

# Results on heavy ion collisions at LHCb

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**28th Rencontres de Blois**

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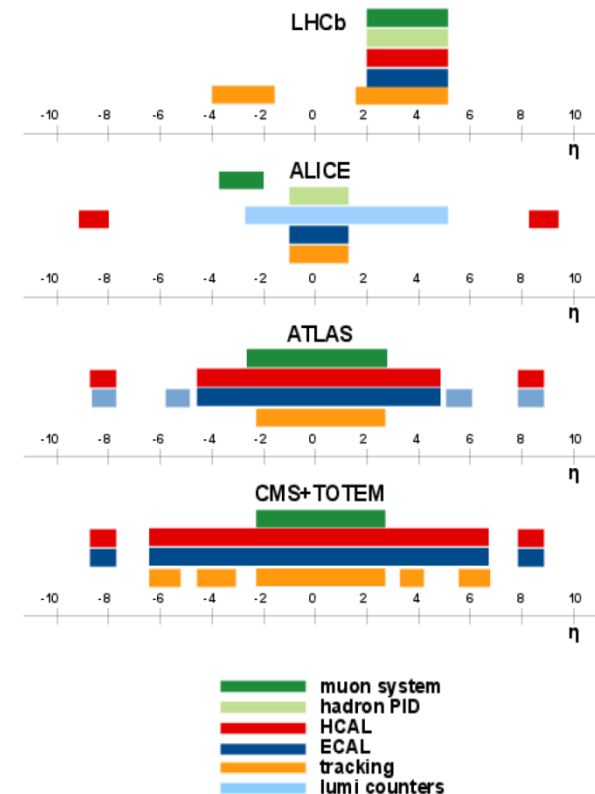
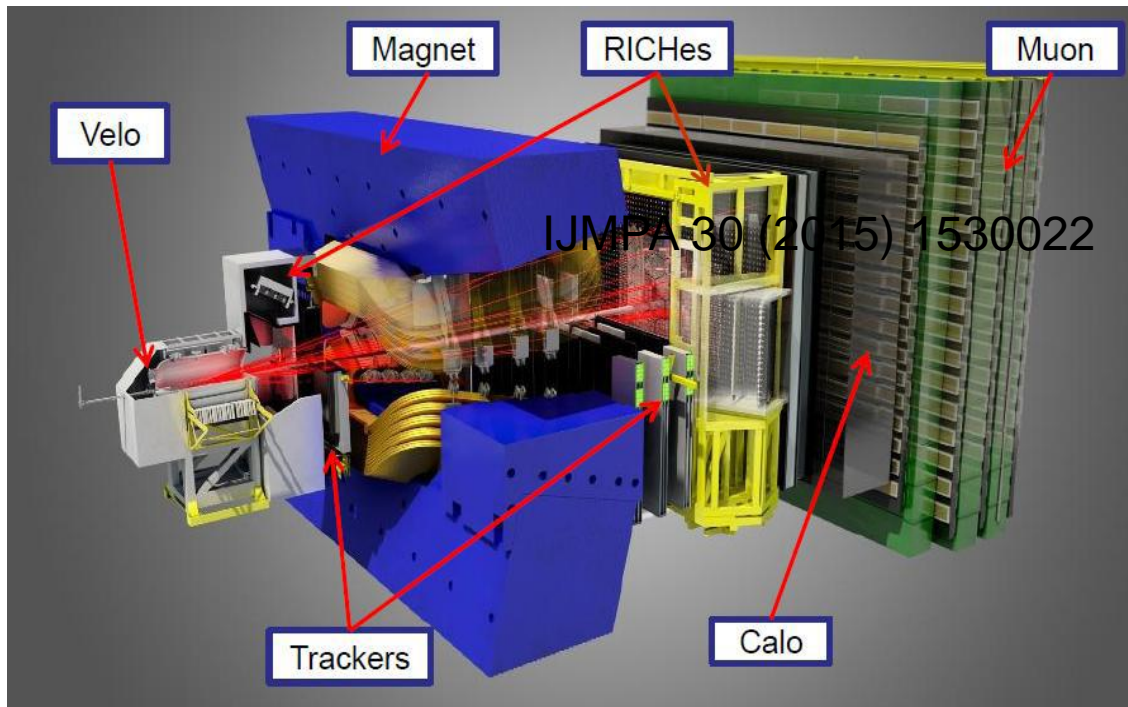
- LHCb - general purpose forward experiment
- Physics motivation
- Results from p-Pb / Pb-p data taking in 2013
- Selected results:
  - $D^0$  production (*recent*)
  - heavy quarkonia production
  - two particle correlations in pPb collisions
- Prospects for heavy ion physics at LHCb
  - fixed-target physics with SMOG system
- Conclusions

# LHCb detector

[JINST 3 (2008) S08005]



- single arm spectrometer fully instrumented in forward region
- designed to study CP violation in B, *but also fixed target, heavy ion physics*
- precision coverage unique for LHCb:  $2.5 < \eta < 4.5$
- forward and backward coverage for asymmetric beams
- able to access low- $p_T$  peripheral collisions



[IJMPA 30 (2015) 1530022]

- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20  $\mu\text{m}$  for high- $p_T$  tracks

# Physics motivation: *proton-nucleus*

*LHCb fully instrumented in a unique kinematic region*

- study proton-ion collisions at low  $p_T$ , large  $y$ , low/high  $x$
- complementary to other LHC experiments
- provides also a reference for heavy ion studies

*Disentangle effects of Quark Gluon Plasma from Cold Nuclear Matter (CNM)*

heavy flavour / quarkonium production

- study *nuclear shadowing*
- parton saturation*
- nuclear absorption*
- radiative/coherent energy loss, ...*

*Sensitive to nuclear PDF (nPDF)*

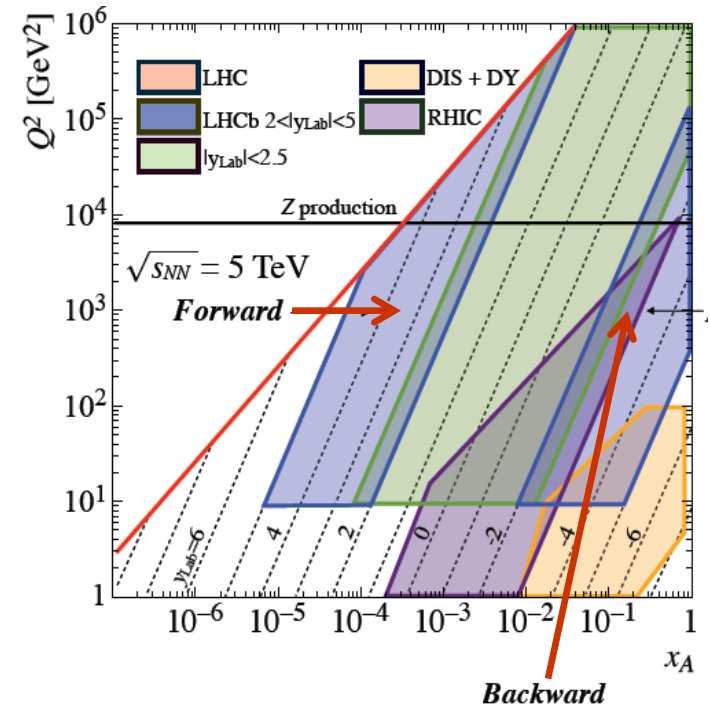
electroweak boson production

- probe very small  $x_A$  ( $10^{-4}$ ) and very large  $x_A$  ( $10^{-1}$ )
- test phenomenological models

*Probe collective effects in dense environment of high energy collisions*

two-particle correlations

- study long-range correlations on the near side (*the ridge*) in forward direction

