Studies on the hadronization of charm and beauty quarks with ALICE

34th Rencontres de Blois
14–19 May 2023

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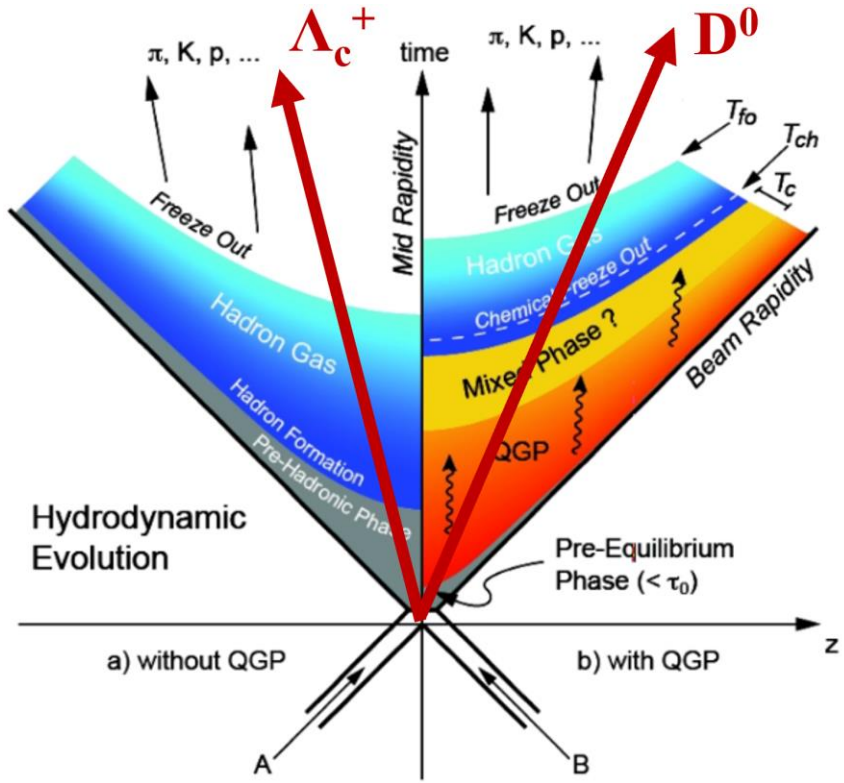
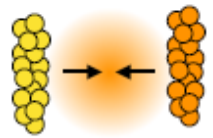
on behalf of the ALICE Collaboration

Physics motivations

- Heavy quarks are produced in the early stage of heavy-ion collisions, in hard-scattering processes. They experience the whole medium evolution.
  Negligible thermal production and annihilation rate.



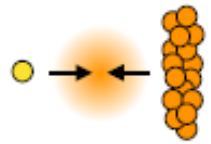


Yield ratios of charm/beauty hadrons are sensitive to **in medium heavy-quark hadronisation**.

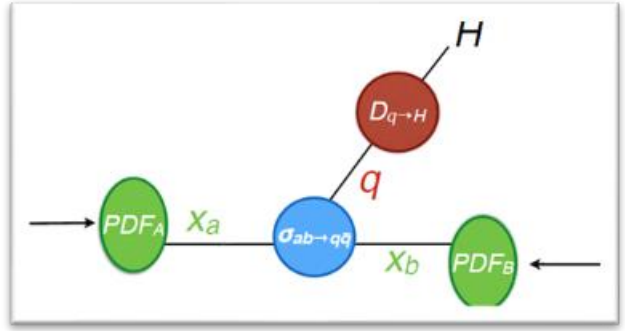
pp collisions test pQCD calculations (factorization approach, with **FF assumed to be universal** across collision systems).

$$d\sigma_{AB\to H} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab\to qq}(x_a, x_b, Q^2) \otimes D_{q\to H}(z_q, Q^2)$$

1. Parton distribution functions — 2. Partonic cross section — 3. Fragmentation functions

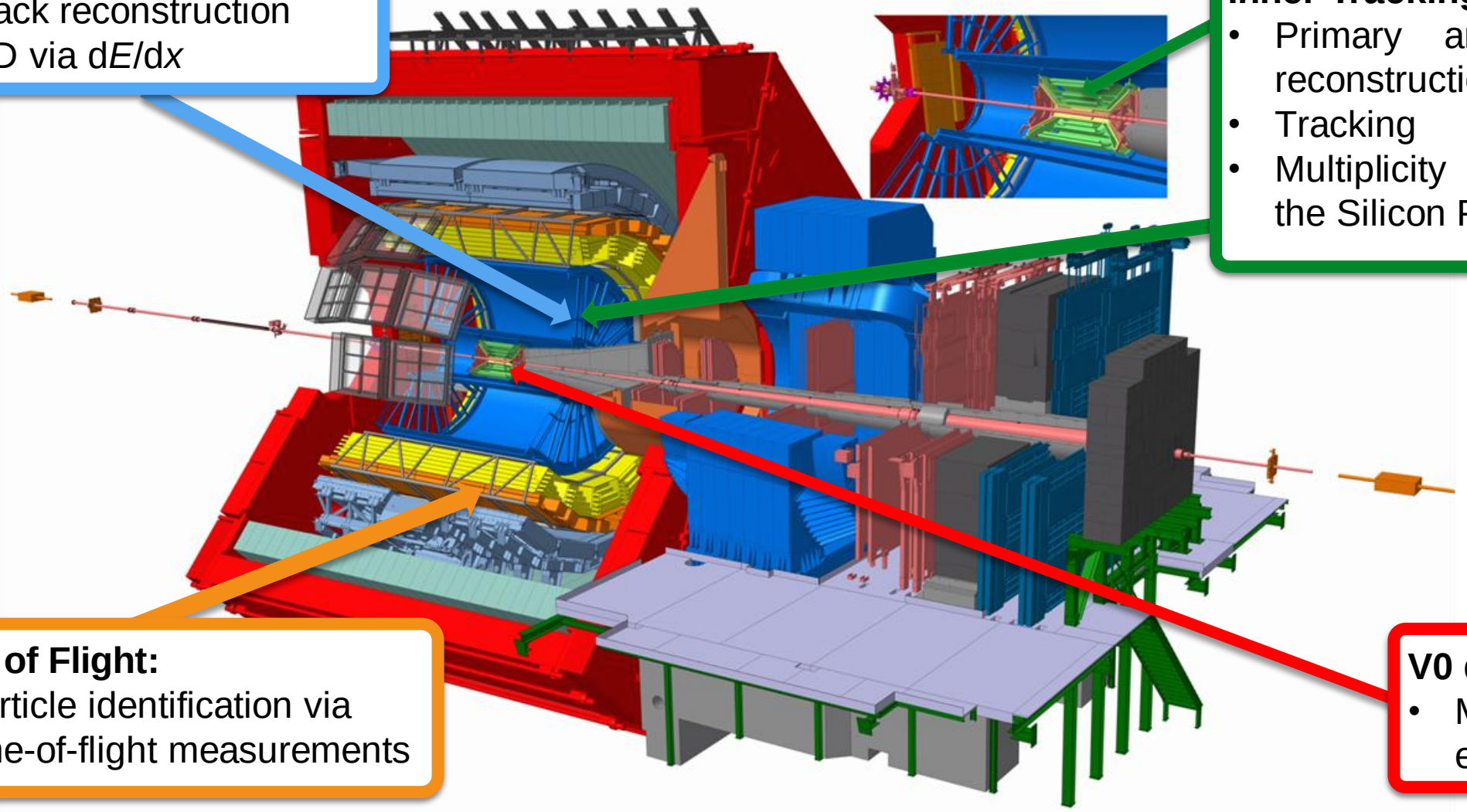


p-Pb collisions to study **cold nuclear matter (CNM) effects**.



The ALICE detector

Time Projection Chamber:
- Track reconstruction
- PID via d*E*/d*x*



Inner Tracking System:
- Primary and decay vertices reconstruction
- Tracking
- Multiplicity measurement with the Silicon Pixel Detector (SPD)

Time of Flight:
- Particle identification via time-of-flight measurements

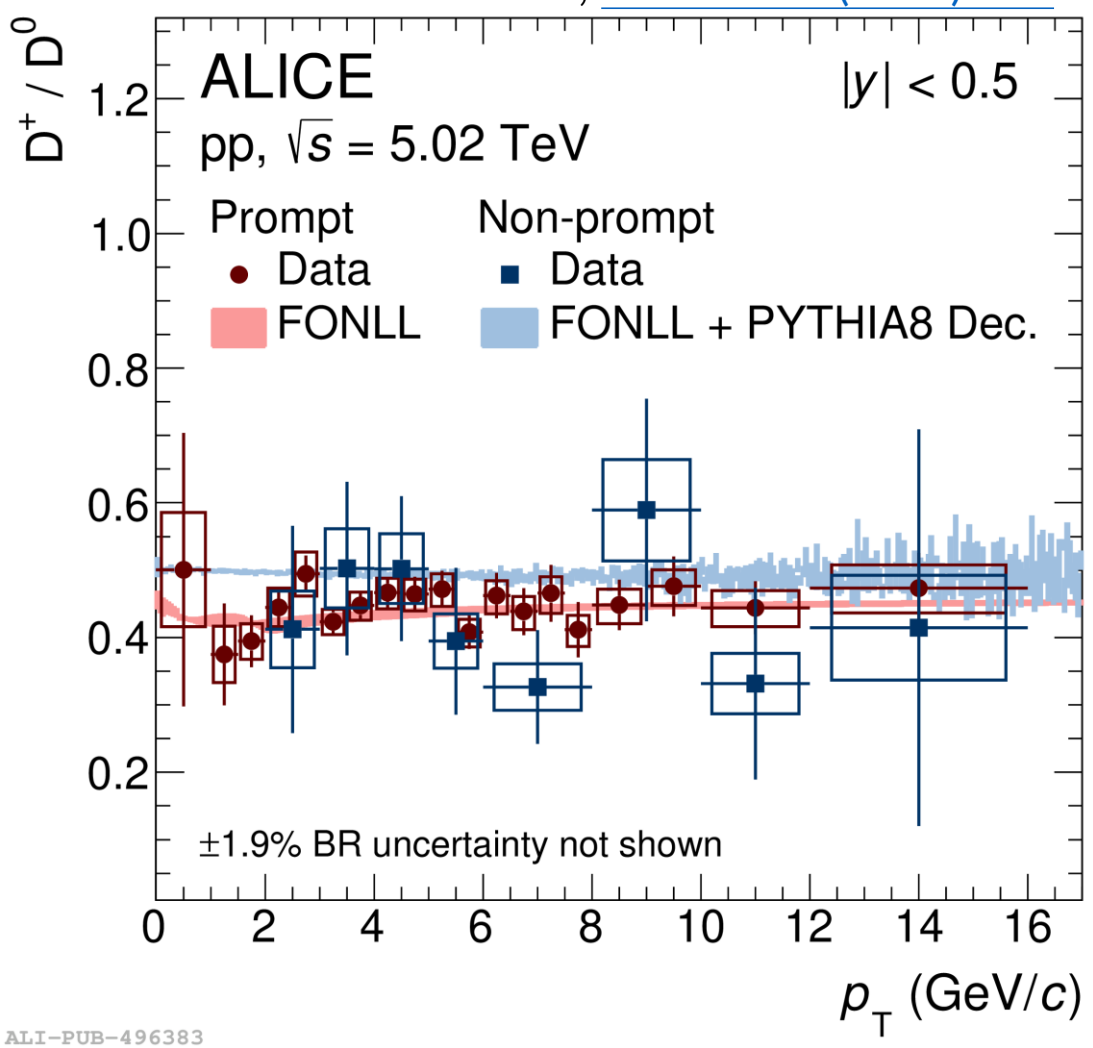
V0 detectors:
- Multiplicity / centrality estimation

Charm and beauty meson production

- No p_T dependence observed for **both prompt** and **non-prompt** D^+/D^0 meson-to-meson ratios.
- Good agreement with FONLL model calculations based on **factorisation approach** and assuming **FFs universality** (FFs measured in e^+e^- collisions).

