Open heavy flavour production at LHCb

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1. Physics background
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3. Results
   - Study of initial-state effects
   - Study of hadronisation
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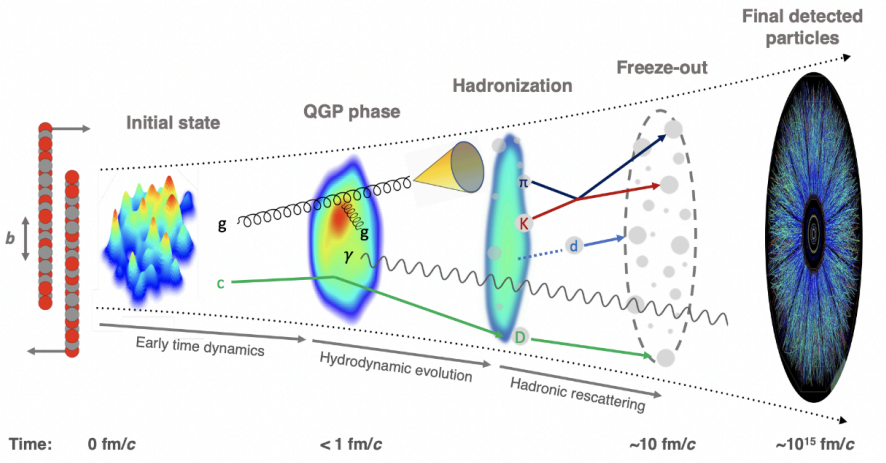
Heavy quarks in heavy-ion collisions

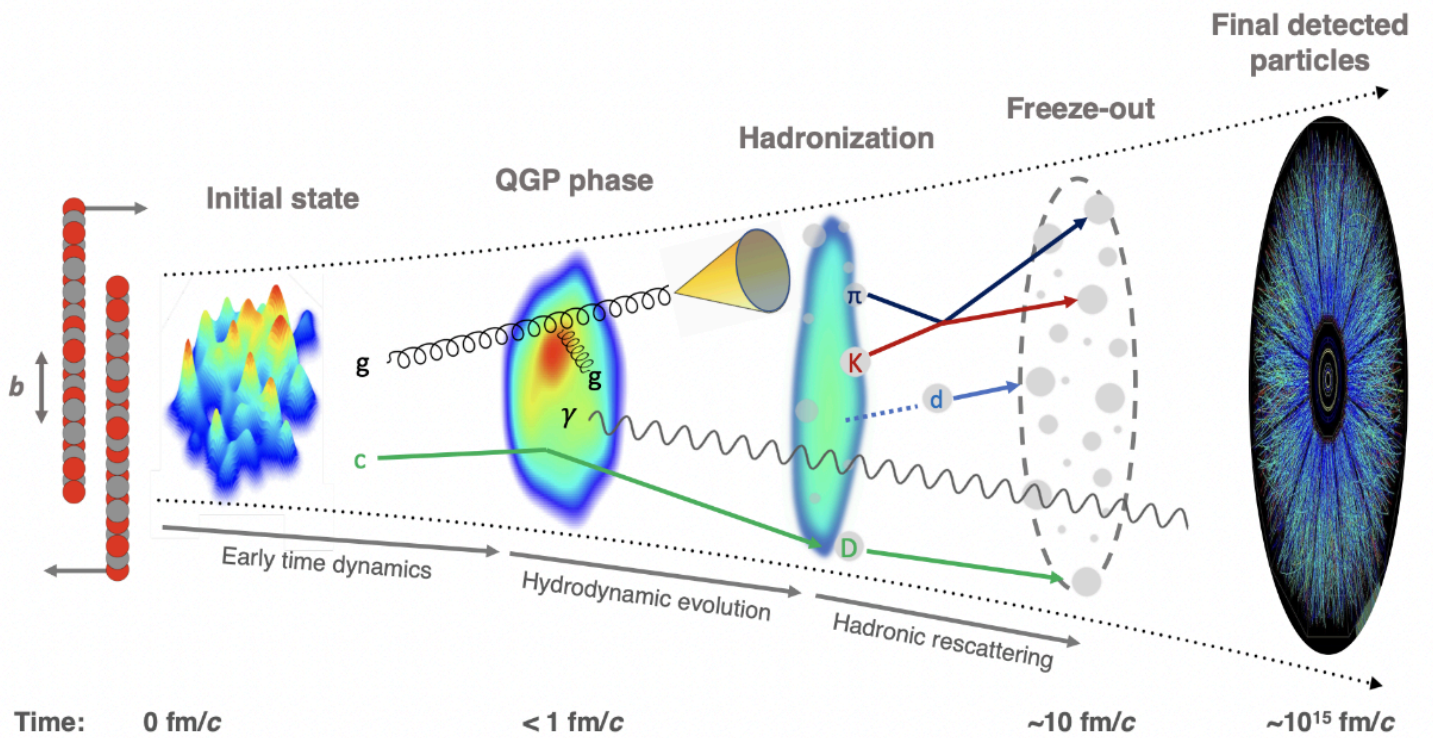


- Initial stages
- Pre-equilibrium
- Hydrodynamic evolution
- Freeze-out and post-equilibrium
- Final-state production

- Heavy quarks are excellent probes for studying nuclear matter in heavy-ion collisions
  - Produced in hard process at early stage of the collisions ($\tau \sim 1/m_Q$)
  - Can be predicted by perturbative QCD
  - Experience the whole evolution of QGP medium during their long lifetime

Nuclear matter effects

- Due to the presence of hot and cold nuclear matter, the production of heavy quarks in heavy-ion collisions exhibits different characteristics compared with pp collisions

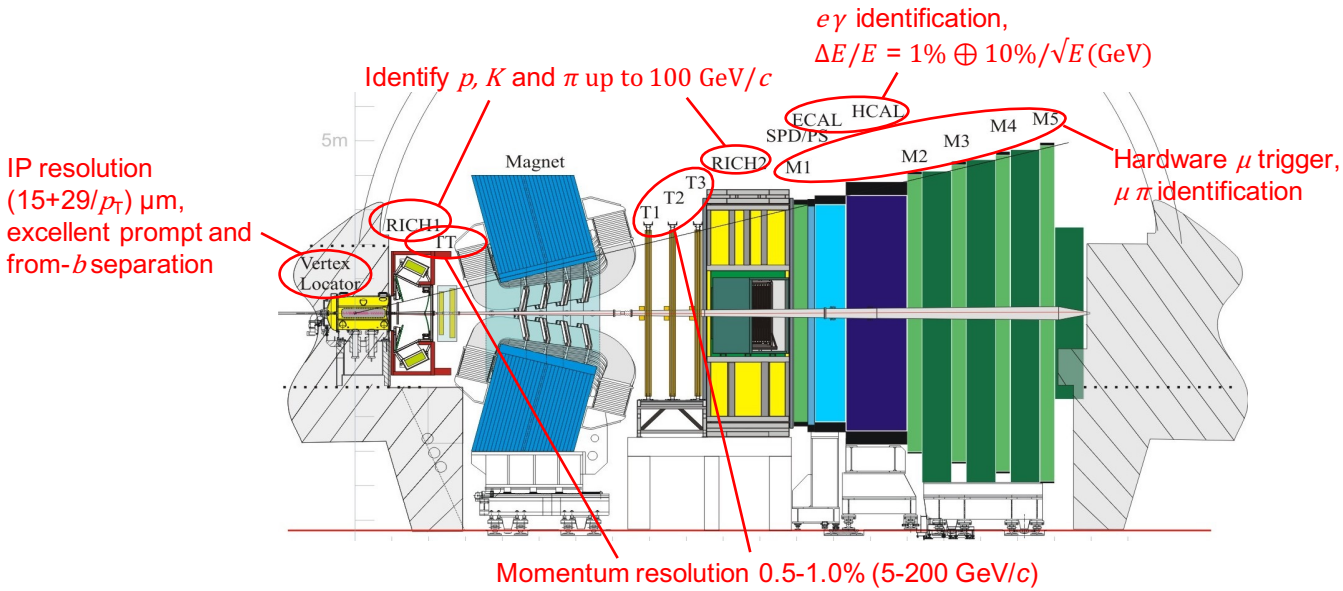


- Nuclear shadowing
- Gluon saturation
- Initial-state scattering
- Collective flow
- Parton energy loss
- Co-mover effect
- Colour screening
- Hadronisation mechanism
- Heavy quarkonium regeneration