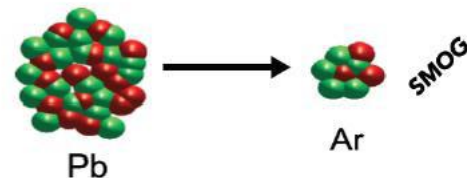
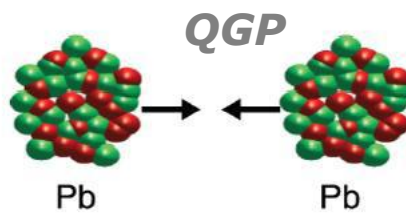
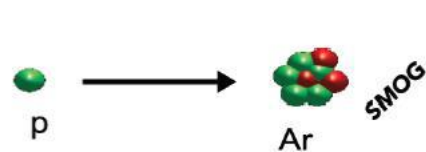
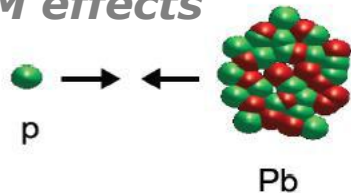


# Physics motivation: *nucleus-nucleus*

*LHCb allows for precise measurements in nucleus-nucleus collisions in forward region*

- ideal to test cosmic-ray interaction models
- possible to study nuclear PDFs at large  $x$
- study dynamics of multi-particle production
- probe ultra-peripheral collisions

*CNM effects*



← colliding beam mode

← fixed target mode

colliding beam mode → *forward / backward coverage*  
fixed target mode → *central to backward acceptance*

*LHCb can bridge the gap between SPS and RHIC*

→ in fixed target mode densities between the ones achieved in SPS and RHIC

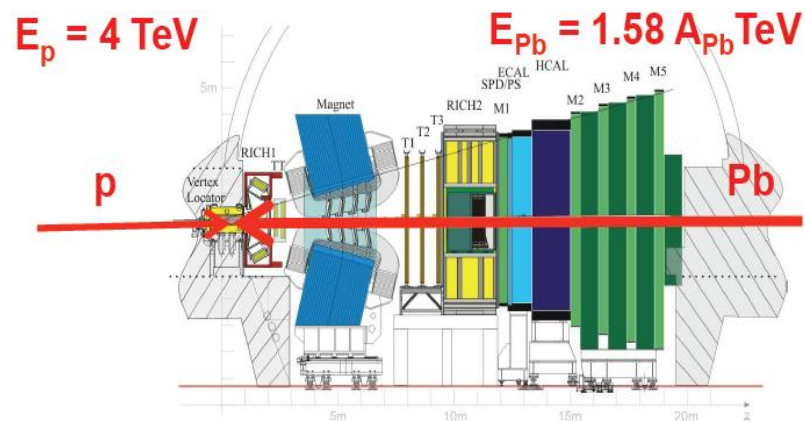
**p-Pb / Pb-p**

# Setup for proton-nucleus

- p-Pb / Pb-p data collected at  $\sqrt{s_{NN}} = 5$  TeV
- **Asymmetric beams:** nucleon-nucleon center-of-mass system shifted by  $\Delta y = 0.47$  in the proton beam direction

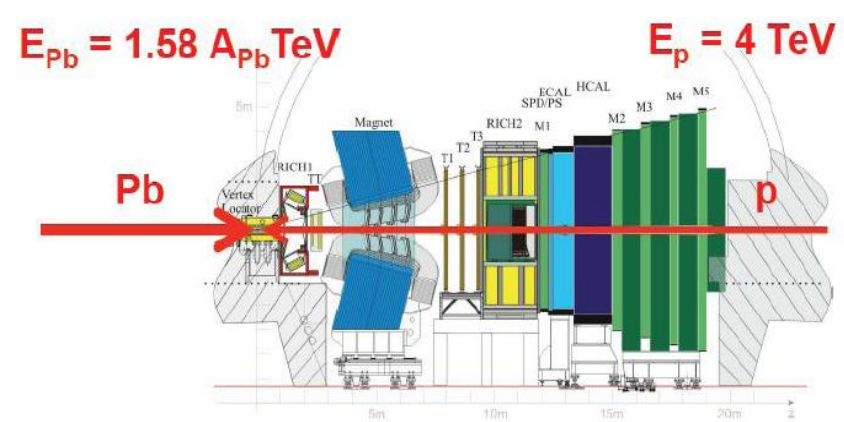
## Forward production (p-Pb)

rapidity coverage:  $1.5 < y_{CMS} < 4.5$   
collected data (2013):  $\sim 1.1 \text{ nb}^{-1}$



## Backward production (Pb-p)

rapidity coverage:  $-5.5 < y_{CMS} < -2.5$   
collected data (2013):  $\sim 0.5 \text{ nb}^{-1}$



Rapidity coverage  $2.5 < |y_{CMS}| < 4.5$  for both configurations

$y_{CMS} = y^*$ : rapidity in nucleon-nucleon centre-of-mass system, with forward direction (*positive values*) in direction of the proton/beam

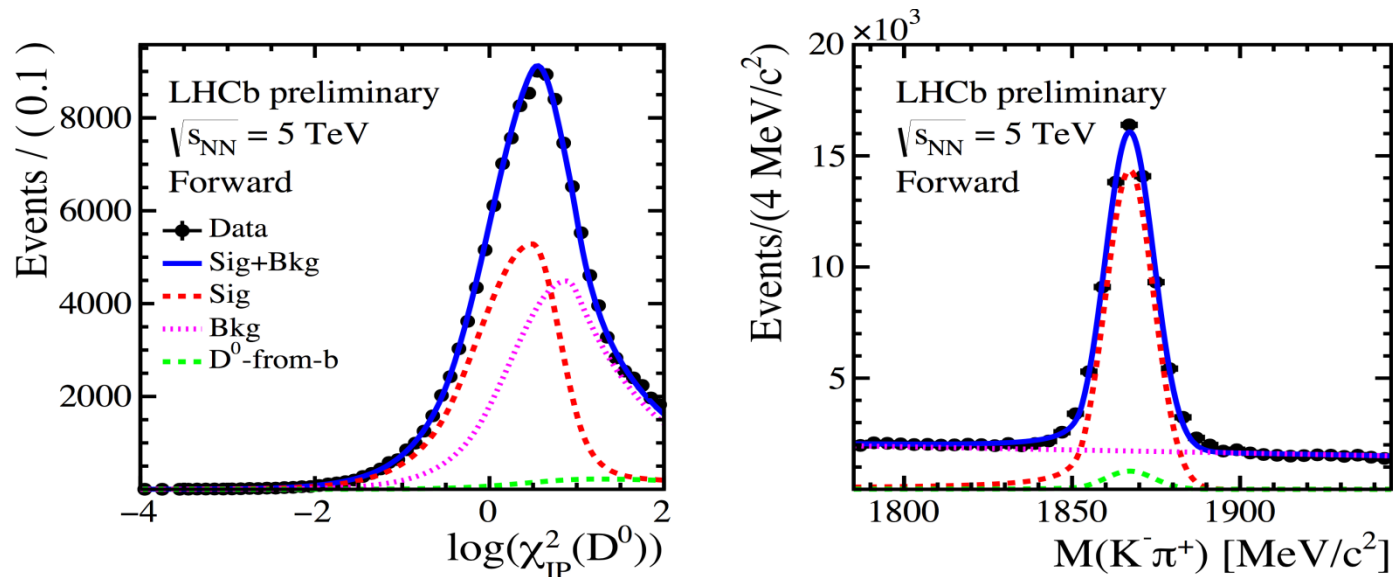


# Prompt $D^0$ production (*recent*)

[LHCb-CONF-2016-003]



