Heavy ion physics at LHCb

Émilie Maurice on behalf of the LHCb collaboration

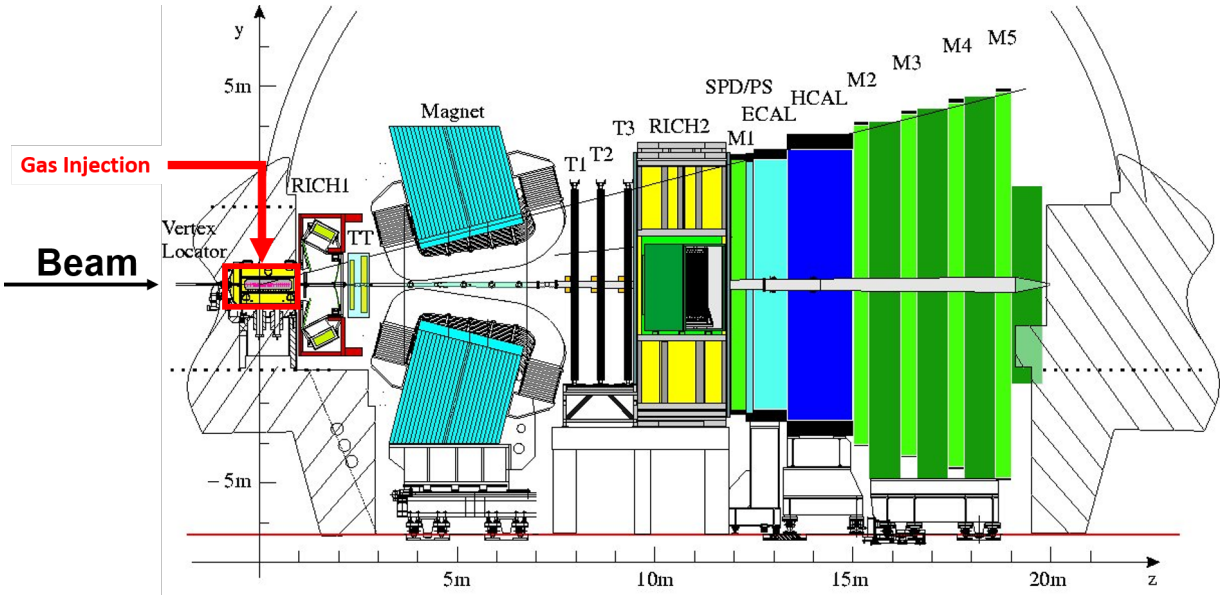
ICFNP

25$^{\text{th}}$ August 2017, Kolymbari, Creta

August 22, 2017

LHCb detector and the fixed-target system [JINST 3 (3008) S08005]

LHCb was designed for heavy flavor physics but is now a general purpose detector



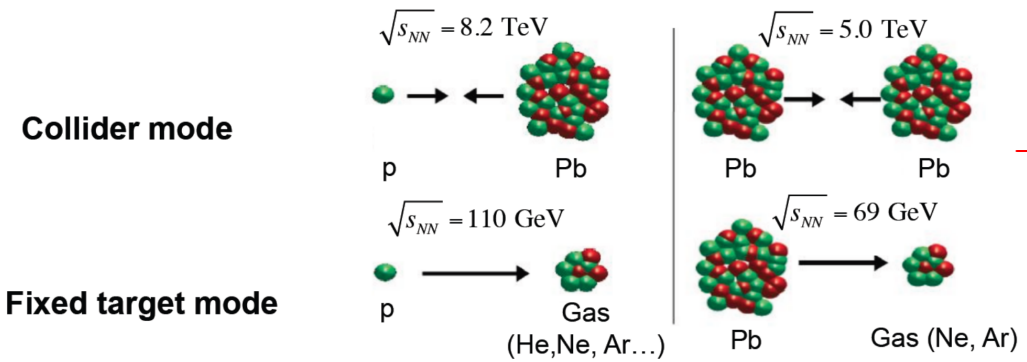
Fully instrumented in $2 < y < 5$

Excellent performance:

- ✓ Vertex, IP and decay time resolution
- ✓ Momentum resolution
- ✓ Particle identification

$\epsilon_{K\to K} \approx 95\%$, $\epsilon_{\pi\to K} \approx 5\%$

$\epsilon_{\mu\to\mu} \approx 97\%$, $\epsilon_{\pi\to\mu} \approx 1\text{-}3\%$



Heavy ions program: novelty for LHCb

Reversal of p and Pb beams

→ backward and forward rapidity region

Fixed-target mode: unique at LHC !

→ $\sqrt{s_{NN}} \in [69, 115]$ GeV

→ backward rapidity region

Selected results

1. J/ψ production in pPb collisions at 8.2 TeV, arXiv:1706.07122
2. D^0 production in pPb collisions at 5 TeV, arXiv:1707.02750
3. Λ_c^+ production in pPb collisions at 5 TeV, LHCb-CONF-2017-005
4. J/ψ and D^0 production in pAr collisions at 110 GeV LHCb-CONF-2017-001

J/ψ production measurement in pPb collisions [arXiv:1706.07122]

First analysis of pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, from November 2016

Extraction of prompt J/ψ and J/ψ from b-decays

Simultaneous fit of mass and pseudo-proper decay time

$$t_z = \frac{(Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}}{p_z}$$

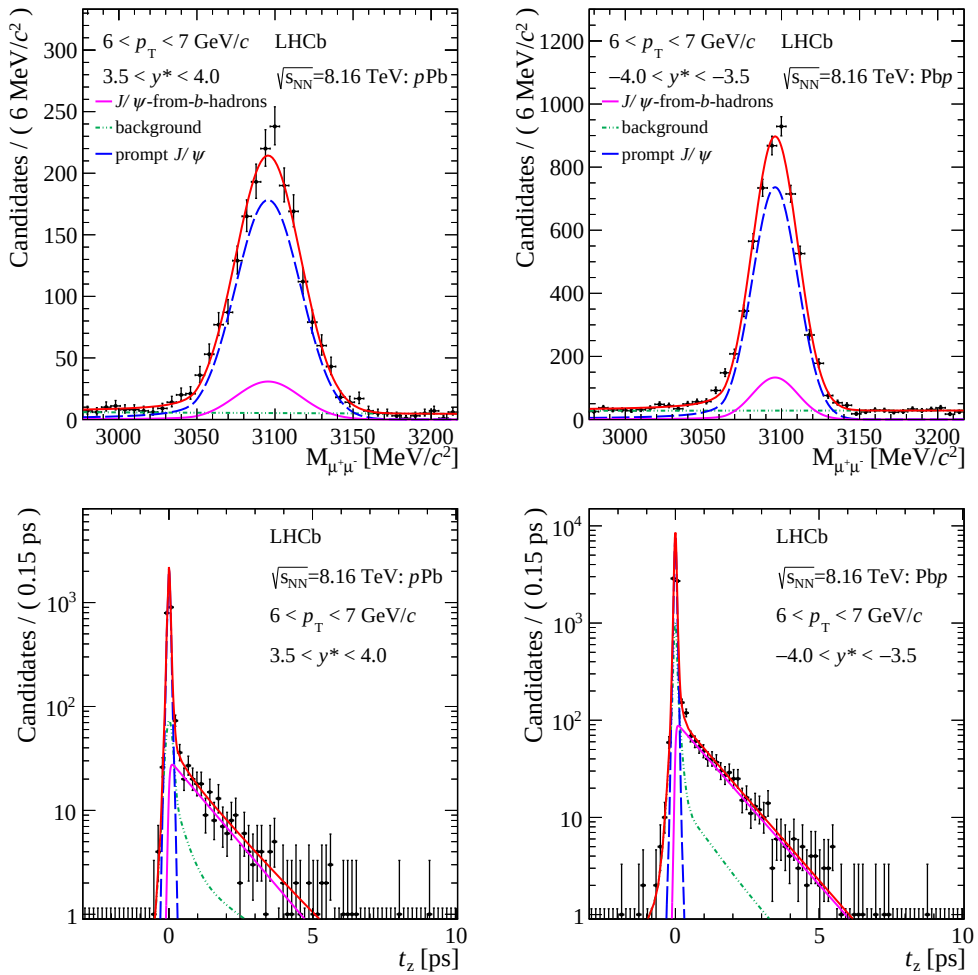
Mass distributions described by:

- Signal: Crystal Ball
- Background: Exponential

t_z distributions described by:

- Signal: $\delta(t_z)$ for prompt, exponential for b-decays
- Background: empirical function from sideband

Forward: pPb **Backward: Pbp**

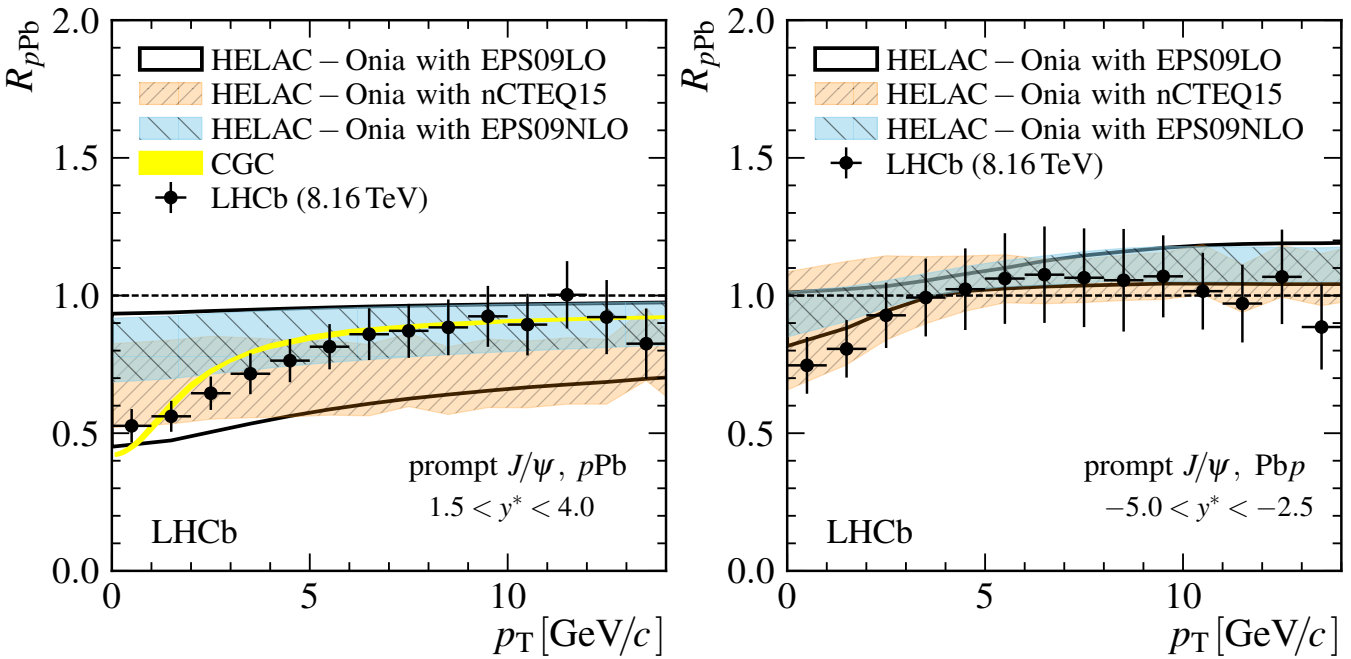


Prompt J/ψ modification factor [arXiv:1706.07122]

