Experimental overview of open HF production in small systems

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Outline

- Total charm/bottom cross-sections in pp
- Nuclear modification factors of heavy flavor hadrons
- Charm and bottom hadronization
- Summary

$$\sigma_{\mathrm{AB}\to\mathrm{H}} = \mathrm{PDF}(x_a, Q^2)\mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}}(x_a, x_b, Q^2) \otimes D_{q\to\mathrm{H}}(z = \mathrm{p_H}/\mathrm{p}_q, Q^2)$$

Parton distribution functions

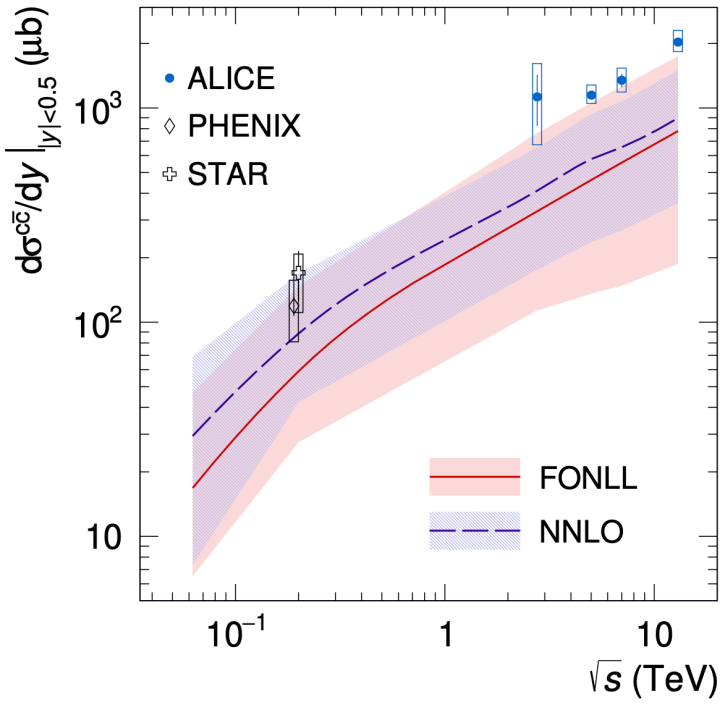
Hard scattering cross section

Fragmentation function (hadronization)

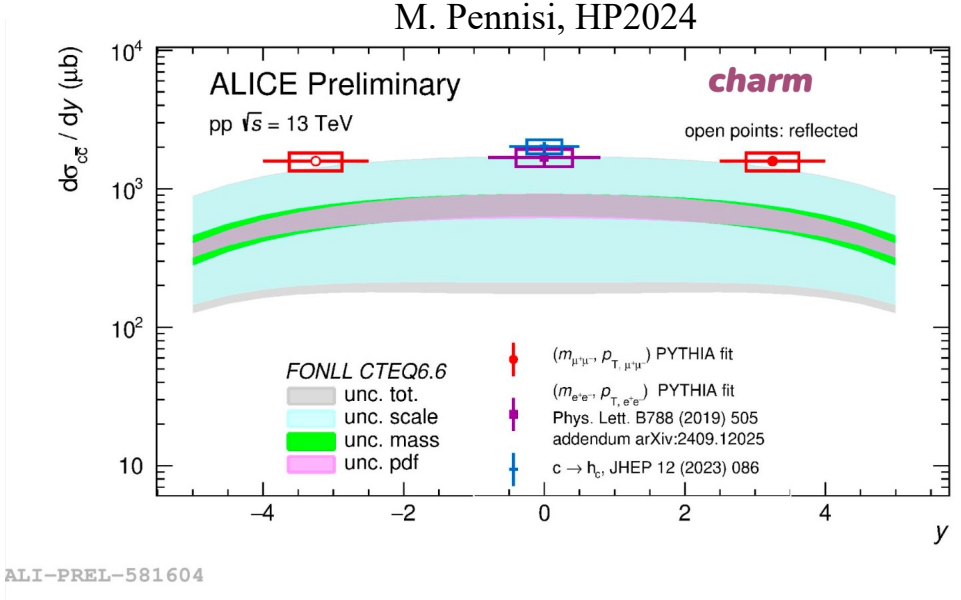
F. Zanone, HP2024

Total charm cross-sections in pp

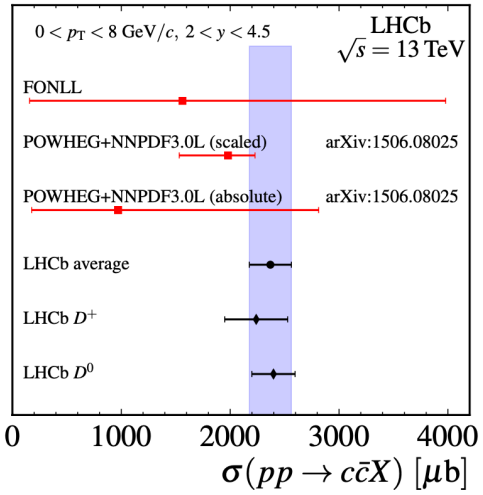
ALICE, JHEP 12 (2023) 086



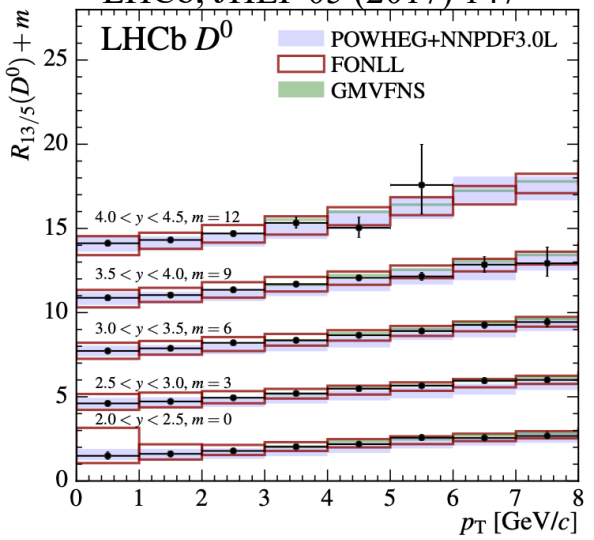
M. Pennisi, HP2024



LHCb, JHEP 05 (2017) 074



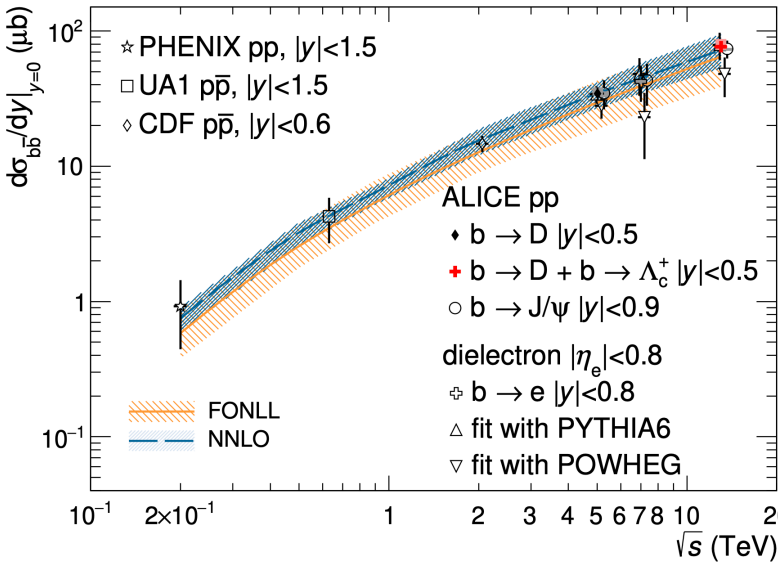
LHCb, JHEP 05 (2017) 147

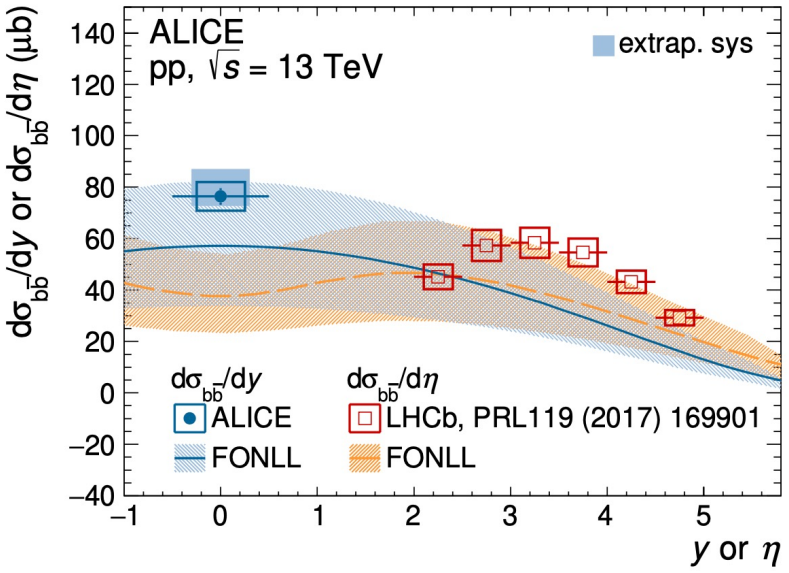


- Lies at the upper edge of pQCD predictions at both mid and forward rapidities
- Ratios of the cross-sections for different energies consistent with theoretical predictions

