



Open heavy-flavour and quarkonia production at LHCb

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on behalf of the LHCb collaboration

Initial Stages 2023

June 21, 2023

1 Introduction

2 LHCb detector

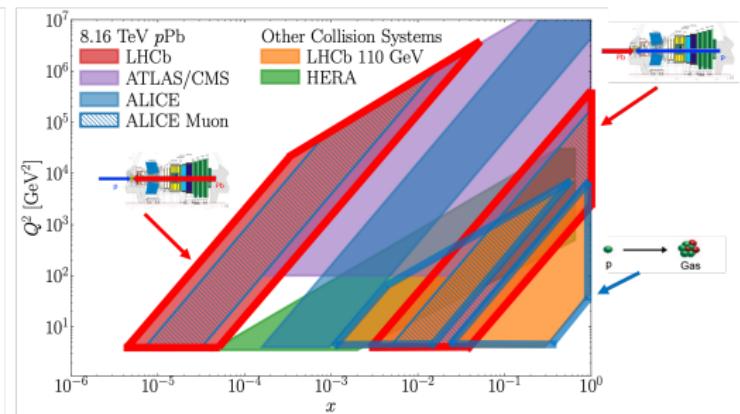
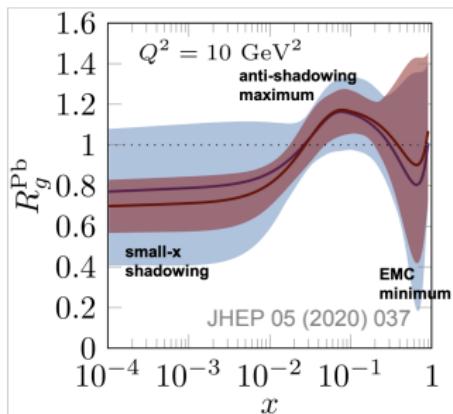
3 Results from heavy-flavour production at LHCb

- Prompt D^+ and D_s^+ production in $p\text{Pb}$ at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
- Prompt D^0 production in $p\text{Pb}$ at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$
- Prompt Ξ_c^+ production in $p\text{Pb}$ at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$
- Υ production in pp at $\sqrt{s} = 5 \text{ TeV}$

4 Summary and prospects

Heavy flavour in heavy-ion collisions

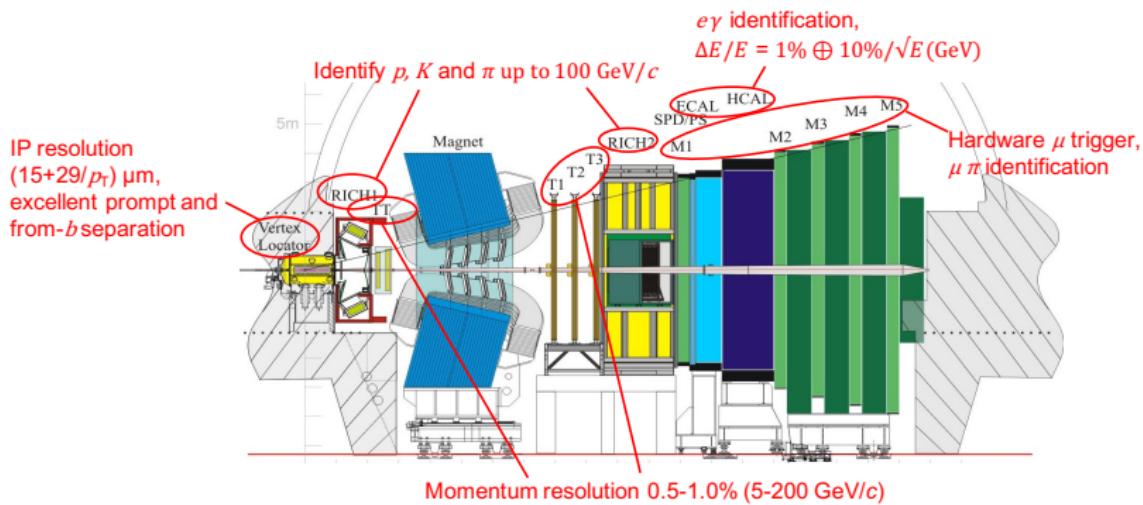
- Heavy-flavour particles are excellent probes in heavy-ion collisions
 - ▶ Large quark masses allow perturbative QCD calculation
 - ▶ Sensitive to the nuclear medium due to their long lifetime
- Related nuclear matter effects
 - ▶ Modification of nPDF
 - ▶ Strangeness enhancement
 - ▶ Baryon enhancement
 - ▶ Heavy quarkonia suppression



LHCb detector in Run2

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

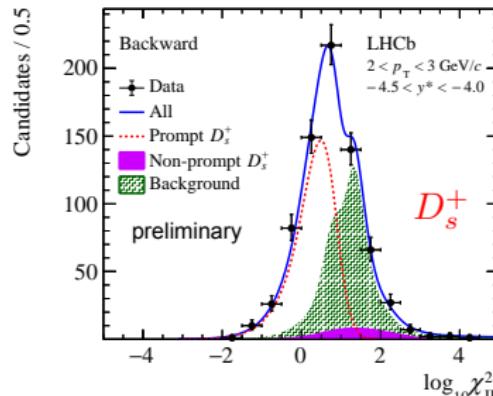
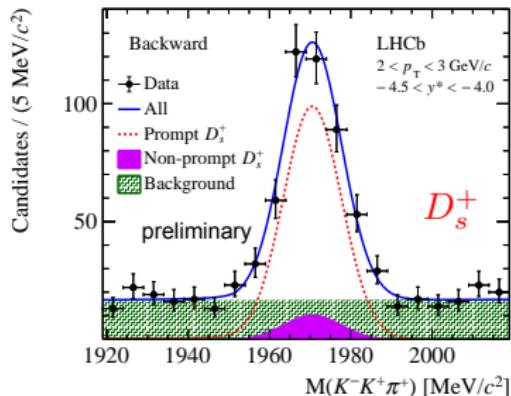
- A single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$
- Designed for studying particles containing b or c quarks
- A general purpose detector collecting $pp/p\text{Pb}/\text{PbPb}$ data, providing unique fix-target mode at the LHC



