

# Heavy flavour and quarkonium production at the LHC

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presenting results from the ATLAS, CMS and LHCb collaborations

## Outline:

- Conventional quarkonium production and polarization
- Exotic quarkonium production
- B hadron production

Many more results can be found at:

ATLAS: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults>

CMS: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH>

LHCb: <http://cds.cern.ch/collection/LHCb%20Papers?ln=en>

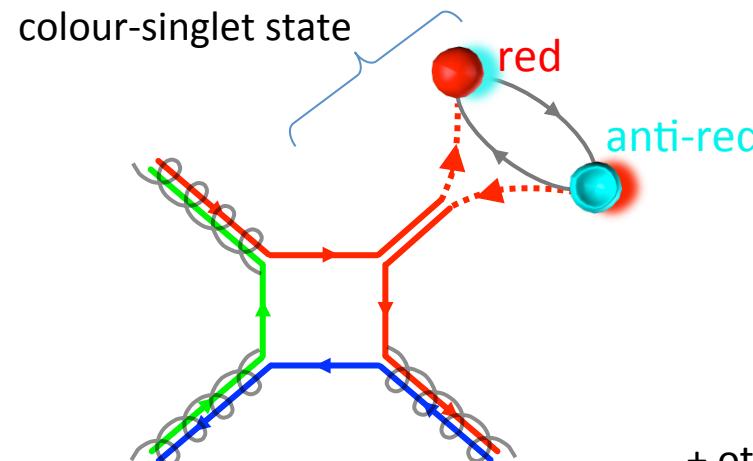
# Quarkonium studies: a one-slide motivation

*the illustrated edition*

- Quarkonia: ideal probes of hadron formation (QCD); but production is not yet understood
- How/when do the observed  $Q\text{-}Q\bar{b}$  bound states acquire their quantum numbers?

- **Colour Singlet Model:**

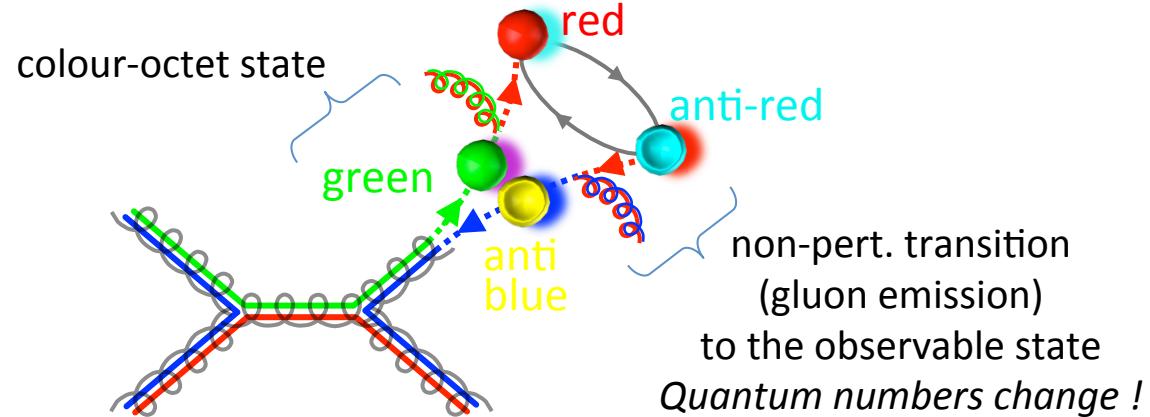
quarkonia always produced directly as observable **colour-neutral**  $Q\text{-}Q\bar{b}$  pairs



+ other colour combinations

- **NRQCD factorization:**

quarkonia also produced as **coloured**  $Q\text{-}Q\bar{b}$  pairs of any possible quantum numbers

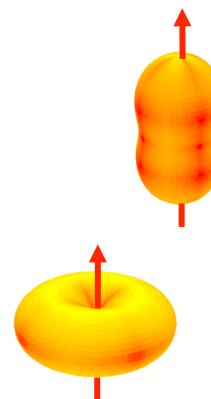


- Two options leading to strong polarizations (longitudinal and transverse, resp.) for the directly-produced S-states → polarization measurements are fundamental

# Polarization (measurements): status before LHC

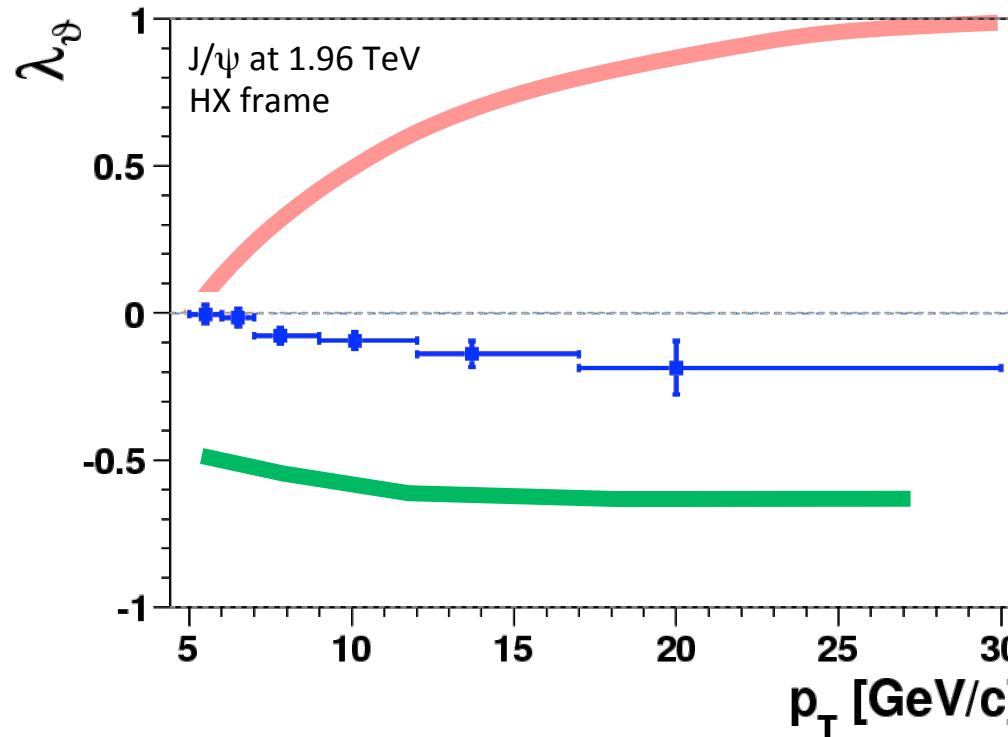
- $J/\psi, \psi', \Upsilon(nS) \rightarrow \mu\mu$
- Polarization measured through the decay angular dist. of  $J = 1$  particles:

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos \varphi$$



$J_z = \pm 1 \rightarrow \lambda_\varphi = +1$   
“transverse” polarization

$J_z = 0 \rightarrow \lambda_\varphi = -1$ :  
longitudinal polarization



## NRQCD factorization

Braaten, Kniehl & Lee, PRD62, 094005 (2000)

## CDF Run II

CDF Coll., PRL 99, 132001 (2007)

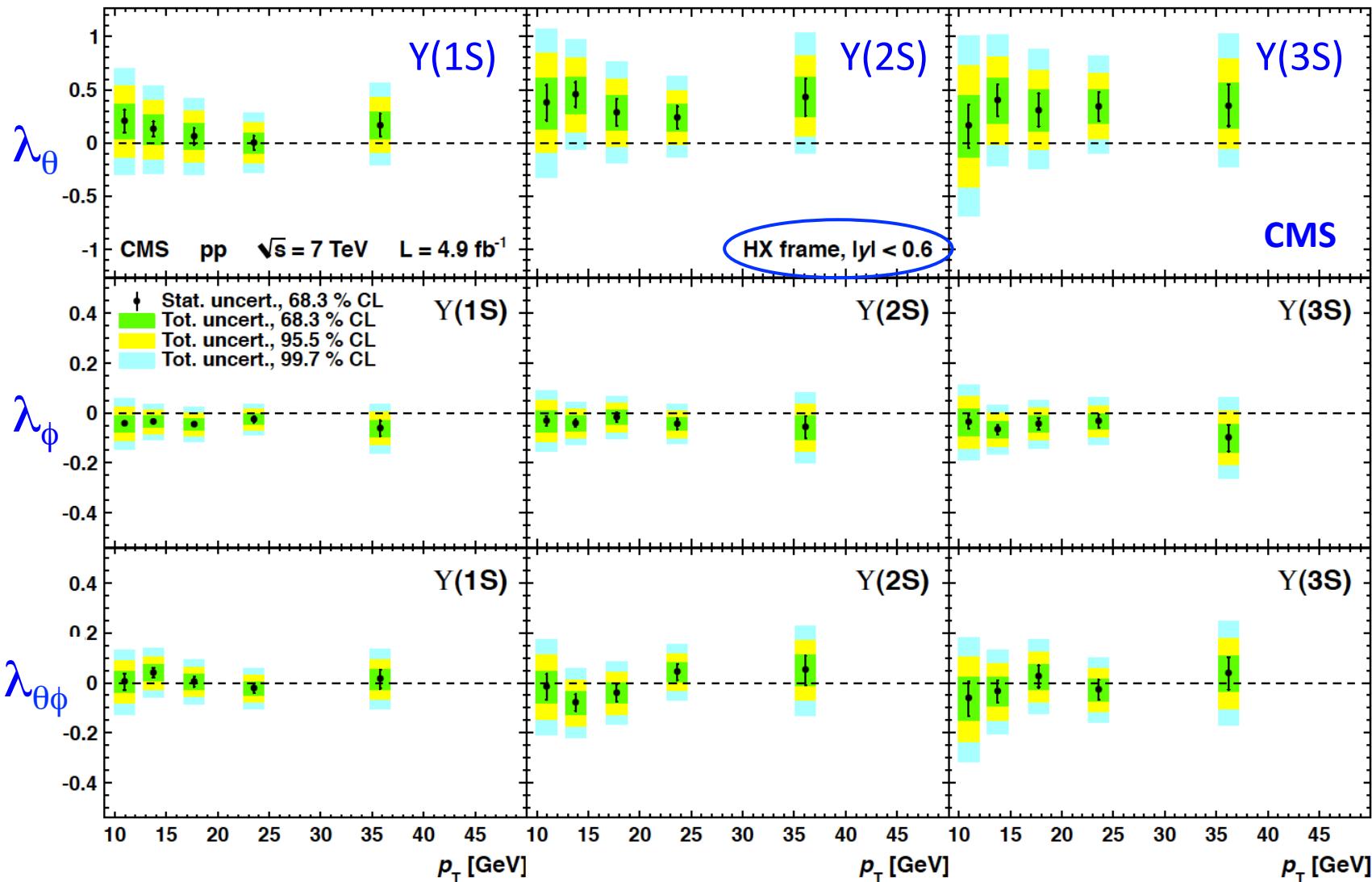
## CSM

Gong & Wang, PRL 100, 232001 (2008)  
Artoisenet et al., PRL 101, 152001 (2008)

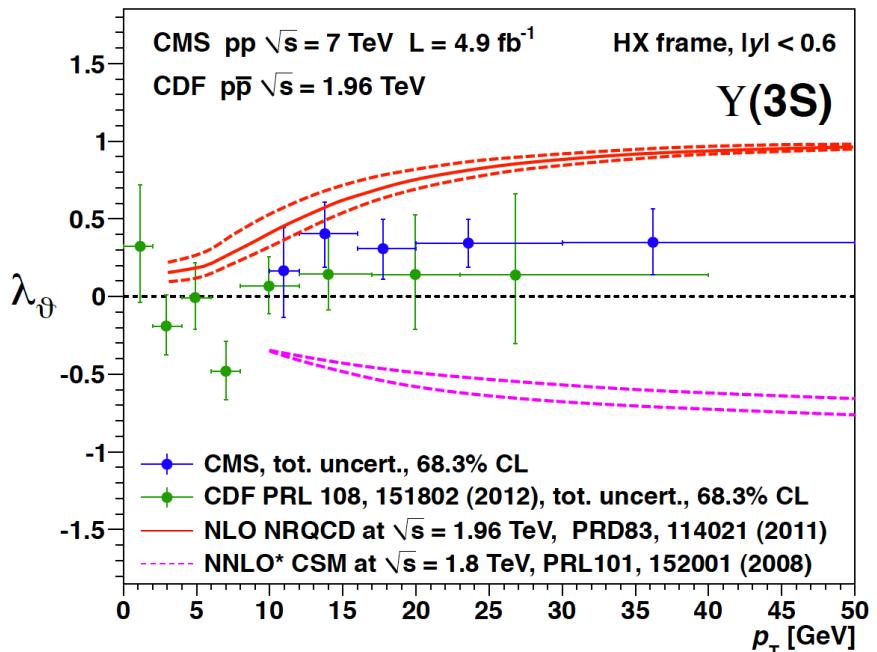
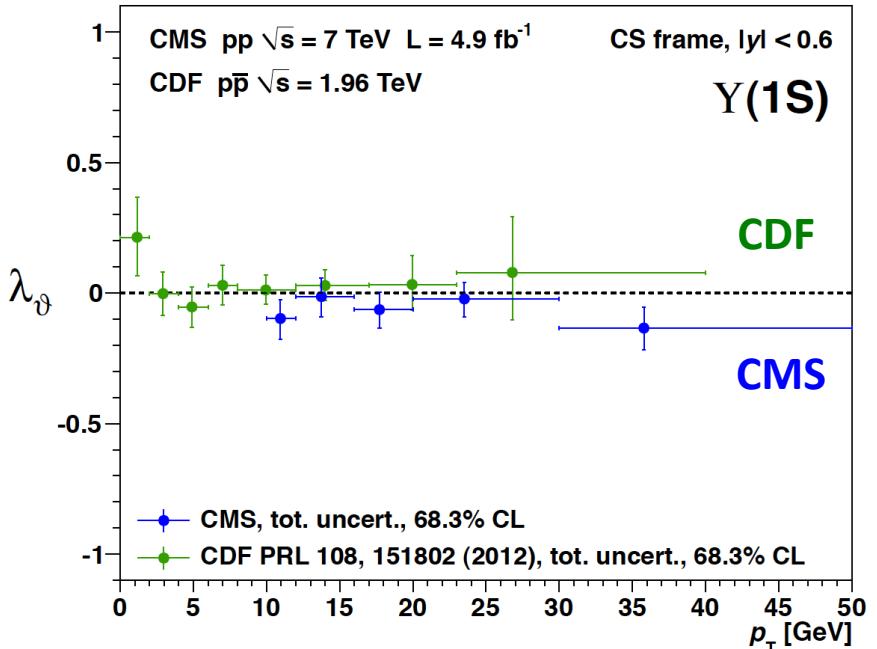
# Upsilon polarization at the LHC

CMS, PRL 110 (2013) 081802

- CMS measured the  $\Upsilon(nS)$  polarizations vs.  $p_T$  in two  $|y|$  bins and three polarization frames: helicity (HX), Collins-Soper (CS) and perpendicular helicity (PX)



- CMS extends the  $p_T$  and  $|y|$  coverage probed by CDF
- Theory is more reliable for  $p_T \gg m$
- $\Upsilon(1S)$  has a very large  $\chi_b$  feed-down contribution, of unknown polarization ...
- $\Upsilon(3S)$  should be almost free from feed-down
- Measured polarizations are much weaker than expected by the theory models



