Modification of heavy quark hadronization in high-multiplicity collisions at LHCb

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on behalf of the LHCb collaboration

EuroTechPostdoc2 Programme
Excellence in Science and Technology

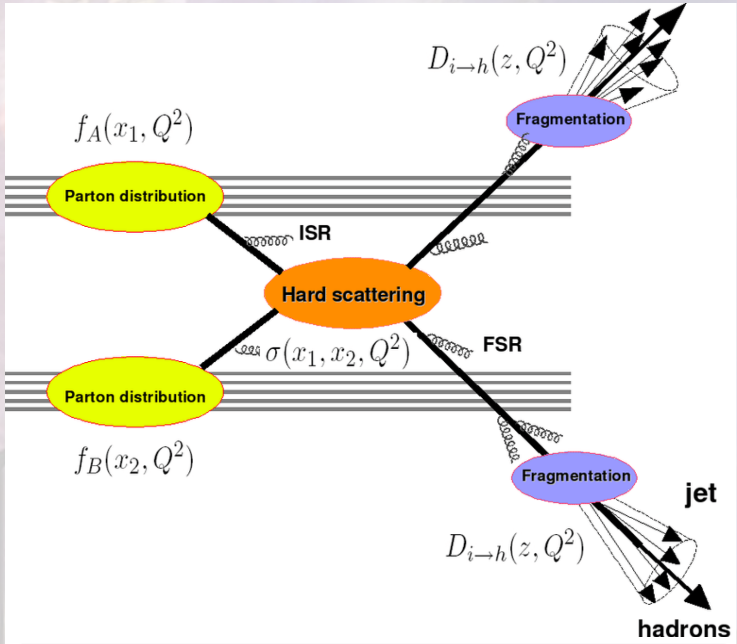
Outline

- Motivation
- LHCb detector
- Measurement of prompt D_s^+ and D^+ production in pPb collisions LHCb-PAPER-2023-006, in preparation LHCb-PAPER-2023-021, in preparation
- Measurement of prompt Ξ_c^+ production in pPb collisions arXiv:2305.06711
- Measurement of Λ_b^0/B^0 ratio in high multiplicity pp collisions LHCb-PAPER-2023-027, in preparation
- Summary

Motivation

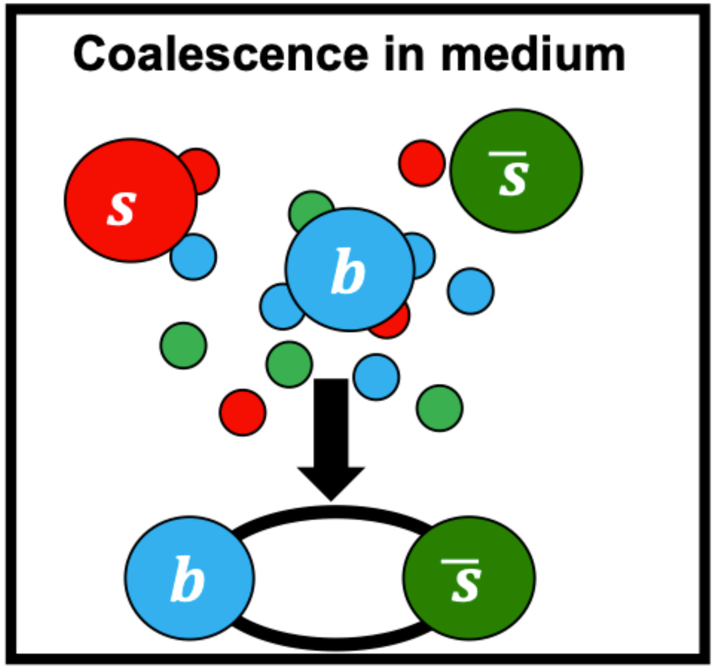
- Heavy quark offers unique probe of the hadronization process
  - ➢ Heavy quark is produced at early stages of the collision, well described by pQCD.
  - ➢ Fragmentation mechanism: lots of partons produced by outgoing quarks fragment into hadrons.
  - ➢ Coalescence mechanism: multiple overlapping quarks in position-velocity phase space combine to form hadrons.

Baryon/meson ratios are sensitive to hadronization.



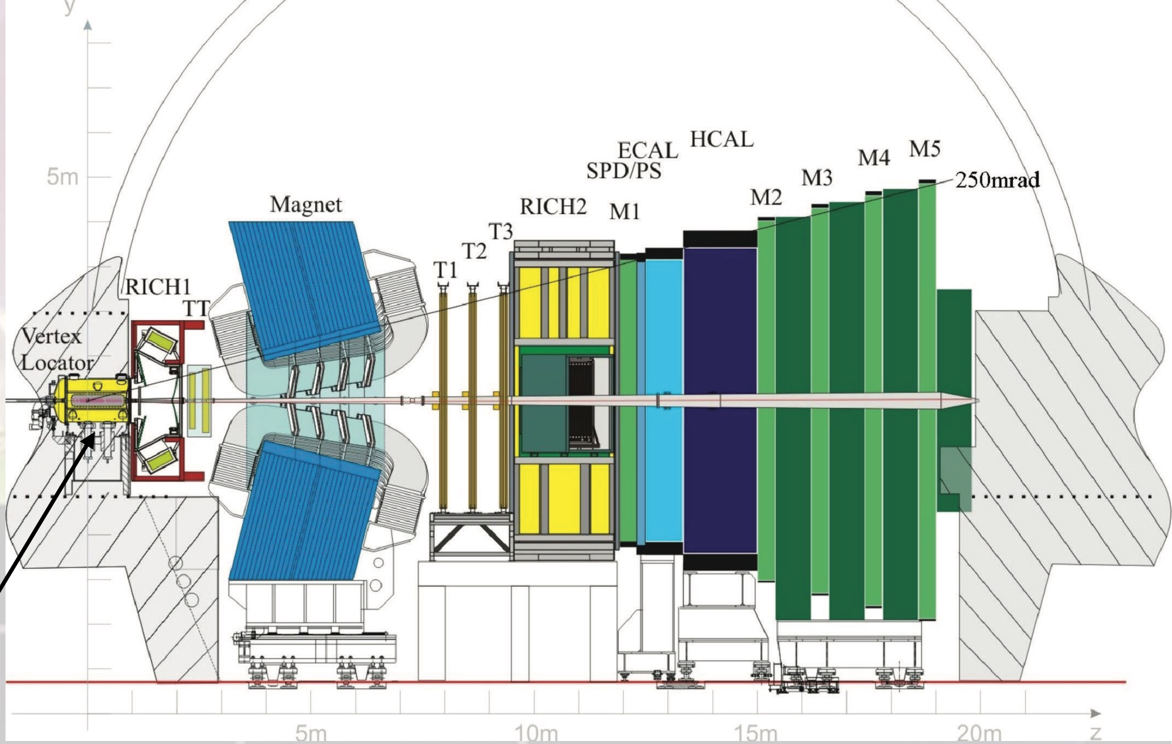
- High multiplicity collisions are often accompanied by strangeness enhancement
  - ➢ In big systems (PbPb, AuAu): *s* quark enhancement mainly comes from gluon fusion in QGP.
  - ➢ In small systems (*pp*, *p*Pb): *s* quarks enhancement mechanism is still debated (dynamical core-corona initialization, rope hadronization, color reconnection…).

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



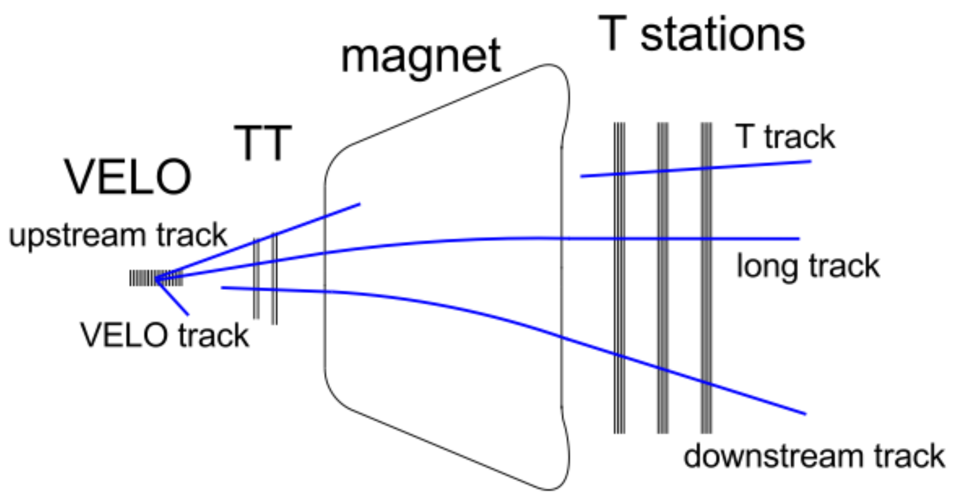
LHCb detector

- 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 away from the LHCb
- PV tracks : tracks used to reconstruct primary vertex