LHCb detector

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

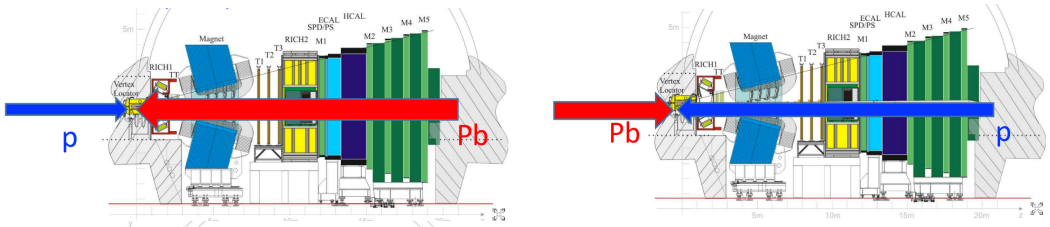
- Single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$
- Designed for studying particles containing b or c quarks
- Playing more and more important roles in heavy-ion physics



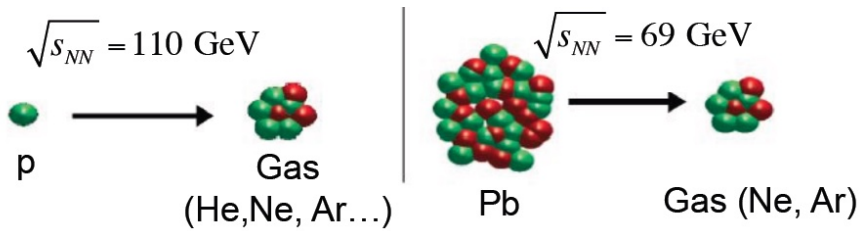
- Provide excellent vertex reconstruction and seperation, precise tracking, full PID, efficient and fast trigger, and unique acceptance for heavy-ion physics

LHCb detector and data sets

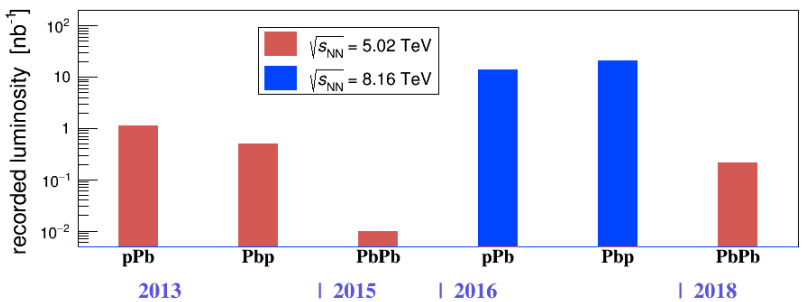
- Forward (pPb) and backward (Pbp) rapidities covered for pPb collisions

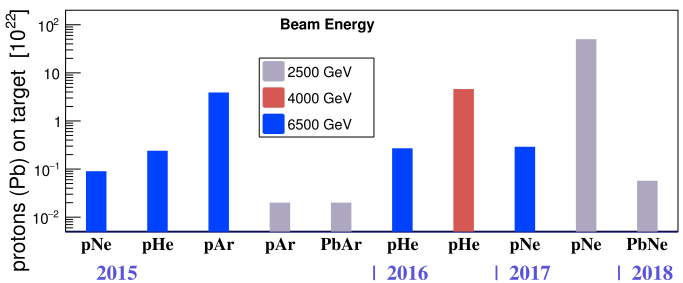


- Beam-gas fixed target mode can be aquired by injecting gases in VELO detector

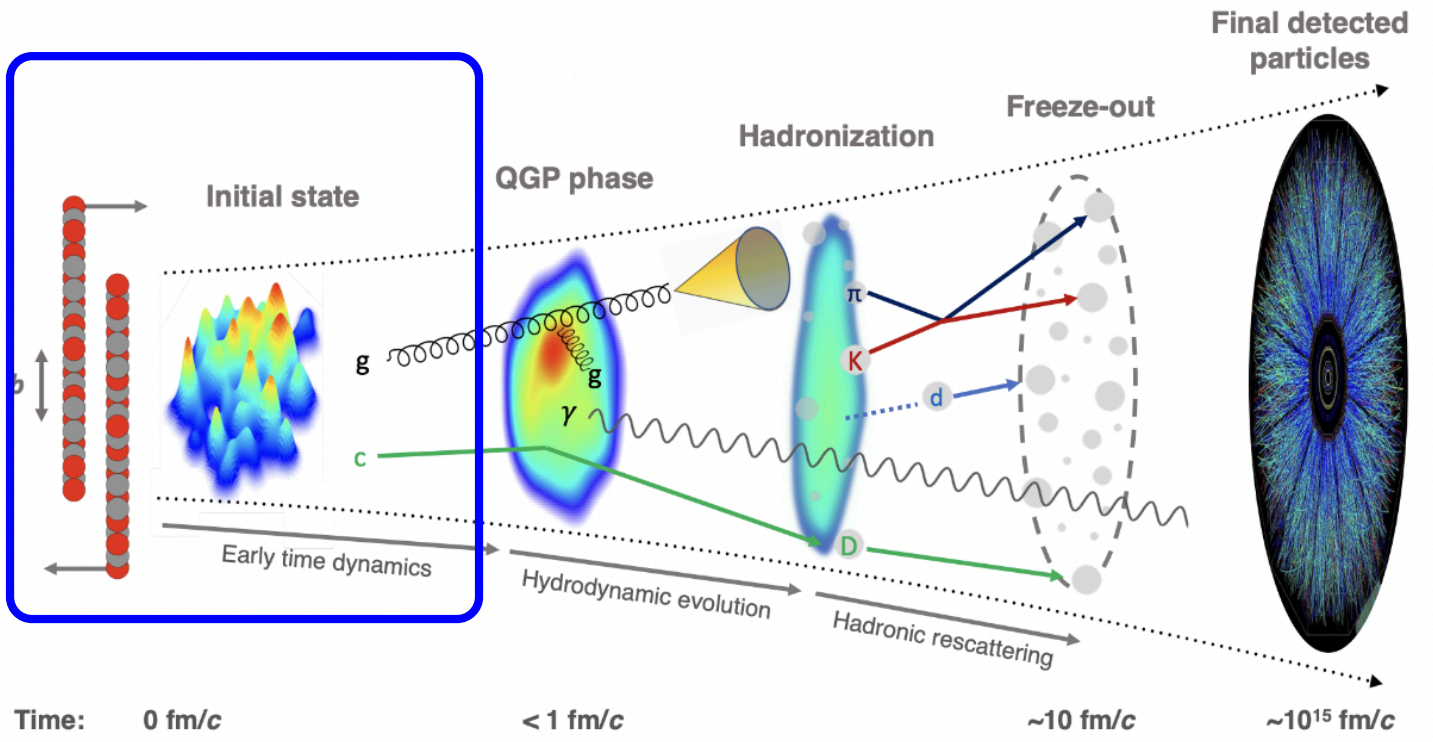


- Huge pp collision datasets for small-system studies





Study of initial-state effects



- **Nuclear shadowing**
- **Gluon saturation**
- **Initial-state scattering**
- Collective flow
- Parton energy loss
- Co-mover effect
- Colour screening
- Hadronisation mechanism
- Heavy quarkonium regeneration

