

# Heavy Flavour and quarkonium Production at the LHC



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with results from the **ATLAS**, **CMS** and **LHCb** Collaborations



public results can be found at:

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

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

<http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php>

Incontri di Fisica delle Alte Energie (IFAE)  
Gran Sasso, Italia  
April 18<sup>th</sup>, 2014

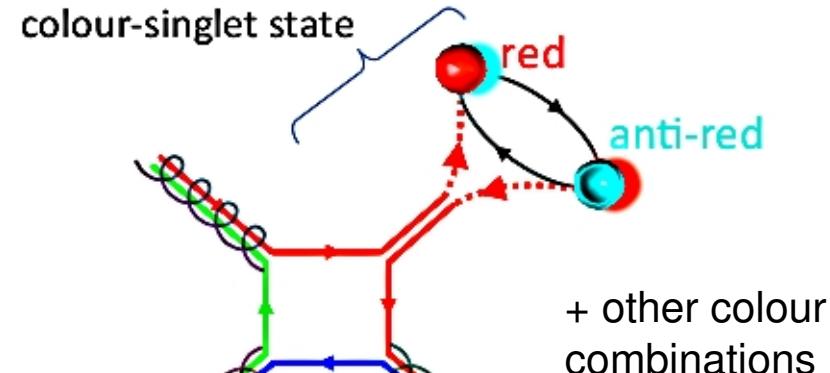
# Quarkonium studies: motivations

Ideal probes of hadron formation (QCD), but production is not yet understood

How/when do the observed  $q\bar{q}$  bound states acquire their quantum numbers?

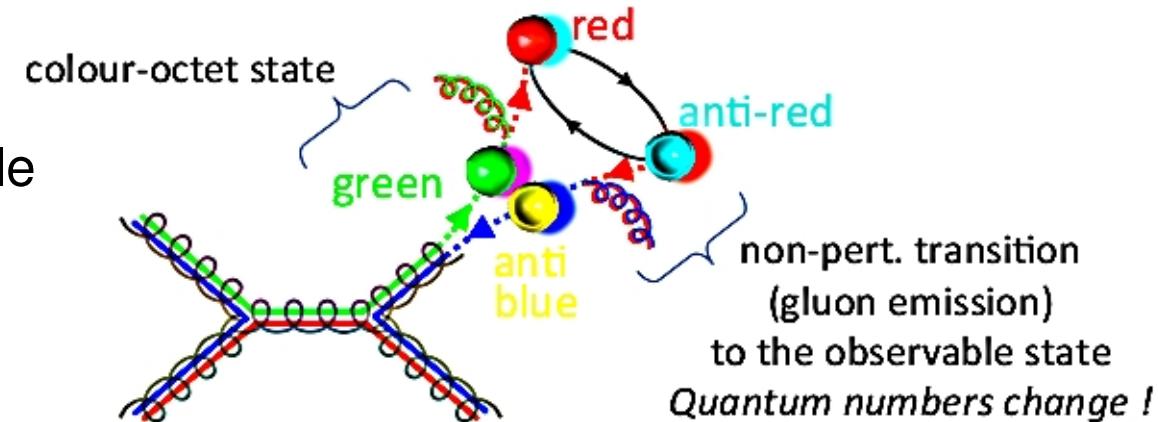
Colour Singlet Model:

quarkonia always produced directly  
as observable colour-neutral  $q\bar{q}$  pairs



NRQCD factorization:

quarkonia also produced as  
coloured  $q\bar{q}$  pairs of any possible  
quantum numbers



