Heavy flavour and quarkonia measurements from LHCb

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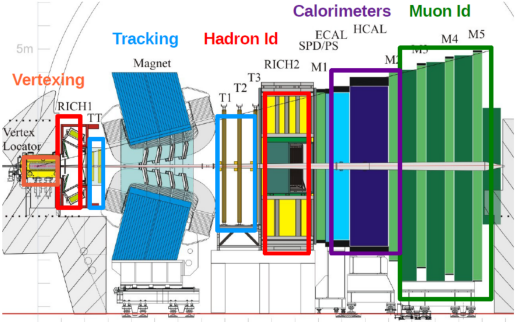
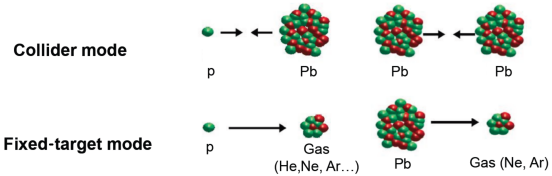
LHCb detector

- fully instrumented in $2 < \eta < 5$
- designed for studies of heavy flavour quarks in pp collisions - excellent vertexing, tracking and PID capability
- but is becoming more of **a general purpose detector** also measuring **pPb** and **PbPb**





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

Heavy quark production in nuclear collisions

Charm and beauty quarks are produced in the initial stages of a nuclear collisions → they experience the whole evolution of the system.

- In **A-A** heavy quarks measurements serve to characterise the produced hot and dense QCD matter - the **Quark Gluon Plasma (QGP)**.
- In **p-A** they serve as a clean probe of the **Cold Nuclear Matter (CNM) effects**.
  - Modification of nuclear parton distribution functions (nPDFs), gluon saturation, initial state/final state radiation, coherent energy loss.
  - CNM are also present in A-A collisions - good understanding of CNM is also vital for correct interpretation of AA results and characterising the QGP.

- Other thing to study in pA and/or AA are nucleon structure, intrinsic charm content of a nucleon, dark matter searches . . .

Recent heavy ion results from LHCb

Heavy flavour production in pPb

- Measurement of B^+, B^0 and Λ_b^0 production in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, PRD 99 (2019) 052011
- Study of Υ production in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, JHEP 11 (2018) 194
- Prompt Λ_c^+ production in pPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, JHEP 02 (2019) 102
- Study of prompt D^0 meson production in pPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, JHEP 10 (2017) 090
- Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, PLB 774 (2017) 159

Fixed target measurements

- First measurement of charm production in fixed-target configuration at the LHC, PRL 122 (2019) 132002
- Measurement of antiproton production in pHe collisions at $\sqrt{s_{\rm NN}} = 110$ GeV, PRL 121 (2018) 222001

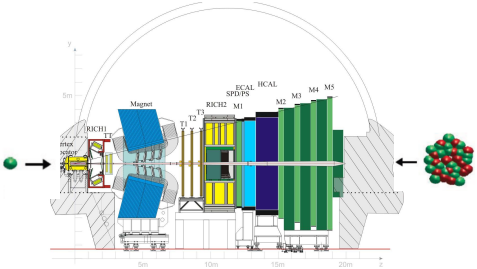
Ultra-peripheral PbPb collisions

- Study of coherent J/ψ production in lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the LHCb experiment, LHCb-CONF-2018-003

pPb measurements

pPb collisions in LHCb

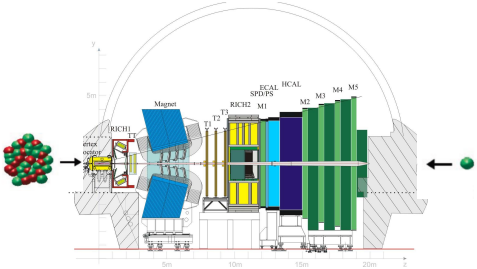
- pPb and Pbp are asymmetric systems → **centre-of-mass rapidity shift** by $\Delta y = \pm 0.465$