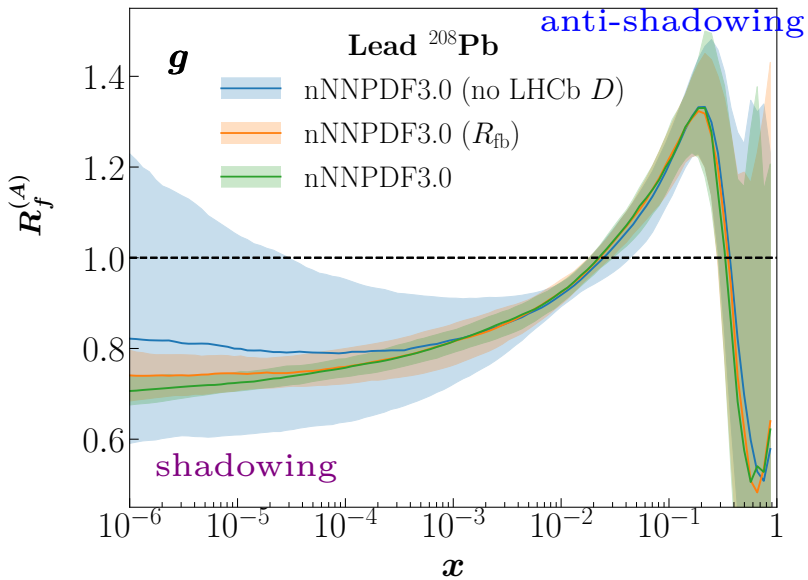
Modification of nuclear PDF (nuclear shadowing)

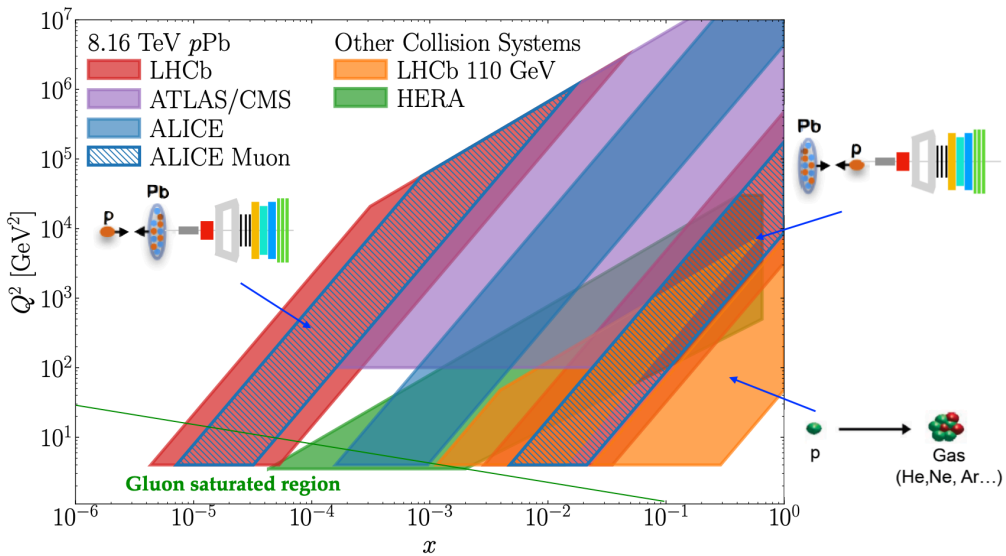
- Production cross section in hadronic collisions can be factorised as:

$$\sigma_{\text{hadronic}} = \sigma_{\text{partonic}}\left(x_i, z_j\right) \otimes \left\{\prod_i f_{i,h_i}\left(x_i\right)\right\} \otimes \left\{\prod_j D_{h_j/j}\left(z_j\right)\right\}$$

- Nuclear matter effects dominated by modification of gluon nPDF

EPJC82(2022)6,507





- Nuclear modification factor suppressed at small Bjorken-x region (shadowing), and enhanced at $x \sim 0.1$ region (anti-shadowing)
- LHCb covers unique kinematic regions of low-x (pPb), medium-x (Pbp) and large-x (fixed target) regions

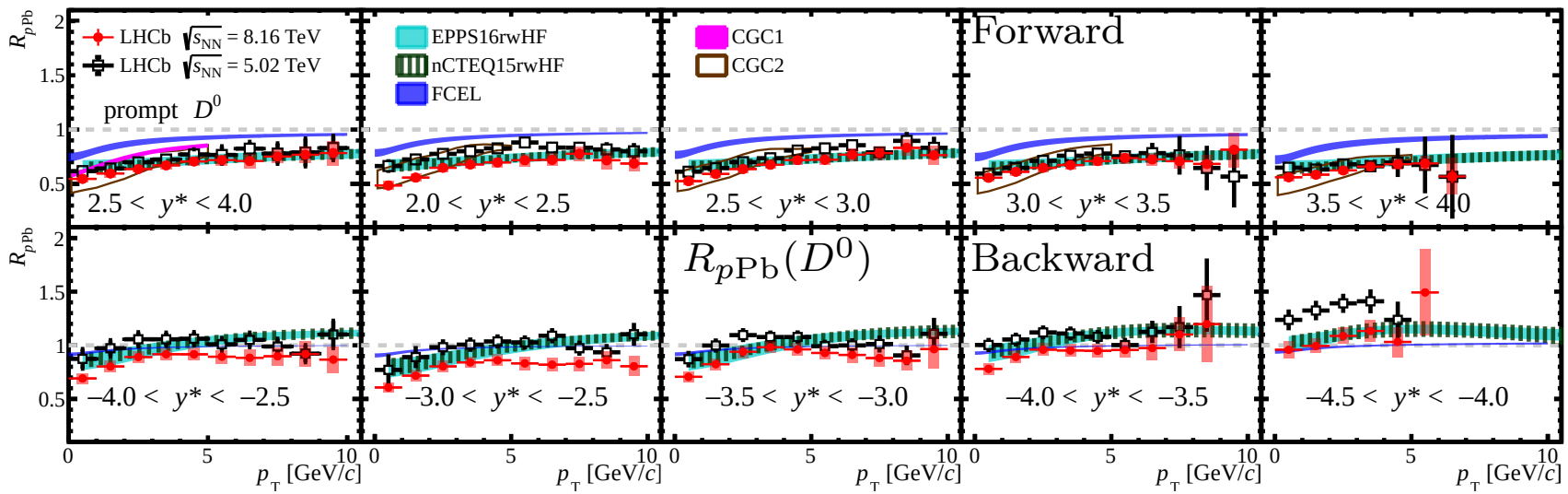
Nuclear modification factor $R_{p\mathrm{Pb}}$

- Other effects canceled by making ratios in pPb and pp collisions

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) = \frac{1}{208} \frac{\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)}{\sigma_{pp}(p_{\mathrm{T}}, y^*)}$$

- $R_{p\mathrm{Pb}}(D^0)$ at $\sqrt{s} = 8.16\,\mathrm{TeV}$

LHCb D^0: JHEP 10 (2017) 090
EPPS16 : EPJC 77 (2017) 3, 163
nCTEQ15 : PRD 93 (2016) 8, 085037
FCEL: JHEP 01 (2022) 164
CGC1: Nucl.Phys.Proc 2017, 289-290
CGC2: PRD 98 (2018) 7, 074025



- Generally consistent with nPDF description at forward and backward rapidities
- Stronger suppression observed in the low-p_{T} region at forward rapidity, hinting at possible additional gluon saturation and initial-state energy loss effects
- Indications of suppression compared to theory in the moderate-p_{T} region at backward $y^* > -3.5$, suggesting possible final-state effects such as multiple parton scattering and final-state energy loss [PLB 740 (2015) 23]

