Recent results on open heavy flavor production (p-Gas, pp, pPb) from LHCb

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on behalf of the LHCb collaboration

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Outline

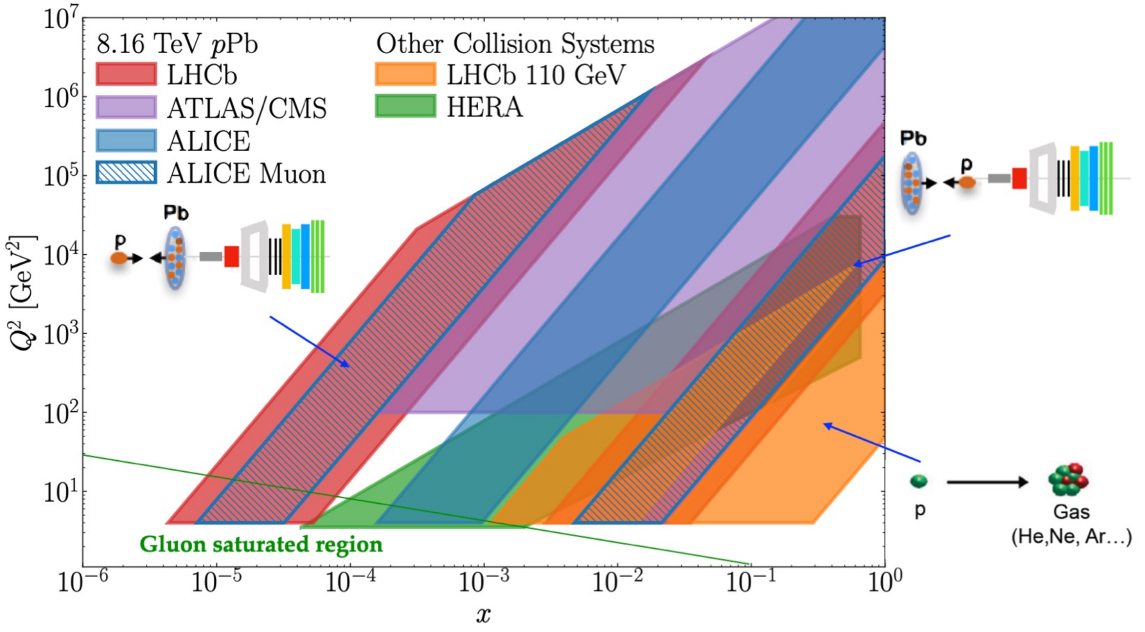
- Motivation
- LHCb detector
- D^0 production in pNe and PbNe collisions Eur. Phys. J. C83 (2023) 541 Eur. Phys. J. C83 (2023) 658
- Λ_b^0/B^0 ratio in high multiplicity pp collisions Phys. Rev. Lett. 132 (2024) 081901
- Prompt D_s^+ and D^+ production in pPb collisions JHEP 01 (2024) 070 arXiv:2311.08490
- Prompt Ξ_c^+ production in pPb collisions arXiv:2305.06711
- Summary

Motivation

- Study nuclear structure in different collisions.
  - ➢ Access different Bjorken x and Q^2 region.
  - ➢ Constrain nuclear PDFs.

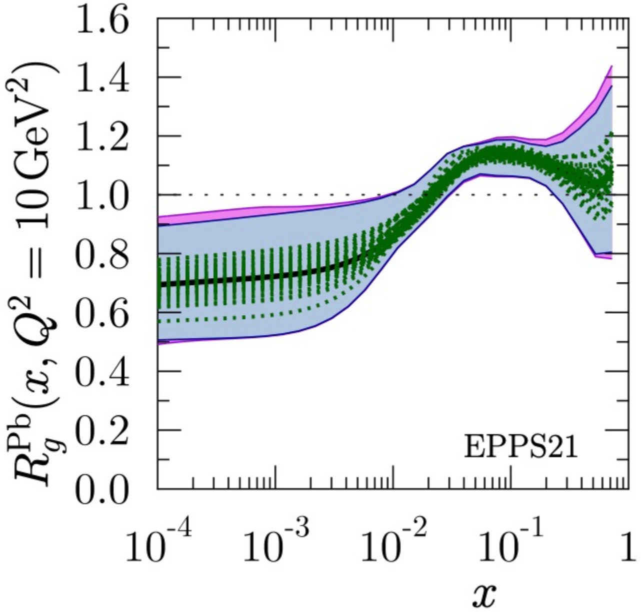
$$R_i^A(x,Q^2) = \frac{Zf_i^{p/A}(x,Q^2) + Nf_i^{n/A}(x,Q^2)}{Zf_i^{p}(x,Q^2) + Nf_i^{n}(x,Q^2)},$$

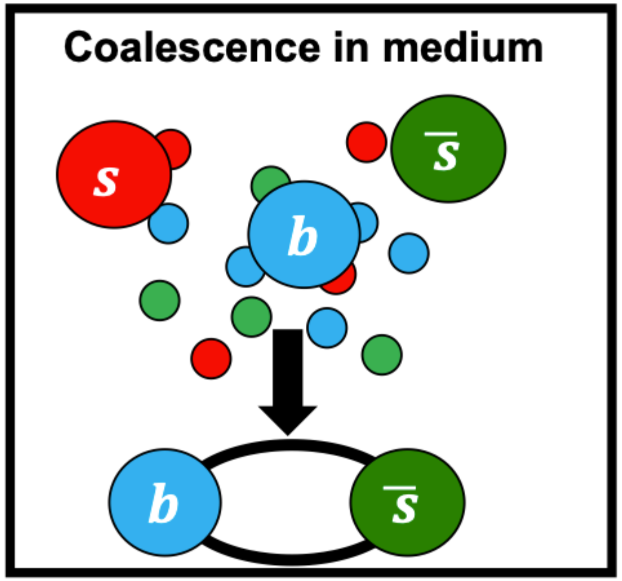
- Study hadronization process in different collisions.
  - ➢ *ee* collisions: fragmentation mechanism dominates.
  - ➢ *pp*/*p*Pb collisions: it was thought that the fragmentation mechanism was dominant.
  - ➢ PbPb/AuAu collisions: fragmentation and coalescence mechanisms mixed.



