

# Heavy Ion Physics at LHCb

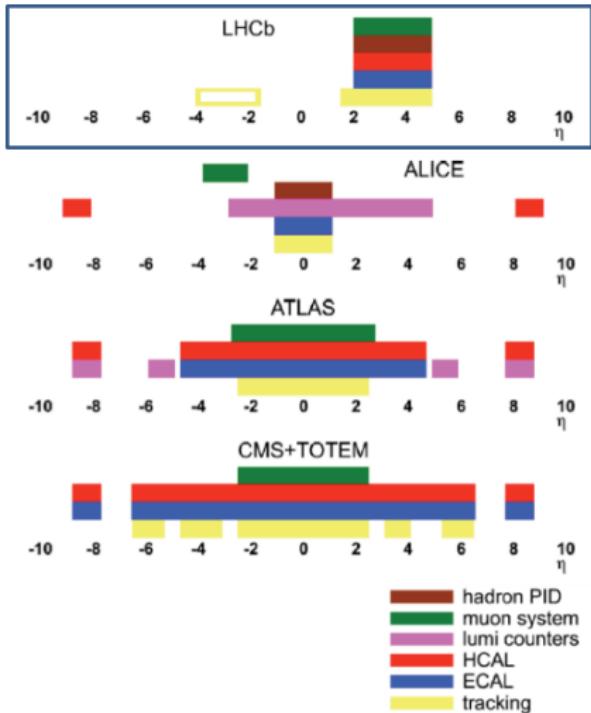
J. Blouw, on behalf of the LHCb collaboration

Max-Planck-Institut für Kernphysik, Heidelberg

XXX-th International Workshop on High Energy Physics: Particle and Astroparticle Physics, Gravitation and Cosmology: Predictions, Observations and New Projects

- Motivation
- The LHCb spectrometer
- Beam Configurations
- Analysis strategy for  $J/\Psi$  &  $\Upsilon$  reconstruction
- Measurement of  $J/\Psi$  &  $\Upsilon$  cross sections
- Determination of nuclear modification for  $J/\Psi$  &  $\Upsilon$
- Calculation of forward-backward asymmetries
- Conclusions & Outlook

- Study multi-parton interactions
- Soft QCD, low- $x$
- Particle yield ratios for testing hadronization models
- Study of proton-ion collisions with LHCb accesses unique kinematic region
- Constraint nuclear PDF(s) at large  $x$  and  $x \approx 5 \cdot 10^{-6}$



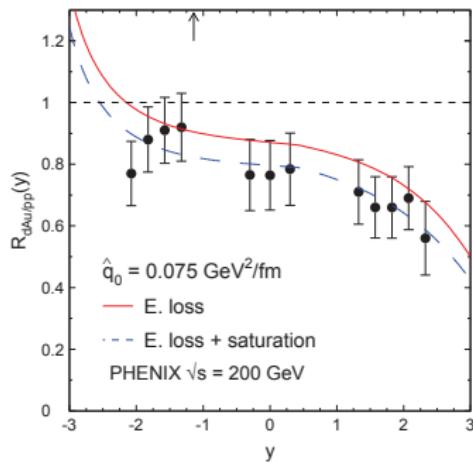
## Focus on:

- $J/\Psi, \ Upsilon \rightarrow \mu^+ \mu^-$ 
  - Cold-nuclear effects (decouple cold-nuclear matter from quark-gluon plasma effects)
  - Soft QCD; energy-loss vs. saturation
  - Useful as reference for ion-ion collision analyses
  - $\Upsilon(1S, 2S, 3S)$  survive higher temperatures in QGP than  $J/\Psi$
  - Production ratios probe sequential dissociation of  $b\bar{b}$  pairs
  - Determine sequential suppression of  $\Upsilon$  in cold nuclear matter
- $Z \rightarrow \mu^+ \mu^-$ 
  - nPDF's based on data from fixed-target experiments
  - $\Rightarrow$  no or little data available at  $Q^2 > 10 \text{ GeV}^2$ ,
  - $x \sim 1.0$  and
  - $x < 0.01$
- $2 < \eta_{\text{lab}} < 5$
- $x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$

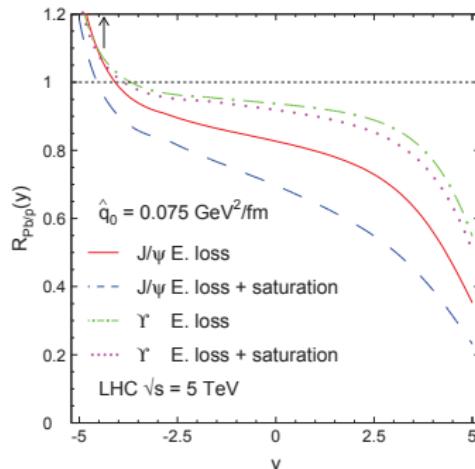
Nuclear modification factor:

$$R_{pA}(y, \sqrt{s}) = \frac{1}{A} \frac{\frac{d\sigma_{pA}(y, \sqrt{s})}{dy}}{\frac{d\sigma_{pp}(y, \sqrt{s})}{dy}}$$

From PHENIX data: heavy quarkonia suppressed at large rapidity:  
 (PRL 107, 2011, 142301)

