Heavy-flavour production in proton-lead collisions

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on behalf of the LHCb collaboration

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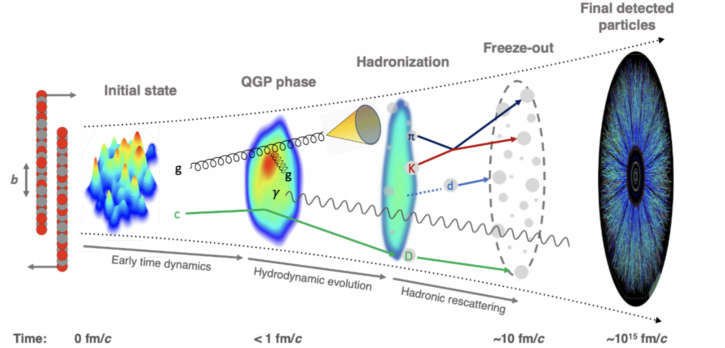
1. Physics background
2. LHCb detector
3. Analysis strategy
4. Open-charm results with LHCb pPb data
    - Prompt D^+ and D_s^+ production in pPb
    - Prompt Ξ_c^+ production in pPb at $\sqrt{s_{\rm NN}} = 8.16\,$TeV
5. Summary and prospect

Charm quarks in heavy-ion collisions

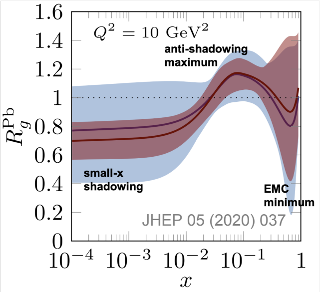
- Charm quarks are excellent probes in heavy-ion collisions
  - Produced in hard processes at early stage of collisions
  - Experience the evolution of the nuclear medium due to their long lifetime

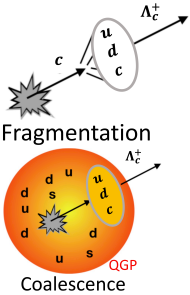
arXiv:2303.17254



Nuclear matter effects in charm production

- Dominant nuclear matter effects in charm hadron production
  - Nuclear shadowing
  - Hadronisation in medium (fragmentation / coalescence)

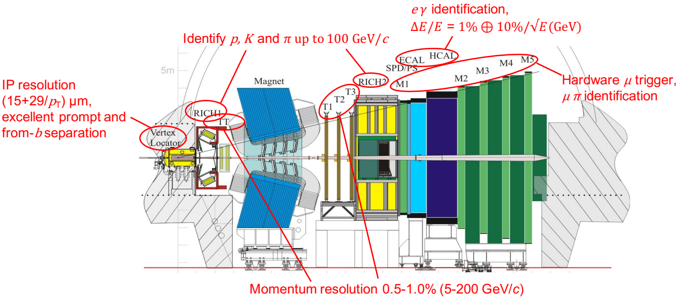




LHCb detector in Run2

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

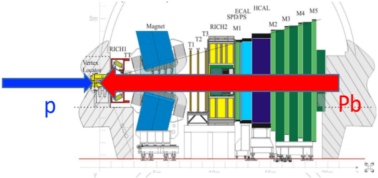


- Provide excellent track finding, vertex reconstruction and particle identification (PID)

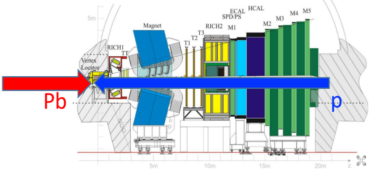
LHCb pPb data

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

pA: forward



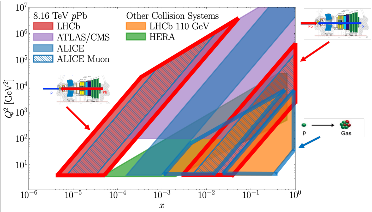
Ap: backward



- $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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

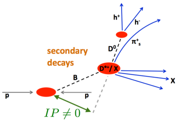
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} ,$$

- Forward-backward production ratio:

