D^0 modification factor in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ in LHCb

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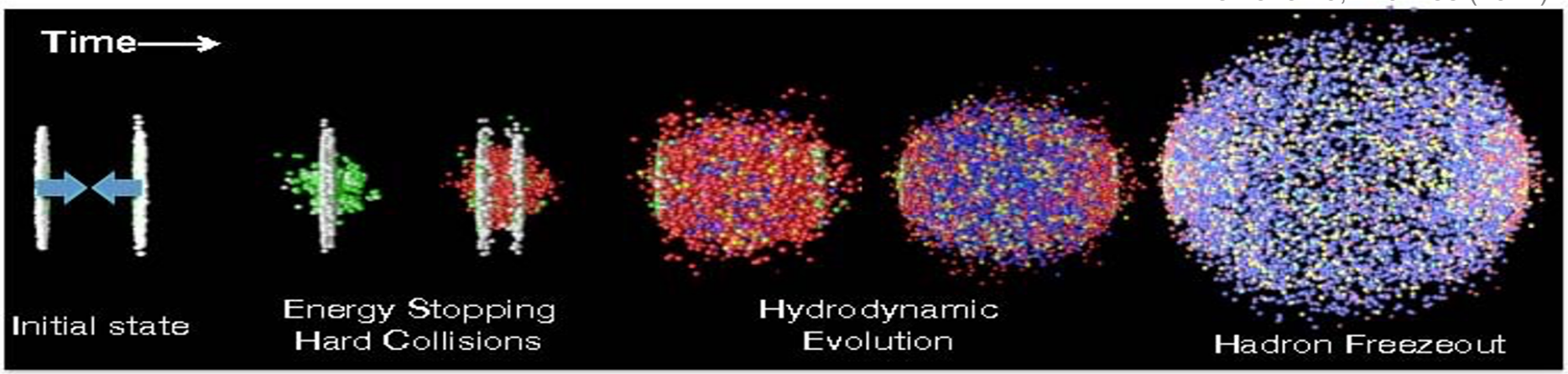
Heavy quarks in heavy-ion collisions

- Heavy quarks are excellent probes of the cold and hot nuclear matter effects
  - Produced in initial hard scatterings
  - $m_Q \gg \Lambda_{\mathrm{QCD}}$: allow perturbative calculations on cross-sections
  - $t_{\mathrm{prod}} \ll t_{\mathrm{QGP}}$: experience whole time evolution of collisions

Pramana 79, 719–735 (2012)



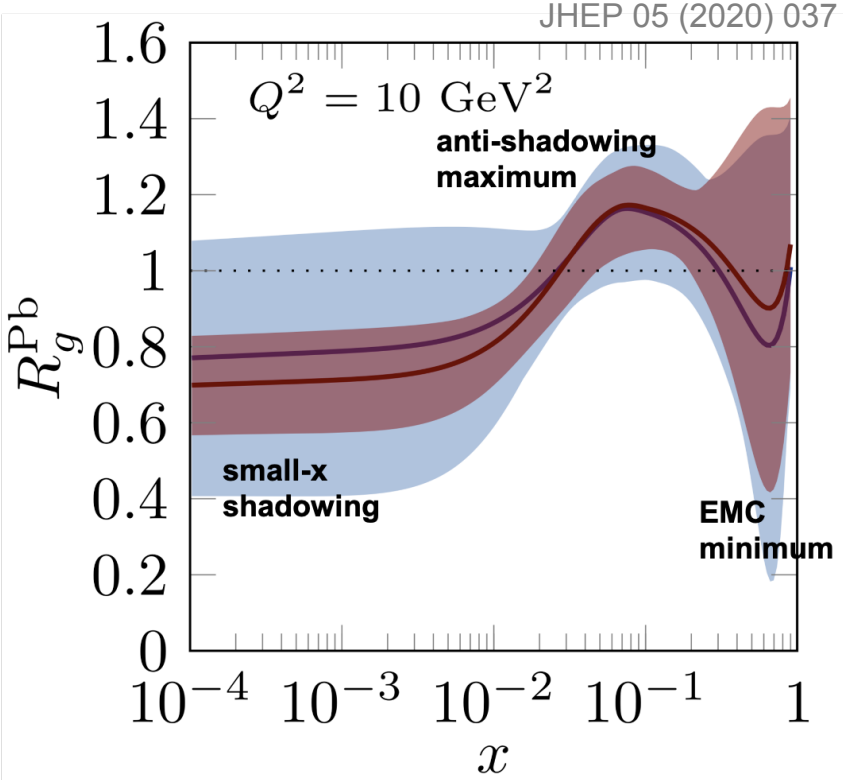
- Modification of nPDFs: $R_{p\mathrm{A}}$
- Initial-state and final-state energy loss
- Heavy quarkonium suppression
- Parton QCD energy loss: R_{AA}
- Collective behaviour: v_2
- Strangeness enhancement: D_s^+/D^+ ratio *etc.*
- Hadronisation: baryon/meson ratio