Prompt D^+ and D_s^+ production in $p\text{Pb}$ at 5.02 TeV

LHCb-PAPER-2023-006, in preparation

- Enhanced strangeness production can be induced by QGP due to the large $s\bar{s}$ abundance
- Possible strangeness enhancement seen in high multiplicity small systems by **ALICE** Ω (Ξ)/ π and **LHCb** B_s^0/B^0
- Impact parameter (IP) used for discriminating prompt and non-prompt (from b) components, yields determined from simultaneous fits on invariant mass and $\log_{10}(\chi^2_{\text{IP}})$ ($\chi^2_{\text{IP}} \sim \text{IP}/\sigma_{\text{IP}}$)

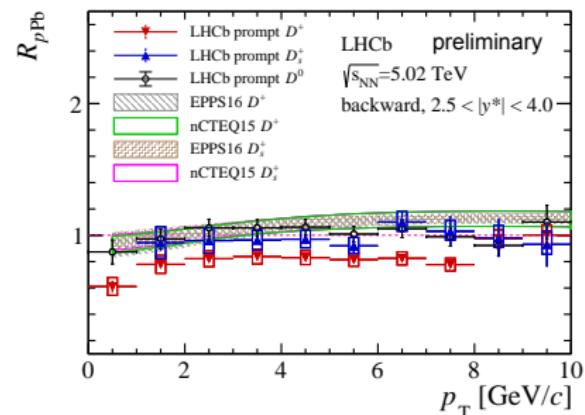
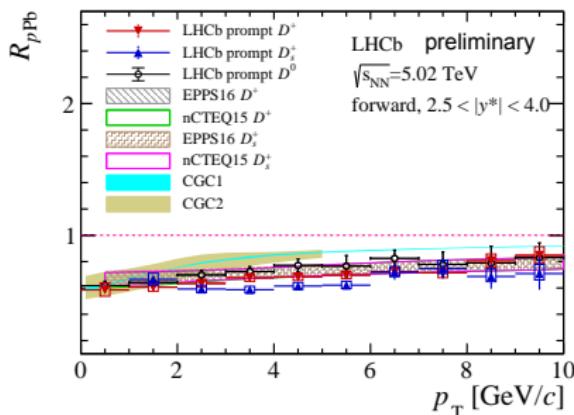


D^+ and D_s^+ nuclear modification factor

- Nuclear modification factor calculated using LHCb pp results as reference

$$R_{p\text{Pb}} = \sigma_{p\text{Pb}} / (A \cdot \sigma_{pp})$$

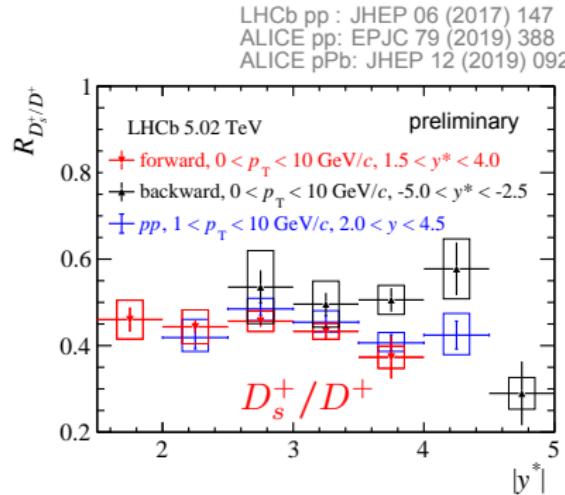
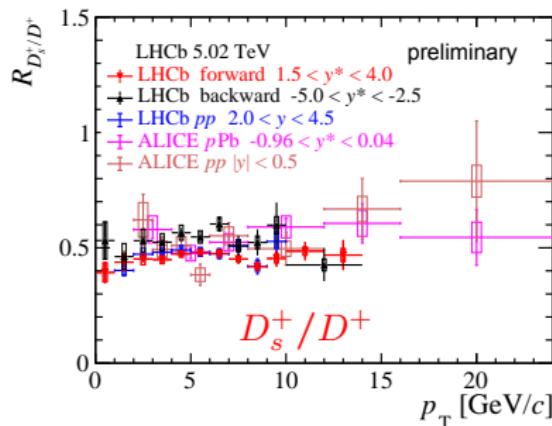
LHCb D^0 : JHEP 10 (2017) 090
EPPS16 : EPJC 77 (2017) 3, 163
nCTEQ15 : PRD 93 (2016) 8, 085037



- General consistency with LHCb D^0 in 5 TeV $p\text{Pb}$ as well as theories
- More suppressed $R_{p\text{Pb}}(D^+)$ at backward rapidity

D_s^+/D^+ production ratio

- D_s^+/D^+ ratios are consistent with both LHCb pp and ALICE $pp/p\text{Pb}$ results
- Higher D_s^+/D^+ ratios at backward rapidity, hinting at potential coalescence contribution

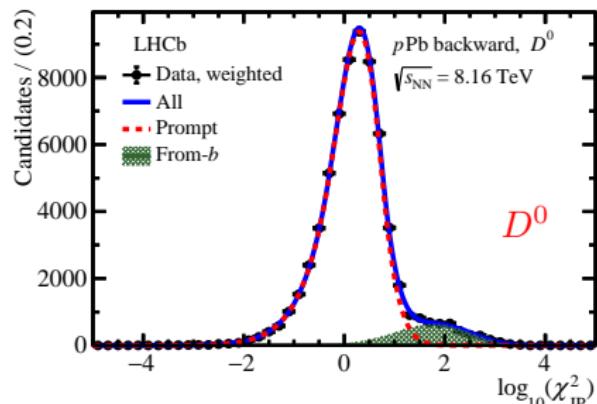
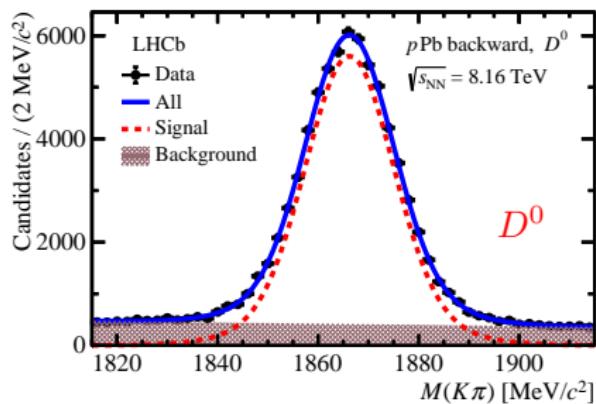