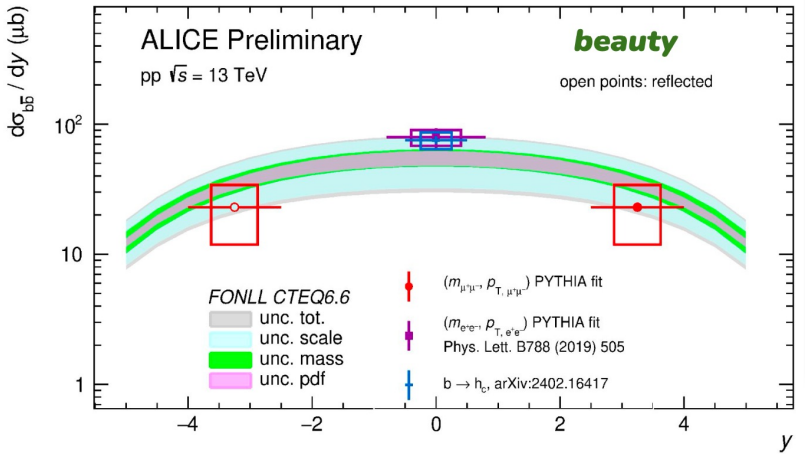
Total bottom cross-sections in pp

ALICE, JHEP 10 (2024) 110





M. Pennisi, HP2024



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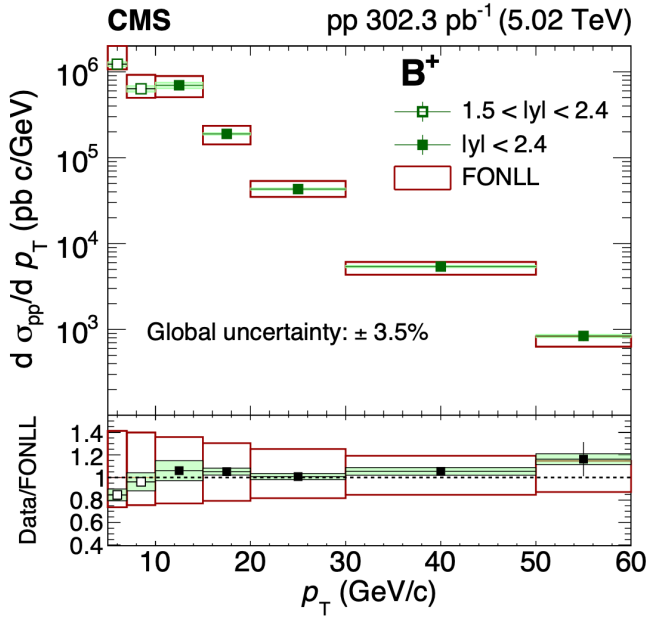
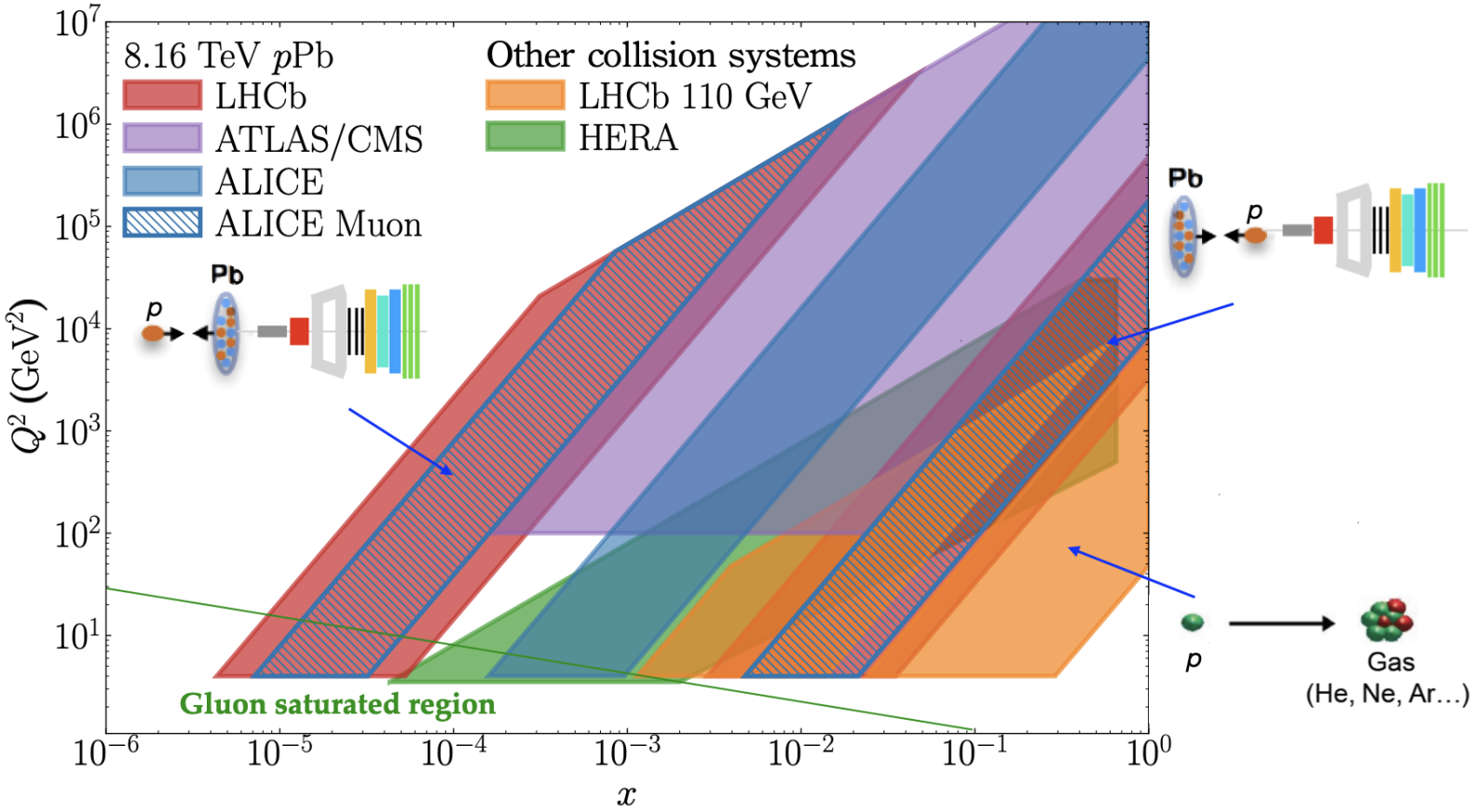


- Lies at the upper edge of NLO pQCD predictions at mid rapidity, closer to NNLO
- But pQCD calculations reproduce well the energy/ rapidity/p_T dependence

CMS, arXiv: 2409.07258

Cold nuclear matter effects studied in pA collisions

- nPDF; CGC; energy loss; multiple scattering (Cronin effect)



nPDF (x, Q^2) coverage of different experiments

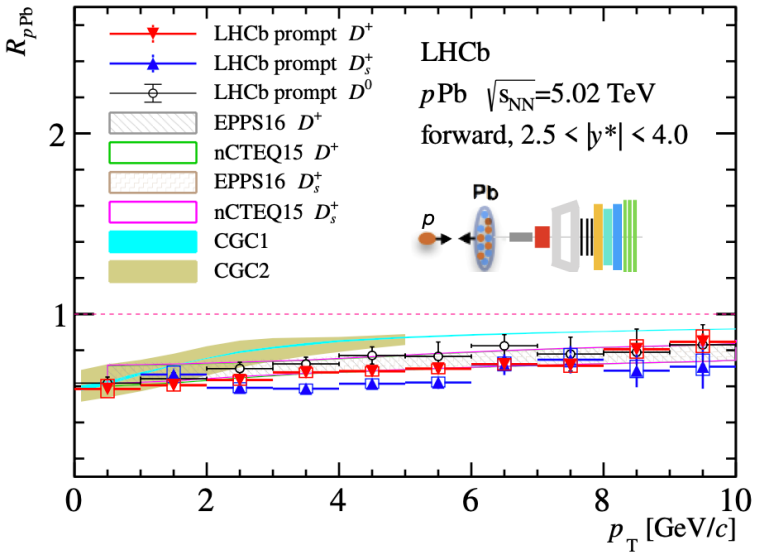
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

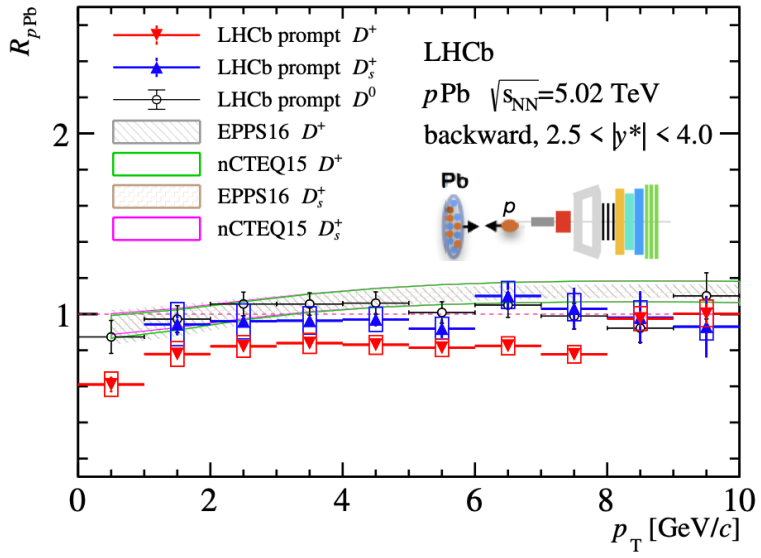
$$x_{\mathrm{exp}} \equiv 2\frac{\sqrt{p_\mathrm{T}^2 + M^2}}{\sqrt{s_{\mathrm{NN}}}}\mathrm{e}^{-y^*}$$

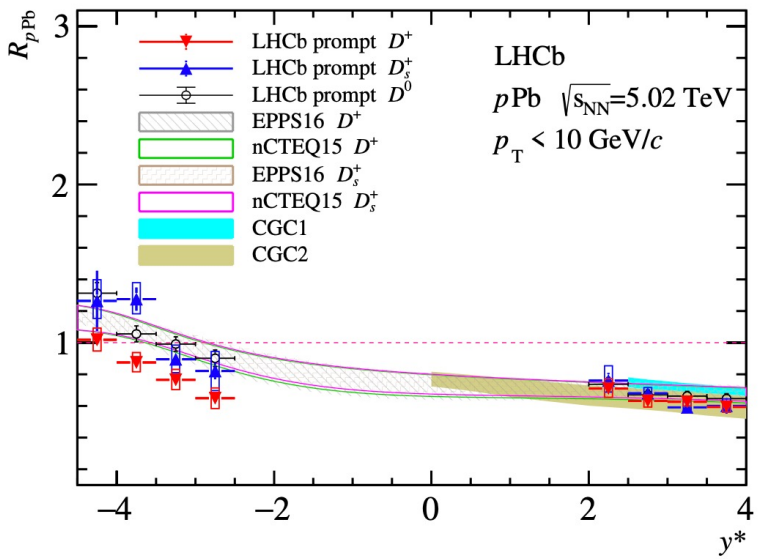
$$Q^2_{\mathrm{exp}} \equiv p_\mathrm{T}^2 + M^2$$

Prompt *D* meson production in pPb at 5.02 TeV

LHCb, JHEP 01 (2024) 070; JHEP 10 (2017) 090

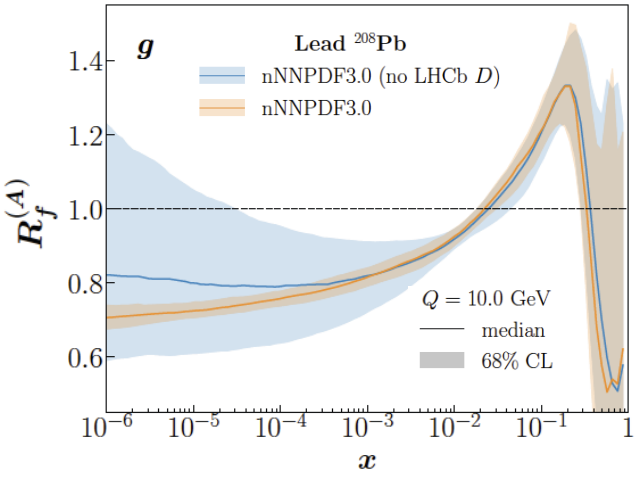




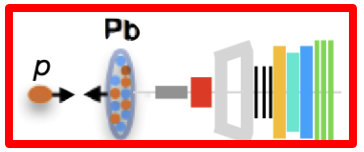


- One of the strongest constraint on gluon nPDF
- All *D* mesons suppressed at forward rapidity
  → gluon shadowing at small x
- *D* meson species dependence at backward rapidity
  → final state effects become important