- 2013 p-Pb and Pb-p data at  $\sqrt{s_{NN}} = 5$  TeV
- **prompt  $D^0$  signal reconstructed through  $D^0 \rightarrow K \pi$**
- $p_T < 8$  GeV,  $1.5 < y_{CMS} < 4.0$  (*forward*),  $-5.0 < y_{CMS} < -2.5$  (*backward*)
- reconstruction and PID efficiency calibrated using data



- fraction of  $D^0$ 's from  $b$ -hadrons from IP significance distribution
- signal yield from extended unbinned maximum likelihood to  $M(K^+\pi^-)$   
→ signal: *Crystal Ball* → background: *linear function*

**Able to remove  $D^0$ 's from  $b$ -hadrons down to zero- $p_T$**



# Prompt $D^0$ production x-section

[LHCb-CONF-2016-003]

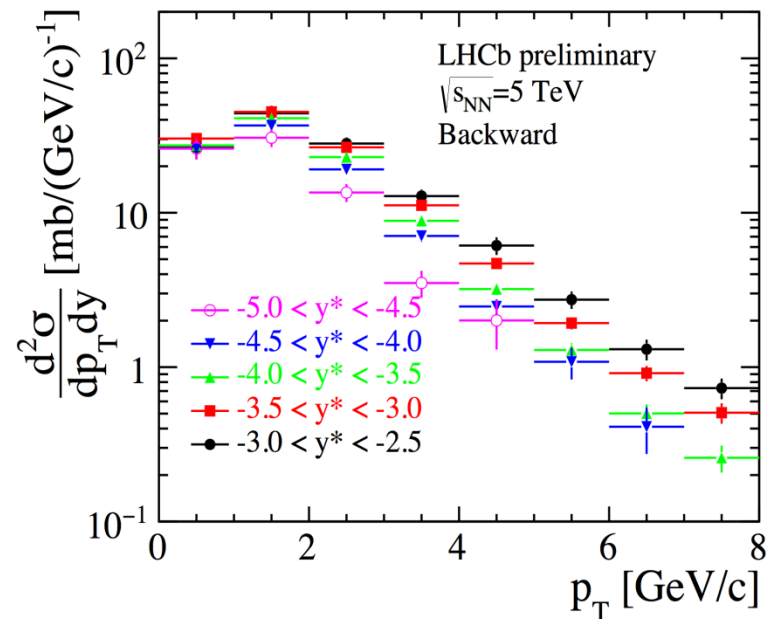
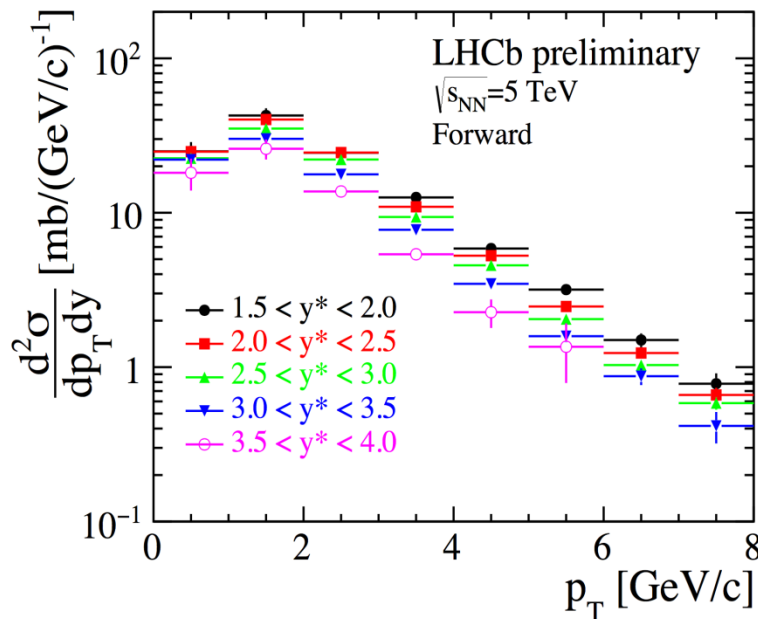


Differential, double differential and integrated x-section in forward and backward directions

Integrated cross-sections of prompt  $D^0$  in pPb forward data

$$\sigma_{\text{Fwd}}(p_T < 8 \text{ GeV}/c, 1.5 < |y^*| < 4) = 237 \pm 1 \pm 15 \text{ mb}$$
$$\sigma_{\text{Fwd}}(p_T < 8 \text{ GeV}/c, 2.5 < |y^*| < 4) = 124 \pm 1 \pm 8 \text{ mb.}$$

Double differential cross-section down to zero- $p_T$



# Prompt $D^0$ production

[LHCb-CONF-2016-003]



## Nuclear modification factor $R_{pPb}$ & forward-backward ratio $R_{FB}$

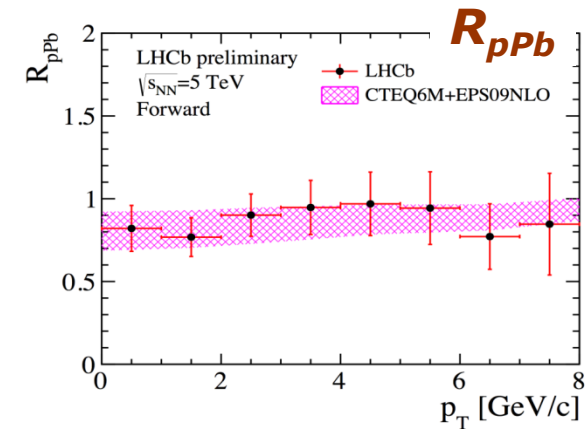
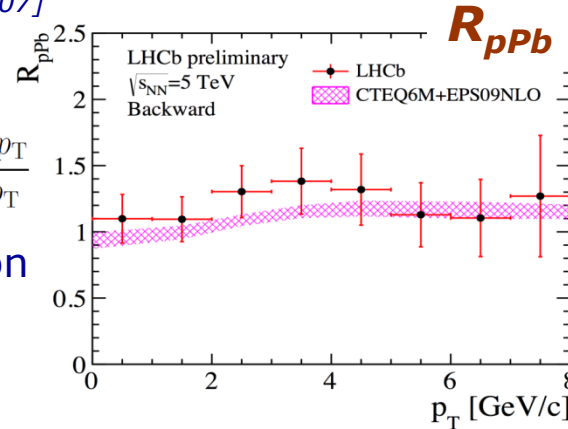
$R_{pPb}$ : production x-section in pPb collisions relative to that in pp collisions with the same  $\sqrt{s_{NN}}$

→  $D^0$  x-section in pp at  $\sqrt{s} = 5$  TeV extrapolated from LHCb results at 7 and 13 TeV

[Nucl. Phys. B87 (2013), arXiv:1510.01707]

$$R_{pPb}(y^*, p_T, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})/dy^*dp_T}{d^2\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})/dy^*dp_T}$$

