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

MinJung Kweon
Inha University
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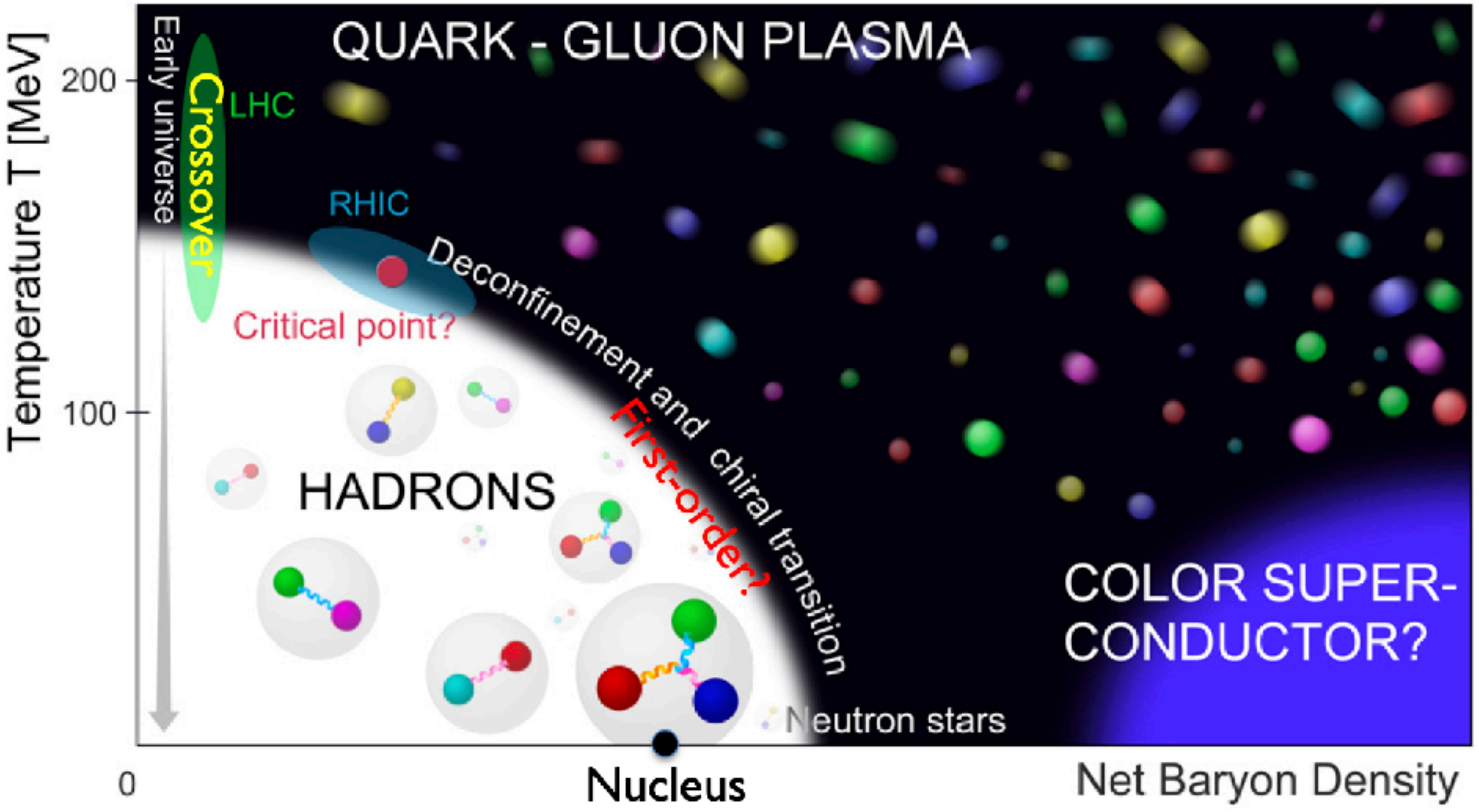
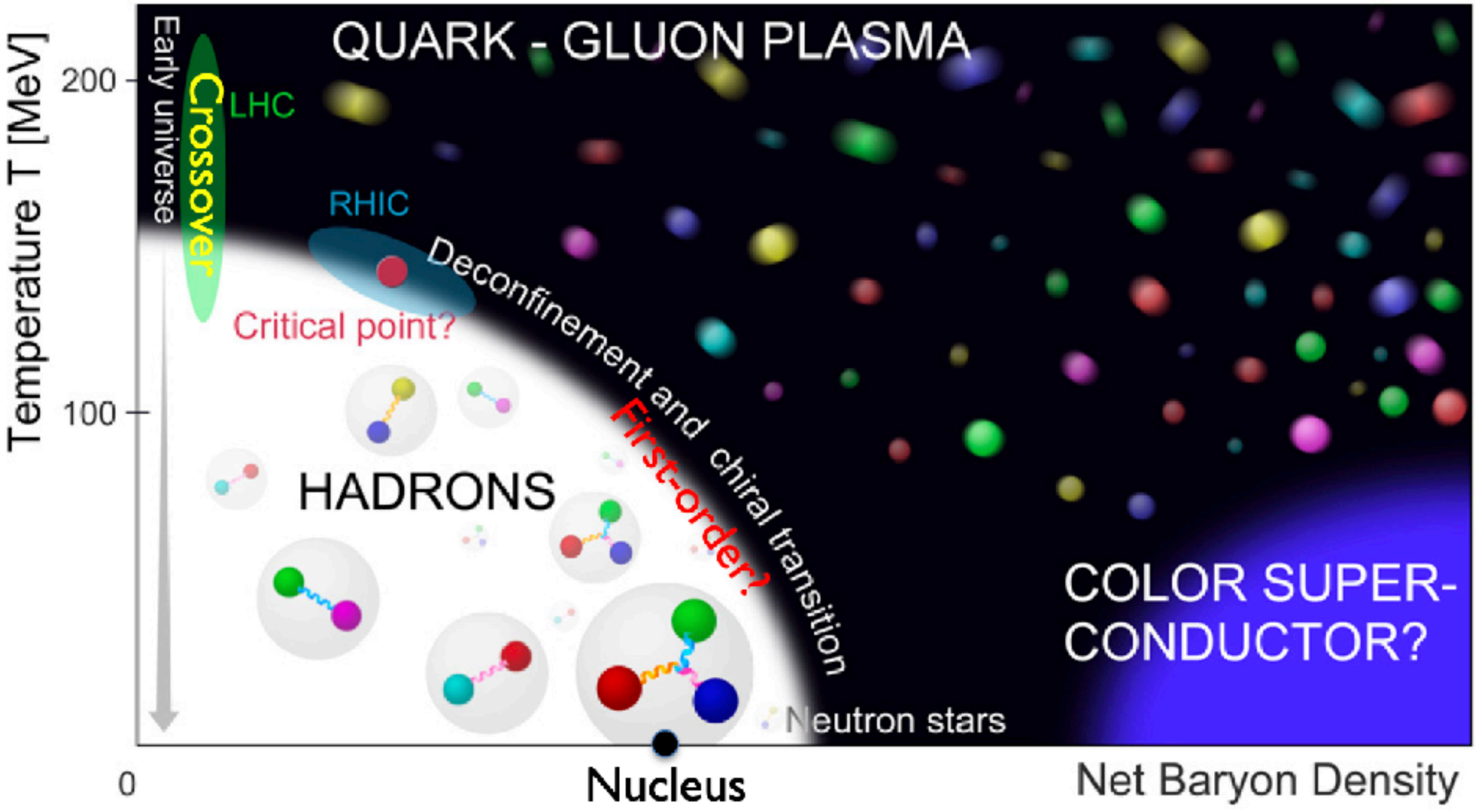
Hadronization



- 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



- 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.

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

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

Parton interaction with the medium

(Modified?) hadronization

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

Initial-state effects

"Vacuum" parton spectra

What we want to probe

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: hadronization

Parton interaction with the medium

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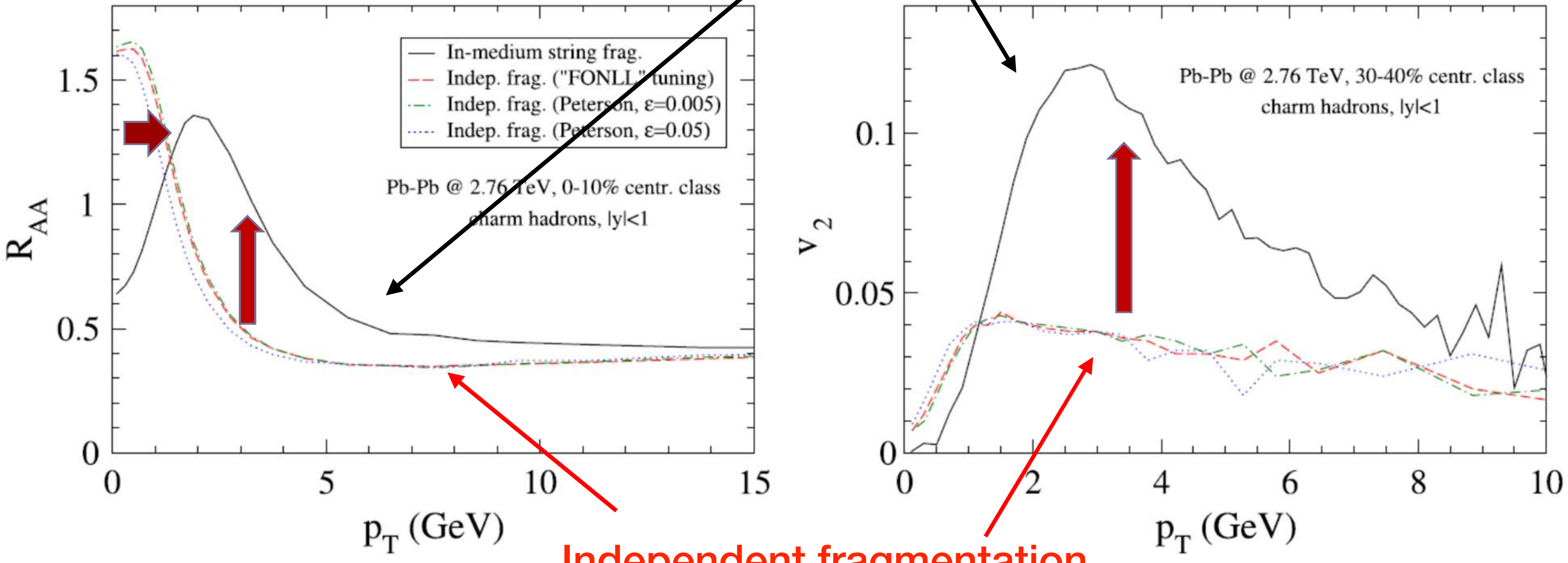
“Vacuum” parton spectra

In-medium hadronization



Independent fragmentation

Van Hees et al., PRC73 (2006) 034907

Rapp et al., NPA 979 (2018) 21

Heavy flavour production in medium: hadronization

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

Initial-state effects

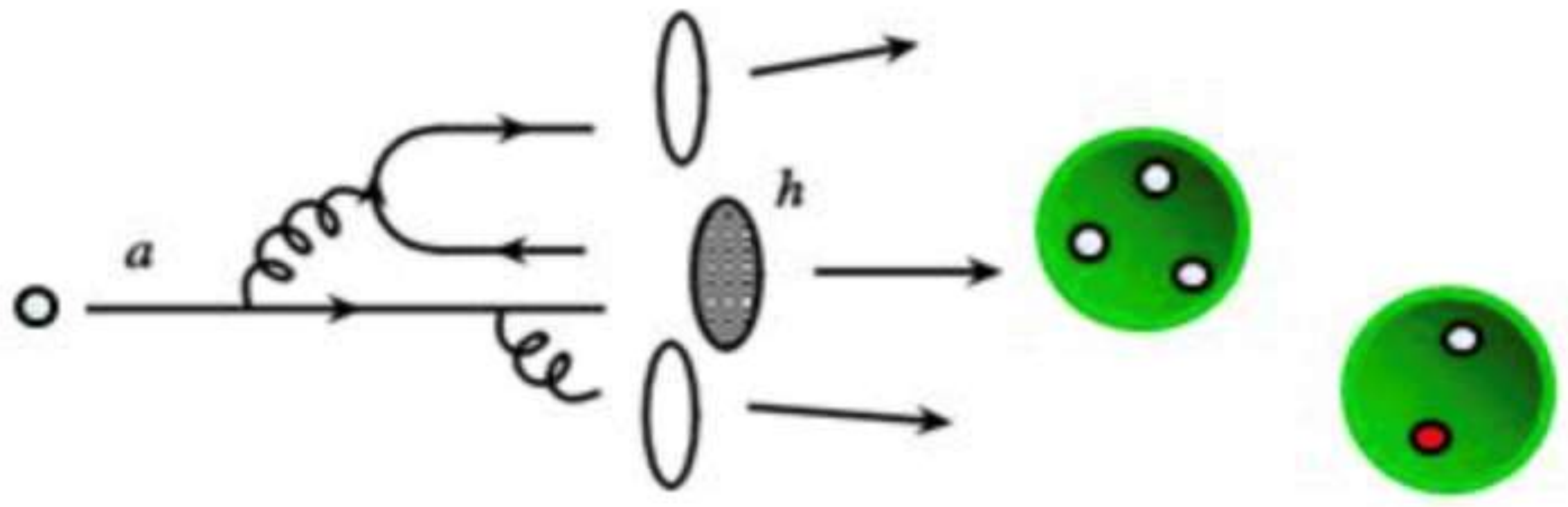
"Vacuum" parton spectra

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"



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

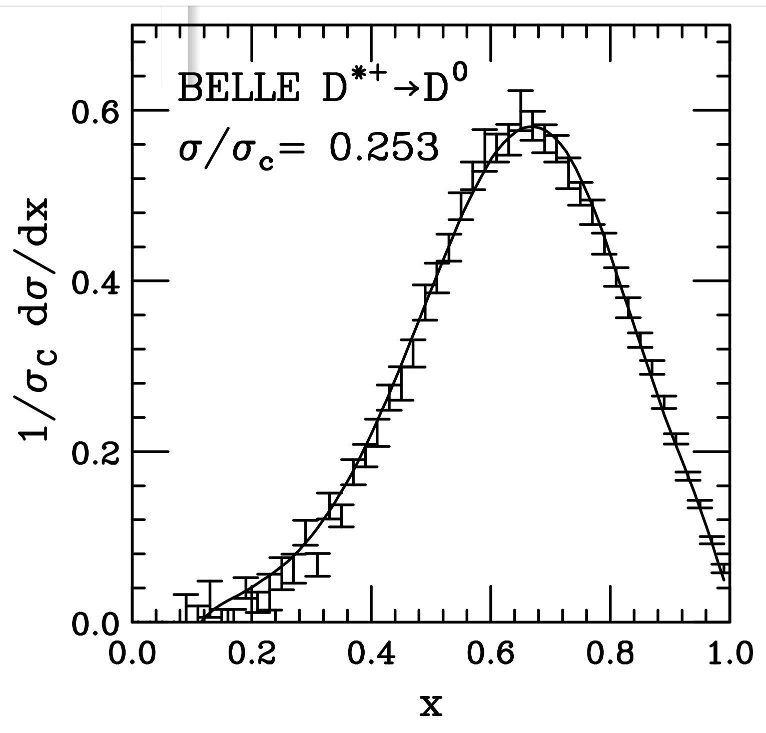
▷ is fragmentation function **universal**?
(i.e. are FF portable from e^+e^- to ep and pp?)

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 $\mathrm{FF}_{\mathrm{np}}$ not hold?

Zuzana Rúriková — Charm Fragmentation Function – June 7, 2006

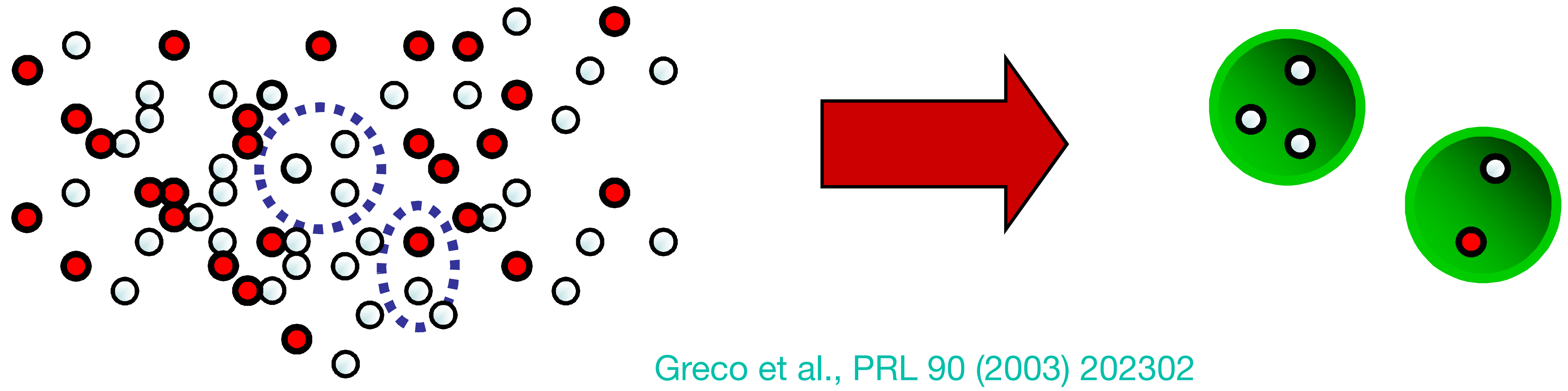
Hadronization in medium

- 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

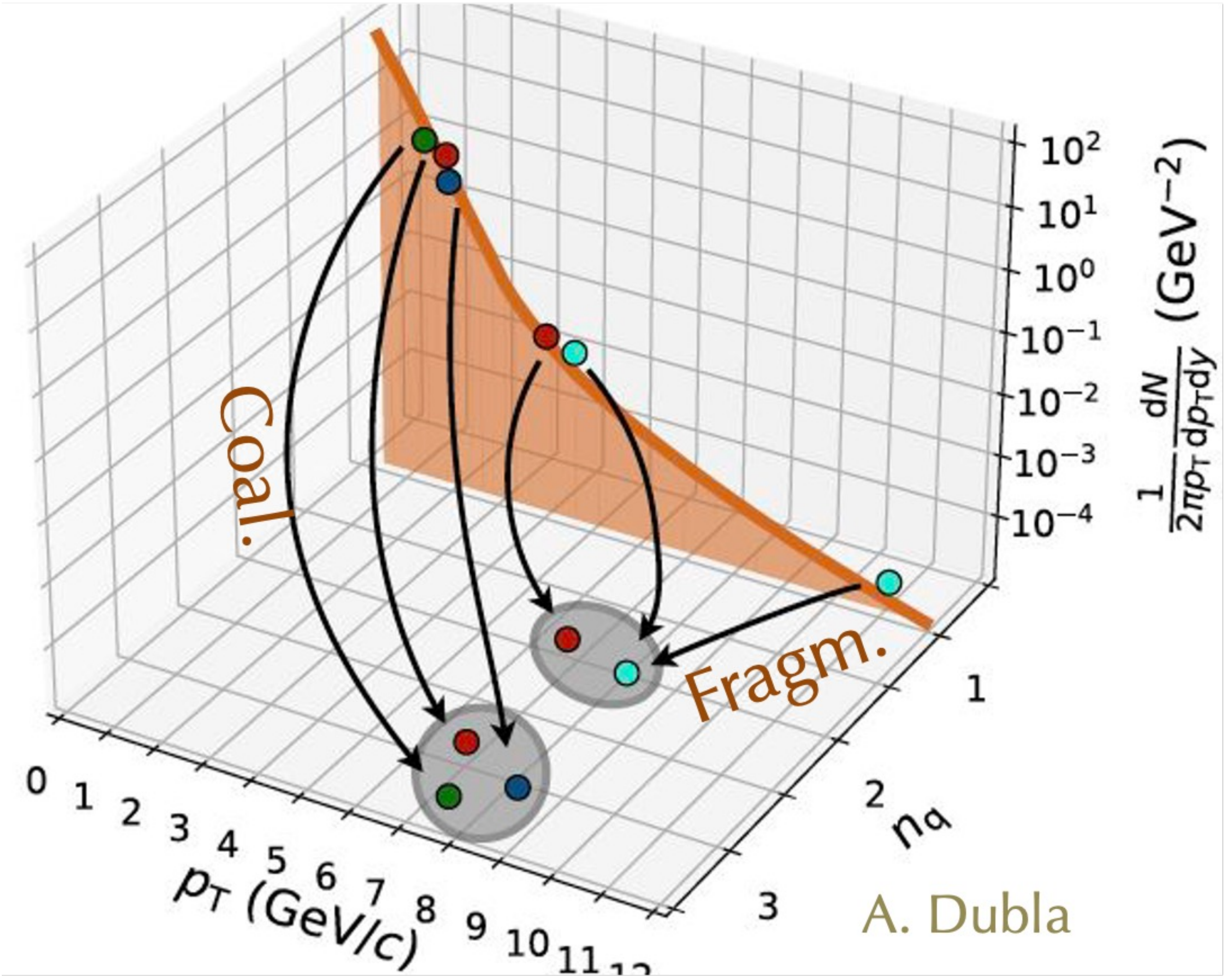
  → Partons that are “close” to each other in phase space (position and momentum) can simply recombine into hadrons



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

$$\frac{dN^D_{pp}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes D_{c\to D}(z)$$

