Recent results on hadronisation of beauty at the LHC

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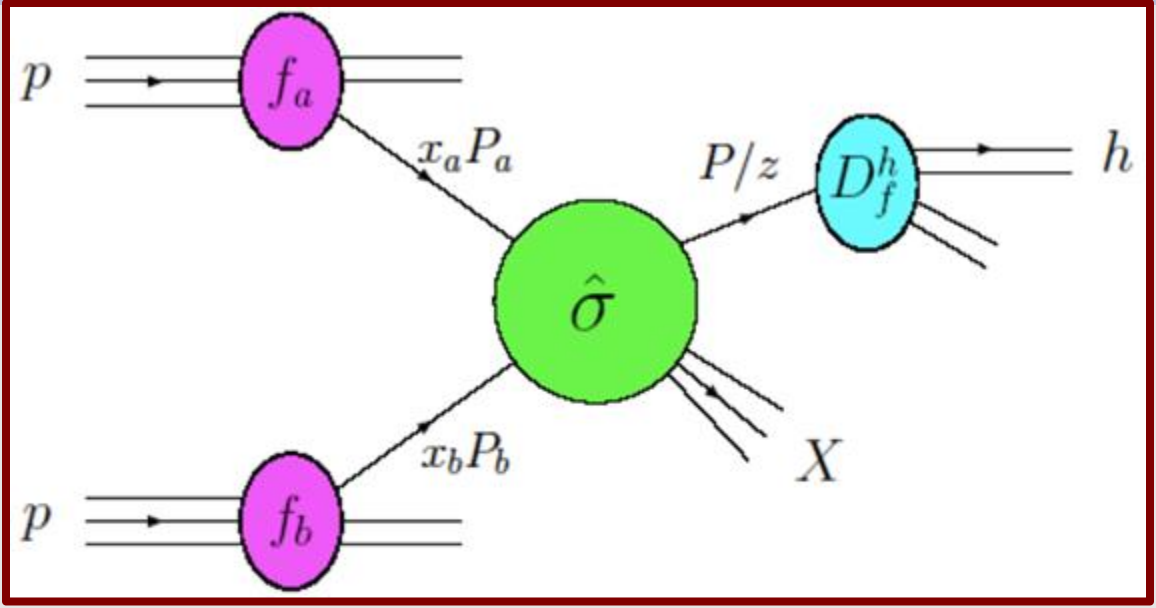
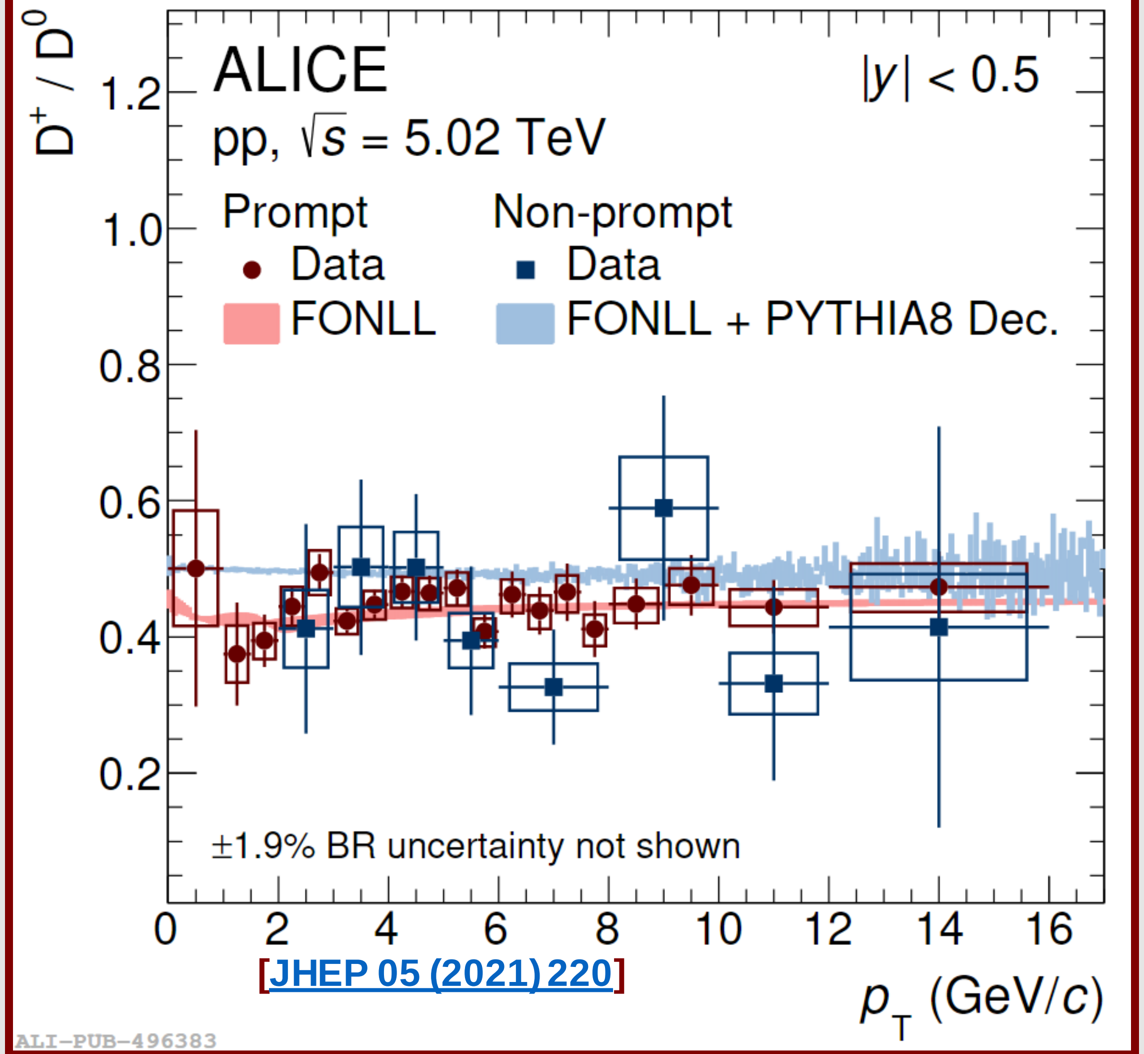
Motivation: Heavy-flavour baryon production



- Heavy quarks (c and b): $m_q >> \Lambda_{QCD} \Rightarrow$ production can be calculated using **perturbative QCD**
- Cross section of hadron production typically factorised to **PDFs**, **partonic cross sections**, and **fragmentation functions (FF)**
- Key assumption: fragmentation functions universally applicable for hadronisation between collision systems
  → Yield ratios, **especially baryon-to-meson ratios,** a sensitive probe to test this hypothesis

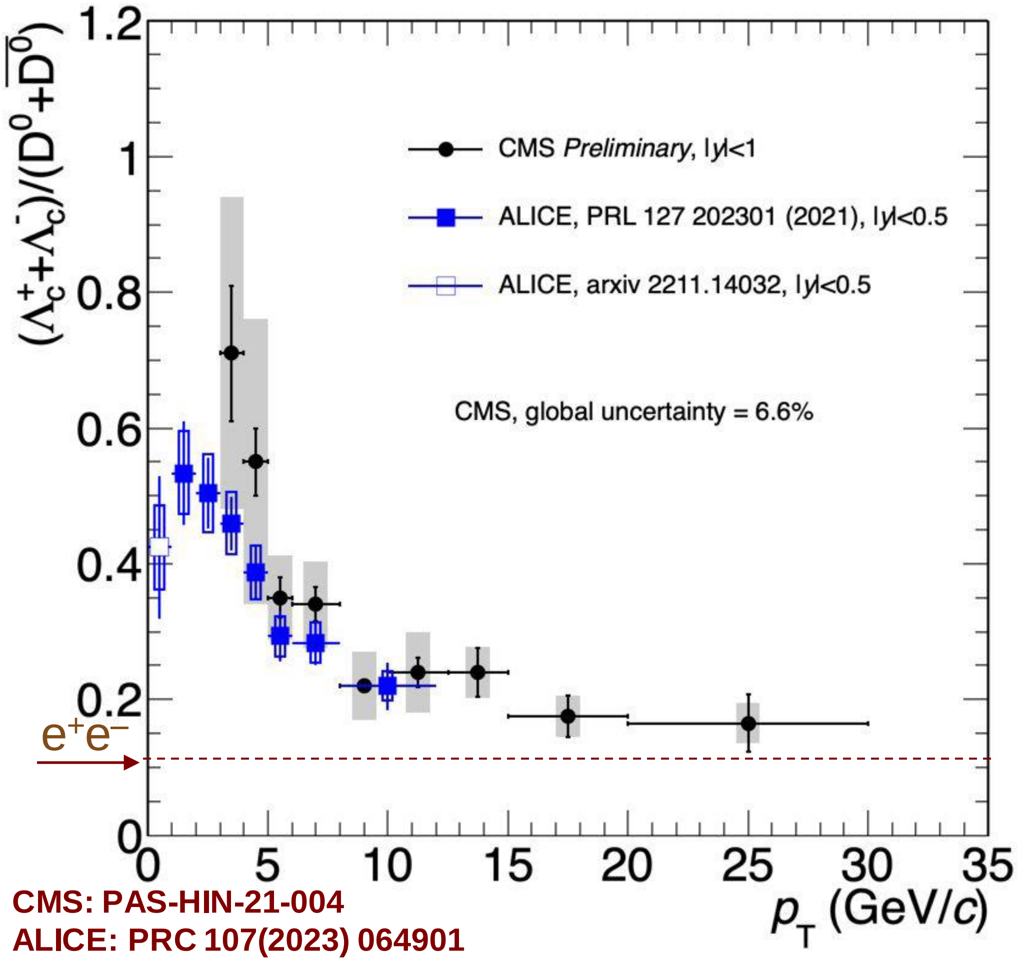
Motivation: Heavy-flavour meson-to-meson ratios



[JHEP 05 (2021) 220]

- Prompt and non-prompt D^+/D^0 production ratios: Flat as function of momentum in pp collisions at $\sqrt{s}$ = 5.02 TeV
- Both charm and beauty meson-to-meson ratios described well by FONLL pQCD calculations
  - Similar charm/beauty hadronisation, relative meson fragmentation consistent with e^+e^-

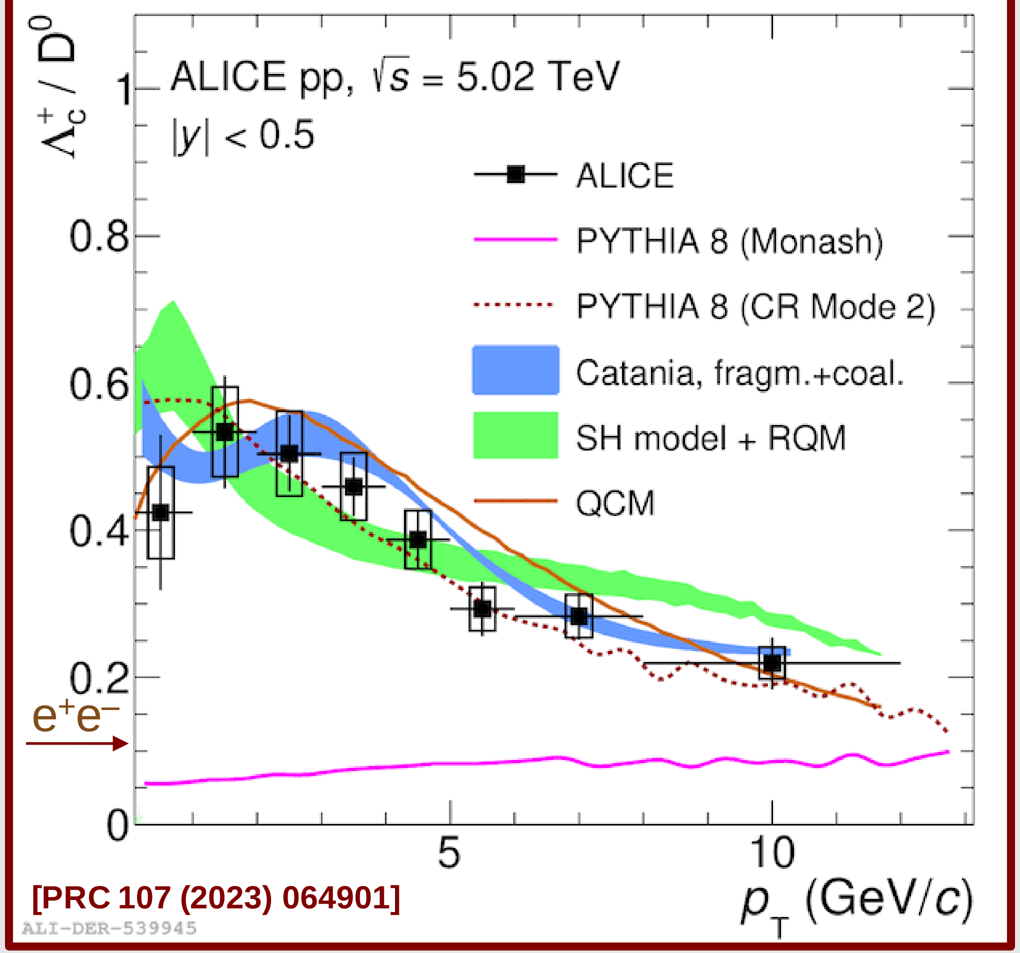
Motivation: Λ_c/D^0 ratios in pp collisions at the LHC



CMS: PAS-HIN-21-004
ALICE: PRC 107(2023) 064901

- Most recent measurements of Λ_c production at mid-rapidity in pp collisions by the ALICE and CMS Collaborations
- Charm baryon-to-meson ratio in e^+e^- and e^-p collisions: Expected to be **independent of p_T**, at ~0.12
- Hadronic collision systems: Significantly higher than e^+e^- expectation