Nuclear modification factor $R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{pPb}(p_T,y^*)/\mathrm{d}p_T\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_T,y^*)/\mathrm{d}p_T\mathrm{d}y^*}$

σ_{pp} at $\sqrt{s} = 8.16$ TeV: interpolation of LHCb measurements, and extrapolation for bins not covered by pp data

Forward: pPb **Backward: Pbp**



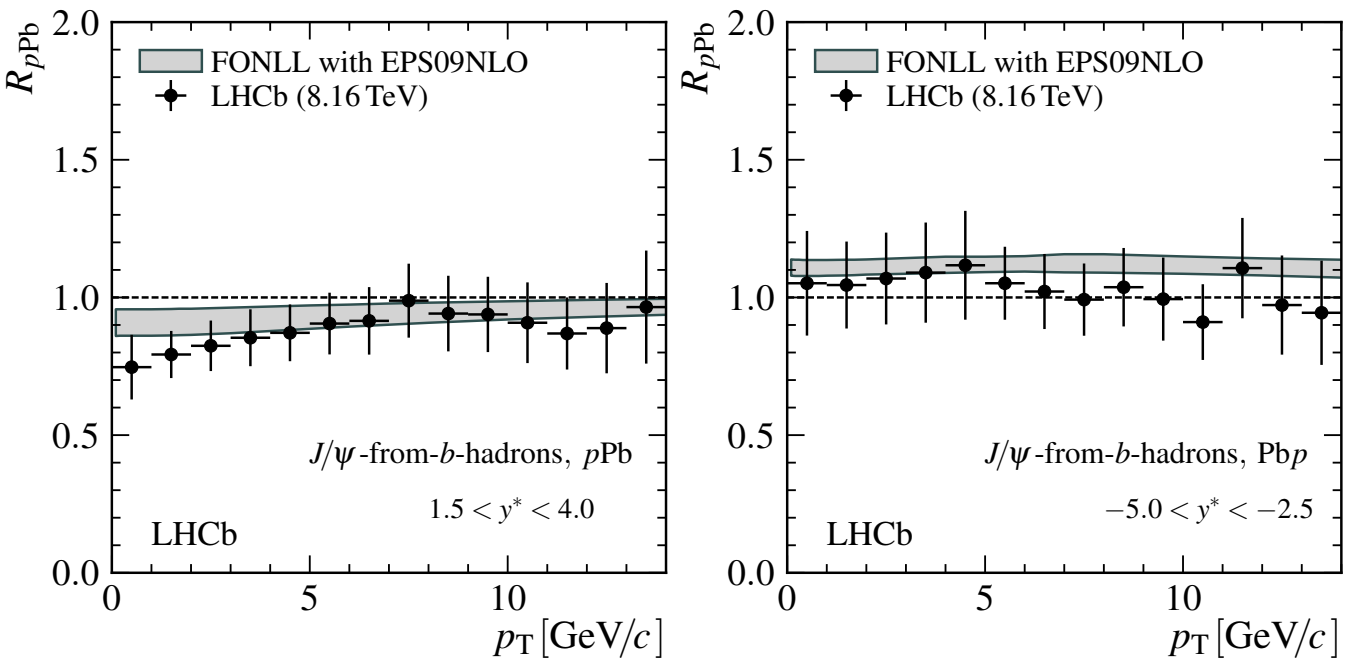
Theoretical references
cf. slides 9, 10

Prompt J/ψ R_{pPb} as a function of p_T

- Strong suppression at low p_T, decreasing with increasing p_T
- Collinear factorization including PDF modification in nuclei in agreement with data
- p_T dependence at fwd rapidity reproduced by Colour Glass Condensate calculations

Non prompt J/ψ modification factor [arXiv:1706.07122]

Forward: pPb **Backward: Pbp**



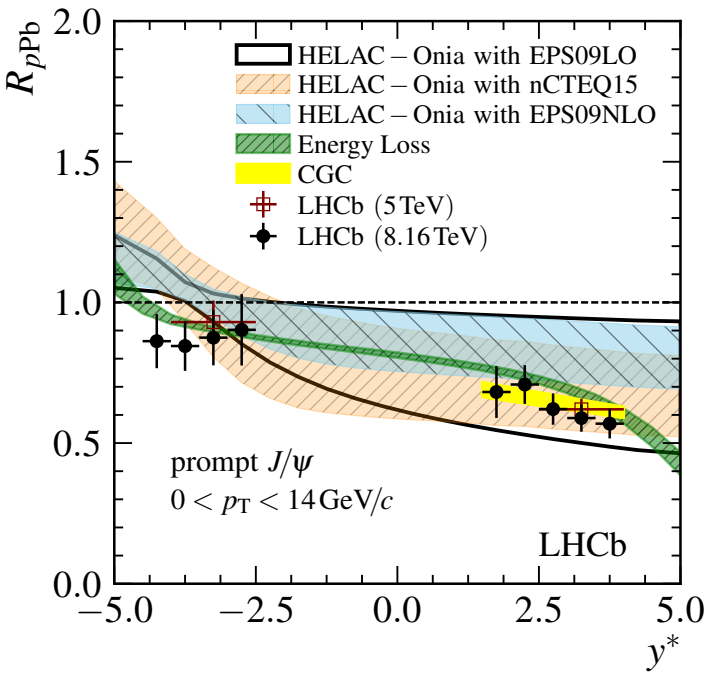
Theoretical references

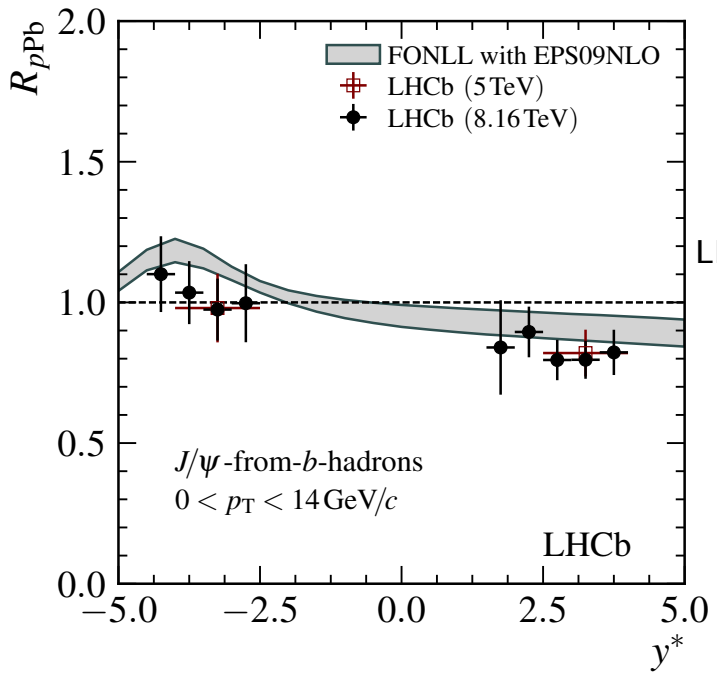
cf. slides 9, 10

Non prompt J/ψ R_{pPb} as a function of p_T

- Access the production of b hadrons
- At forward rapidity: small suppression at low p_T
- At backward rapidity: compatible with unity
- pQCD calculations with nPDFs in agreement with data

Prompt and non prompt J/ψ modification factor [arXiv:1706.07122]





Theoretical references

cf. slides 9, 10

LHCb 5TeV, arXiv:1308.6729

Prompt and non prompt J/ψ R_{pPb} as a function of y^*

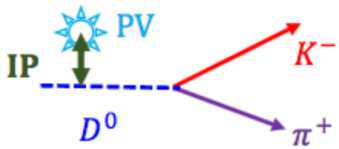
- At backward rapidity: suppression of prompt J/ψ not well reproduced
- At forward rapidity: good agreement of CGC and coherent energy loss calculations with the experimental data
- Large uncertainties on the gluon PDFs at low x

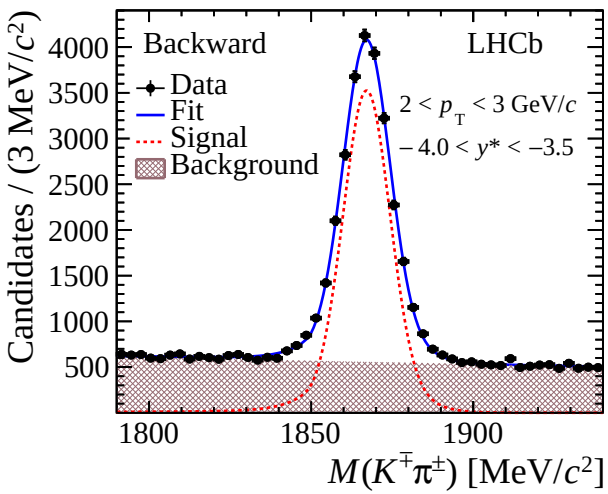
D^0 production in pPb collisions at 5 TeV [arXiv:1707.02750]