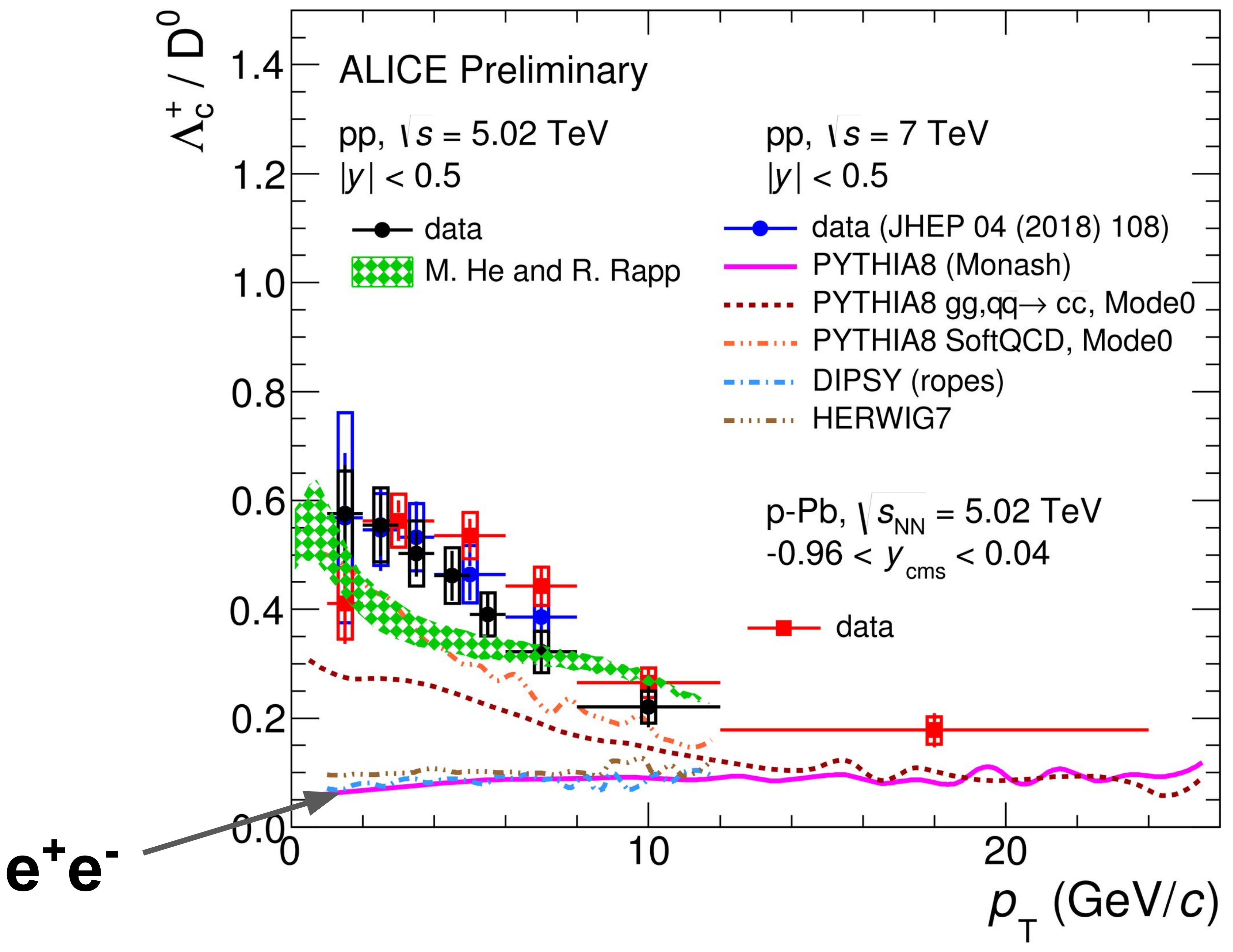
Initial-state effects

"Vacuum" parton spectra

hadronization

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

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



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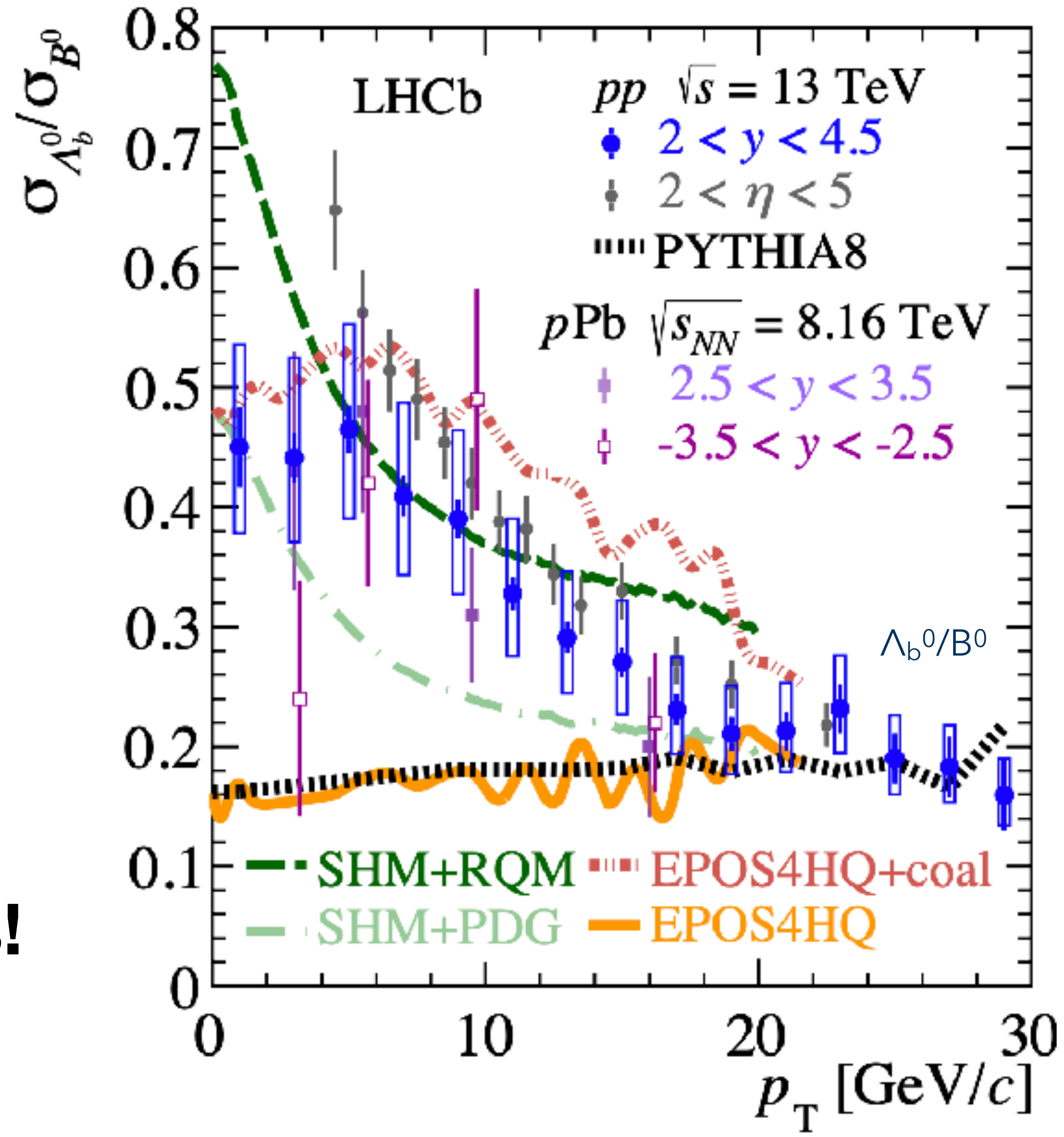
Λ_b/B^0 → Similar trend in charm and beauty sectors!



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)

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

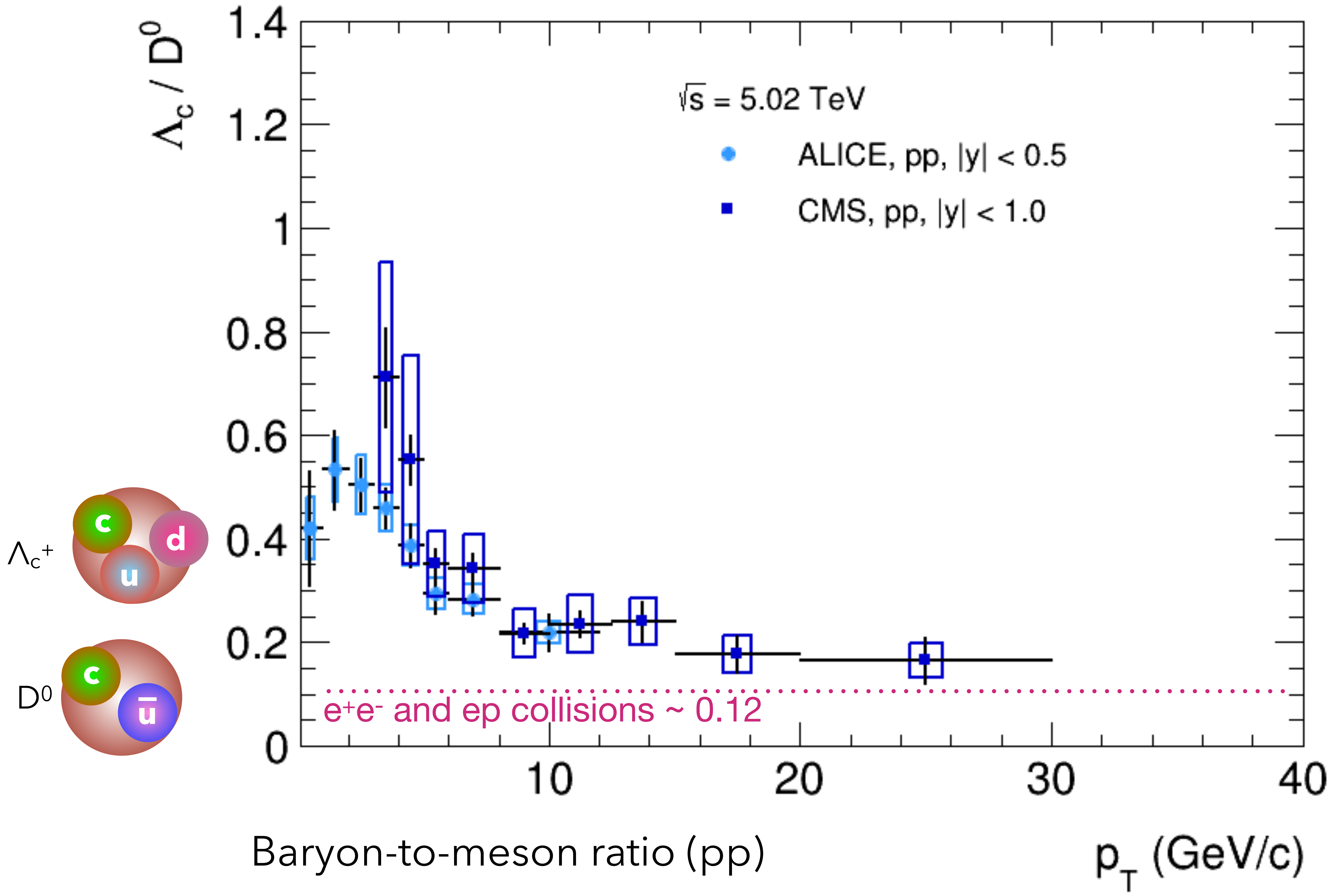
- **Coalescence:**
  → recombination of partons in QGP close in phase space

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

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

- **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

Charm baryon vs. meson production

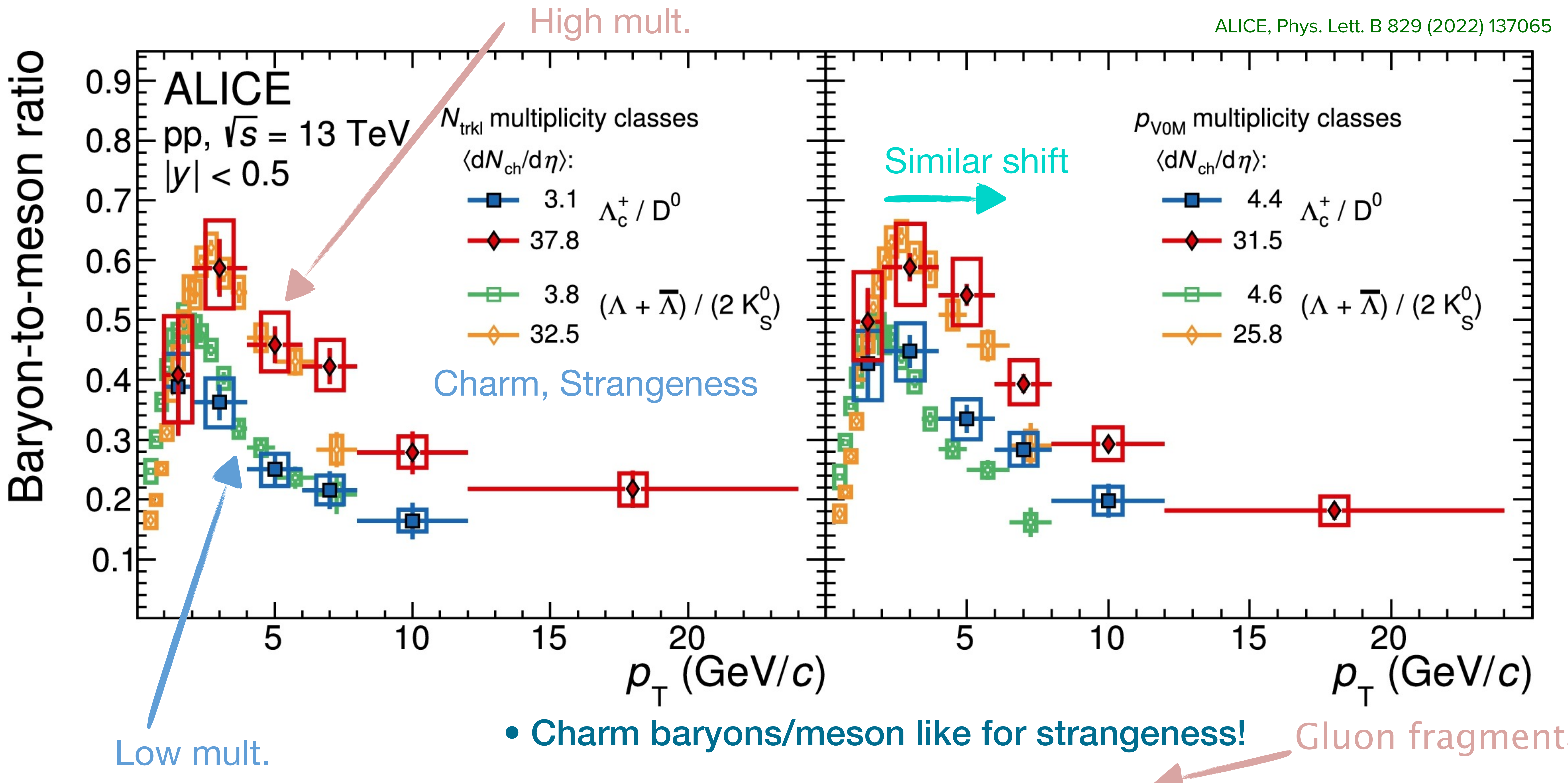


Baryon-to-meson ratio (pp)

- Strong p_T dependence in charm sector
- Enhancement compared to the measurement in e^+e^- and e^-p collisions
- Similar to the light flavor sector?

ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, pp, JHEP 12 (2023) 086
CMS, pp, PbPb, JHEP 01 (2024) 128

Charm vs. light baryon-to-meson ratio



pp

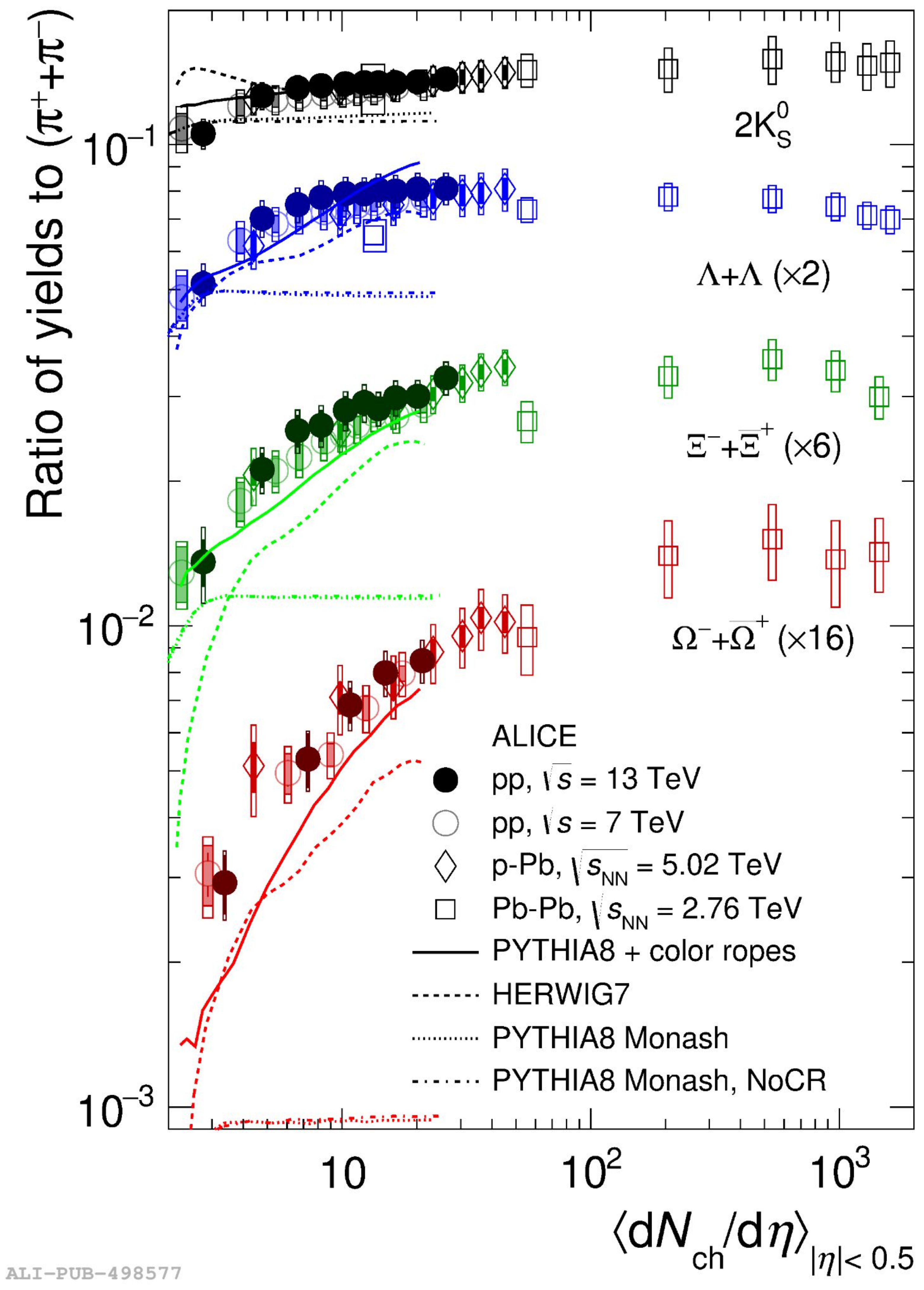
- Charm baryons/meson like for strangeness!
- Hint at a common mechanism for light- and charm-baryon formation in hadronic collisions at LHC energies.

Gluon fragmentation…

Charm quark fragmentation…

Role of strangeness in heavy-quark hadronization

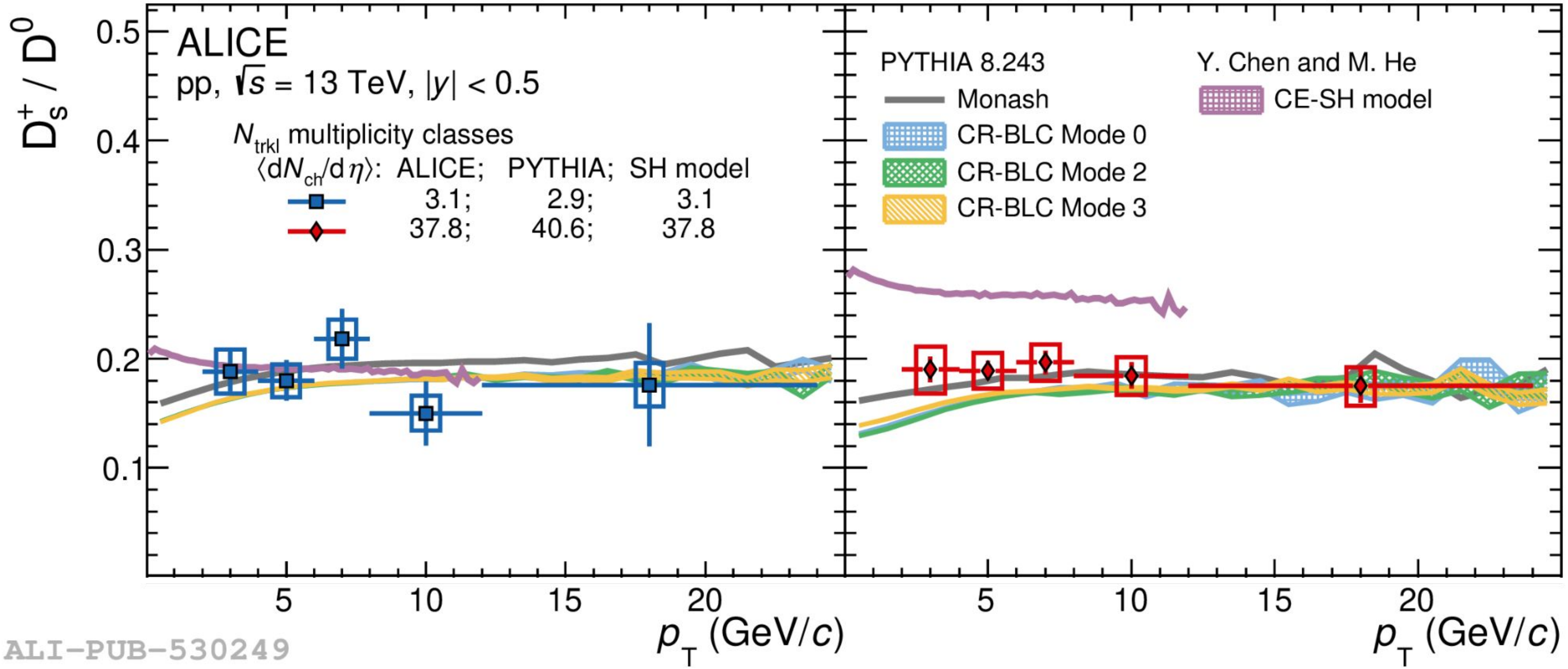
Eur. Phys. J. C 80 (2020) 693

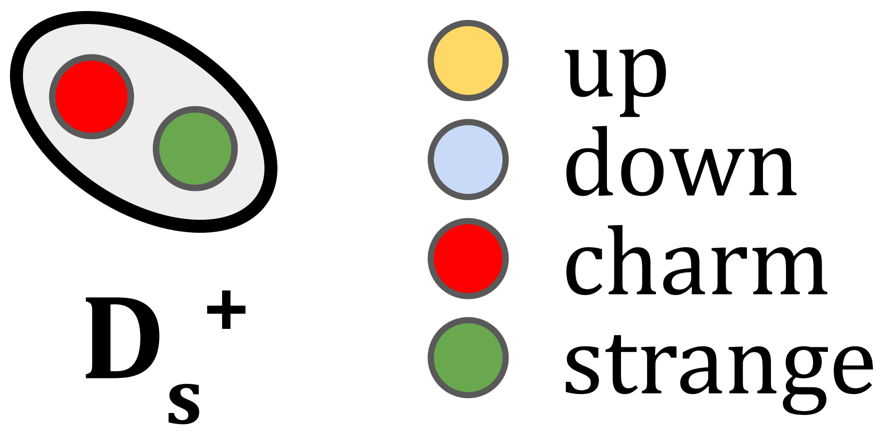


- Strangeness enhancement: yield-ratio between (multi)strange hadrons and pion larger in heavy-ion collisions than minimum-bias pp collisions
- Smooth increase vs. event multiplicity, without a clear collision-system dependence
- What do we learn from strange D-meson production about heavy-quark hadronization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

D_s^+: strange charm meson

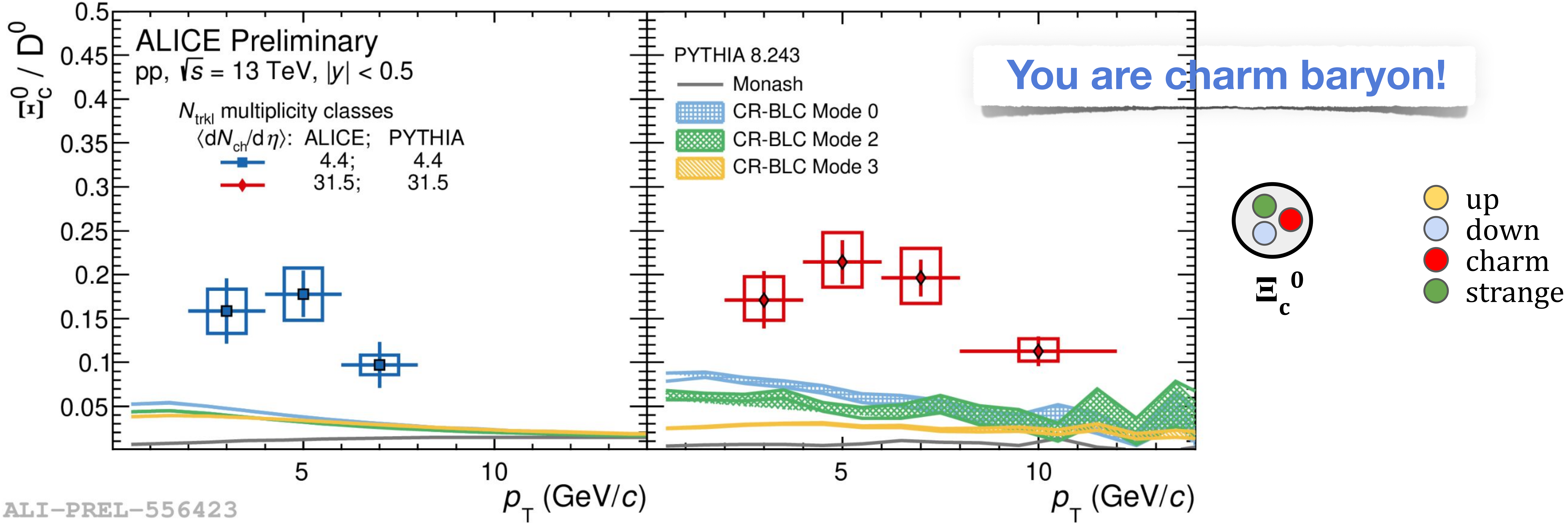
📚 Phys.Lett.B 829 (2022) 137065





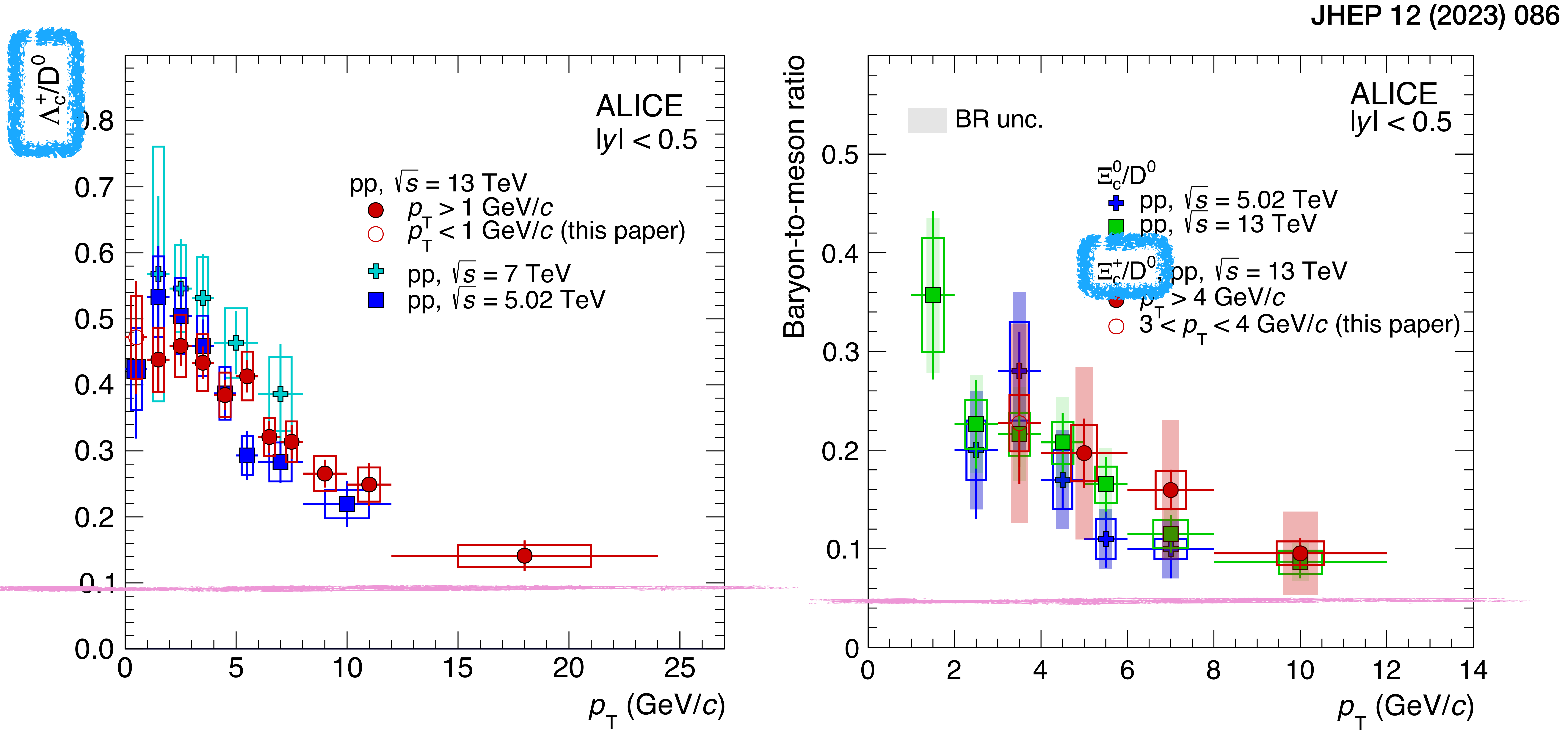
- D_s^+/D^0 ratio are independent of p_T
- No strong multiplicity dependency
- Comparable with measurement at e^+e^- and e^-p collisions

What about strangeness charm baryon?



