



# Open-charm production in $p\text{Pb}$ collisions with the LHCb experiment

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on behalf of the LHCb collaboration

中国物理学会高能物理分会第十四届全国粒子物理学术会议

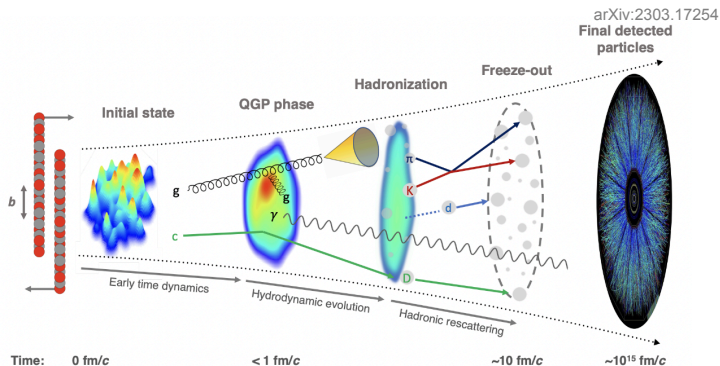
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中国物理学会高能物理分会  
HIGH ENERGY PHYSICS BRANCH OF CPS

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

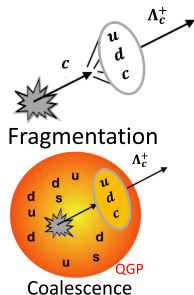
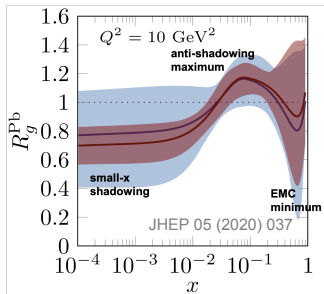
# Charm quarks in heavy-ion collisions

- 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

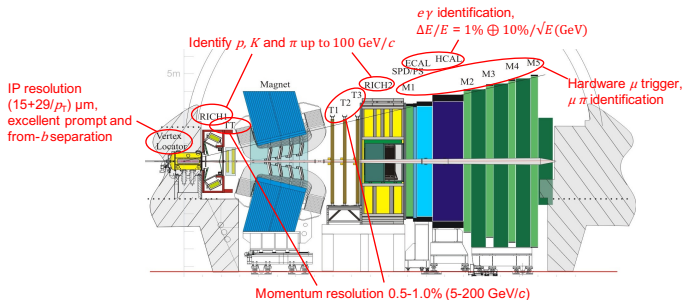


# Nuclear matter effects in charm production

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



- 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

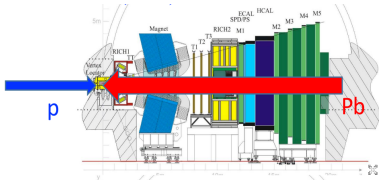


- Provide excellent track finding, vertex reconstruction and particle identification (PID)

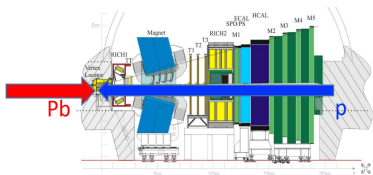
# LHCb $p$ Pb data

- Asymmetric  $p$ Pb data taken in 2013 and 2016, two collision configurations.

$p$ A: forward



$A$ p: backward

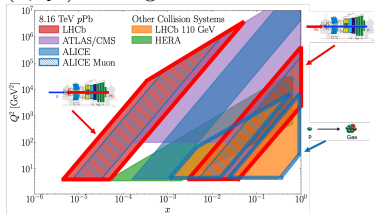


- $\sqrt{s_{NN}} = 5.02$  and 8.16 TeV
- Boosted in lab frame by 0.465
- Rapidity coverage:

$$pA : 1.5 < y^* < 4.0$$

$$Ap : -5.0 < y^* < -2.5$$

- $(x, Q^2)$  coverage



# Analysis strategy

- Double-differential cross-section:

$$\frac{d^2\sigma}{dp_T dy^*} \equiv \frac{N}{\mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B} \times \Delta p_T \times \Delta y^*} ,$$