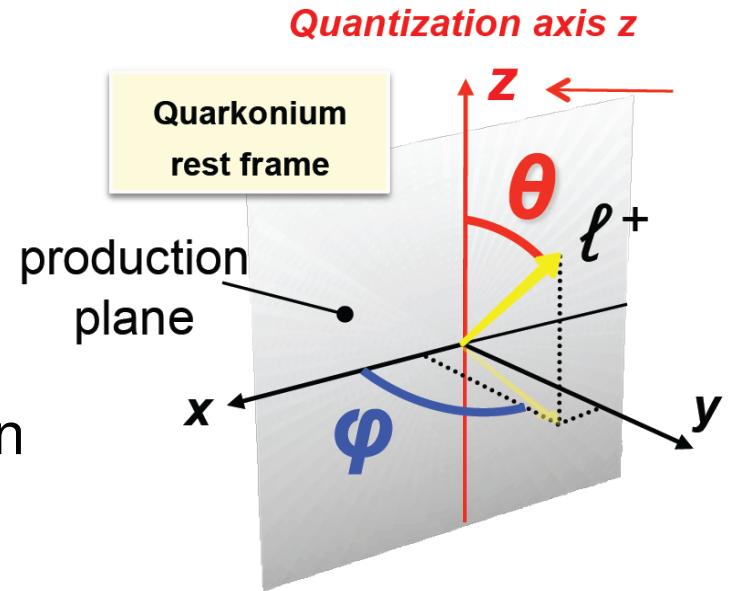
Two options leading to strong polarizations (longitudinal and transverse, resp.)  
for the directly produced states

→ polarization measurements are fundamental

# Polarisation (measurements)

NLO NRQCD describes reasonably well data on  $J/\psi$  and  $\Upsilon$  production, but not on polarisation:

Information about  $J/\psi$  (to  $\mu^+\mu^-$ ) polarisation encoded in  $\mu$  angular distribution



Full angular analysis to determine polarisation parameters  $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$  with  $\theta$  the angle between the  $\mu^+$  and the chosen polarisation axis and  $\phi$  the azimuthal angle with respect to the production plane

Polarisation frames:

helicity ( $HX$ ): polarisation axis given by  $J/\psi$  flight direction

Collins-Soper ( $CS$ ): beam line direction

perpendicular helicity ( $PX$ ): in the dilepton rest frame, axis along  $v_1+v_2$

Transverse Polarisation  $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1, 0, 0)$

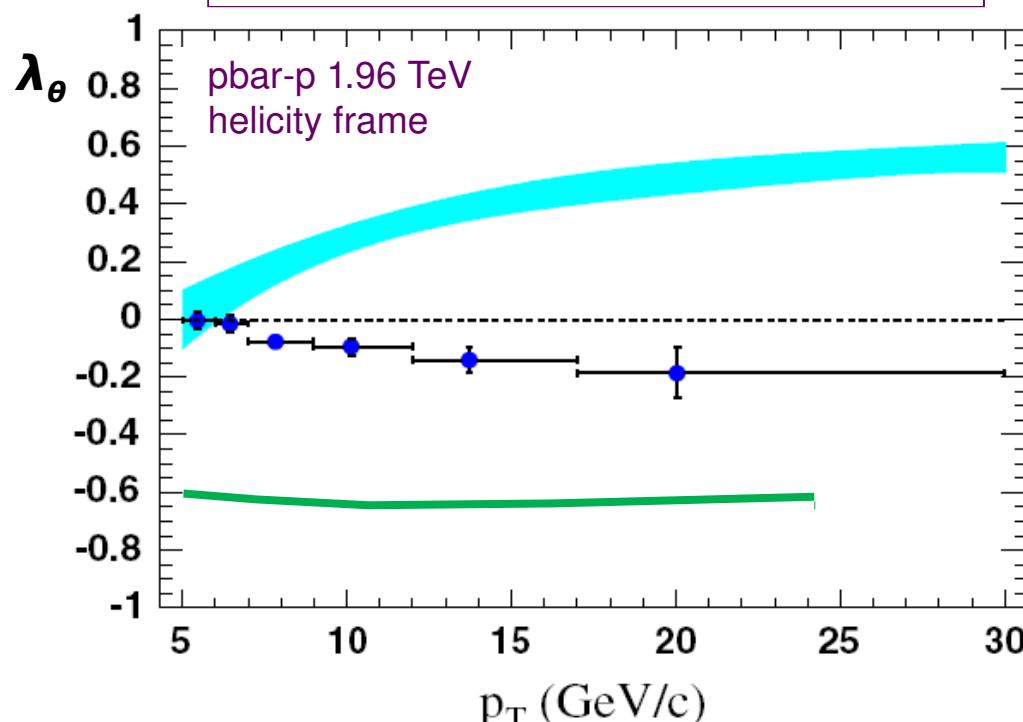
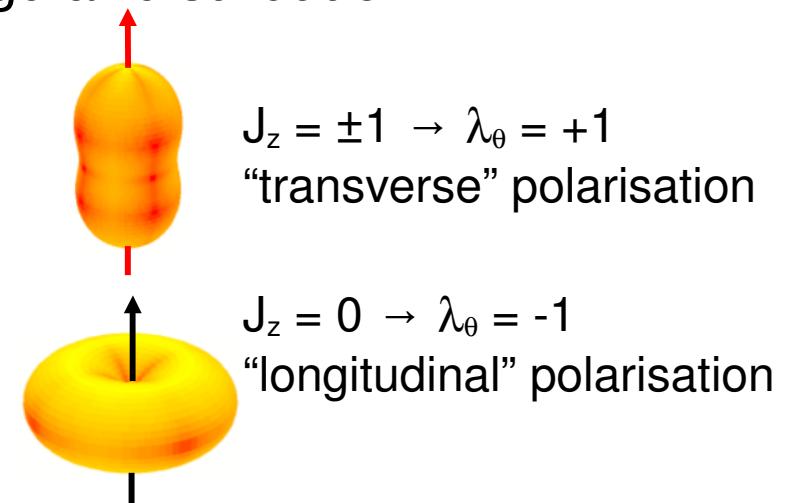
Longitudinal Polarisation  $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0)$