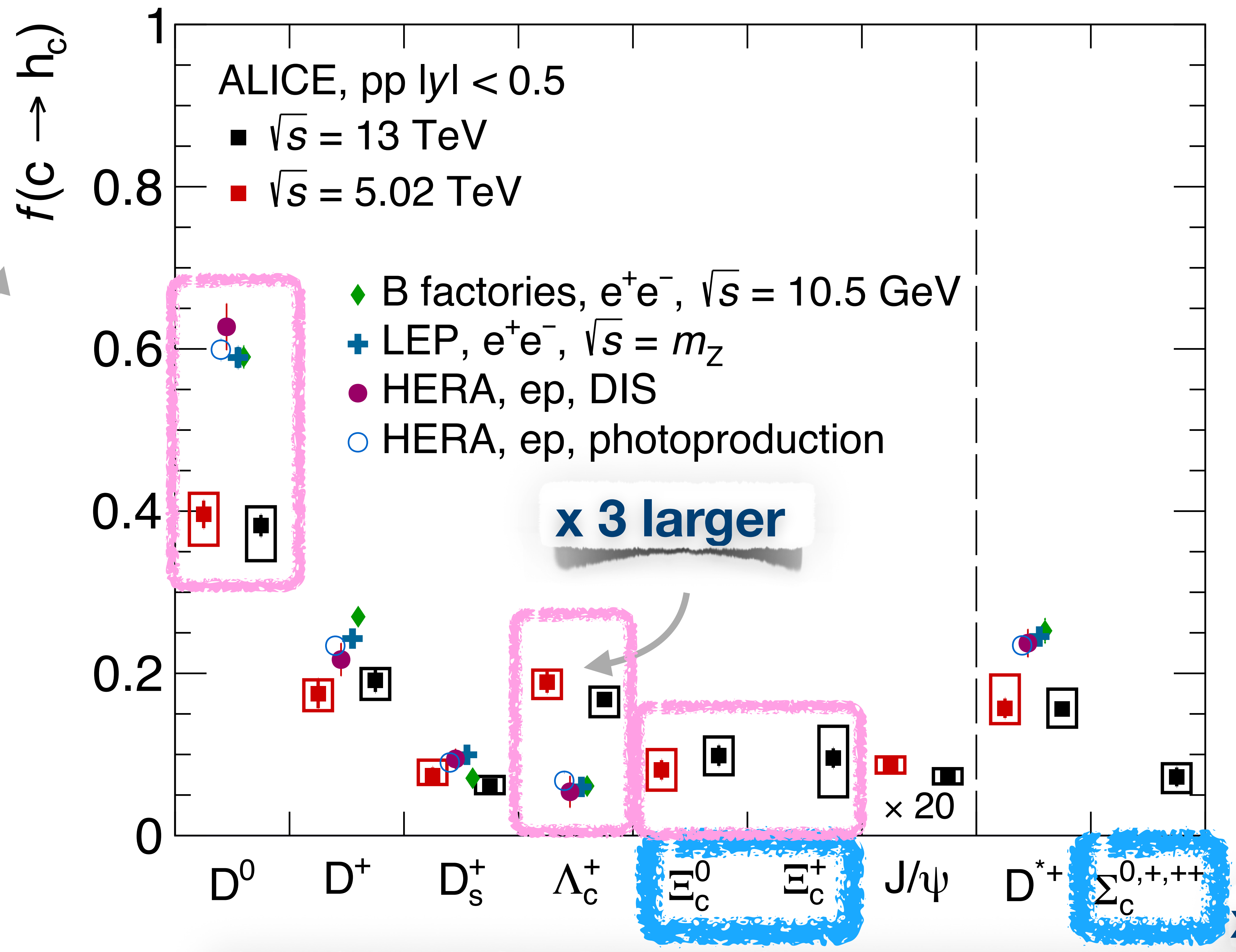
- Strong p_T dependence
- Enhancement compared to the measurement in e^+e^- and e^-p collisions

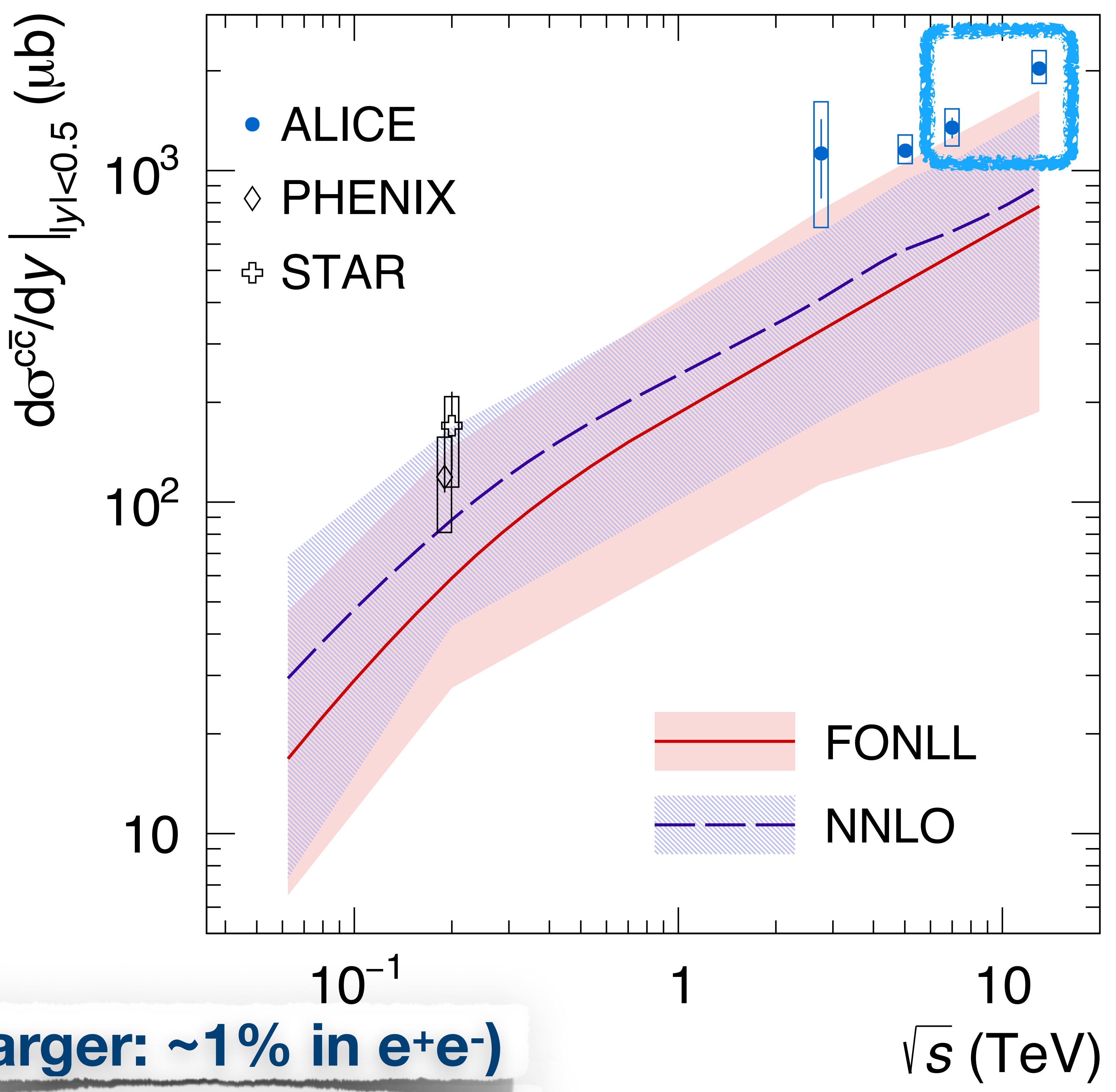
Charm baryon production in pp at a glance



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

Charm-quark fragmentation fraction





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^+

JHEP 12 (2023) 086

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

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

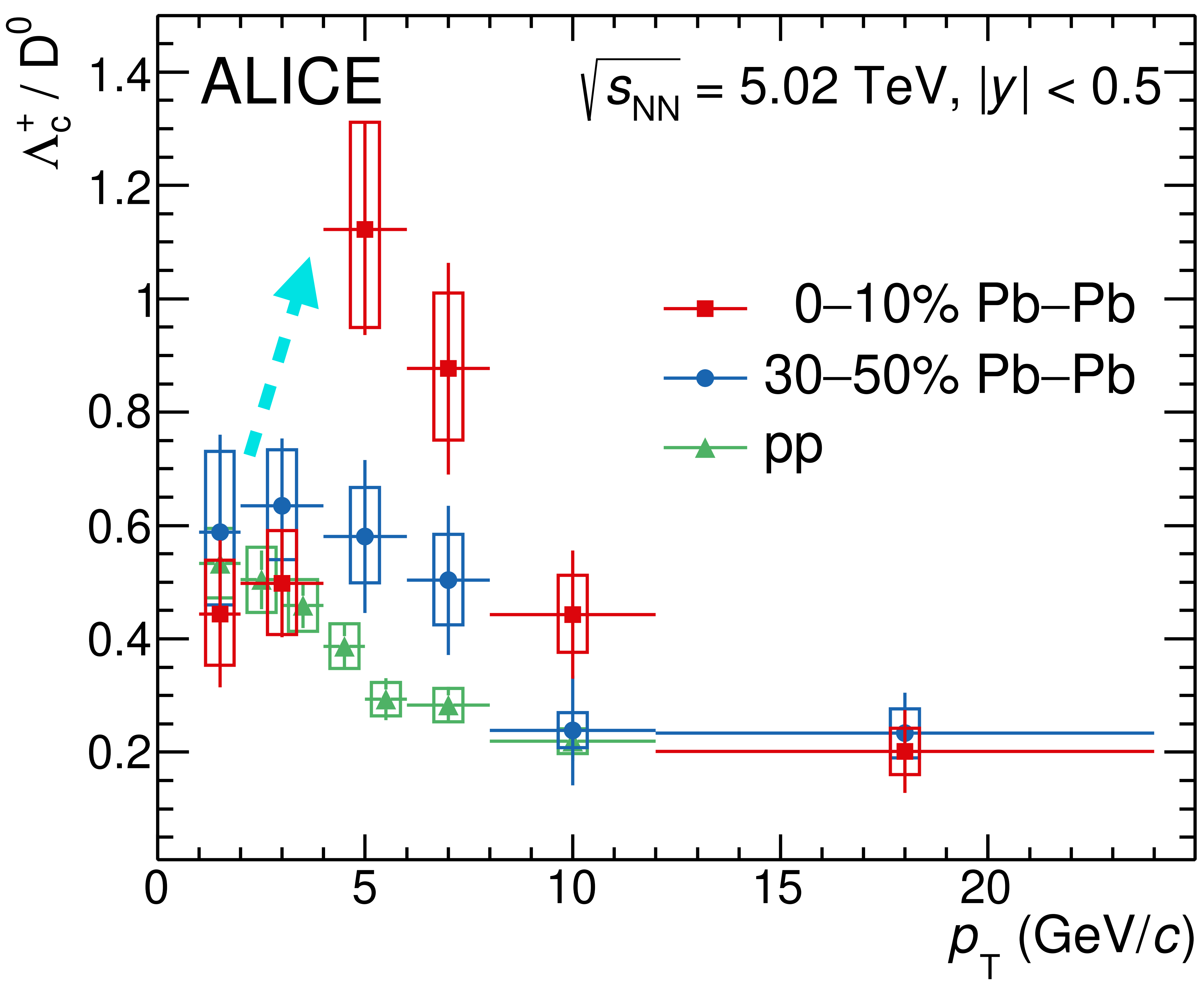
Σ_c^0: Larger feed-down to Λ_c^+ (40%, 17% in e^+e^-)

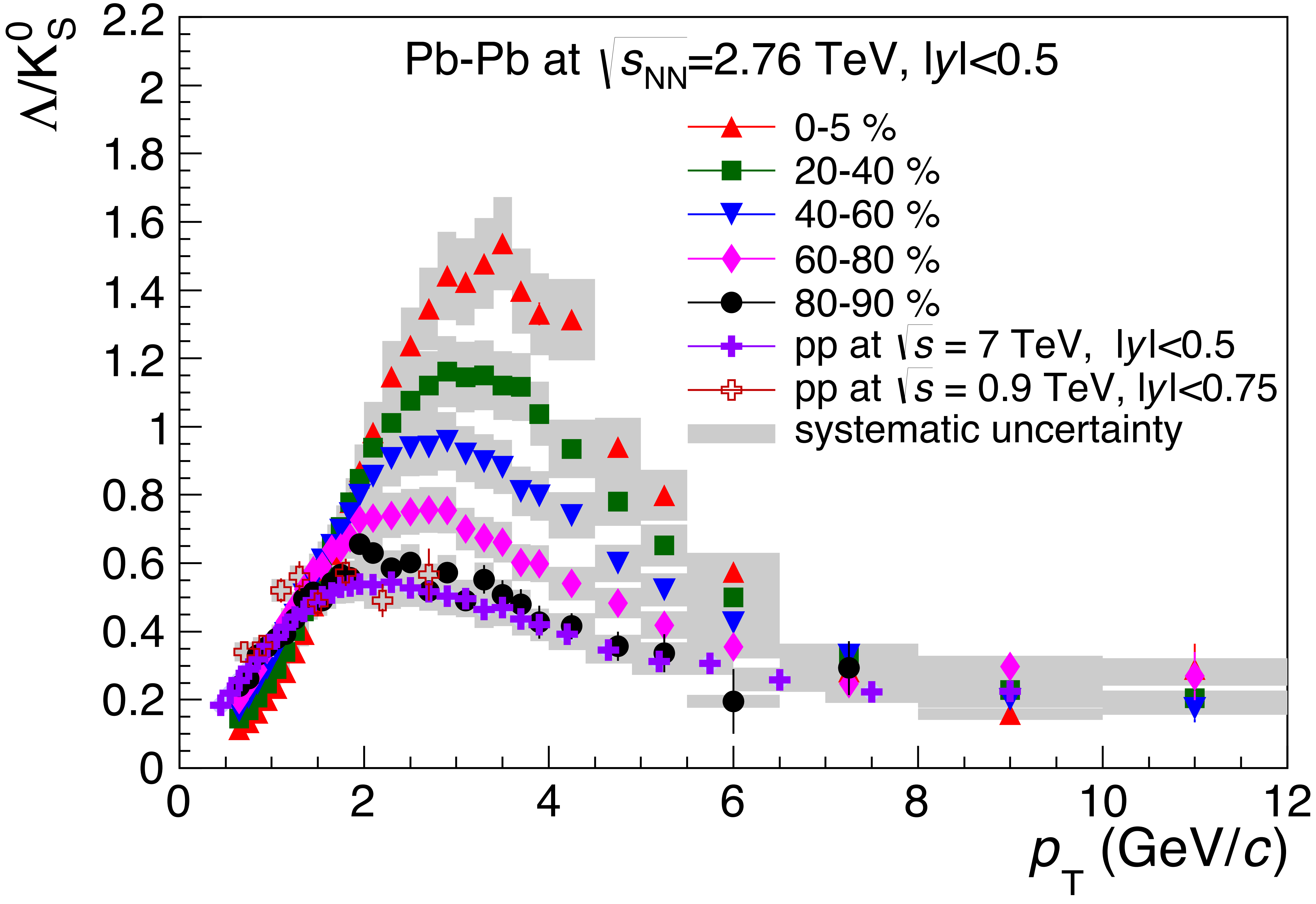
Normalized by the sum of the p_T-integrated cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+ , Ξ_c^0, Ξ_c^+

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

How about in Pb–Pb?

Physics Letters B 839 (2023) 137796

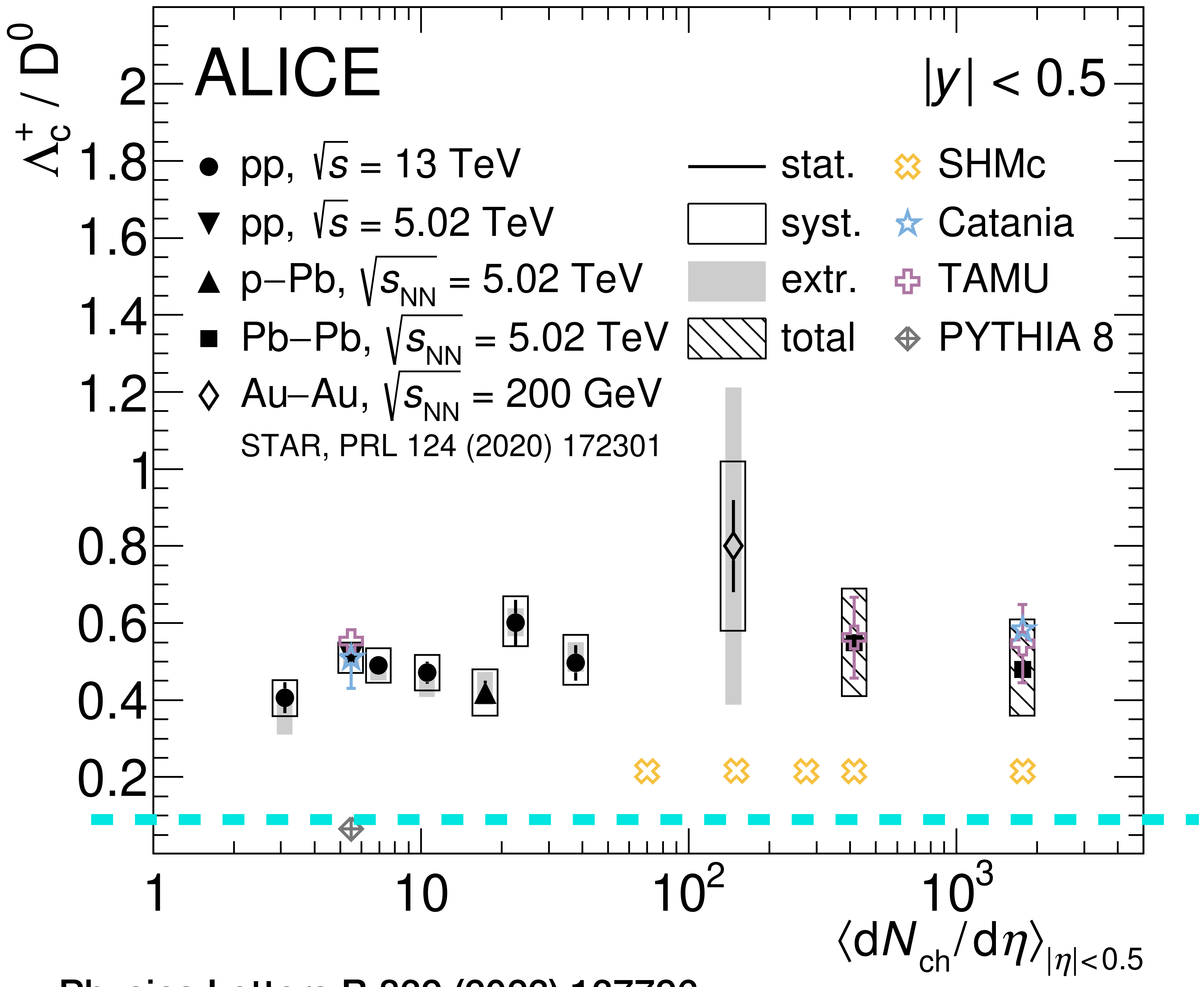




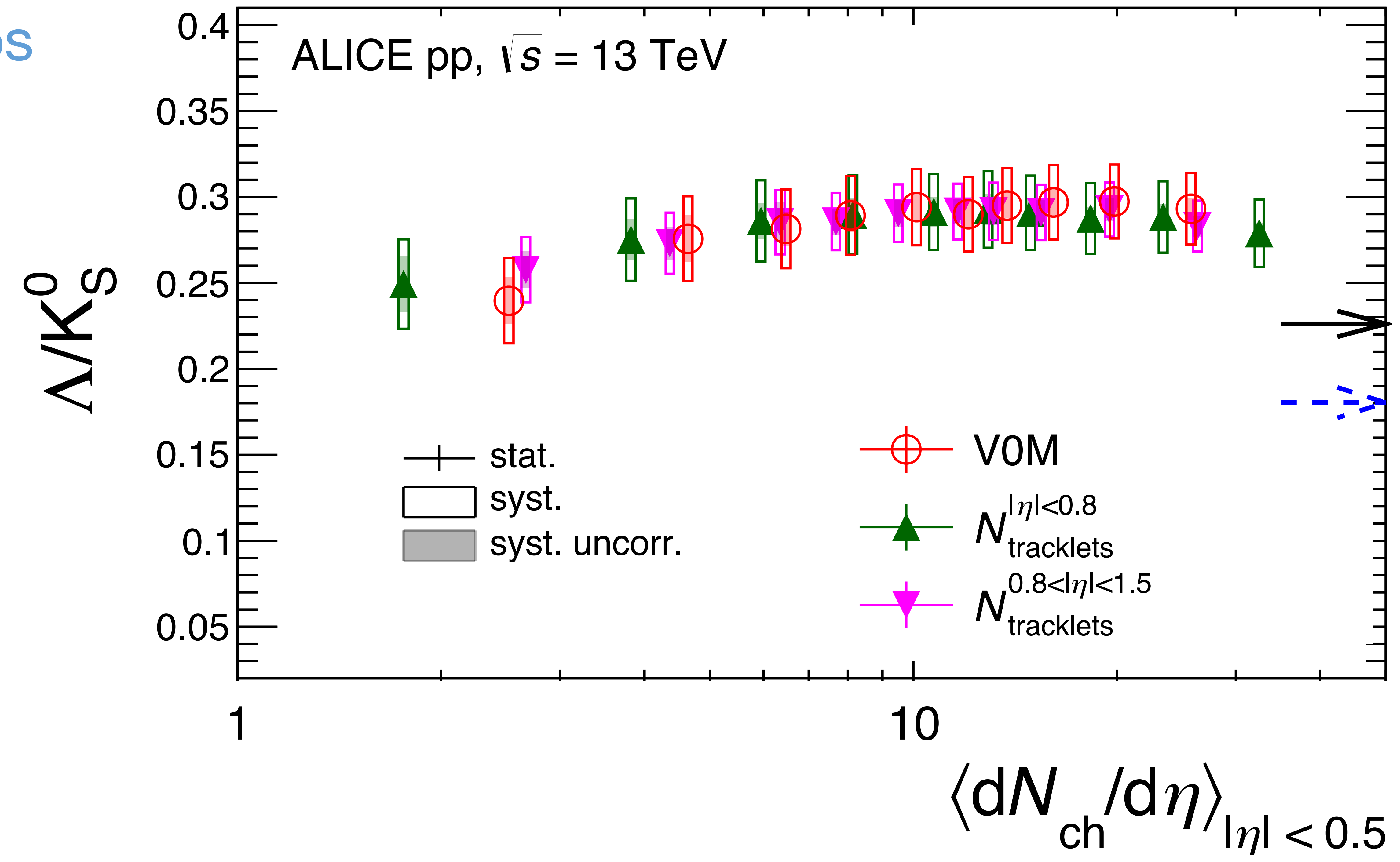
- Ratio increases from pp to mid-central and central Pb-Pb at intermediate p_T
- Trend qualitatively similar to what is observed for Λ/K_s^0 ratios

Where does the p_T differential enhancement come from?

p_T-integrated and to $p_T > 0$ extrapolated Λ_c^+/D^0 ratios



Physics Letters B 839 (2023) 137796



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

Moving to beauty sector

Phys. Rev. D 108, 112003 (2023)

FONNL calculations based on using fragmentation fraction from e^+e^- and $f(b\to\Lambda_b^0)/f(b\to B)$ LHCb measurement

Non-prompt Λ_c^+ largely from the beauty baryons: good to investigate beauty baryon hadronization via non-prompt Λ_c^+

Note: should consider different decay kinematics
→ slightly modify p_T dependence

Similar trend to the charm measurement!