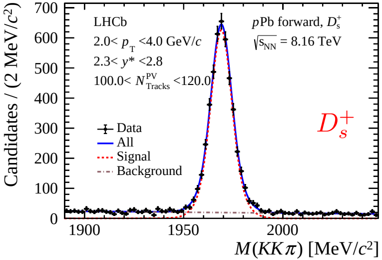
$$R_\mathrm{FB}\ (p_\mathrm{T}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, +|y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_\mathrm{T}, -|y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} .$$

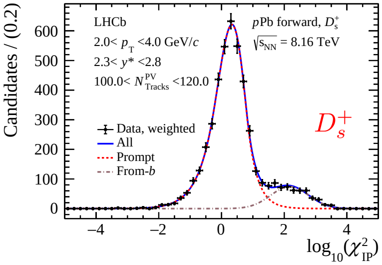
Cross-section determination

- 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.D 110,L031105





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

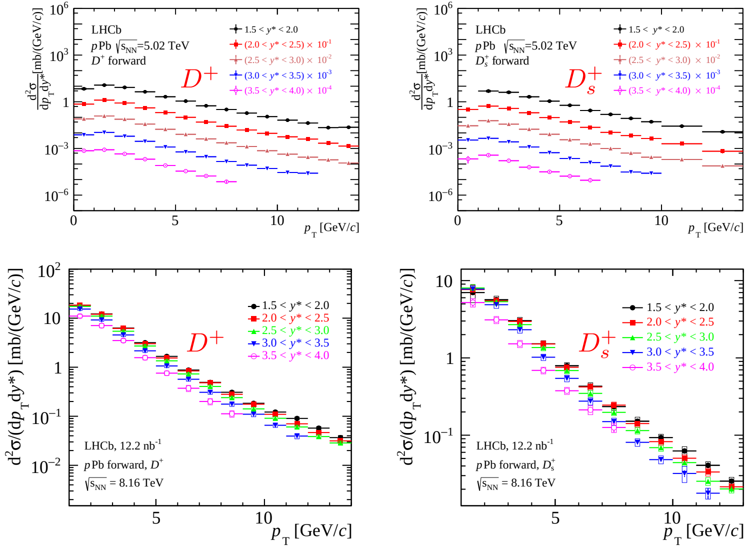
Prompt D^+ and D_s^+ production

JHEP 01 (2024) 070

Phys.Rev.D 110,L031105

Production cross-section

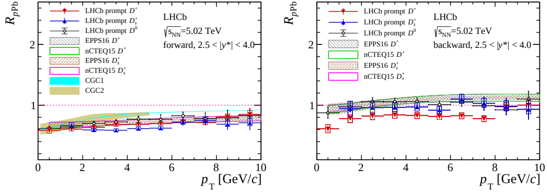
- Prompt D^{+} and D_s^{+} double-differential cross-sections with p_{T} and y^{*} at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ and $8.16\,\mathrm{TeV}$

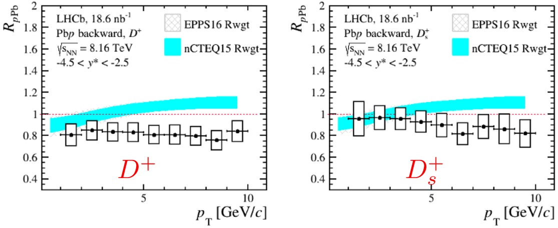


D^+ and D_s^+ nuclear modification factor

- *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



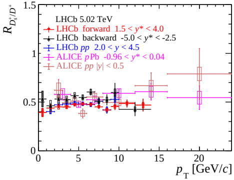


- Significant suppression at forward due to modification of nPDFs
- More suppressed $R_{pPb}(D^+)$ at backward rapidity than $R_{pPb}(D_s^+)$

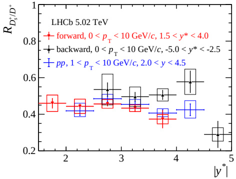
D_s^+/D^+ production ratio in p_{T} and y^*

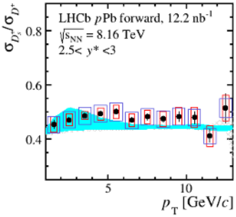
- Strangeness enhancement considered as an important QGP signature
- Possible strangeness enhancement seen in high multiplicity small-system collisions by ALICE Ω $(\Xi)/\pi$ and LHCb B_s^0/B^0