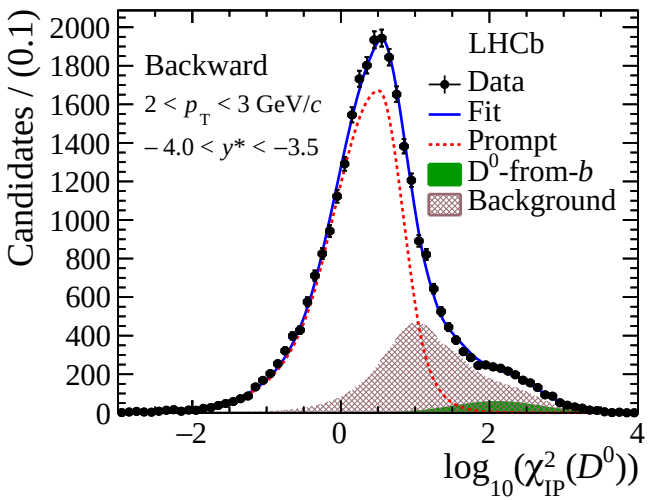
Update of previous preliminary results with 10 times more statistics

Number of inclusive candidates is extracted from a fit to the mass distribution

Then separation between prompt D^0 and B-component with the D^0 impact parameter to PV



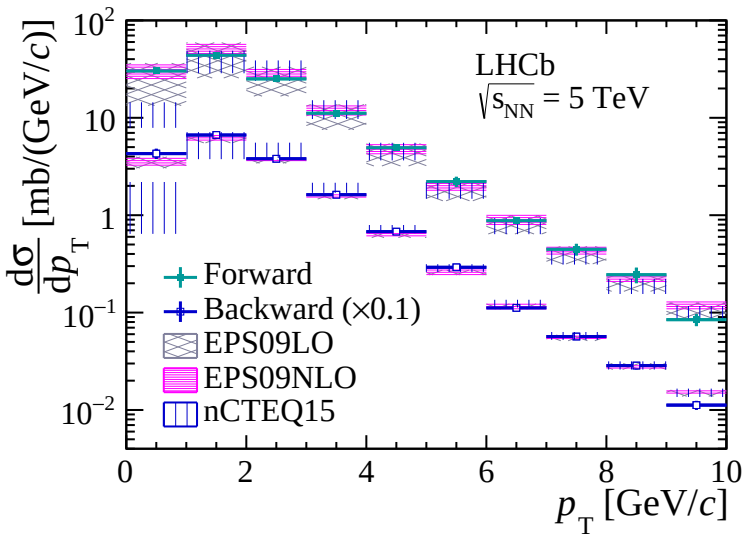


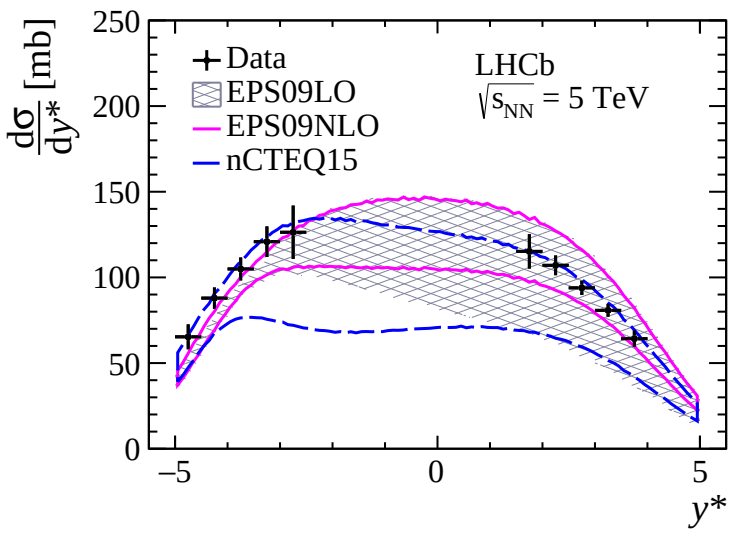


D^0 cross section at 5 TeV [arXiv:1707.02750]

Cross section integrated over the full range

$$\sigma_{\text{forward}}(p_T < 10\text{GeV}/c, 1.5 < y^* < 4.0) = (230.6 \pm 0.5 \pm 13.0)\ \text{mb}$$
$$\sigma_{\text{backward}}(p_T < 10\text{GeV}/c, -5.0 < y^* < -2.5) = (252.7 \pm 1.0 \pm 20.0)\ \text{mb}$$





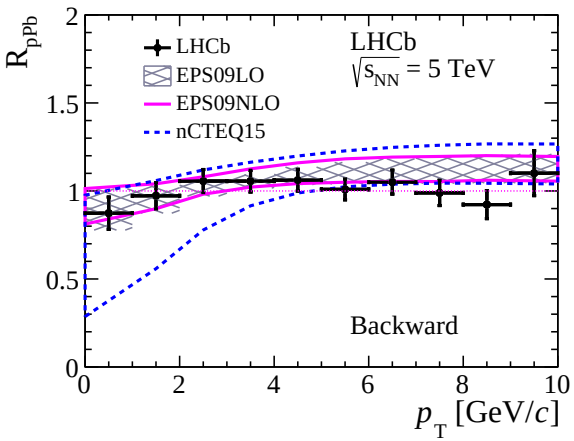
Compared with HELAC-Onia [J.-P. Lansberg, H.-S. Shao, EPJC77 (2017) 1]

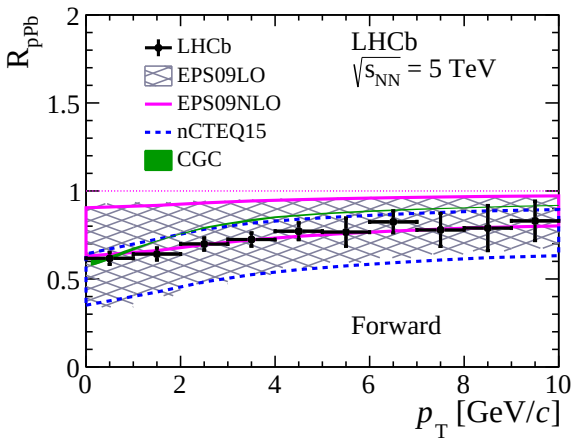
tuned to reproduced pp data with the PDF set CT10NLO [H.-L. Lai et al, PRD82 (2010) 074024] using nuclear PDFs: EPS09LO or EPS09NLO [K. J. Eskola, H. Paukkunen, C. A. Salgado, JHEP04 (2009) 065], nCTEQ15 [K. Kovarik et al, PRD93 (2016) 085037]

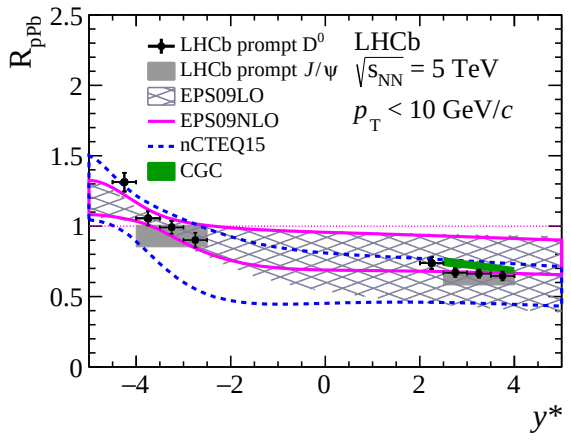
D^0 nuclear modification factor in pPb collisions at 5 TeV [arXiv:1707.02750]

Nuclear modification factor $R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{pPb}(p_T,y^*)/\mathrm{d}p_T\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_T,y^*)/\mathrm{d}p_T\mathrm{d}y^*}$

Computed in the kinematic range common to pPb and pp, or Pbp and pp







Compared with

- HELAC-Onia as for the integrated cross-section
- Color Glass Condensate [B. Ducloué, T. Lappi, H. Mäntysaari, PRD91 (2015) 114005]
- Prompt J/ψ R_{pPb} measured at 5 TeV in LHCb [JHEP02 (2014) 072]

Λ_c^+ production in pPb collisions at 5 TeV [LHCb-CONF-2017-005]

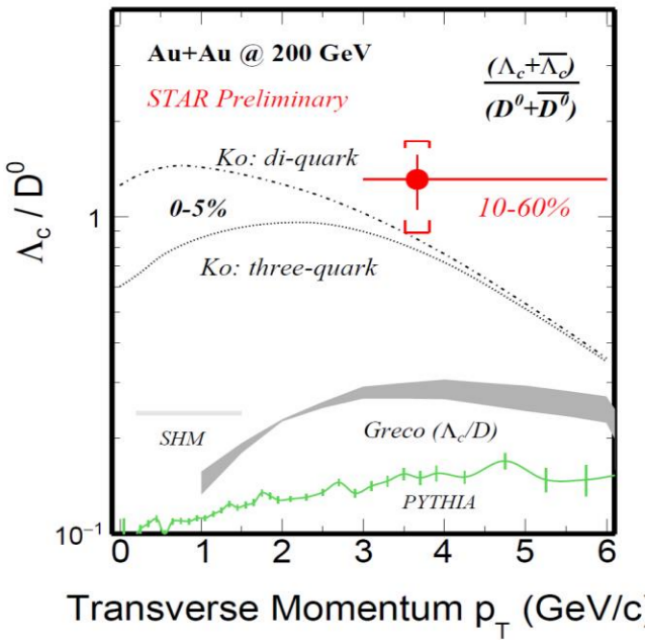
Λ_c^+ **cross section measurements ?**

$\rightarrow$ Baryon to meson production ratio: $\frac{\Lambda_c^+}{D^0}$

- Comparison to AA collisions
- Relevant to charmed hadron hadronisation mechanism

