Open-charm production in pPb collisions with the LHCb experiment

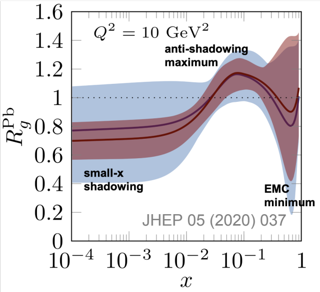
Jianqiao Wang
on behalf of the LHCb collaboration

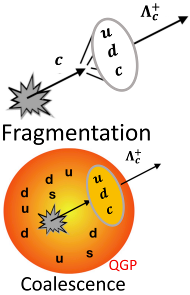
Spicy Gluons 2024 workshop

May 21, 2024

Charm quark in heavy-ion collisions

- Charm quarks are excellent probes in heavy-ion collisions
  - Large quark masses allow perturbative QCD calculation
  - Sensitive to the nuclear medium due to their long lifetime
- Related nuclear matter effects
  - Nuclear shadowing
  - Gluon saturation
  - Strangeness enhancement
  - Modification of baryon-to-meson ratio (fragmentation / coalescence)

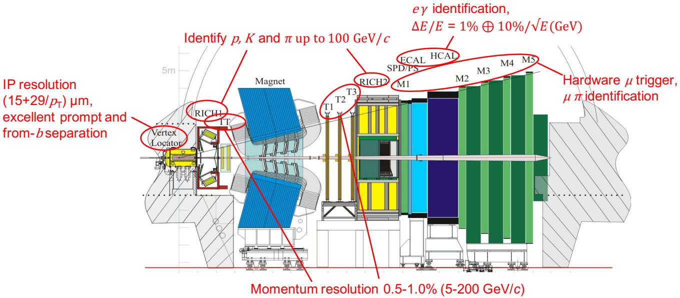




LHCb detector in Run2

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
- A general purposed detector collecting pp/pPb/PbPb data, providing unique fix-target mode at the LHC

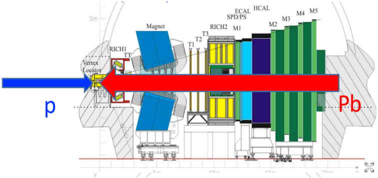


- Provide excellent track finding, vertex reconstruction and particle identification (PID)

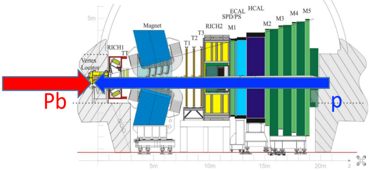
LHCb pPb data

- Asymmetric pPb data taken in 2013 and 2016, two collision configurations.

pA: forward



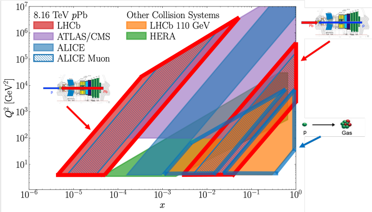
Ap: backward



- $\sqrt{s_{\mathrm{NN}}} = 5.02$ and $8.16\,\mathrm{TeV}$
- Boosted in lab frame by 0.465
- Rapidity coverage:

$$pA : 1.5 < y^* < 4.0$$
$$Ap : -5.0 < y^* < -2.5$$

- (x, Q^2) coverage



Analysis strategy

- Double-differential cross-section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} \equiv \frac{N}{\mathcal{L} \times \varepsilon_\mathrm{tot} \times \mathcal{B} \times \Delta p_\mathrm{T} \times \Delta y^*} \ ,$$

  - Prompt yield N and efficiency ε_tot to be determined
  - Integrated luminosity $\mathcal{L}$ and branching fraction $\mathcal{B}$ already known

- Nuclear modification factor

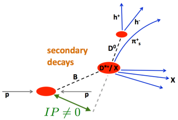
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} \ ,$$

- Forward-backward production ratio:

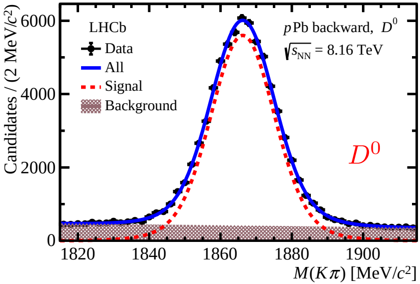
$$R_\mathrm{FB}\ (p_\mathrm{T}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, +|y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_\mathrm{T}, -|y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} \ .$$