arXiv:2106.13661

$\sqrt{s}$ **(incident *p* or A beams)**

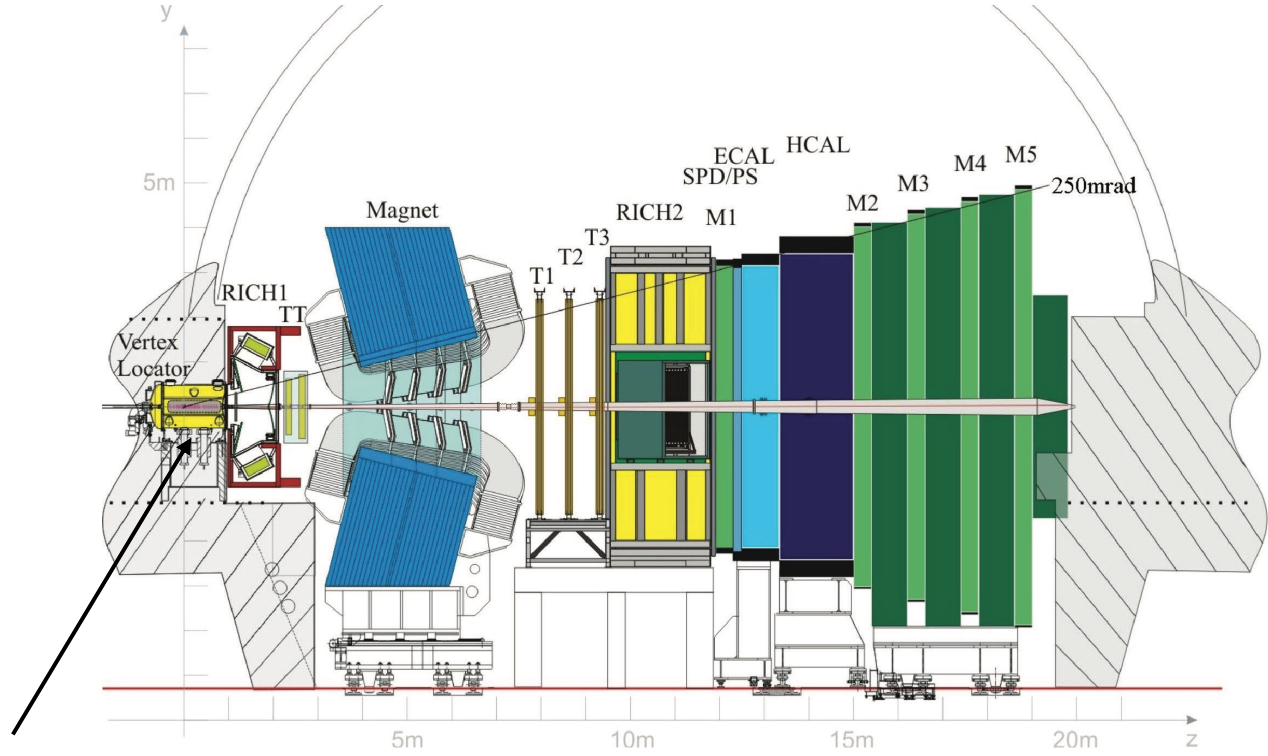




LHCb detector

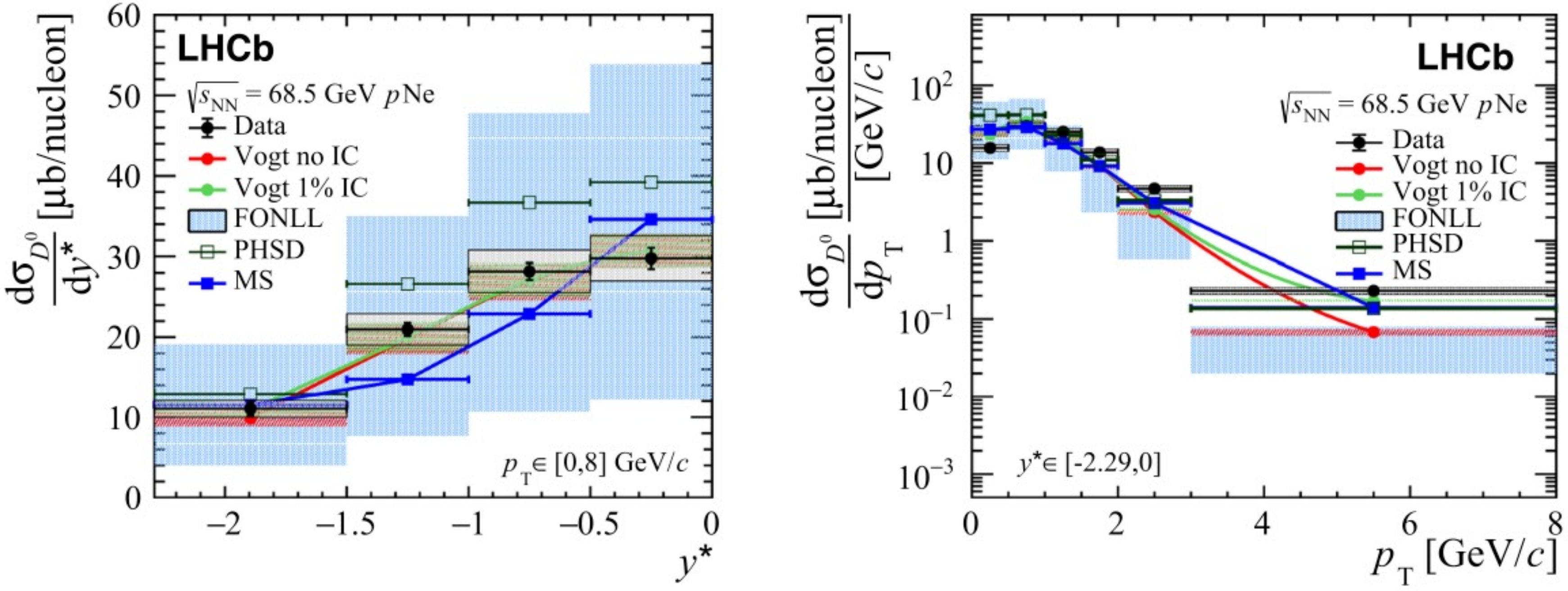
- A single-arm spectrometer in the forward direction, charm & beauty factory
  - ➢ Vertex Locator (~20 μm IP resolution)
  - ➢ Tracking system ($\Delta p/p = 0.5 - 1.0\%$)
  - ➢ PID optimal for μ, p, K, π
    - ❖ $\varepsilon(K \rightarrow K) \sim 95\%$
    - ❖ $\varepsilon(\mu \rightarrow \mu) \sim 97\%$
  - ➢ Flexible software trigger
- Fixed-target mode in Run 2: proton or lead beams collide with noble gas injected into Vertex Locator
  - ➢ Noble gases: Ar, He, Ne
  - ➢ Gas pressure: ~10^{-7} mbar

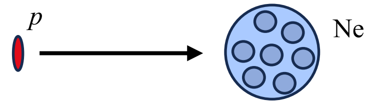
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



VErtex LOcator

D^0 differential cross sections in pNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV





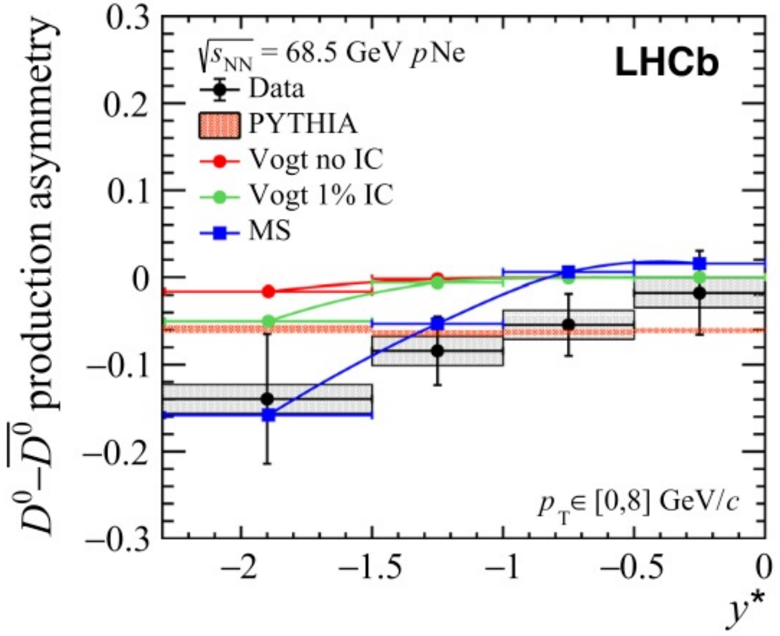
y^*: center mass system rapidity
y: lab system rapidity

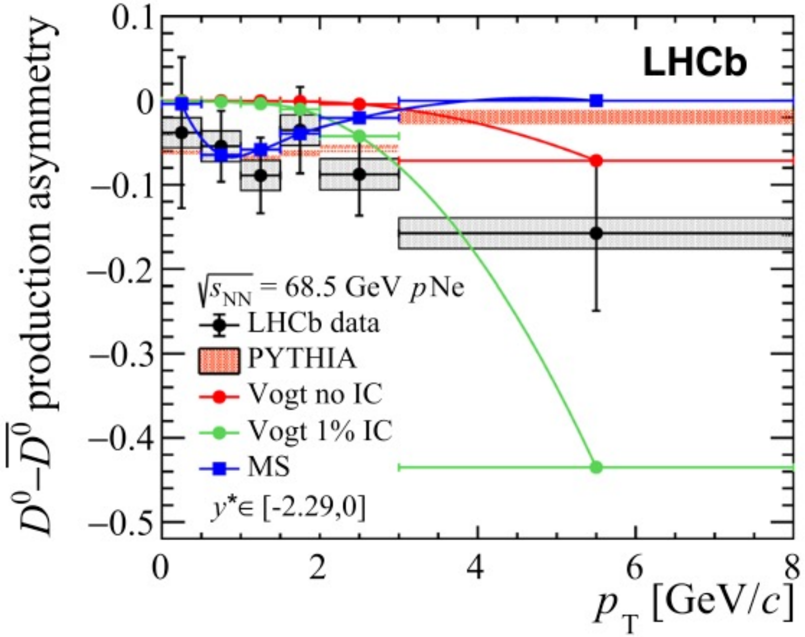
LHCb *p*Ne: EPJC 83 (2023) 541

- Both FONLL and PHSD calculations fail to reproduce the p_{T} distribution, while the rapidity distributions are in better agreement with the data.
- The data are well described by calculations with (Vogt 1% IC) or without (Vogt no IC) intrinsic charm contributions and calculations (MS) includes 1% intrinsic charm and 10% recombination contributions.

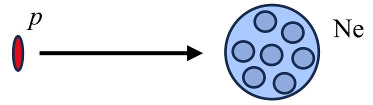
Vogt: PRC 103 (2021) 035204
MS: PLB 835 (2022) 137530
PHSD: PRC 96 (2017) 014905
FONLL: PRL 95 (2005) 122001, JHEP 05 (1998) 007

D^0 production asymmetry in pNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV





LHCb *p*Ne: EPJC 83 (2023) 541



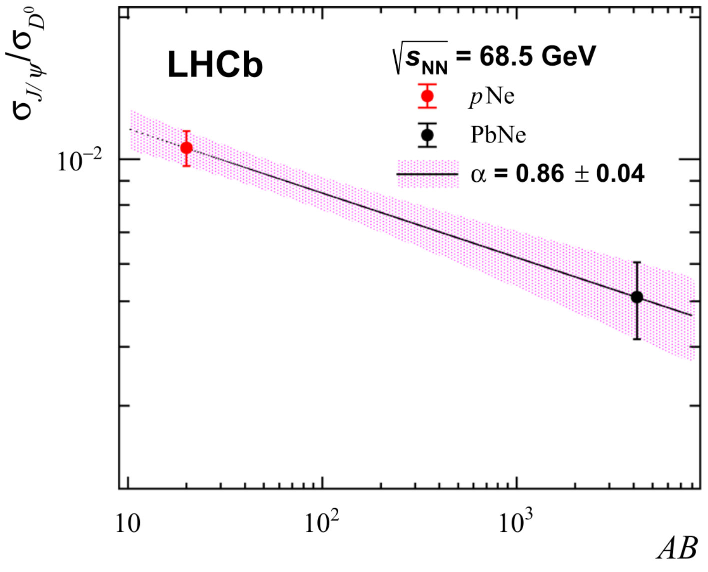
$$\mathcal{A}_{\mathrm{prod}} = \frac{Y_{\mathrm{corr}}(D^0) - Y_{\mathrm{corr}}(\overline{D}^0)}{Y_{\mathrm{corr}}(D^0) + Y_{\mathrm{corr}}(\overline{D}^0)}$$

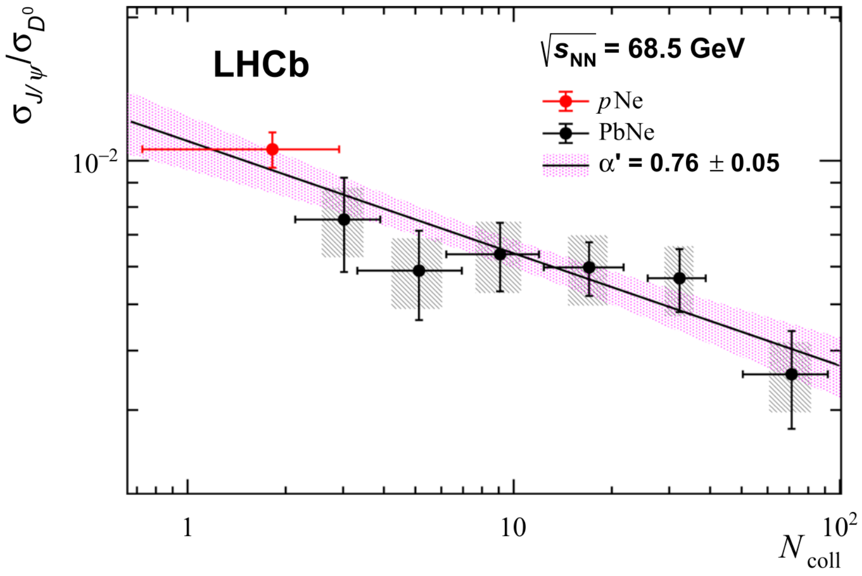
The production asymmetry probes charm hadronization with a high-x valence quark.