Motivation: Λ_c/D^0 ratios in pp collisions at the LHC



[PRC 107 (2023) 064901]

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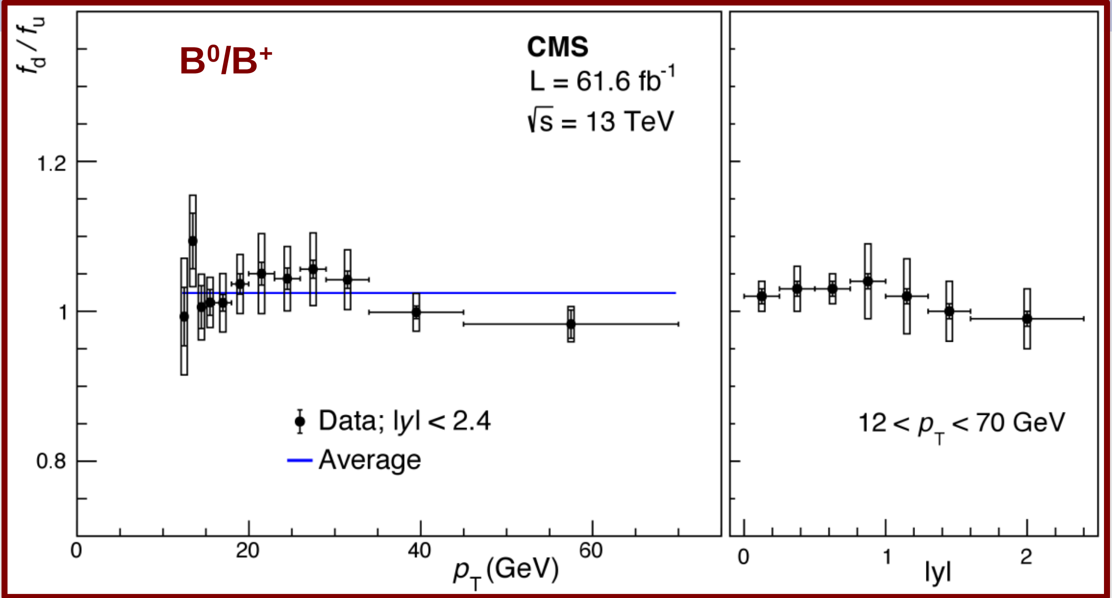
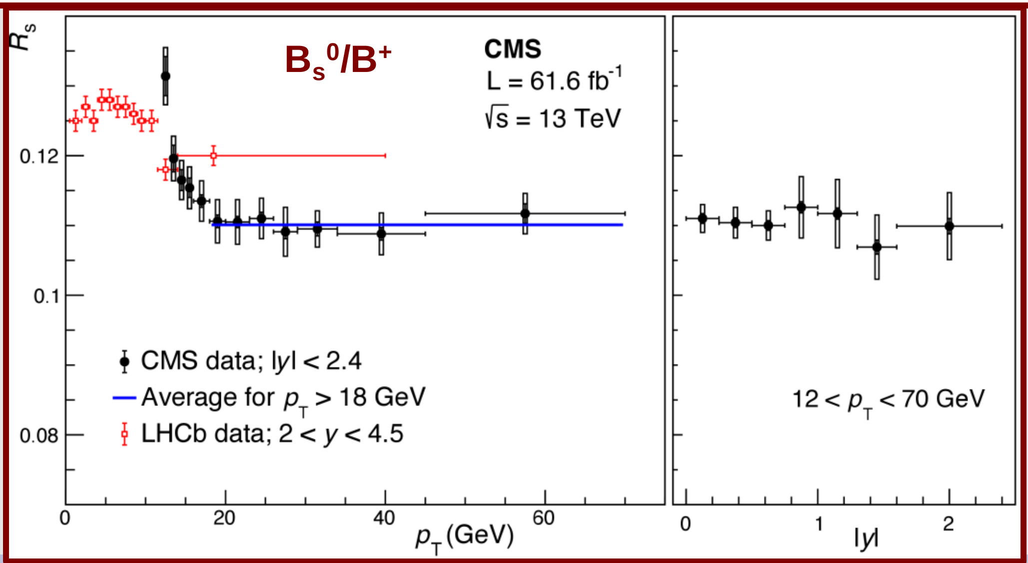
- Hadronic collision systems: Significantly higher than e^+e^- expectation
- **Additional hadronisation processes** must be considered to properly account for the pp results
  - **Collision system dependence** of charm hadronisation?
  - To what extent does this hold for the beauty sector?

B-meson production in pp collisions

- Direct CMS measurements of ground-state B mesons at 13 TeV:
  - → Non-strange B-meson ratio: No dependence on p_T or rapidity
  - → Average = 1.015±0.051, consistent with strong isospin symmetry

- B_s^0/B^+ yield ratio: No rapidity dependence, but increase towards lower p_T
- Consistent with measurements by LHCb at forward rapidity

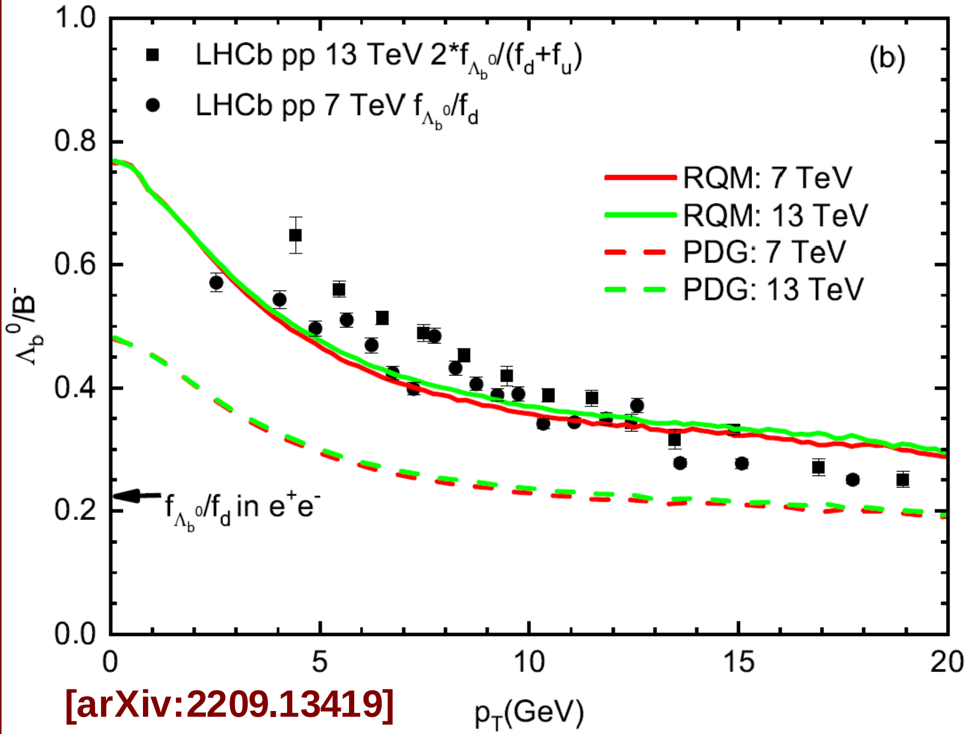




Λ_b production in pp collisions

- At forward rapidity: B^-, Λ_b^0 measured by LHCb Collaboration at $\sqrt{s}$ = 7 and 13 TeV
- Λ_b/B ratio in pp collisions is consistently above e^+e^- values
- Both ratios described best by including feed-down from additional beauty-baryon states

  → Similar picture in beauty sector as for charm-baryon hadronisation



[arXiv:2209.13419]

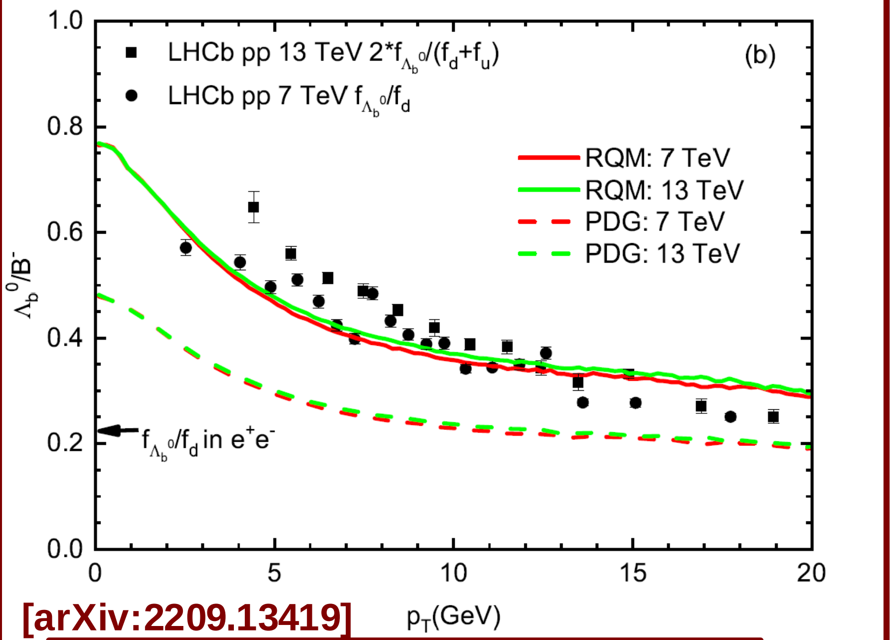
Λ_b production in pp collisions

- Results from ALICE Collaboration for non-prompt (i.e. from beauty decays) Λ_c / non-prompt D^0

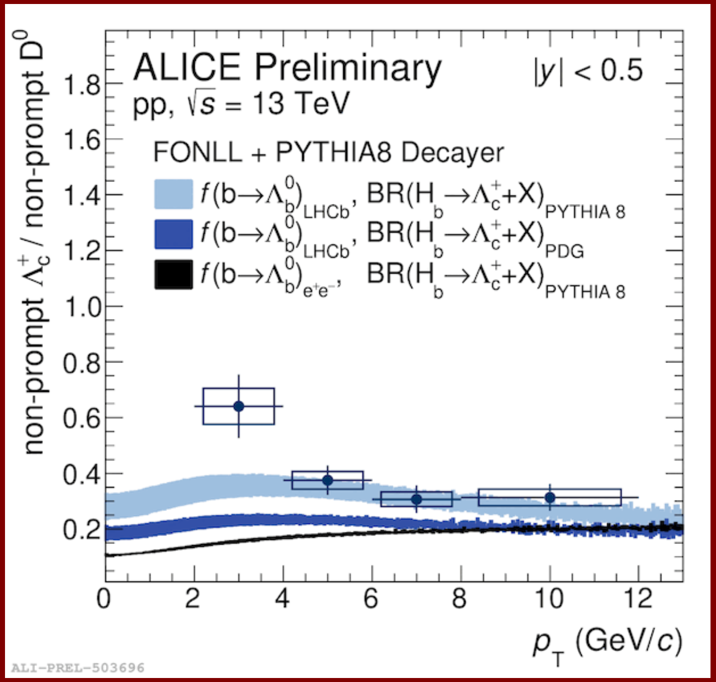
  → a proxy for Λ_b/B ratio at mid-rapidity

- Results are consistent with those from LHCb ➔ no significant rapidity dependence for beauty hadronisation effects

- To be examined with direct beauty measurements by ALICE starting from Run 3

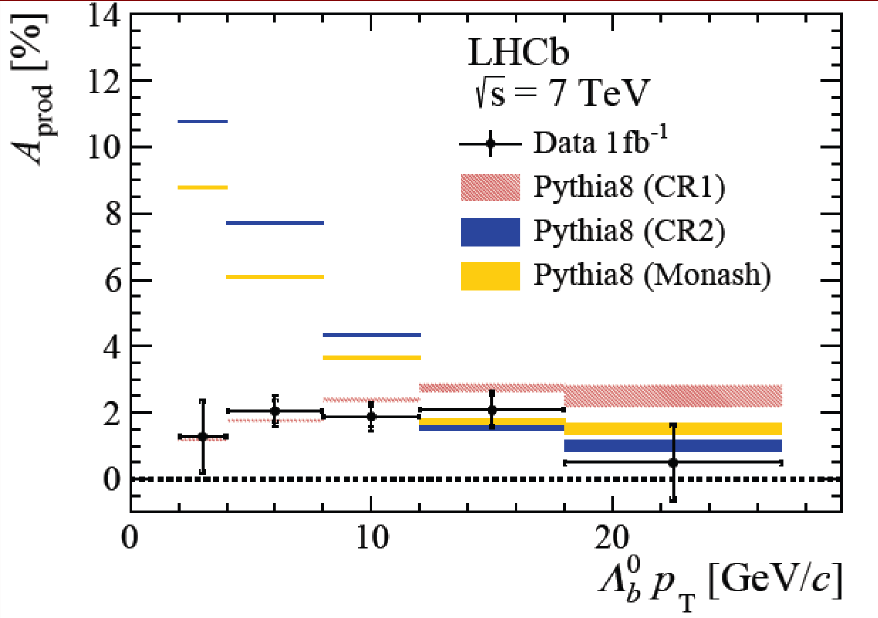


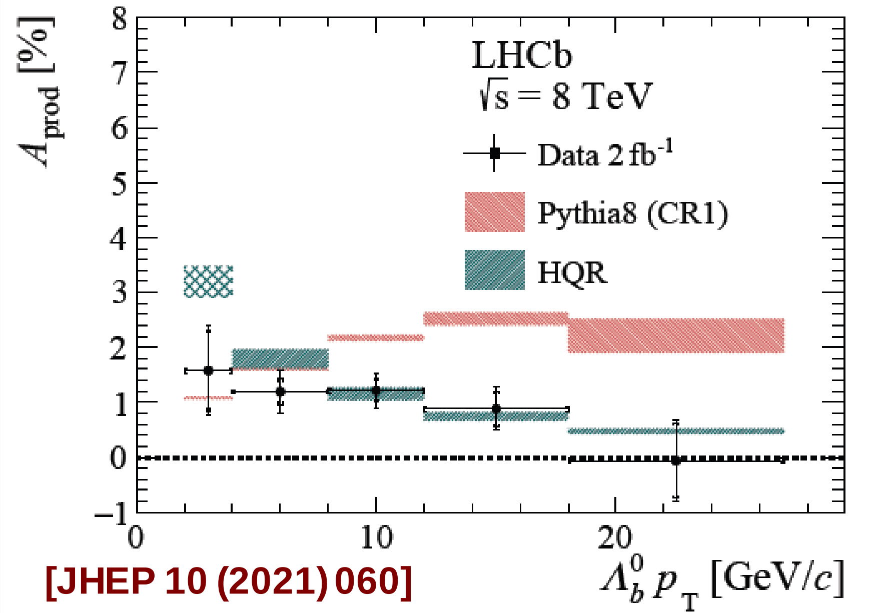
[arXiv:2209.13419]



