Hadronization of heavy quarks at LHCb

Chenxi Gu, Laboratoire Leprince-Ringuet (École Polytechnique, CNRS-IN2P3)
on behalf of the LHCb collaboration

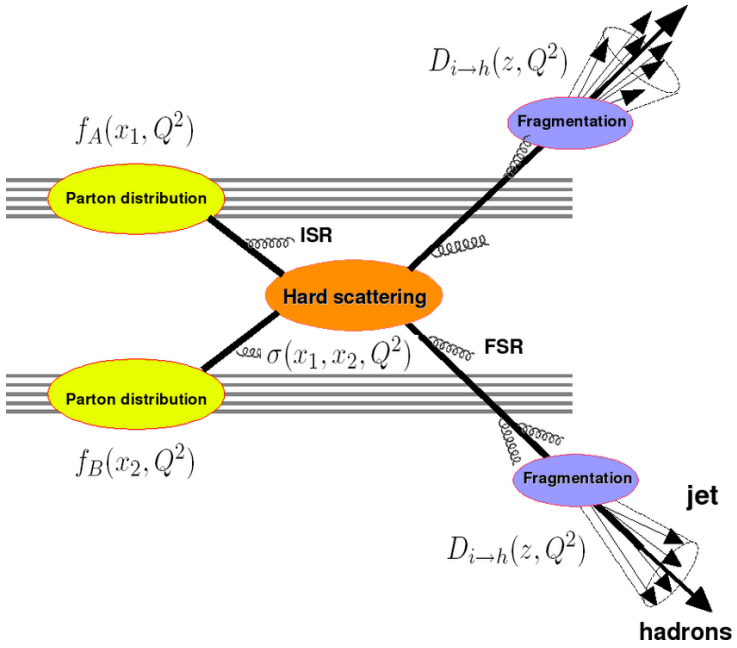
Outline

- Motivation
- LHCb detector
- B_s^0/B^0 ratio in high multiplicity pp collisions Phys. Rev. Lett. 131 (2023) 061901
- Λ_b^0/B^0 ratio in high multiplicity pp collisions Phys. Rev. Lett. 132 (2024) 081901
- D_s^+/D^+ ratio in pPb collisions JHEP 01 (2024) 070 arXiv:2311.08490
- Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 ratios in pPb collisions Phys. Rev. C 109 (2024) 044901
- Λ_c^+/D^0 ratios in peripheral PbPb collisions JHEP06 (2023) 132
- Summary

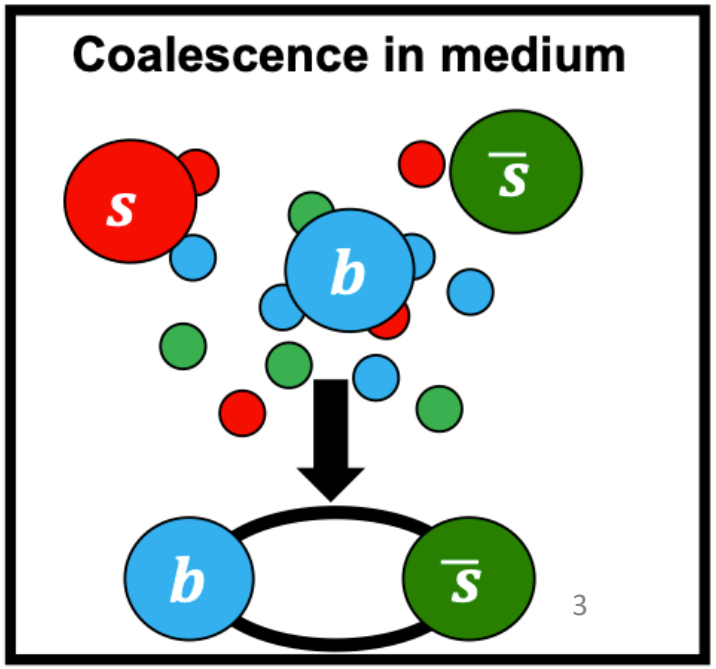
Motivation

- Heavy flavor hadrons production are based on factorization approach.
- Production ratio of heavy flavor hadrons offer unique probe of the hadronization process
  - ➢ *ee* collisions : fragmentation mechanism dominates.
  - ➢ *pp*/*p*Pb collisions : it was thought that the fragmentation mechanism was dominant.
  - ➢ PbPb/AuAu collisions : fragmentation and coalescence mechanisms mixed.
- High multiplicity collisions are often accompanied by strangeness enhancement
  - ➢ In big systems (PbPb, AuAu): *s* quark enhancement mainly comes from gluon fusion in QGP.
  - ➢ In small systems (*pp*, *p*Pb): *s* quarks enhancement mechanism is still debated (dynamical core-corona initialization, rope hadronization, color reconnection…).

Baryon/meson ratios are sensitive to hadronization.

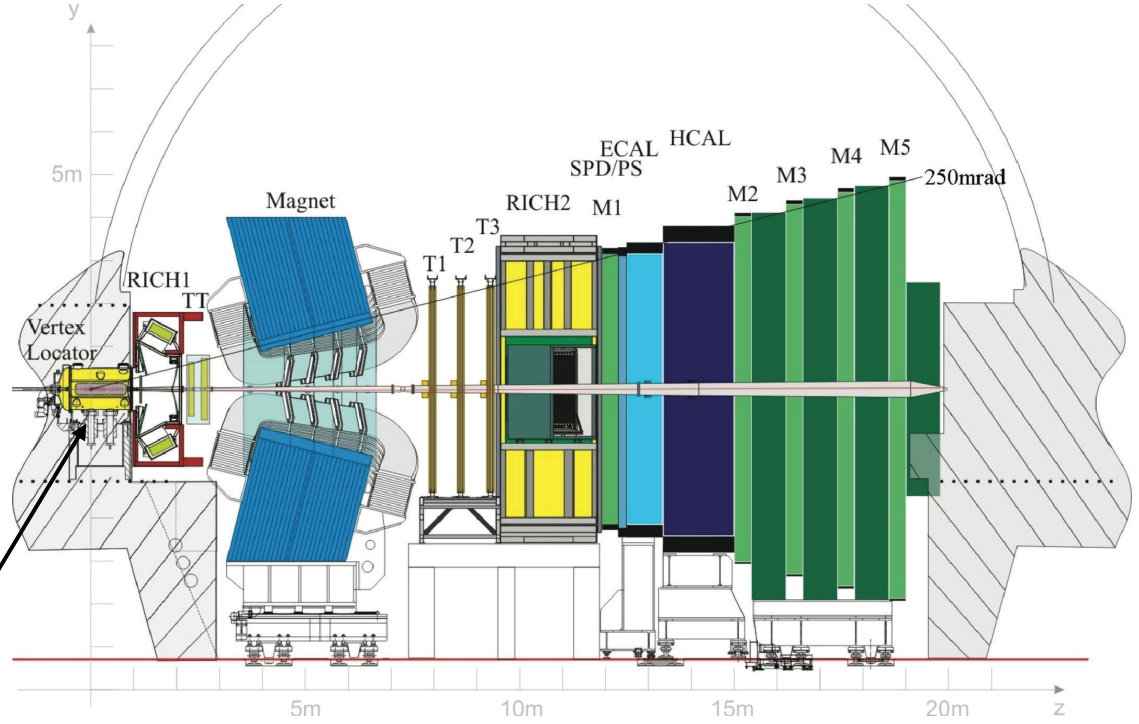


Strange hadron/non strange hadron ratios are sensitive to hadronization and strangeness enhancement.



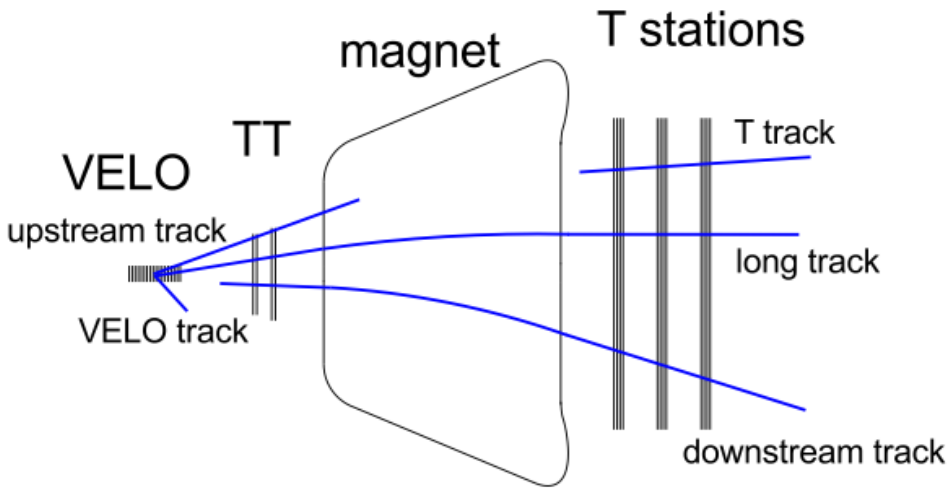
LHCb detector

- A single-arm spectrometer in the forward direction, charm & beauty factory
  - ➢ Vertex Locator (20 μm IP resolution)
  - ➢ Tracking system ($\Delta p/p = 0.5 - 1.0\%$)
  - ➢ PID optimal for μ, p, K, π
    - ❖ $\varepsilon(K \to K) \sim 95\%$
    - ❖ $\varepsilon(\mu \to \mu) \sim 97\%$
  - ➢ Flexible software trigger



VErtex LOcator

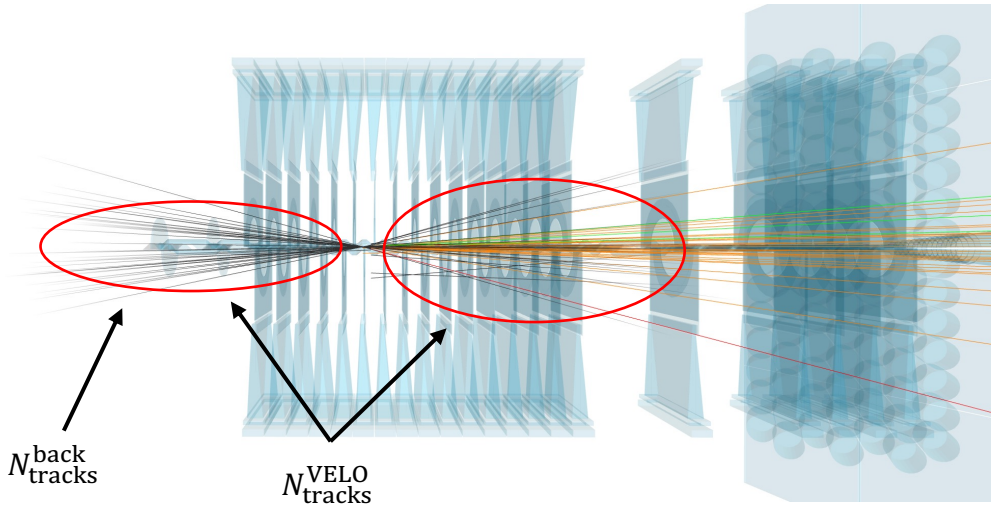
- VELO tracks : have hits in the VELO
- Back tracks : subset of VELO tracks, point in the backward direction

