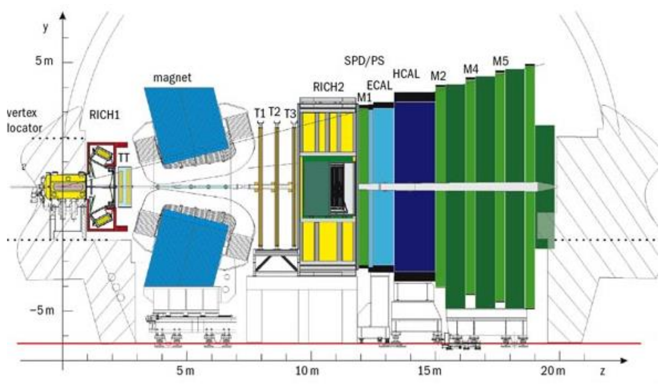
New results on hard probes in heavy-ion collisions with LHCb



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On behalf of the LHCb collaboration

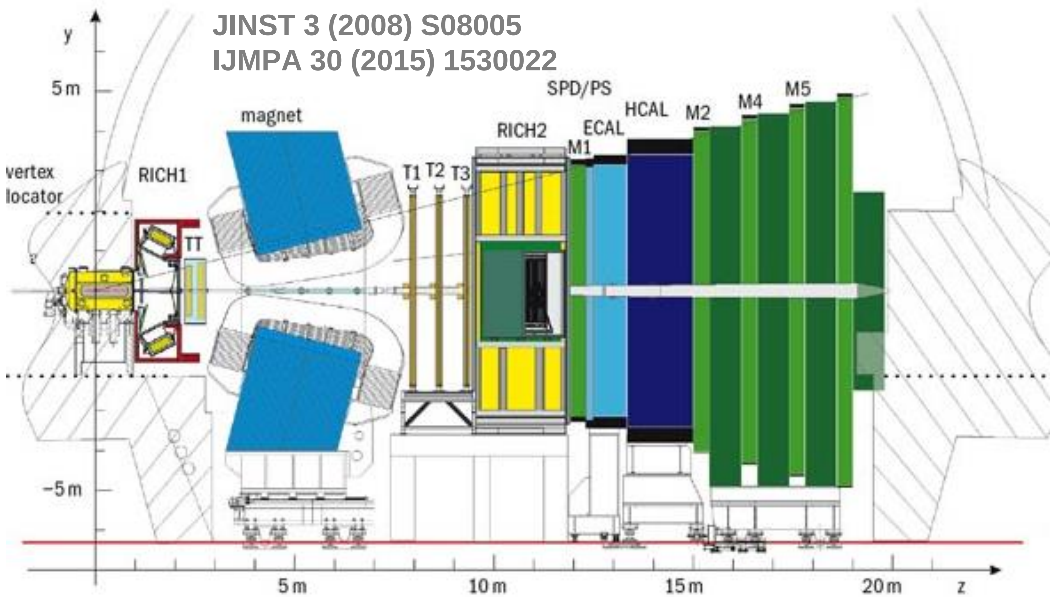
LHCP
Bologna, 2018

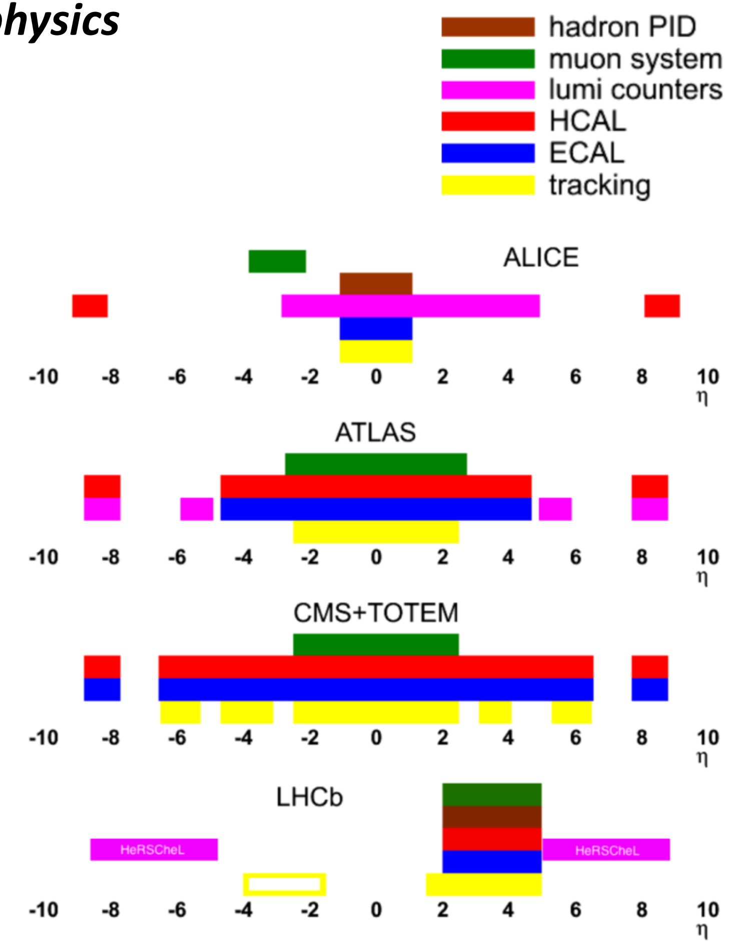
08/06/2018

The LHCb detector

Single arm spectrometer, the only LHC experiment fully instrumented in $2 < \eta < 5$

Designed for heavy flavor physics





Excellent vertex, IP and decay time resolution

$\sigma(IP) \approx 20\ \mu m$

Very good momentum resolution

$\delta p/p \approx 0.5{-}1\%$ for $0<p<200$ GeV/c

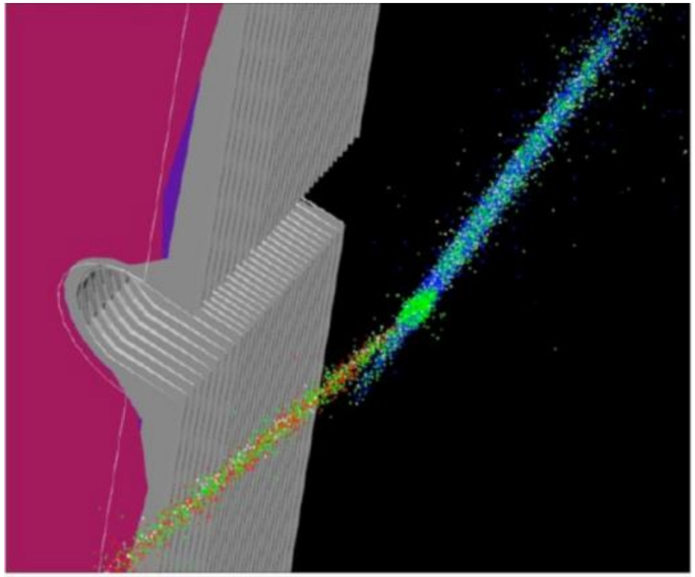
Particle identification

$\varepsilon_{K\to K} \approx 95\%$ for $\varepsilon_{\pi\to K} \approx 5\%$ up to 100 GeV/c

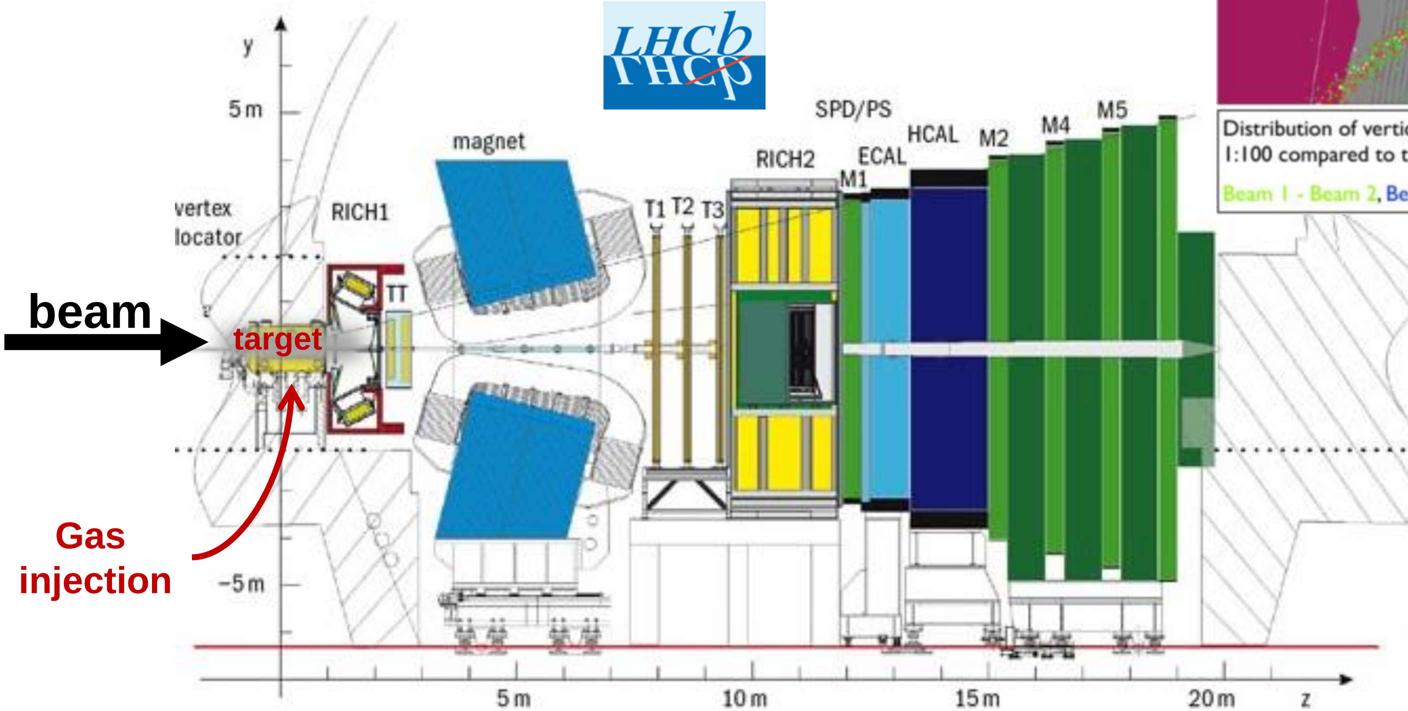
$\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx 1{-}3\%$