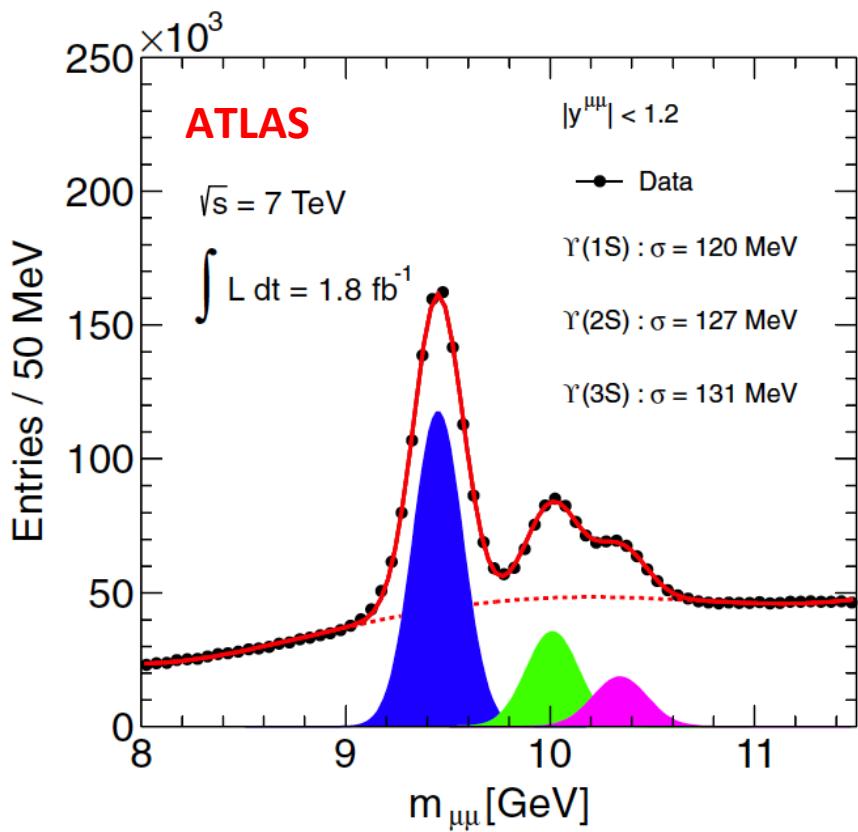
# $\Upsilon(nS)$ production at $\sqrt{s} = 7$ TeV and mid-rapidity



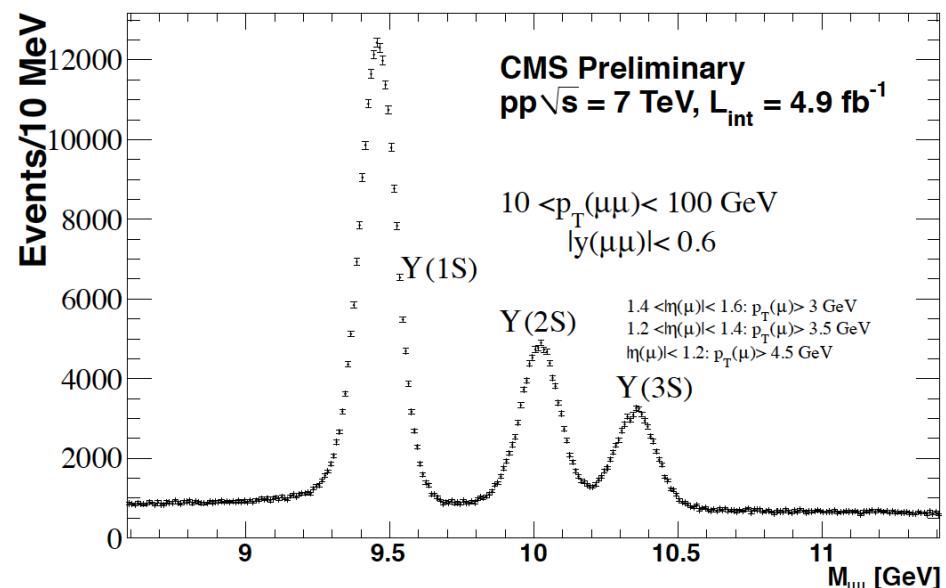
ATLAS, PRD87 (2013) 052004

CMS-BPH-12-006

CMS

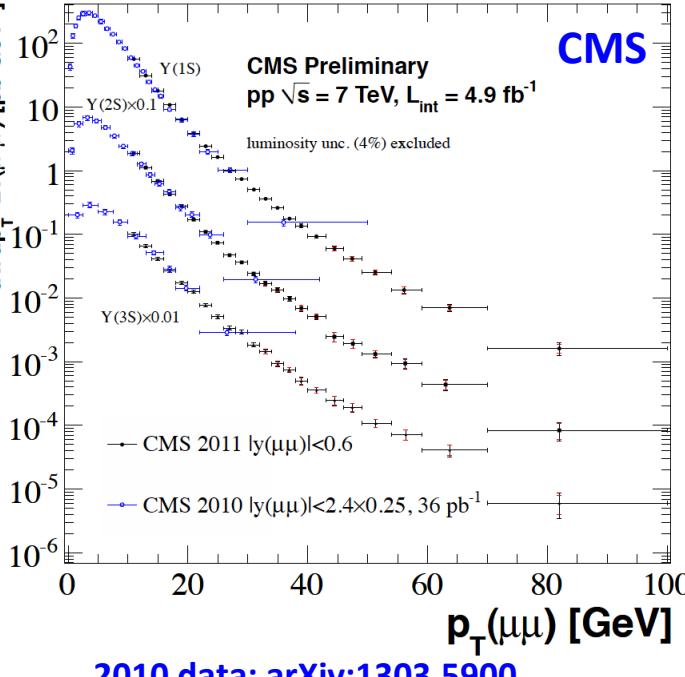
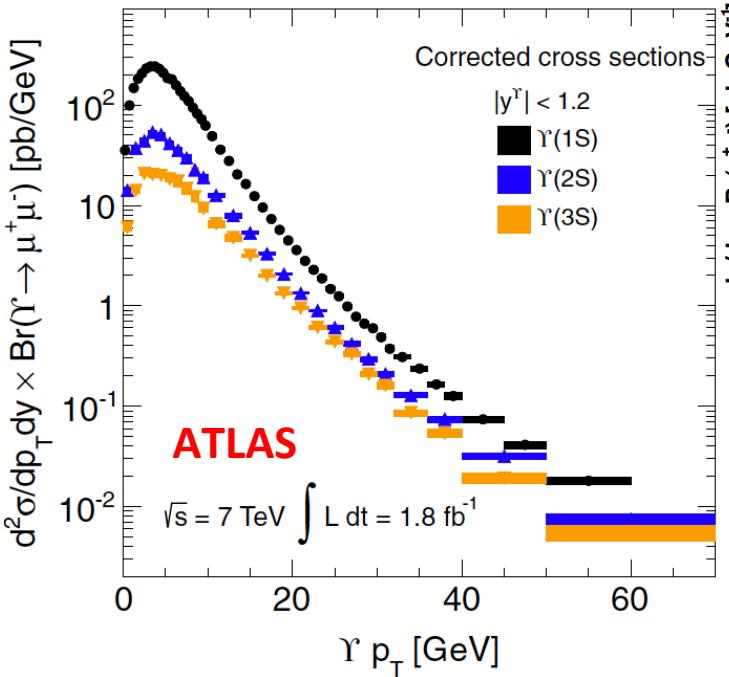


Acceptance assumes unpolarized  $\Upsilon(nS)$

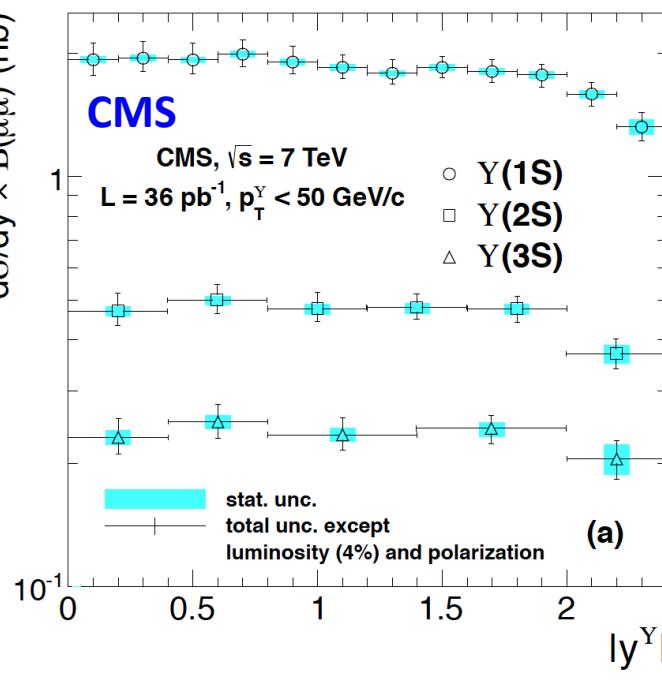
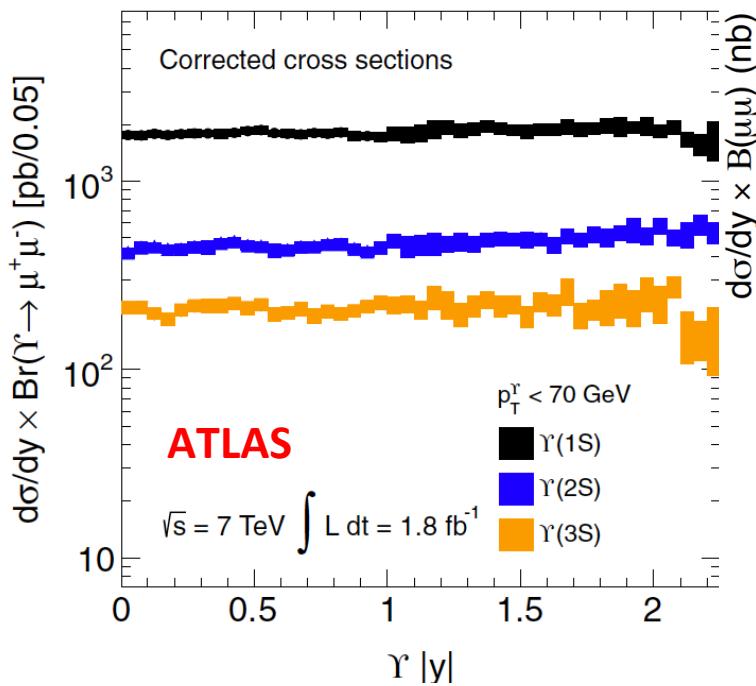


Acceptance from  
measured  $\Upsilon(nS)$  polarization

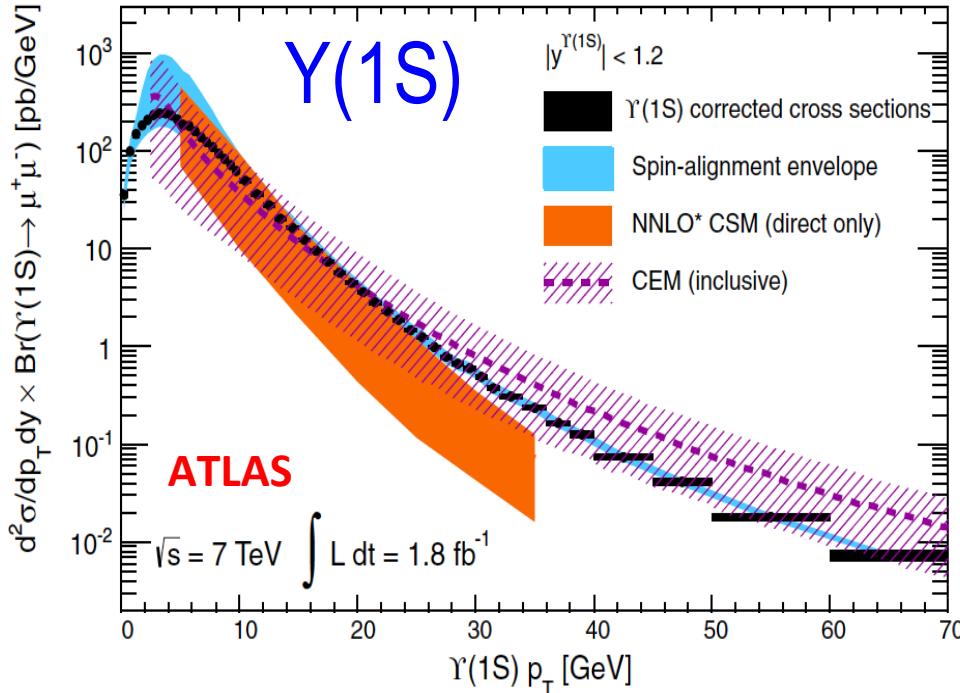
Both experiments evaluated the muon efficiencies from data-driven methods



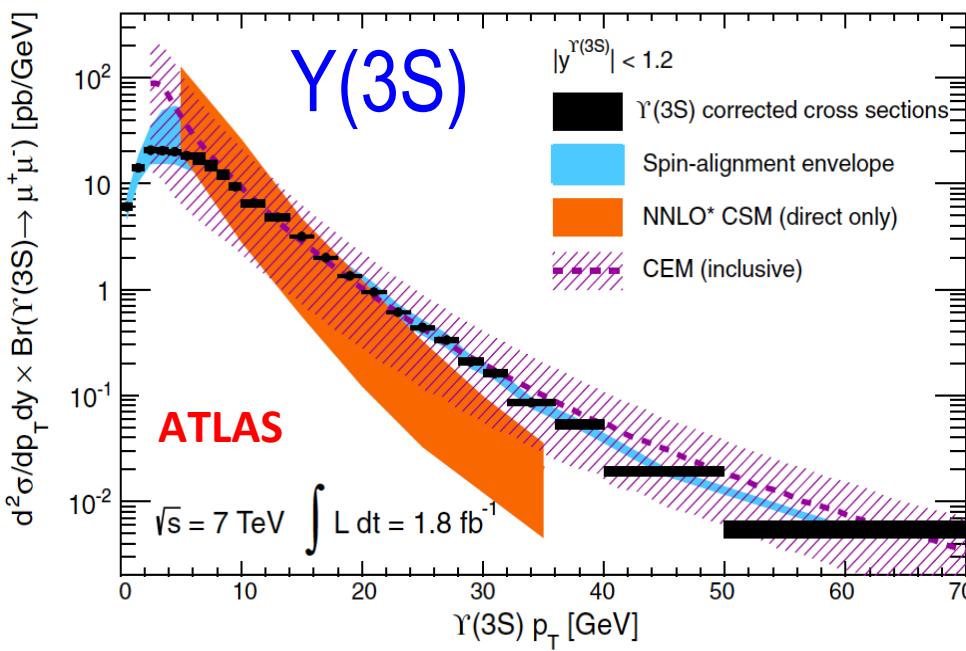
Cross sections measured up to very large  $p_T$  ( $p_T \gg m$ )  
→ stringent QCD test