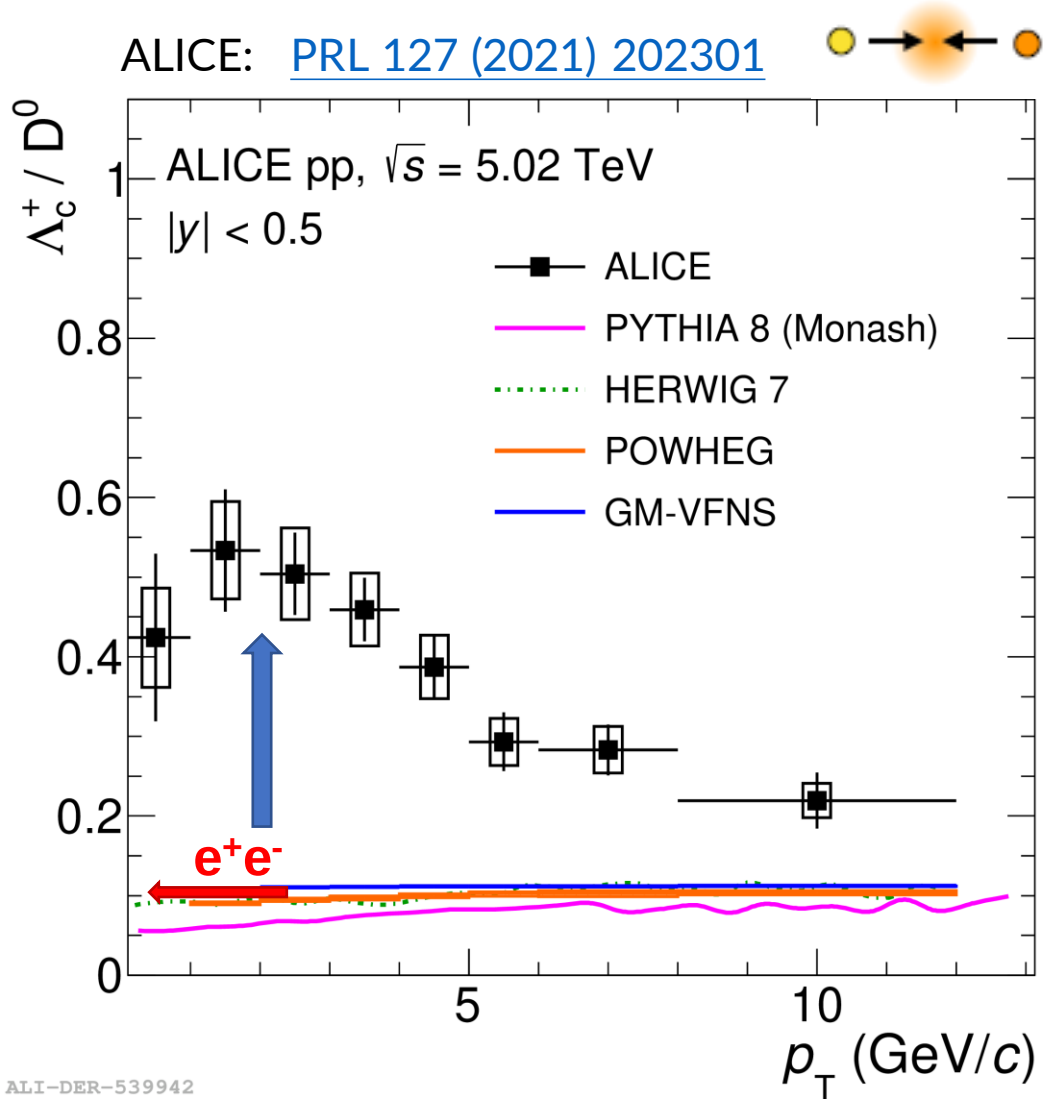
Nothing unexpected in the meson sector!

ALICE: JHEP 05 (2021) 220
FONLL: *Cacciari et al.*, JHEP 1210 (2012) 137



Charm baryon production at LHC

ALICE: PRL 127 (2021) 202301



- Λ_c^+/D^0 baryon-to-meson ratio in pp is significantly enhanced with respect to e^+e^- collisions.

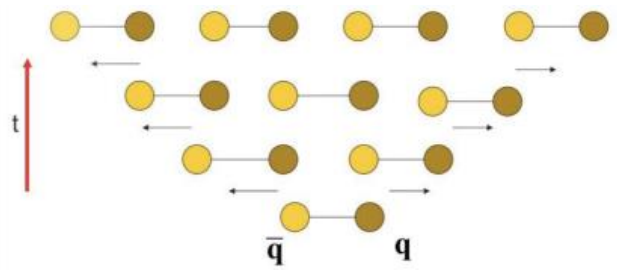
  LEP average: $(0.113 \pm 0.013 \pm 0.006)$

  EPJC 75 (2015) 19

- p_T dependence observed.

- Models based on **simple fragmentation with FF tuned on e^+e^-** collisions cannot describe the data.

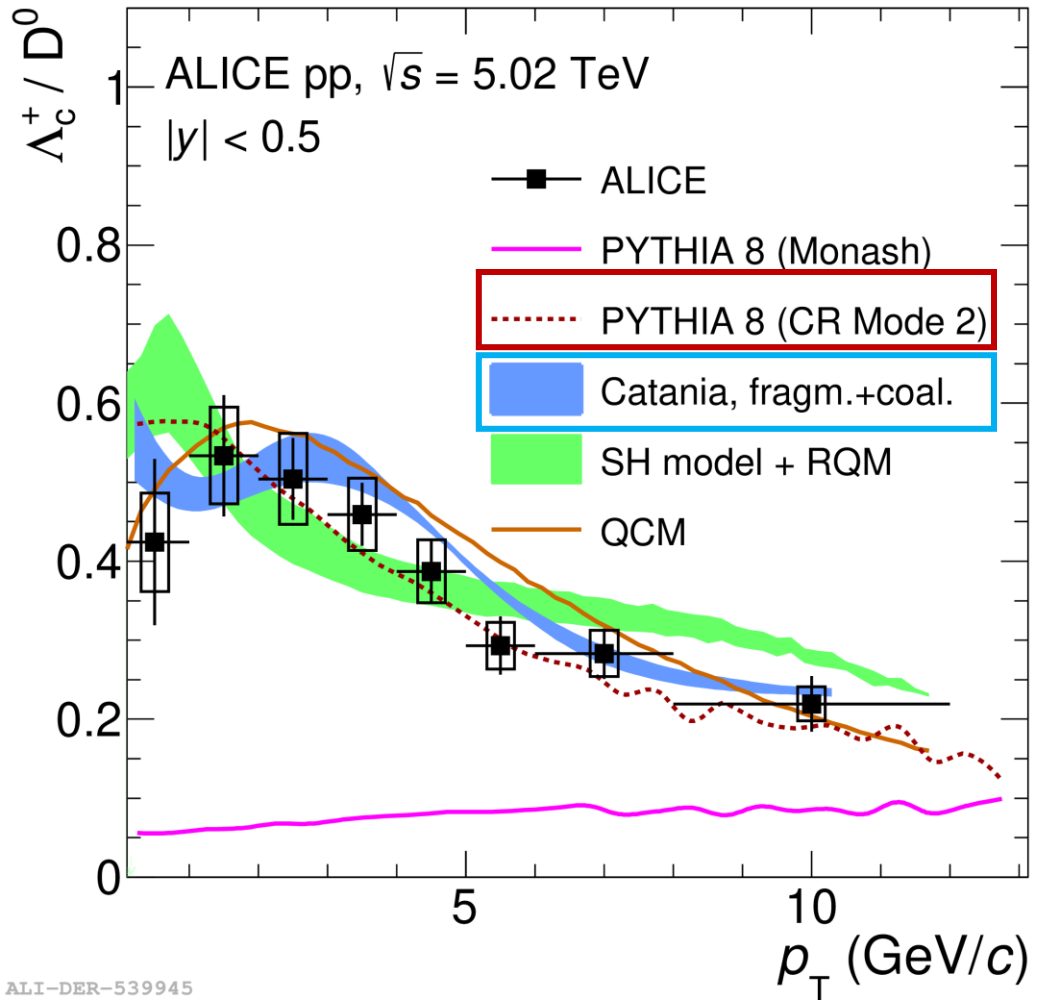
  → Non universality of the charm FFs among different collision systems.



Modified hadronization mechanisms needed to catch the data!

Charm baryon production at LHC

ALICE: PRL 127 (2021) 202301



PYTHIA 8 (CR Mode 2)

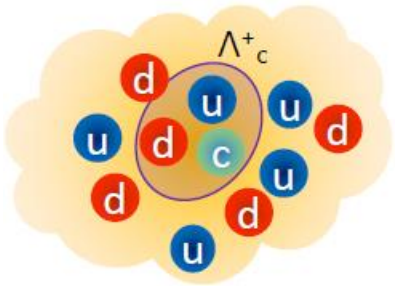
- Colour reconnection mechanisms beyond leading colour (BLC) approximation with new junction topologies that favour baryon formation.

Christiansen & Skands, JHEP 1508 (2015) 003

Catania

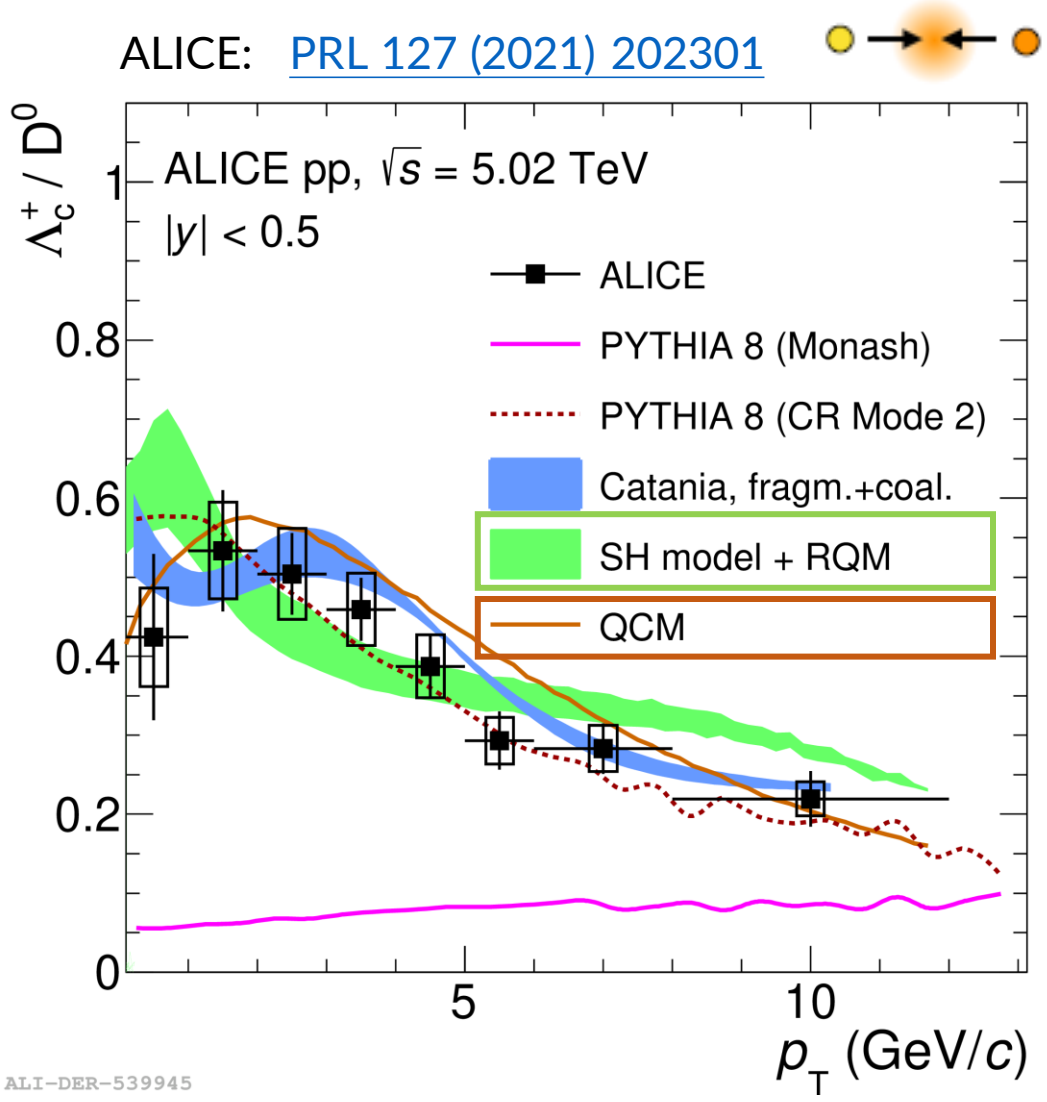
- Thermalized system of u,d,s and gluons.
- Hadronization via interplay of fragmentation and coalescence

V. Minissale et al., PLB 821 (2021) 136622



Charm baryon production at LHC

ALICE: PRL 127 (2021) 202301



SH model + RQM

- Quark hadronisation driven by statistical weights governed by hadron masses.
- Feeddown from excited baryon states predicted by the Relativistic Quark Model (RQM).

Hee & Rapp, PLB 795 (2019) 117-121

QCM

- Pure coalescence model.
- Charm is combined with co-moving light antiquark or two quarks.