- Further work desired involving multiplicity classification with higher statistics

Prompt D^0 production in $p\text{Pb}$ at 8.16 TeV

arXiv:2205.03936

- Measurement of D^0 production for both forward and backward rapidity regions down to $p_T \sim 0 \text{ GeV}/c$, giving insights into partonic structures at both shadowing and anti-shadowing regions
- Approximately 20 times more statistics compared to 5 TeV

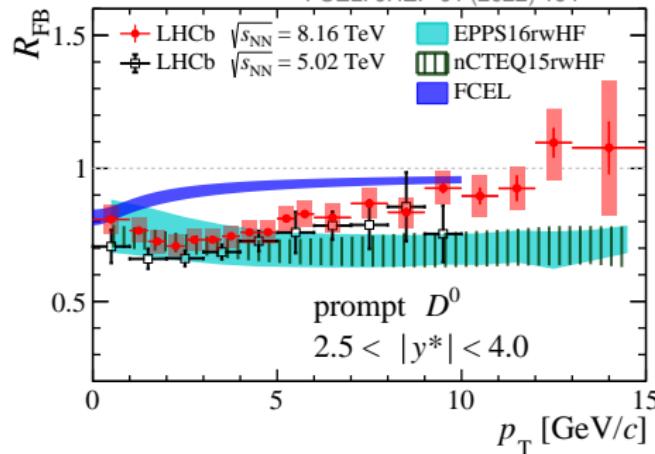


D^0 forward-backward production ratio

- Forward-backward production ratio R_{FB} given as

$$R_{\text{FB}}(p_{\text{T}}, y^*) \equiv \frac{d\sigma_{D^0}(p_{\text{T}}, +|y^*|)/(dp_{\text{T}}dy^*)}{d\sigma_{D^0}(p_{\text{T}}, -|y^*|)/(dp_{\text{T}}dy^*)}$$

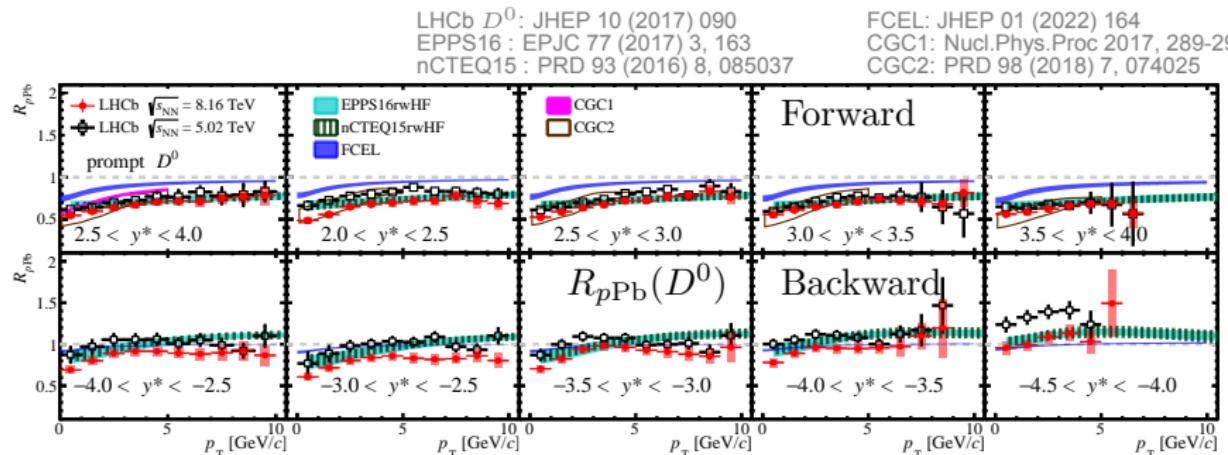
EPPS16 : EPJC 77 (2017) 3, 163
nCTEQ15 : PRD 93 (2016) 8, 085037
FCEL: JHEP 01 (2022) 164



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

D^0 nuclear modification factor

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

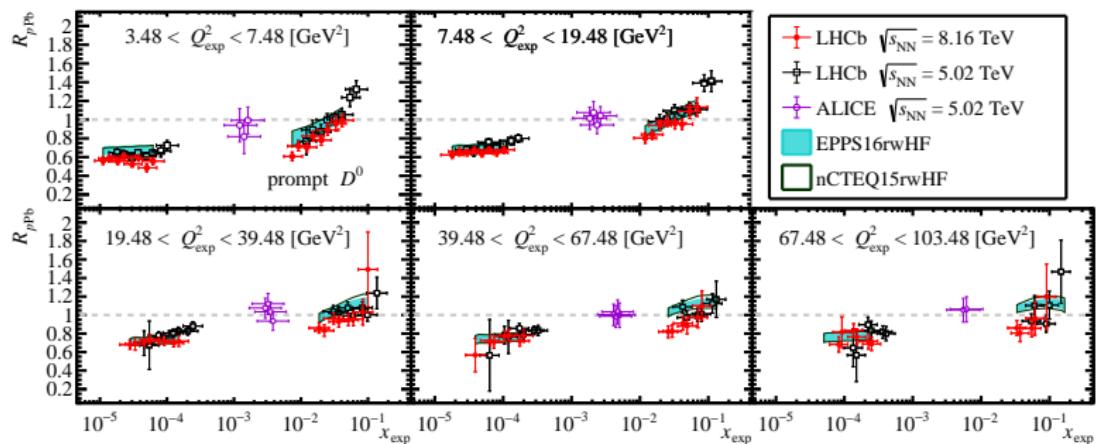


- More suppressed $R_{p\text{Pb}}$ in low p_T at forward, possibly attributed to FCEL effects
- Discrepancy of $\sim 2.0 - 3.8\sigma$ in high p_T at backward, indicating additional initial / final-state effects