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

- Nuclear modification factor

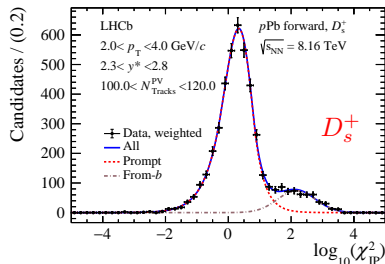
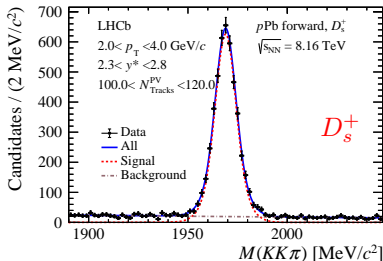
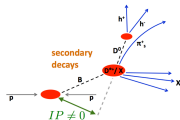
$$R_{p\text{Pb}}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*} ,$$

- Forward-backward production ratio:

$$R_{\text{FB}}(p_T, y^*) \equiv \frac{d^2\sigma_{p\text{Pb}}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{\text{Pb}p}(p_T, -|y^*|)/dp_T dy^*} .$$

# 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 ( $\chi_{IP}^2 \sim IP/\sigma_{IP}$ )



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



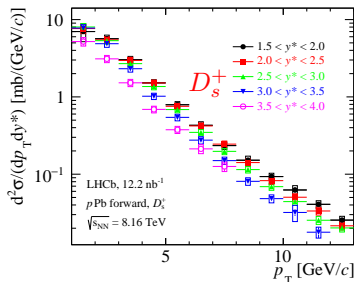
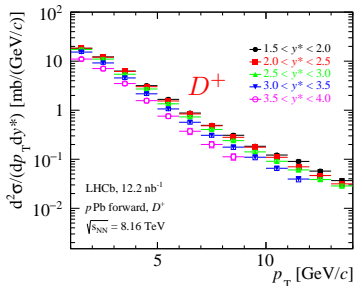
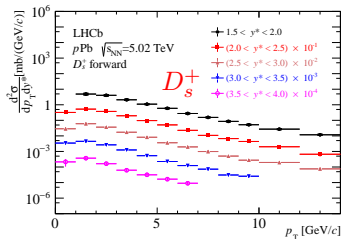
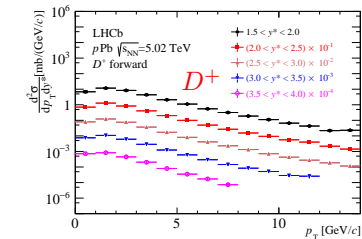
# Prompt $D^+$ and $D_s^+$ production

JHEP 01 (2024) 070

arXiv:2311.08490 (accepted by PRD)

# Production cross-section

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



# $D^+$ and $D_s^+$ nuclear modification factor

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

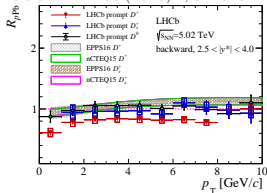
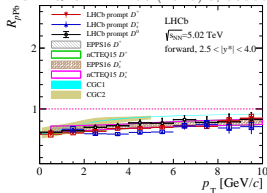
LHCb  $D^0$ : JHEP 10 (2017) 090

EPPS16: EPJC 77 (2017) 3, 163

nCTEQ15: PRD 93 (2016) 8, 085037

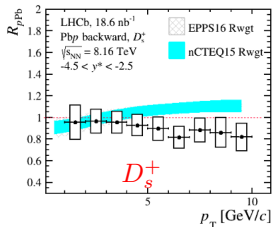
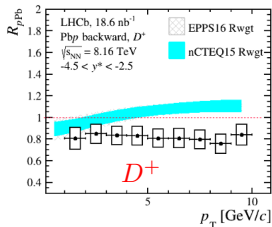
CGC1: Nucl.Phys.Proc 2017, 289-290