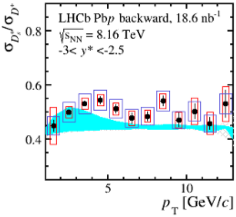
ALICE pPb: JHEP 12 (2019) 092



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





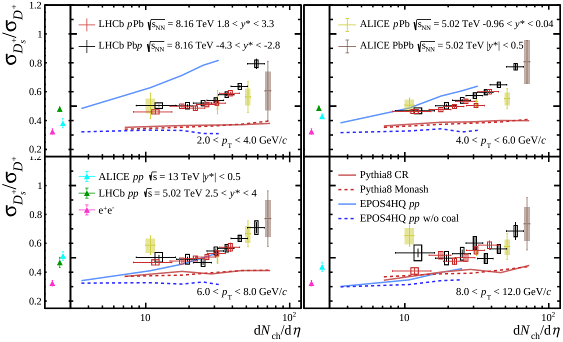


- Slightly higher D_s^+/D^+ ratios at backward rapidity, where particle multiplicity is higher
- Limitted by statistics for 5 TeV
- Invesigation on D_s^+/D^+ dependence on system size needed

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

- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at 8 TeV estimated with simulation samples

Pythia8+CR: EPJC 74 (2014) 3024
Pythia8+Monash: JHEP 08 (2015) 003
EPOS4HQ pp: PRC 110 (2024) 2,024909
ALICE pPb: JHEP 12 (2019) 092
ALICE PbPb: JHEP 10 (2018) 174



- **First** observation of strangeness enhancement with charm hadrons in small systems ($> 6\sigma$ for intermediate p_{T})
- Similar rising trend with charge particle density across different rapidities, indicating that final-state effects dominate this ehancement
- EPOS4HQ+coalescence gives the best description on data except for low p_{T}, suggesting the coalescence contribution in charm quark hadronisation

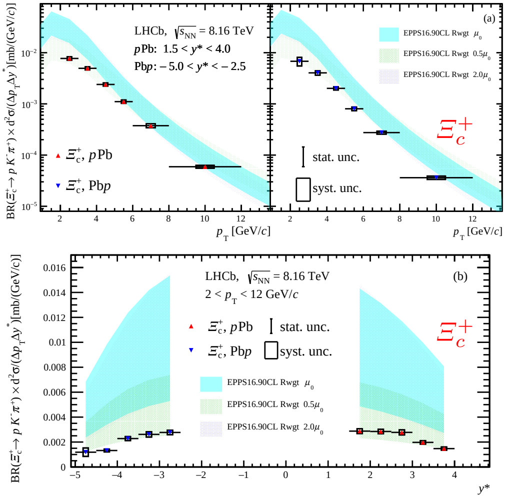
Prompt Ξ_c^+ production

Phys. Rev. C 109 (2024) 044901

Production cross-section

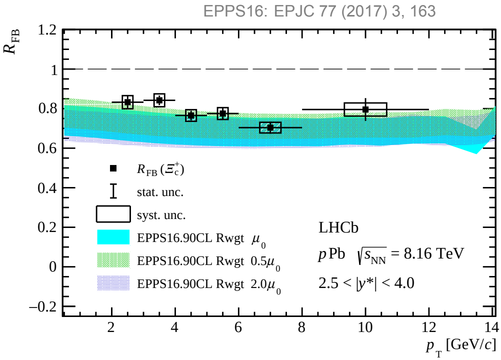
- **First** measurement of Ξ_c^+ baryons in heavy-ion collisions
- Prompt Ξ_c^+ production cross-sections with p_T and y^* at $\sqrt{s_{NN}} = 8.16\,\text{TeV}$

EPPS16: EPJC 77 (2017) 3, 163



Ξ_c^+ forward-backward production ratio

- Measured in the common integrated rapidity region $2.5 < |y^*| < 4.0$

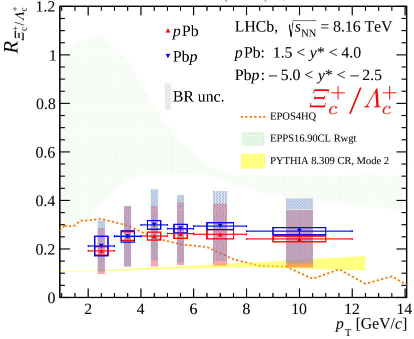


- The suppression at forward rapidity well reproduced by EPPS16 prediction
- Flat trend versus p_{T} in constrast to increasing R_{FB} of charm mesons