LHCb can operate *p*-Pb and Pb-Pb collisions

- **Can also operate in fixed-target mode: unique at LHC**
  - Injecting gas in the LHCb VErtex LOcator (VELO) tank, primarly done to perform luminosity measurement.
  - Can be used as an **internal gas target**
  - Allows measurement of *p*-gas and ion-gas interactions



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.



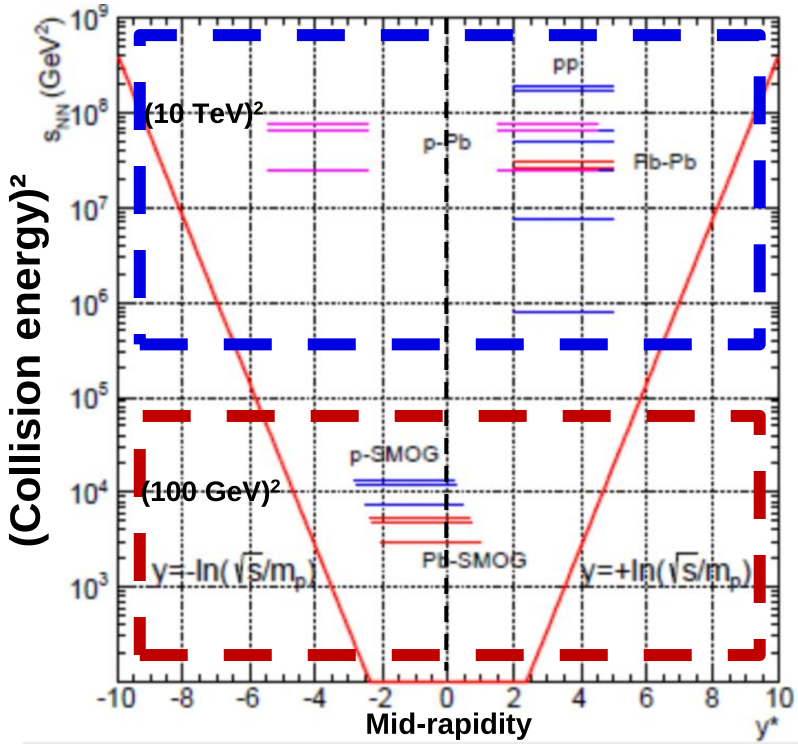
Noble gas only :
(very low chemical reactivity)

He, Ne, Ar, Kr, Xe
A = 4, 20, 40, 84, 131

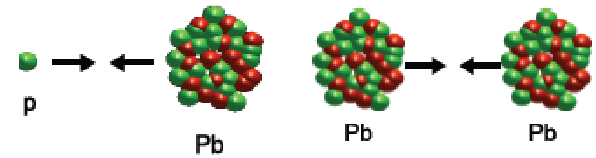
Gas pressure:
10^{-7} to 10^{-6} mbar

LHCb operations for heavy ion physics

LHCb rapidity coverage in the centre-of-mass system

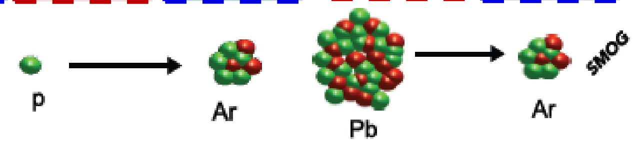


Colliding mode



E_{beam}(p)	pp	p-SMOG	p-Pb/Pb-p	Pb-SMOG	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV	5. TeV	54 GeV	
6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.02 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

Fixed-target mode

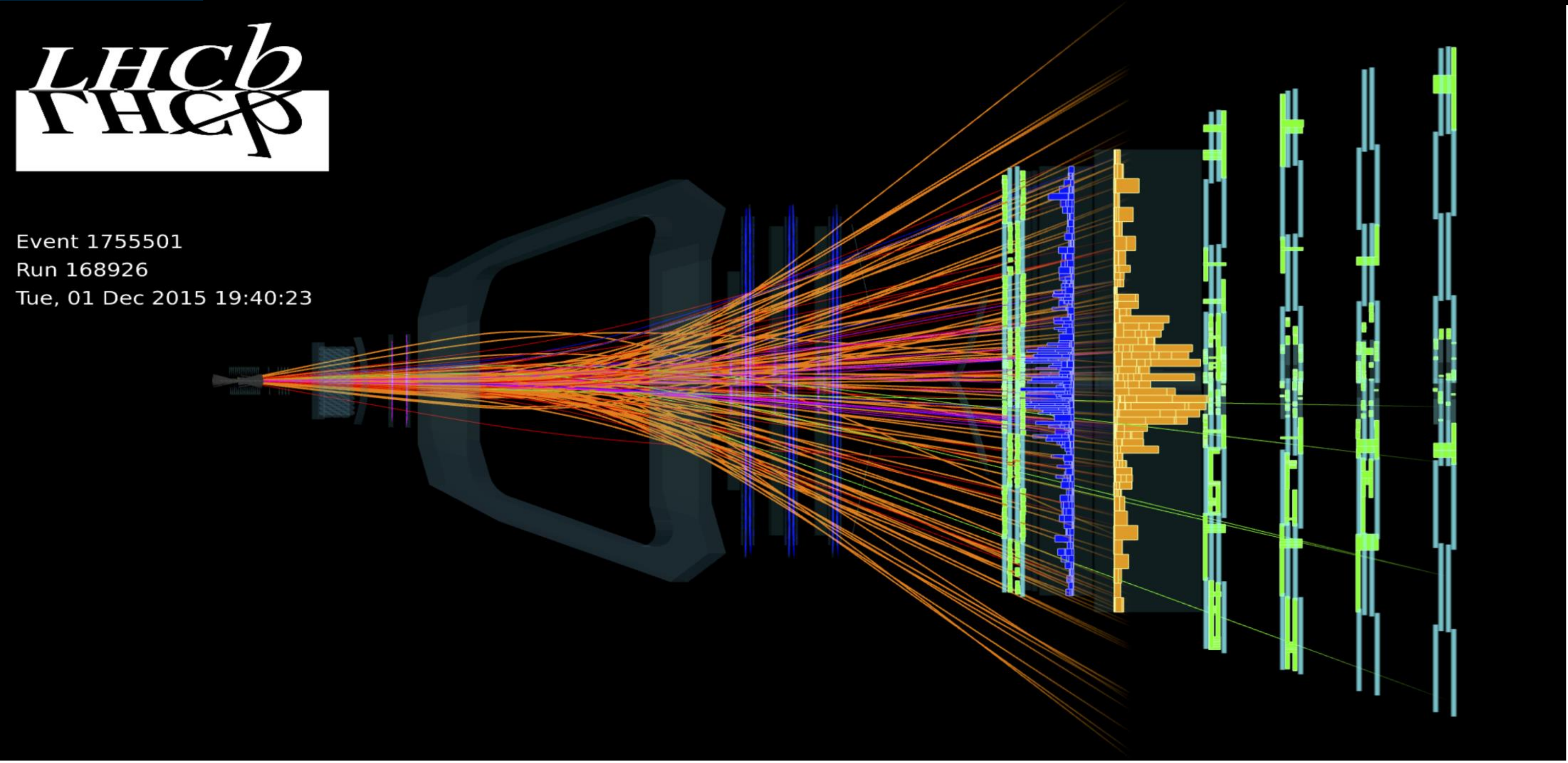


At $\sqrt{s_{NN}} = 110$ GeV $y^* = y_{lab} - 4.77$

Outline of this talk

1. Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV
2. *p*-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV and $\sqrt{s_{NN}}$ = 8.16 TeV
3. *p*-Ar and *p*-He collisions at ~100 GeV scale