$1.5 < y^* < 4.0 \quad \Rightarrow \quad x_{\mathrm{Pb}} \sim 10^{-6}$

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with 1.1 nb^{-1}

$\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with 13.6 nb^{-1}



$-5.0 < y^* < -2.5 \quad \Rightarrow \quad x_{\mathrm{Pb}} \sim 10^{-2}$

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with 0.5 nb^{-1}

$\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with 20.8 nb^{-1}

Cold nuclear matter effects in theory

Modifications of nuclear PDFs

- *Gluon shadowing/antishadowing*: Parton distribution functions are modified by the nuclear environment ⇒ suppression or enhancement of HF hadrons as a function of the parton momentum fraction x in the nucleon.
  - HELAC-Onia: H.-S. Shao, Comp. Phys. Comm. 198 (2016) 238.
  - FONLL: M. Cacciari *et al.*, JHEP 05 (1998) 007.
- *Gluon saturation*: Result of gluon recombination at small x at the LHC ⇒ suppression of HF hadrons.
  - Colour Glass Condensate (CGC): B. Ducloué *et al.*, PRD 94 (2016) 074031.

Coherent energy loss

- The medium induced gluon radiation in initial and/or final state modifies the HF hadron yields.
  - F. Arleo, S. Peigné, JHEP 03 (2013) 122.

Dissociation with comovers

- Interaction of HF hadrons with the comoving matter breaks the bound states ⇒ suppression.
  - E. G. Ferreiro, PLB 731 (2014) 57; E. G. Ferreiro and J. P. Lansberg, JHEP 1810 (2018) 094.

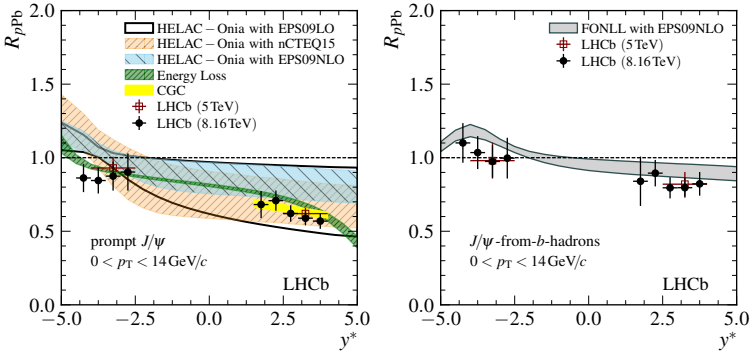
J/ψ production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

PLB 774 (2017) 159

- $J/\psi \to \mu^+\mu^-$
- Separated prompt and non-prompt.

- Nuclear modification factor

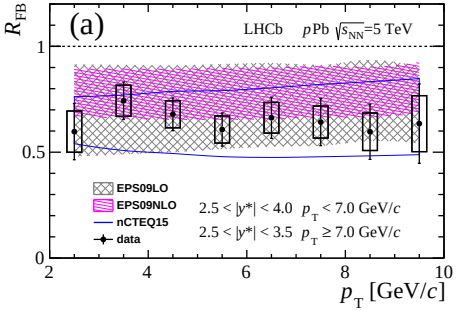
$$R_{pPb}(p_T, y) = \frac{1}{208}\frac{d^2\sigma_{pPb}/dp_T dy}{d^2\sigma_{pp}/dp_T dy}$$

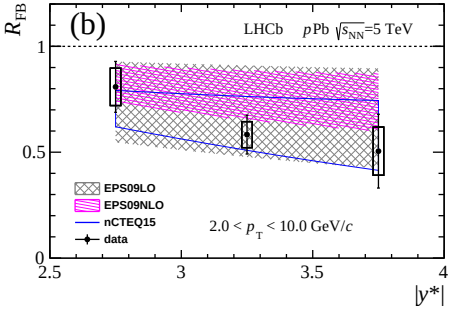


- Strong suppression of prompt J/ψ at forward rapidity, non-prompt consistent with unity.
- Suppression pattern described by calculations including modificatons of nPDFs and coherent energy loss.
- No evidence of energy dependence for CNM effects at LHC energy scales.

Prompt Λ_c^+ production in pPb at $\sqrt{s_{NN}} = 5.02$ TeV

JHEP 02 (2019) 102



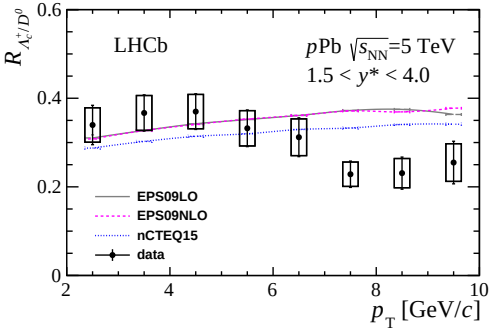


- Λ_c^+ measured down to low p_T from $\Lambda_c^+ \longrightarrow pK^-\pi^+$.
- Forward-to-backward ratio studies difference in CNM effects between forward and backward rapidity.
- Larger production rate in backward region reproduced in HELAC-Onia.