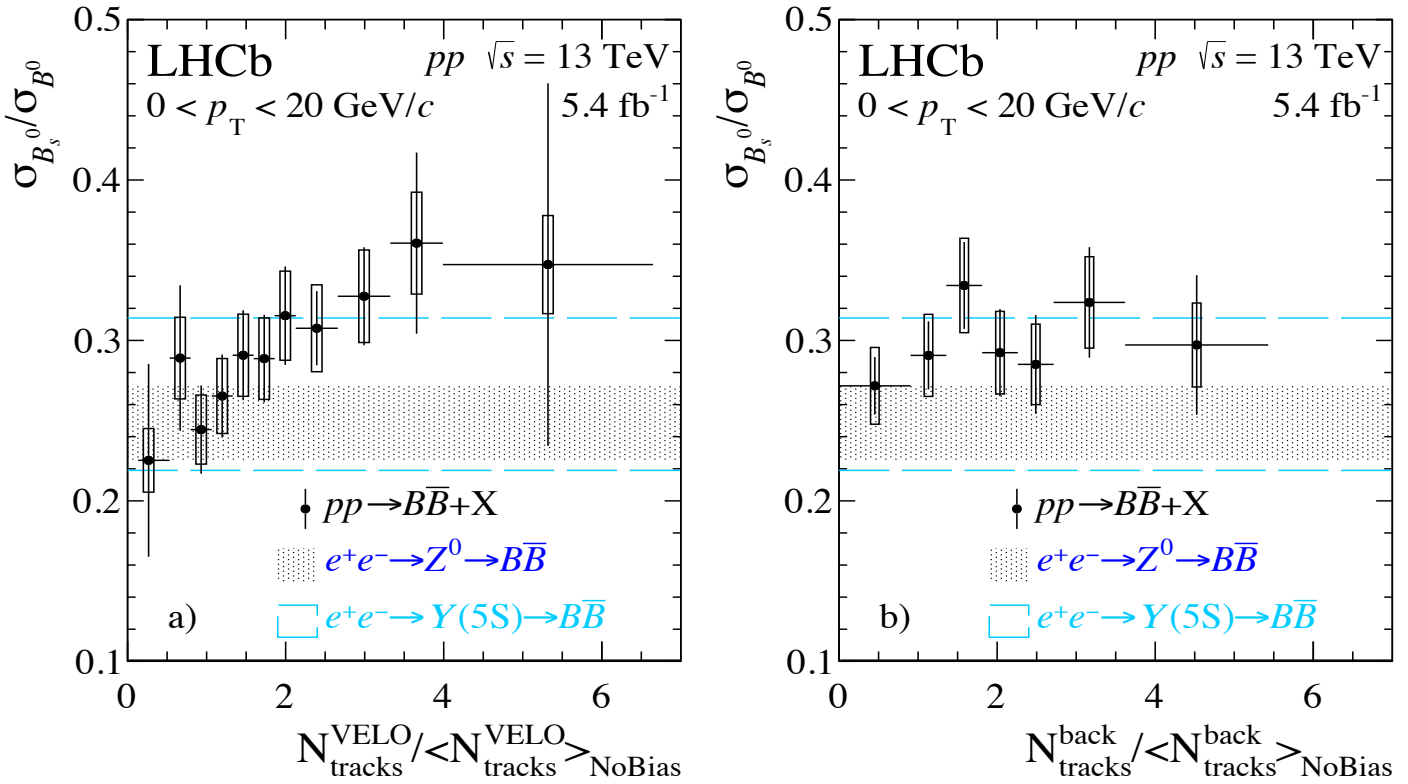


LHCb, JINST 3 (2008) S08005
LHCb, IJMPA 30 (2015) 1530022
JINST 10 (2015) 02 P02007

B_s^0/B^0 ratio in pp collisions at $\sqrt{s_{\mathrm{NN}}} = 13$ TeV

- The B_s^0/B^0 ratio shows an increasing trend with the VELO tracks, consistent with fragmentation in vacuum (measured in e^+e^- collisions) at low multiplicity.
- No significant dependence of forward B_s^0/B^0 ratios on backward multiplicity.

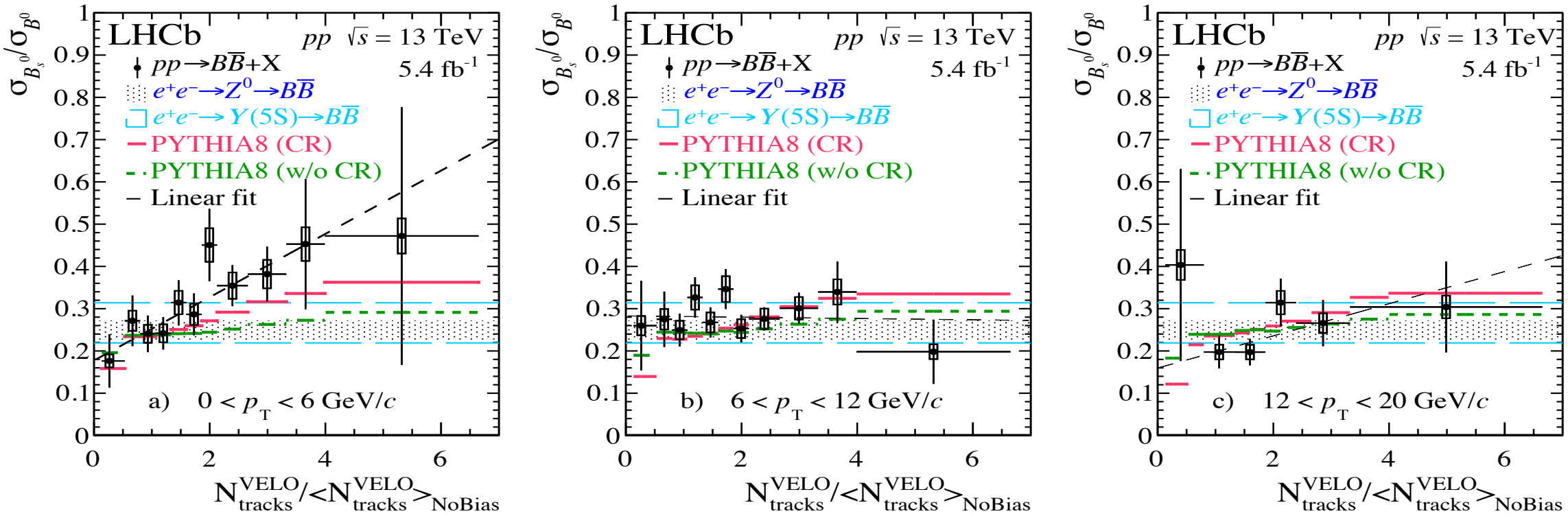




LHCb *pp* : Phys. Rev. Lett. 131 (2023) 061901
ee : Eur. Phys. J. C 81, 226 (2021)

B_s^0/B^0 in different p_T regions

- The $\sigma_{B_s^0}/\sigma_{B^0}$ ratios increases with multiplicity (slope significance = 3.4σ). Has a closer trend to the PYTHIA8 with color reconnection.
- At low multiplicity, the ratio is consistent with values measured in e^+e^- collisions.
- No significant dependence on multiplicity and consistent with values measured in e^+e^- collisions and PYTHIA8 simulation.
- High p_T b quarks have less overlap with the low- p_T bulk of the quarks, thereby dominantly hadronize via fragmentation.

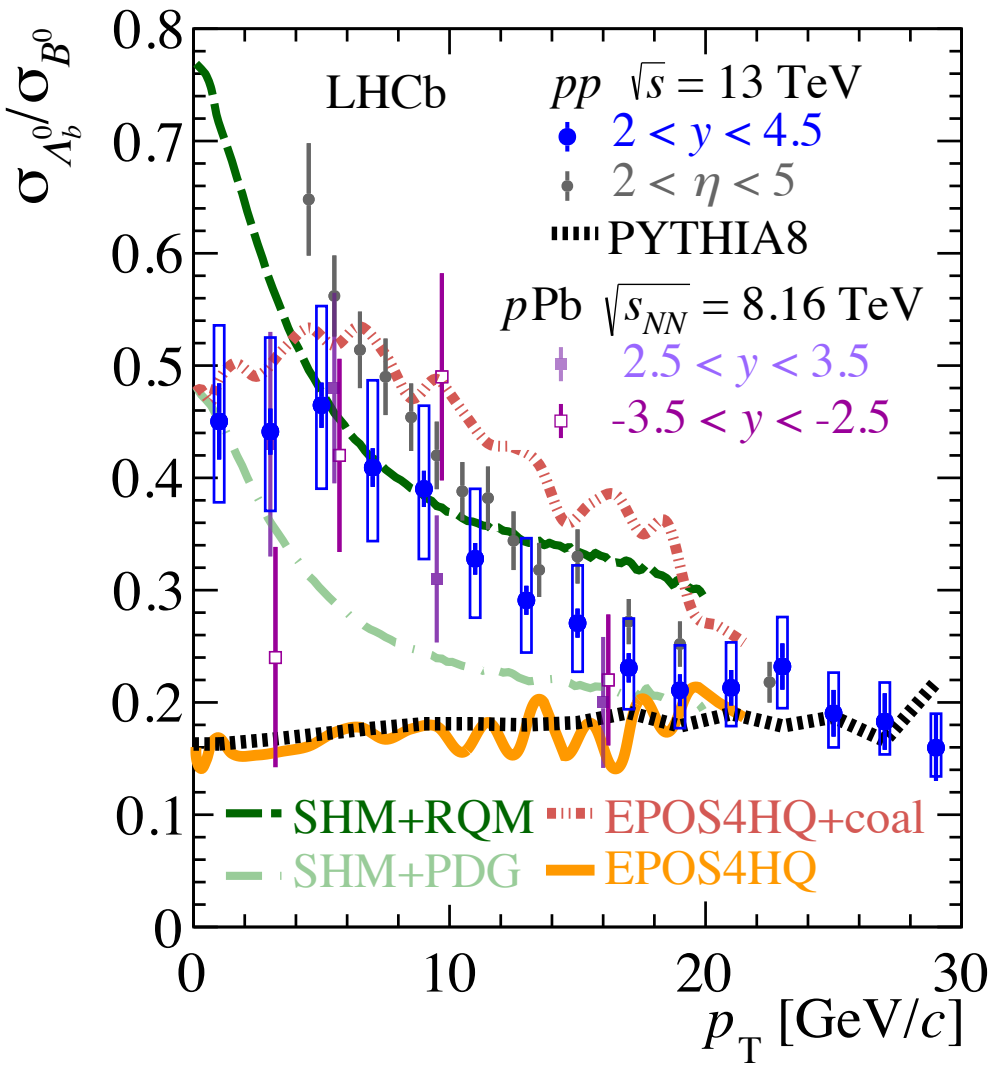


LHCb *pp* : Phys. Rev. Lett. 131 (2023) 061901
ee : Eur. Phys. J. C 81, 226 (2021)
PYTHIA8 CR: arXiv:1310.8073