D^0 nuclear modification factor

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

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

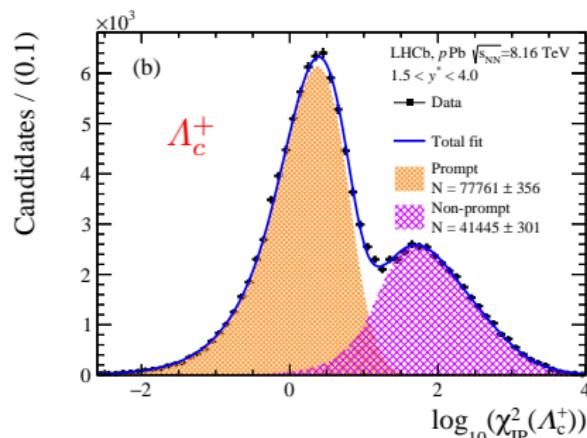
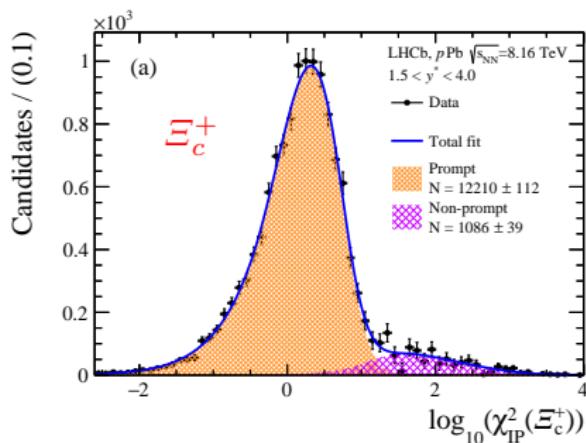


- Consistency between LHCb results at 5.02 TeV and 8.16 TeV in (x, Q^2) space
- Stronger suppression than nPDF calculations in $x \sim 0.01$ at larger Q^2

Prompt Ξ_c^+ production in $p\text{Pb}$ at 8.16 TeV

arXiv:2305.06711

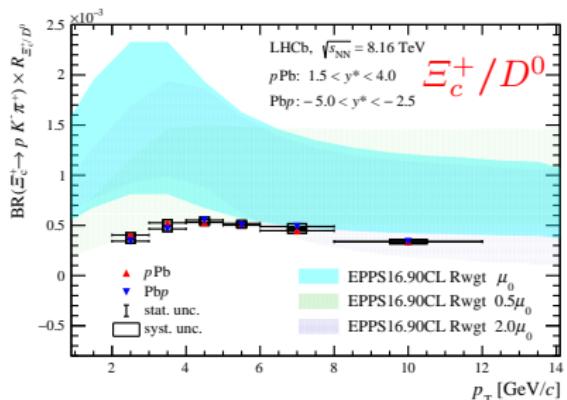
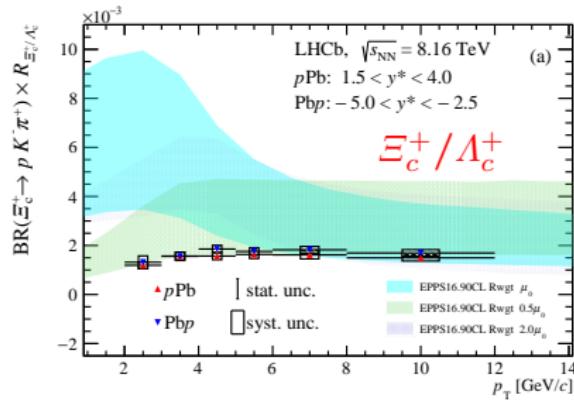
- **First** measurement of Ξ_c^+ baryons in heavy-ion collisions, powerful probe of strangeness enhancement and hadronisation
- $\Xi_c^+ [usc] (\Lambda_c^+ [udc]) \rightarrow p K^- \pi^+$ channels employed



- Comparison also made with D^0 results

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

- Production ratios multiplied by the branching fraction due to the large $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)$ uncertainties



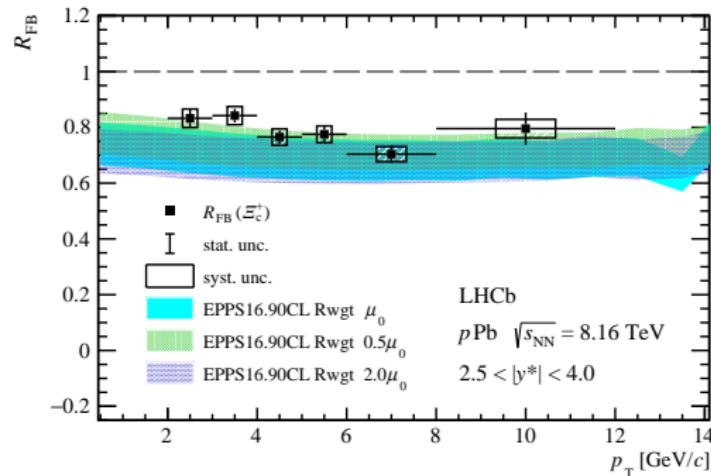
- No significant dependence on p_T of $R_{\Xi_c^+ / \Lambda_c^+}$ and $R_{\Xi_c^+ / D^0}$
- In agreement with [HELAC-onia calculation](#) incorporating [EPPS16 nPDF](#)

Ξ_c^+ forward-backward production ratio

- Uncertainty of branching fraction cancelled in the ratio

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

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

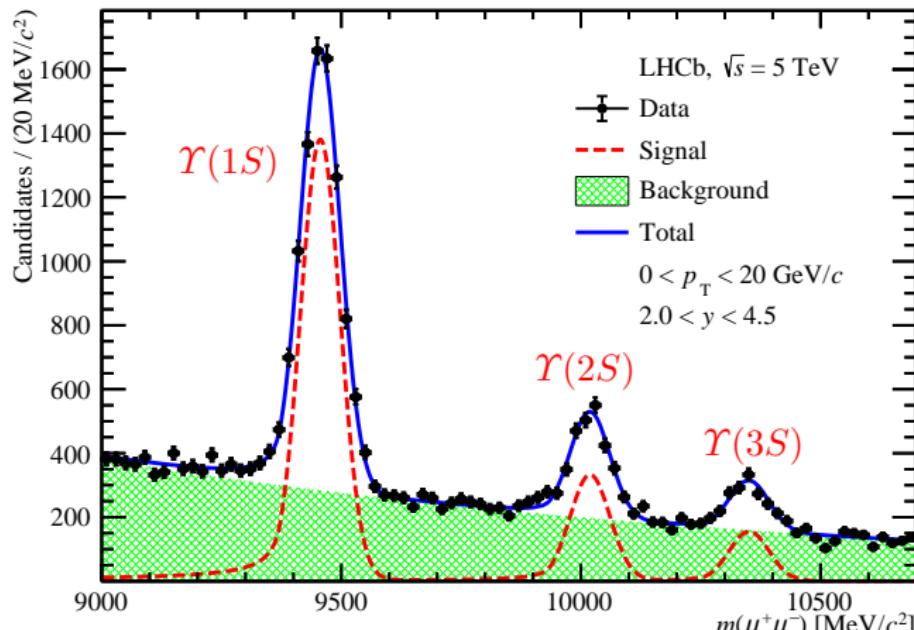


- The suppression at forward well described by nuclear shadowing

Υ production in pp at 5 TeV

arXiv:2212.12664

- Aim to study hadronisation of quark pairs into quarkonium states (non-perturbative regime)
- Υ mesons reconstructed via $\mu^-\mu^+$ final states