Prompt Λ_c^+ production in pPb at $\sqrt{s_{NN}} = 5.02$ TeV (cont.)

JHEP 02 (2019) 102

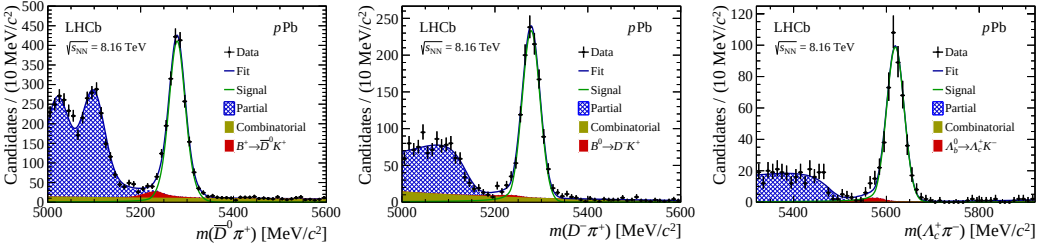
- Light and strange hadrons show increase in baryon-to-meson ratio in central A-A collisions ⇒ consistent with hadronisation via coalescence.
- Recent measurements show the same behaviour for charmed hadrons.
- Baryon-to-meson ratio consistent at low p_T with theory calculations based on pp data but are overestimated at high p_T.



Open beauty hadron production in pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

PRD 99 (2019) 052011

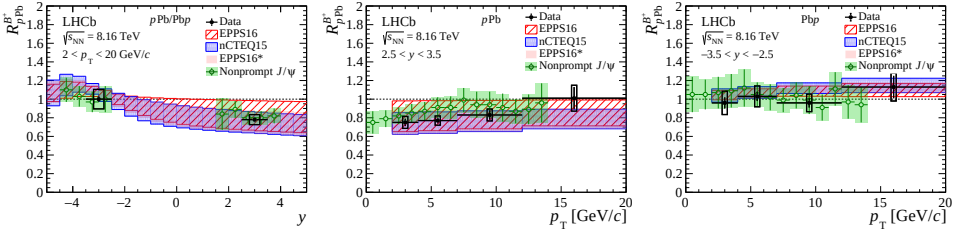
- First measurement of B^+, B^0, and Λ_b^0 down to low p_{T} in nuclear collisions.
- Clear signal reconstructed from exclusive decays.

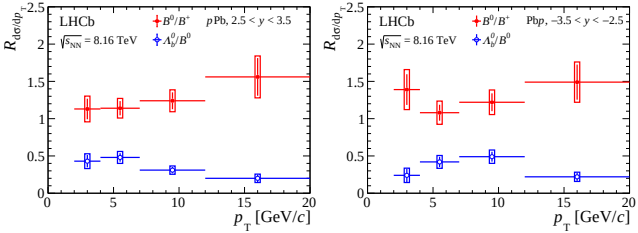


Open beauty hadron production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV (cont.)

PRD 99 (2019) 052011

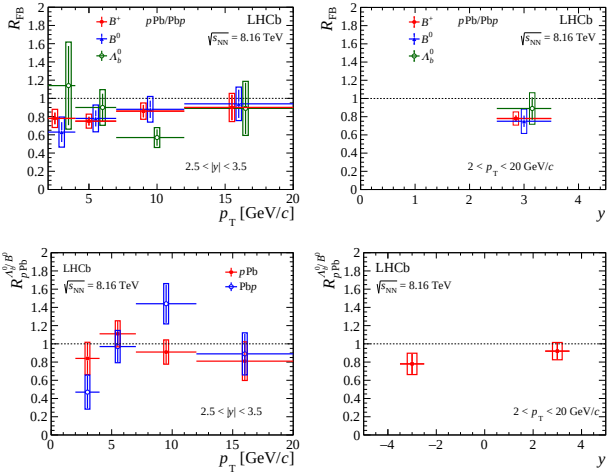
- Suppression pattern consistent with J/ψ-from-b.
- Baryon-to-meson ratio consistent with the pp result.





Open beauty hadron production in pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV (cont.)