CGC2: PRD 98 (2018) 7, 074025



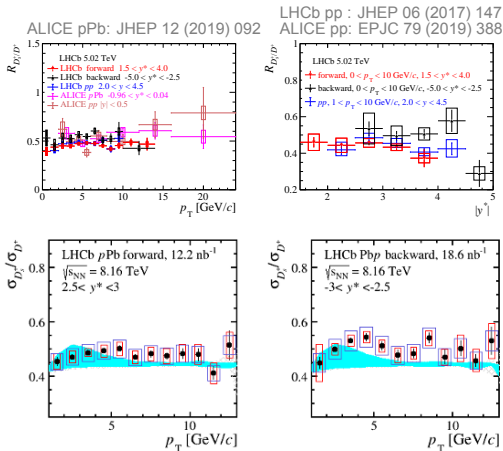
- Significant suppression at forward due to modification of nPDFs

- More suppressed  $R_{pPb}(D^+)$  at backward rapidity than  $R_{pPb}(D_s^+)$



# $D_s^+ / D^+$ production ratio in $p_T$ and $y^*$

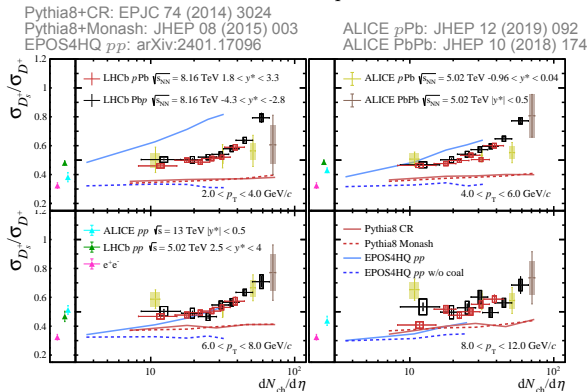
- Strangeness enhancement considered as an important QGP signature
- Possible strangeness enhancement seen in high multiplicity small-system collisions by ALICE  $\Omega (\Xi) / \pi$  and LHCb  $B_s^0 / B^0$



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

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

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



- **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 enhancement
- EPOS4HQ+coalescence gives the best description on data except for low  $p_T$ , suggesting the coalescence contribution in charm quark hadronization

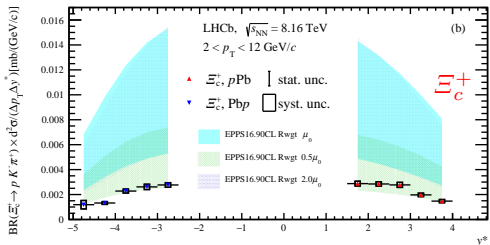
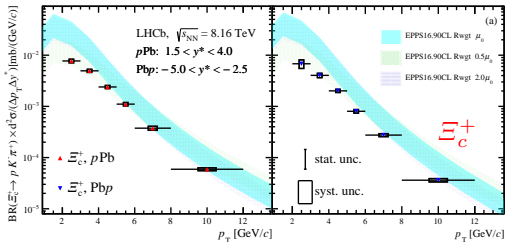
# Prompt $\Xi_c^+$ production

Phys. Rev. C 109 (2024) 044901

# Production cross-section

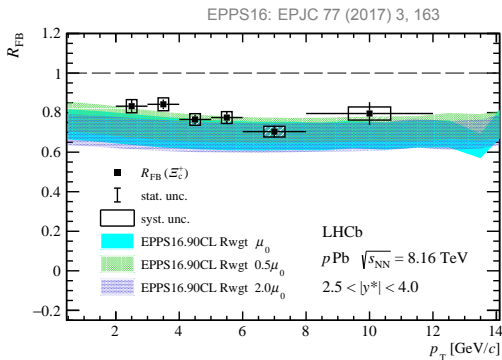
- **First** measurement of  $\Xi_c^+$  baryons in heavy-ion collisions
- Prompt  $\Xi_c^+$  production cross-sections with  $p_T$  and  $y^*$  at  $\sqrt{s_{NN}} = 8.16$  TeV

