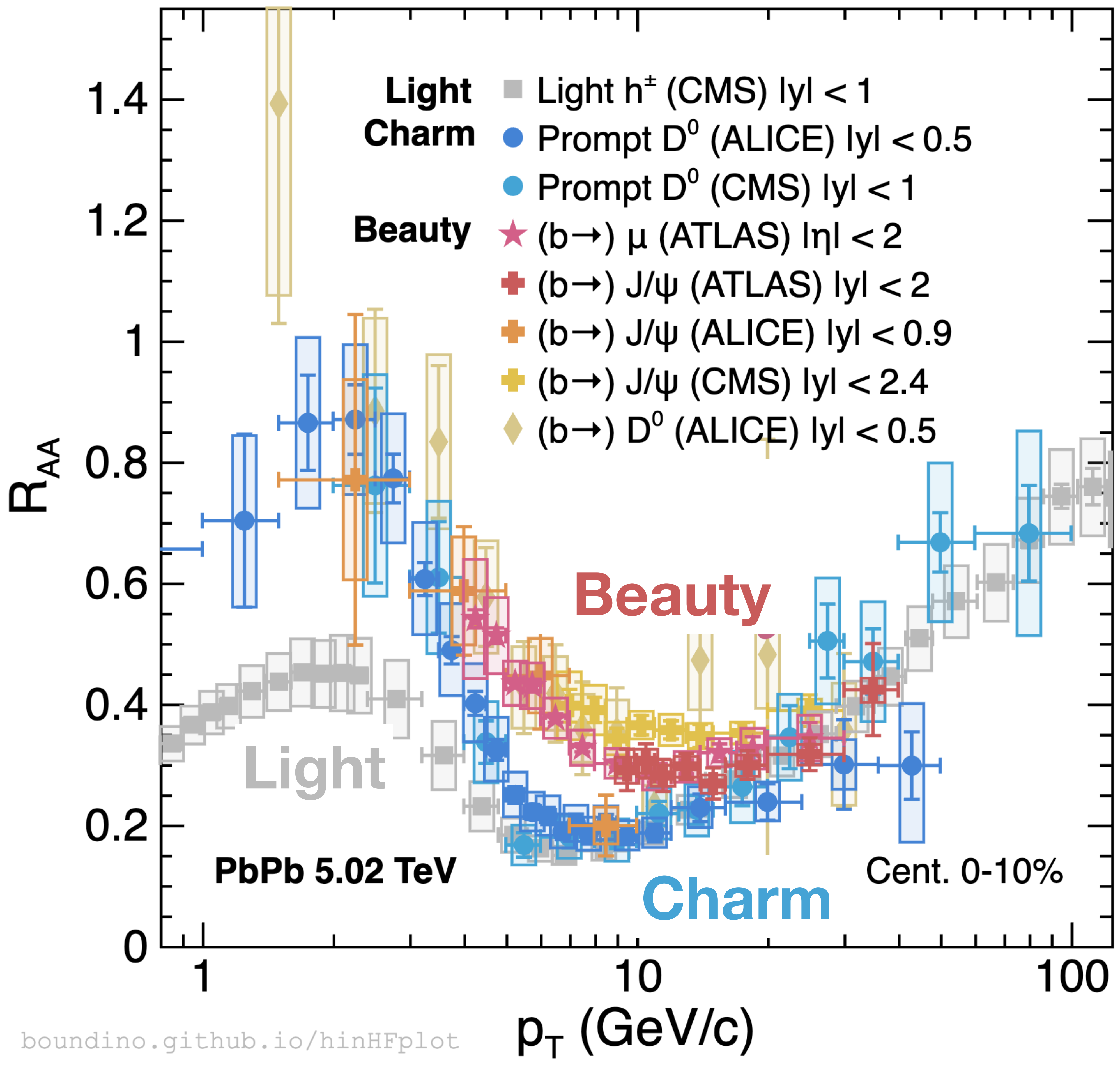
radiative E loss

JHEP 01 (2022) 174

- Very strong coupling between heavy quarks and medium
- Strong suppressions are fairly described by transport models
  - nPDF changes the total yields
  - Suppression at low p_T via collisional energy loss
  - Suppression at high p_T via radiative energy loss (ΔE/E decreases)
  - Push by radial flow (low p_T to high p_T)
  - Hadronization picks light quark kinematics

- However, describing full p_T is still challenging…

Mass and color charge dependence of energy loss: via R_{AA}



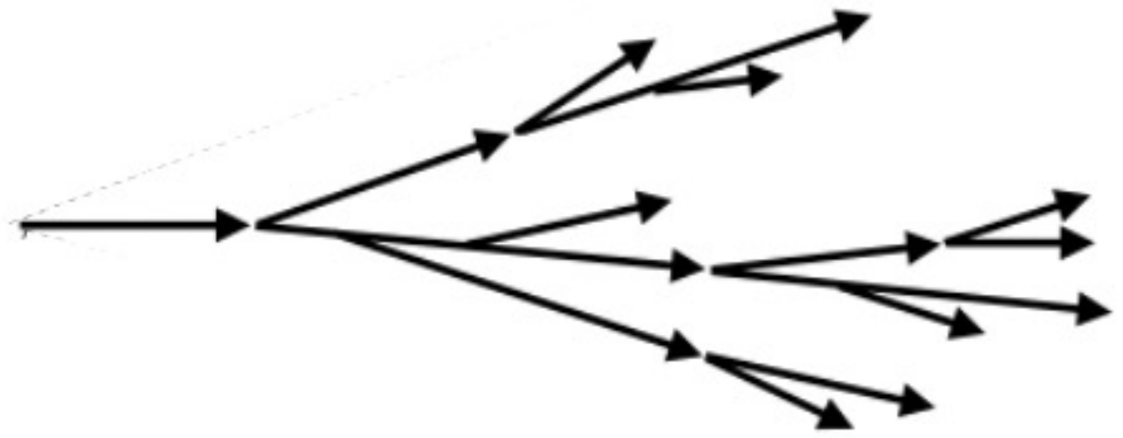
ATLAS PLB 829 (2022) 137077, ATLAS EPJC 78 (2018) 762
ALICE HEP 02 (2024) 066, ALICE JHEP 12 (2022) 126
CMS EPJC 78 (2018) 509

- Mass and color charge dependent suppression

In terms of energy loss

$$\text{Gluons} > \text{Light Quarks (u, d, s)} > \text{Charm Quarks (c)} > \text{Beauty Quarks (b)}$$

Gluon-initiated shower



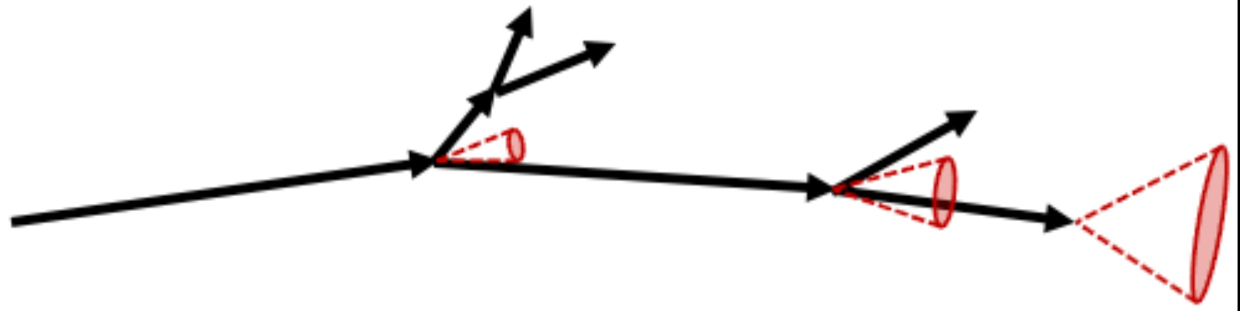
Broader shower profile
Higher number of emissions

relevant to light quark suppression

Quark-initiated shower

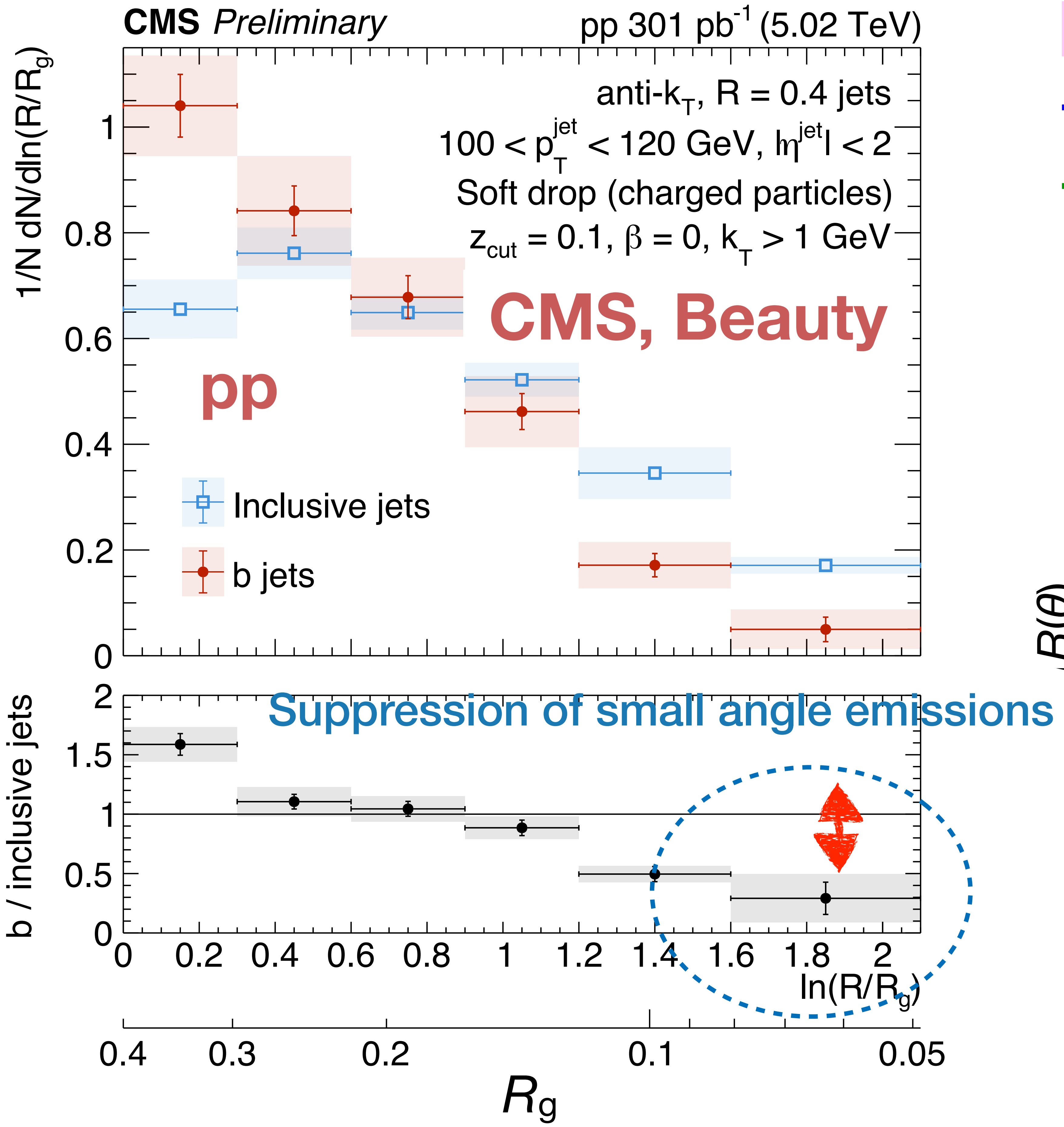
Narrower shower profile
Fewer emissions in the shower

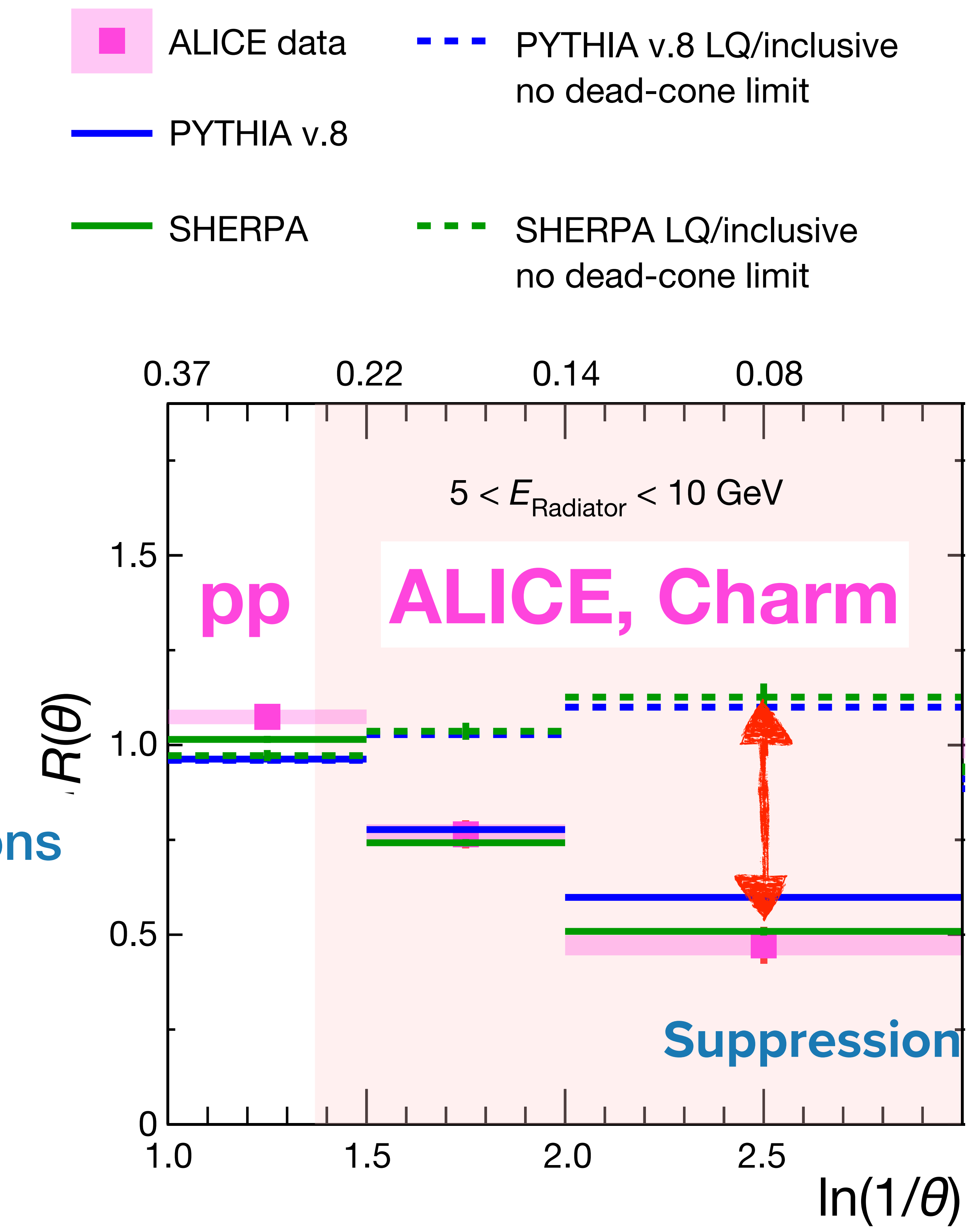
Heavy-quark-initiated shower



Suppression of small angle emissions
Harder fragmentation

Mass dependence of energy loss: via dead cone

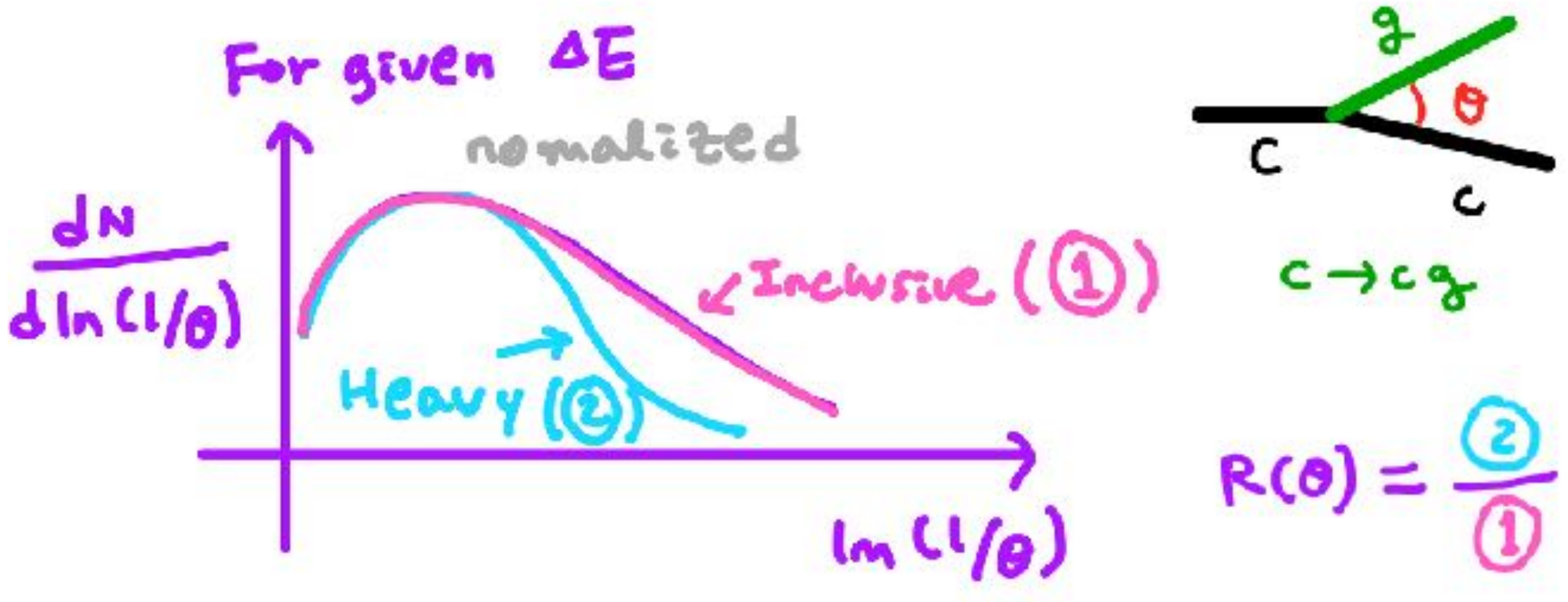




Suppression of c→cg splittings at small angles

The ratio of the splitting angle (θ) distributions

for D⁰-meson tagged jets & inclusive jets

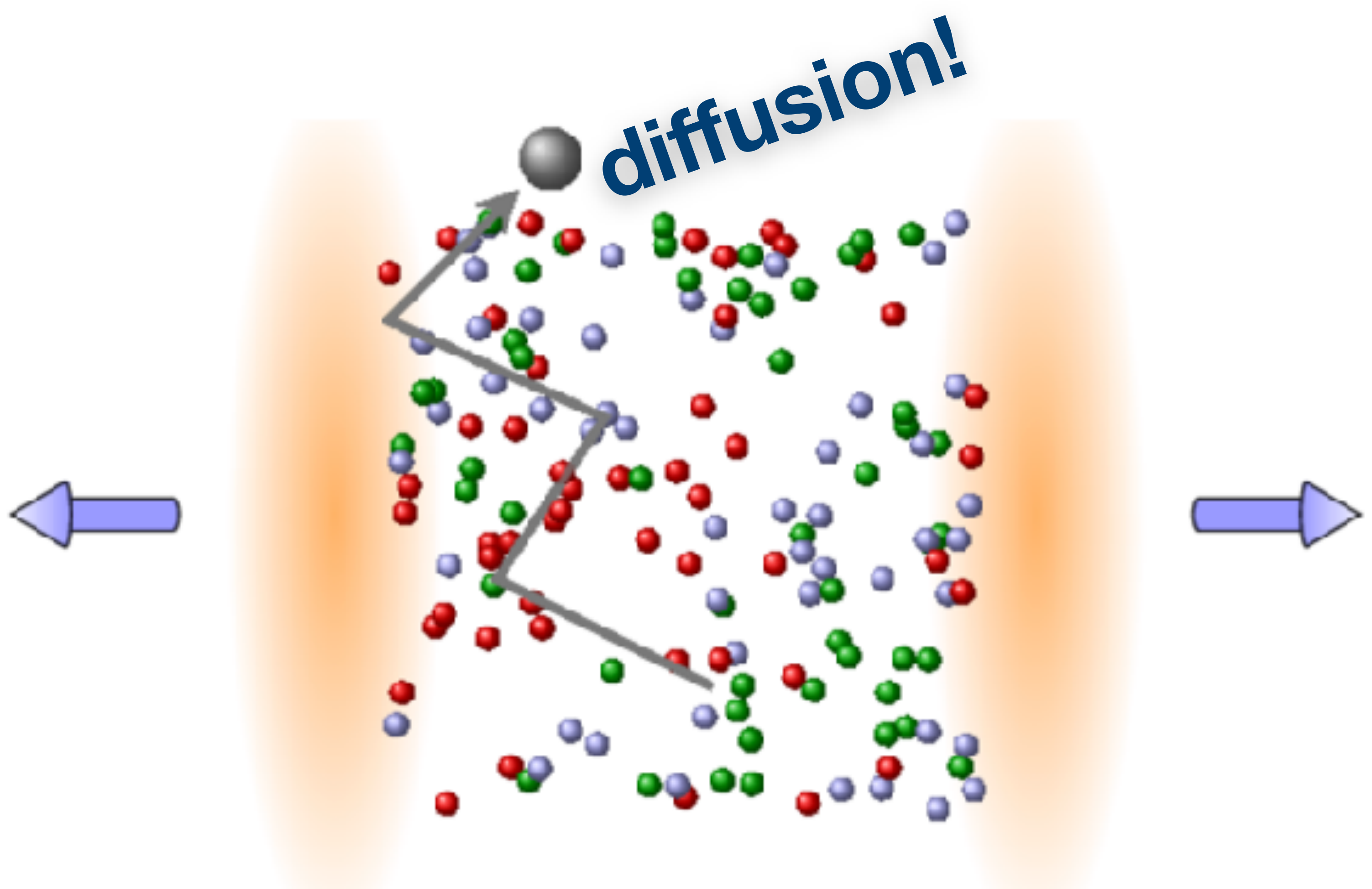


- Direct observation of dead cone in pp collisions
- The medium-induced radiation in a QGP can alter the same observables
  → to be understood to separate the contributions of parton mass effects and QGP-induced modifications.