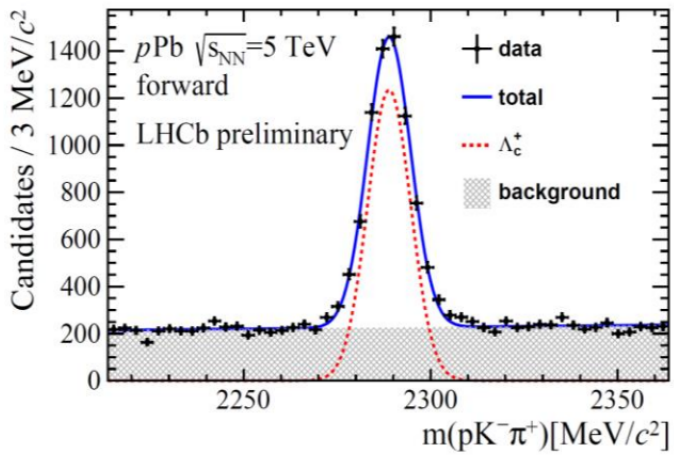
First charmed baryon measurement in pA

STAR, arXiv:1704.04353



Λ_c^+ analysis in pPb collisions at 5 TeV

- Same data sample as D^0
- Same strategy: inclusive $\Lambda_c^+ \rightarrow pK^-\pi^+$ determine from mass fit, then prompt fraction extracted from IP fit



Λ_c^+/D^0 ratio in pPb collisions at 5 TeV [LHCb-CONF-2017-005]

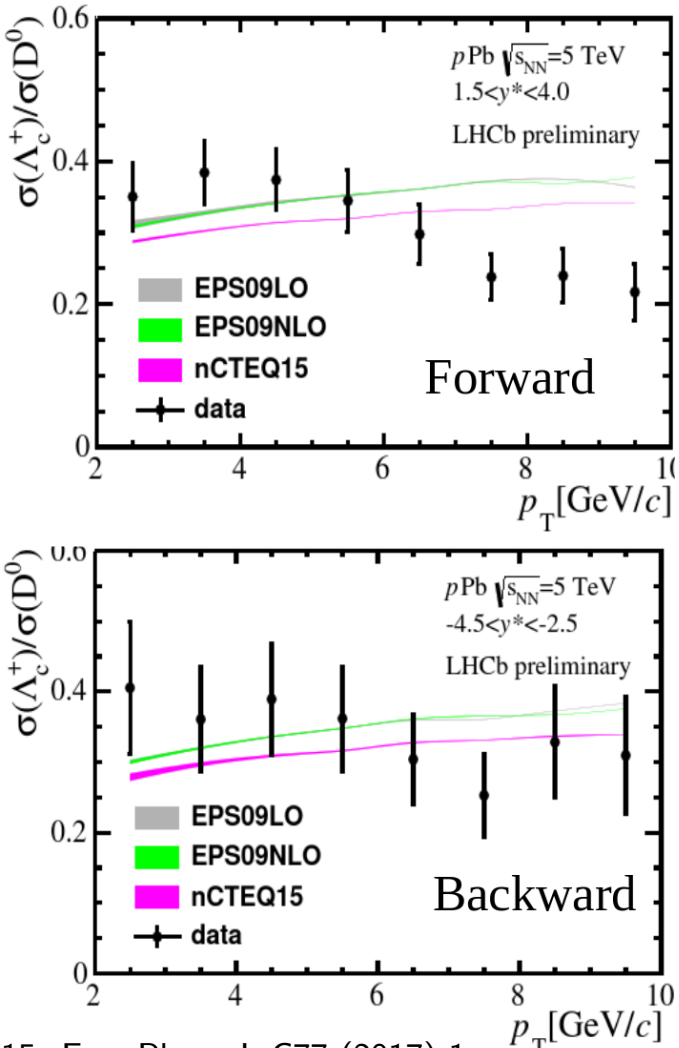
$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(p_T, y^*)}{\sigma_{D^0}(p_T, y^*)}$$

Predictions

- Similar for EPS09LO and EPS09NLO
- nCTEQ15 slightly lower

At forward rapidity: Λ_c^+/D^0 is consistent at lower p_T, but below theories at higher p_T

At backward rapidity: Λ_c^+/D^0 is consistent for all p_T



nCTEQ15: Eur. Phys. J. C77 (2017) 1,
EPS09LO: Comput. Phys. Commun. 184 (2013) 2562,
EPS09NLO: Comput. Phys. Commun. 198 (2016) 238

Λ_c^+/D^0 ratio in pPb collisions at 5 TeV [LHCb-CONF-2017-005]

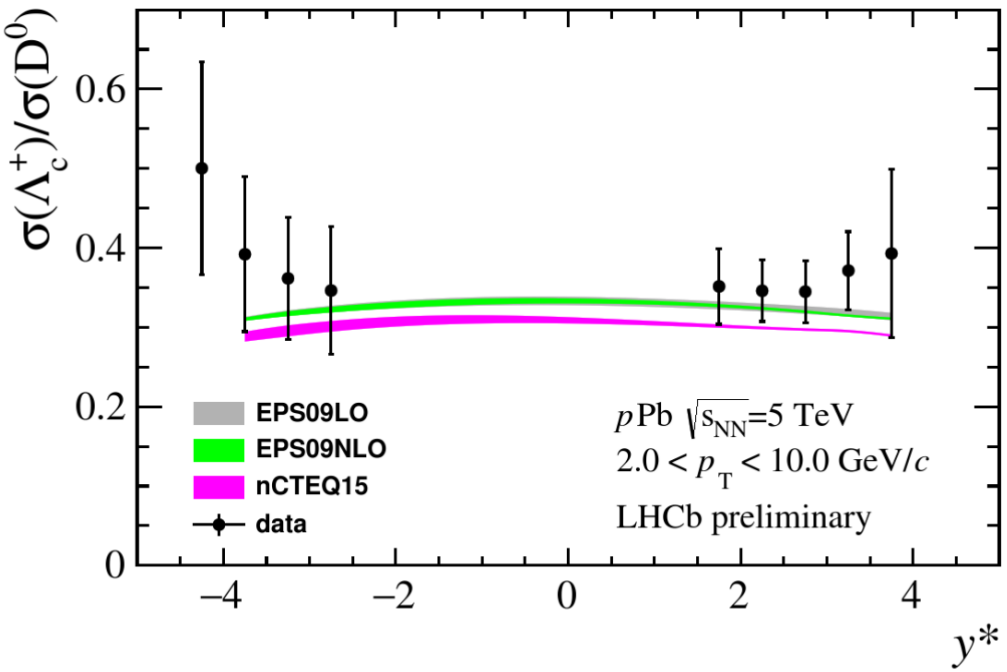
$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*)}{\sigma_{D^0}(y^*)}$$

At forward rapidity:

Λ_c^+/D^0 is consistent for all y^*

At backward rapidity:

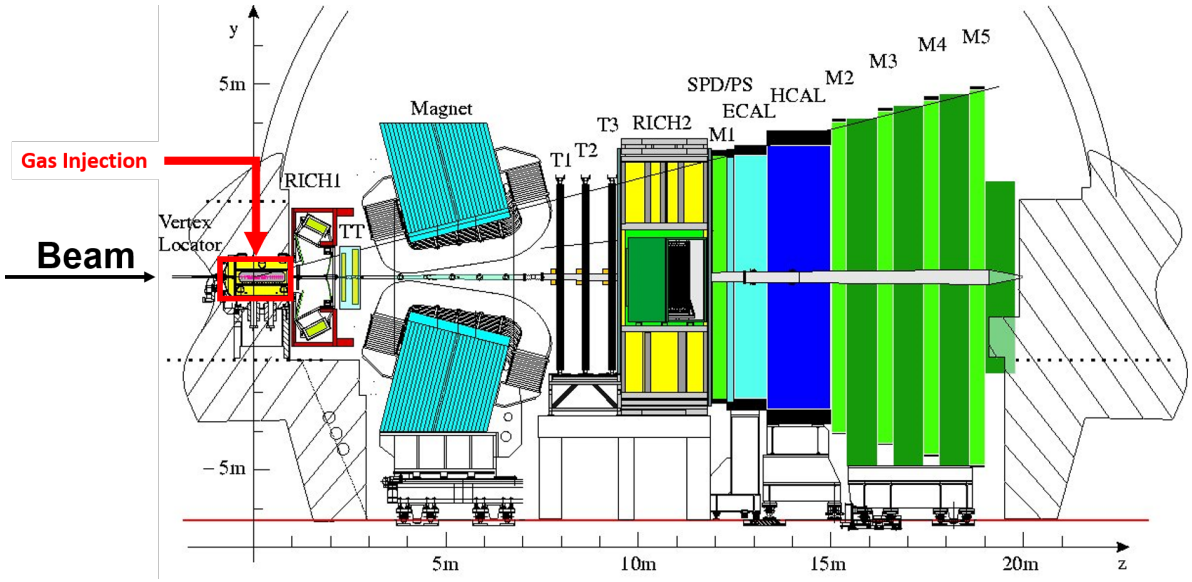
Λ_c^+/D^0 is consistent at lower y^* but display a rising trend with increasing $|y^*|$



nCTEQ15: Eur. Phys. J. C77 (2017) 1,
EPS09LO: Comput. Phys. Commun. 184 (2013) 2562,
EPS09NLO: Comput. Phys. Commun. 198 (2016) 238

→ Charmed baryon to meson production ratio in cold nuclear matter measured
Results consistent with NLO predictions but display a rising trend with increasing $|y^*|$

LHCb fixed target: data taking



Data recorded with gas pressure in the VELO [arXiv:1410.0149]

- Parasitic to the collider mode
- Gas spreads in the beam pipe up to ±20m around LHCb
- Use non-colliding bunches