- The largest asymmetry (-15%) is obtained at $y^* = -2.29$.
- PYTHIA 8 predicts an asymmetry of approximately -6%, which shows little dependence on p_T and rapidity.
- Vogt calculations represent an upper limit on the asymmetry.

Pythia8: JHEP 08 (2015) 003
Vogt: PRC 103 (2021) 035204
MS: PLB 835 (2022) 137530

Relative nuclear effects ($J/\psi/D^0$) vs collisions size





PbNe: EPJC 83 (2023) 658 ***p*Ne:** EPJC 83 (2023) 625

AB is the product of the beam (A) and target (B) atomic mass numbers.

$$\frac{\sigma_{J/\psi}^{AB}}{\sigma_{D^0}^{AB}} = \frac{\sigma_{J/\psi}^{pp}}{\sigma_{D^0}^{pp}} \times (AB)^{\alpha-1} = C \times (AB)^{\alpha-1}$$

N_{coll} is the number of binary nucleon-nucleon collisions and evaluated by Glauber model.

$$\frac{\sigma_{J/\psi}^{AB}}{\sigma_{D^0}^{AB}} \propto (N_{coll})^{\alpha'-1}$$

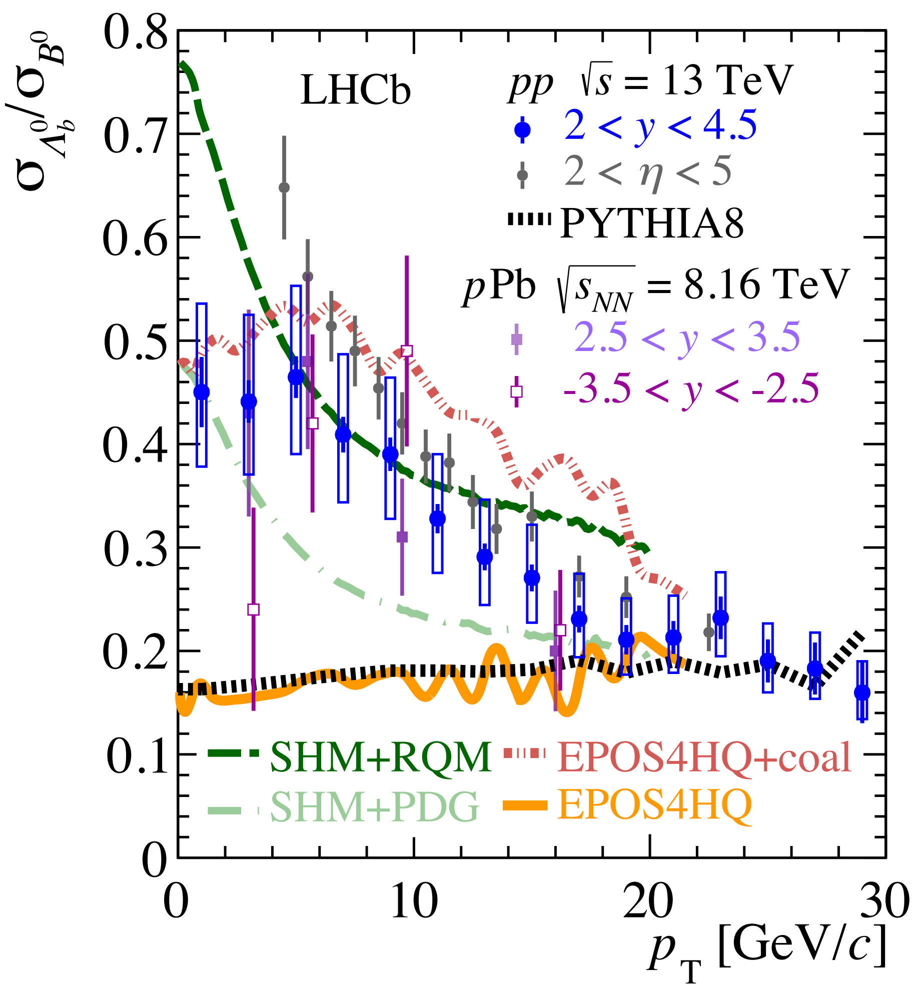
- Study $\sigma_{J/\psi}/\sigma_{D^0}$ as a function of the collisions size (represented by AB or N_{coll}).
- $\alpha < 1$ indicates that J/ψ mesons experience additional nuclear effects than D^0 mesons
- At the current precision, there is no significant difference in the J/ψ suppression trend when comparing pNe and peripheral PbNe collisions with central PbNe collisions.

Λ_b^0/B^0 cross-section ratio in pp collisions at $\sqrt{s} = 13$ TeV

$\Lambda_b^0 = udb$
$B^0 = d\bar{b}$

- 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.
- By incorporating a coalescence mechanism, the EPOS4HQ model provides a more accurate description of the data.

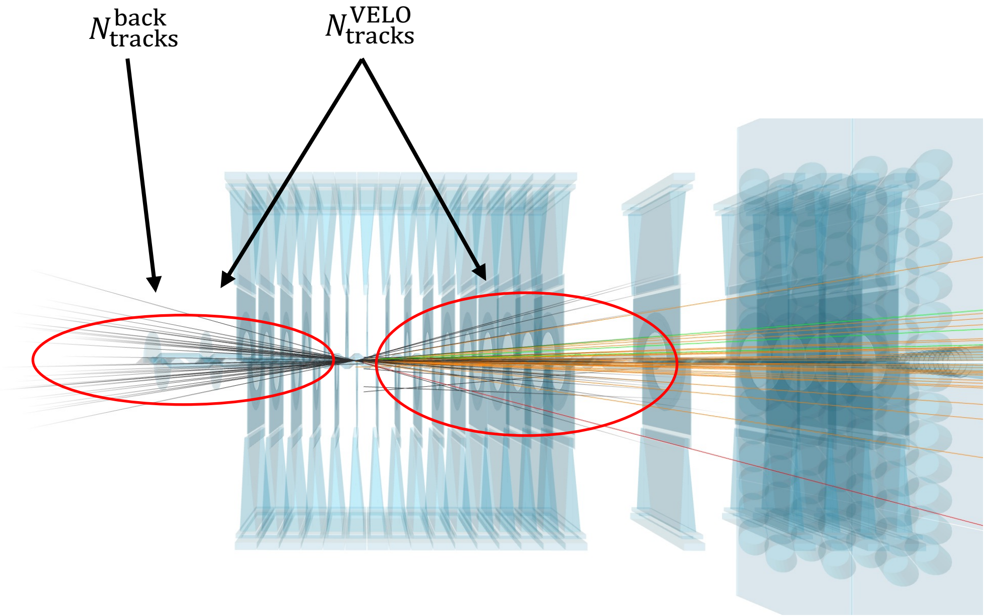
LHCb *pp*: Phys. Rev. Lett. 132 (2024) 081901