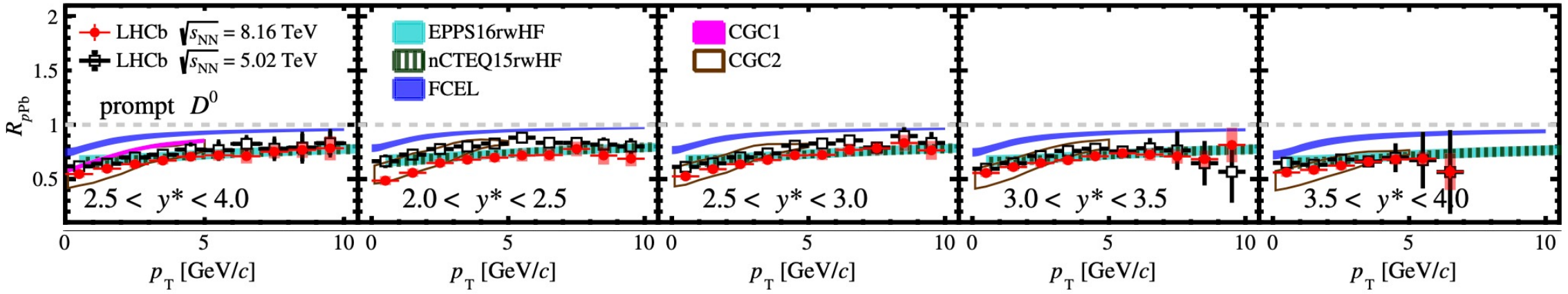
nNNPDF3.0, EPJC 82 (2022) 507



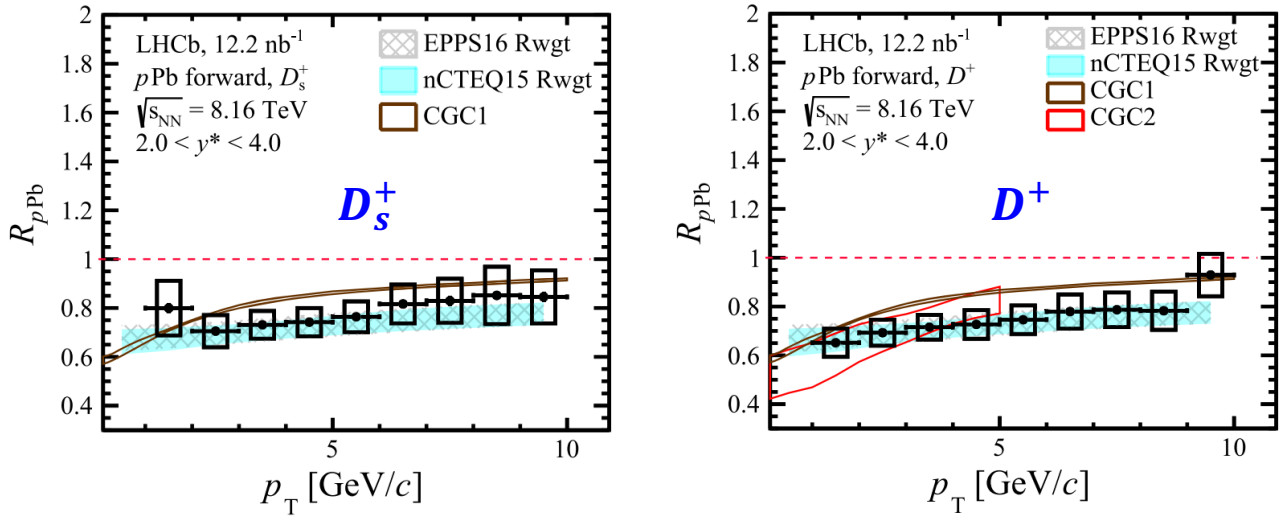
Prompt D meson production in pPb at 8.16 TeV



LHCb, PRL 131 (2023) 102301 D^0

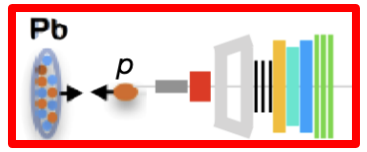


- Precise differential measurements in different rapidity regions → gluon shadowing at forward rapidity
- D^0 data at low p_T closer to CGC prediction, or initial state energy loss becomes more important

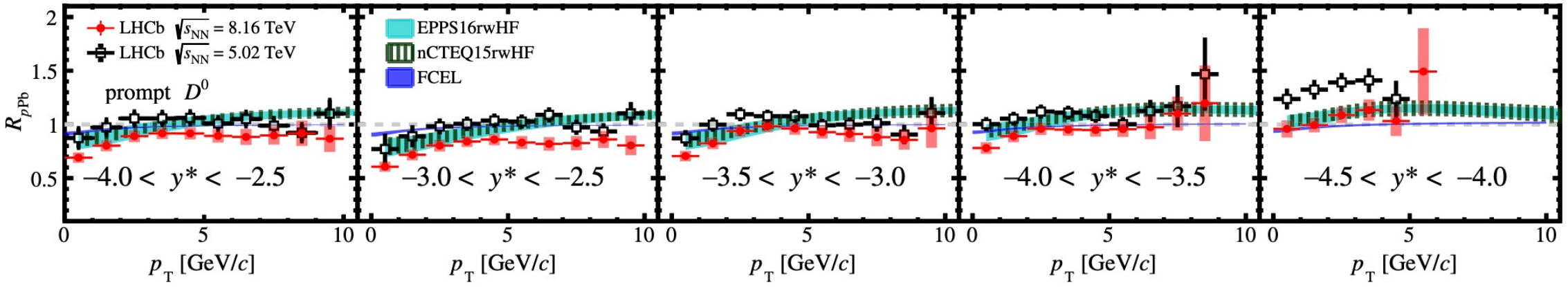


LHCb, PRD 110 (2024) L031105

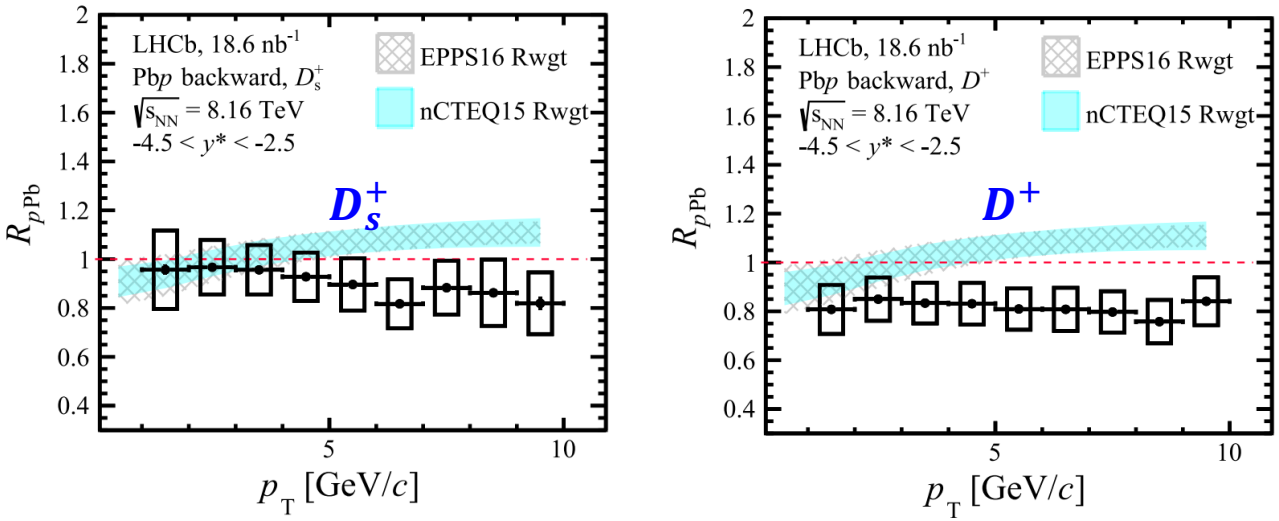
Prompt D meson production in pPb at 8.16 TeV



LHCb, PRL 131 (2023) 102301 D^0



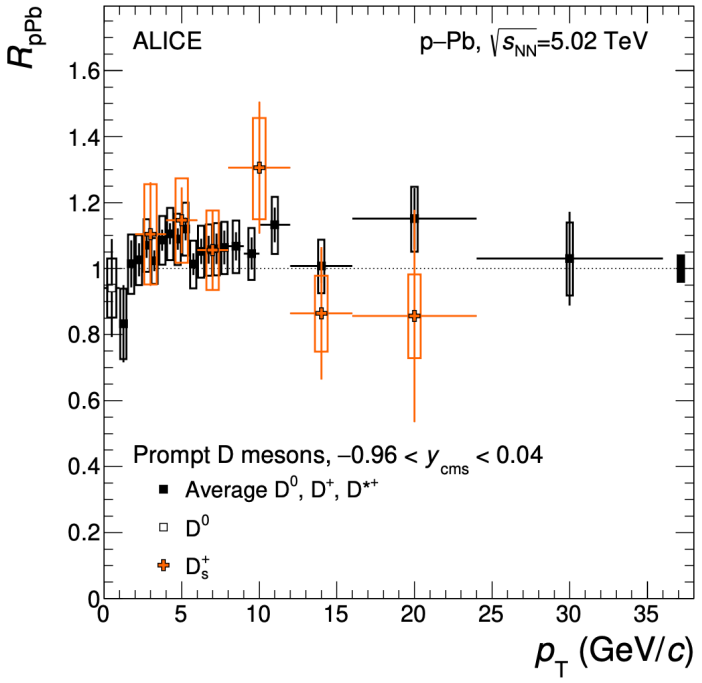
- All D meson data lower than nPDF calculations at high p_T !
  → Onset of charm energy loss in cold/hot nuclear matter ?
  Model comparisons desired
  → Or charmed baryon enhanced ?
  More measurements expected