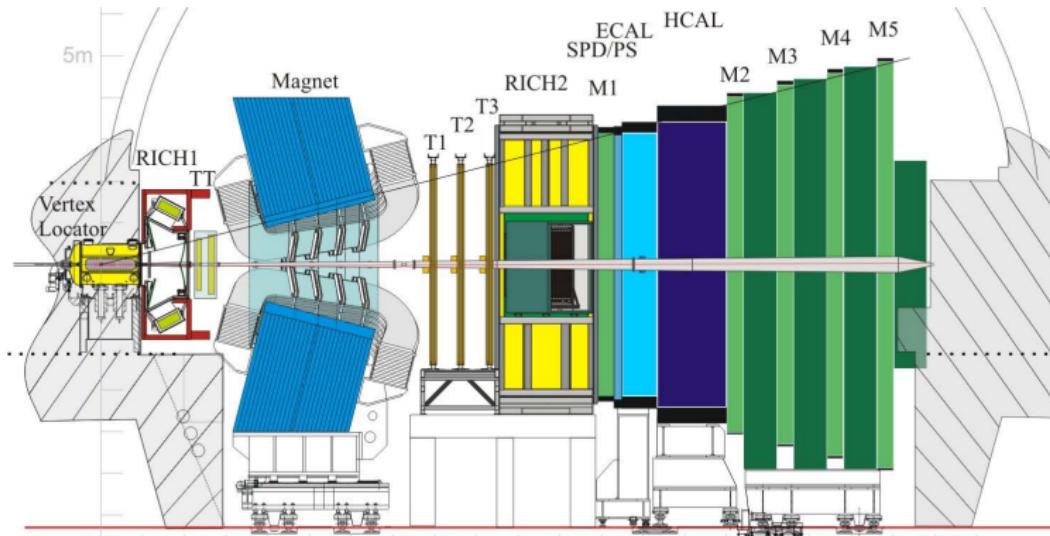


prediction for LHC energies (5 TeV)  
 from JHEP 1303(2013) 122



Theoretical calculations by Arleo & Payne

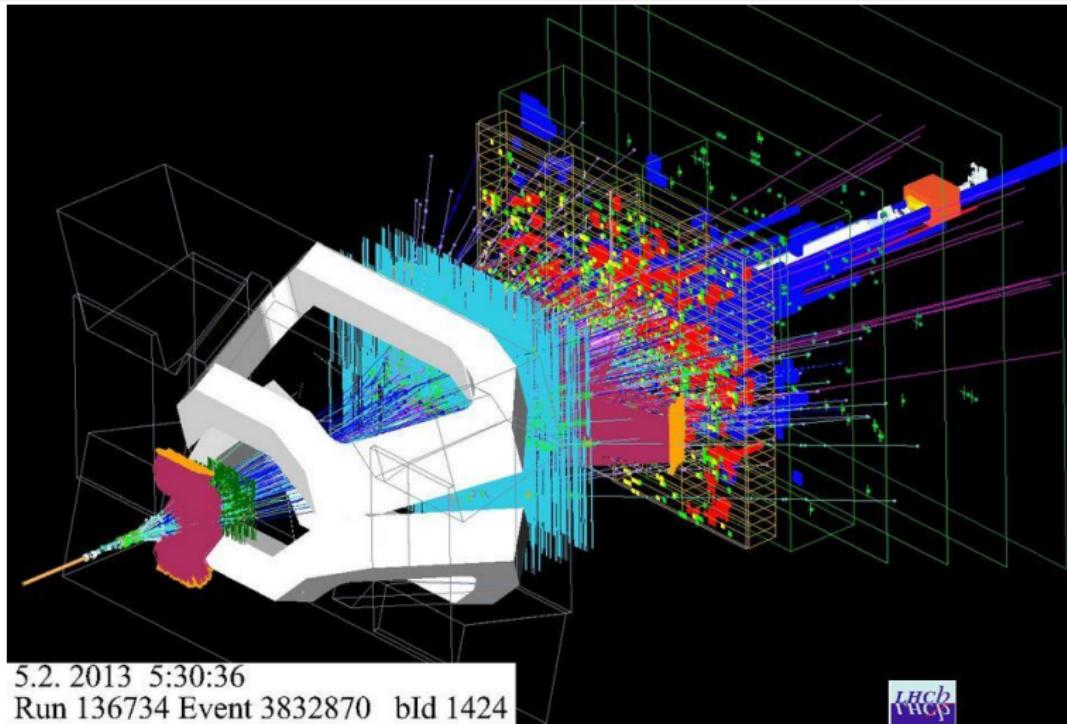
# LHCb Spectrometer



- Pseudo-rapidity:  $2 < \eta < 5$
- good IP measurement:  $\langle \delta\text{IP} \rangle = 20\mu\text{m}$  for  $p_T > 2 \text{ GeV}$ :
  - excellent vertex reconstruction to select e.g.  $J/\Psi$  mesons
  - separation of prompt from secondary  $J/\Psi$ 's
- $\mu$  ID efficiency:  $\sim 97\%$  for  $< 3\% \pi \rightarrow \mu$  mis-id probability from  $p = 2 - 100 \text{ GeV}$ 
  - reconstruct open charm
  - very useful for particle-yield ratios
  - $V_0$  reconstruction