Bars = stat ⊕ sys
Boxes = BR uncertainty

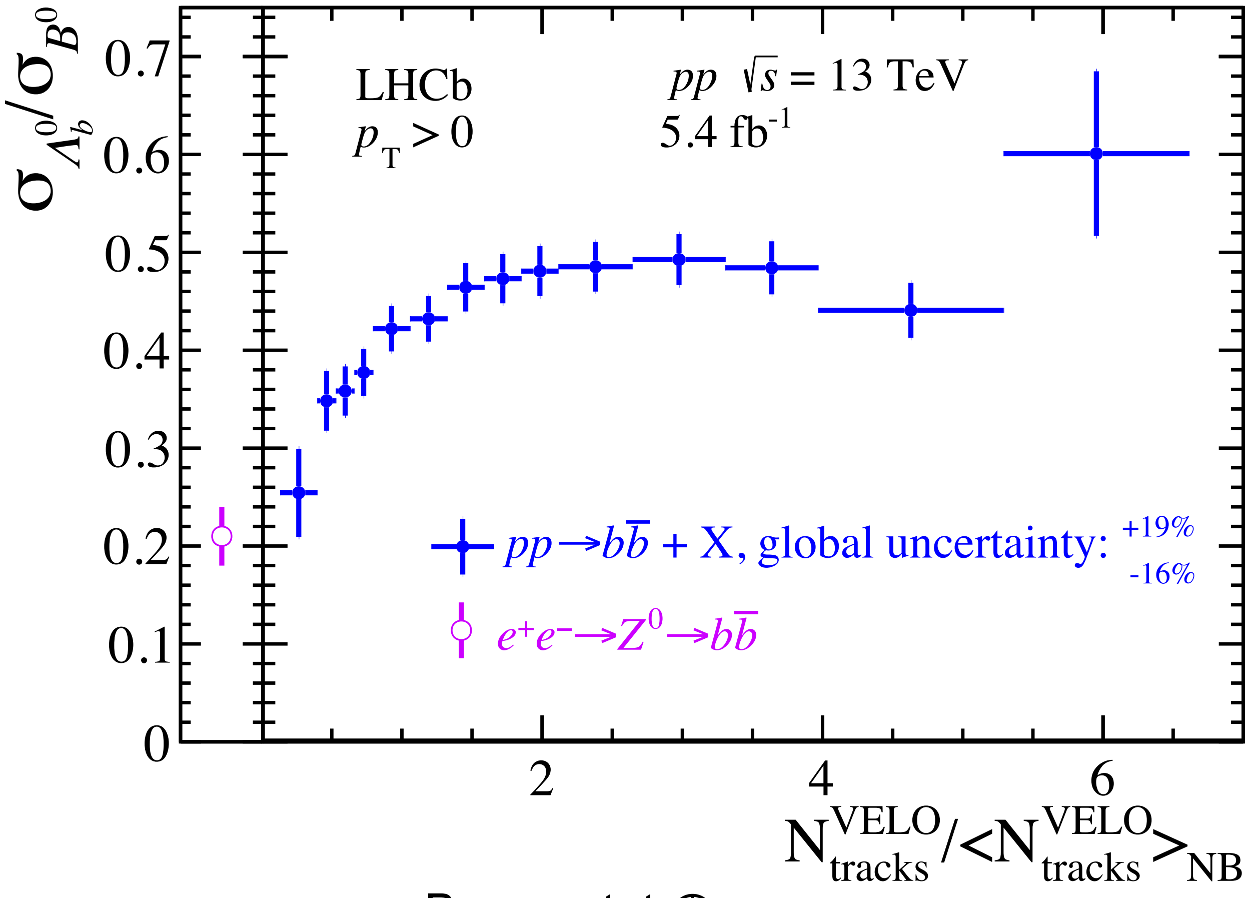
LHCb *pp*: Phys. Rev. D 100, 031102(R)
LHCb *p*Pb: Phys.Rev.D 99 (2019) 5, 052011
SHM: Phys. Rev. Lett. 131, 012301
EPOS4HQ: Phys.Rev.D 109 (2024) 5, 054011
PYTHIA8: Comput.Phys.Commun. 178 (2008) 852-867

Λ_b^0/B^0 ratio vs multiplicity 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

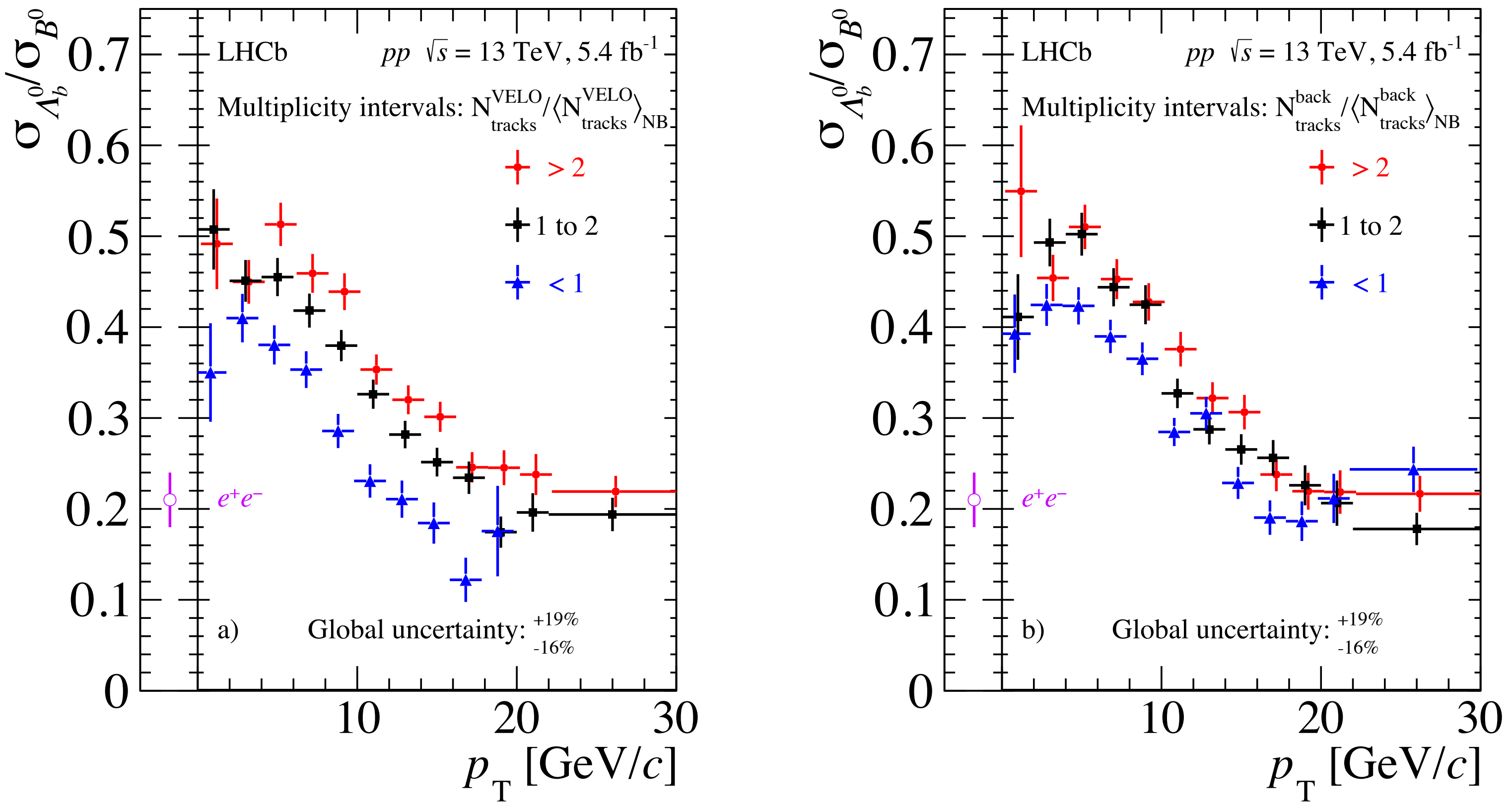


Bars = stat ⊕ sys

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

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

- Λ_b^0/B^0 ratio significantly higher than e^+e^- result at low p_T, and shows strong multiplicity dependence.
- Λ_b^0/B^0 ratio consistent with e^+e^- result at high p_T, shows weaker multiplicity dependence.
- Λ_b^0/B^0 ratio shows weaker multiplicity dependence on backward VELO tracks.

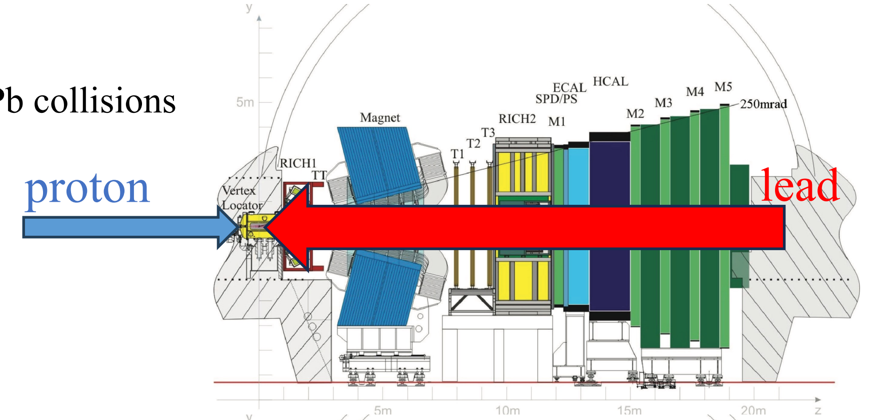


Bars = stat ⊕ sys

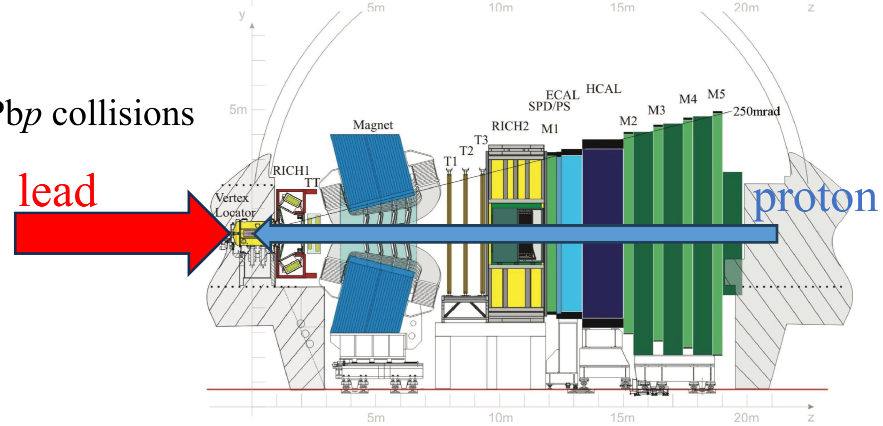
Proton-lead collisions at LHCb

- The pPb collisions at $\sqrt{s_{NN}} = 5.02$ (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).