Λ_b^0/B^0 ratio vs p_T in pp collisions at $\sqrt{s} = 13$ TeV

$\Lambda_b^0(5619) = udb$
$B^0(5279) = d\bar{b}$

- Λ_b^0/B^0 ratio (blue points) is consistent with previous LHCb pp, pPb results within uncertainties.
- The light green dashed curve uses the measured spectrum of baryons collected by Particle Data Group (PDG).
- The dark green dashed curve uses the expanded set of excited states that are expected by the Relativistic Quark Model (RQM).
- The enhancement of RQM relative to the PDG is attributed to the feed down from thus far unobserved excited b baryons.
- By incorporating a coalescence mechanism, the EPOS4HQ model provides a more accurate description of the data.

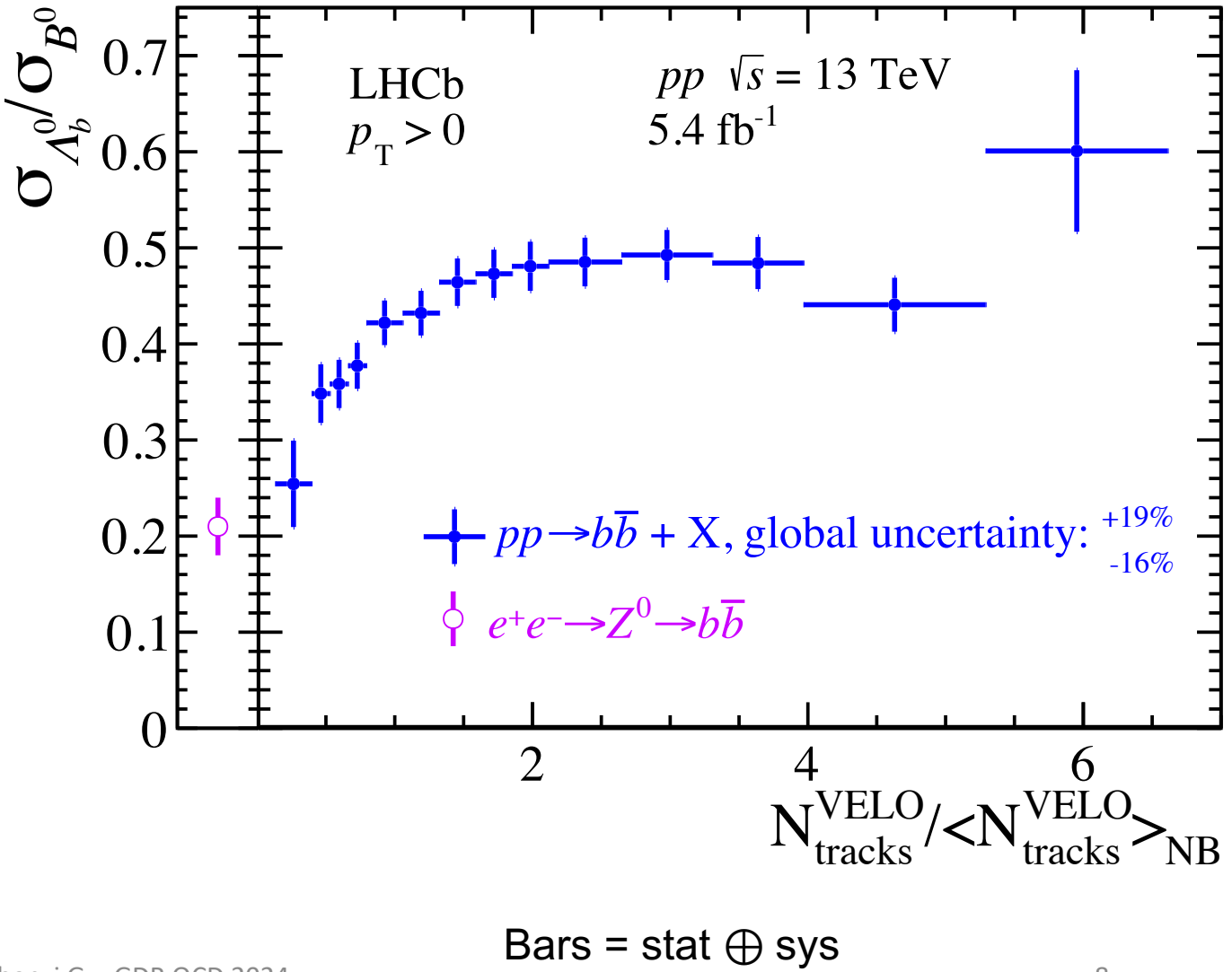


Bars = stat ⊕ sys
Boxes = BR uncertainty

LHCb *pp* : Phys. Rev. Lett. 132 (2024) 081901
Phys. Rev. D 100, 031102(R)
LHCb *p*Pb : Phys.Rev.D 99 (2019) 5, 052011
SHM : Phys. Rev. Lett. 131, 012301
EPOS4HQ : Phys.Rev.D 109 (2024) 5, 054011
PYTHIA8 : Comput.Phys.Commun. 178 (2008) 852-867

Λ_b^0/B^0 ratio vs normalized tracks in pp collisions at $\sqrt{s} = 13$ TeV

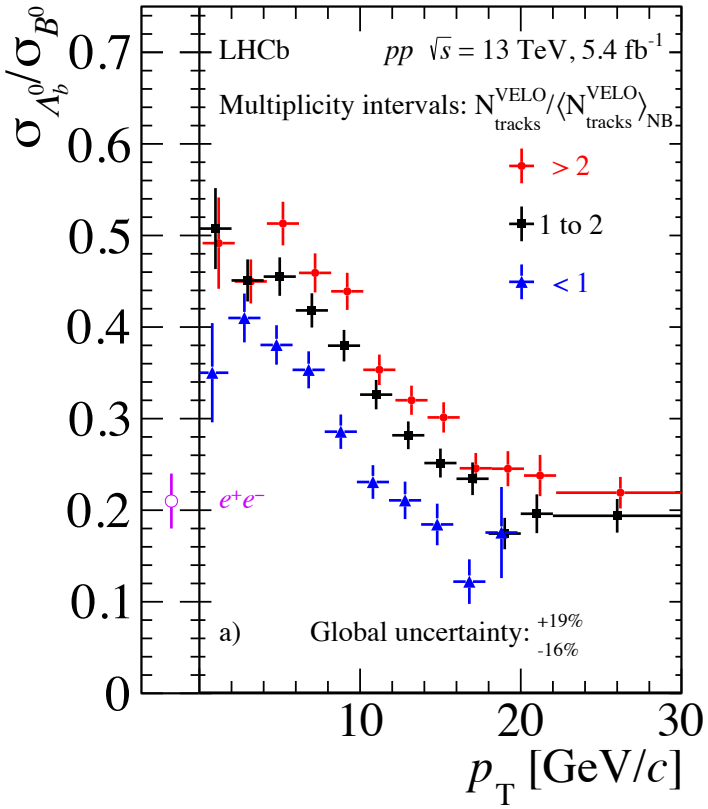
- Λ_b^0/B^0 ratio increases with multiplicity.
- In the lowest multiplicity bin, Λ_b^0/B^0 ratio can reach the value in e^+e^- collisions.
- This indicates that coalescence emerges as an additional hadronization mechanism for baryons at high multiplicity events.

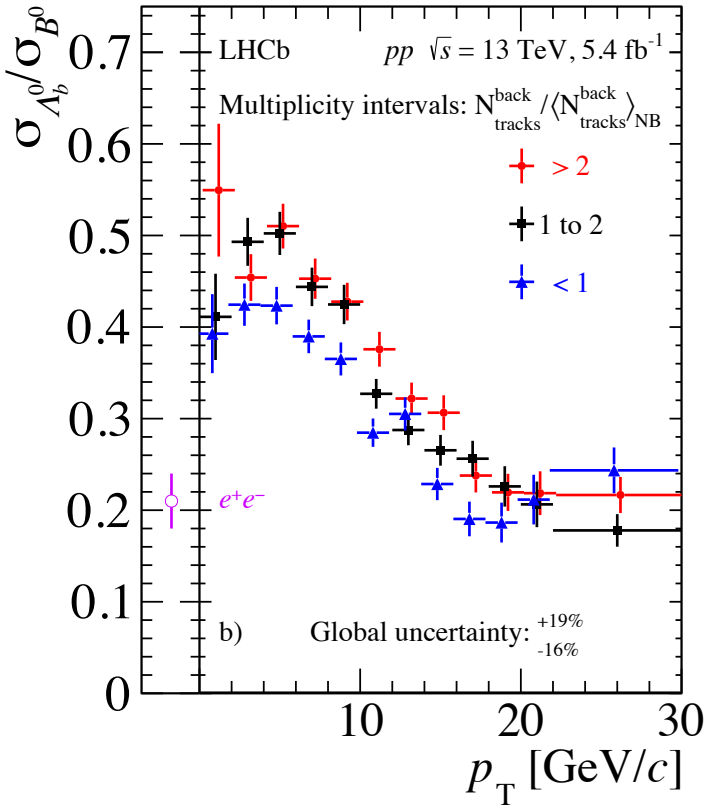


LHCb *pp* : Phys. Rev. Lett. 132 (2024) 081901

Λ_b^0/B^0 ratio vs p_{T} in pp collisions at $\sqrt{s} = 13$ TeV

- Λ_b^0/B^0 ratio significantly higher than e^+e^- result at low p_{T}, and shows strong multiplicity dependence (coalescence may contribute here).
- Λ_b^0/B^0 ratio consistent with e^+e^- result at high p_{T}, shows weaker multiplicity dependence (fragmentation dominant).
- Λ_b^0/B^0 ratio shows weaker multiplicity dependence on backward VELO tracks.