Beauty-quark fragmentation fraction

Phys. Rev. D 108, 112003 (2023)

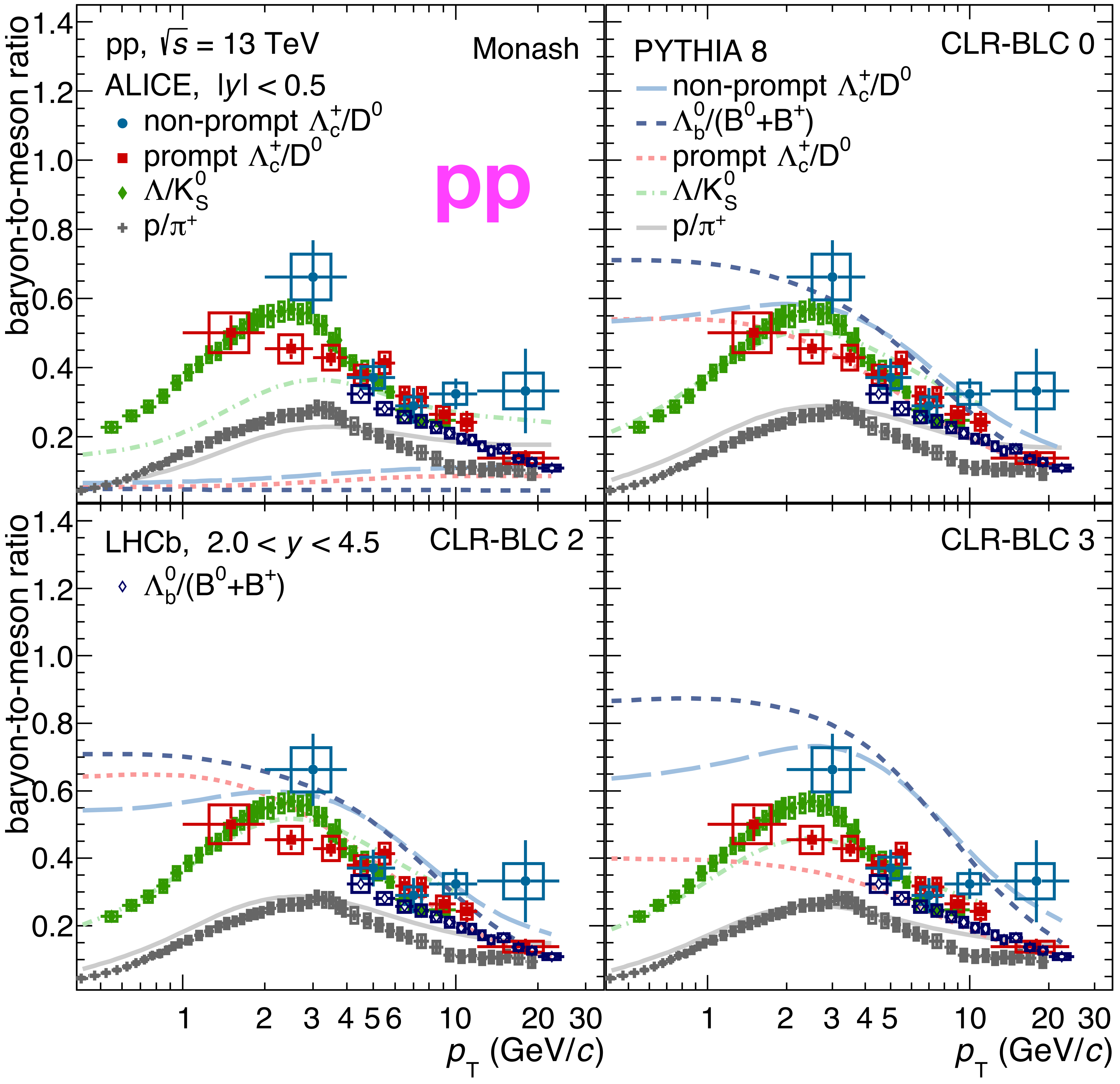
Table 2: p_T-integrated Λ_c^+/D^0 production ratio measured at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 13$ TeV and in e^+e^- collisions at LEP [68] for prompt and non-prompt production.

	pp: ALICE	e^+e^-: LEP average [68]
prompt Λ_c^+/D^0	$0.49 \pm 0.02(\text{stat})^{+0.05}_{-0.04}(\text{syst})^{+0.01}_{-0.03}(\text{syst})$ [60]	0.105 ± 0.013
non-prompt Λ_c^+/D^0	$0.47 \pm 0.06(\text{stat}) \pm 0.04(\text{syst})^{+0.03}_{-0.04}(\text{extrap})$	0.124 ± 0.016

Significantly higher than that measured in e^+e^-

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

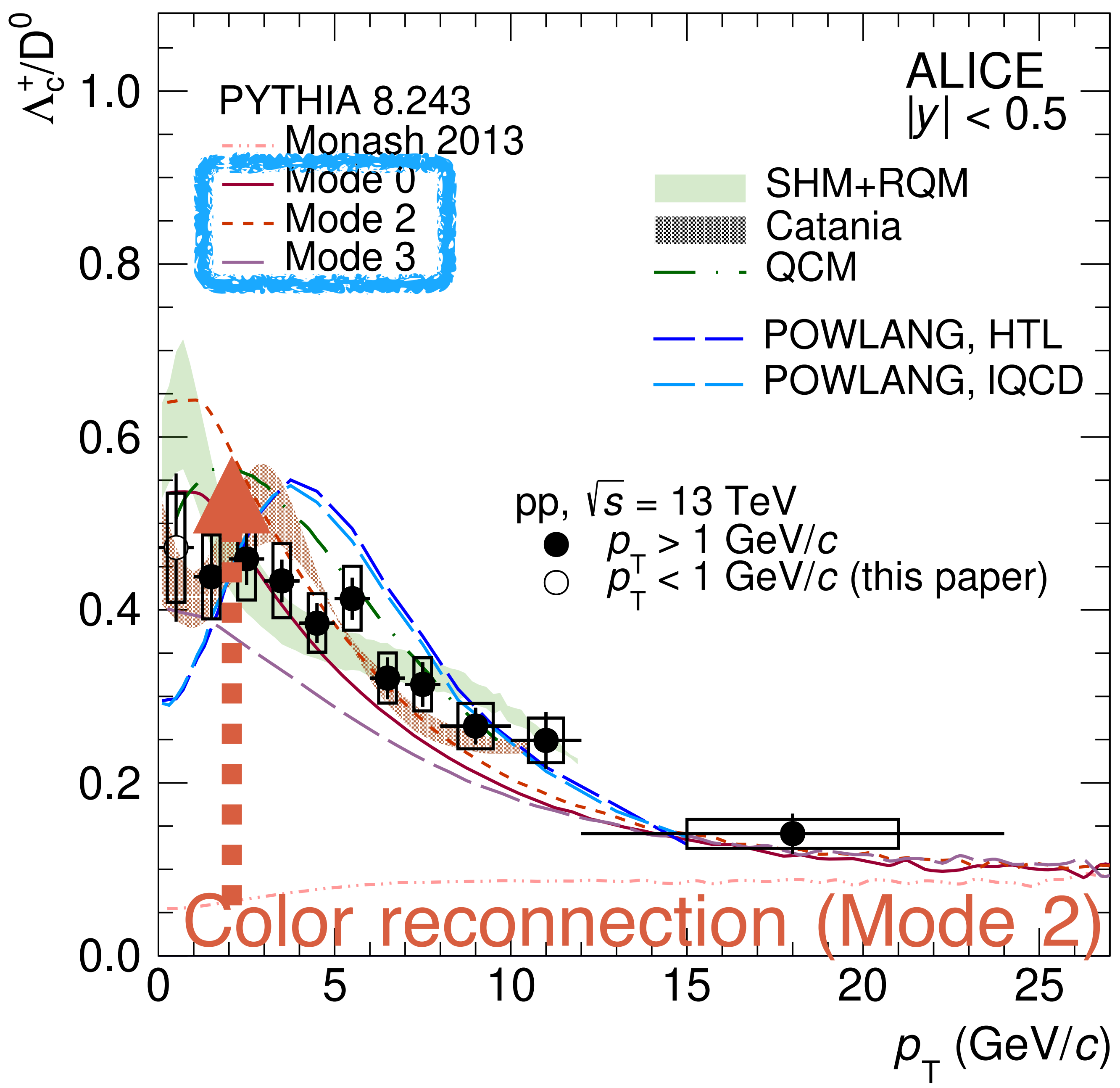
→ Similar baryon-formation mechanism among light, strange, charm and beauty hadrons?

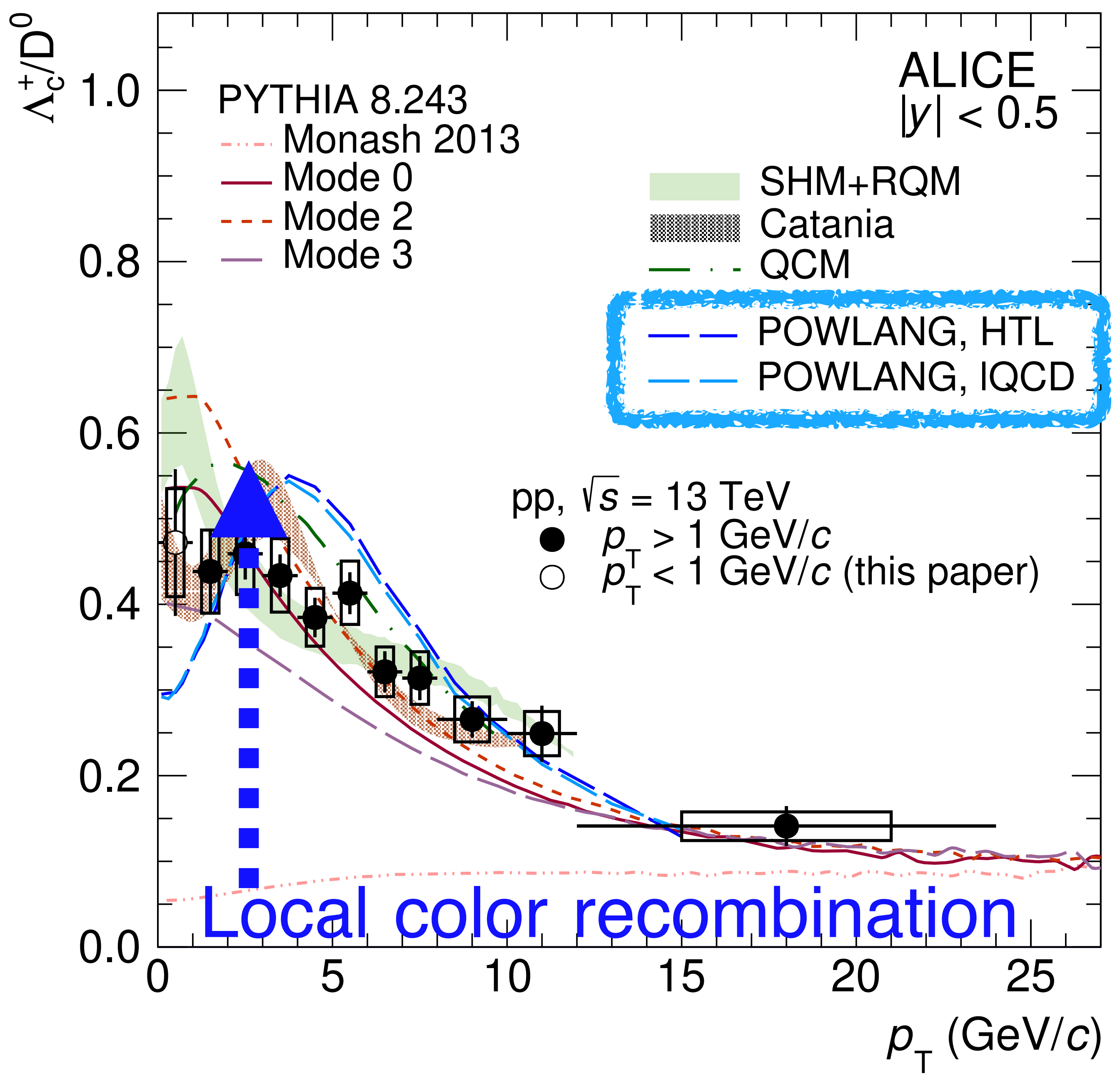
- non-prompt Λ_c^+/D^0
- prompt Λ_c^+/D^0
- Λ/K^0_S
- p/π^+
- $\Lambda_b^0/(B^0+B^+)$

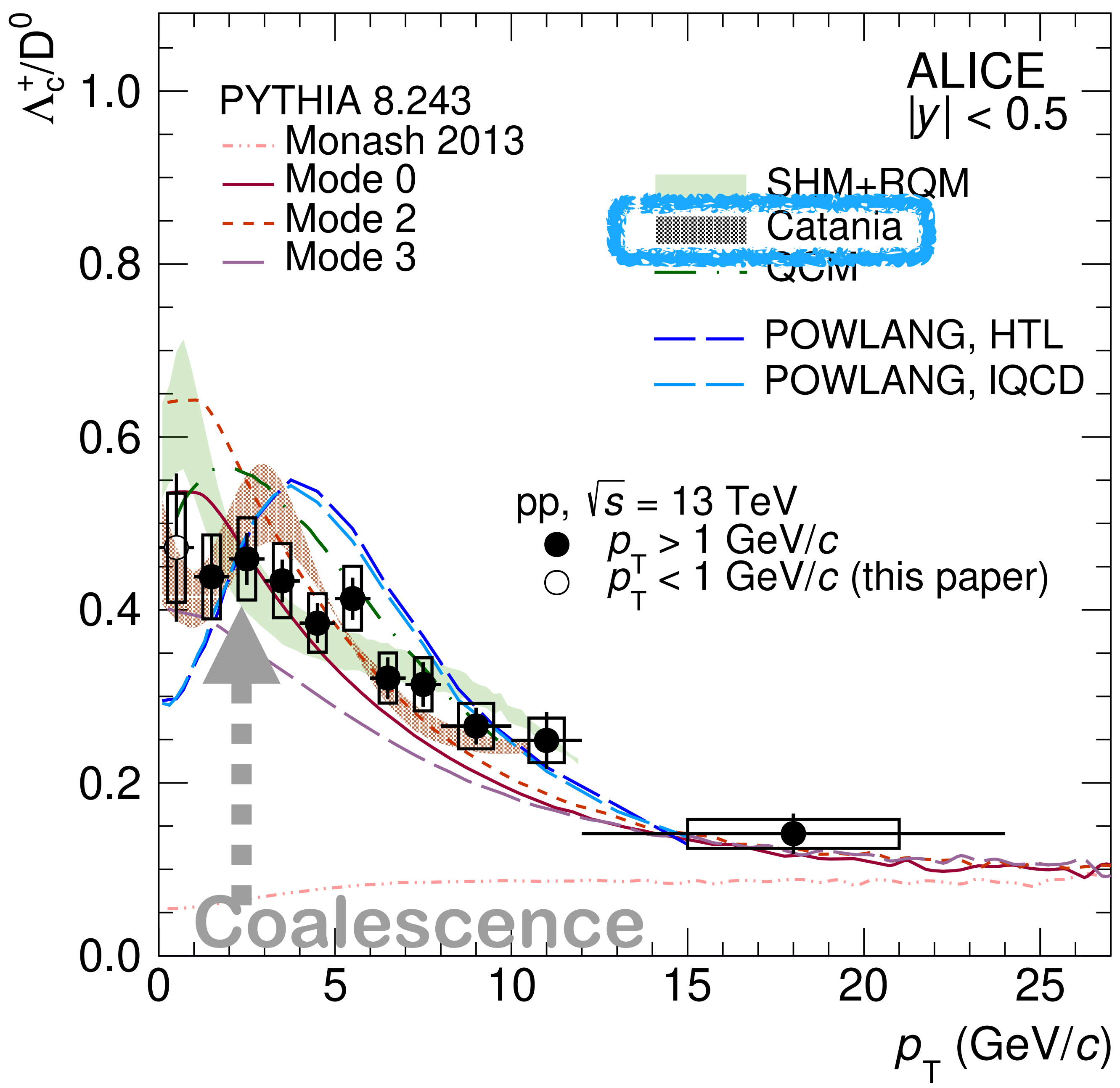
Note: for LHCb, different normalization & should consider decay kinematics (for the other case)
* These three tunes are characterized by different constraints on the time dilation and causality

OK, how do we explain? HF 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)

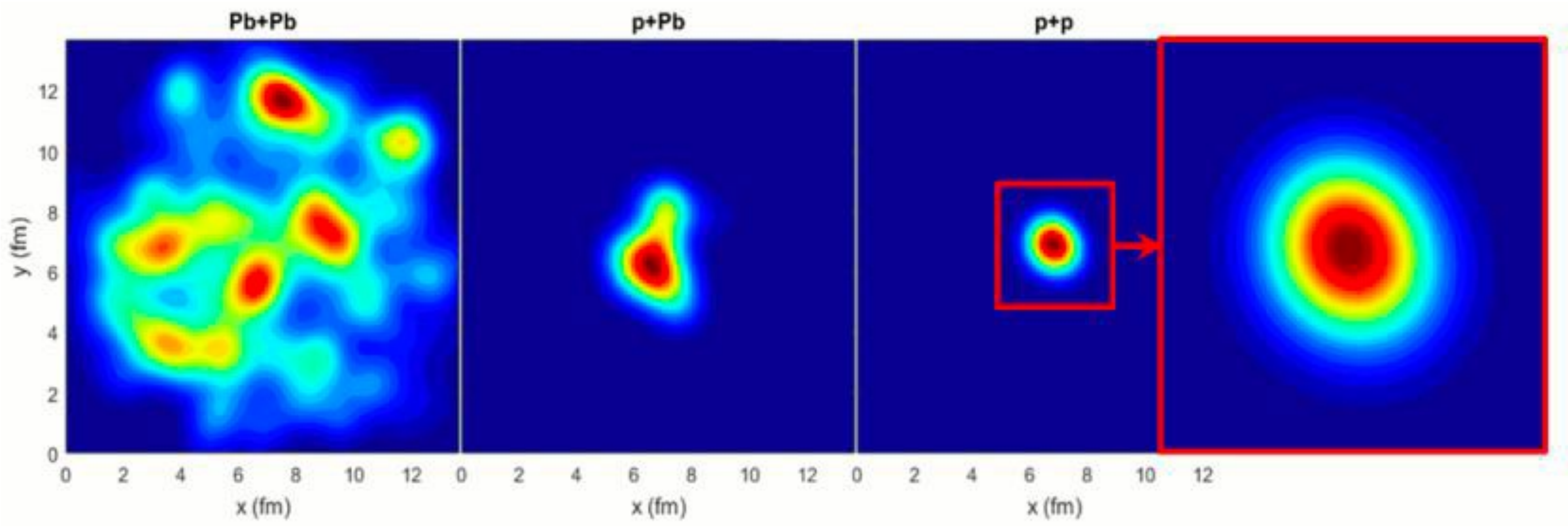






- Different hadronization mechanisms proposed!
- Similar to the light flavor sector?