$R_{p\mathrm{Pb}}(D^+)$ and $R_{p\mathrm{Pb}}(D_s^+)$

- $R_{p\mathrm{Pb}}(D^+)$ and $R_{p\mathrm{Pb}}(D_s^+)$ at 5.02 and 8.16 TeV

LHCb D^0: JHEP 10 (2017) 090
EPPS16 : EPJC 77 (2017) 3, 163
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CGC1: Nucl.Phys.Proc 2017, 289-290
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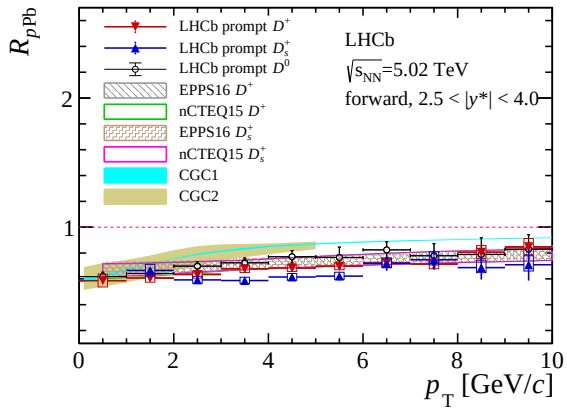
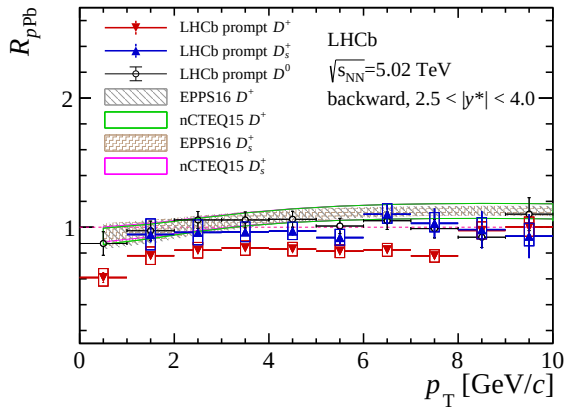
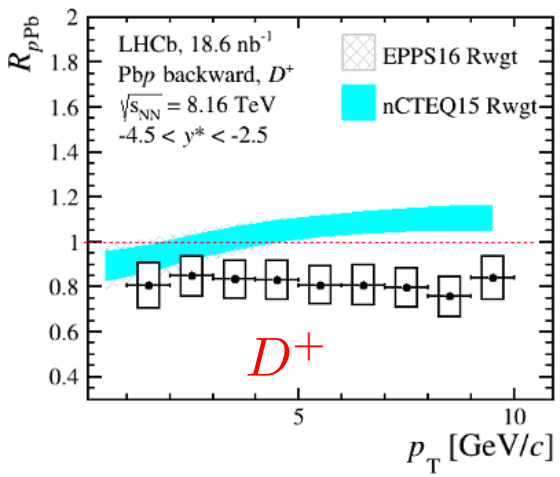
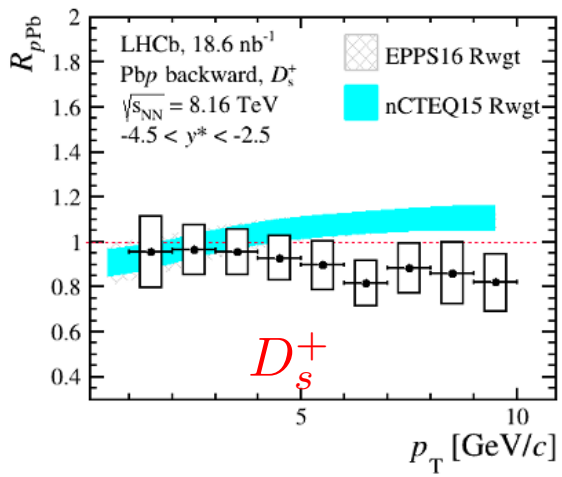






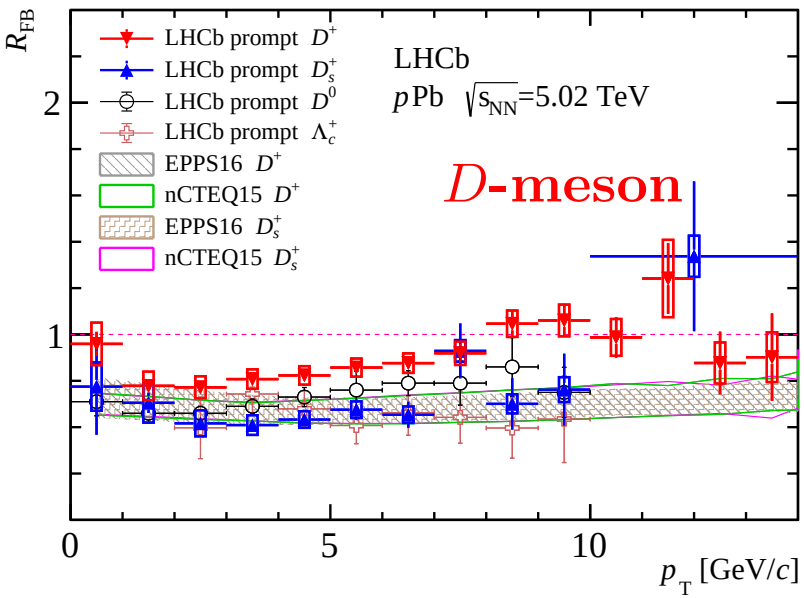


- Suppressed at low p_T at forward rapidity for all charm mesons, consistent with nuclear shadowing expectations
- Slight differences between hadron species at backward, hinting at possible final-state effects

