Charmonium and Bottomonium in Proton-Lead collisions at LHCb

Quarkonium 2014 , CERN, November 10-14

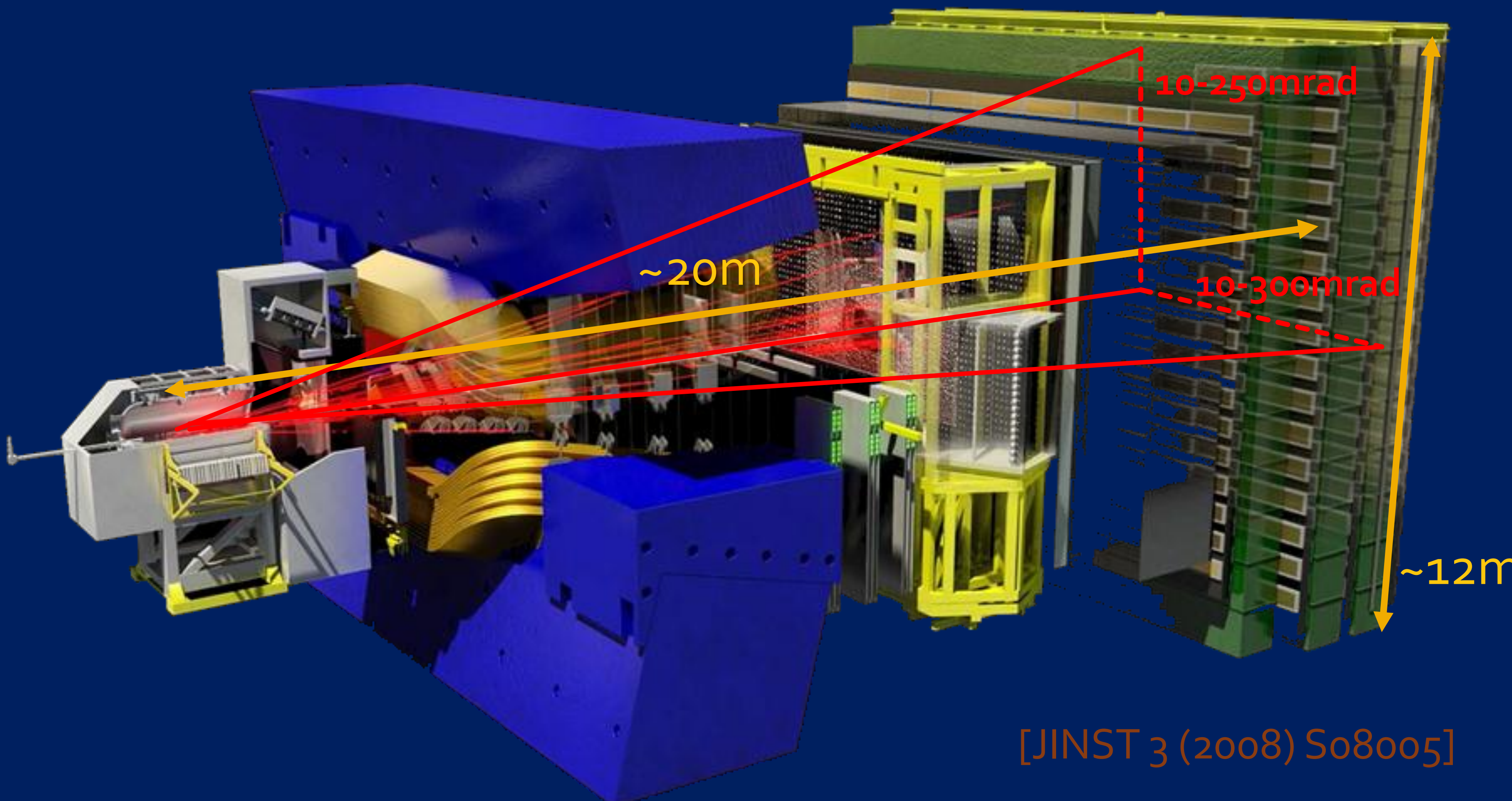
Burkhard Schmidt, CERN, for the LHCb collaboration

Outline

- Introduction
  - LHCb detector
  - Beam configurations and 2013 p-Pb data taking
  - Motivation for pA physics with LHCb
- Quarkonium production in p-Pb collisions
  - Measurement of the J/ψ and Υ-production cross-sections
  - Study of Cold Nuclear Matter effects
- Conclusions and Prospects

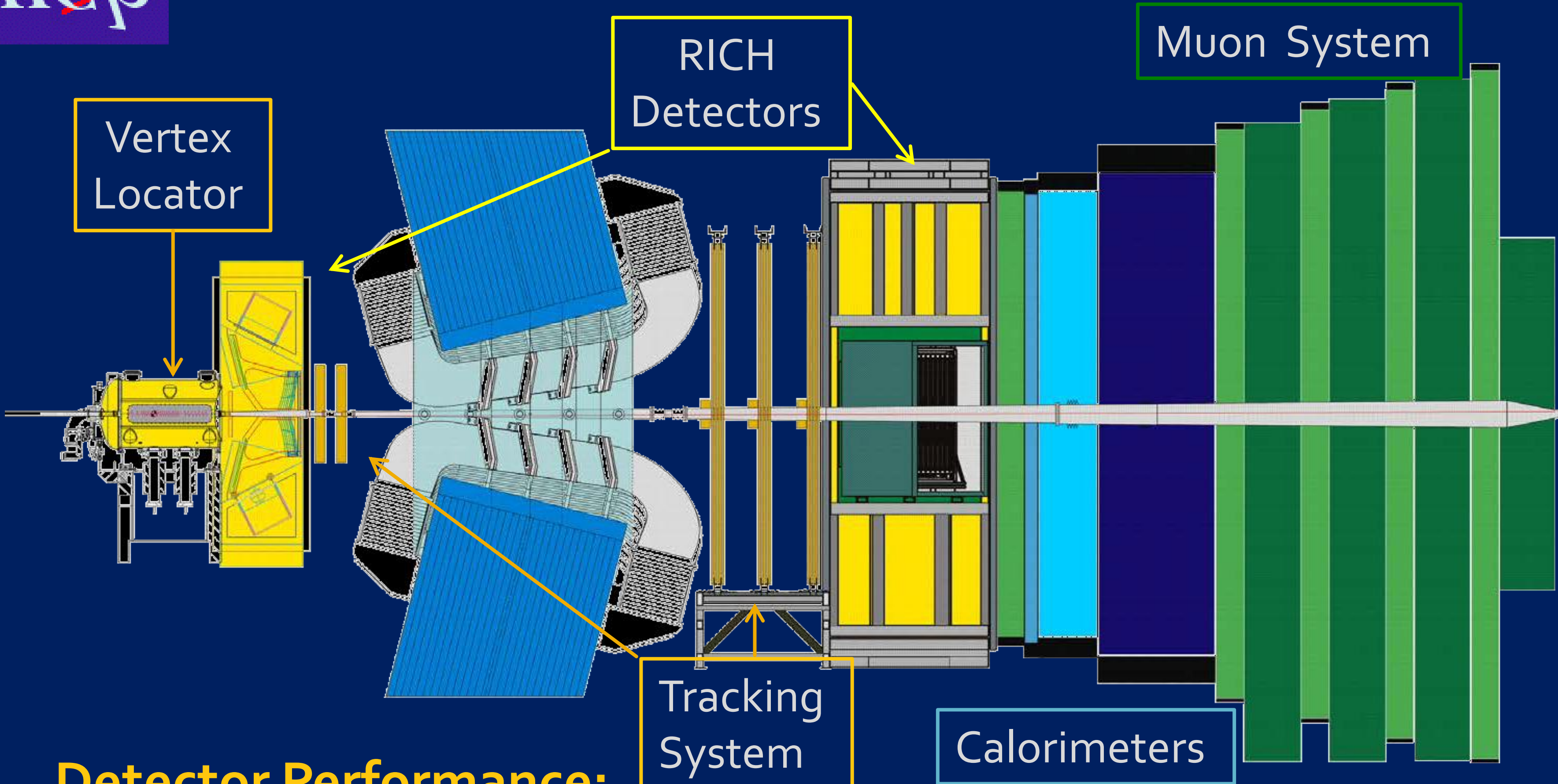
LHCb Detector

- Single arm spectrometer in the forward direction, covering ~4% of solid angle, but 40% of heavy quark production cross-section



[JINST 3 (2008) S08005]

LHCb Detector



Detector Performance:

- **Impact parameter resolution:** 20 μm
- **Momentum resolution:** $\Delta p/p$ = 0.4 % – 0.6 % (5 GeV/c – 100 GeV/c)
- **RICH π-K separation:** ε(K→K) ~ 95 %, mis-ID ε(π→K) ~ 5 %
- **Muon ID:** ε(μ→μ) ~ 97 %, mis-ID ε(π→μ) ~ 1-3 %
- **ECAL energy resolution** $\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

Beam configurations

p-Pb

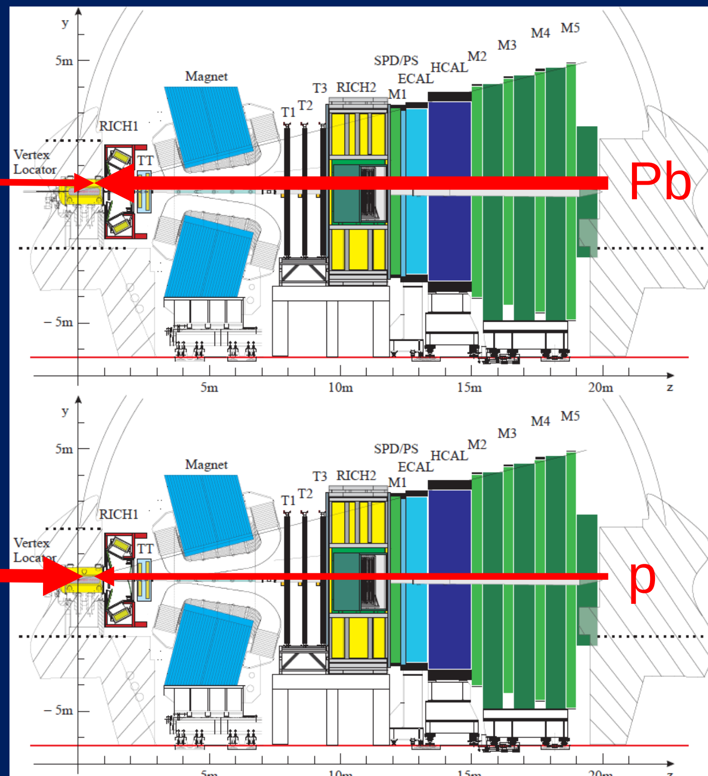
p → ← Pb

E_p=4 TeV

Pb-p

Pb → ← p

E_{Pb}= 1.58 TeV



Rapidity coverage

pp: $2 < y < 5$

Forward production

$y = 0.47$ in lab

p-Pb: $1.5 < y < 4.5$

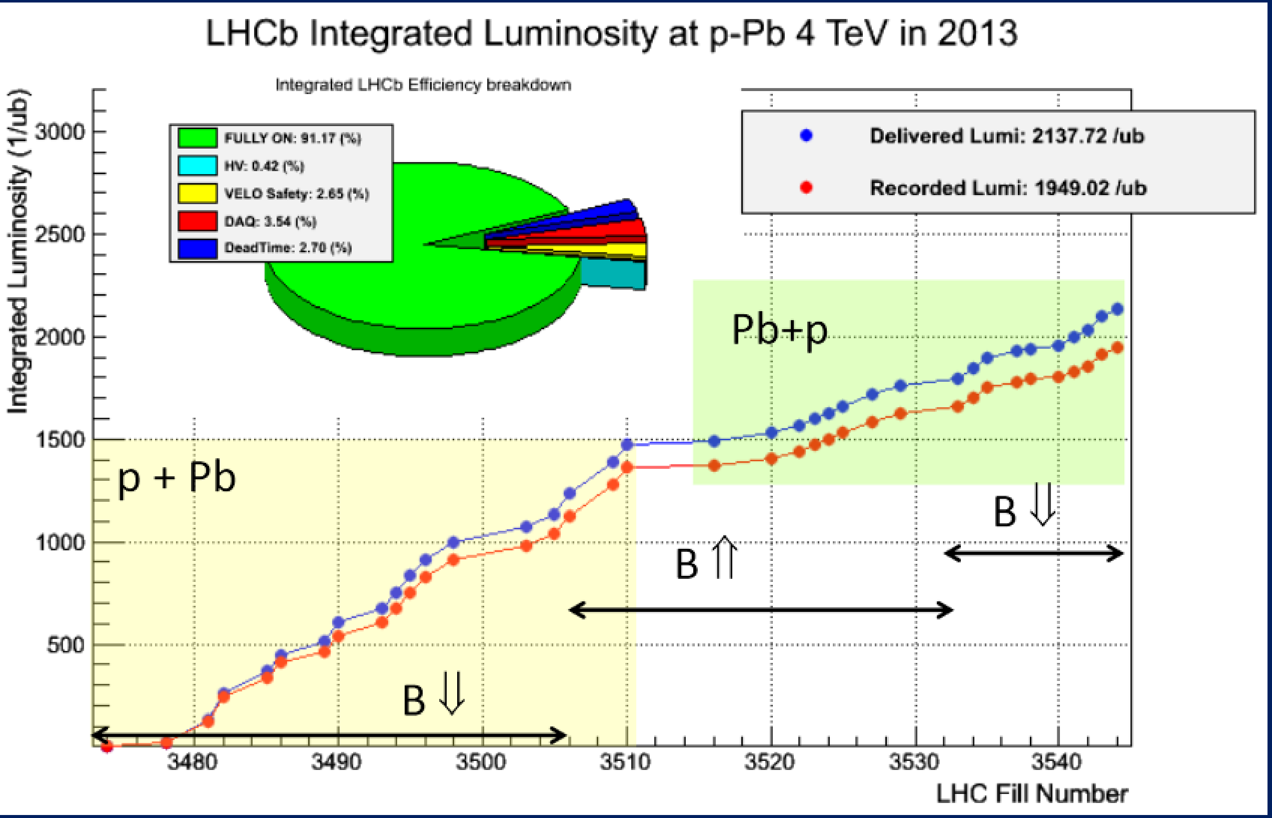
Backward production

$y = -0.47$ in lab

Pb-p: $-5.5 < y < -2.5$

- Common range for measurements: $2.5 < |y| < 4$
- Center-of-mass energy : $\sqrt{s_{NN}} \approx 5$TeV