Λ_b production in pp collisions

- Significant $\overline{\Lambda}_b^0$ / Λ_b^0 asymmetry measured by LHCb Collaboration in pp collisions at 7 and 8 TeV
- No significant dependence of baryon asymmetry on p_T
- Asymmetry strongly overpredicted at low p_T by Monash tune
- Heavy-quark recombination model and colour reconnection beyond leading colour describe the data well

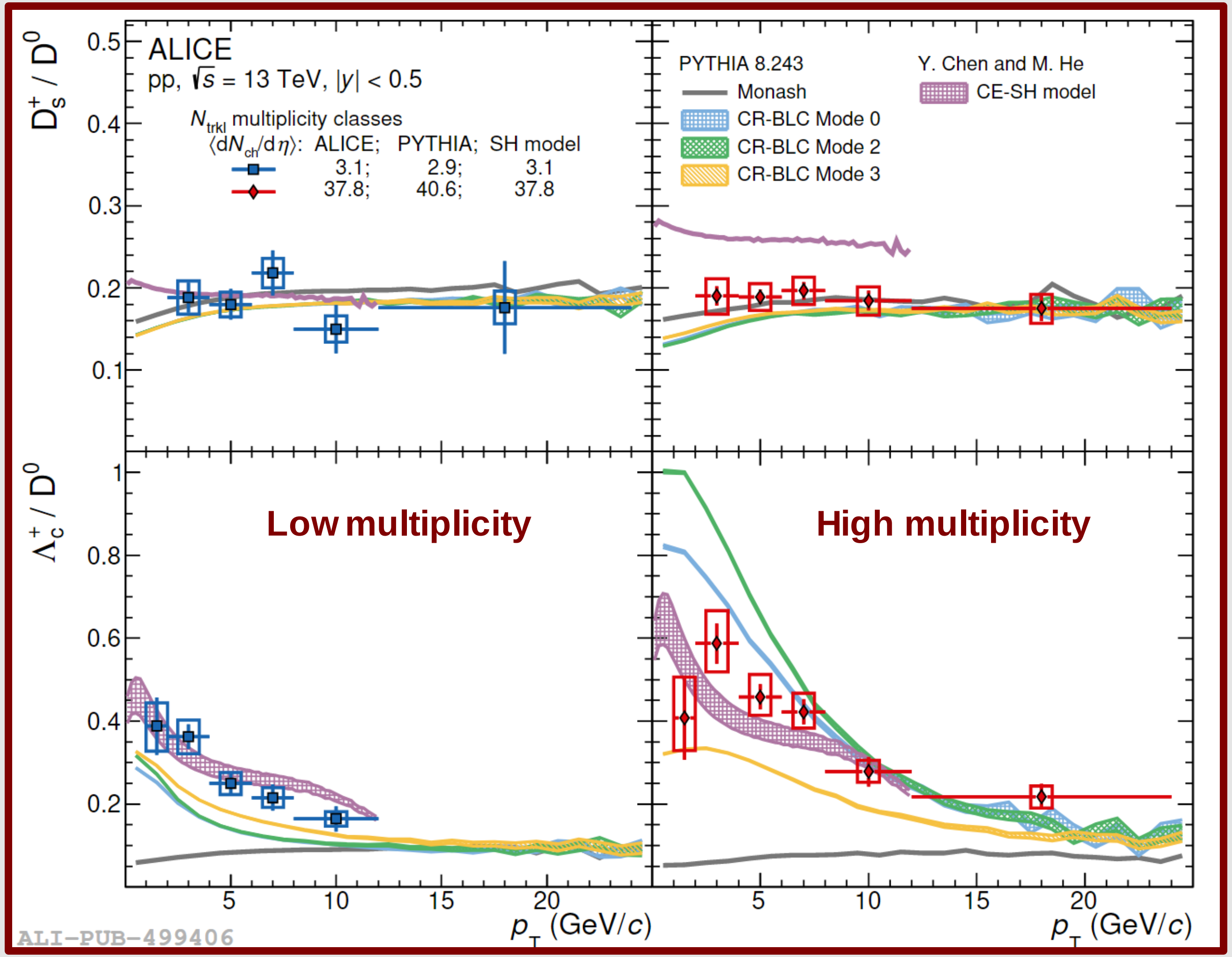




[JHEP 10 (2021) 060]

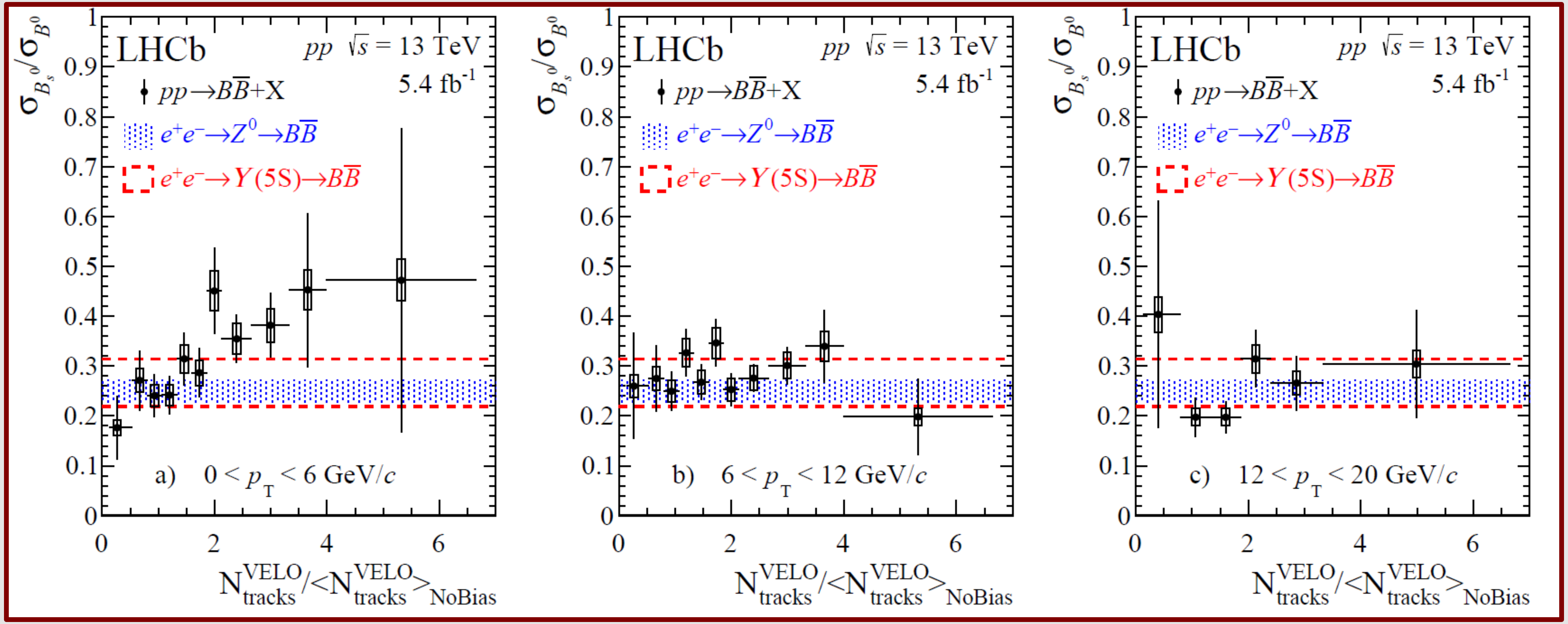
Multiplicity dependence of charm production

- D_s^+/D^0 production ratio: flat as function of p_T at both low and high multiplicity, **no multiplicity dependence seen**
- Λ_c^+/D^0 ratio: **Significant modification of p_T spectrum** between low and high multiplicity
  - → Monash tune: reproduces D_s^+ but not Λ_c^+
  - → CE-SH: predicts Λ_c^+ within uncertainties, but does not describe multiplicity (in)dependence for D_s^+



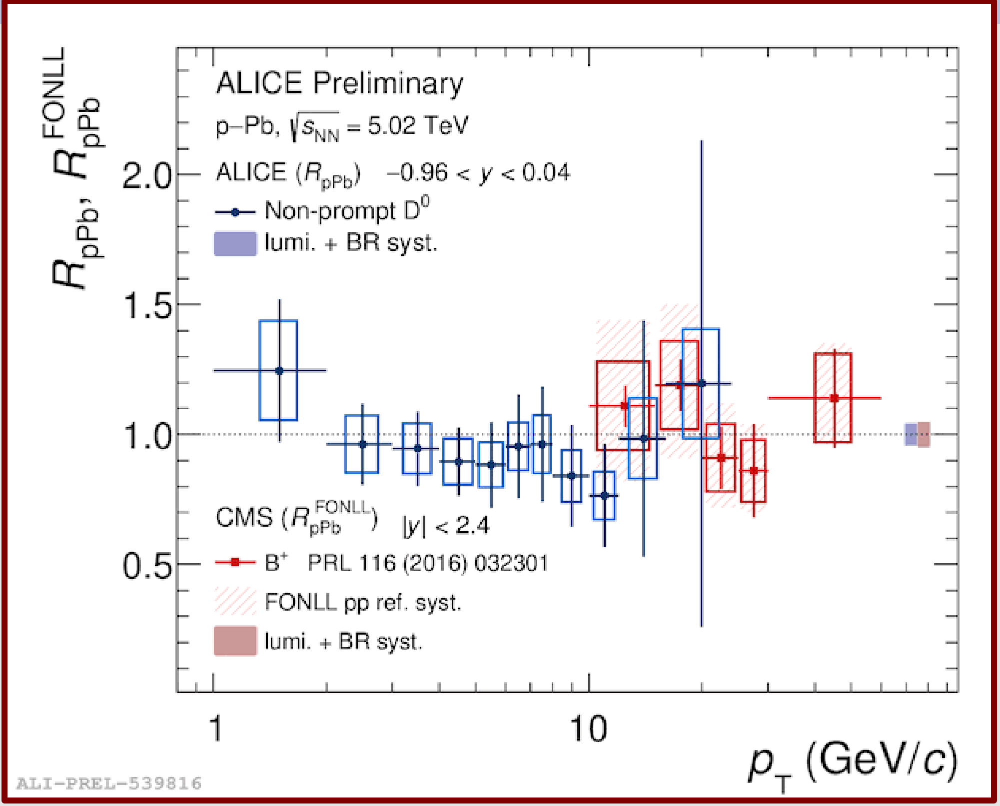
[PLB 829 (2022) 137065]

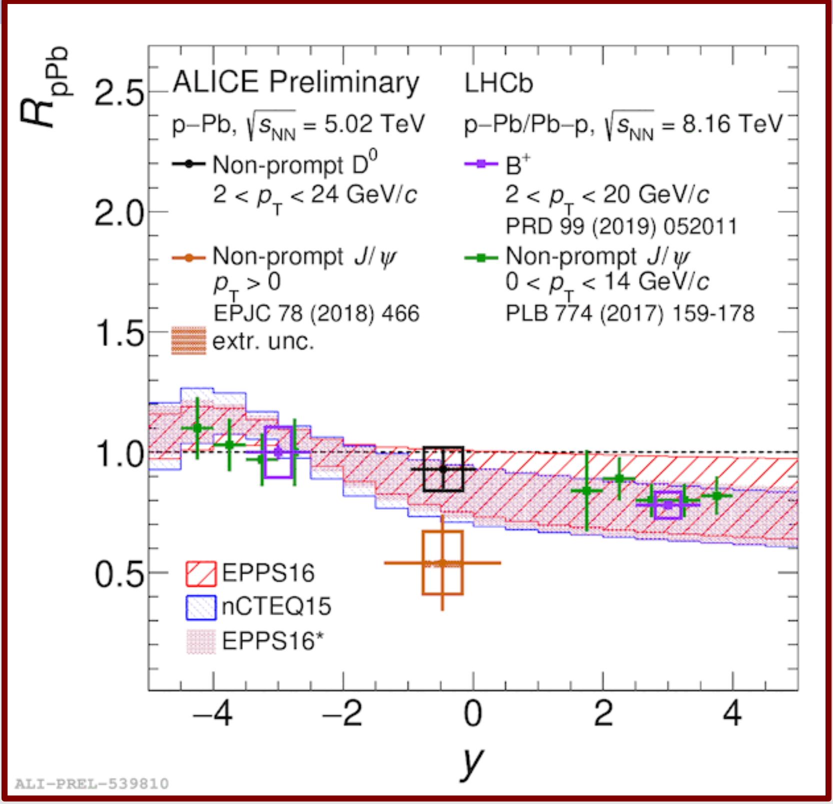
Multiplicity dependence of beauty production