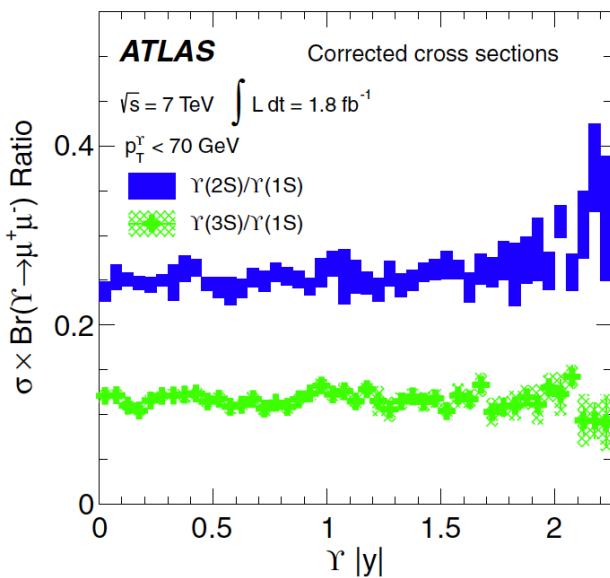
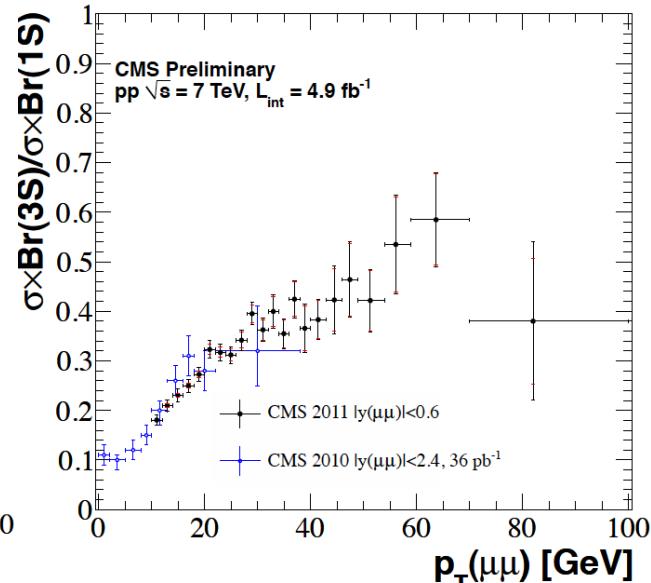
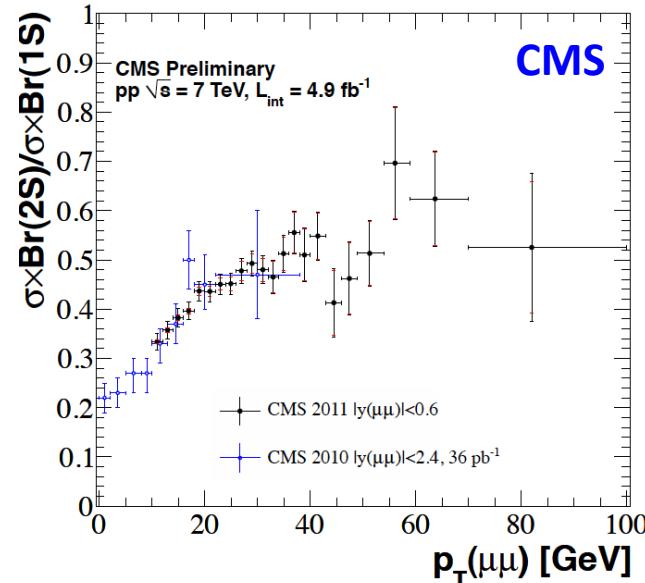
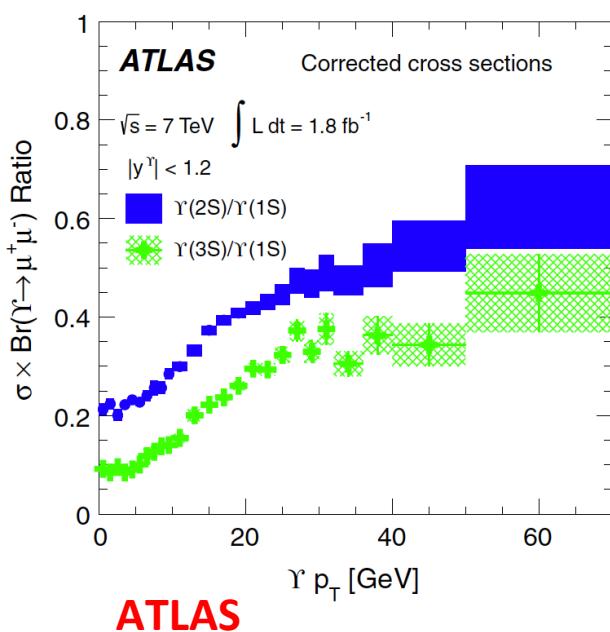
$\gamma(nS)$  cross section is flat until  $|y| \sim 2$



- $\gamma(3S)$  is less affected by feed-down : “easier” comparison to theory
- NNLO\* Colour Singlet Model (CSM) : steeper slope than data
- CEM model shows a fairly reasonable agreement with data for  $p_T > 8 \text{ GeV}$



# $\Upsilon(3S,2S) / \Upsilon(1S)$ production ratios



The  $\Upsilon(nS) / \Upsilon(1S)$  ratios are flat versus rapidity

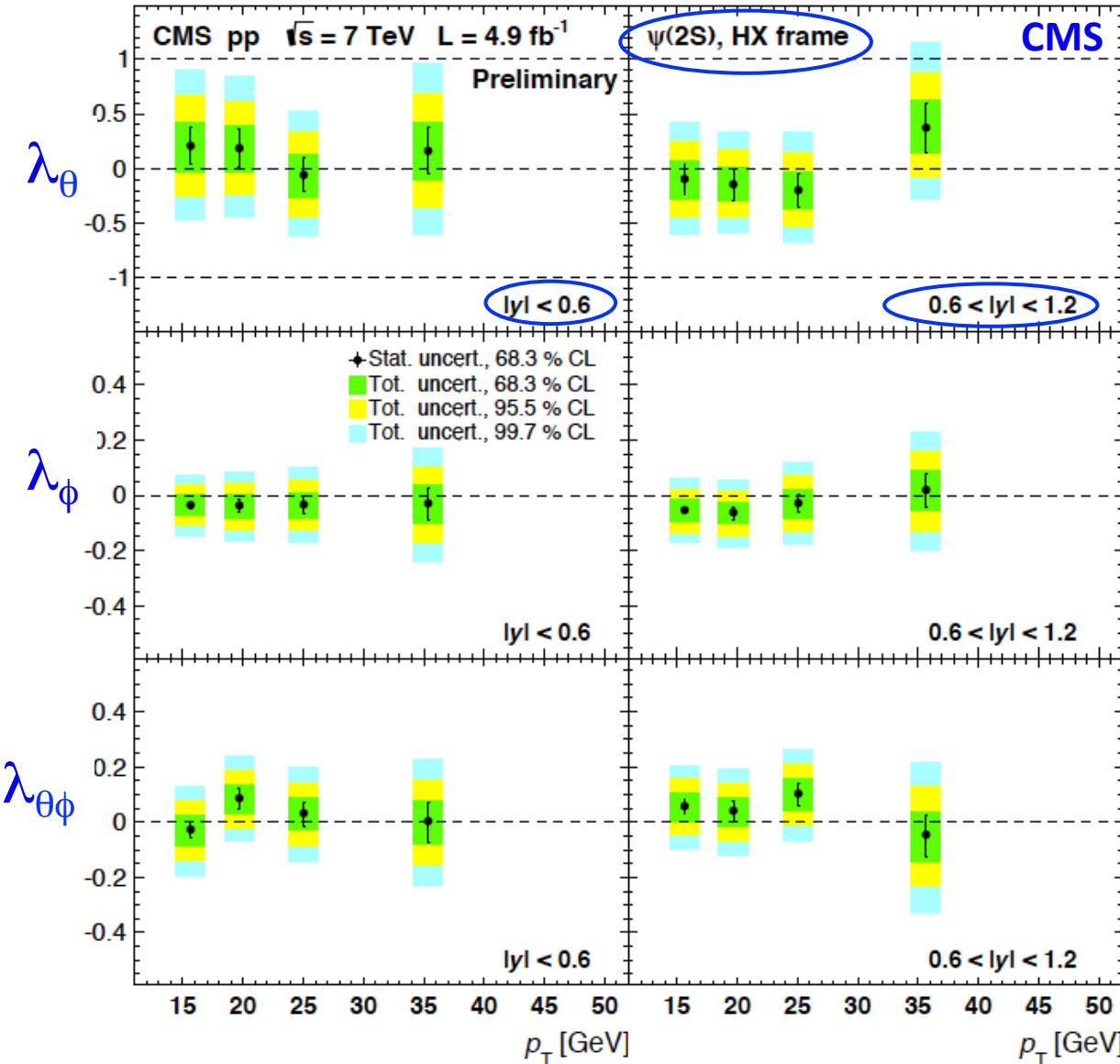
They steadily increase with  $p_T$   
 and seem flatter for  $p_T > \sim 30 \text{ GeV}$

# Prompt $\psi(2S)$ polarization at the LHC

CMS, BPH-13-003

10

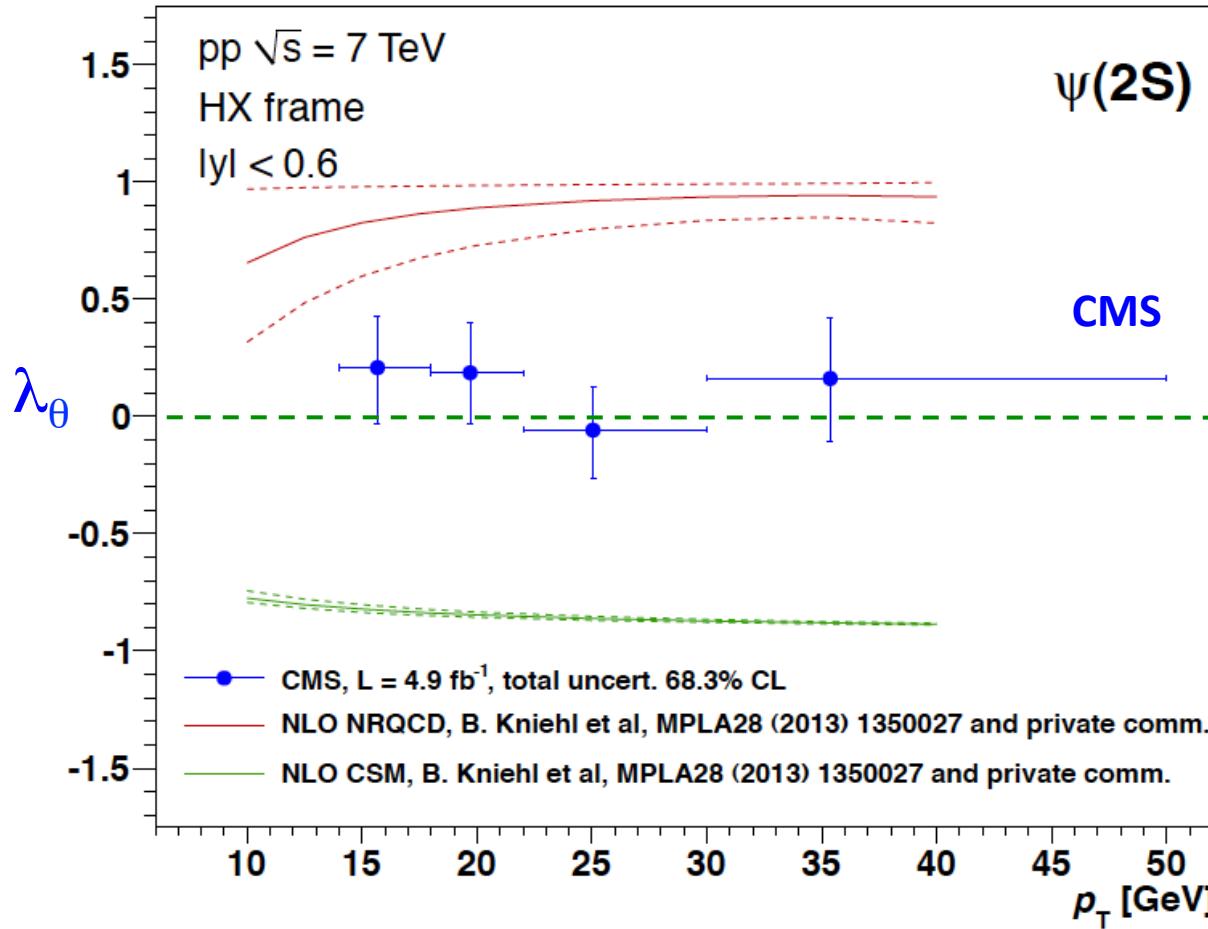
➤ CMS measured the  $\psi(2S)$  polarizations vs.  $p_T$  in two  $|y|$  bins and three polarization frames



➤ Measured polarizations are rather weak

# Prompt $\psi(2S)$ polarization at the LHC: data vs. theory

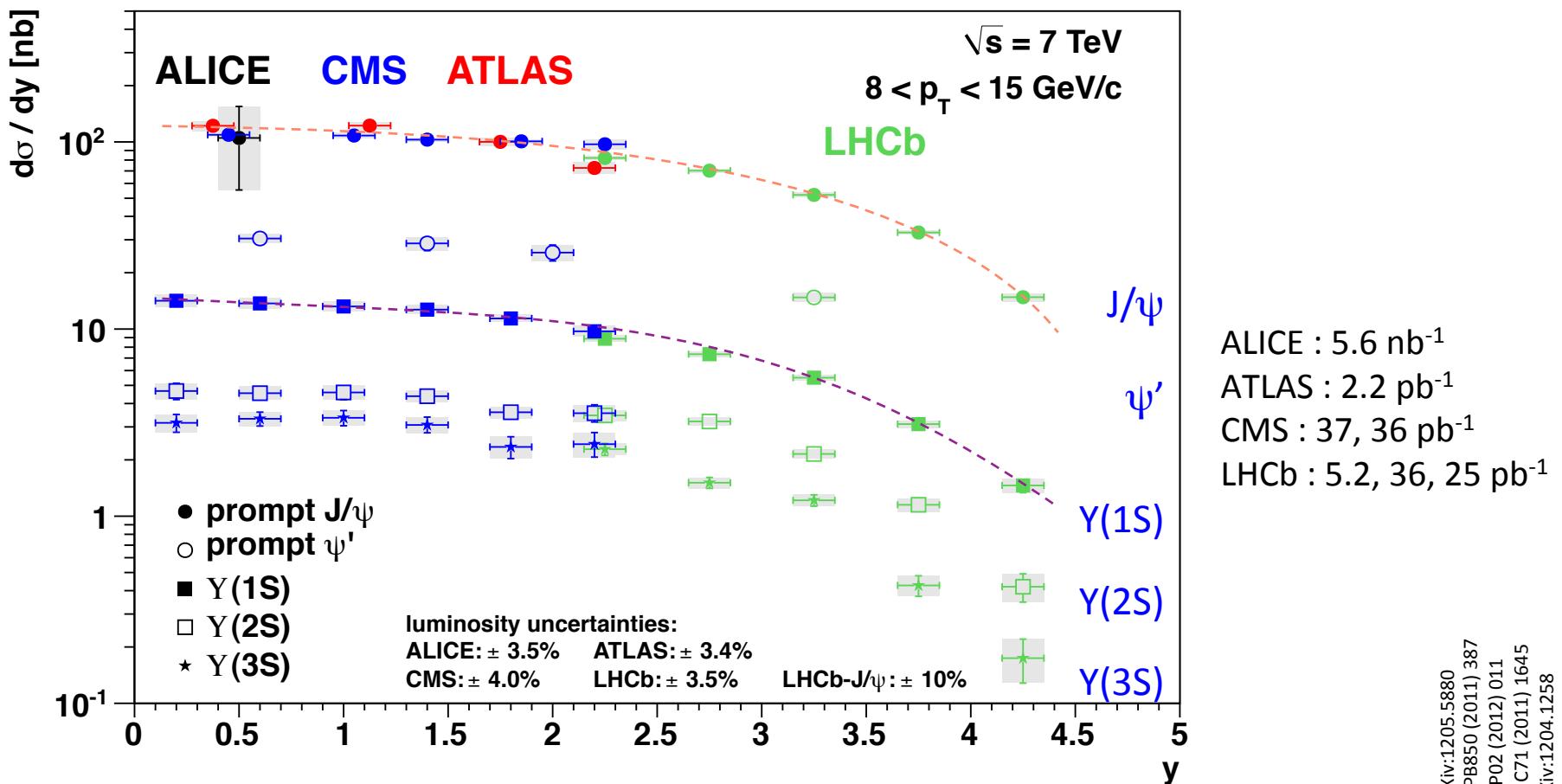
- The  $\psi(2S)$  is not affected by feed-down → we measure the *directly* produced  $\psi(2S)$