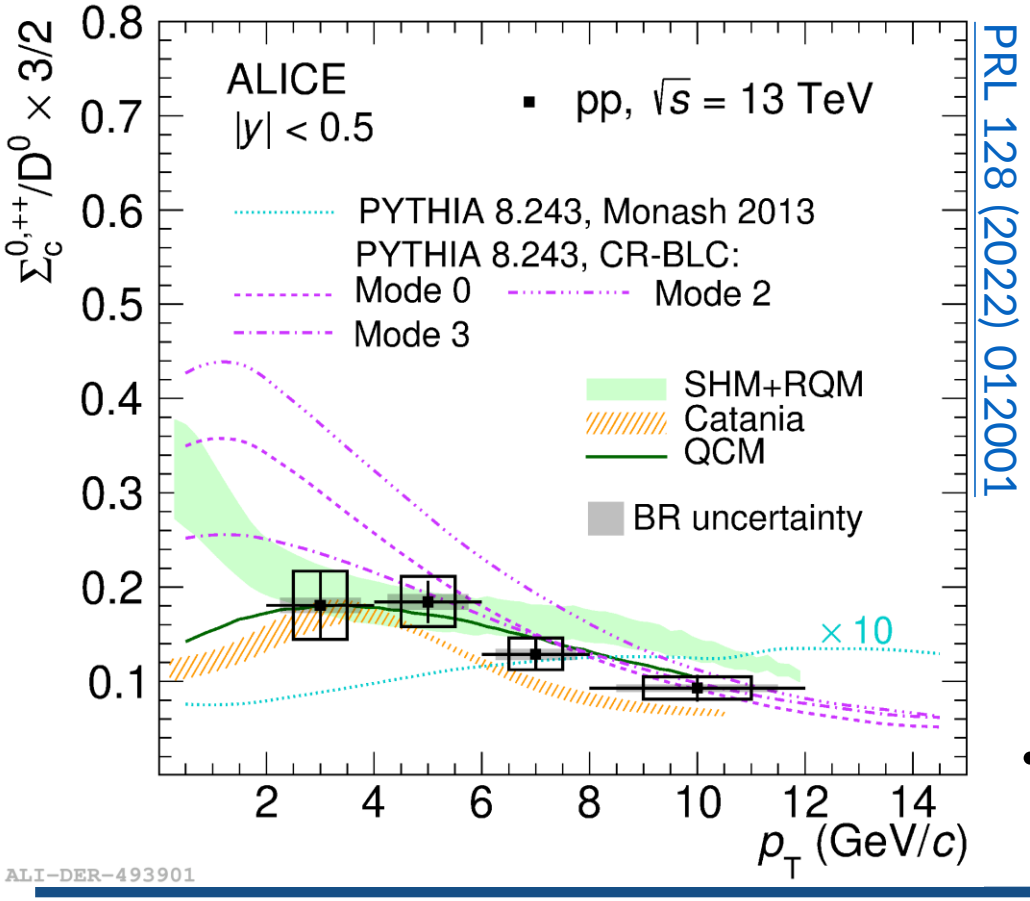
Song, Lii & Shao, EPJC 78 (2018) 344

Λ_c^+/D^0 ratio properly described by Pythia8 (CR-BLC), Catania, SHM+RQM and QCM

Charm baryon production at LHC

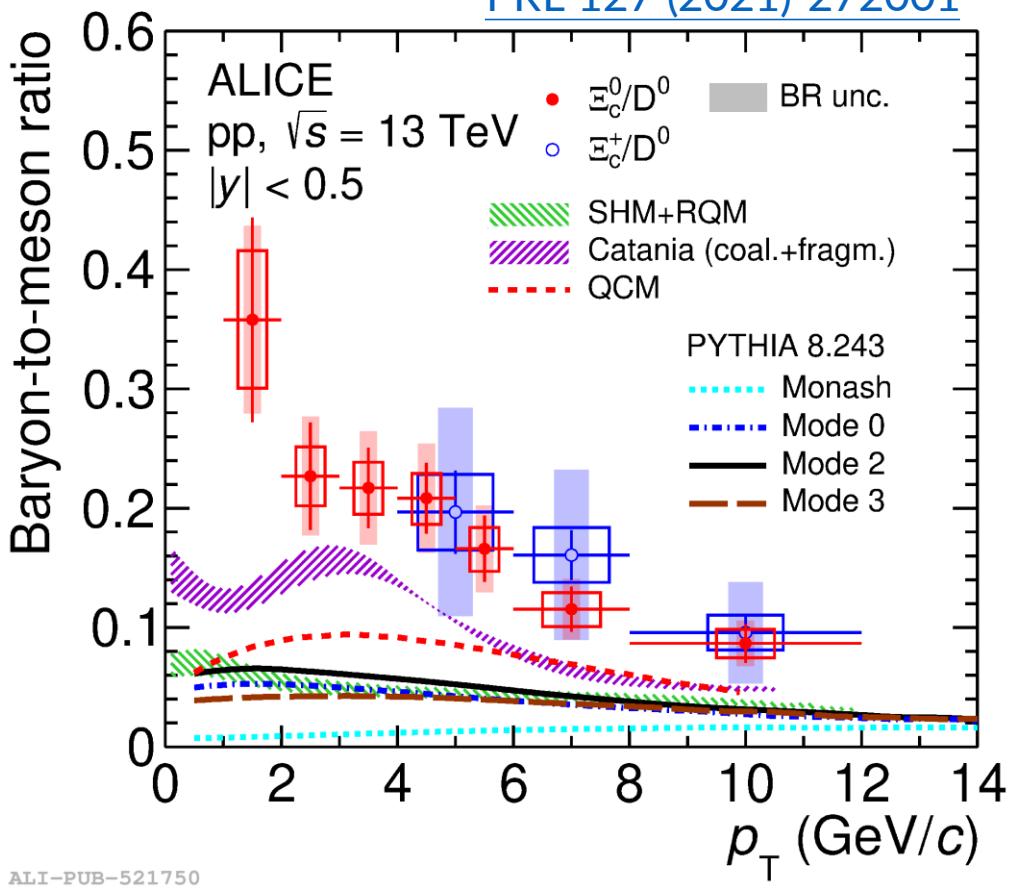
- Enhancement observed also for heavier charm baryons ($\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0).

- **Pythia with CR beyond LC**, **Catania** and **QCM** models describe the $\Sigma_c^{0,++}/D^0$ ratio.



PRL 128 (2022) 012001

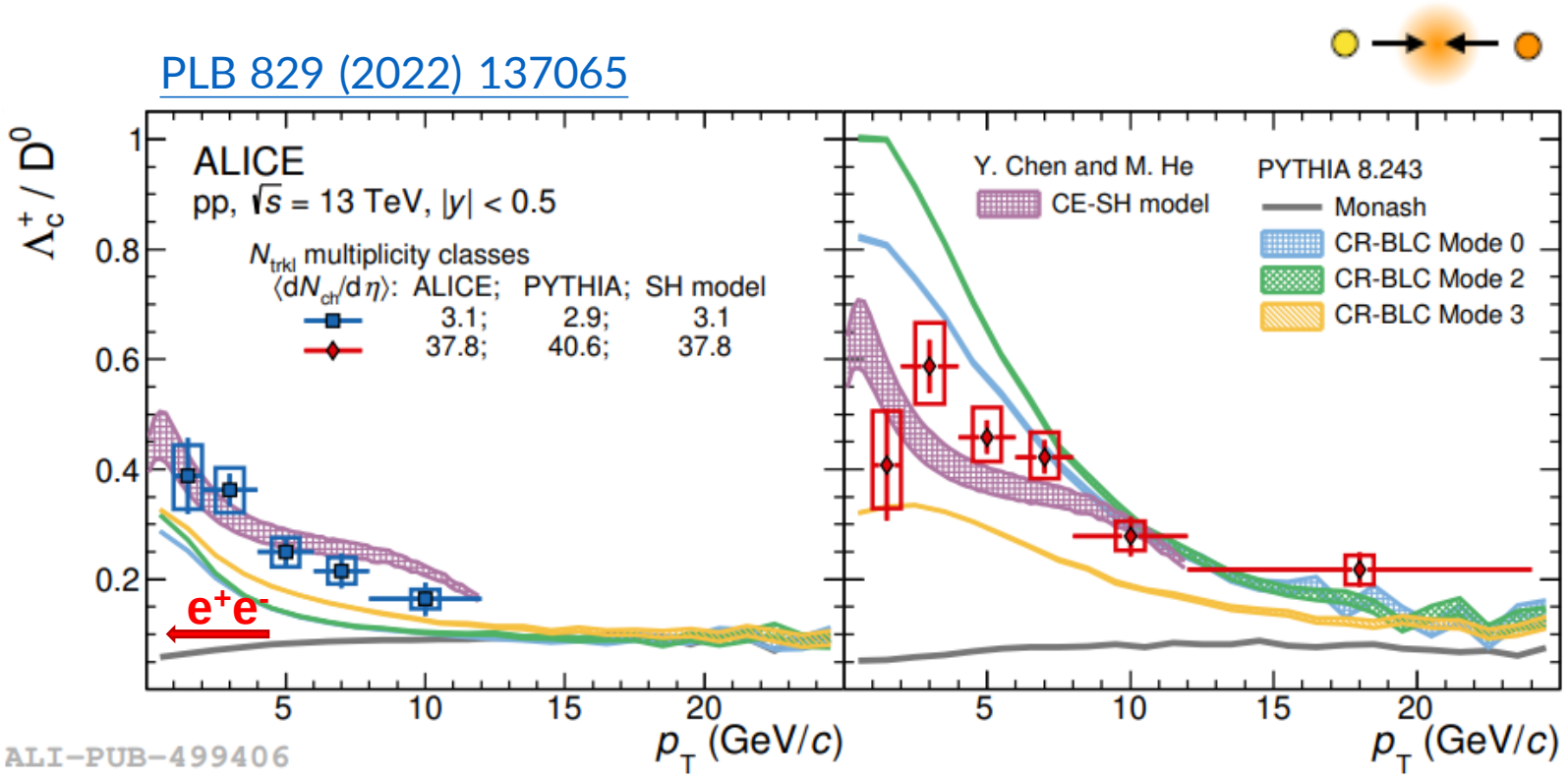
PRL 127 (2021) 272001



- Enhancement in the charm-strange sector even larger. $\Xi_c^{0,+}$ qualitatively described only by **Catania** model.

Charm baryon-to-meson ratio vs multiplicity

PLB 829 (2022) 137065

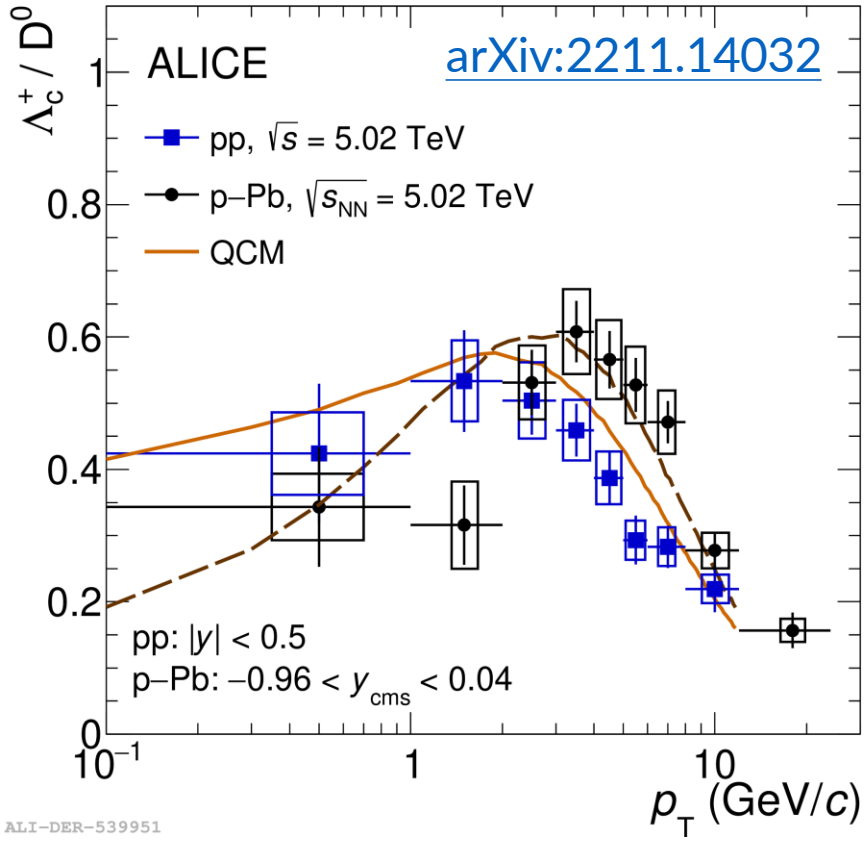


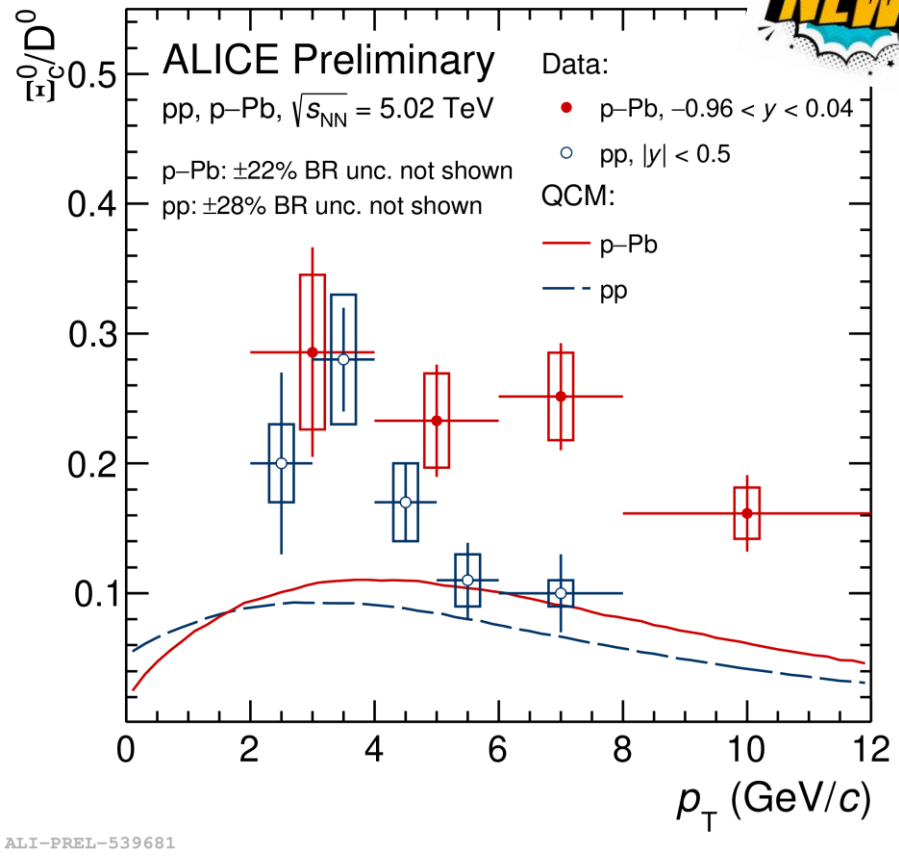
- Significant (5.3σ) dependence on multiplicity in $1 \leq p_T < 12$ GeV/c.
- Λ_c^+/D^0 ratios in pp are enhanced w.r.t. e^+e^- collisions also in the lowest multiplicity interval.

- **Pythia Monash** underestimates the data and fails to reproduce the multiplicity dependence.
- Λ_c^+/D^0 ratios p_T and multiplicity dependence qualitatively described by **Pythia with CR beyond LC** and by **SHM** with an augmented set of charm baryon states.