PRD 99 (2019) 052011

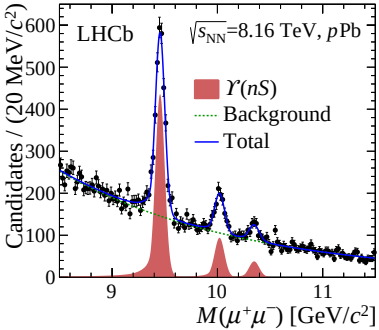


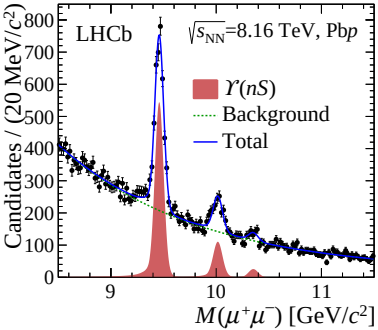
- Forward-to-backward ratios show the same suppression in both pPb and Pbp for all three species.
- Ratio of Λ_b^0/B^0 modification factors allows to study the difference in overall CNM effects relevant for the two species.

Hints of deviation from unity in p_{T}, however more data required to make strong conclusions.

Υ production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

JHEP 11 (2018) 194

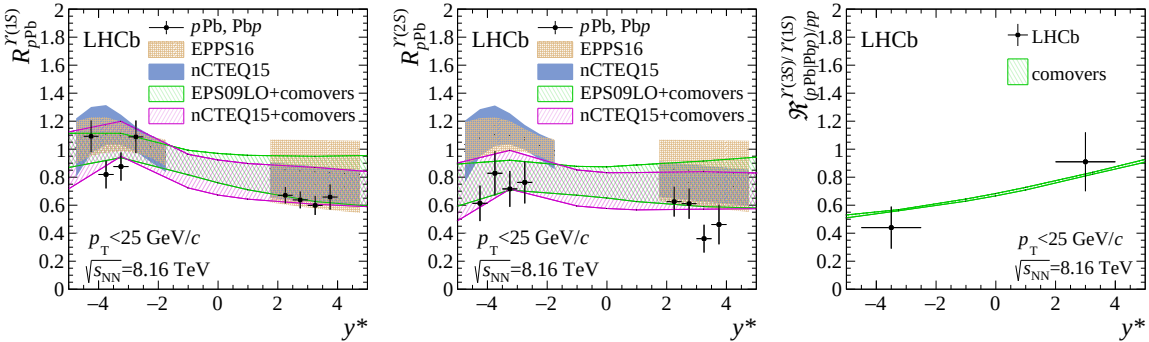




- LHCb measured $\Upsilon(nS) \to \mu^+\mu^-$.
- The three states are clearly separated in both rapidity regions.

Υ production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV (cont.)

JHEP 11 (2018) 194



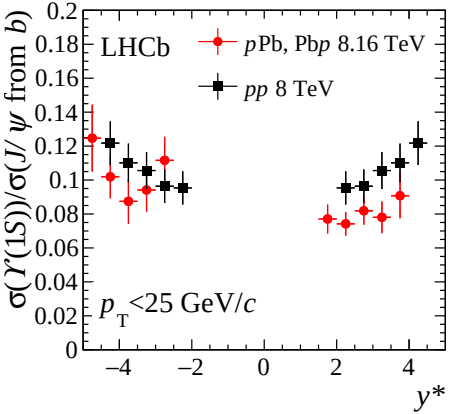
- $\Upsilon(nS)$ suppression is consistent with models and previous measurements.
- $\Upsilon(3S)$ shows stronger suppression in the backward region than $\Upsilon(1S)$ and $\Upsilon(2S)$.

Υ production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV (cont.)

Υ: JHEP 11 (2018) 194
J/ψ: PLB 774 (2017) 159

- Cross-section ratio of $\Upsilon(1S)/J/\psi$-from-b compared between measurement in pp and pPb.
- Different hadronisation of close and open beauty $\Rightarrow$ different sensitivity to final state CNM effects.

Hionts of different final CNM effects at forward rapidity.