2013 p-Pb data-taking

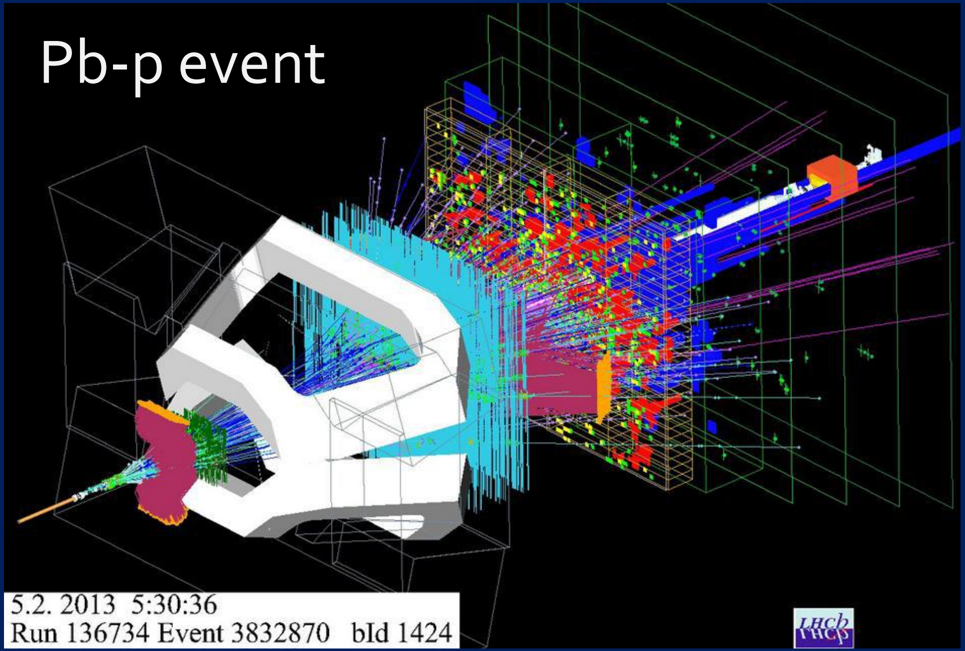


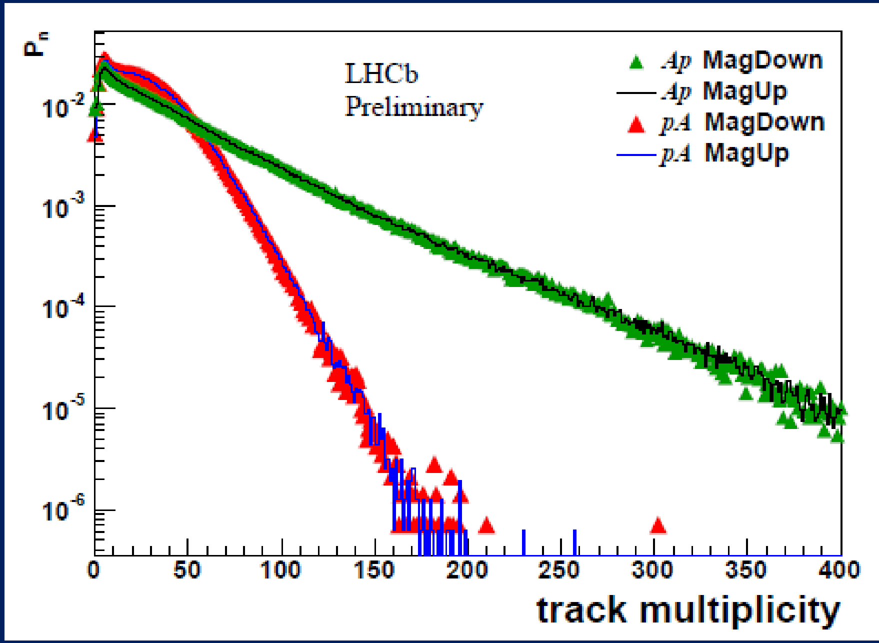
Integrated luminosity (after data quality)

~1.1/nb p-Pb
~0.5/nb Pb-p

- Data taking with four different configurations:
  p-Pb / Pb-p ; magnet up (B⇑) / down (B⇓)
- Instant. luminosity ~ 5 x 10^{27} /cm²/s
- low pile-up: < 1 primary vertex per interaction

Event properties





[LHCb-CONF-2013-008]

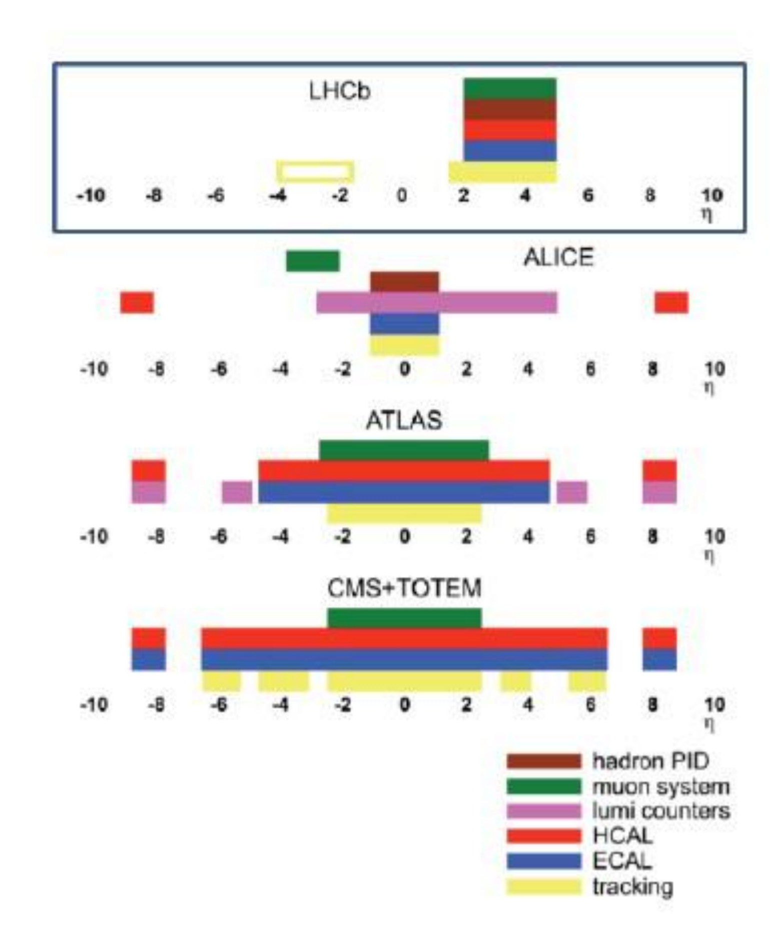
- Magnet up/down agree for both beam configurations
- Higher track multiplicity in Pb-p, as expected

Physics Motivation

- **LHCb fully instrumented in the forward region**
  - Allows to study proton-ion collisions in a unique kinematic region

- **Study of pA collisions important for HI physics**
  - provides essential input to the under-standing of nucleus-nucleus collisions
  - pA collisions important as a reference sample for heavy ion collisions, but also interesting by themselves.
  - Sensitive probes of nuclear matter
    - Nuclear parton distribution function (nPDF)

→Tests phenomenological models



Quarkonium production in pA

- Heavy flavour / quarkonium production is an important probe to
  - understand energy-loss and medium-transport mechanisms in nucleon-nucleon collisions.
  - investigate gluon saturation and quark confinement
  - disentangle QGP effects from Cold-Nuclear-Matter (CNM) effects.
- The nuclear attenuation factor R_{pA} tests modeling of cold nuclear effects:

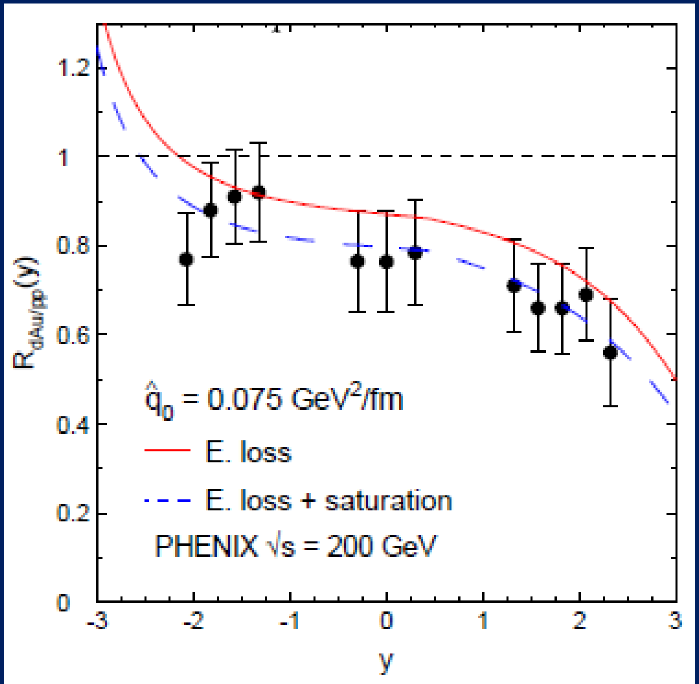
$$R_{p\mathrm{A}}(y, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{p\mathrm{A}}(y, \sqrt{s_{NN}})/\mathrm{d}y}{\mathrm{d}\sigma_{pp}(y, \sqrt{s_{NN}})/\mathrm{d}y}$$

- The Forward/Backward asymmetry can be measured:

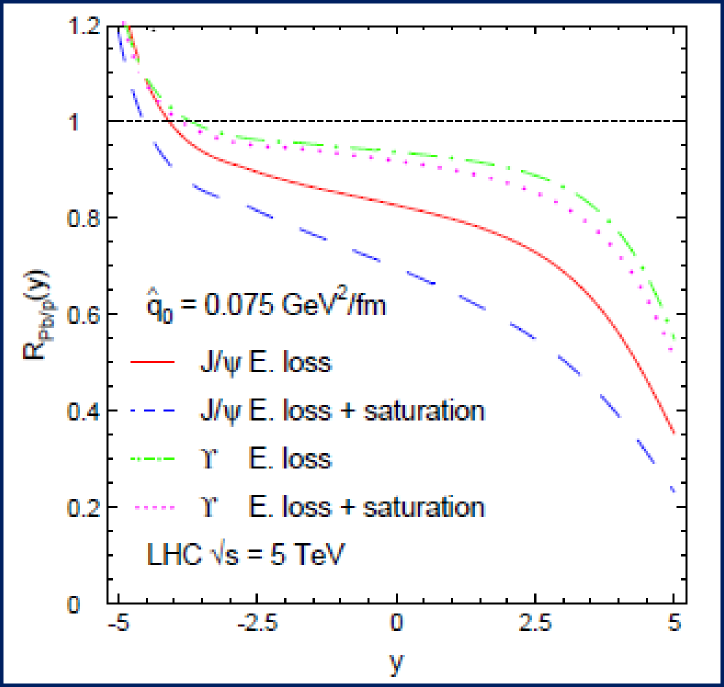
$$R_{\mathrm{FB}}(y, \sqrt{s_{NN}}) \equiv \frac{R_{p\mathrm{Pb}}(+|y|, \sqrt{s_{NN}})}{R_{p\mathrm{Pb}}(-|y|, \sqrt{s_{NN}})}$$