- B_s^0/B^0 ratio measured by LHCb as function of multiplicity
- Contrast to D_s^+/D^0 ratio: significant multiplicity dependence at low p_T
- Consistent with quark coalescence picture for strange hadron production

Beauty production in p–Pb collisions

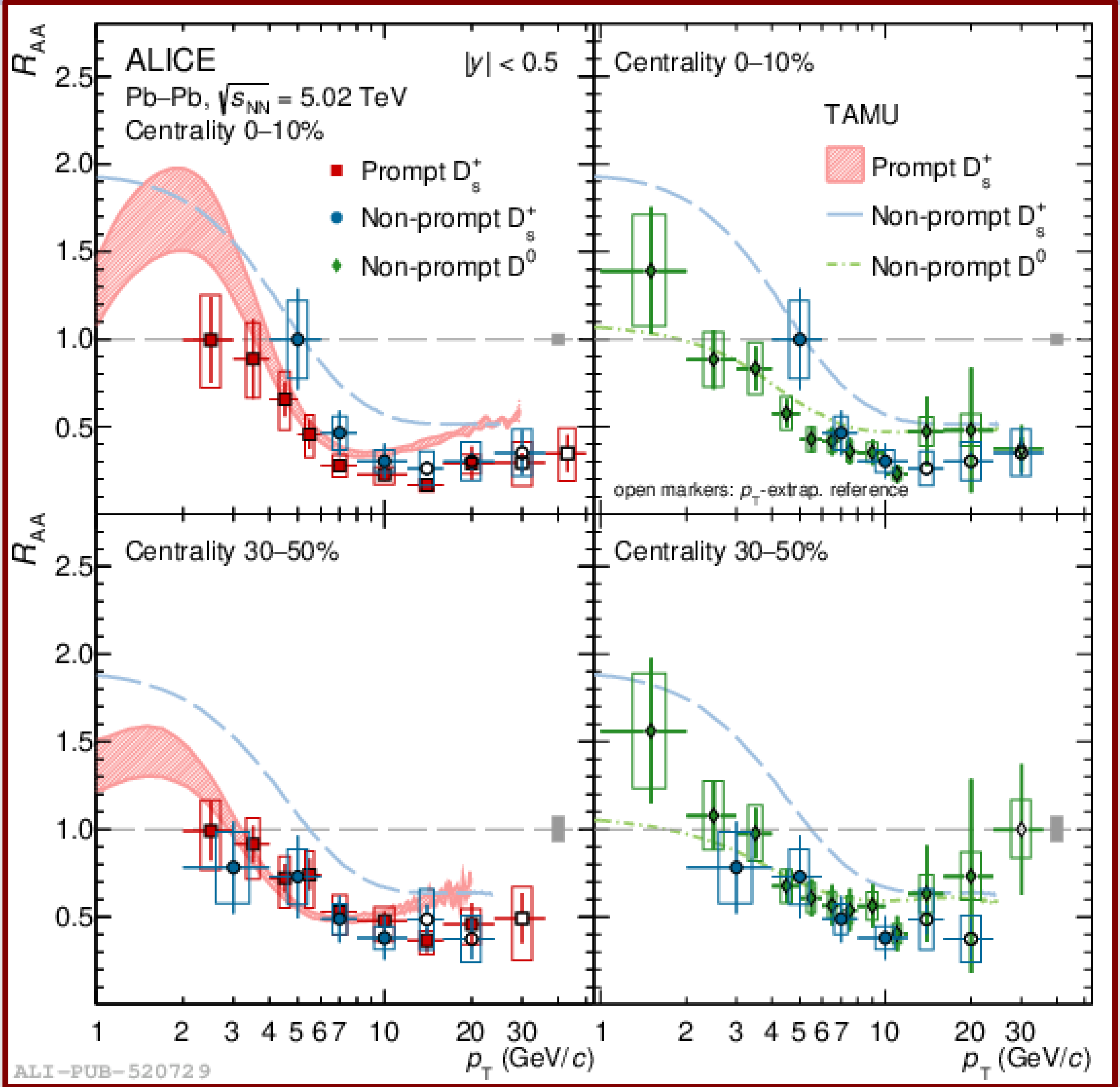




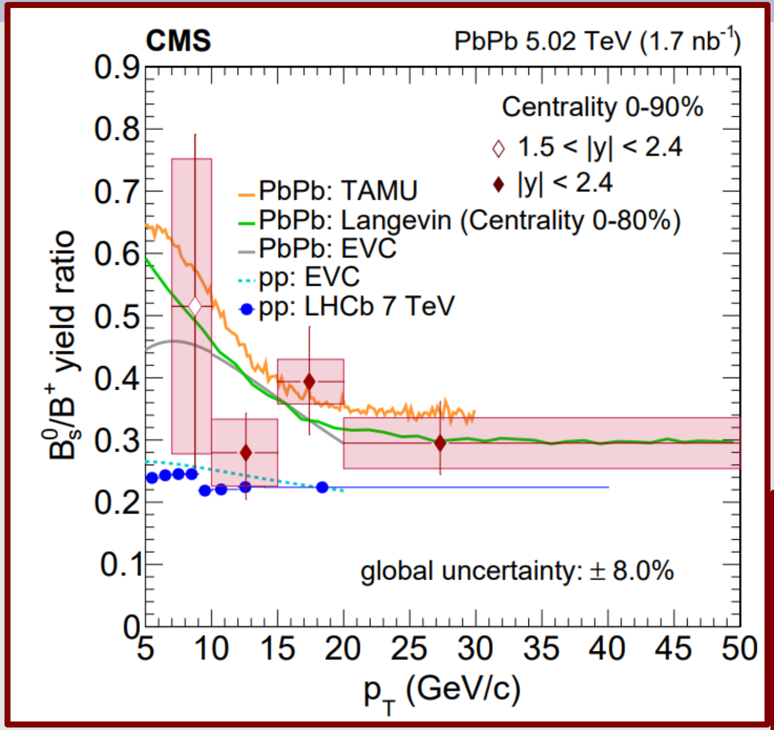
- ALICE measurement of non-prompt D^0 R_{pPb} is consistent with B^+ from CMS
- No significant cold nuclear matter effects on beauty at mid-rapidity
- Rapidity trend for non-prompt D^0 / non-prompt J/ψ / B^+ described by modified nPDFs

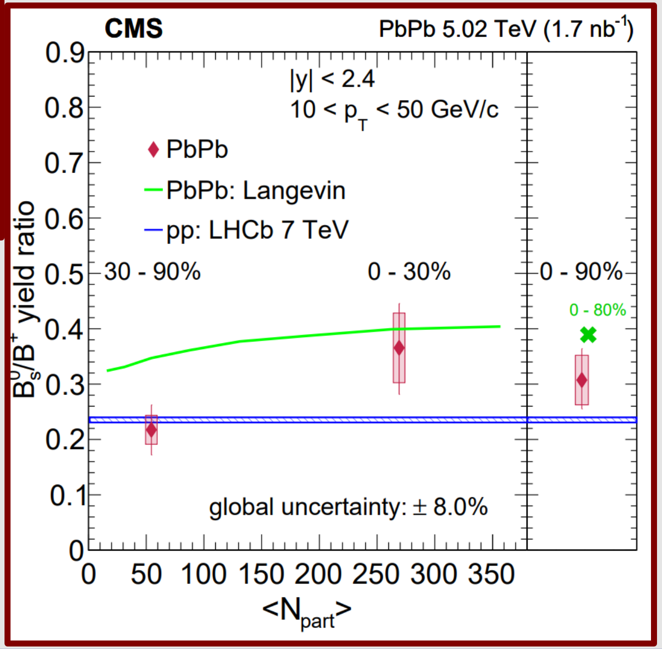
Non-prompt D-meson production in Pb–Pb

- Non-prompt D^0 and D_s^+ measured in Pb–Pb collisions, compared with prompt D_s^+
- Central Pb–Pb collisions: non-prompt D_s^+ higher at low p_T than prompt D_s^+ and non-prompt D^0
  - → Consistent with mass-dependent energy loss for heavy & light quarks
  - → Indication of strangeness enhancement at low p_T, similar to charm sector
- Semicentral Pb–Pb collisions: No separation observed between species
- Prompt+non-prompt D^0 described by TAMU model, but D_s^+ results overpredicted



Beauty-meson production in Pb–Pb collisions

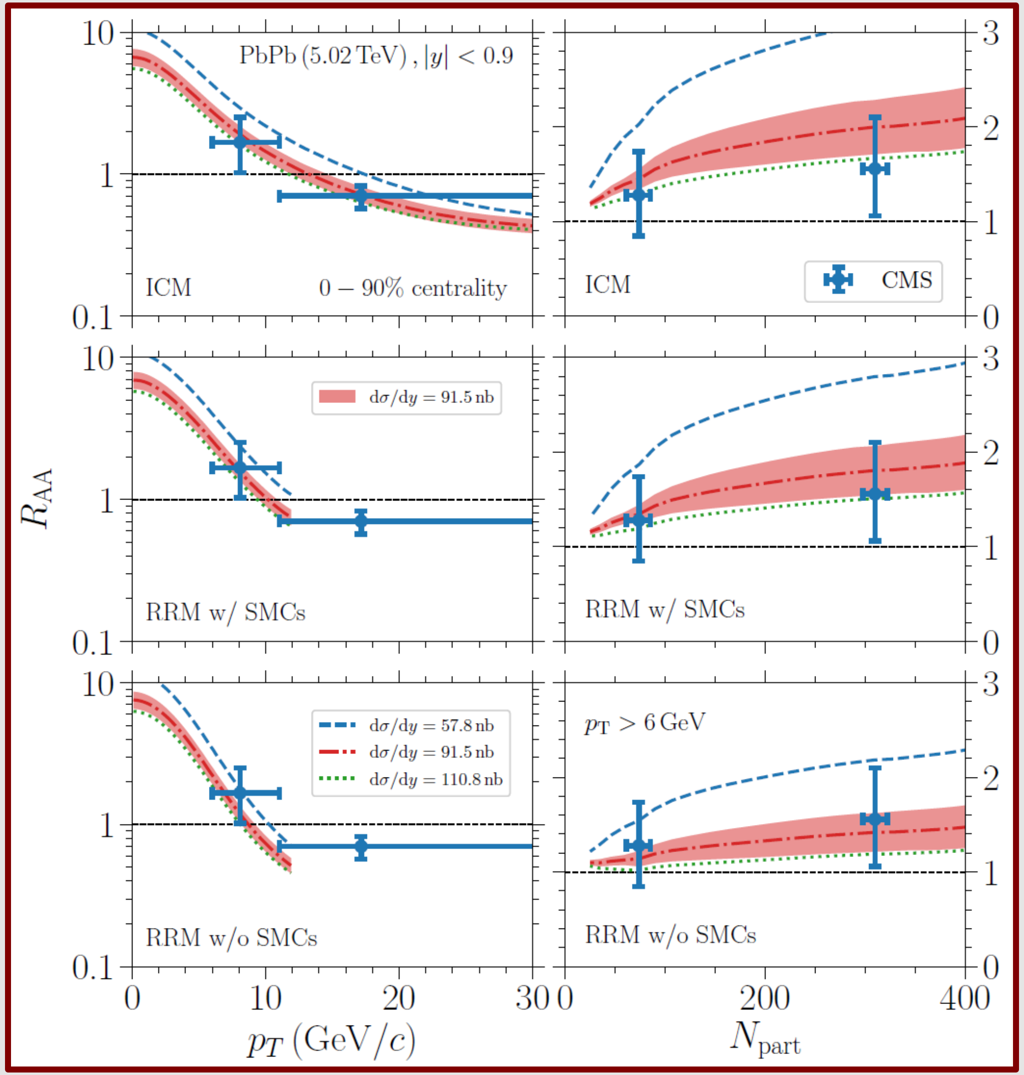




- LHCb and CMS measurements of B_s^0/B^+ ratio in pp and Pb–Pb collisions paint a similar picture as charm sector:
  - → Strange/nonstrange production largely independent of p_T within uncertainties
  - → Systematic enhancement of B_s with respect to B^0 in Pb–Pb collisions
  - → p_T distribution described within uncertainties by hydrodynamic approach
  - → No significant dependence on rapidity or centrality

