Results in proton-nucleus collisions at LHCb

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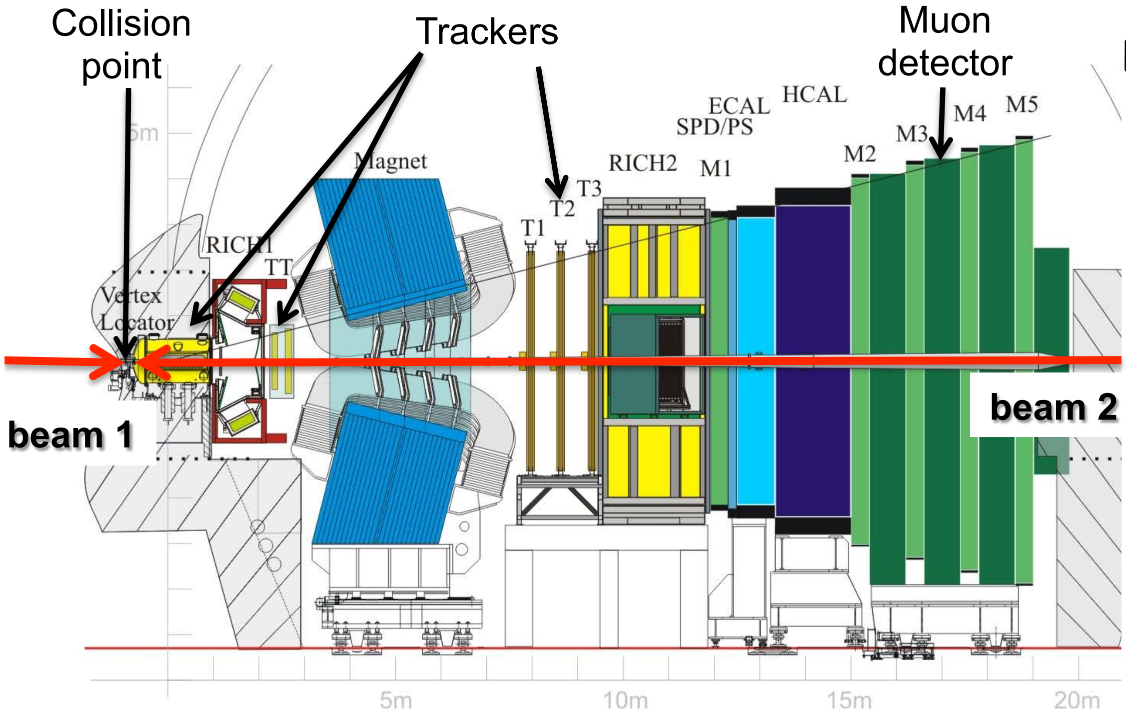
Introduction

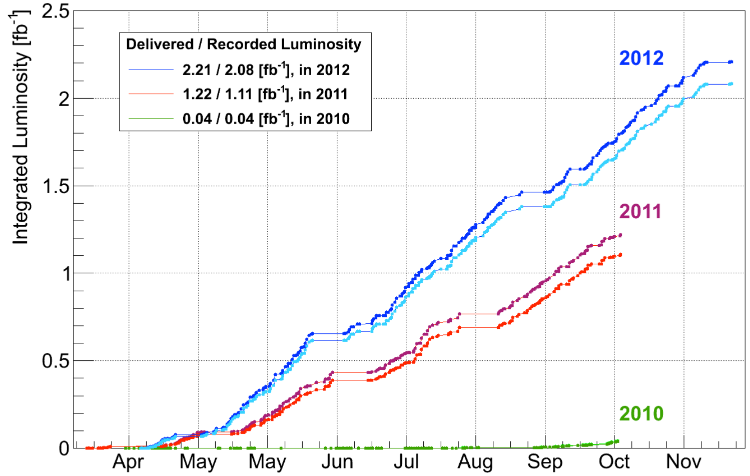
- LHCb detector has already shown excellent performances for studies of resonances production in *pp* collisions
- Many studies in $\mu\mu$ final states: J/ψ, $\psi(2S)$, $\Upsilon(nS)$ production, J/ψ and $\psi(2S)$ polarisation, ...
- Quarkonium = powerful probe of Quark-Gluon Plasma (QGP):
  - Suppression of quarkonium in hot medium formed by collisions with high energy densities (PbPb)
  - Other mechanisms in normal « cold » nuclear matter can also lead to quarkonium suppression
  - Study of quarkonium production in *p*A collisions necessary to characterise cold nuclear matter effects
- LHCb joined this effort in 2013, taking data with *p*Pb and Pb*p* collisions at the LHC

LHC and LHCb



LHC pp collider : 2010-2013 at LHCb

- ➡ @ $\sqrt{s}$ = 2.76, 7, 8 TeV
- ➡ Tot L ≈3 fb^{-1}

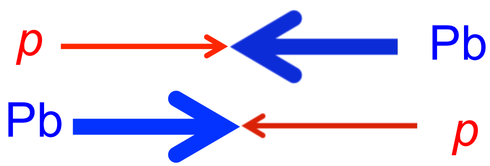


- Acceptance in pp : 2 < η < 5 (partial overlap with Alice)

In the nucleon-nucleon center-of-mass frame: two different rapidity ranges (w.r.t. the proton beam) covered :

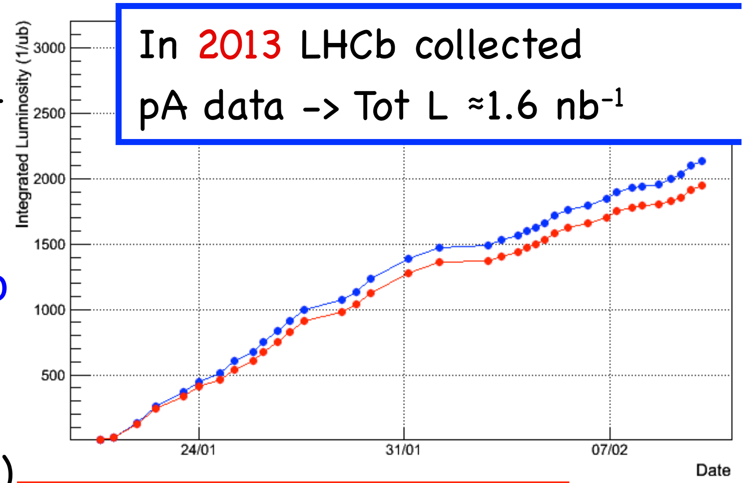
Forward: 1.5 < y < 4.0: 1.1 nb^{-1}

Backward: -5.0 < y < -2.5: 0.5 nb^{-1}



- **Centre of mass energy $\sqrt{s_{NN}}$=5 TeV** (p:4 TeV, Pb: 1.58 TeV)

LHCb Integrated Luminosity at p-Pb 4 TeV in 2013



In 2013 LHCb collected pA data -> Tot L ≈1.6 nb^{-1}

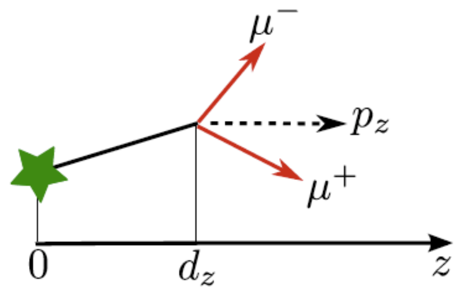
Uncertainty on Luminosity: 2-3.5% (JINST 7 (2012) P01010)

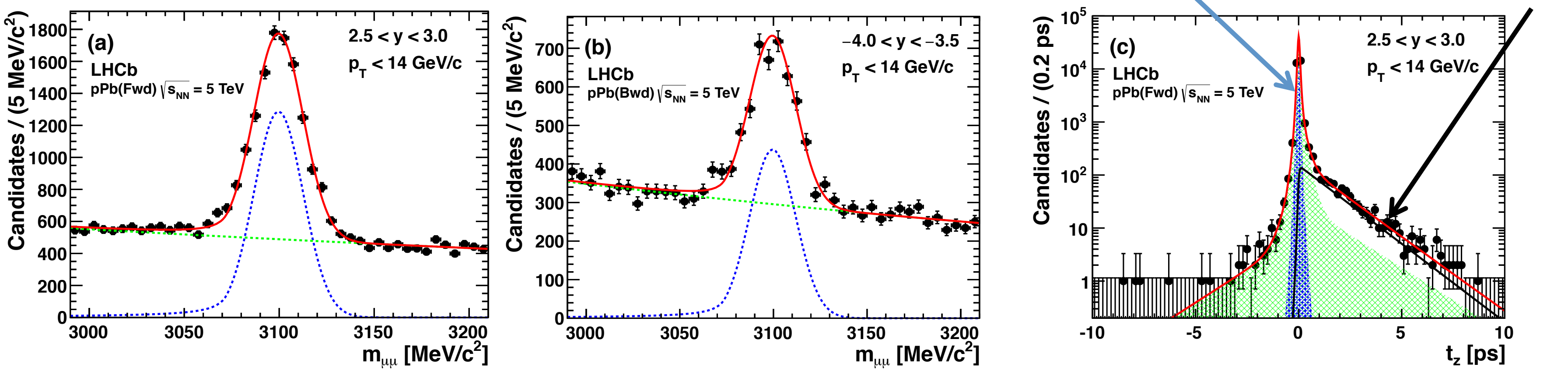
J/ψ production [JHEP 02 (2014) 072]

➡ Measured production cross-section using $J/\psi \to \mu^+\mu^-$:

- as a function of the p_T and rapidity of the J/ψ
- In the range : $p_T < 14$ GeV/c and $1.5 < y < 4.0$ or $-5.0 < y < -2.5$
- Separately for prompt J/ψ and J/ψ from *B* decays, using the J/ψ pseudo-propertime:

$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$

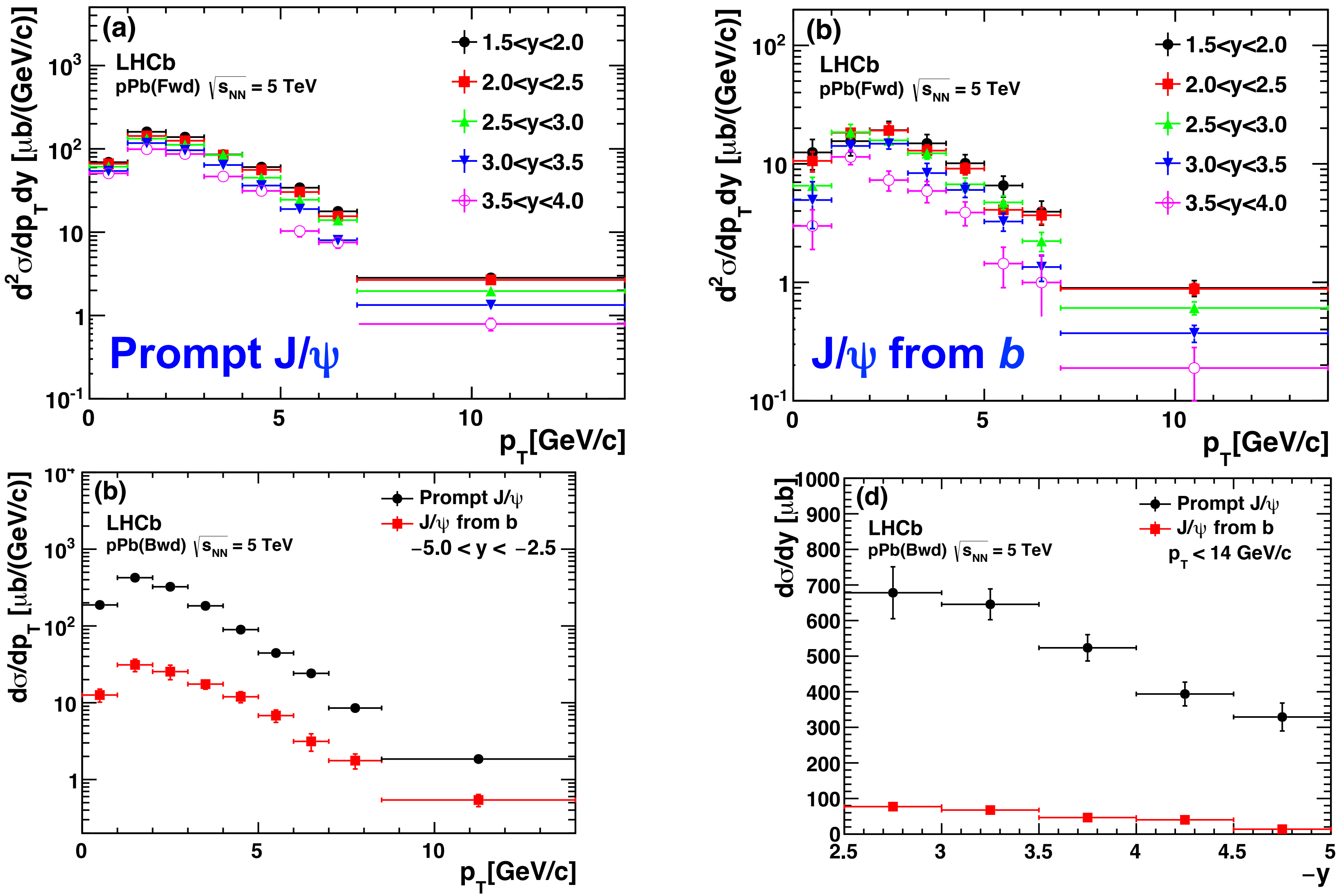




Cross section J/ψ : results

Forward

Backward



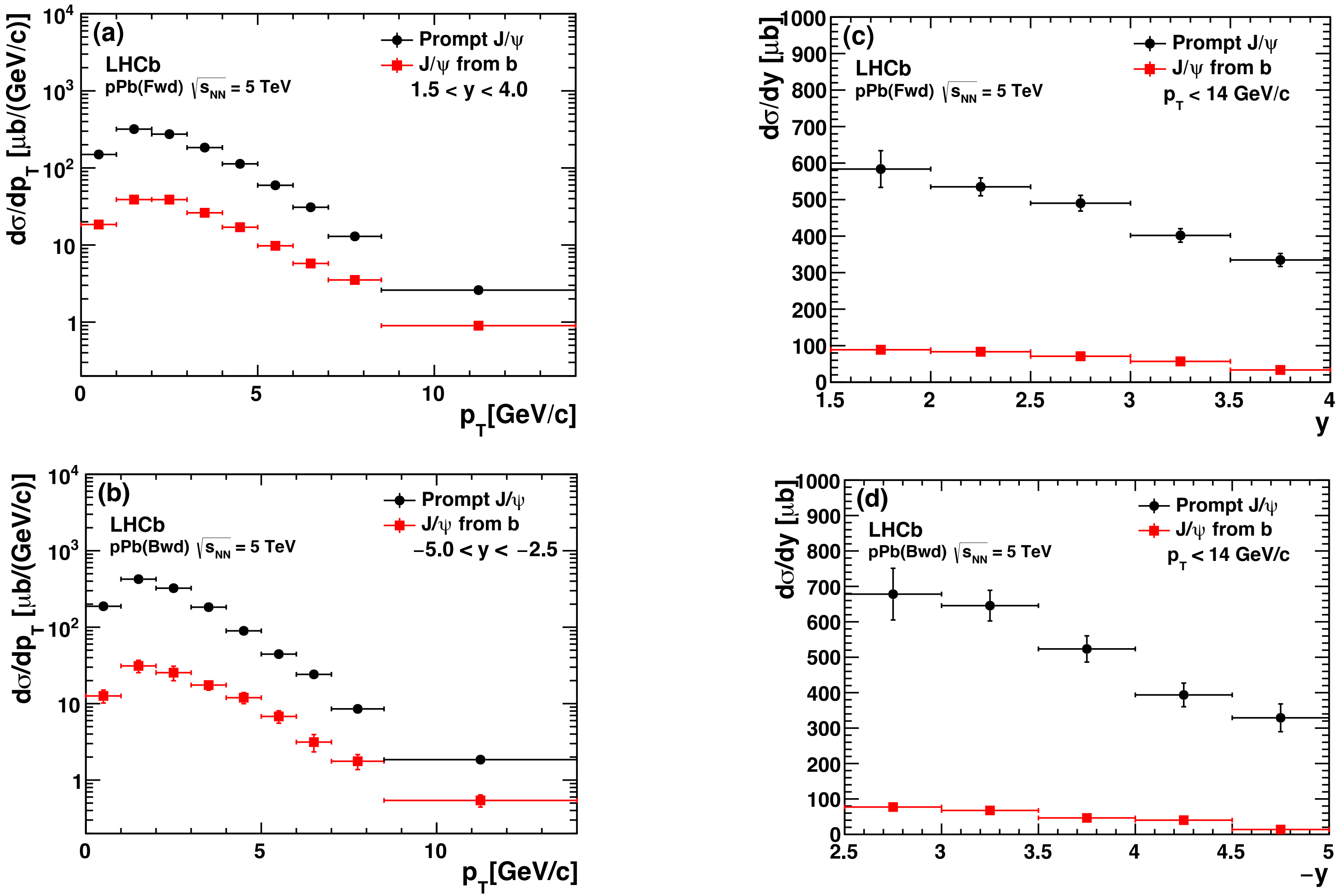
σ_F(prompt J/ψ,+1.5<y<+4.0) = 1168± 15± 54 μb
σ_B(prompt J/ψ,-2.5<y<-5.0) = 1293± 42± 75 μb

σ_F(J/ψ from B, +1.5<y<+4.0) = 166.0± 4.1± 8.2 μb
σ_B(J/ψ from B, -2.5<y<-5.0) = 118.2± 6.8± 11.7μb

Cross section J/ψ : results

Forward

Backward



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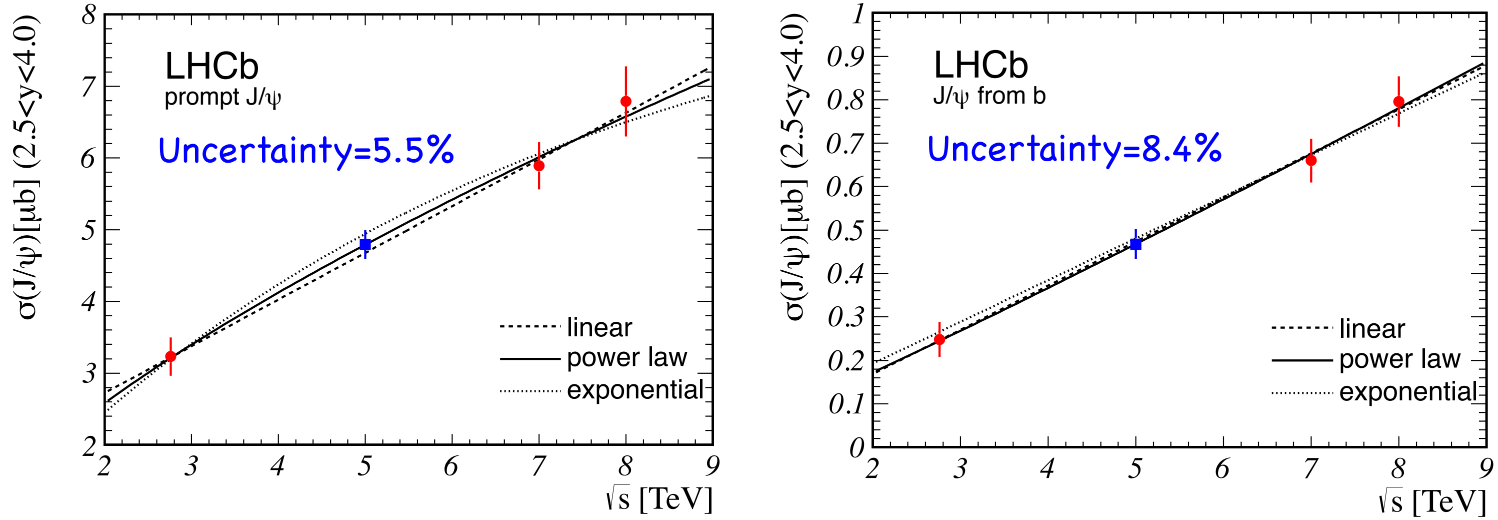
More J/ψ results [JHEP 02 (2014) 072]

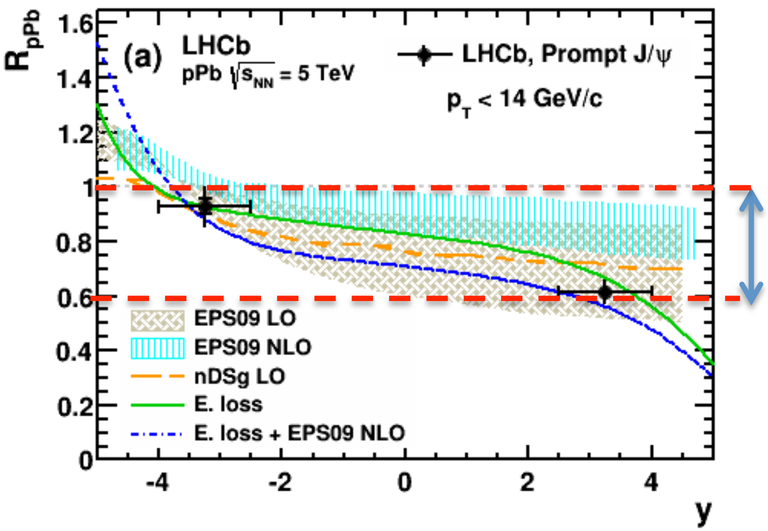
- Quantities important for Cold Nuclear Matter effects:
  - ***Nuclear modification factor*** $R_{pA}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{d^2\sigma_{pA}(y, p_T, \sqrt{s_{NN}})/dy dp_T}{d^2\sigma_{pp}(y, p_T, \sqrt{s_{NN}})/dy dp_T}$
    - 1 if a *pA* collision is superposition of A *pp* collisions
    - <1 in case of suppression due to the medium
  - ***Forward-backward production ratio*** $R_{FB}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{d^2\sigma_{pPb}(+|y|, p_T, \sqrt{s_{NN}})/dy dp_T}{d^2\sigma_{pPb}(-|y|, p_T, \sqrt{s_{NN}})/dy dp_T}$
- ***pp* cross-section at 5 TeV not measured directly:**
  - extrapolated from *pp* measurements at 2.76 TeV [JHEP 02 (2013) 041], 7 TeV [EPJC (2011) 71 1645] and 8 TeV [JHEP 06 (2013) 064].