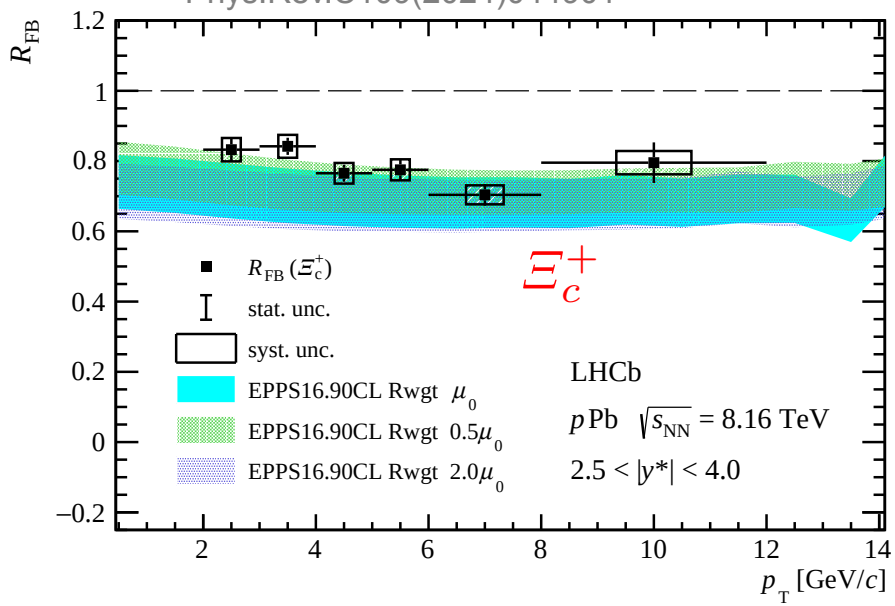
Forward-backward production ratio

- Forward-backward production ratio can be calculated without pp reference

JHEP01(2024)070

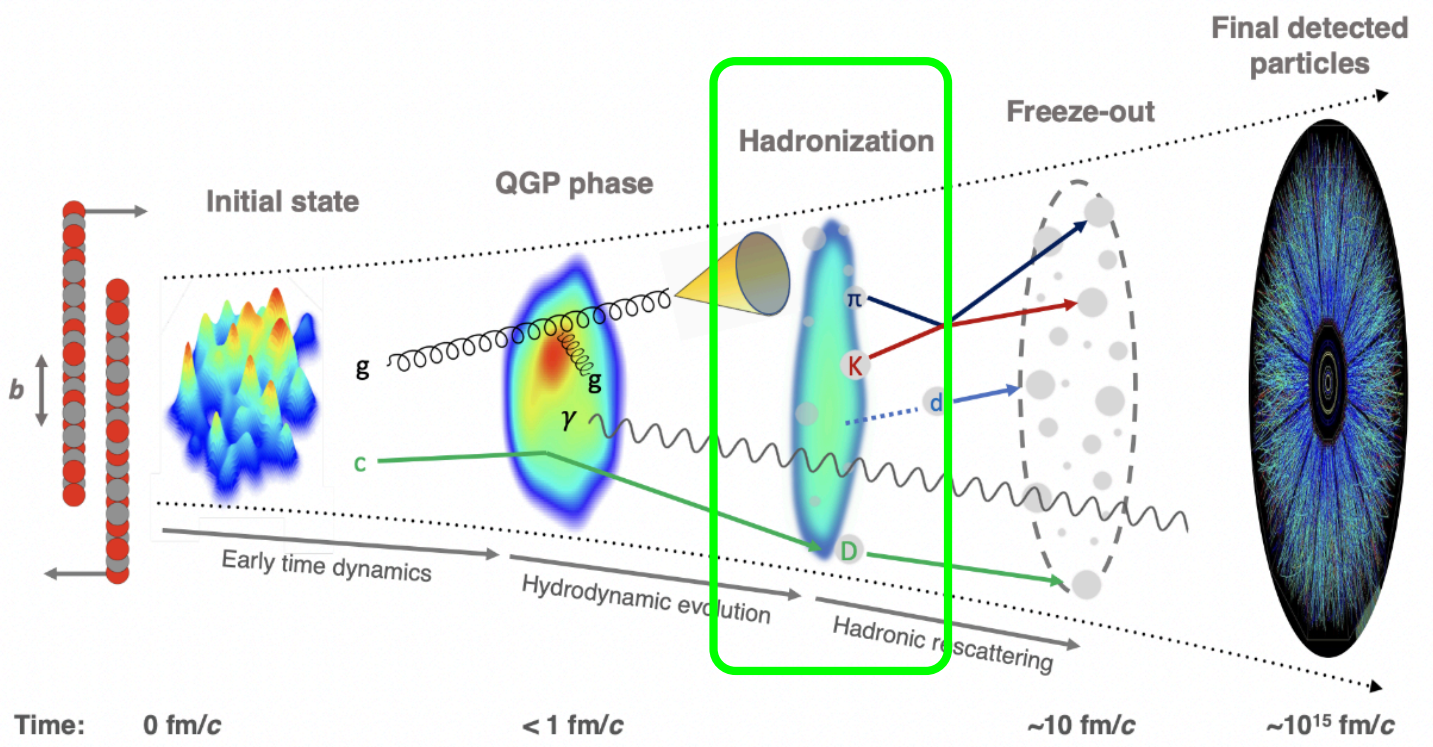


Phys.Rev.C109(2024)044901



- The suppression at forward rapidity well reproduced by nPDF predictions
- Different trends towards high p_T for different hadrons

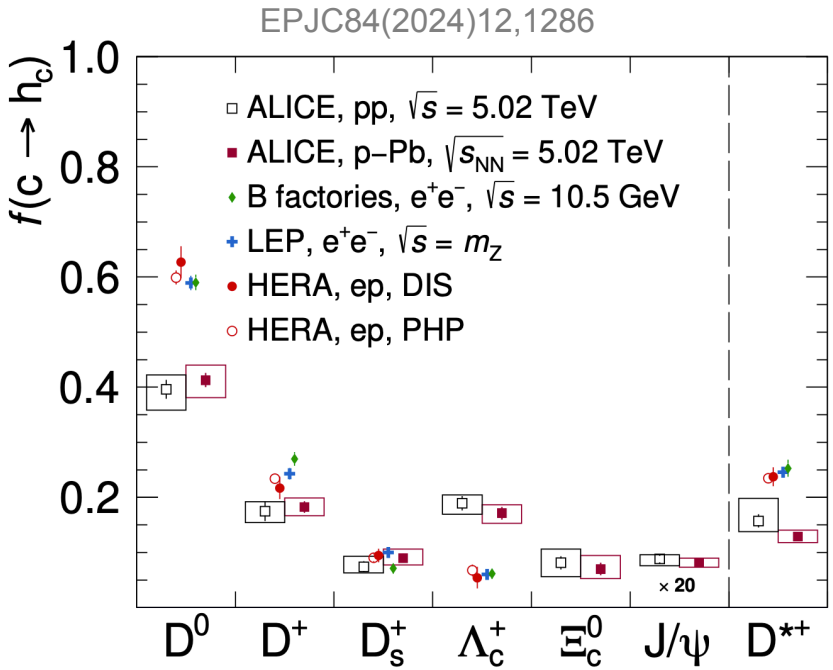
Study of hadronisation

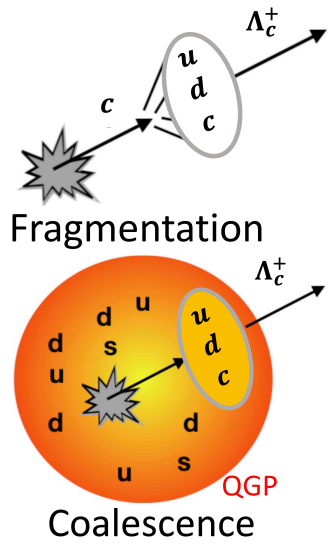


- Nuclear shadowing
- Gluon saturation
- Initial-state scattering
- Collective flow
- Parton energy loss
- Co-mover effect
- Colour screening
- **Hadronisation mechanism**
- Heavy quarkonium regeneration

Modification of hadronisation

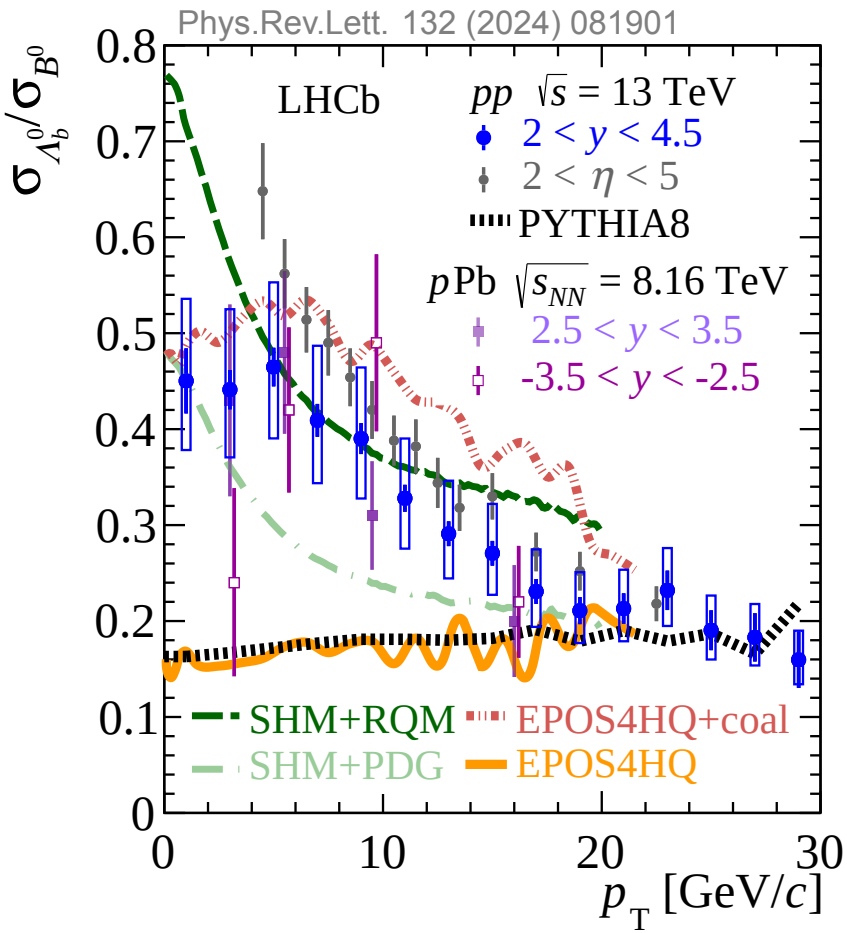
- Fragmentation universality expected across all collision systems
  - Different fragmentation fraction observed