# Polarisation (measurements): status before LHC

$J/\psi, \psi, Y(nS) \rightarrow \mu\mu$

Polarisation measured through the decay angular distribution of  $J = 1$  particles:

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



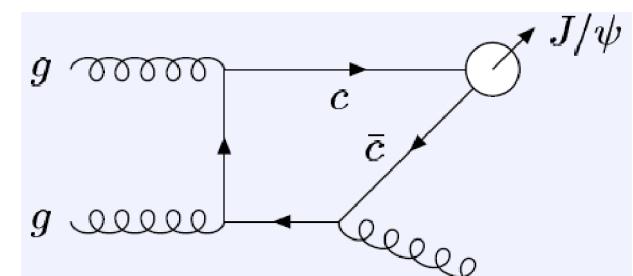
NRQCD : prompt  $J/\psi$   
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

CDF : prompt  $J/\psi$   
CDF Coll., PRL 99, 132001 (2007)

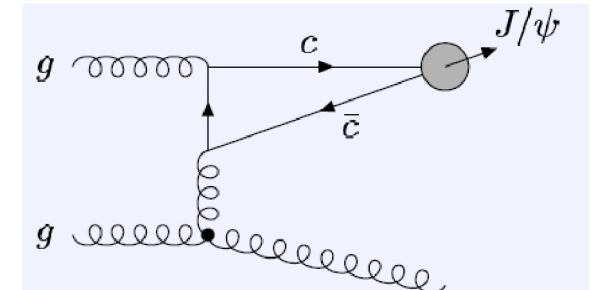
Colour-singlet @NLO : direct  $J/\psi$   
Gong & Wang, PRL 100, 232001 (2008)  
Artoisenet et al., PRL 101, 152001 (2008)

# heavy quarkonium physics

- ▶ Charmonia ( $cc$ ) and bottomonia ( $bb$ ) provide a good testing ground for p-QCD studies
- ▶ Production not well understood, Color Singlet (CS) and Color Octet (CO) mechanisms describe  $p_T$  spectrum observed at Tevatron but polarisation predictions disagree with measurements
- Onia production occurs through:
  - Prompt production:
    - Direct production,
    - Feed-down from higher quarkonium states.
  - Non-prompt production:
    - From decays of B hadrons (only charmonium).
- ▶ Experimental hadron spectroscopy has an essential role in understanding of the QCD, LHC allows reaching higher  $p_T$  and rapidity regions.