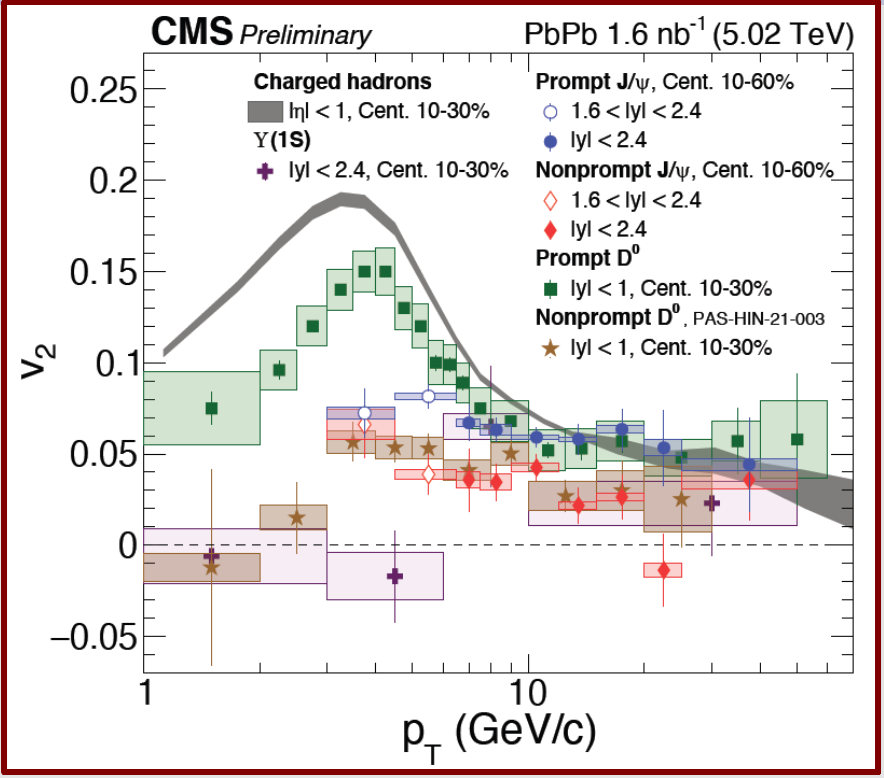
B_c^+ production in Pb–Pb collisions

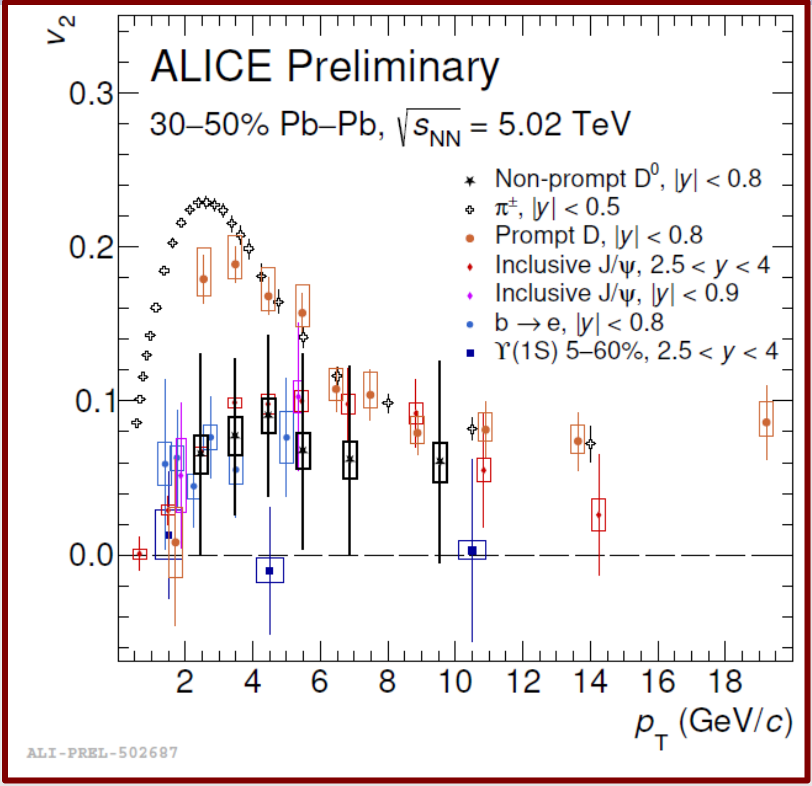
- CMS measurements of B_c^+ production in Pb–Pb collisions:
  - → Indication of a suppression at high p_T, stronger recombination of B_c state at low p_T
  - → No significant dependence of yield on collision centrality
- Results are consistent with different recombination scenarios:
  - → **Instantaneous Coalescence Model (ICM)**: accounts for unthermalised quark spectra
  - → **Resonance Recombination Model (RRM)**: recovers equilibrium limit for heavy-quark spectra
  - → **with space momentum correlations (SMC)**: enhanced recombination due to flow effects in medium



[CMS: PRL 128 (2022) 252301]
[Model comparison: arXiv:2302.11511]

Beauty flow in Pb–Pb collisions





- CMS + ALICE measurements of HF v_2 in different centrality classes:
  - → Clear mass ordering of flow coefficients from b → c → LF
  - → Υ(1S) v_2 compatible with 0 → open-beauty v_2 may be driven by coalescence with light quarks in medium

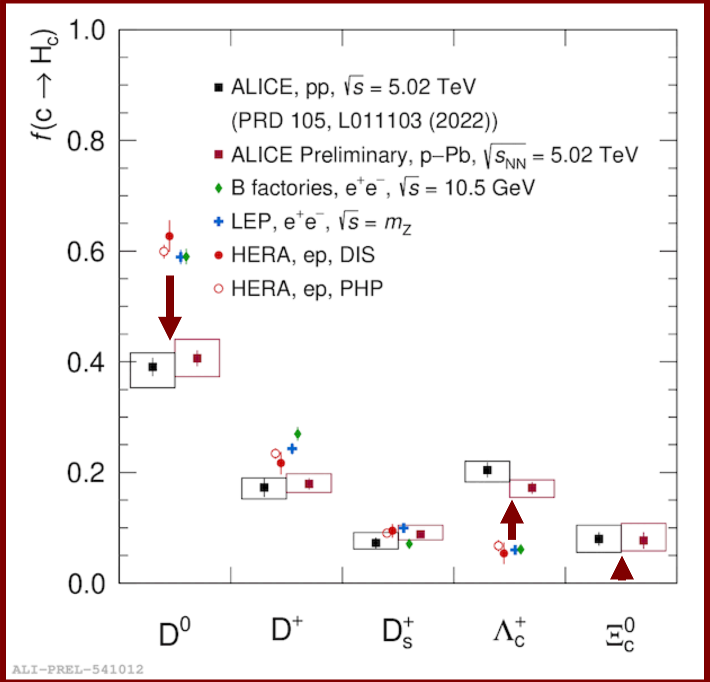
Summary & Outlook

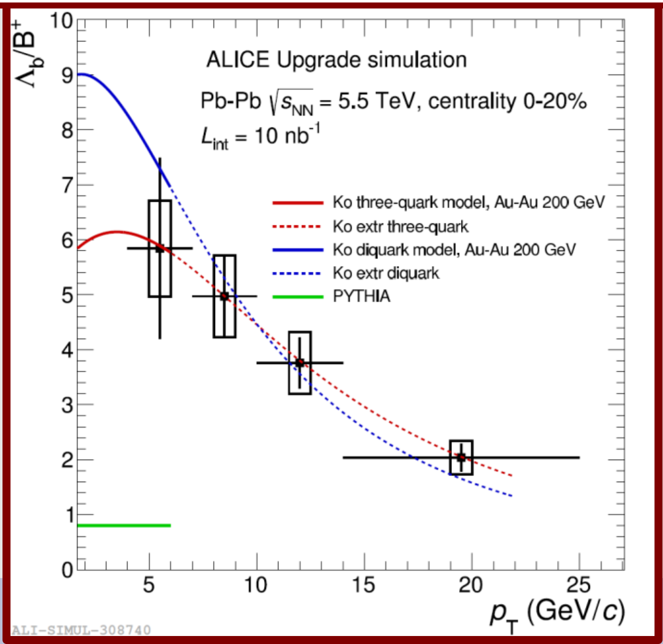
- Universal "vacuum" fragmentation assumption for HQ hadronisation significantly ruled out by results at the LHC

- Λ_b in pp collisions, B mesons in pp + Pb–Pb: Analogous features appearing as for charm sector ➔ hadronisation appears to be affected by similar mechanisms across flavours.

- Hadronisation fractions for beauty a key target for future measurement

- Direct measurements of Λ_b production in Pb–Pb collisions in Run 3 and beyond will allow further investigation of hadronisation effects in beauty sector

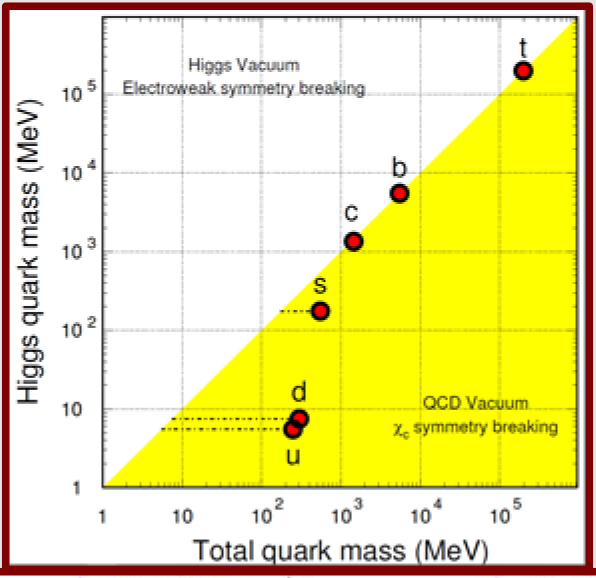


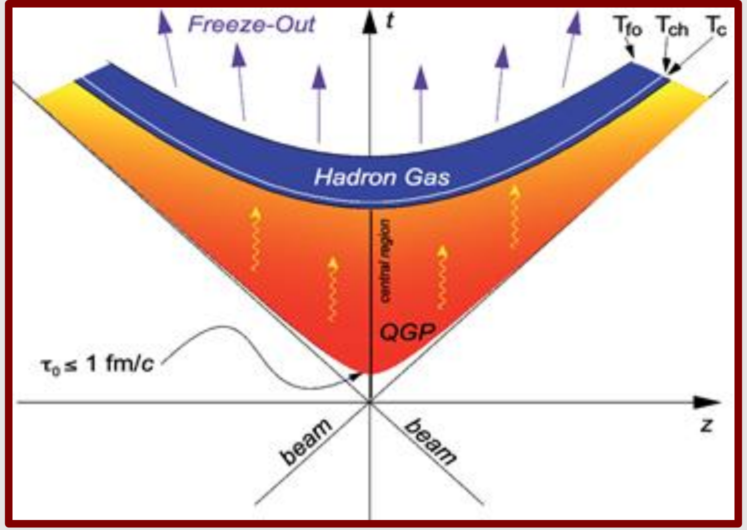


Backup

Why open heavy flavours in heavy-ion collisions?

- Charm and beauty are **unique probes of the QGP** in heavy-ion collisions
- Produced at **early times** in **hard partonic scatterings** (high-Q^2)
  - → $\tau_{c/b}$ (≈0.01–0.1 fm/c) < QGP formation time (≈0.1–1fm/c) ⟶ experience full evolution of the system and interact with the medium
- Study multiple different systems at the LHC:
  - → **pp collisions**: Measure production cross sections, baseline for nuclear collisions, test for pQCD calculations.
  - → **p–Pb collisions**: Study cold nuclear matter effects to distinguish initial-state nuclear modifications from final-state in-medium effects
  - → **Pb–Pb collisions**: Study transport properties of quark–gluon plasma

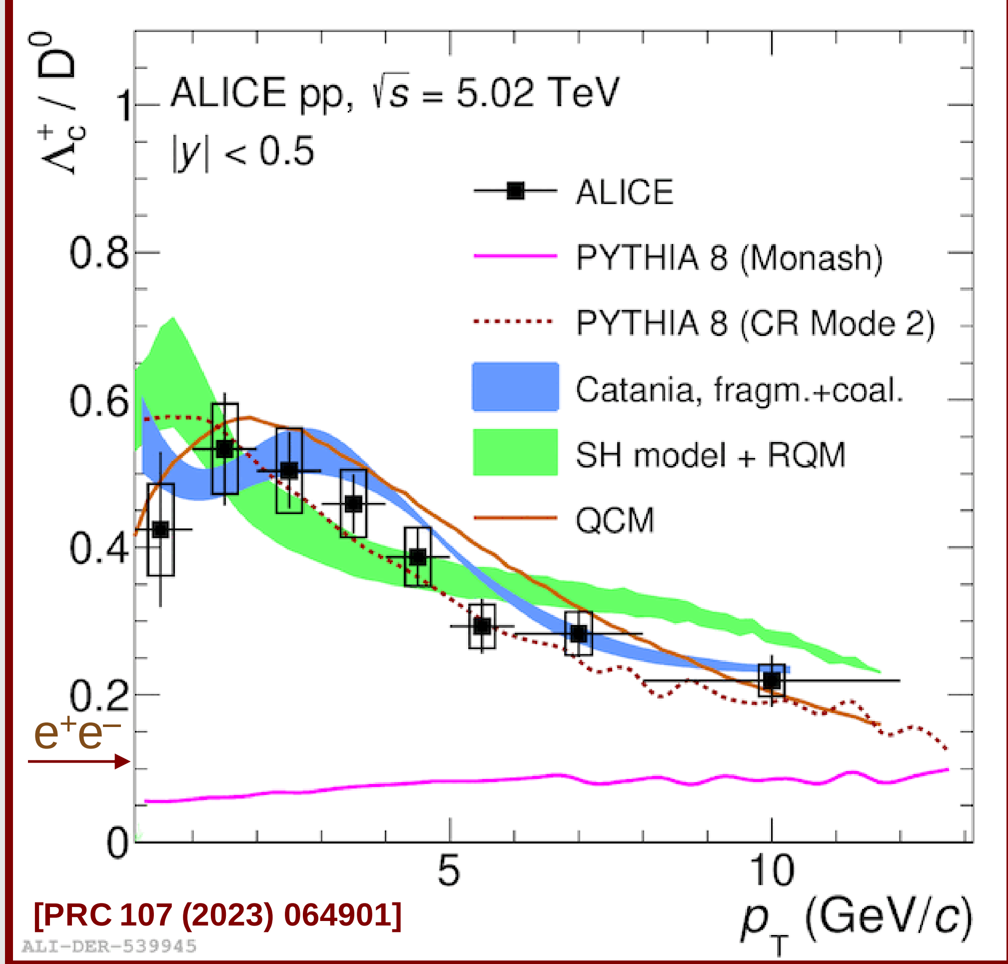




Motivation: Heavy-flavour baryon-to-meson ratios

- Additional hadronisation mechanisms included to predict Λ_c/D^0 ratio
  - → Described by models including:
    - Enhanced colour reconnection beyond leading order (PYTHIA 8 CR, J. Christiansen & P. Skands, JHEP 08(2015) 003)
    - Coalescence effects (Catania, V. Minissale et al., PLB 821 (2021), 136622)
    - Stat. hadronisation with feed-down from unmeasured resonant states (SH+RQM, M. He & R. Rapp, PLB 795 (2019), 117)

- **A collision-system-dependent effect?**
  - → To what extent does this extend into the beauty sector?
  - → What is the impact of collectivity in central Pb–Pb collisions?