- In high-density medium, quarks can hadronise via coalesence mechanism
  - Strangeness enhancement (abundent $s\bar{s}$ pairs in medium)
  - Higher baryon to meson ratio

Λ_b^0/B^0 ratio versus p_{T}

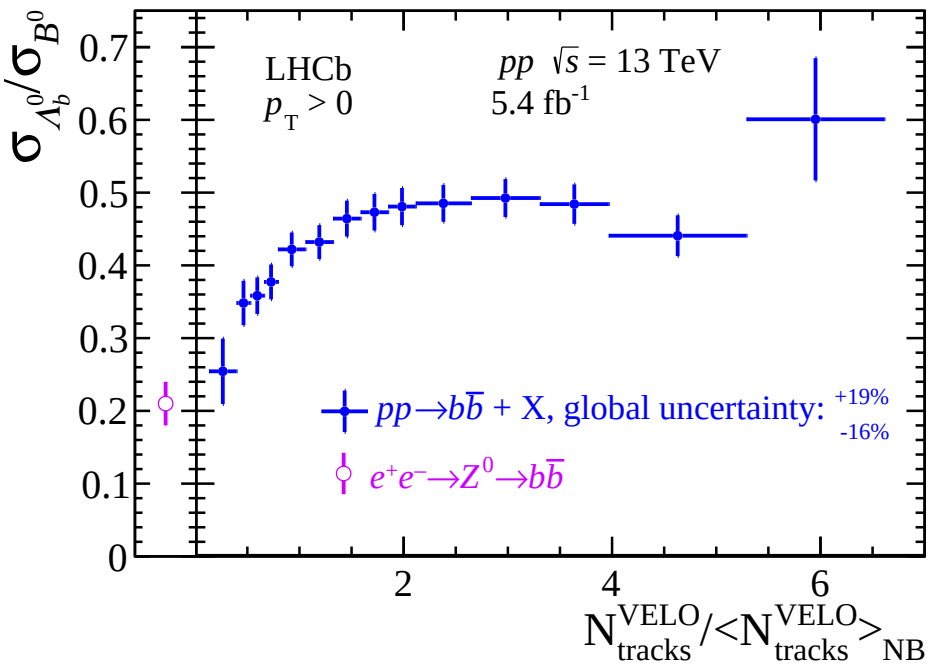


LHCb pp: Phys.Rev.D 100, 031102(R) (2019)
LHCb pPb: Phys.Rev.D 99, 052011 (2019)
SHM: Phys.Rev.Lett. 131, 012301 (2023)
EPOS4HQ: Phys.Rev.D 109 (2024) 5, 054011
PYTHIA8: Comput.Phys.Commun. 178, 852 (2008)

- $R_{\Lambda_b^0/B^0}$ enhanced at low p_{T} observed, where coalesence is expected to dominate
- In agreement with previous LHCb pp and pPb measurements
- Statistical hadronisation model (SHM) with relativistic quark model (RQM) gives better description than with PDG data by considering Λ_b^0 feed-down from excited baryons
- EPOS4HQ reproduces the enhancement at low p_{T} by incorporating coalescence

Λ_b^0/B^0 ratio versus multiplicity

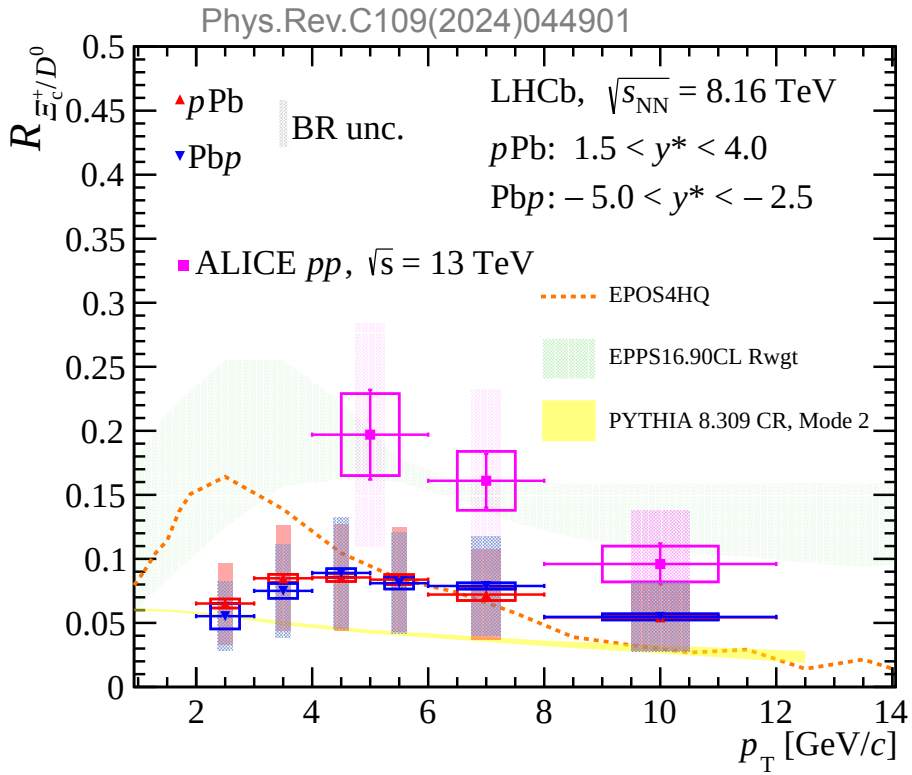
Phys. Rev. Lett. 132 (2024) 081901



- $R_{\Lambda_b^0/B^0}$ reach e^+e^- result as multiplicity goes lower
- Significant increasing trend of Λ_b^0/B^0 with multiplicity, suggesting the contribution from coalescence in addition to fragmentation in b quark hadronisation

Ξ_c^+/D^0 production ratio

- Hadronisation in heavy-ion collisions studied with baryon-to-meson ratio



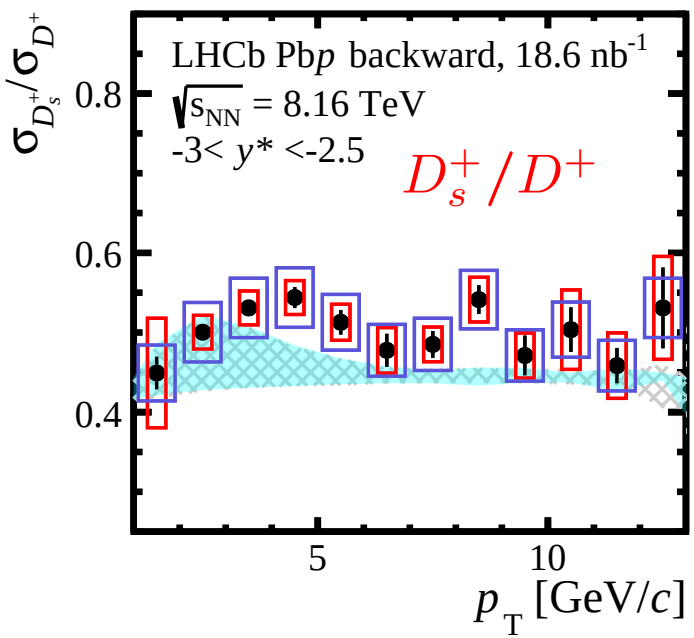
- No significant dependence on p_{T} of $R_{\Xi_c^+/D^0}$, different from enhancement observed in Λ_b^0/B^0 at LHCb pp
- Discrepancy with ALICE results, hinting at rapidity dependence of the ratio