- Measured polarizations are much weaker than expected by NRQCD

# A compilation of quarkonium cross sections at $\sqrt{s} = 7$ TeV

- Prompt J/ $\psi$  production has been measured by four LHC experiments for  $p_T > 8$  GeV/c
- Rapidity dependences (of ATLAS, CMS and LHCb) are similar but not perfectly overlapping
- CMS and LHCb trends can also be compared for prompt  $\psi'$  and for the three Upsilon states

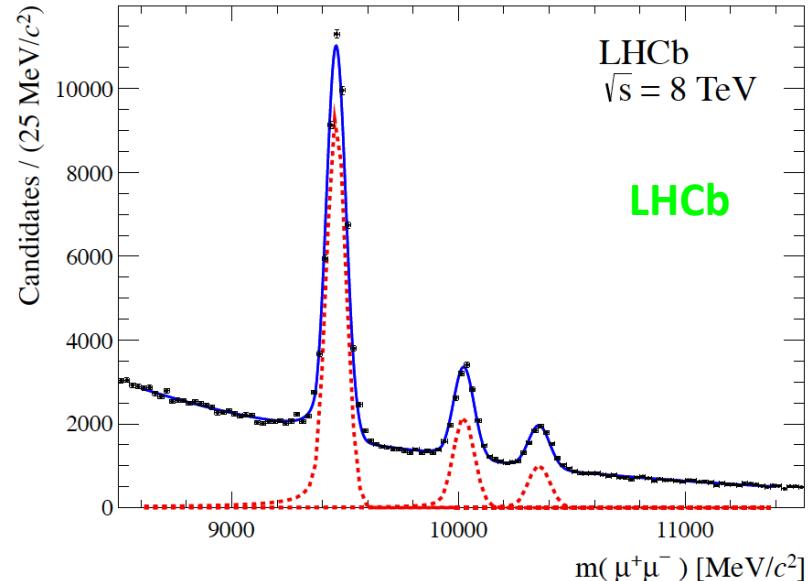
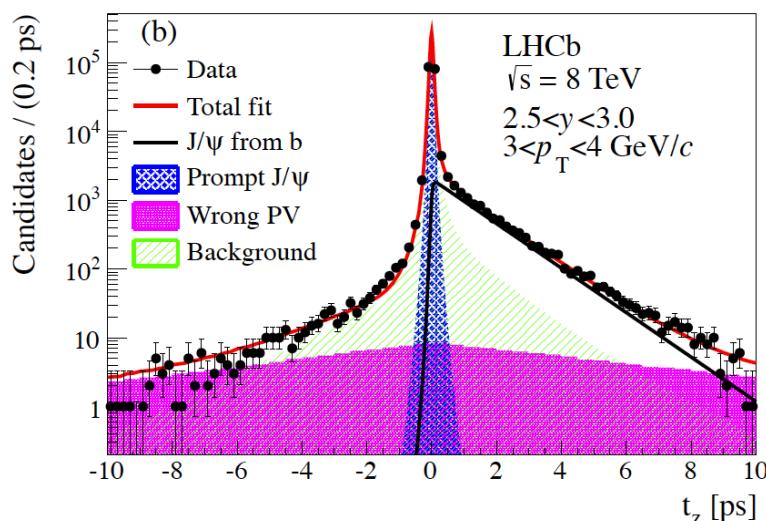
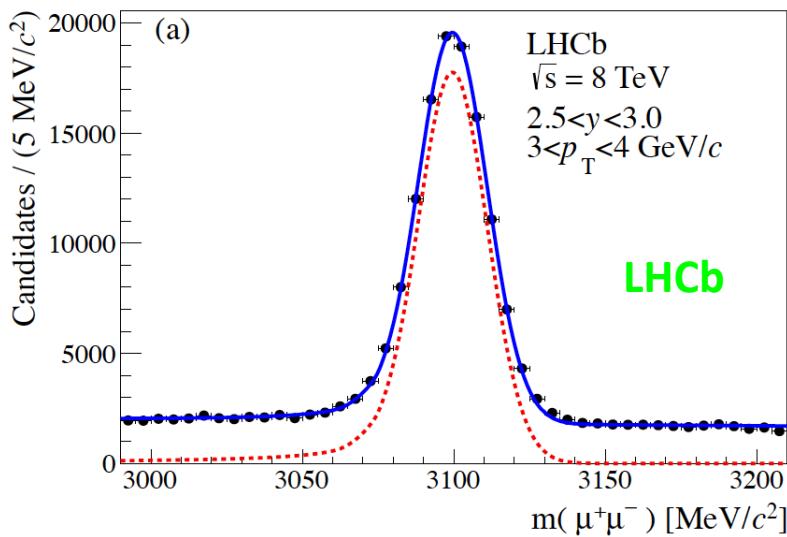


Note: the lines do not represent any theoretical model;  
they are added to help guiding the eye through the points

# J/ $\psi$ and Y production at $\sqrt{s} = 8$ TeV

LHCb, arXiv:1304.6977

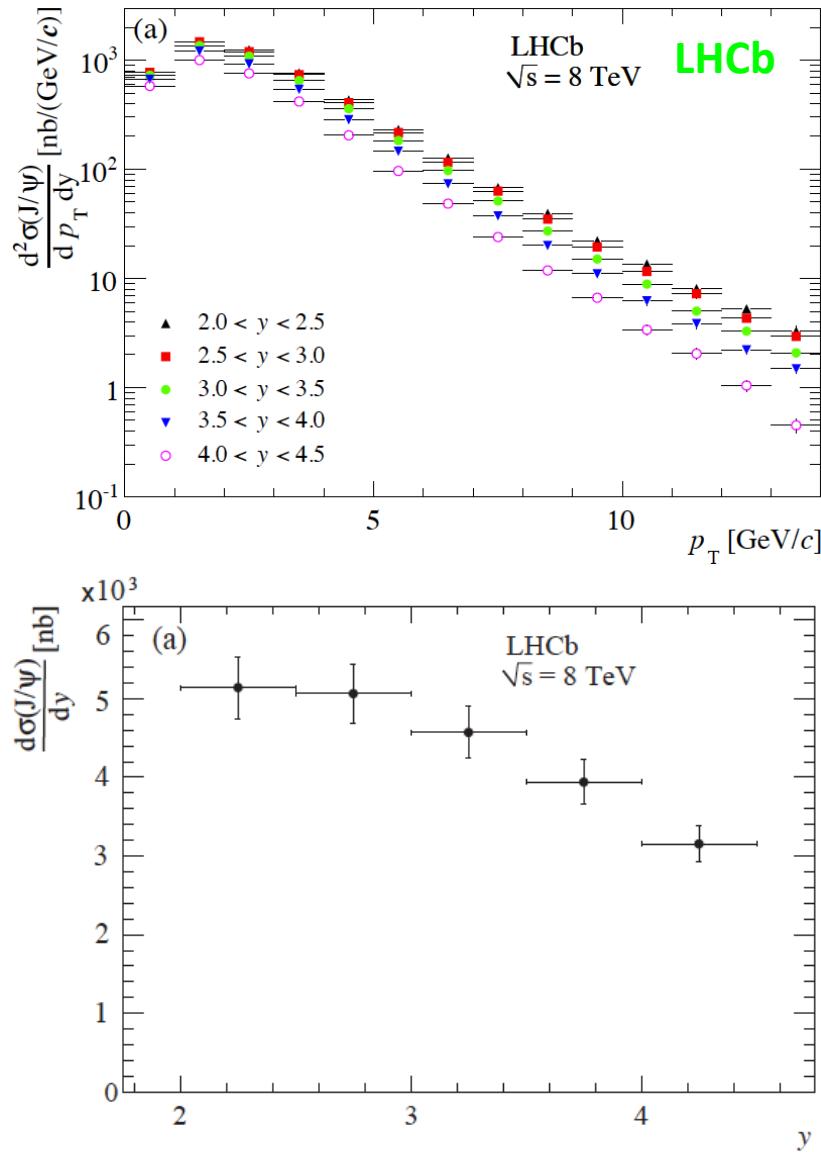
- Quarkonium cross sections measured at  $\sqrt{s} = 8$  TeV,  $2.0 < y < 4.5$ ,  $p_T < 14$  (15) GeV for J/ $\psi$  (Y)
- $L_{\text{int}} = 18.4 \pm 0.9 \text{ pb}^{-1}$  (J/ $\psi$ ) and  $50.6 \pm 2.5 \text{ pb}^{-1}$  (Y)
- 2.6 Mio. inclusive J/ $\psi$  and 44 k Y(1S), 11 k Y(2S) and 5k Y(3S)



Prompt J/ $\psi$  are isolated from background and  $B \rightarrow J/\psi X$  decays through a 2D mass vs. lifetime fit, using the longitudinal decay time  $t_z$ ,

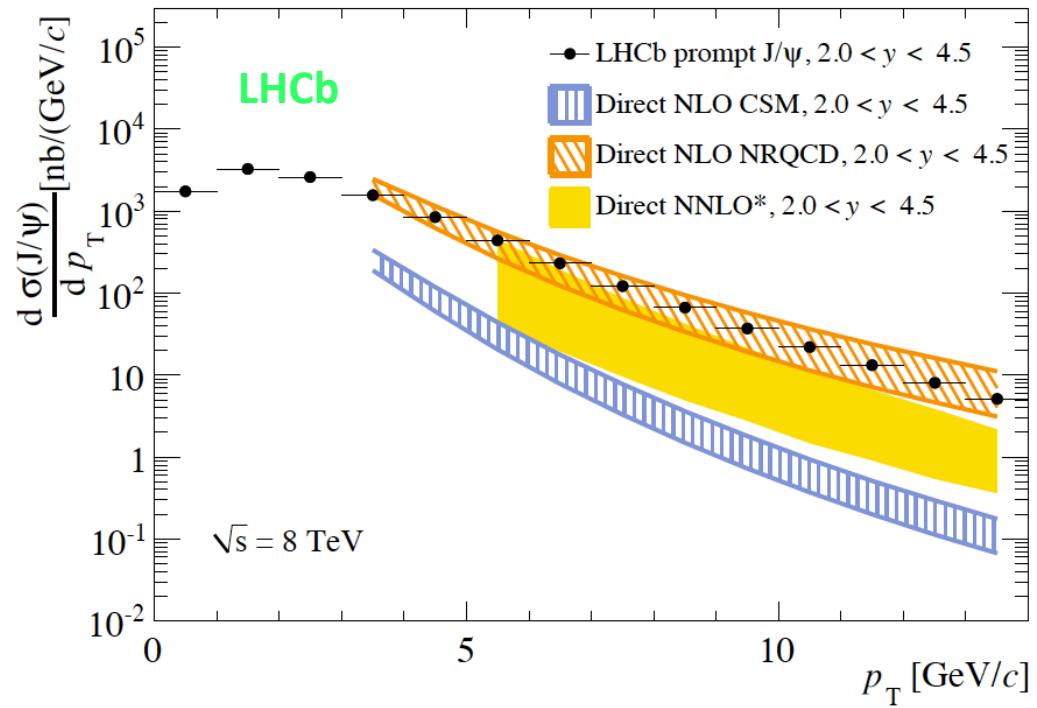
$$t_z = \frac{(z_{J/\psi} - z_{\text{PV}}) \times M_{J/\psi}}{p_z}$$

Acceptance calculations assume zero polarization; given the weak polarizations measured by ALICE and CMS, no corresponding systematic uncertainty is assigned



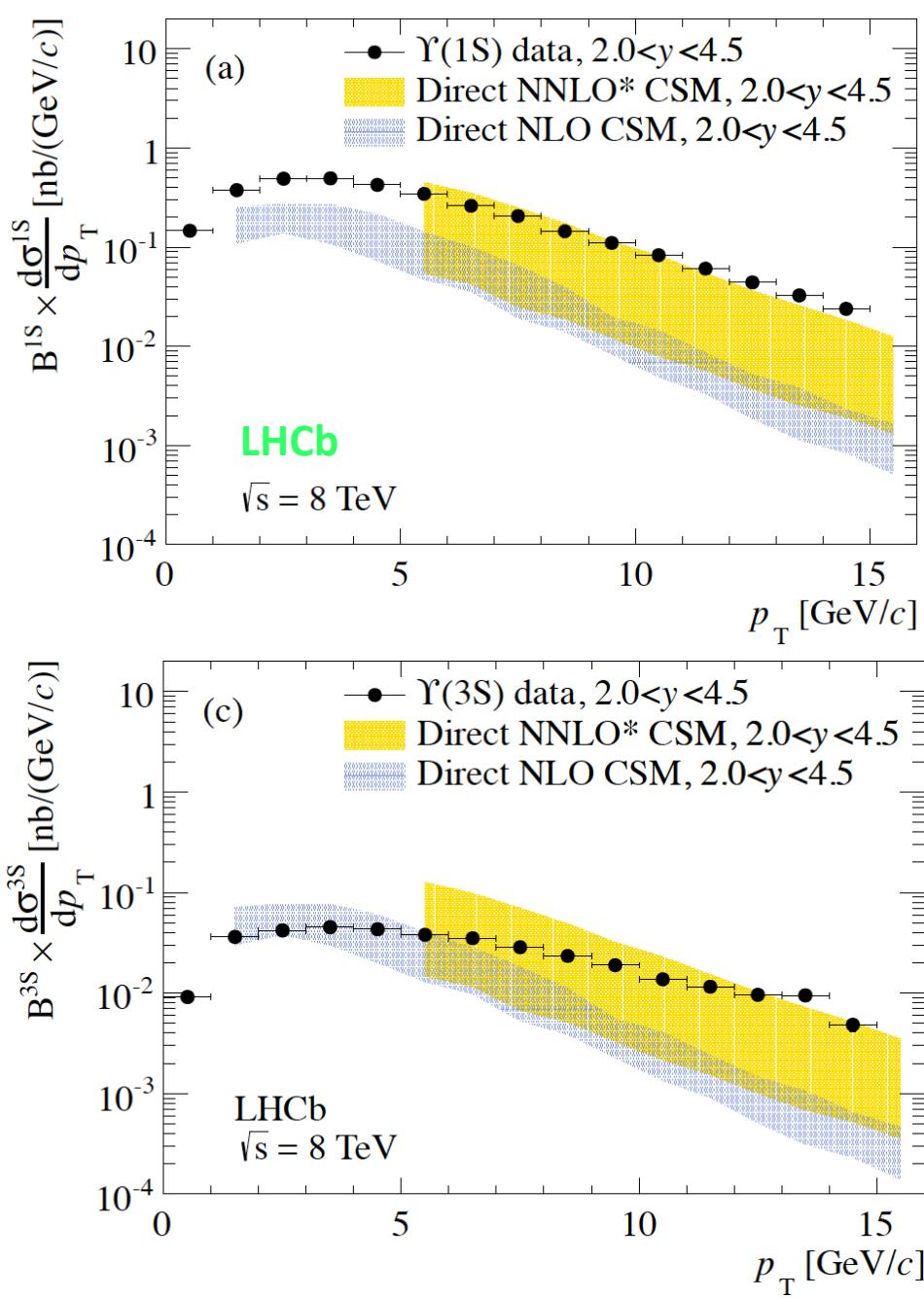
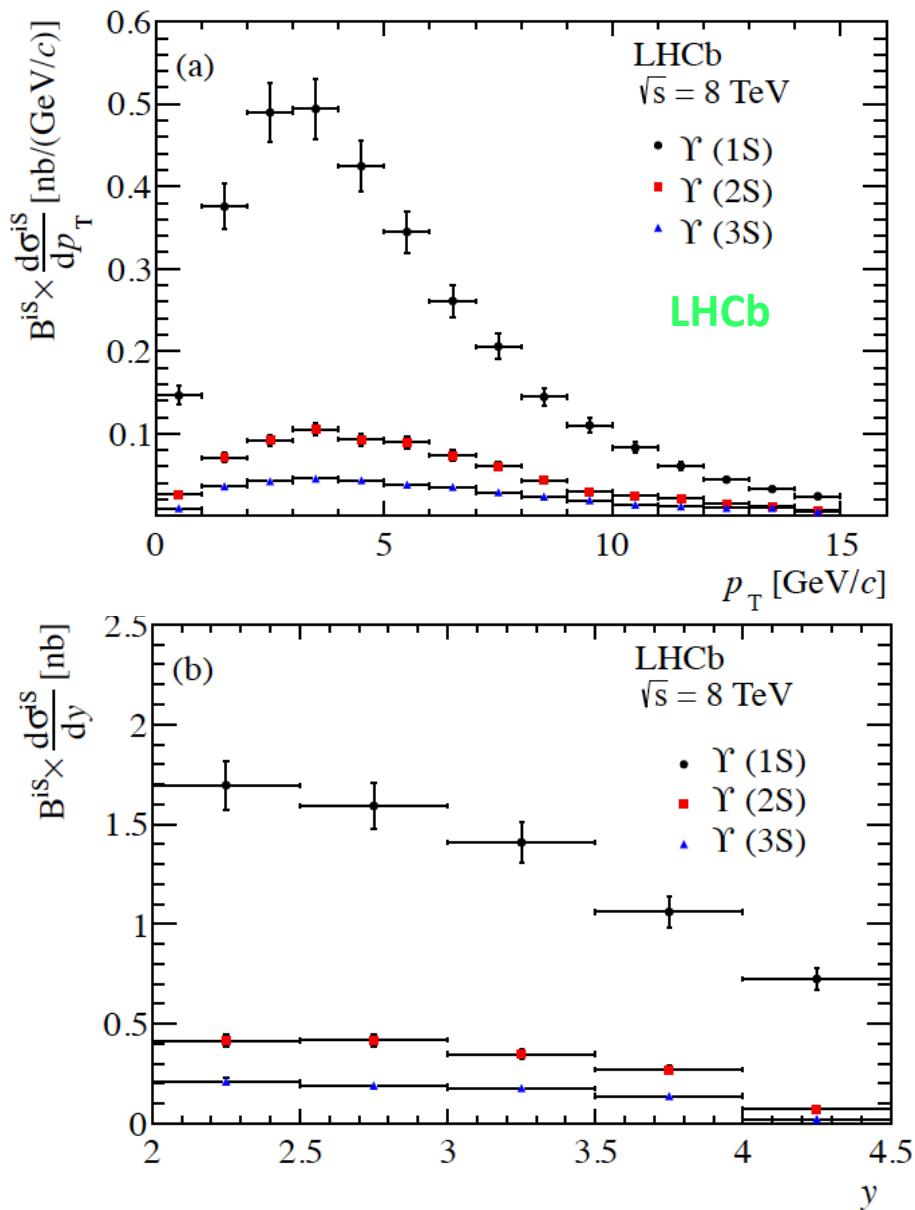
### Prompt $J/\psi$ :