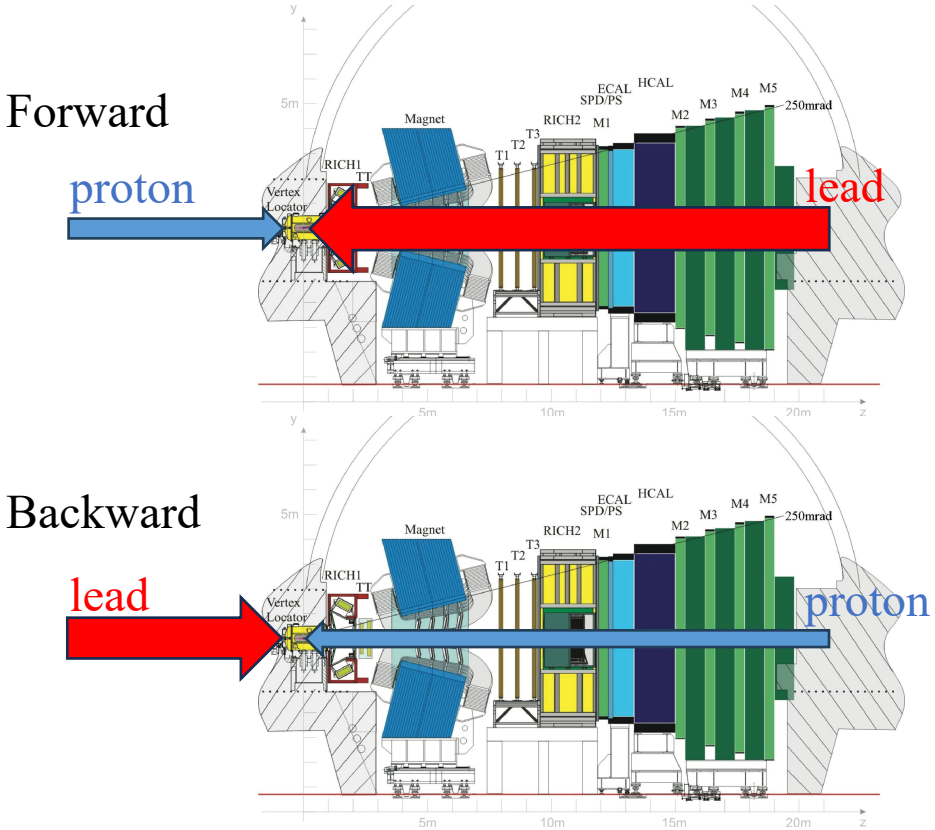


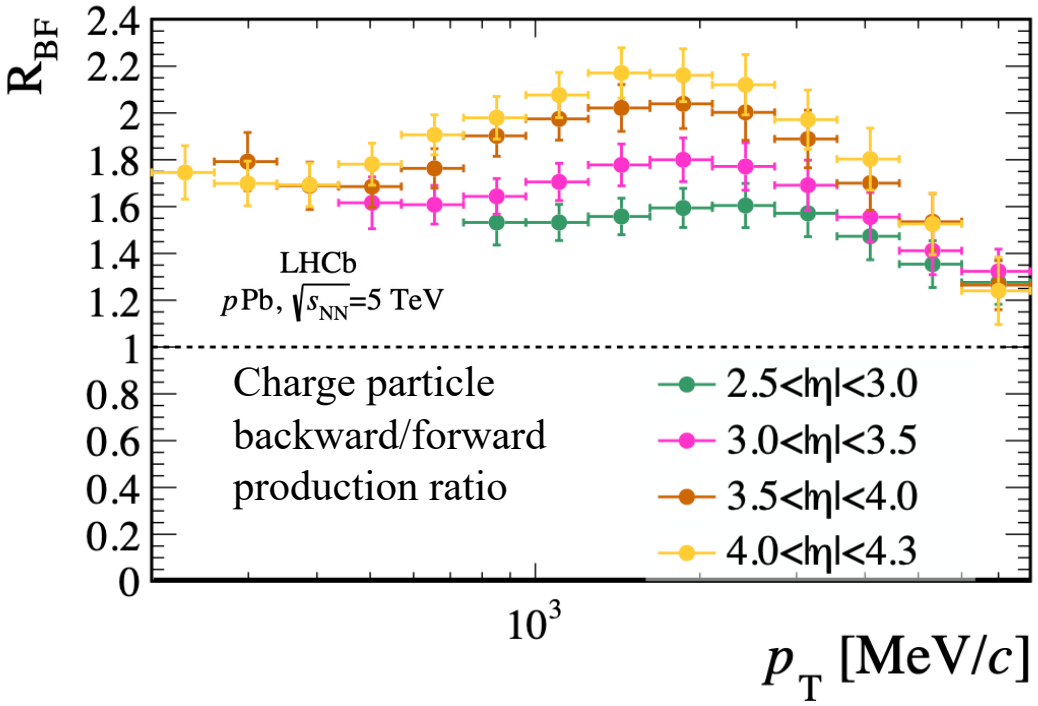
Bars = stat ⊕ sys

LHCb *pp* : Phys. Rev. Lett. 132 (2024) 081901

Proton-lead collisions at LHCb

- The pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ (8.16) TeV LHCb data was taken in 2013 (2016) with asymmetric collision configuration.
  - Forward : $1.5 < y^* < 4$ (center mass system rapidity)
  - Backward : $-5 < y^* < -2.5$
- Backward collisions have higher multiplicity on average than forward collisions (~1.6x).