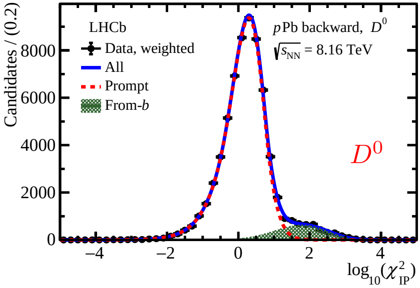
Cross-section determination

- Production mechanisms different for charm and beauty quarks. Necessary to separate prompt and from-b charm hadrons
- Fit to impact parameter (IP) for prompt yield extraction ($\chi^2_{\rm IP} \sim {\rm IP}/\sigma_{\rm IP}$)



Phys.Rev.Lett. 131 (2023) 10, 102301





- Efficiency $\varepsilon_{\rm tot}$ estimated with simulation samples

Prompt D^0 production

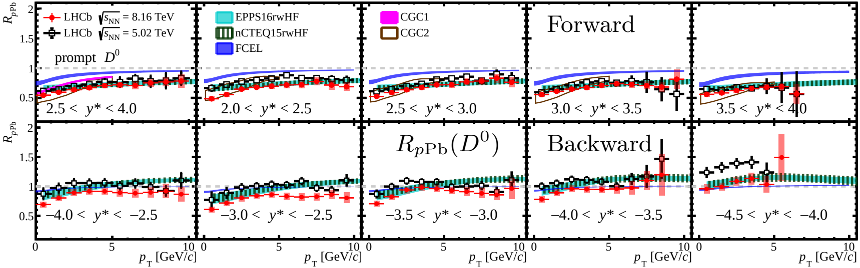
D^0 nuclear modification factor

Phys. Rev. Lett. 131 (2023) 102301

- pp reference obtained from interpolation on LHCb 5 TeV and 13 TeV D^0 results
- In general agreement with nPDF and CGC calculations

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

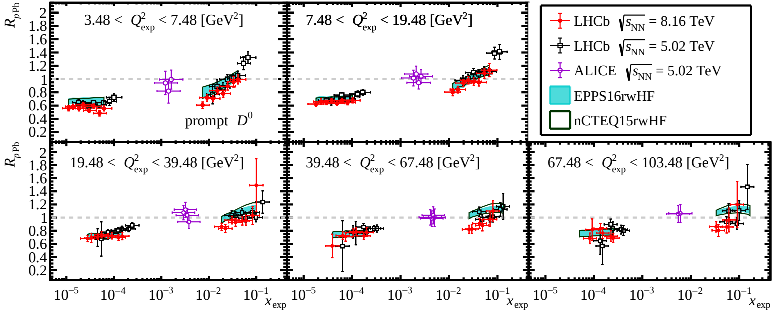


- More suppressed $R_{p\mathrm{Pb}}$ at forward low p_T, possibly attributed to FCEL effects
- Discrepancy of $\sim 2.0 - 3.8\sigma$ in high p_T at backward, indicating additional initial / final-state effects

D^0 nuclear modification factor in (x, Q^2)

- The experimental proxies $x_{\rm exp}$ and $Q^2_{\rm exp}$ used for comparing results in different energy and kinematic regions

$$x_{\rm exp} \equiv 2\frac{\sqrt{p_{\rm T}{}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\rm NN}}} e^{-y^*} \text{ and } Q^2_{\rm exp} \equiv p_{\rm T}{}^2(D^0) + M^2(D^0)$$



- Consistency between LHCb results at 5.02 TeV and 8.16 TeV in (x, Q^2) space
- Stronger suppression than nPDF calculations in $x \sim 0.01$ at larger Q^2

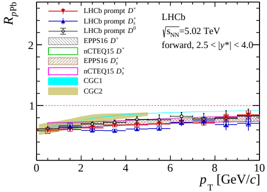
Prompt D^+ and D_s^+ production

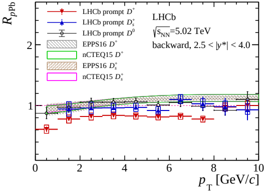
D^+ and D_s^+ nuclear modification factor

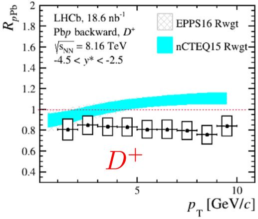
5TeV: JHEP 01 (2024) 070
8TeV: arXiv:2311.08490

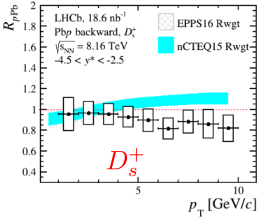
- *pp* reference derived from LHCb 5 TeV and 13 TeV D^+ and D_s^+ results