- Large data samples: double differential x-sections
- Cross section decreases for large rapidities
- Calculations performed for direct  $J/\psi$ 's
- Need to account for feed-down from  $\chi_c$  and  $\psi'$
- NLO NRQCD and NNLO\* CSM describe the data



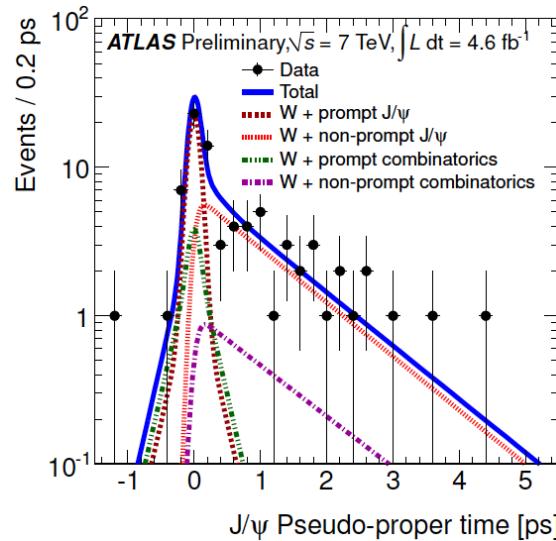
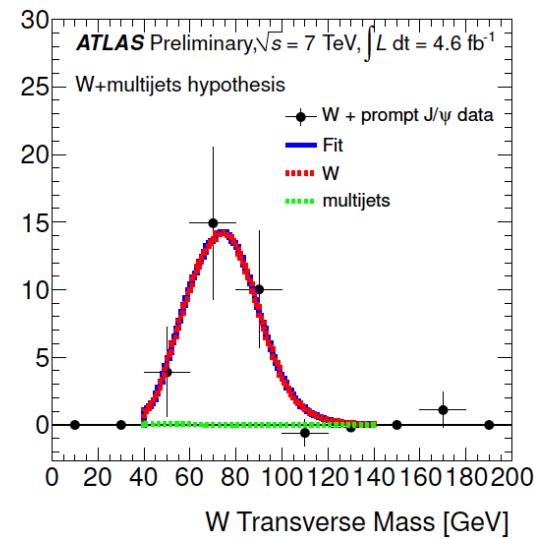
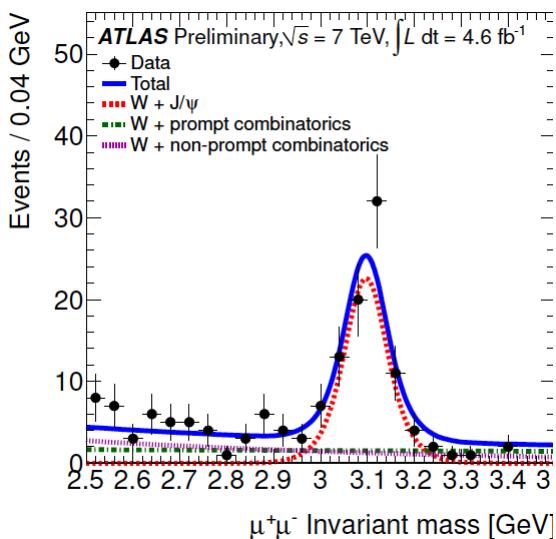
## $\Upsilon(nS)$ production:

- Feed-down not included in calculations
- NNLO\* CSM describes the data



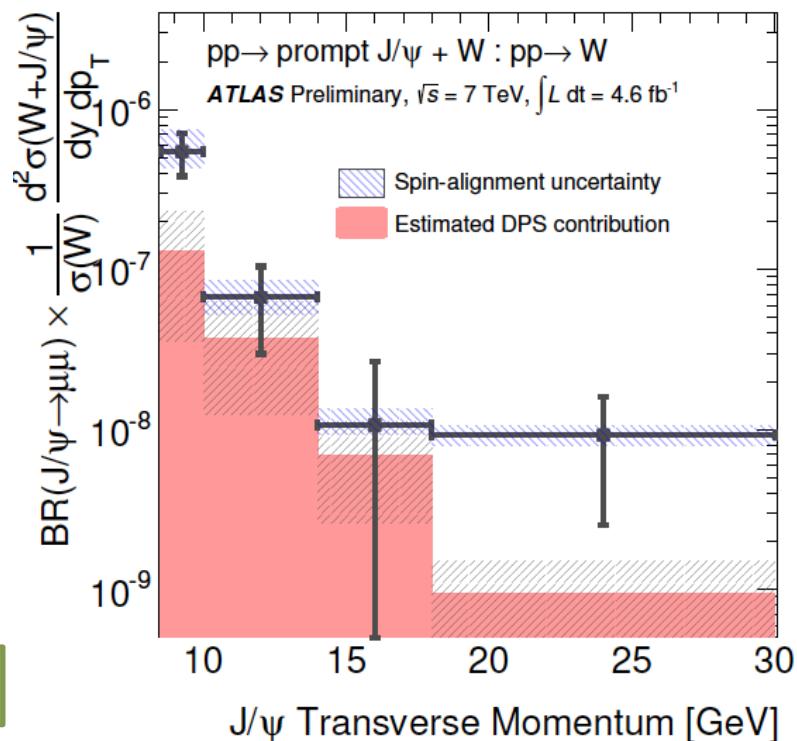
# Associated J/ $\psi$ and W $^\pm$ production at $\sqrt{s} = 7$ TeV

ATLAS



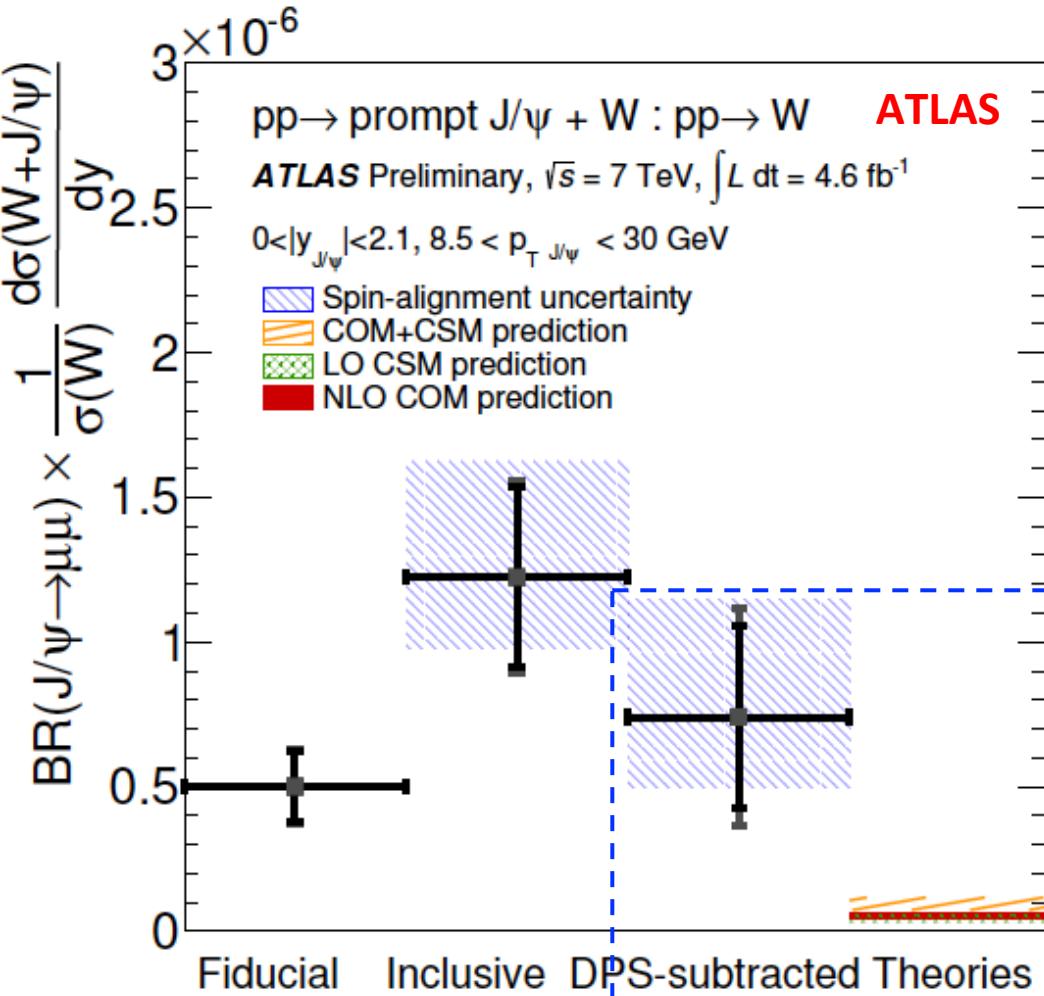
ATLAS

- 14.8 M inclusive W $^\pm$   
 $\rightarrow$  (W $^\pm$  + J/ $\psi$ ) to W $^\pm$  incl. cross-section ratio



$(W^\pm + J/\psi)$  to  $W^\pm$  cross-section ratio ( $R$ ) for  $|y_{J/\psi}| < 2.1$  and  $8.5 < p_T^{J/\psi} < 30$  GeV:

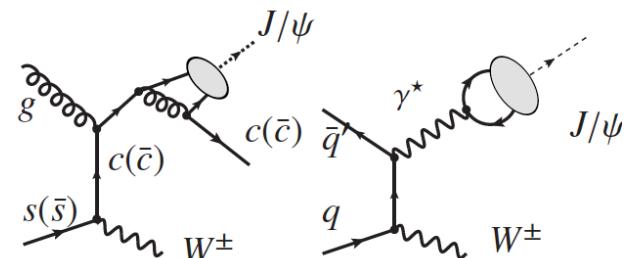
$$\begin{aligned} R_{J/\psi}^{\text{fid}} &= (50 \pm 12 \pm 4) \times 10^{-8} \\ R_{J/\psi}^{\text{incl}} &= (123 \pm 31 \pm 10^{+40}_{-24}) \times 10^{-8} \\ R_{J/\psi}^{\text{DPS sub}} &= (74 \pm 31 \pm 21^{+40}_{-24}) \times 10^{-8}, \end{aligned}$$



Comparison with Quarkonium Models after subtracting the DPS contribution:

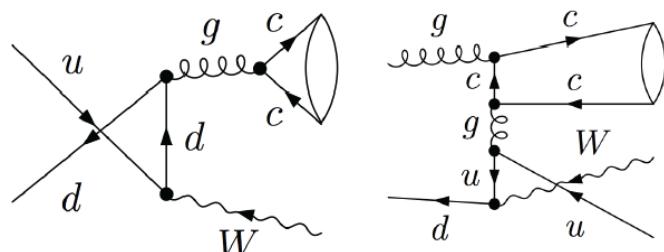
**LO CSM**

[arXiv:1303.5347]



**NLO NRQCD**

[arXiv:1304.4670]