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

D_s^+/D^+ ratio in pPb collisions

Strangeness enhancement in QGP → D_s^+/D enhancement in heavy ion collisions

Phys. Rev. Lett. 48, 1066

Phys. Lett. B 827 (2022) 136986
Phys. Rev. Lett. 127 (2021) 092301

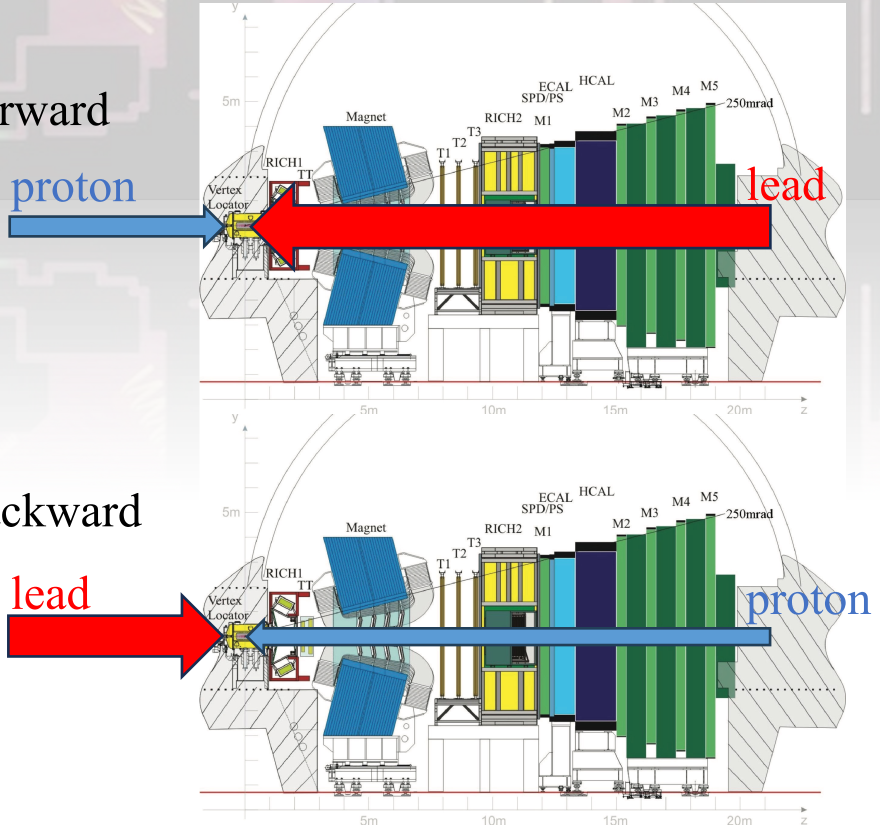
Strangeness enhancement in pp collisions. ? D_s^+/D enhancement in pp or pPb collisions.

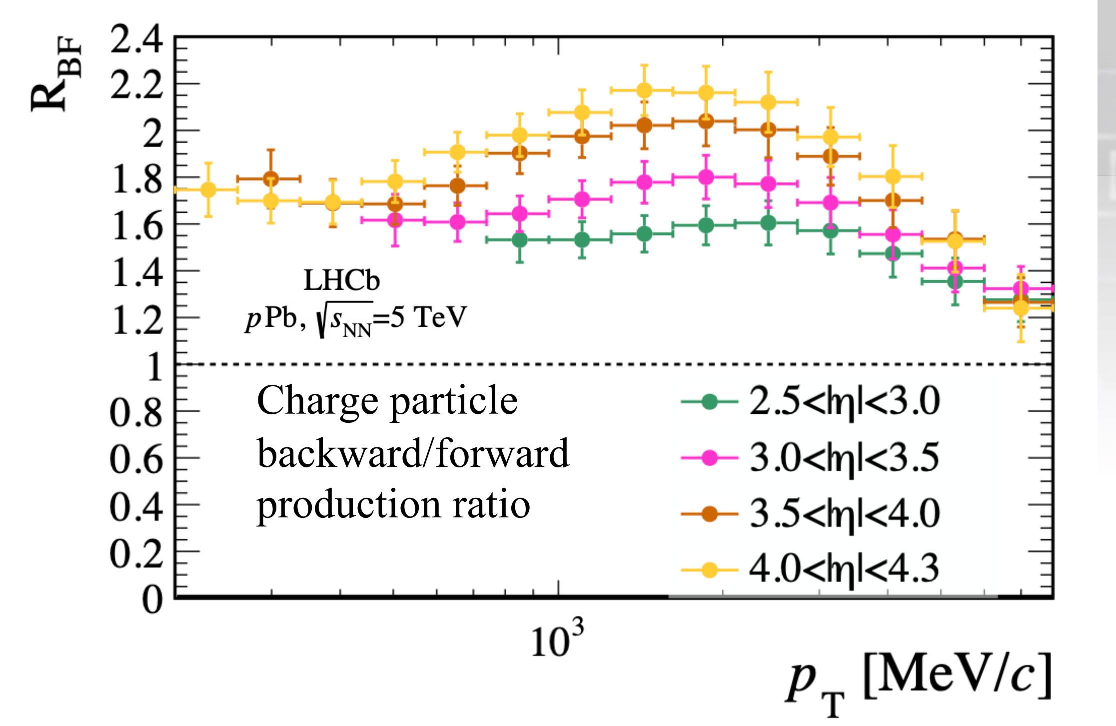
Nature Phys 13, 535–539 (2017)

- The pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ (5.02) TeV LHCb data was taken in 2016 (2013) 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).