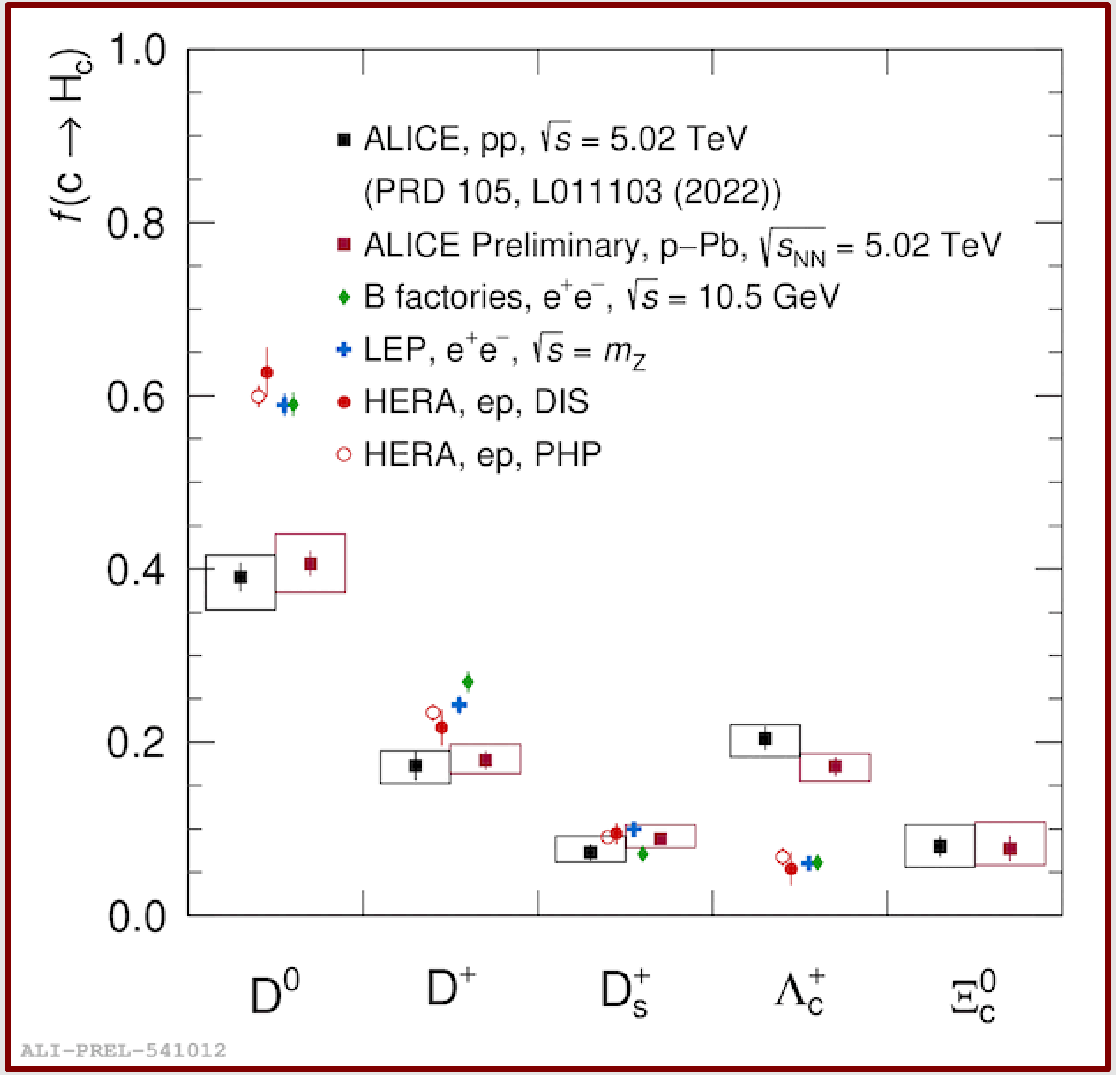
[PRC 107 (2023) 064901]

Charm hadronisation ratios in small systems

- Measurement of all ground-state charm-hadron species in pp and p–Pb collisions allows for new evaluation of hadronisation fractions
- With respect to e^+e^- and e^-p: significant depletion of D mesons and enhancement of Λ_c in hadronic collisions

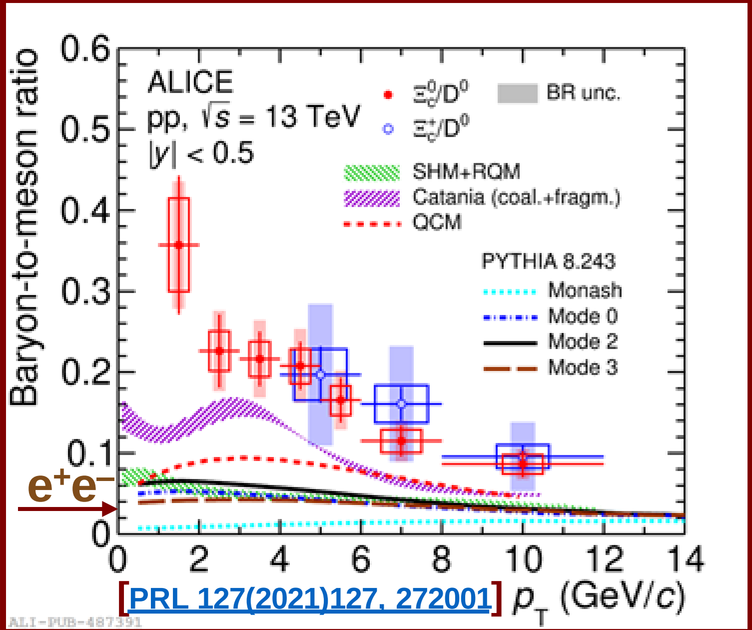
  ➔ Fragmentation fractions can no longer be assumed to apply universally between collision systems

- No significant difference between pp and p–Pb collisions within uncertainties

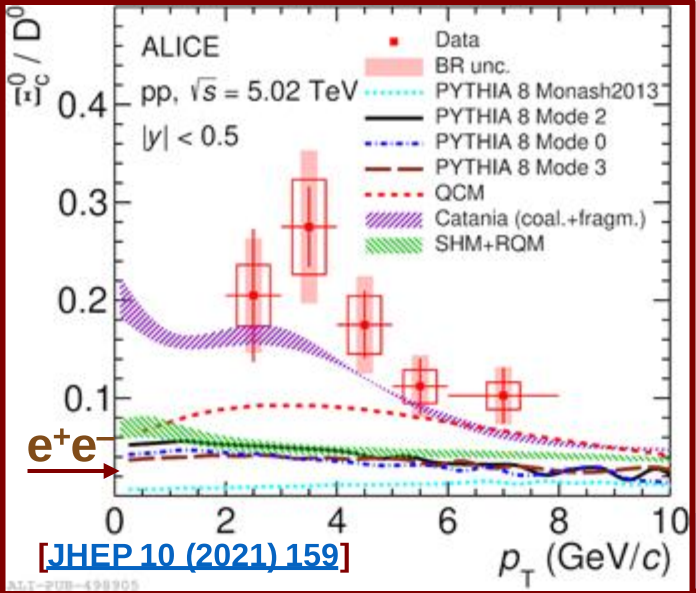


Strange-charmed baryon production

- Ξ_c/D^0 ratio measured in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV in hadronic and semileptonic decay channels
- Production of Ξ_c^0 and Ξ_c^+ consistent with each other within uncertainties
- Discrepancy with e^+e^- prediction / Monash tune: factor ~30. **Universality of fragmentation significantly ruled out**
- Comparison with models:
  - → PYTHIA with enhanced colour reconnection, SHM + RQM : Able to describe Λ_c^+ production well, but significantly underestimate Ξ_c
  - → Catania model with coalescence describes shape reasonably well down to p_T = 2 GeV/c



[PRL 127(2021)127, 272001]



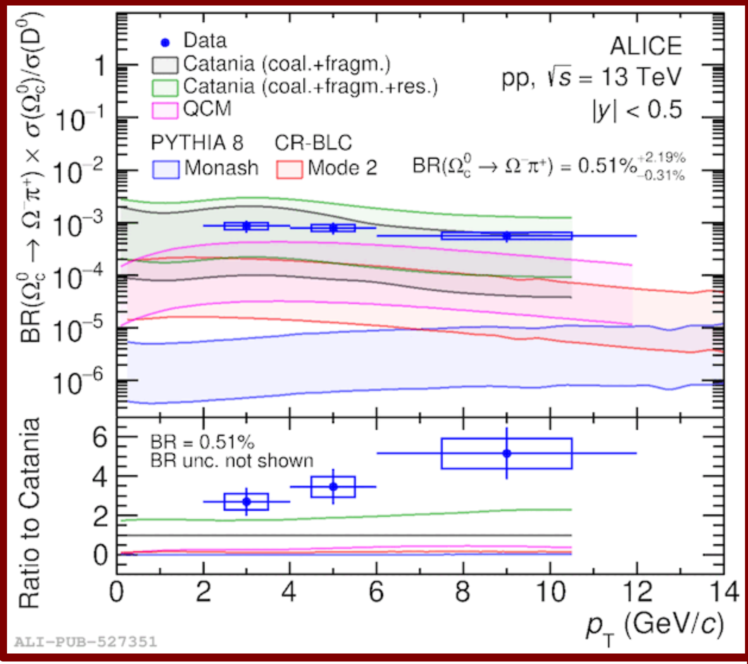
[JHEP 10 (2021) 159]

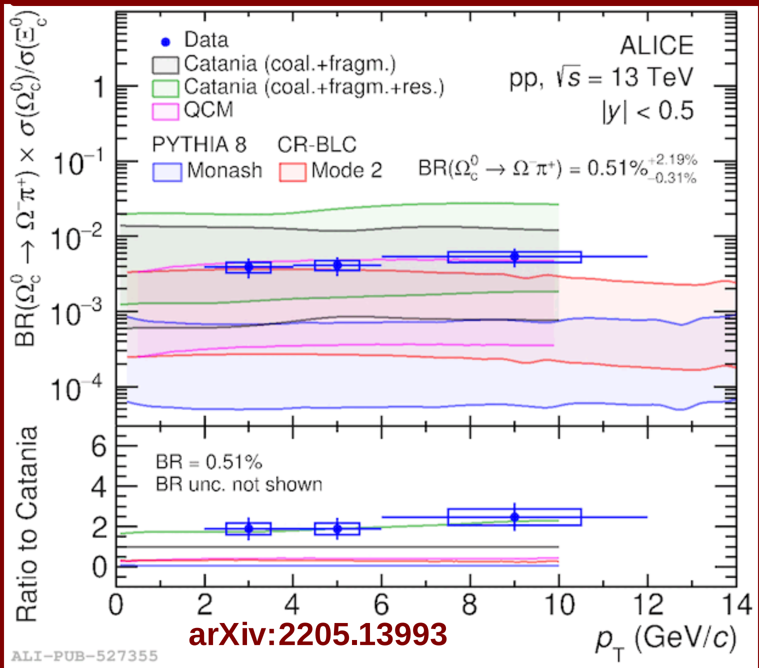
Doubly strange charmed baryons: Ω_c^0

- Ω_c^0/D^0 and Ω_c^0/Ξ_c^0 ratio: **first measurement in pp collisions at $\sqrt{s}$ = 13 TeV**
- Branching ratio not experimentally known, calculated as 0.51±0.07% [Y. Hsiao et al., EPJ.C. 80, 1066(2020)]
- Both baryon-to-meson and baryon-to-baryon ratio show significant increase over most model predictions
- Catania model gives best description of baryon-to-baryon ratio for all p_T

  → Feed-down from additional resonances better describes data
- Previous assumption by Belle: Ω_c^0/Ξ_c^0 = 0.1 [PRD 97, 072005 (2018)]
- ALICE result: $\Omega_c^0/\Xi_c^0 \approx 1$ (using predicted BR), implying ~7% fragmentation fraction