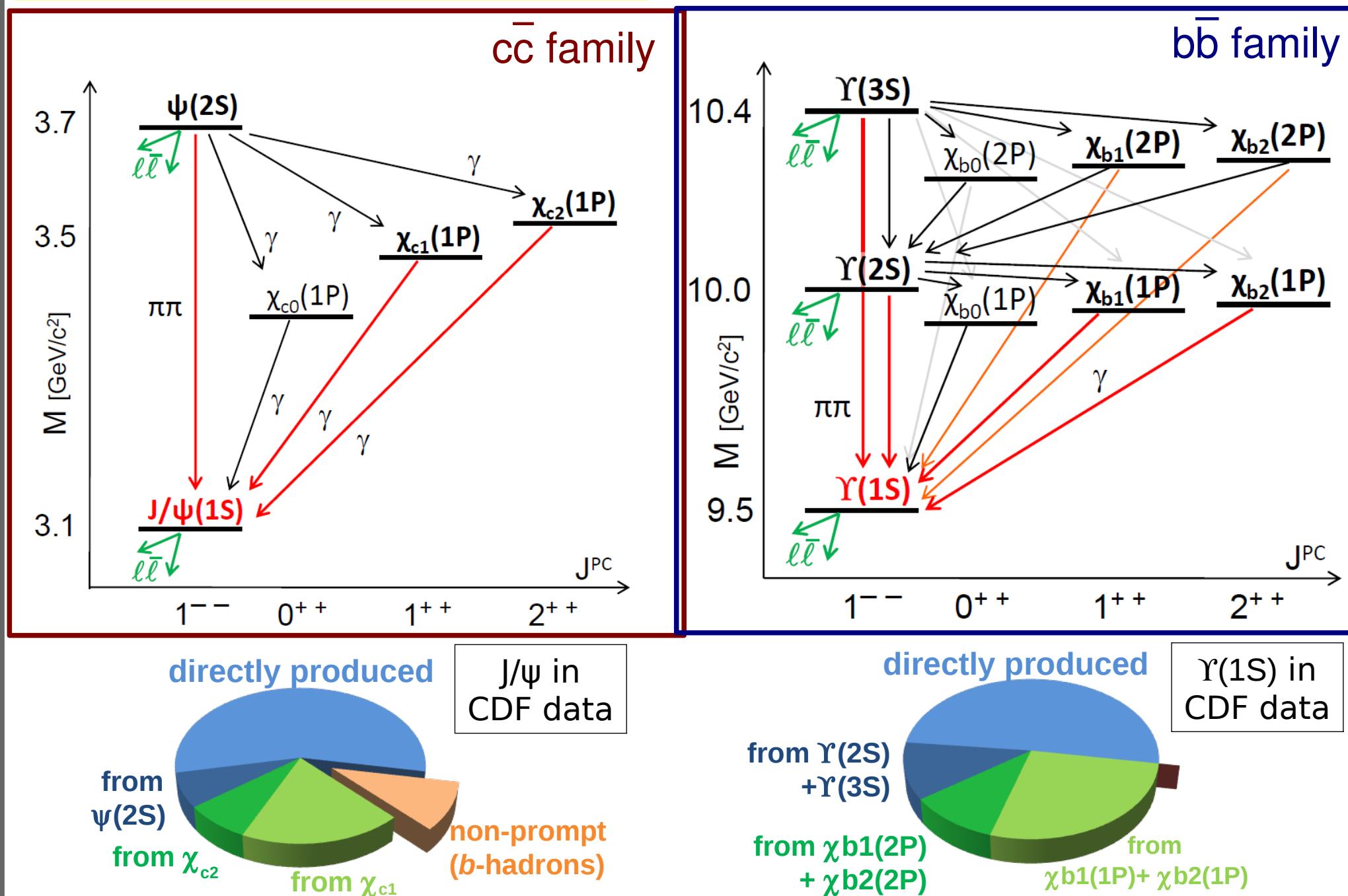


Color singlet (CS) LO diagram



Color octet (CO) LO diagram

# heavy quarkonium physics