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

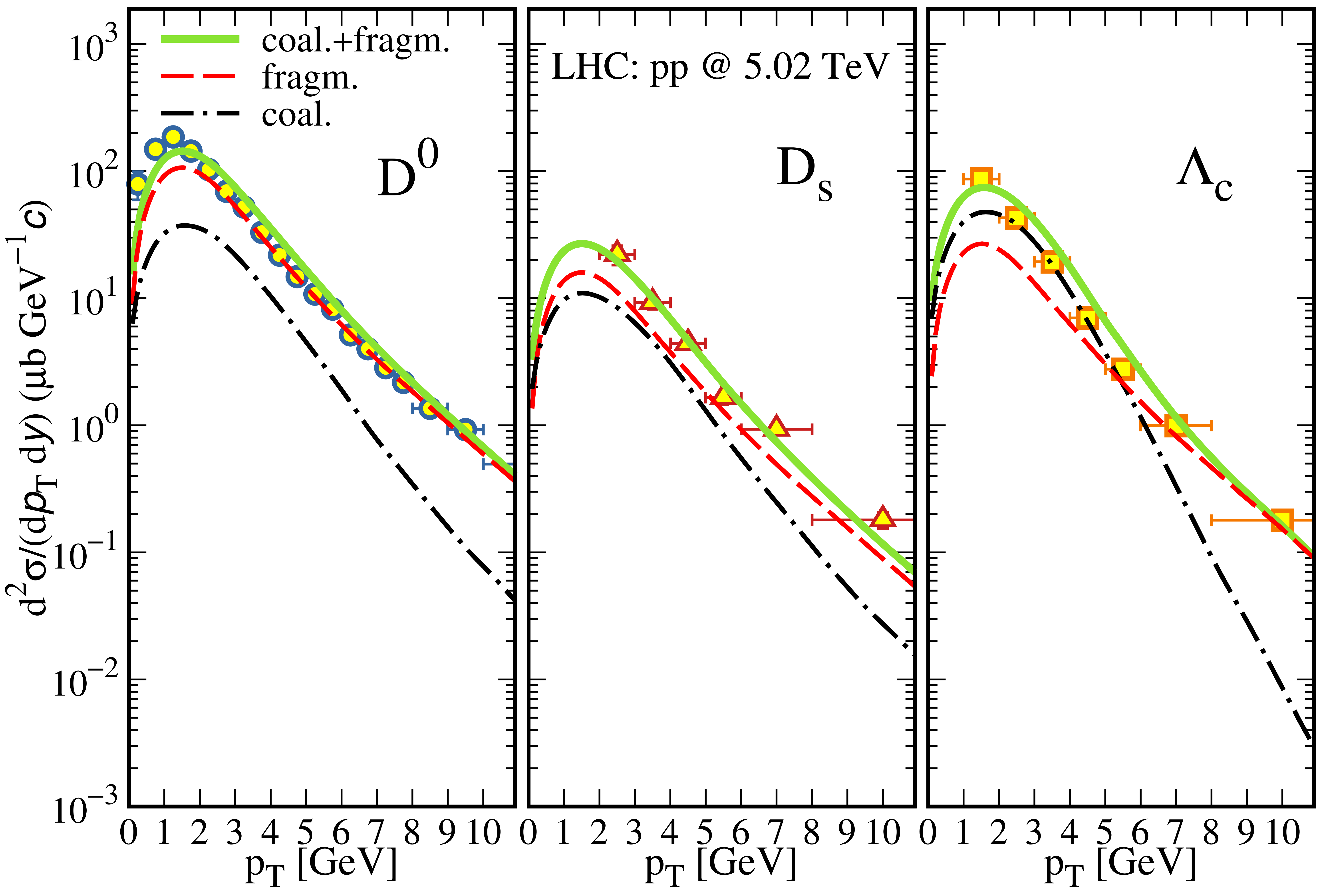
+ $f_c(p)$ from **FONNL distribution**

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

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

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

Coalescence in pp vs p_T in Catania

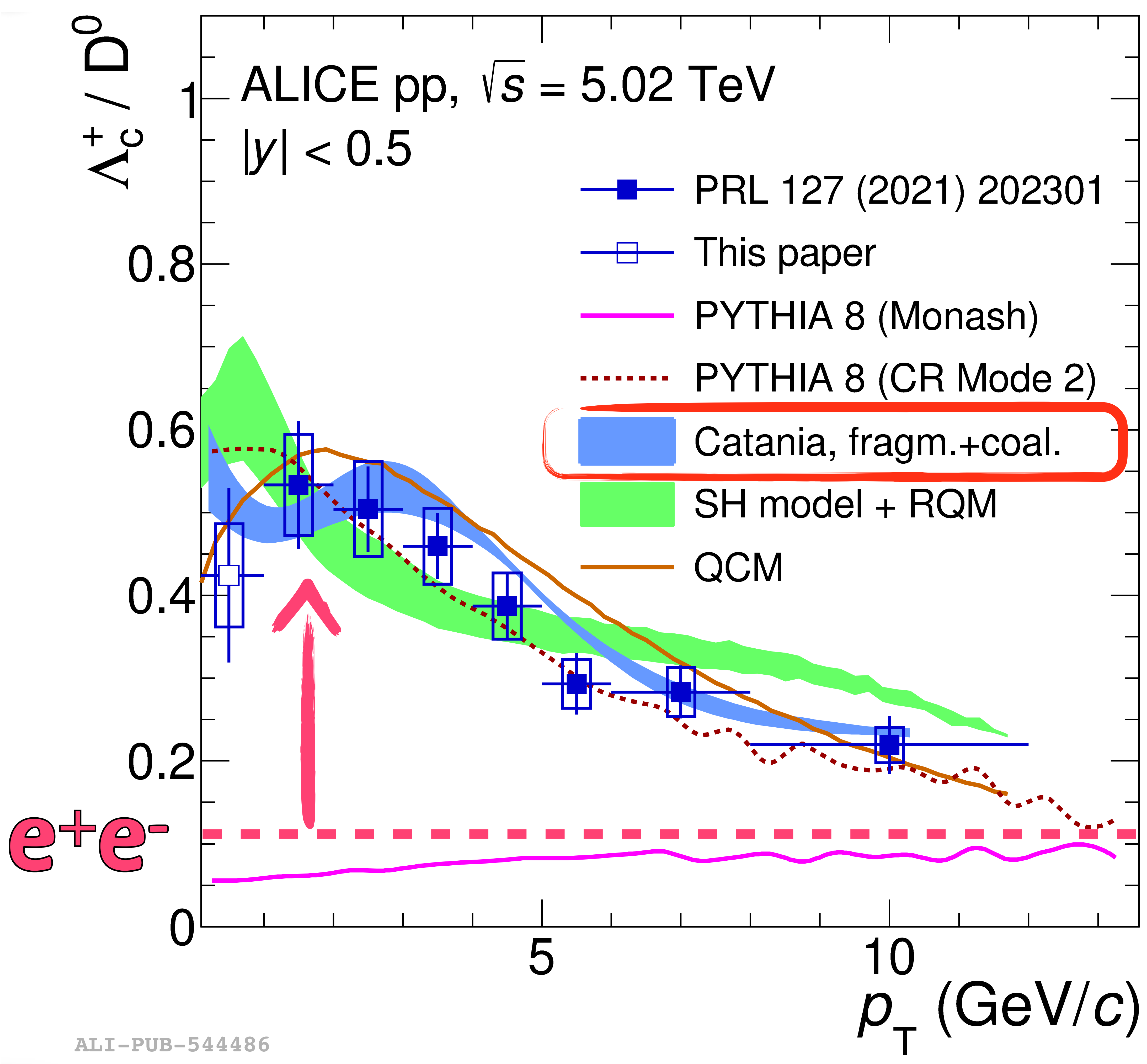


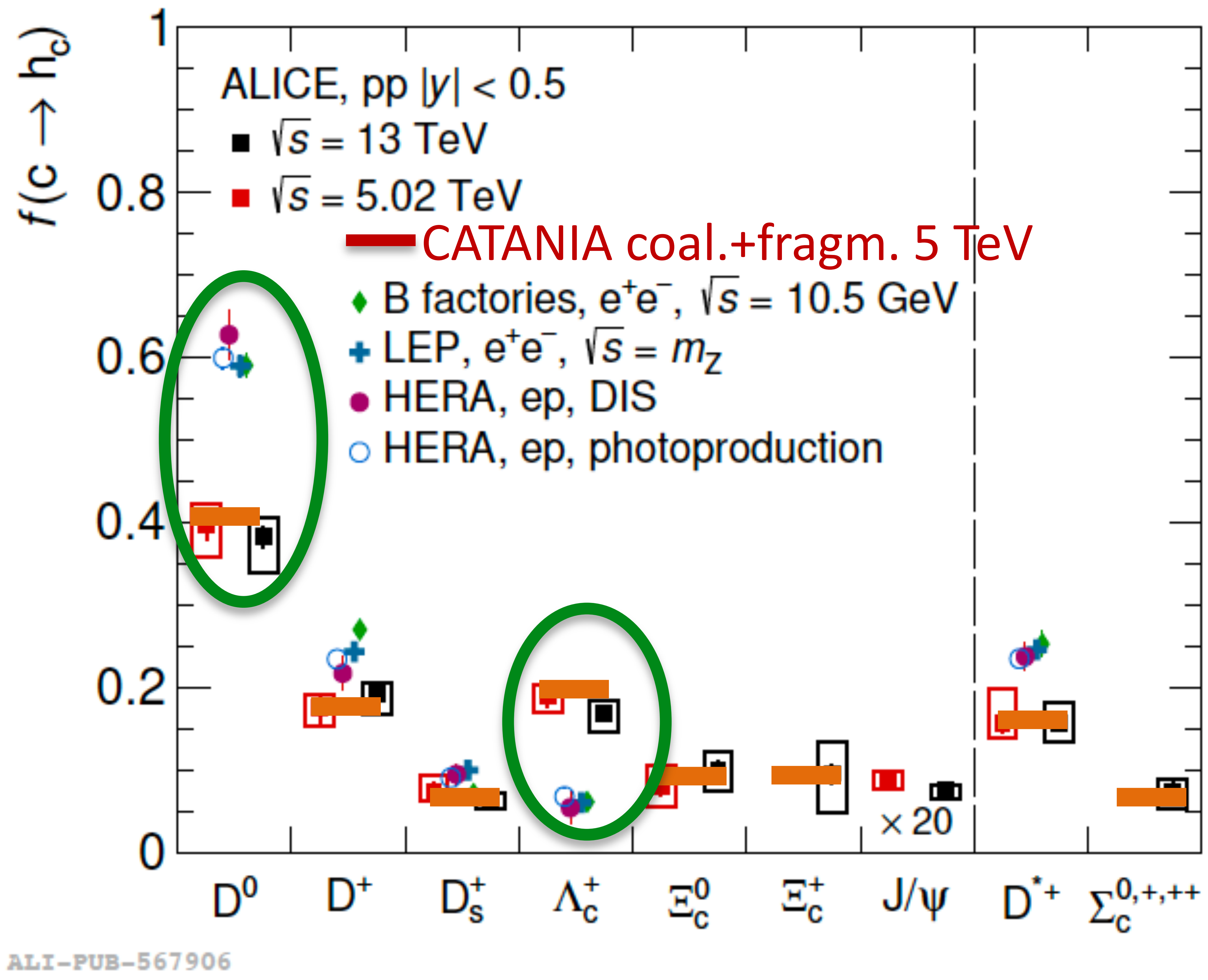
Physics Letters B 821 (2021) 136622

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

Catania baryon to meson ratio

Phys.Rev.C 107 (2023) 064901

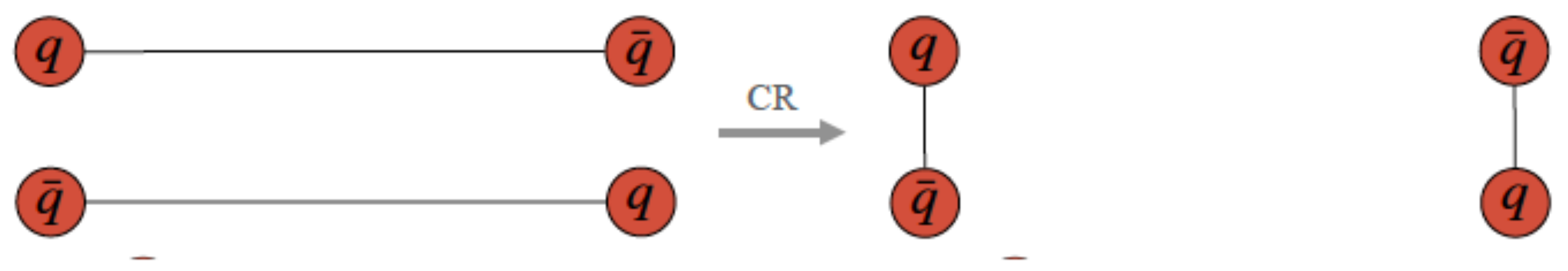




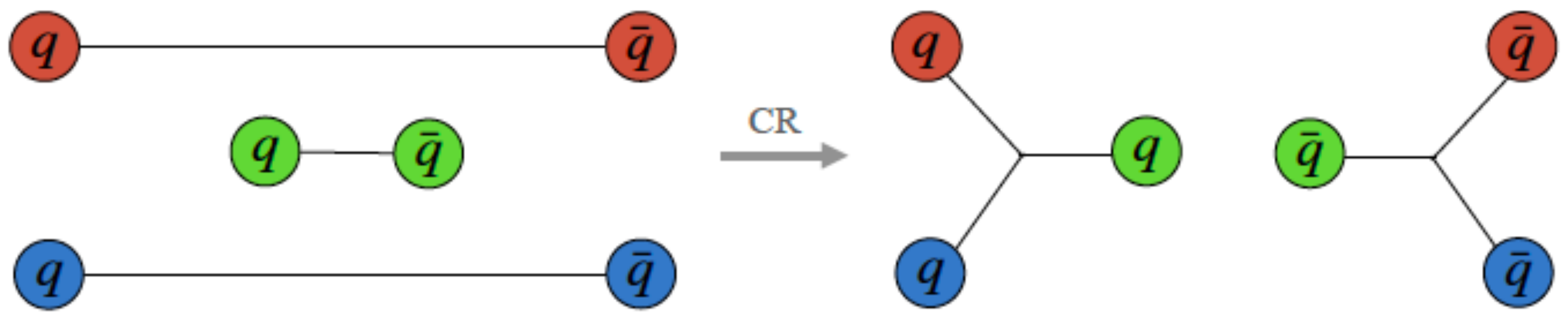
- Catania Coal+Fragm. very close to pp FF

PYTHIA Color Reconnection

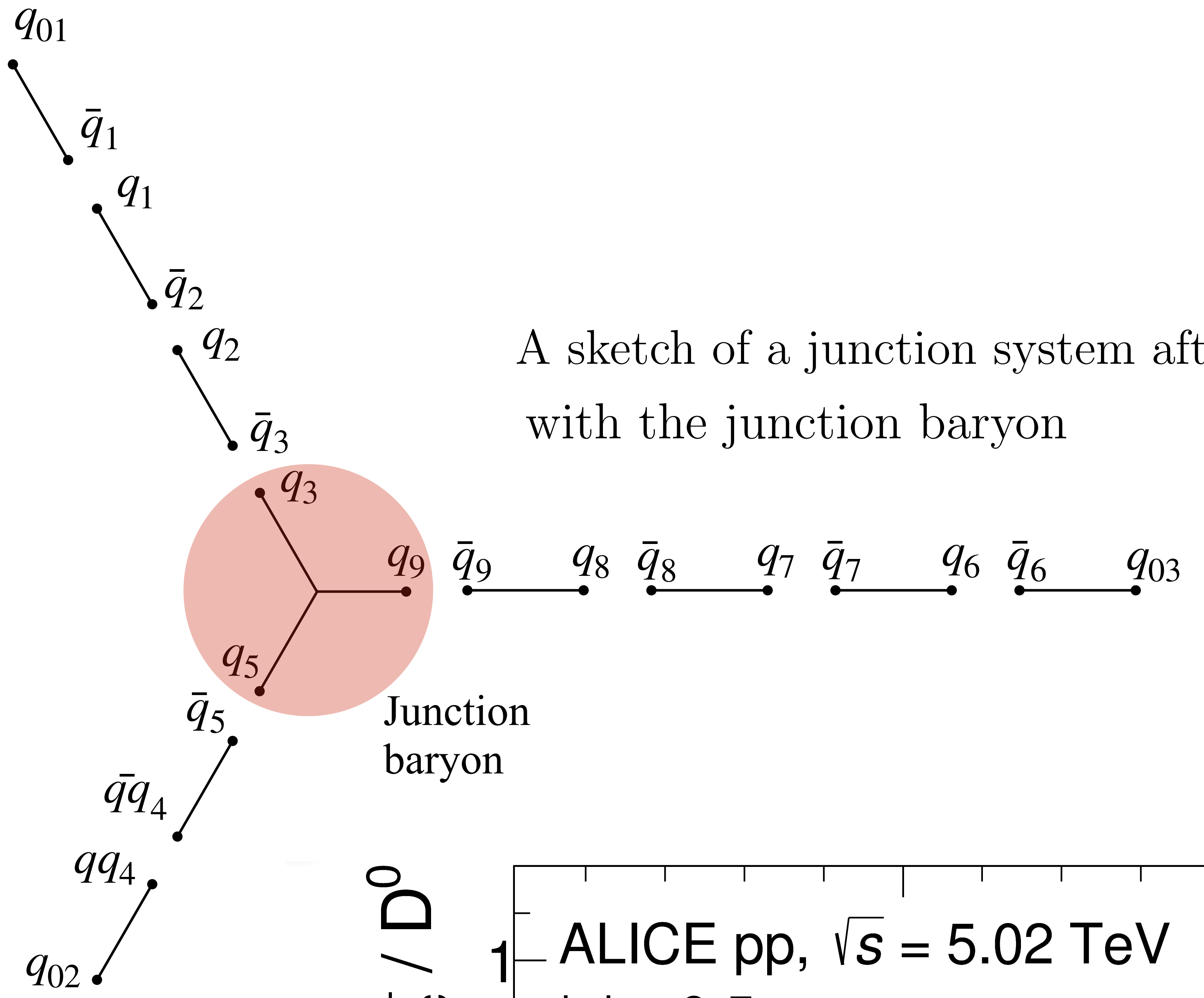
Altmann et al., arXiv 2405.19137



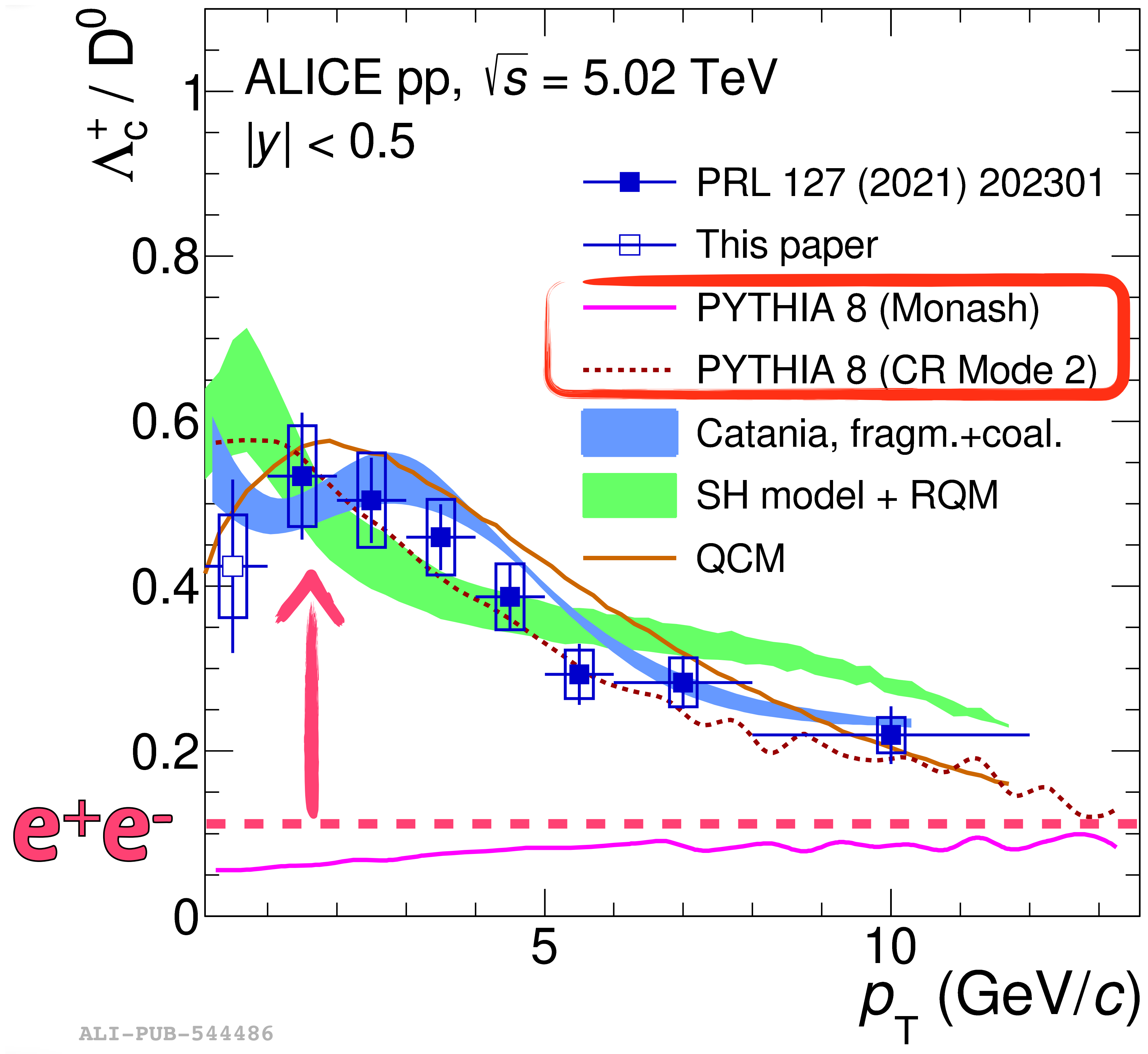
(a) Dipole-type reconnection.



(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

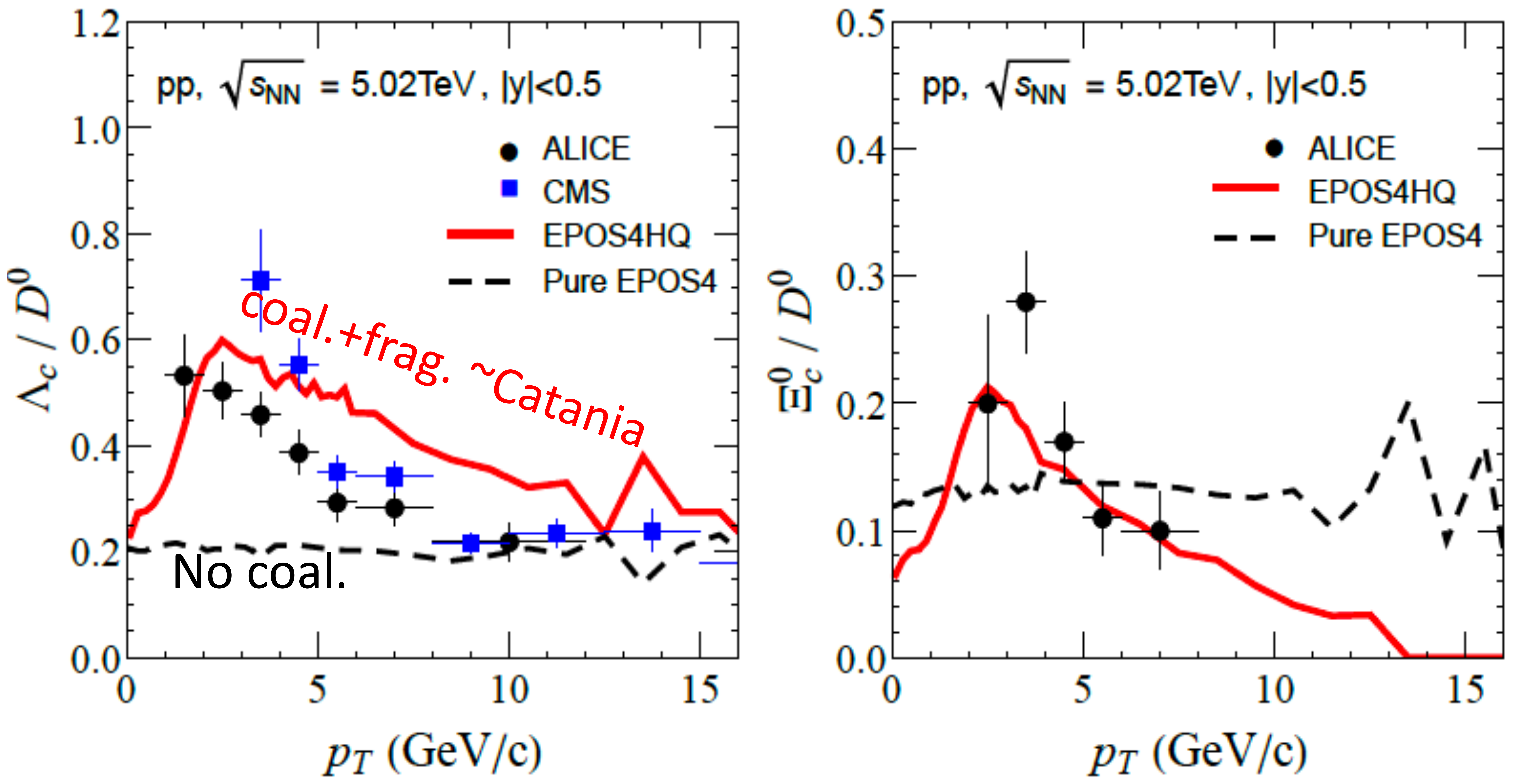
Not so different qualitatively wrt Coalescence and POWLANG Local color recombination

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)



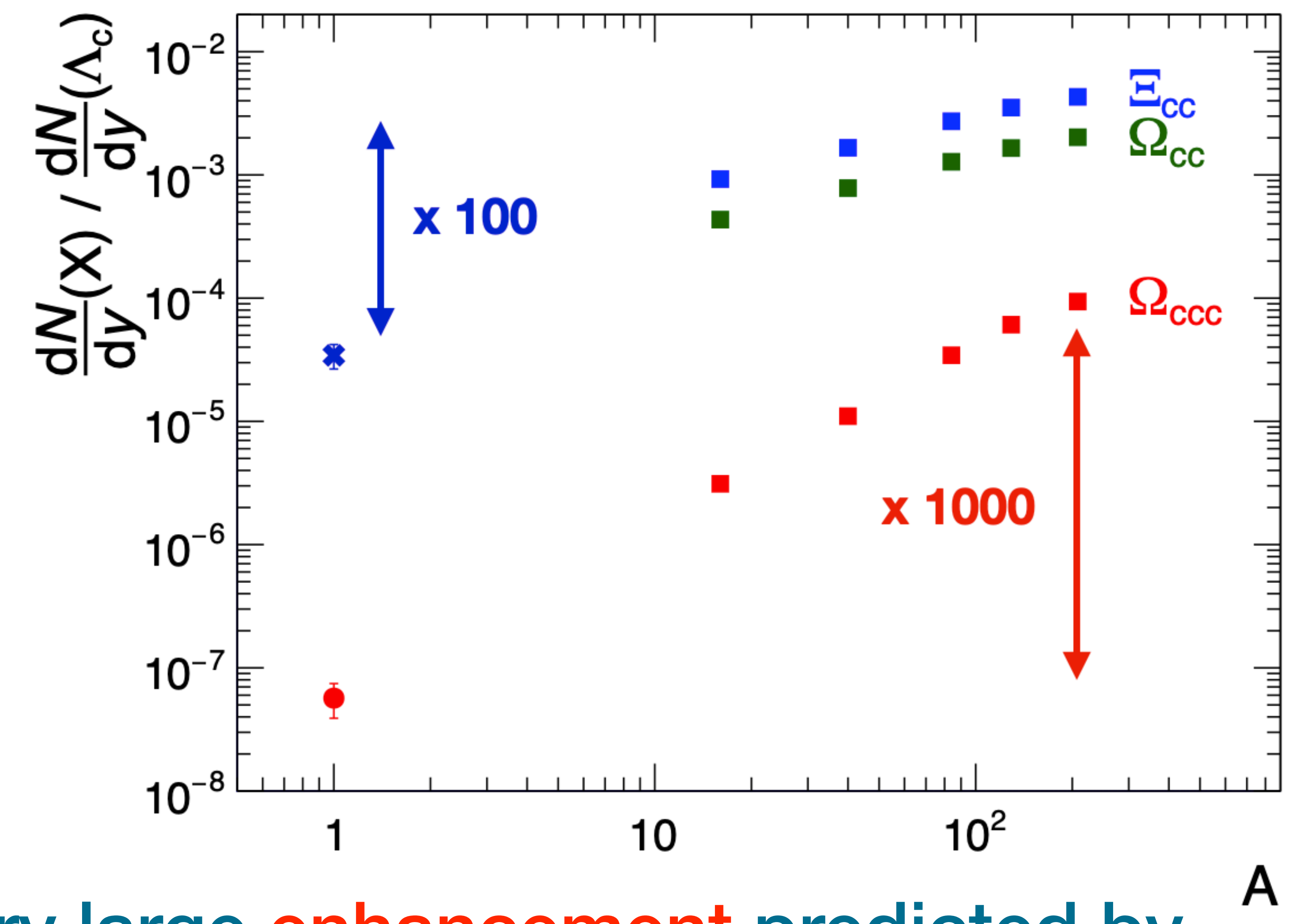
Ex) EPOS4HQ

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

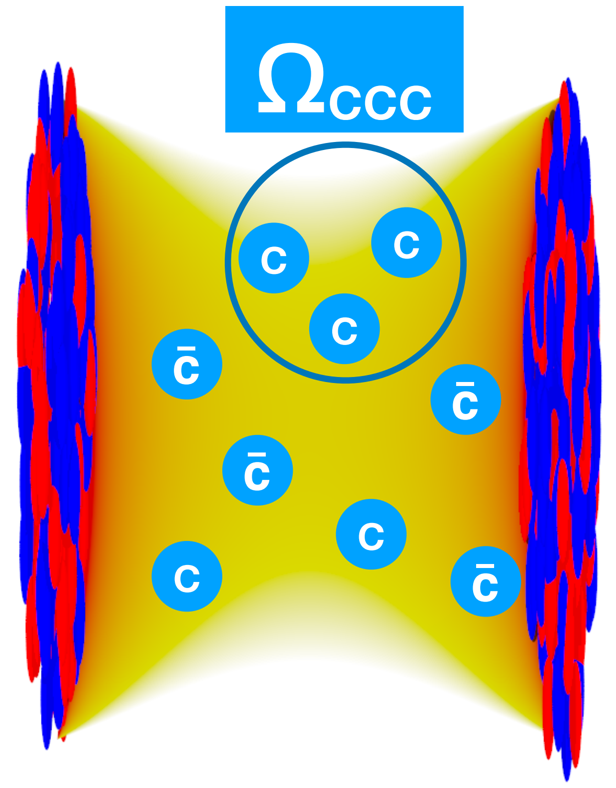
Only difference wrt Catania:
- Assume RQM states like in SHM

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

- 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
- Many open issues
  - Rapidity evolution
  - Extend to bottom
  - Effect on the other observables (ex. v_2)
  - ....