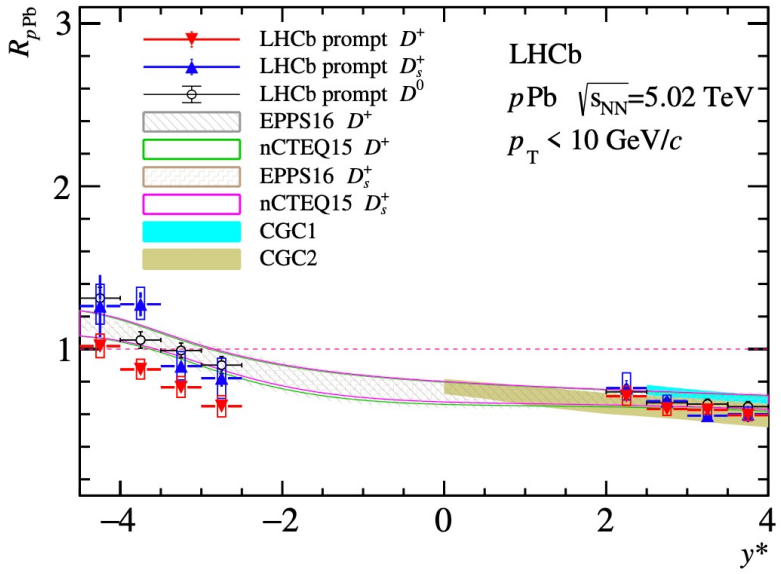
LHCb, PRD 110 (2024) L031105

Charmed hadron R_{pPb} at mid-rapidity

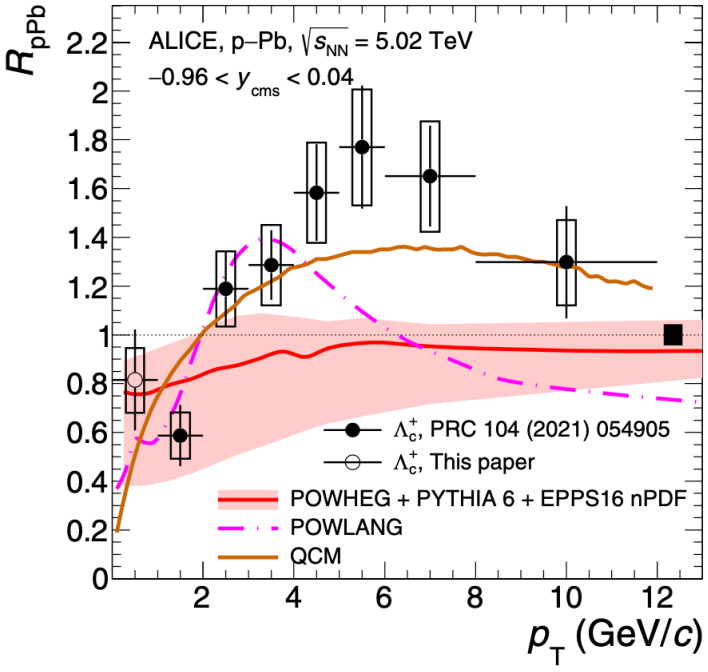
ALICE, JHEP 12 (2019) 092



LHCb, JHEP 01 (2024) 070; JHEP 10 (2017) 090



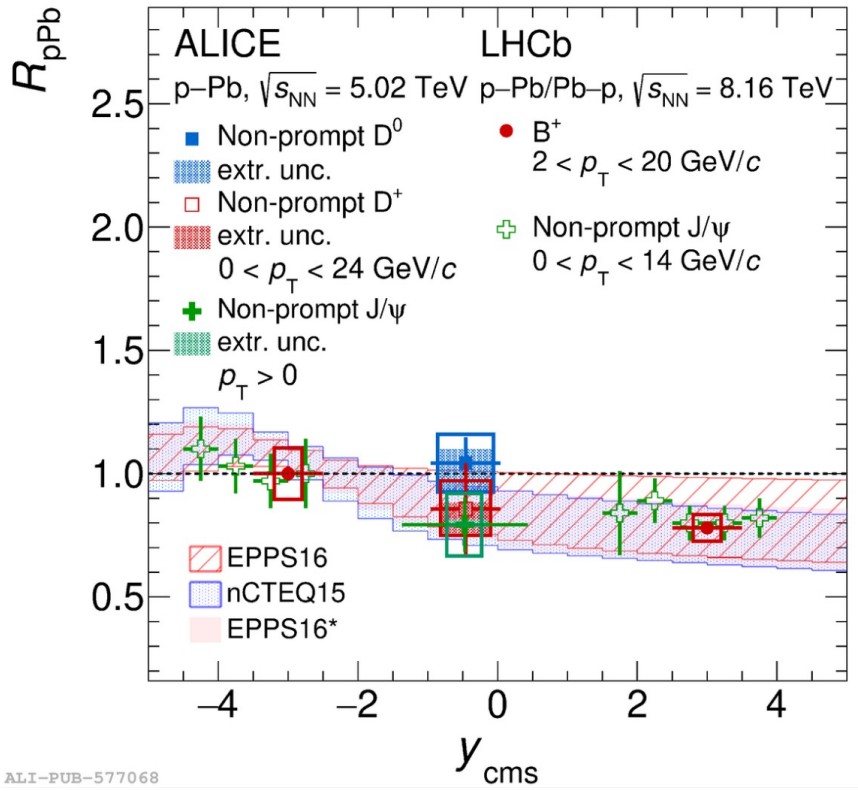
ALICE, PRC 107 (2023) 064901



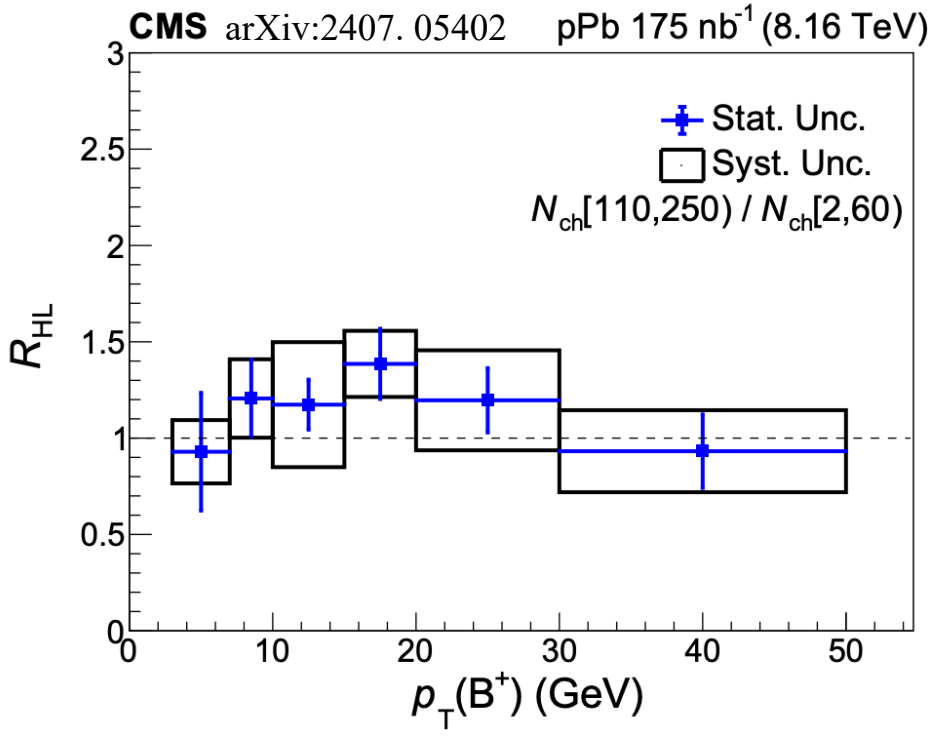
- Prompt *D* mesons not suppressed at mid-rapidity across the whole p_T range ?
  → More precise measurements in Run3 expected
- Prompt Λ_c^+ indeed shows strong enhancement at intermediate to high p_T
  → More precise measurements (Run3, other experiments / charmed baryons) are essential

Bottom hadron R_{pPb}

ALICE, JHEP 11 (2024) 148



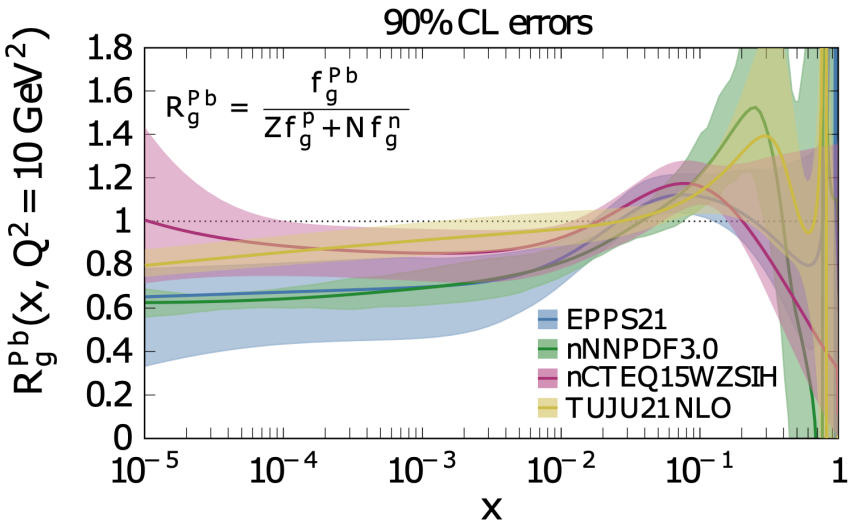
$$R_{HL} = \frac{\langle N_{coll}\rangle|_{low}}{\langle N_{coll}\rangle|_{high}} \frac{(d\sigma/dp_T)|_{high}}{(d\sigma/dp_T)|_{low}}$$



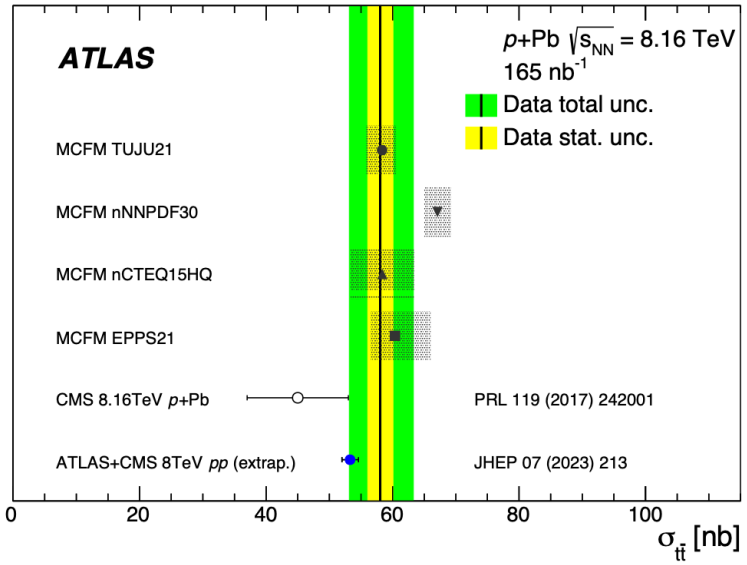
- Non-prompt D and non-prompt J/ψ data consistent with direct B^+ measurements
- Consistent with the nPDF calculations at all rapidity ranges
- R_{HL} data set constraints on medium effect on B^+ production