# LHCb Spectrometer

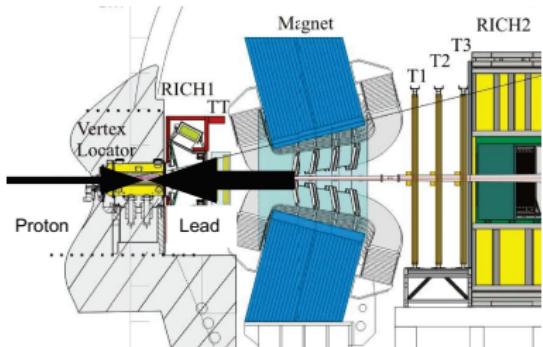
## Event characteristics



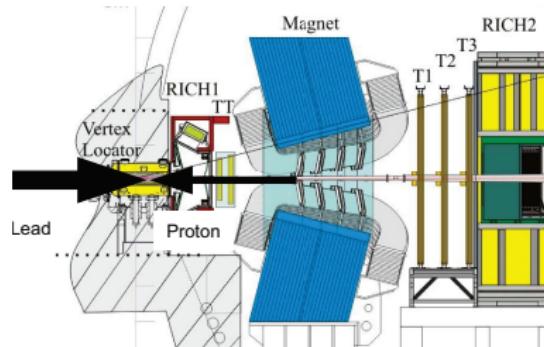
Typical pA collision in LHCb

# LHCb Spectrometer

## Event characteristics



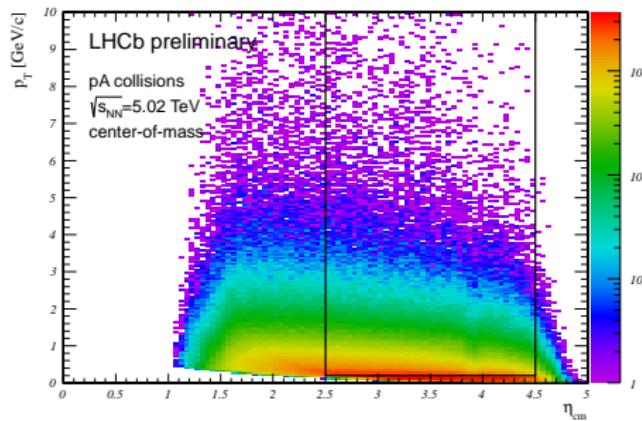
positive rapidity (protons on lead)  
forward



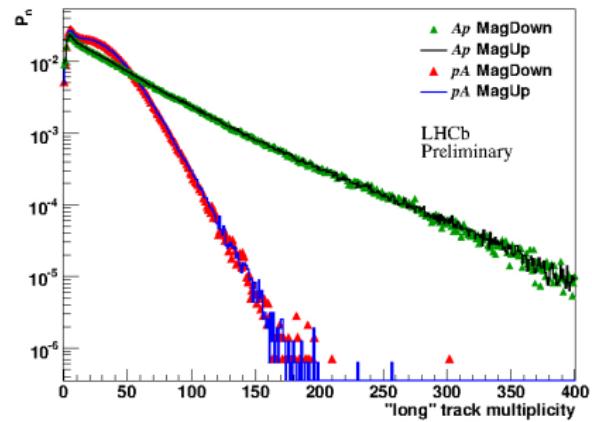
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# LHCb Spectrometer

## Event characteristics

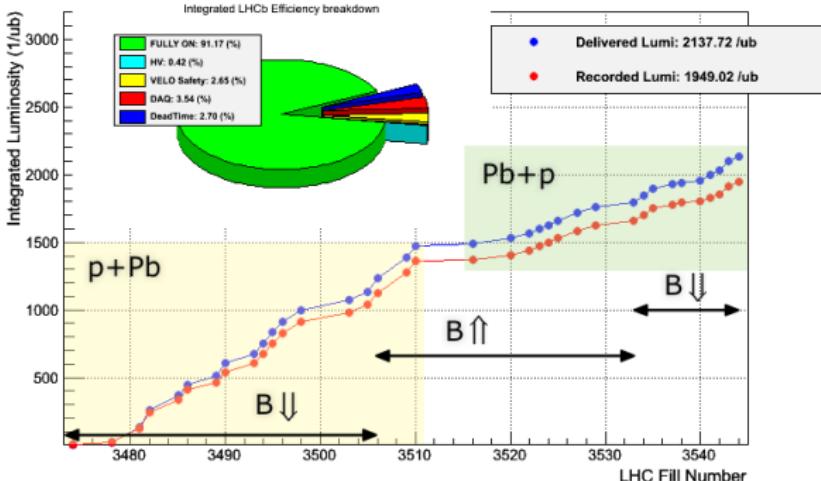


Pseudo-rapidity in LHCb for p-Pb collisions



Multiplicity distribution in pA collisions

## LHCb Integrated Luminosity at p-Pb 4 TeV in 2013



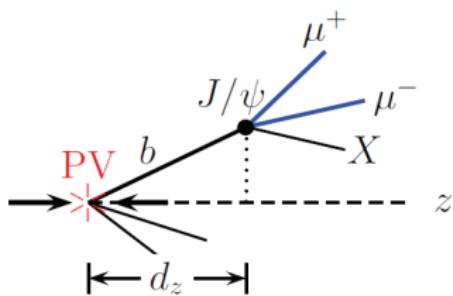
- low instantaneous luminosity:  $\mathcal{L} \approx 5 \times 10^{27} \text{ cm}^{-2} \text{s}^{-1}$
- low pile-up (approx. 1 primary vertex per interaction)
- data-taking efficiency better than 91%.
- results based on 2 beam configurations and 2 magnet configurations.