Forward

Backward



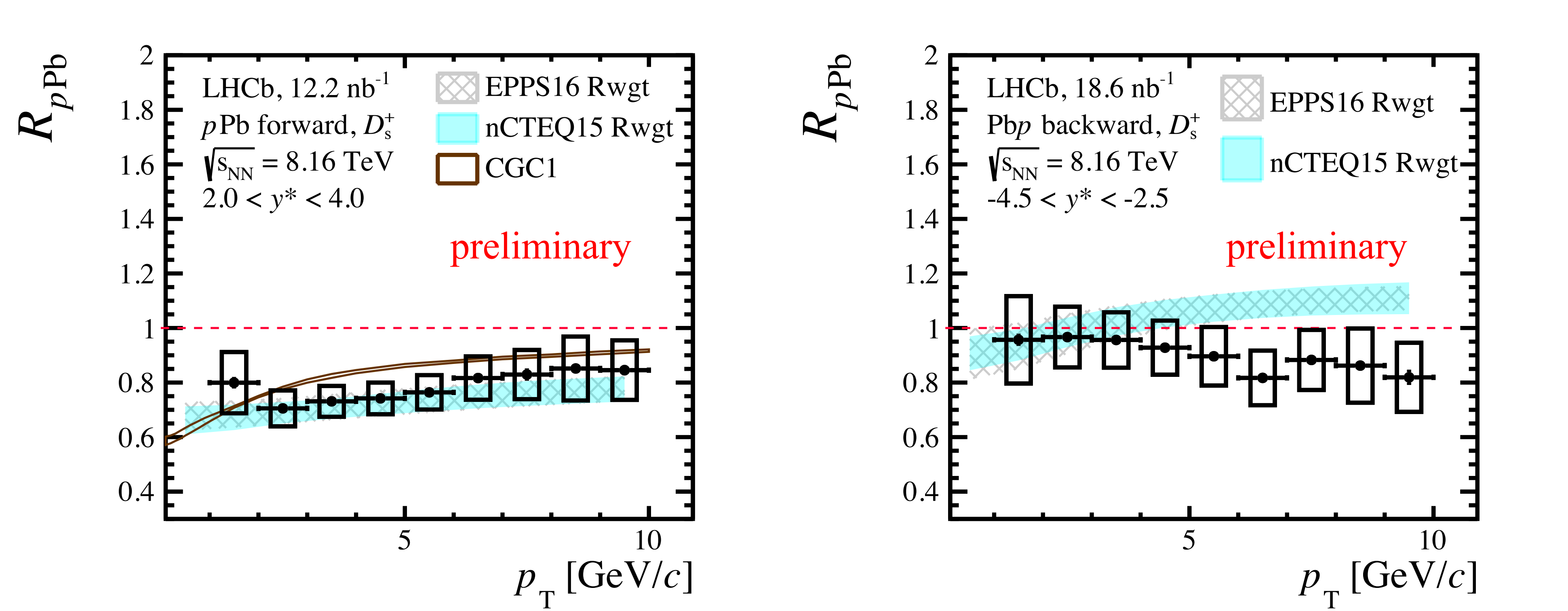


Phys. Rev. Lett. 128, 142004

D_s^+ and D^+ nuclear modification factor

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

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

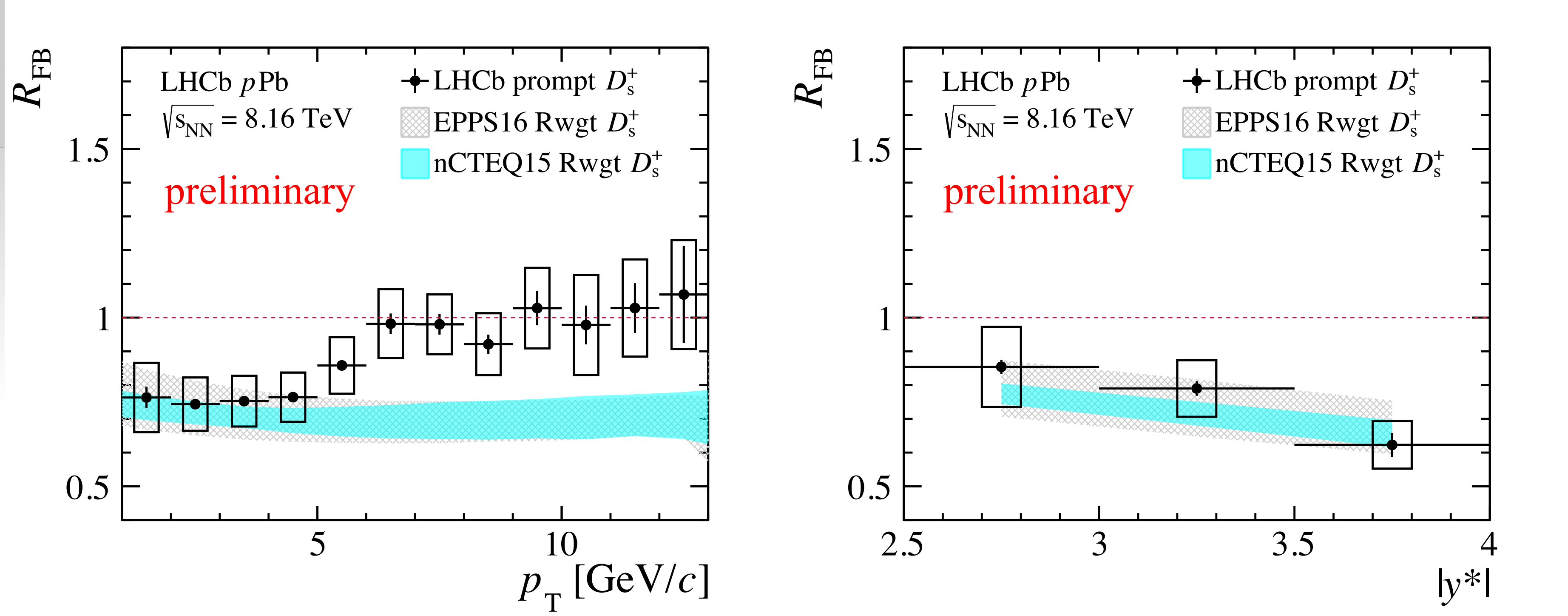


LHCb-PAPER-2023-021, in preparation

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

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

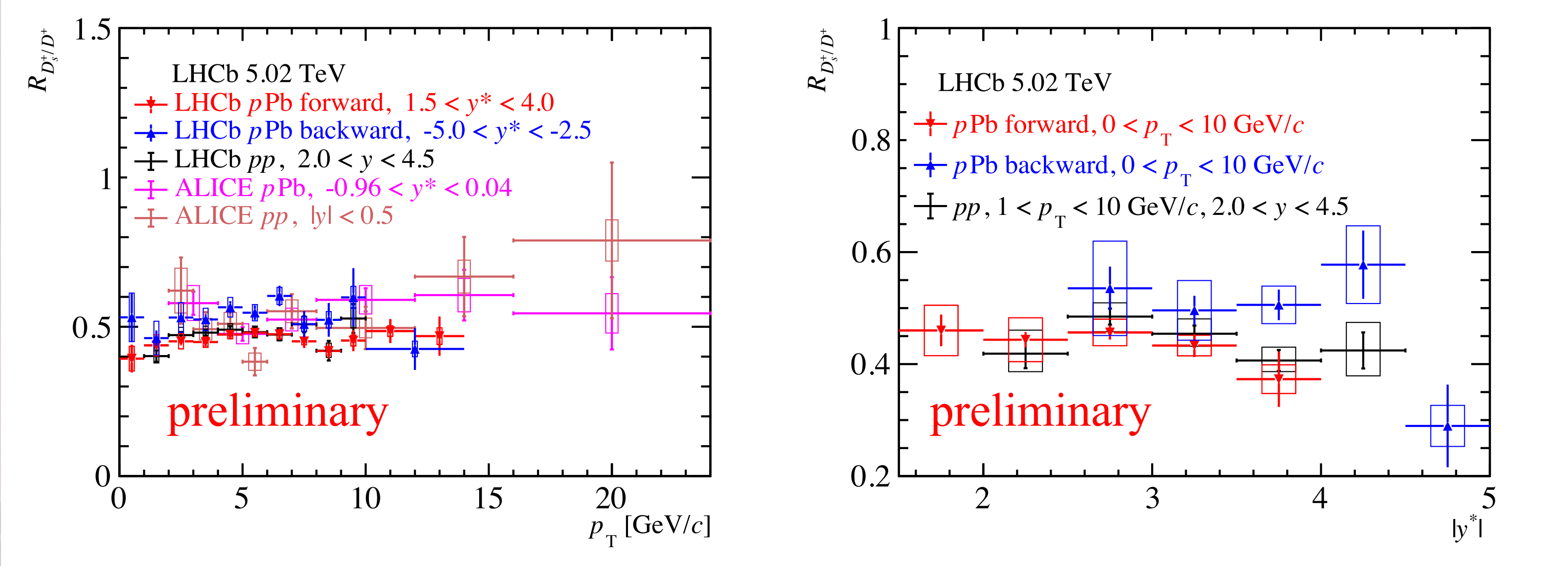
- $R_{\rm FB}$ shows a rising trend with $p_{\rm T}$. Consistent with nPDFs at low $p_{\rm T}$, larger than theoretical calculations at high $p_{\rm T}$.
- $R_{\rm FB}$ shows a slight dependence on y^*, consistent with nPDFs calculations.
- Potential explanations for backward production suppression :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



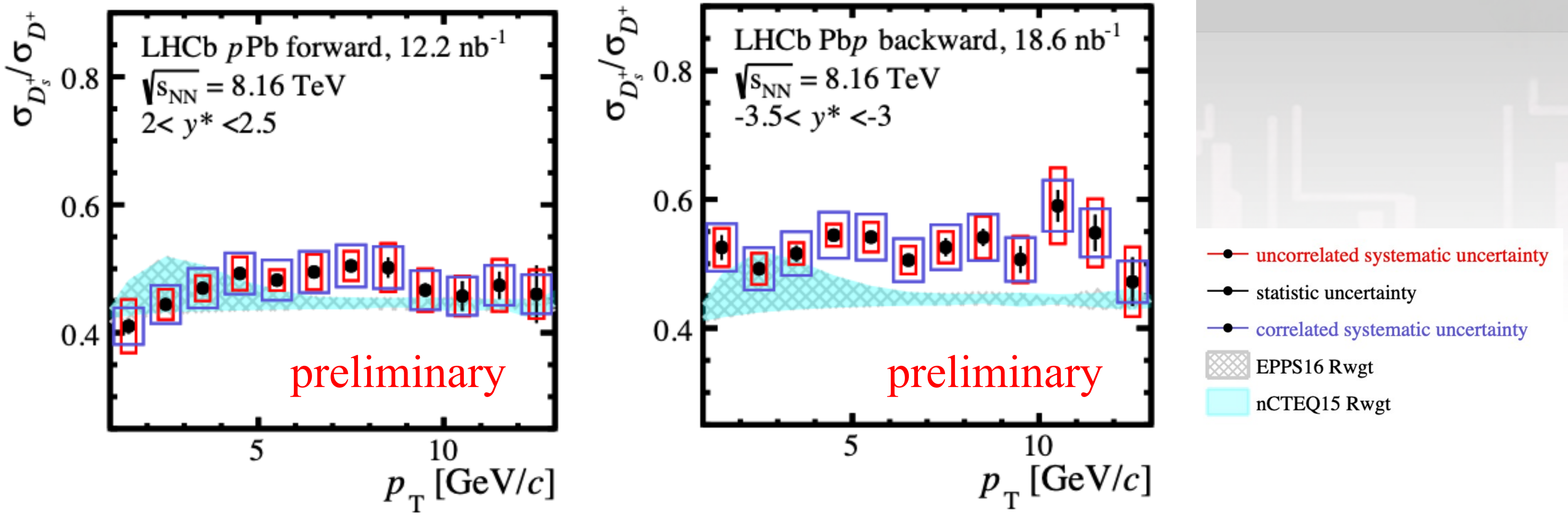
LHCb-PAPER-2023-021, in preparation

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 coalescence contribution.