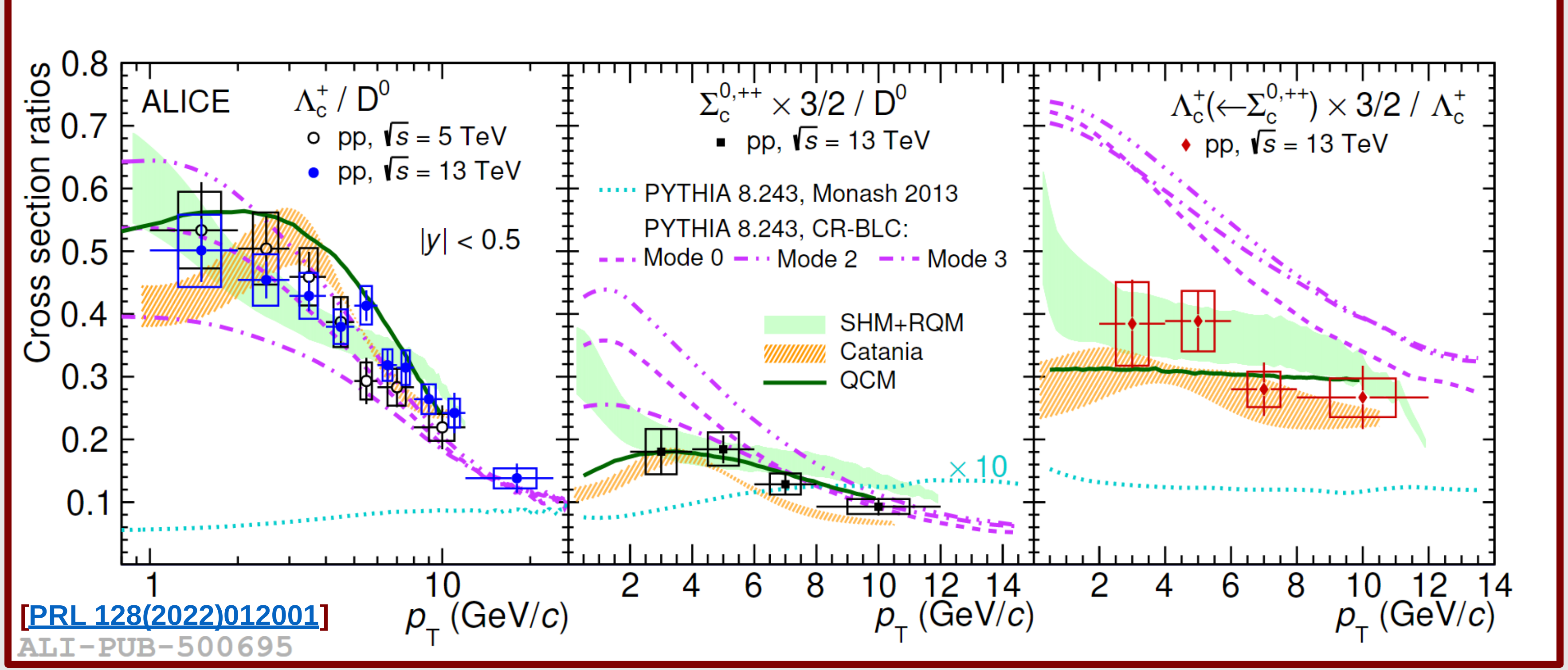
→ **Contribution to σ_{cc} to be better understood once BR measured**





arXiv:2205.13993

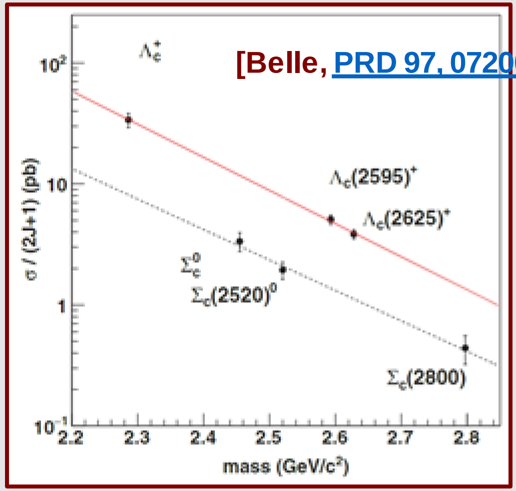
Resonant charmed baryon states: Σ_c

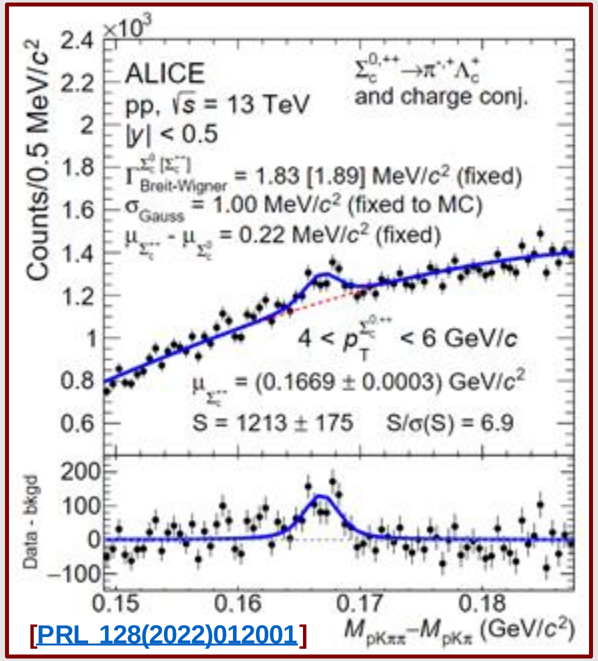


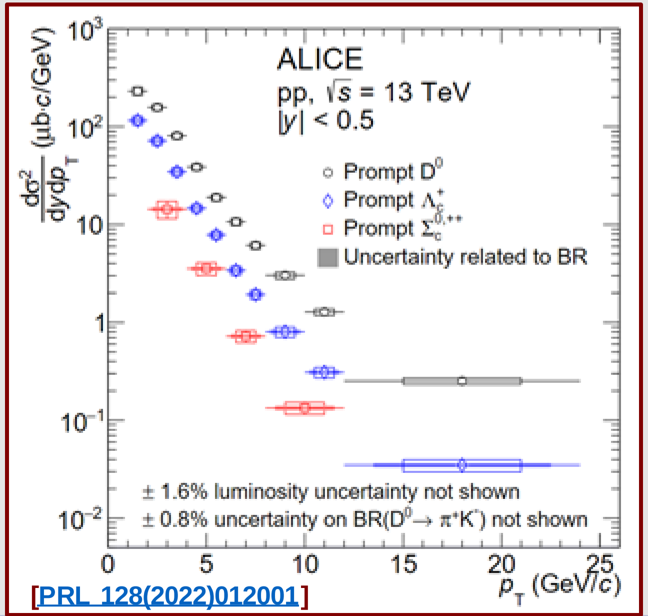
- Σ_c / D^0 ratio significantly enhanced in pp collisions compared to e^+e^-
- **Significant contribution of Σ_c to prompt Λ_c^+ cross section (0.38 ±0.06 (stat.) ± 0.06 (syst.))**
- Σ_c production described well by Catania (frag. + coalescence), QCM (coalescence), SHM+RQM
- PYTHIA with Monash tune significantly underestimates all ratios; enhanced colour reconnection overestimates Σ_c contribution to Λ_c^+

Resonant charmed baryon states: Σ_c

- Σ_c: Isospin-1 partner of Λ_c^+, decays 100% via strong interaction to $\Lambda_c^+\pi^{\pm}$
- Formed by combination of charm quark with spin-1 ud diquark: suppressed due to large mass
- Belle, e^+e^- collisions at $\sqrt{s}$ = 10.52 GeV: Production of Σ_c states **suppressed by factor 3-4** compared to Λ_c^+
- Measured in ALICE in pp collisions at $\sqrt{s}$ = 13 TeV without topological selections, using Breit-Wigner/Gauss fit of $\Delta M = M(pK\pi\pi) - M(pK\pi)$

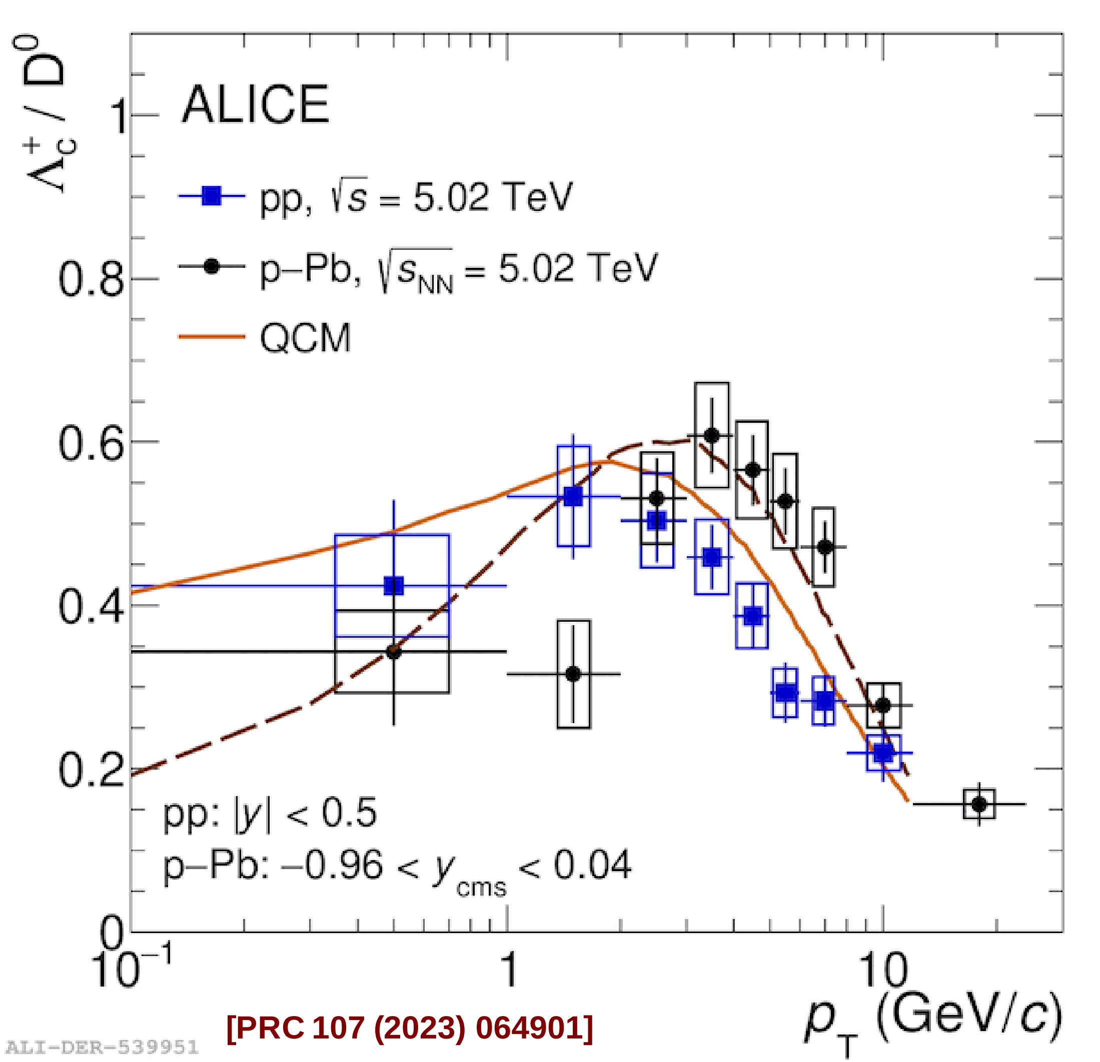






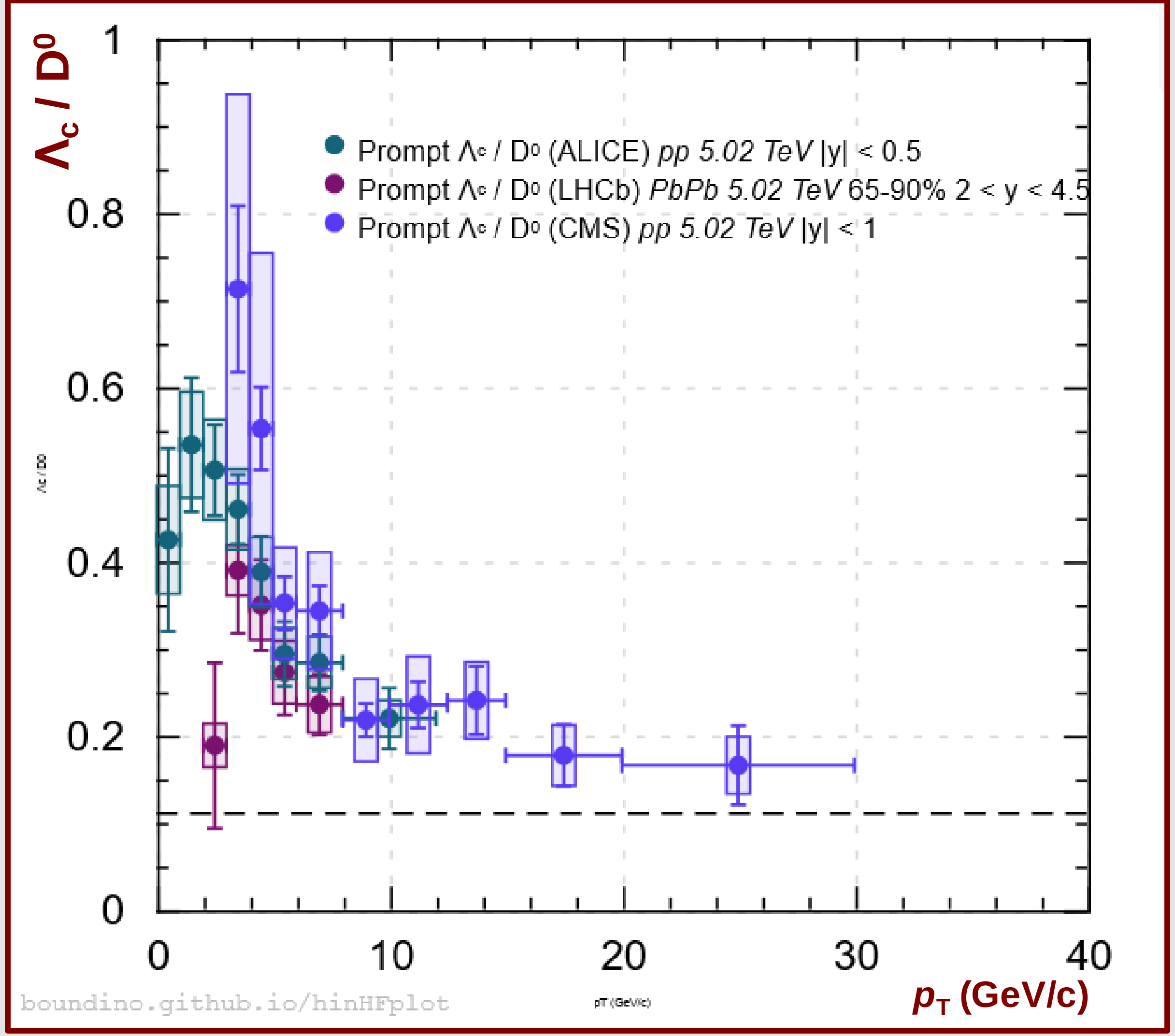
Λ_c/D^0 ratios from low to high event activity