Quarkonium production in pA

- Previous results and predictions:



[PRL 107 (2011) 142301]



[JHEP 1303 (2013) 122]

- PHENIX data shows heavy quarkonia suppression at large rapidity
- Predictions have been made for p-Pb collisions at the LHC

J/ψ production in p-Pb and Pb-p

- Three main sources for J/ψ :
  - direct production
  - feed down from heavier states $\psi(2S)$, χ_c

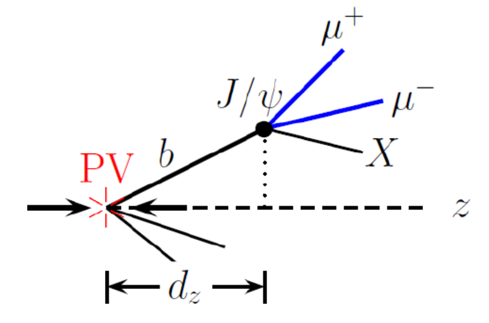
  } prompt J/ψ
  - from b-hadron decays — J/ψ from b

- Analysis strategy (same as in pervious LHCb *pp* studies) :
  - Reconstruct J/ψ from two well identified muons
  - Measurement of the production cross-section both for prompt J/ψ and for J/ψ from b:

$$\sigma = \frac{N(J/\psi \rightarrow \mu^{+} + \mu^{-})}{L \times \epsilon \times B(J/\psi \rightarrow \mu^{+} + \mu^{-})}$$

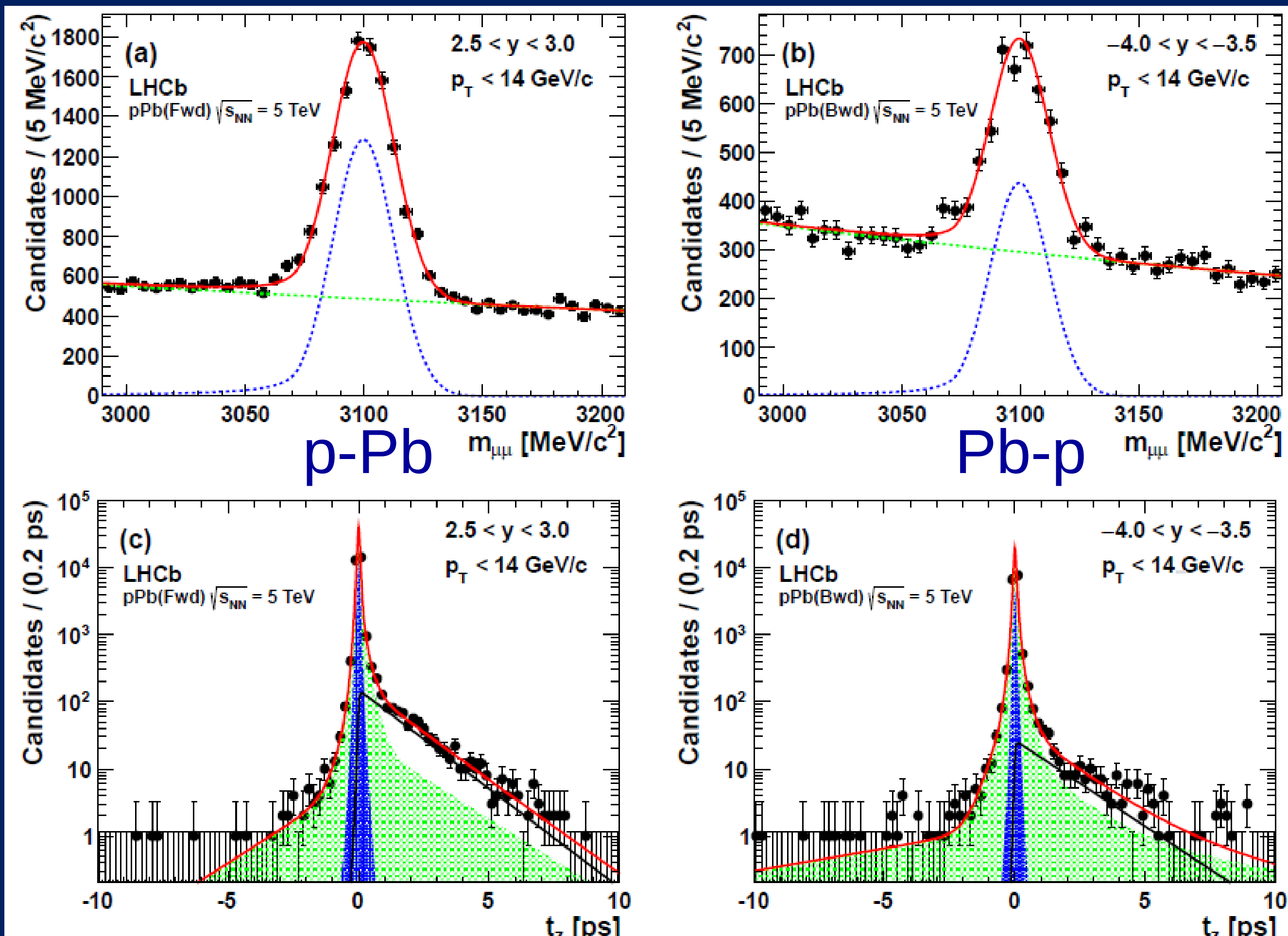
  - Use pseudo-proper time to separate prompt J/ψ and J/ψ from b:

$$t_z = \frac{(Z_{J/\psi} - ZPV) \times MJ_{/\psi}}{p_Z}$$



J/ψ signal extraction

- Yields of prompt J/ψ and J/ψ from b extracted from simultaneous fit of mass and pseudo-proper time
- **Fit projections:** [JHEP 02 (2014) 072]



Mass distributions:

- Signal : Crystal-Ball fct.
- Bkg : exponential

t_z distributions:

- Signal:
  - $\delta(t_z)$ for prompt J/ψ
    expo. for b-component
- Bkg: empirical function from sideband

blue line: prompt J/ψ
black line: J/ψ from b
Green hatched: comb. bkg

J/ψ production cross-sections

Total production of prompt J/ψ and J/ψ from b in LHCb:

[JHEP 02 (2014) 072]

- **Forward:** $p_T < 14$ GeV/c, $1.5 < y < 4.0$

  σ_{pA} (prompt J/ψ) = 1168 ± 15 (stat.) ± 54 (syst.) μb

  σ_{pA} (J/ψ from b) = 166.0 ± 4.1 (stat.) ± 8.2 (syst.) μb

- **Backward:** $p_T < 14$ GeV/c, $-5.0 < y < -2.5$

  σ_{Ap} (prompt J/ψ) = 1293 ± 42 (stat.) ± 75 (syst.) μb

  σ_{Ap} (J/ψ from b) = 118.2 ± 6.8 (stat.) ± 11.7 (syst.) μb

- Prompt J/ψ cross section about 10 times higher than J/ψ from b

➢ similar to the values observed in *pp* collisions at 2.76, 7 and 8 TeV

  [JHEP 02 (2013) 041], [EPJC (2011) 71 1645], [JHEP 06 (2013) 064]