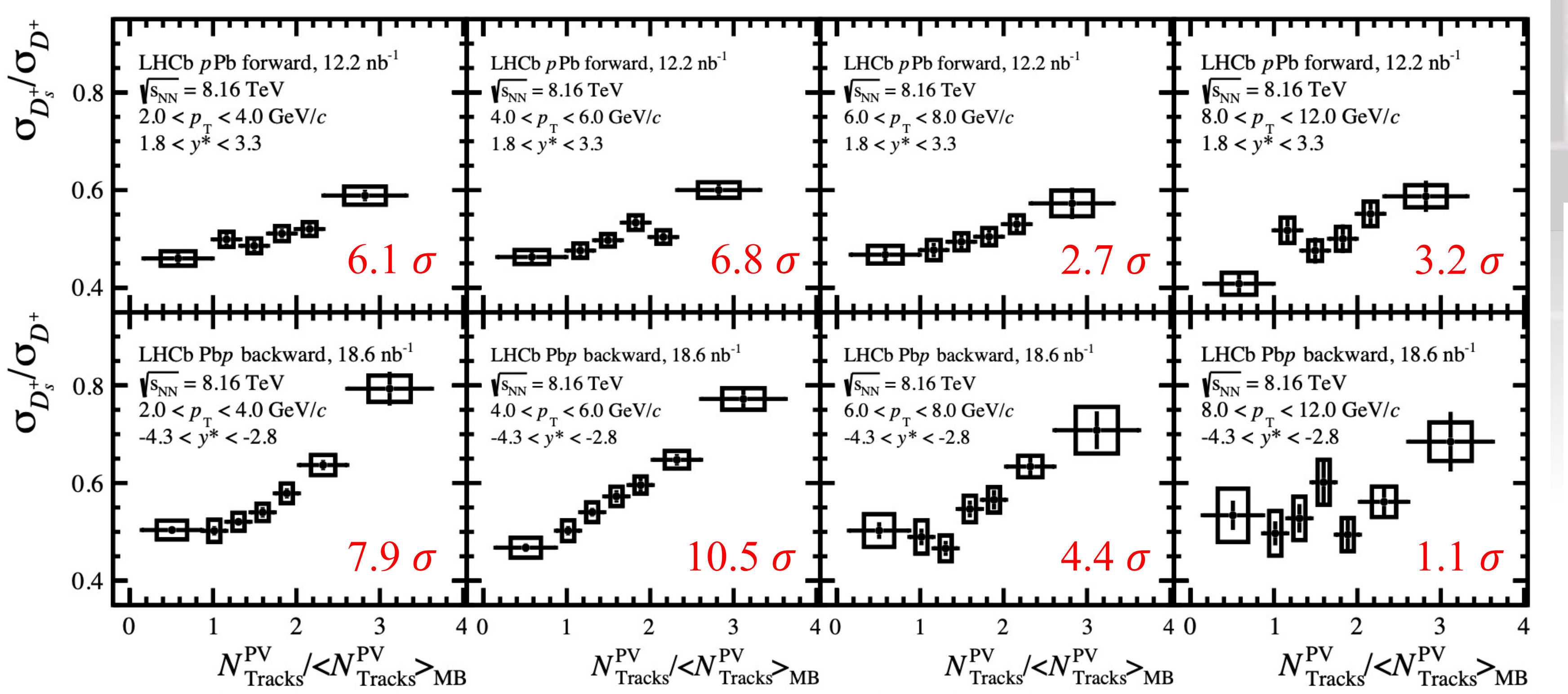


- D_s^+/D^+ ratio also shows no dependence on p_T.
- D_s^+/D^+ ratio is consistent with theoretical calculation (EPPS16, nCTEQ15) in forward.
- The backward D_s^+/D^+ ratio is also slightly higher than the forward ratio.

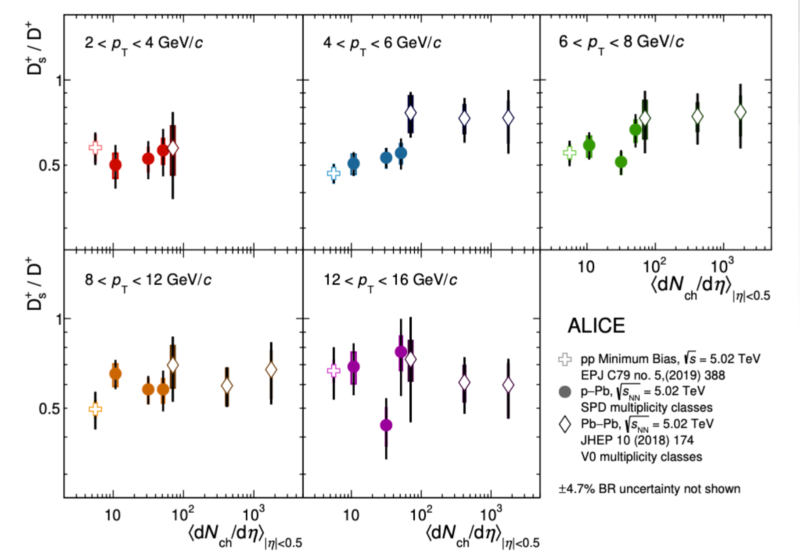
LHCb-PAPER-2023-006, in preparation
LHCb-PAPER-2023-021, in preparation

D_s^+/D^+ ratio vs multiplicity in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- D_s^+/D^+ ratio increases with multiplicity.
- D_s^+/D^+ ratio enhancement is more pronounced in backward rapidity.
- On average, D_s^+/D^+ ratio is consistent with ALICE measurements.
- This implies a modification of charm quark hadronization in high multiplicity pPb collisions.



$N_{\mathrm{Tracks}}^{\mathrm{PV}}$: Number of tracks used to reconstruct primary vertex



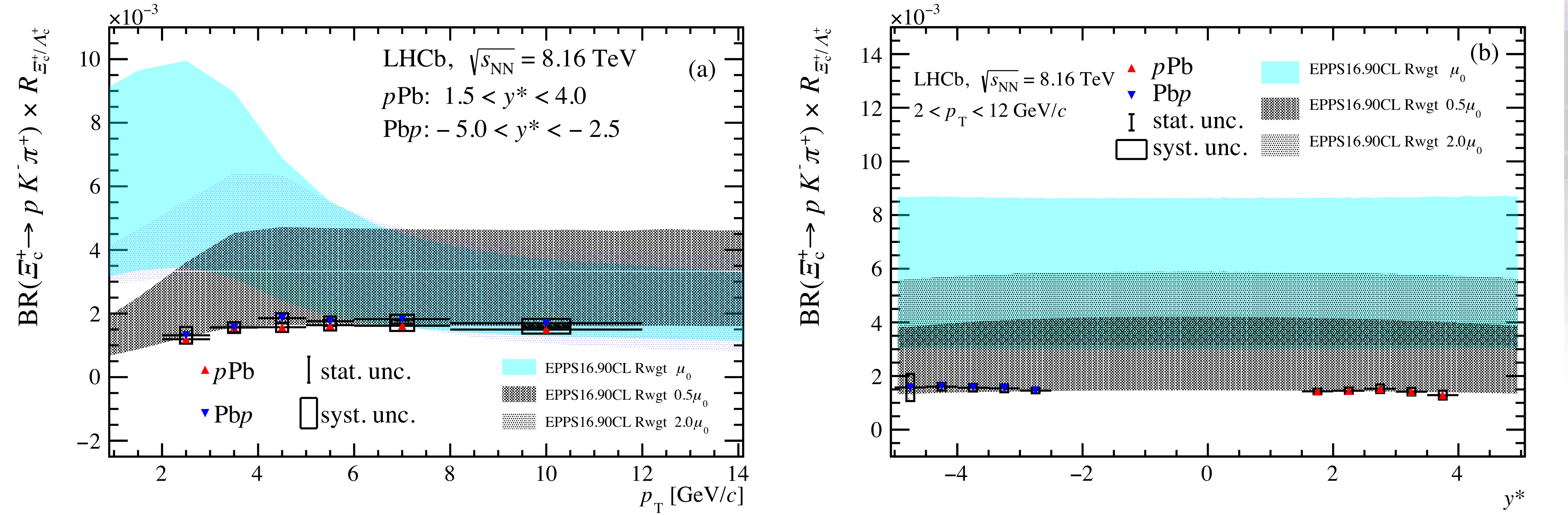
LHCb-PAPER-2023-021, in preparation
JHEP12(2019)092

preliminary

Ξ_c^+/Λ_c^+ ratio vs p_T and y^* in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- Ξ_c^+/Λ_c^+ ratio almost independent of p_T, suggests that similar effects govern the production of Ξ_c^+ and Λ_c^+.
- Ξ_c^+/Λ_c^+ ratio is consistent with theoretical calculation (EPPS16).
- The backward Ξ_c^+/Λ_c^+ ratio is slightly higher than the forward ratio.

