Quarkonia in pPb collisions in LHCb

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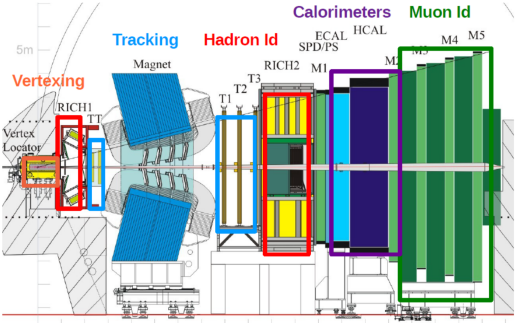
Heavy quark production in nuclear collisions

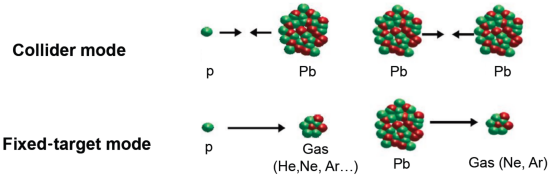
Charm and beauty quarks are produced in the initial stages of a nuclear collisions $\rightarrow$ they experience the whole evolution of the system.

- 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.

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**

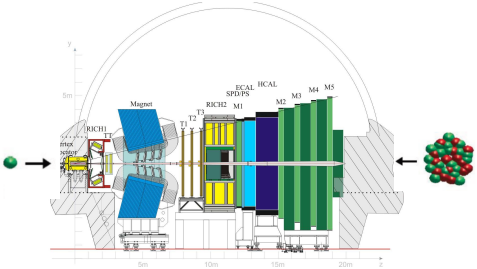




JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

pPb collisions in LHCb

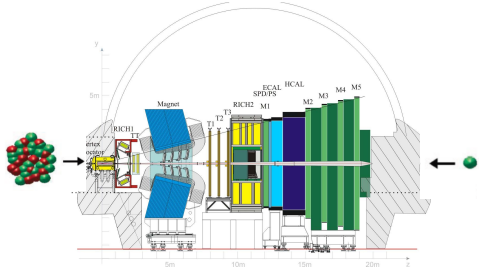
- pPb and Pbp are asymmetric systems → **centre-of-mass rapidity shift** by $\Delta y = \pm 0.465$



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

$\sqrt{s_{\mathrm{NN}}} = 5.02$ 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.

Quarkonia measurements in pPb in LHCb

Run 2

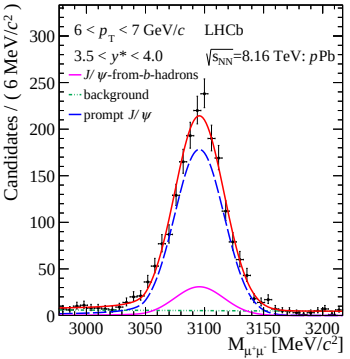
- Study of Υ production in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, JHEP 11 (2018) 194
- Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, PLB 774 (2017) 159

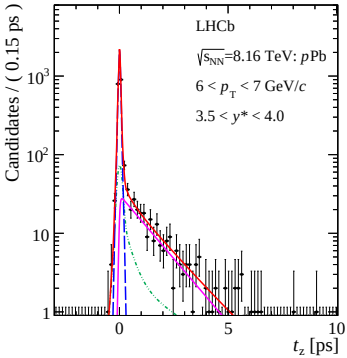
Run 1

- Study of $\psi(2S)$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV, JHEP 02 (2014) 72
- Study of Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV, JHEP 07 (2014) 094
- Study of J/ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV, JHEP 02 (2014) 72

Prompt and non-prompt J/ψ production in pPb collisions

PLB 774 (2017) 159





- $J/\psi \to \mu^+\mu^-$ measured in pPb collisions at 5 and 8 TeV.
- Separated prompt and non-prompt via the pseudo-proper time $t_z = \left(z_{J/\psi} - z_{\mathrm{PV}} \times M_{J/\psi}\right)/p_z$.

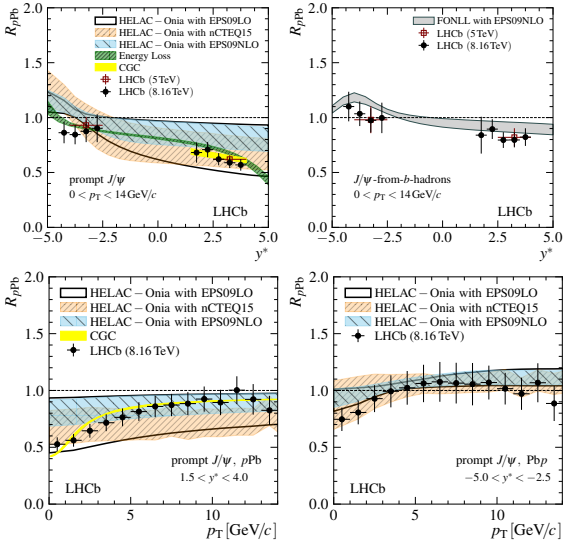
Prompt and non-prompt J/ψ production in pPb collisions (cont.)