Summary of systematic uncertainties

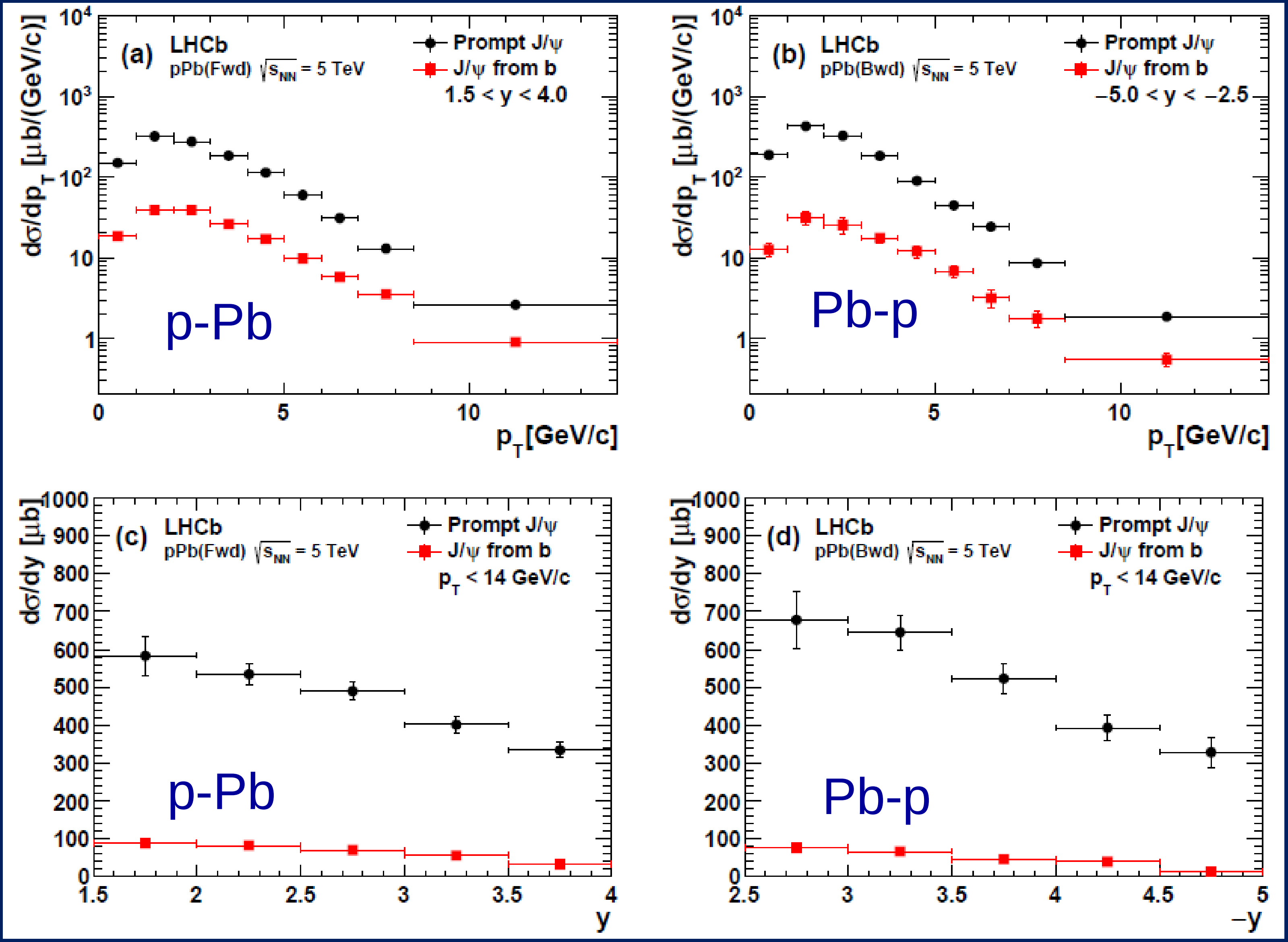
Source of systematic uncertainties: [JHEP 02 (2014) 072]

Source	Forward (%)	Backward(%)
Correlated between bins		
Mass fit from checking dimuon mass with double Crystal Ball	2.3	3.4
Radiative tail with dimuon mass below signal region	1.0	1.0
Muon identification from "tag and probe"	1.3	1.3
Track reconstruction efficiency from pp / pA multiplicity difference	1.5	1.5
Luminosity calibration	1.9	2.1
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$ from PDG	1.0	1.0
Uncorrelated between bins		
$y - p_T$ binning (difference simulation and data)	0.1 – 8.7	0.1 – 6.1
Reweighting of track multiplicity in simulation comp. to no reweighting	0.1 – 3.0	0.2 – 4.3
t_z fit on non-prompt J/ψ by extraction with *s-Plot*	0.2 – 12.0	0.2 – 13.0

→ Systematics are dominated by the fit model and data-MC agreement

- No uncertainty assigned to the effect of $J\psi$ polarisation, but effect measured to be small

Single differential cross-sections

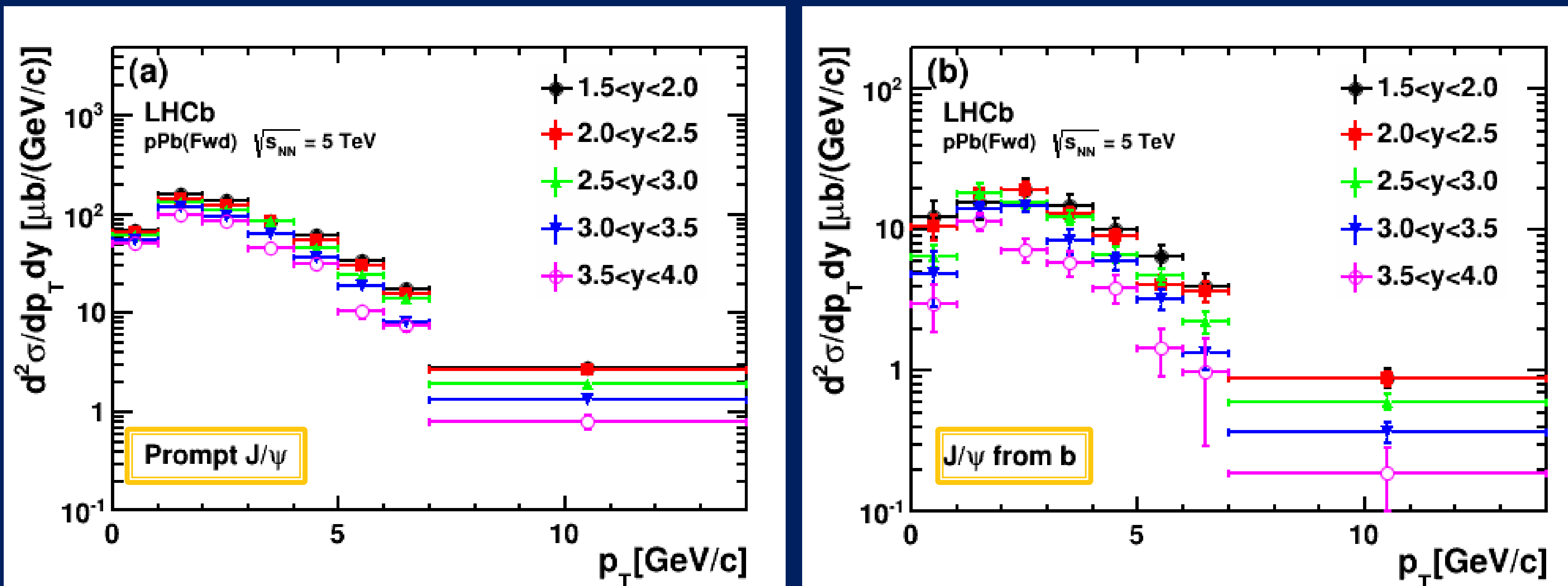


[JHEP 02 (2014) 072]

Double differential cross-section

Forward direction (p-Pb):

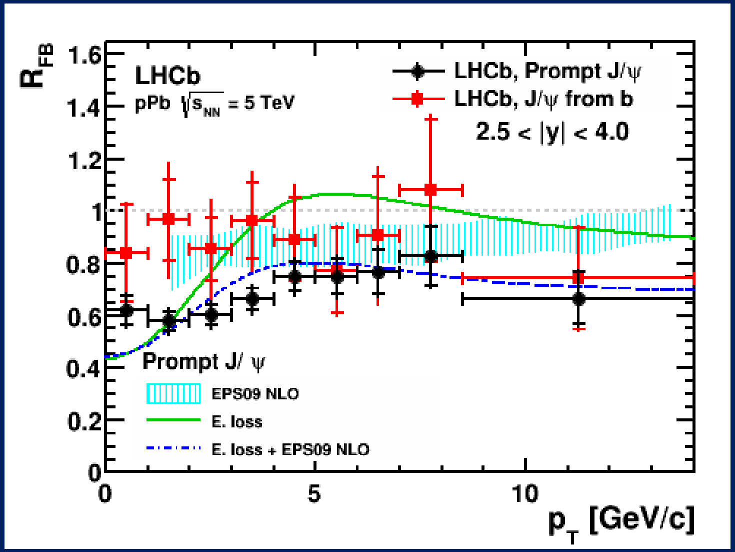
[JHEP 02 (2014) 072]