ALICE Nature 605 (2022) 440, CMS CMS-PAS-HIN-24-007

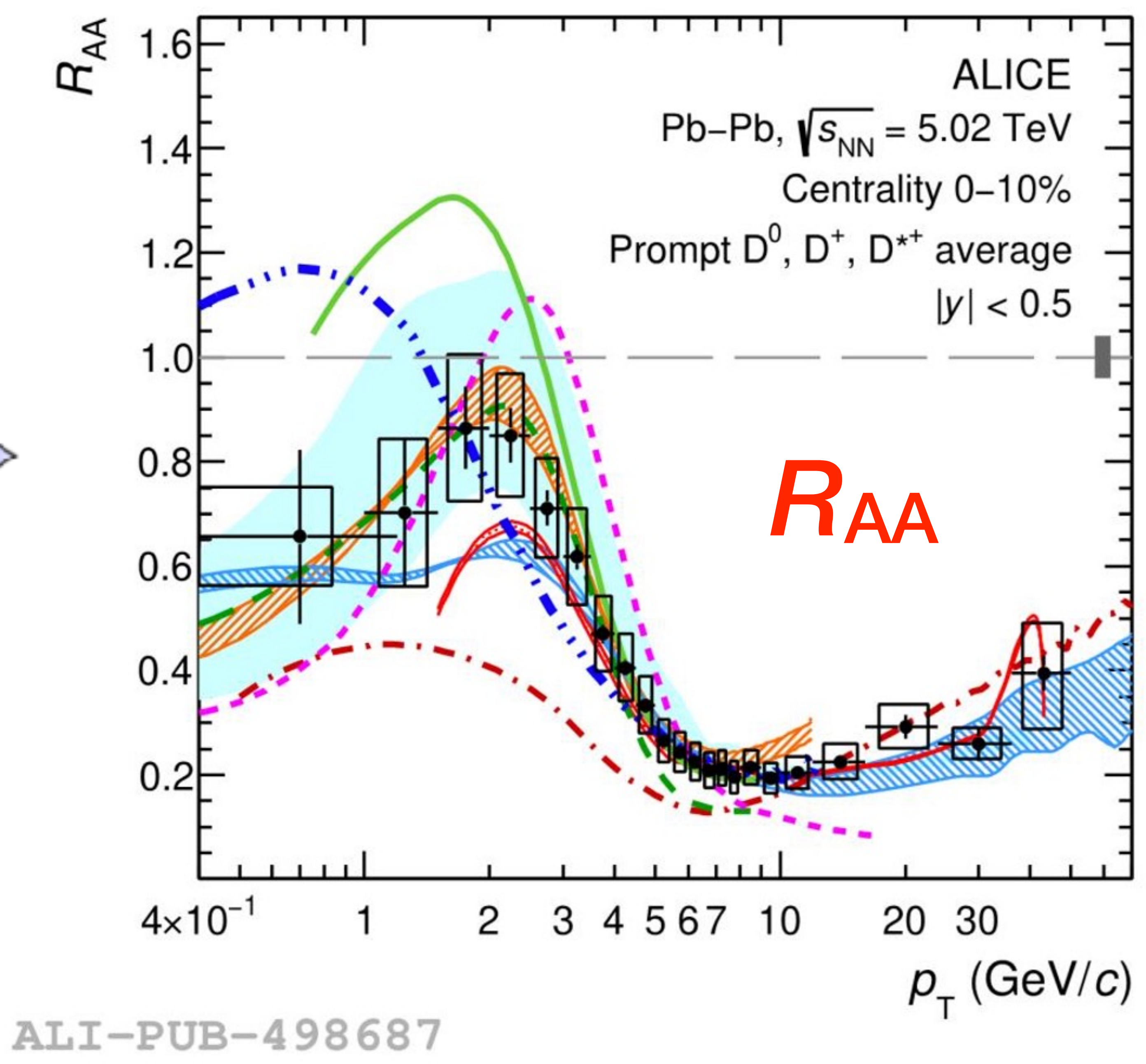
Charm quark transport in the medium

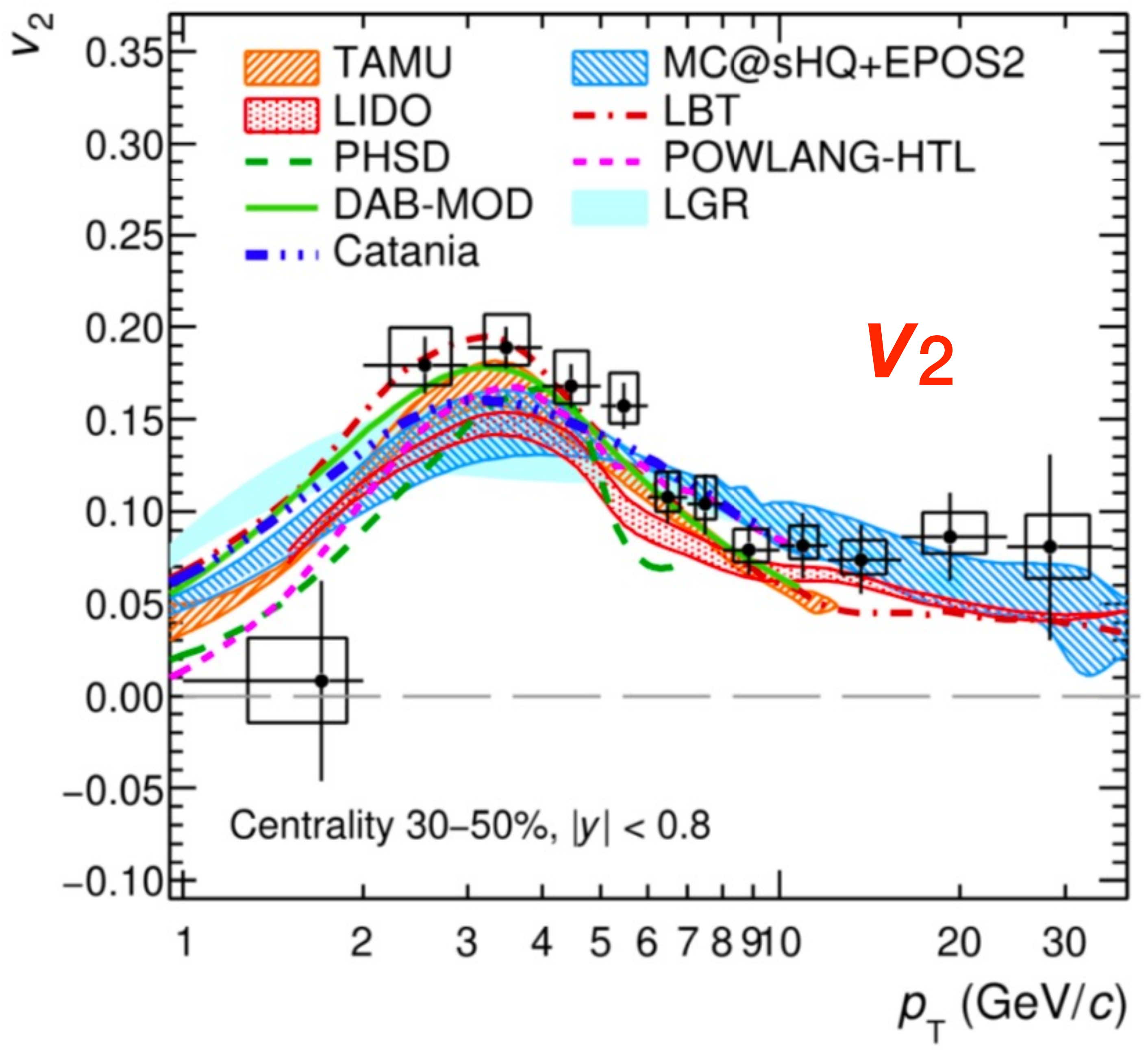
- Low-p_{T} region provides insight into the heavy-quark interactions with the medium (by diffusion, analogous to a ‘Brownian motion’)
- Charm quark interacts with the medium via collisional and radiative processes in heavy-ion collisions → comparison of R_{AA} and v_2 with transport models → constraint on the diffusion coefficient



$$\tau_Q = (m_Q/T)D_s$$

ALICE JHEP 01 (2022) 174



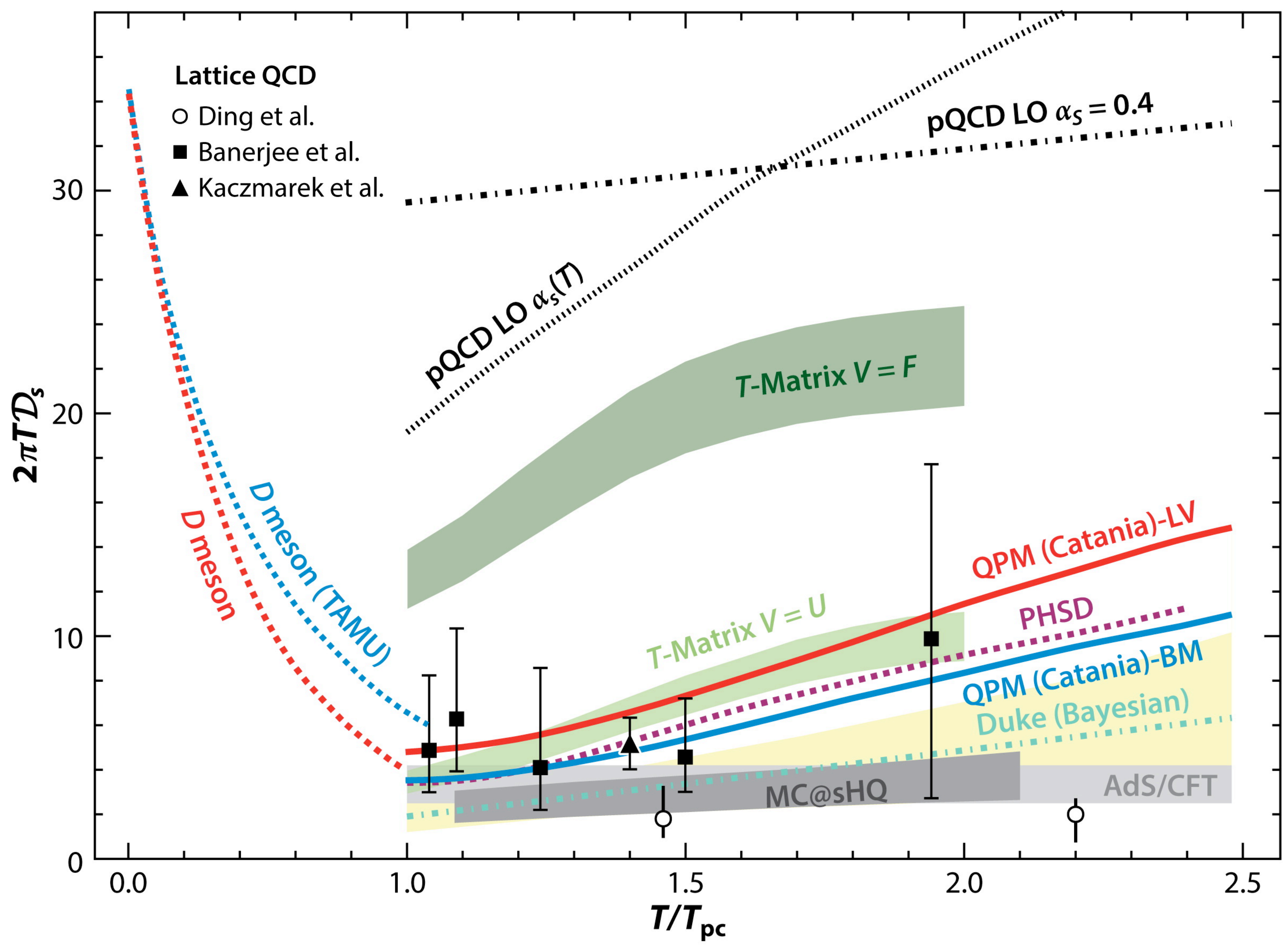


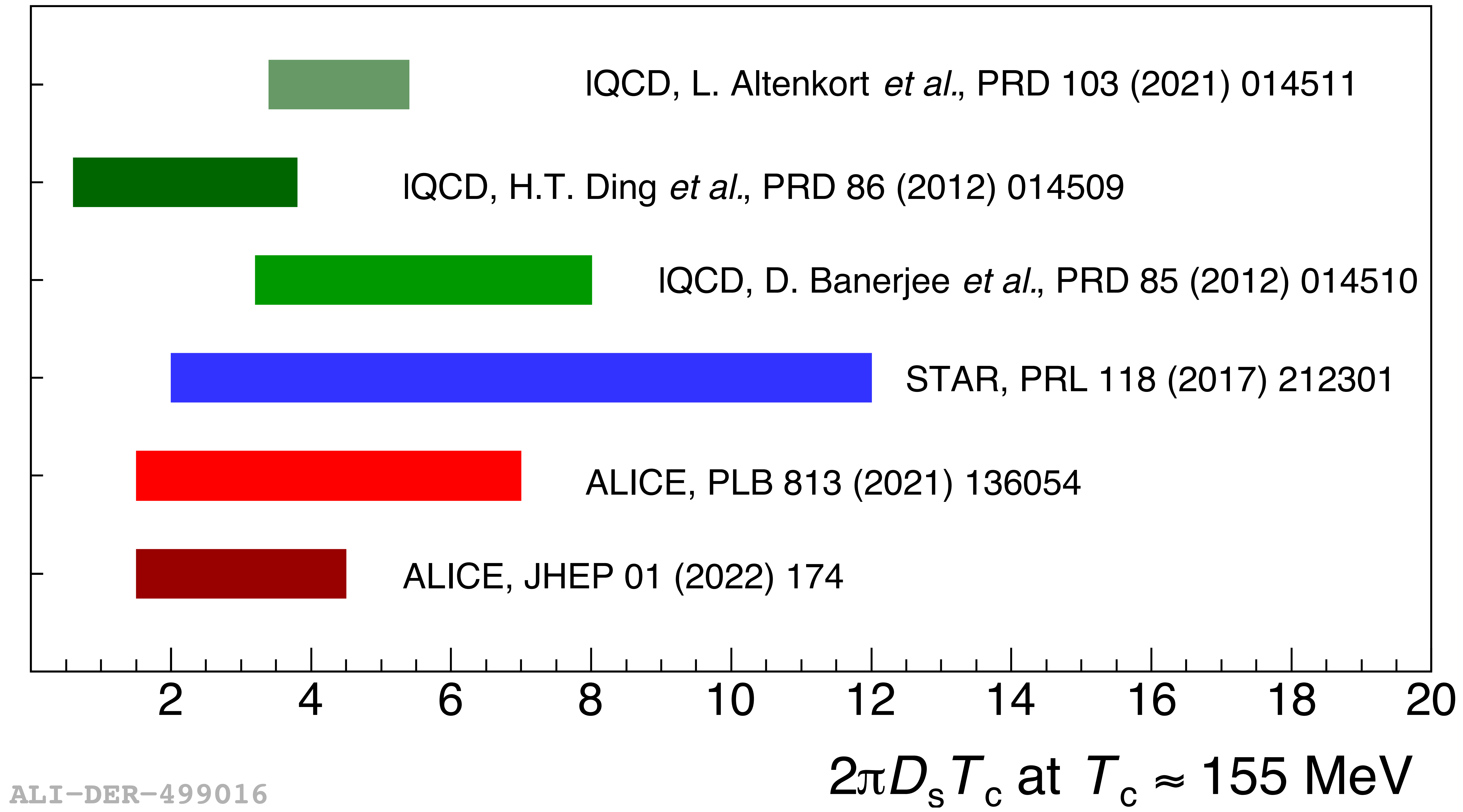
At low-p_{T}, also shadowing & bulk evolution of the medium

- Charm quarks are thermalised with medium (having different thermalization timescales due to their masses) → collective motion (slower thermalization leading to smaller v_2)

Quantitative information via spacial diffusion coefficient

X. Dong et al., Ann.Rev.Nucl.Part.Sci. 69 (2019) 417





Relaxation time

$\tau_Q = (m_Q/T)D_s$ 1.5 < $2\pi D_s T_c$ < 4.5 → direct access to heavy-flavour relaxation time: τ_{charm} ~ 3-8 fm/c

Note: hadronization is hard to control in the model...

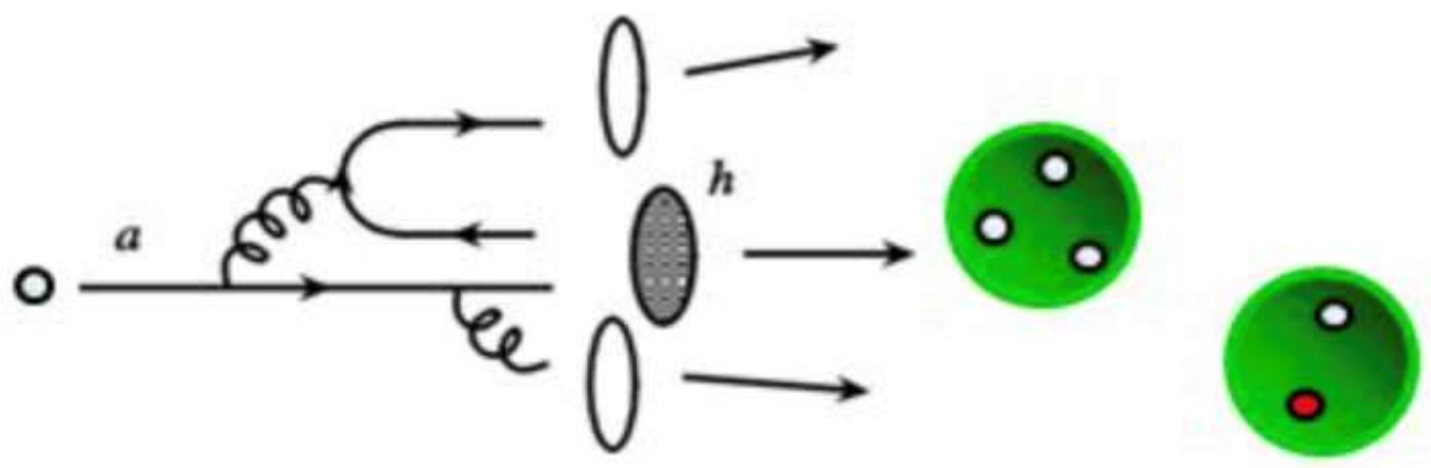
Heavy flavour production in medium: hadronization

Going back to the original assumption…

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

Initial-state effects | "Vacuum" parton spectra | Parton interaction with the medium | (Modified) hadronization

- Fragmentation functions *D*(*z*) are phenomenological functions to parameterize the non-perturbative parton-to-hadron transition
  → *z* = fraction of the parton momentum taken by the hadron h
  → Do not specify the hadronisation mechanism
- Parametrized on data and assumed to be "universal"
- In A-A collisions:
  → Energy-loss of hard-scattered partons while traversing the QGP
  → Modified fragmentation function *D*(*z*) by "rescaling" the variable *z*



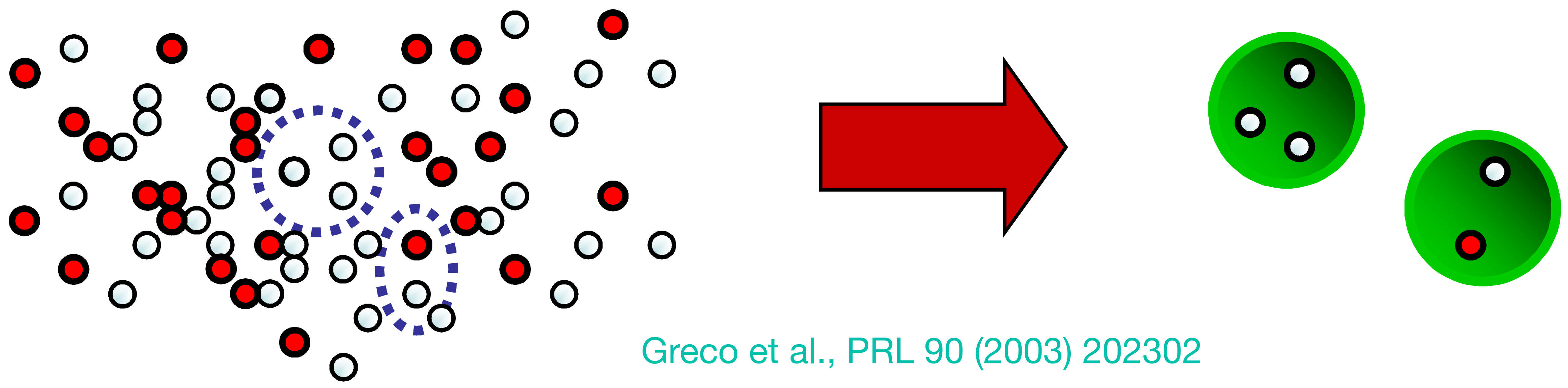
extracted from experiments such as e^+e^- collisions, ex. Peterson

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

$$\epsilon = m_q^2/m_Q^2$$

Hadronization in medium; expectation

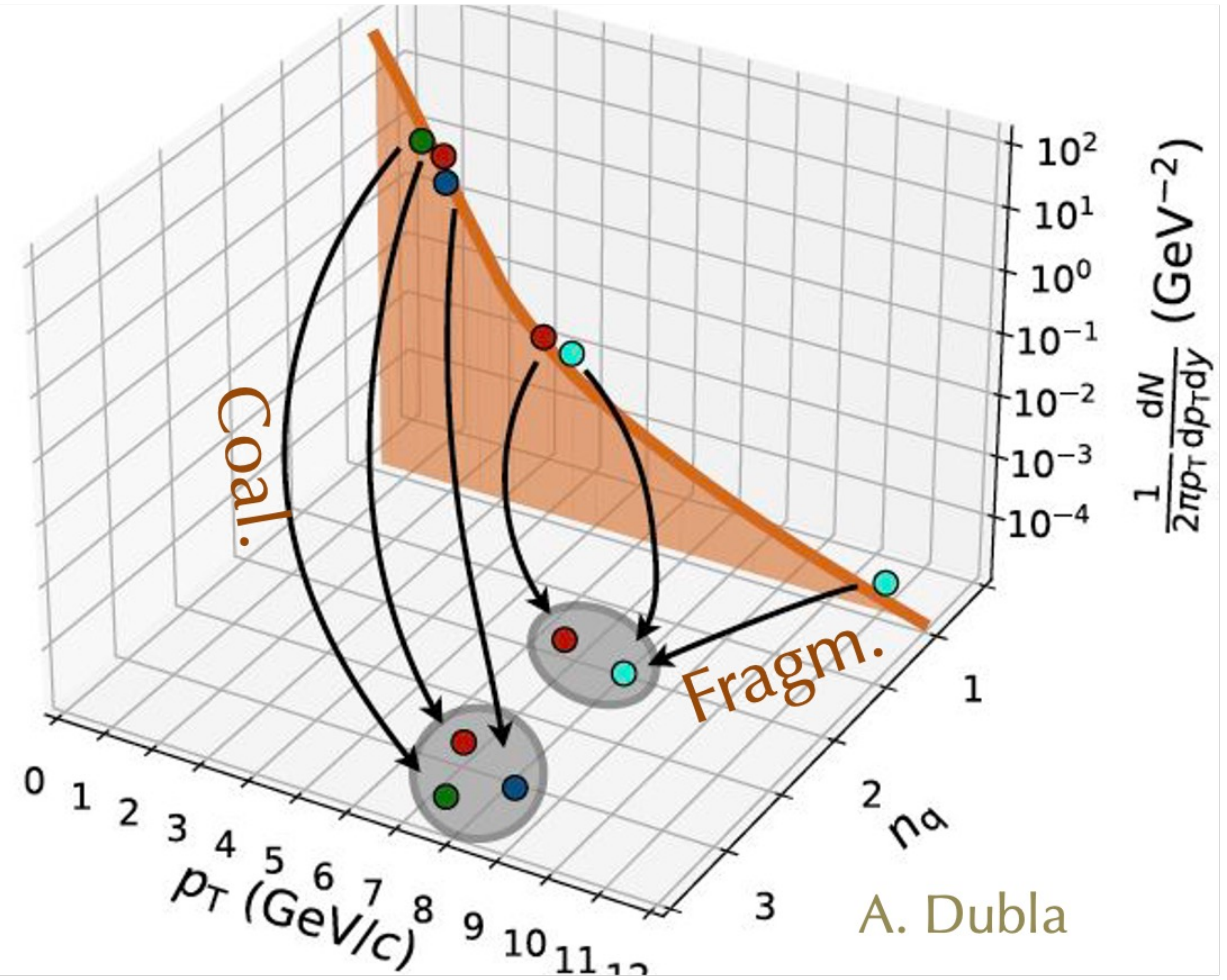
- Phase space at the hadronization is filled with partons
  - → Single parton description may not be valid anymore
  - → No need to create $q\bar{q}$ pairs via splitting / string breaking
  - → Partons that are “close” to each other in phase space (position and momentum) can simply recombine into hadrons



Greco et al., PRL 90 (2003) 202302

Fries et al., PRL 90 (2003) 202303

Hwa, Yang, PRC 67 (2003) 034902



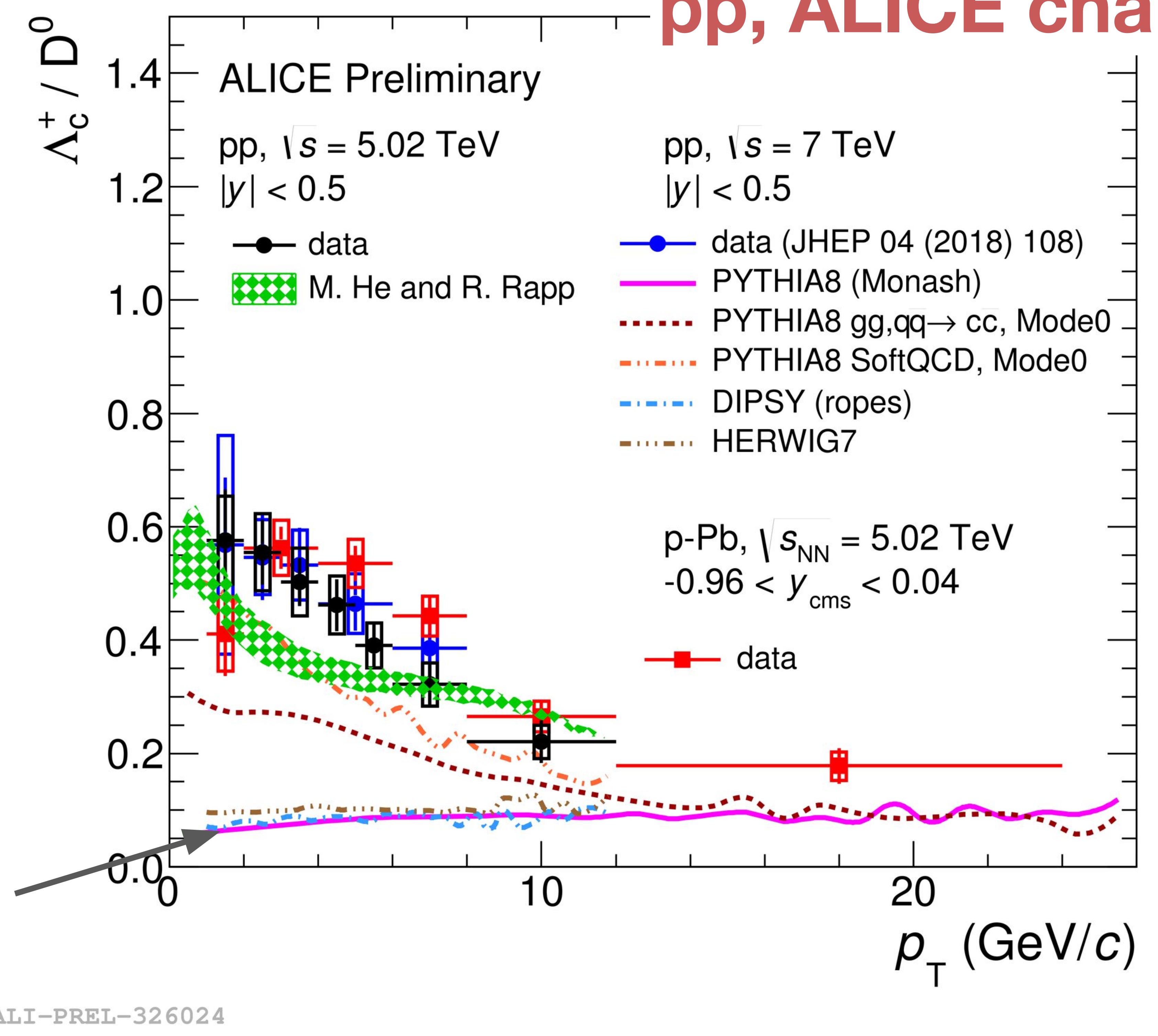
- Recombination vs. fragmentation:
  - → Competing mechanisms
  - → Recombination naturally enhances baryon/meson ratios at intermediate p_T