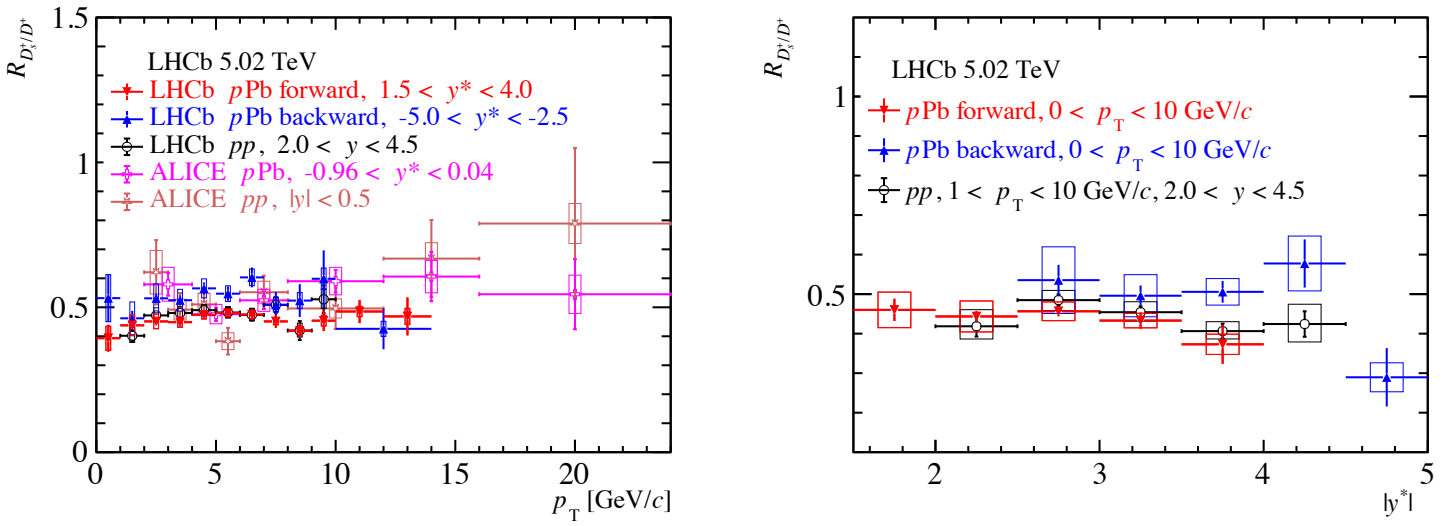


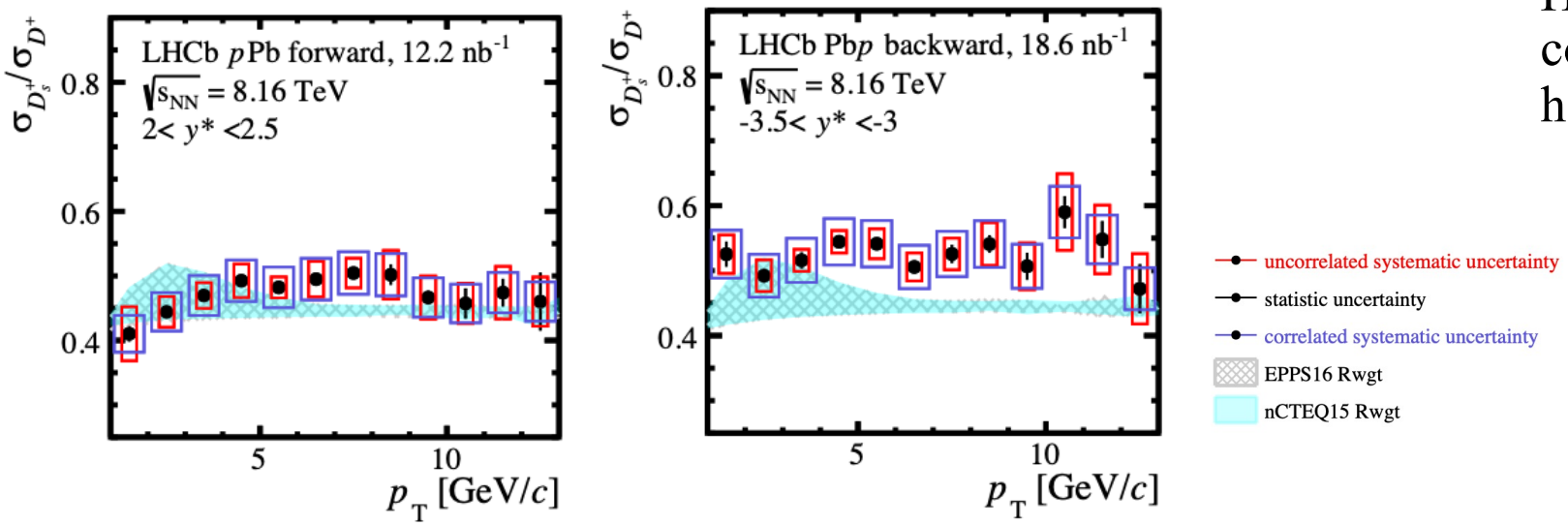


Phys. Rev. Lett. 128, 142004

D_s^+/D^+ ratio vs p_T and y^* in pPb collisions

$D_s^+(1969) = c\bar{s}$
$D^+(1869) = c\bar{d}$





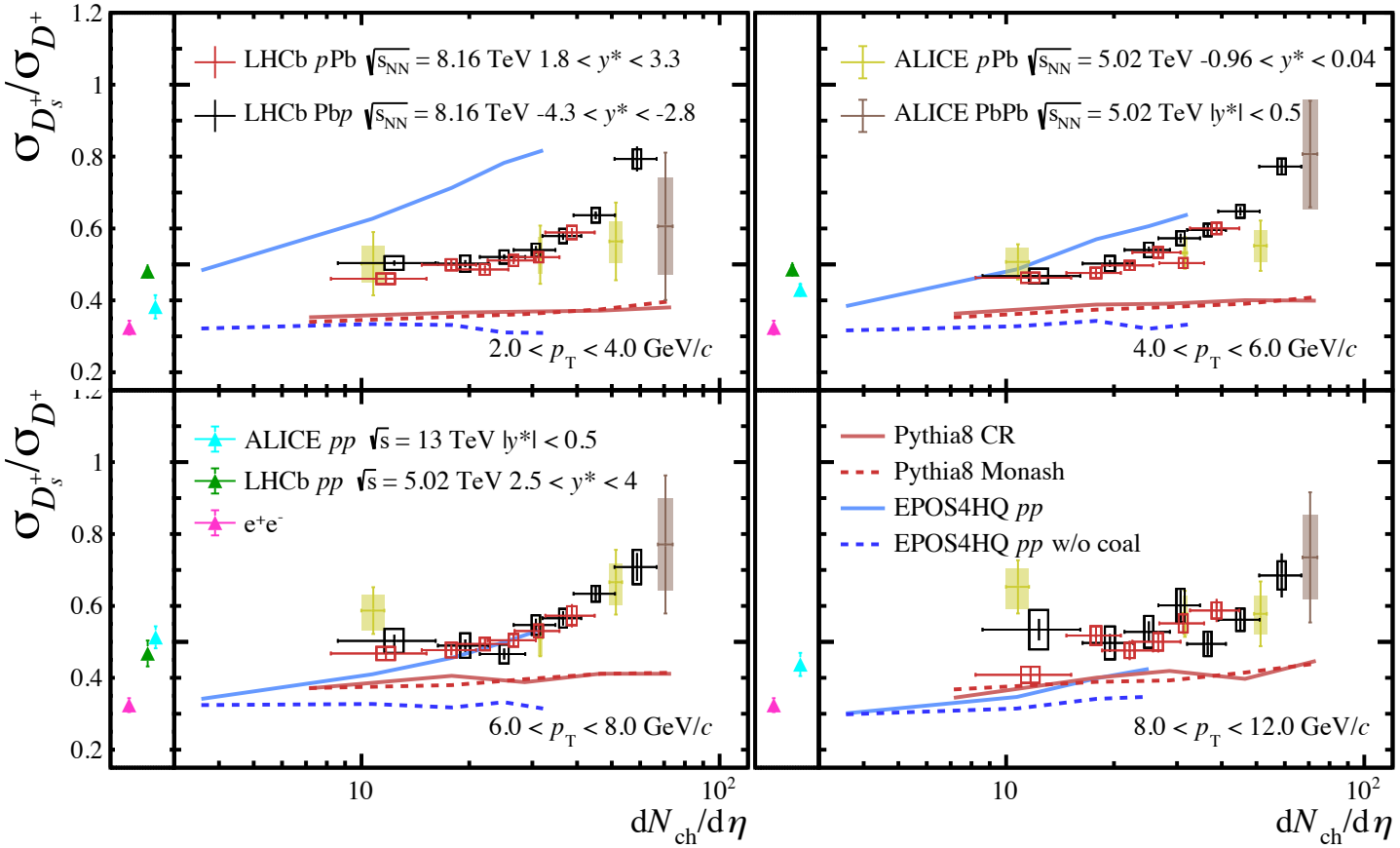
- D_s^+/D^+ ratio shows no dependence on p_T.
- D_s^+/D^+ ratio is consistent with the result of LHCb in pp collisions within uncertainties.
- D_s^+/D^+ ratio is consistent with ALICE measurements with higher precision.
- Higher D_s^+/D^+ ratio for backward compared to forward may be due to hadronization.

- D_s^+/D^+ ratio is consistent with theoretical calculation (EPPS16, nCTEQ15) in forward.

LHCb *p*Pb : JHEP 01 (2024) 070 arXiv:2311.08490
LHCb *pp* : JHEP 06 (2017) 147
ALICE *pp* : Eur. Phys. J. C 79 (2019) 388
ALICE *p*Pb : JHEP 12 (2019) 092

D_s^+/D^+ ratio vs charged particles density in pPb collisions

- The ratio of D_s^+/D^+ increases with $\mathrm{d}N_{ch}/\mathrm{d}\eta$ at all p_T intervals.
- The similar D_s^+/D^+ pattern in the forward and backward rapidity regions indicate the D_s^+/D^+ ratio is independent of rapidity, and the mechanism contributing to this ratio increase is strongly correlated with the charged particle density.
- EPOS4HQ show some discrepancies with experimental data, it can depict the multiplicity-dependent trends across all p_T intervals by introducing coalescence mechanism.

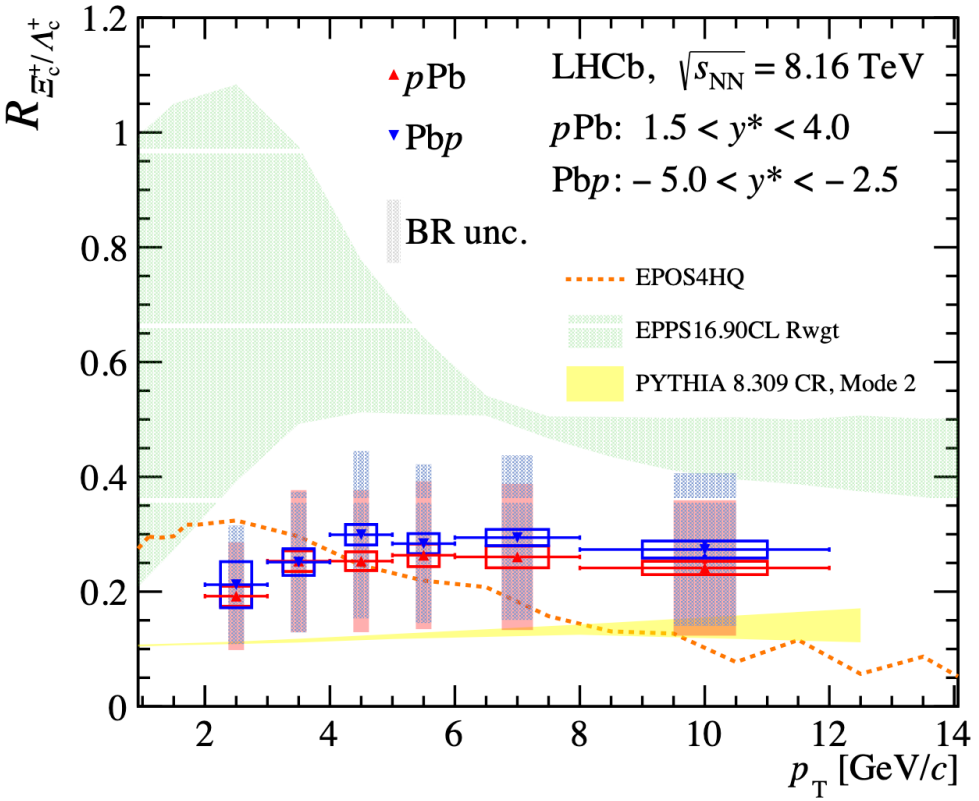


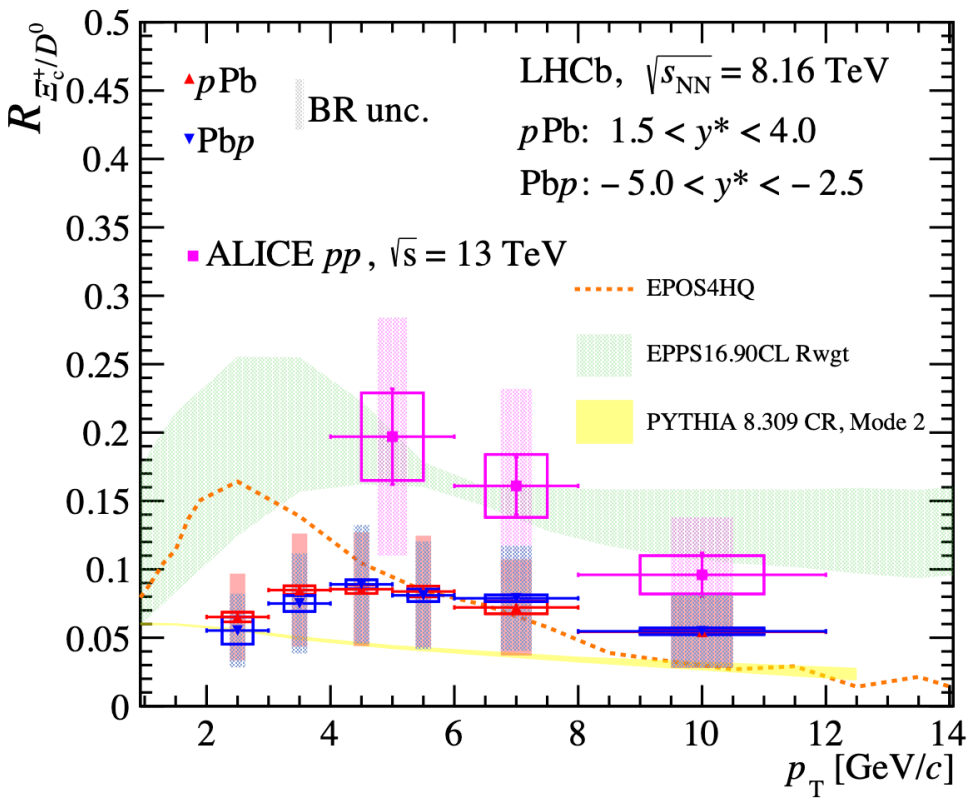
N_{ch} is the number of charged particles originating from the collisions.