# Upsilon polarisation at the LHC

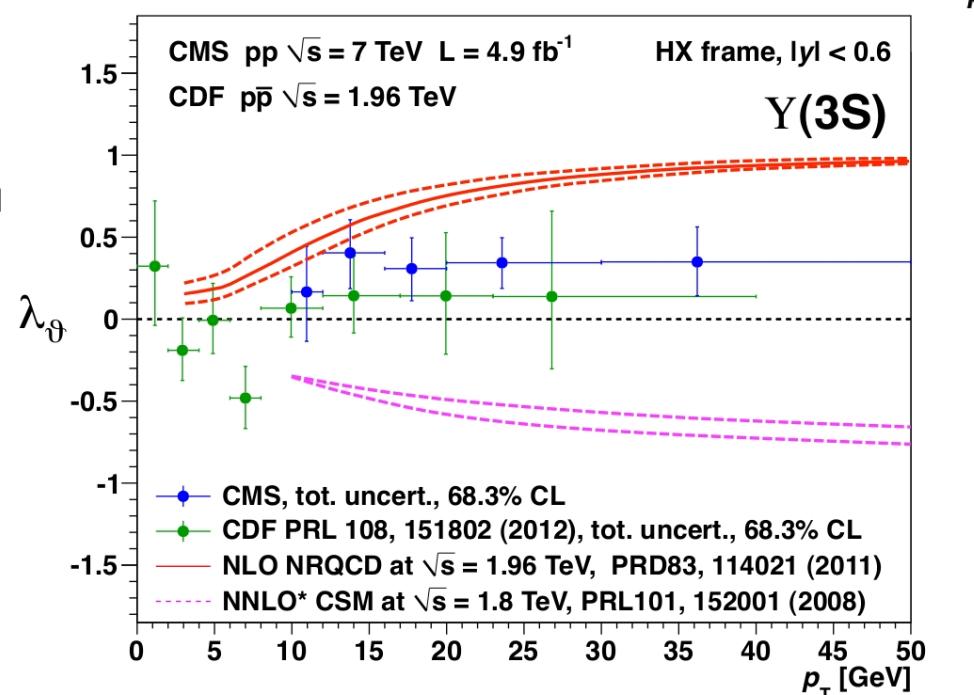
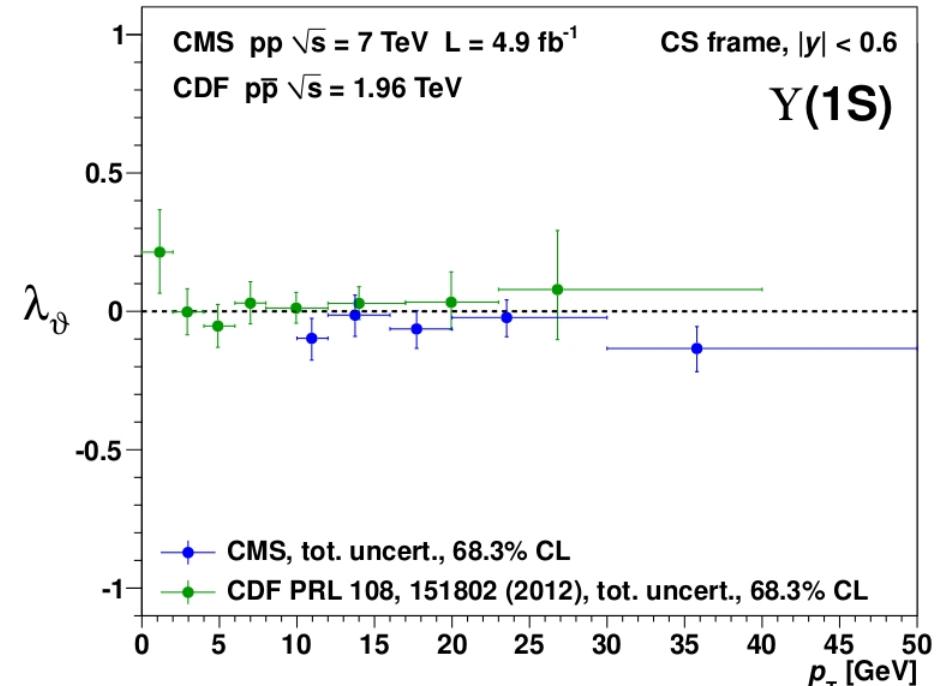
CMS, PRL 110 (2013) 081802