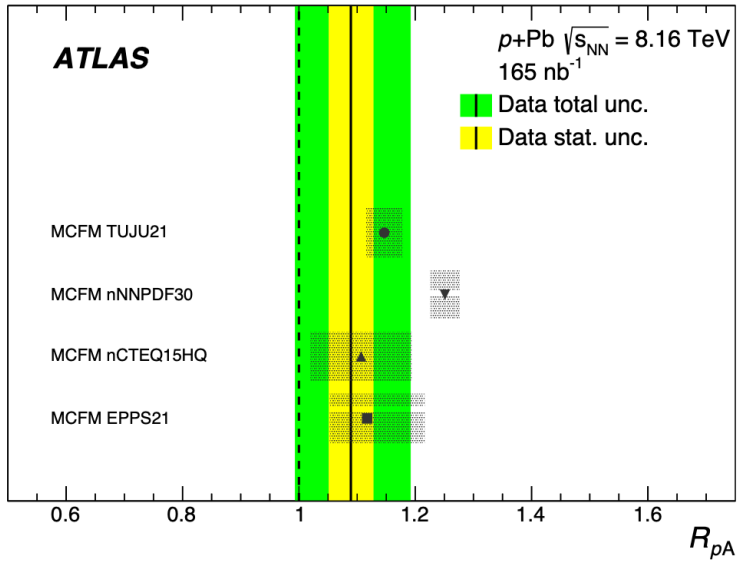
Top-quark pair R_{pPb}

QM2022 P. Paakkinen



ATLAS, JHEP 11 (2024) 101

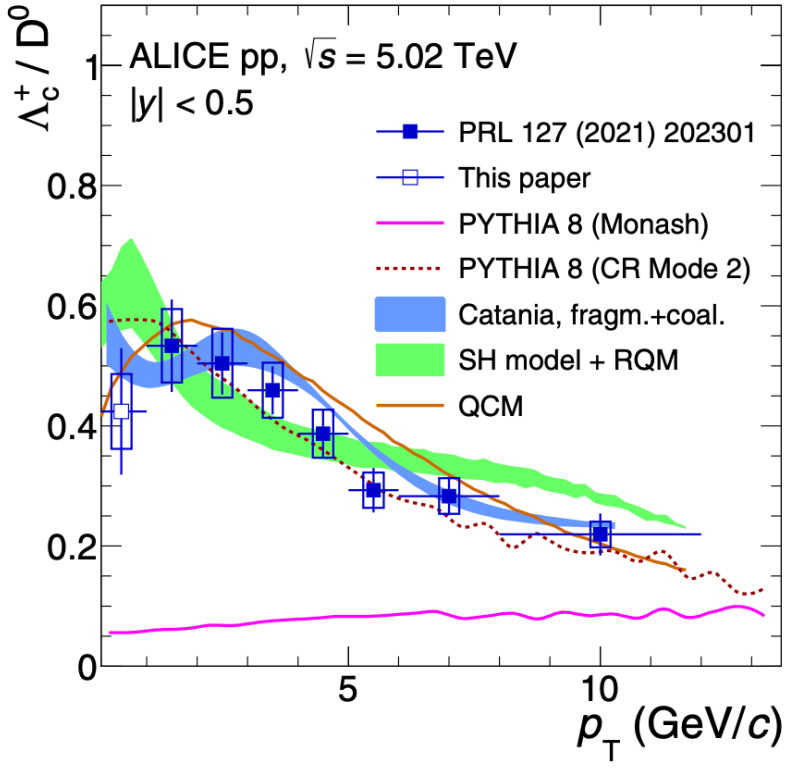


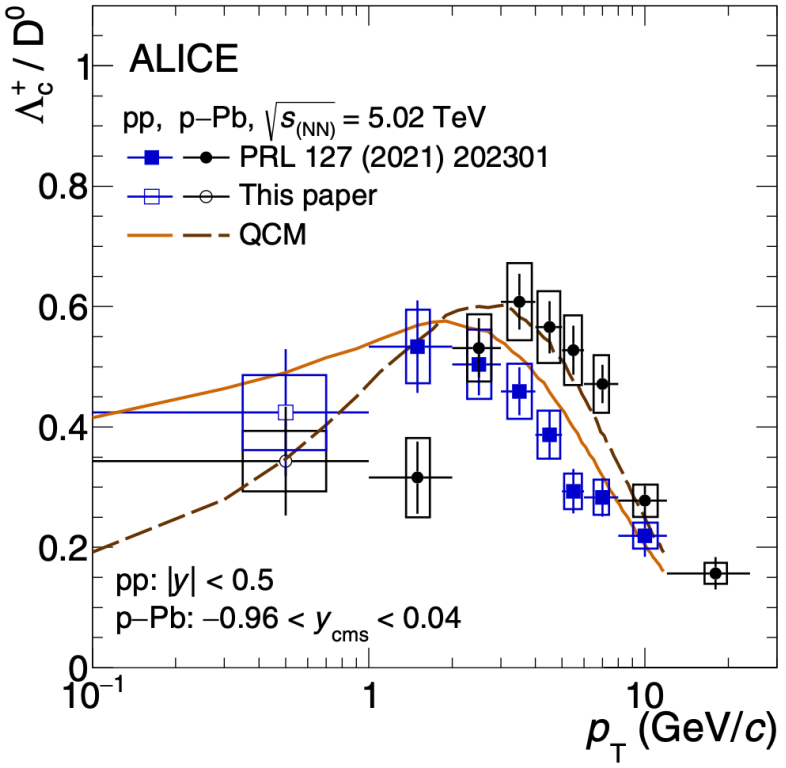


- Sensitive to gluon PDF in the large x (~0.1) and large Q^2 region
- Slightly larger than unity, good agreement with most NNLO+nPDF calculations

Prompt Λ_c^+ to D^0 cross-section ratios in pp and pPb

ALICE, PRC 107 (2023) 064901

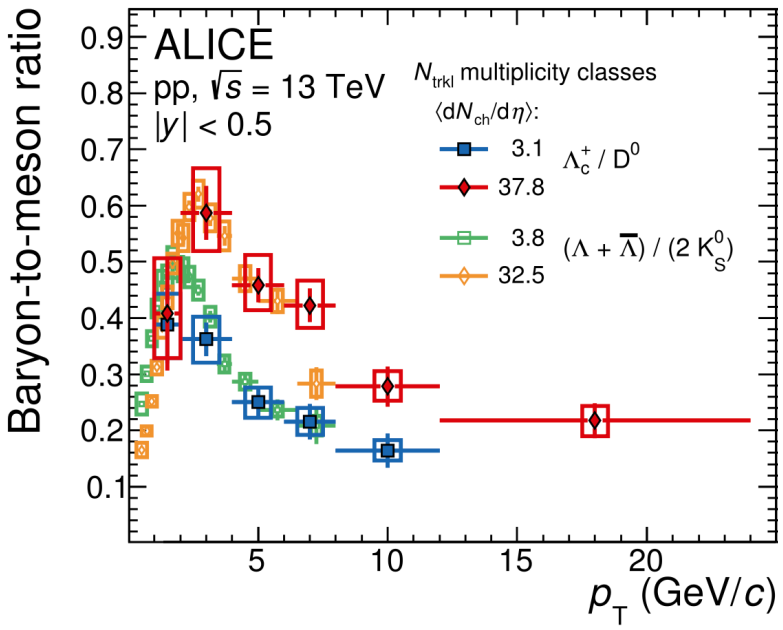




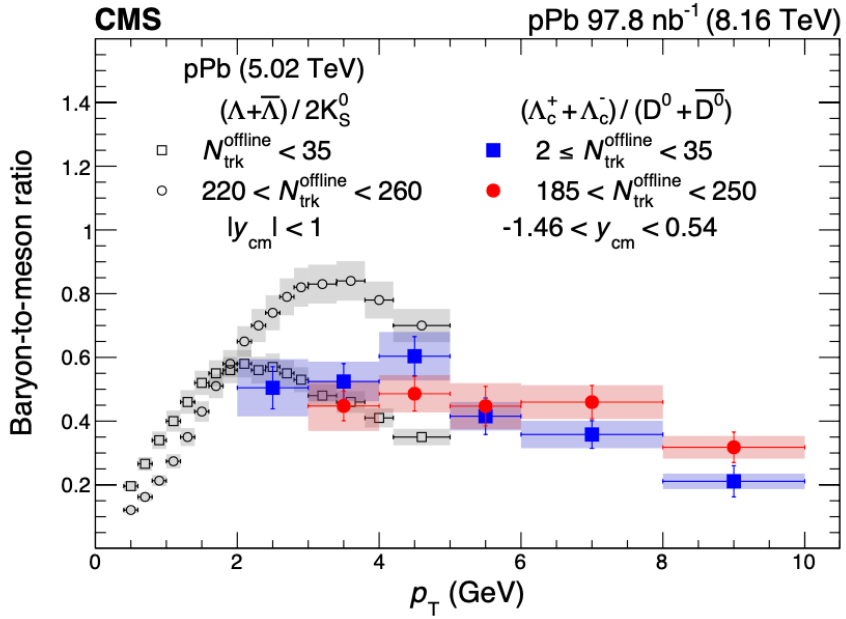
- Charmed baryon-to-meson enhancement (wrt ee/ep) at lower p_T, consistent with color reconnection / coalescence / statistical hadronization models
- Shift of distribution peak towards higher p_T in pPb could be attributed to radial flow. Uncertainties (at low p_T) need to be reduced in future measurements

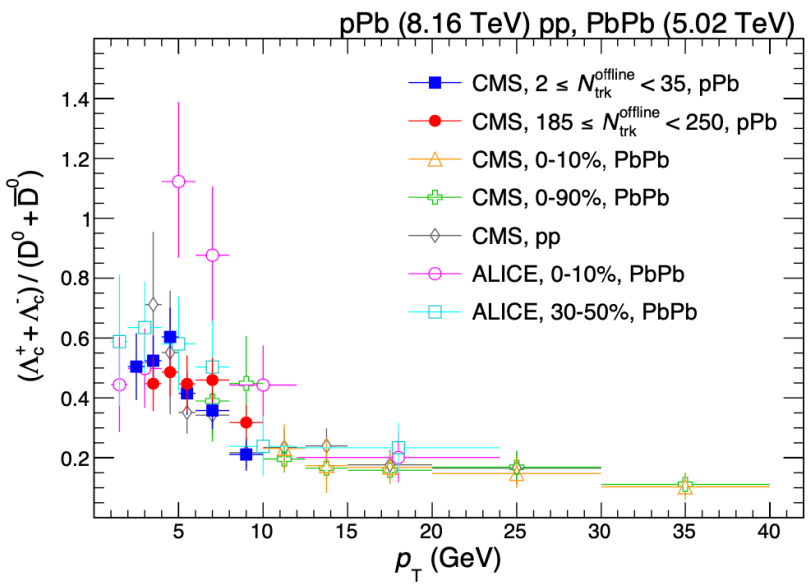
Λ_c^+/D^0 versus multiplicity in pp and pPb

ALICE, PLB 829 (2022) 137065



CMS, arXiv: 2407.13615

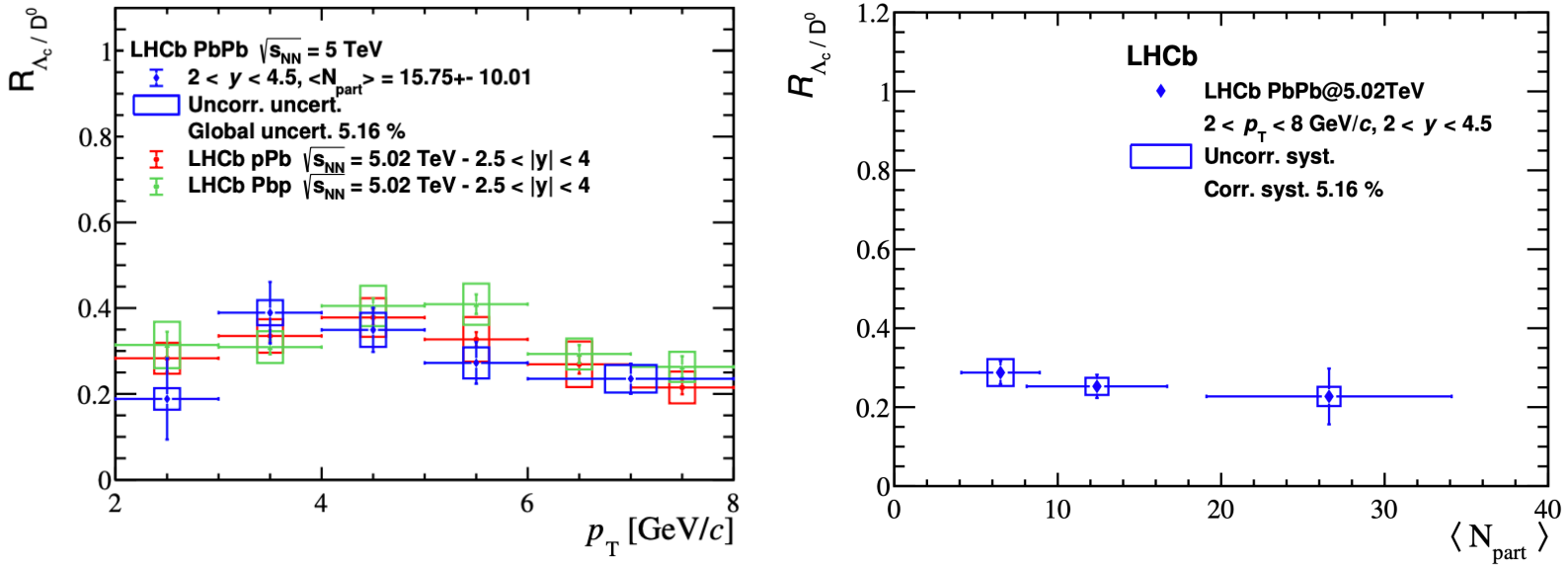




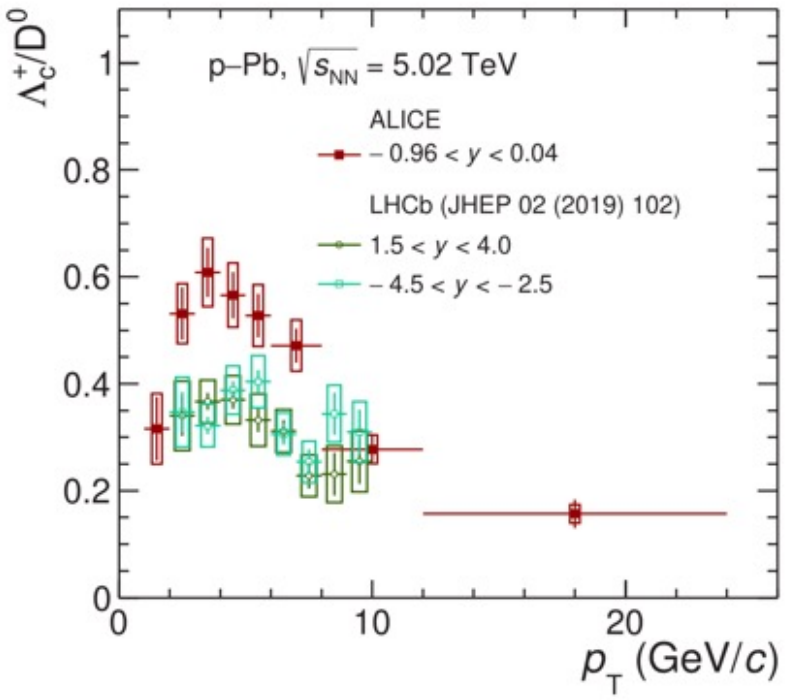
- Increases rapidly with the increasing multiplicity in pp collisions
- Stays almost unchanged in pPb and semi-central PbPb
- Suddenly increases again in most central PbPb, precise Run3 measurement expected