Initial-state effects

- Initial-state effects are expected to dominate in D^0 production
  - Modification of the parton distribution function (PDF). The nuclear PDFs (nPDF) $f^A(x, Q^2)$ and the free-proton $f^p(x, Q^2)$ can be related by the nuclear modification factor $R^A(x, Q^2)$:

    $$R^A(x, Q^2) = f^A(x, Q^2)/(A\, f^p(x, Q^2))$$

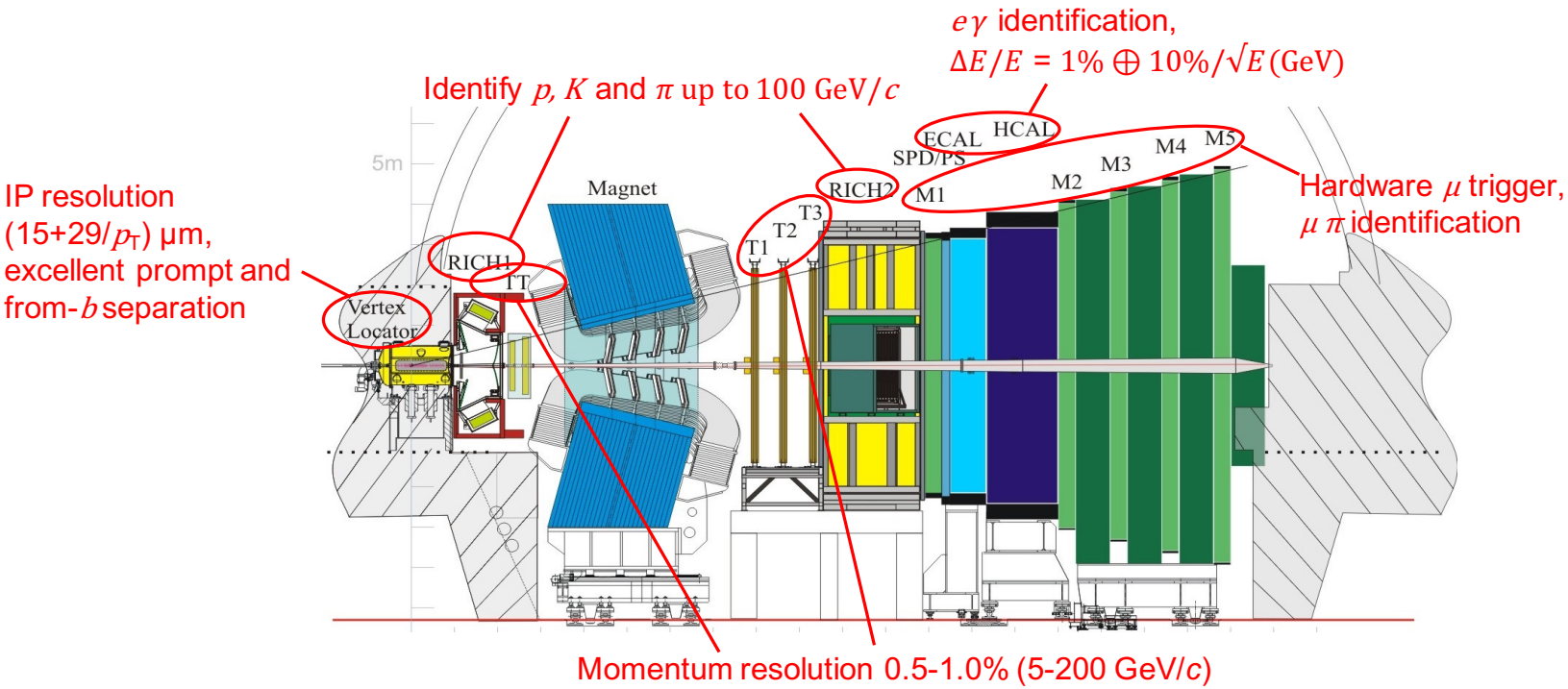
  - Colour glass condensate of heavy ions at low x.
  - Initial-state energy loss from multi-particle scattering.