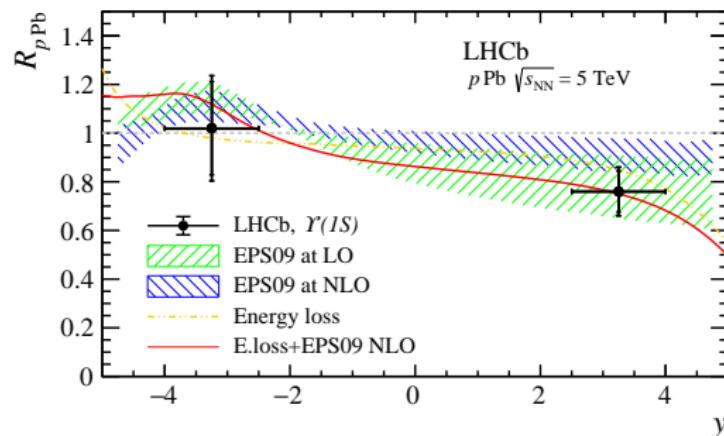
Υ nuclear modification factor

- $R_{p\text{Pb}}(\Upsilon(1S))$ at $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$ updated using the measured pp cross-section

$$R_{p\text{Pb}} = \begin{cases} 1.02 & \pm 0.19 \quad \pm 0.10, \quad -4.0 < y^* < -1.5 \\ 0.76 & \pm 0.08 \quad \pm 0.05, \quad 1.5 < y^* < 4.0 \end{cases}$$

LHCb Υ pPb: JHEP 07 (2014) 094
EPS09 at LO : EPJC 73 (2013) 2427

EPS09 at NLO : IJMPPE 22 (2013) 1330007
Energy loss (+EPS09 NLO) : JHEP 03 (2013) 122



- Consistent with theories with higher precision
- Investigation on multiplicity-dependent $\Upsilon(nS)$ ratios in progress

Summary and prospects

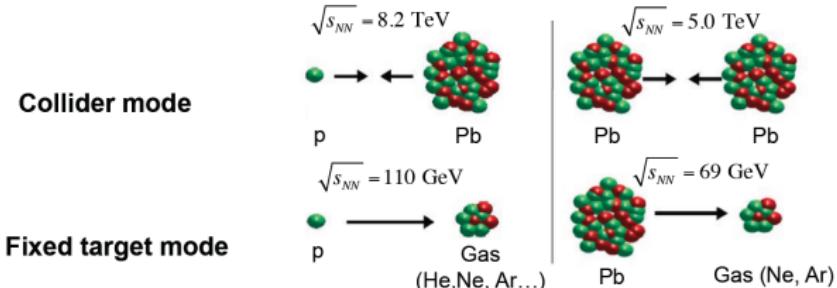
- Heavy-flavour particles are sensitive to nuclear matter effects in heavy-ion collisions, and the LHCb experiment has strong capabilities to studying them
 - ▶ D_s^+ and D^+ $R_{p\text{Pb}}$, as well as D_s^+/D^+ ratio measured in 5 TeV $p\text{Pb}$, in agreement with LHCb pp and ALICE $pp/p\text{Pb}$ results
 - ▶ Tension between prompt D^0 $R_{p\text{Pb}}$ and nPDF predictions in high p_T at backward rapidity at 8.16 TeV
 - ▶ First measurement of Ξ_c^+ baryons in $p\text{Pb}$, suppressed production at forward rapidity well described by nuclear shadowing
 - ▶ $\Upsilon(1S)$ $R_{p\text{Pb}}$ updated with new pp results at 5 TeV, consistent with theories with improved precision
- Stay tuned for more results from Run2 data
 - ▶ Works on light hadrons to be presented by Federica here at 17:10
 - ▶ Results in UPC by [Qiuchan](#)
- Run3 data-taking in progress and more physics opportunities available
 - ▶ More detail on SMOG2 from [Camilla's Poster](#)