LHCb *p*Pb : arXiv:2311.08490
ee : Eur. Phys. J. C 76 (2016) 397
ALICE *pp* : JHEP 12 (2023) 086
LHCb *pp* : JHEP 06 (2017) 147
ALICE *p*Pb : JHEP 12 (2019) 092
ALICE PbPb : JHEP 10 (2018) 174
EPOS4HQ : arXiv:2401.17096
Pythia8 : JHEP 08 (2015) 003

Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 ratios in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 ratios show no significant of p_{T} dependence and similarly for the pPb and Pbp data samples. This indicates that same processes govern heavy quarks hadronisation in pPb and Pbp collisions.
- The EPPS16 shows a similar trend, but significantly overestimates LHCb data.
- The Ξ_c^+/D^0 ratios measured in pp collisions from ALICE are larger than LHCb data.





$D^0(1865) = c\bar{u}$
$\Xi_c^+(2467) = usc$
$\Lambda_c^+(2286) = udc$
Both Ξ_c^+ and Λ_c^+ are reconstructed by $pK^-\pi^+$

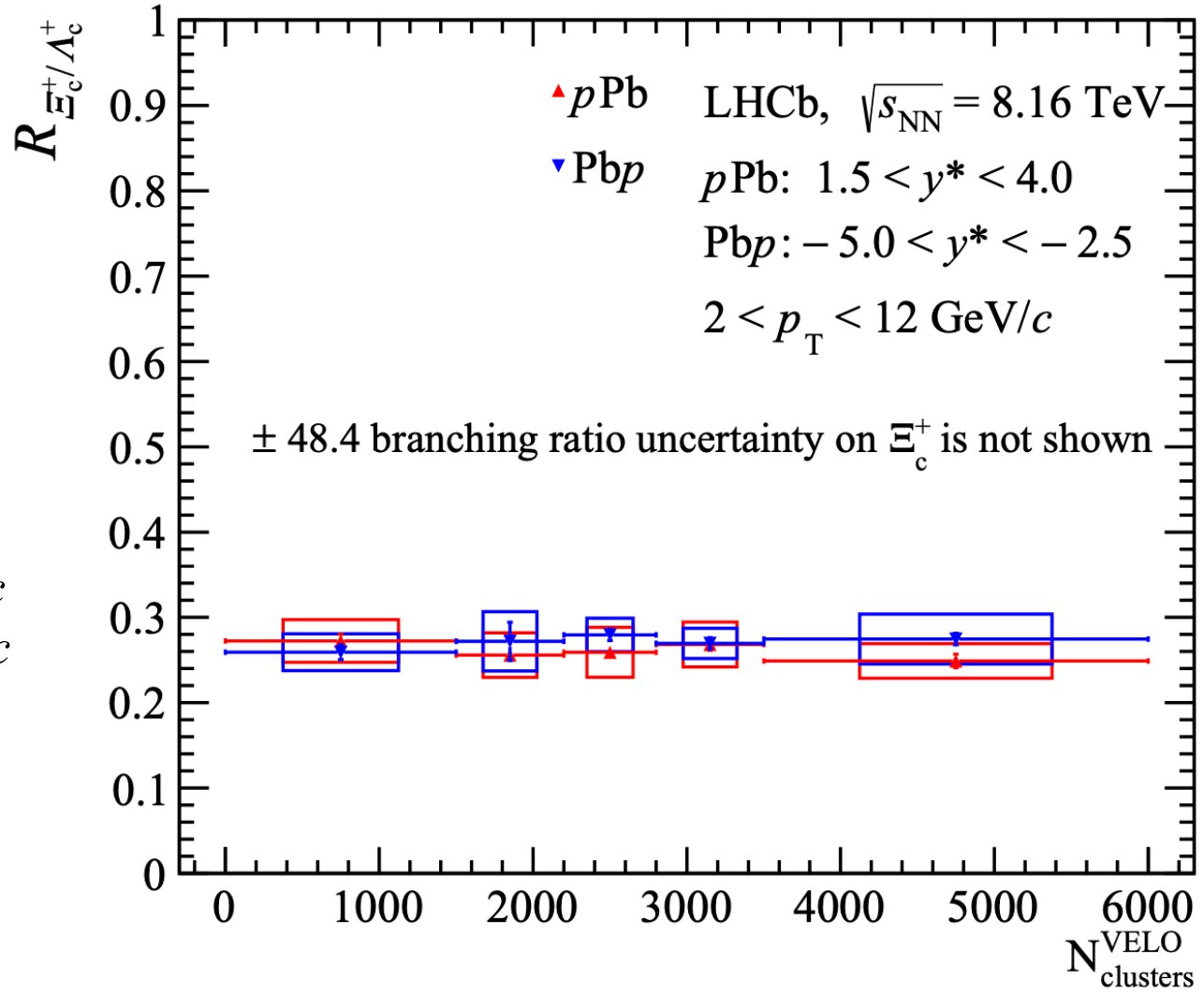
LHCb pPb : Phys. Rev. C 109 (2024) 044901
EPPS16 : Phys.Rev.D 104 (2021) 1, 014010
EPOS4HQ : arXiv:2401.17096
Pythia8 : JHEP 08 (2015) 003

Ξ_c^+/Λ_c^+ ratio vs multiplicity in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV

- The Ξ_c^+/Λ_c^+ ratio is constant as a function of $N^{\rm VELO}_{\rm clusters}$, similarly for the pPb and Pbp data, and the results show no indication of strangeness enhancement.

$\Xi_c^+(2467) = usc$
$\Lambda_c^+(2286) = udc$

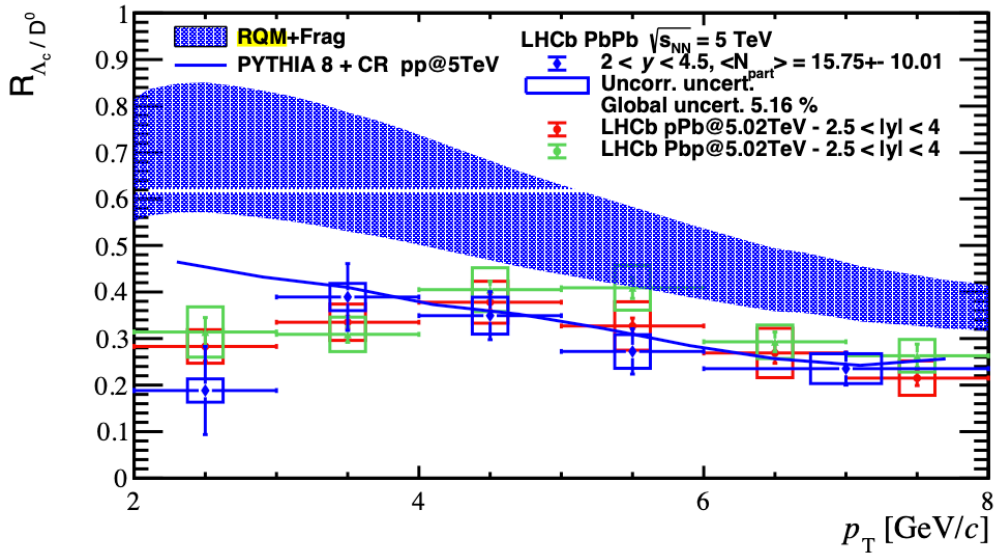
$N^{\rm VELO}_{\rm clusters}$ is the number of clusters reconstructed in the VELO.

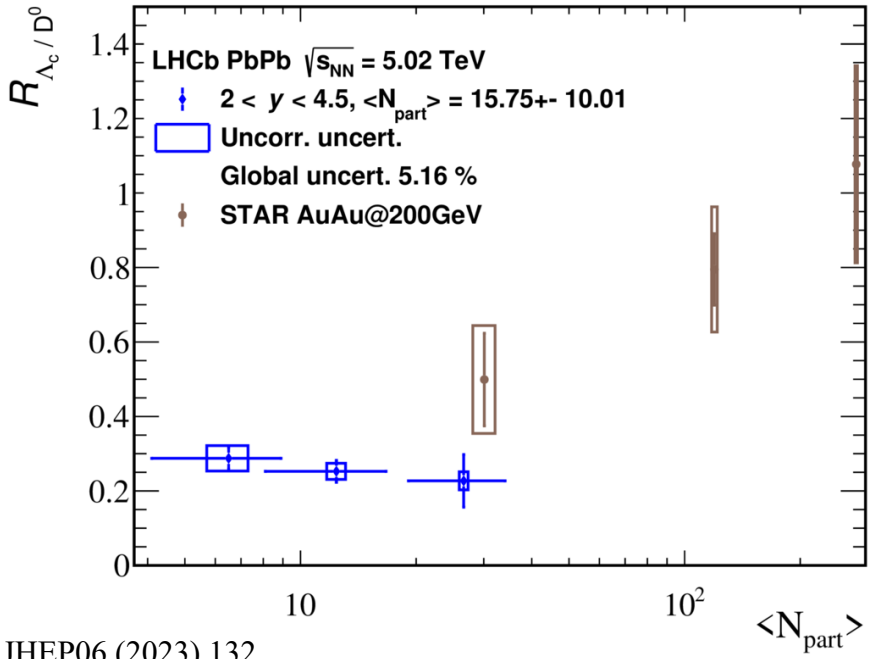


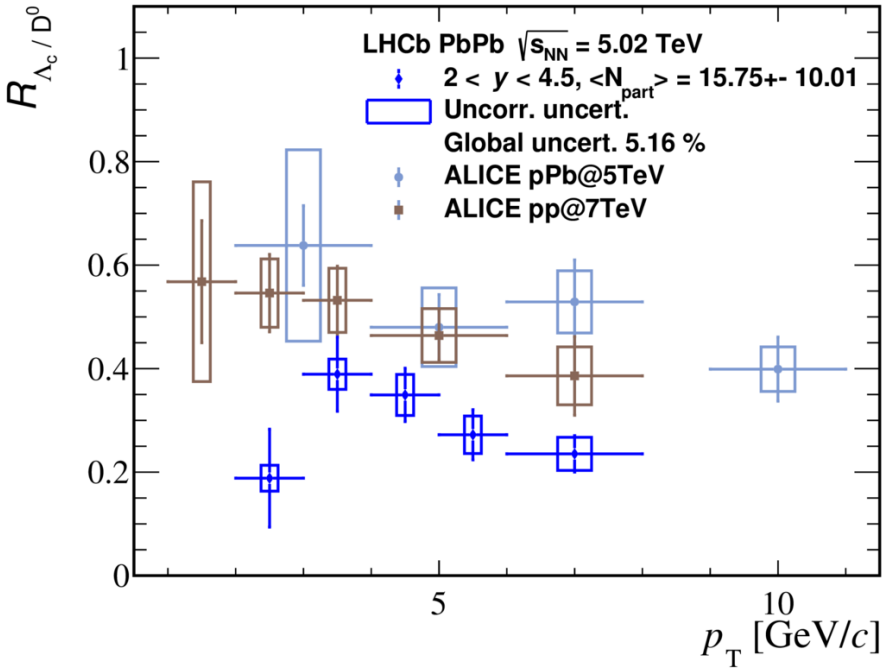
LHCb *p*Pb : Phys. Rev. C 109 (2024) 044901