LHCb detector

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

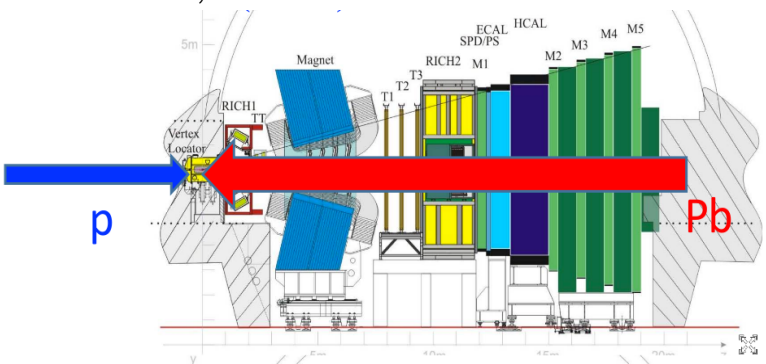
- A single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$
- Designed for studying particles containing b or c quarks
- A general purposed detector measuring pp/pPb/PbPb and in fixed target mode



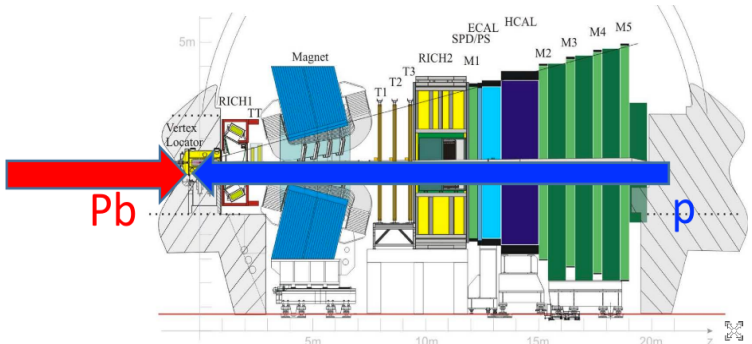
Data configuration

- pPb data taken in 2016 at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, two collision configurations:

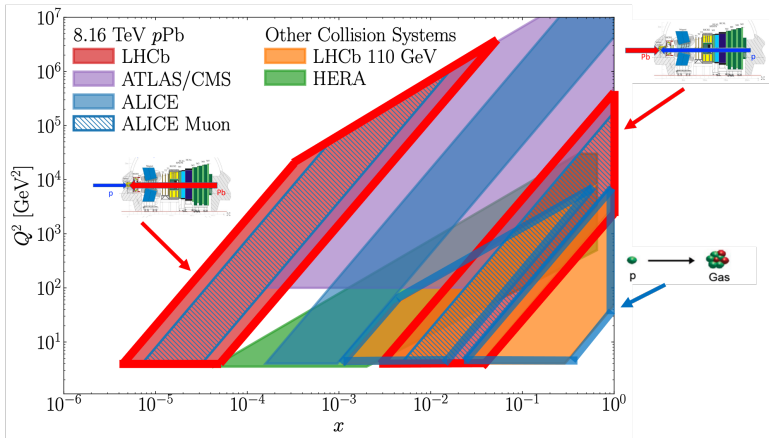
pA: forward ,$\mathcal{L}$=13.6±0.3nb^{-1}