Charm baryon-to-meson ratio in p-Pb and Pb-Pb

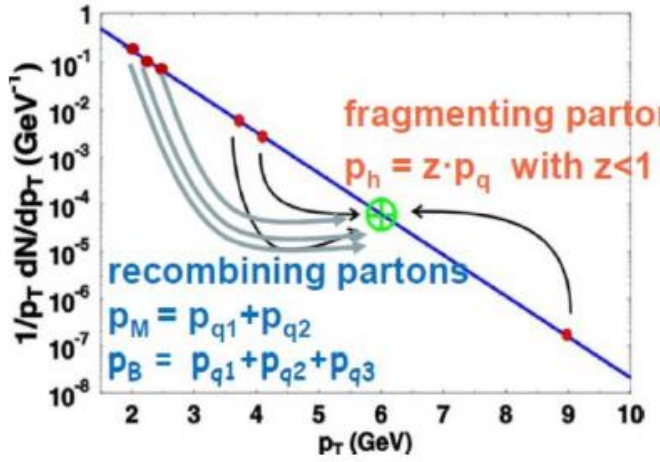
And in **p-A** and **A-A** collisions?





NEW!

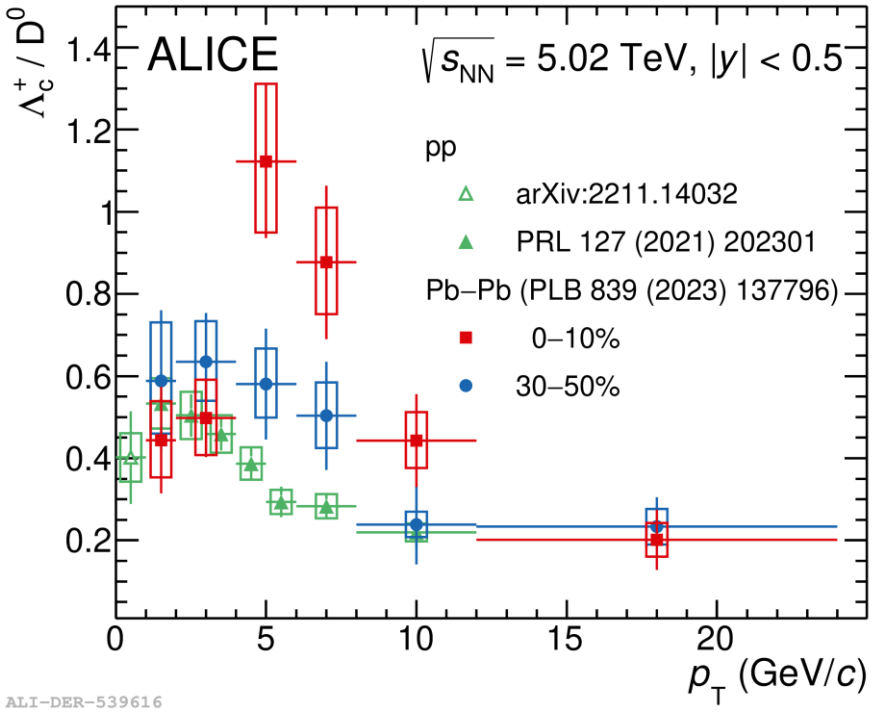
- Charmed baryon-to-meson ratio **enhancement** at intermediate p_T (> 2 GeV/c) **moving from pp to p-Pb collisions**.



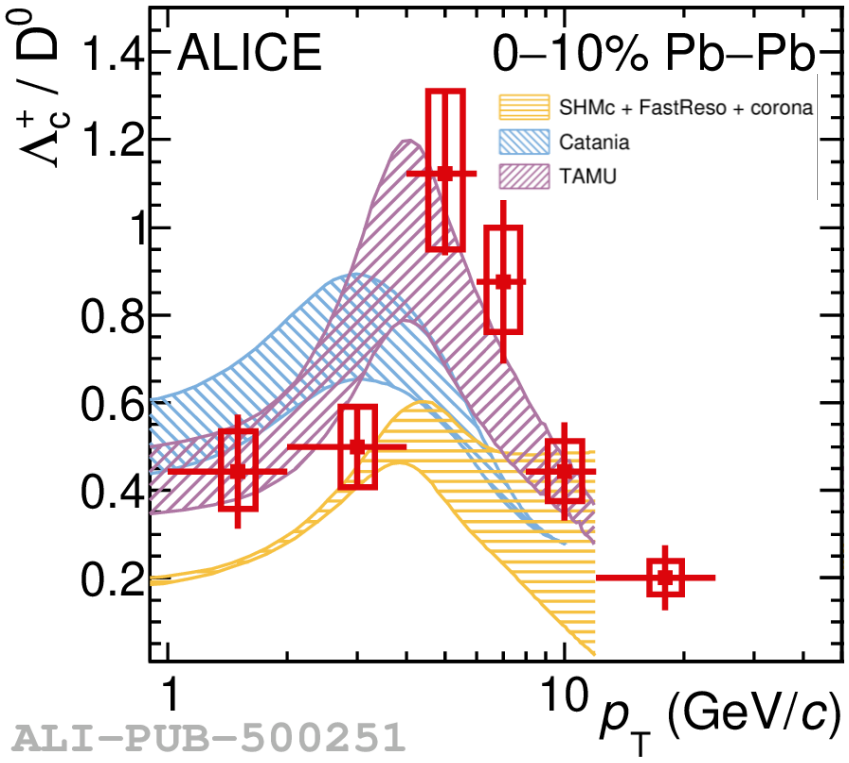
- Shift of the spectra towards higher p_T is predicted by coalescence models.
- **QCM** catches the Λ_c^+/D^0 ratio, but it underestimates the Ξ_c^0/D^0 .

Charm baryon-to-meson ratio in p-Pb and Pb-Pb

And in **p-A** and **A-A** collisions?

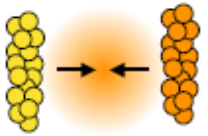


arXiv:2112.08156



SHMc: JHEP 07 (2021) 035
Catania: PRC 96 (2017) 044905
TAMU: PRL 124 (2020) 042301

- Charmed baryon-to-meson ratio **enhancement** at intermediate p_T (> 2 GeV/c) moving from pp to p-Pb **to Pb-Pb** collisions.



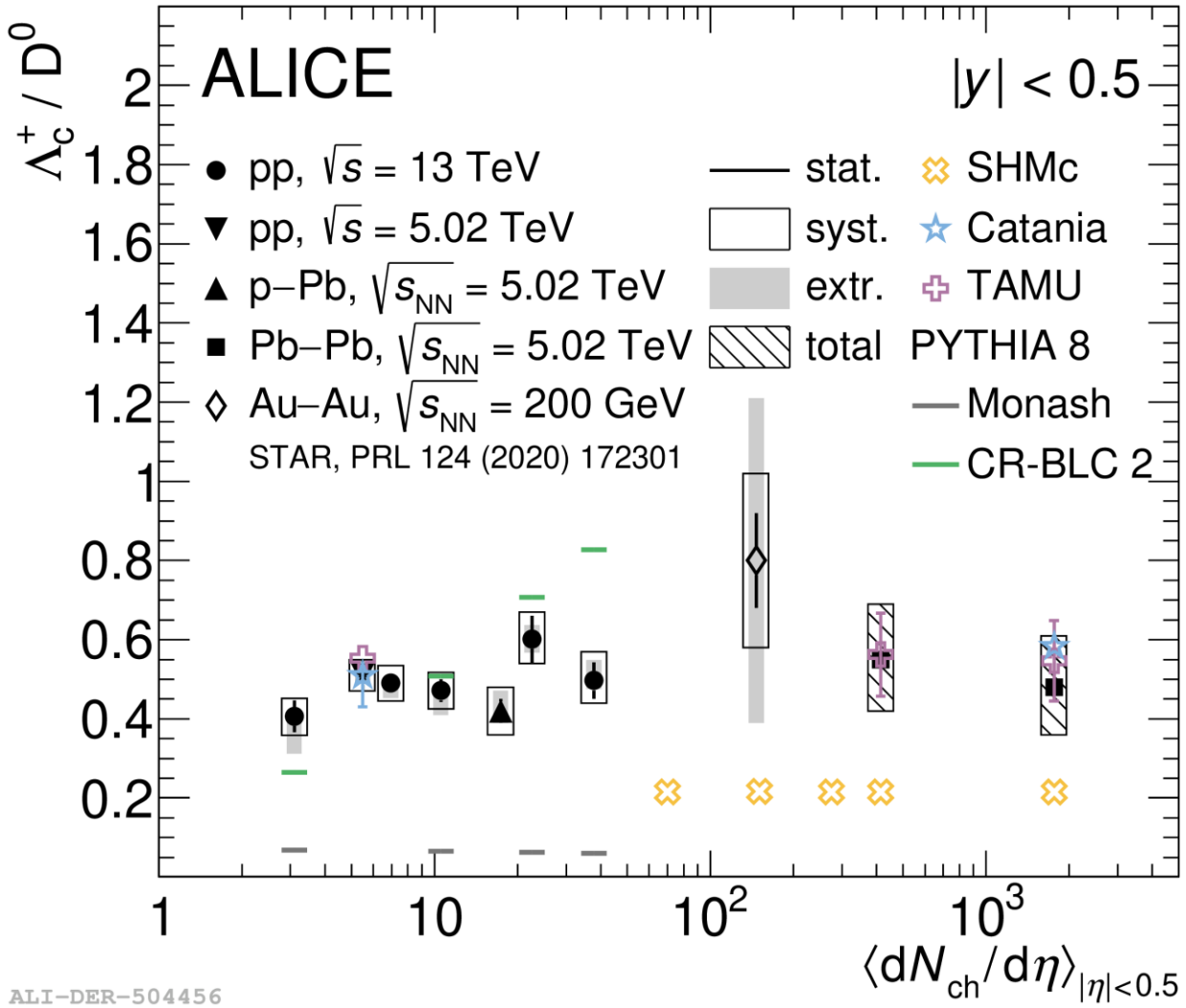
- **Catania** and **SHMc** qualitatively predict the observed shape but underestimate the result at intermediate p_T. **TAMU** catches both the shape and the magnitude of the data.

Overall baryon production enhancement or redistribution of p_T between baryons and mesons?

Integrated Charm baryon-to-meson ratio

p-Pb: Phys. Rev. C **104**, 054905

Pb-Pb: arXiv:2112.08156

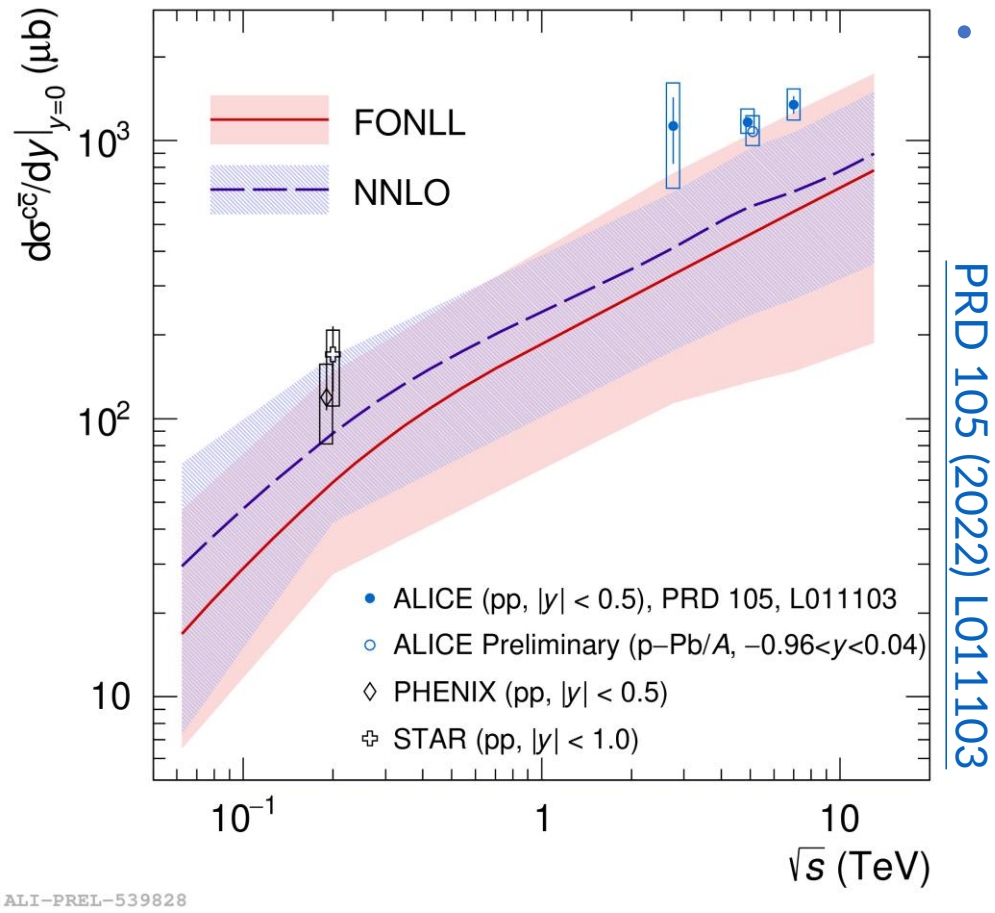


- p_T-integrated Λ_c^+/D^0 ratio measurements in pp, p–Pb and Pb–Pb compatible with one another.
- Re-distribution of p_T that acts differently for baryons and mesons. **No modification of overall p_T-integrated yield ratios**.

Same mechanism in all collision systems? Modified hadronization? Radial flow?

- Flat trend reproduced by models with hadronization via **fragmentation + recombination** (Catania, TAMU).