Thanks

Backups

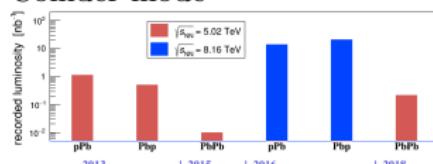
LHCb heavy-ion data

- LHCb beam configurations

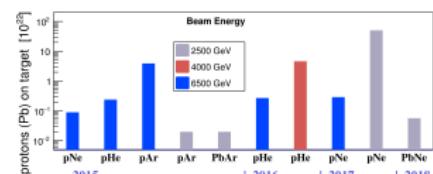


- Data sets

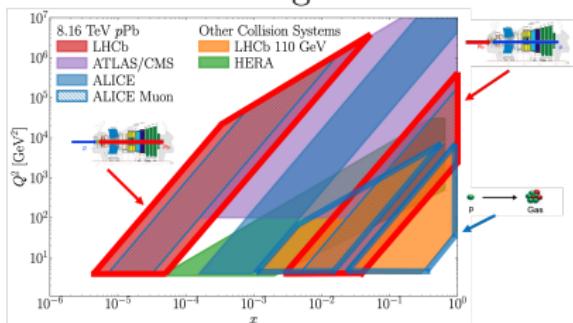
- Collider mode



- Fix-target mode

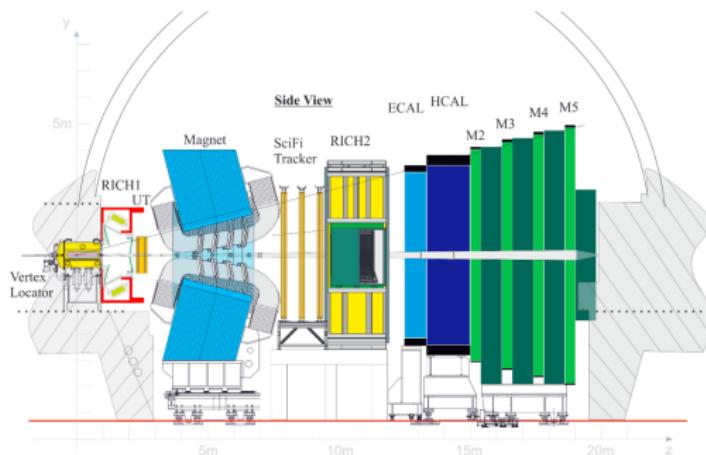


- Kinematic coverage



LHCb detector at Run3

CERN-LHCC-2012-007

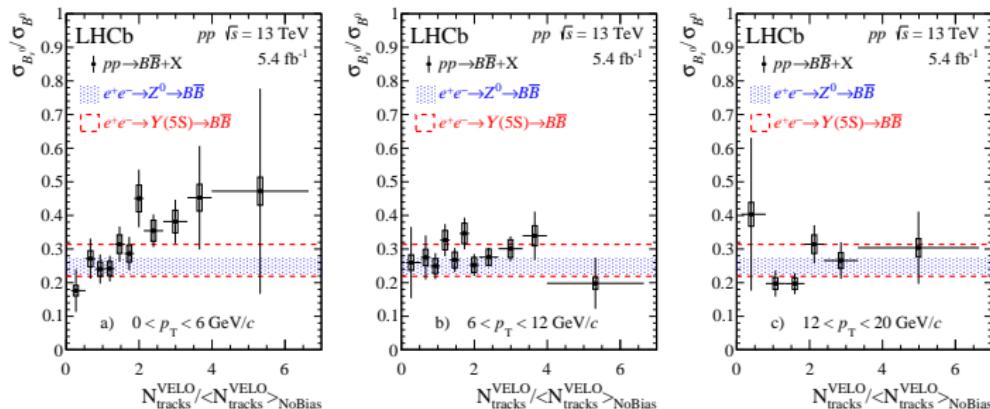


- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- New tracking system:
 - ▶ Silicon upstream detector (UT)
 - ▶ Scintillating tracking fibre (SciFi)
- Full software trigger:
 - ▶ Remove L0 triggers
 - ▶ Read out the full detector at 40 MHz

B_s^0/B^0 ratio vs. multiplicity in pp

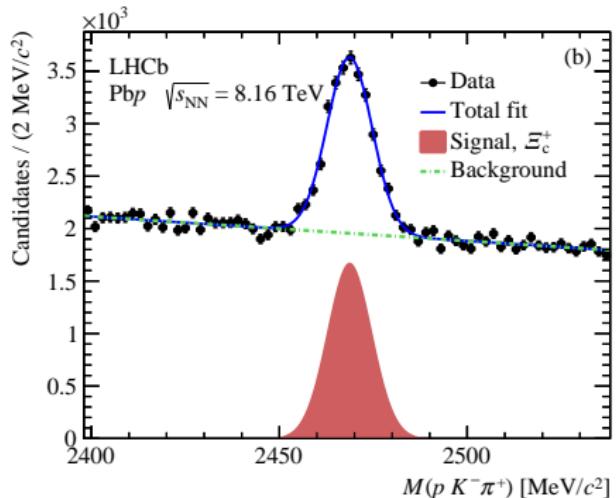
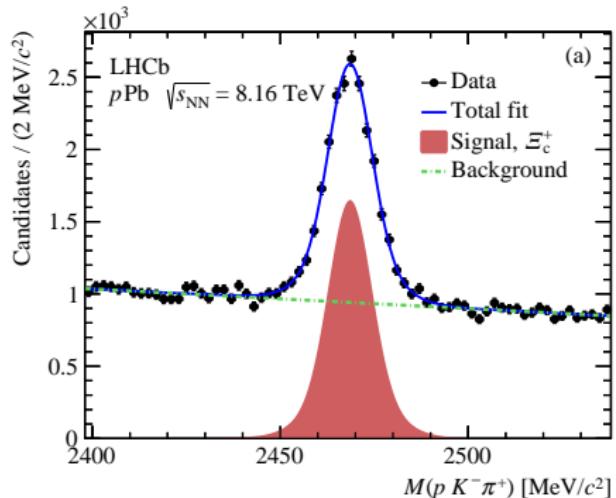
arXiv:2204.13042

- B_s^0/B^0 ratio in different p_T regions:



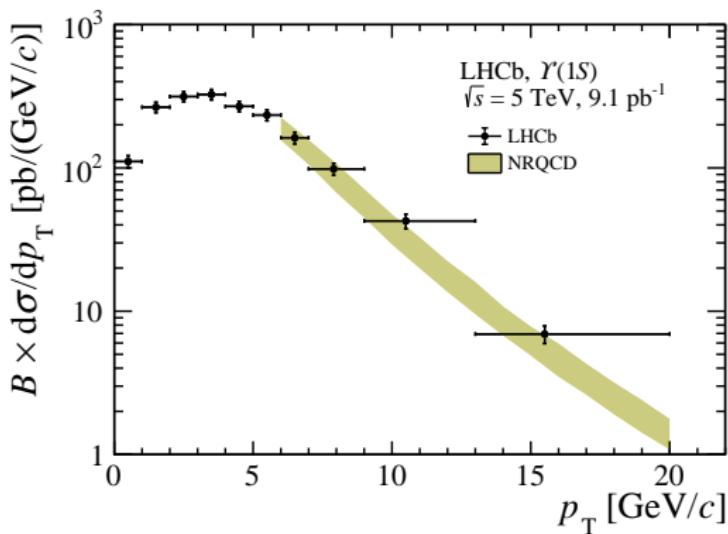
- B_s^0/B^0 ratio increases with multiplicity at low p_T , with a slope significance of 3.4σ (strangeness enhancement), qualitatively consistent with expectations from the coalescence model.
- Flat trend vs. multiplicity at high p_T , in agreement with e^+e^- results.