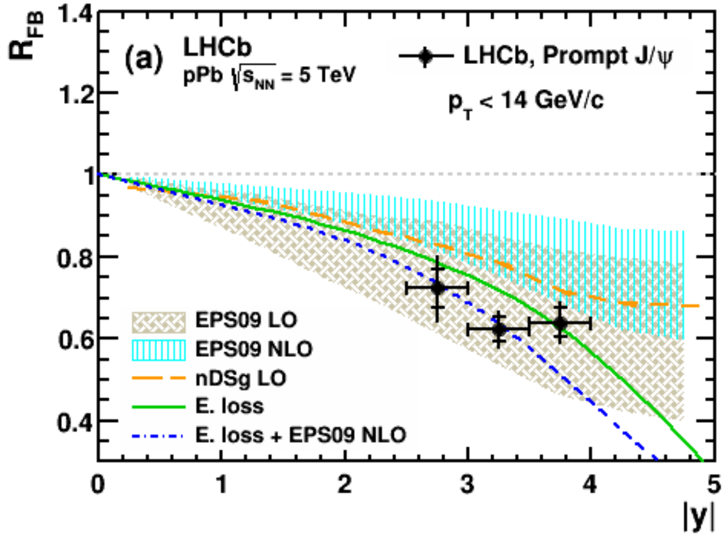
[LHCb-CONF-2013-013/ALICE-PUBLIC-2013-002]

Nuclear effects : prompt J/ψ [JHEP 02 (2014) 072]

Nuclear modification factor, integrated over p_T and y separately for forward and backward regions



Forward-backward ratio, integrated over p_T in 3 y bins



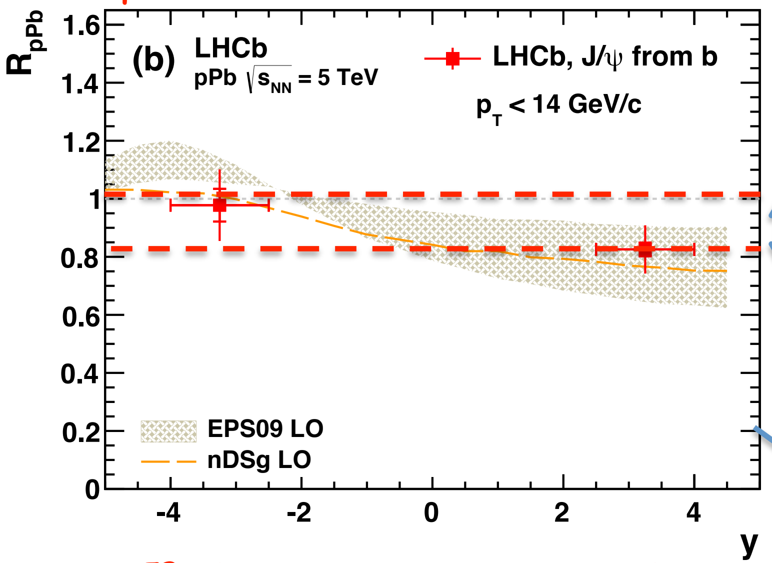
Compared with predictions from: [JHEP 0904 (2009) 65], [Int. J. Mod. Phys. E Vol. 22 (2013) 1330007], [JHEP 1305 (2013) 155]

- LO CSM or NLO CEM with nuclear PDF based on EPS09 or nDSg
- Coherent parton energy loss (initial and final) with or without shadowing (EPS09)

➢ *Significant deviation from unity* = cold nuclear matter effects

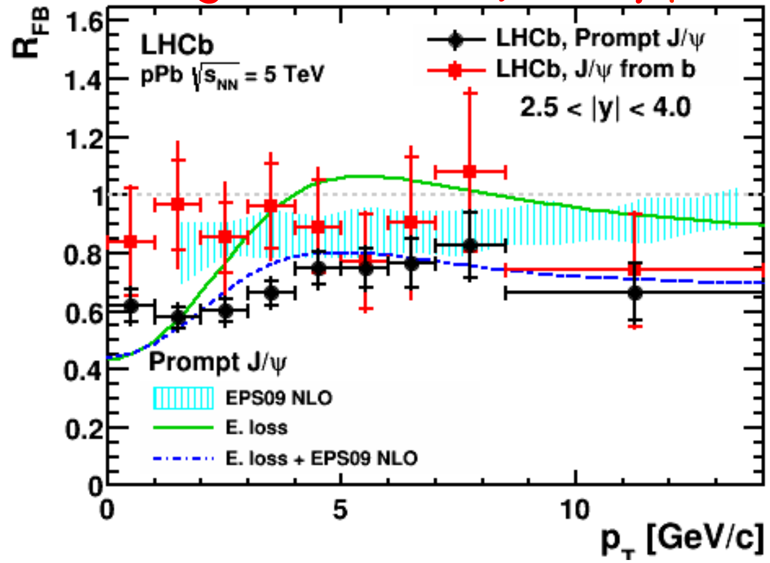
Nuclear effects : J/ψ from B [JHEP 02 (2014) 072]

R_{pPb}, integrated over p_T in y bins

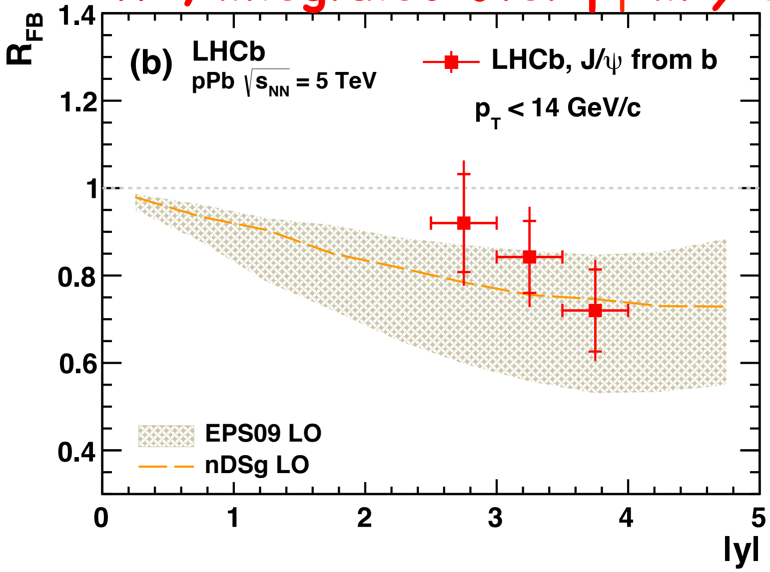


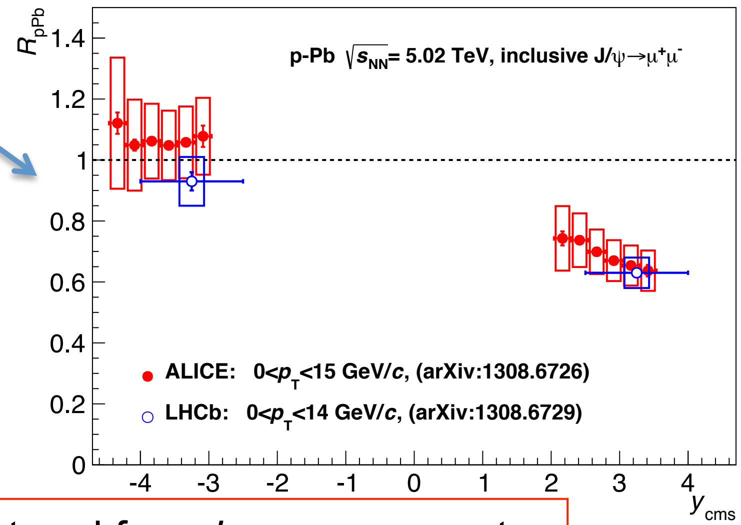
First indication of B supression in pPb data

R^{FB}, integrated over |y| in p_T bins



R^{FB}, integrated over p_T in y bins

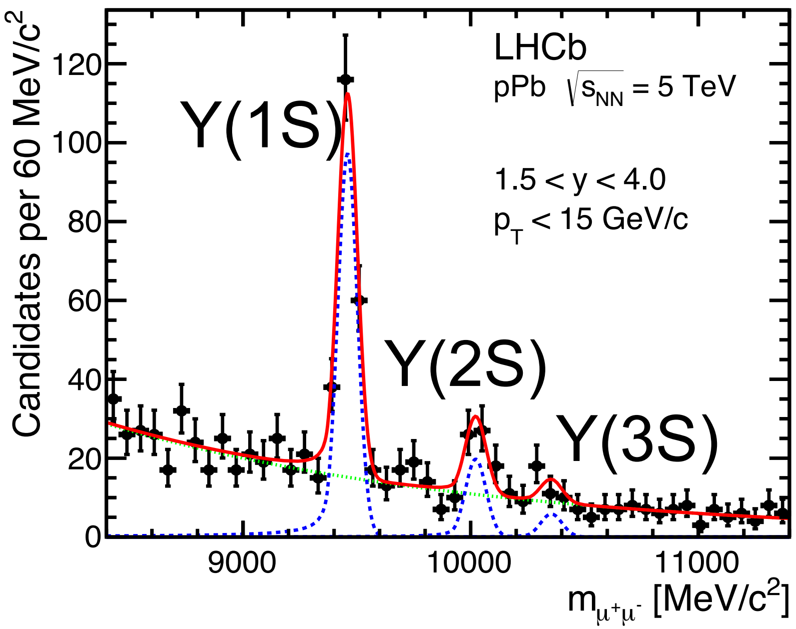




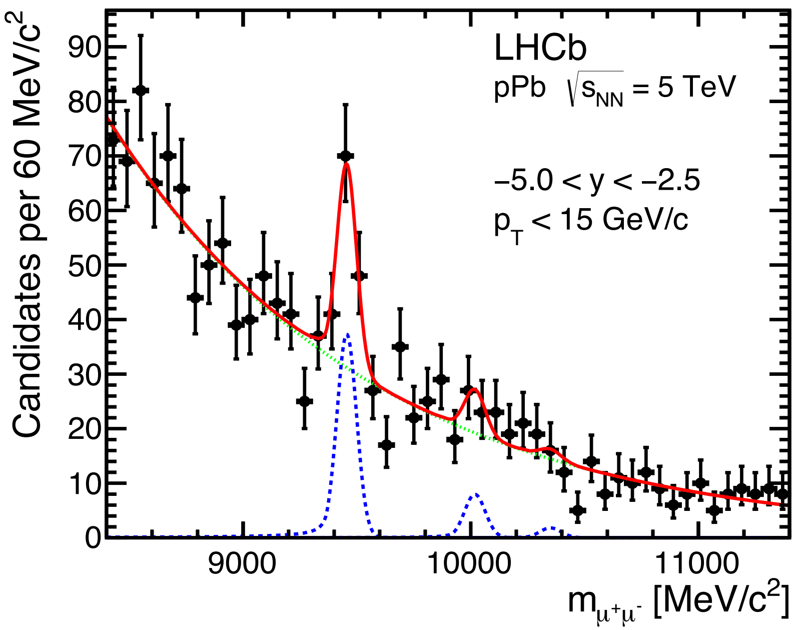
Sum of prompt and from *b* measurements in *good agreement with ALICE* inclusive measurements [JHEP 02 (2014) 073]