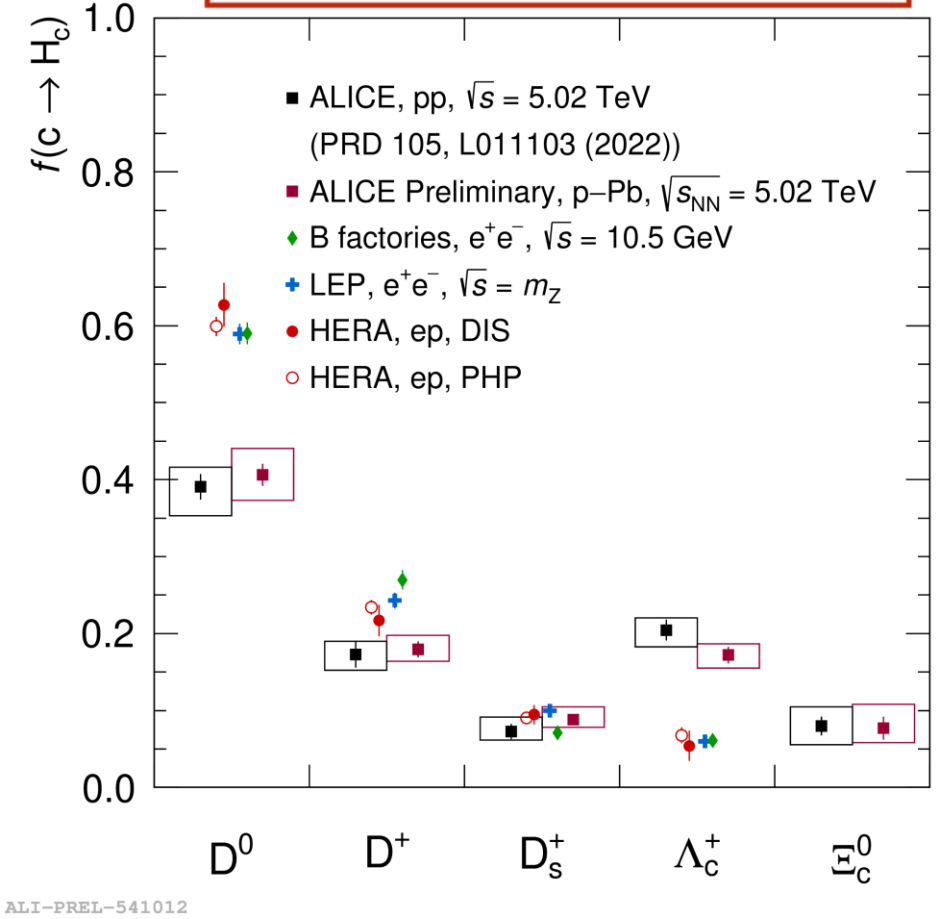
Total charm cross section and FF



PRD 105 (2022) L011103

- **$c\bar{c}$ production cross section** measured at midrapidity compatible with the upper edge of the FONLL and NNLO calculations.

$$f(c \to H_c) = \sigma(H_c)/\Sigma_i \sigma(H_{c,i})$$

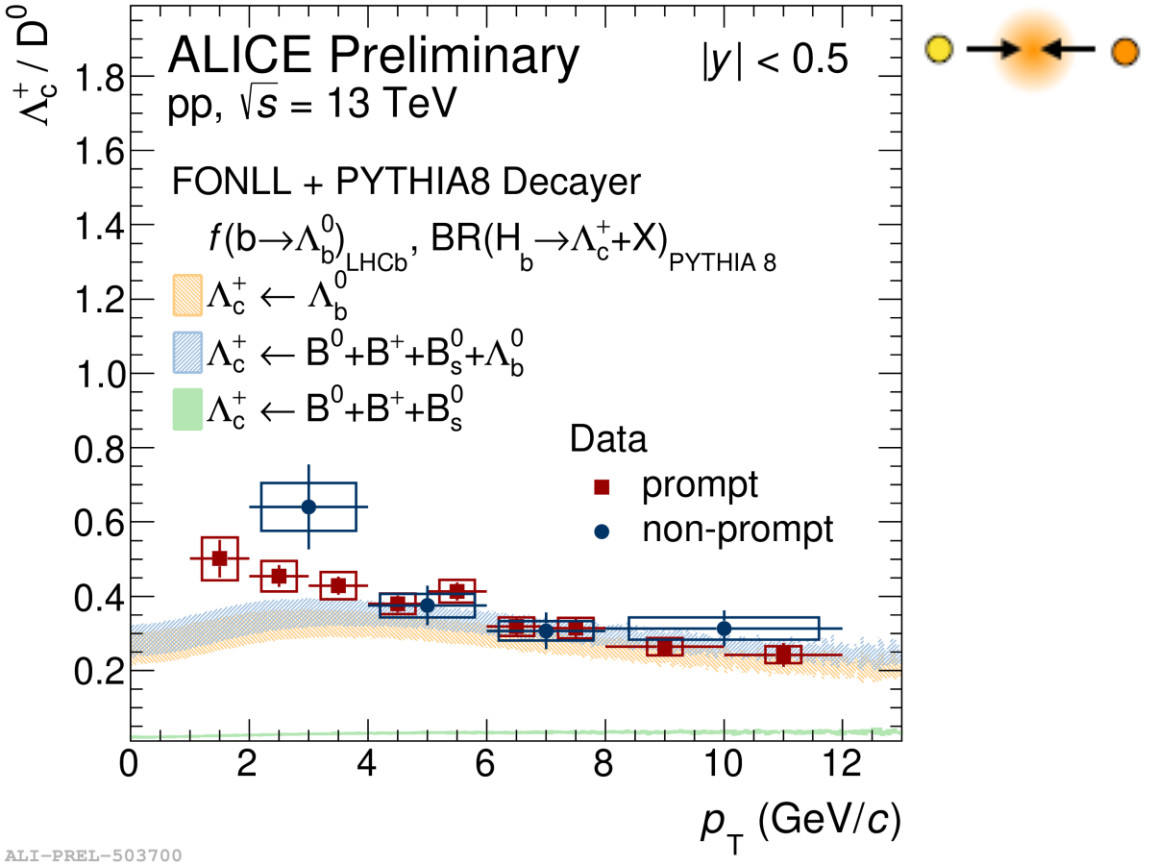


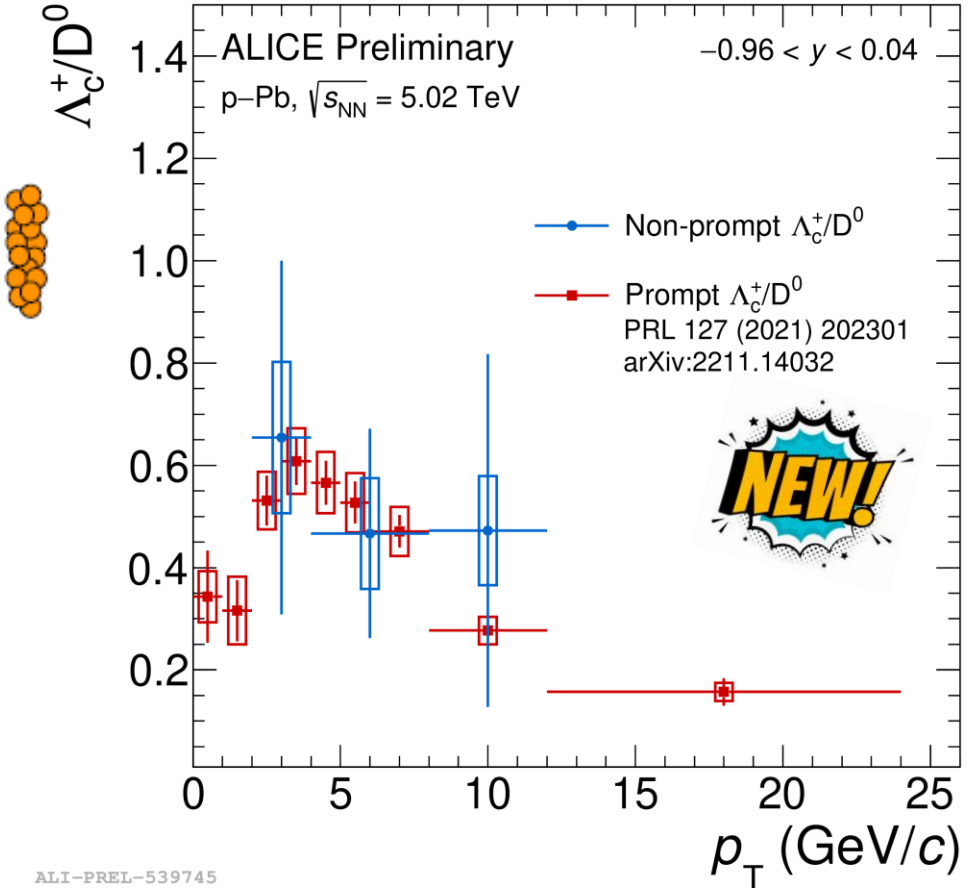
- Significant baryon enhancement with respect to e^+e^- and e^- p.
- Measurements in pp and p-Pb at $\sqrt{s} = 5.02$ TeV compatible within uncertainties.

Beauty baryon-to-meson ratio

What about the **beauty sector**?

- Agreement between prompt and non-prompt Λ_c^+/D^0 in both pp and p-Pb collisions.
- Non-prompt Λ_c^+/D^0 ratio are well described by **FONLL + Pythia8*** model calculations.

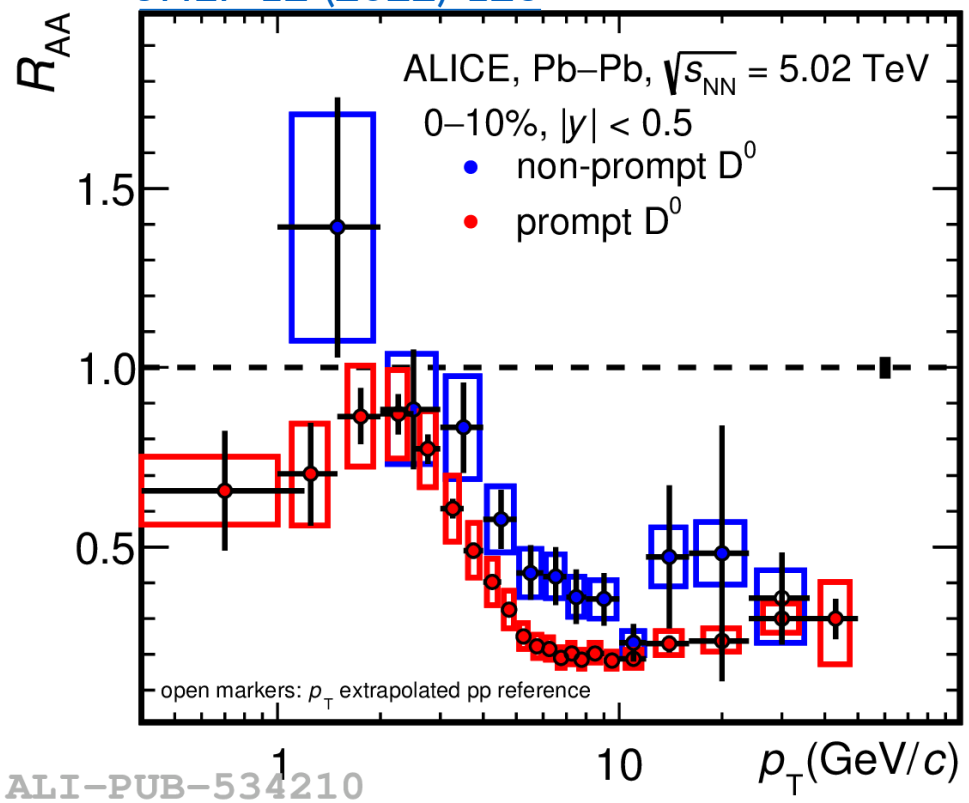




*$b \to \Lambda_b^0$ fragmentation fractions measured by LHCb. Phys. Rev.D 100 (2019) 031102(R)

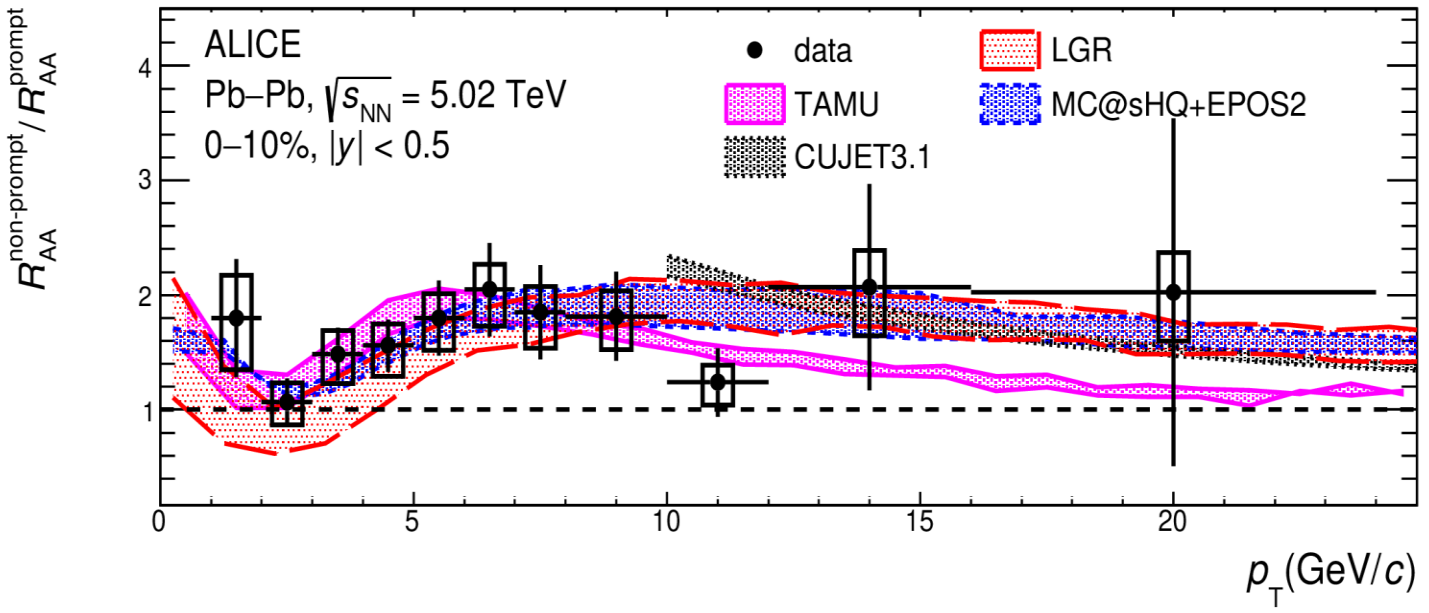
In-medium energy loss

JHEP 12 (2022) 126



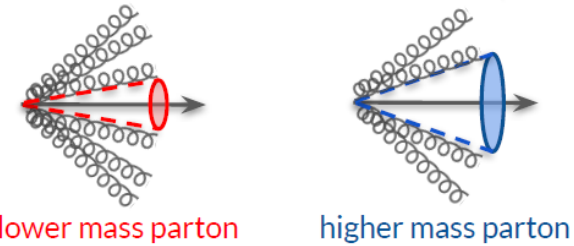
ALI-PUB-534210

LGR: EPJC 80 (2020) 671
CUJET3: JHEP 02 (2016) 169
MC@sHQ+EPOS2: PRC 89 (2014) 014905



ALI-PUB-534213

- R_{AA} (b → D^0) > R_{AA} (c → D^0) at intermediate p_T.
  ➡ in-medium energy-loss mass dependence (dead cone effect)



- Theoretical models that include **quark coalescence** and **collisional** and **radiative energy loss** catch the data.