EPPS16: EPJC 77 (2017) 3, 163



# $\Xi_c^+$ forward-backward production ratio

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

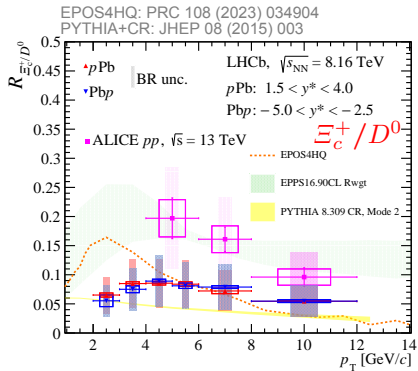
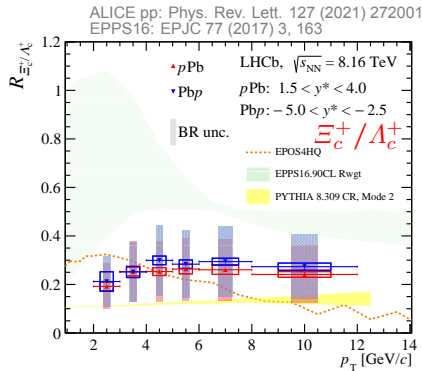


- The suppression at forward rapidity well reproduced by EPPS16 prediction
- Flat trend versus  $p_T$  in contrast to increasing  $R_{FB}$  of charm mesons



# $\Xi_c^+/\Lambda_c^+$ and $\Xi_c^+/D^0$ production ratio

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



- No significant dependence on  $p_T$  of  $R_{\Xi_c^+/\Lambda_c^+}$  and  $R_{\Xi_c^+/D^0}$
- ALICE result in  $pp$  slightly higher than data
- EPOS4 calculation gives best description, while shows a different trend towards low  $p_T$

## Summary and prospect

- $p$ Pb 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  $\Xi_c^+$  baryons in  $p$ Pb, flat  $\Xi_c^+/D^0$  and  $\Xi_c^+/\Lambda_c^+$  ratios versus  $p_T$  found
- $\Lambda_c^+/D^0$ ,  $D^*/D^0$  coming soon, for a better understanding of hadronisation in small systems
- Large samples with higher multiplicity from ongoing Run3 data taking being analysed