$$\text{forward : } \mathcal{L} = 1.1 \text{ nb}^{-1} \quad \text{backward : } \mathcal{L} = 0.5 \text{ nb}^{-1}$$

# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

## Analysis strategy

- reconstruct  $J/\Psi$  in p-Pb and Pb-p data
- separate prompt  $J/\Psi(\Upsilon)$ s from secondaries
- determine double-differential  $J/\Psi$  cross sections
- use total prompt  $J/\Psi(\Upsilon)$  cross section for nuclear modification
- determine forward-backward asymmetry in prompt  $J/\Psi(\Upsilon)$  production



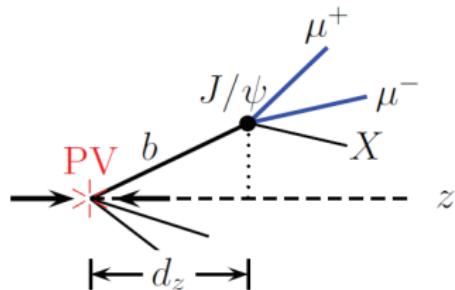
Pseudo-proper time:

$$t_z = \frac{(z_{J/\Psi} - z_{PV})M_{J/\Psi}}{p_z}$$

# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

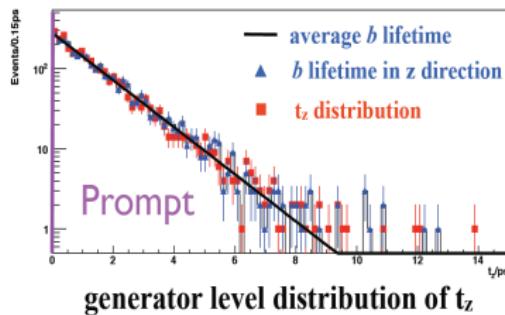
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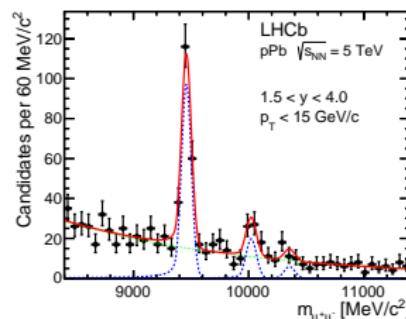
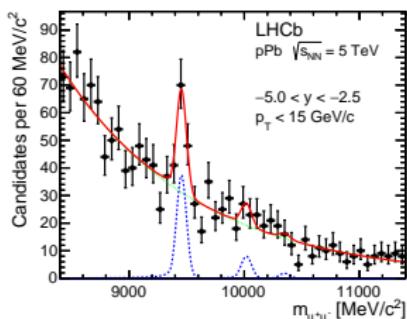
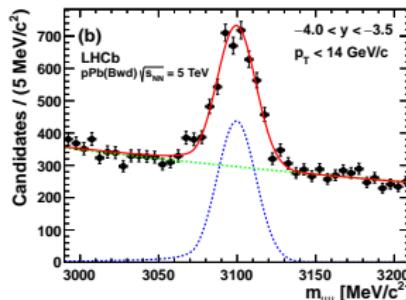
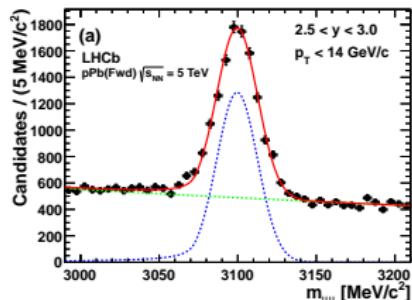
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# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

Mass- and pseudo-proper time fit

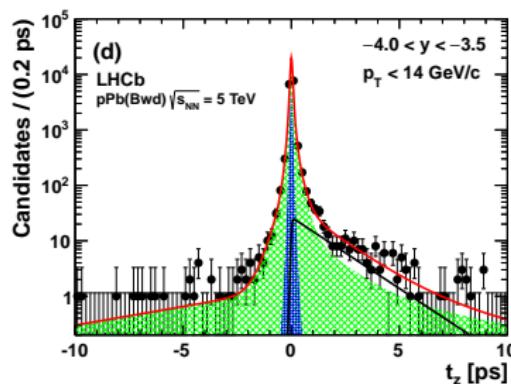
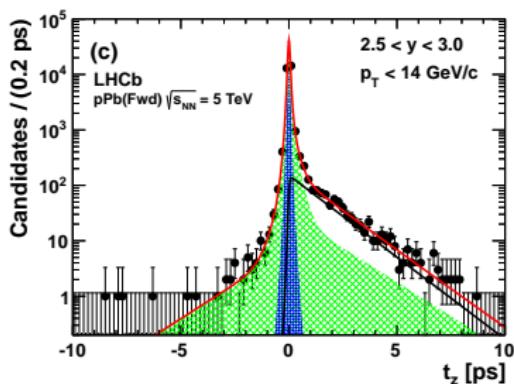
- determine yields by simultaneous mass & pseudo-proper time fit
- **mass model:** Crystal-Ball signal and exponential background



# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

Mass- and pseudo-proper time fit

- determine yields by simultaneous mass & pseudo-proper time fit
- mass model: Crystal-Ball signal and exponential background
- $t_z$  model: exponential for  $J/\Psi$ 's from b's
- convoluted with double Gaussian
- delta function for signal
- empirical function from side-band for background



Results from LHCb: JHEP 02 (2014) 072 (arXiv:1308.6729), arXiv:1405.5152

# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

$J/\Psi$  total and double-differential cross sections

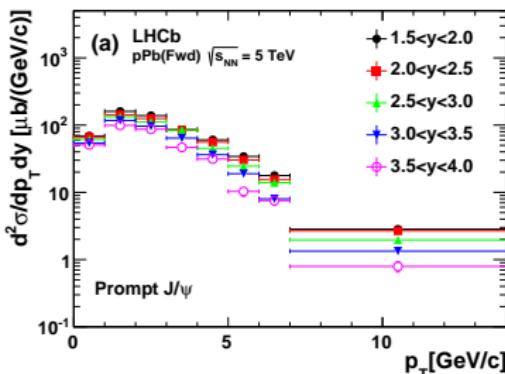
- pA:  $1.5 < y < 4.0$

pA prompt:

$$\sigma_{pA} = 1168 \pm 15 \text{ (stat)} \pm 60 \text{ (sys)} \mu\text{b}$$

pA from b's:

$$\sigma_{pA} = 166 \pm 4.1 \text{ (stat)} \pm 9.2 \text{ (sys)} \mu\text{b}$$



Prompt  $J/\Psi$

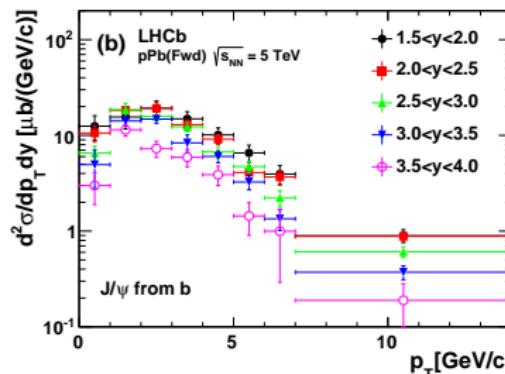
- Ap:  $-5.0 < y < -2.5$

Ap prompt:

$$\sigma_{Ap} = 1293 \pm 49.8 \text{ (stat)} \pm 82 \text{ (sys)} \mu\text{b}$$

Ap from b's:

$$\sigma_{Ap} = 118 \pm 6.8 \text{ (stat)} \pm 12.2 \text{ (sys)} \mu\text{b}$$



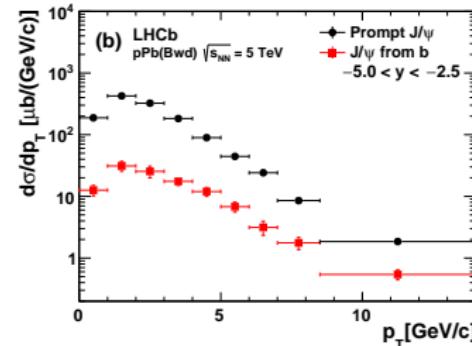
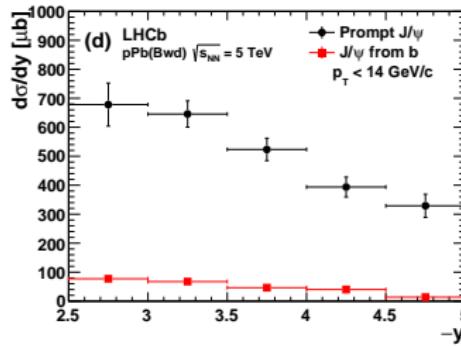
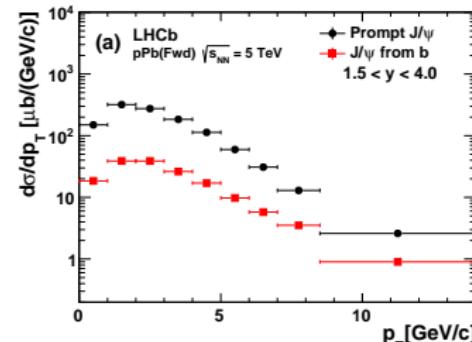
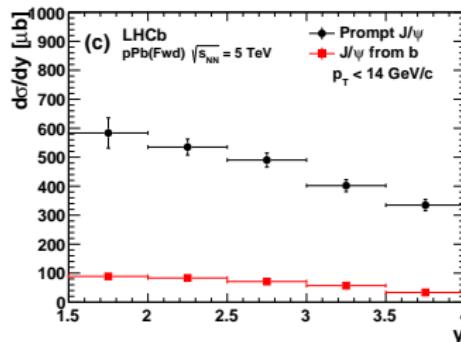
$J/\Psi$  from b's