Summary and outlook

- Models based on **in-vacuum fragmentation** assuming **universal FF** among collision systems **do not describe charm-baryon production** in hadronic collisions at the LHC.

  - **Charm hadronization not** a **universal** process across different collision systems.

  - **Modified hadronisation mechanisms** needed to describe the heavy-flavour baryon measurements.

More on heavy-flavour measurements with ALICE:

Vit Kucera, May 16 (18:40):
"Heavy-flavour jet measurements in pp and Pb-Pb collisions with ALICE"

Thomas Herman, May 16 (17:40):
"Recent results on J/psi photoproduction in UPCs with ALICE"

- **LHC Run 3 data taking**:

  - **Upgraded apparatus** → ITS 2 with improved impact parameter resolution.
  - **Larger data samples** → Continuous readout at 50 kHz interaction rate for Pb–Pb collisions.

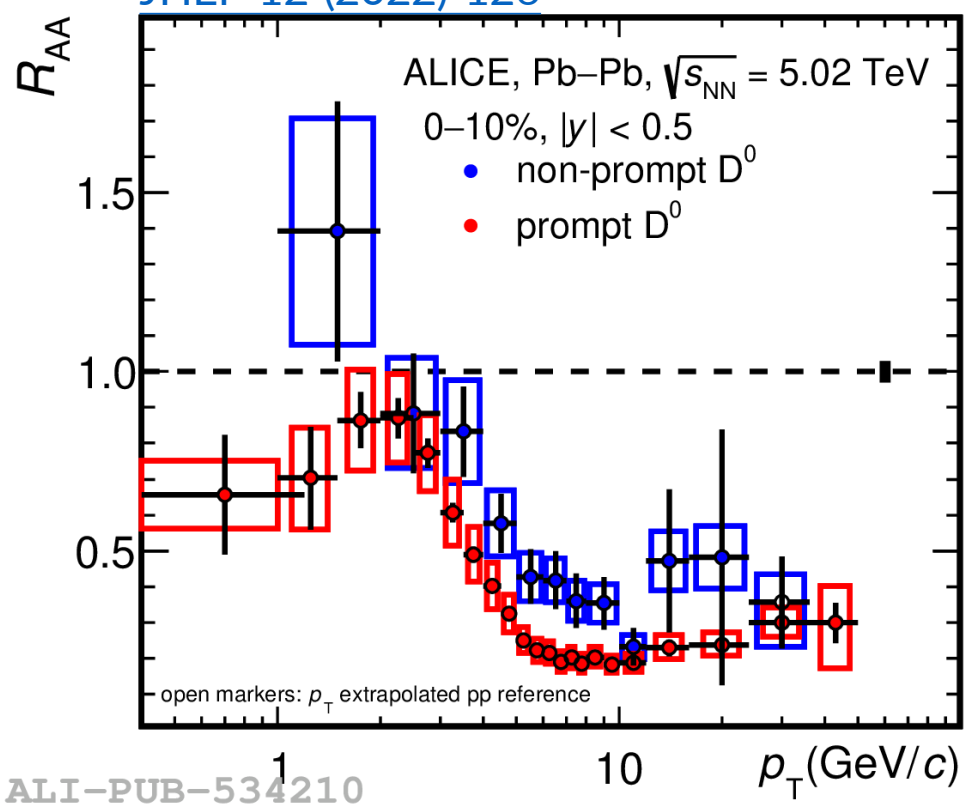
New precise measurements of charm and beauty hadrons!

Stay Tuned

Backup

Beauty in-medium energy loss

JHEP 12 (2022) 126



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LGR: EPJC 80 (2020) 671
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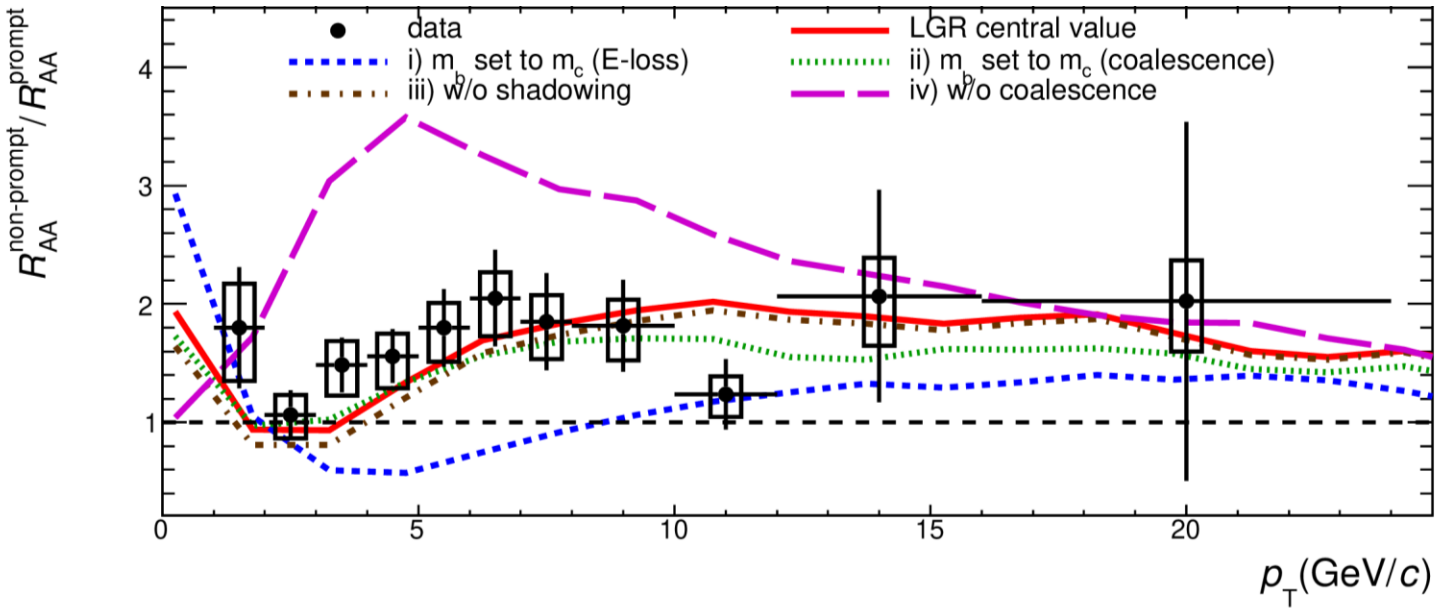
MC@sHQ+EPOS2: PRC 89 (2014) 014905



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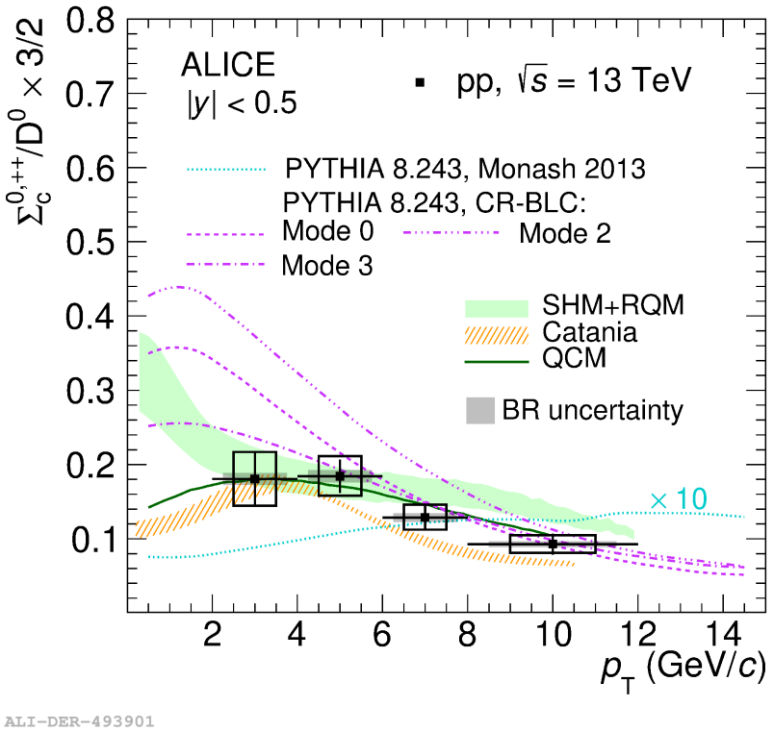
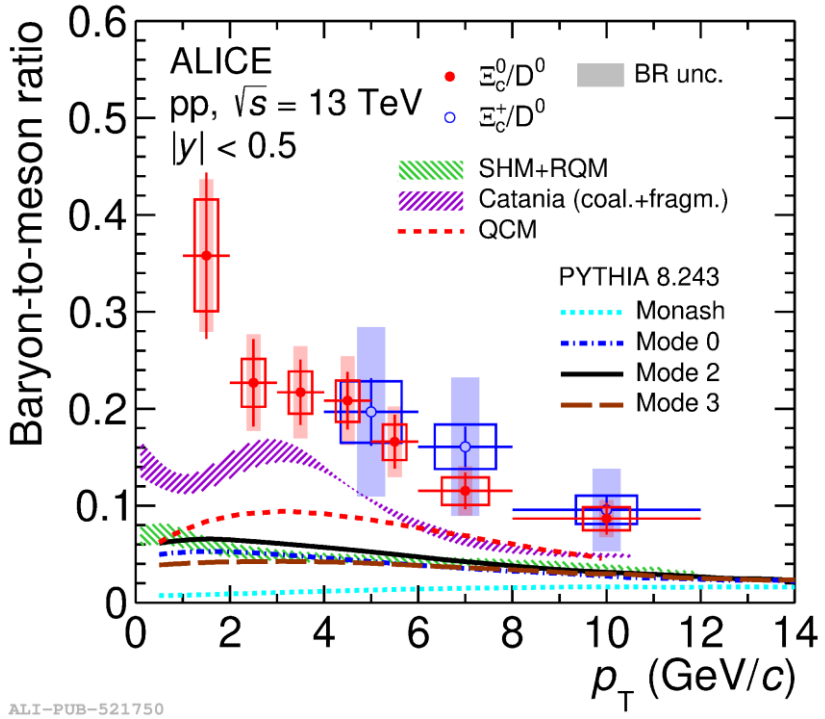
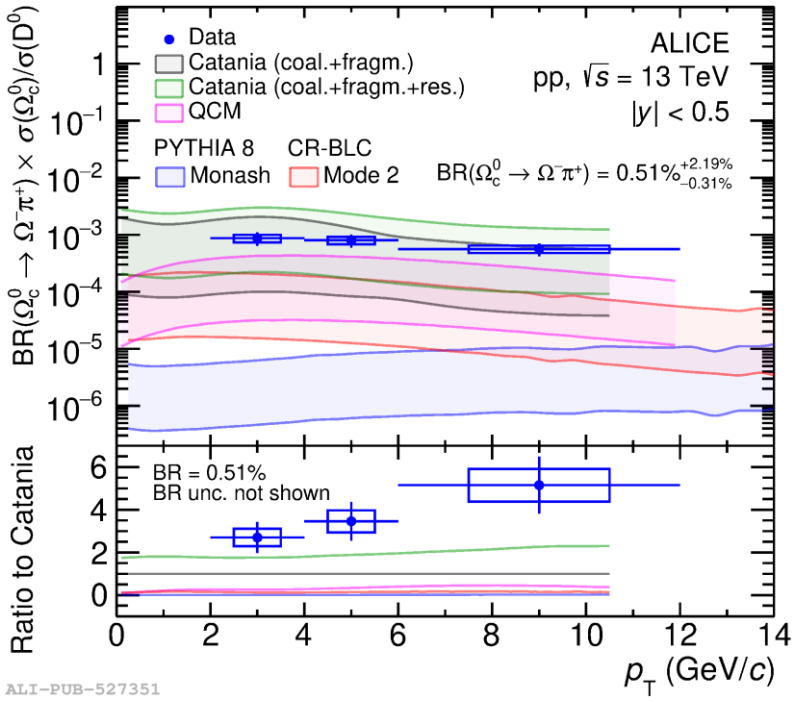
Testing different assumptions with LGR model:

- Valley structure at low p_T explained by **quark coalescence** (case iv).
- Beauty R_{AA} enhancement at high p_T due by **mass dependent quark in-medium energy loss** effect (case i).