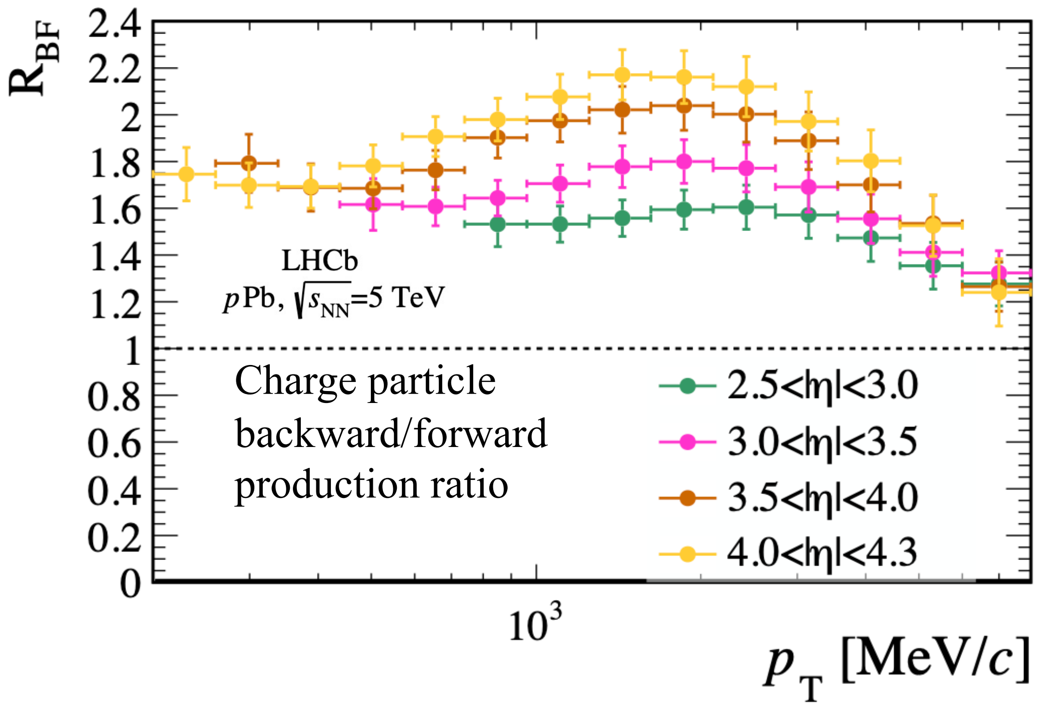
Forward pPb collisions



Backward Pbp collisions

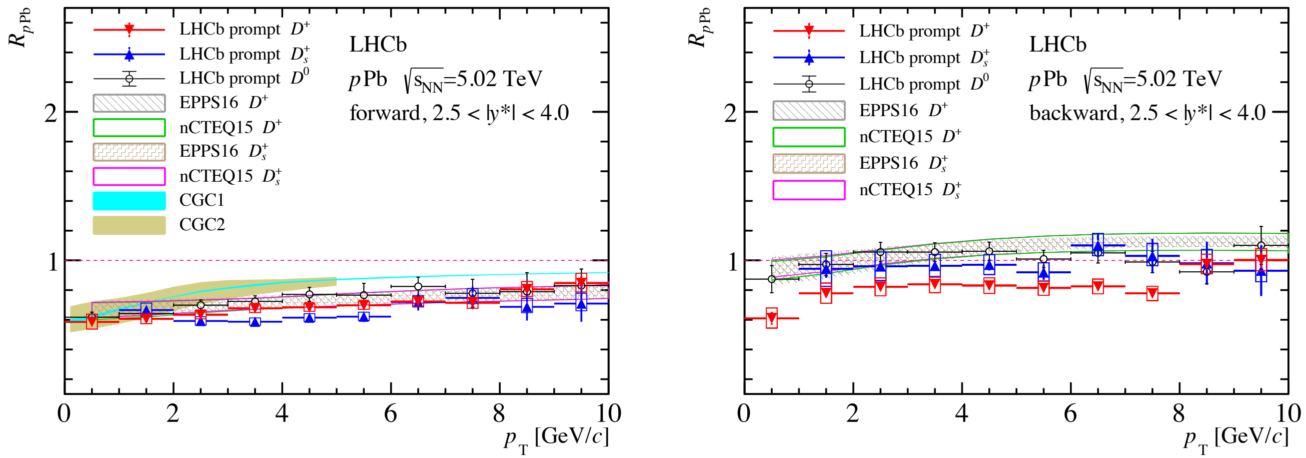


Phys. Rev. Lett. 128, 142004

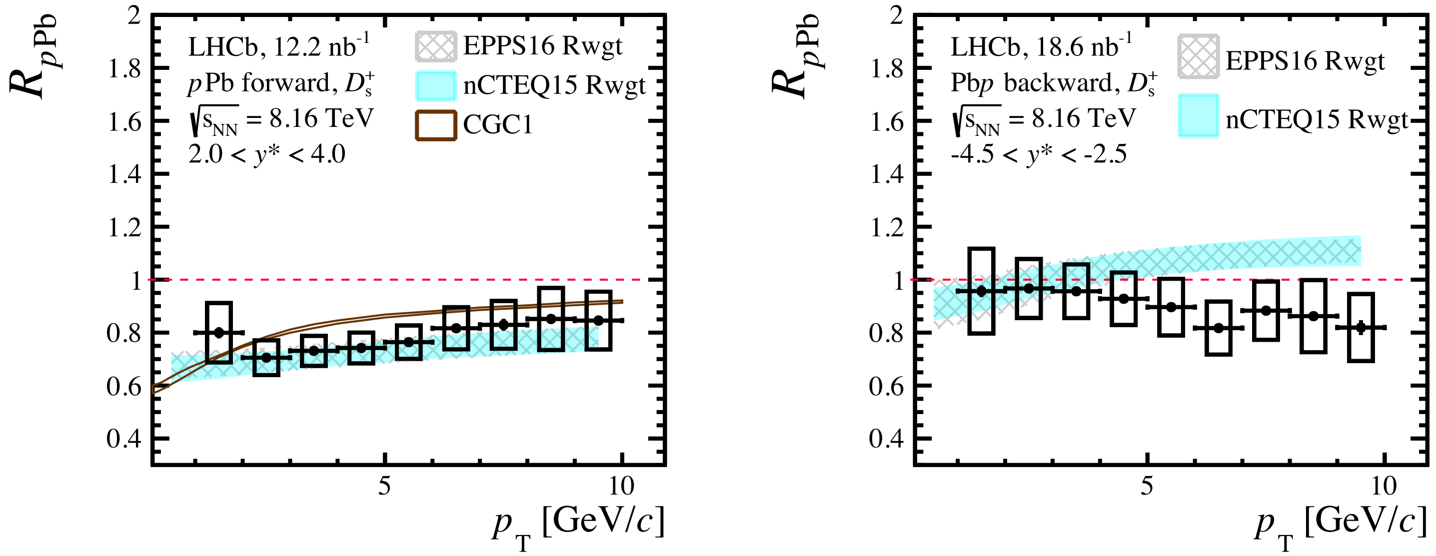


D_s^+ and D^+ production in pPb collisions

LHCb 5.02 TeV *p*Pb: JHEP 01 (2024) 070



LHCb 8.16 TeV *p*Pb: arXiv:2311.08490



The nuclear modification factor is usually performed to study cold nuclear matter effects.

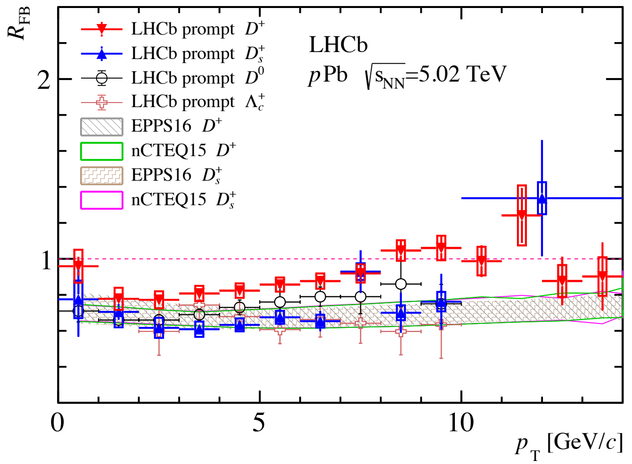
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

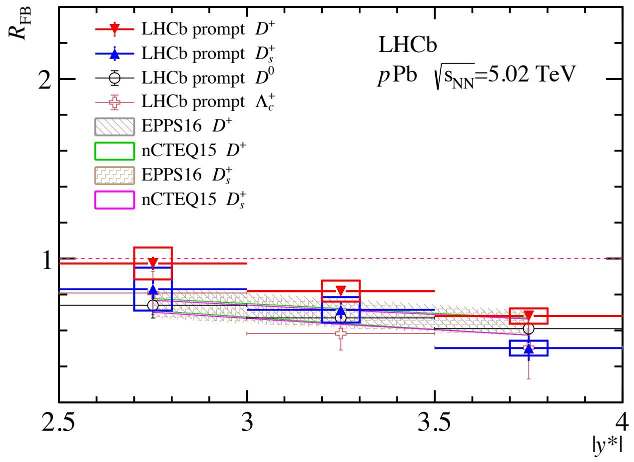
- $R_{p\mathrm{Pb}} < 1$ means that the production of D mesons are suppressed by cold nuclear matter effects.
- $R_{p\mathrm{Pb}}$ consistent with nPDFs calculations in the forward, lower than nPDFs calculations in the backward high p_T region.