- Dominated by systematics from luminosity (3%), fit model and data-MC agreement

# $J/\Psi$ & $\Upsilon$ production in p-Pb collisions

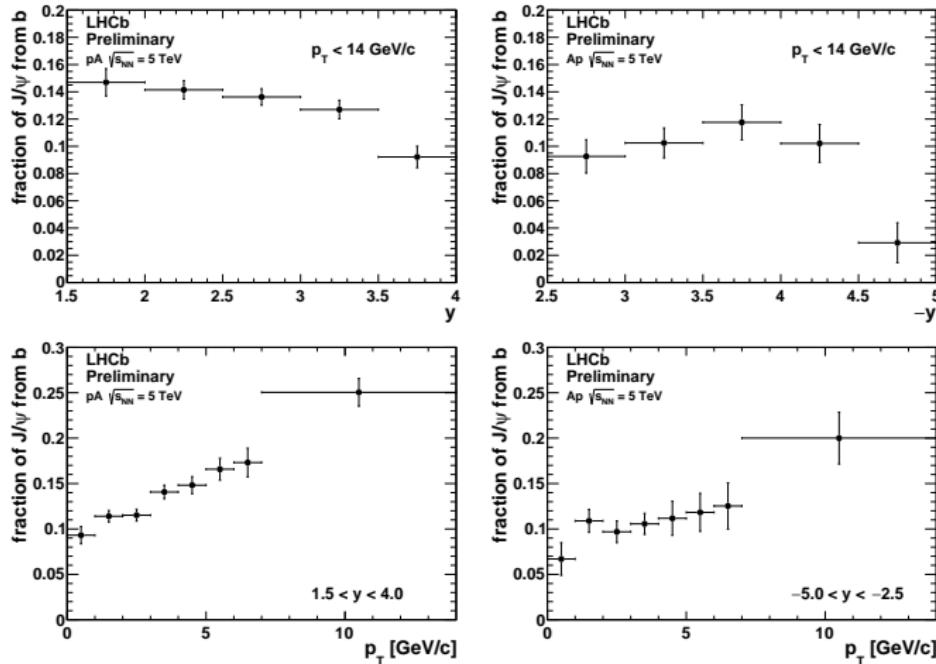
$J/\Psi$  single-differential cross sections

$J/\Psi$  production suppressed at large rapidity



# $J/\Psi$ from b's

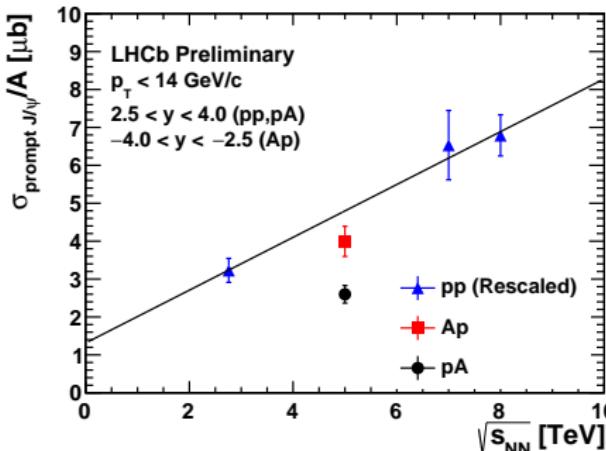
Fraction of  $J/\Psi$  from b-quarks:



From: LHCb-CONF-2013-008

# Prompt $J/\Psi$ cross sections at LHCb

Comparison of prompt  $J/\Psi$  production in p-p, p-Pb and Pb-p:



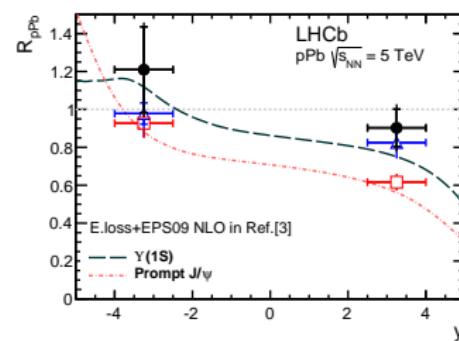
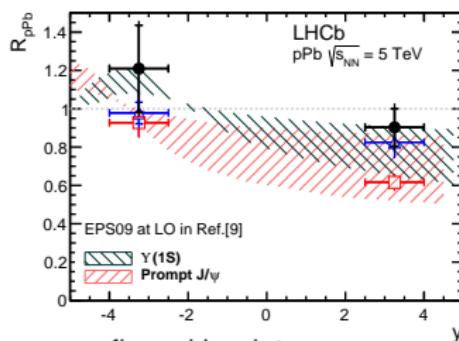
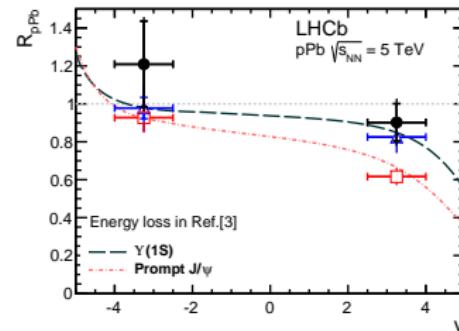
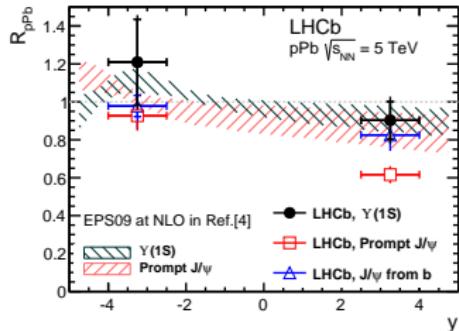
- re-scale  $\sigma_{\text{pp}}$  to common rapidity range
- scale  $J/\Psi$  cross section by  $\frac{1}{A}$
- perform linear interpolation between  $\sigma_{\text{pp}}$  cross sections
- obtain  $\sigma_{\text{pp}} @ \sqrt{s_{\text{NN}}} = 5 \text{ TeV}$