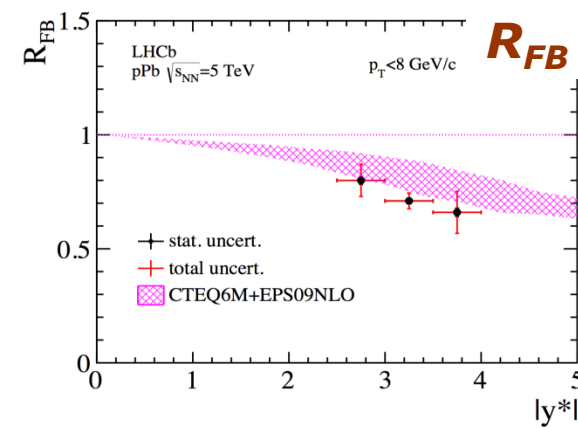
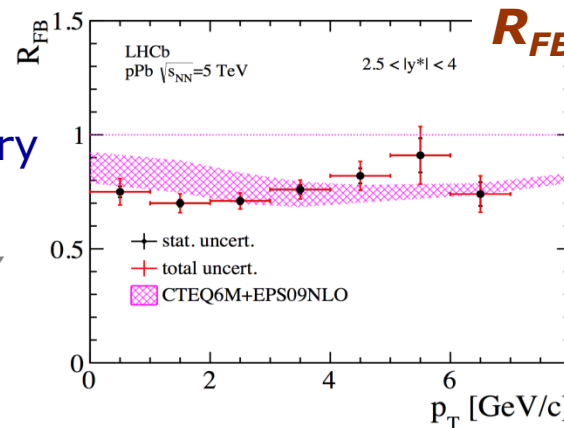
$R_{pPb}$  lower in forward direction



$$R_{FB}(y^*, p_T, \sqrt{s_{NN}}) \equiv \frac{\sigma_{pPb}(+|y^*|, p_T, \sqrt{s_{NN}})}{\sigma_{pPb}(-|y^*|, p_T, \sqrt{s_{NN}})}$$

Large production asymmetry in forward-backward

(systematic uncertainty largely cancels)



results consistent with theoretical predictions (strong CNM effect)

Models: CTEQ6M+EPS09NLO: Nucl. Phys. B373 (1992) 295, JHEP 10 (2003) 046, JHEP 04 (2009) 065

# Heavy quarkonia production

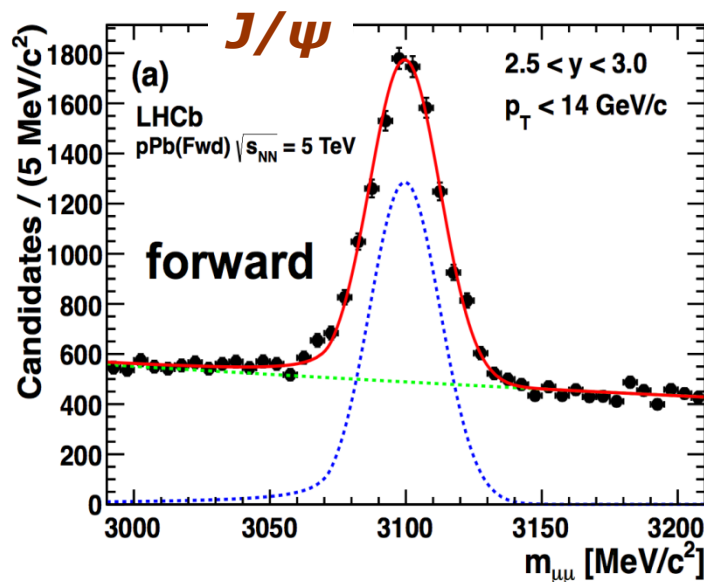
[JHEP 02 (2014) 072]

[arXiv:1601.07878]



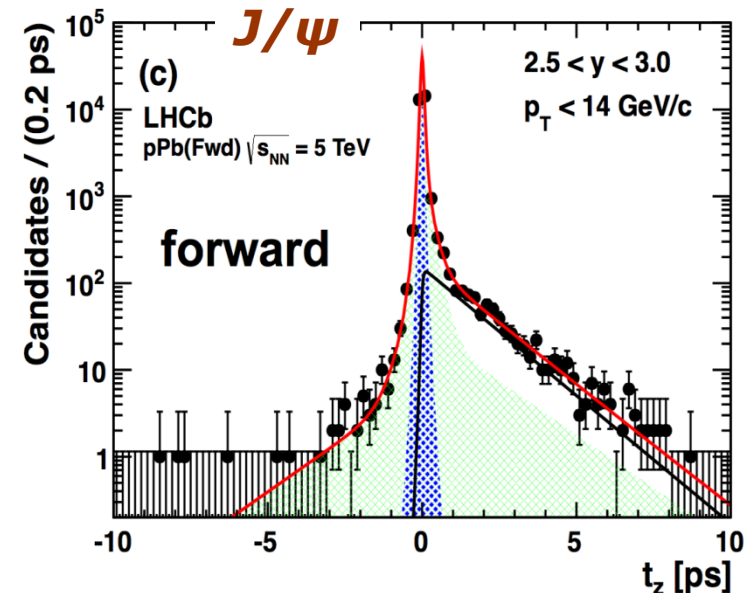
## $J/\psi$ and $\Psi(2S)$ production in p-Pb and Pb-p

- reconstructed using dimuon final states
- prompt  $J/\psi$ 's ( $\Psi(2S)$ 's) and those from  $b$ 's separated by fits to mass and  $t_z$
- yields from simultaneous fit to mass and pseudo-proper time



### mass model

- signal: *Crystal-Ball*
- background: *exponential*  
(higher for Pb-p → higher multiplicities)



### pseudo-proper time model

- signal: *exponential* ( $J/\psi$ 's from  $b$ 's) +  $\delta(t_z)$  for prompt  $J/\psi$
- background: *empirical function* (sPlot) from sideband

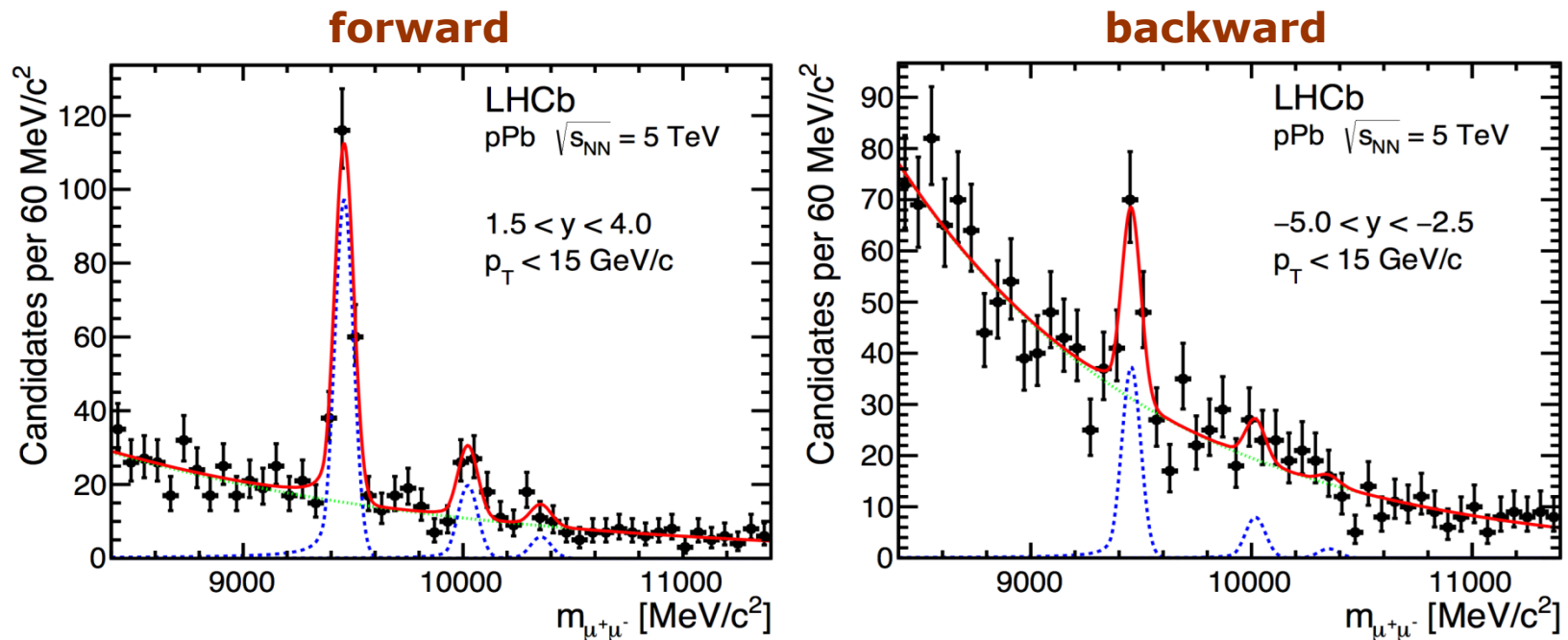
# Heavy quarkonia production

[JHEP 07 (2014) 094]