Hadronization in vacuum; observation

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

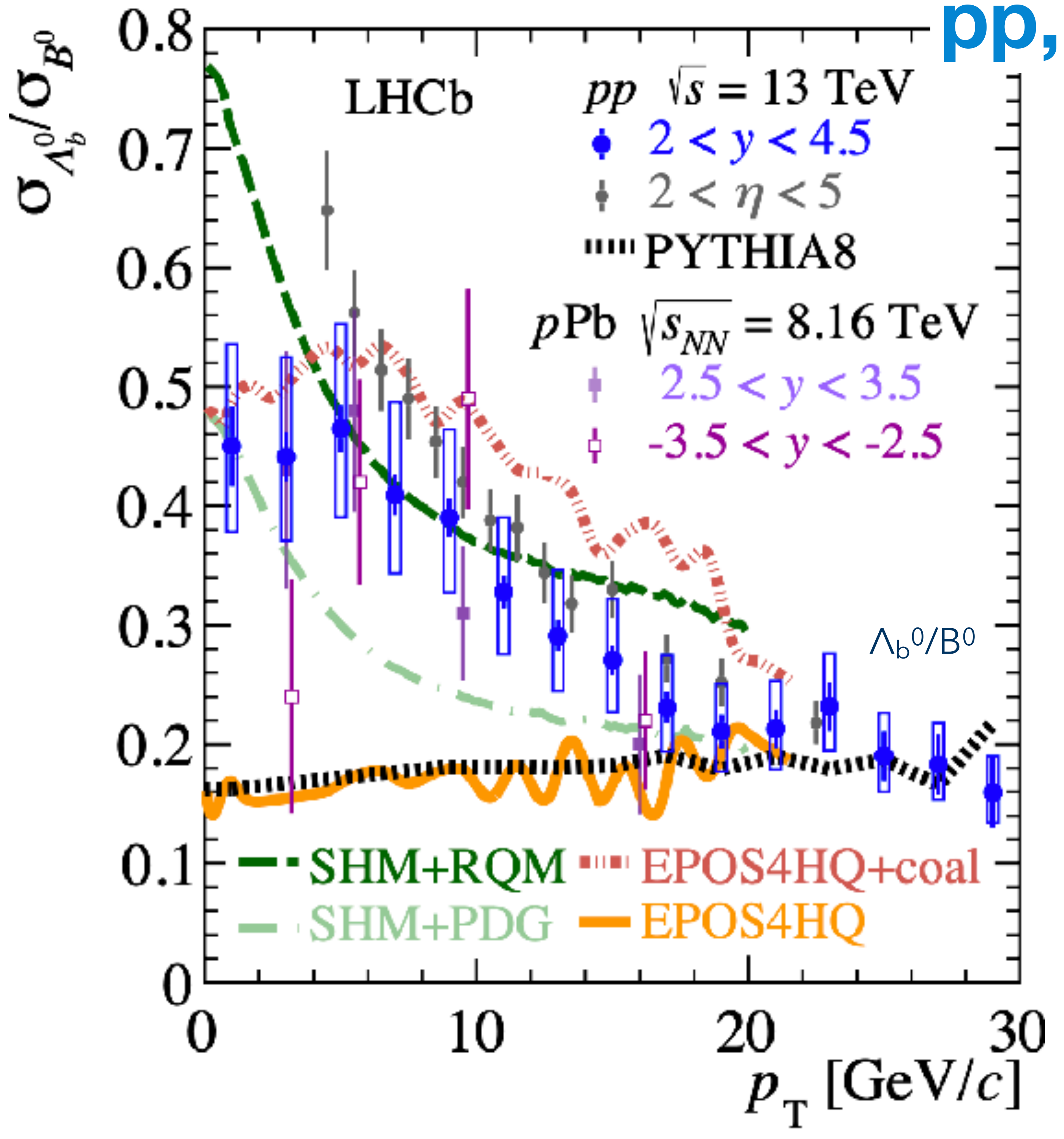
Surprises: Λ_c/D^0 ~0.5 (at intermediate p_T) not only in AA but even in pp → strong enhancement wrt e^+e^-

pp, ALICE charm



e^+e^-

pp, LHCb beauty



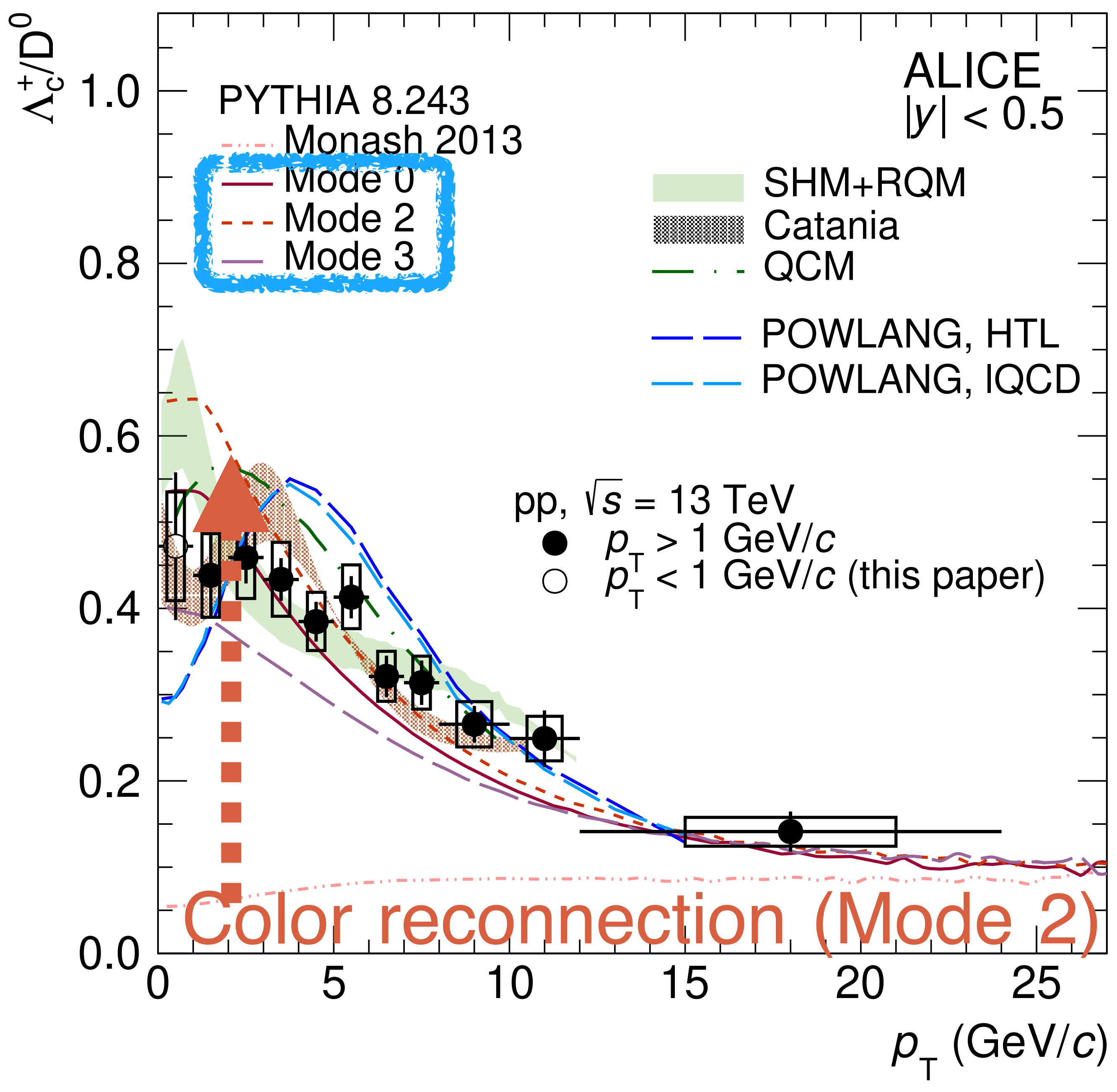
PRL 132, 081901 (2024)

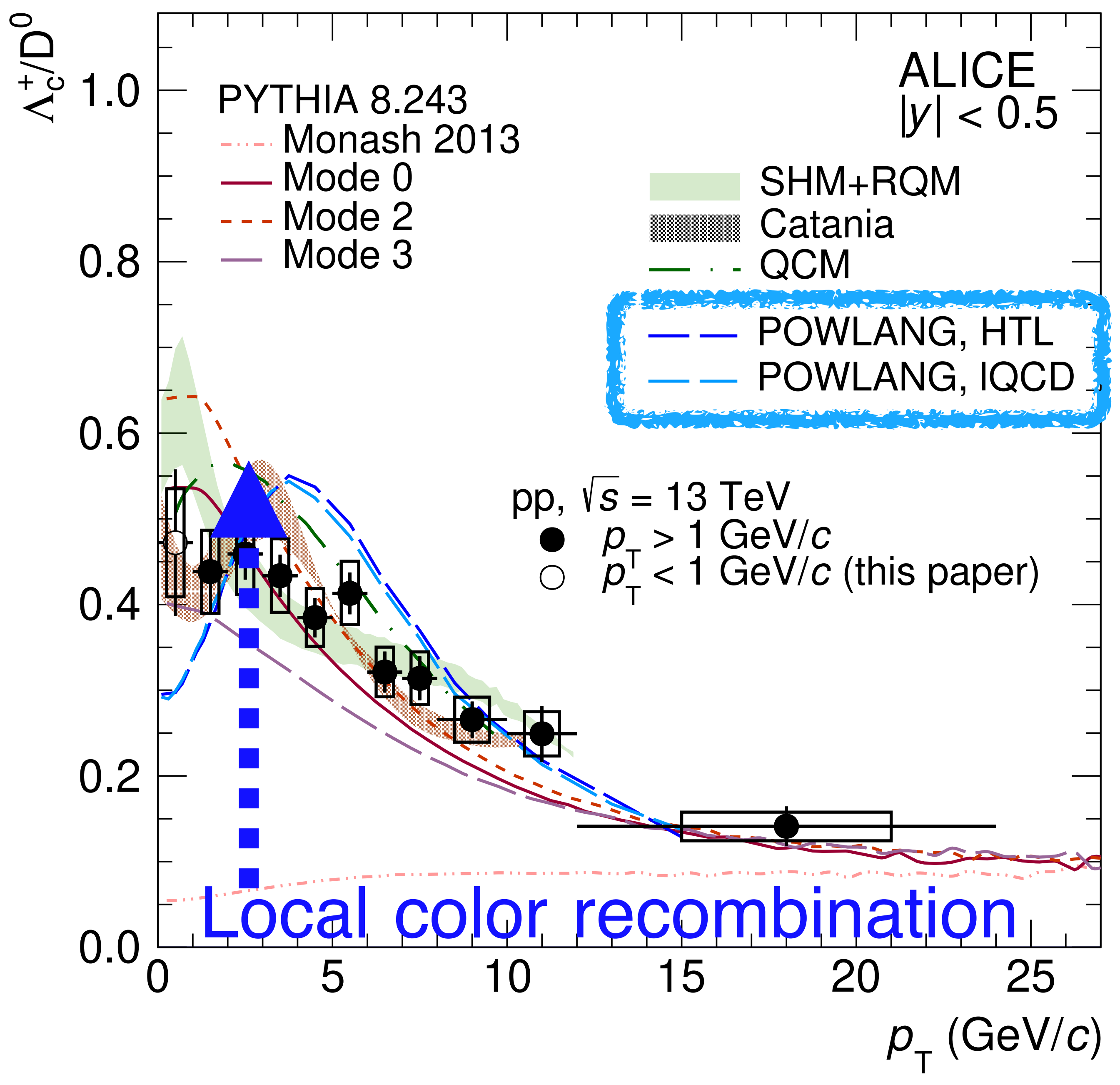
Λ_b/B^0 → Similar trend in charm and beauty sectors!

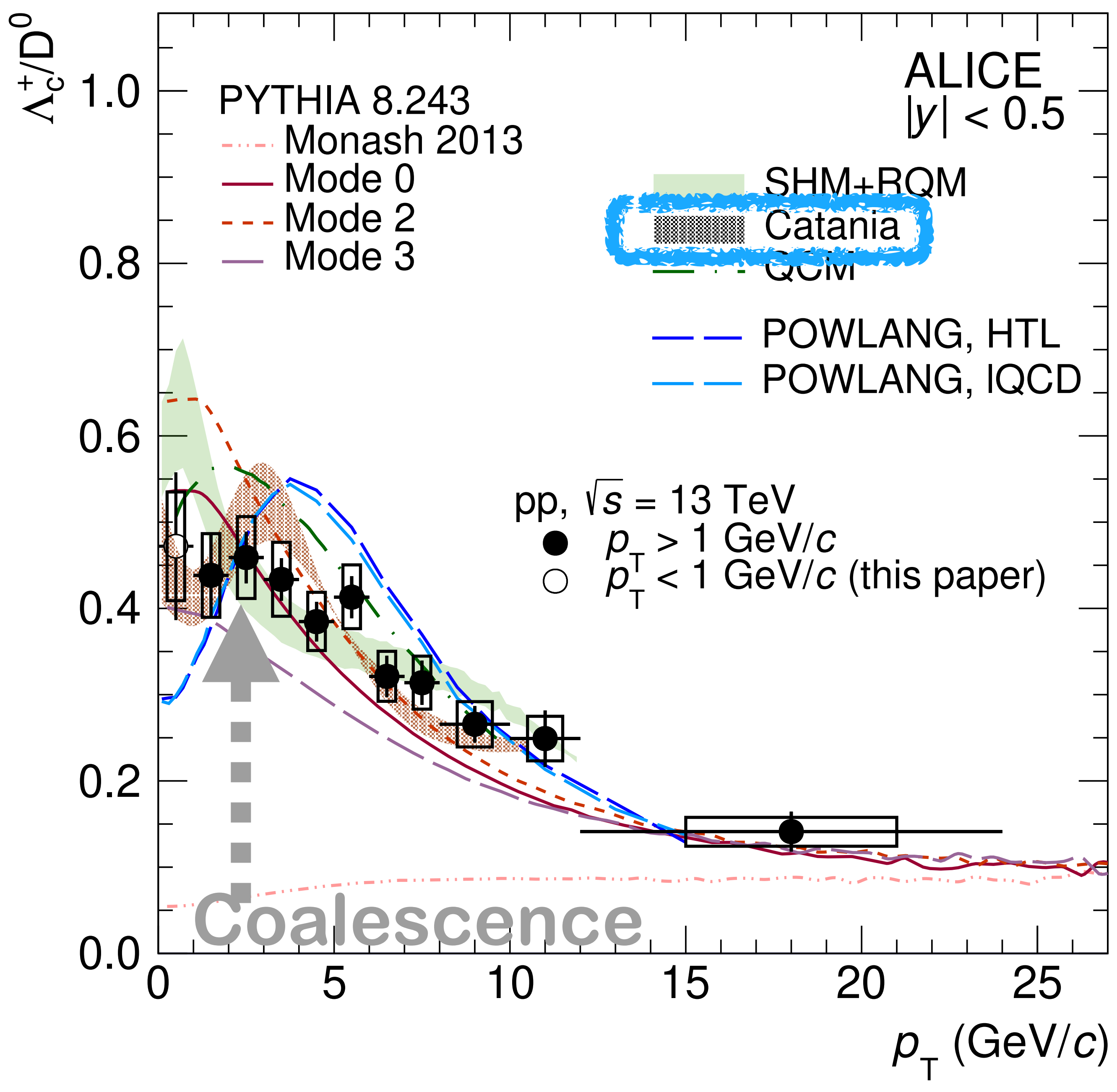
OK, how do we explain? Heavy flavour baryon enhancement impact…

- Heavy-flavour hadronization stimulated the model developments
  - PYTHIA with Color Reconnection (CR) beyond Leading Color (LC) in pp
  - 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

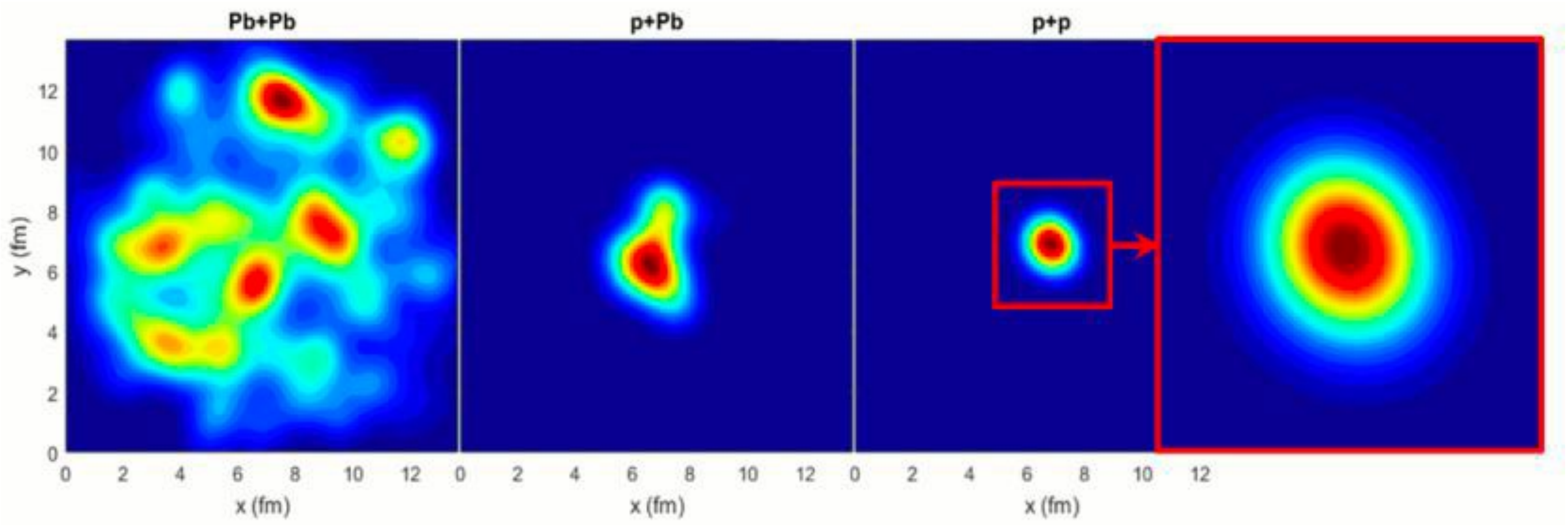






- Different hadronization mechanisms proposed!

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 fm^3

+ $\boldsymbol{f}_c(p)$ from **FONNL distribution**

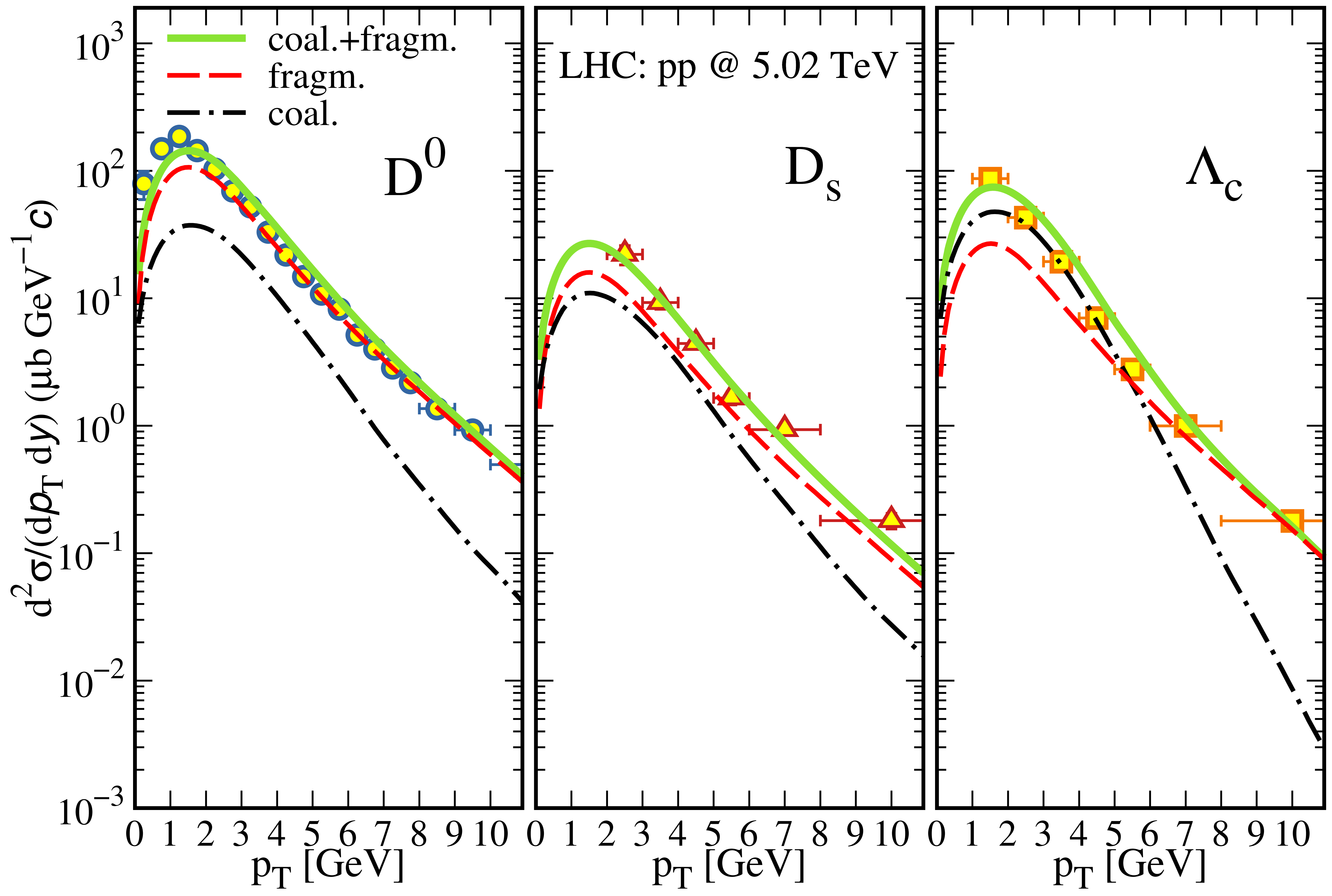
$$f_q(p) \sim \frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T \mp \mu_q)}{T}\right)$$