Total prompt  $J/\Psi$  cross section

- clear observation of  $J/\Psi$  suppression in pA and Ap
- but Ap cross section only slightly suppressed

- $\sigma_{\text{pp}} @ 2.76 \text{ TeV}$ : JHEP 1302 (2013) 041  
(arXiv:1212.1045)
- $\sigma_{\text{pp}} @ 7 \text{ TeV}$ : EPJ C71 (2011) 1645  
(arXiv:1103.0423)
- $\sigma_{\text{pp}} @ 8 \text{ TeV}$ : JHEP 06 (2013) 064  
(arXiv:1304.6977)

# Nuclear modification



Theory confirmed by data

$$R_{pA}(y, \sqrt{s}) = \frac{1}{A} \frac{\frac{d\sigma_{pA}(y, \sqrt{s})}{dy}}{\frac{d\sigma_{pp}(y, \sqrt{s})}{dy}}$$

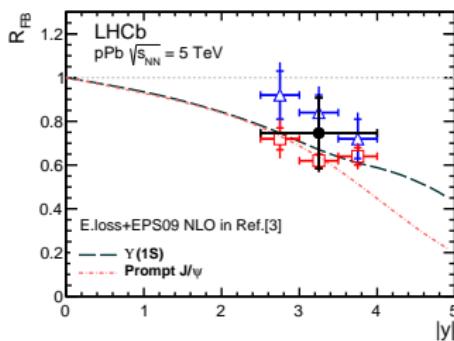
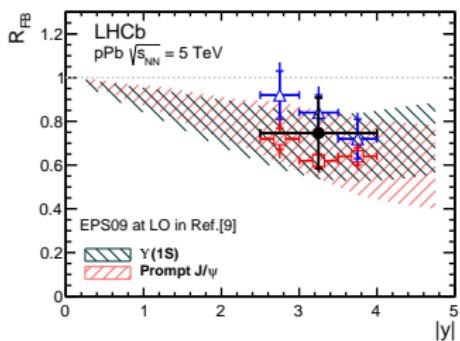
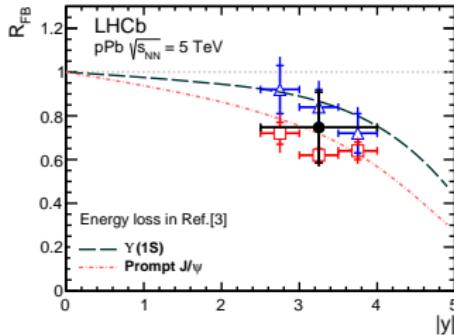
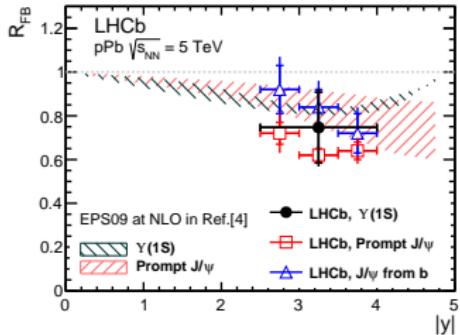
Results from JHEP 02 (2014) 072 (arXiv:1308.6729)

Predictions from IJM Phys. E 22 (2013) 1330007 (arXiv:1301.3395),

LAPTH-058/12 (arXiv:1212.0434), EPJC (2013) 73:2427 (arXiv:1110.5047)