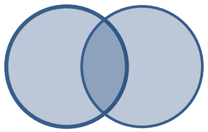
1. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV



December 2015. First participation of LHCb in Pb-Pb data taking
Only 24 colliding bunches. Very small luminosity ~ 10 μb^{-1}
Minimum bias trigger configuration: all inelastic interactions recorded

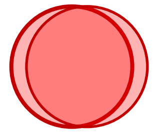
1. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV

Low Ecal Energy



peripheral

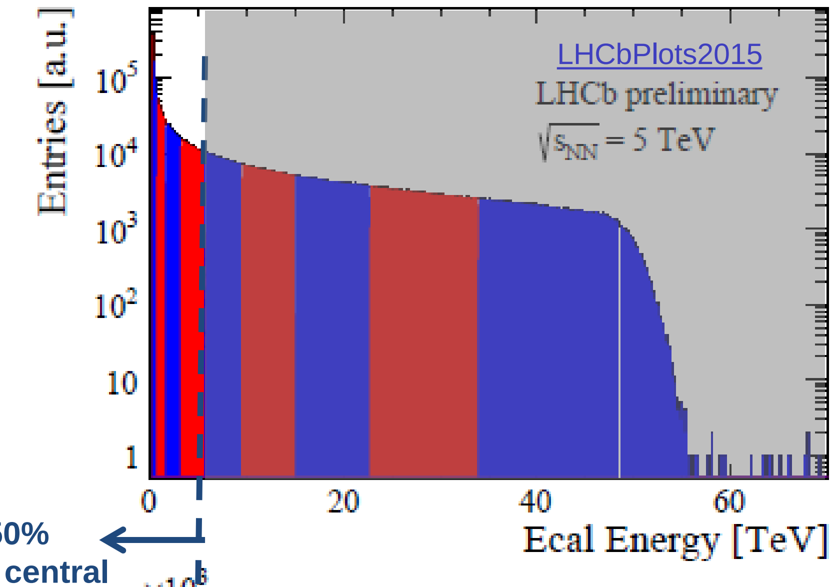
High Ecal Energy

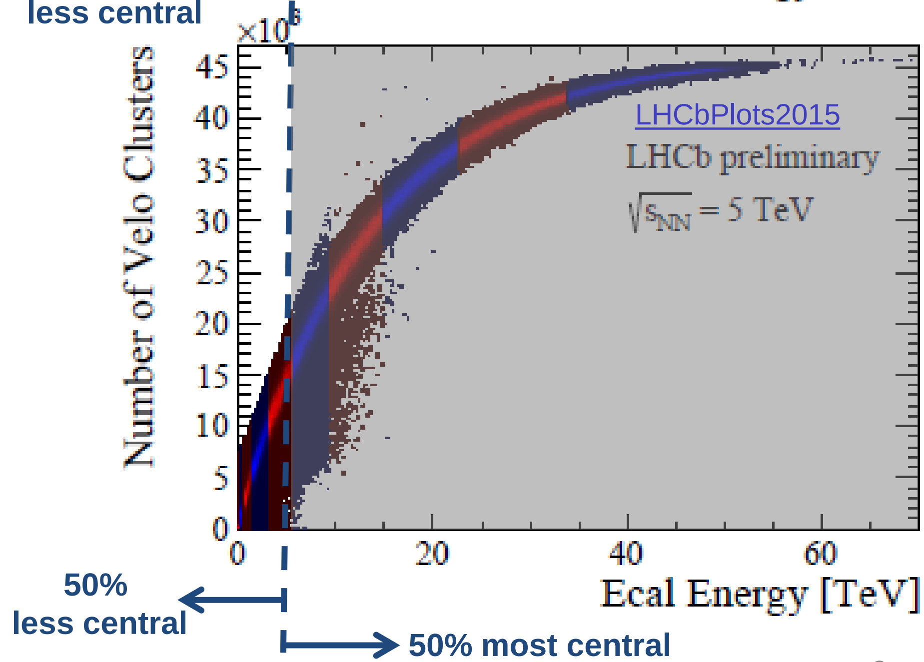


central

- **LHCb centrality reach**
  - Detector limitation due to high occupancy in Pb-Pb collisions
  - No saturation of the calorimeter
  - But, saturation in the Vertex Locator (VELO)

- **LHCb current limitations**
  - Current tracking algorithm efficient up to 50% most central
  - **Physics studies limited to 50% less central events**

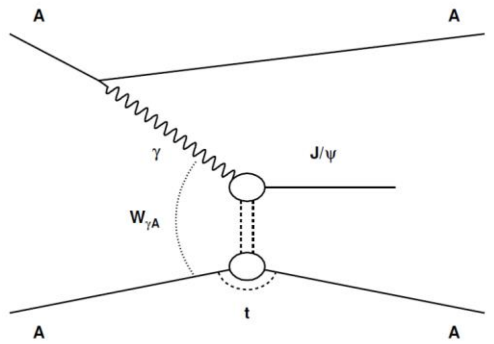


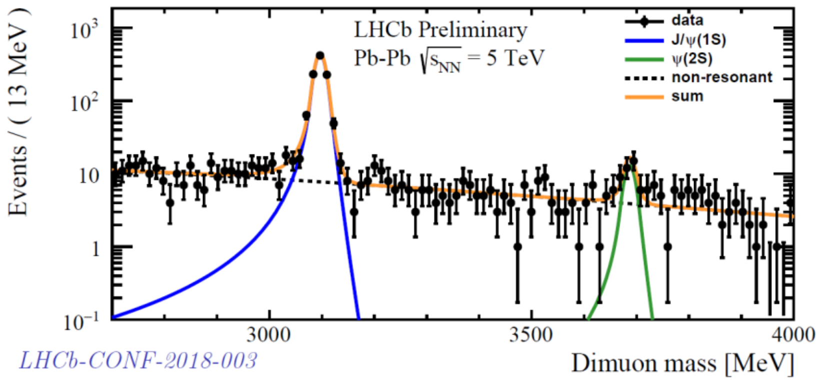


1. Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV

New results

- **J/ψ→μ⁺μ⁻ in Ultra-Peripheral Collisions**

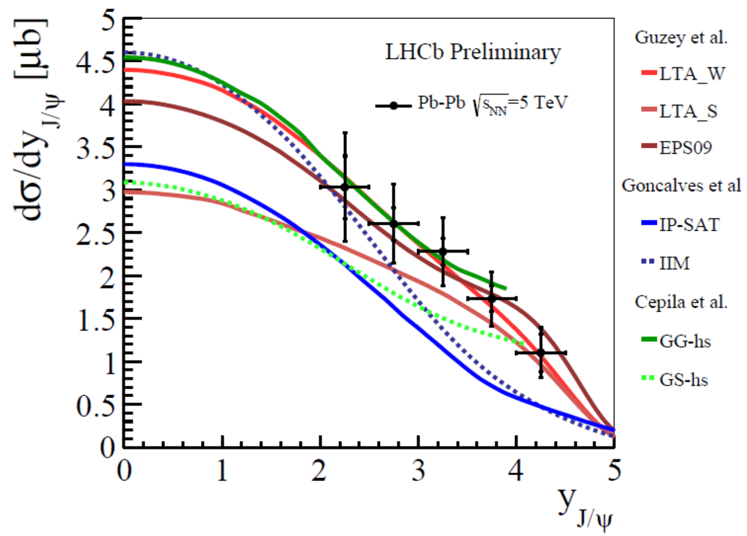




Nothing in the detector but two tracks

One ion interacts with the electromagnetic field of the other : coherent J/ψ photo-production

Sensitive to nPDF, saturation, …



$$\sigma_{J/\psi}^{\text{coherent}} = 5.27 \pm 0.21 \pm 0.49 \pm 0.68 \text{ mb}$$

(stat.) (syst.) (lumi.)