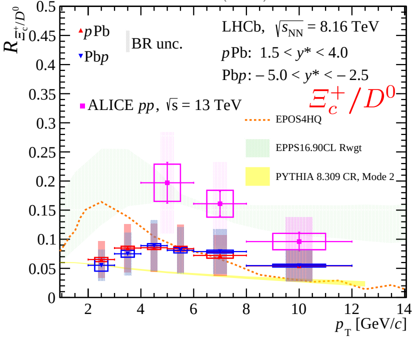
Ξ_c^+/Λ_c^+ and Ξ_c^+/D^0 production ratio

- Aim to study strageness enhancement and modification of baryon-to-meson ratio in pPb

ALICE pp: Phys. Rev. Lett. 127 (2021) 272001
EPPS16: EPJC 77 (2017) 3, 163



EPOS4HQ: PRC 108 (2023) 034904
PYTHIA+CR: JHEP 08 (2015) 003



- No significant dependence on p_T of $R_{\Xi_c^+/\Lambda_c^+}$ and $R_{\Xi_c^+/D^0}$
- Discripancy with ALICE results, hinting at rapidity dependence of the ratio
- EPOS4 calculation gives best description, while shows a different trend towards low p_T

Summary and prospect

- pPb system can serve as a benchmark for PbPb collisions, but also help to investigate the boundary of *small* and *large* systems
- 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 different species of charm hadrons
  - First observation of strangeness enhancement in charm hadron production in small systems, suggesting modification of hadronisation in addition to fragmentation
  - First measurement of Ξ_c^+ baryons in pPb, possible rapidity dependence of Ξ_c^+/D^0 and Ξ_c^+/Λ_c^+ ratios indicated by conflicts between LHCb and ALICE results.
- Λ_c^+/D^0, D^*/D^0 coming soon, for a better understanding of hadronisation in small systems
- Stay tuned for heavy flavour results from SMOG2 data!