Λ_c^+/D^0 ratios in peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Due to LHCb hardware limitations, Λ_c^+ and D^0 are measured in the centrality range of about 65–90%. But we can cover forward rapidity, $2 < y < 4.5$.
- Λ_c^+/D^0 ratios show no dependence on centrality.
- Λ_c^+/D^0 ratios are consistent with the LHCb results in pPb at 5.02 TeV.
- Λ_c^+/D^0 ratios are systematically lower than ALICE result, but with higher precision.







LHCb PbPb : JHEP06 (2023) 132

Summary

- LHCb have observed an enhancement of B_s^0/B^0, Λ_b^0/B^0, D_s^+/D^+ as a function of multiplicity. These indicate the modification of heavy quarks hadronization in *pp* and *p*Pb collisions.
- The production ratios Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 are study in *p*Pb collisions. By comparing forward and backward results, it is suggested that they are governed by similar hadronization processes.
- The production ratio Λ_c^+/D^0 is study in peripheral PbPb collisions, and is systematically lower than ALICE result. This may imply that the contribution of the coalescence mechanism is different in different rapidity ranges.

Thanks for listening!

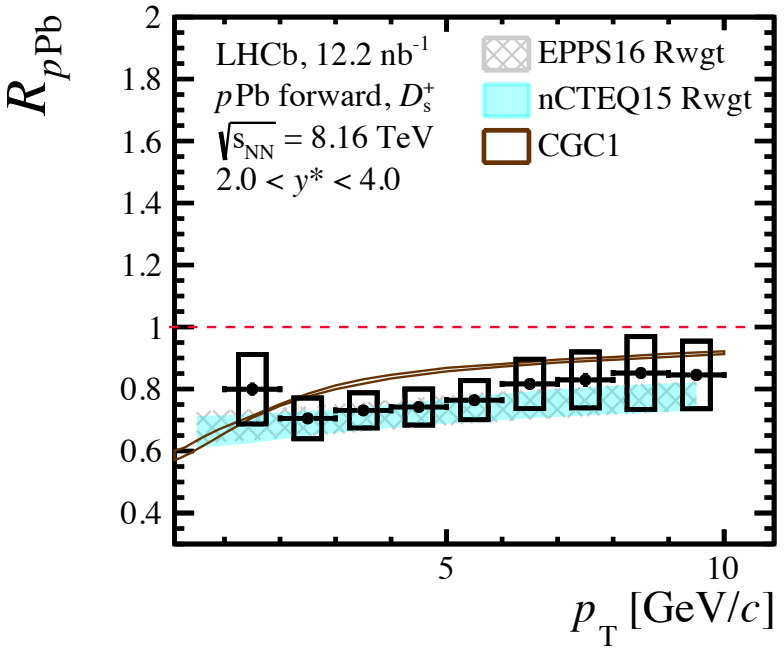
Back up

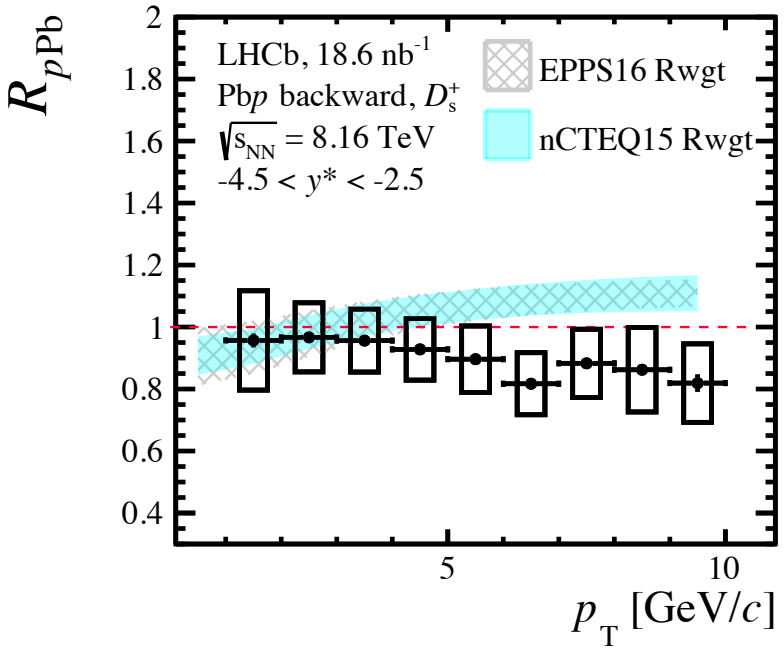
D_s^+ and D^+ nuclear modification factor

- $R_{p\mathrm{Pb}}$ consistent with nPDFs calculations in the forward, lower than nPDFs calculations in the backward high p_{T} region.
- The main systematic uncertainty comes from the *pp* results and interpolation.

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

D_s^+ and D^+ production cross-section in *pp* collision at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV is obtained from the interpolation of $\sqrt{s_{\mathrm{NN}}} = 5$ TeV and $\sqrt{s_{\mathrm{NN}}} = 13$ TeV.
JHEP 06 (2017) 147 JHEP 03 (2016) 159



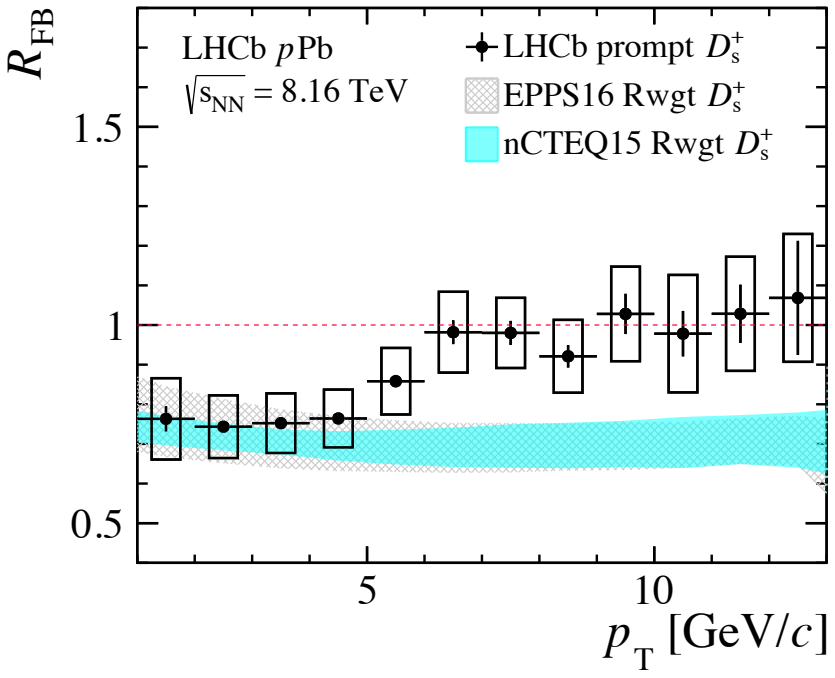


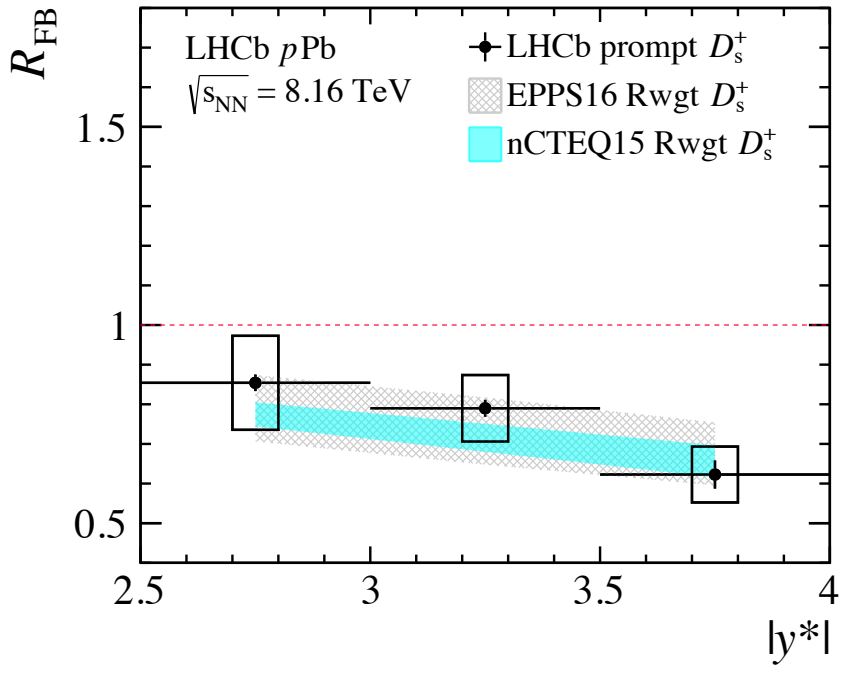
LHCb *p*Pb : arXiv:2311.08490
EPPS16 : Eur.Phys.J.C 77 (2017) 3, 163
nCTEQ : Phys.Rev.D 93 (2016) 8, 085037
CGC : Phys. Rev. D91 (2015) 114005

D_s^+ and D^+ forward-backward production ratio

- R_{FB} shows a rising trend with p_{T}. Consistent with nPDFs at low p_{T}, larger than theoretical calculations at high p_{T}.
- R_{FB} shows a slight dependence on y^*, consistent with nPDFs calculations.
- Potential explanations for backward production suppression :
  - Weaker antishadowing effect in initial state.
  - Higher energy loss for backward in final state (high p_{T} $D \rightarrow$ low p_{T} D).