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

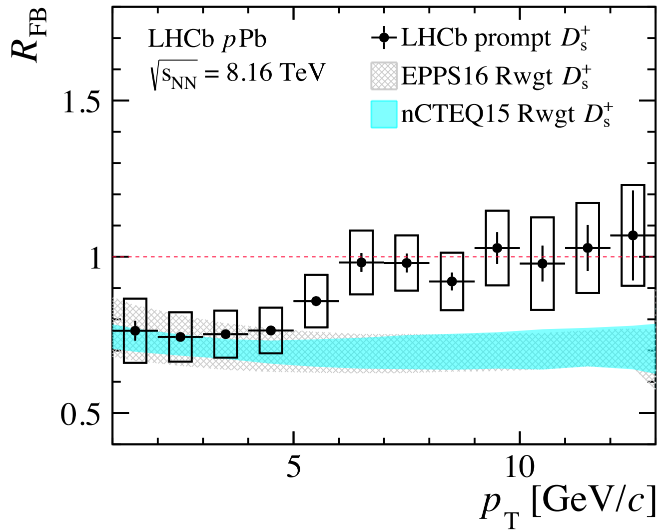
D_s^+ and D^+ forward-backward production ratio

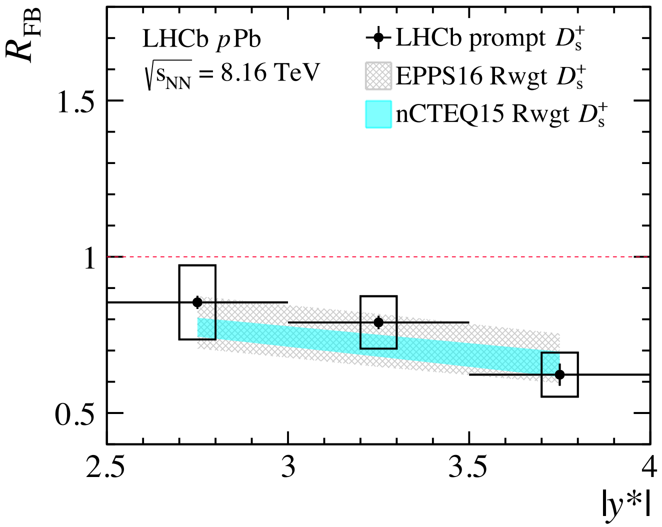
LHCb 5.02 TeV *p*Pb: JHEP 01 (2024) 070





LHCb 8.16 TeV *p*Pb: arXiv:2311.08490





$$R_{FB}(p_T, y^*) = \frac{d^2\sigma_{pPb}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{Pbp}(p_T, -|y^*|)/dp_T dy^*},$$

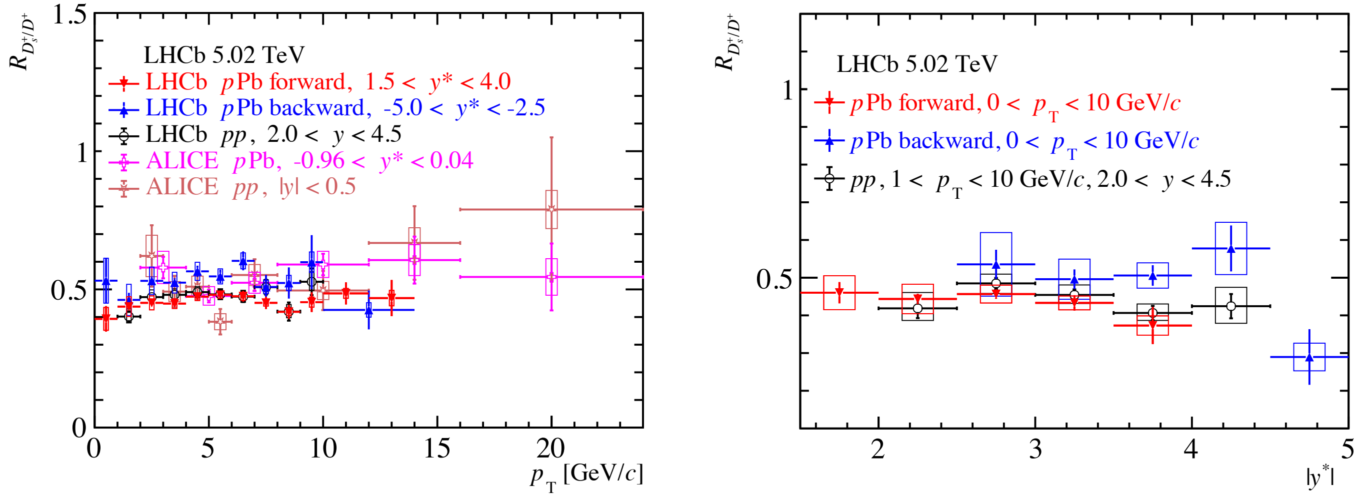
- R_{FB} shows a rising trend with p_T. Consistent with nPDFs at low p_T, larger than theoretical calculations at high p_T.
- R_{FB} shows a slight dependence on y^*, consistent with nPDFs calculations.
- Potential explanations for backward production suppression:
  - ➢ Weaker antishadowing effect in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

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

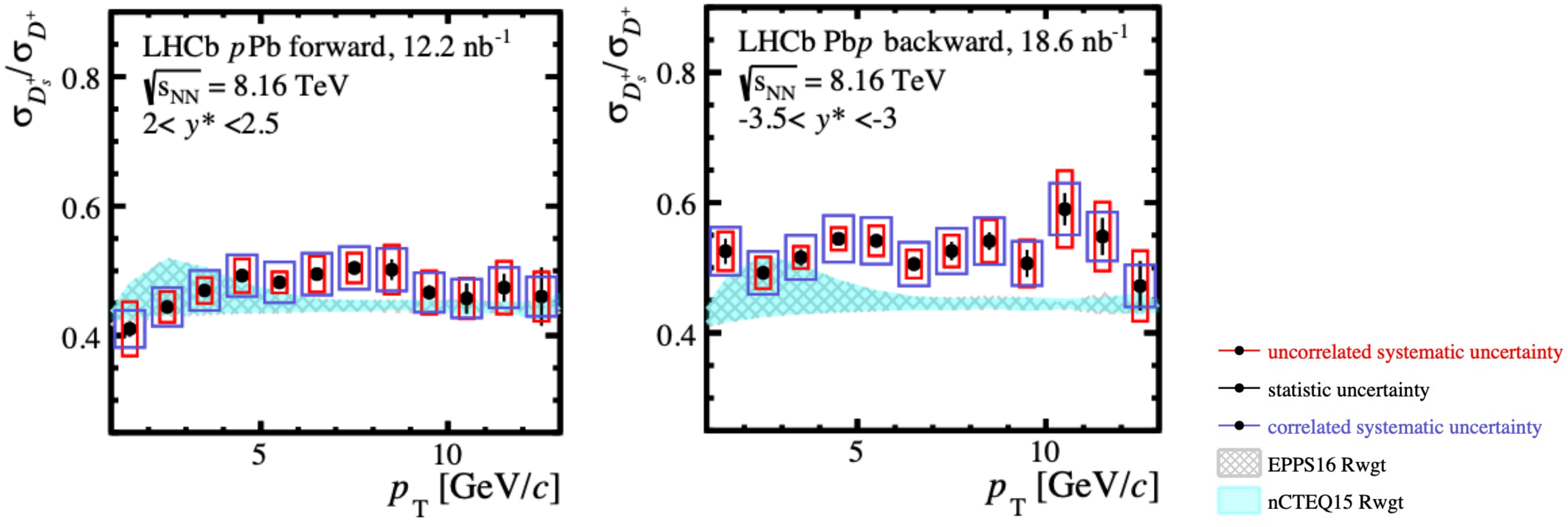
D_s^+/D^+ ratio vs p_T and y^* in pPb collisions

$D_s^+ = c\bar{s}$
$D^+ = c\bar{d}$

LHCb 5.02 TeV *p*Pb: JHEP 01 (2024) 070



LHCb 8.16 TeV *p*Pb: arXiv:2311.08490



- D_s^+/D^+ ratio shows little 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.

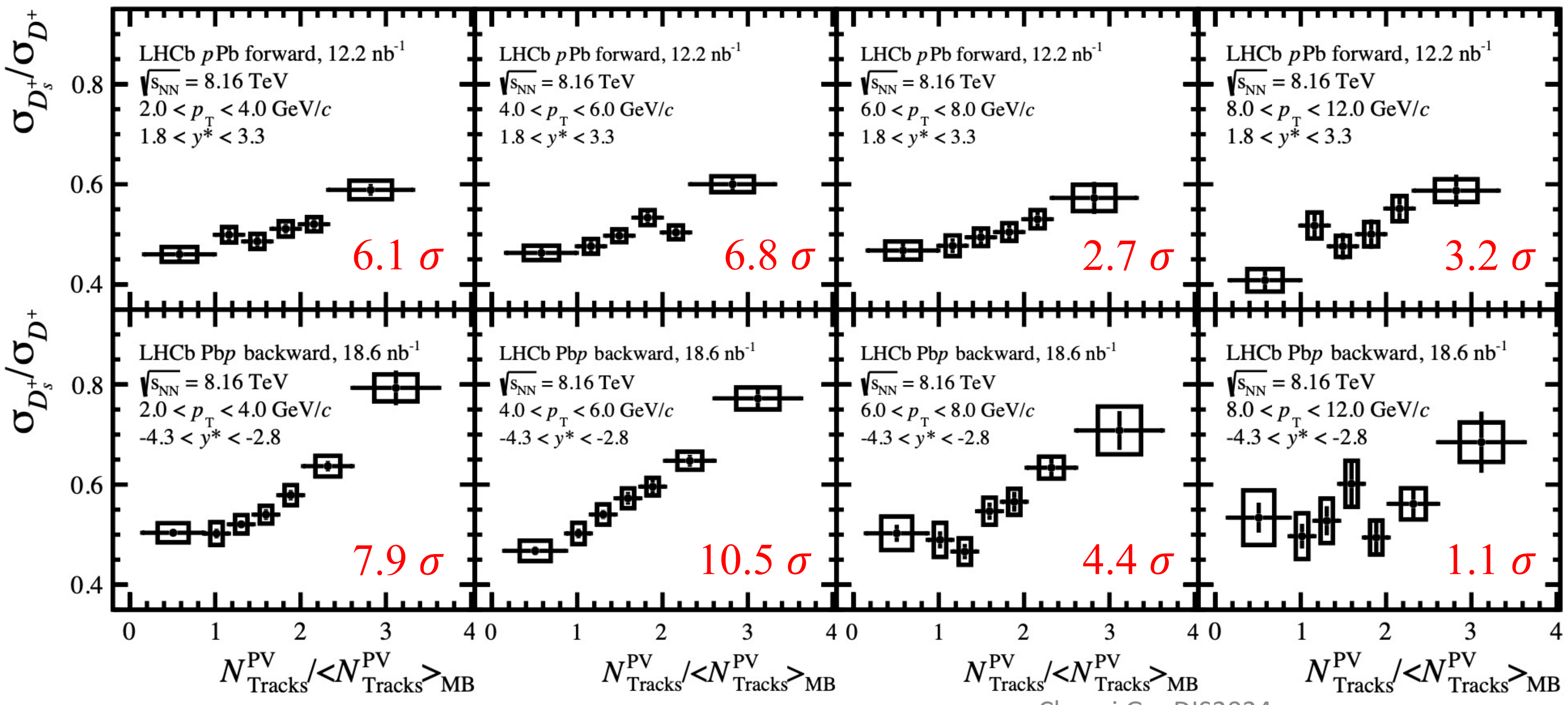
  - D_s^+/D^+ ratio also shows little dependence on p_T.
  - D_s^+/D^+ ratio is consistent with theoretical calculation (EPPS16, nCTEQ15) in forward.
  - The backward D_s^+/D^+ ratio is also slightly higher than the forward ratio.