Υ production in pPb [arXiv:1405.5152]

- Measurement of the production cross-section using $\Upsilon \to \mu^+\mu^-$:
  - Integrated over the p_T and rapidity of the Υ (not enough statistics for differential measurements)
  - With $p_T < 15$ GeV/c and $1.5 < y < 4.0$ or $-5.0 < y < -2.5$
  - Resolution ~ 43 MeV/c^2 , combined efficiency > 90%



Forward



Backward

Υ Results [arXiv:1405.5152]

- Integrated over p_T and *y*, in the *forward* (1.5 < *y* < 4.0) and *backward* (-5.0 < *y* < -2.5) regions, times branching fraction

$\sigma(\Upsilon(nS))\times B(\Upsilon(nS)\to\mu^+\mu^-)$		
Type	Forward	Backward
Υ(1S)	$380 \pm 35_{stat} \pm 21_{syst}$ nb	$295 \pm 56_{stat} \pm 29_{syst}$ nb
Υ(1S)	$75 \pm 19_{stat} \pm 5_{syst}$ nb	$81 \pm 39_{stat} \pm 18_{syst}$ nb
Υ(1S)	$27 \pm 16_{stat} \pm 4_{syst}$ nb	$5 \pm 26_{stat} \pm 5_{syst}$ nb [< 39 nb (90%CL)]

- Ratio of production of the different states (times branching fraction) in the common y region 2.5 < | *y* |< 4.0

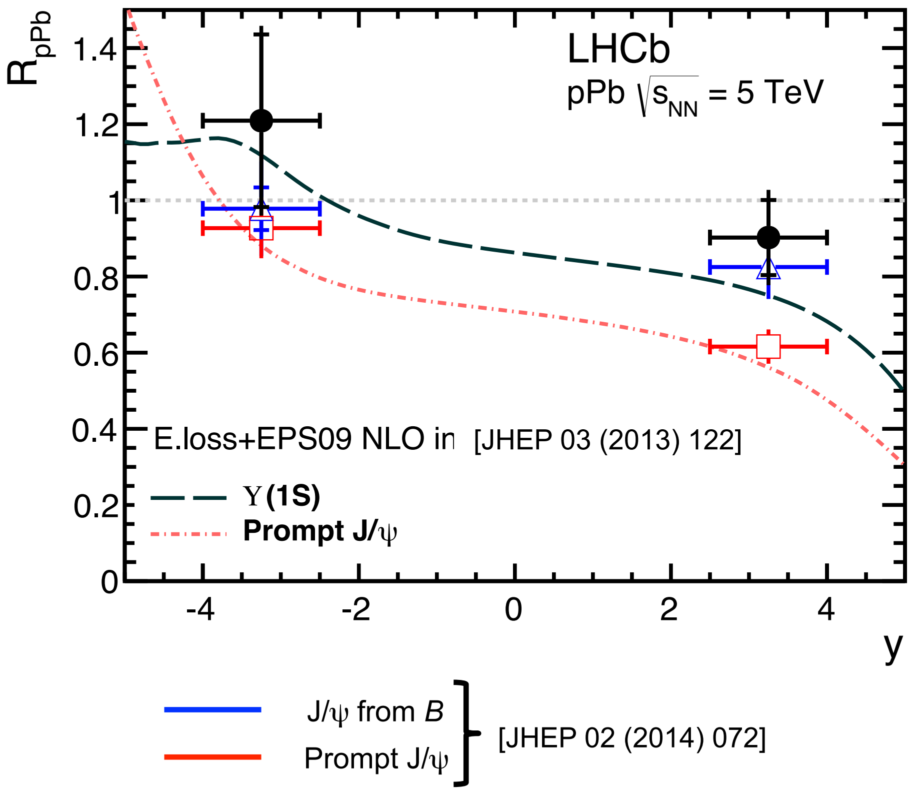
Relative suppression factor $R^{nS/1S}$		
Type	Forward	Backward
$R^{2S/1S}$	$0.20 \pm 0.05_{stat} \pm 0.01_{syst}$	$0.28 \pm 0.14_{stat} \pm 0.05_{syst}$
$R^{3S/1S}$	$0.07 \pm 0.04_{stat} \pm 0.01_{syst}$	$0.02 \pm 0.09_{stat} \pm 0.02_{syst}$ [< 0.13 (90%CL)]

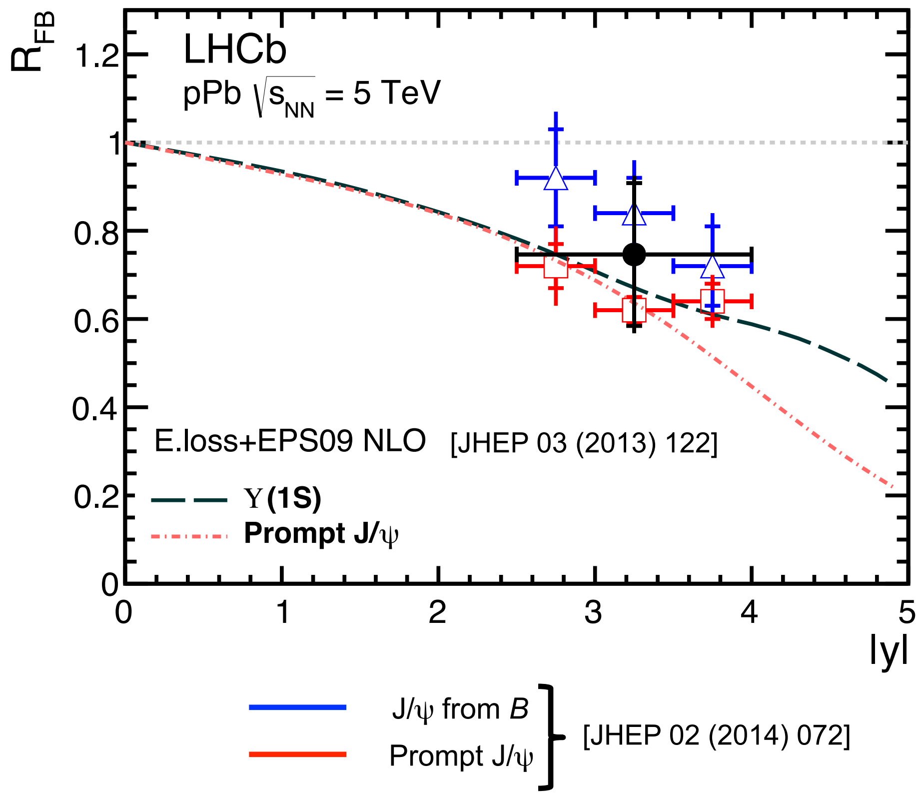
- Most systematic effects cancel in the ratio

Nuclear effects for Υ [arXiv:1405.5152]

➡ Similar ratios as for the J/ψ measured with the $\Upsilon(1S)$:

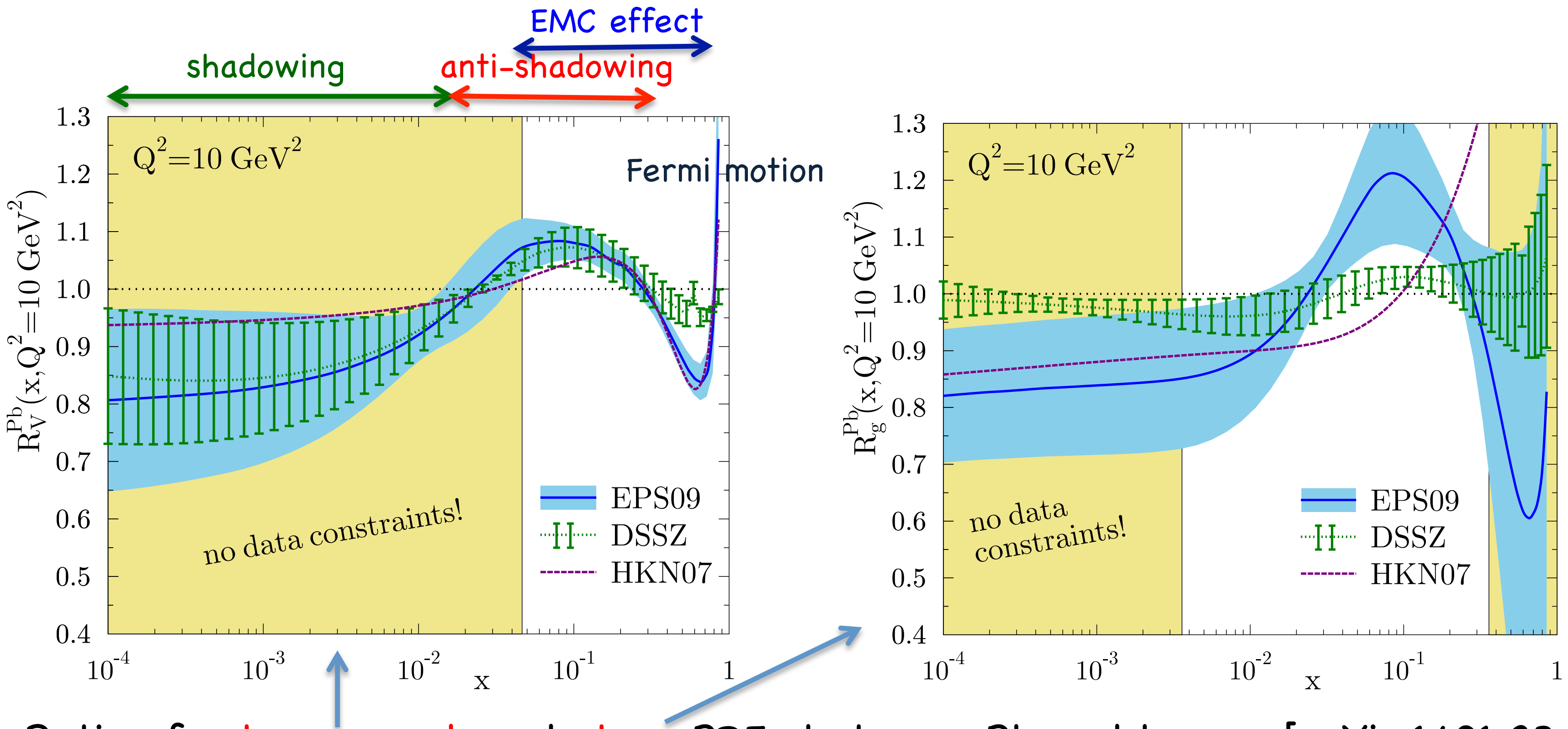
- complementary measurements of cold nuclear effects probing a different PDF scale





Z production in pPb [arXiv:1406.2885]

➡ Measurement of *Z* production at LHCb can help constraining nuclear PDF at *very low* and *very high* *x* values.