Ap: backward ,$\mathcal{L}$=20.8±0.5nb^{-1}



- Kinematic coverage in (x, Q^2) space



- pPb system boosted in lab frame

$$y_{\mathrm{lab}} = y_{p\mathrm{A}} + 0.465$$

- $\sim$ 20 times more statistics than 5.02 TeV pPb

Cross-section determination

arXiv:2205.03936

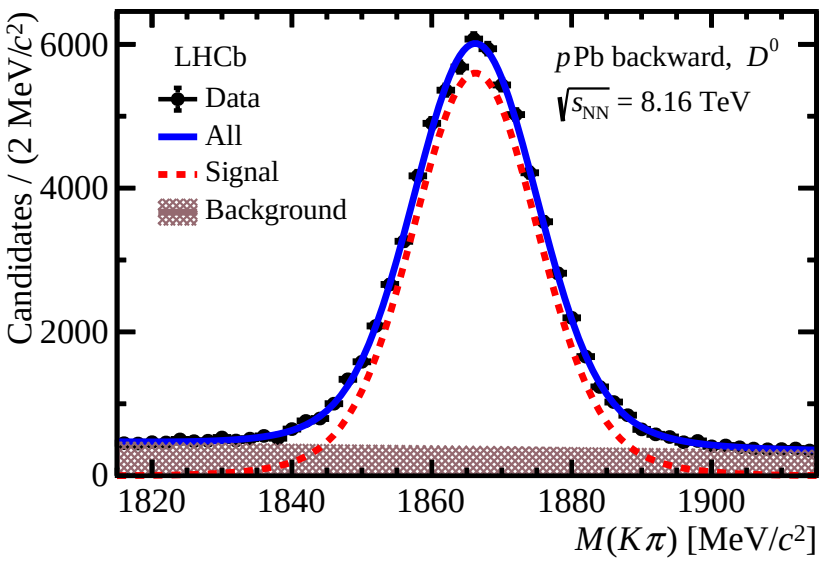
- D^0 candidates reconstructed from the $K\pi$ channel, charge conjugate channels included
- The double differential cross-section defined as:

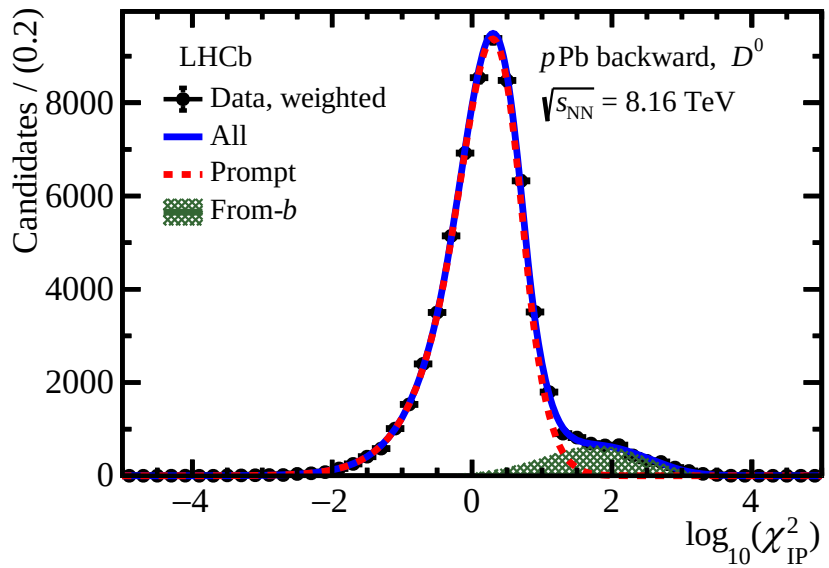
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}} = \frac{N(D^0 \to K\pi)}{\mathcal{L} \times \varepsilon_{\mathrm{tot}} \times \mathcal{B}(D^0 \to K\pi) \times \Delta y \times \Delta p_{\mathrm{T}}} \,,$$

  - $N(D^0 \to K\pi)$: prompt D^0 yield, measured by invariant-mass fit and $\log_{10}(\chi^2_{\mathrm{IP}})$ fit
  - $\varepsilon_{\mathrm{tot}}$: total efficiencies, estimated for each kinematic intervals using simulation samples
  - $\mathcal{L}$: Luminosity
  - Δp_{T}: $0.5\,\mathrm{GeV}/c$ for $1 < p_{\mathrm{T}} < 6\,\mathrm{GeV}/c$ and $1\,\mathrm{GeV}/c$ otherwise
  - Δy: 0.25
  - Kinematic coverage: $0 < p_{\mathrm{T}} < 30\,\mathrm{GeV}/c$, $2.5 < y^* < 4.0$ (forward), $-5.0 < y^* < -2.5$ (backward)
  - $\mathcal{B}$: branching fraction ,both $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ included