Λ_c^+/D^0 versus multiplicity in forward rapidities

LHCb, JHEP 06 (2023) 132



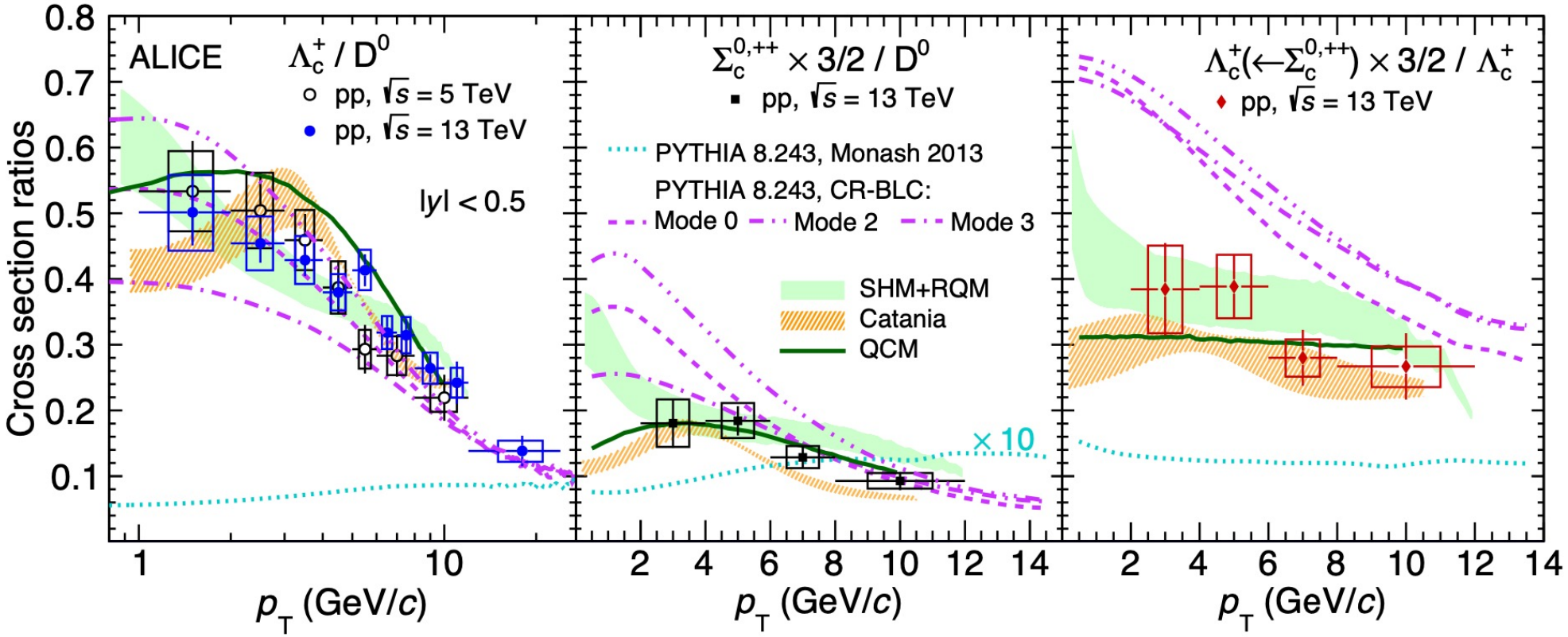
ALICE, PRC 104 (2021) 054905



- Stays almost unchanged in pPb/Pbp and peripheral PbPb collisions, much larger than ee/ep, charm hadronization changed in forward rapidity as well
- Tension with values at mid-rapidity, since rapidity independence predicted
- More independent measurements are desired

Prompt $\Sigma_c^{0,++}$ to D^0 cross-section ratios in pp @ 13 TeV

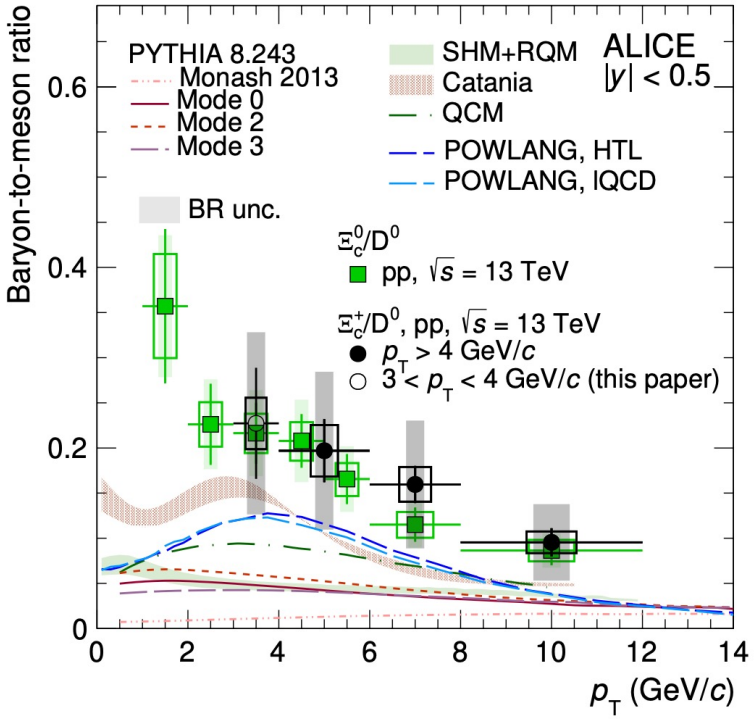
ALICE, PRL 128 (2022) 012001



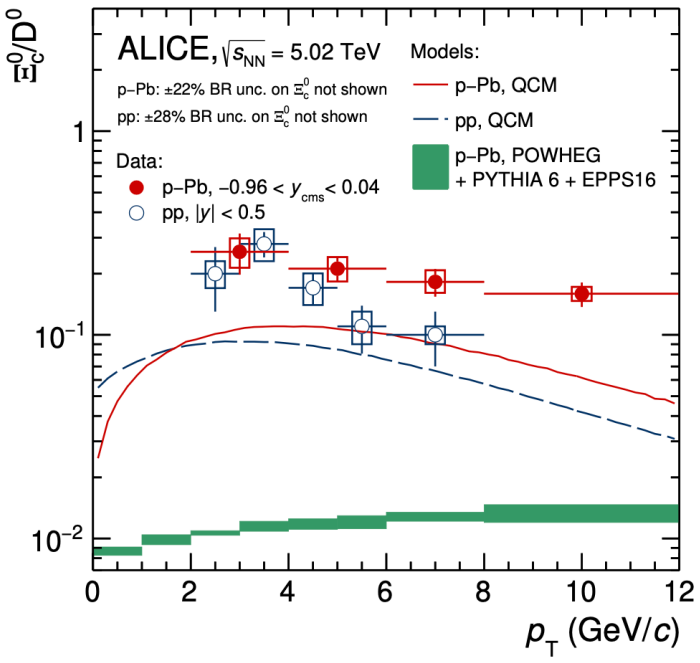
- Λ_c^+/D^0 values almost energy independent
- $\Sigma_c^{0,++}/D^0$ production significantly enhanced, described by same models
- 40% Λ_c^+ from $\Sigma_c^{0,+,++}$ decays, enhanced feed-down contributes to Λ_c^+/D^0 enhancement