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^*) = \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, +|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_{\mathrm{T}}, -|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*} ,$$

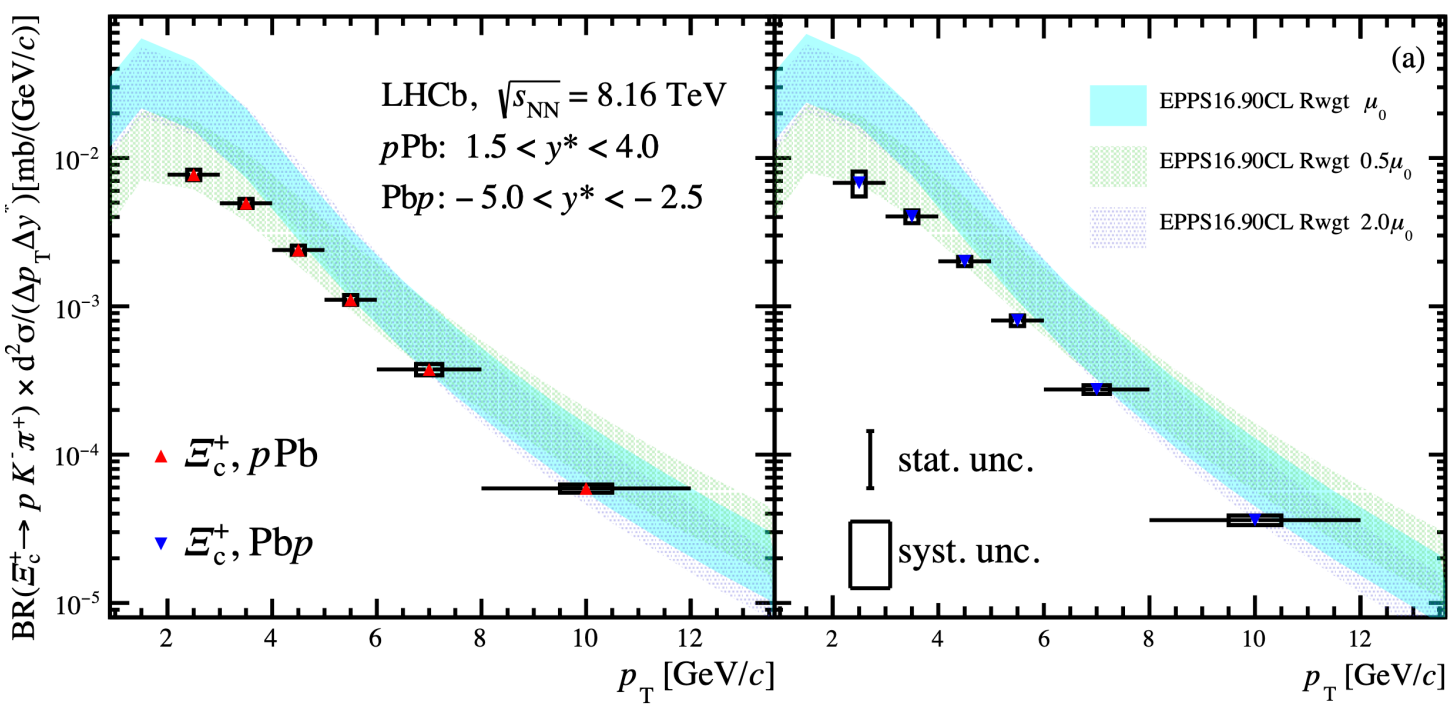


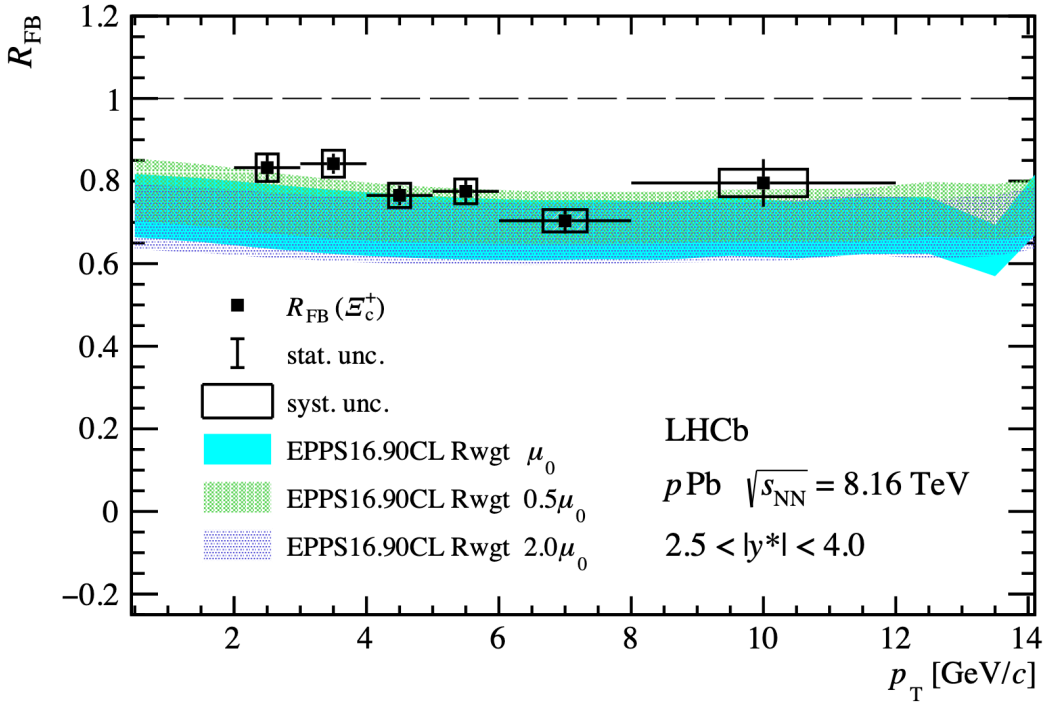


LHCb *p*Pb : arXiv:2311.08490
EPPS16 : Eur.Phys.J.C 77 (2017) 3, 163
nCTEQ : Phys.Rev.D 93 (2016) 8, 085037

Ξ_c^+ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- The double-differential cross-section of the prompt Ξ_c^+ are compared with EPPS16 predictions.
- The forward-backward ratio is independent of p_{T} and agrees with the EPPS16 predictions within uncertainty.





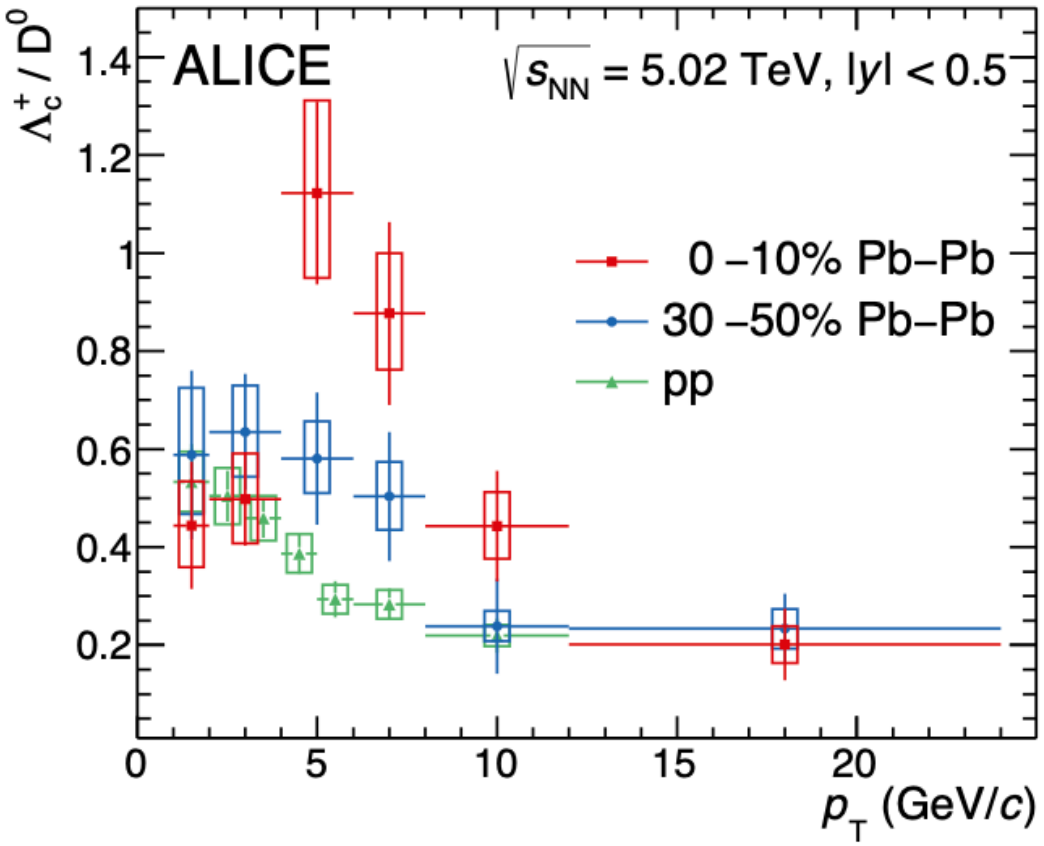
LHCb pPb : arXiv:2305.06711
EPPS16 : Phys.Rev.D 104 (2021) 1, 014010

Λ_c^+/D^0 ratios in peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Coalescence mechanism is expected to be stronger in heavy ion collisions due to the presence of QGP, baryons are more strongly enhanced than mesons under the influence of coalescence mechanisms. Λ_c^+/D^0 ratio is an excellent tool to study coalescence contribution.
- Recently, ALICE has measured Λ_c^+/D^0 ratio in PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV at mid-rapidity.

- The PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV data were taken in 2018 with luminosity ~210 μb^{-1}.
- Due to LHCb hardware limitations, Λ_c^+ and D^0 are measured in the centrality range of about 65–90%. But we can cover forward rapidity, $2 < y < 4.5$.

Phys.Lett.B 839 (2023) 137796



LHCb PbPb : JHEP06 (2023) 132