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

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

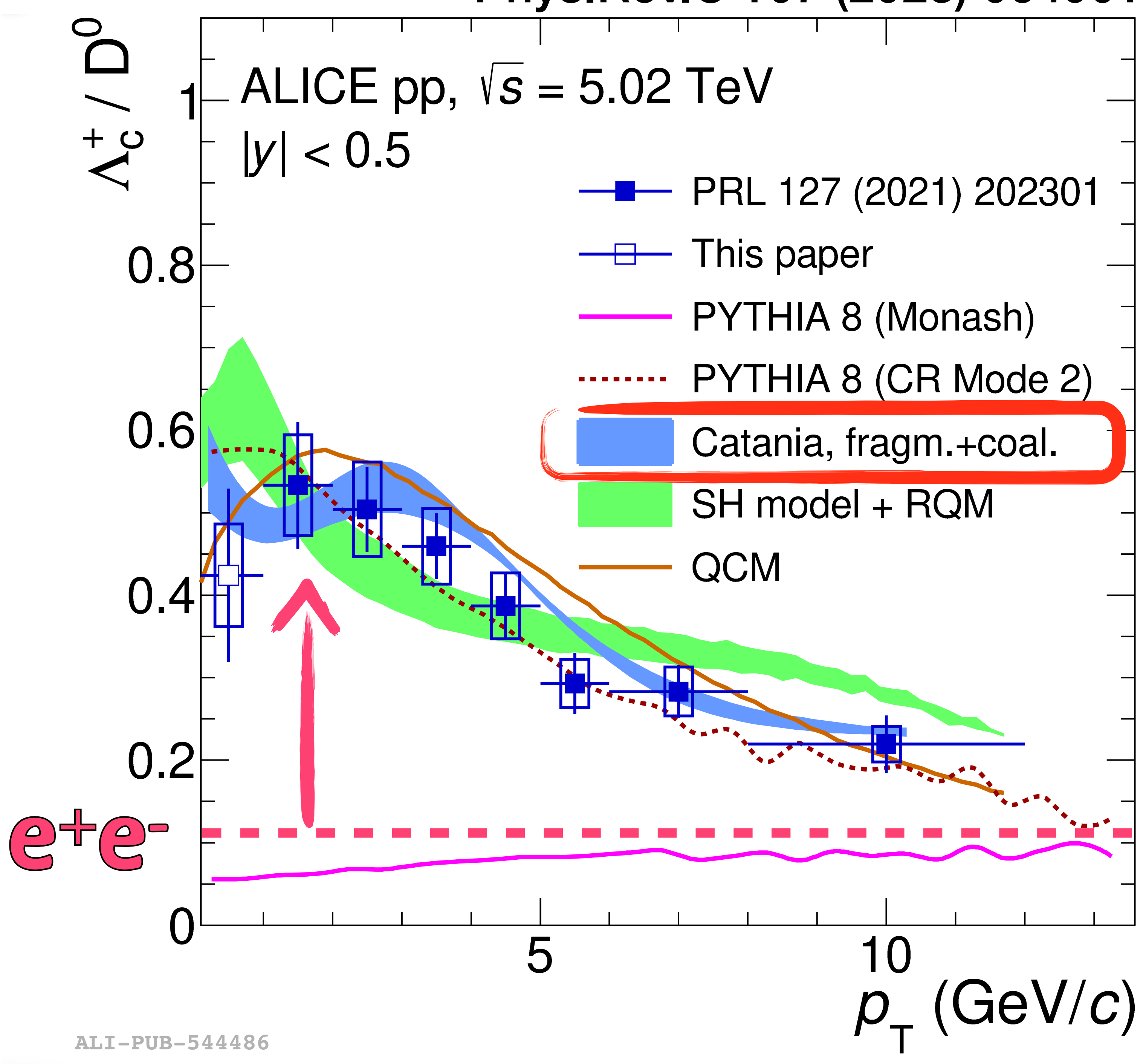
Coalescence in pp vs p_T in Catania

Phys. Lett. B 821 (2021) 136622



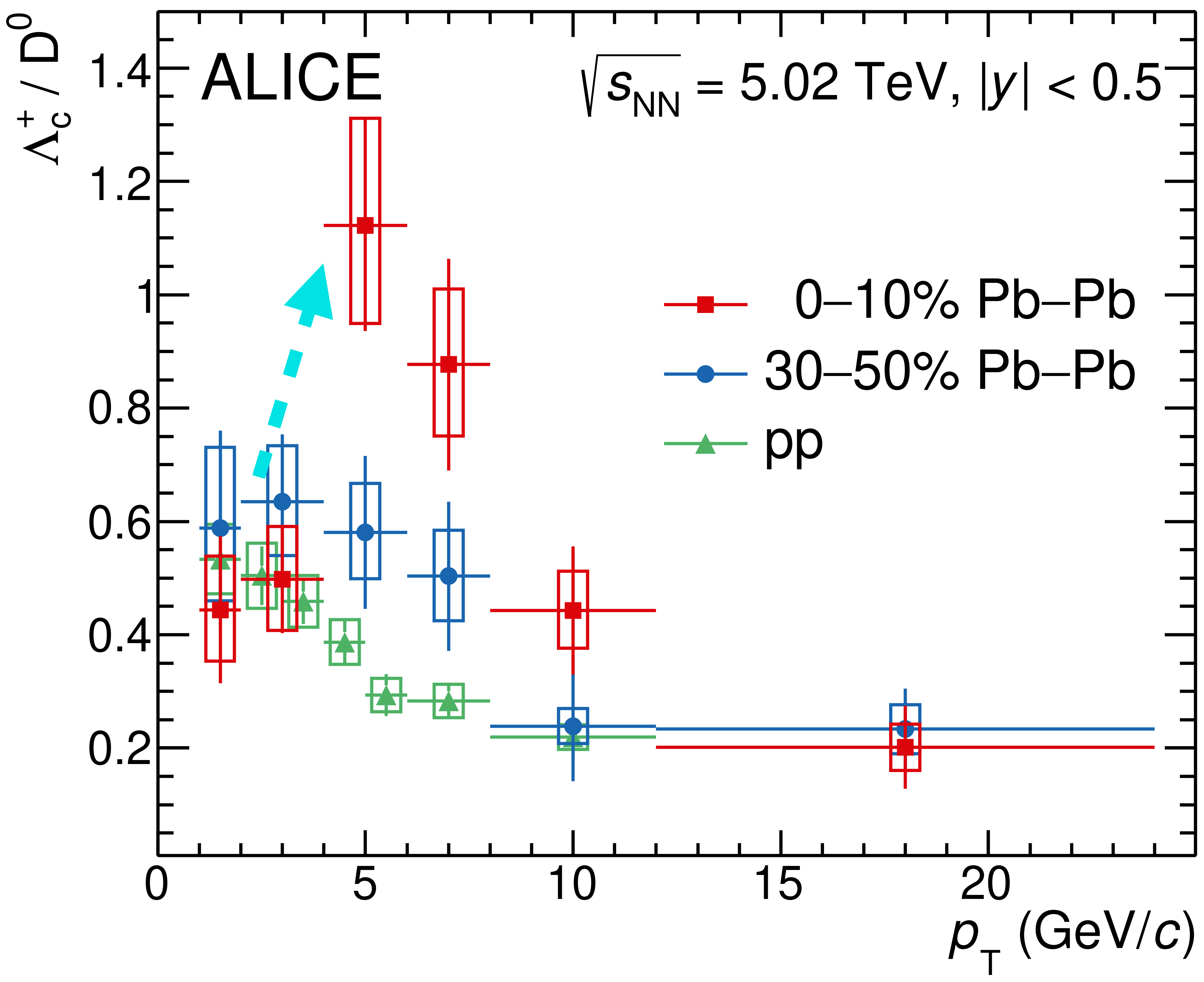
- All the coalescence does not affect significantly D^0, but is dominant for baryons Λ_c and Ξ_c

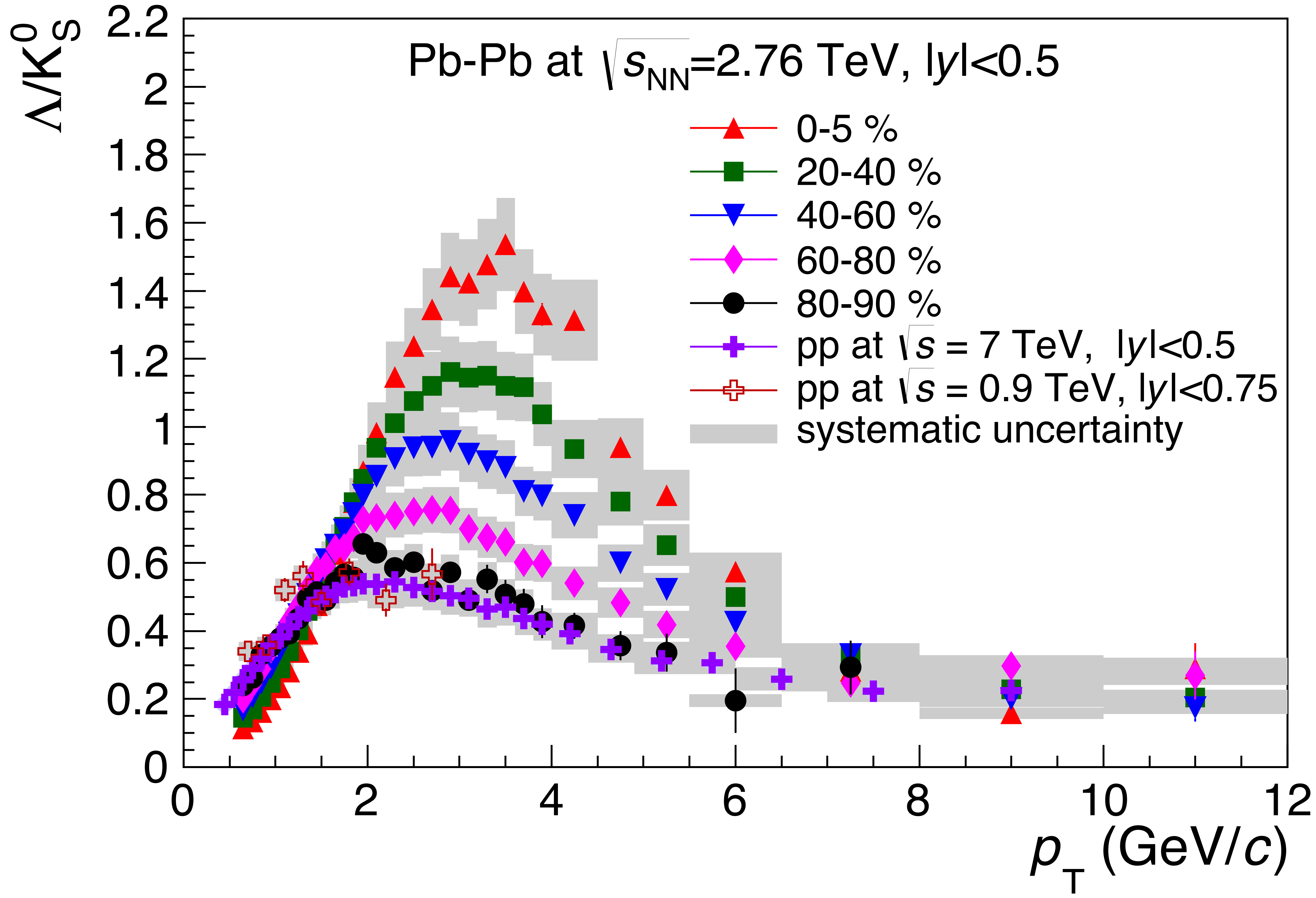
Phys.Rev.C 107 (2023) 064901



How about in Pb–Pb?

Phys. Lett. B 839 (2023) 137796

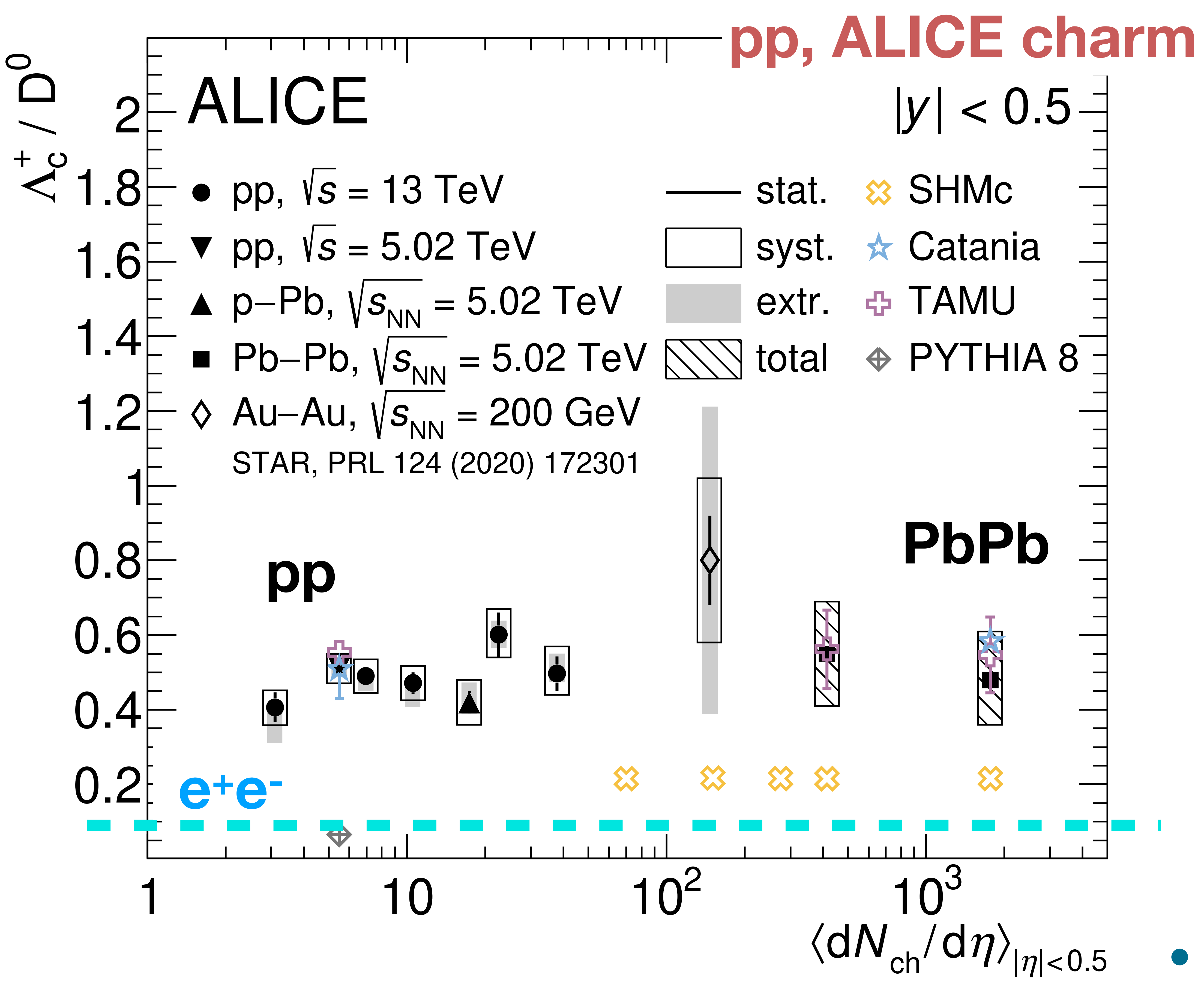




- Ratio increases from pp to mid-central and central Pb-Pb at intermediate p_T
- Trend qualitatively similar to what is observed for Λ/K_s^0 ratios

p_T–Integrated yield ratio in pp collisions

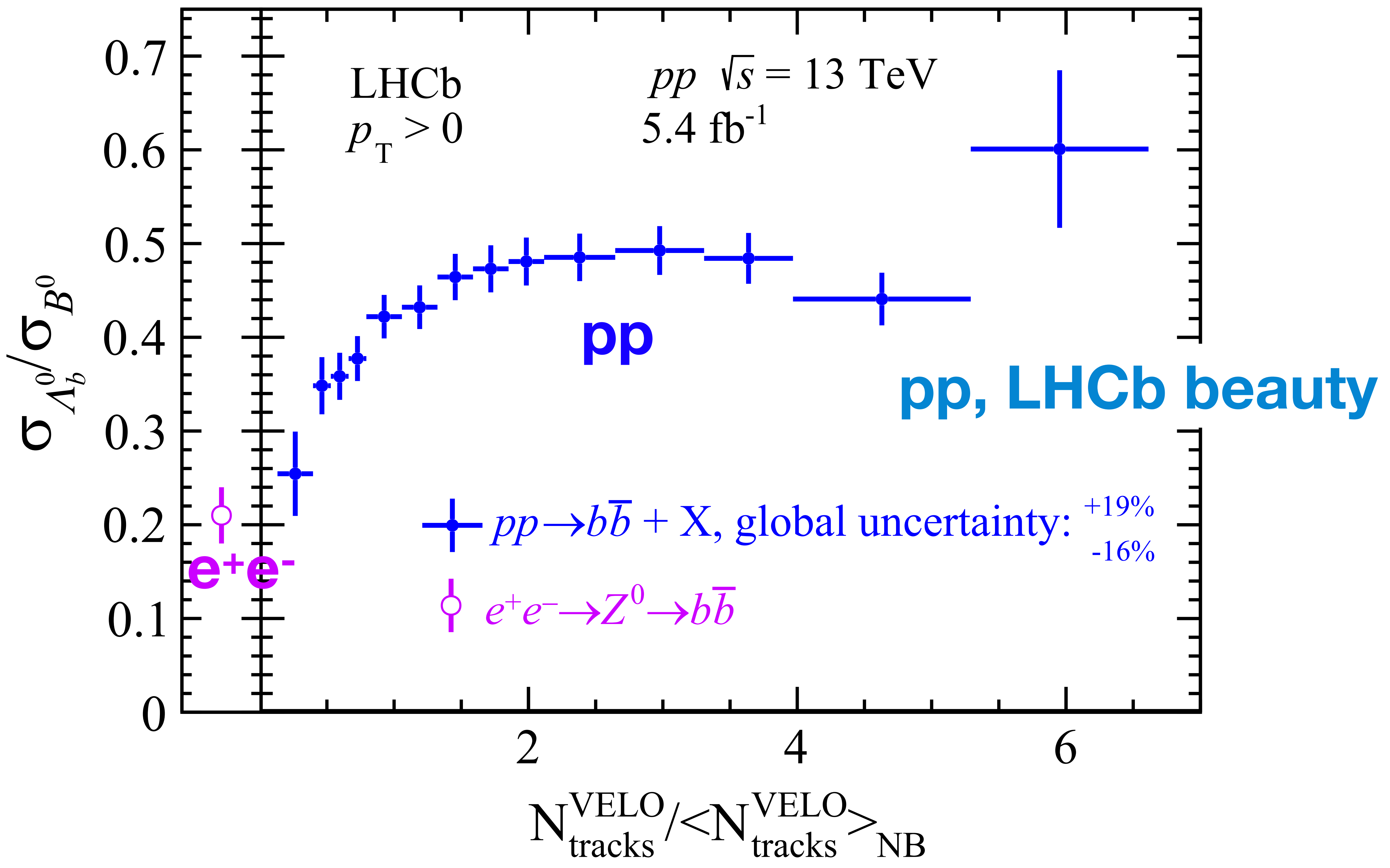
p_T-integrated Λ_c^+/D^0 ratios



Phys. Lett. B 839 (2023) 137796

p_T-integrated Λ_b^+/B^0 ratios

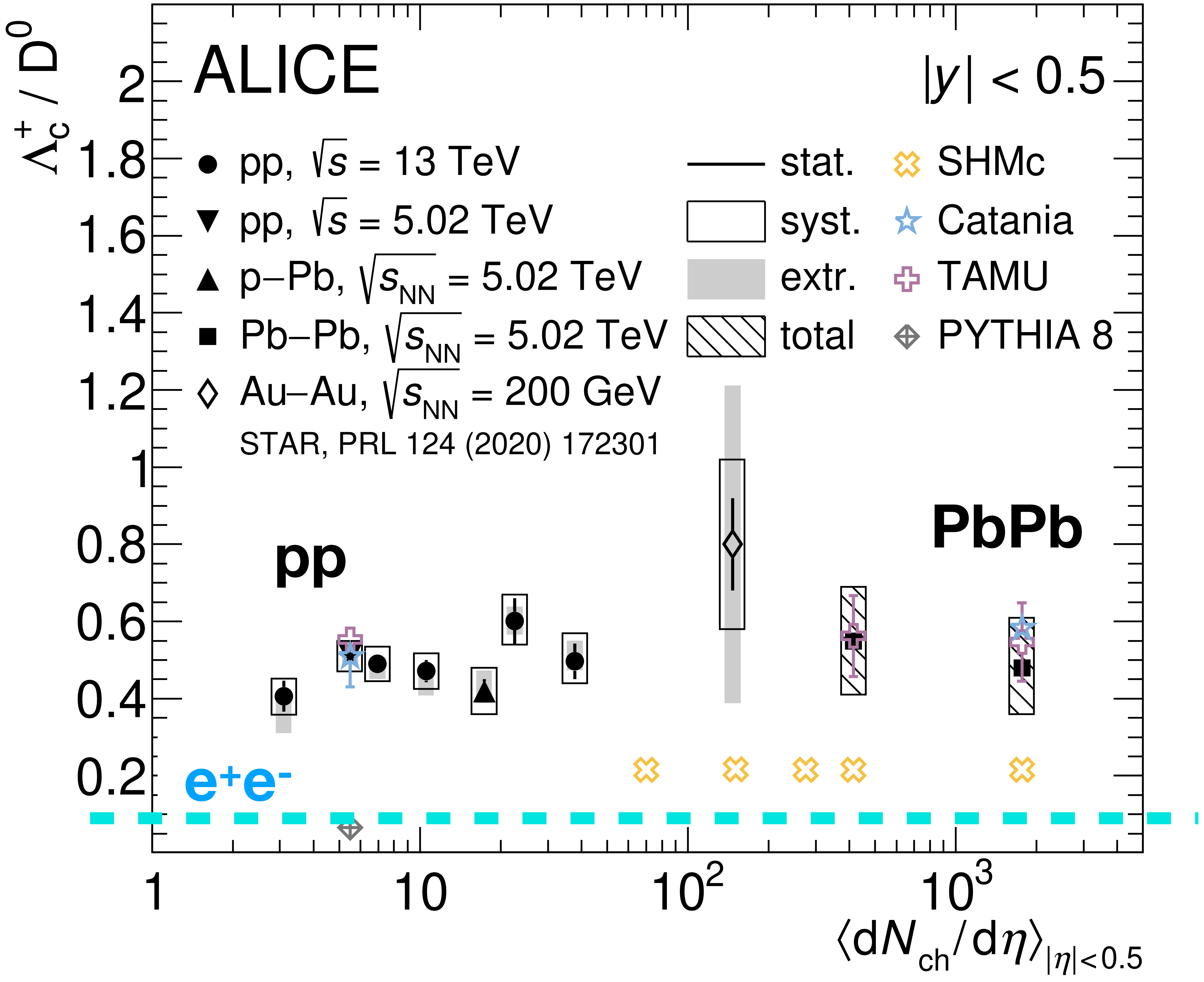
PRL 132, 081901 (2024)



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

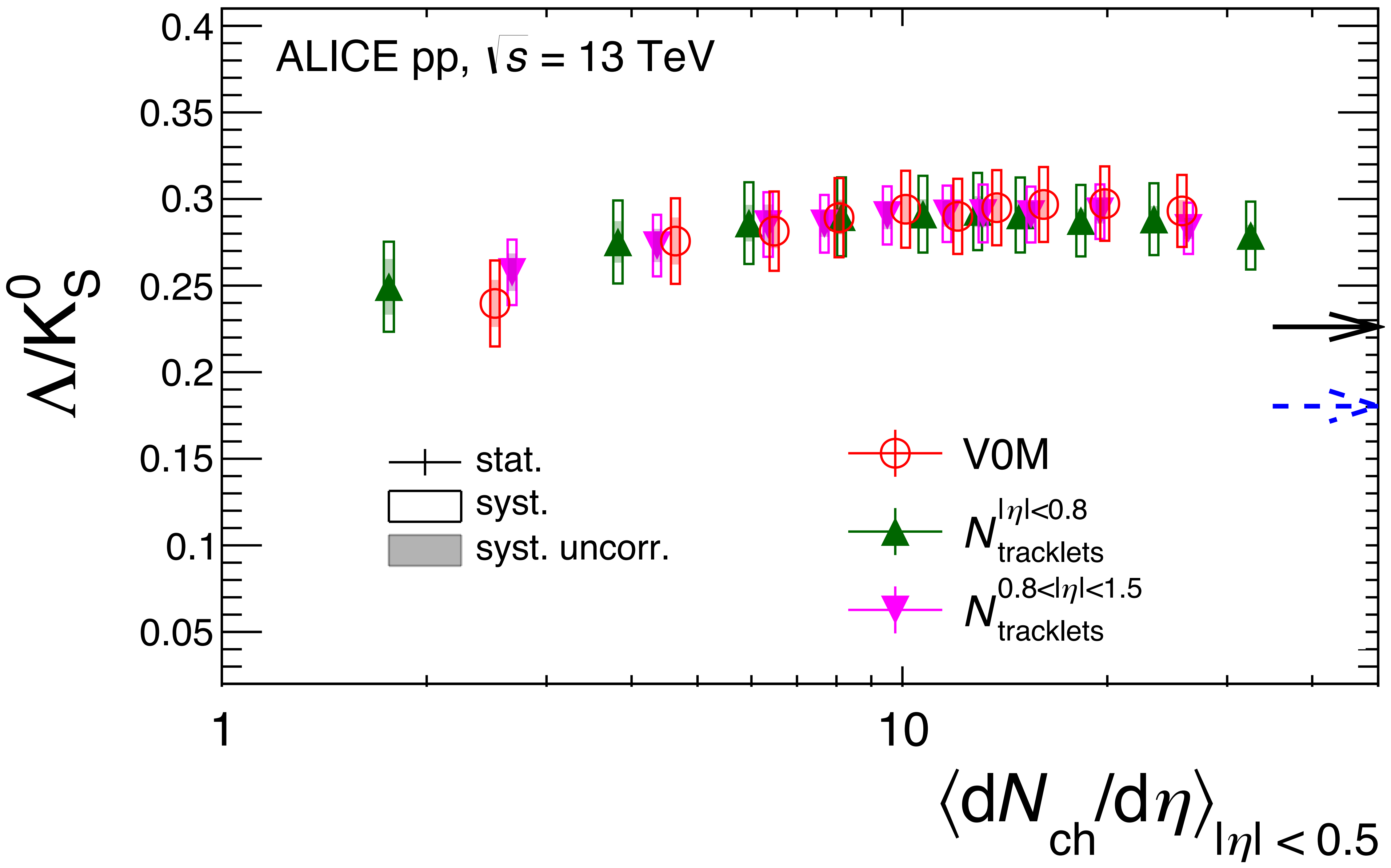
Where does the p_T differential enhancement come from?