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



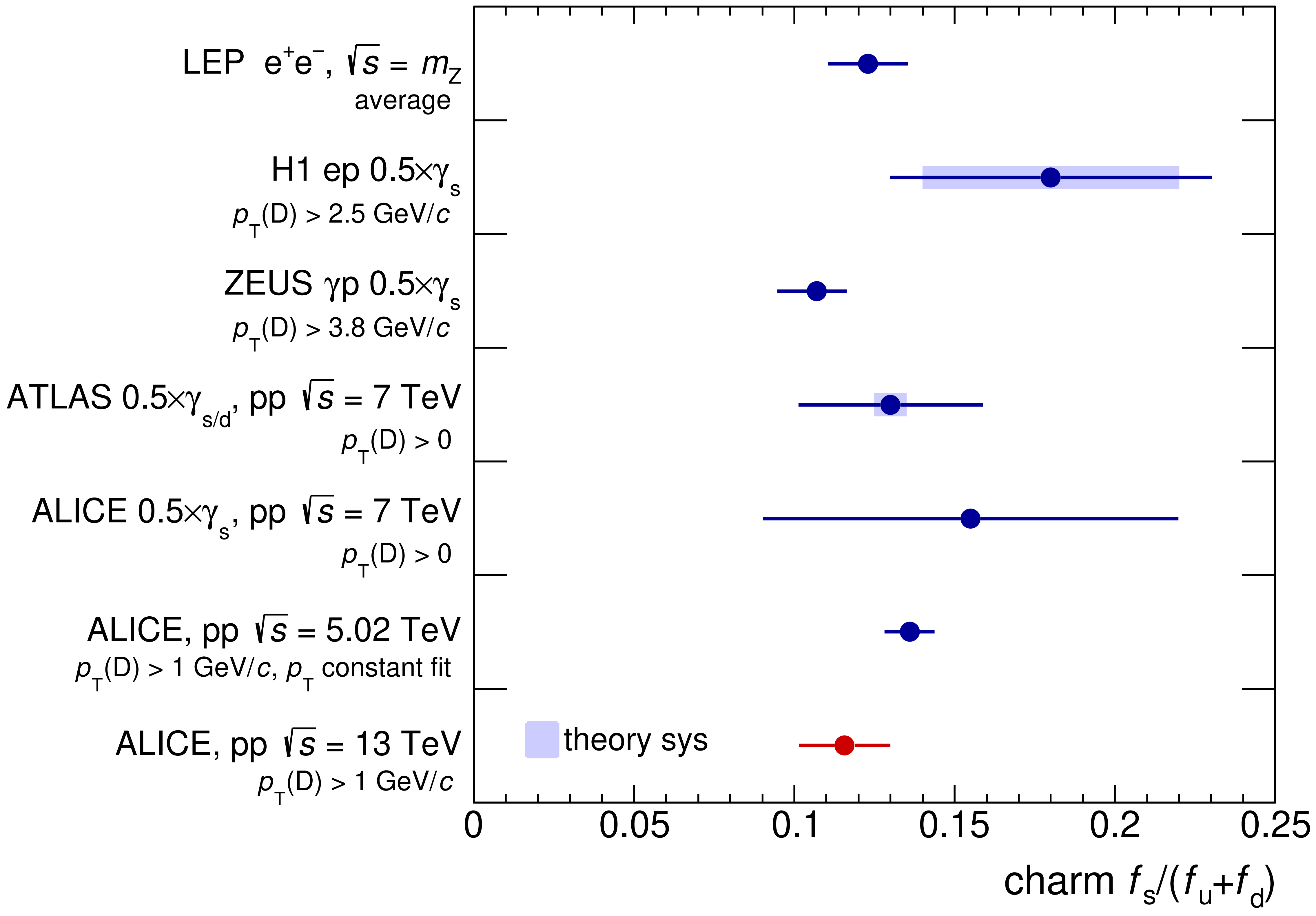
⇨ Require new detector ALICE 3!


Extra Slides

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)

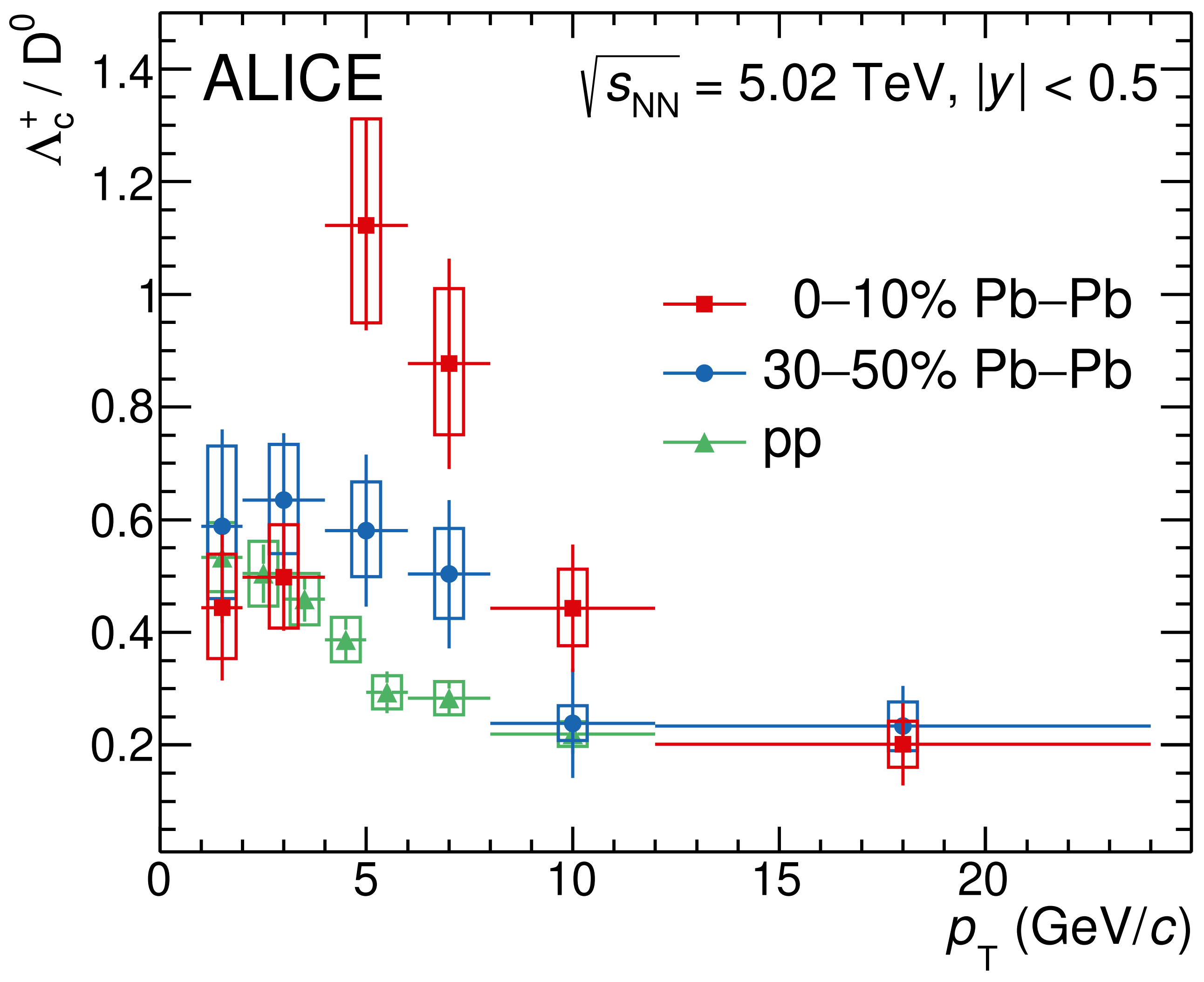
f_x: probability for a charm quark to hadronize with another quark of flavour x

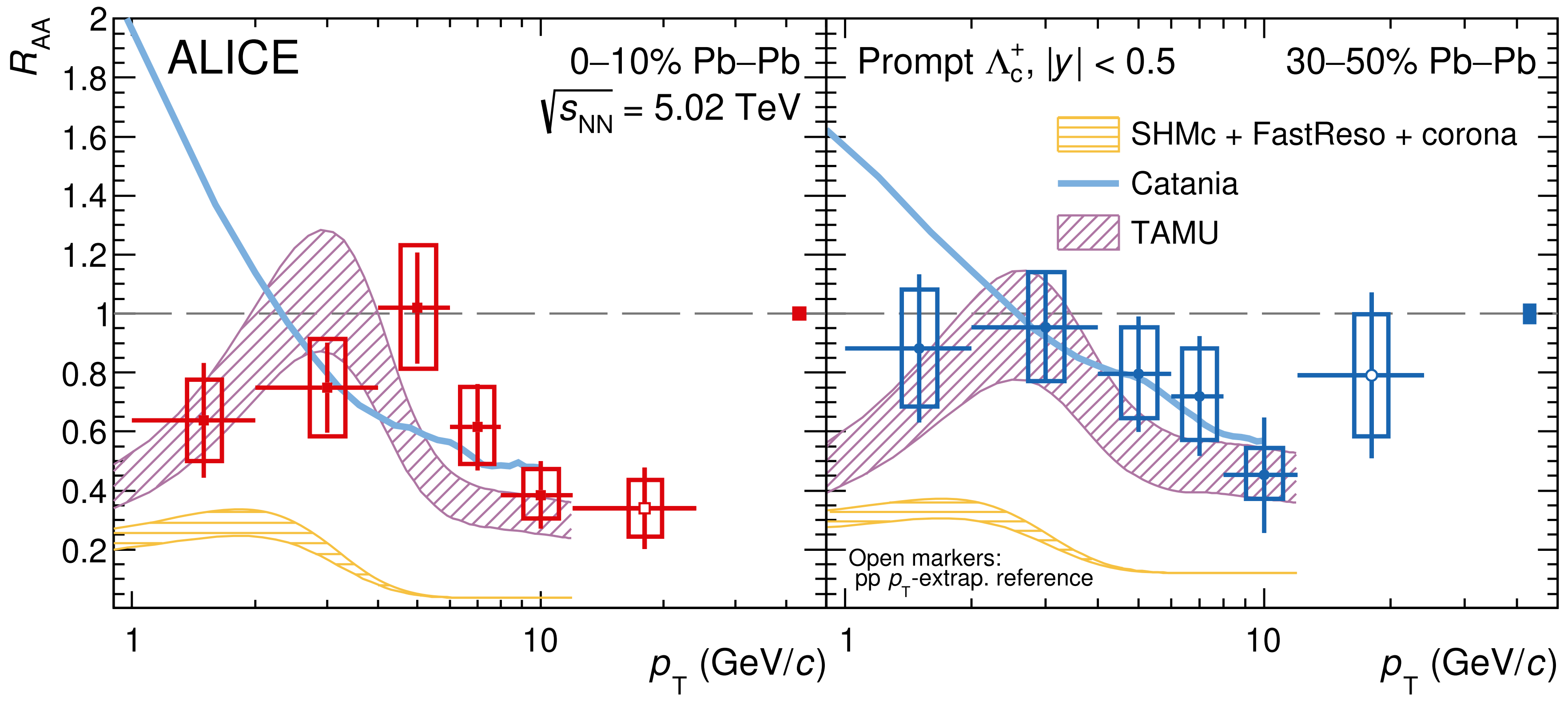
⇨ D_s^+/D^0+D^+

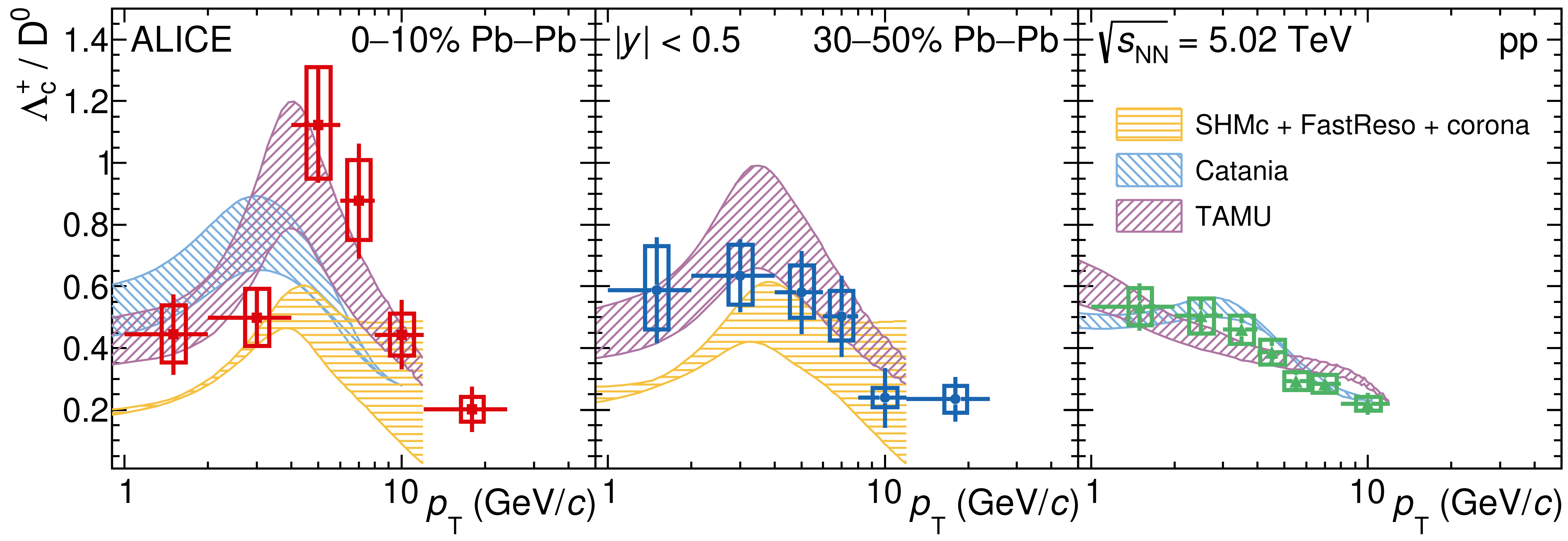
Production of prompt strange D mesons / prompt non-strange D mesons in e^+e^-, ep and pp collisions doesn't show any significant dependence of the collision system & energy!

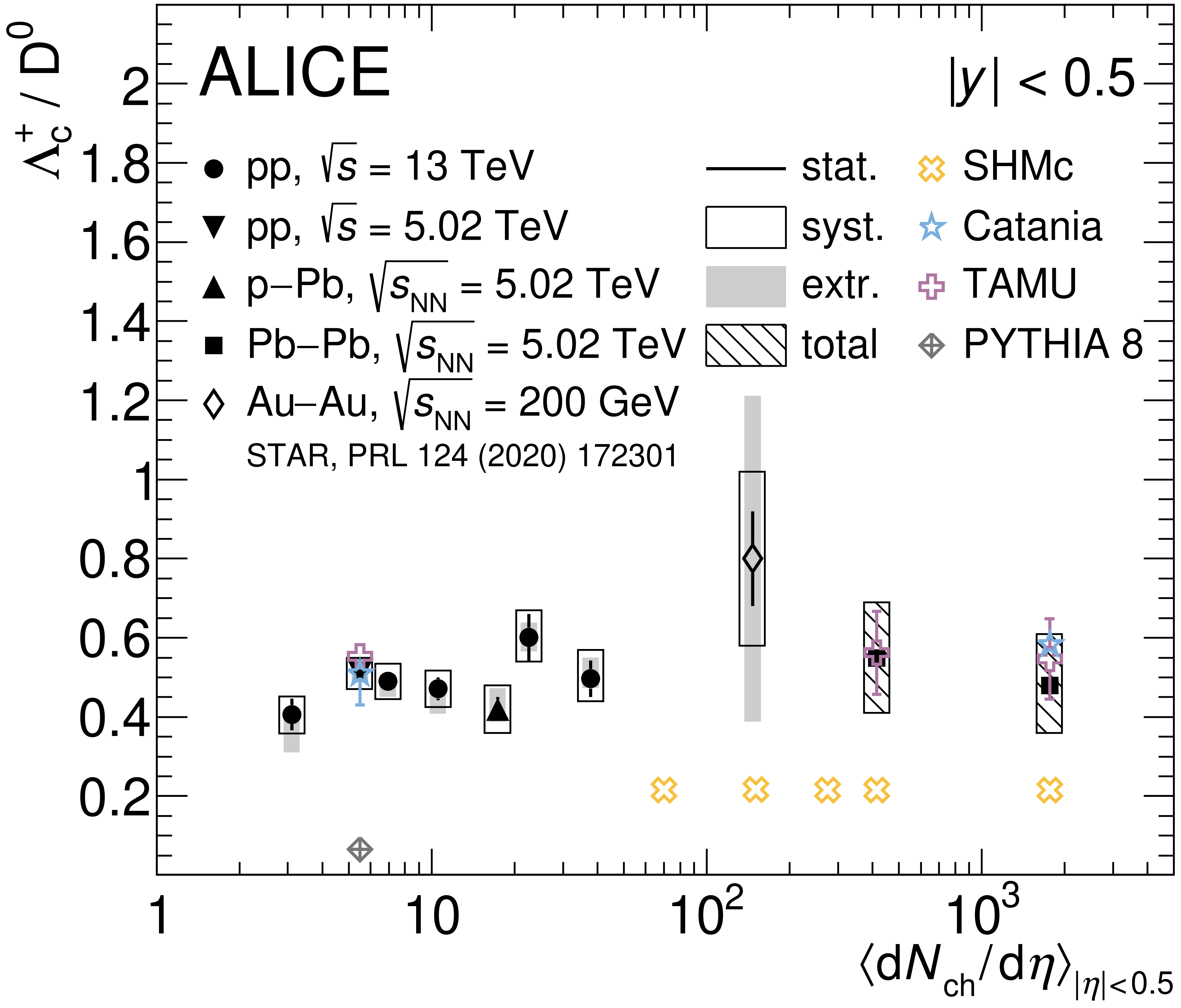
How about in Pb–Pb?