Charm baryon production at LHC



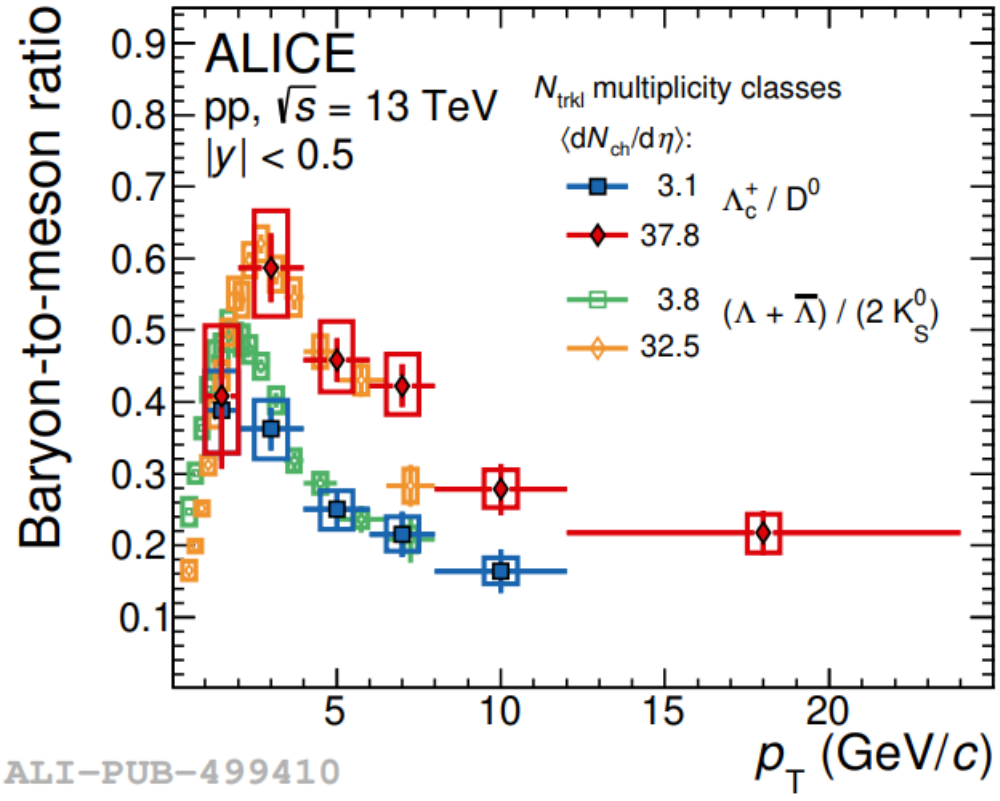




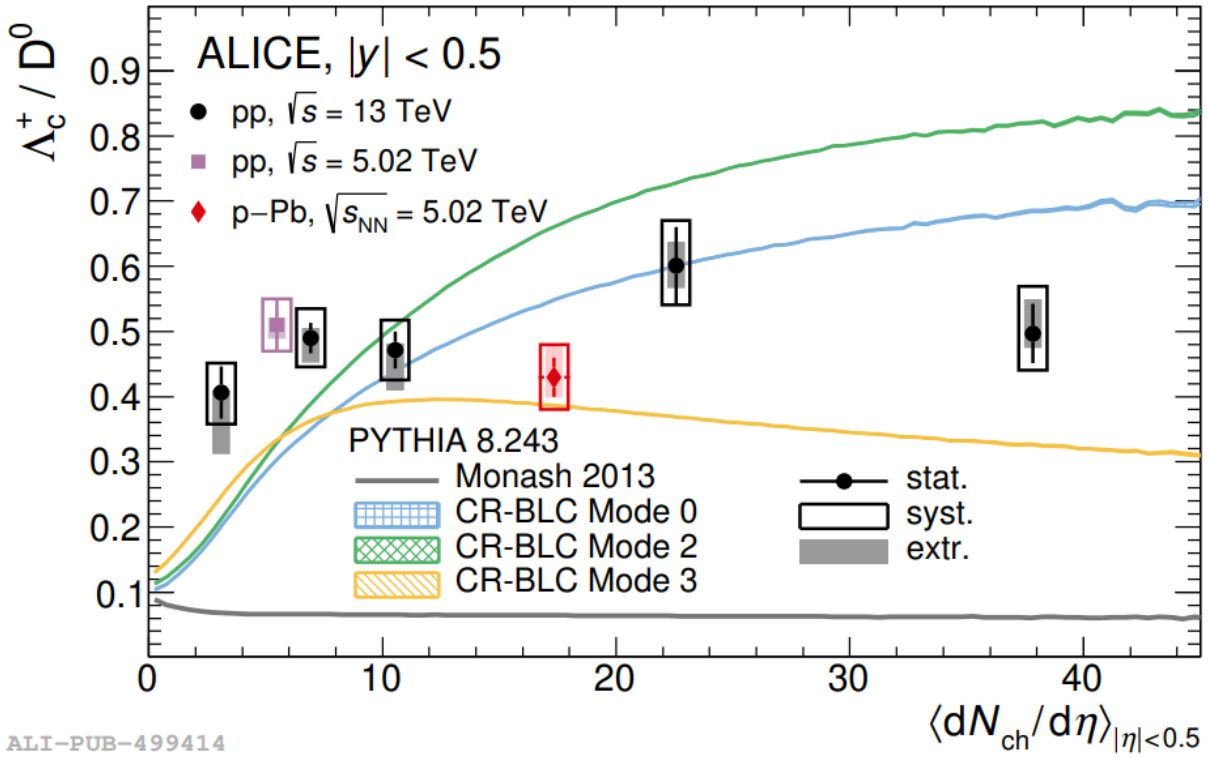
Baryon-to-meson ratio

- Similar trend as a function of multiplicity for light- and heavy-flavour baryon-to-meson ratios, Λ/K_s^0 and Λ_c^+/D^0 .

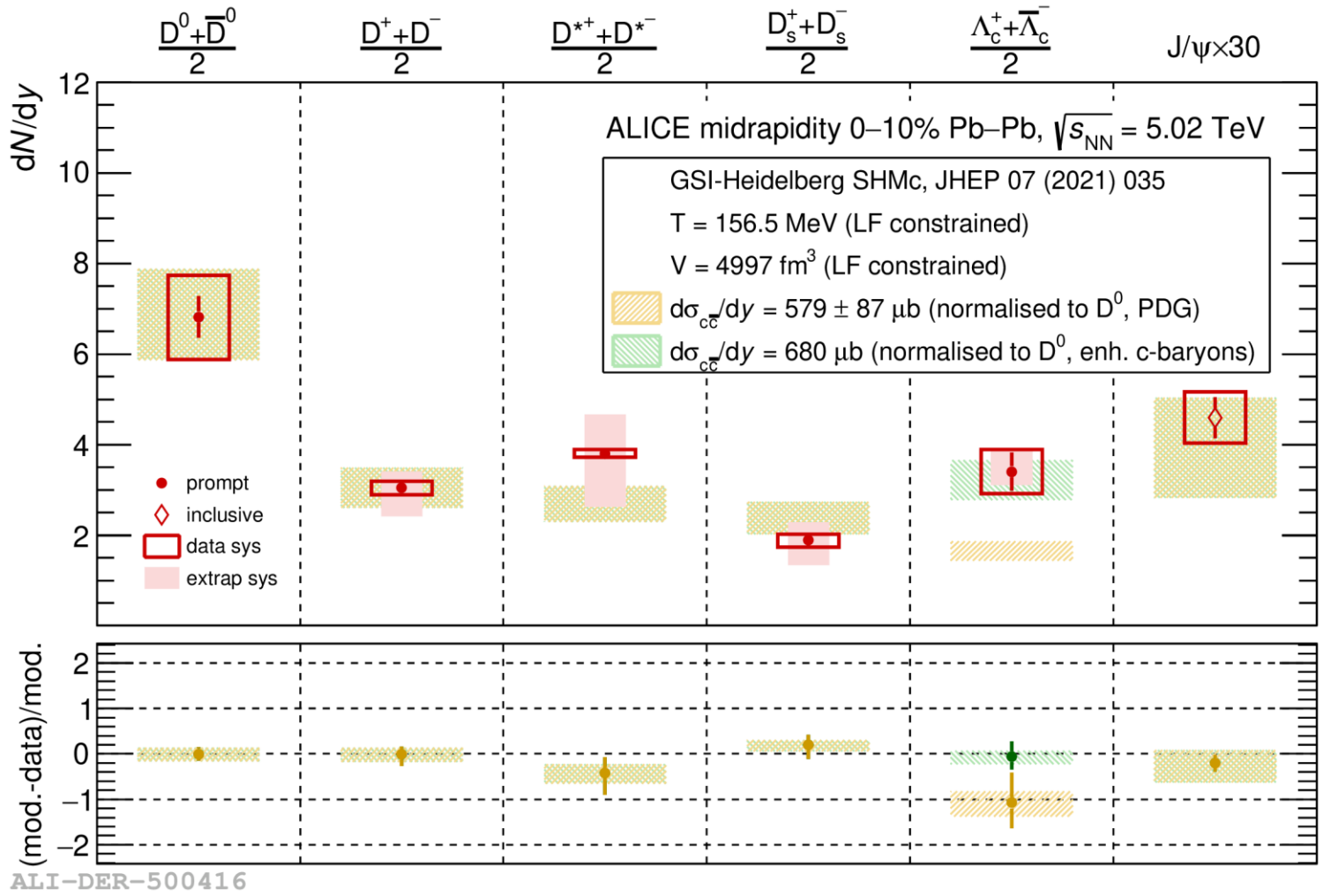
- Hint of a potential common mechanism for light- and charm-baryon formation in hadronic collisions at LHC energies.



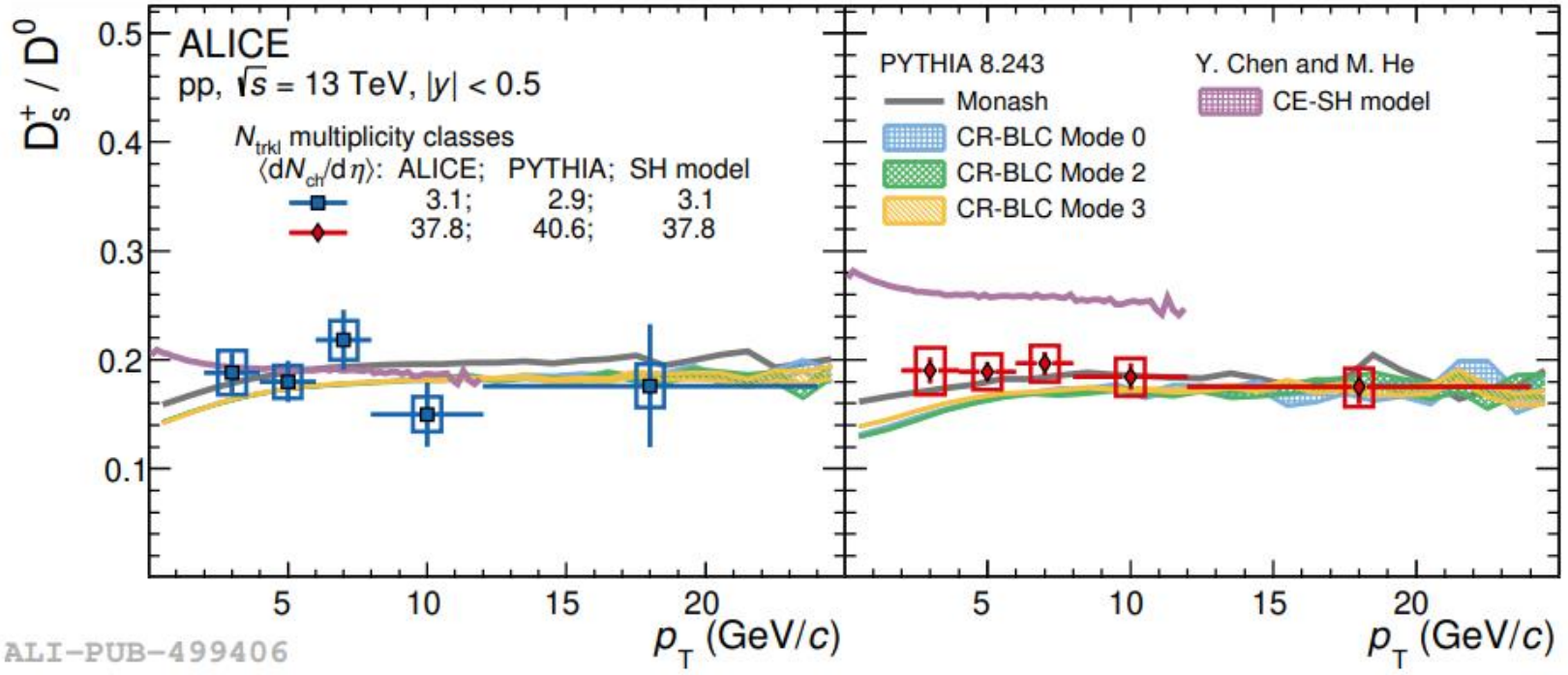
Integrated prompt Λ_c^+/D^0 baryon-to-meson ratio