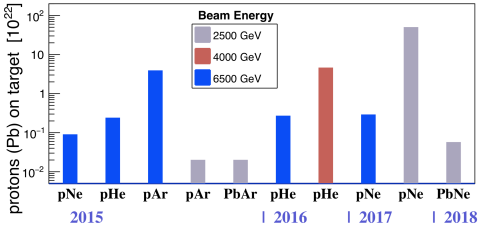


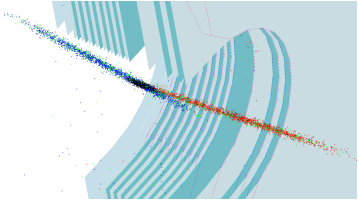
Fixed target results

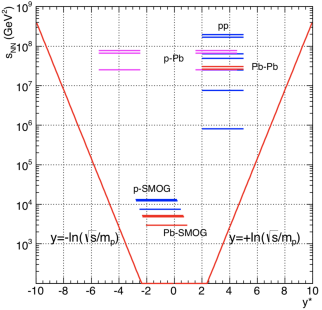
p-Gas collisions in LHCb

System for Measuring Overlap with Gas (SMOG)

- Originally conceived to perform precise luminosity measurements (2014 JINST 9 P12005).
- Gas target created by injecting noble gases Ne, Ar, He at pressure of order $10^{-6} - 10^{-7}$ mbar into the VELO.
- Energies cover the gap between SPS and RHIC.
- Collisions with protons, newly in 2018 also with Pb!



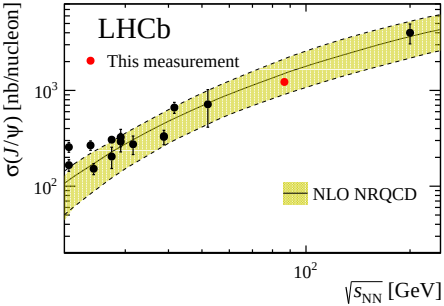


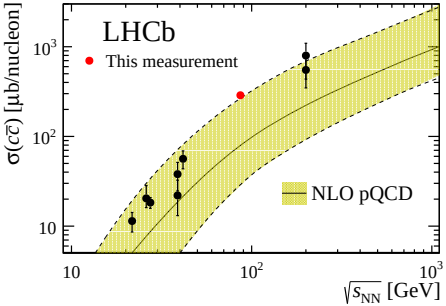


Charm production in fixed target

PRL 122 (2019) 132002

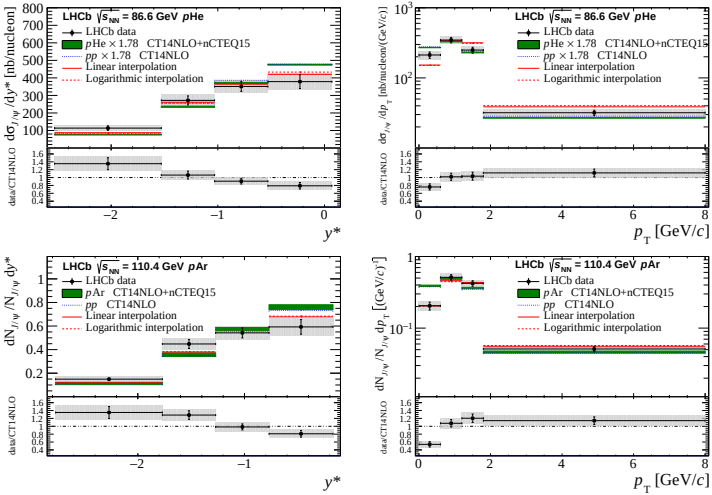
- First J/ψ and D^0 measurements in pHe at $\sqrt{s_{NN}} = 86.6$ GeV and pAr at $\sqrt{s_{NN}} = 110.4$ GeV.
- J/ψ and $c\bar{c}$ integrated cross section extrapolated to full phase-space to allow comparison with other available results $\Rightarrow$ good agreement with NLO NRQCD (Nucl. Phys. B 373 (1992) 295).





Charm production in fixed target (cont.)

PRL 122 (2019) 132002



- Differential cross-sections compared with HELAC-Onia.
- $\sigma(J/\psi)$ underestimated, rescaled calculations describe the shape well in p_T and $y*$.
- Similar conclusion for D^0 (plots in backup).

No evidence of substantial intrinsic charm content.

Antiproton production in p-He collisions

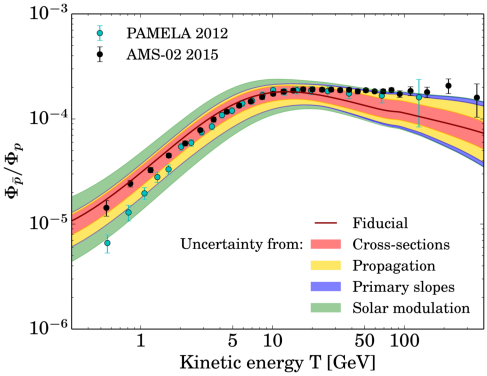
PRL 121 (2018) 222001

LHCb performed the first $\bar{p}$ measurement in pHe at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV.