PLB 774 (2017) 159

- Nuclear modification factor

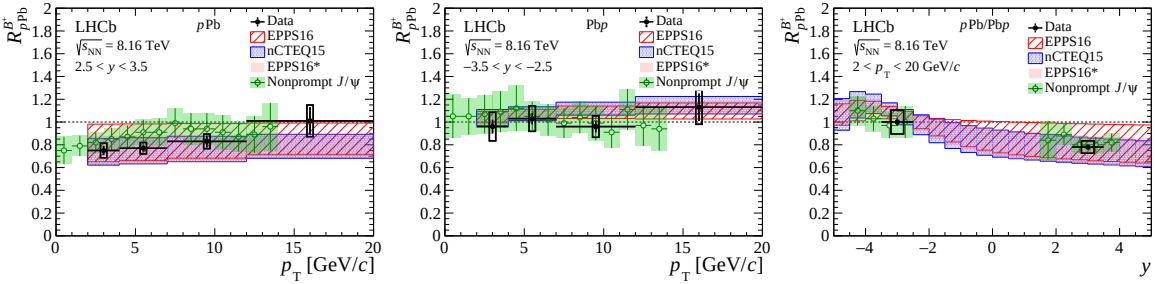
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y) = \frac{1}{208} \frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

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



Prompt and non-prompt J/ψ production in pPb collisions (cont.)

J/ψ: PLB 774 (2017) 159
B: PRD 99 (2019) 052011



- Open beauty production ($B^+ \to J/\psi + \pi^+$ and $B^+ \to \bar{D}^0\pi^+$) also measured in pPb at 8 TeV.
- Suppression pattern consistent with non-prompt J/ψ.

Nuclear modification of $\psi(2S)$ at 5 TeV

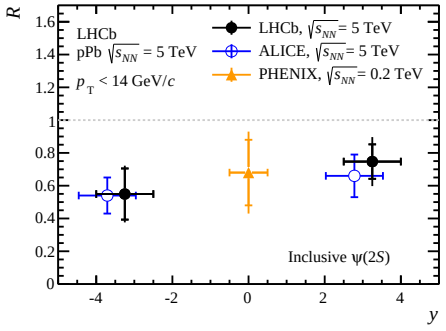
LHCb: JHEP 1603 (2016) 133
ALICE: JHEP 12 (2014) 073
PHENIX: PRL 111 (2013) 202301

- LHCb measured $\psi(2S) \to \mu^+\mu^-$ in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV.
- Measured the ratio of $R_{\rm pPb}$ between $\psi(2S)$ and J/ψ

$$R \equiv \frac{\sigma^{\psi(2S)}_{\rm pPb}(5\text{ TeV})}{\sigma^{J/\psi}_{\rm pPb}(5\text{ TeV})} \times \frac{\sigma^{J/\psi}_{\rm pp}(7\text{ TeV})}{\sigma^{\psi(2S)}_{\rm pp}(7\text{ TeV})}$$

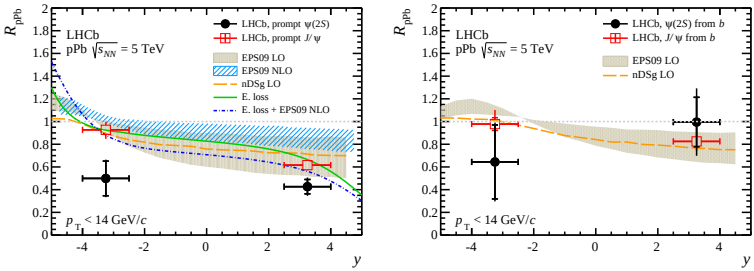
  to compensate for the lack of $\sigma^{\psi(2S)}_{\rm pp}(5\text{ TeV})$ measurement.

- Results from ALICE and LHCb at forward y and PHENIX at mid-y suggest stronger suppression for inclusive and prompt $\psi(2S)$.



Nuclear modification of $\psi(2S)$ at 5 TeV (cont.)