$\Xi_c^+(2467) = usc$
$\Lambda_c^+(2286) = udc$
Both are reconstructed by $pK^-\pi^+$

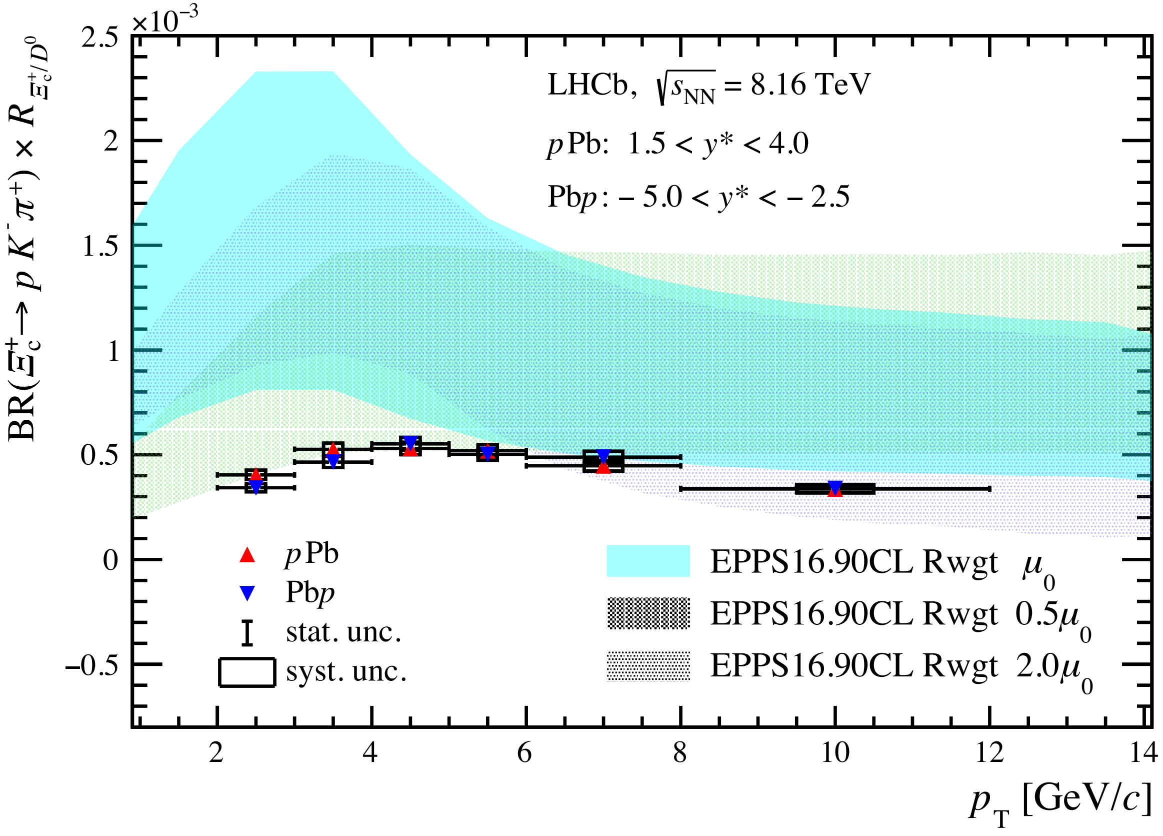


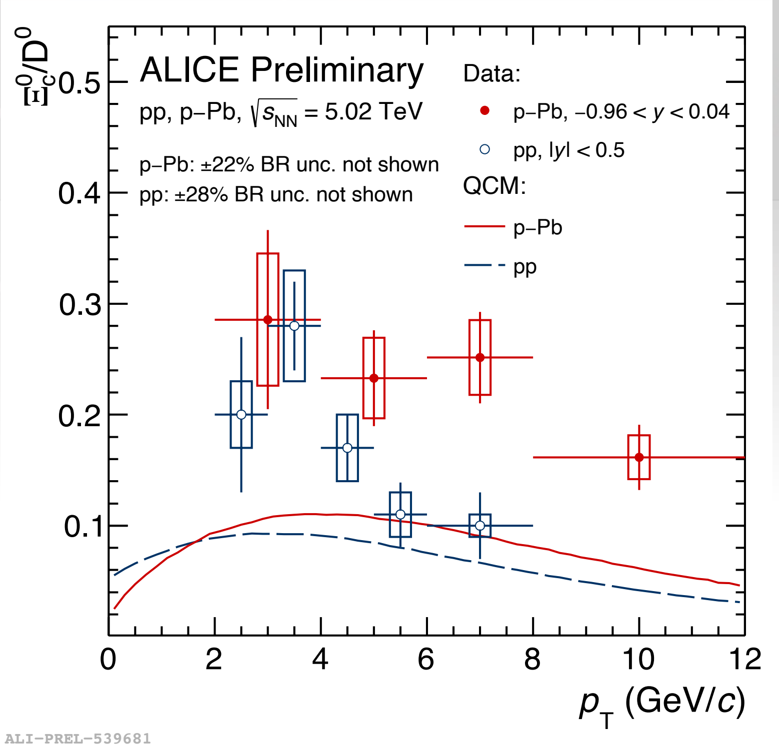
arXiv:2305.06711
arXiv:2012.11462

Ξ_c^+/D^0 ratio vs p_T in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

$D^0(1865) = c\bar{u}$

- D^0 cross-section at $\sqrt{s_{NN}} = 8.16$ TeV is taken from another LHCb analysis. arXiv:2205.03936
- Ξ_c^+/D^0 ratio is consistent with theoretical calculation (EPPS16).
- Ξ_c^+/D^0 ratio is similar in forward and backward rapidity.





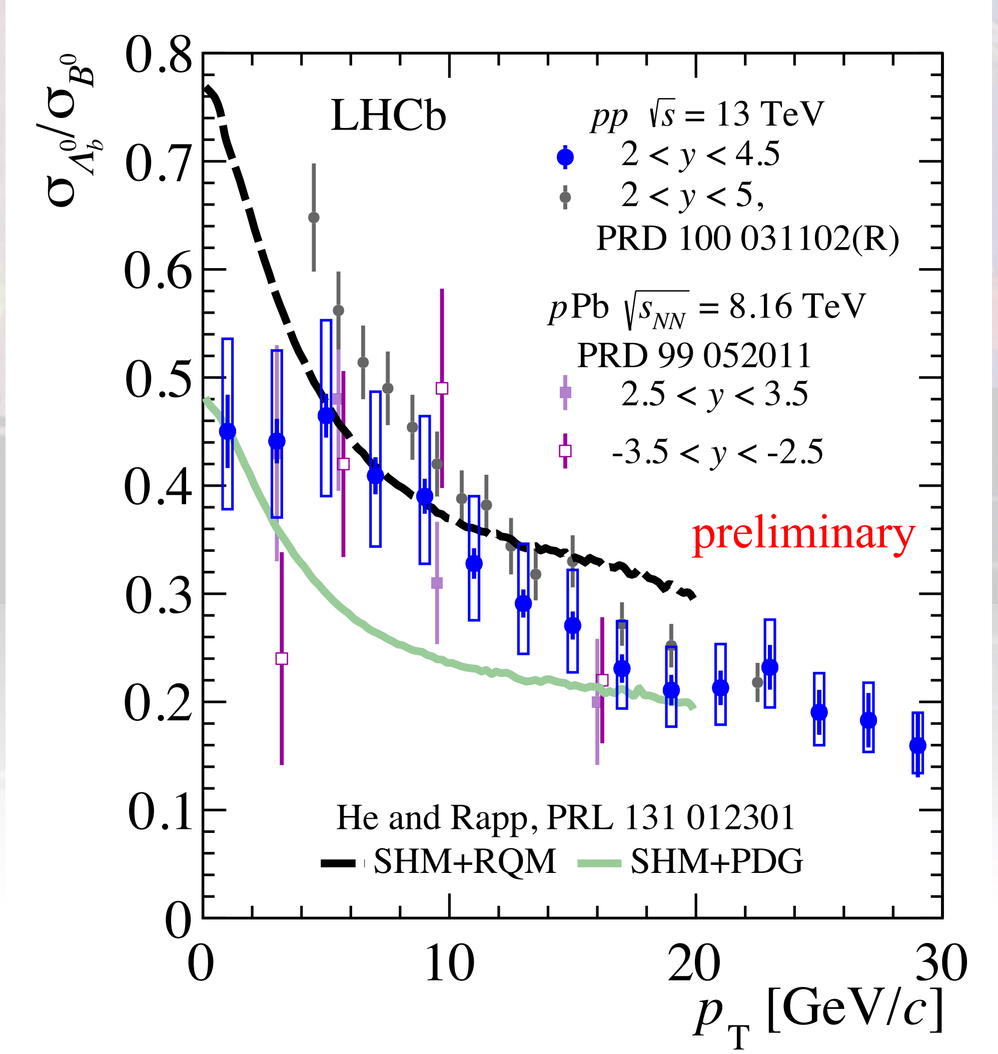
- The Ξ_c^0/D^0 ratios measured in pPb collisions from ALICE are significantly larger than that in pp collisions.