p_T-integrated Λ_c^+/D^0 ratios



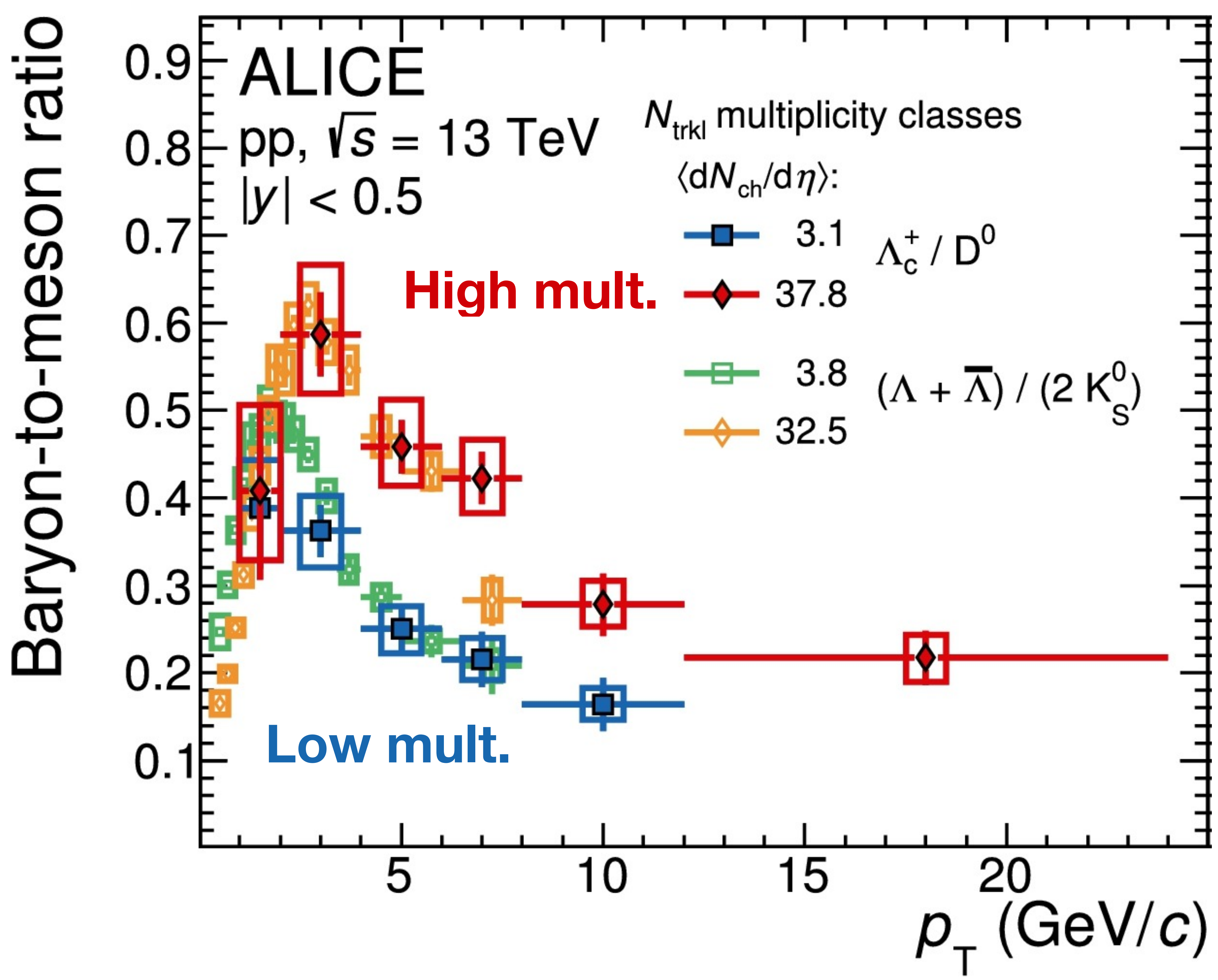
Phys. Lett. B 839 (2023) 137796

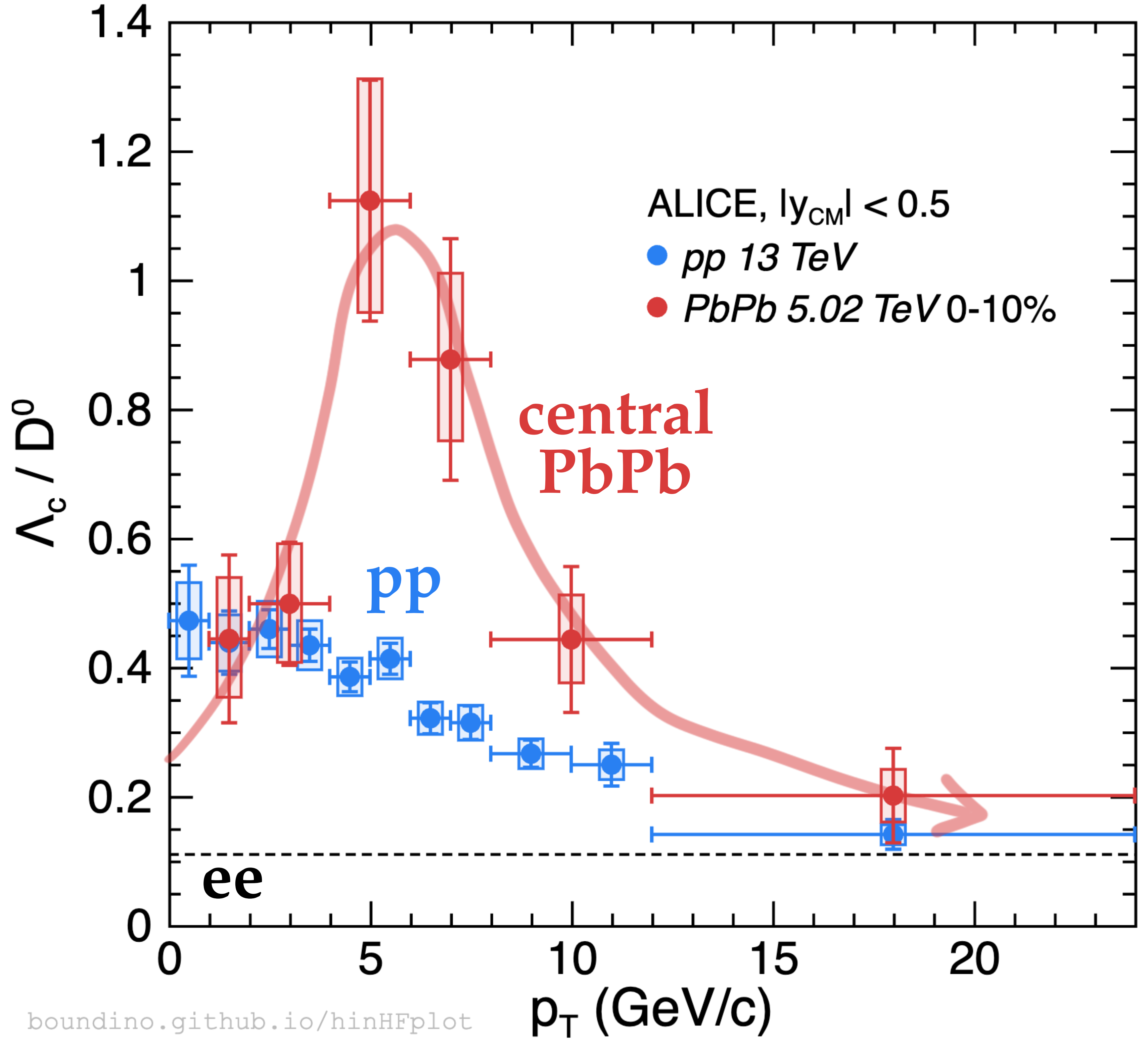
- Due to different p_T redistribution for baryons and mesons rather than multiplicity dependence in hadronization process itself?
- Modified mechanism of hadronization in all hadronic collision systems with respect to charm fragmentation tuned on e^+e^- and e^-p measurements?



p_T redistribution

Phys. Lett. B 829 (2022) 137065

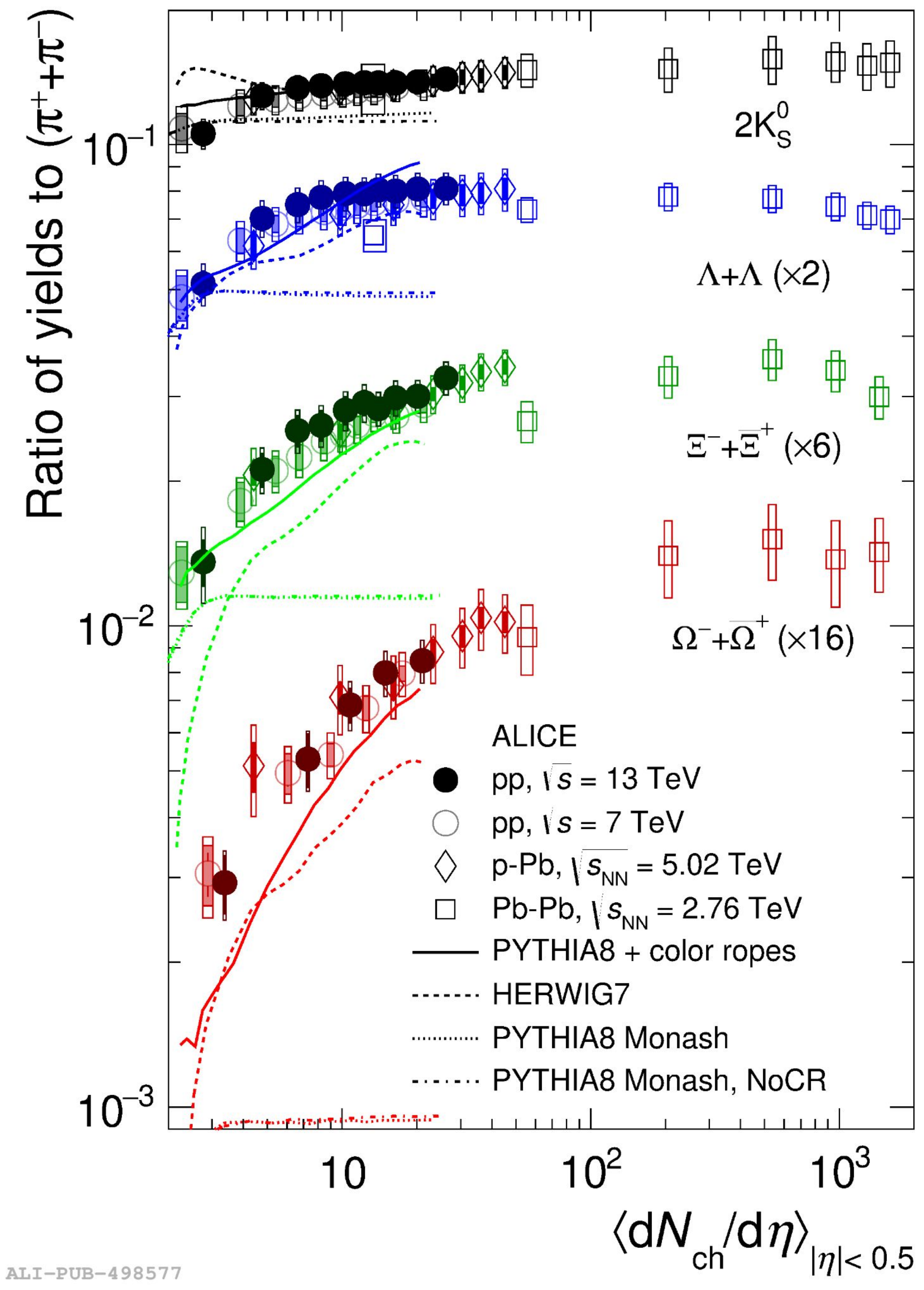




- Charm baryons/meson like for strangeness!
- Common mechanism for light- and charm-baryon formation in hadronic collisions? (unlikely) or coincidence in a redistribution?
- Shape changes dramatically in central PbPb → Strongest radial flow?

Role of strangeness in heavy-quark hadronization

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



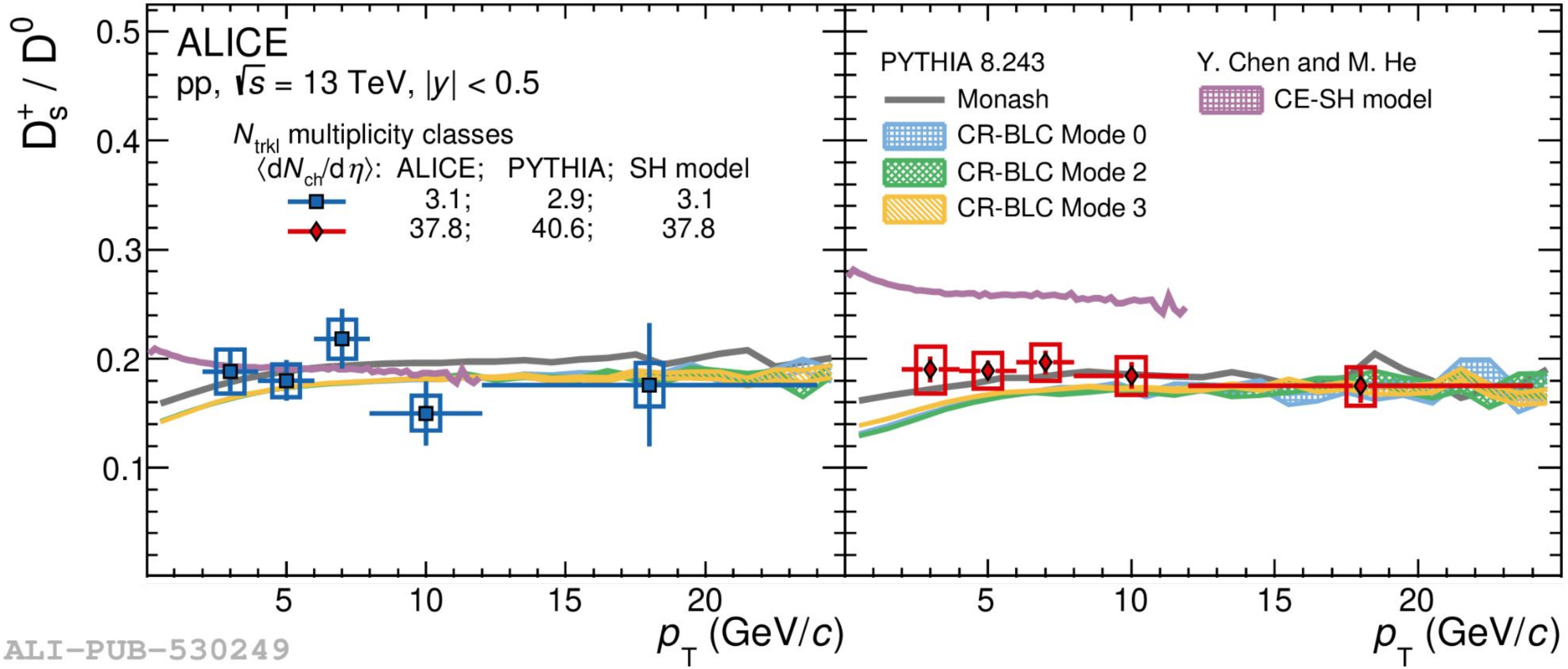
- Strangeness enhancement: yield-ratio between (multi)strange hadrons and pion larger in heavy-ion collisions than minimum-bias pp collisions

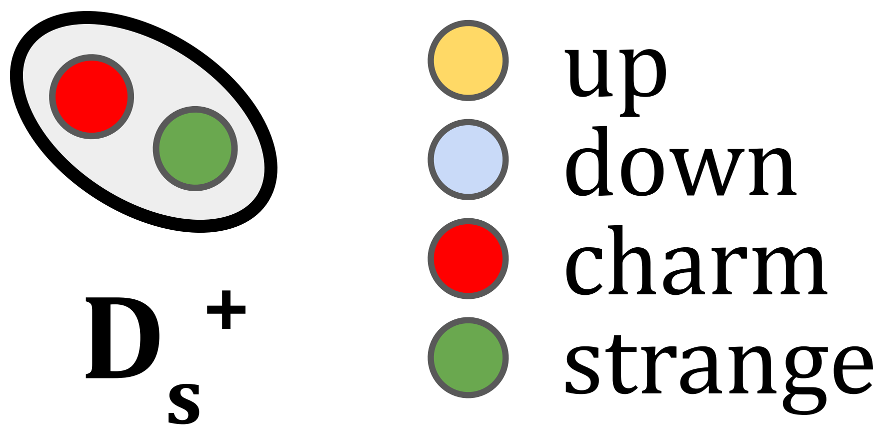
- Smooth increase vs. event multiplicity, without a clear collision-system dependence

- 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

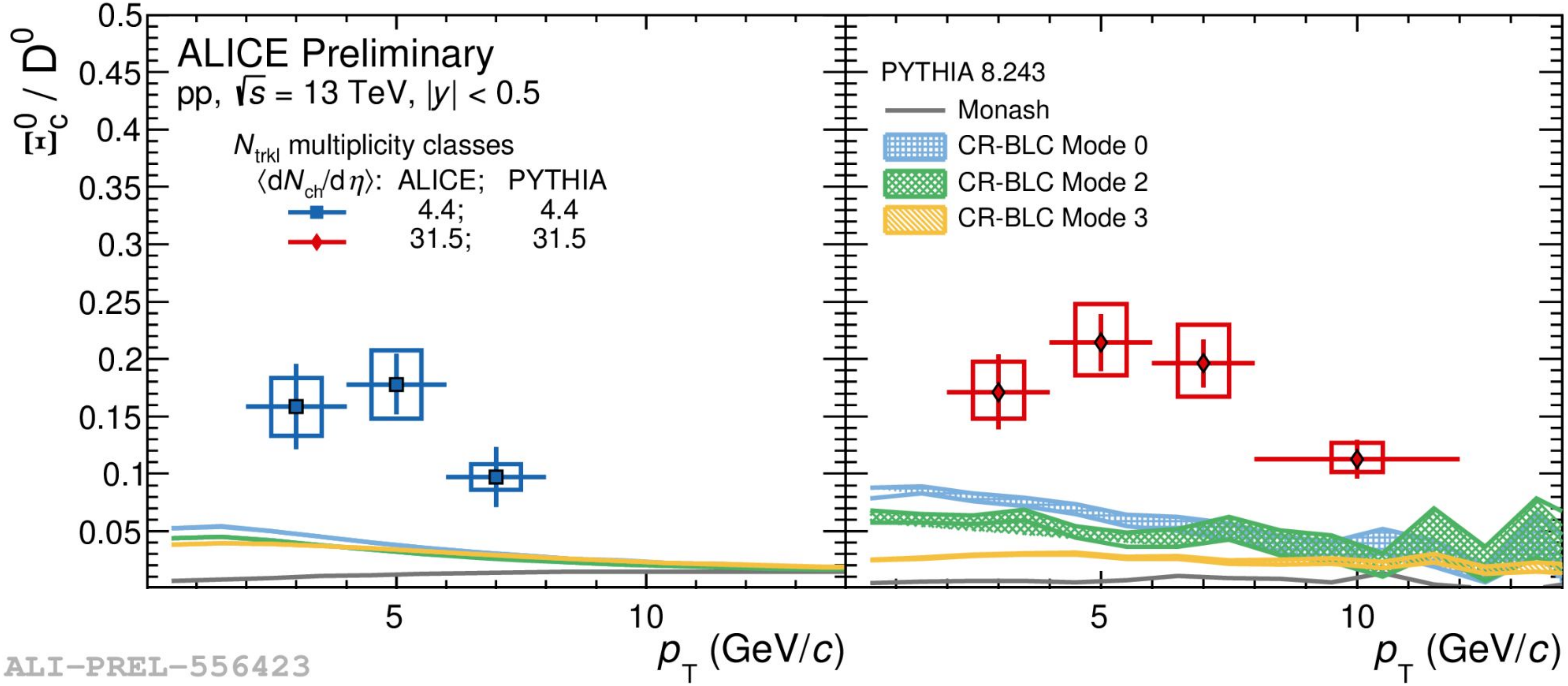




- D_s^+/D^0 ratio are independent of p_T
- No strong multiplicity dependency
- Comparable with measurement at e^+e^- and e^-p collisions

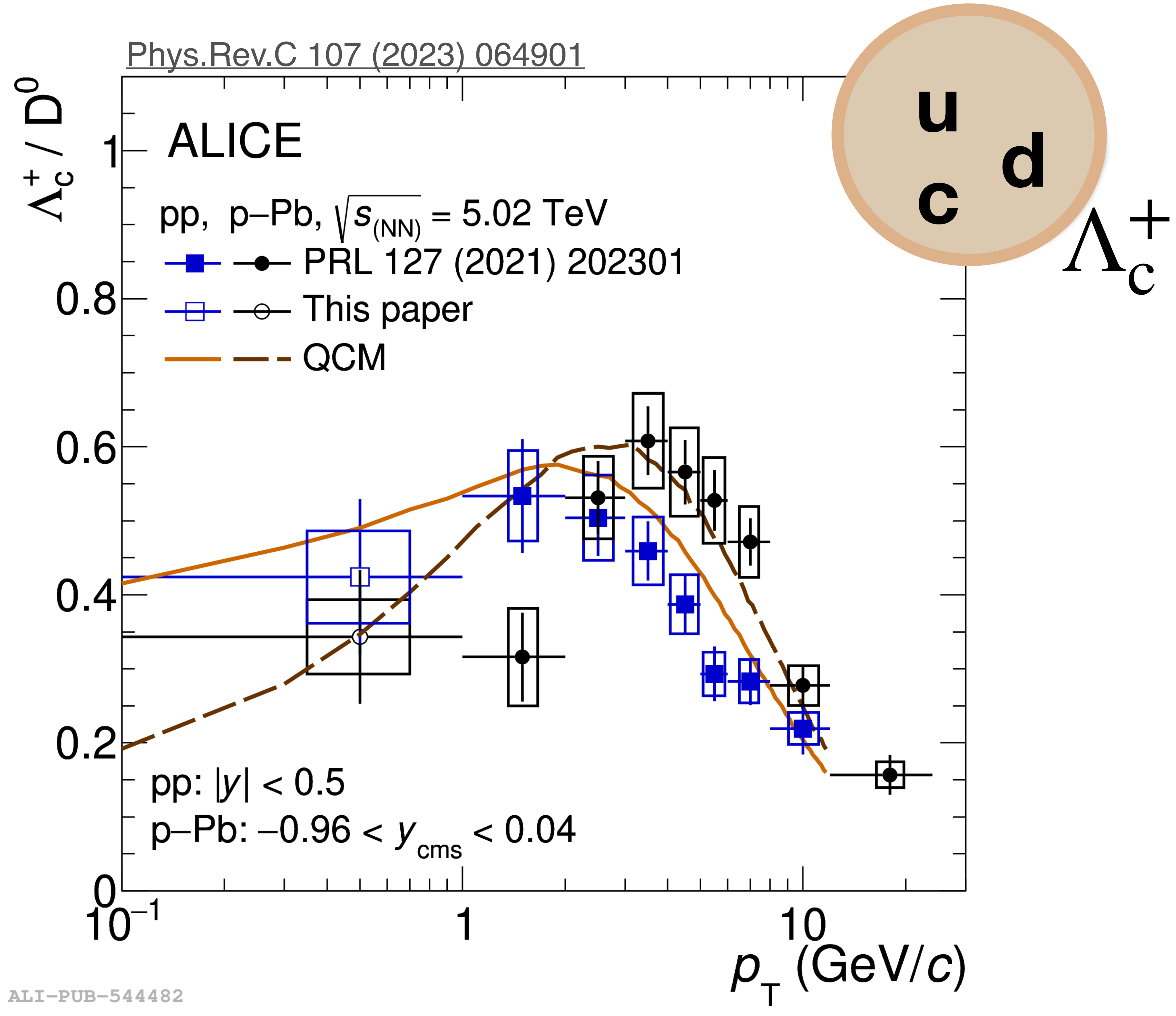
What about strangeness charm baryon?