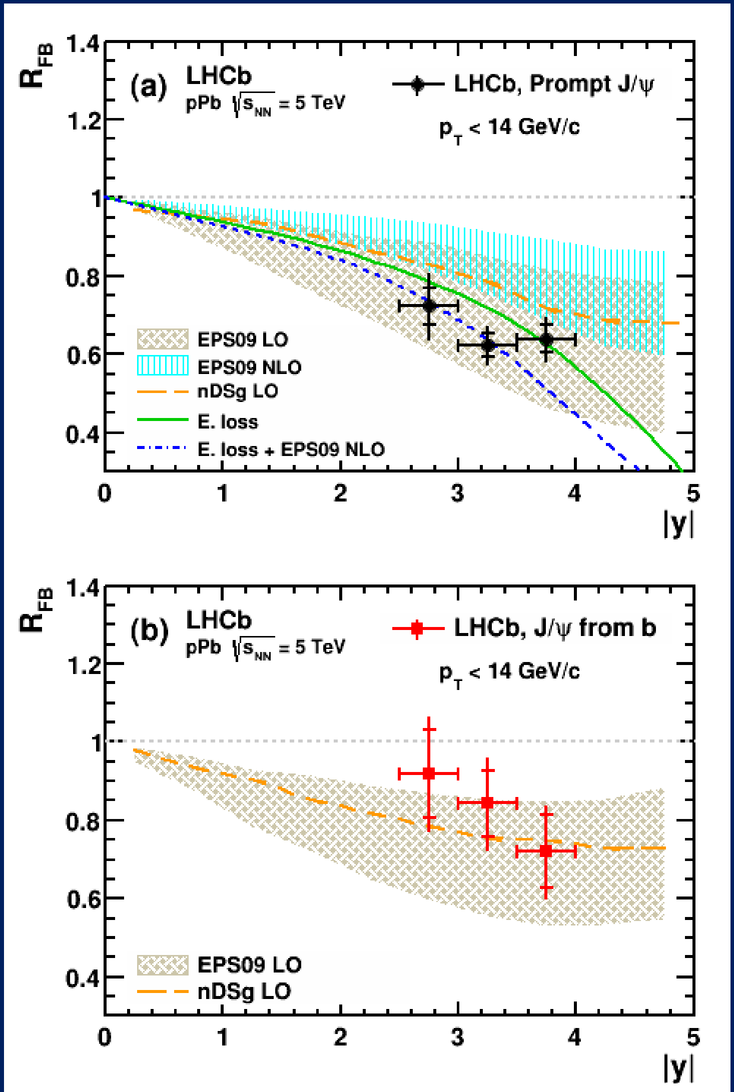


Insufficient statistics for double differential cross-section in the backward direction

Forward-backward asymmetry

- Clear forward-backward asymmetry
- Agreement with theoretical predictions, but currently unable to distinguish between different models.





Data: JHEP 02 (2014) 072
Models: JHEP 03 (2013) 122 , JHEP 05 (2013) 155
PRC 88 (2013) 047901, NPA 926 (2014) 236

Reference J/ψ cross-section in pp

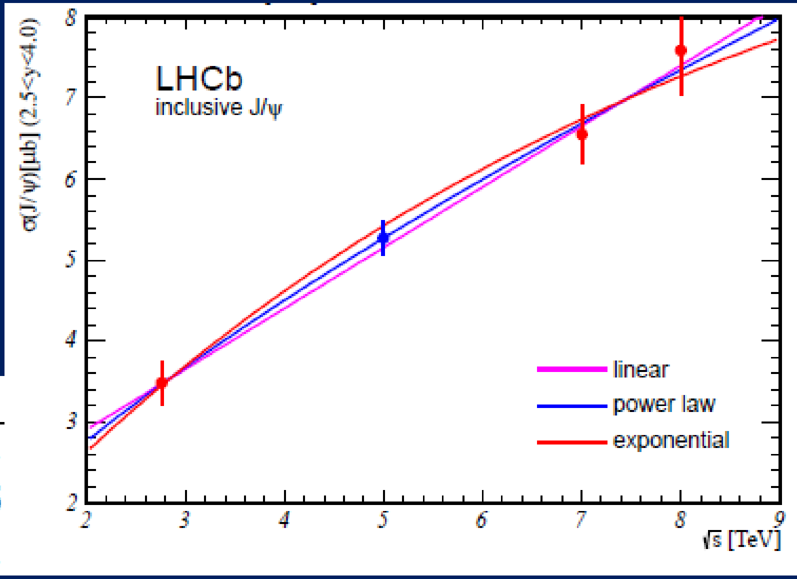
- J/ψ production cross-section in pp collisions at 5 TeV needed for the determination of the nuclear modification factor.
  - Interpolation from measurements at 2.76 TeV, 7 TeV and 8 TeV
  - Rescaling to common rapidity range: $2.5 < y < 4.0$

[LHCb-CONF-2013-013]

- Interpolation functions:

$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}\, p_1 \\ (\sqrt{s}/p_0)^{p_1}{}_1 \\ p_0(1 - \exp(-\sqrt{s}/p_1)) \end{cases}$$

linear
power-low
exponential



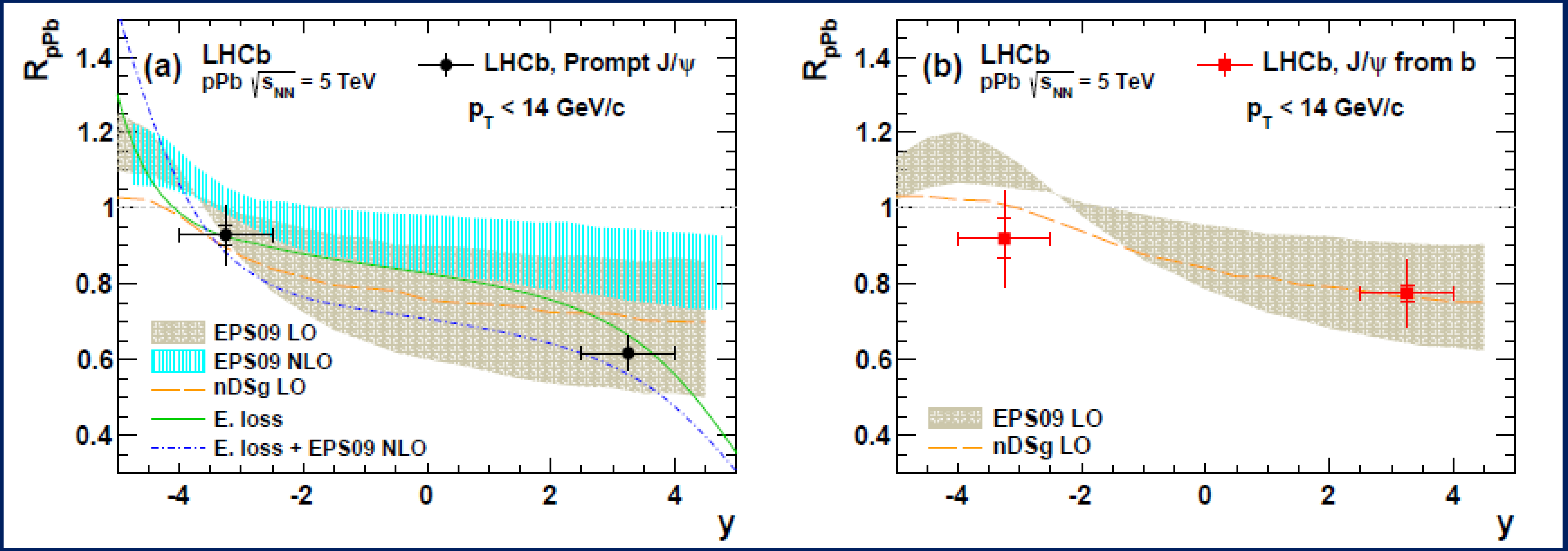
- Interpolated cross-sections:

model	prompt J/ψ	inclusive J/ψ	J/ψ from b
linear	4.68 ± 0.21	5.15 ± 0.23	0.473 ± 0.031
power law	4.79 ± 0.22	5.27 ± 0.24	0.468 ± 0.036
exponential	4.94 ± 0.25	5.42 ± 0.27	0.481 ± 0.031

- Values from power-law extrapolation have been chosen
- Functions checked against predictions of LO-CEM and FONLL

Nuclear modification factor

- Nuclear modification factor $R_{pPb}(y)$:
  - Agreement with theoretical predictions
  - Current precision insufficient to distinguish nuclear effects with or without saturation [JHEP 02 (2014) 072]



  - Inner error bars stat., outer error bars stat. and syst. added in quadrature

Theoretical predictions from JHEP 03 (2013) 122, JHEP 05 (2013) 155
PRC 88 (2013) 047901, NPA 926 (2014) 236 and Int.J.Mod.Phys. E22 (2013) 1330007