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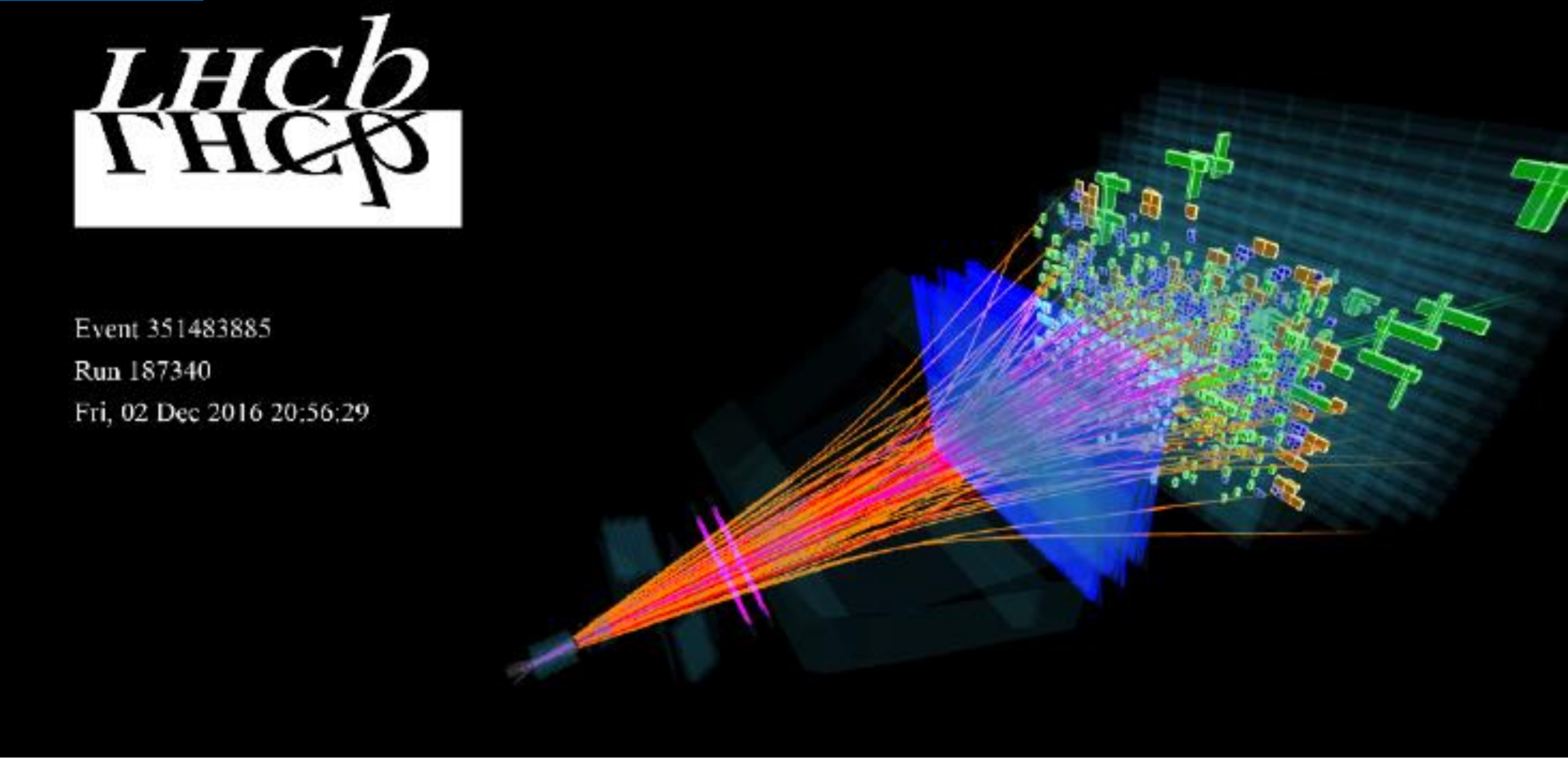
LHCb will participate in the 2018 PbPb run (expect ×10 larger luminosity than 2015)

2. Proton-Pb/Pb-proton collisions



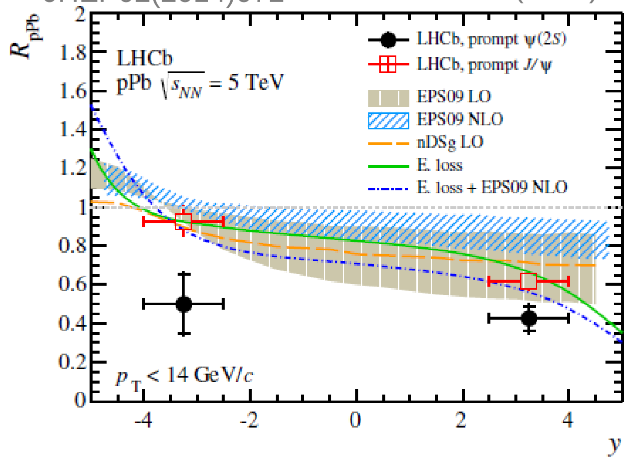
Two data sets presented here:

- $\sqrt{s_{NN}}$ **= 5 TeV proton-Pb interactions recorded in 2013: ~ 1.6 nb^{-1}**
- $\sqrt{s_{NN}}$ **= 8.16 TeV proton-Pb interactions recorded in 2016: ~ 30 nb^{-1}**

2. $\sqrt{s_{NN}}$ = 5 TeV (2013) *p*Pb collisions

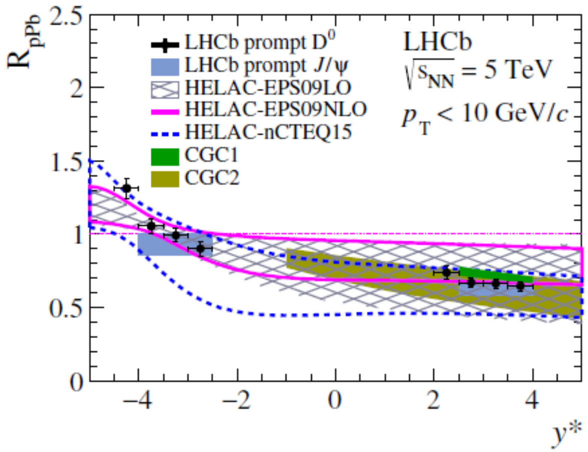
- **Charm: Prompt J/ψ, ψ(2S) and D^0**
  - Baseline for nucleus-nucleus collisions
  - Study of nuclear PDF (nPDF), coherent energy loss, gluon saturation (CGC), interaction with outcoming hadrons,…

JHEP02(2014)072 JHEP03(2016)133



$$R_{pPb} = \frac{\sigma_{pPb}}{A_{Pb}\sigma_{pp}} = \frac{\sigma_{pPb}}{208\ \sigma_{pp}}$$

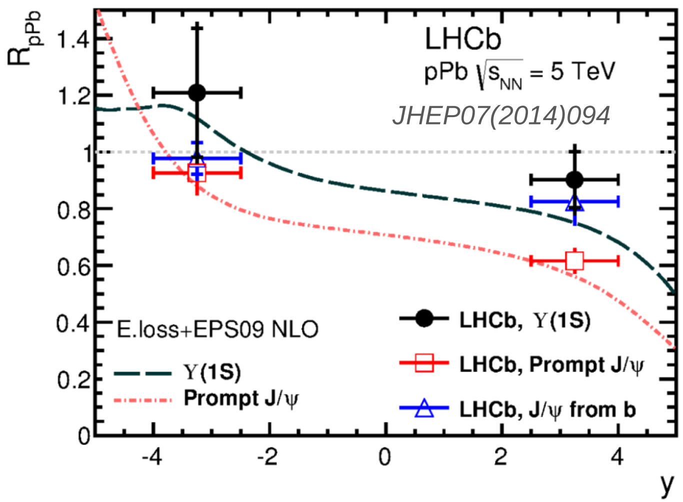
JHEP10(2017)090



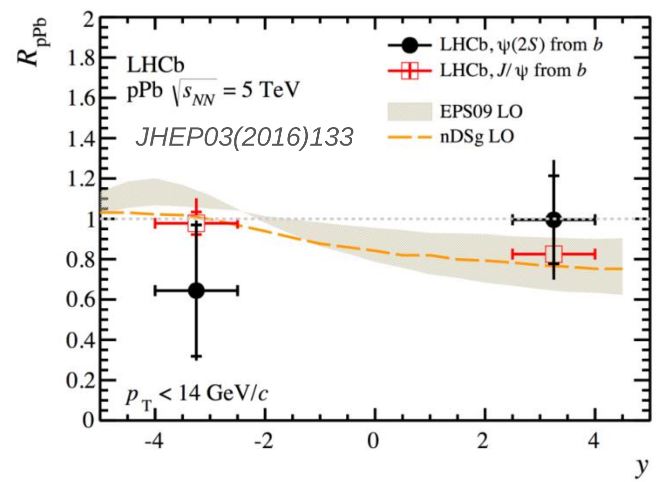
- **Forward rapidity region (y*>0) : *p*-Pb collisions**
  - **Significant J/ψ, ψ(2S) and D^0 suppression with respect to p-p yieds**
  - J/ψ and D^0 compatible with nPDF, coherent energy loss mechanism (JHEP 03 (2013) 122) and CGC (PRD 91 (2015) 114005)
- **Backward rapidity region (y*<0) : Pb-*p* collisions**
  - **J/ψ and D^0 modification compatible with theoretical expectations**
  - **Strong ψ(2S) suppression w.r.t. J/ψ**, not compatible with nPDF and coherent energy loss. Could be due to the interaction of the lightly-bound ψ(2S) with the outcoming partons/hadrons. (*Phys. Lett. B 749(2015)98, Nucl.Phys. A943 (2015), Phys. Rev. C97, 014909 (2018)*)