Strangeness ratio with p_{T}

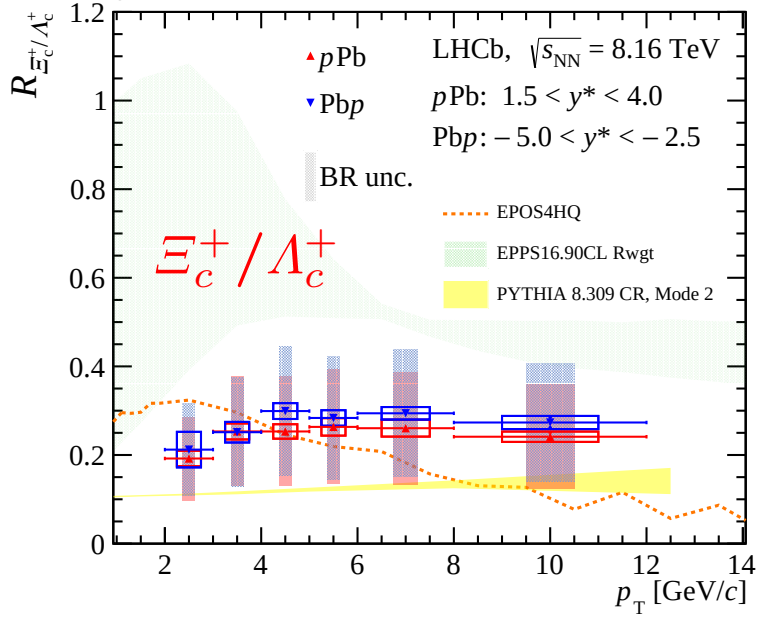
- Strangeness enhancement considered as a QGP signature
- Seen in high multiplicity small systems by ALICE Ω $(\Xi)/\pi$ and LHCb B_s^0/B^0

  $D^+ : c\bar{d}$ $D_s^+ : c\bar{s}$ $\Lambda_c^+ : cud$ $\Xi_c^+ : cus$

Phys.Rev.D110(2024)L031105



Phys.Rev.C109(2024)044901

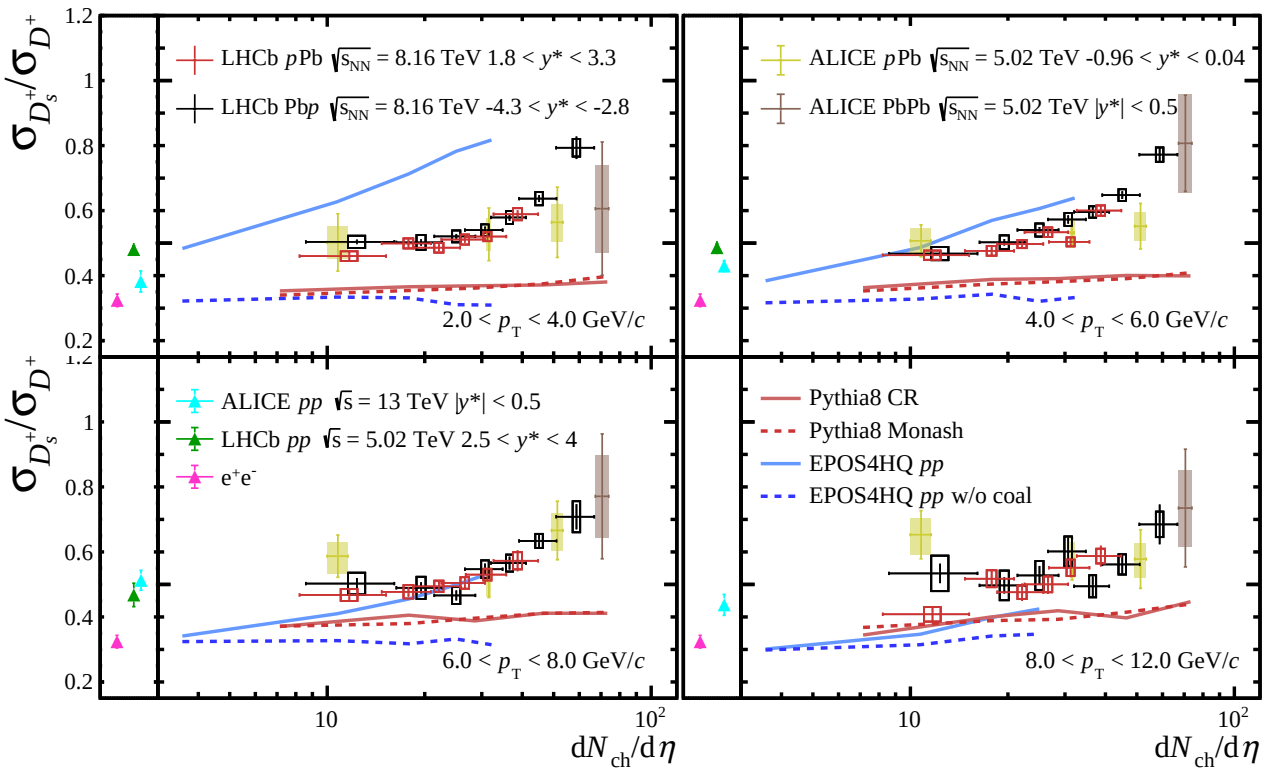


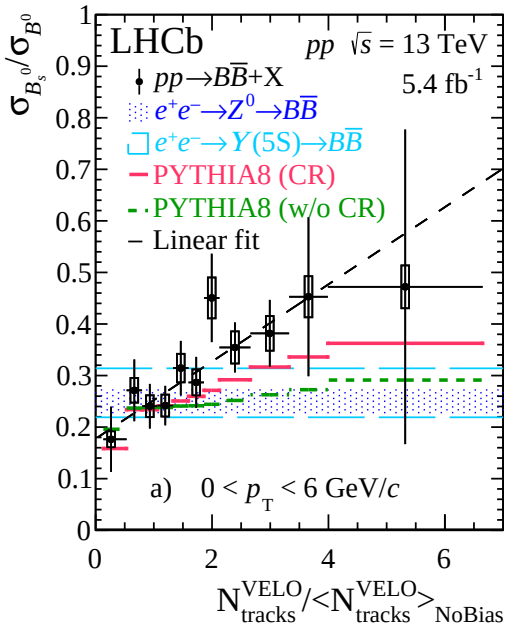
- No signficant dependence on p_{T} for multiplicity-integrated ratios

D_s^+/D^+ production ratio with multiplicity

- **First observation** of strangness enhancement for charm production in small systems, consistent with the evidence from B_s^0/B^0 ratio