# Forward-backward asymmetry

$$r_{\text{FB}} \equiv \frac{R_{\text{pA}}(y)}{R_{\text{Ap}}(-y)}$$

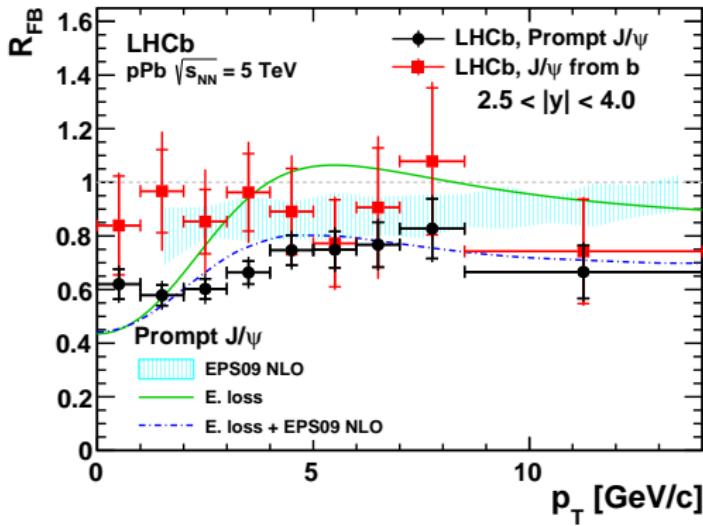


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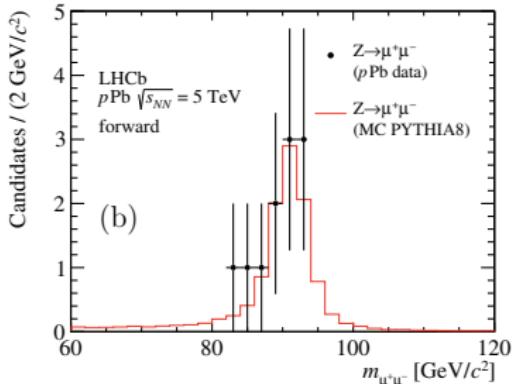
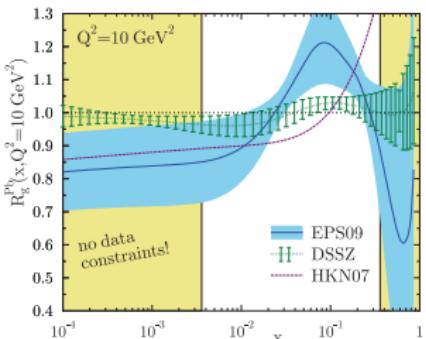
LAPTH-058/12 (arXiv:1212.0434), EPJC (2013) 73:2427 (arXiv:1110.5047)

Forward-backward asymmetry vs. transverse momentum:



Results from JHEP 02 (2014) 072 (arXiv:1308.6729),  
predictions from Albacete (PR. C88:047901(2013) (arXiv:1305.4569)),  
and Arleo *et al.* (JHEP 1305 (2013) 155 (arXiv:1304.0901))

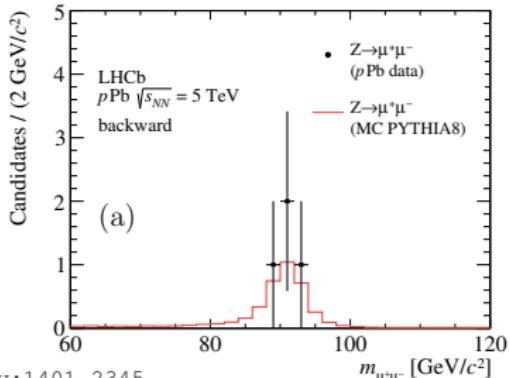
# Z-production in proton-lead collisions



- $Z \rightarrow \mu^+\mu^-$  reconstructed in pA & Ap data
- $1.10 \pm 0.02 \text{ fb}^{-1}$  pA (forward) data
- $0.52 \pm 0.01 \text{ fb}^{-1}$  Ap (backward) data
- pA:  $x_A \approx (0.2-3) \cdot 10^{-3}$
- Ap:  $x_A \approx 0.2-1.0$
- Apply track-multiplicity reweighting to get
  - Purity from  $Z \rightarrow \mu^+\mu^-$  from  $pp$  collisions
  - Efficiencies from  $Z$  candidates in  $pp$  collisions

Theoretical curves from: arXiv:1401.2345

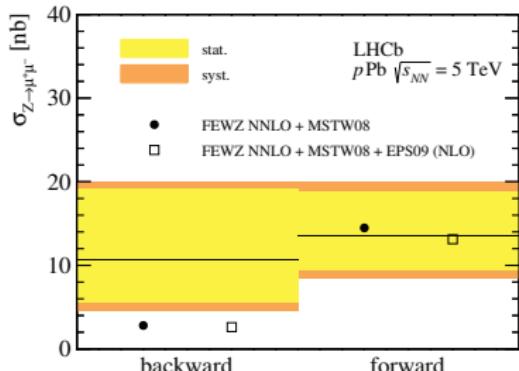
LHCb: arXiv:1406.2885



## Cross section measurements:

$$\sigma_{Z \rightarrow \mu^+ \mu^-} (\text{fwd}) = 13.5^{+5.4}_{-4.0} (\text{stat.}) \pm 1.2 (\text{sys}) \text{ nb}$$

$$\sigma_{Z \rightarrow \mu^+ \mu^-} (\text{bwd}) = 10.7^{+8.4}_{-5.1} (\text{stat.}) \pm 1.0 (\text{sys}) \text{ nb}$$



Compare to:

- NNLO calculations (Lie & Petriello: PRD 86 (2012) 094034 (arXiv:1208.5967))
- Nuclear modification (EPS09) (Eskola, Paukkunen & Salgado PLB 675 (2009) 123 (arXiv:0902.4145))

- $\sim 1.7 \text{ nb}^{-1}$  recorded by LHCb in 2013 p-Pb & Pb-p runs
- unique kinematic reach complements other experiments
- important for understanding of heavy ion physics
- probe specific QCD phenomena

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- probe specific QCD phenomena
- Measurement of (prompt)  $J/\Psi$  and  $\Upsilon$  cross sections in  $(y, p_T)$  at  $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$
- Nuclear modification determined, using interpolated LHCb  $\sigma$ 's to  $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$
- Nuclear modification in p-Pb collisions in agreement with theoretical predictions
- Forward-backward asymmetry as function of rapidity; agrees with theory
- First observation of  $Z$  production in proton-lead collisions