Prompt Ξ_c to D^0 cross-section ratios in pp and pPb

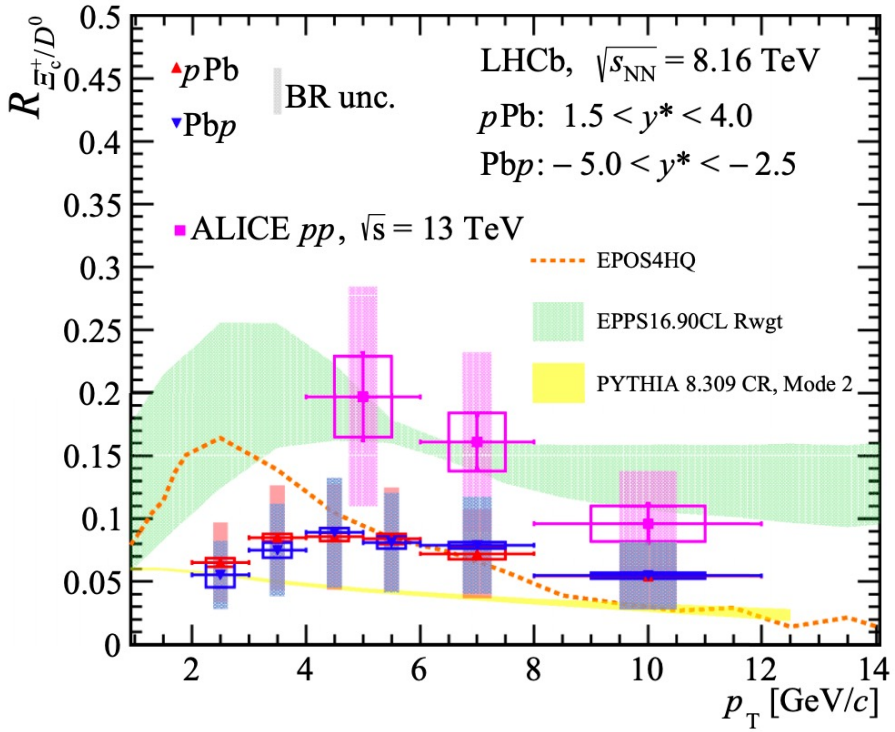
ALICE, JHEP 12 (2023) 086



ALICE, arXiv: 2405.14538



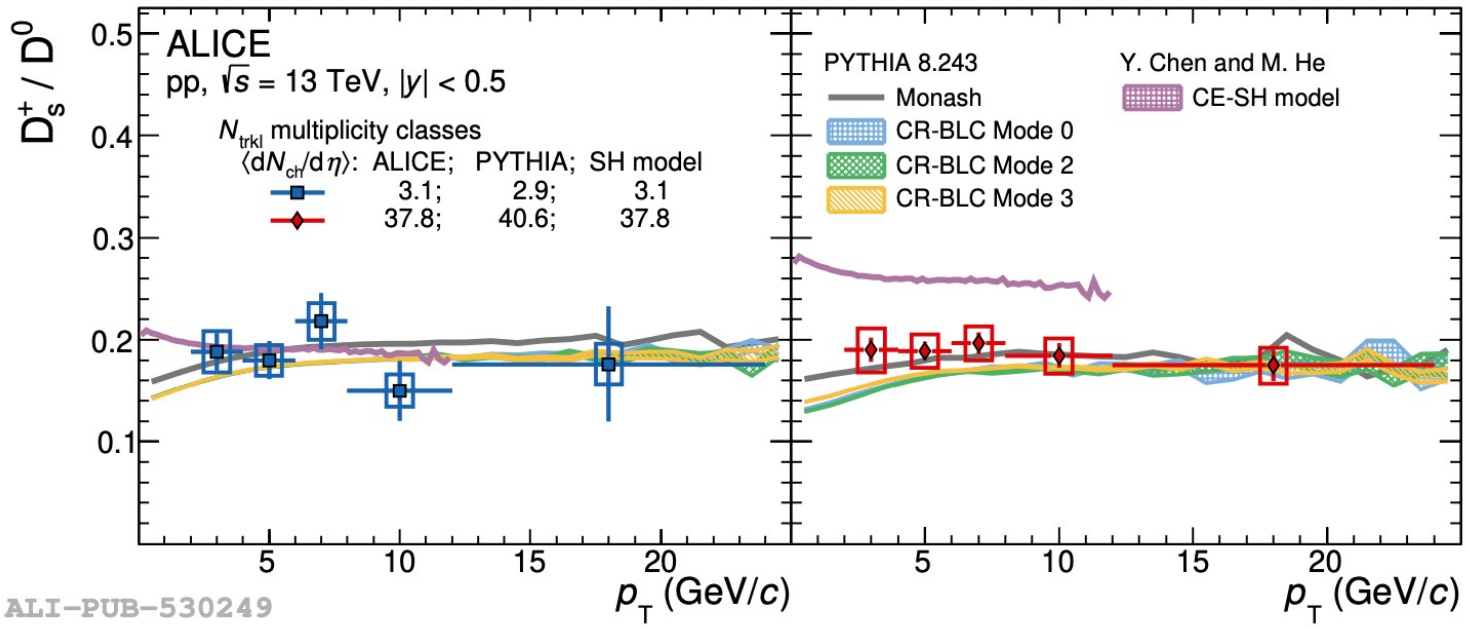
LHCb, PRC 109 (2024) 044901



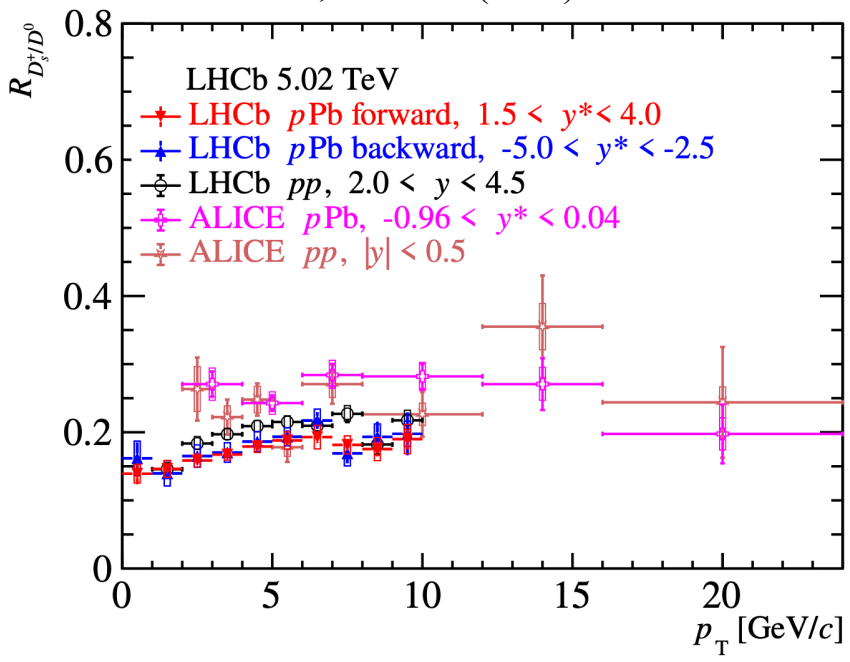
- Significant enhancement also in strange-charmed-baryon to D^0 ratios
- Even stronger than coalescence model predictions, pp/pPb consistent
- Values at forward rapidity systematically lower than mid-rapidity

Prompt D_s^+ to D^0 ratios in pp and pPb

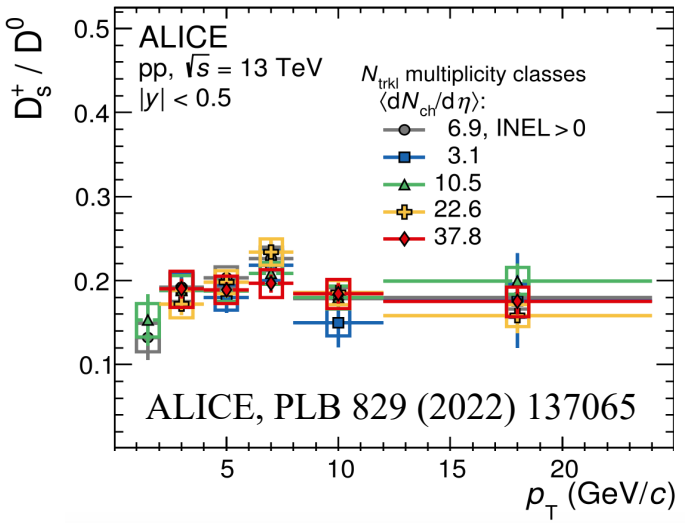
ALICE, PLB 829 (2022) 137065



LHCb, JHEP 01 (2024) 070

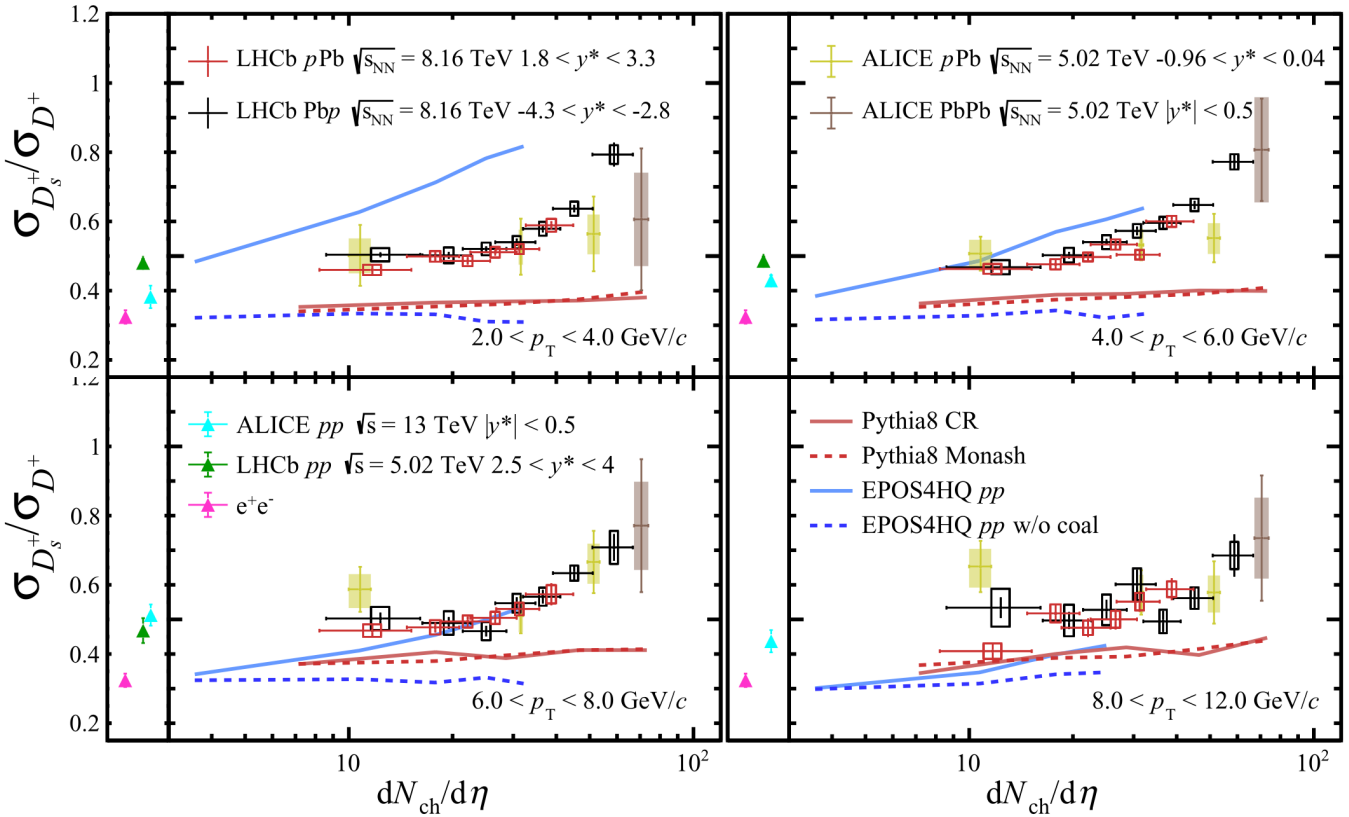


- Consistent D_s^+/D^0 cross-section ratios in pp between forward and mid rapidities
- Independent of event multiplicity in pp collisions at mid-rapidity
- Consistent with PYTHIA8 calculations, CR mechanism almost does not affect this ratios