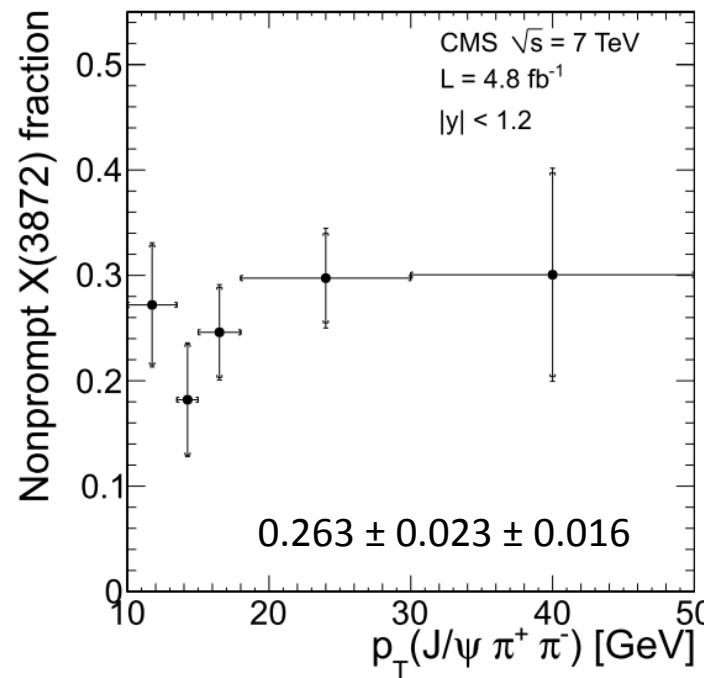
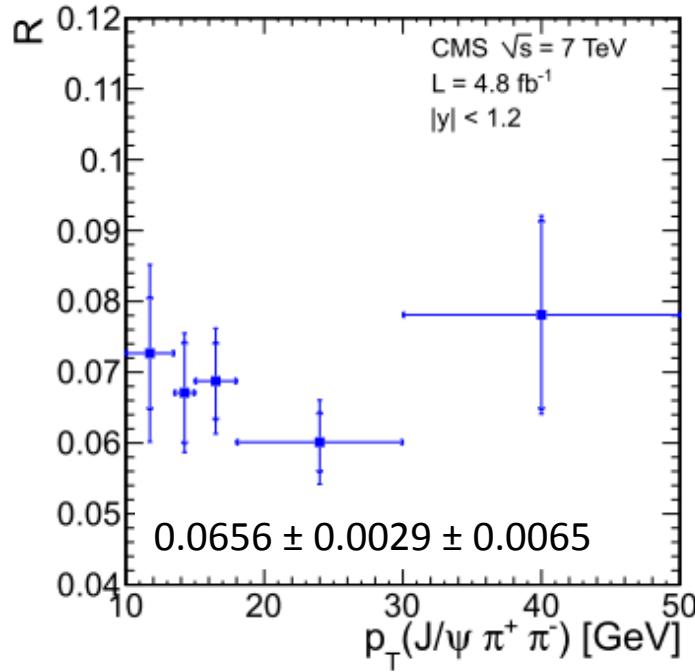
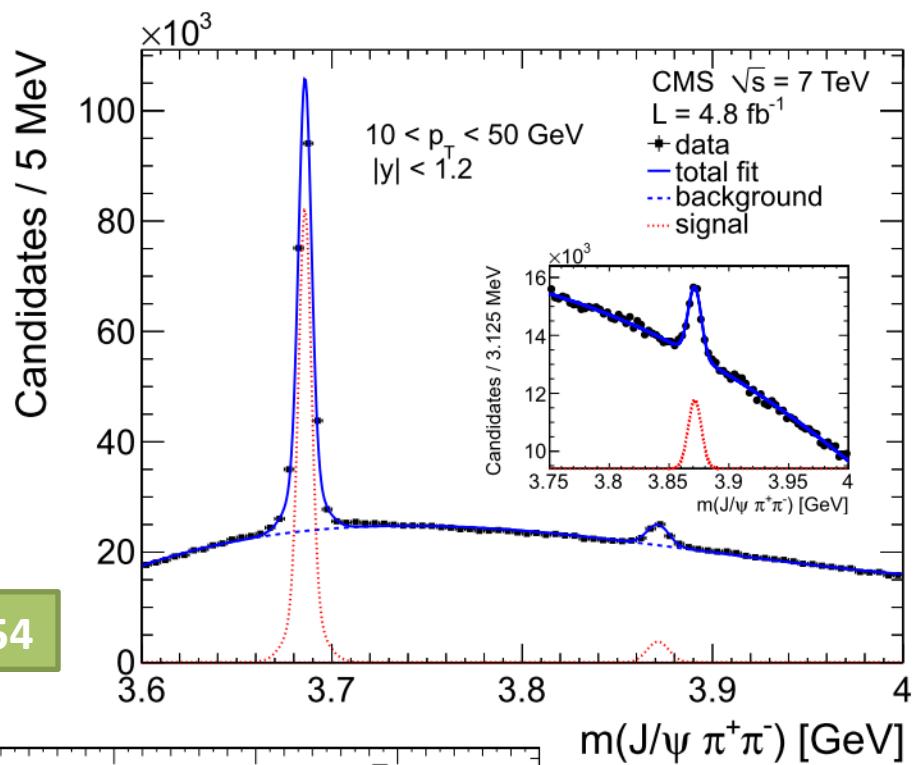
Data show roughly an order of magnitude larger cross section than theory predictions

# X(3872) production

CMS measures  $X \rightarrow J/\psi \pi\pi$  decays  
within  $|y| < 1.2$ ,  $10 < p_T < 50$  GeV

$L_{int} = 4.8 \text{ fb}^{-1}$  :  $\sim 12.000$  X candidates  
with  $p_T^\mu > 4$  GeV,  $p_T^\pi > 600$  MeV

CMS, JHEP 04 (2013) 154



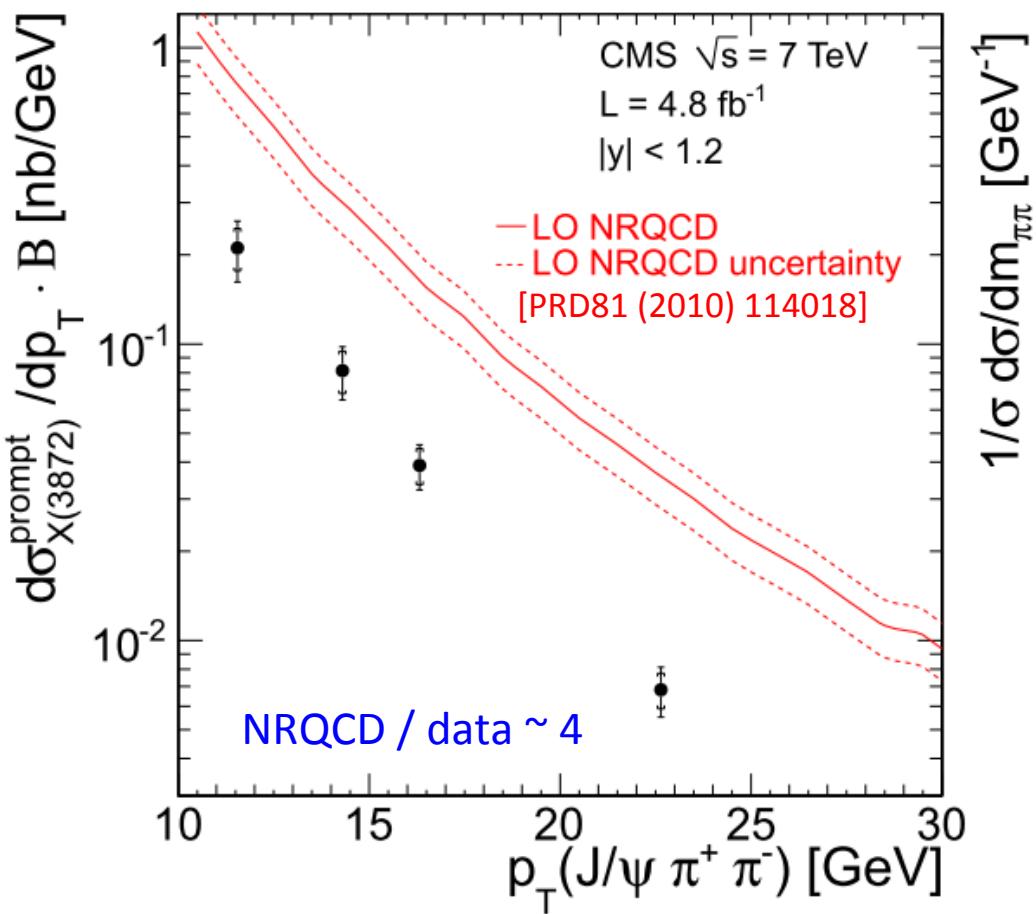
① X /  $\psi(2S)$   
cross-section ratio  
reduces systematics

② Discriminate  
prompt X from  $B \rightarrow X$   
through transverse  
decay length

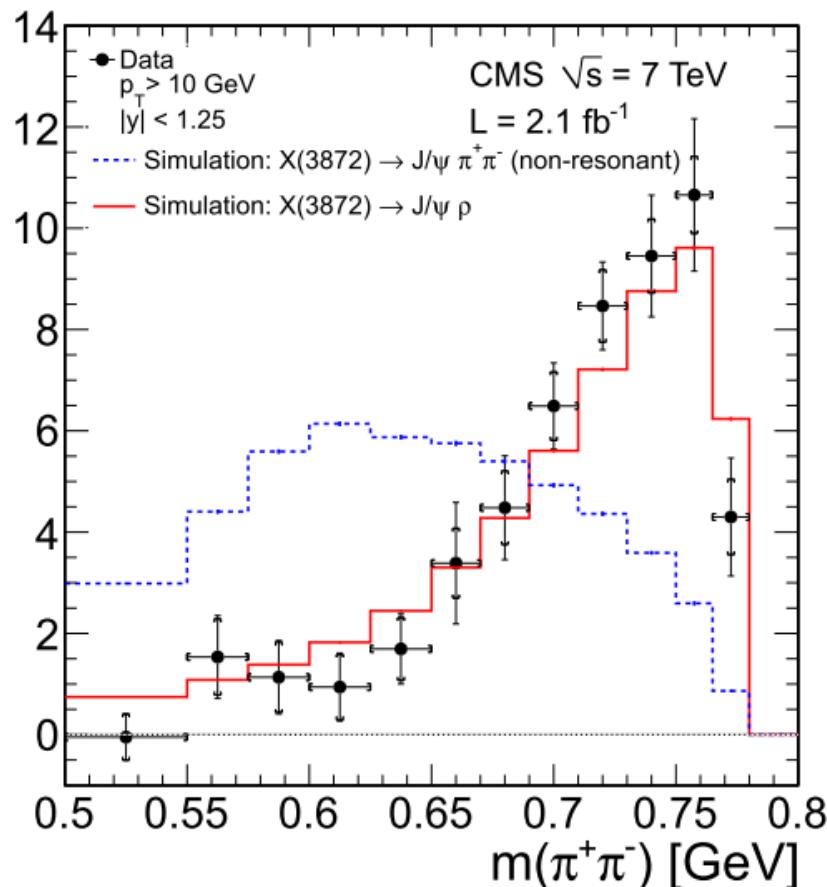
### ③ Compute prompt X cross section

$$\sigma \cdot \text{BR} = 1.06 \pm 0.11 \text{ (stat.)} \pm 0.15 \text{ (syst.) nb}$$

using the CMS  $\psi(2S)$  data [JHEP 02 (2012) 011]



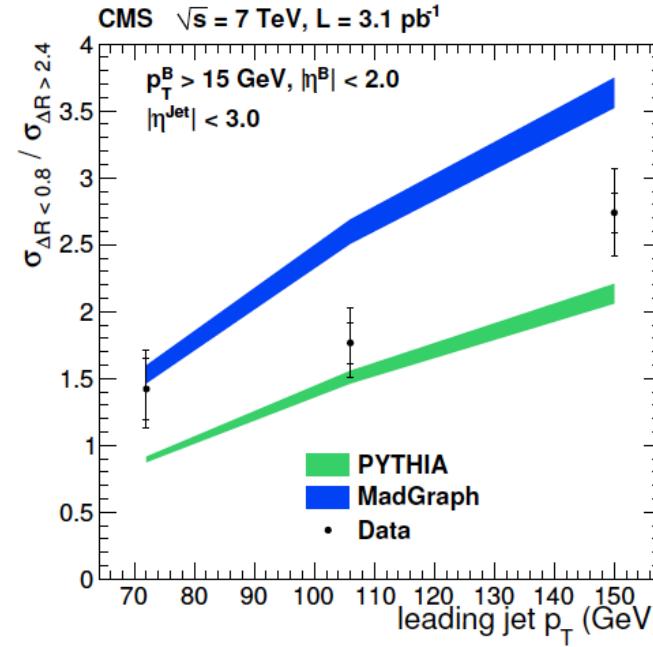
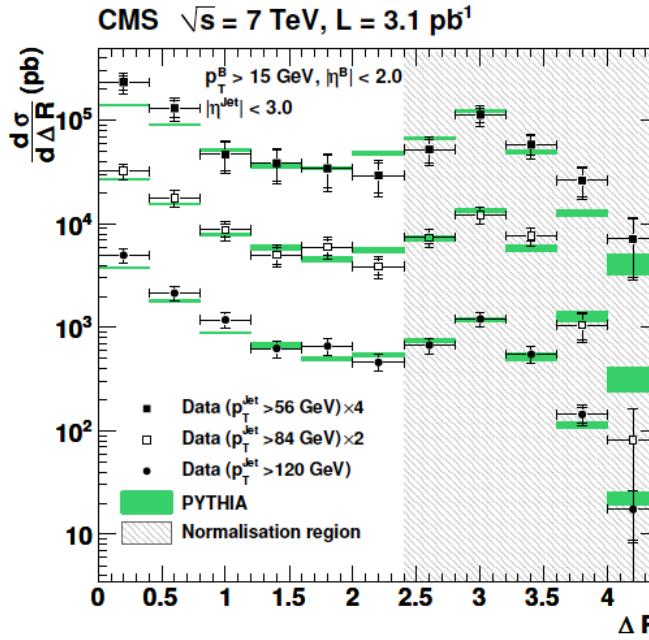
### ④ Fits to $J/\psi \pi\pi$ spectrum in $m(\pi\pi)$ bins → confirm resonant decay through $J/\psi \rho$



# B hadron production at the LHC

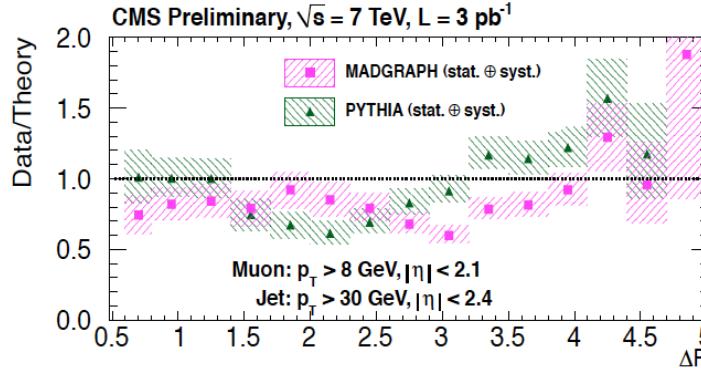
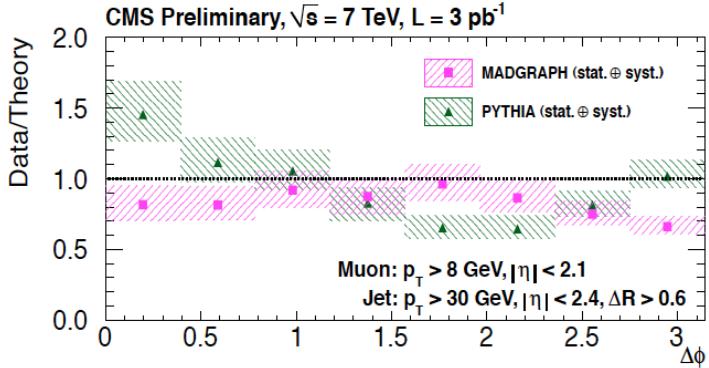
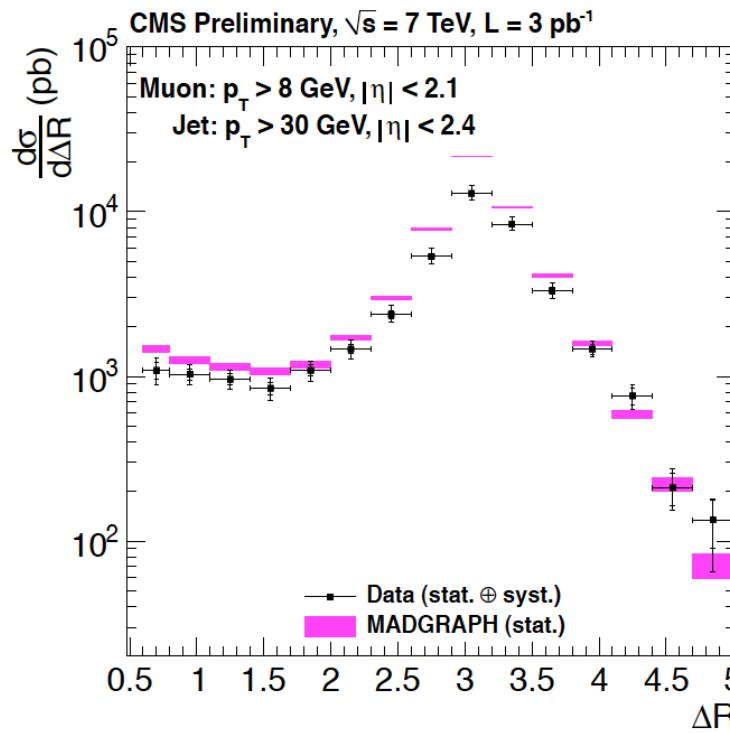
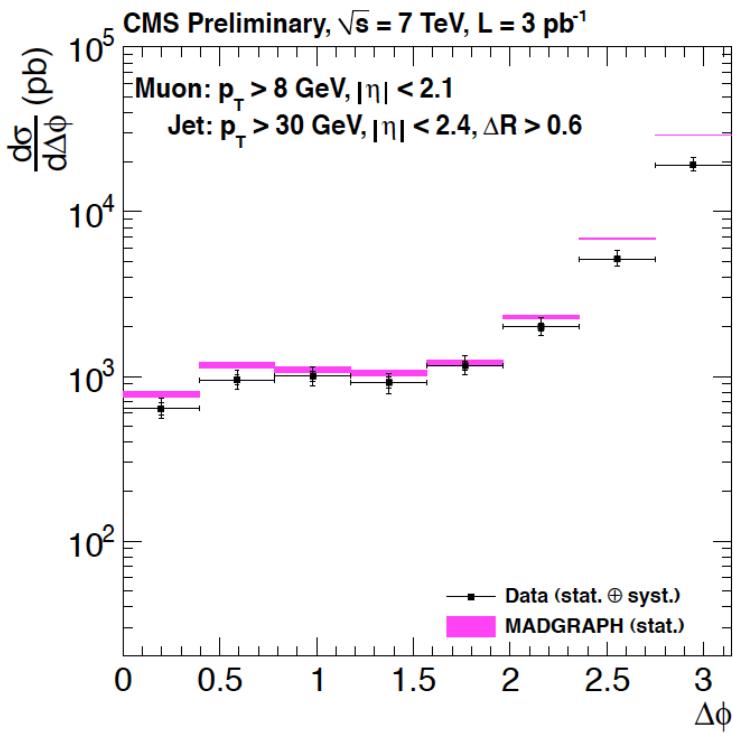
- Angular correlations between two b-quarks allow us to test pQCD:
  - At LO: only back-to-back configuration
  - At higher orders: different topologies
- First CMS study:
  - big fraction of BBbar pairs produced with small opening angles
  - more pronounced for harder QCD scales (higher  $p_T$  jets)