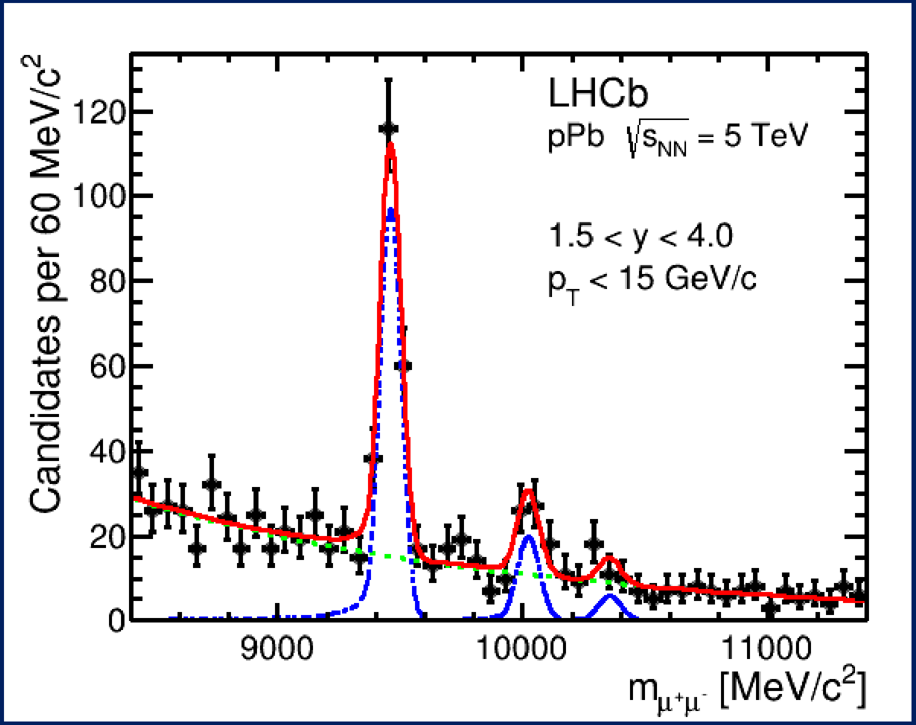
Υ(nS) - production in pPb collisions

reconstruct Υ-states in di-muon channel

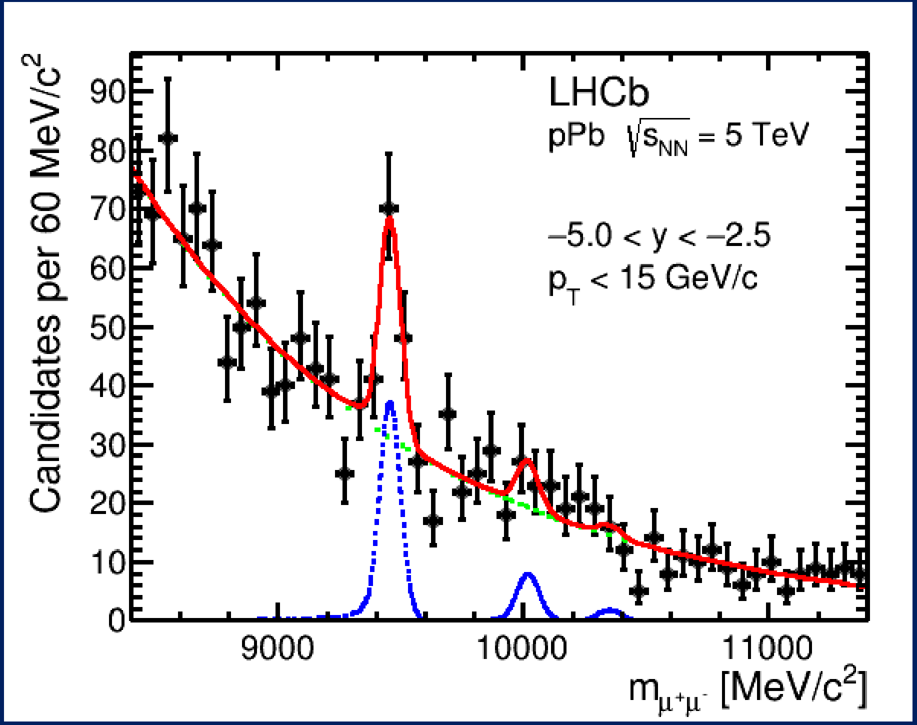
- forward $1.5 < y < 4.0$ and backward $-5.0 < y < -2.5$; $p_T < 15$ GeV
- Mass model: three Crystal-Balls for signal and exponential background
- low statistics errors → No differential measurement

[JHEP 07 (2014) 094]

- Forward production



- Backward production



Υ(nS) - production in pPb collisions

- Cross-section times branching fraction, integrated over p_T and y

$\sigma(\Upsilon(nS)) \times \mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$	Forward	Backward
$\Upsilon(1S)$	$380 \pm 35_{\text{stat}} \pm 19_{\text{syst}}$ nb	$295 \pm 56_{\text{stat}} \pm 27_{\text{syst}}$ nb
$\Upsilon(2S)$	$75 \pm 19_{\text{stat}} \pm 5_{\text{syst}}$ nb	$81 \pm 39_{\text{stat}} \pm 17_{\text{syst}}$ nb
$\Upsilon(3S)$	$27 \pm 16_{\text{stat}} \pm 4_{\text{syst}}$ nb	$<$ 39 nb @ 90 % C.L.

Relative suppression factor $R^{nS/1S}$	**Forward**	**Backward**
$R^{2S/1S}$	$0.20 \pm 0.05_{\text{stat}} \pm 0.01_{\text{syst}}$	$0.28 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$
$R^{3S/1S}$	$0.07 \pm 0.04_{\text{stat}} \pm 0.01_{\text{syst}}$	$<$0.13 @ 90 % C.L.

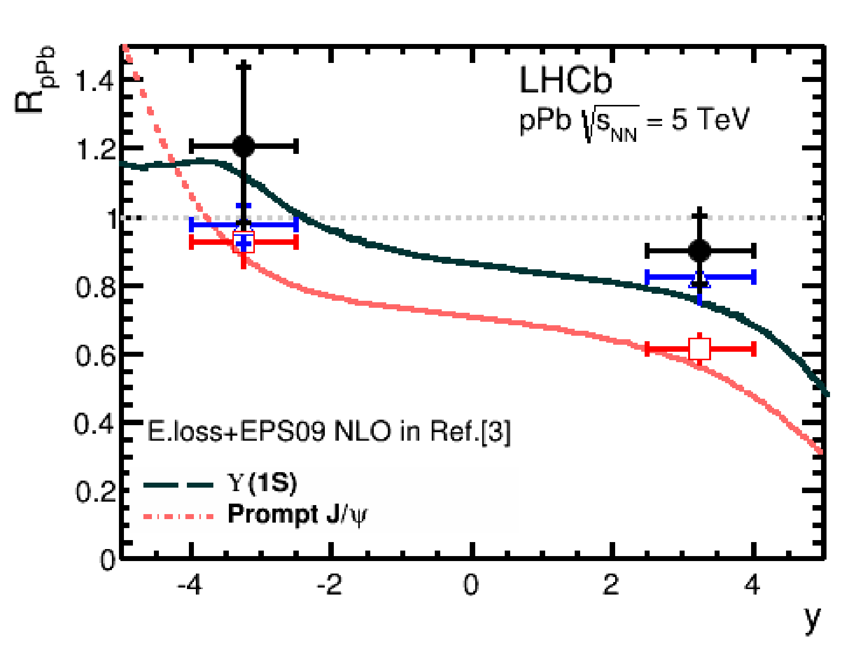
- Statistical uncertainty is dominating

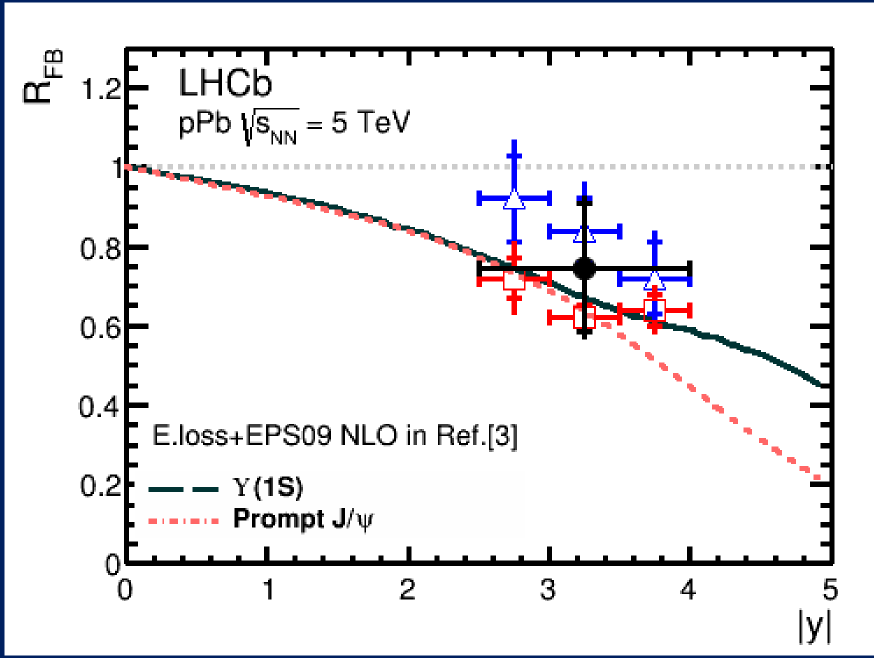
[JHEP 07 (2014) 094]