LHCb *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 multiplicity in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

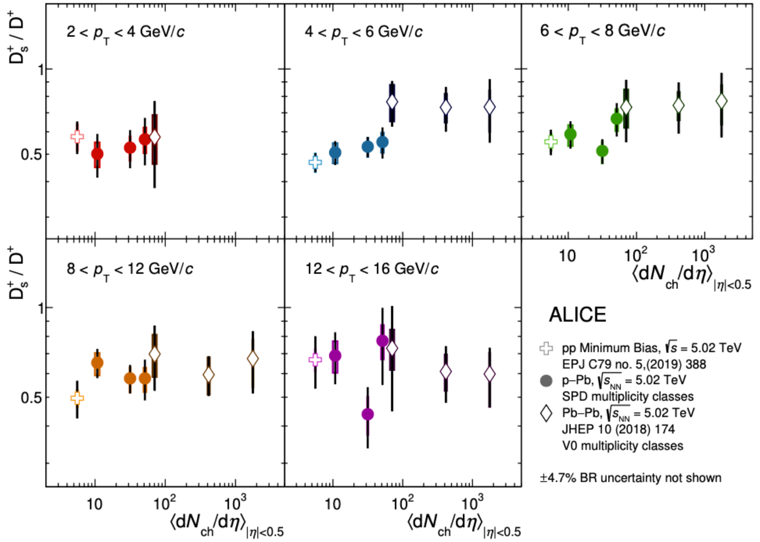
- D_s^+/D^+ ratio increases with multiplicity across all p_{T} intervals.
- D_s^+/D^+ ratio enhancement is more pronounced in backward rapidity.
- On average, D_s^+/D^+ ratio is consistent with ALICE measurements.
- This implies a modification of charm quark hadronization in high multiplicity pPb collisions.