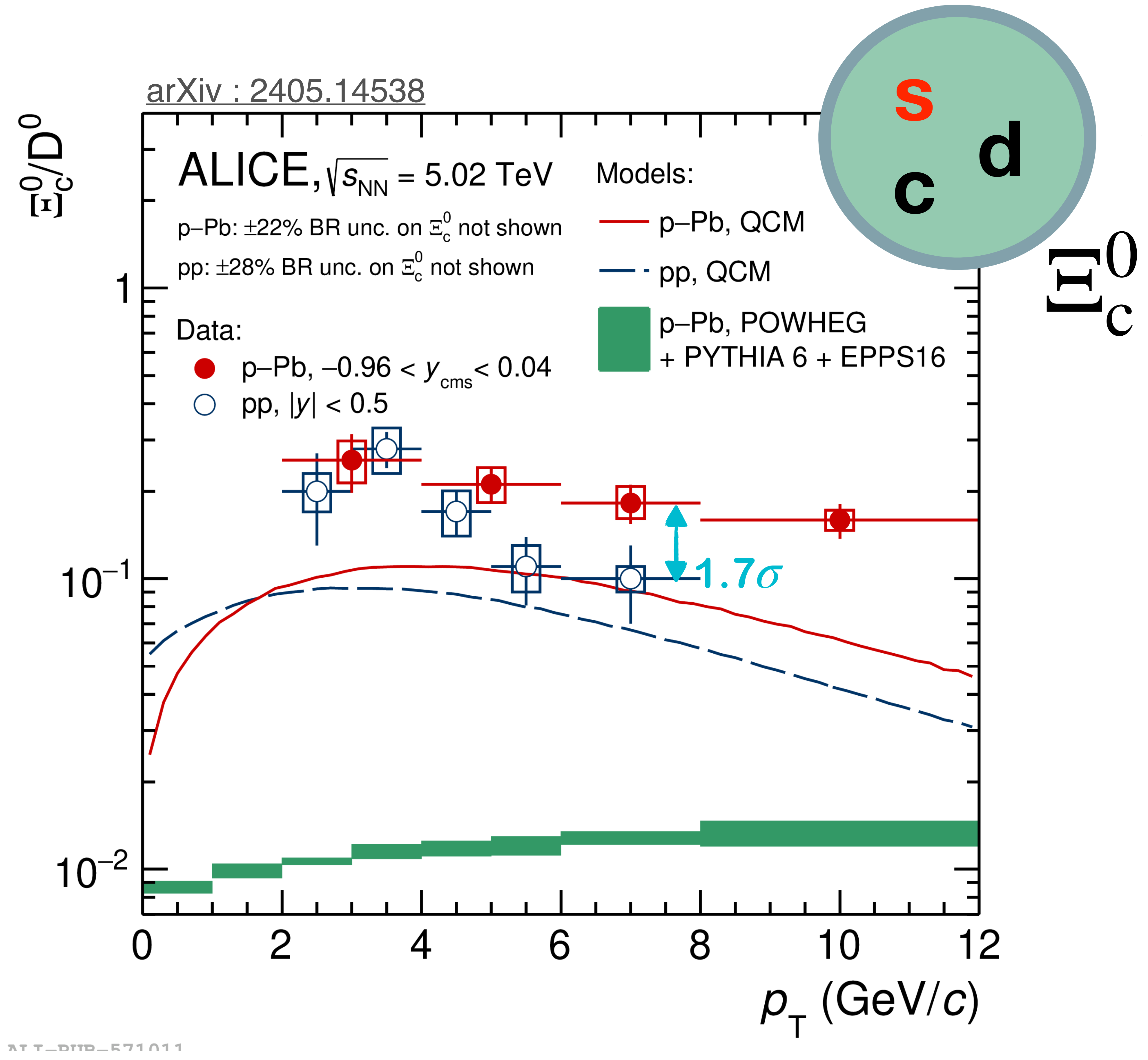
More challenges!



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

Challenging models

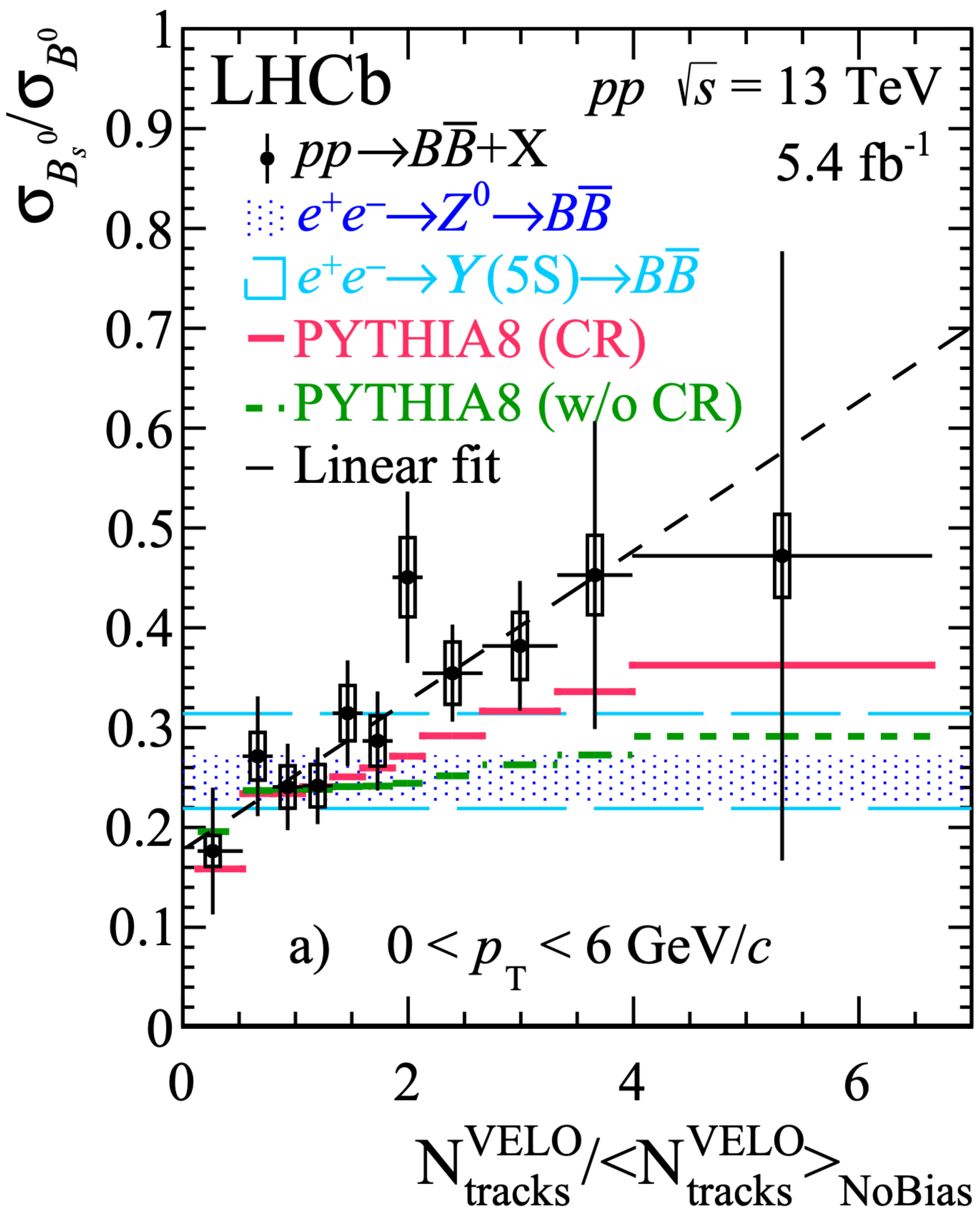




- Shift of distribution peak towards higher p_T could be attributed to radial flow
- QCM describes the magnitude of the ratio for Λ_c^+/D^0, but underestimate for Ξ_c^0

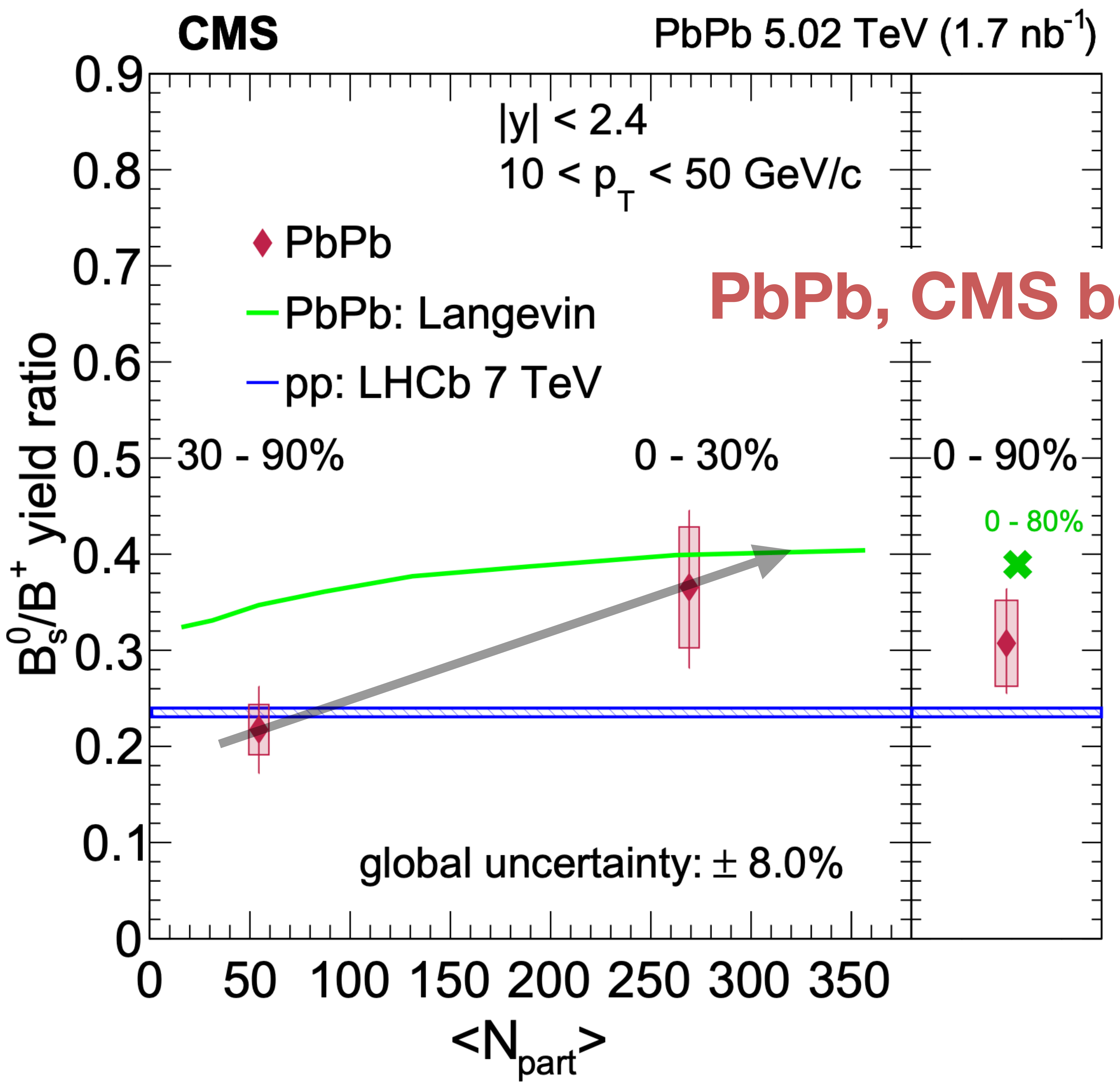
Is beauty different?

pp, LHCb beauty



B^0_s/B^+

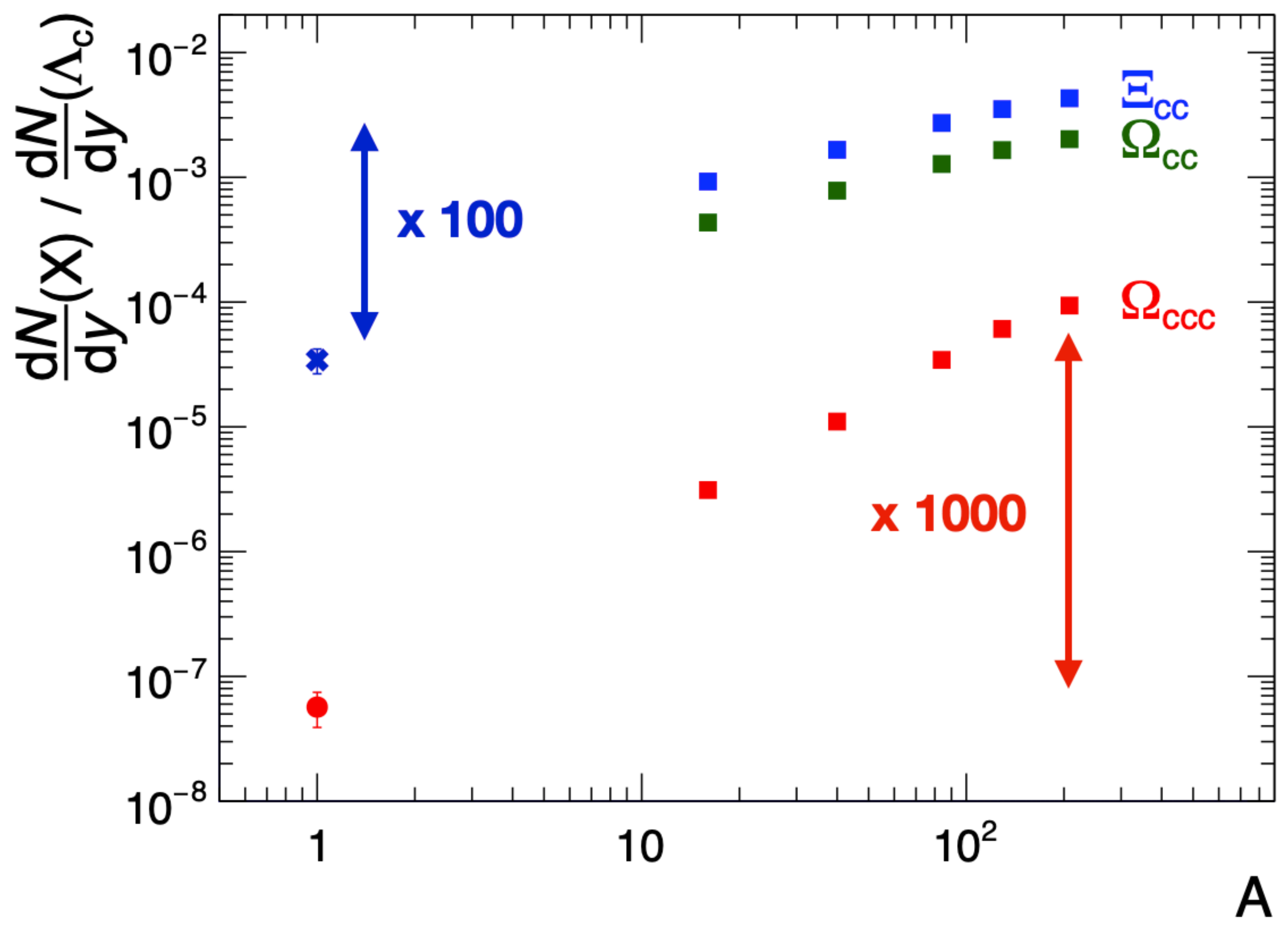
PbPb, CMS beauty

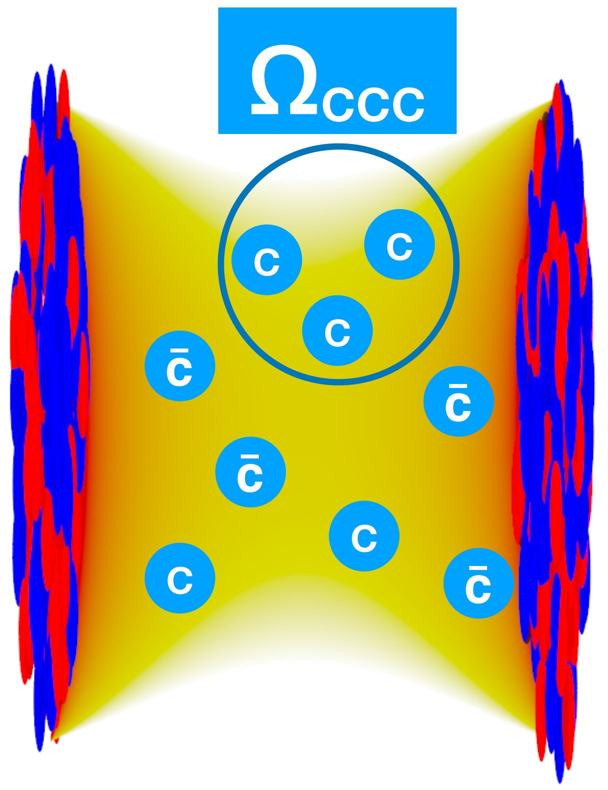


- Hint of different behavior of beauty
- Need precision measurement

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!



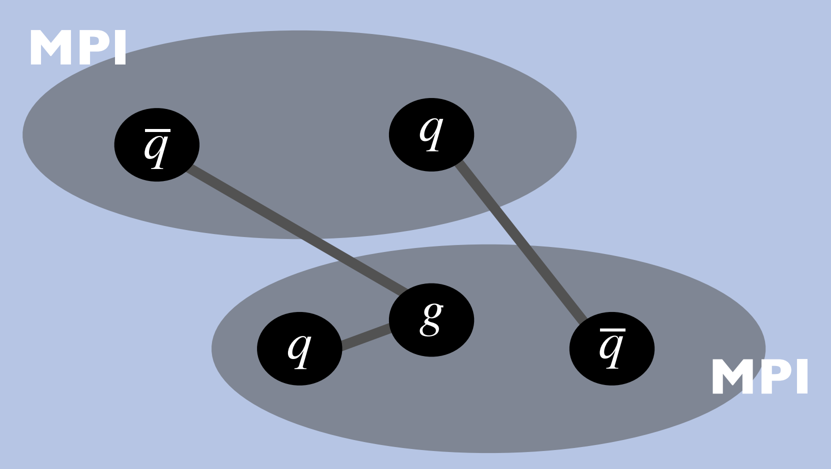
Thank you for your attention!

Extra Slides

Heavy-flavour hadronization modelings

PYTHIA 8

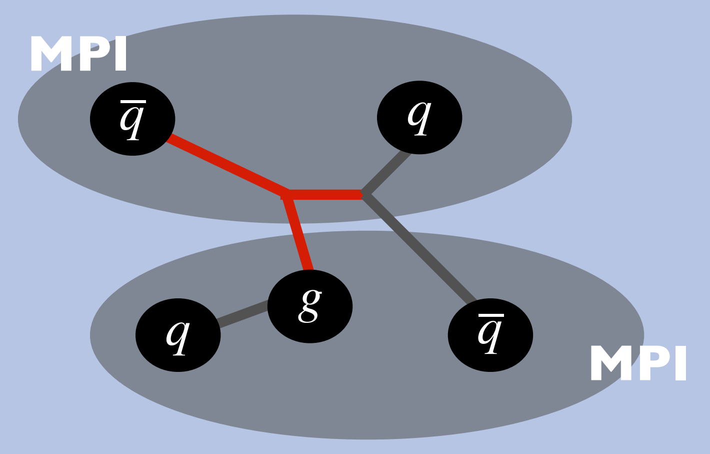
Hadronization via **fragmentation**, color reconnection between partons from different multiparton interactions



Monash tune

(tuned to e^+e^- measurements)

Eur.Phys.J. C 74 (2014) 3024



Mode 2

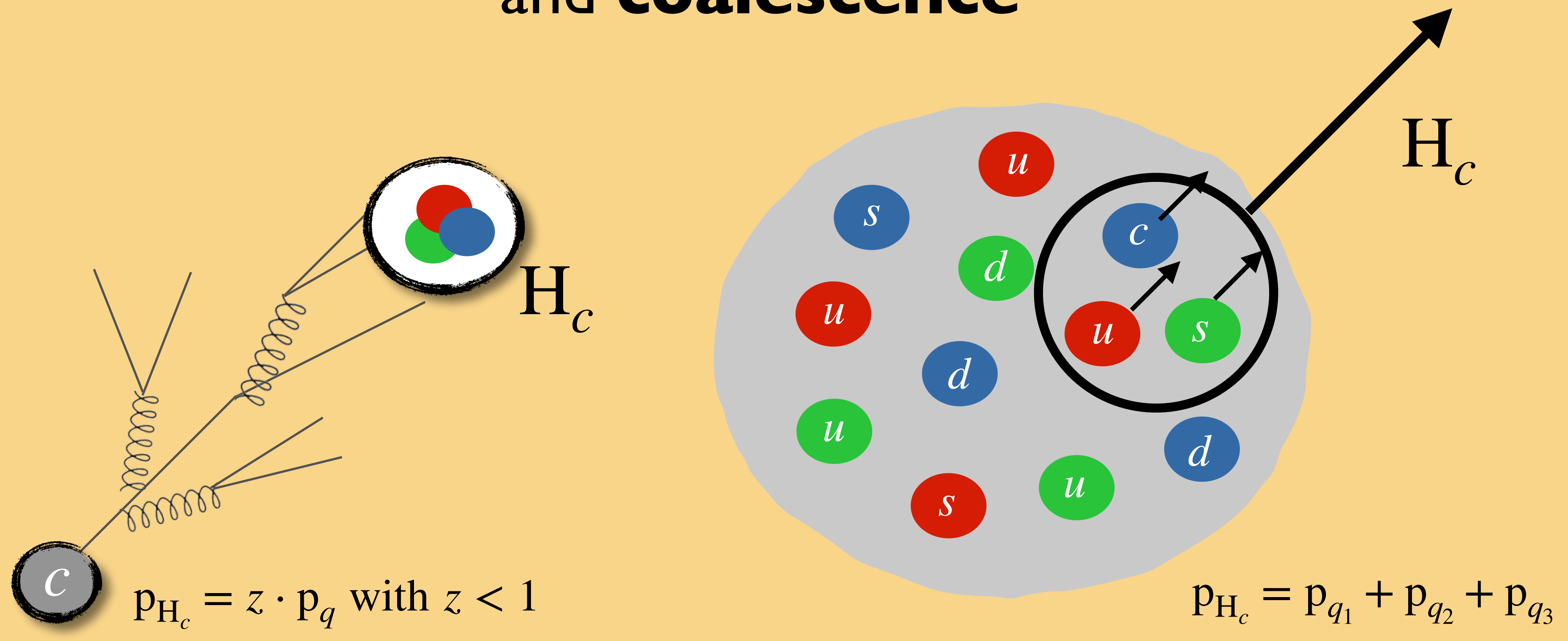
the **junction** topology leads to an increase of baryon production

JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

Hadronization via both **fragmentation** and **coalescence**

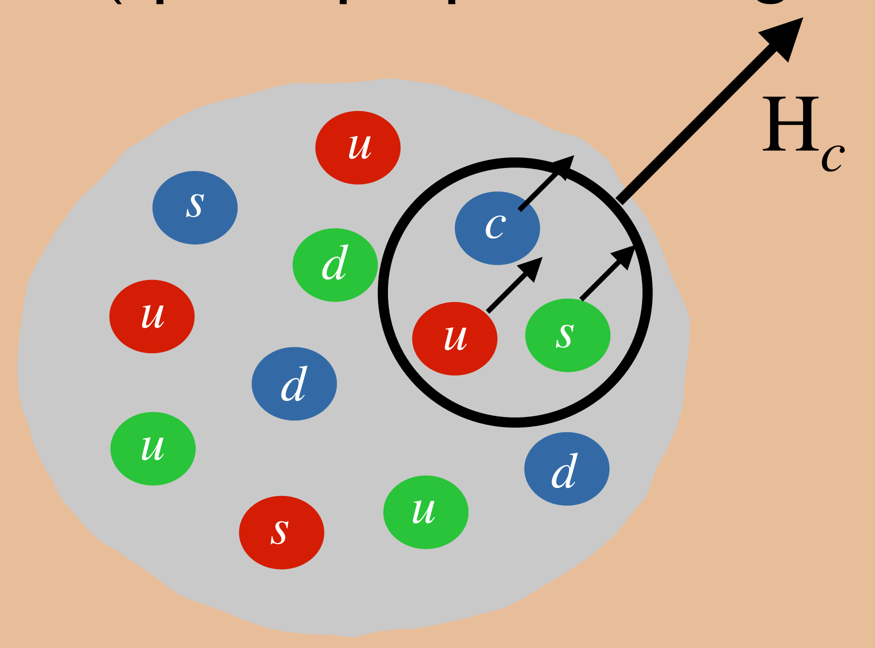


QCM

Eur.Phys.J.C 78 (2018) 344

Quark (re-)Combination Mechanism

equal-velocity combination of charm quark and light quarks (spatial properties neglected)



SHM + RQM

Phys.Lett.B 795 (2019) 117-121

Phys.Rev.D. 84 (2011) 014025

- Complexity of hadronization process replaced by **statistical weights** governed by hadron mass
- Feed-down from largely **augmented set of charm baryon stated** beyond the ones currently listed in the PDG, as predicted by Relativistic Quark Model

Fragmentation

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.