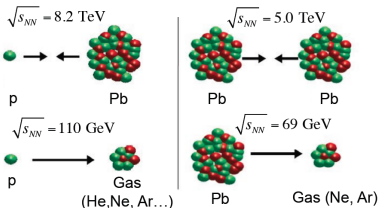
# Thanks

# Backups

# LHCb heavy-ion data

- LHCb beam configurations

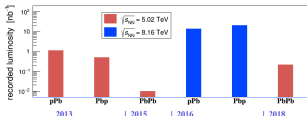
Collider mode



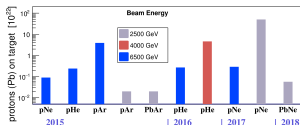
Fixed target mode

- Data sets

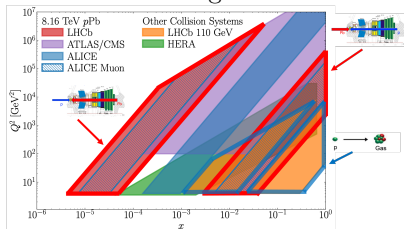
- Collider mode



- Fix-target mode

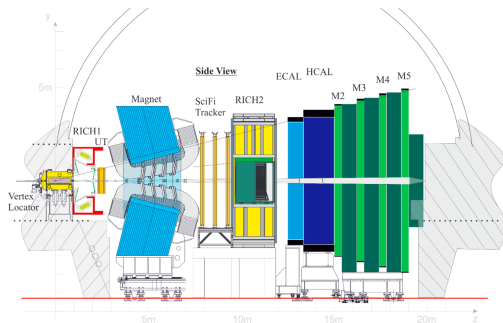


- Kinematic coverage



# 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

# Prompt $D^0$ production

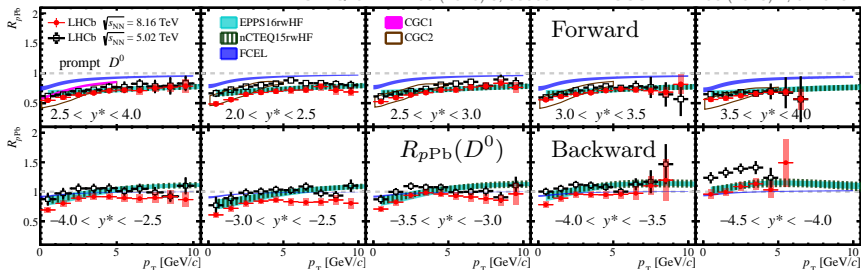
# $D^0$ nuclear modification factor

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



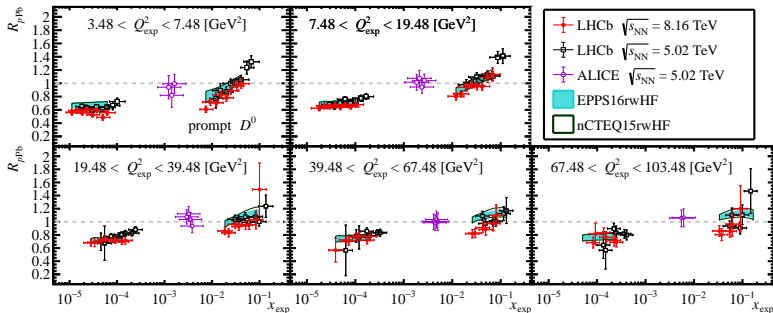
- More suppressed  $R_{pPb}$  at forward low  $p_T$ , possibly attributed to FCEL effects
- Discrepancy of  $\sim 2.0 - 3.8\sigma$  in high  $p_T$  at backward, indicating additional initial / final-state effects



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

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

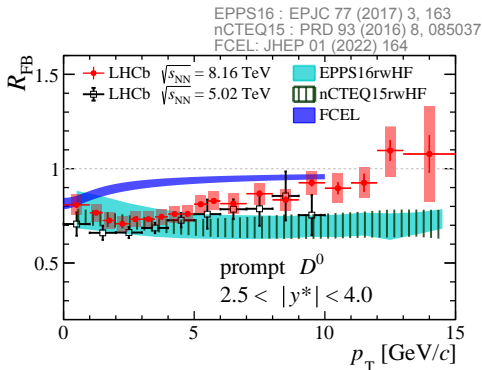
$$x_{\text{exp}} \equiv 2 \frac{\sqrt{p_{\text{T}}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\text{NN}}}} e^{-y^*} \quad \text{and} \quad Q_{\text{exp}}^2 \equiv p_{\text{T}}^2(D^0) + M^2(D^0)$$



- 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

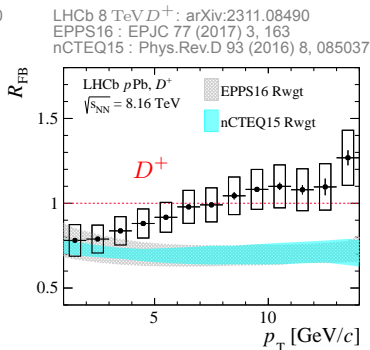
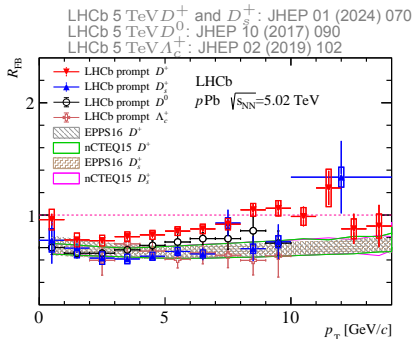
- Forward-backward production ratio  $R_{\text{FB}}$  versus  $p_{\text{T}}$



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

# Forward backward production ratio

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



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