Phys.Rev.D110(2024)L031105 Phys.Rev.Lett.131(2023)061901

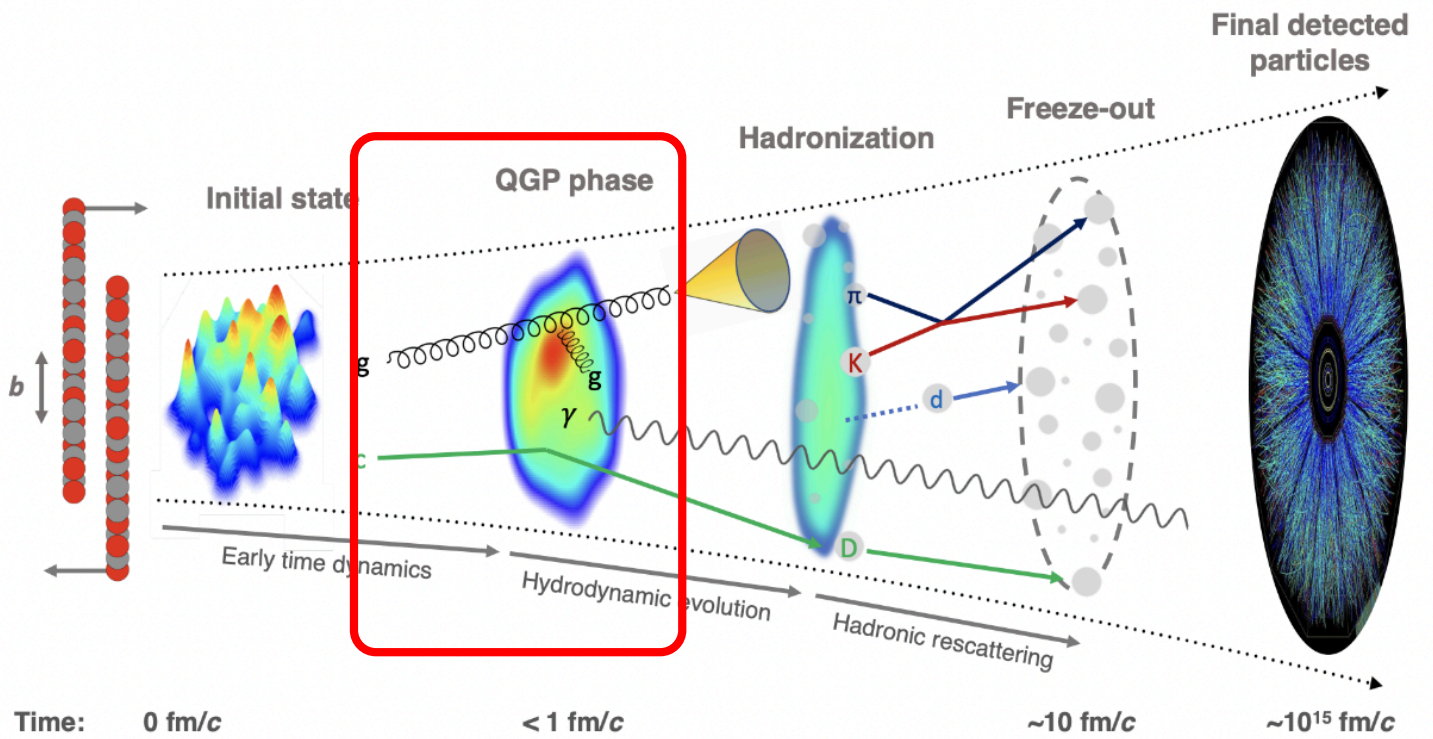




- Consistent trend in different rapidity regions, as well as with ALICE results
- Coalescence contribution need to be considered for a better description of data points

Prospect: collective flow

- Collective flow considered an excellent probe to study both initial geometry and hydrodynamic properties of the medium
- Measurement of heavy-flavour hadron flow at LHCb on the way ...



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- **Collective flow**
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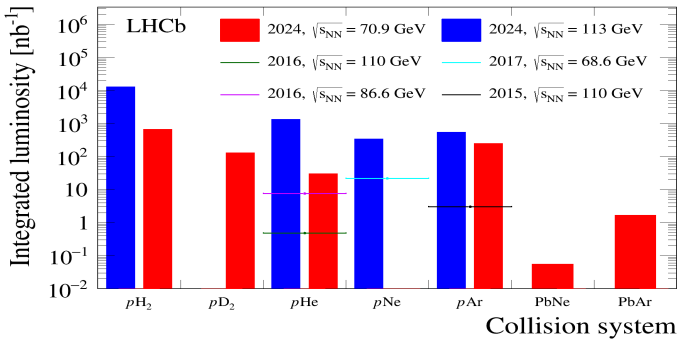
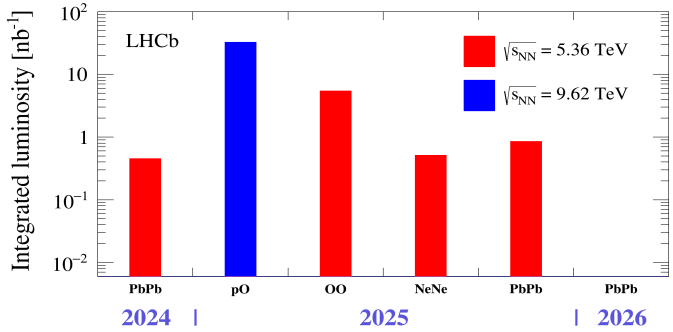
- Heavy quarkonium regeneration

Prospect: heavy flavour data in Run3

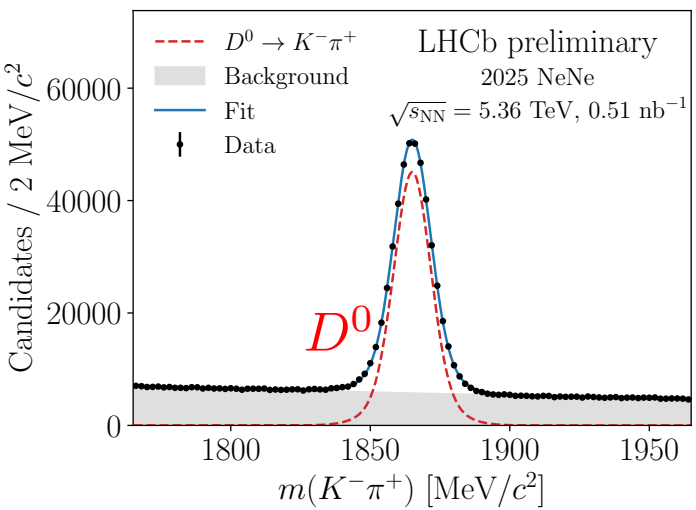
- Large samples collected for both colliding and fixed-target modes

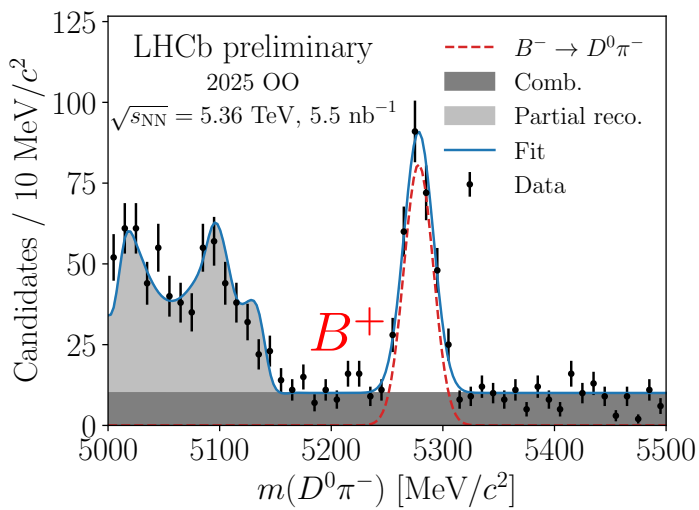




- Clear D^0, B^+ peaks in OO and NeNe collisions

LHCb-FIGURE-2025-017





Summary

- Heavy quarks are sensitive to nuclear matter effects in heavy-ion collisions
- LHCb provide unique access to probes of nuclear matter with heavy-flavour production
  - Nuclear shadowing: $R_{p\mathrm{Pb}}$ and R_{FB}
  - Hadronisation: Λ_b^0/B^0, D_s^+/D^+, Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0
- Stay tuned for more results with newly collected Run3 data!

Thank you for listening