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: $f(z) \propto \frac{1}{z^{1+r_b m_t^2}}(1-z)^a \exp(-\frac{bm_t^2}{z})$

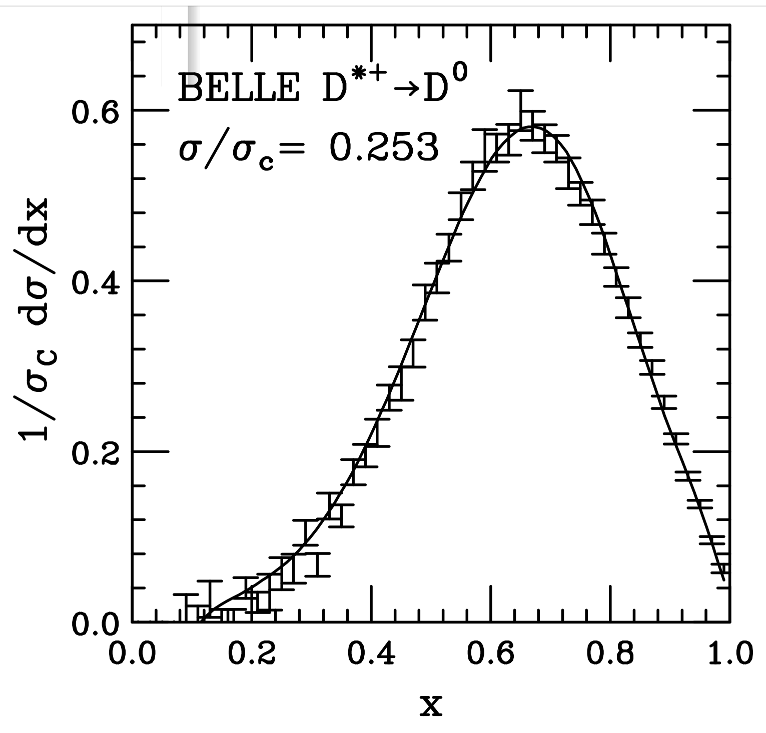
▷ is fragmentation function **universal**?
(i.e. are FF portable from e^+e^- to ep and pp?)

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

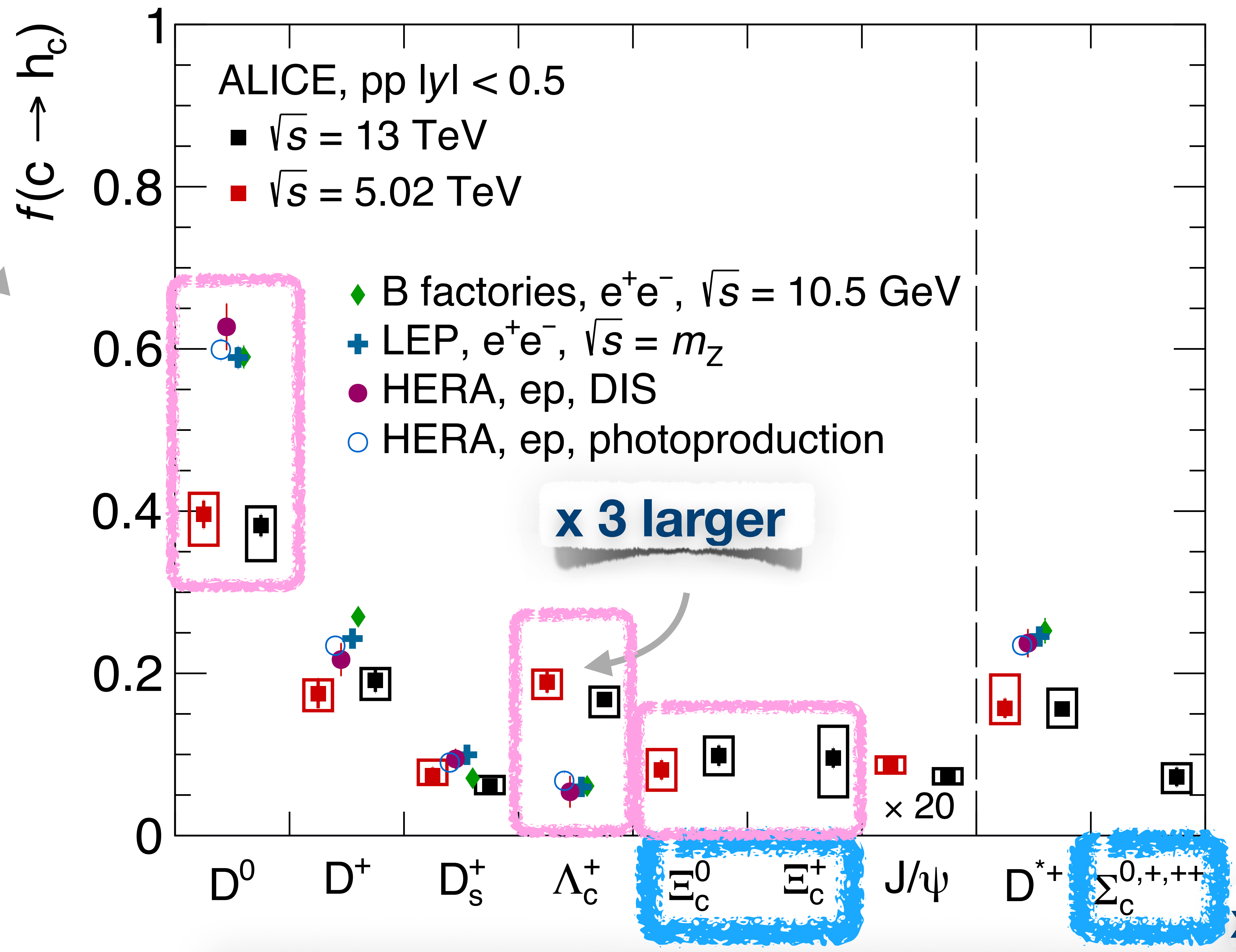
▷ **ALEPH:** a= 2.4±1.2, b=13.9±5.7, c=5.9±1.7

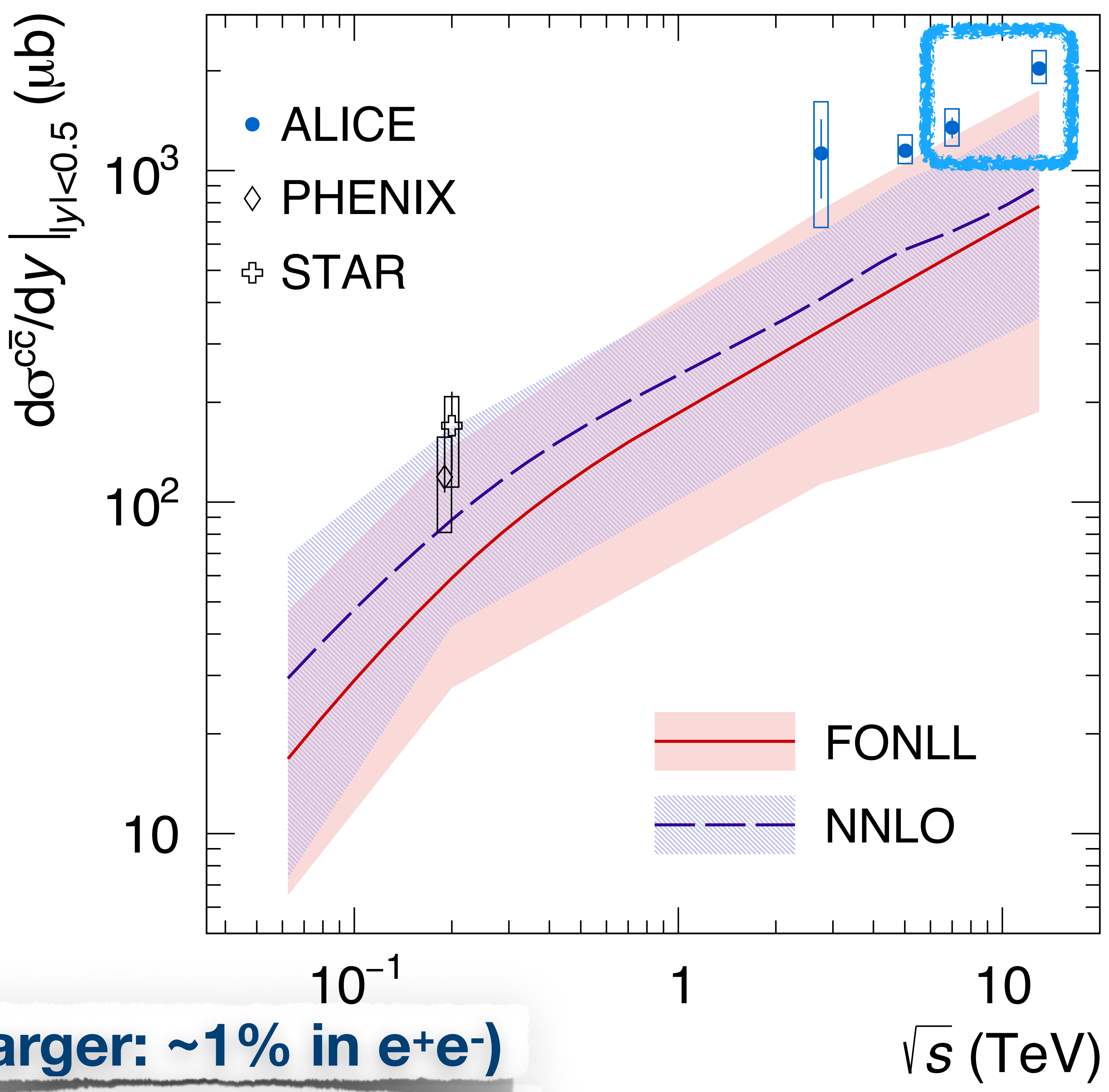
▷ **CLEO/BELLE:** a= 1.8±0.2, b=11.3±0.6, c=2.46±0.07

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

Zuzana Rúriková Charm Fragmentation Function – June 7, 2006

Charm-quark fragmentation fraction





x 3 larger

Used the sum of the p_T-integrated cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+ , Ξ_c^0, Ξ_c^+

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x 7 larger: ~1% in e^+e^-)

10% of total charm cross section (considered negligible in e^+e^-)

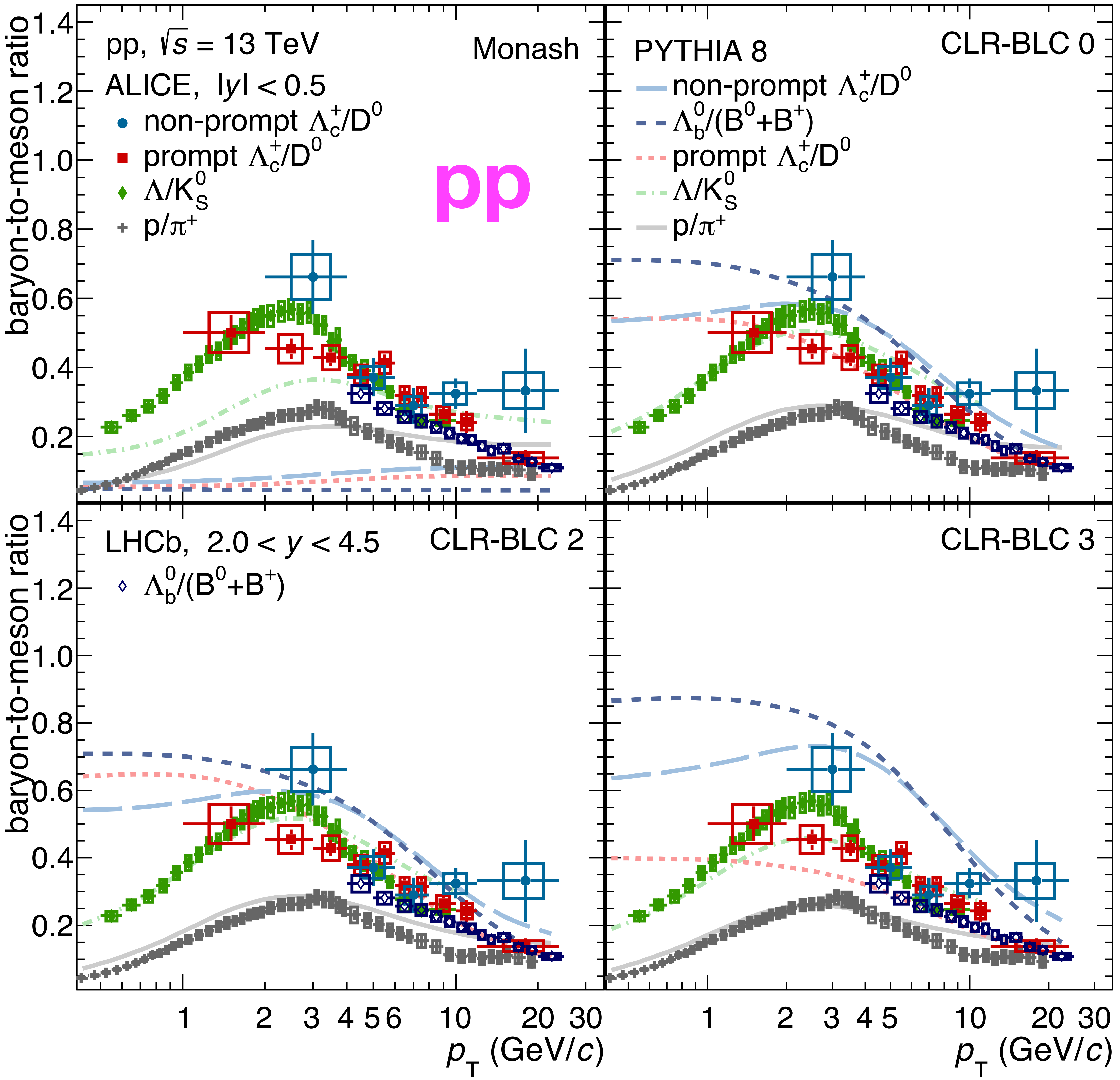
Σ_c^0: Larger feed-down to Λ_c^+ (40%, 17% in e^+e^-)

Normalized by the sum of the p_T-integrated cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+ , Ξ_c^0, Ξ_c^+

Conclusion: baryon enhancement at the LHC with respect to e^+e^- collisions is caused by different hadronisation mechanisms at play in the parton-rich environment produced in pp 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

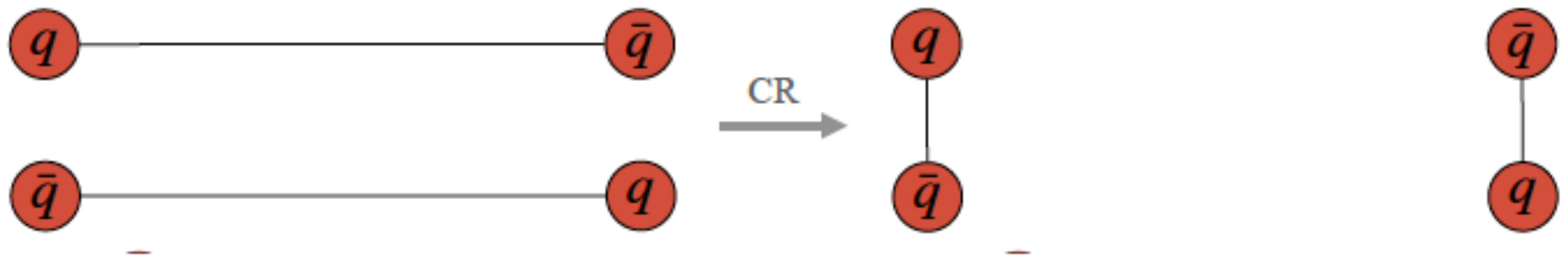
→ Similar baryon-formation mechanism among light, strange, charm and beauty hadrons?

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

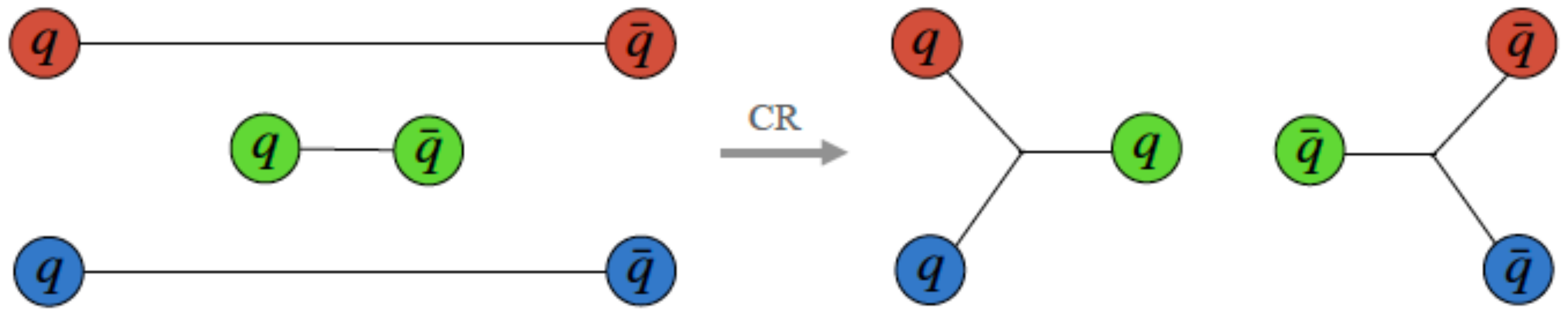
Note: for LHCb, different normalization & should consider decay kinematics (for the other case)
* These three tunes are characterized by different constraints on the time dilation and causality

PYTHIA Color Reconnection

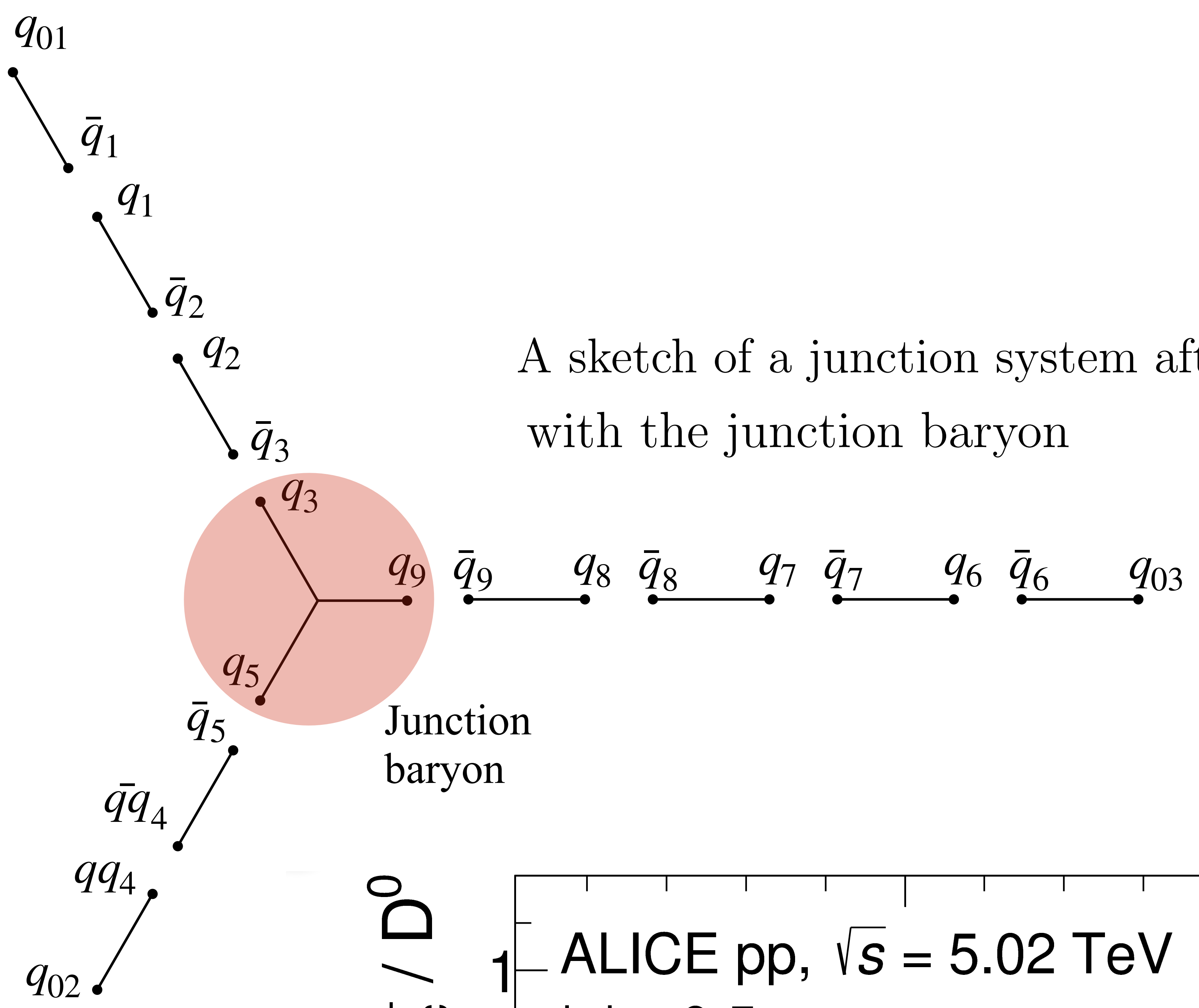
Altmann et al., arXiv 2405.19137



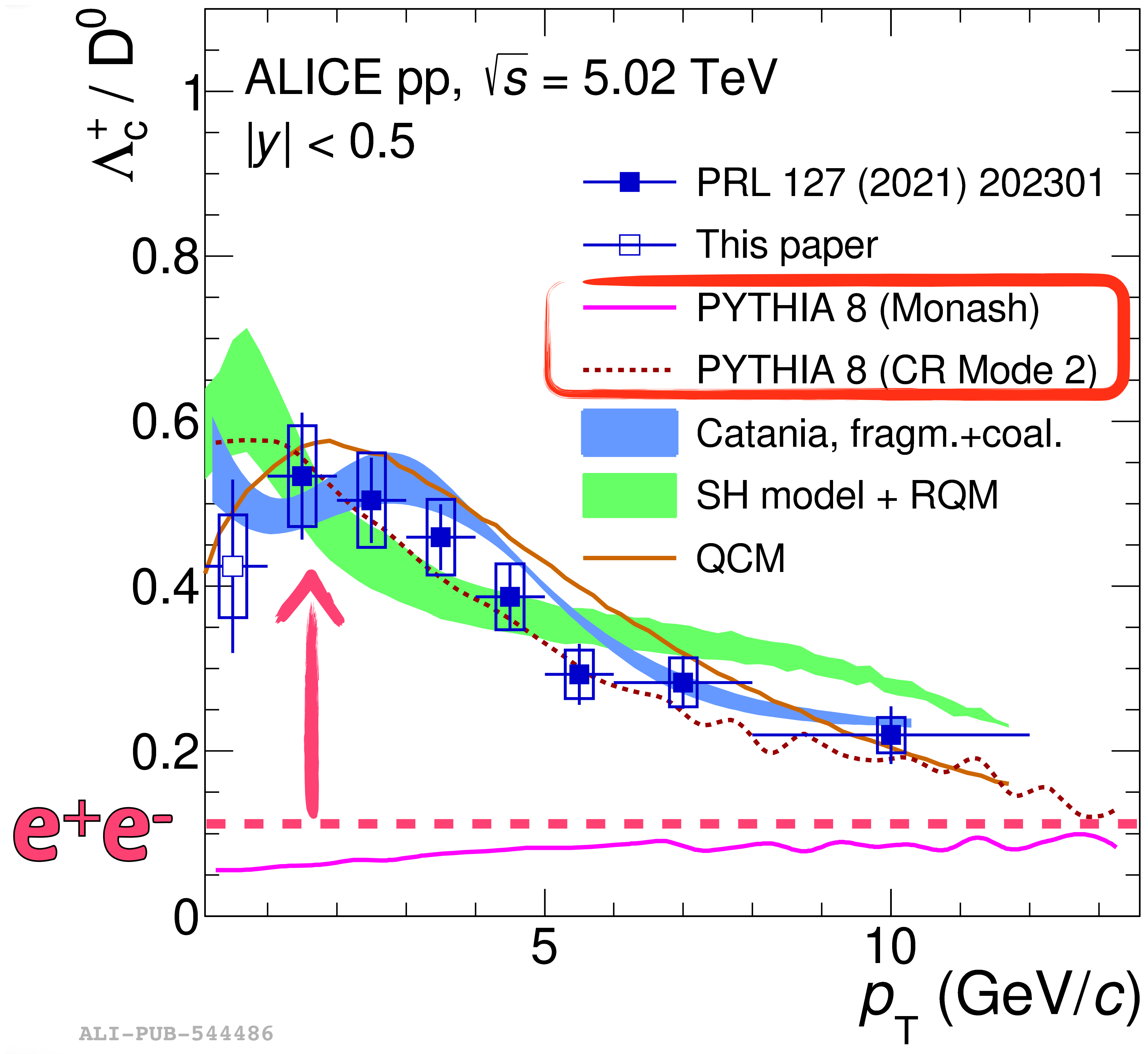
(a) Dipole-type reconnection.