➡ Ratio of valence quark and gluon PDFs between Pb and bare *p* [arXiv:1401.2345]

➡ LHCb is sensitive with *Z* production to $2.10^{-4} < x < 3.10^{-3}$ and $0.2 < x < 1.0$

Forward **Backward**

Z production in pPb

[arXiv:1406.2885]

- FIRST measurement in pPb

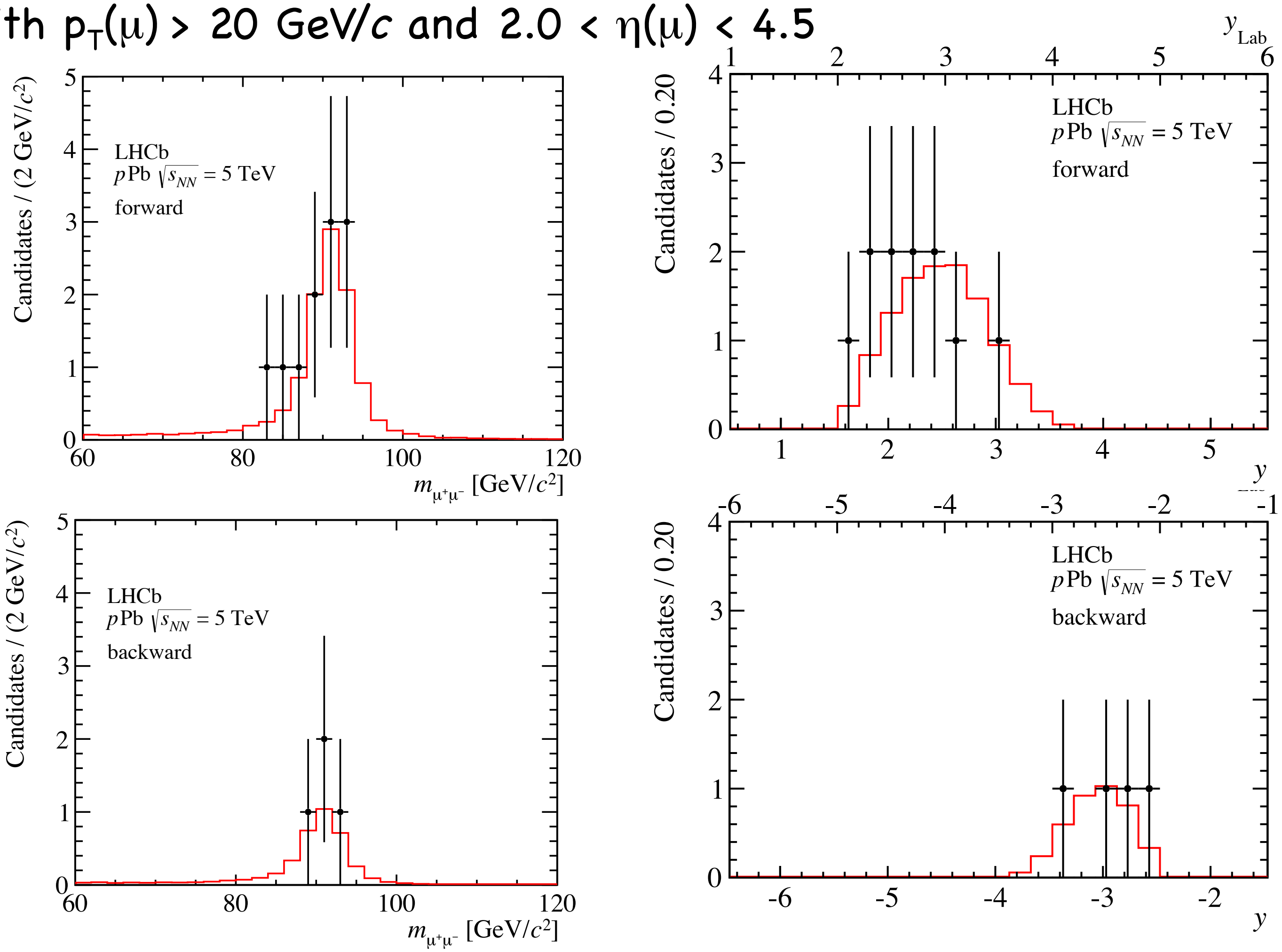
$$\sigma_{Z\to\mu^+\mu^-} = \frac{N_{\rm cand} \times \rho}{\mathcal{L} \times \varepsilon},$$

Efficiency ε~73% (estimated with simulation)

  - Integrated over p_T and rapidity, $60<M_{\mu+\mu-}<120$ GeV/c²
  - With $p_T(\mu) > 20$ GeV/*c* and $2.0 < \eta(\mu) < 4.5$

Forward

Backward

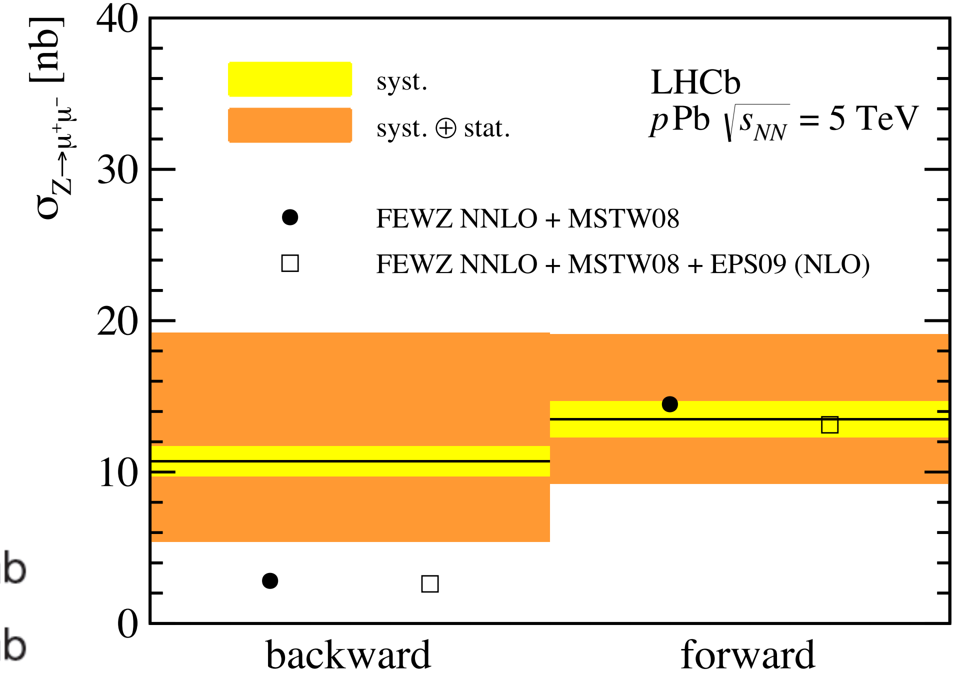


11 candidates
purity ρ=99.7%

4 candidates
purity ρ=99.6%

Z in pPb: Results

➡ LHCb measurements



Forward $\sigma_{Z\to\mu^+\mu^-} = 13.5^{+5.4}_{-4.0}\ \text{stat} \pm 1.2_{\text{syst}}\ \text{nb}$

Backward $\sigma_{Z\to\mu^+\mu^-} = 10.7^{+8.4}_{-5.1}\ \text{stat} \pm 1.0_{\text{syst}}\ \text{nb}$

$$R_{\text{FB}}(2.5 < |y| < 4.0) = 0.094^{+0.104}_{-0.062}(\text{stat.})^{+0.004}_{-0.007}(\text{syst.})$$

➡ Predictions from NNLO calculation with EPS09 NLO nPDF [PRD86 (2012) 094034, EPJC63 (2009) 189, JHEP04 (2009) 065]

Forward $\sigma_{Z\to\mu^+\mu^-} = 13.12^{+0.11}_{-0.08}\ \text{theo}\ ^{+0.27}_{-0.24}\ \text{PDF}\ ^{+0.03}_{-0.10}\ \text{nPDF}\ \text{nb}$

Backward $\sigma_{Z\to\mu^+\mu^-} = 2.61^{+0.03}_{-0.03}\ \text{theo}\ ^{+0.07}_{-0.06}\ \text{PDF}\ ^{+0.03}_{-0.08}\ \text{nPDF}\ \text{nb}$

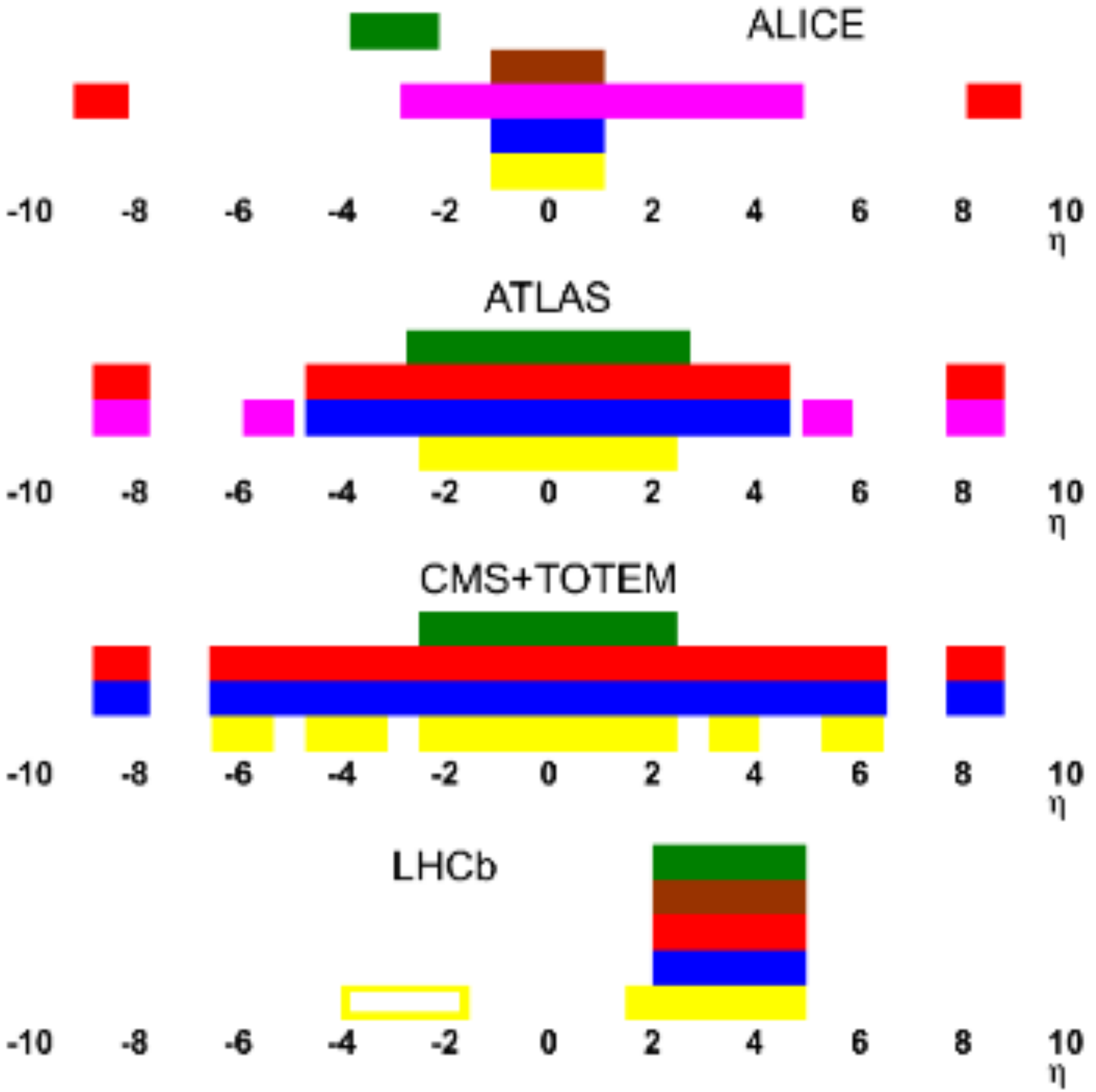
$$R_{\text{FB}}(2.5 < |y| < 4.0) = 0.943^{+0.012}_{-0.027};$$