Ξ_c mass spectrum in forward and backward rapidities



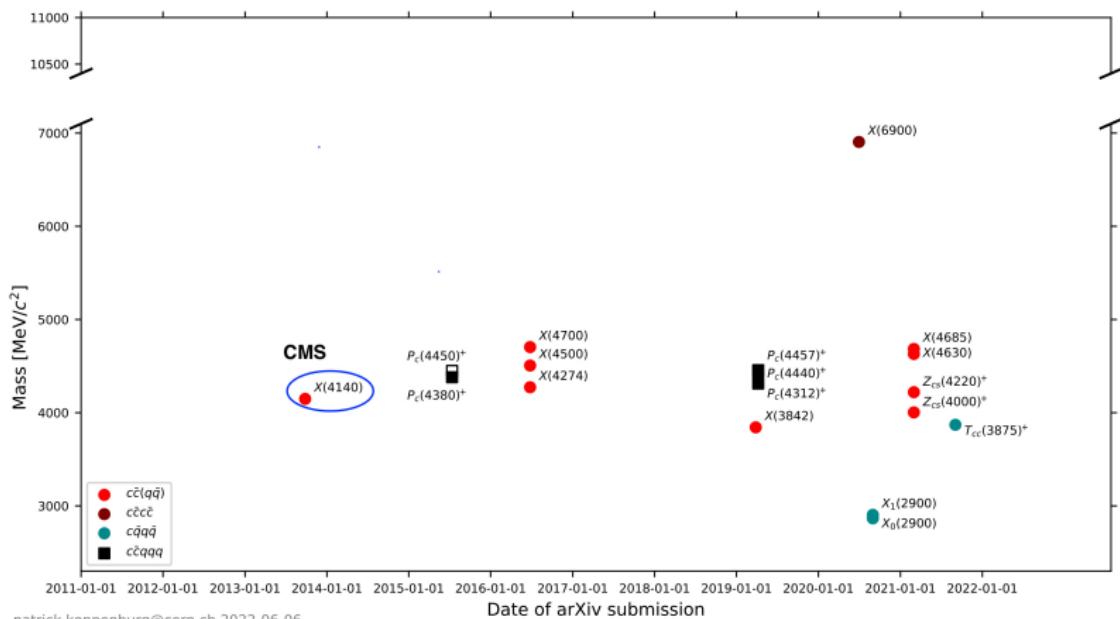
Υ cross-section

- $\Upsilon(1S)$ cross-section compared with NRQCD at high p_T



Exotic production at LHCb

- LHCb is very active in studying exotic states.
- Exotic states observed at the LHC.
 - ▶ All but one observed by LHCb.



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$\chi_{c1}(3872)$ structure

- The structure of $\chi_{c1}(3872)$ state still not clear: compact tetraquark / hadronic molecule ?

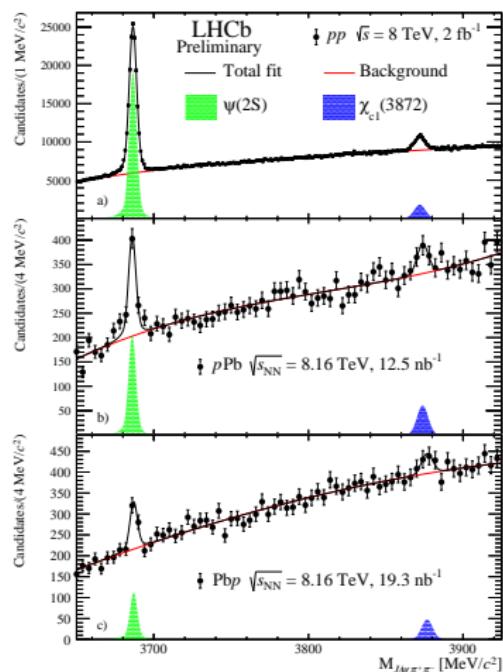
Compact tetraquark Hadronic molecule



- Or superposition of different states:
 $\chi_{c1}(3872) = a|c\bar{c}\rangle + b|c\bar{c}q\bar{q}\rangle$?
- Compare the $\chi_{c1}(3872)$ state with conventional $c\bar{c}$ meson $\psi(2S)$.
- Probe the final-state effects on $\chi_{c1}(3872)$ according to comover/coalescence model.

Prompt $\chi_{c1}(3872)$ production in heavy-ion collisions

LHCb-CONF-2022-001



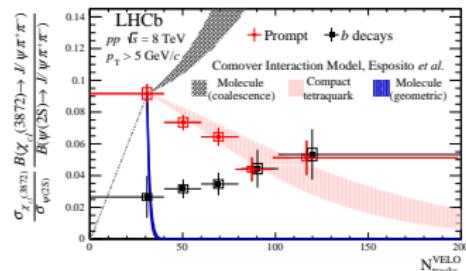
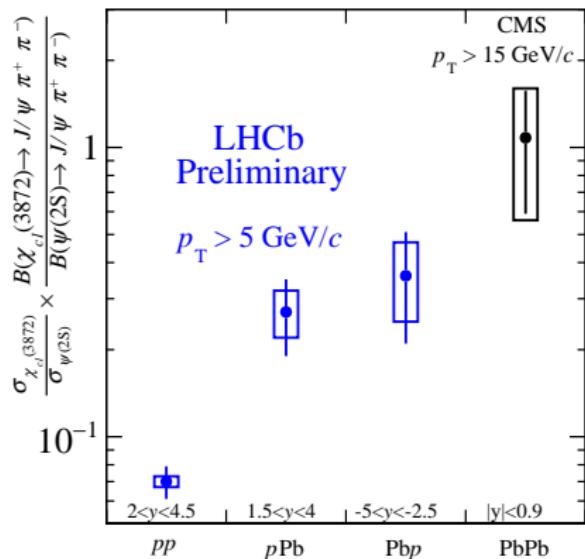
- **First** measurement on $\chi_{c1}(3872)$ in $p\text{Pb}$ collisions
- Provide unique insights into the structure of $\chi_{c1}(3872)$ states
- $\chi_{c1}(3872)$ and $\psi(2S)$ states reconstructed via common final states $J/\psi\pi^+\pi^-$

System	Rapidity	Energy	Luminosity
pp	$2 < y < 4.5$	8 TeV	2 fb^{-1}
$p\text{Pb}$	$1.5 < y_{\text{cm}} < 4$	8.16 TeV	12.5 nb^{-1}
Pbp	$-5 < y_{\text{cm}} < -2.5$	8.16 TeV	19.3 nb^{-1}