Physics Letters B 839 (2023) 137796



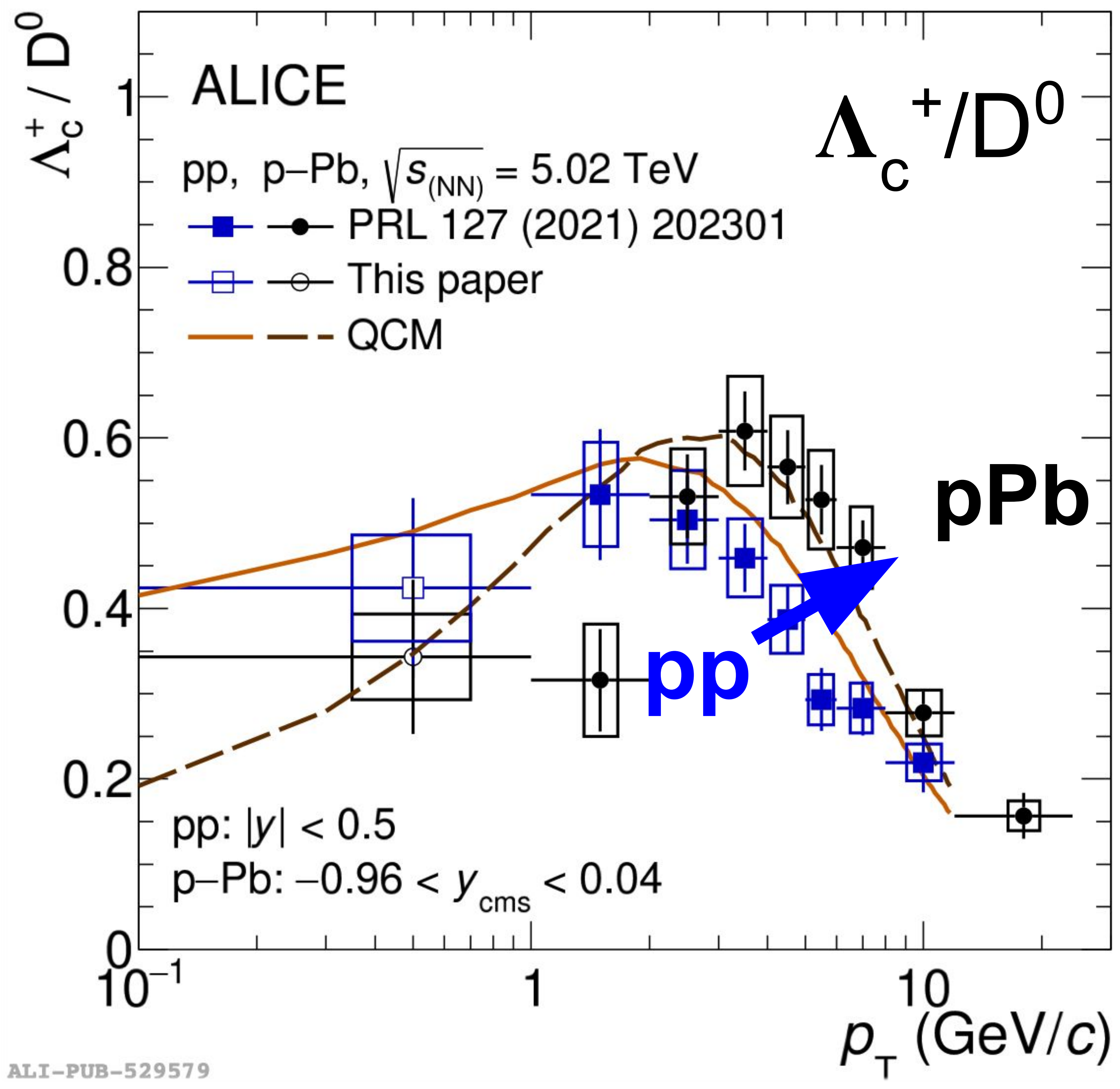




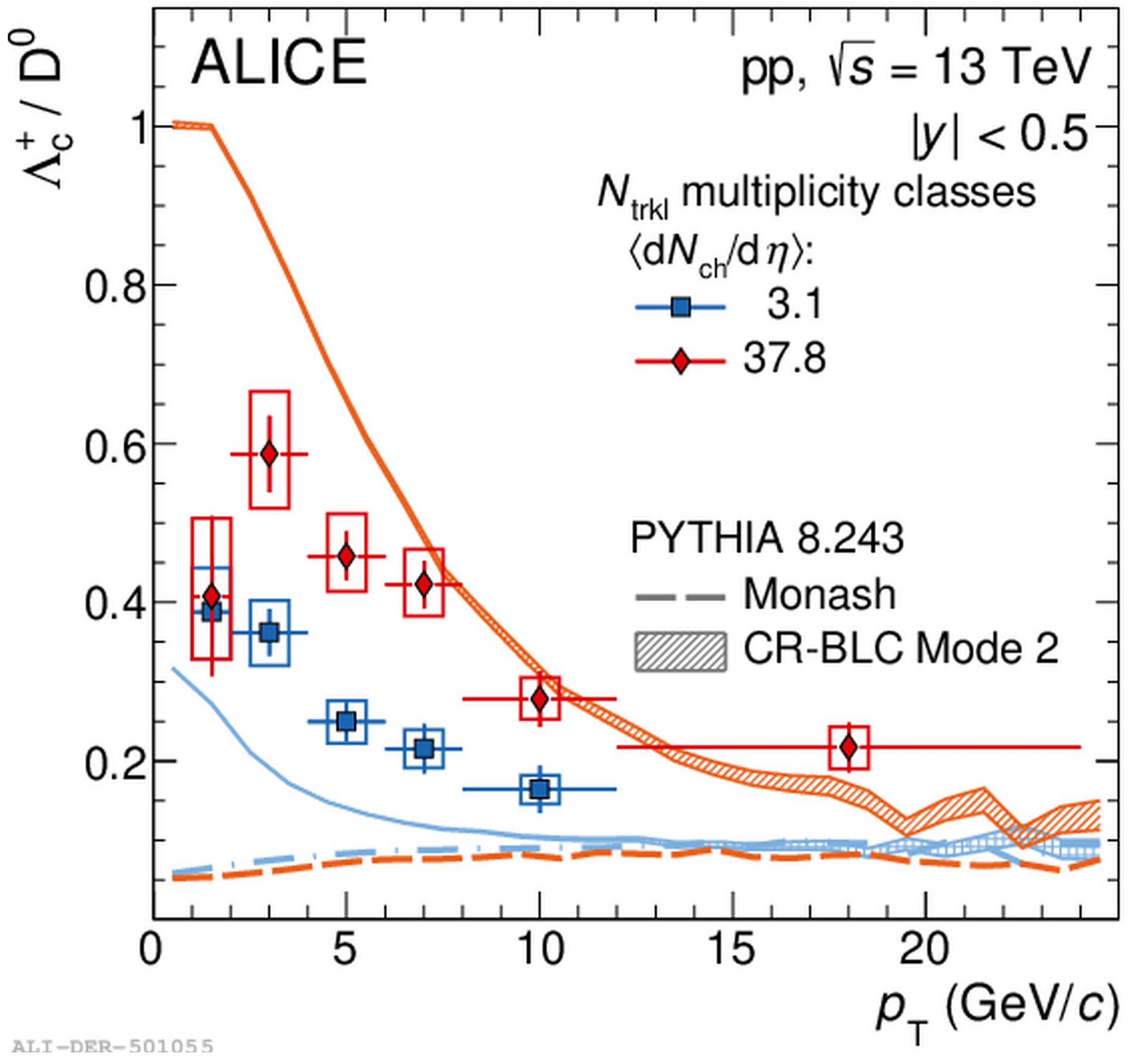


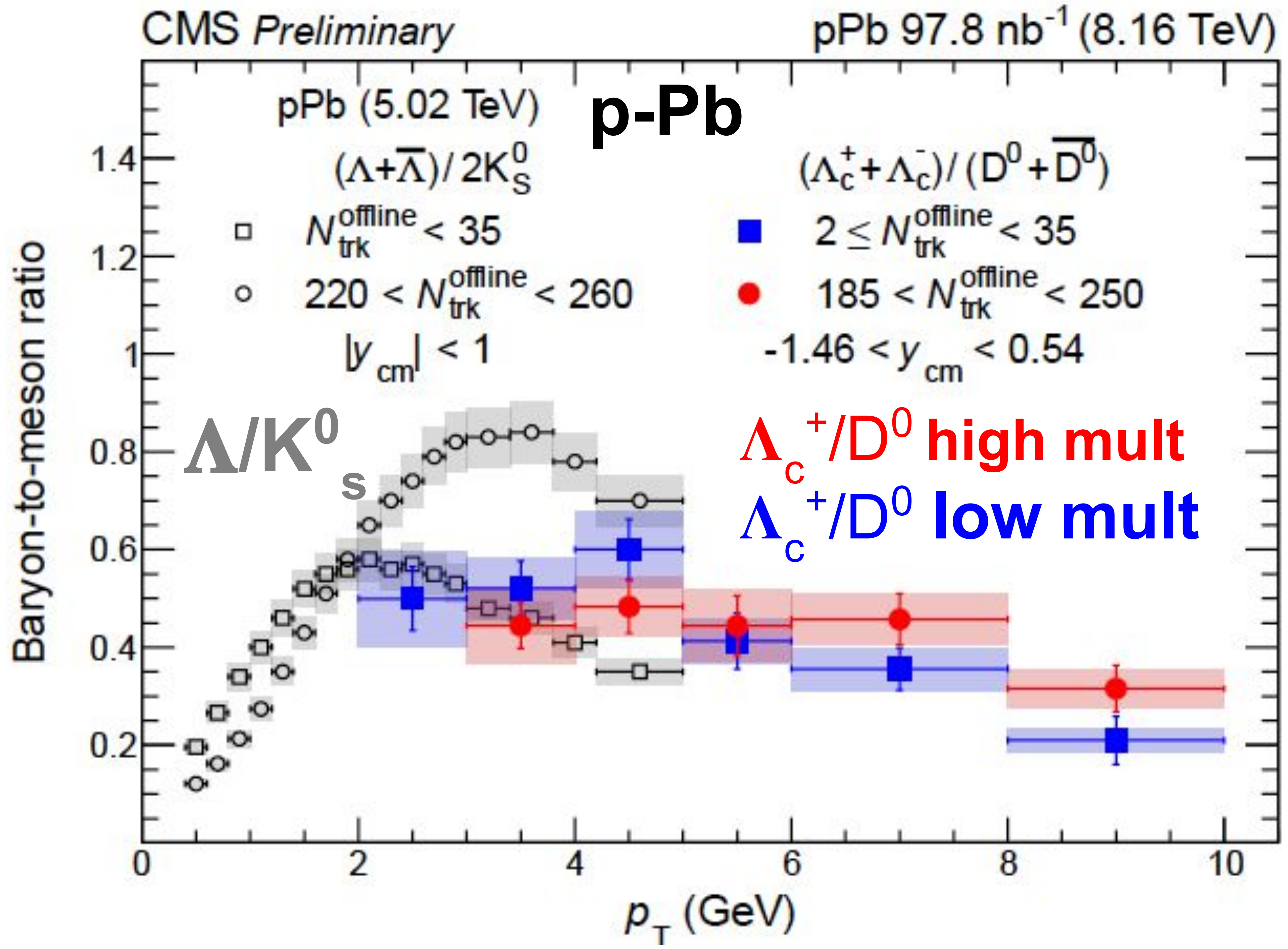
Modified mechanism of hadronization in all hadronic collision systems with respect to charm fragmentation tuned on e+e- and e-p measurements?

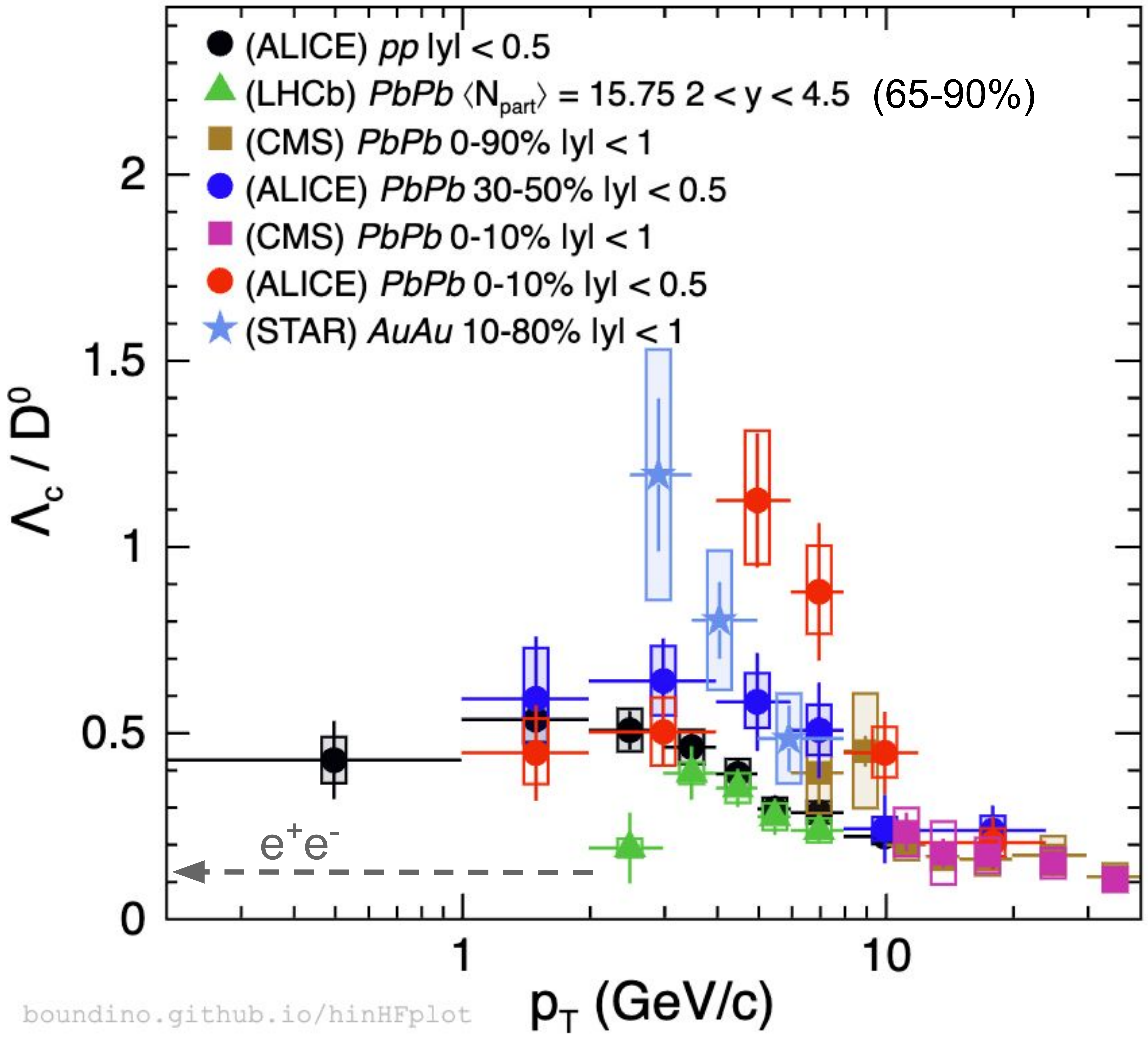
PRC 104 054905 (2021)



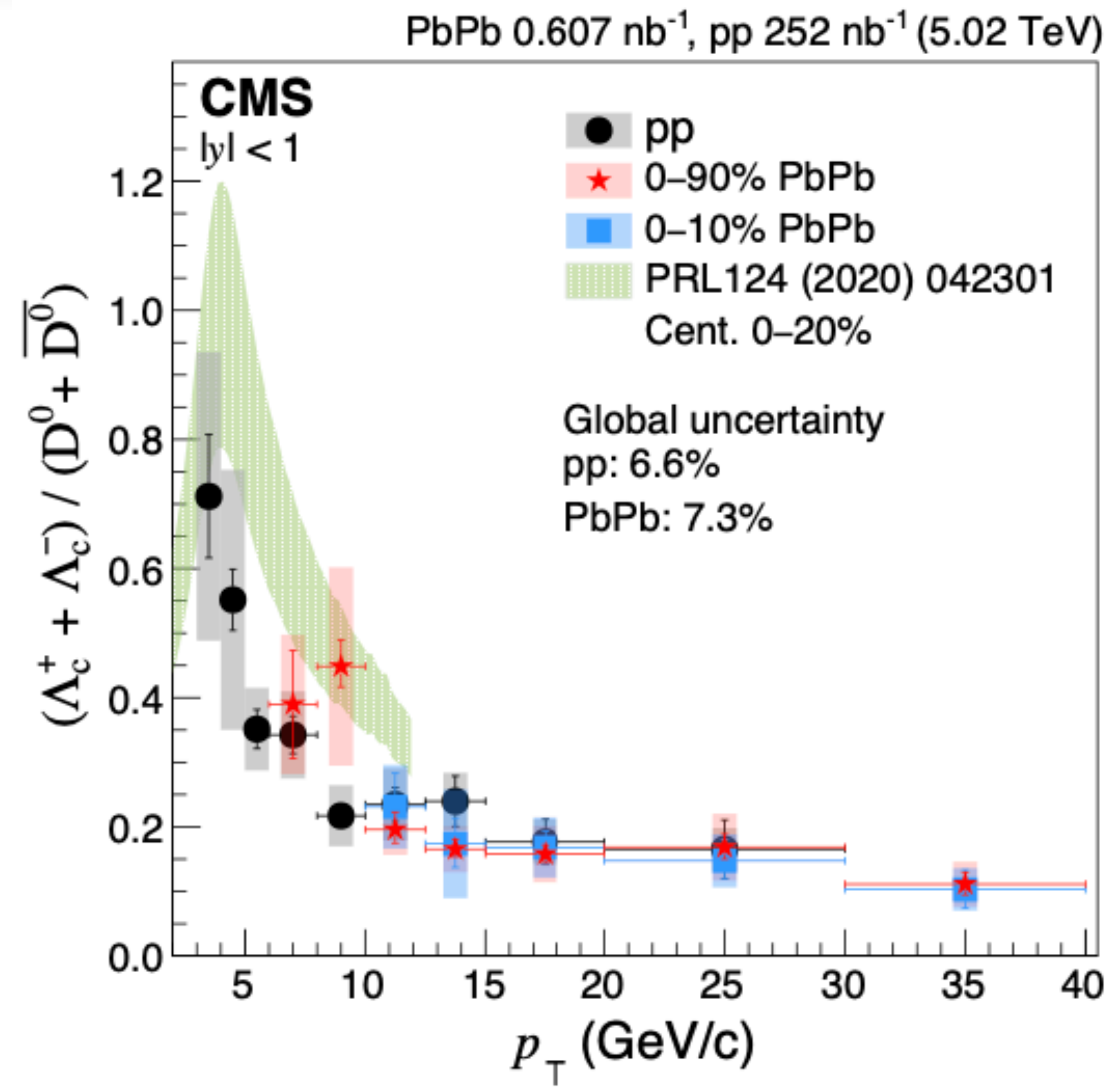
PLB 829 (2022) 137065



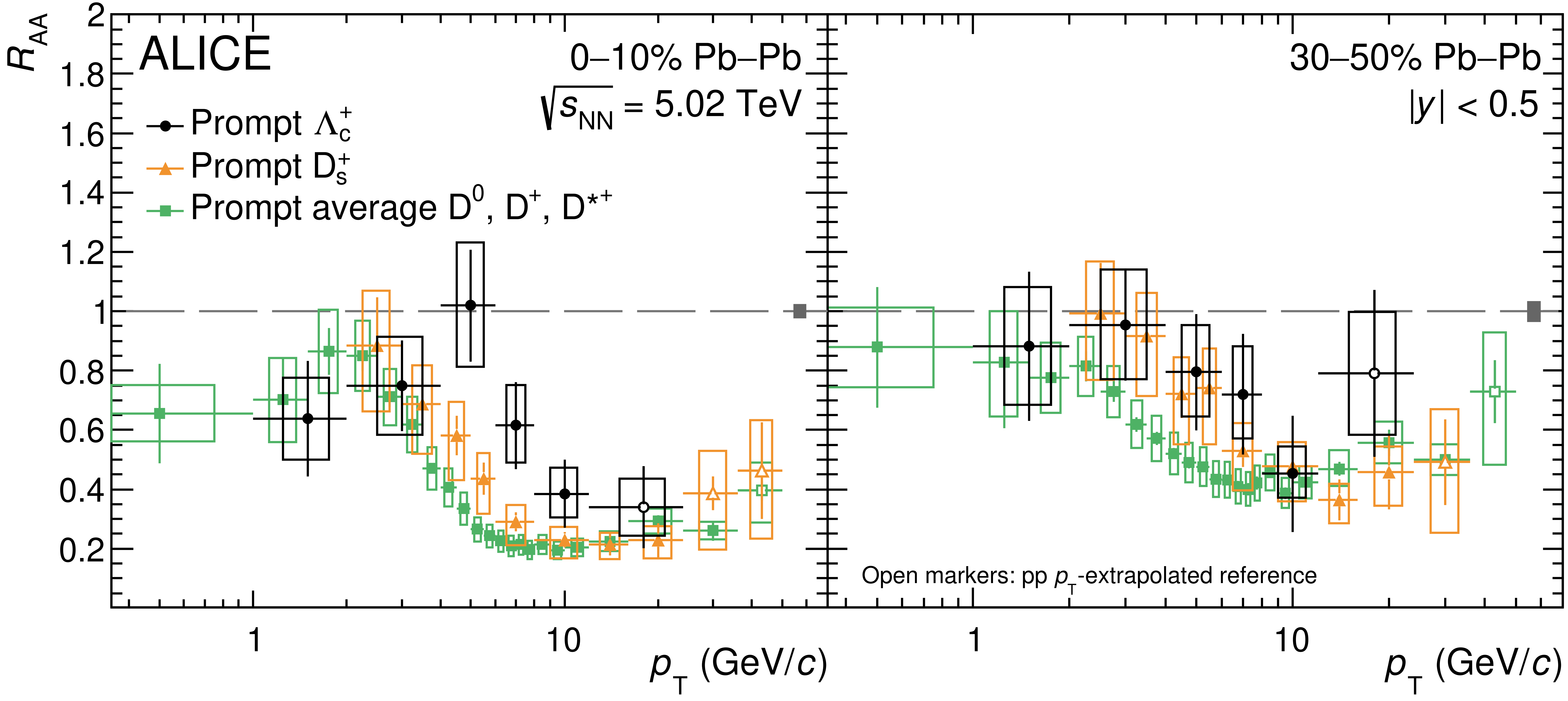




(ALICE) pp |y| < 0.5
(LHCb) PbPb ⟨N_part⟩ = 15.75 2 < y < 4.5 (65-90%)
(CMS) PbPb 0-90% |y| < 1
(ALICE) PbPb 30-50% |y| < 0.5
(CMS) PbPb 0-10% |y| < 1
(ALICE) PbPb 0-10% |y| < 0.5
(STAR) AuAu 10-80% |y| < 1
Λc / D0
pT (GeV/c)
e+e-
boundino.github.io/hinHFplot

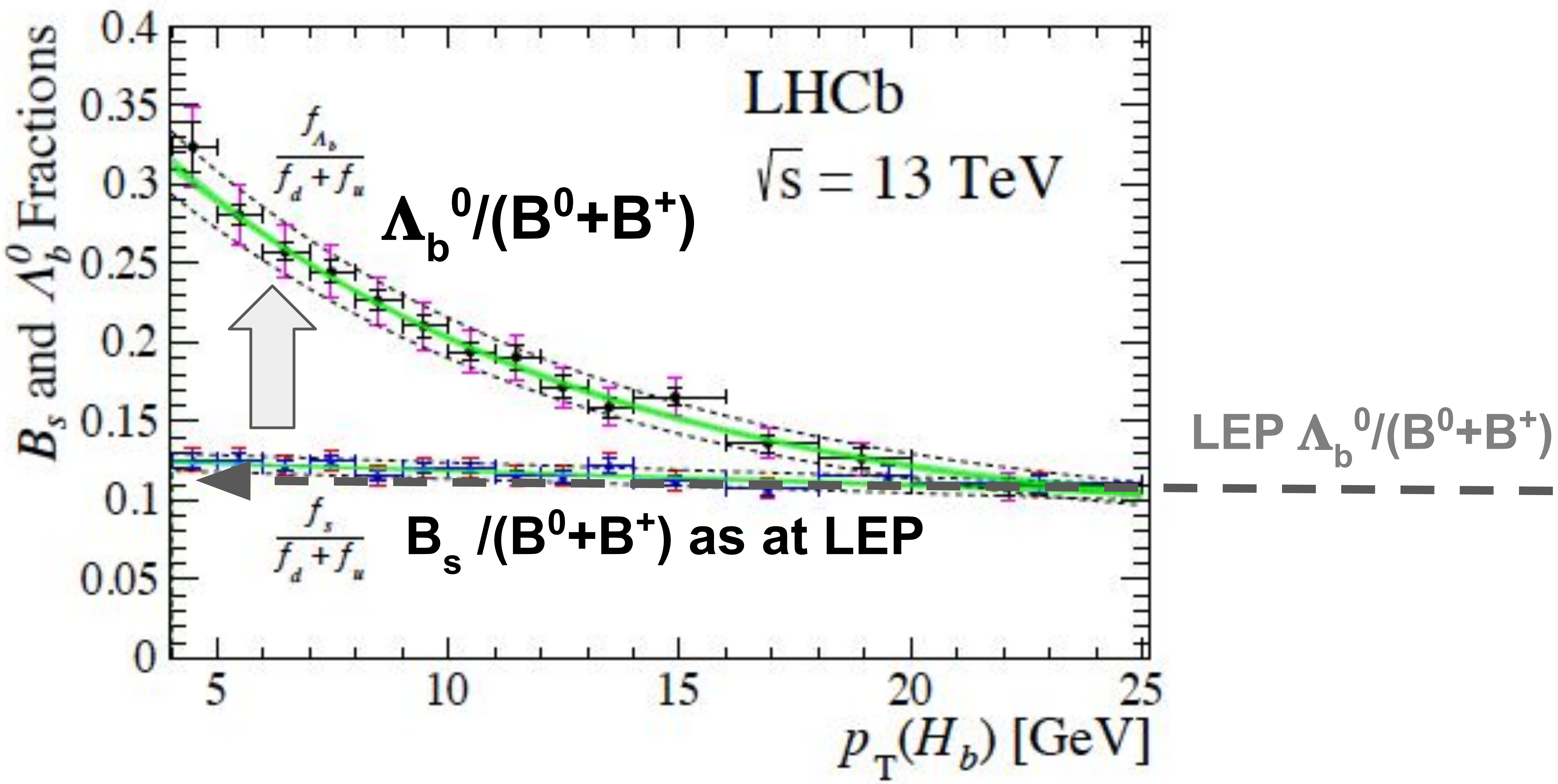


PbPb 0.607 nb-1, pp 252 nb-1 (5.02 TeV)
CMS
|y| < 1
pp
0–90% PbPb
0–10% PbPb
PRL124 (2020) 042301
Cent. 0–20%
Global uncertainty
pp: 6.6%
PbPb: 7.3%
(Λc+ + Λc−) / (D0 + D̄0)
pT (GeV/c)


ALICE
0–10% Pb–Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
30–50% Pb–Pb
|y| < 0.5
Prompt Λ_c^+
Prompt D_s^+
Prompt average D^0, D^+, D^{*+}
Open markers: pp p_T-extrapolated reference
R_{AA}
p_T (GeV/c)

Beauty

PRD100 (2019) no.3, 031102



Similar trend in charm and beauty sectors

Hadronization in vacuum

Parton interaction with the medium

(Modified?) hadronization

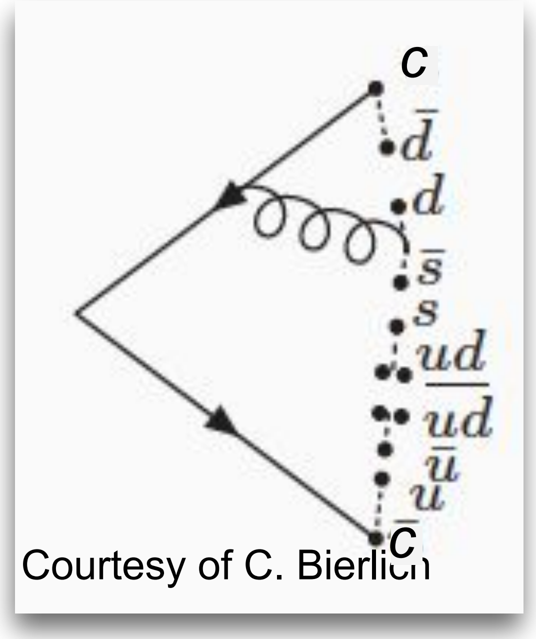
$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c \to D}(z)$$