- Main systematic uncertainties:
  - p_T and y dependence of signal (4% (forward) and 7% (backward)) and trigger efficiency (2% (forward) and 5% (backward))

Υ(1S) – production: CNM effects

- Measurement of R_{pPb} and R_{FB} with Υ(1S) complementary to J/Ψ (probing different x_A) [JHEP 07 (2014) 094]





➢ Cold nuclear effects (CNM) are also visible with Υ(1S) production
  - Suppression in forward region smaller than for J/Ψ
  - Possible enhancement in backward region due to anti-shadowing
  - Agreement with prediction EPS09(NLO) for nPDF and with and without energy loss

Summary and Conclusions

- Study of p-Pb collisions is important to better understand cold nuclear matter effects and for probing some particular QCD physics phenomena
- LHCb recorded a data sample of ~1.6/nb of p-Pb / Pb-p collisions in a unique kinematic range

- A number of interesting measurements has been performed so far:
  - Measurement of J/ψ and Y production cross-section as function of p_{T} and y
    $\rightarrow$ cold nuclear matter effects visible in J/ψ and Υ(1S) production
  - More results are expected soon, e.g. Ψ(2S) production

- Measurements limited by statistics

➢ Looking forward to > 10x more integrated luminosity in LHC Run II

Backup

Check of interpolation with theory

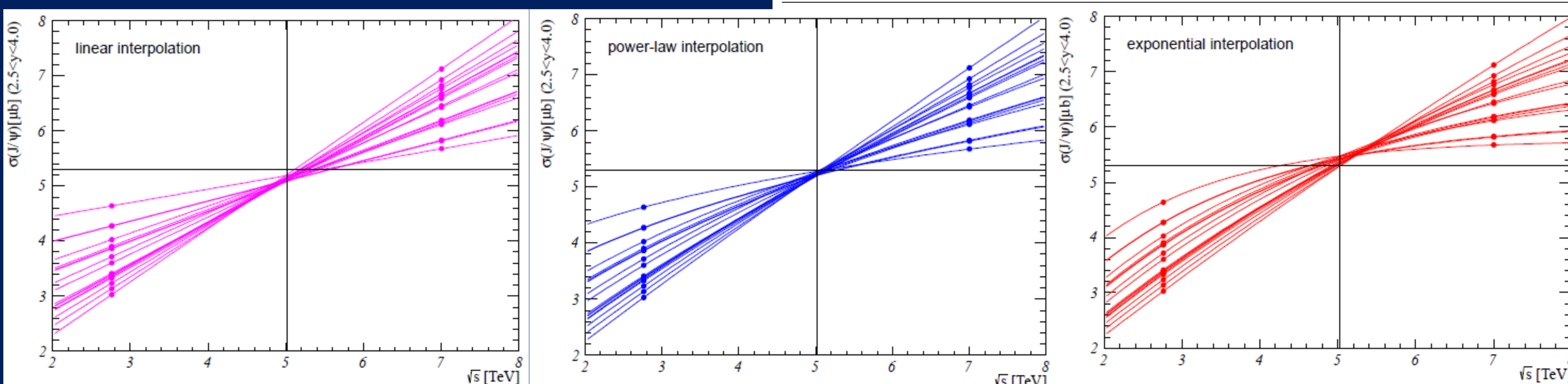
Cross-section predictions from theory:

[LHCb-CONF-2013-013]

- Absolute cross-sections unconstrained
- Cross-sections have been scaled such that the cross-section at 5 TeV is 5.3μb.
- To check the interpolation, adjust parameters of the int. fct. to cross-section values at 2.76 and 7 TeV and compare interpolated value to fixed reference.

→ The power -law parameterisation gets closest to the reference points.

Model/PDF	factorization scale	σ(2.76 TeV)	σ(5.02 TeV)	σ(7 TeV)
LO-CEM/CTEQ6L	m_c, $m_c/2$	4.271	5.300	5.815
LO-CEM/CTEQ6L	$2m_c$	3.382	5.300	6.619
LO-CEM/MRST98L	$m_c/2$	4.294	5.300	5.837
LO-CEM/MRST98L	m_c	3.880	5.300	6.188
LO-CEM/MRST98L	$2m_c$	3.236	5.300	6.820
LO-CEM/CTEQ5L	$m_c/2$	3.891	5.300	6.180
LO-CEM/CTEQ5L	m_c	3.604	5.300	6.450
LO-CEM/CTEQ5L	$2m_c$	3.138	5.300	6.928
LO-CEM/MRST01L	$m_c/2$	4.584	5.300	5.586
LO-CEM/MRST01L	m_c	4.018	5.300	6.131
LO-CEM/MRST01L	$2m_c$	3.391	5.300	6.670
LO-CEM/GRV98L	$m_c/2$	3.697	5.300	6.412
LO-CEM/GRV98L	m_c	3.352	5.300	6.765
LO-CEM/GRV98L	$2m_c$	3.029	5.300	7.124
FONLL	(nominal)	3.331	5.300	6.670
FONLL	(min)	3.872	5.300	6.142
FONLL	(max)	3.413	5.300	6.587

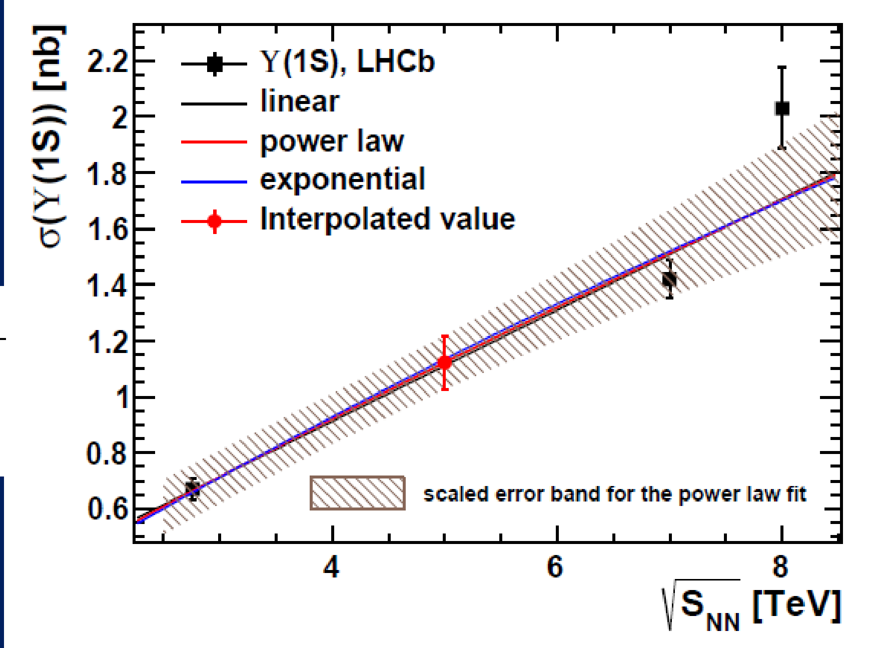


Reference Υ(1S) cross-section in *pp*

[LHCb-CONF-2014-003]

- Use phenomenological functions to fit the experimental data, as for J/Ψ.
  - In the fit the experimental uncertainties are considered uncorrelated
  - The results of the different fits are:

model	interpolated cross section (nb)	$\tilde{\chi}^2$
linear	1.111 ± 0.036	6.73
power law	1.123 ± 0.036	7.06
exponential	1.134 ± 0.038	7.52



  - The uncertainties are obtained by propagation of the unscaled experimental uncertainties.

  → **Fit quality is not satisfactory.**

  - To safeguard against underestimating the uncertainty of the interpolated value, the final experimental uncertainty is obtained by scaling the error of the interpolated value by $\sqrt{\chi^2/\text{ndf}}$.
  - The nominal result is taken to be that from the power-law interpolation, which provides the central curve, as was done for the J/ψ reference cross-section, together with its systematic uncertainty of 4.1%.
- **Result for the reference cross-section:**

$$\sigma(5.02\ \text{TeV}, \Upsilon(1S)) \times \text{BF}(\mu^+\mu^-) = 1.123 \pm 0.096_{\text{exp}} \pm 0.046_{\text{interp.}} = 1.12 \pm 0.11\ \text{nb}.$$