First production measurements in fixed-target mode

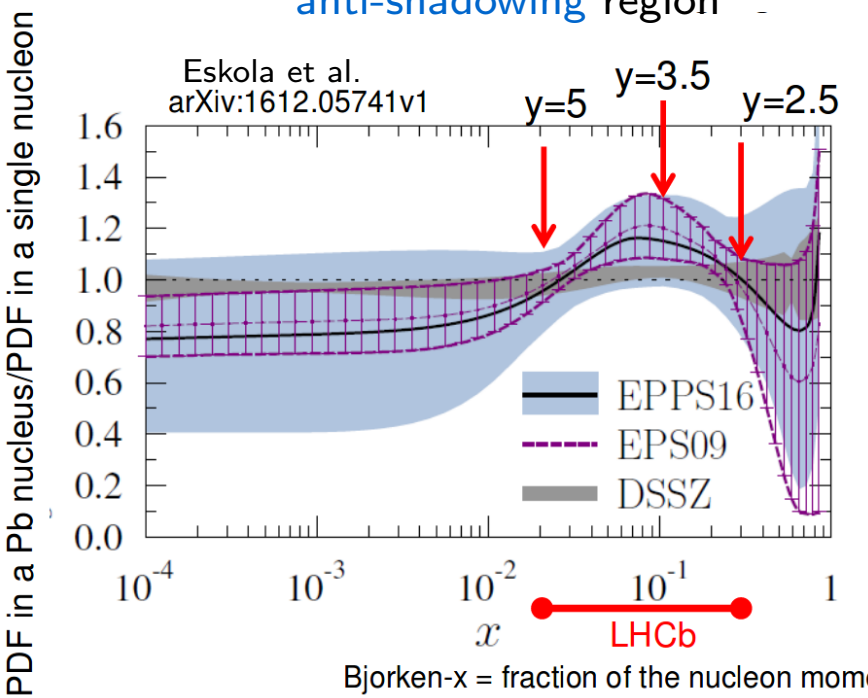
- J/ψ and D^0 in pAr collisions, $\sqrt{s_{NN}} = 110$ GeV, with 4×10^{22} protons on target
- $\overline{p}$ cross section measurement in pHe collisions, $\sqrt{s_{NN}} = 110$ GeV, with 3×10^{21} protons on target [LHCb-CONF-2017-002]

Fixed target heavy flavour program at LHCb

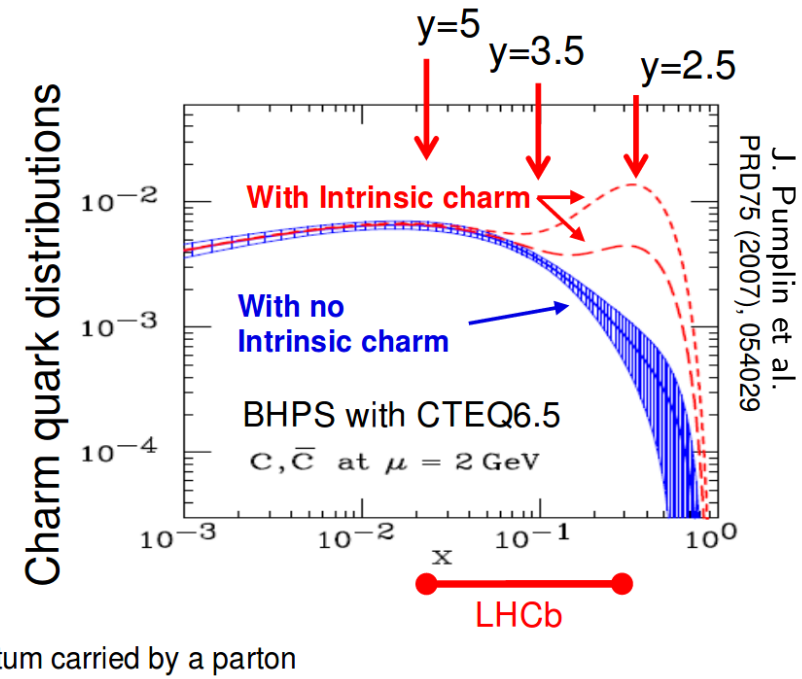
Unique opportunity to perform fixed-target heavy ion physics at LHC:

- Forward measurement of open and hidden charm production ($J/\psi, D^0$...)
- Measurement down to low p_{T}
- Large rapidity coverage ($\sim$ 3 rapidity units) at large Bjorken-x

Access to nPDF anti-shadowing region



Access to intrinsic charm content in the nucleon



Bjorken-x = fraction of the nucleon momentum carried by a parton

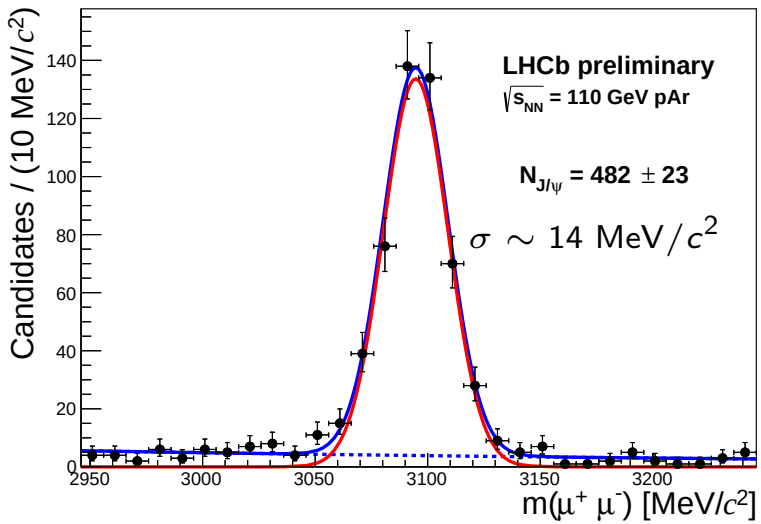
Proton-nucleus collisions provide reference for heavy ions studies

Charm production analysis in pAr collisions – LHCb-CONF-2017-001

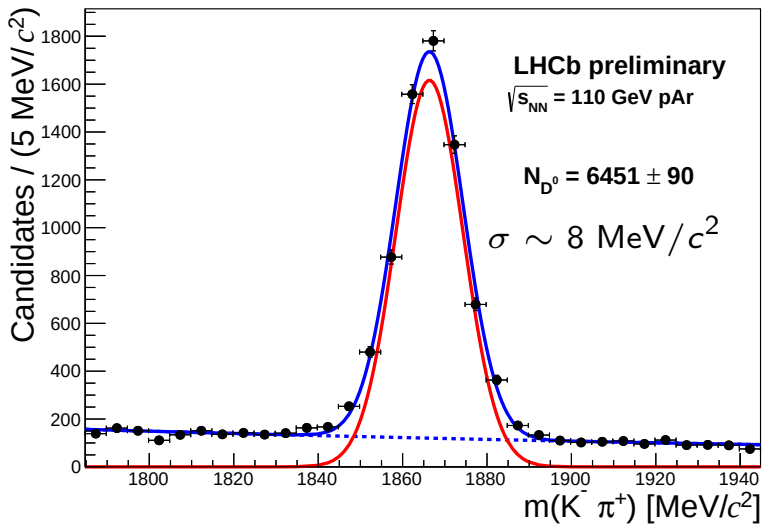
Study the J/ψ and D^0 production in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV

Analysis of data collected in 2015, with 6.5 TeV proton beam on argon gaseous target

- Reconstructed collision vertices extended over ∼1m
- J/ψ and D^0 selected with Z_{vertex} inside the Vertex Detector, $[-200, +200]$ mm, extracted with Crystal Ball functions



$\sim 500\ J/\psi \to \mu^+\mu^-$

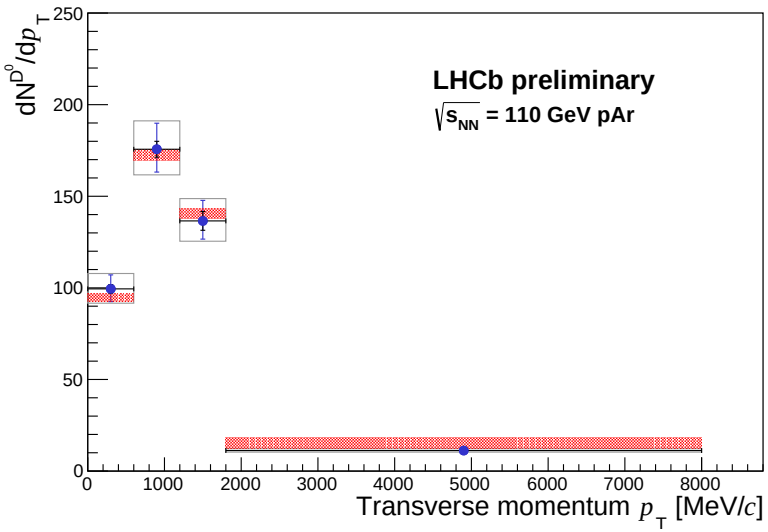


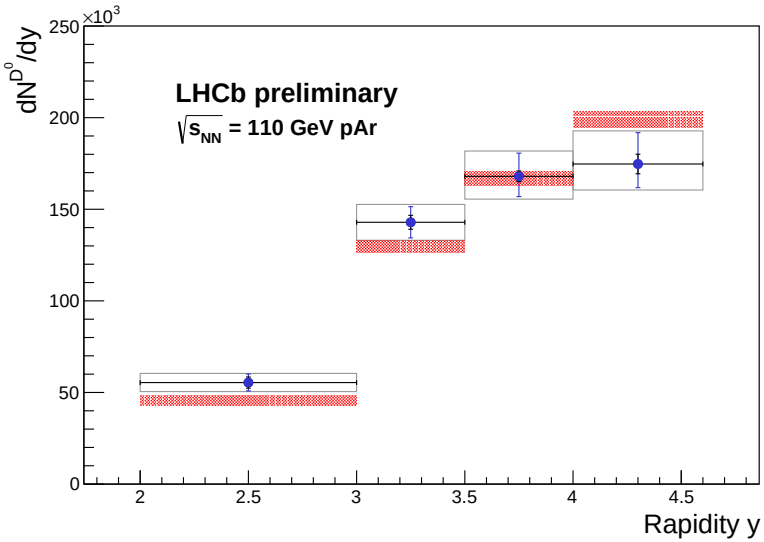
$\sim 6\,500\ D^0 \to K^\mp\pi^\pm$

- Split data in 4 rapidity bins: [2, 3], [3, 3.5], [3.5, 4], [4, 4.6]
- Split data in 4 p_T bins: [0, 600], [600, 1200], [1200, 1800], [1800, 8000] MeV/c