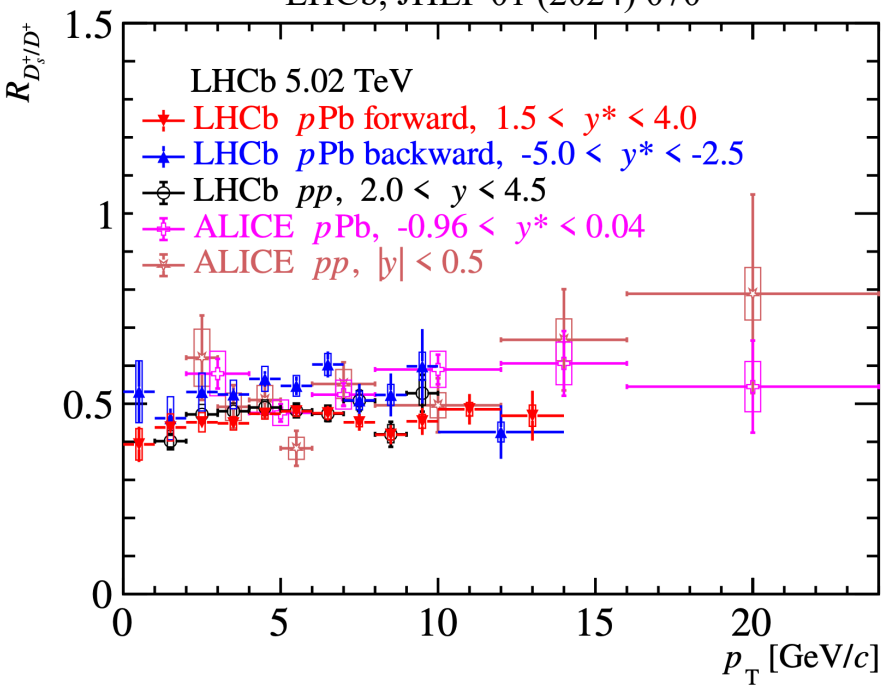


Prompt D_s^+ to D^+ ratios in pp and pPb

LHCb, PRD 110 (2024) L031105



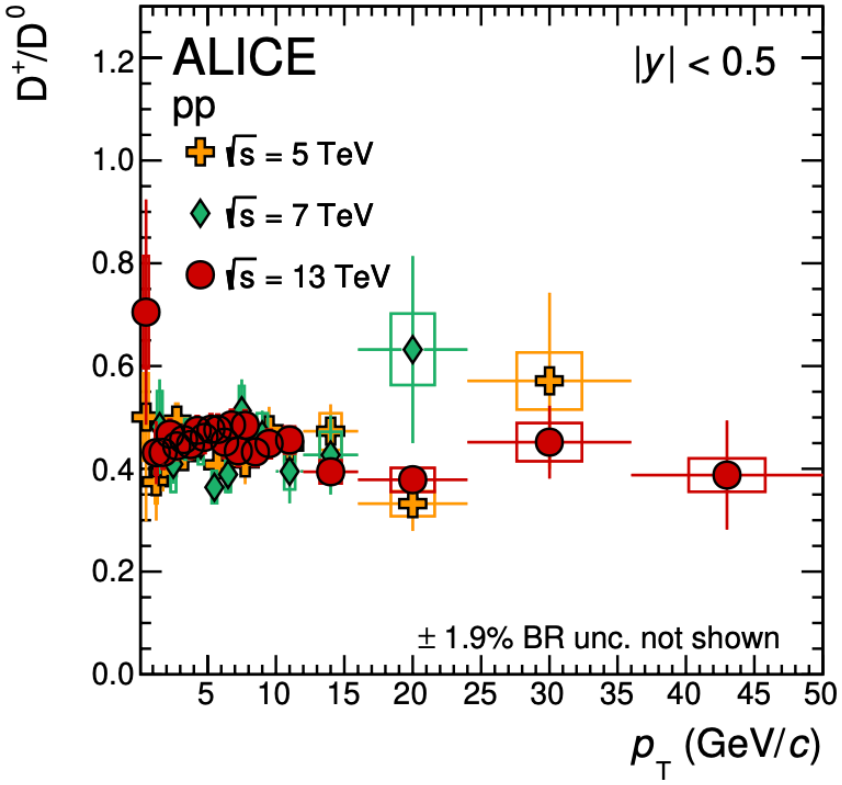
LHCb, JHEP 01 (2024) 070



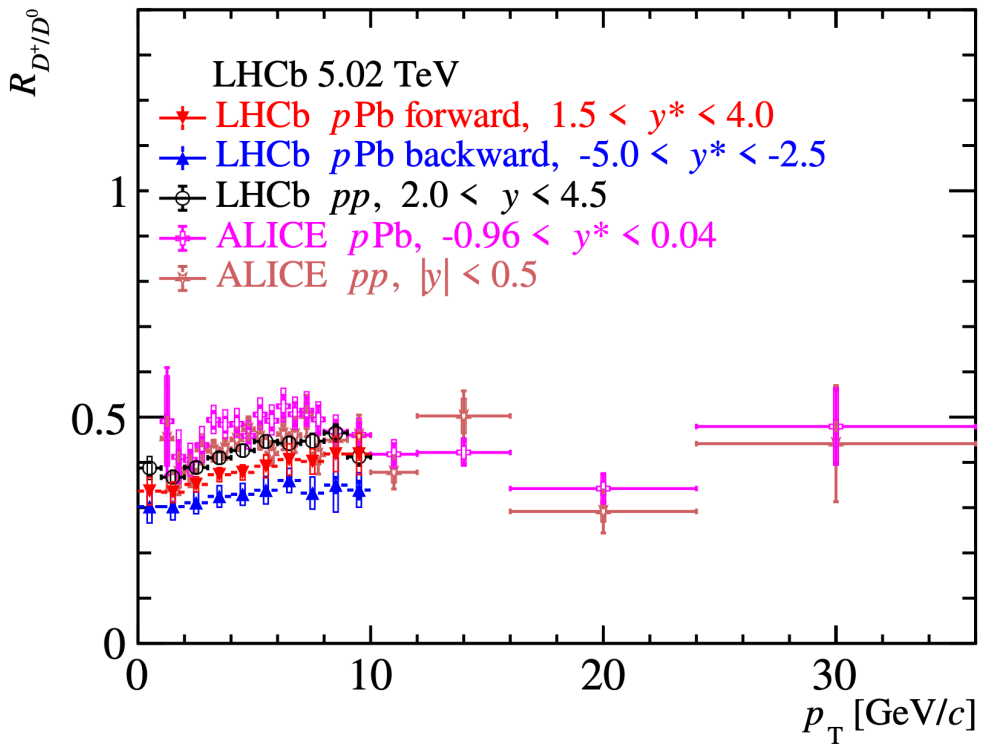
- Consistent D_s^+/D^+ cross-sections ratios in pp between forward and mid rapidities
- Significant enhancement at high multiplicity in pPb, in particular for low p_T
- Contradiction to the D_s^+/D^0 measurement in pp at mid-rapidity?

Prompt D^+ to D^0 ratios in pp and pPb

ALICE, JHEP 12 (2023) 086



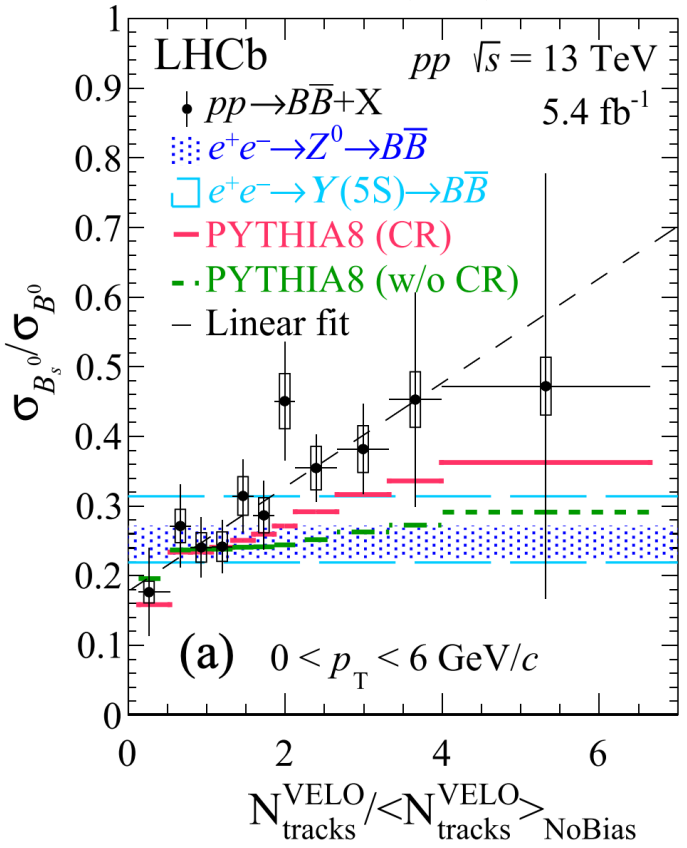
LHCb, JHEP 01 (2024) 070

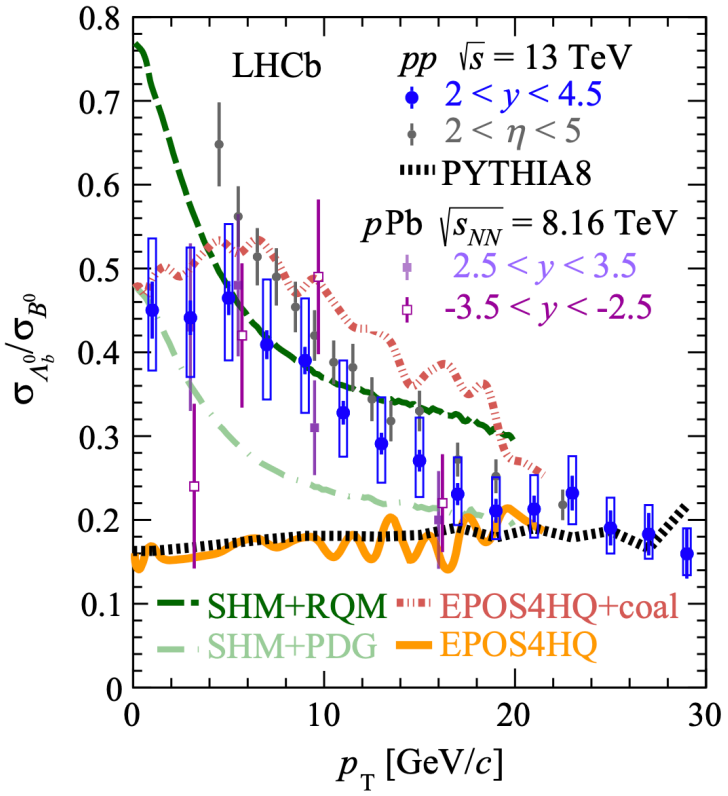


- Consistent D^+/D^0 values in pp between forward and mid rapidities
- Tension in pPb between forward and mid-rapidities
- At forward rapidities, clear hierarchy of D^+/D^0 ratios: pp > pPb > Pbp
- D^+/D^0 decreases with the increasing event multiplicity? More measurements expected

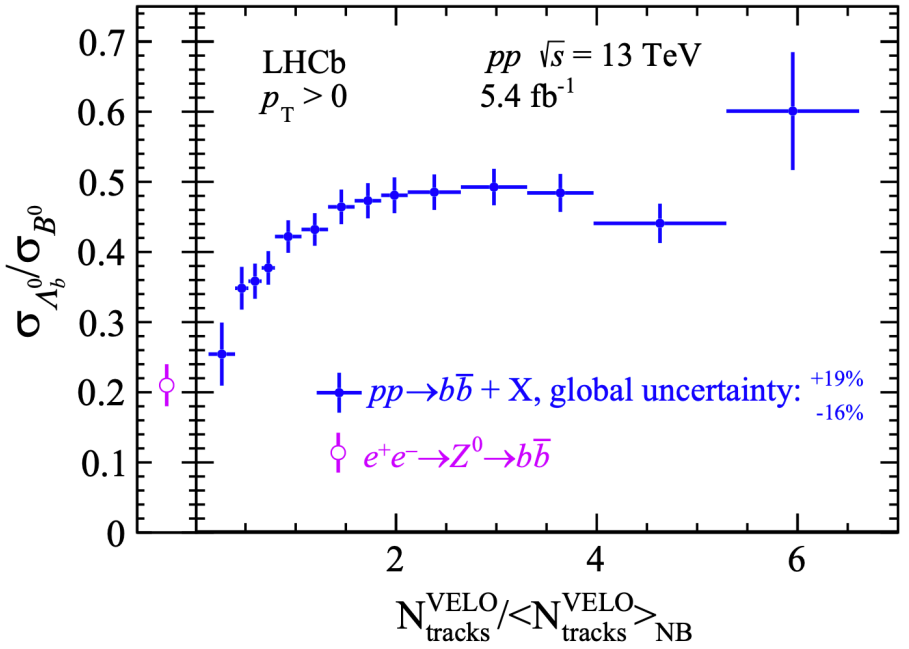
Bottom hadronization in pp

LHCb, PRL 131 (2023) 061901





LHCb, PRL 132 (2024) 081901



- Evidence of B_s^0/B^0 enhancement (at low p_T) in high multiplicity events
- A strong baryon enhancement of with multiplicity is observed
  - Ratio recovers e^+e^- value (QCD-vacuum) at low multiplicity
  - Ratio consistent with e^+e^- at high p_T

Summary & outlook

- pQCD well reproduces the energy/p_T/rapidity dependence of total charm/bottom productions
- Heavy flavor R_{pPb} measurements at mid/forward rapidities constrain cold nuclear matter effects: e.g. gluon nPDF at various x and Q^2
- D mesons R_{pPb} shows mild high p_T suppression at backward rapidity
- Charm and bottom hadronization modified in pp/pPb collisions (wrt ee/ep)
- Future precision measurements across different energies/size/rapidity ranges are essential to fully understand heavy flavor production in small system collisions