Thanks

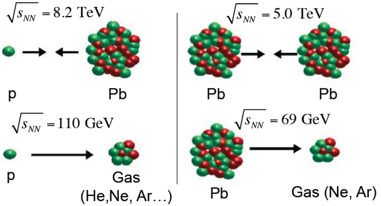
Backups

LHCb heavy-ion data

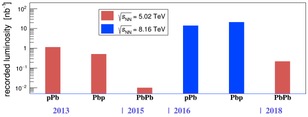
- LHCb beam configurations

Collider mode

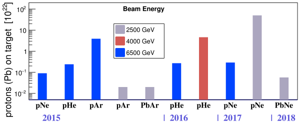
Fixed target mode



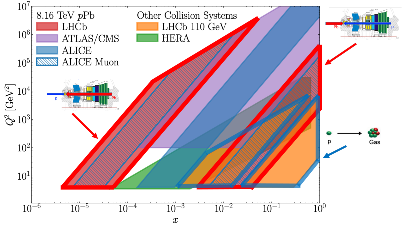
- Data sets
  - Collider mode



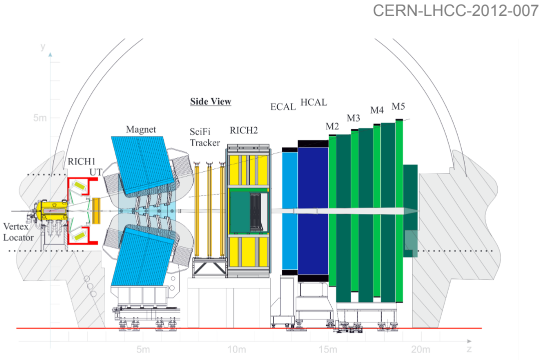
  - Fix-target mode



- Kinematic coverage



LHCb detector at Run3



- 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

Prompt D^0 production

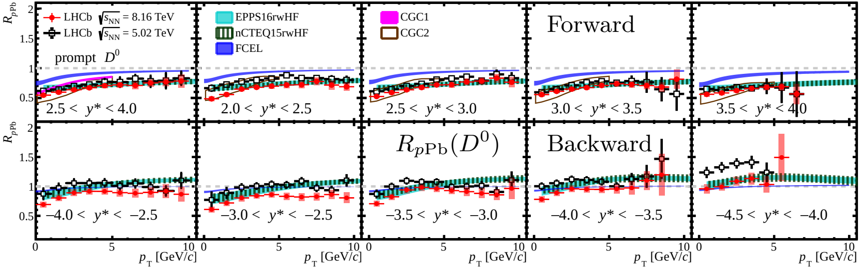
D^0 nuclear modification factor

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

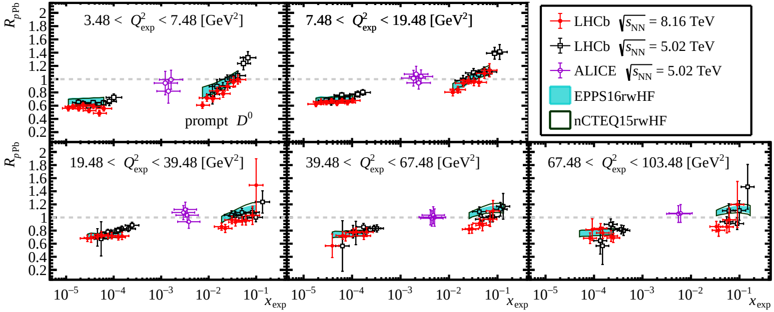


- More suppressed $R_{p\text{Pb}}$ at forward low p_{T}, possibly attributed to FCEL effects
- Discrepancy of $\sim 2.0 - 3.8\sigma$ in high p_{T} at backward, indicating additional initial / final-state effects

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

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

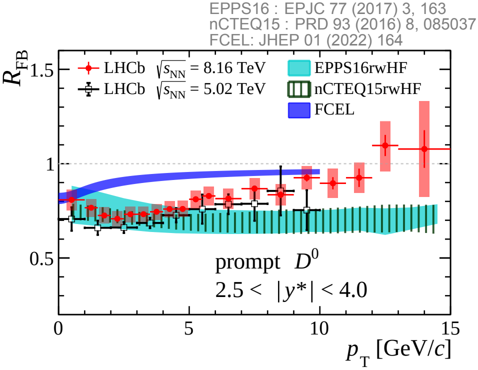
$$x_{\text{exp}} \equiv 2\frac{\sqrt{p_{\text{T}}{}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\text{NN}}}} e^{-y^*} \text{ and } Q^2_{\text{exp}} \equiv p_{\text{T}}{}^2(D^0) + M^2(D^0)$$



- 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

D^0 forward-backward production ratio

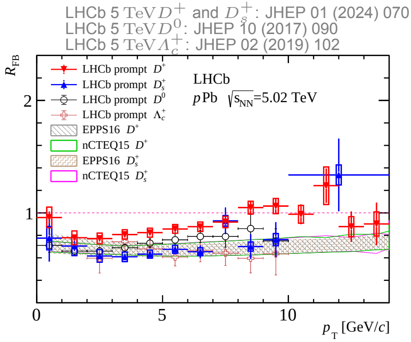
- Forward-backward production ratio R_{FB} versus p_{T}

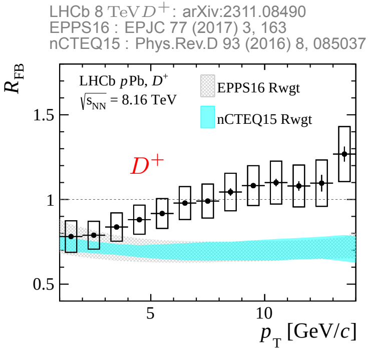


- Significant production asymmetry at low p_{T}
- Rising trend towards unity with increasing p_{T}, higher than nPDF calculations

Forward backward production ratio

- $R_{\mathrm{FB}}\ (D^+)$ and $R_{\mathrm{FB}}\ (D_s^+)$ at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ and $8.16\,\mathrm{TeV}$





- Significant suppression at low p_{T}, in agreement with nPDF predictions
- $R_{\mathrm{FB}}\ (D^+)$ goes higher than nPDF predictions with increasing p_{T}, while for other charm hadrons, R_{FB} is consistent with the flat trend from nPDF models
- Consistency of $R_{\mathrm{FB}}\ (D^+)$ bewteen 5.02 TeV and 8.16 TeV