LHCb *p*Pb: arXiv:2311.08490



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

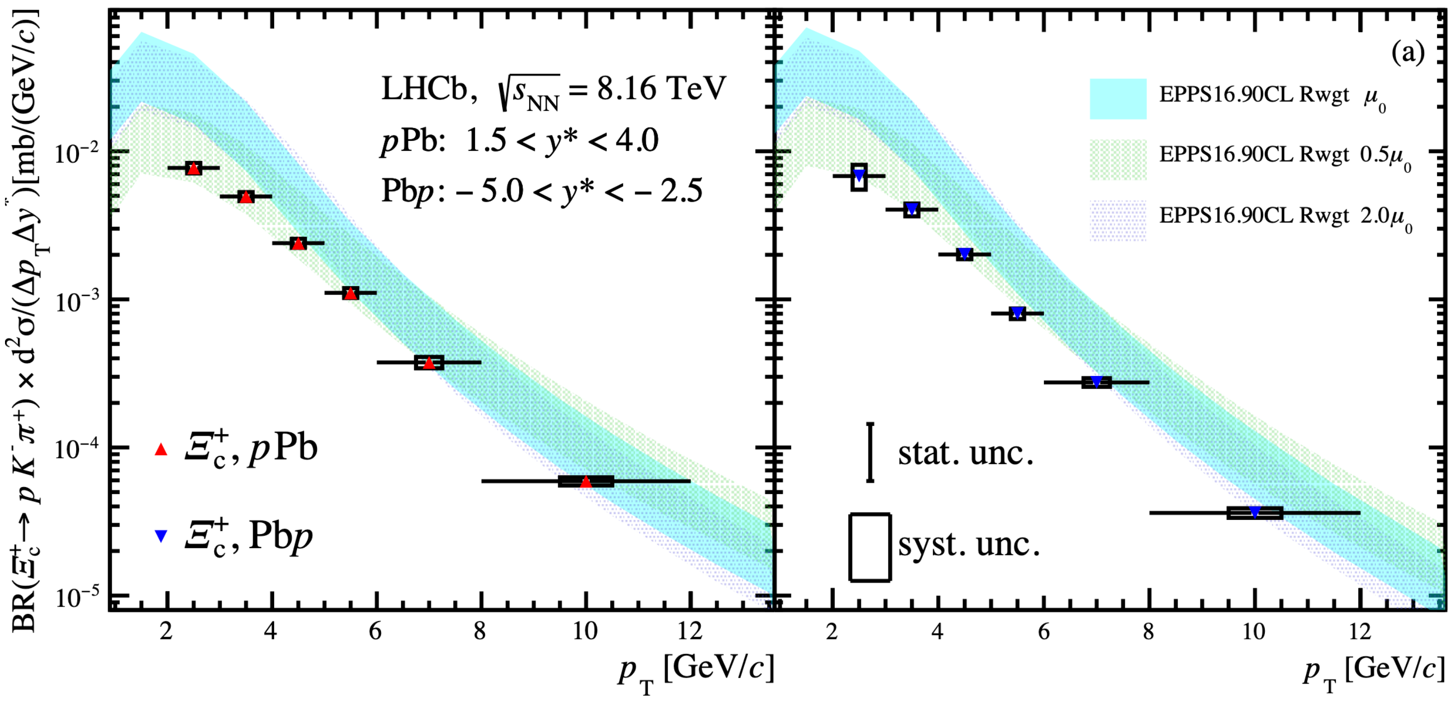
ALICE *p*Pb: JHEP 12 (2019) 092

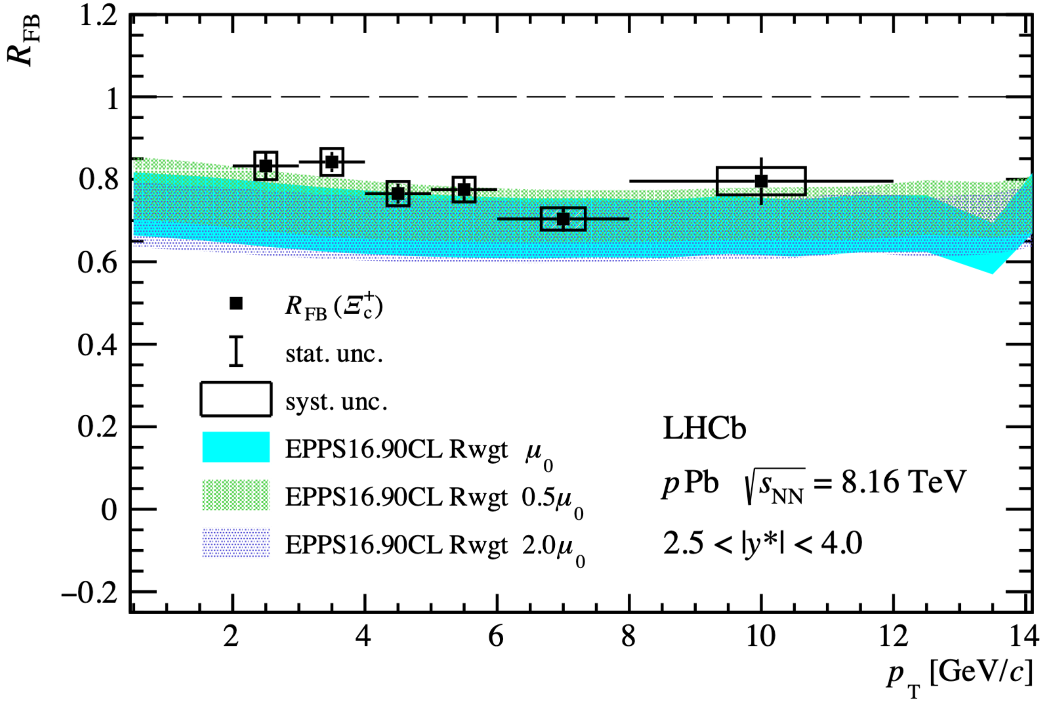


Ξ_c^+ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

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

LHCb *p*Pb: arXiv:2305.06711

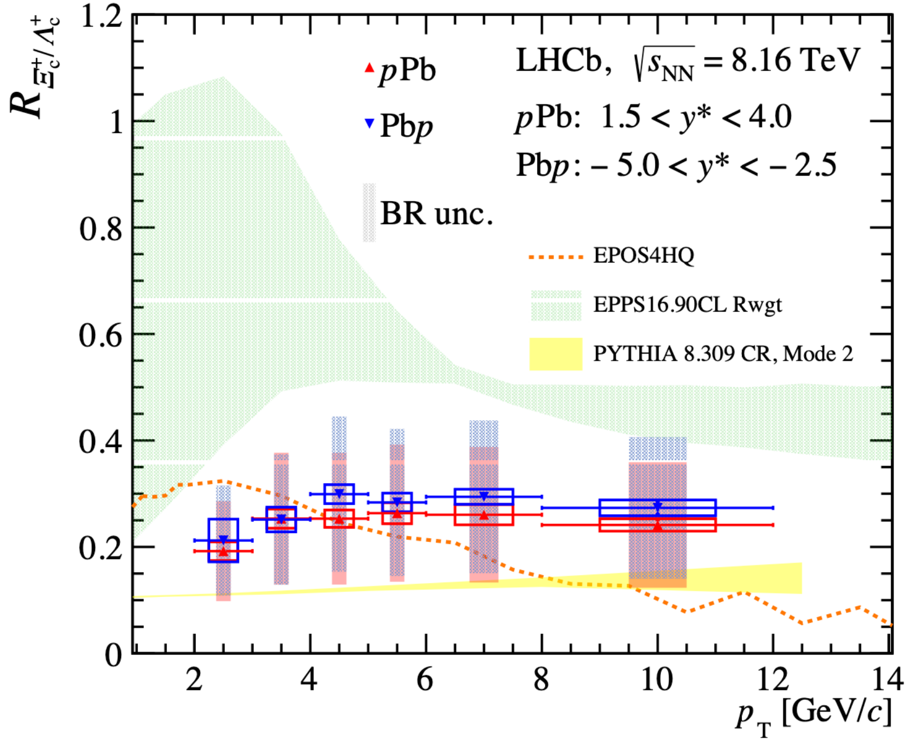


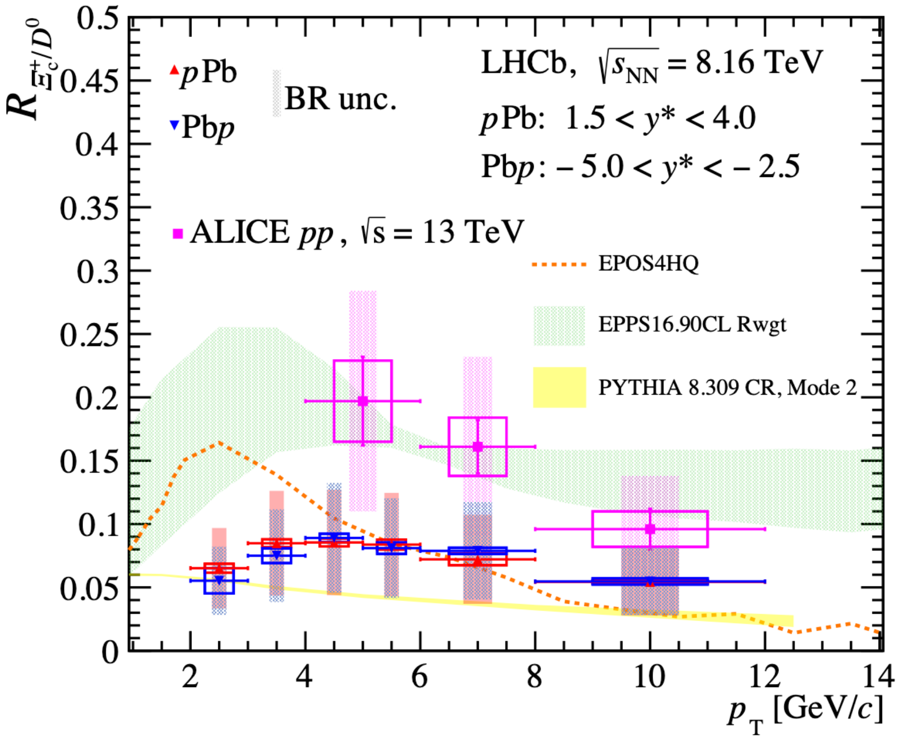


EPPS16: Phys.Rev.D 104 (2021) 1, 014010

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 forward and backward data samples. This indicates that same processes govern heavy quarks hadronization in forward and backward 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 significantly larger than LHCb data.





LHCb *p*Pb: arXiv:2305.06711

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

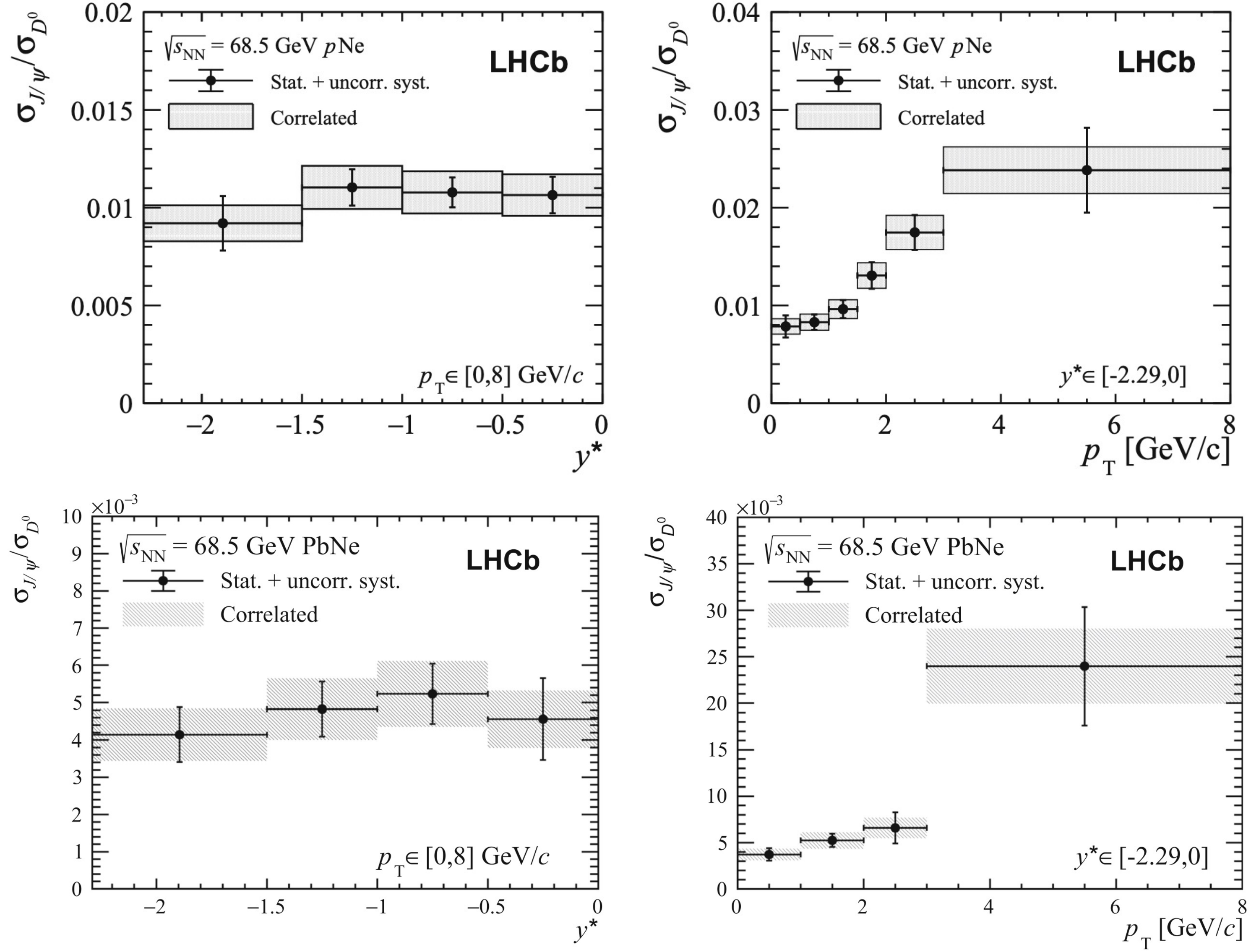
EPPS16: Phys.Rev.D 104 (2021) 1, 014010
EPOS4HQ: arXiv:2401.17096
Pythia8: JHEP 08 (2015) 003

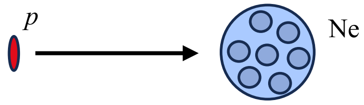
Summary

- LHCb has conducted measurements on D^0 and charmonium production in pNe and PbNe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 68.5 GeV. By comparing the $J/\psi/D^0$ in pNe and PbNe collisions, there are no conclusive evidence for anomalous suppression or the formation of a hot nuclear medium.
- The productions of D_s^+, D^+ and Ξ_c^+ are measured in pPb collisions and compared with theoretical calculations.
- LHCb has observed an enhancement of D_s^+/D^+, Λ_b^0/B^0 as a function of multiplicity. These indicate the modification of heavy quarks hadronization in pp and pPb collisions.
- The production ratios Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 study in pPb collisions. By comparing forward and backward results, it is suggested that they are governed by similar hadronization processes.

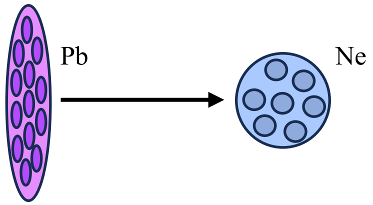
Thanks for listening!

$\sigma_{J/\psi}/\sigma_{D^0}$ cross-section ratios in pNe and PbNe collisions





- Measure $\sigma_{J/\psi}/\sigma_{D^0}$ ratios in different types collisions but with same $\sqrt{s_{NN}}$
- $\sigma_{J/\psi}/\sigma_{D^0}$ ratio show little dependence on y^* and a strong dependence on p_T



PbNe: EPJC 83 (2023) 658
***p*Ne:** EPJC 83 (2023) 625