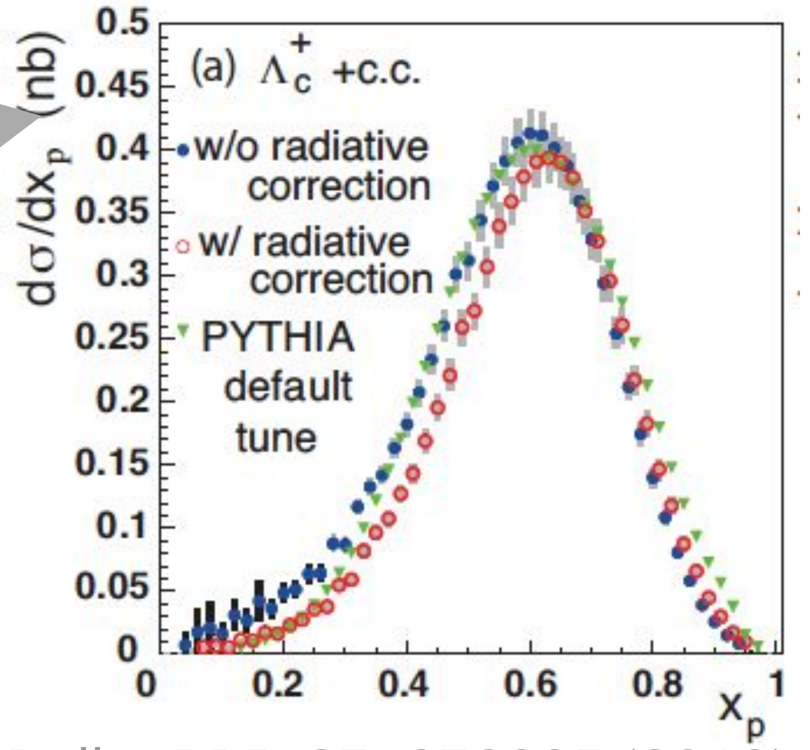
Initial-state effects

"Vacuum" parton spectra

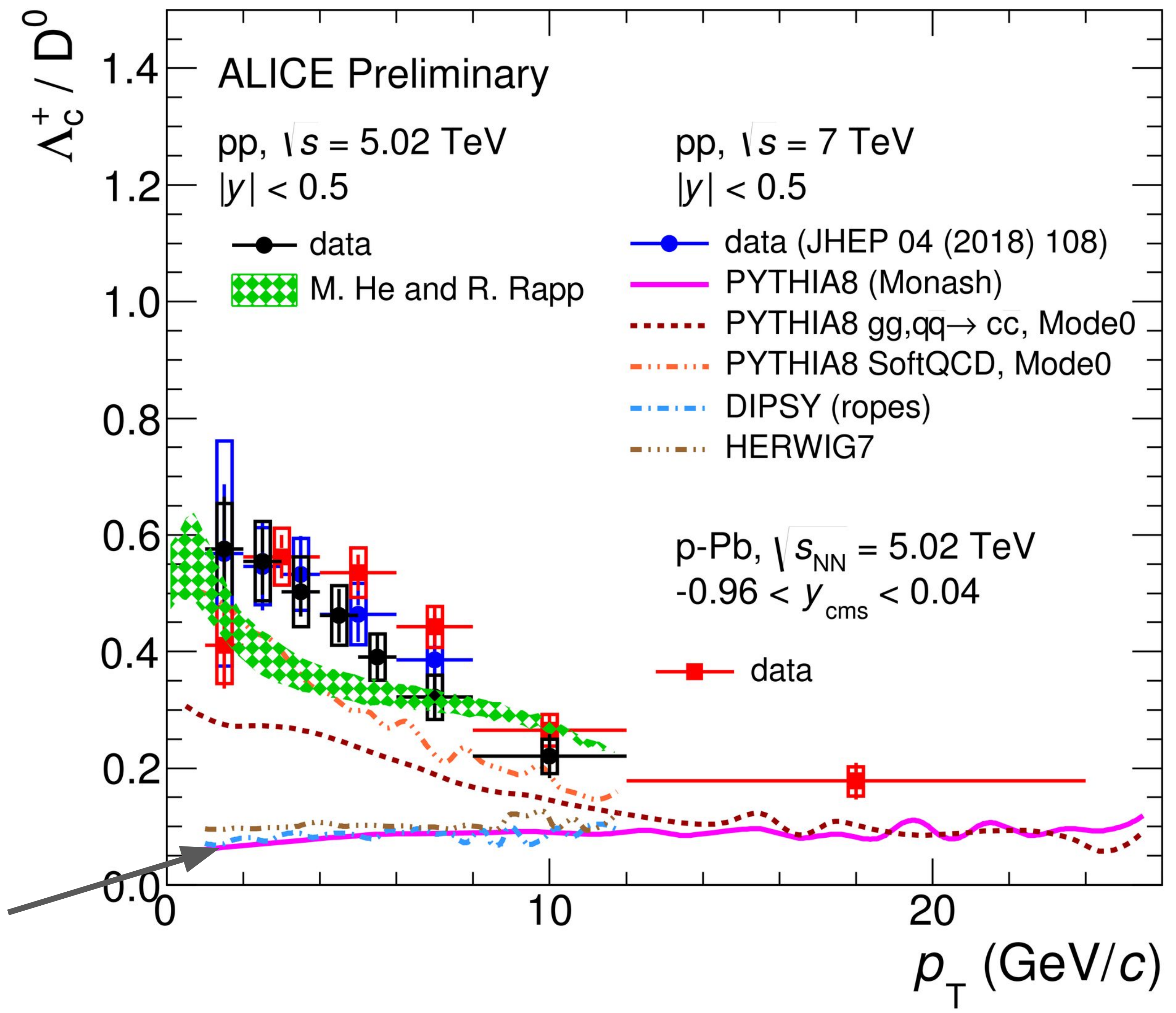
What we want to probe

- Light quark/diquark pairs popping out from QCD color-confinement potential (← strings)
  - **Diquarks ↔ baryons**
- Hadronisation of different MPI products largely independent
- Reproduces e^+e^- data ~ fragmentation functions used in pQCD-based calculations





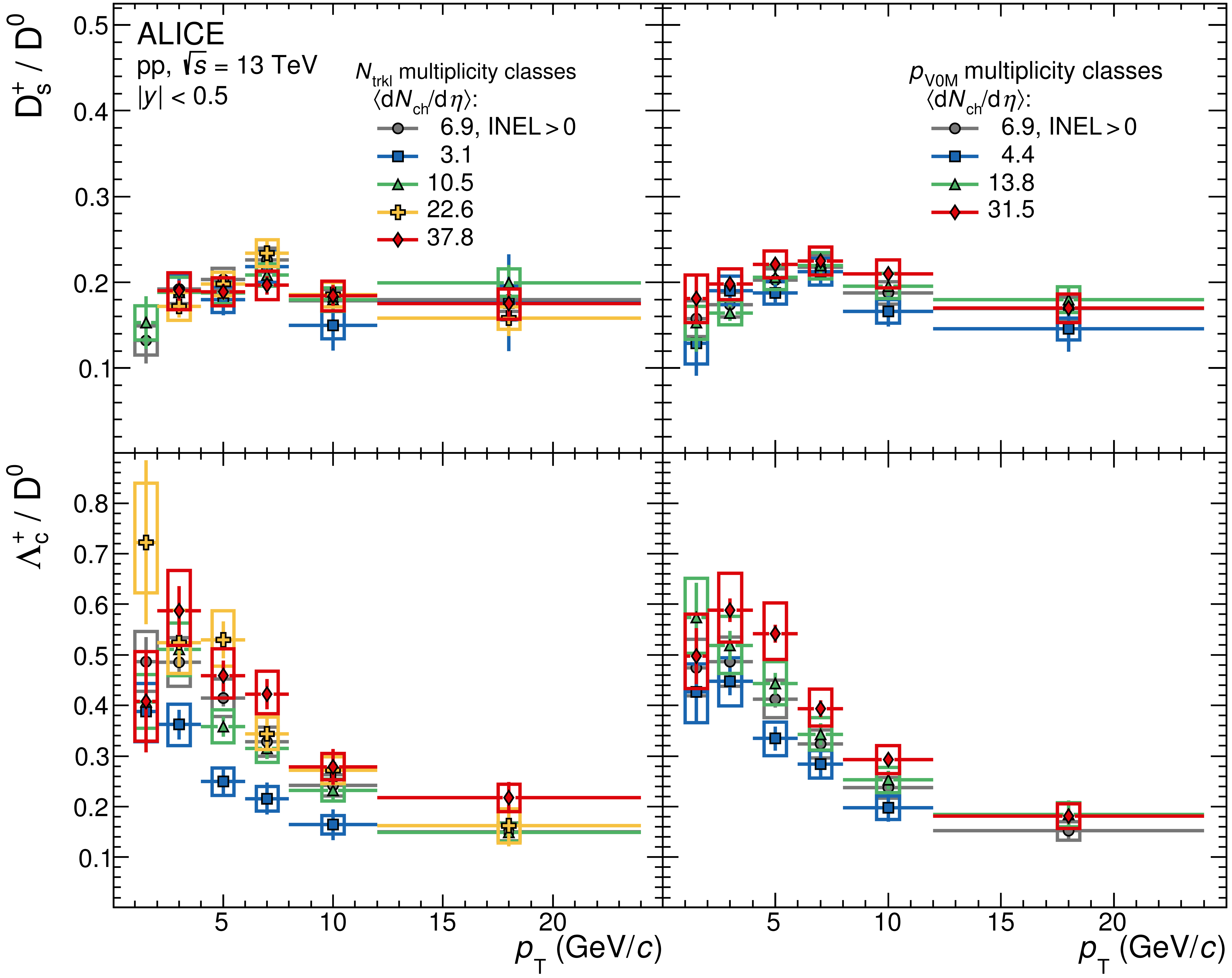
Belle, PRD 97, 072005 (2018)



e^+e^-

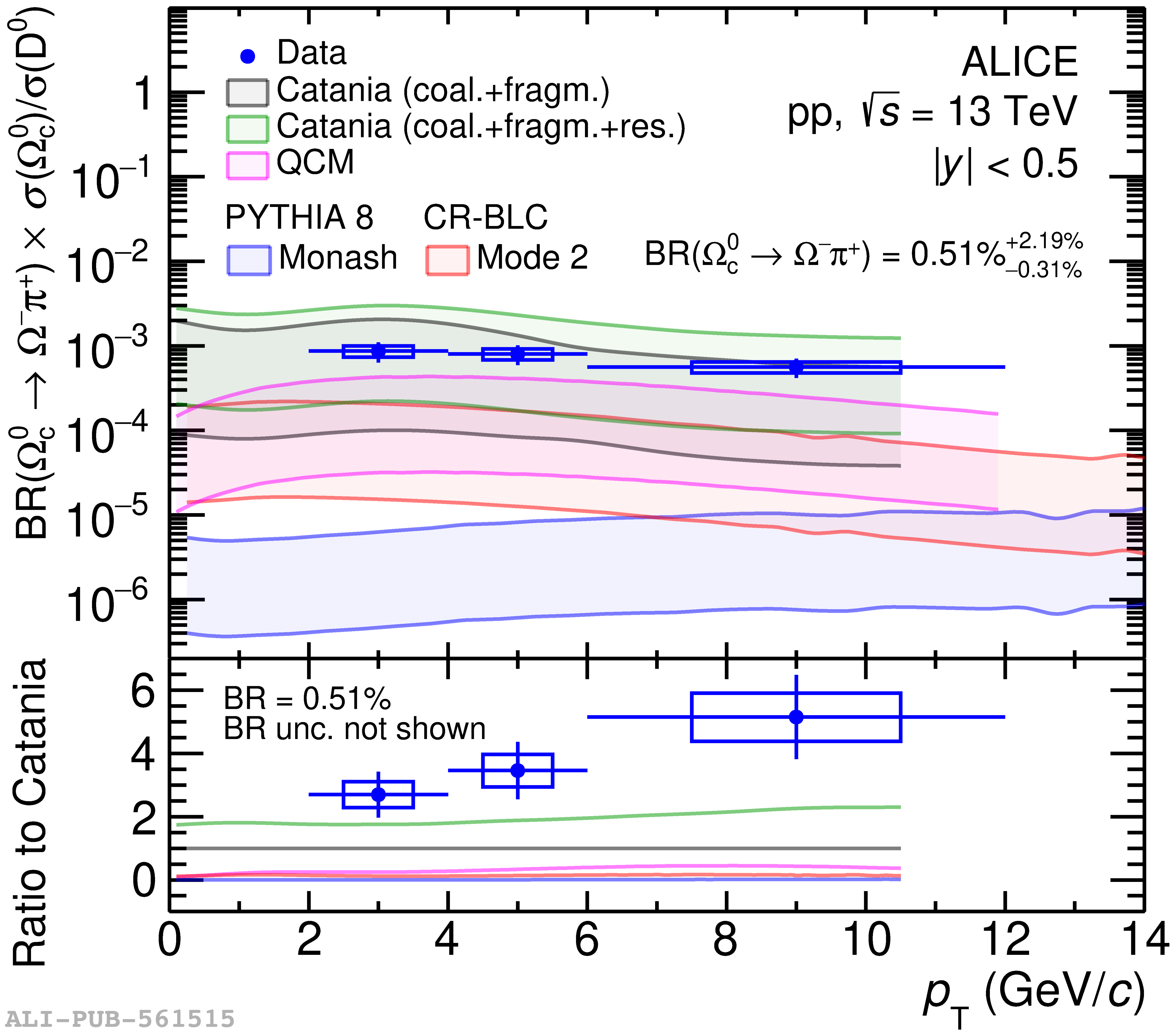
D_s^+ meson vs. Λ_c^+ baryon production

Physics Letters B 829 (2022) 137065

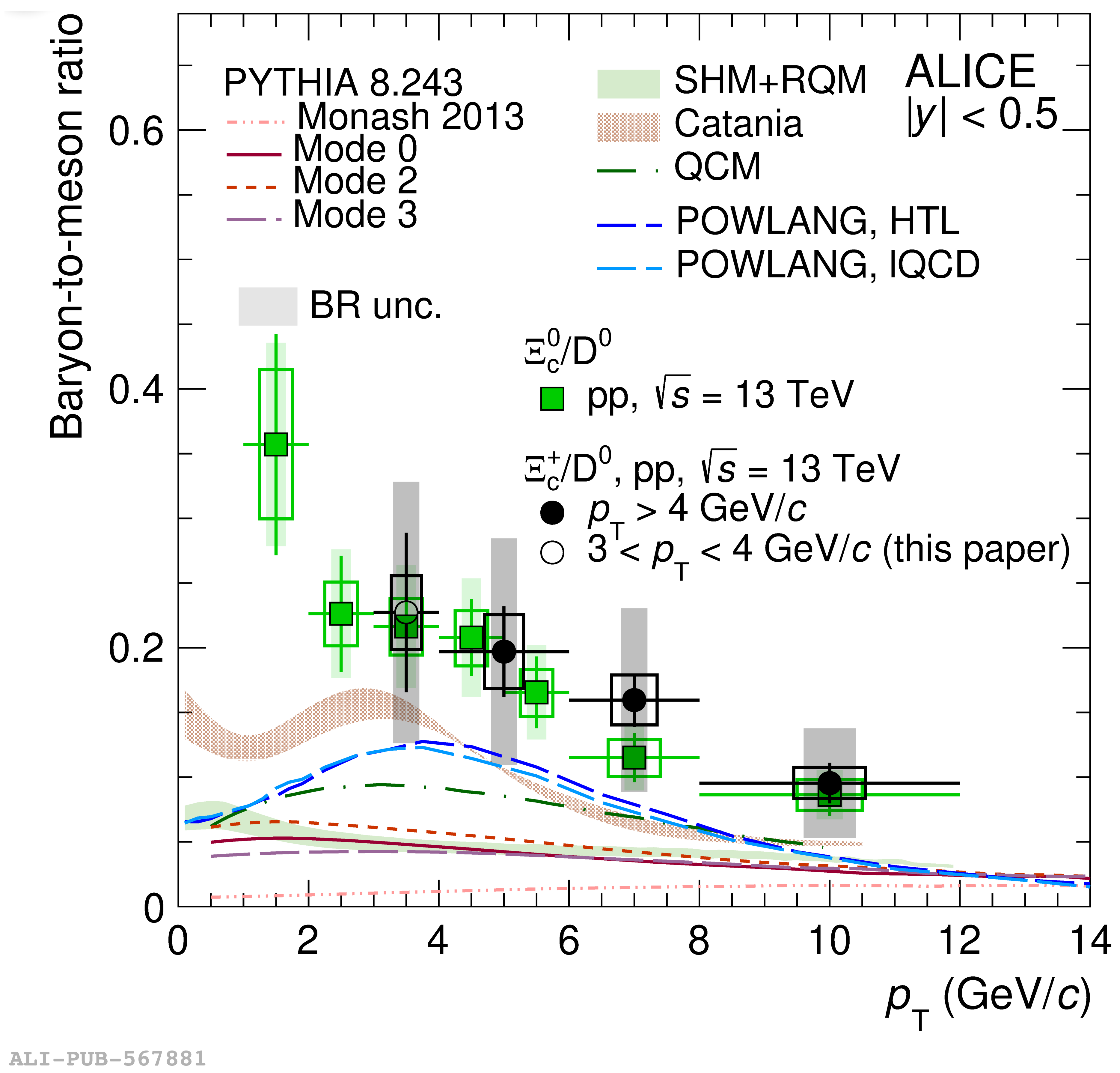


With 2 strangeness

Phys.Lett.B 846 (2023) 137625

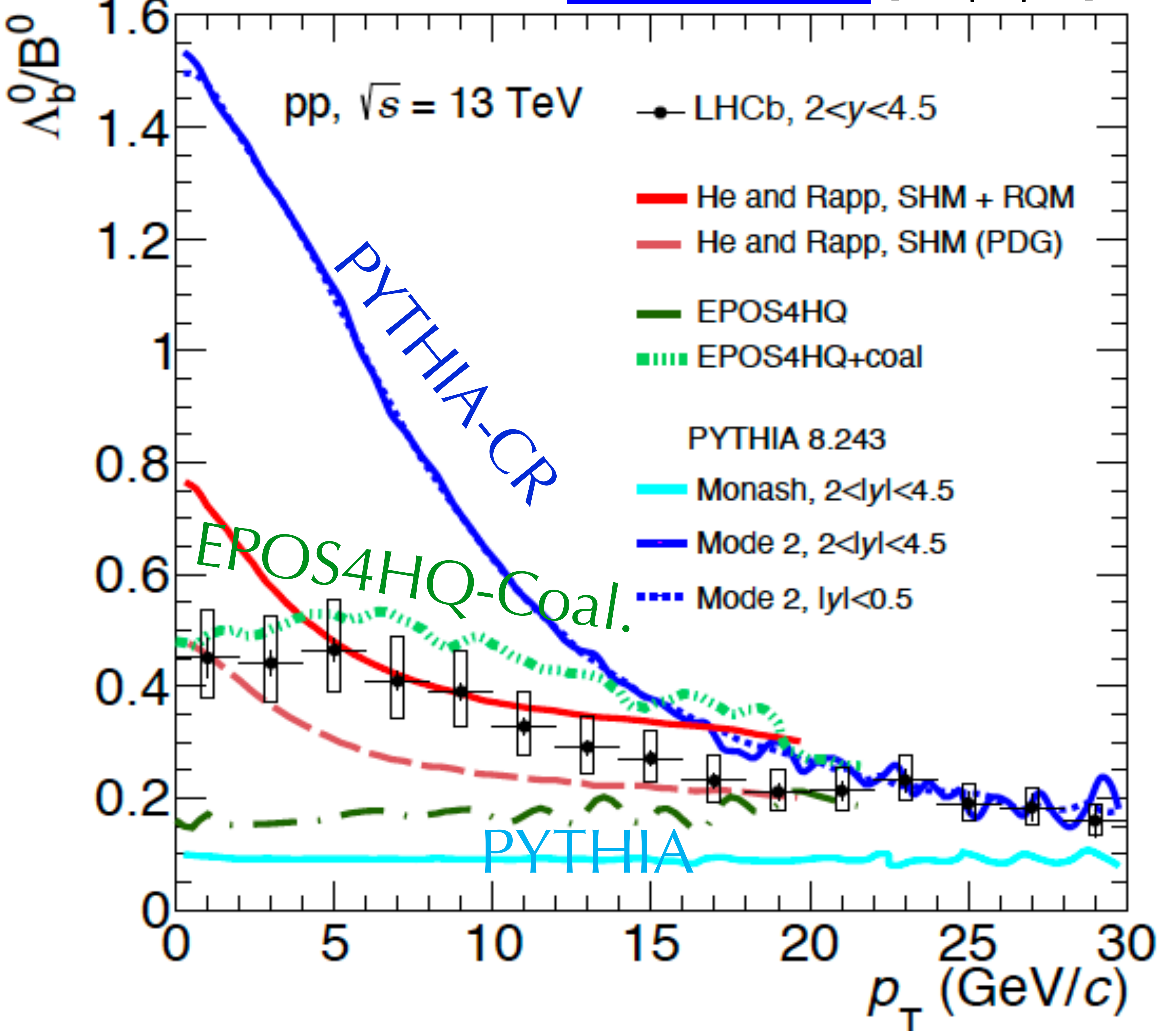


JHEP 12 (2023) 086



Many models in market enhancing baryon production

Altmann et al., 2405.19137 [hep-ph]



- EPOS4HQ

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

  Only difference wrt Catania:

  - Assume RQM states like in SHM

Heavy flavour production in medium: hadronization

Parton interaction with the medium

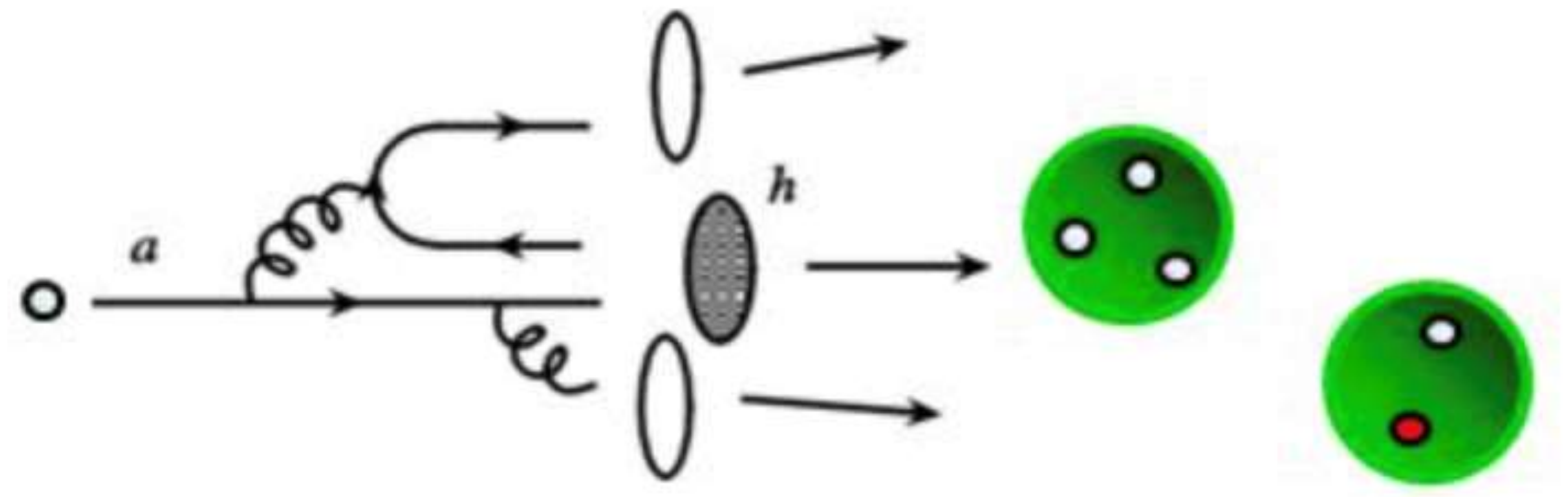
(Modified?) hadronization

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

Initial-state effects

"Vacuum" parton spectra

- 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*