CMS JHEP 03 (2011) 136



- New CMS analysis:
  - different experimental technique (jets vs. secondary vertices)
  - lower QCD scales reached; smaller statistical uncertainties; absolute cross sections

CMS BPH-10-019



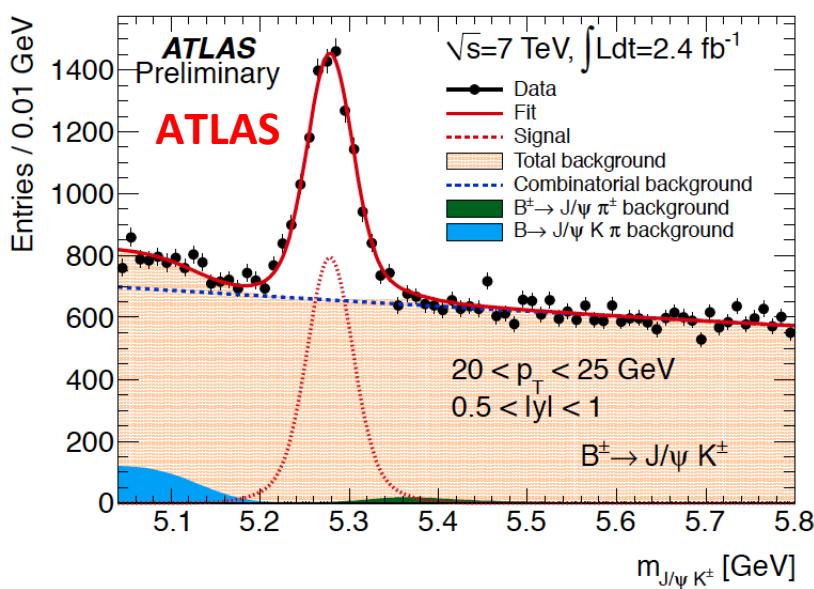
PYTHIA gets norm.  
 $(13.18 \pm 0.02 \text{ nb})$   
 but disagrees at  
 low  $\Delta\phi$

MADGRAPH  
 describes shape  
 but overestimates  
 $\sigma: 17.1 \pm 0.1 \text{ nb}$

- Cross section within phase space :  $12.2 \pm 0.2^{+1.6}_{-1.2} \text{ nb}$
- Good agreement of this analysis with previous CMS result

# $B^+ \rightarrow J/\psi K^+$ at $\sqrt{s} = 7 \text{ TeV}$

ATLAS-CONF-2013-008



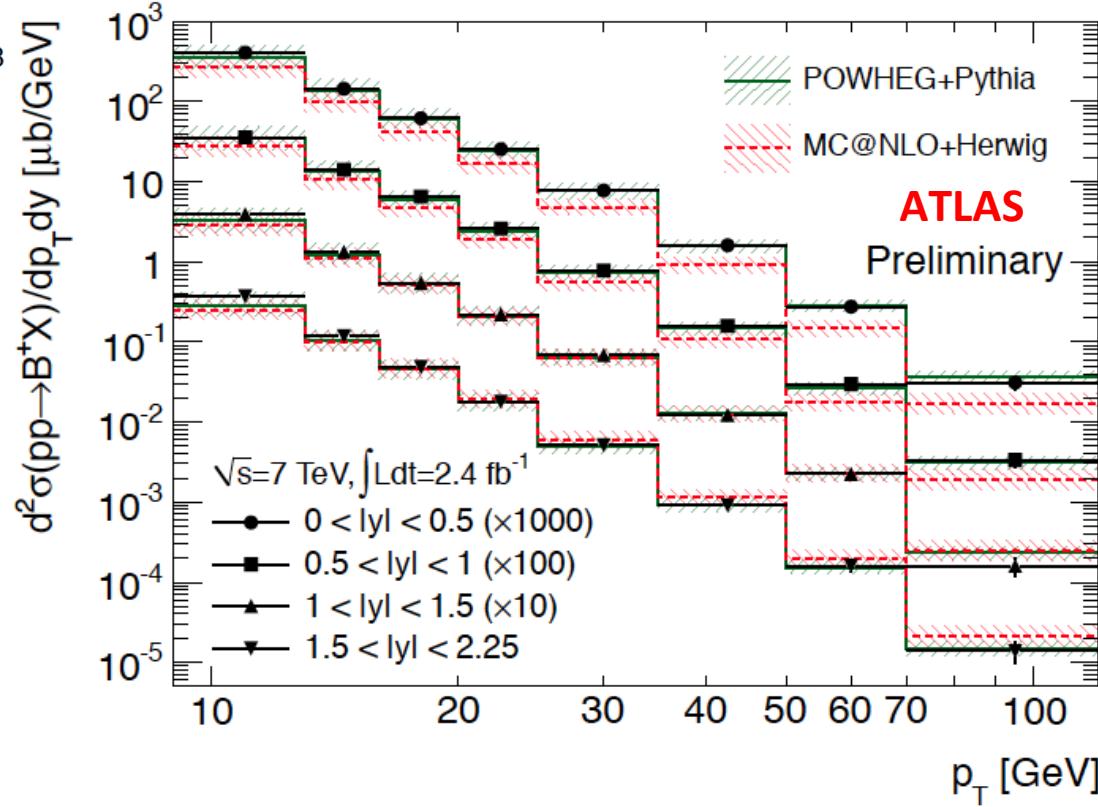
Double differential c.s. compared to:

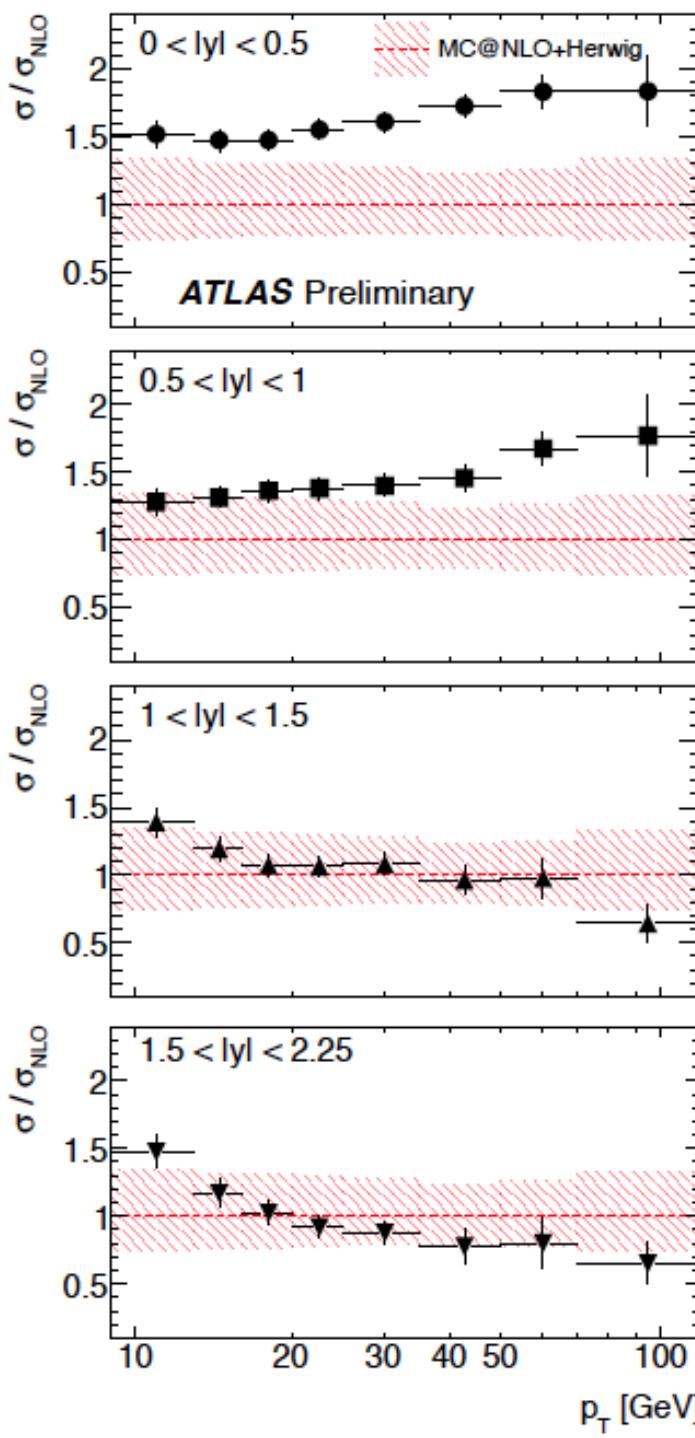
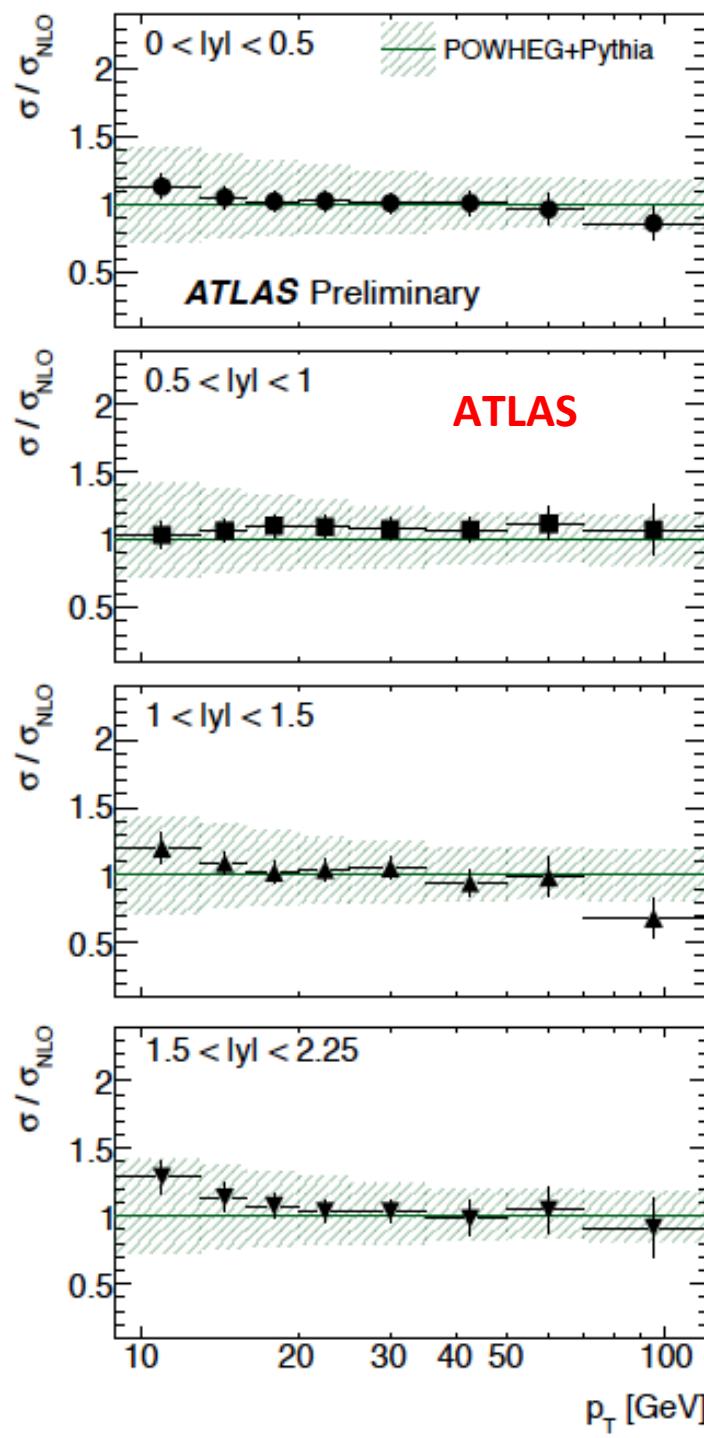
- NLO POWHEG (+PYTHIA)  
with CT10 PDFs and  $m_b = 4.75 \text{ GeV}$
- MC@NLO (+Herwig)  
with CTEQ6.6 and  $m_b = 4.75 \text{ GeV}$

Uncertainties from independent renormalization and factorization scales and  $\pm 0.25 \text{ GeV}$   $m_b$  variations

- For  $9 < p_T < 120 \text{ GeV}$ ,  $|y| < 2.25$
- Inclusive  $J/\psi$  sample (no lifetime cuts)
- (Small) peaking + (large) comb. background

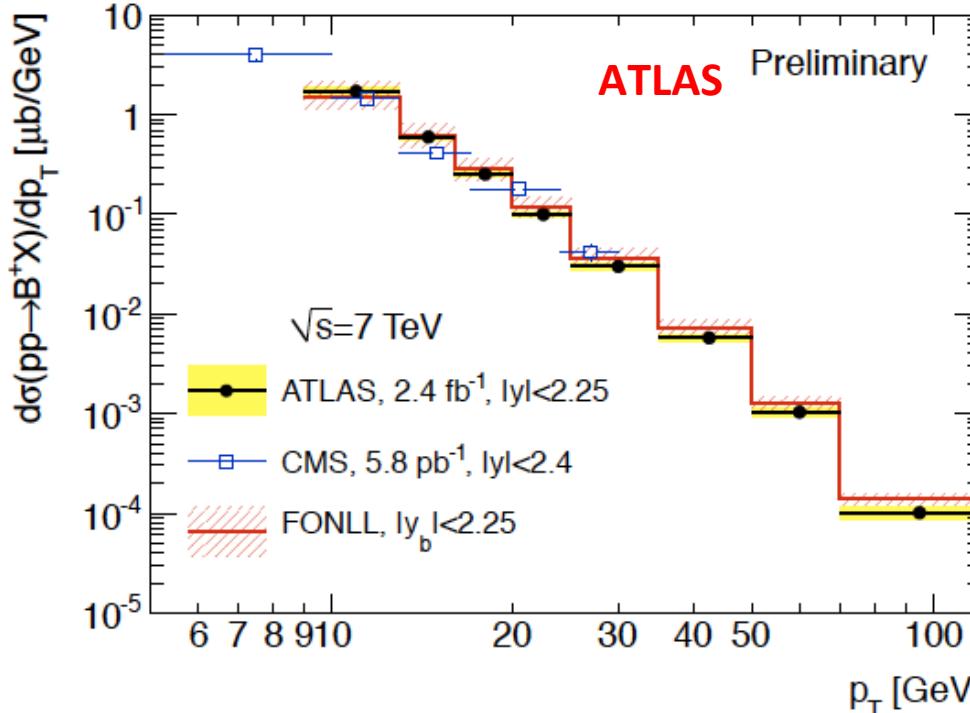
$125600 \pm 1201$   $B^+$  split in 4  $|y|$  and 8  $p_T$  bins