- The $\bar{p}$ fraction in cosmic rays is a sensitive indirect probe of dark matter.
- PAMELA and AMS-02 observe an excess in the $\bar{p}/p$ flux ratio for high energy cosmic rays.
- The uncertainty on the predictions is limited by the determination of the $\bar{p}$ production cross section in pH and pHe collisions.

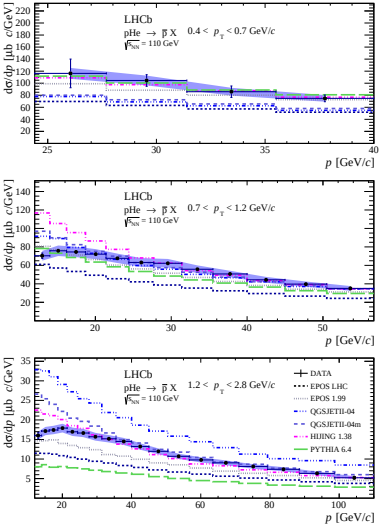
- Measurement of $\bar{p}/p$ ration in pHe will help to improve the accuracy of future predictions.

arXiv:1504.04276 [astro-ph.HE]



Antiproton production in p-He collisions (cont.)

PRL 121 (2018) 222001



- $\bar{p}$ momentum distributions in several kinematic bins compared with multiple predictions:
  - EPOS LHC PRC92 (2015) 034906
  - EPOS 1.99 Nucl.Phys.Proc.Suppl. 196 (2009) 102
  - QGSJETII-04 PRD83 (2011) 014018
  - QGSJETII-04m Astr. J. 803 (2015) 54
  - HIJING 1.38 Comp. Phys. Comm. 83 307
  - PYTHIA 6.4 2(pp+pn) JHEP 05 (2005) 026
- The momentum shapes are well reproduced save for the lowest momenta.
- Absolute yields on the other hand deviate by up to factor 2.

The relative uncertainty on the data of $\lesssim 10\%$ is way below the spread from the models.

Ultra-peripheral collisions

Coherent J/ψ photoproduction in PbPb at $\sqrt{s_{NN}} = 5.02$ TeV

LHCb-CONF-2018-003

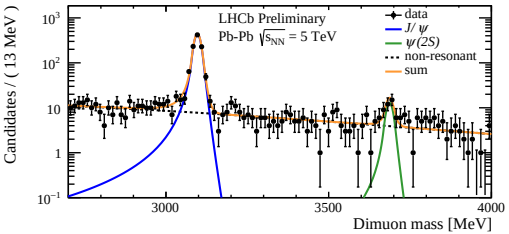
LHCb studied the photoproduction of J/ψ in UPC collisions

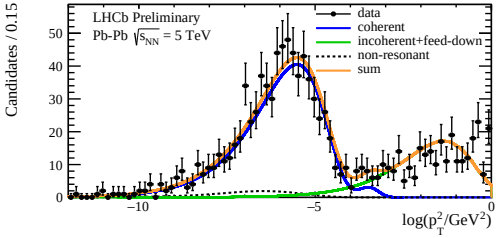
$$\mathbf{Pb} + \mathbf{Pb} \rightarrow \mathbf{Pb} + J/\psi + \mathbf{Pb}$$

- Coherent photoproduction of forward J/ψ in PbPb probes the gluon nPDFs at low-to-intermediate Bjorken x

$$2 < y < 4.6 \quad \Rightarrow \quad 10^{-5} \lesssim x_{Bj} \lesssim 10^{-2}$$

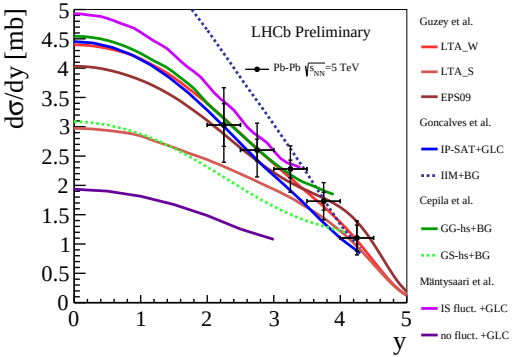
- Clean J/ψ signal, hints of $\psi(2S)$.
- The coherent and incoherent photoproduction can be distinguished from their p_T shape:
  - Signal and backround fit with different STARlight templates.
  - Non-resonant component constraint from the invariant mass fit.