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







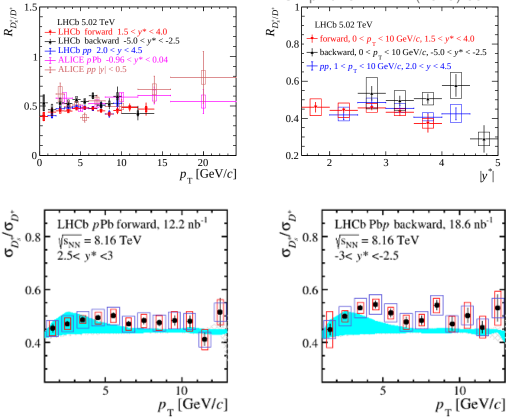


- Significant suppression at forward due to modification of nPDFs
- More suppressed $R_{pPb}(D^+)$ at backward rapidity than $R_{pPb}(D_s^+)$

D_s^+/D^+ production ratio in p_{T} and y^*

- Strangeness enhancement considered as an important QGP signature
- Possible strangeness enhancement seen in high multiplicity small-system collisions by ALICE Ω $(\Xi)/\pi$ and LHCb B_s^0/B^0

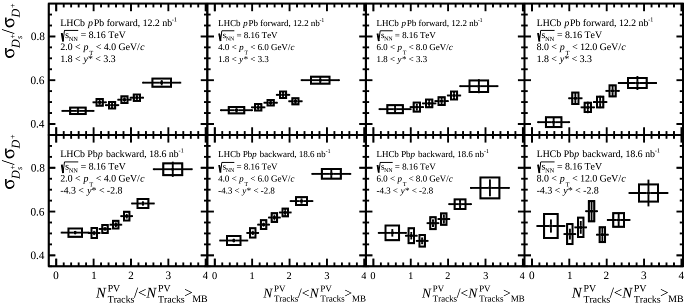
LHCb pp : JHEP 06 (2017) 147
ALICE pp: EPJC 79 (2019) 388
ALICE pPb: JHEP 12 (2019) 092



- Slightly higher D_s^+/D^+ ratios at backward rapidity, where event multiplicity is larger
- Limitted by statistics for 5 TeV
- Invesigation on D_s^+/D^+ dependence on system size needed

D_s^+/D^+ production ratio versus multiplicity at 8 TeV

- $N_{\text{Tracks}}^{\text{PV}}$: number of (primary) tracks for PV reconstruction



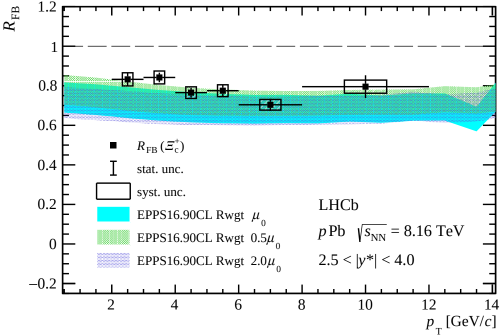
- Increasing trend with multiplicity for D_s^+/D^+ ratio across all p_{T} intervals
- More pronounced strangeness enhancement at intermediate p_{T} ($2<p_{\text{T}}$ $<6\,\text{GeV}/c$) and in backward rapidity
- Indicate modification of charm quark hadronization in high multiplicity pPb

Prompt Ξ_c^+ production

Ξ_c^+ forward-backward production ratio

Phys. Rev. C 109 (2024) 044901

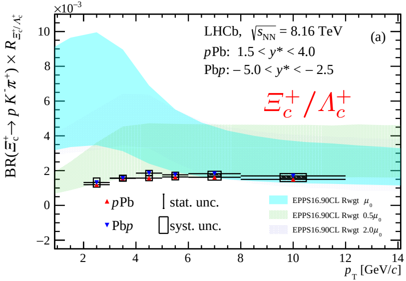
- **First** measurement of Ξ_c^+ baryons in heavy-ion collisions, powerful probe of strangeness enhancement and hadronization
- Measured in the common integrated rapidity region $2.5 < |y^*| < 4.0$

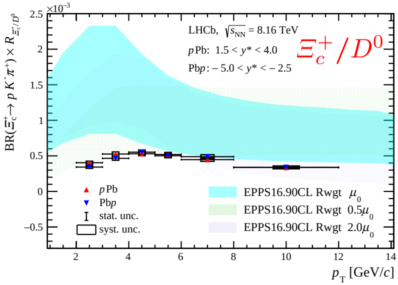


- The suppression at forward well reproduced by nPDF models

Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 production ratio

- Similar final-state channels $\Xi_c^+[usc](\Lambda_c^+[udc]) \to pK^-\pi^+$ employed
- Production ratios multiplied by the branching fraction due to large $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ uncertainty





- No significant dependence on p_T of $R_{\Xi_c^+/\Lambda_c^+}$ and $R_{\Xi_c^+/D^0}$
- In agreement with HELAC-onia calculation incorporating EPPS16 nPDF