(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

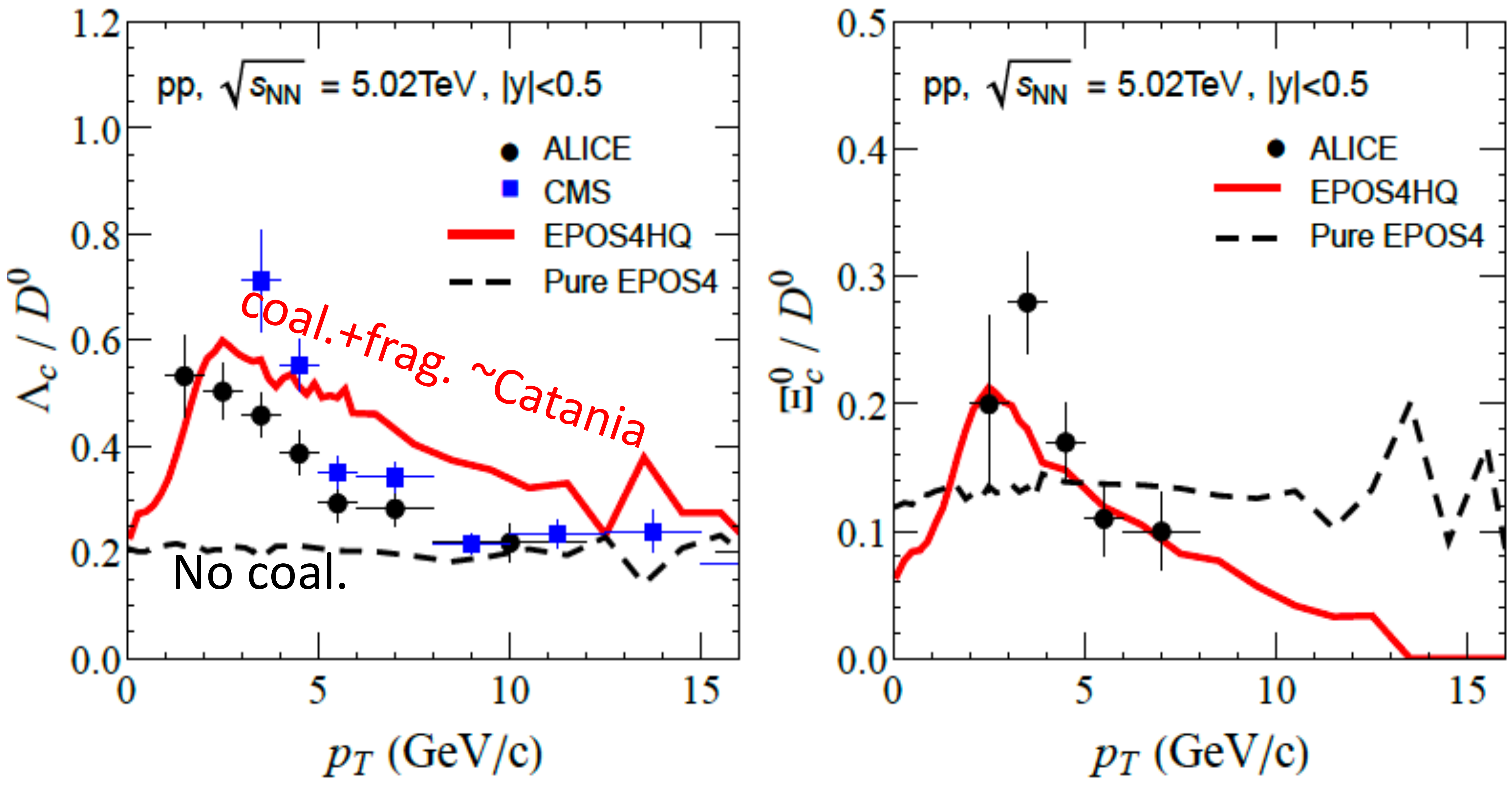
Not so different qualitatively wrt Coalescence and POWLANG Local color recombination

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

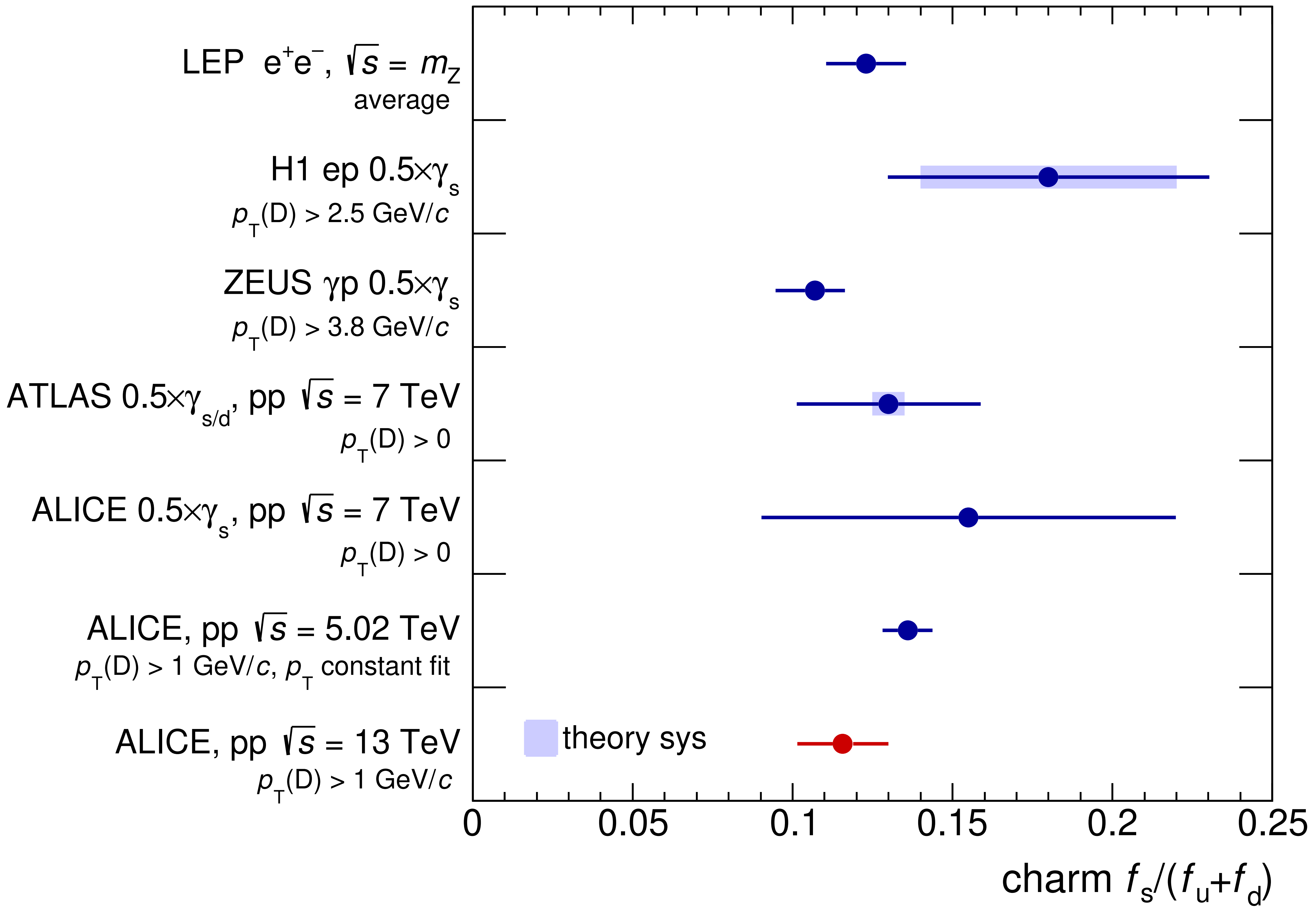
Only difference wrt Catania:

- Assume RQM states like in SHM

Charm-quark fragmentation-fraction ratio

arXiv:2308.04877

Strange to non-strange charm-meson production ratio

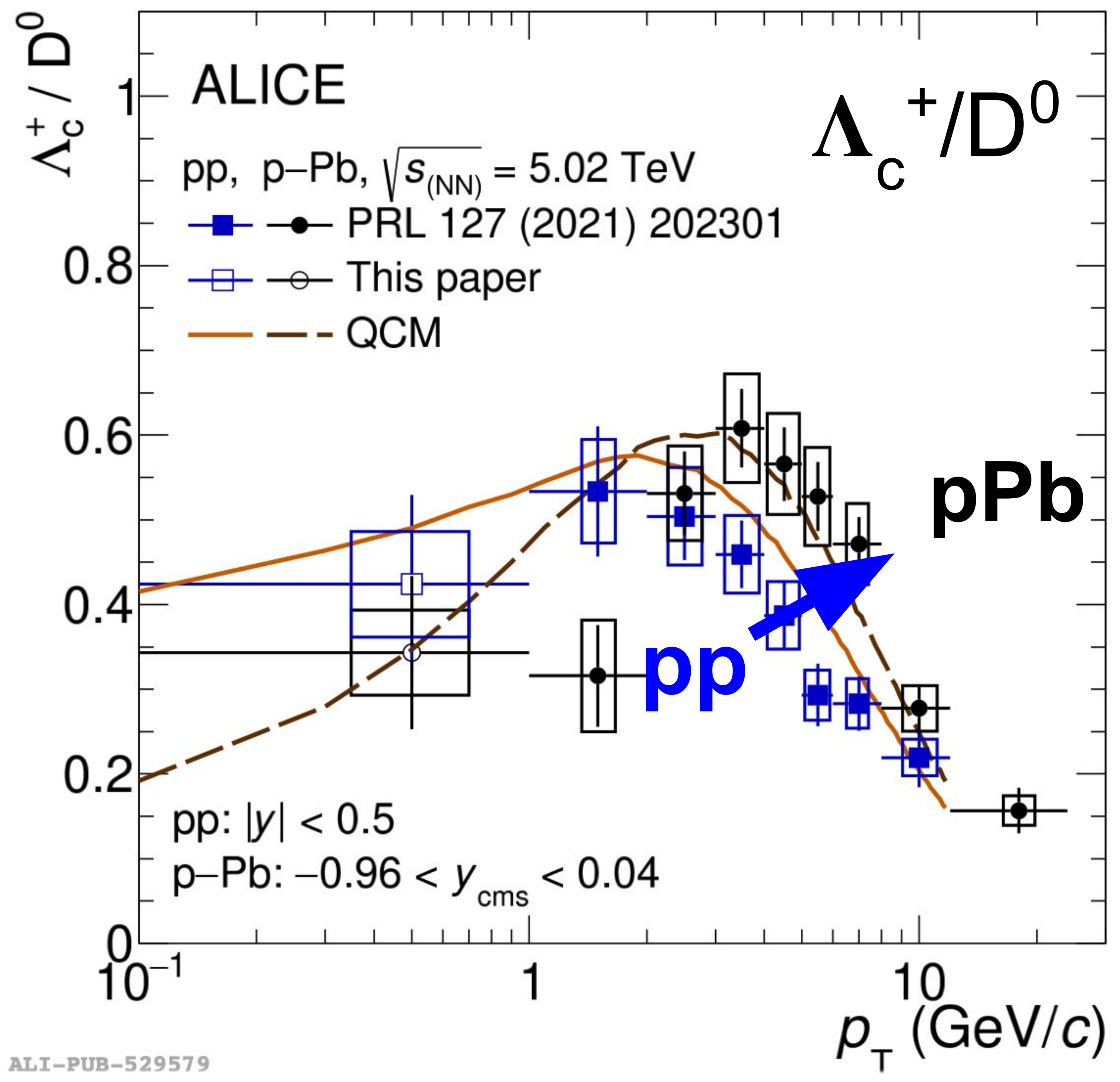


	$d\sigma/dy\|_{\|y\|<0.5}$ (μb), $p_T > 0$
D^0	749 ± 27 (stat.) $^{+48}_{-50}$ (syst.) $\pm$ 12 (lumi.) $\pm$ 6 (BR)
D^+	375 ± 32 (stat.) $^{+35}_{-35}$ (syst.) $\pm$ 6 (lumi.) $\pm$ 6 (BR)
D_s^+	120 ± 11 (stat.) $^{+12}_{-13}$ (syst.) $^{+25}_{-10}$ (extrap.) $\pm$ 2 (lumi.) $\pm$ 3 (BR)
Λ_c^+	329 ± 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)

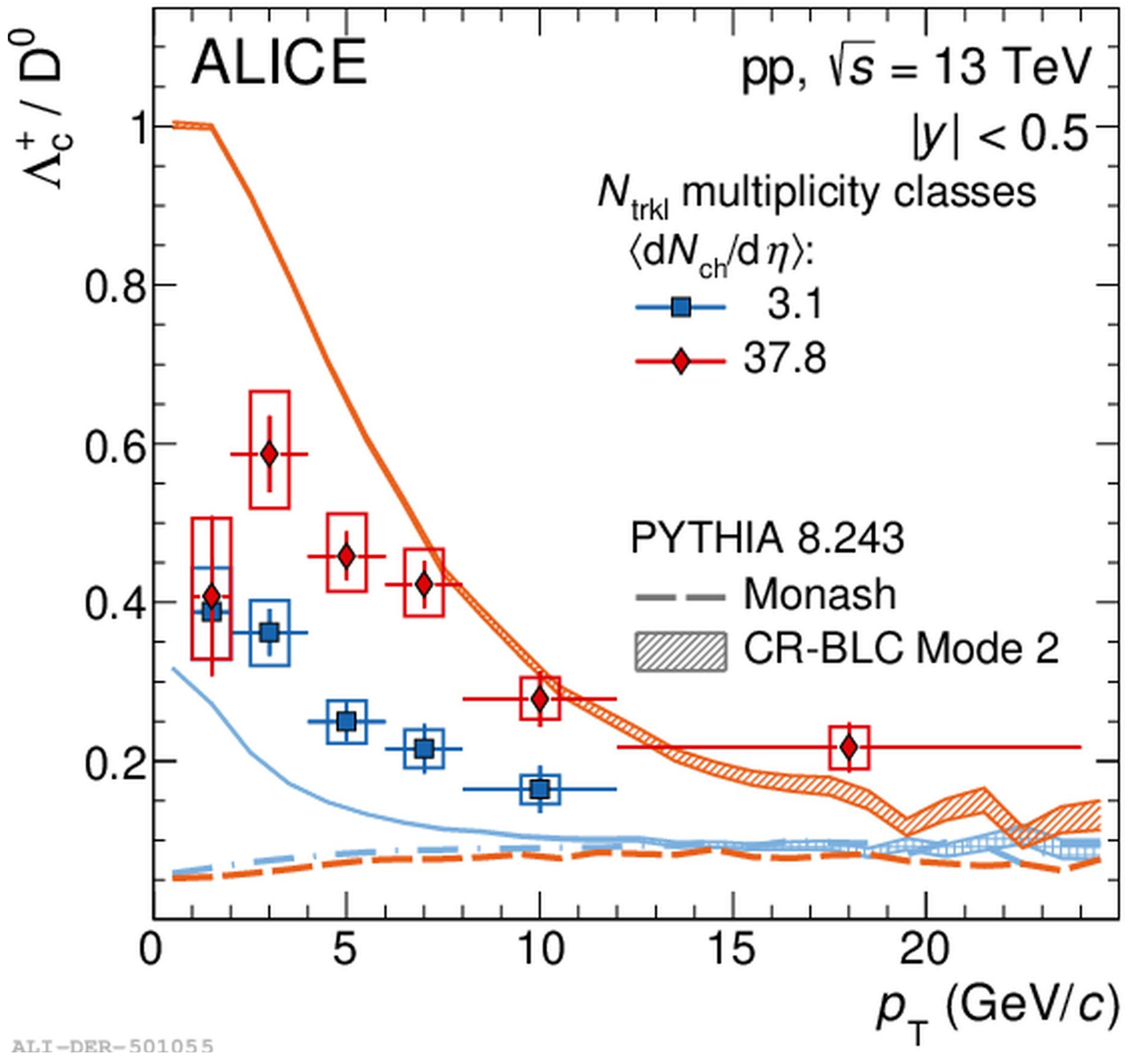
f_x: probability for a charm quark to hadronize with another quark of flavour x
⇨ D_s^+/D^0+D^+

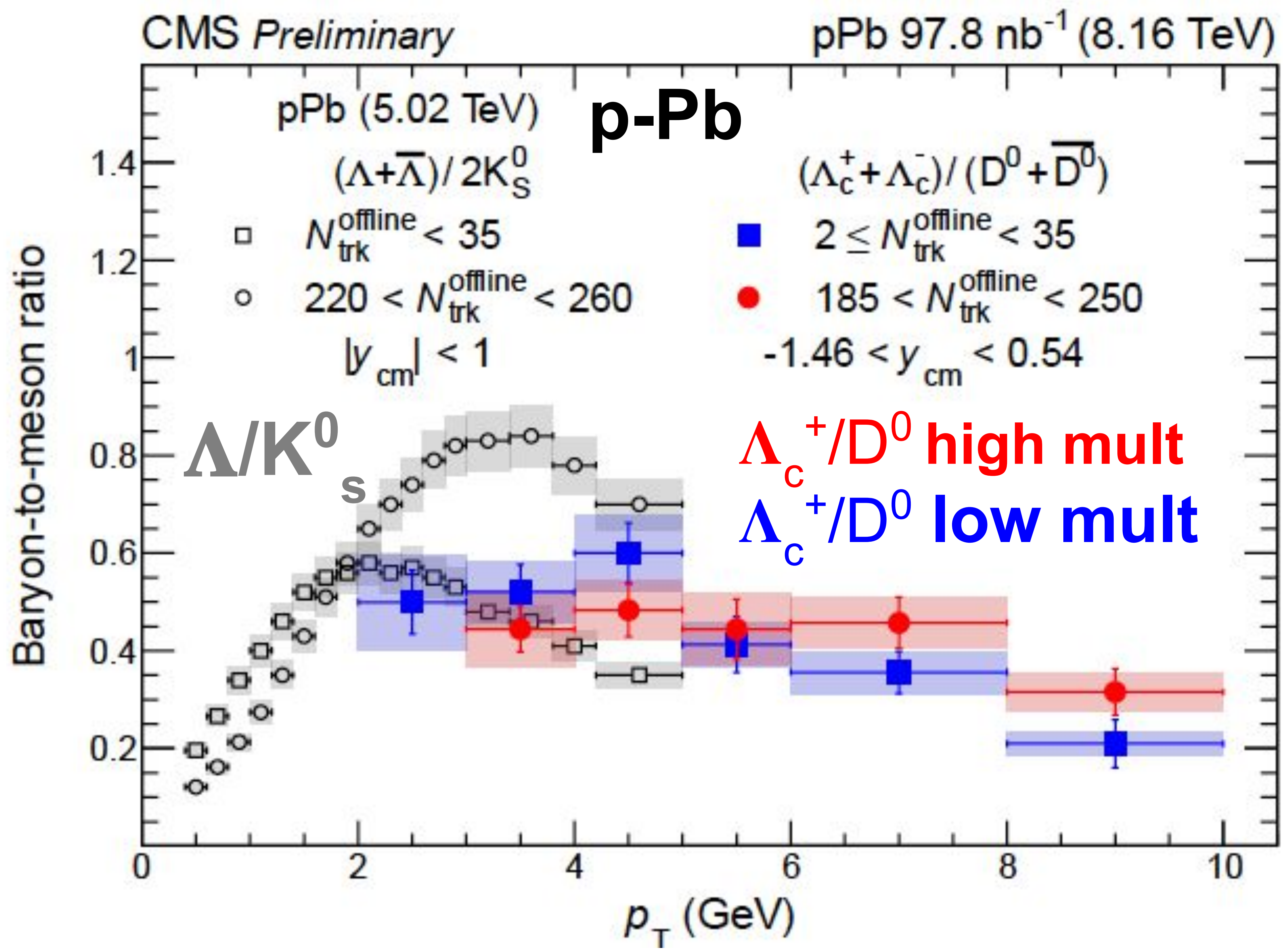
Production of prompt strange D mesons / prompt non-strange D mesons in e^+e^-, ep and pp collisions doesn't show any significant dependence of the collision system & energy!

PRC 104 054905 (2021)



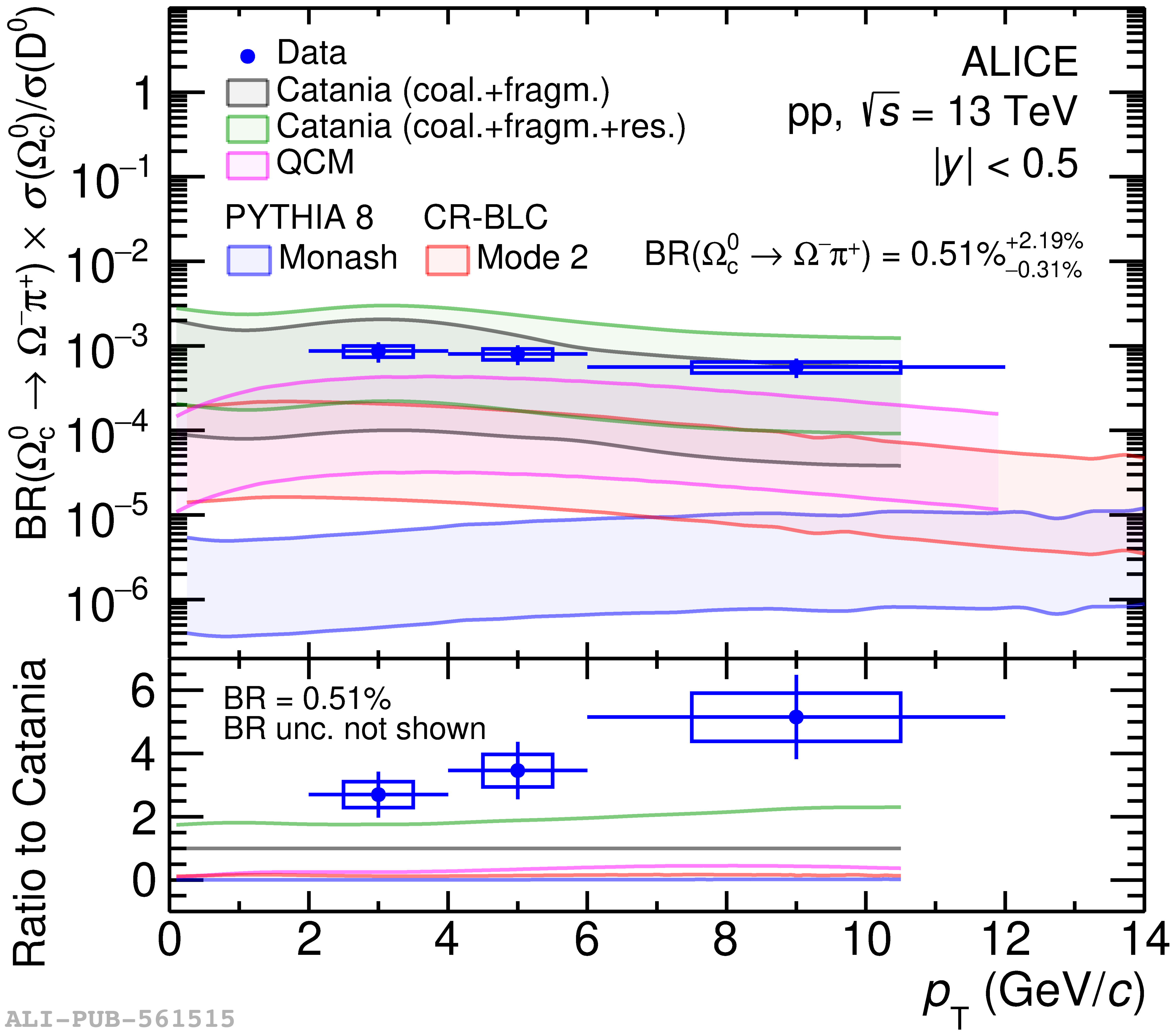
PLB 829 (2022) 137065





With 2 strangeness

Phys.Lett.B 846 (2023) 137625



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