Conclusions and Outlook

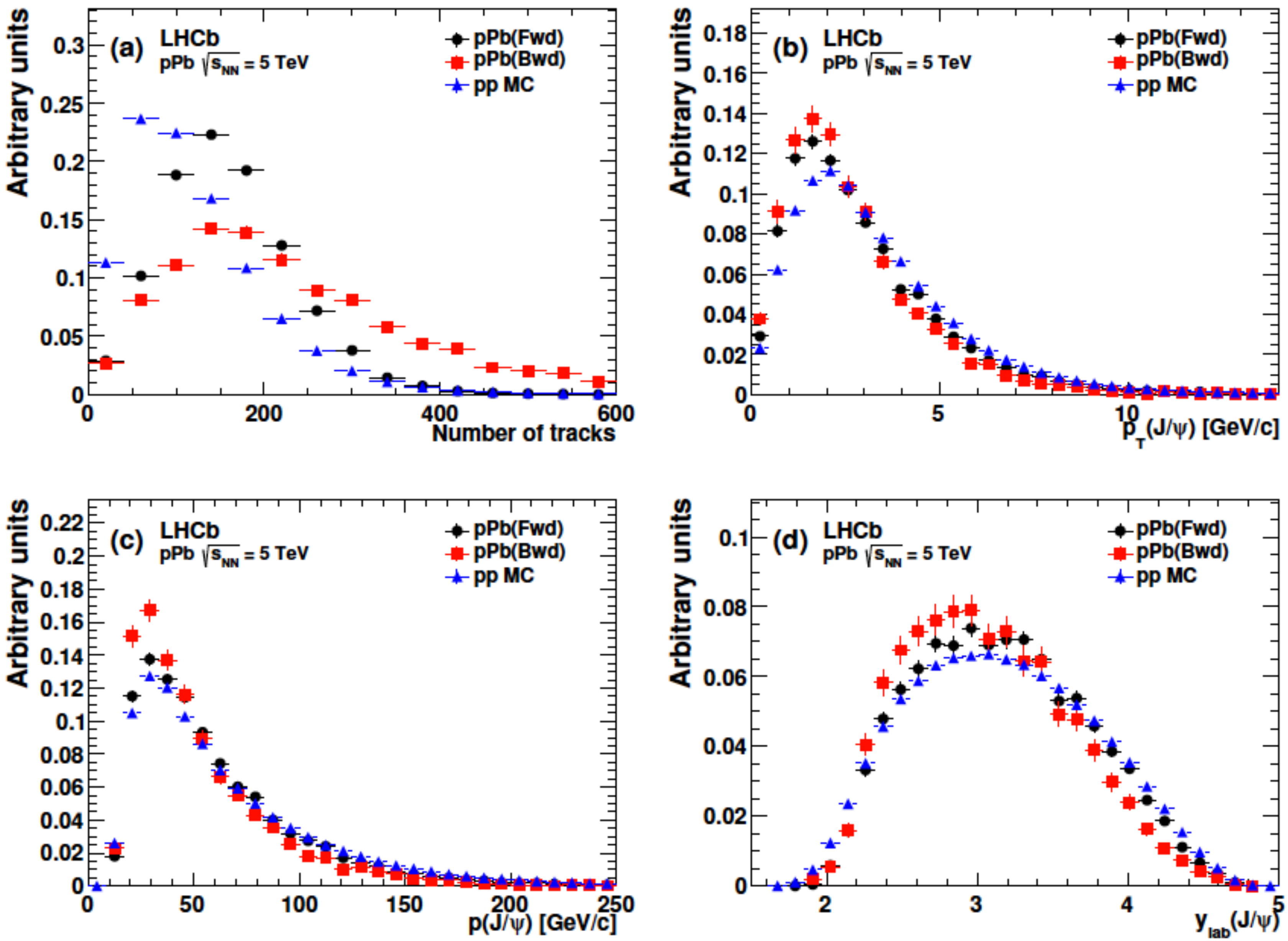
- ➡ LHCb entered the game !!! Participation for the first time to the *p*Pb LHC runs of 2013 was very successful thanks to LHCb unique acceptance ☺
  - Measurements of visible cold nuclear effects with J/ψ and Υ (1S)
  - First observation of *Z* boson production in proton-nucleus collisions
- ➡ Other measurements are ongoing with the 2013 dataset !
- ➡ We expect that the statistics will be 10 times higher in the next LHC *p*Pb run (2016 or 2017), allowing us to reach better precisions
- ➡ In addition, we have a sample of *p*Ne and PbNe data on tape (see talk of D. Volyanskyy)
  - Measurements can reach precision similar to dedicated heavy ion experiments !!

Back up

Different Coverages at LHC



Differences pp vs. pPb



Jpsi Systematic

Source	Forward (%)	Backward (%)
Correlated between bins		
Mass fits	2.3	3.4
Radiative tail	1.0	1.0
Muon identification	1.3	1.3
Tracking efficiency	1.5	1.5
Luminosity	1.9	2.1
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1.0	1.0
Uncorrelated between bins		
Binning	0.1 – 8.7	0.1 – 6.1
Multiplicity weight	0.1 – 3.0	0.2 – 4.3
t_z fit (*only for* J/ψ *from* b)	0.2 – 12	0.2 – 13

Table 1. Relative systematic uncertainties on the differential production cross-sections. The uncertainty due to the radiative tail and branching fraction cancels in both $R_{p\mathrm{Pb}}$ and R_{FB}. The uncertainty due to the tracking efficiency and the luminosity partially cancels for R_{FB}.

Υ systematics

Table 1: Relative systematic uncertainties on the cross-sections, in percent, in the full rapidity range. The values in parenthesis refer specifically to $\Upsilon(1S)$ measurements when systematic uncertainties in the common rapidity range $2.5 < |y| < 4.0$ are notably different.

	Forward			Backward		
Source	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Muon identification	1.3	1.3	1.3	1.3	1.3	1.3
Tracking efficiency	1.5	1.5	1.5	1.5	1.5	1.5
Mass fit model	1.1 (1.0)	4.9	13	1.8 (1.7)	19	90
Luminosity	1.9	1.9	1.9	2.1	2.1	2.1
Trigger	2.1	2.1	2.1	5.0	5.0	5.0
Binning	3.9 (3.8)	3.9	3.9	7.6 (6.3)	7.6	7.6
Reconstruction	1.5	1.5	1.5	1.5	1.5	1.5
Total	5.5 (5.4)	7.3	14	9.8 (8.8)	21	91

Upsilon

➡ Cold nuclear matter effects

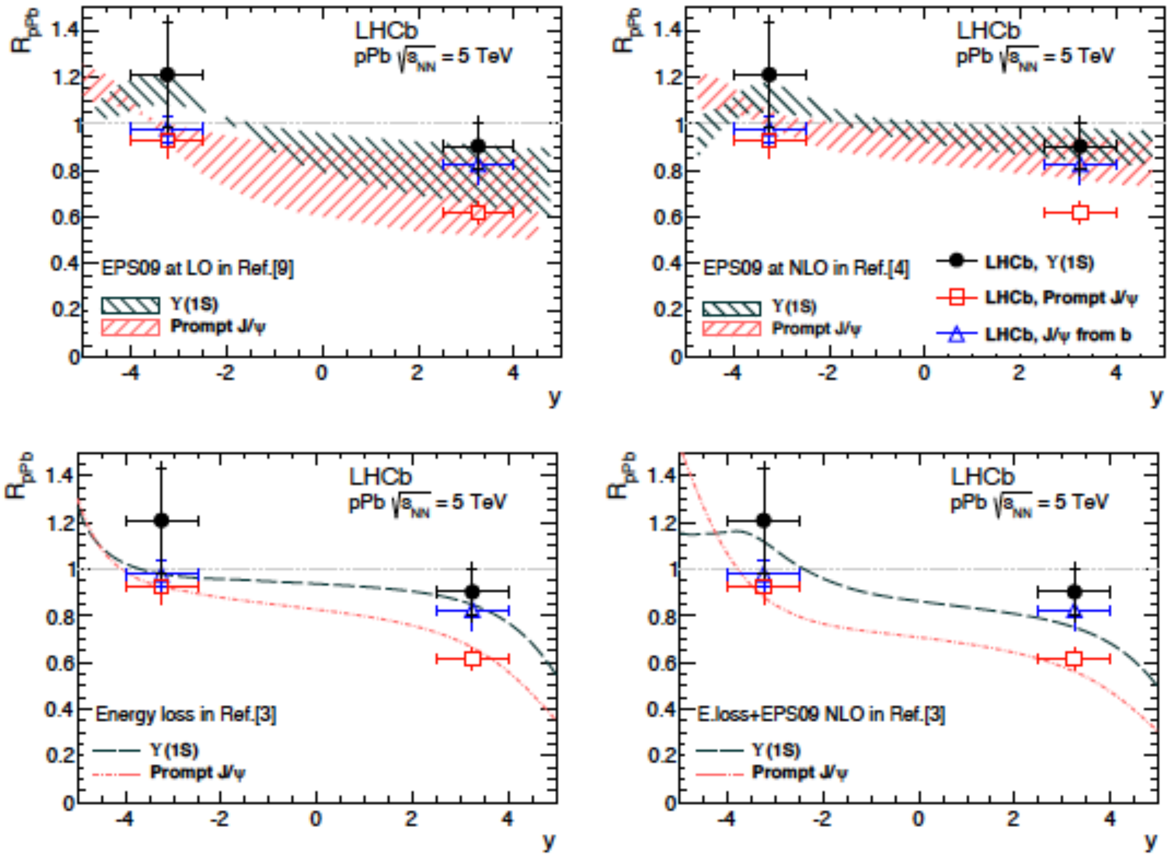


Figure 2: Nuclear modification factor, R_{pPb}, compared to other measurements and theoretical predictions. The black dots, red squares, and blue triangles indicate the LHCb measurements for $\Upsilon(1S)$ mesons, prompt J/ψ mesons, and J/ψ from b-hadron decays, respectively [19]. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. The data are compared with theoretical predictions for Υ and prompt J/ψ mesons from different models. The shaded areas indicate the corresponding uncertainties of the theoretical calculations.