Summary and prospect

- Charm quarks are sensitive to nuclear matter effects in heavy-ion collisions, and the LHCb experiment has strong capabilities to studying them
  - Nuclear shadowing and forward-backward production asymmetry observed for all species of charm hadrons
  - Tension between prompt D^0 $R_{p\mathrm{Pb}}$ and nPDF predictions in high p_{T} at backward rapidity at 8.16 TeV
  - First observation of strangeness enhancement in charm quark production in small systems, suggesting the contribution from coalscence
  - First measurement of Ξ_c^+ baryons in pPb, compared with D^0 and Λ_c^+ production
- Λ_c^+/D^0, D^*/D^0 and charm hadron v_2 under progress, for a better understanding of hadronization in small systems
- Data samples with larger statistics and higher multiplicity available, thanks to Run3 data-taking and LHCb upgrade

Thanks

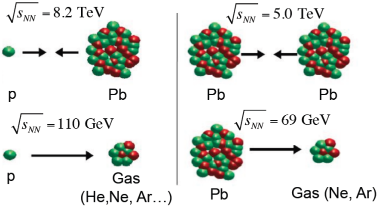
Backups

LHCb heavy-ion data

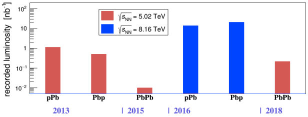
- LHCb beam configurations

Collider mode

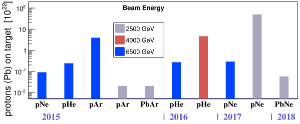
Fixed target mode



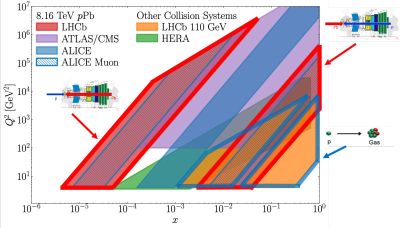
- Data sets
  - Collider mode



  - Fix-target mode

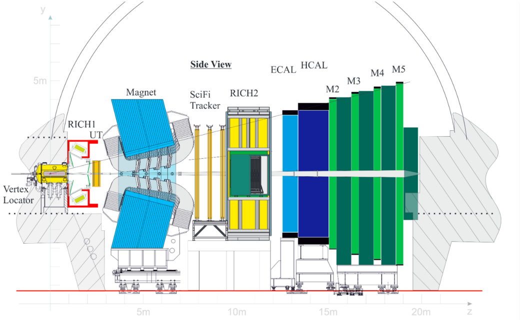


- Kinematic coverage



LHCb detector at Run3

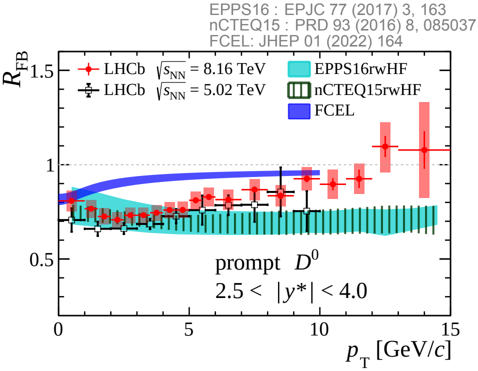
CERN-LHCC-2012-007



- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- New tracking system:
  - Silicon upstream detector (UT)
  - Scintillating tracking fibre (SciFi)
- Full software trigger:
  - Remove L0 triggers
  - Read out the full detector at 40 MHz

D^0 forward-backward production ratio

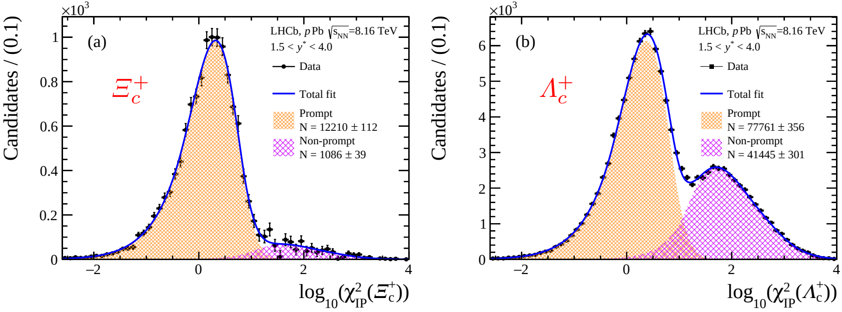
- Forward-backward production ratio R_{FB} versus p_{T}



- Significant production asymmetry at low p_{T}
- Rising trend towards unity with increasing p_{T}, higher than nPDF calculations

Prompt Ξ_c^+ production in pPb at 8.16 TeV

- **First** measurement of Ξ_c^+ baryons in heavy-ion collisions, powerful probe of strangeness enhancement and hadronisation
- $\Xi_c^+[usc](\Lambda_c^+[udc]) \to pK^-\pi^+$ channels employed



- Comparison also made with D^0 results