## $Y(1S)$ production in p-Pb and Pb-p

- $Y$  states in dimuon decay channel
- $p_T < 15$  GeV,  $1.5 < y_{CMS} < 4.0$  (forward),  $-5.0 < y_{CMS} < -2.5$  (backward)
- fit with 3 Crystal Balls for signal and exponential for background



**statistics insufficient to:**

- study  $Y(2S)$  and  $Y(3S)$  production
- perform differential measurement

# Nuclear modification factor $R_{pPb}$

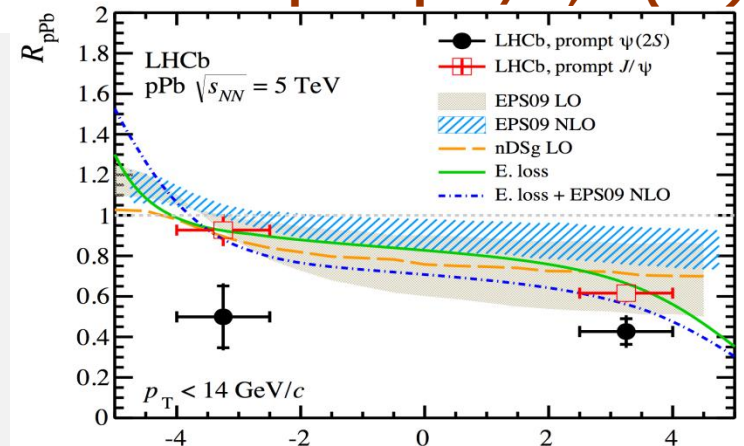
[JHEP 02 (2014) 072]  
 [JHEP 07 (2014) 094]  
 [arXiv:1601.07878]



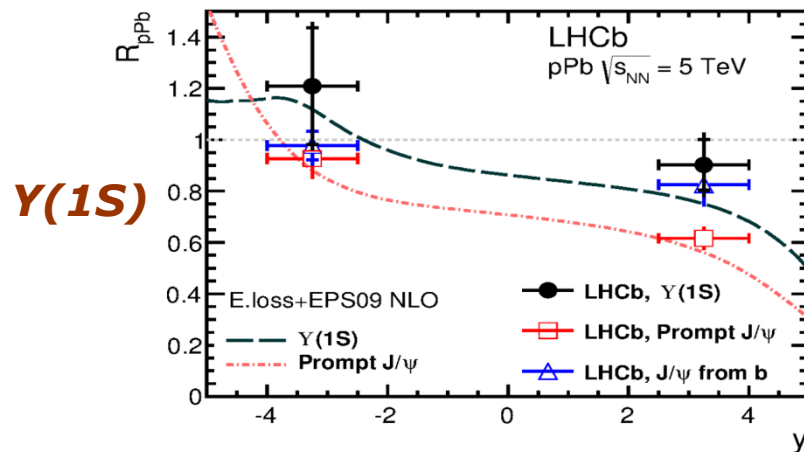
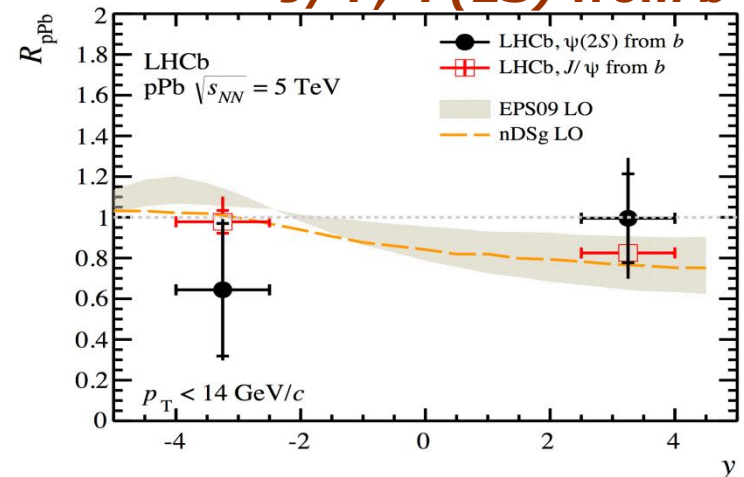
$$R_{pPb}(y) = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy^*}{d_{pp}/dy} \quad \begin{array}{l} \text{forward: } 2.5 < y^* < 4 \\ \text{backward: } -4 < y^* < -2.5 \end{array}$$

- **prompt  $J/\psi$ ,  $\Psi(2S)$** : strong suppression in forward  
 → strong CNM effect  
 → prompt  $\Psi(2S)$  more suppressed than  $J/\psi$
- **$J/\psi$ ,  $\Psi(2S)$  from  $b$** : small suppression in forward  
 → first indication of suppression of  $b$  hadron production  
 → agreement with predictions in forward region
- compatible suppression between  **$Y(1S)$**  and  $b$  hadrons

## prompt $J/\psi$ , $\Psi(2S)$



## $J/\psi$ , $\Psi(2S)$ from $b$



**Models:** EPS09LO (CSM): PRC88 (2013) 047901; NPA 926 (2014) 236, EPS09LNO (shadowing + CEM): IJMP E22 (2013) 1330007, Energy Loss: JHEP 03 (2013) 122; JHEP 05 (2013) 155, nDSg LO: PRC88 (2013) 047901



# Two particle angular correlations

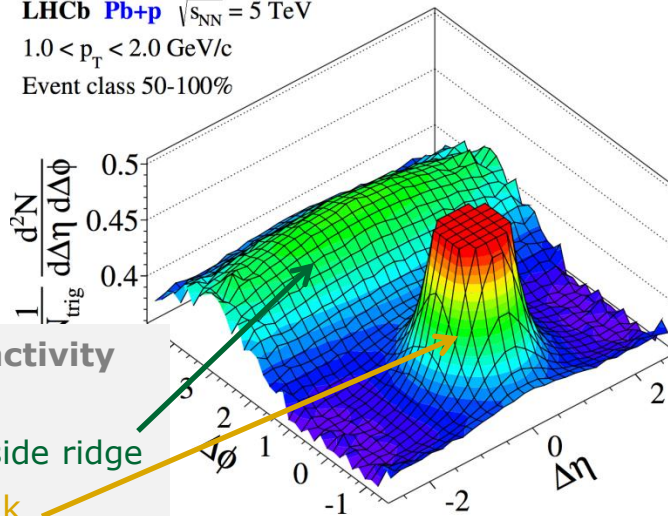
[arXiv:1512.00439]