Upsilon CNM effects

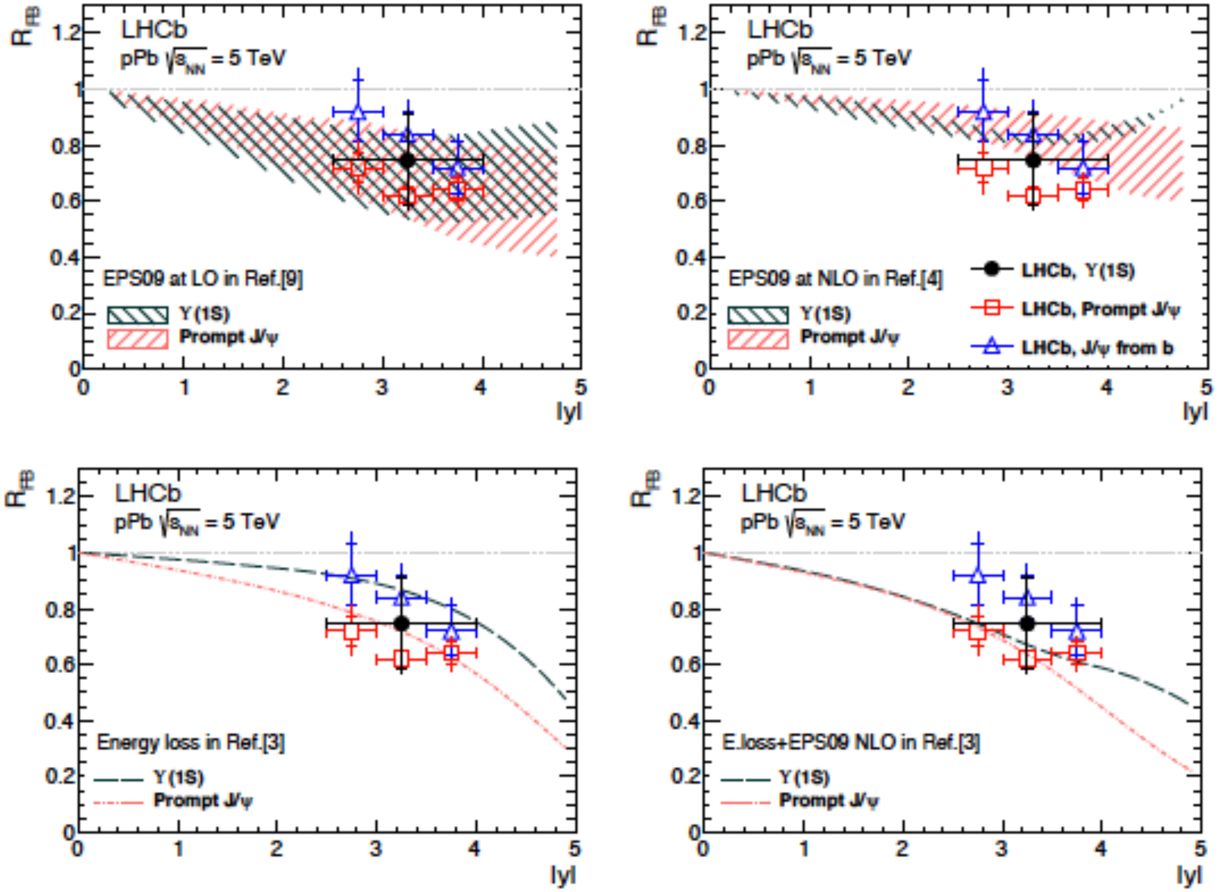


Figure 3: Forward-backward production ratio, R_{FB}, as a function of absolute rapidity. The black dots, red squares, and blue triangles indicate the LHCb measurements for $\Upsilon(1S)$ mesons, prompt J/ψ mesons, and J/ψ from b-hadron decays, respectively [19]. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. The data are compared with theoretical predictions for Υ and prompt J/ψ mesons from different models. The shaded areas indicate the corresponding uncertainties of the theoretical calculations.

Systematic on Z in pPb

➡ Uncertainty on the cross section

Table 1: Systematic uncertainties in the cross-section calculation for $\sigma_{Z\to\mu^+\mu^-}$. The uncertainties on ρ and $\varepsilon^{\text{cand}}$ are assumed to be fully correlated between the forward and the backward sample.

Source	Forward	Backward
Sample purity	0.5 %	0.5 %
GEC efficiency	0.0 %	1.9 %
Candidate efficiency	8.4 %	8.7 %
Multiplicity reweighting	1.5 %	2.0 %
Luminosity	1.9 %	2.1 %
Total	8.8 %	9.4 %

Statistical significance of Z

The statistical signicance of the Z signal is evaluated by the probability that a Poisson distribution with the expected background yield

$N^{th}_{bkg} = \sigma^{th}_{Z\to\mu\mu}\varepsilon^{GEC}\varepsilon^{cand}L(1-\rho)/\rho$

as expectation value fluctuates to the observed signal.

The theoretical cross-section σ^{th} is defined as the value obtained from NNLO calculation using Fewz and nuclear modifications based on the EPS09 nPDF set.

This gives a signicance of 10.4 sigmas for the Z signal in the forward direction and 6.8 sigmas for the backward direction.

R^{FB} for Z in pPb

The value of R_{FB} measured in the overlap region $2.5 < |y| < 4.0$ is defined as

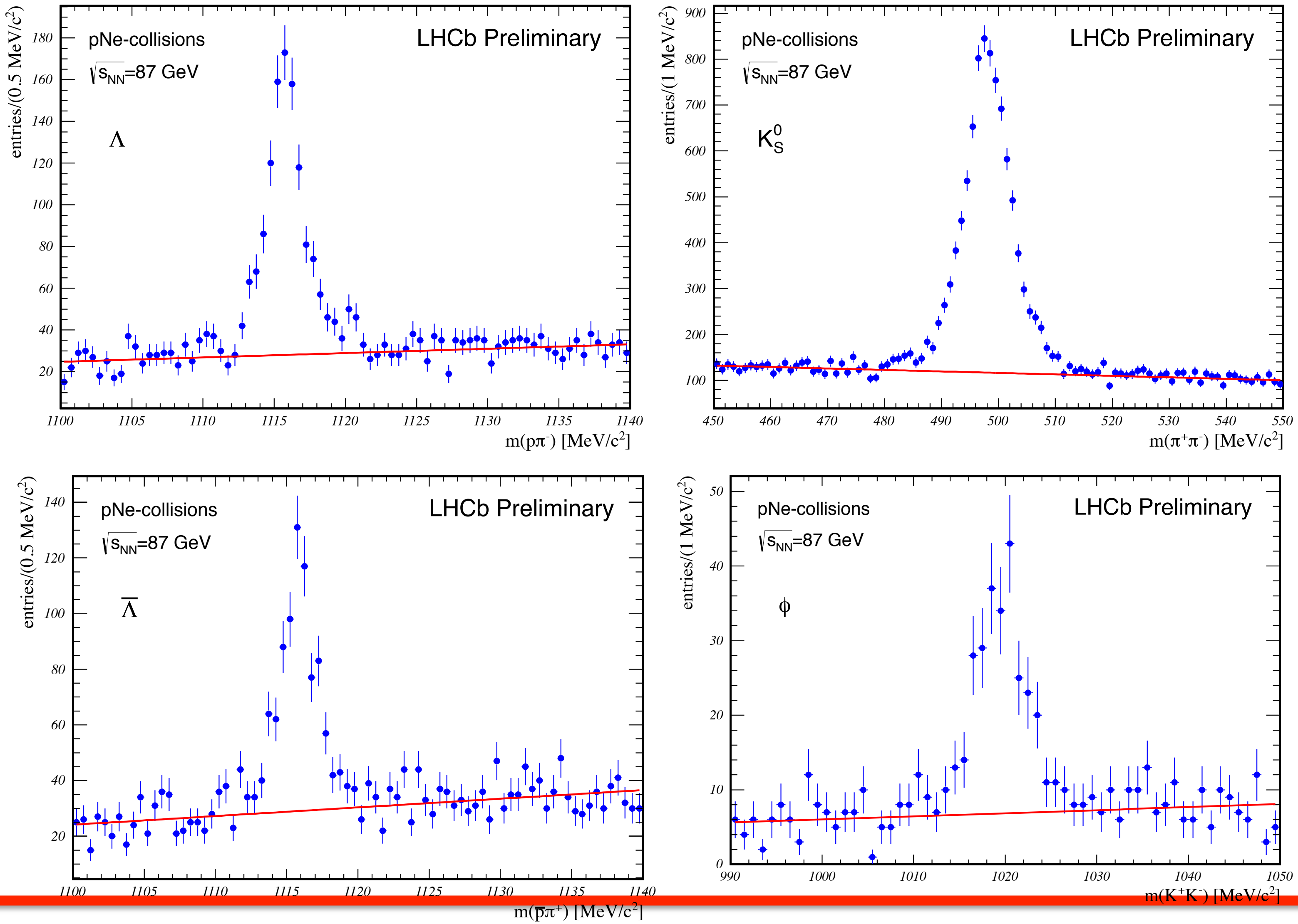
$$R_{\mathrm{FB}}(2.5 < |y| < 4.0) = \frac{N_{\mathrm{cand,fwd}}}{N_{\mathrm{cand,bwd}}} \times \frac{\rho_{\mathrm{fwd}}}{\rho_{\mathrm{bwd}}} \times \frac{\varepsilon_{\mathrm{bwd}}}{\varepsilon_{\mathrm{fwd}}} \times \frac{\mathcal{L}_{\mathrm{bwd}}}{\mathcal{L}_{\mathrm{fwd}}} \times \frac{1}{\beta}, \quad (3)$$

where β is the correction factor for the difference in the detector acceptance of the muons between the forward and backward directions. It is evaluated using NNLO FEWZ calculations to be $\beta = 2.419^{+0.127}_{-0.000}(\mathrm{theo.}) \pm 0.008(\mathrm{num.})^{+0.009}_{-0.010}(\mathrm{PDF})$, where the first uncertainty is from the variation of the renormalisation and factorisation scale, the second the numerical and the last the uncertainty from the PDF uncertainties. The scale variation always leads to an enhancement of β.

The probability to observe a value of $\mathbf{R_{FB}}$ no larger than that measured, assuming no nuclear modications (i.e. the true value is $\mathbf{R_{FB}}$ = 1), is 1.2%. This corresponds to a deviation with a 2.2 significance.

The probability is estimated with a toy Monte Carlo assuming Poissonian distributions for the number of candidates.