$\chi_{c1}(3872)/\psi(2S)$ ratio across collision systems

LHCb-CONF-2022-001

Phys. Rev. Lett. 126, (2021) 9, 092001



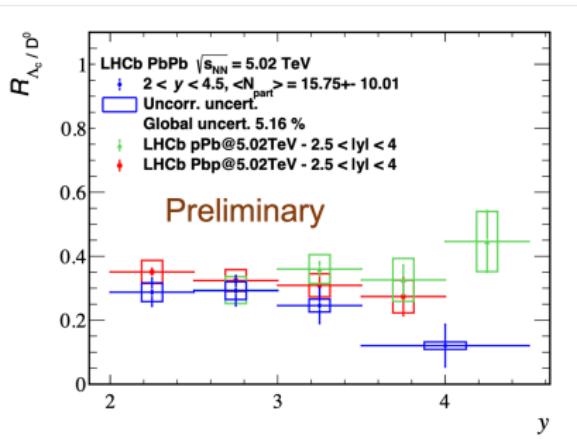
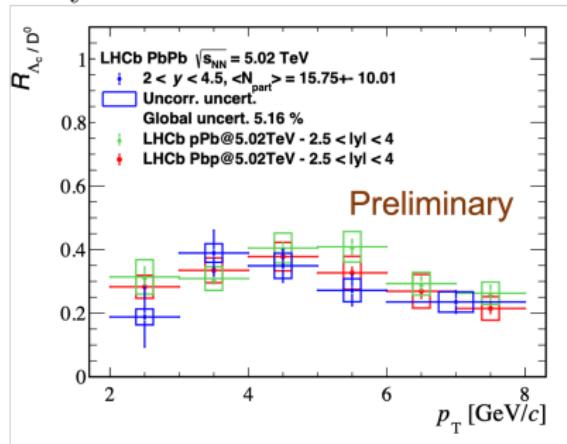
- Initial-state effects largely cancelled in ratio
- Final-state effects dominant

- The ratio increases with the system size, different from the decreasing trend as multiplicity in pp
- Indicate that coalescence may dominate the $\chi_{c1}(3872)$ production in $p\text{Pb}$?

Prompt Λ_c^+/D^0 ratio in peripheral PbPb at 5 TeV

LHCb-PAPER-2021-046, in preparation

- First Λ_c^+/D^0 ratio measurement in peripheral PbPb collisions at forward rapidity, up to $\sim 60\%$ centrality.
- Baryon to meson ratio sensitive to hadronisation mechanism.

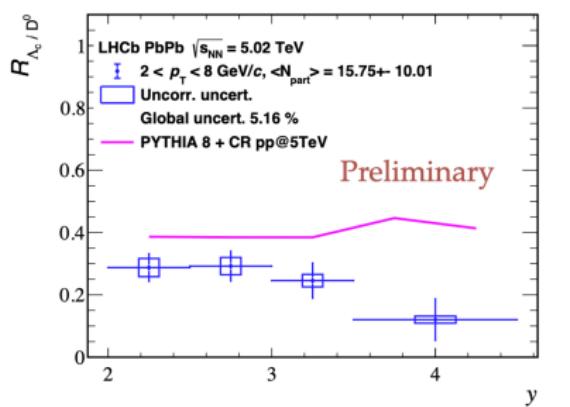
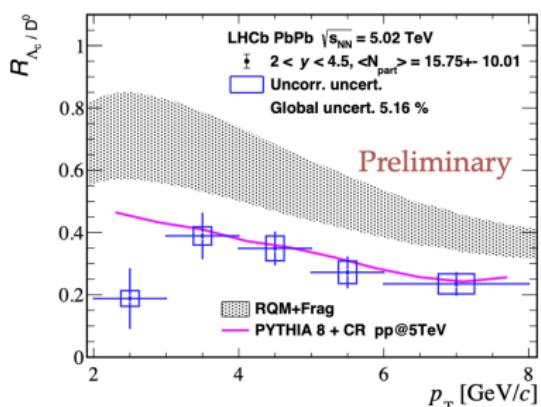


- A relative enhancement at intermediate p_T .
- Consistent with LHCb results in $p\text{Pb}$ at $\sqrt{s_{NN}} = 5.02$ TeV.

Prompt Λ_c^+ / D^0 ratio in peripheral PbPb

LHCb-PAPER-2021-046, in preparation

- Comparisons with theoretical calculations:

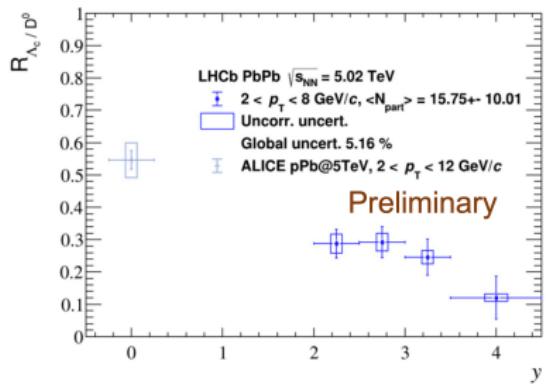
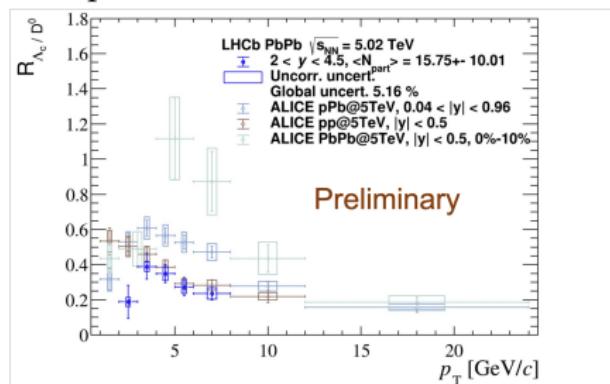


- Compatible with PYTHIA 8 + Colour reconnection prediction for $p_T > 4 \text{ GeV}/c$.
- Standard Hadronisation Model does not reproduce the data.

Prompt Λ_c^+ / D^0 ratio in peripheral PbPb

LHCb-PAPER-2021-046, in preparation

- Comparisons with measurements from ALICE:



- Similar p_T trend with ALICE for $p_T > 4 \text{ GeV}/c$.
- $R_{\Lambda_c^+ / D^0}$ vs. y at forward rapidity lower than ALICE results at mid rapidity.