## Two-particle angular ( $\Delta\eta, \Delta\phi$ )-correlations of prompt charged particles

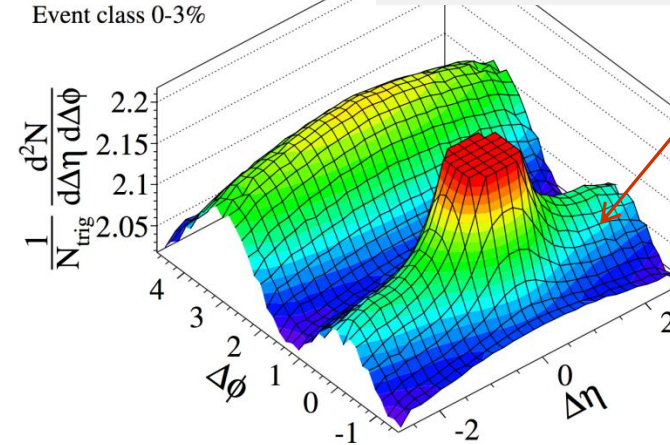
- long-range correlations on the near side (*ridge*) already reported by RHIC in *PbPb*, and ATLAS, CMS, ALICE in *PbPb*, *pp* and *p-Pb* collisions at central rapidities ( $\eta < 2.5$ )
- **LHCb result at 5 TeV in *p-Pb* ( $\sim 0.5 \text{ nb}^{-1}$ ) and *Pb-p* ( $\sim 0.3 \text{ nb}^{-1}$ ) at large rapidities**
  - kinematic range:  $p > 2 \text{ GeV}$ ,  $p_T > 150 \text{ MeV}$ ,  $2.0 < \eta < 4.9$
  - different  $p_T$  regions and activity classes

LHCb **Pb+p**  $\sqrt{s_{NN}} = 5 \text{ TeV}$   
 $1.0 < p_T < 2.0 \text{ GeV}/c$   
 Event class 50-100%



**Low event-activity**  
 (50-100%)  
 $\Delta\phi = \pi$  away-side ridge  
 $\Delta\phi = 0$  jet peak

LHCb **Pb+p**  $\sqrt{s_{NN}} = 5 \text{ TeV}$   
 $1.0 < p_T < 2.0 \text{ GeV}/c$   
 Event class 0-3%



**High event-activity (0-3%)**  
 $\Delta\phi = \pi$  away-side ridge  
 $\Delta\phi = 0$  jet peak + near side ridge

- correlation function described as a per-trigger particle associated yield
- event-mixed reference sample

# Ridge evolution

## Projection of the correlation function on $\Delta\phi$

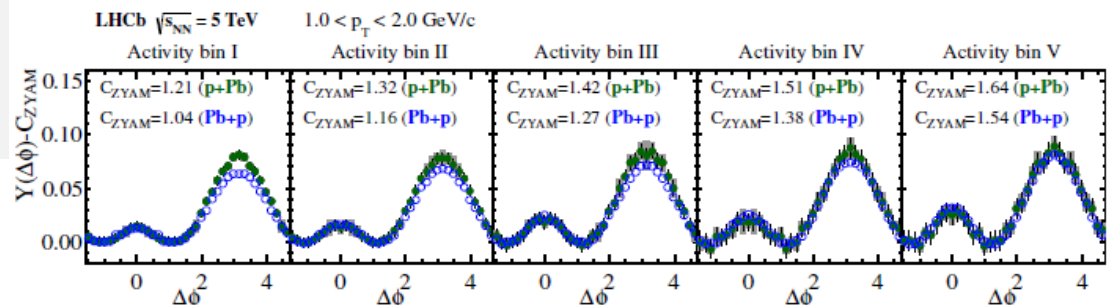
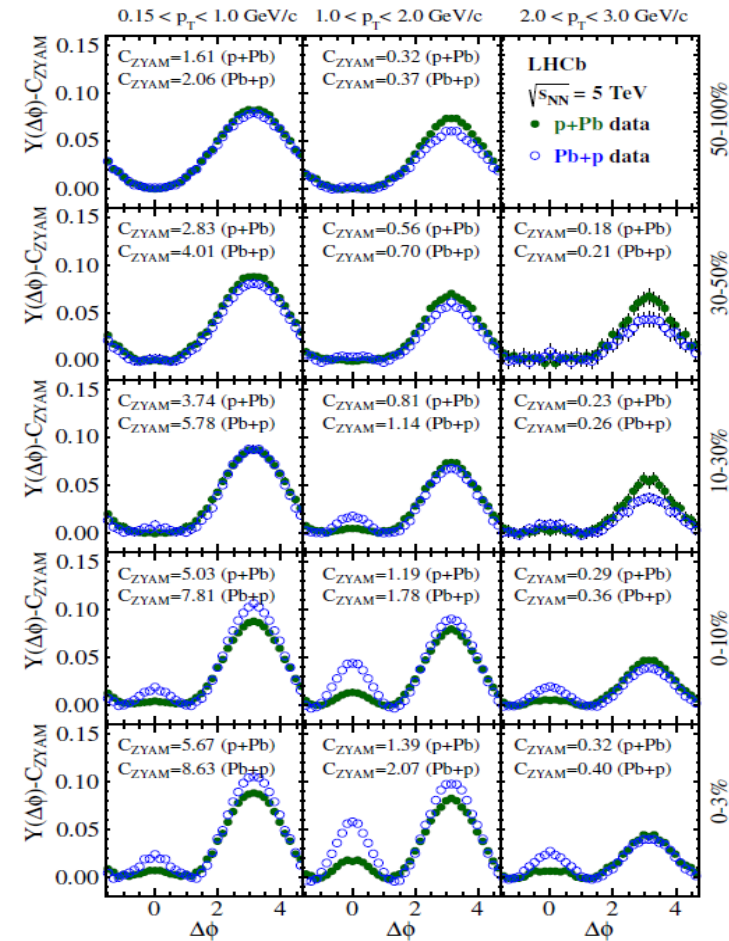
→  $2 < |\eta| < 2.9$  (exclude jet peak)

→ subtract zero-yield-at-minimum (ZYAM)

- correlation yield increases with event activity
- away-side ridge decreases for higher  $p_T$
- near side ridge more pronounced in Pb-p than in p-Pb  
→ larger event activity in backward configuration

### Common absolute activity ranges

- 5 identical activity ranges for p-Pb and Pb-p
- away-side and near-side ridge depends only on activity in the direction of measurement
- near-side correlation yields compatible for both configurations





**Fixed target**

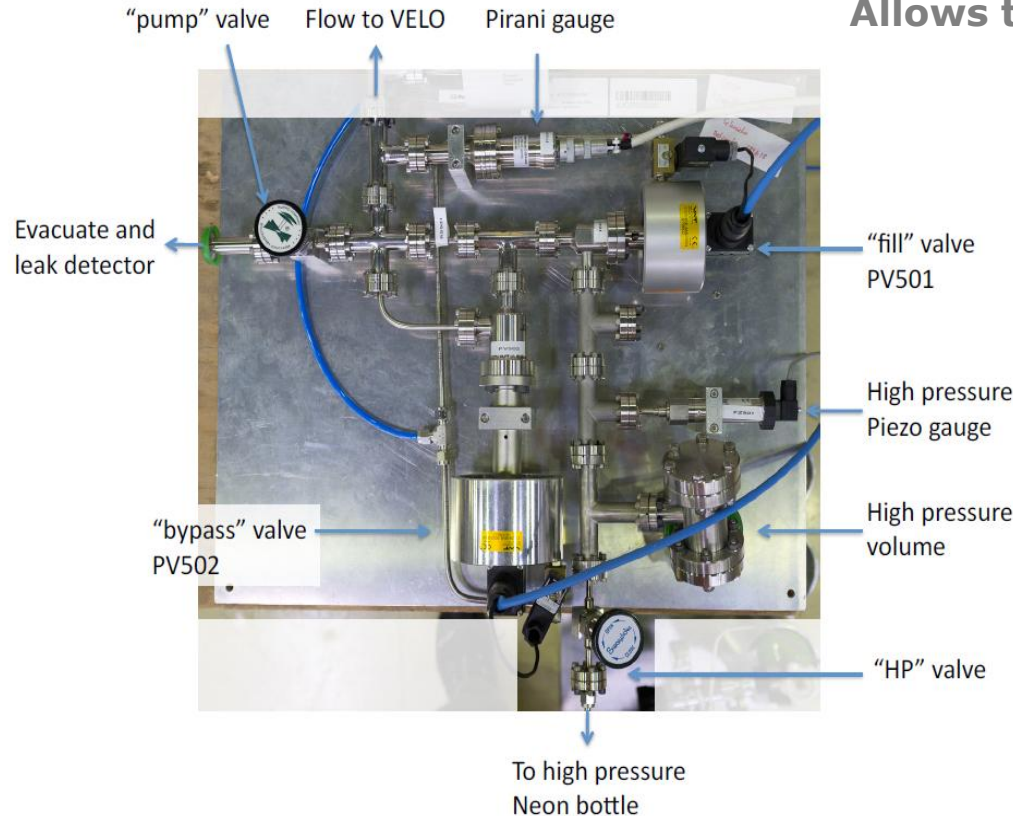
# Fixed target at LHCb

[JINST 7 (2012) P01010]