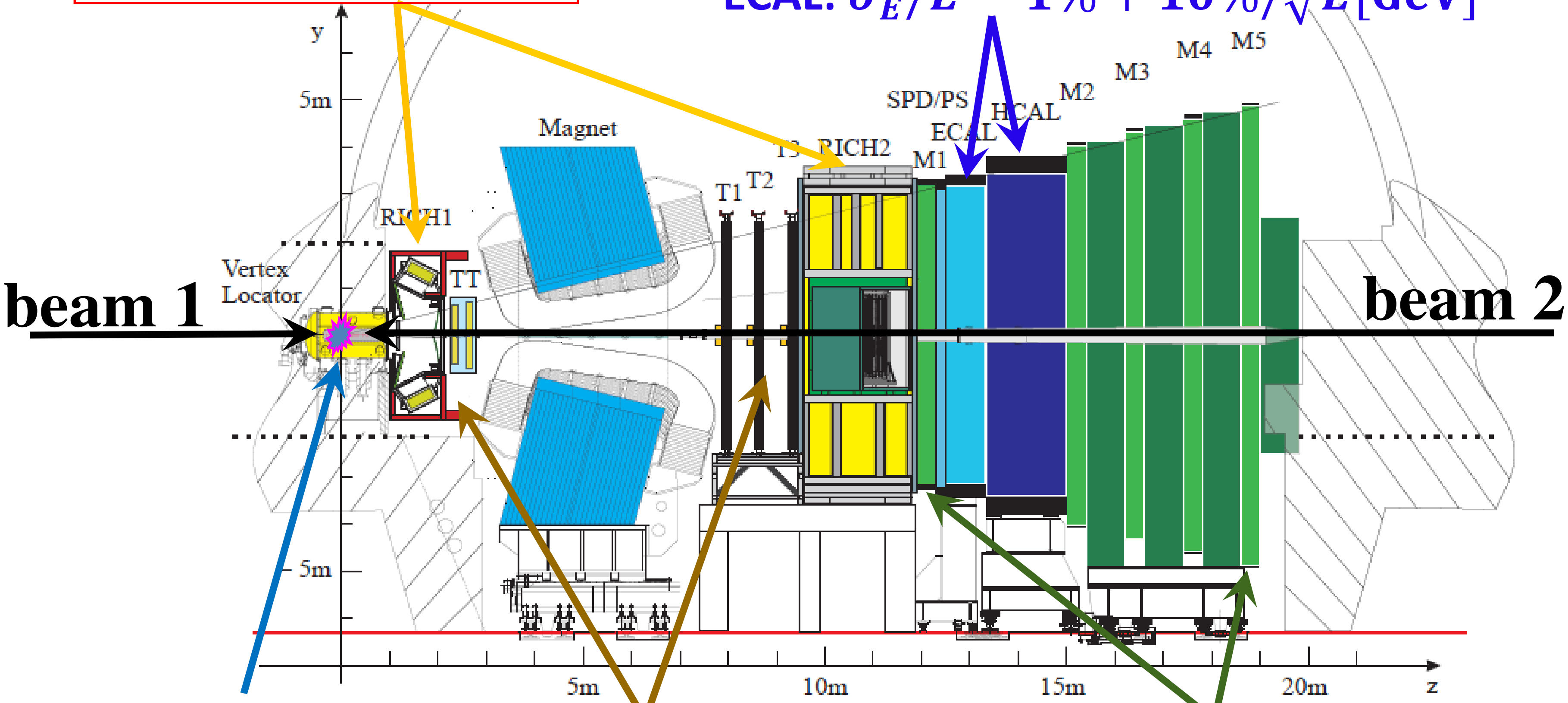
*p*Ne [LHCb-CONF-2012-034]



LHCb

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\text{GeV}]}$

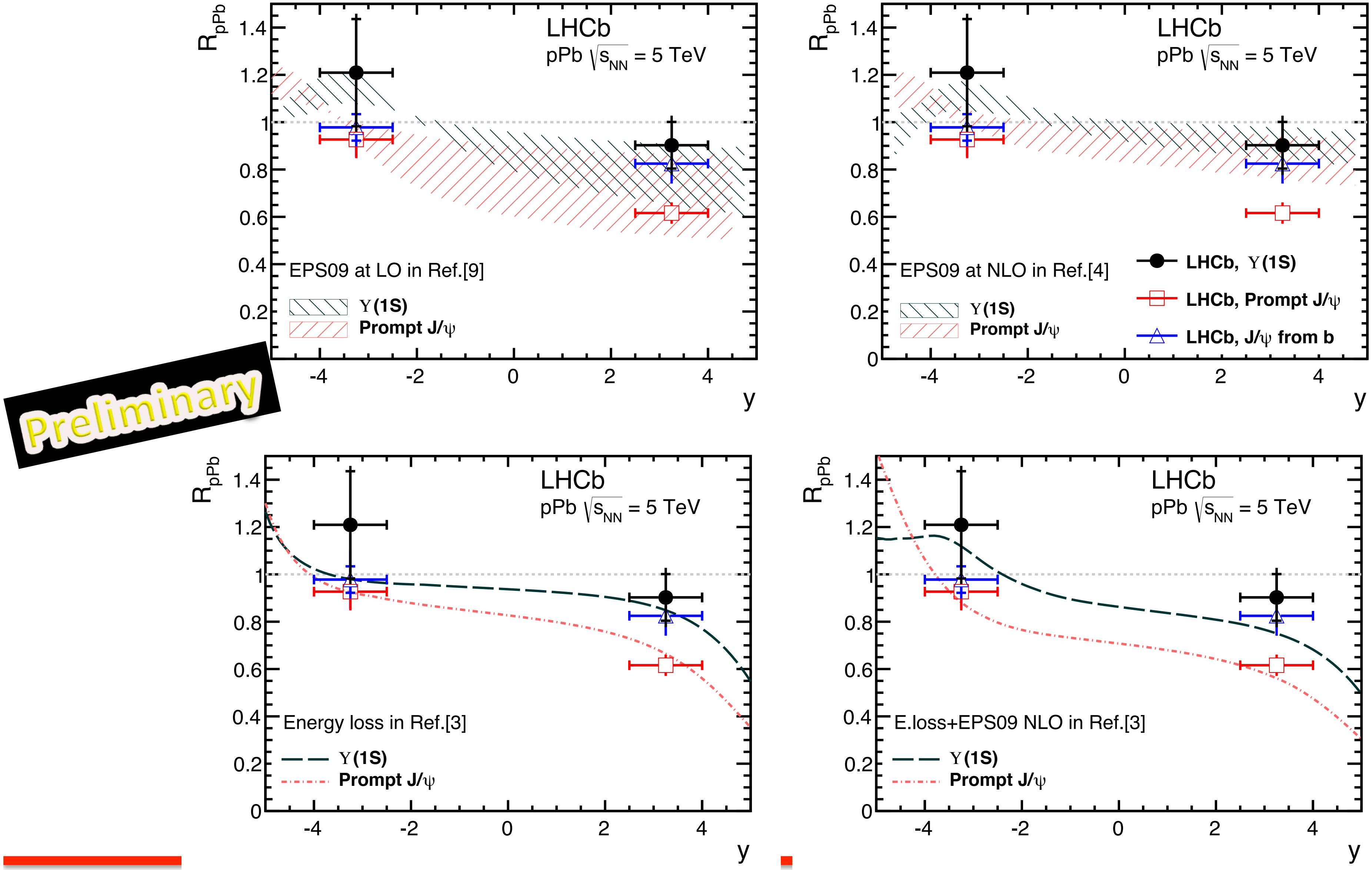


VELO
$\sigma_{\text{IP}} \sim 20\ \mu\text{m}$
for high-p_{T} tracks

Tracking System
$\Delta p/p = 0.4\%@5\ \text{GeV}/c$
to $0.6\%@100\ \text{GeV}/c$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

Cold Nuclear Modification Factor RpPb



R_{FB}

Preliminary

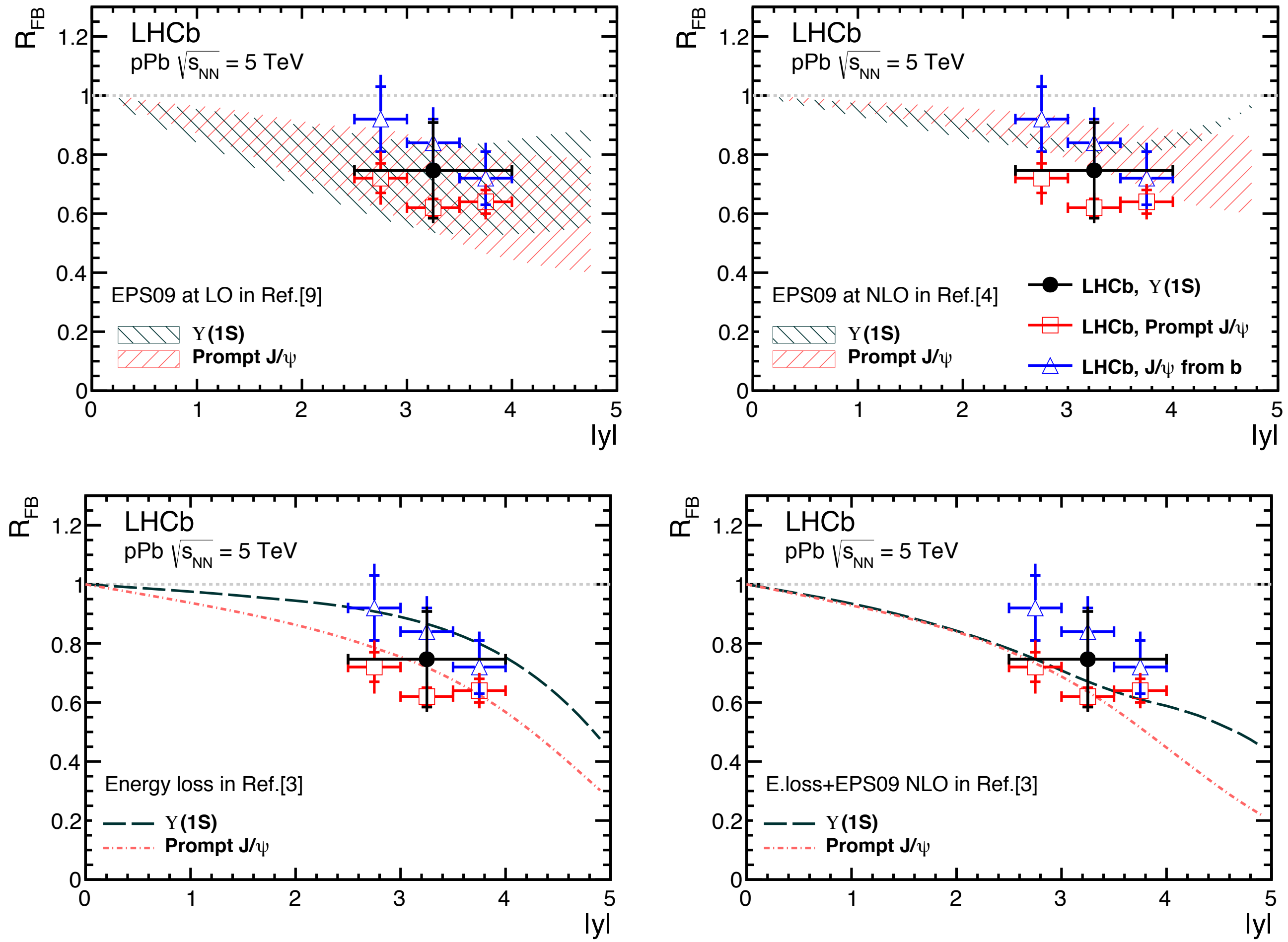


Figure 3: Forward-backward production ratio, R_{FB}, as a function of absolute rapidity. The black dots, red squares, and blue triangles indicate the LHCb measurements for $\Upsilon(1S)$ mesons, prompt J/ψ mesons, and J/ψ from b-hadron decays, respectively [19]. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. The data are compared with theoretical predictions for Υ and prompt J/ψ mesons from different models. The shaded areas indicate the corresponding uncertainties of the theoretical calculations.