2. $\sqrt{s_{NN}}$ = 5 TeV (2013) *p*Pb collisions

- **Beauty: ϒ(1S), non-prompt J/ψ and ψ(2S)**
  - Baseline for nucleus-nucleus collisions
  - Study of nuclear PDF (nPDF), coherent energy loss, gluon saturation (CGC), interaction with outcoming hadrons,…



$$R_{pPb} = \frac{\sigma_{pPb}}{A_{Pb}\sigma_{pp}} = \frac{\sigma_{pPb}}{208\ \sigma_{pp}}$$

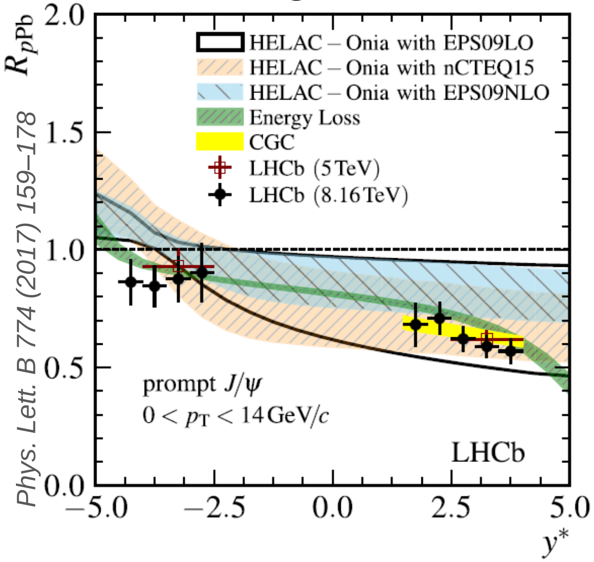


- **Forward rapidity region ($y^*>0$) : *p*-Pb collisions**
  - **Little non-prompt J/ψ (J/ψ from b-hadrons) and ϒ suppression**
  - compatible with nPDF and coherent energy loss mechanism

- **Backward region ($y^*<0$) : Pb-*p* collisions**
  - **No significant non-prompt J/ψ (from b) and ϒ modification,** compatible with expectations
  - **Large stat. uncertainty for non-prompt ψ(2S) suppression**, see 2016 data.

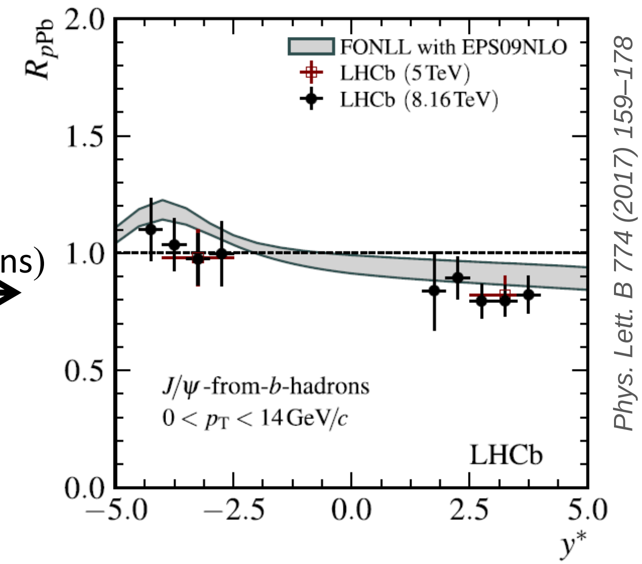
2. $\sqrt{s_{NN}}$ = 8.16 TeV (2016) *p*Pb collisions

- **Prompt and non-prompt J/ψ**
  - Baseline for nucleus-nucleus collisions
  - Study of nuclear PDF (nPDF), coherent energy loss, gluon saturation (CGC), interaction with outcoming hadrons,…



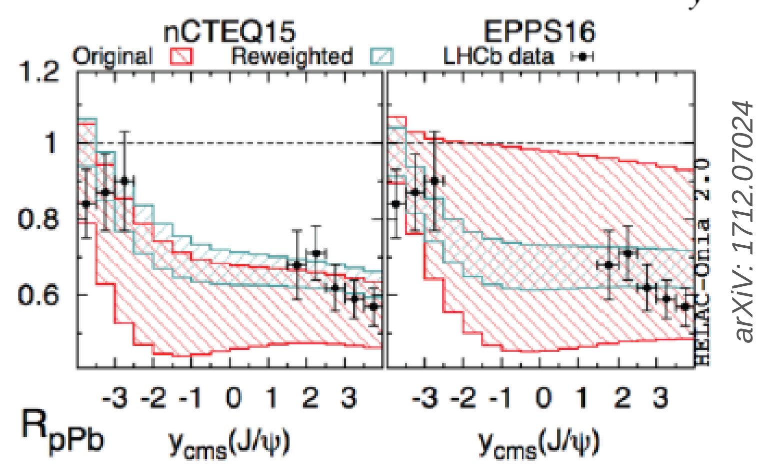
Prompt J/ψ

Non-prompt J/ψ
(J/ψ from b-hadrons)



- **Prompt and non-prompt J/ψ results compatible with lower energy data and theoretical expectations**

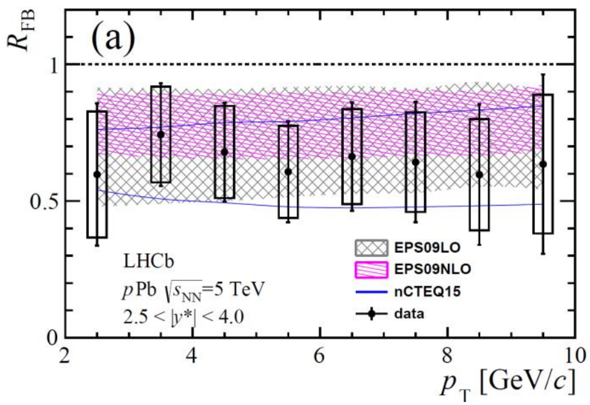
- ***Put strong constraints on nPDF parametrizations (arXiV: 1712.07024)***



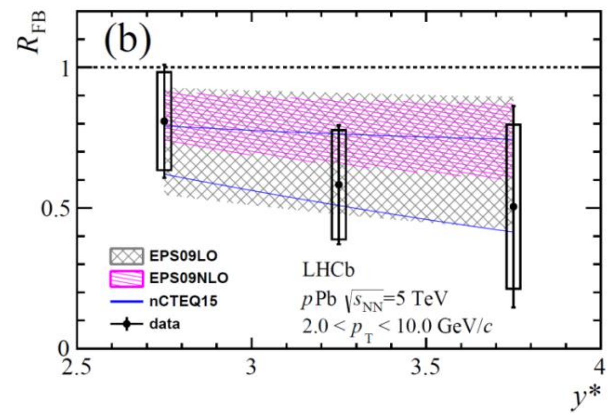
2. $\sqrt{s_{NN}}$ = 5 TeV *p*Pb collisions

New results

- **Charm baryon: prompt Λ_c production**



Forward/backward ratio: $R_{FB} = \frac{\sigma(+|y^*|, p_T)}{\sigma(-|y^*|, p_T)}$



- **Data are consistent with nPDF predictions**

- **Baryon/meson: prompt Λ_c / prompt D^0**
  - Most of the nPDF uncertainties cancel out
  - Λ_c/D^0 ratio sensitive to quark fragmentation
  - Model based on measured *pp* cross sections
- **Forward rapidity region (y^*>0) : *p*-Pb**
  - **Some discrepancies observed at high p_T**
- **Backward rapidity region (y^*<0): Pb-*p***
  - **Compatible with expectations**