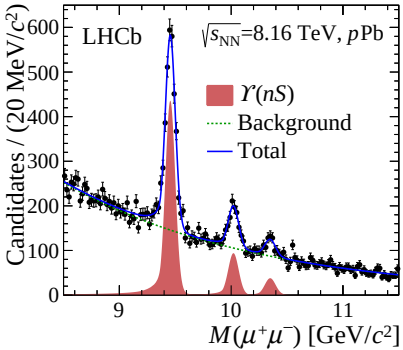
JHEP 1603 (2016) 133

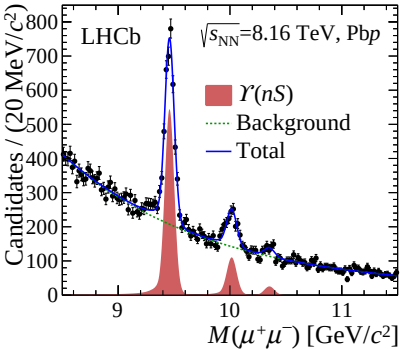


- Nuclear modification factor computed from the ratio $R_{\rm pPb}^{\psi(2S)} = R_{\rm pPb}^{J/\psi} \times R$.
- Observe similar level of suppression at both forward and backward rapidity.
- Models with initial final state effects cannot explain the difference between the two $c\bar{c}$ states $\Rightarrow$ different final state effects.

Υ production in pPb collisions

JHEP 11 (2018) 194



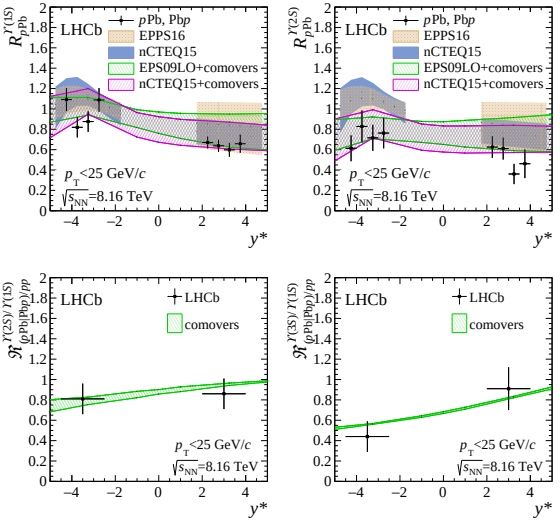


- LHCb measured $\Upsilon(nS) \to \mu^+\mu^-$ in pPb at 5 and 8 TeV.
- At 8 TeV, the three states are clearly separated in both rapidity regions.

Υ production in pPb collisions (cont.)

JHEP 11 (2018) 194

- Suppression of prompt $\Upsilon(1S)$ and $\Upsilon(2S)$ at forward rapidity, backward consistent with unity.
- The 2S and 2S states show a similar suppression pattern consistent with comover models, hint of stronger suppression at $y < 0$.
- $\Upsilon(3S)$ shows a stronger suppression at backward rapidity than 1S.
- Stronger suppression of excited states at backward rapidity observed both for charm and beauty.

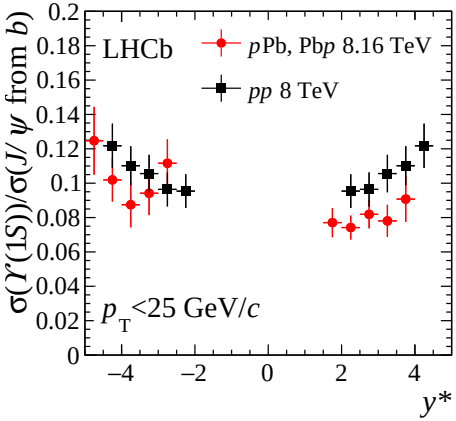


Υ production in pPb collisions (cont.)

JHEP 11 (2018) 194

- Cross section ratio of $\Upsilon(1S)$ over non-prompt J/ψ measured in pp and pPb.
- Different hadronisation of close and open beauty $\Rightarrow$ different sensitivity to final state CNM effects.
- At backward rapidity, pp and pPb consistent within uncertainty while at forward the ratio is lower i pPb than in pp.

Hints of different final CNM effects affecting beauty production at forward rapidity.



Summary

LHCb has an ever-growing heavy ion physics programme with some unique measurements.

So far LHCb measured J/ψ, $\psi(2\mathrm{S})$, and $\Upsilon(n\mathrm{S})$ in pPb at 5.02 and 8.16 TeV from dimuon decay channel.

Suppression pattern of J/ψ shows no evidence of energy dependence at LHCb energies.

Separation of prompt/non-prompt J/ψ - comparison with B hadrons and Υ resuts allows to study the final CNM effects.

Measurements of charmonia and bottomonia in pPb show stronger suppression of excited states, which is reproduced in models with final-state effects (comovers, CGC).