CMS measured the  $\Upsilon(nS)$  polarisations versus  $p_T$  in two  $|y|$  bins and three polarisation 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 polarisation

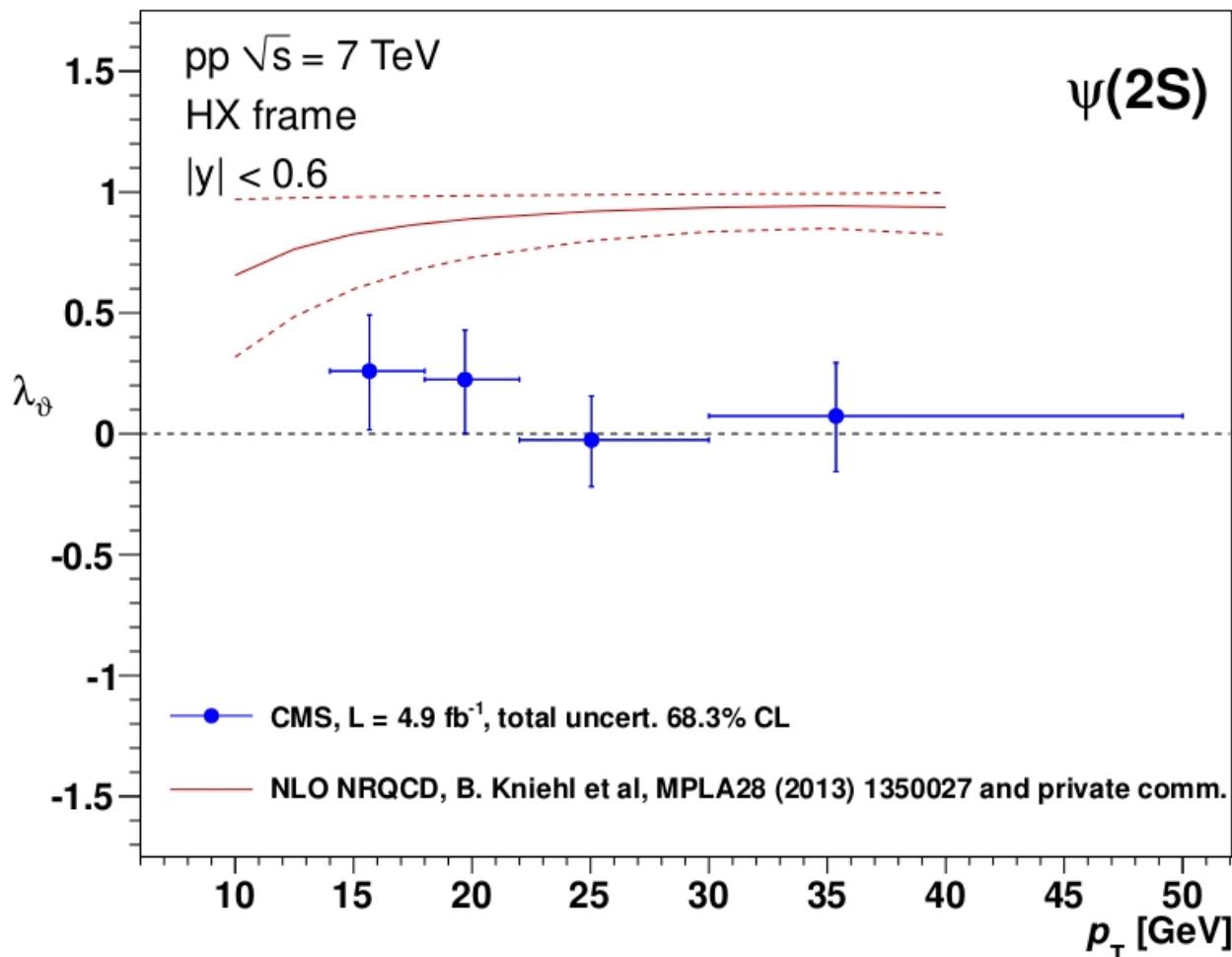
$\Upsilon(3S)$  should be almost free from feed-down  
 Measured polarisations are much weaker than expected by the theory models