## SMOG: System for Measuring Overlap with Gas

Allows to study p/Pb - Gas at different energies



| $E_{\text{beam}}(p)$ | p-GAS   | Pb-GAS |
|----------------------|---------|--------|
| 450 GeV              |         |        |
| 1.38 TeV             |         |        |
| 2.5 TeV              | 69 GeV  |        |
| 3.5 TeV              |         |        |
| 4.0 TeV              | 87 GeV  | 54 GeV |
| 6.5 TeV              | 110 GeV | 69 GeV |
| 7.0 TeV              | 115 GeV | 72 GeV |

### Preferred targets

| element | He | Ne | Ar | Kr | Xe  |
|---------|----|----|----|----|-----|
| A       | 2  | 20 | 40 | 84 | 131 |

- injection of (Ne) gas into collision region (VELO) with SMOG system
- designed to improve luminosity measurement with beam-gas imaging method
- LHCb: backward direction in nucleon-nucleon center-of-mass

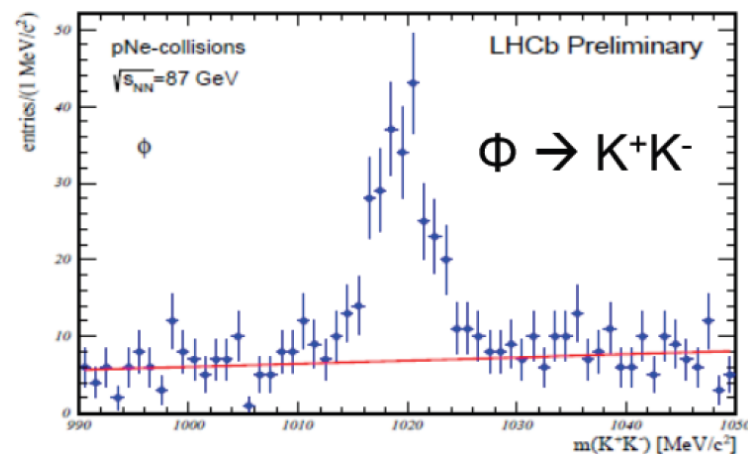
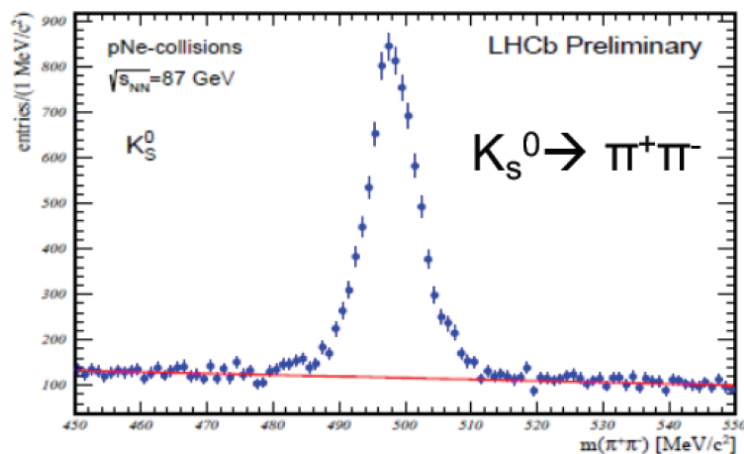
# Strangeness production

[LHCb-CONF-2012-034]

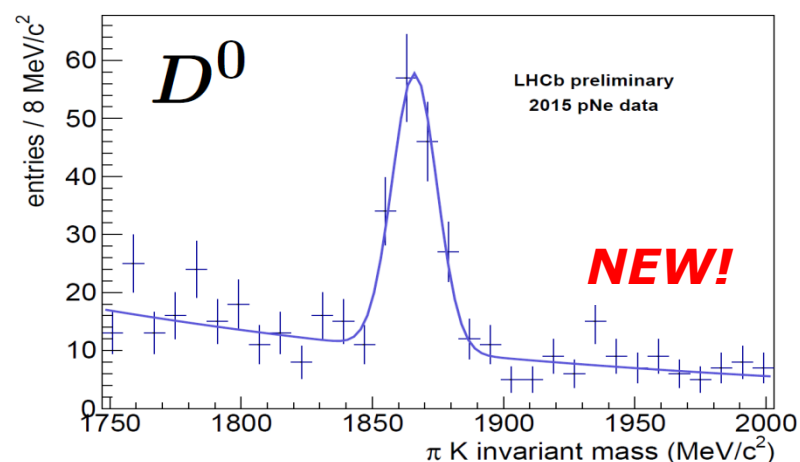
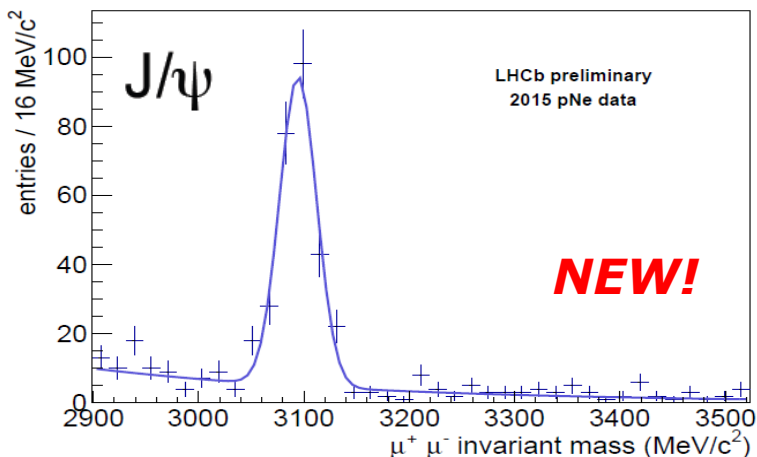


p-Ne collisions at  $\sqrt{s_{NN}} = 87$  GeV (2012 pilot run)