- **To be improved with larger 2016 data set**

Model from Lansberg, Shao EPJ C77 (2015) 1

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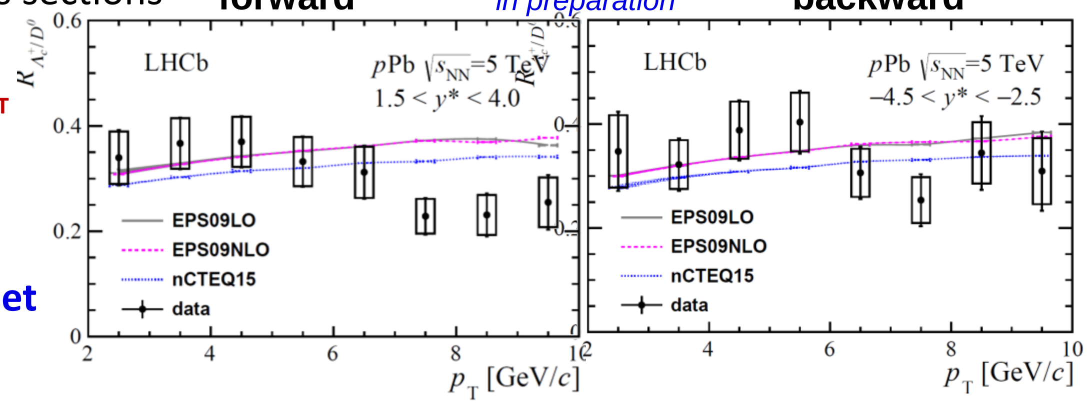
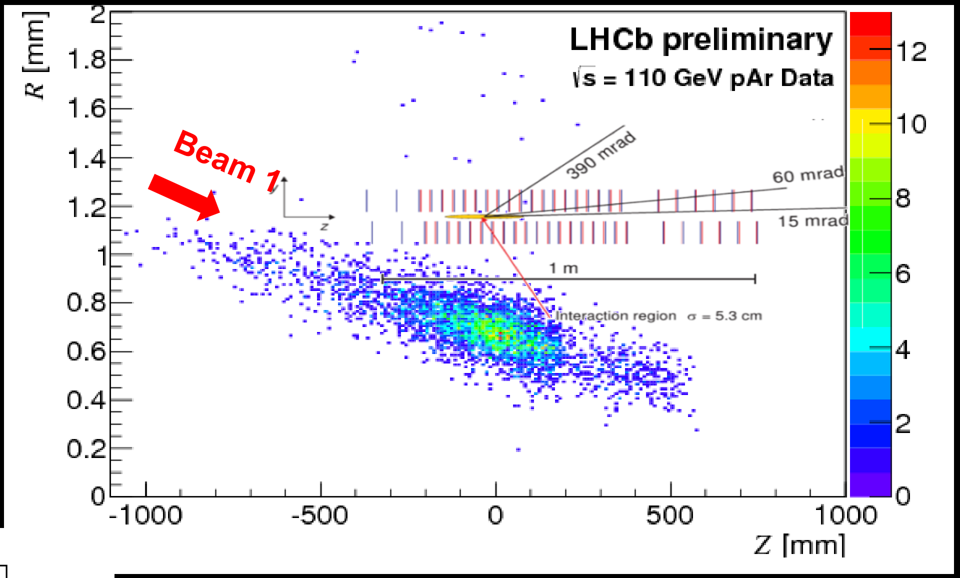
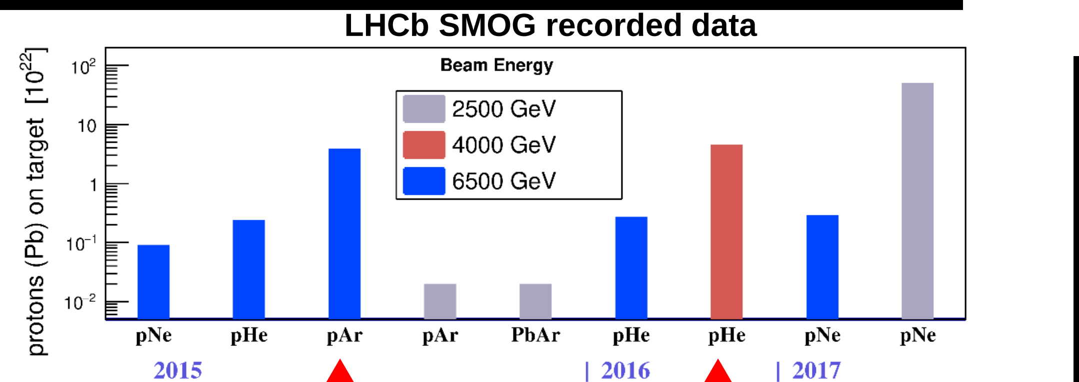
forward **backward**



3. Fixed-target collisions





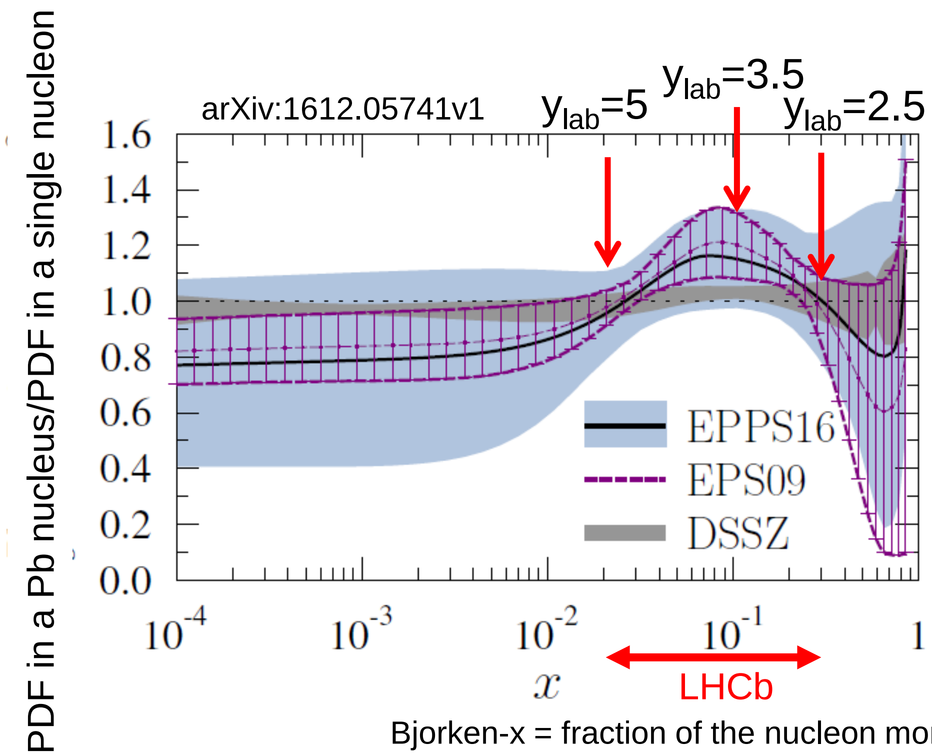
Two data sets presented here:

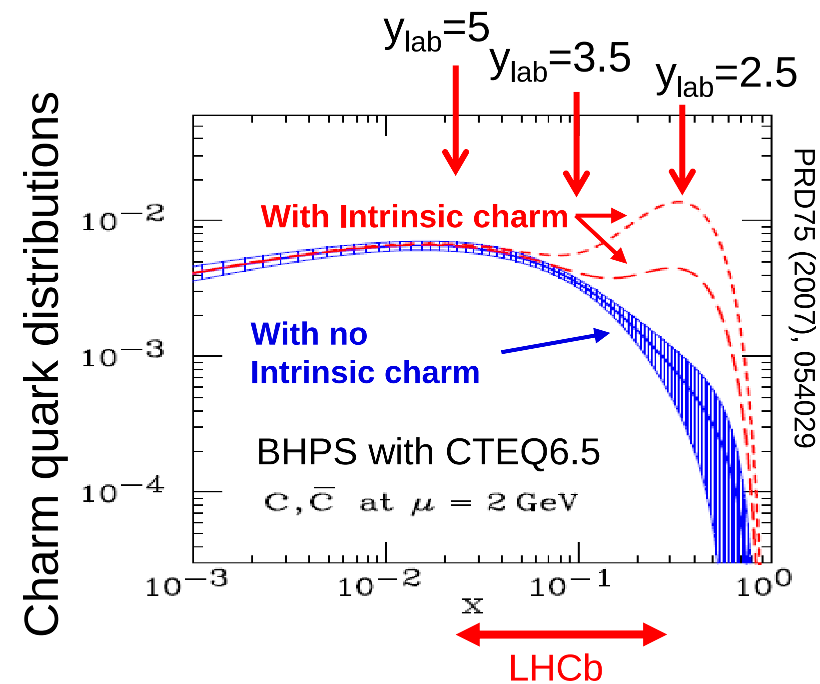
- $\sqrt{s_{NN}}$ = 110 GeV proton-Ar interactions 2015: ~ 4×10^{22} Protons On Target (17h)
- $\sqrt{s_{NN}}$ = 86.6 GeV proton-He interactions 2016: ~ 4×10^{22} POTs (87h)

$$\mathcal{L}_{pHe} = 7.6 \pm 0.5\ \mathrm{nb}^{-1}$$

- ***p*A collisions**
  - Serve as a baseline for nucleus-nucleus collisions
  - Study of nuclear PDF (nPDF), nuclear absorption, …

- **With LHCb-SMOG**, large rapidity coverage (~3 rapidity units) at **large Bjorken-x in the target (x_2)**
  - Give access to **nPDF anti-shadowing** region and **intrinsic charm** content in the nucleon





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

3. Charm in fixed-target proton-nucleus collisions

New results

- **$J/\psi \to \mu^+\mu^-$ and $D^0 \to K^\mp\pi^\pm$ inclusive cross sections in *p*He @86.6 GeV**