Prompt yield extraction

- Extended unbinned maximum likelihood fit performed in each kinematic bin to get the signal yield
- The inclusive D^0 yield obtained by fitting invariant mass $M(K\pi)$ distribution
- The prompt component extracted using the information of impact parametre of D^0 candidates, for which D^0 mesons from beauty decays have larger values





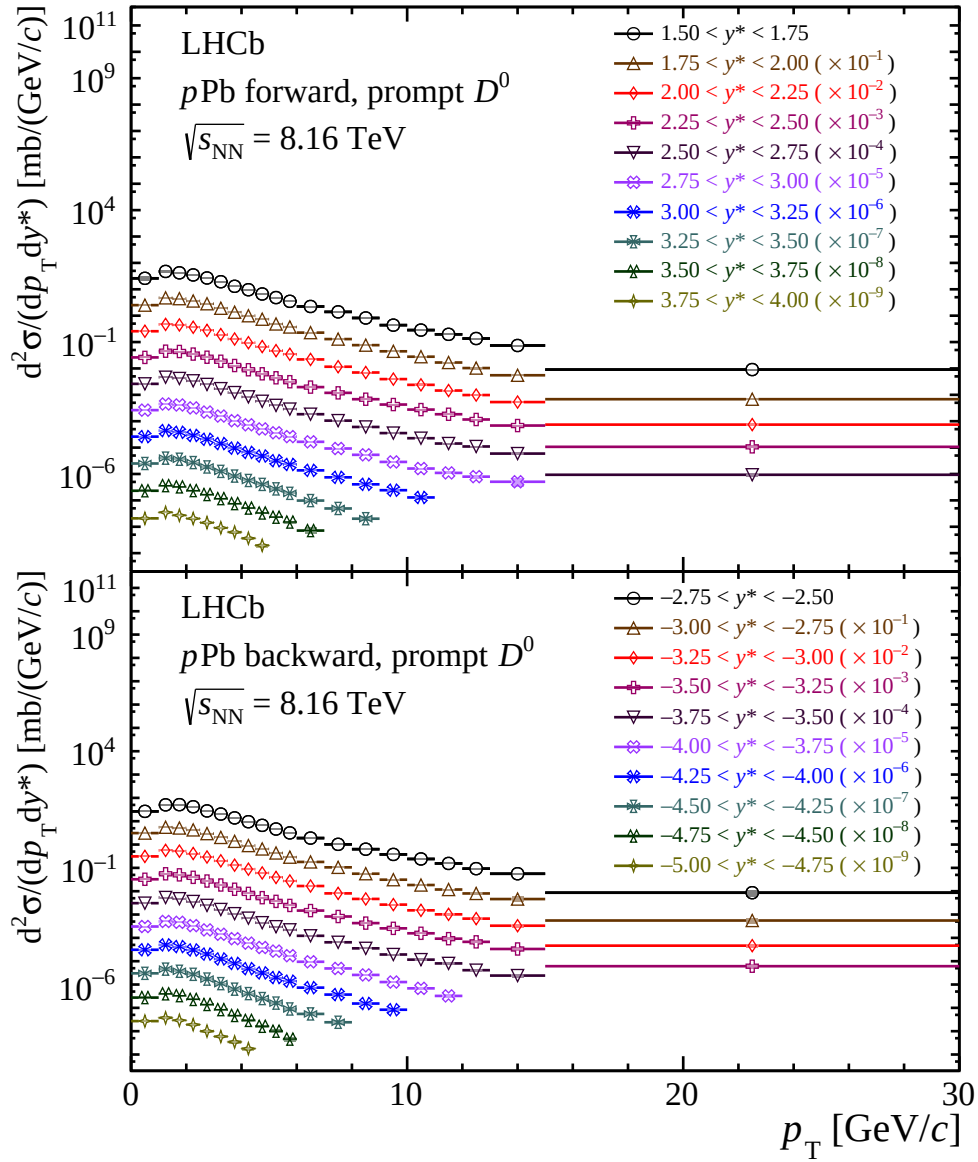
Efficiency and systematic uncertainties

- $\varepsilon_{\text{tot}} = \varepsilon_{\text{acc}} \times \varepsilon_{\text{rec\&sel}} \times \varepsilon_{\text{PID}} \times \varepsilon_{\text{trigger}}$
- The summary table for systematic uncertainties
  - Dominate term: tracking calibration at low p_{T}, simulation sample size at high p_{T}

Uncertainty source	Forward [%]	Backward [%]