arXiv:2305.06711
arXiv:2012.11462

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

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

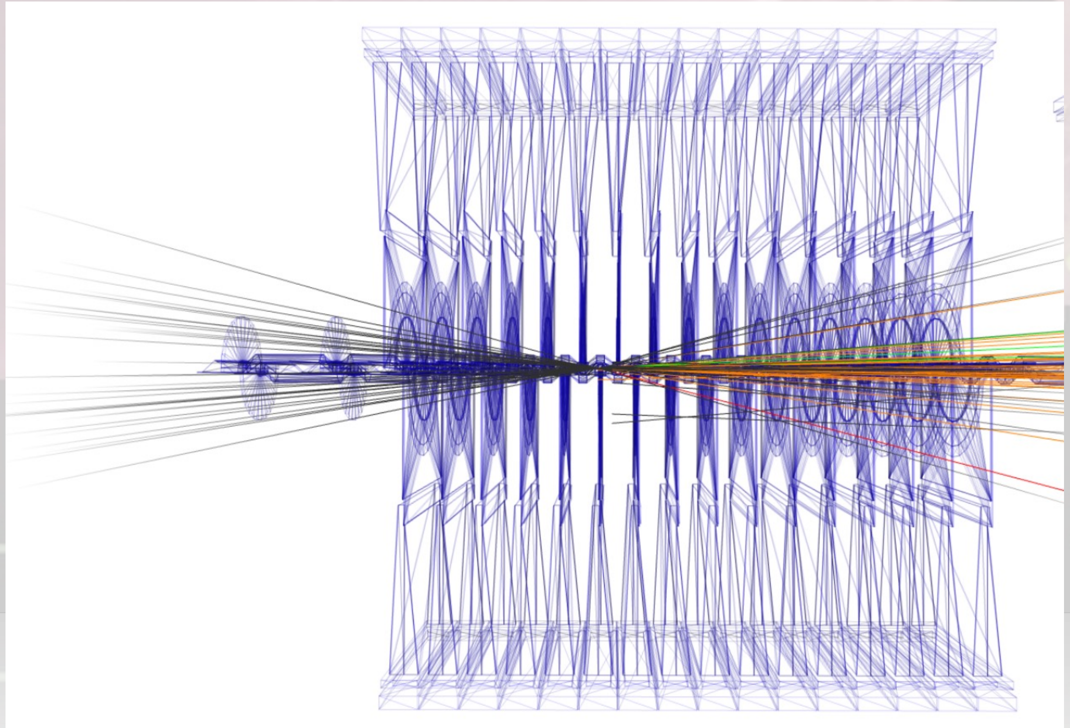
- Λ_b^0/B^0 ratio (blue points) is consistent with previous LHCb pp, pPb results within uncertainties.
- The green solid curve uses the measured spectrum of baryons collected by Particle Data Group (PDG).
- The black dashed curve uses the expanded set of excited states that are expected by the Relativistic Quark Model (RQM).
- The enhancement of RQM relative to the PDG is attributed to the feed down from thus far unobserved excited b baryons.
- LHCb data tend to favor RQM at p_T<15 GeV/c



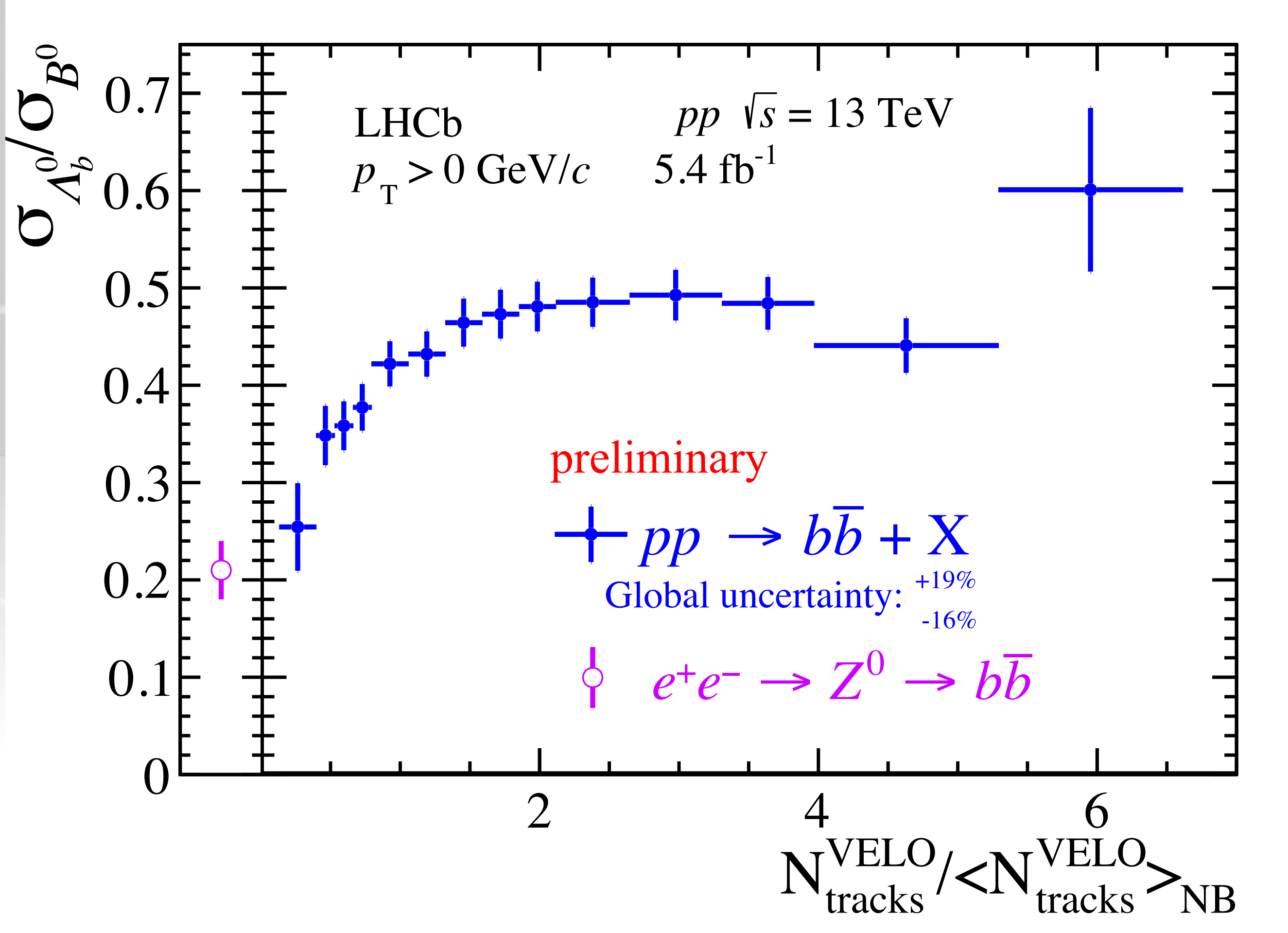
Bars = stat ⊕ sys
Boxes = BR uncertainty

LHCb-PAPER-2023-027, in preparation
Phys. Rev. D 100, 031102(R)
Phys. Rev. Lett. 131, 012301

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



$N_{\text{tracks}}^{\text{VELO}}$: Number of track with hits in VELO



Bars = stat $\oplus$ sys

- 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.