- Modification of mean p_T also seen for Λ_c in p–Pb collisions with respect to pp
- Shift in p_T distribution is predicted by QCM model between the two collision systems
- Possibly explained by radial flow effects at high multiplicities: charm quark hadronising with co-moving light diquark state



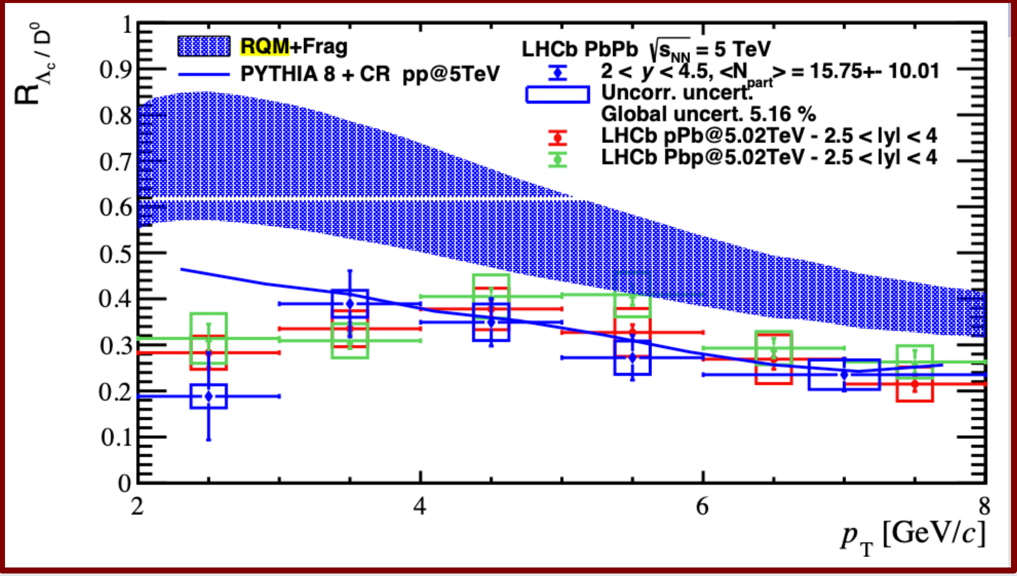
[PRC 107 (2023) 064901]

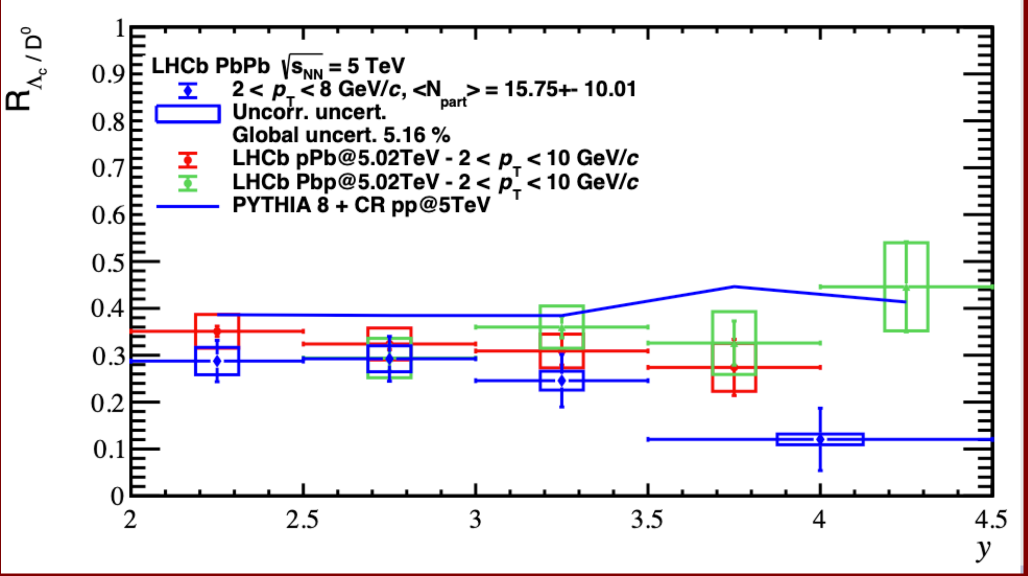
Latest Λ_c/D^0 ratios between LHCb/ALICE/CMS



Λ_c/D^0 ratios from low to high event activity

- LHCb measurement of Λ_c in p–Pb and peripheral Pb–Pb collisions: Similar p_T-dependent behaviour as measured by ALICE at midrapidity
- No significant difference between forward/backward rapidity in p–Pb collisions
- Model with additional resonant states from RQM tends to overpredict the data at forward rapidity
- Values are consistent with those measured at mid-rapidity within uncertainties



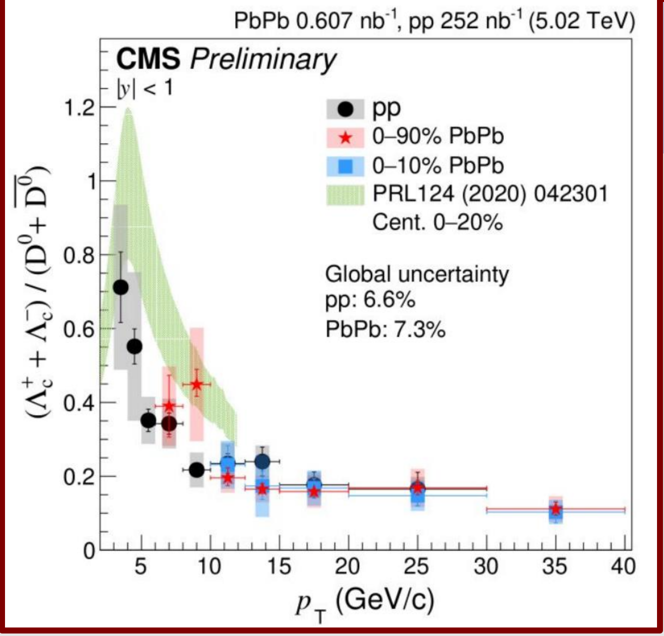


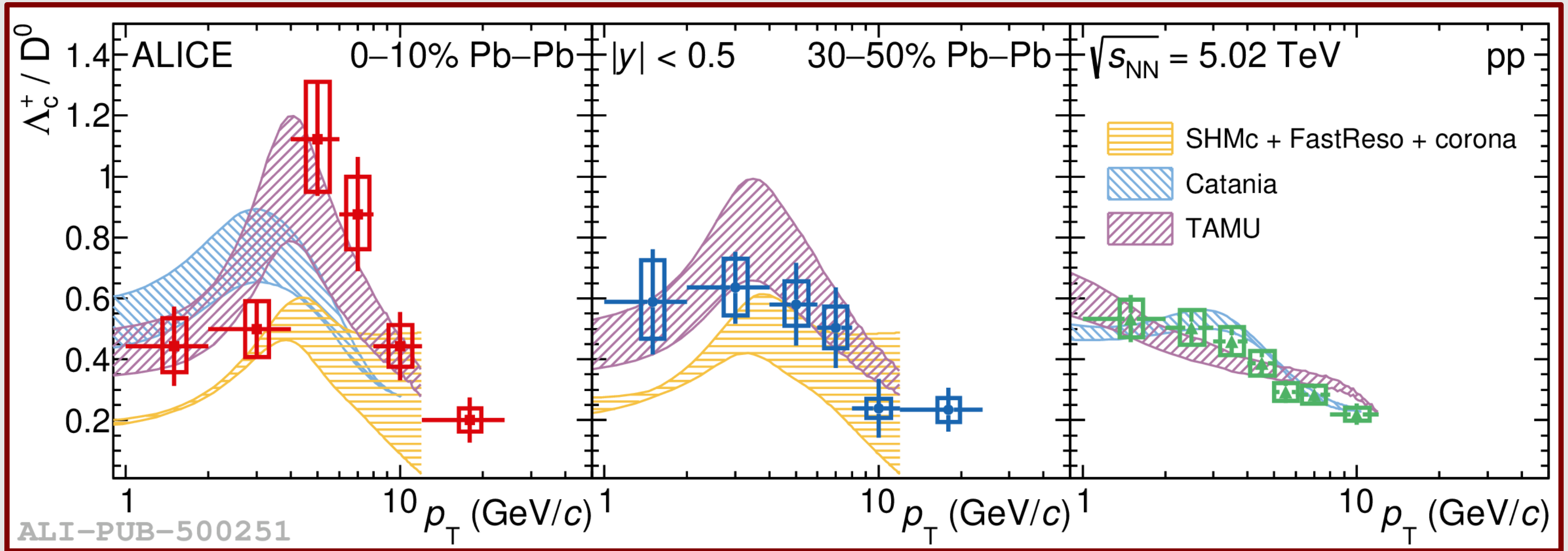
[arXiv:2210.06939]

Λ_c production in Pb–Pb collisions

- Λ_c^+/D^0 ratio at mid-rapidity: Peak in central collisions at ~4-8 GeV/*c* consistent with radial flow effect

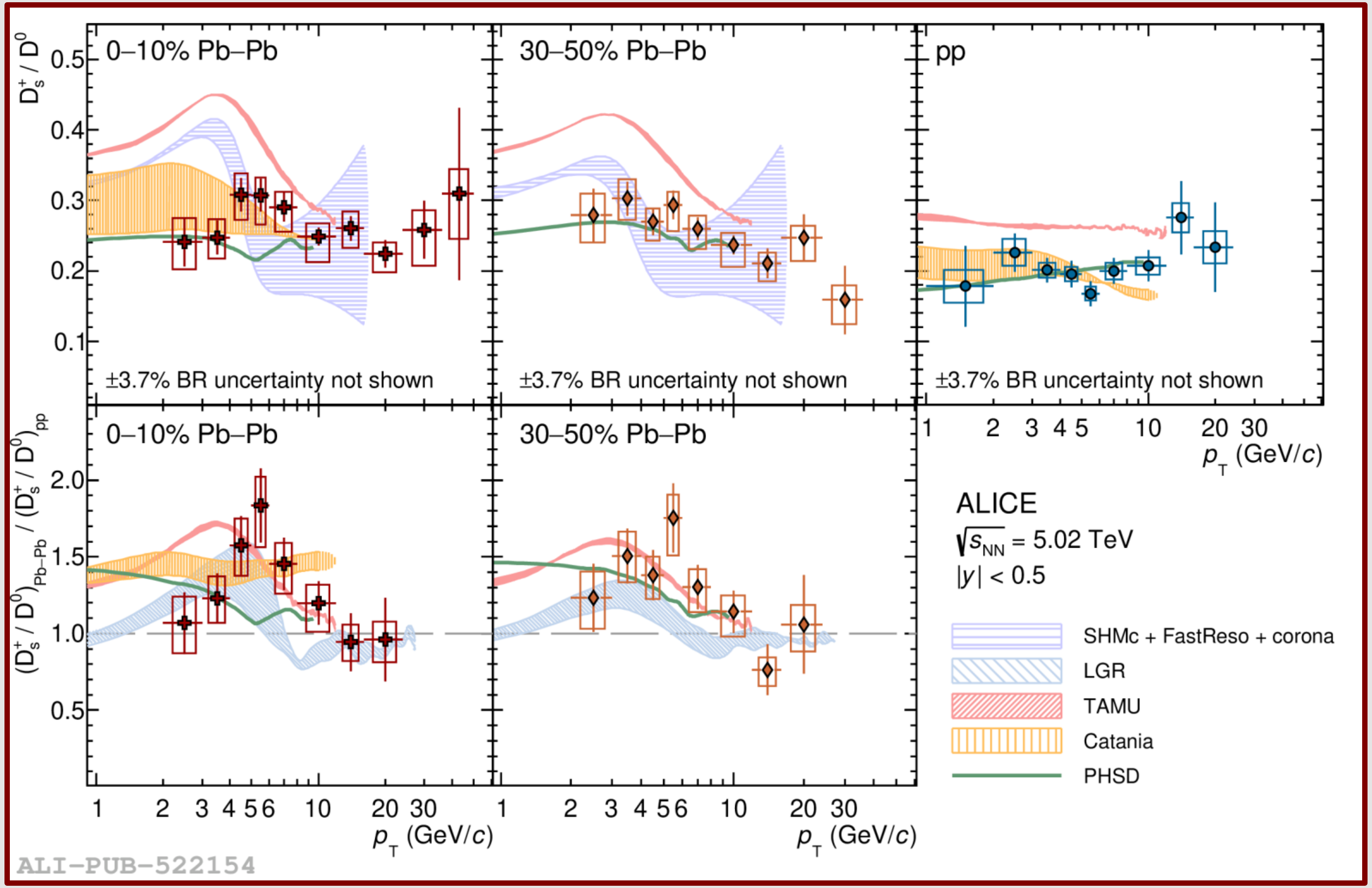
  ➔ Indication that coalescence plays an important role in Λ_c formation
- Results consistent between ALICE + CMS at high p_T





[ALICE: arXiv:2112.08156]
[CMS: CMS-PAS-HIN-21-004]

Strange-charm production in Pb–Pb collisions



- D_s^+/D^0 ratios measured by ALICE Collaboration: No significant dependence on centrality between central / midcentral collisions
- Double ratio for Pb–Pb/pp collisions: Peak at intermediate p_T predicted by
  - LGR model (instantaneous coalescence at phase boundary)
  - TAMU (coalescence via resonant states)