D^0 corrected yields – LHCb-CONF-2017-001

D^0 traverse momentum and rapidity distributions



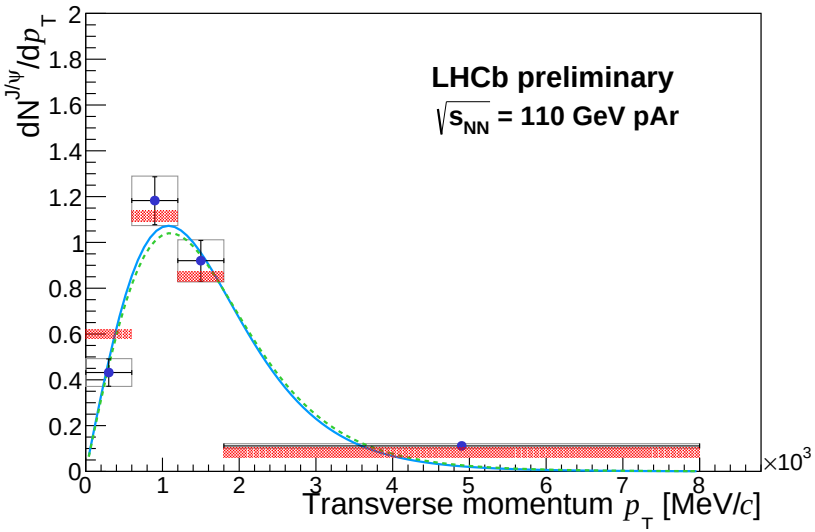


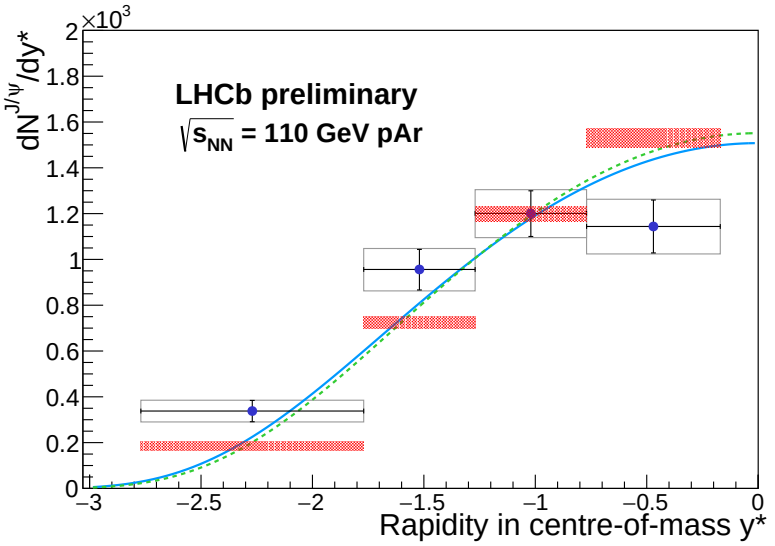
Box: quadratic sum of all uncertainties

Red area: Monte Carlo

- Pythia8-CT09MCS
- Overall MC yields normalized to overall data yields

J/ψ corrected yields – LHCb-CONF-2017-001





$y^* = y - 4.77$

Phenomenological parametrizations based on

Arleo, F. & Peigné, S. J. High Energ. Phys. (2013) 2013: 122
Arleo, F. et al. J. High Energ. Phys. (2013) 2013: 155
MC and phenomenological distributions are normalized to data

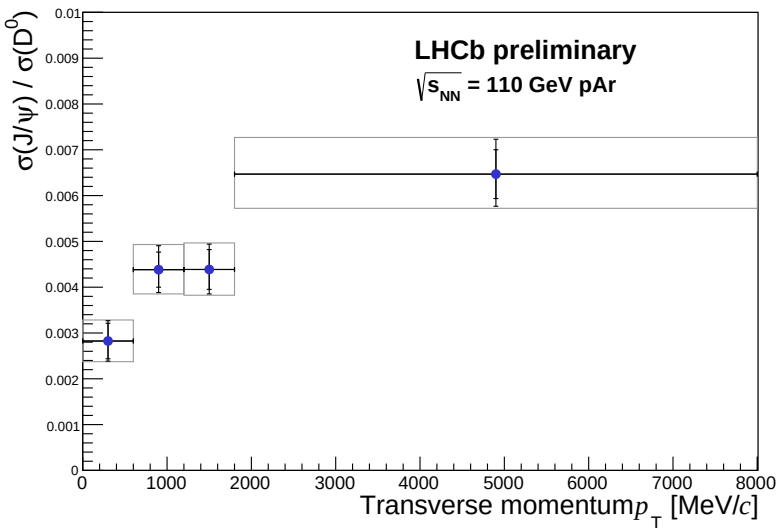
Phenomenological parameters

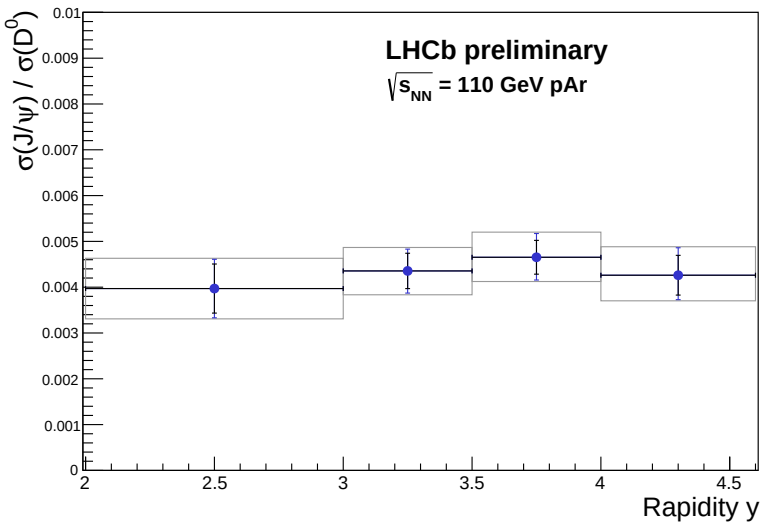
Extracted from linear and logarithmic interpolations between 41.5 GeV and 200 GeV measurements

→ **No strong difference observed within uncertainties**

Comparison between J/ψ and D^0 cross sections – LHCb-CONF-2017-001

$J/\psi/D^0$ cross sections ratio vs transverse momentum and rapidity



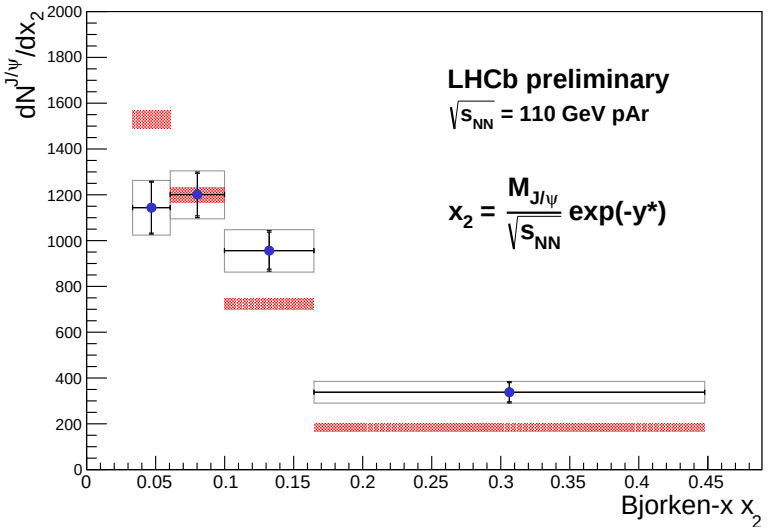


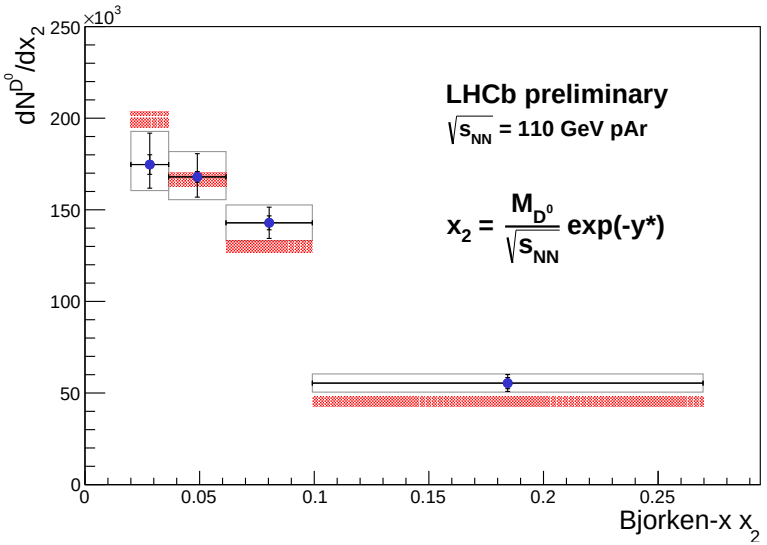
- Luminosity cancel out in the cross section ratio: $\frac{\sigma(J/\psi)}{\sigma(D^0)} = \frac{Y(J/\psi)}{\mathcal{L}} \times \frac{\mathcal{L}}{Y(D^0)}$
- $\frac{\sigma(J/\psi)}{\sigma(D^0)}$ ratio increases with transverse momentum
- No significant dependence of $\frac{\sigma(J/\psi)}{\sigma(D^0)}$ with rapidity

→ Need theoretical predictions

Bjorken-x distribution – LHCb-CONF-2017-001

Bjorken-x definition: $x_2 = \frac{M}{\sqrt{s_{NN}}} exp(-y^*)$, **with rapidity in CMS** $y^* = y - 4.77$