Tracking calibration	3.0 – 4.7	3.1 – 10.7
PID	0.2 – 6.9	0.2 – 26.5
Trigger efficiency	0.0 – 16.5	0.0 – 4.7
Multiplicity correction	0 – 9	0 – 16
Luminosity	2.6	2.5
Branching fraction	0.8	0.8
Mass fit	0.0 – 19.3	0.1 – 6.1
$\log_{10}\left(\chi^2_{\text{IP}}\right)$ fit	0.3 – 19.5	0.4 – 7.0
Simulation sample size	1 – 40	1 – 26

Double differential cross-section

- A similar trend of $\mathrm{d}^2\sigma/(\mathrm{d}y\mathrm{d}p_\mathrm{T})$ as a function of p_T in different y^* intervals
- Integrated cross-sections of $297.6 \pm 0.6 \pm 14.0\,\mathrm{mb}$ for forward and $315.2 \pm 0.2 \pm 17.8\,\mathrm{mb}$ for backward

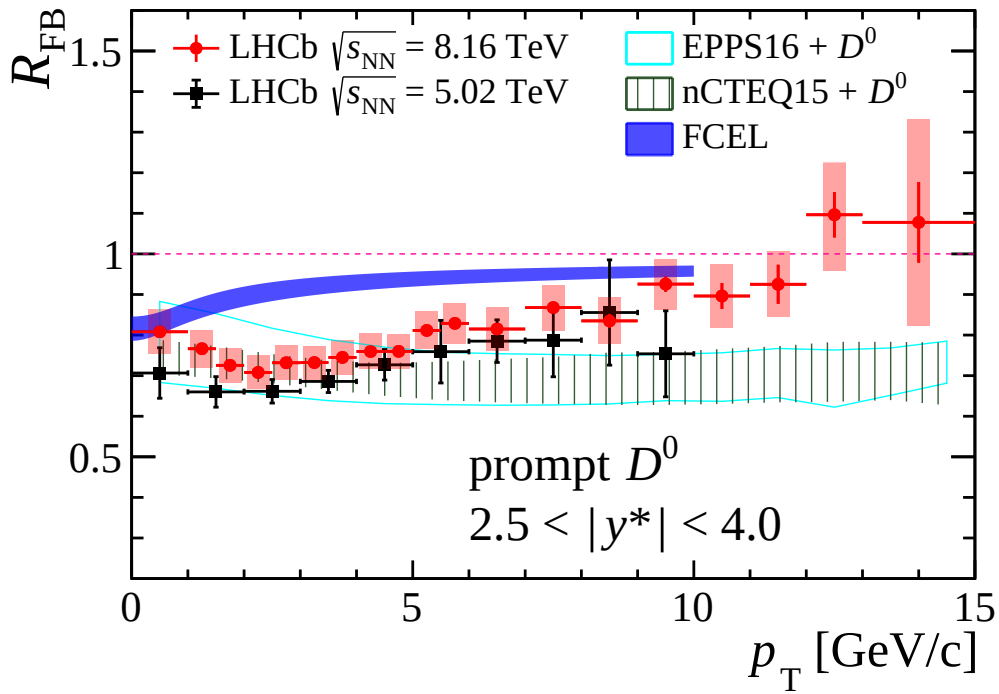


Forward-backward production ratio

- Forward-backward production ratio is defined as :