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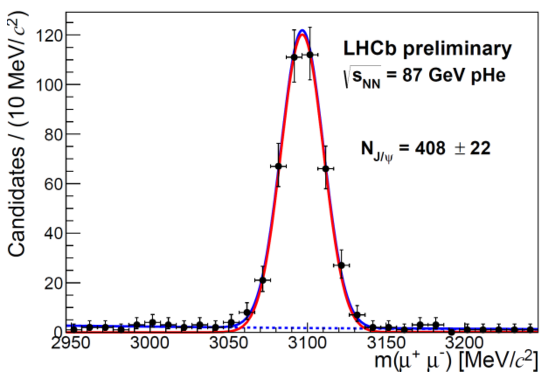
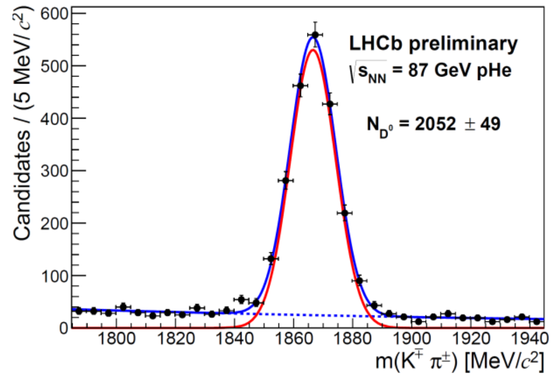
J/ψ

D^0



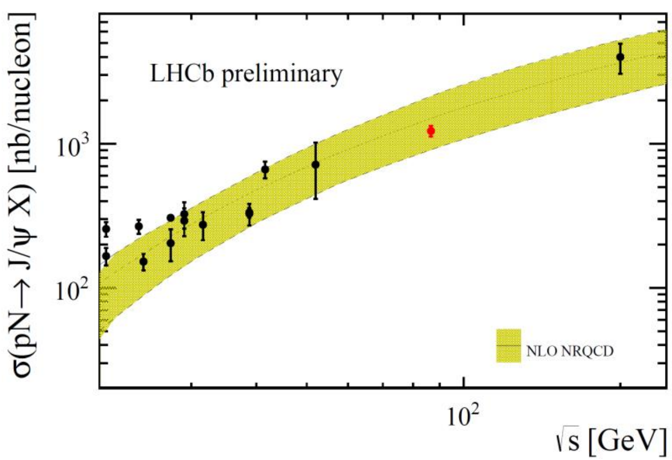
$$\sigma_{J/\psi} = 1225.6 \pm 62.0\ (\text{stat}) \pm 81.6\ (\text{syst})\ \text{nb/nucleon}$$



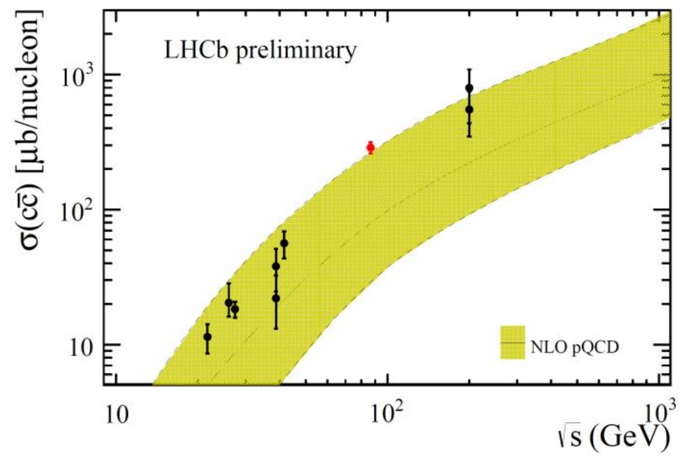
$$\sigma_{D^0} = 156.0 \pm 4.6\ (stat) \pm 12.3\ (syst)\ \mu\text{b/nucleon}$$

with fraction ($c \to D^0$) = 0.542±0.024

$$\sigma_{c\bar{c}} = 287.8 \pm 8.5\ (stat) \pm 25.7\ (syst)\ \mu\text{b/nucleon}$$



LHCb result in good agreement with NRQCD fit and other measurements

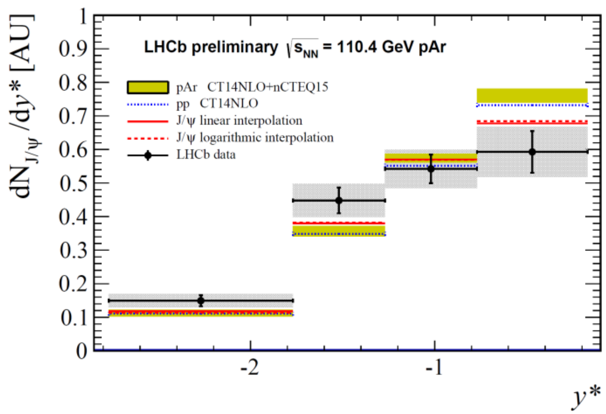


LHCb result in reasonable agreement with NLO pQCD (MNR) predictions and other measurements

3. Charm in Fixed-target proton-nucleus collisions

New results

- **J/ψ Differential yields (pAr@110 GeV) and cross sections (pHe@86.6 GeV)**
  - Plain and dashed **red lines**, **phenomenological parametrization**: JHEP 05 (2013) 155
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1



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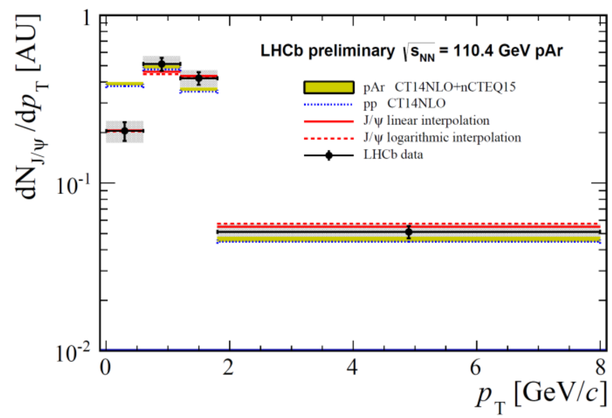
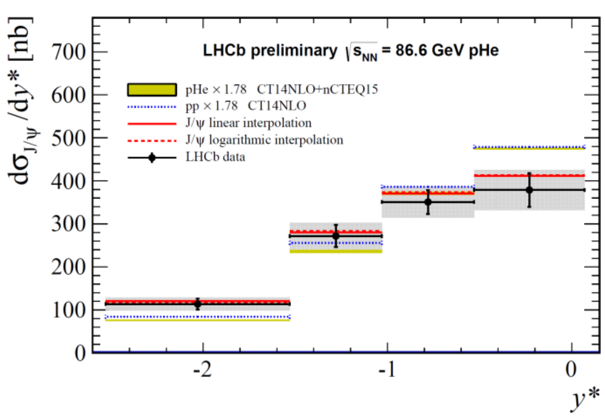
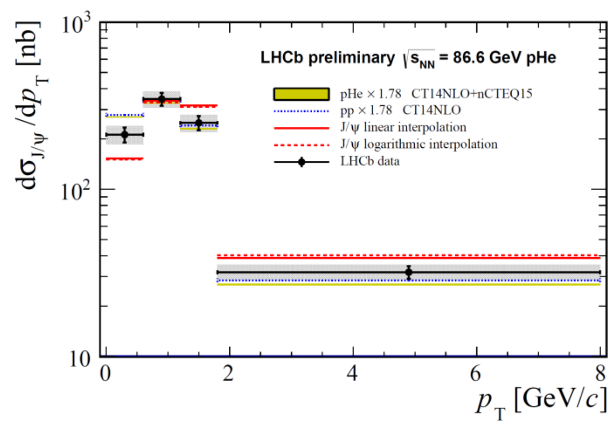
pAr @ 110 GeV
yields





pHe @ 86.6 GeV
Cross sections



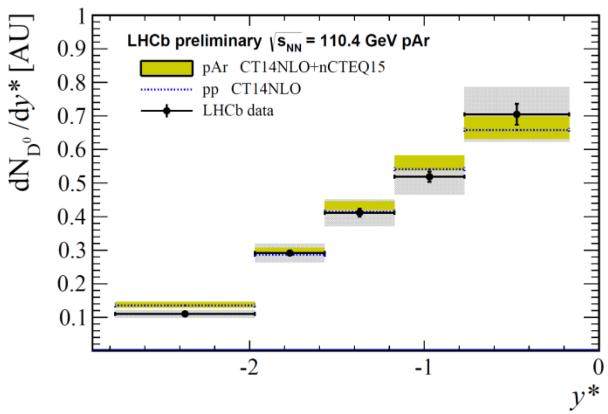
  - **HELAC-ONIA under-estimate J/ψ cross section (pHe) by a factor 1.78**
  - **Good shape agreement with phenomenological predictions**