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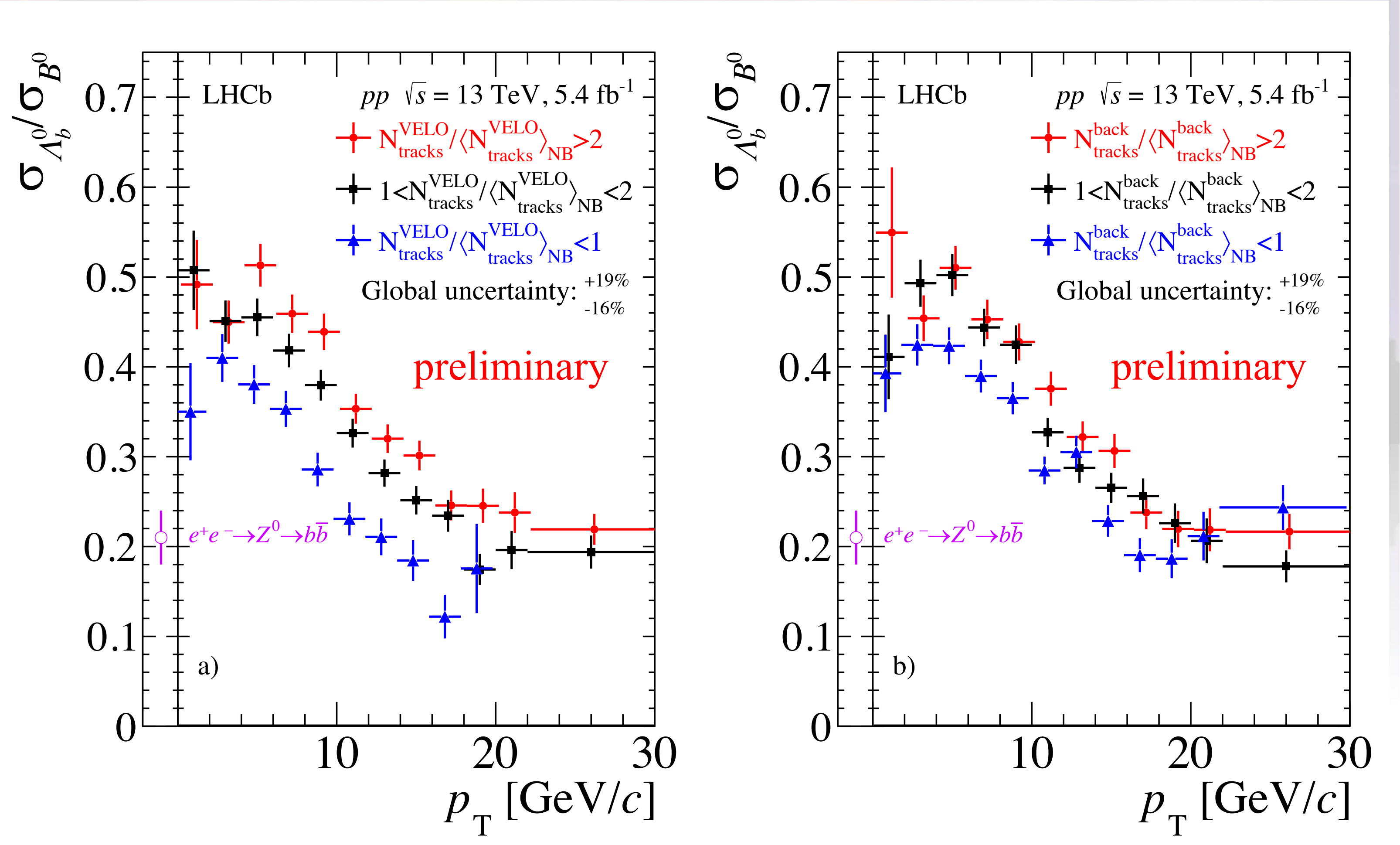
Λ_b^0/B^0 ratio vs p_{T} in pp collisions at $\sqrt{s} = 13$ TeV

- 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.

$N_{\mathrm{tracks}}^{\mathrm{back}}$: Subset of VELO tracks, point away from the LHCb



Bars = stat ⊕ sys

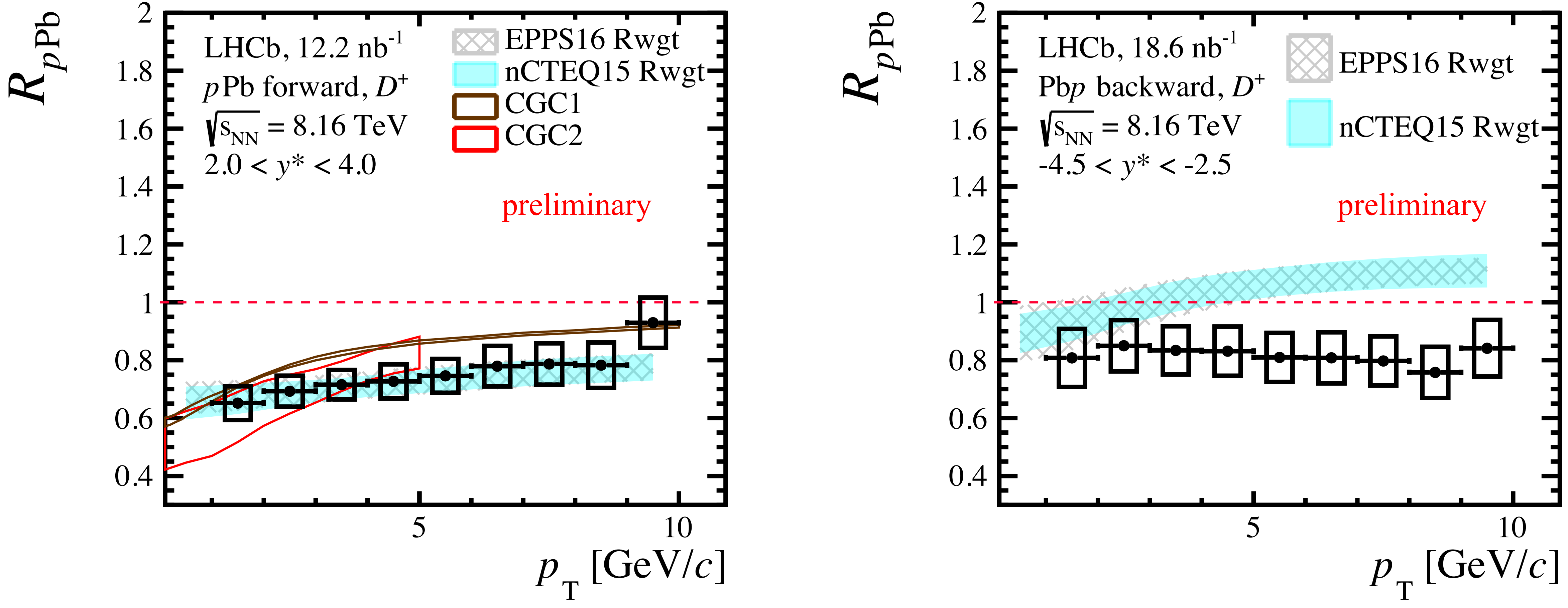
LHCb-PAPER-2023-027, in preparation

Summary

- In *pp* and *p*Pb collisions, LHCb have observed an enhancement of D_s^+/D^+, Λ_b^0/B^0 as a function of multiplicity, with this enhancement being particularly pronounced in the low p_{T} region. It is qualitatively consistent with expectations arising from quark coalescence as an adjunct hadronization mechanism and strangeness enhancement.
- From a theoretical perspective, this baryon/meson ratio enhancement may also be caused by feed down from excited states. To test this hypothesis, further measurements from excited states are required.
- In $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV *p*Pb collisions, The backward Ξ_c^+/Λ_c^+ ratio is slightly higher than the forward ratio. Ξ_c^+/D^0 ratio doesn't show a difference in the forward and backward. Further measurements are needed on these ratios in *pp* collisions.