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

- Significant asymmetry between forward and backward collisions, suggesting the existence of cold nuclear matter effect
- Consistent with the LHCb 5.02 TeV pPb result
- In agreement with nPDF models at low p_{T} but discrepancy found for $p_{\mathrm{T}} > 6\,\mathrm{GeV}/c$
- Fully coherent energy loss (FCEL) considered as an additional effect other than nPDFs, which may not explain the differences



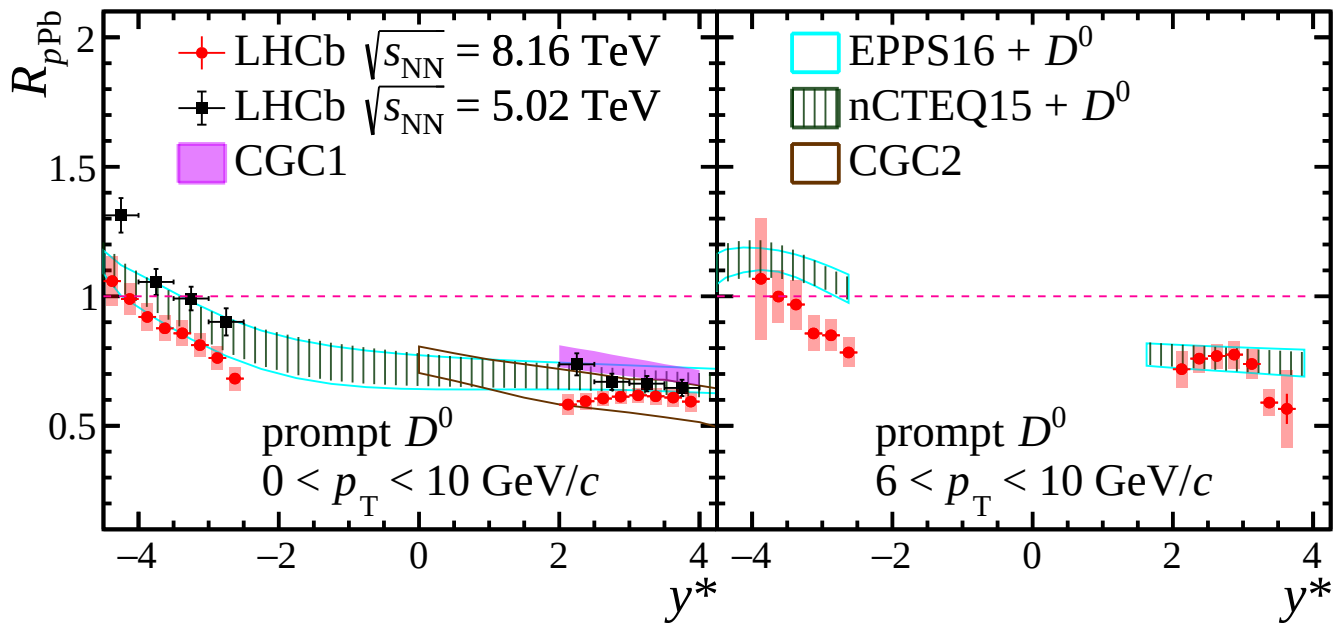
LHCb 5.02 TeV: JHEP 10 (2017) 090
nCTEQ: Phys. Rev. D93 (2016) 085037
EPPS16: Eur. Phys. J. C77 (2017) 163
FCEL: JHEP 01 (2022) 164

Nuclear modification factor

- Nuclear modification factor is defined as:

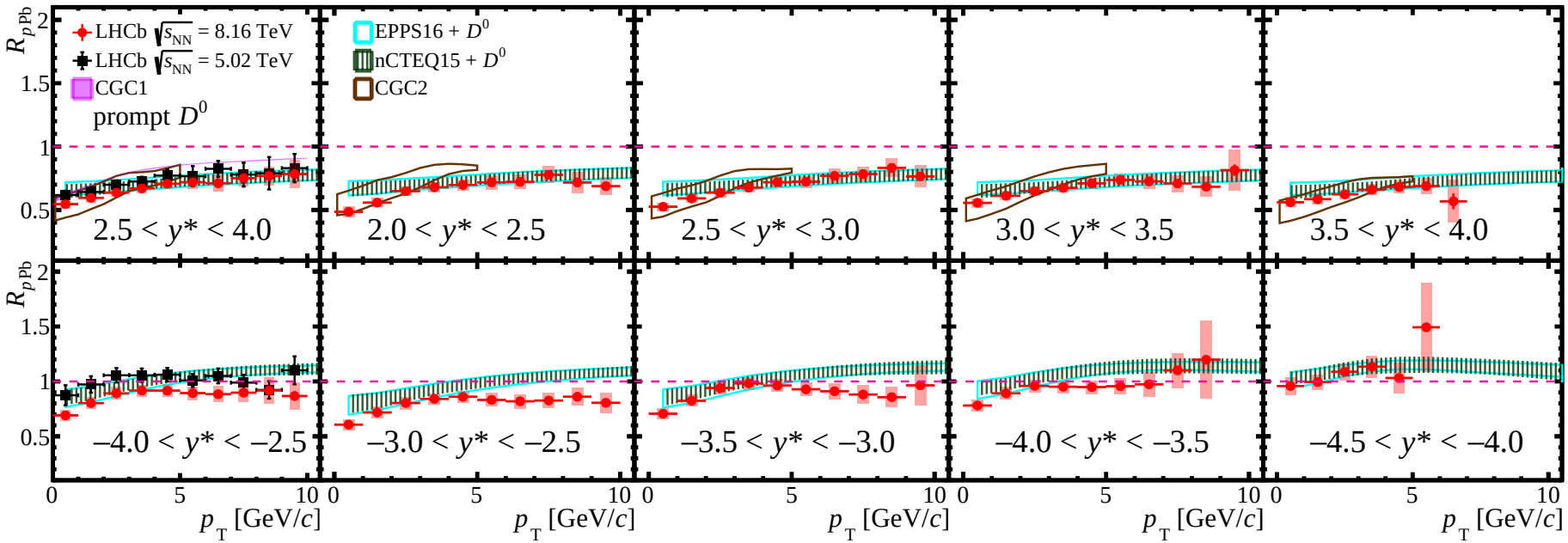
$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A} \frac{\sigma_{p\mathrm{Pb}}(\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV})}{\sigma_{pp}(\sqrt{s} = 8.16\,\mathrm{TeV})}$$

- The pp reference $\sigma_{pp}(\sqrt{s} = 8.16\,\mathrm{TeV})$ obtained from a power-law interpolation of σ_{pp} at $\sqrt{s} = 5.02\,\mathrm{TeV}$ and $13\,\mathrm{TeV}$
- Comparable uncertainty from the interpolation to that from $\sigma_{p\mathrm{Pb}}$



CGC1: Phys. Rev. D 91 (2015) 114005
CGC2: Phys. Rev. D 98 (2018) 074025

Nuclear modification factor



- Suppression compared to unity in forward rapidities, consistent with the LHCb 5.02 TeV result as well as CGC and nPDF calculations
- Lower than 5.02 TeV result in backward rapidities, possibly attributed to different Bjorken-x coverage of two energies
- Discrepancy between data and nPDF calculations for $p_{\mathrm{T}} > 6\,\mathrm{GeV}/c$ and $-2.5 < y^* < -3.5$ $(2.7 - 3.7\sigma)$
- Potential initial- or final-state effects beyond modification of nPDF?

Summary and outlook

- D^0 production cross-sections measured in pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ for both forward and backward rapidities, with ~ 20 times more statistics than LHCb $5.02\,\mathrm{TeV}$ pPb results
- Forward backward production asymmetry observed by measuring the forward-backward production ratio R_{FB}
- Nuclear modification factor $R_{p\mathrm{Pb}}$ obtained by comparing the cross-section in pPb to that in pp
  - Significant suppression compared to unity in forward rapidity, consistent with the previous result and theoretical calculations
  - Discrepancy with nPDF calculations at high-p_{T} in backward rapidity, indicating possible initial- or final-state effects
- More models, *e.g.* FCEL, to be considered in the $R_{p\mathrm{Pb}}$ calculation
- The measurements of D^+, D_s^+, Λ_c^+ hadrons to further study the final-state effects and hadronisation mechanism for heavy-flavour production
- The investigation of collective behaviour of heavy-flavour particles

Thanks