Integrated prompt Λ_c^+/D^0 baryon-to-meson ratio



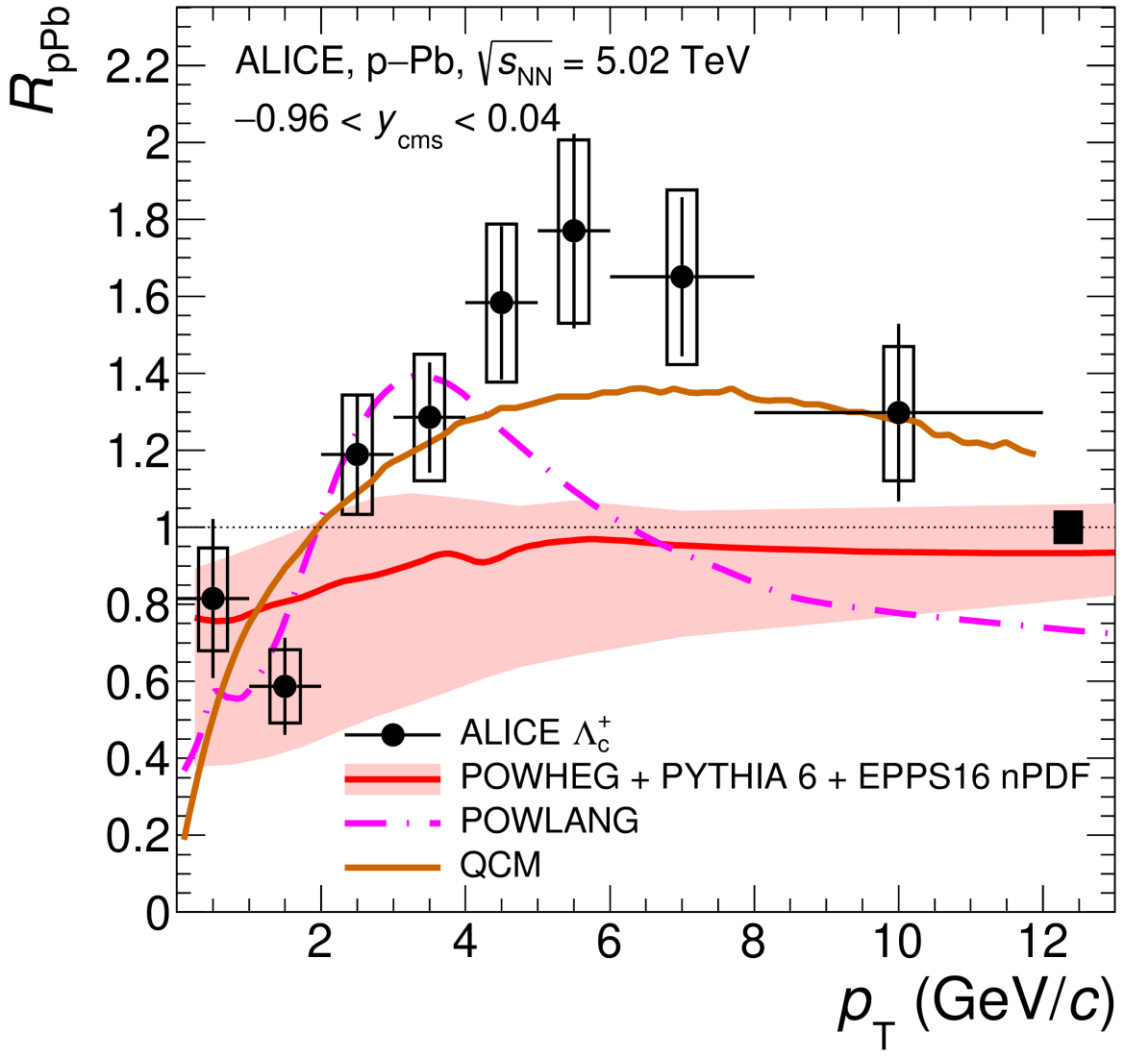
Prompt D_s^+/D^0 strange to non-strange meson ratio



- D_s^+/D^0 ratios are p_T independent in the measured p_T range.
- Dependence of D_s^+/D^0 ratio on multiplicity not observed within the uncertainties.
- The results are comparable with the measurements performed in e^+e^- collisions.

- D_s^+/D^0 ratios compatible with **PYTHIA Monash** and **CR-BLC**.
- The **CE-SH** model describes the low multiplicity D_s^+/D^0 measurement, but it overestimates the data in the highest multiplicity interval.

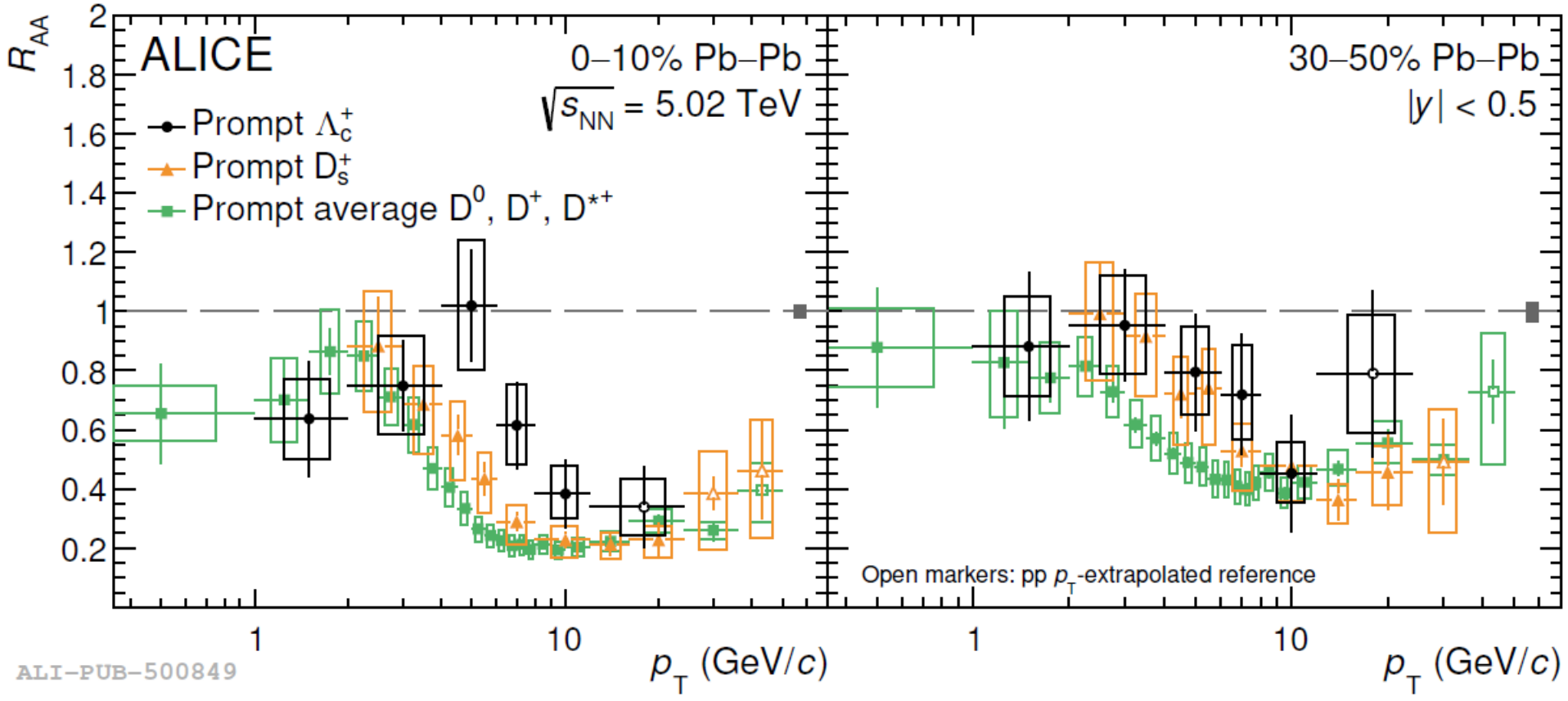
Λ_c^+ R_{pPb}



Enhancement of the Λ_c^+ R_{pPb} at intermediate p_T.
Radial flow from hydrodynamic evolution?

What could be the reason of such flow?

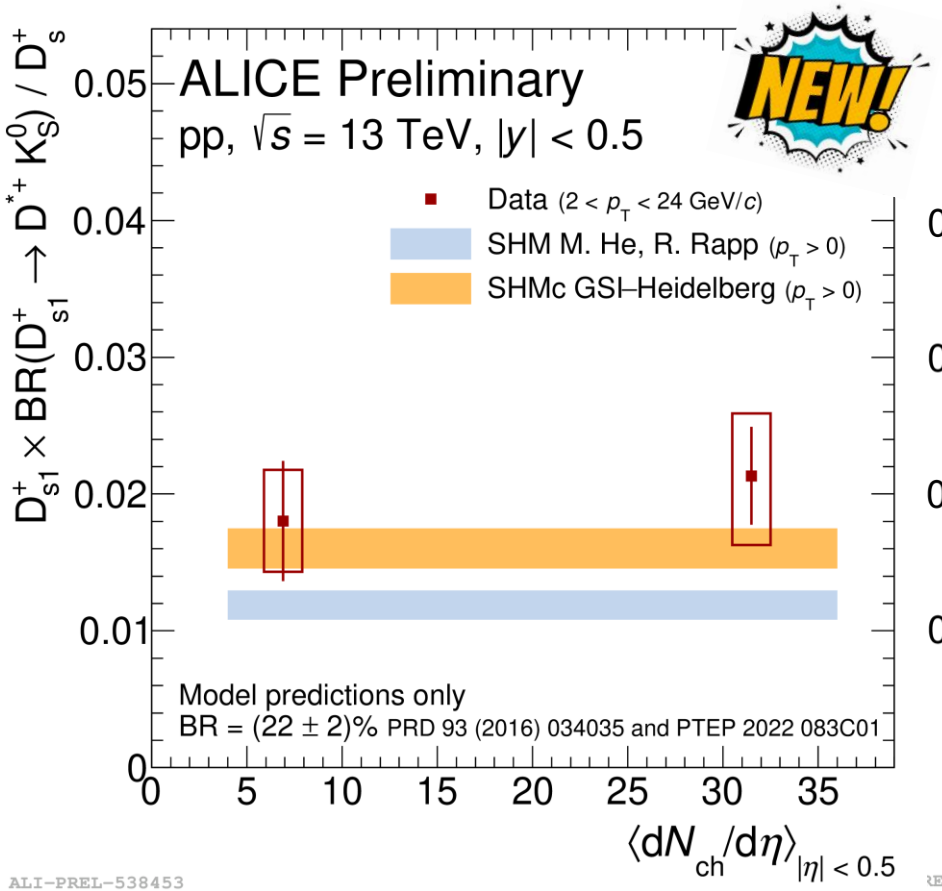
D meson and Λ_c^+ R_{AA}

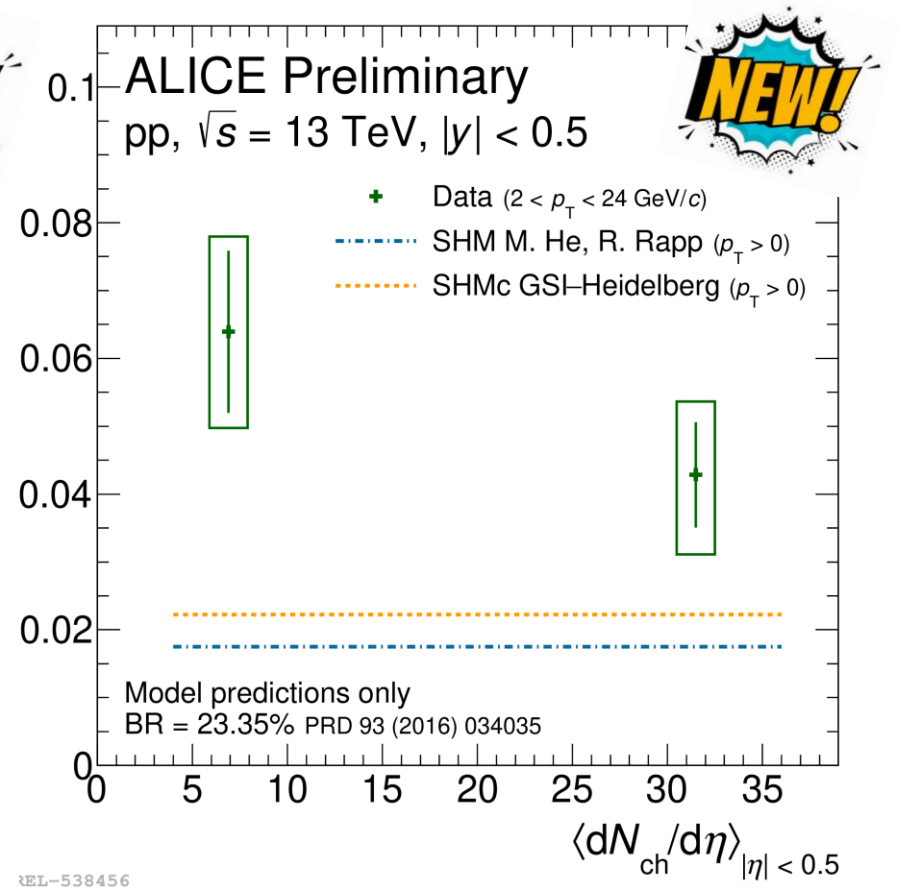


D_s^+ excited states p_T-integrated yield ratio

- First measurement of D_{s1}^+ and D_{s2}^{*+} production at the LHC.

SHM: *Hee & Rapp*, PLB 795 (2019) 117-121
SHMc: *Andronic et al.*, JHEP 07 (2021) 035





- Compared to ground state (D_s^+) in MB and HM vs. multiplicity.
- No clear multiplicity dependence observed in data.

- **SHM** and **SHMc** models compatible with the D_{s1}^+/D_s^+.
- Tension between models and D_{s2}^{*+}/D_s^+ measurements (2.5σ at low multiplicity).