→ rate sufficient to measure light quark and strangeness production



Results from p-Ne at  $\sqrt{s_{NN}} = 110$  GeV from end of August 2015

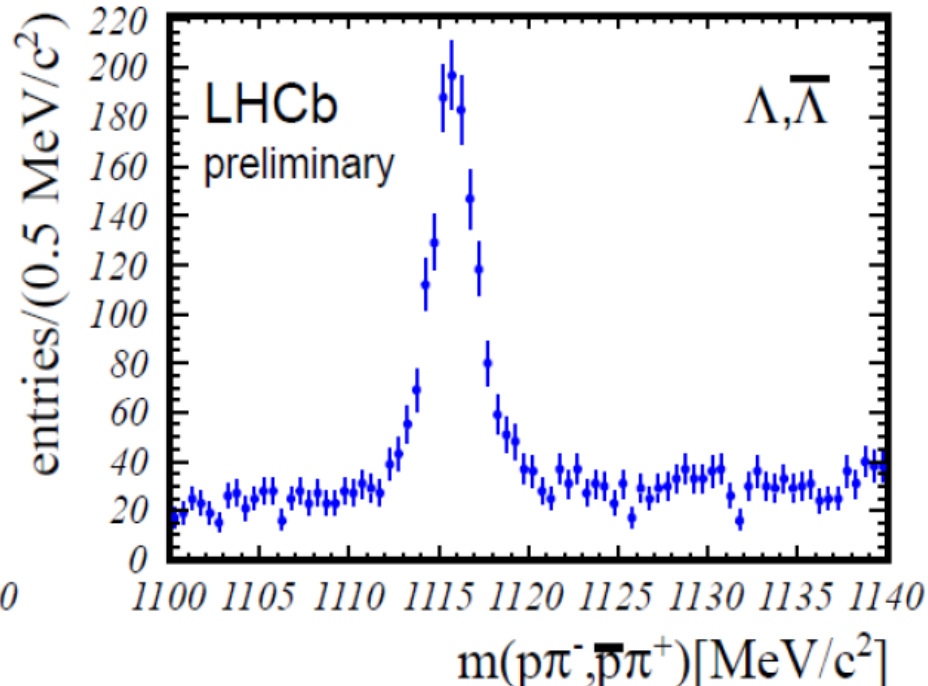
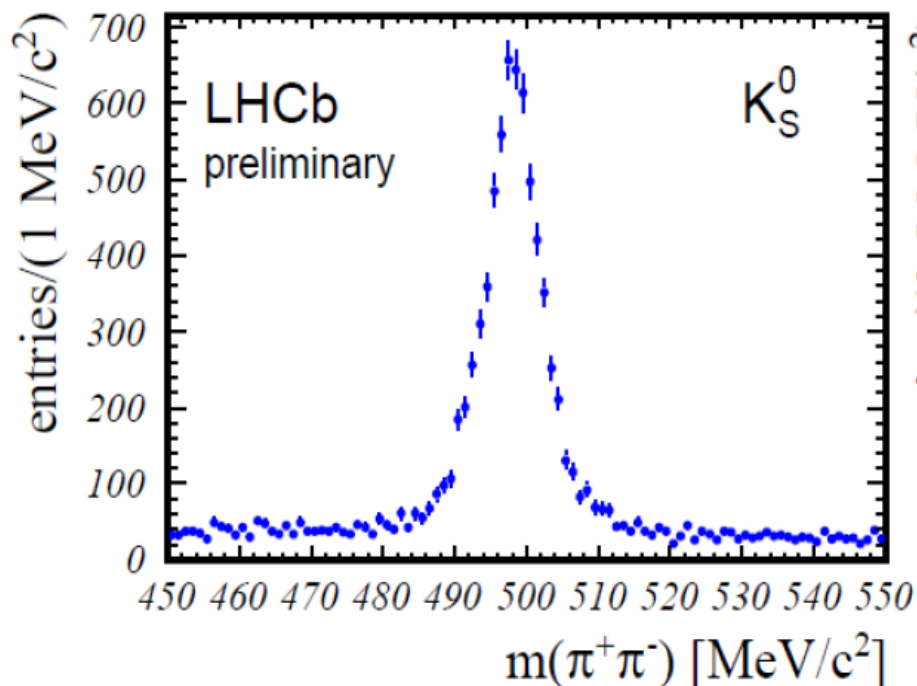


# Pb-Ne fixed target interactions

[LHCb-CONF-2012-034]



Pb-Ne collisions at  $\sqrt{s_{NN}} = 54.4$  GeV ( $\sim 30$  min. run in 2012)



LHCb also collected PbPb and Pb-Ar data in 2015

→ more expected in the next years

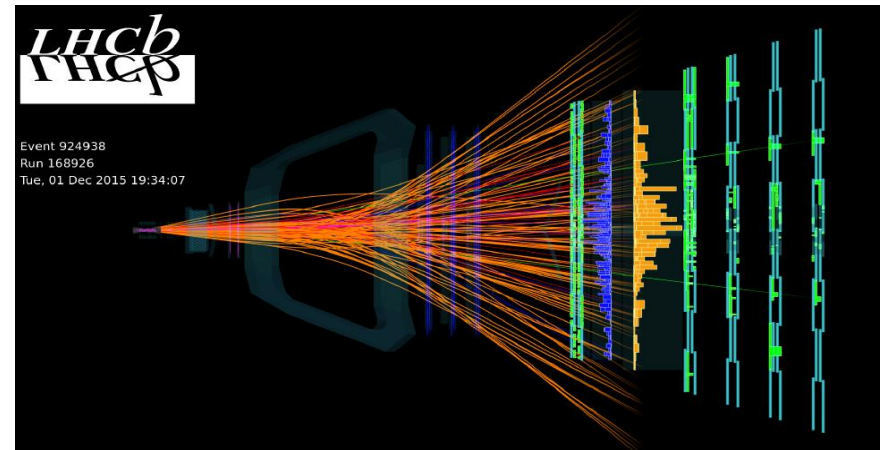
# Most recent LHCb results on heavy ion

Most recent results have appeared few days ago!

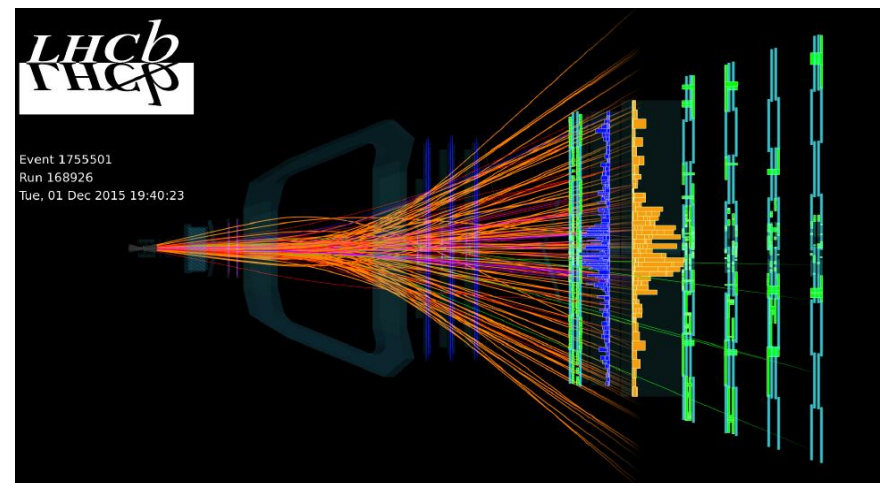
<https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015>, <https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016>

## Pb-Pb collisions at $\sqrt{s_{NN}} = 5$ TeV in 2015

Pb-Pb event display with  $J/\psi$  candidate



Pb-Pb event display with large number of reconstructed tracks (1130) and with a  $J/\psi$  candidate



## **LHCb: general purpose forward experiment**

- successfully participated in proton-lead runs
- contribute to heavy ion studies in a unique kinematic range

## **Measurement of $D^0$ , $J/\psi$ , $\psi(2S)$ , $Z$ and $Y$ production, particle correlations + *ongoing studies***

- cold nuclear matter effects visible in  $J/\psi$ ,  $\psi(2S)$ ,  $Y(1S)$  and  $D^0$  production
- long-range correlations on the near-side (*the ridge*) observed for the first time in the forward region
- statistically limited - *more data expected from Run II*

## **LHCb is unique for fixed target physics**

- exploiting the SMOG system with different noble gases at different energies
- bridge the gap from SPS to LHC physics with a single experiment

## **LHCb collected PbPb data in 2015**

- rich program in heavy flavour physics, EW, (soft)QCD and QGP - *ongoing!*