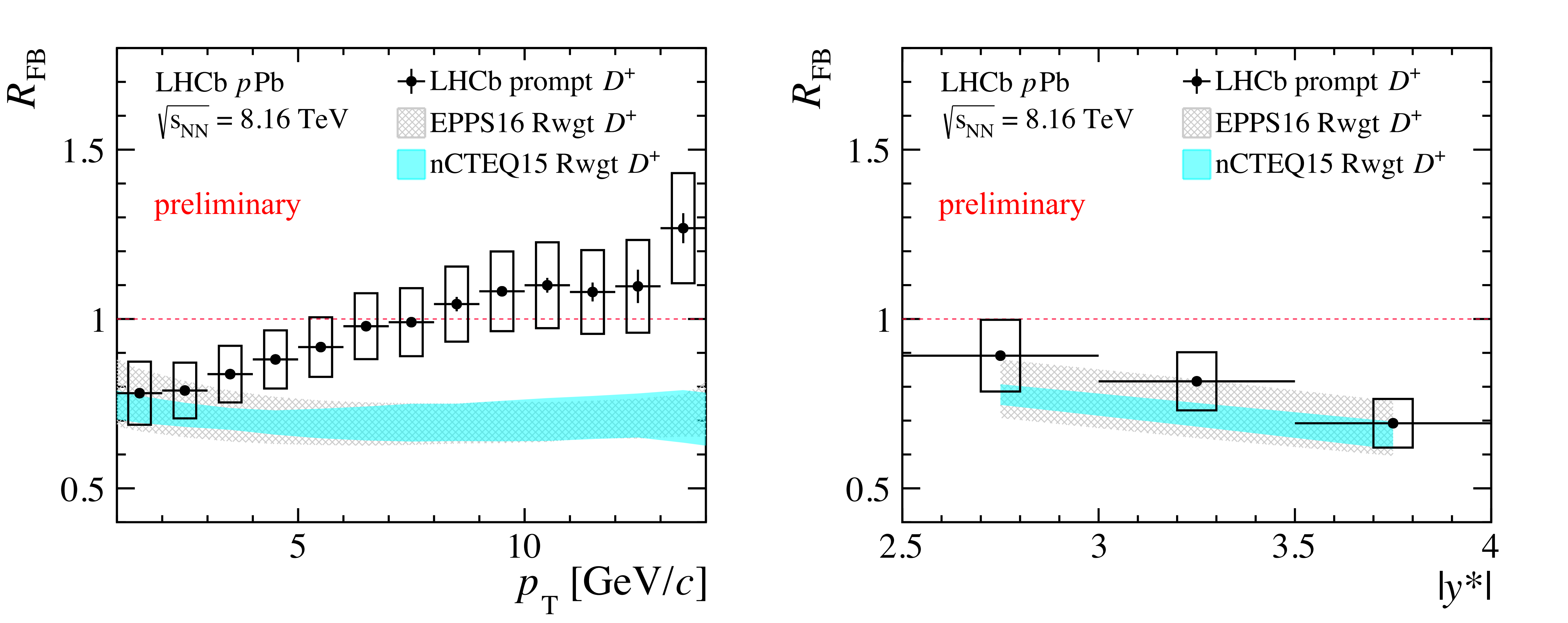
Thanks for listening!

D_s^+ and D^+ nuclear modification factor



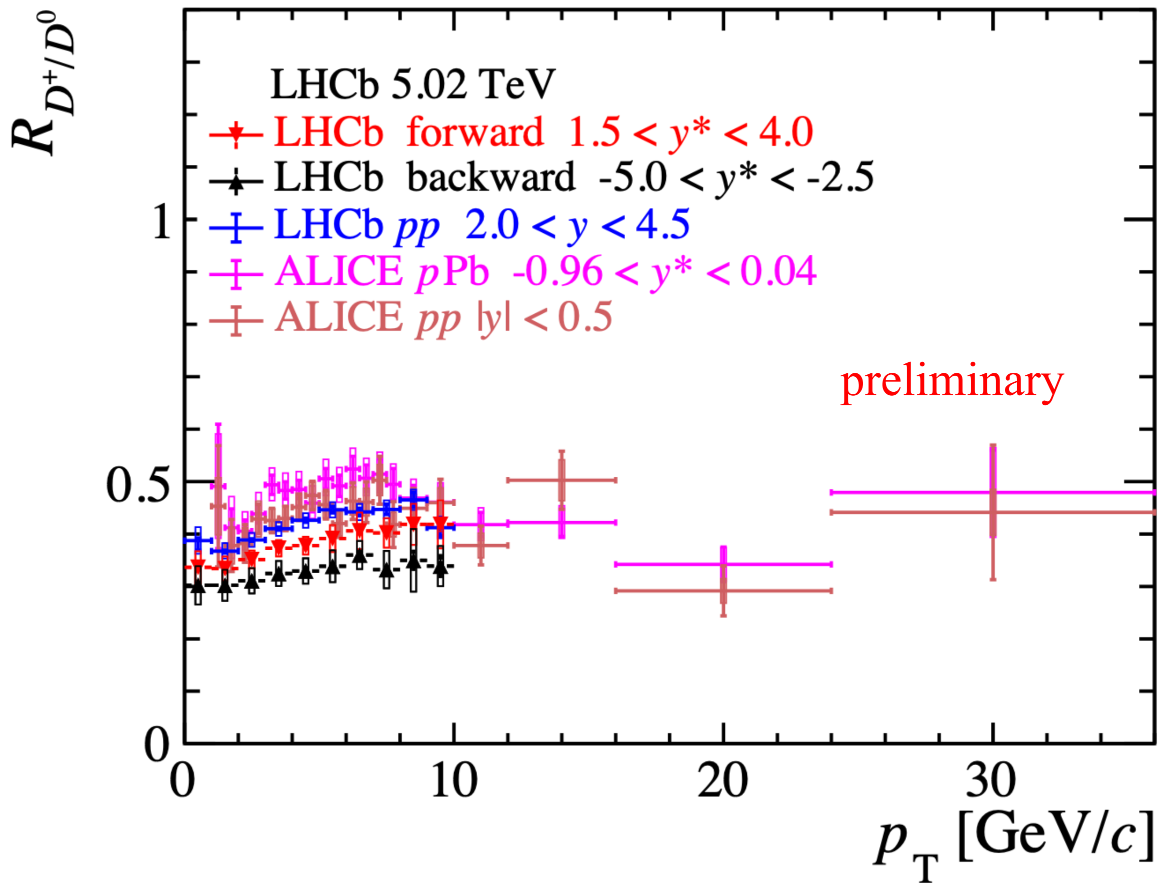
LHCb-PAPER-2023-021

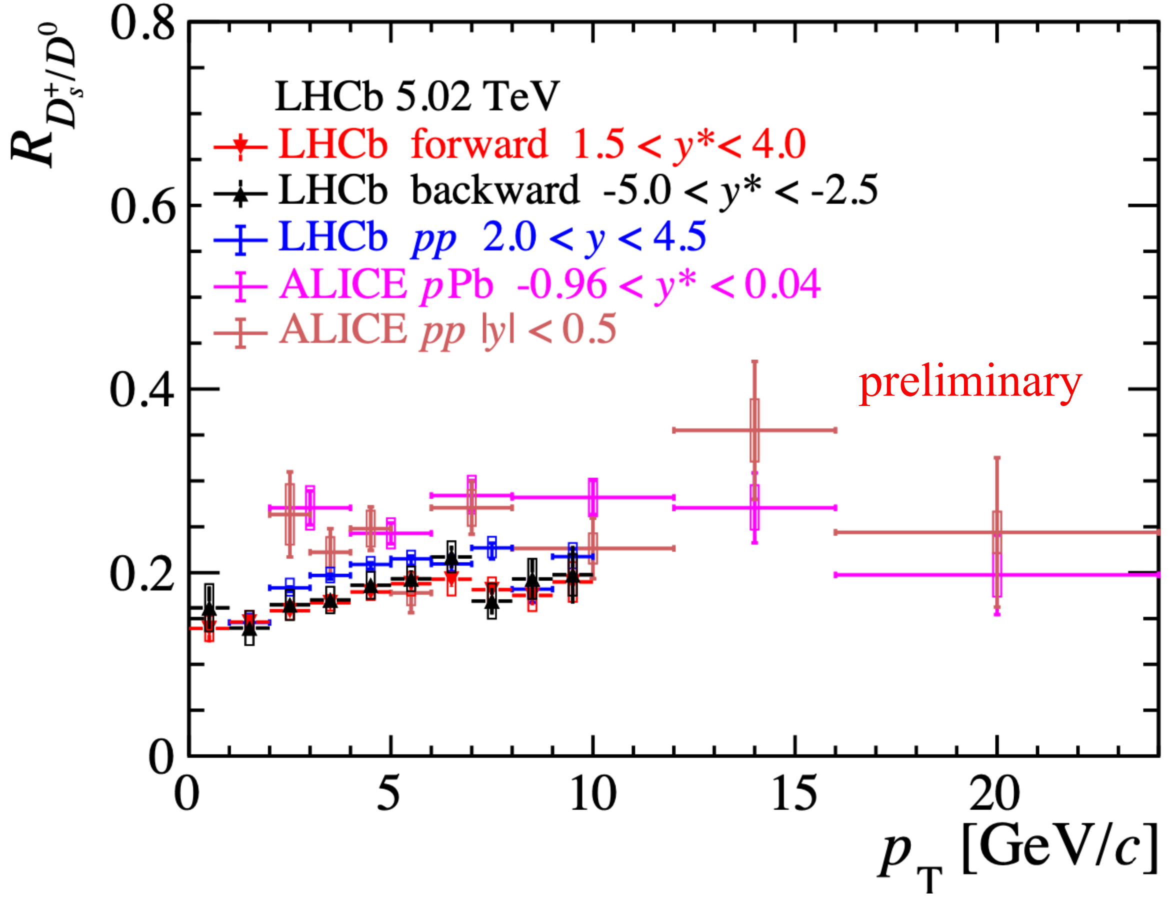
D_s^+ and D^+ forward-backward production ratio



LHCb-PAPER-2023-021

D_s^+/D^+ ratio in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV





LHCb-PAPER-2023-006