3. Charm in Fixed-target proton-nucleus collisions

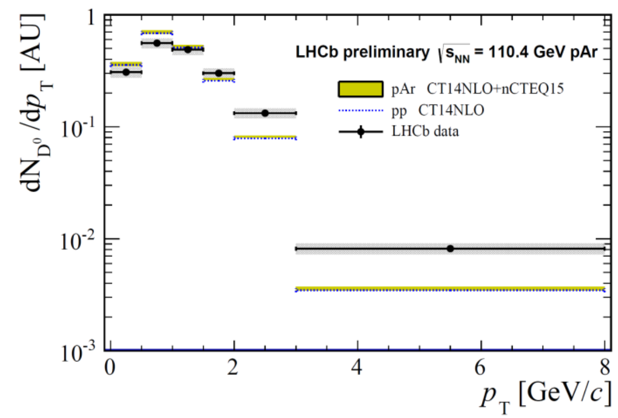
New results

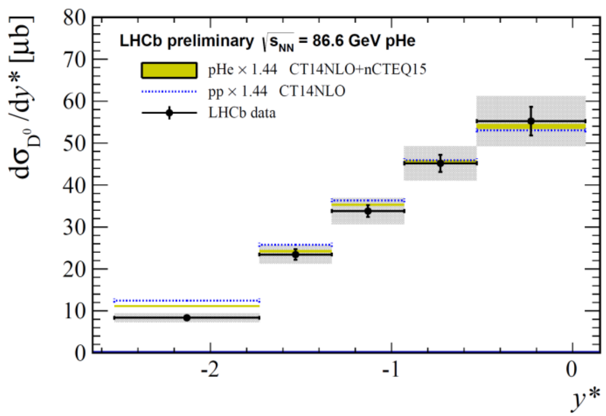
- **D^0 Differential yields (pAr@110 GeV) and cross sections (pHe@86.6 GeV)**
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1

LHCb-PAPER-2018-021
in preparation

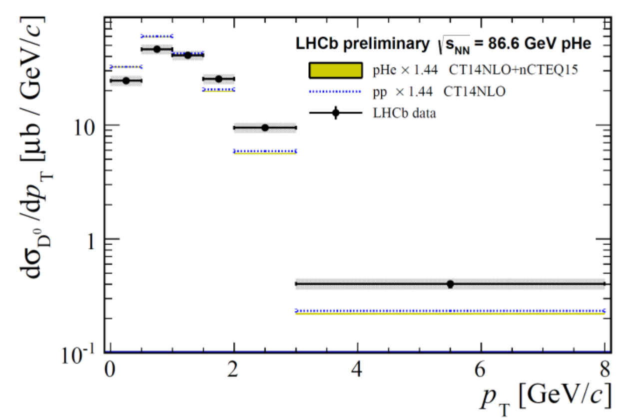


pAr @ 110 GeV
yields





pHe @ 86.6 GeV
Cross sections



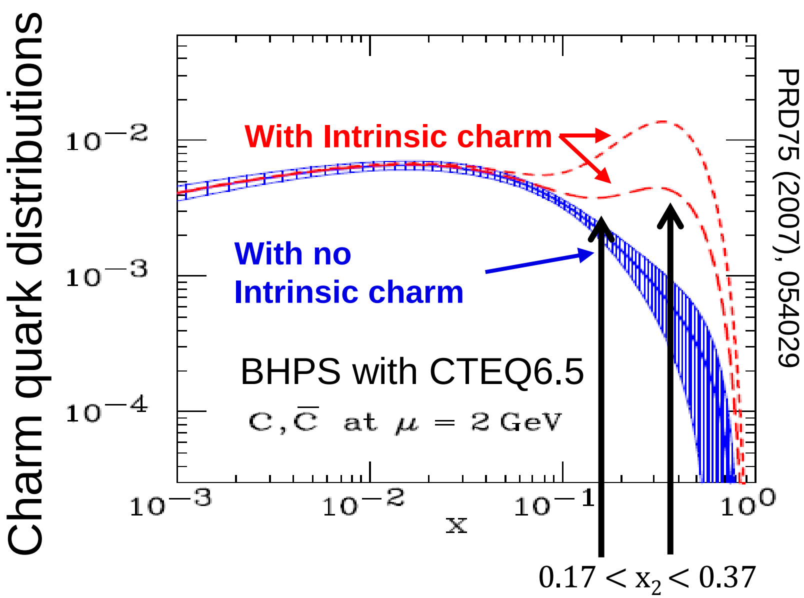
  - **HELAC-ONIA under-estimate D0 cross section (pHe) by a factor 1.44**
  - **Good agreement in rapidity shapes between data and predictions**

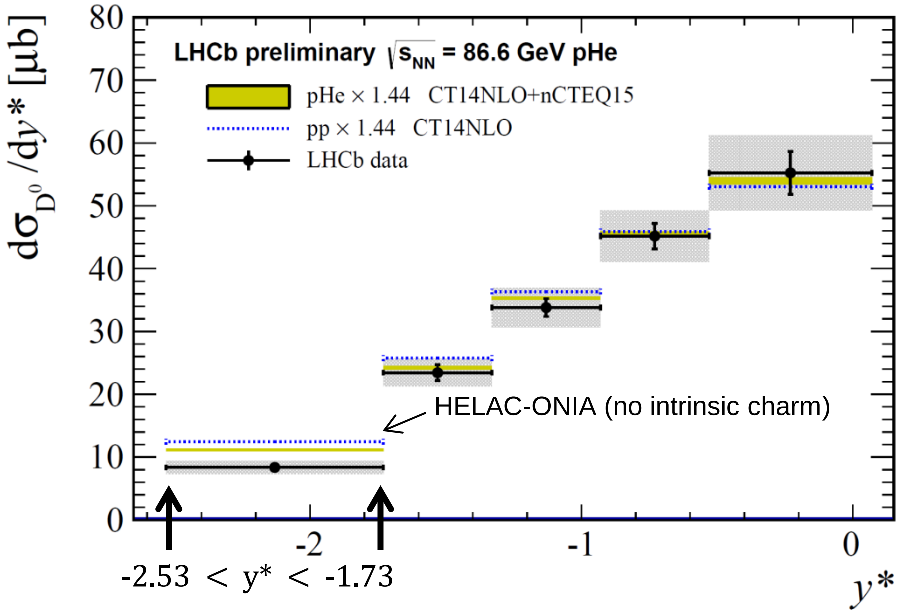
3. Charm in Fixed-target proton-nucleus collisions

New results

LHCb-PAPER-2018-021
in preparation

- **D^0 cross sections (pHe@86.6 GeV) .vs. Intrinsic charm**
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1
  - With $x_2 \simeq \frac{2\times m_c}{\sqrt{s_{NN}}} \exp(-y^*)$ $y^* \in$[-1.73, -2.53] ⟺ $x_2 \in$[0.17, 0.37]





  - HELAC-ONIA does not contain intrinsic charm contribution
  - **No evidence of strong intrinsic charm contribution**

Conclusions

- **The LHCb detector**
  - has unique capabilities for heavy flavor measurements at LHC
  - Currently limited to peripheral collisions in Pb-Pb, but **full performances in *p*-Pb collisions**
  - Can operate a **fixed-target program**, unique at LHC

- **Current results**
  - Demonstrate **capabilities to run in Pb-Pb** collisions
  - Performed prompt J/ψ, ψ(2S), D^0 and non-prompt J/ψ and Υ measurements in $\sqrt{s_{NN}}$ **= 5 TeV *p*-Pb** collisions
    - *J/ψ, D^0 and Υ measurements compatible with theoretical expectations*
    - *Strong backward-rapidity ψ(2S) suppression, maybe due to interactions with outcoming partons/hadrons.*
  - Performed prompt and non-prompt J/ψ measurements in $\sqrt{s_{NN}}$ **= 8.16 TeV *p*-Pb** collisions
    - *Compatible with lower energy data and theoretical expectations*
  - Performed prompt Λ_c measurements in $\sqrt{s_{NN}}$ **= 5 TeV p-Pb** collisions
    - *Λ_c / D^0 ratio shows possible discrepancy with models at forward rapidity and high p_T*
  - Performed J/ψ and D^0 measurements in $\sqrt{s_{NN}}$ **= 110 GeV *p*-Ar** and $\sqrt{s_{NN}}$ **= 86.6 GeV *p*-He** collisions
    - *No evidence of strong intrinsic charm contribution*

Conclusions

- **Still to come**
  - ψ(2S) in *p*-Pb at $\sqrt{s_{NN}}$ = 8 TeV
  - Υ(1S), Υ(2S), Υ(3S) in *p*-Pb at $\sqrt{s_{NN}}$ = 8 TeV
  - D^0, $D^{\pm}$, Λ_c^+ in *p*-Pb at $\sqrt{s_{NN}}$ = 8 TeV
  - B^0, $B^{\pm}$, Λ_b in *p*-Pb at $\sqrt{s_{NN}}$ = 8 TeV
  - **LHCb will participate to the 2018 Pb run:**
    - **x10 lumi. in 5 TeV PbPb collisions**
    - **PbNe @ 69 GeV fixed-target**

We have only scratched the surface of LHCb capabilities in Ion collisions