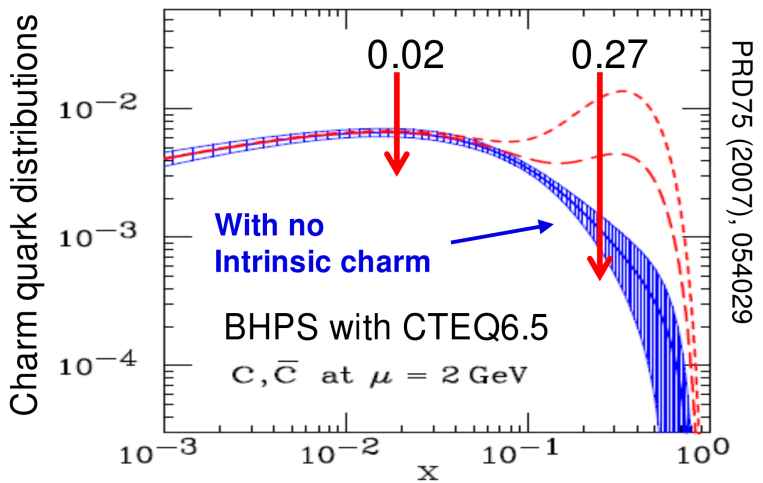


Bjorken-x range covered by the data:

$$J/\psi \; x_2 \in [0.03, 0.45]$$
$$D^0 \; x_2 \in [0.02, 0.27]$$

→ **Access intrinsic charm regime**

→ **Need theoretical predictions**



Conclusion

Recent results of LHCb heavy ions program

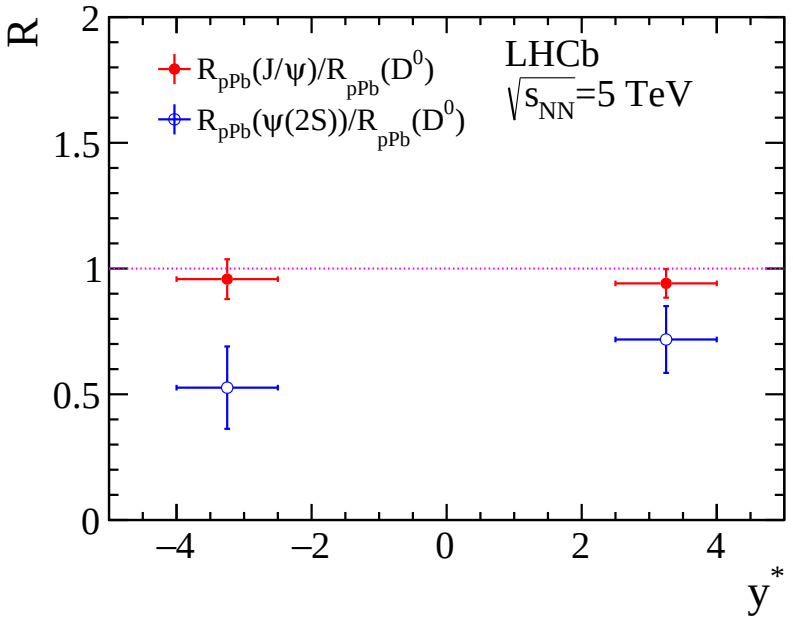
- Successful data taking in pPb collisions at $\sqrt{s} = 8.16$ TeV in 2016
  $\rightarrow$ Precise measurement of prompt and non prompt J/ψ production
- Analysis of pPb collisions at $\sqrt{s} = 5$ TeV in 2013
  $\rightarrow$ Precise measurement of prompt D^0 production
  $\rightarrow$ First measurement of prompt Λ_c^+ production
- Demonstration of the feasibility of the LHCb heavy-flavor fixed-target program
  $\rightarrow$ First measurement of $J/\psi/D^0$ production in pAr collisions at $\sqrt{s} = 110$ GeV
  $\rightarrow$ Access nPDF anti-shadowing region and intrinsic charm content in the nucleon
  $\rightarrow$ With future larger data samples: $\psi(2S), \chi_c$

More results to come !

Extra slides

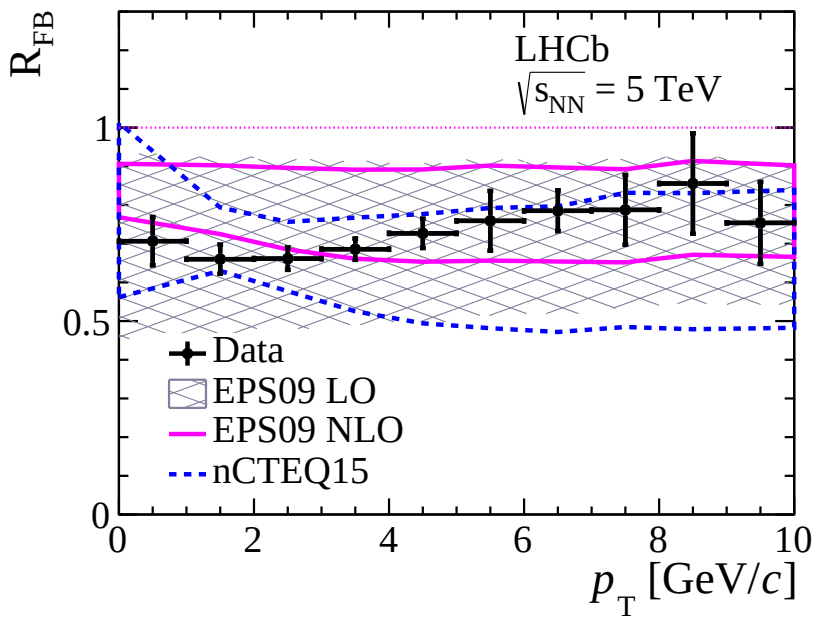
D^0 nuclear modification factor in pPb collisions at 5 TeV [arXiv:1707.02750]

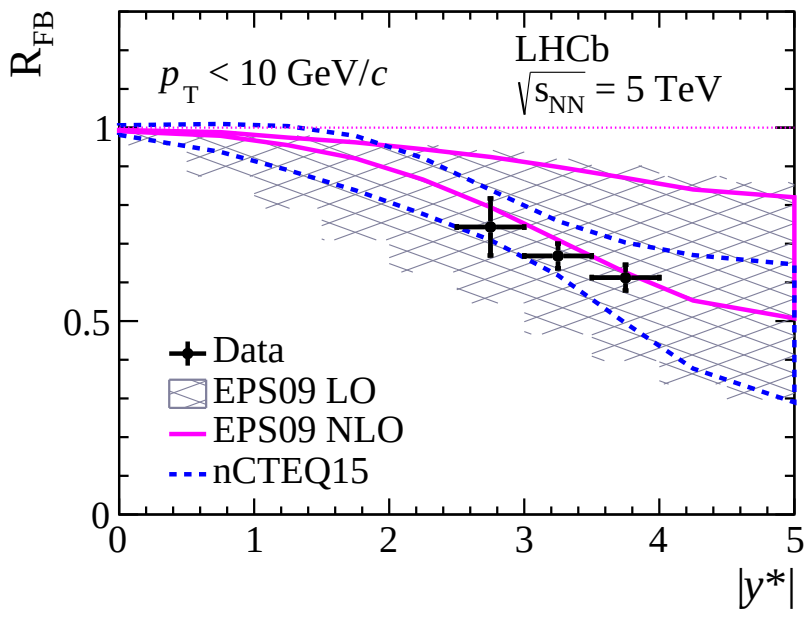
Comparison of D^0 suppression with J/ψ and $\psi(2S)$ suppression measured by LHCb [HEP02 (2014) 072, JHEP03 (2016) 133]



R_{FB} for prompt D^0 meson production

Forward-backward ratio R_{FB} for prompt D^0 meson production





see slides 9, 10 for theoretical predictions

LHCb fixed target: data taking

Data recorded with gas pressure in the VELO

System	Duration	$\sqrt{s_{NN}}$	Protons on target
pHe	7h	110 GeV	2×10^{21}
pNe	12h	110 GeV	1×10^{21}
pAr	17h	110 GeV	4×10^{22}
pAr	11h	69 GeV	2×10^{20}
PbAr	100h	69 GeV	2×10^{20}
pHe	18h	110 GeV	9×10^{20}
pHe	87h	87 GeV	4×10^{22}

Fixed target data for cosmic rays ?

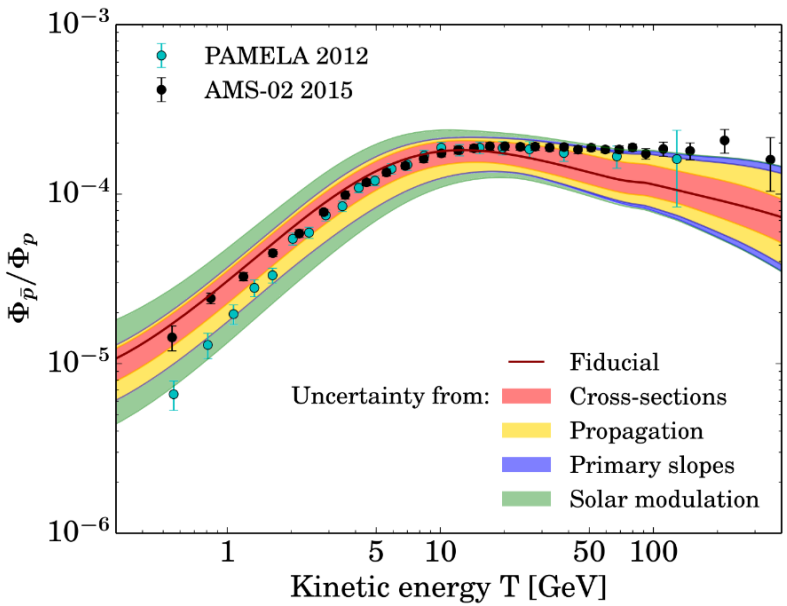
Fixed target data at 100 GeV provides inputs to MC models describing underlying event: Important for modeling cosmic ray showers in the atmosphere

AMS02 measurement of $\overline{p}/p$ ratio in cosmic rays shows hints of excess at high energies

$\overline{p}/p$ predictions from spallation of primary cosmic rays on interstellar medium (H or He):

- Limitation from uncertainties on $\overline{p}$ production cross-sections
- No previous measurement in pHe
- Predictions from soft QCD models vary within a factor 2

PRL 117, 091103 (2016)



LHCb in fixed-target mode is well suited to measure $\overline{p}$ production cross section in pHe

$\overline{p}$ cross section measurement in pHe collisions – LHCb-CONF-2017-002

Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV

Analysis of data collected in May 2016, with 6.5 TeV proton beam: **count antiprotons**

- Minimum bias trigger, fully efficiency on candidate events
- Exploit excellent LHCb PID capabilities
- In (p, p_T) bins within the range: $12 < p < 110$ GeV$/c$, $p_T > 0.4$ GeV$/c$