Coherent J/ψ photoproduction in PbPb at $\sqrt{s_{NN}} = 5.02$ TeV (cont.)

LHCb-CONF-2018-003



Results for coherent cross section were compared with multiple phenomenological models - several reproduce the rapidity dependence.

- Guzey et al.: PRC 93 (2016) 055206
- Gonçalves et al.: PRC 84 (2011) 011902, PRD 96 (2017) 094027
- Čepila et al.: PRC 97 (2018) 024901
- Mäntysaari et al.: PLB 772 (2017) 832-838

2018 PbPb data 20× more statistics than in 2015 ⇒ more precise measurements in the future!

Summary

LHCb has an extensive heavy ion physics programme with some unique measurements.

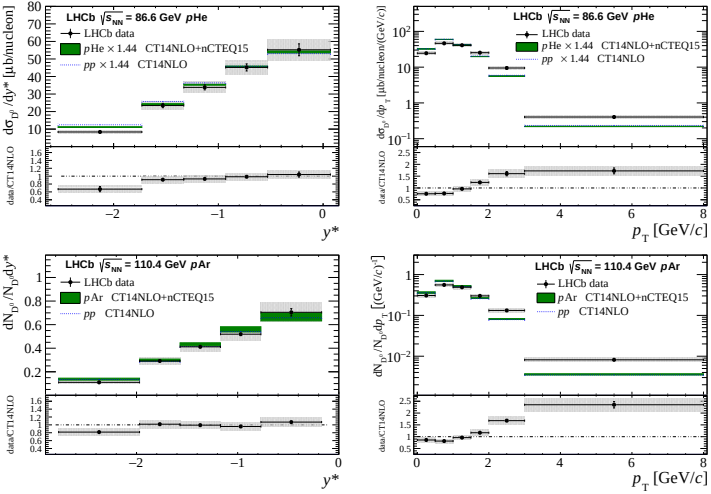
- Measurements in pPb in collider mode provide new data to constrain CNM and hadronisation in nuclear medium.
  - Open and close HF R_{FB}, R_{pPb}, baryon-to-meson ratios,. . .
- Measurements in fixed target mode to fill the energy gap between SPS and RHIC.
  - At present uncertainty found no evidence of intrinsic charm content.
  - Results on $\bar{p}$ production will help improve models for dark matter searches.
- New results on coherent photoproduction are reproduced in models.
  - 2018 statistics 20$\times$ the one in 2015 expected to provide more conclusive data.

And the future?

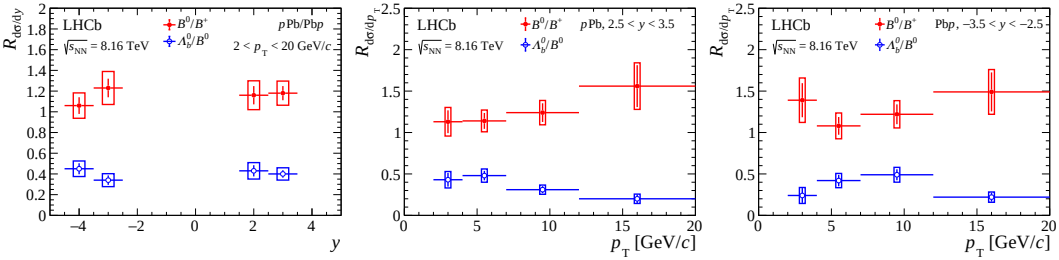
- More precise results to come from Run 2 data: more quarkonia states, vector bosons, dihadron correlations, flow measurements. . .
- Higher statistics pNe and PbPb data from Run 2 are being analysed, also new PbNe datasample.
- Upgrade of LHCb detector for Run 3 also includes SMOG2 - higher pressure under more precise control, more gas species.

Back-up

Charm production in fixed target - D^0



Open beauty hadron production in pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

PRD 99 (2019) 052011

- First measurement of B^+, B^0, and Λ_b^0 down to low p_{T} in nuclear collisions.
- Baryon-to-meson ratio consistent with the pp result.