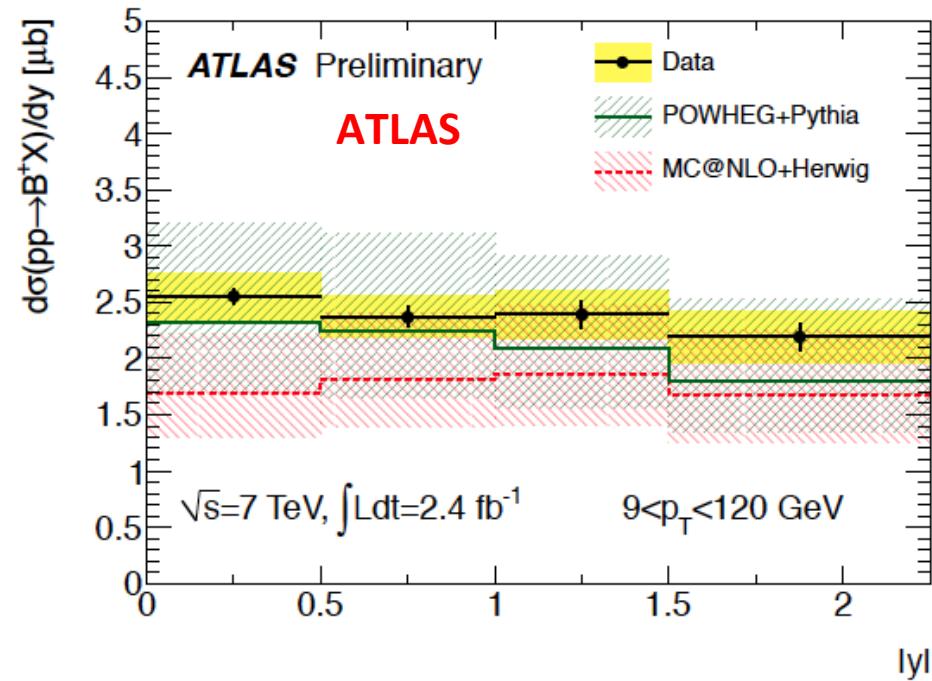


POWHEG + Pythia  
good description  
(shape and norm.)

MC@NLO + Herwig  
 $|\text{y}| < 1$ : c.s.  
underpredicted and  
too soft spectrum  
 $|\text{y}| > 1$ :  
too hard spectrum



- Good agreement with CMS result [PRL106 (2011) 112001] (similar phase space,  $|y| < 2.4$ )



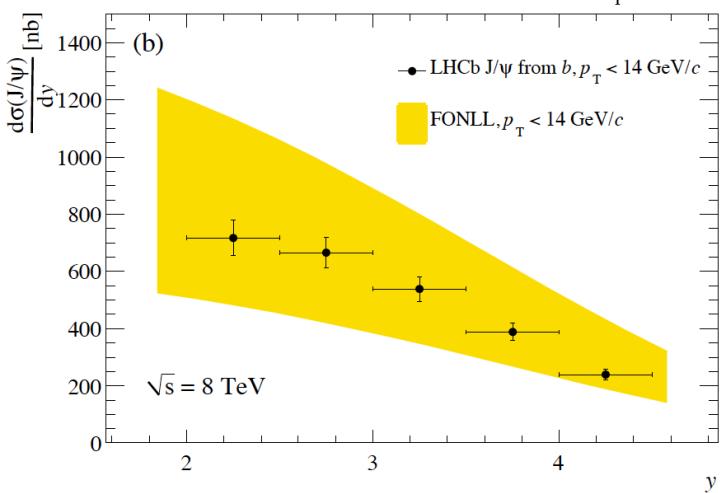
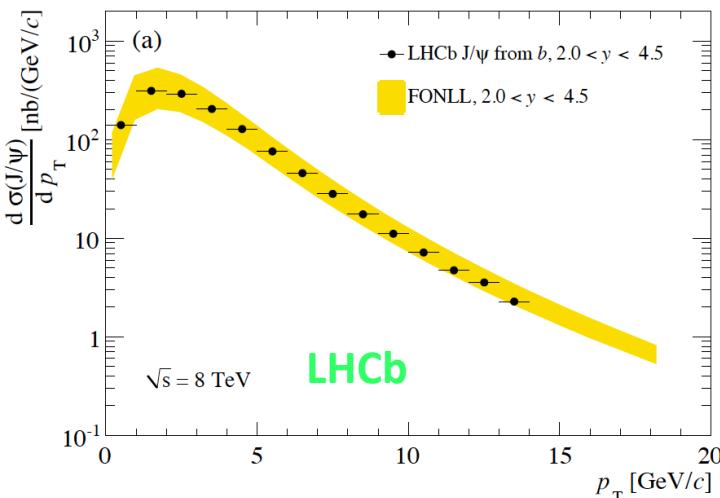
- $B^+$  rapidity dependence (integrated for  $9 < p_T < 120 \text{ GeV}$ ) rather weak up to  $|y| = 2.25$

# $B \rightarrow J/\psi X$ production at $\sqrt{s} = 8$ TeV

LHCb, arXiv:1304.6977

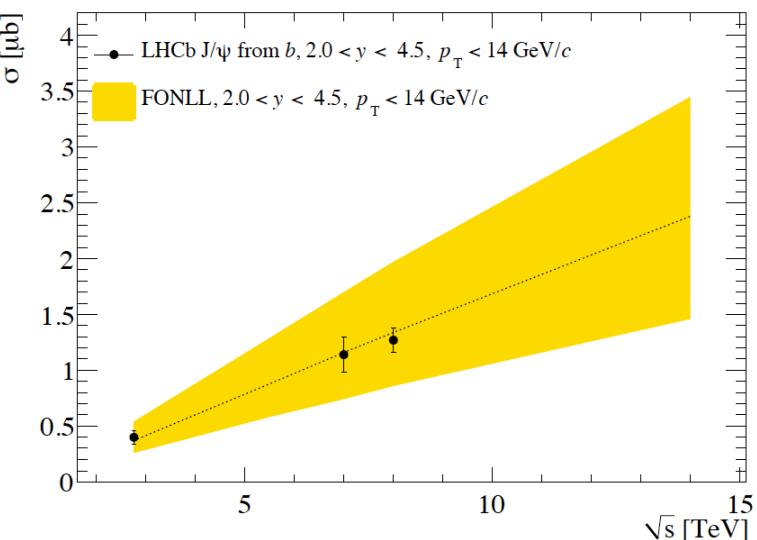
- B cross section obtained through non-prompt  $J/\psi$ , performing a mass-lifetime fit
- Measured cross section for  $2.0 < y(J/\psi) < 4.5$  and  $p_T(J/\psi) < 14$  GeV:  $1.28 \pm 0.01 \pm 0.11 \mu\text{b}$
- Total  $b\bar{b}$  production cross section can be derived as

$$\sigma(pp \rightarrow b\bar{b}X) = \alpha_{4\pi} \frac{\sigma(J/\psi \text{ from } b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5)}{2 \mathcal{B}(b \rightarrow J/\psi X)} = 298 \pm 2 \pm 36 \mu\text{b} \quad \text{with } \alpha_{4\pi} = 5.4$$



- FONLL calculations reproduce the  $p_T$  and  $y$  dependence of  $J/\psi$ 's from  $B$  decays, and the total cross section  $1.34^{+0.63}_{-0.49} \mu\text{b}$
- The  $\sqrt{s}$  dependence at LHC energies was established by LHCb from 2.76 to 8 TeV

- Increase is reproduced by FONLL



# Conventional quarkonium production at LHC energies

$\text{J}/\psi$  production,  $314 \text{ nb}^{-1}$ , CMS [EPJ C71 (2011) 1575]

$\text{J}/\psi$  production,  $5.2 \text{ pb}^{-1}$ , LHCb [EPJ C71 (2011) 1645]

$\text{J}/\psi$  production,  $2.3 \text{ pb}^{-1}$ , ATLAS [NPB 850 (2011) 387]

$\psi'$  production,  $36 \text{ pb}^{-1}$ , LHCb [EPJC 72 (2012) 2100]

$\text{J}/\psi$  and  $\psi'$  production,  $37 \text{ pb}^{-1}$ , CMS [JHEP 02 (2012) 011]

$\text{J}/\psi$  production,  $71 \text{ nb}^{-1}$ , LHCb [JHEP 02 (2013) 041],  $\sqrt{s} = 2.76 \text{ TeV}$

$\text{J}/\psi$  production,  $18.4 \text{ pb}^{-1}$ , LHCb [arXiv:1304.6977],  $\sqrt{s} = 8 \text{ TeV}$

$\Upsilon(nS)$  production,  $3 \text{ pb}^{-1}$ , CMS [PRD 83 (2011) 112004]

$\Upsilon(1S)$  fiducial production,  $1.1 \text{ pb}^{-1}$ , ATLAS [PLB 703 (2011) 428]

$\Upsilon(nS)$  production,  $25 \text{ pb}^{-1}$ , LHCb [EPJ C72 (2012) 2025]

$\Upsilon(nS)$  production,  $36 \text{ pb}^{-1}$ , CMS [arXiv:1303.5900]

$\Upsilon(nS)$  production,  $1.8 \text{ fb}^{-1}$ , ATLAS [PRD 87 (2013) 052004]

$\Upsilon(nS)$  production,  $4.9 \text{ fb}^{-1}$ , CMS [CMS BPH-12-006]

$\Upsilon(nS)$  production,  $50.6 \text{ pb}^{-1}$ , LHCb [arXiv:1304.6977],  $\sqrt{s} = 8 \text{ TeV}$

$\chi_{c2} / \chi_{c1}$  prompt production,  $36 \text{ pb}^{-1}$ , LHCb [PLB 714 (2012) 215]

$\chi_{c2} / \chi_{c1}$  prompt production,  $4.6 \text{ fb}^{-1}$ , CMS [EPJ C72 (2012) 2251]

Observation of the  $\chi_{cb}(3P)$  state,  $4.4 \text{ fb}^{-1}$ , ATLAS [PRL 108 (2012) 152001]

Prompt  $\chi_c$  to  $\text{J}/\psi$  production,  $36 \text{ pb}^{-1}$ , LHCb [PLB 718 (2012) 431]

$\chi_b(1P)$  to  $\Upsilon(1S)$  feed-down,  $32 \text{ pb}^{-1}$ , LHCb [JHEP 11 (2012) 031]

Double  $\text{J}/\psi$  production,  $37.5 \text{ pb}^{-1}$ , LHCb [PLB 707 (2012) 52]

Prompt  $\text{J}/\psi + W$  production,  $4.6 \text{ fb}^{-1}$ , ATLAS [ATLAS-CONF-2013-042]

$\Upsilon(nS)$  polarization,  $4.9 \text{ fb}^{-1}$ , CMS [PRL 110 (2013) 081802]

$\psi'$  polarization,  $4.9 \text{ fb}^{-1}$ , CMS [CMS BPH-13-003]

Many other results  
have not been  
covered in this talk

# b-hadron cross-section measurements at LHC energies

Inclusive bbbar c.s.,  $2.9 \text{ nb}^{-1}$ , **LHCb**, [PLB694 (2010) 209]

Inclusive b-hadron c.s. with muons,  $85 \text{ nb}^{-1}$ , **CMS** [JHEP 1103 (2011) 090]

Inclusive b-jet c.s.,  $3\text{-}34 \text{ pb}^{-1}$ , **CMS** [JHEP 1204 (2012) 84]

Inclusive bbar  $\rightarrow \mu\mu$  c.s.,  $28 \text{ pb}^{-1}$ , **CMS** [1206 (2012) 110]

Inclusive b-hadron c.s. through  $b \rightarrow D^*\mu X$ ,  $3.3 \text{ pb}^{-1}$ , **ATLAS** [NPB864 (2012) 341]

Inclusive ,  $34 \text{ pb}^{-1}$ , **ATLAS** [EPJ C71 (2011) 1846]

$B^+$  c.s.,  $5.8 \text{ pb}^{-1}$ , **CMS** [PRL 106 (2011) 112001]

$B^+$  c.s.,  $35 \text{ pb}^{-1}$ , **LHCb** [JHEP 1204 (2012) 93]

$B^+$  c.s.,  $2.4 \text{ fb}^{-1}$ , **ATLAS** [ATLAS-CONF-2013-008]

$B^0$  c.s.,  $40 \text{ pb}^{-1}$ , **CMS** [PRL 106 (2011) 252001]

$B_s$  c.s.,  $40 \text{ pb}^{-1}$ , **CMS** [PRD 84 (2011) 052008]

$\Lambda_b$  c.s.,  $1.9 \text{ fb}^{-1}$ , **CMS** [PLB 714 (2012) 136]

$B \rightarrow J/\psi X$ ,  $314 \text{ nb}^{-1}$ , **CMS** [EPJ C71 (2011) 1575]

$B \rightarrow J/\psi X$ ,  $5.2 \text{ pb}^{-1}$ , **LHCb** [EPJC 71 (2011) 71]

$B \rightarrow J/\psi X$  and  $B \rightarrow \psi(2S) X$ ,  $37 \text{ pb}^{-1}$ , **CMS** [JHEP 1202 (2012) 011]

$B \rightarrow J/\psi X$ ,  $71 \text{ nb}^{-1}$ , **LHCb** [JHEP 02 (2013) 041],  $\sqrt{s} = 2.76 \text{ TeV}$

$B \rightarrow J/\psi X$ ,  $2.3 \text{ pb}^{-1}$ , **ATLAS** [NPB 850 (2011) 387]

$B \rightarrow J/\psi X$ ,  $18.4 \text{ pb}^{-1}$ , **LHCb** [arXiv:1304.6977],  $\sqrt{s} = 8 \text{ TeV}$

BBbar Angular correlations,  $3.1 \text{ pb}^{-1}$ , **CMS** [JHEP 1103 (2011) 136]

Angular correlations between 2 beauty jets,  $3.0 \text{ pb}^{-1}$ , **CMS** [CMS-BPH-10-019]

Many other results  
have not been  
covered in this talk

# Summary

- ✓ The LHC accelerator is a heavy quarkonia and B “factory”
- ✓ The LHC detectors are very good to study beauty and quarkonium physics
- ✓ All experiments have ongoing efforts in this physics area
- ✓ A wealth of results already available
- ✓ Studies of the 8 TeV data (ongoing) will trigger further progress

# Posters and talks on Quarkonium and B-hadron production

## Heavy Flavour 1, Tuesday, 14:30 – 16:30

15:30 "Quarkonia and quarkonia-like spectroscopy at [LHCb](#)", Monica Pepe-Altarelli

16:00 "Quarkonium Production and Polarization in [CMS](#)", Carlos Lourenço

## Poster session, Tuesday, 18:30 – 19:30

"Heavy flavor production and spectroscopy in [ATLAS](#)", Constantinos Melachrinos

## Plenary: Soft QCD / forward physics, Wed, 14:30 – 16:15

15:25 "Hadron spectroscopy and exotic states from [LHCb](#)", Antonio A. Alves Jr.