Background: gas impurity measurement $(0.6 \pm 0.2)\%$

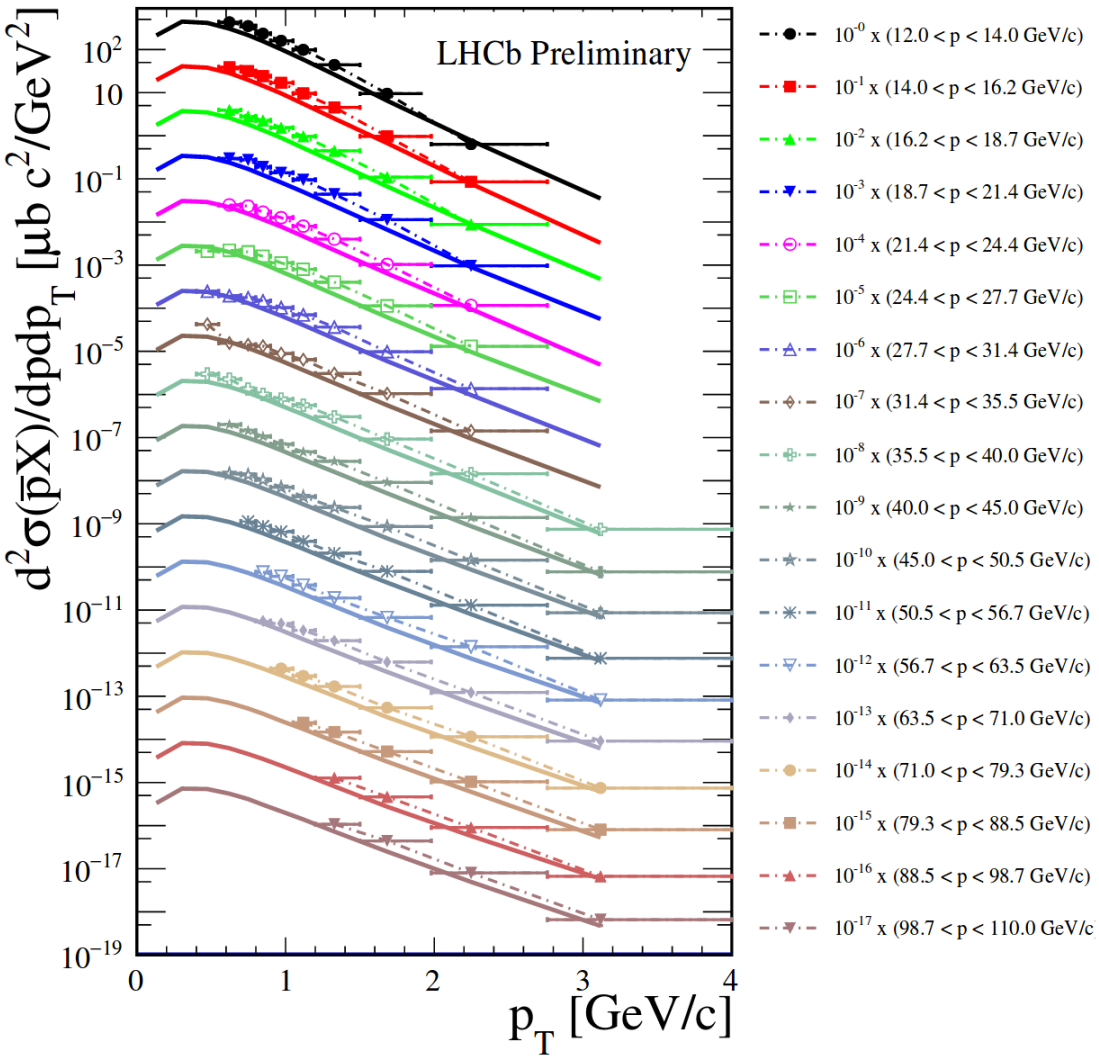
- Residual vaccum in LHC: $\sim 10^{-9}$ mbar
- Measurement in data before He injection

Normalization: use $p - e^-$ elastic scattering to evaluate the luminosity

- Cross section very well known
- Distinct signature with single low-p and very low p_T electron track, nothing else

$\rightarrow \mathcal{L} = 0.443 \pm 0.011 \pm 0.027$ nb^{-1}

$\overline{p}$ cross section measurement in pHe collisions – LHCb-CONF-2017-002



LHCb measured the total inelastic cross section

$$\sigma_{inel}^{\mathrm{LHCb}} = (140 \pm 10)\ \mathrm{mb}$$

The EPOS LHC prediction: 118 mb

[T. Pierog et al. Phys. Rev. C92 (2015), 034906]

$\rightarrow$ Ratio is 1.19 ± 0.08

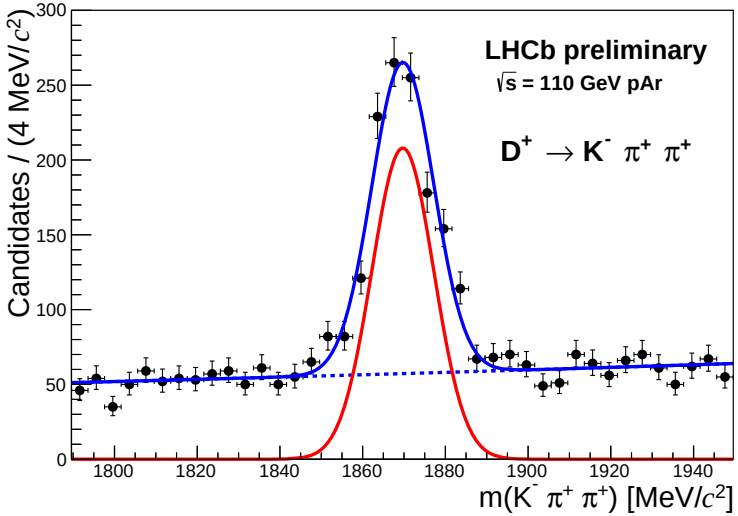
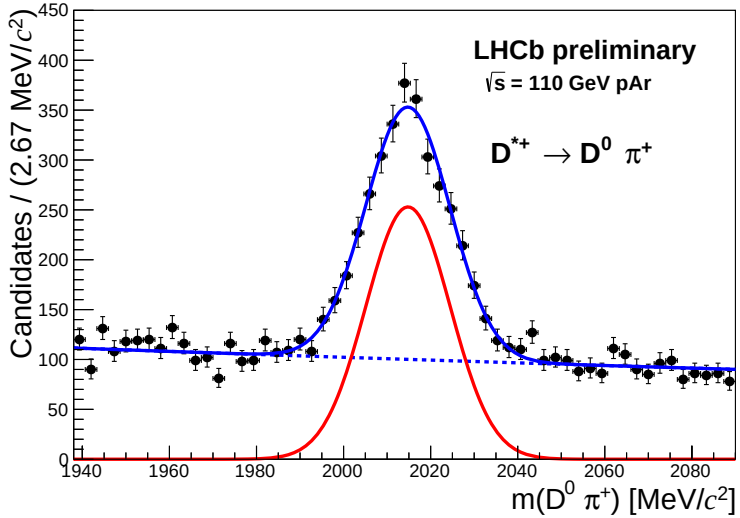
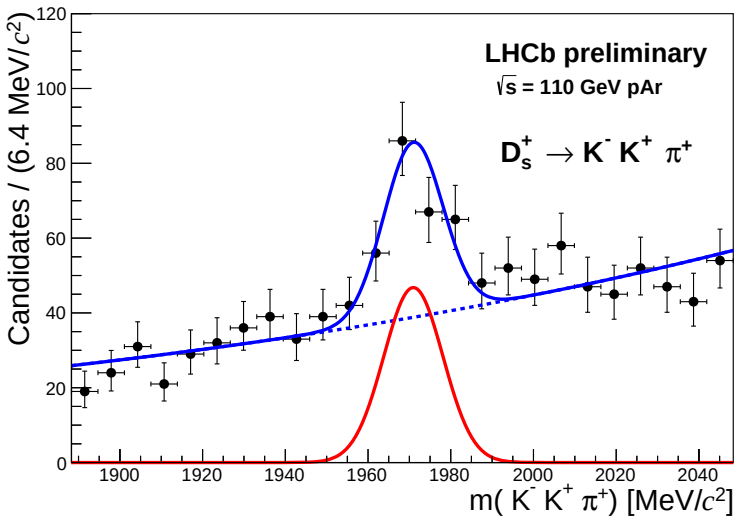
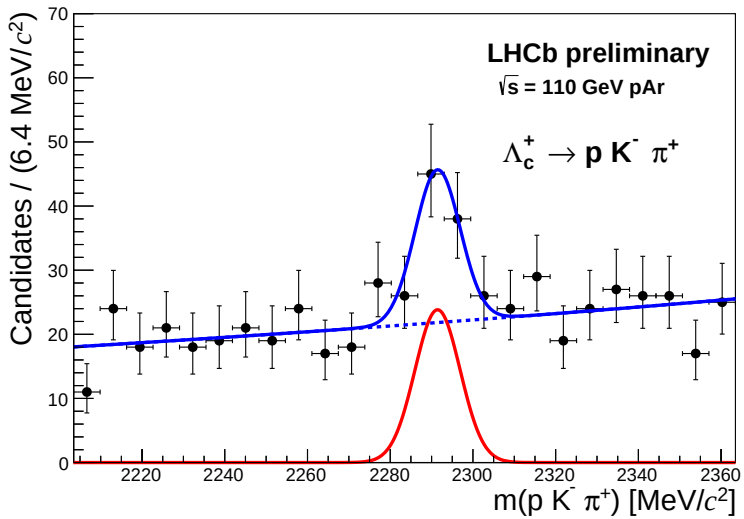
Result for prompt production compared to EPOS LHC predictions:

Excluding weak decays of hyperons

Cross section data larger by a factor $\sim$ 1.5 wrt EPOS LHC

LHCb plans:

Measure $\overline{p}$ from strange decays

Analyze pHe data, $\sqrt{s_{NN}} = 87$ GeV

Other charmed hadrons in pAr data – LHCb-CONF-2017-001