# Prompt $\psi(2S)$ polarisation: data vs. theory

CMS, PLB 727 (2013) 381

CMS measured the  $\psi(2S)$  polarisations versus  $p_T$  in two  $|y|$  bins and three polarisation frames

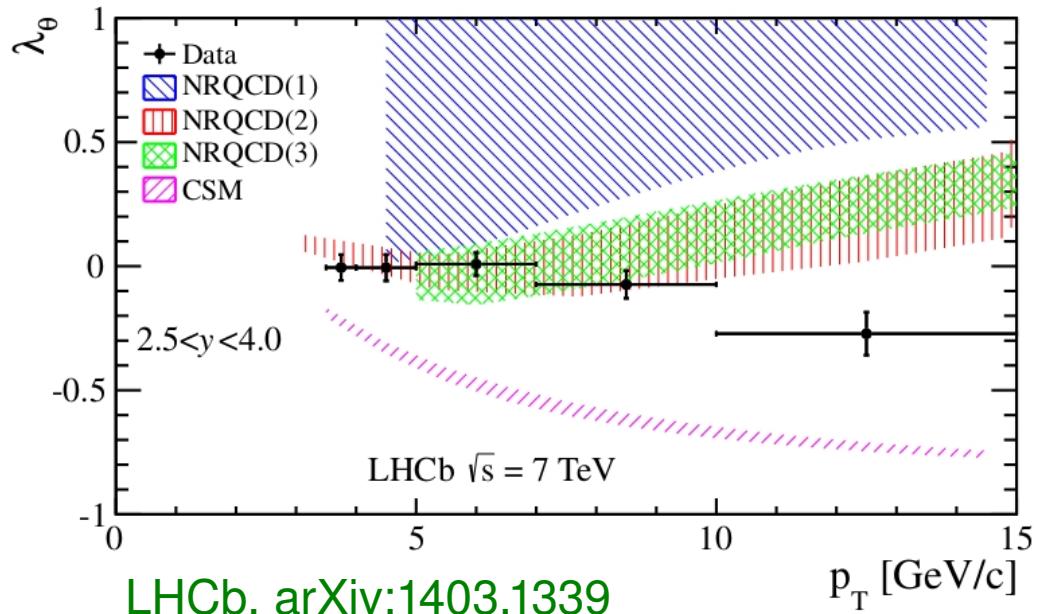
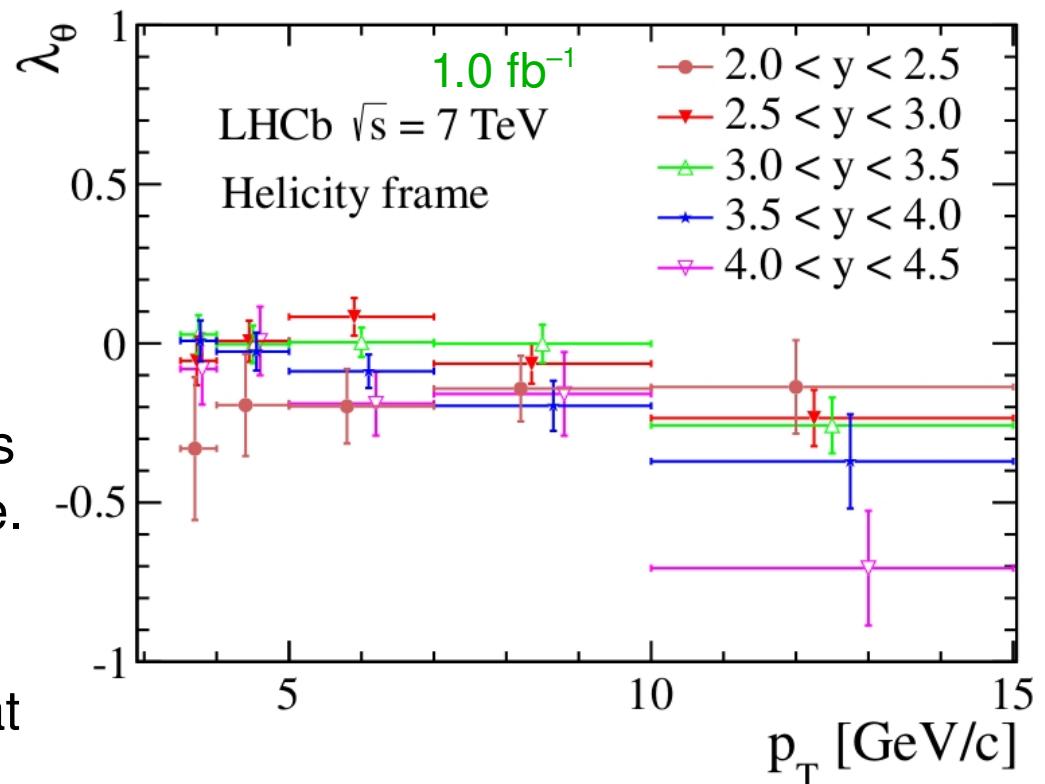
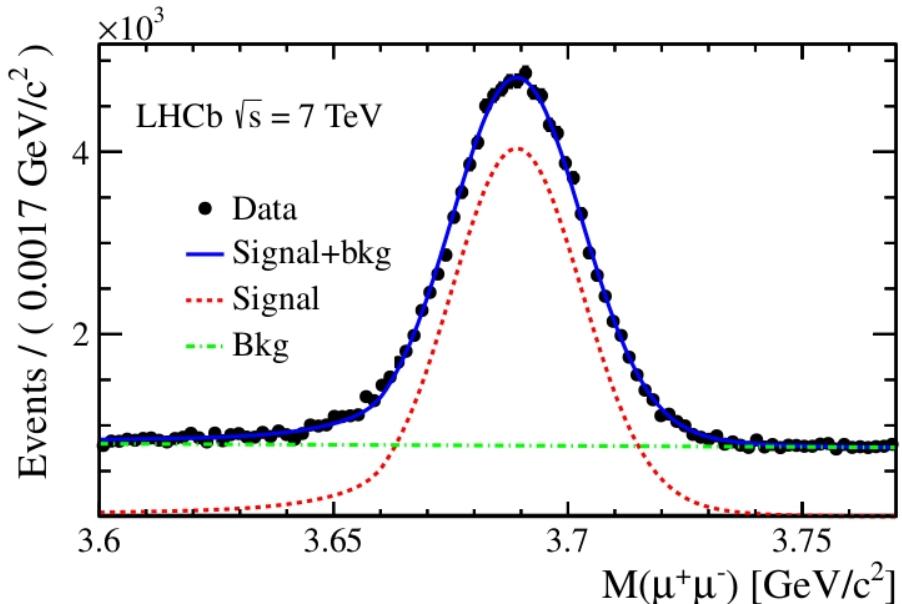


Measured polarisations are much weaker than expected by NRQCD

# Measurement of $\psi(2S)$ polarisation at $\sqrt{s}=7$ TeV

Prompt J/ $\psi$ (2S)  
 $3.5 < p_T < 15$  GeV  
 $2.0 < y < 4.5$

The polarisation measured disagrees with CSM in size and  $p_T$  dependence.  
The NRQCD models provide a good description at low- $p_T$  but predicts transverse polarisation at high- $p_T$  that is not observed.

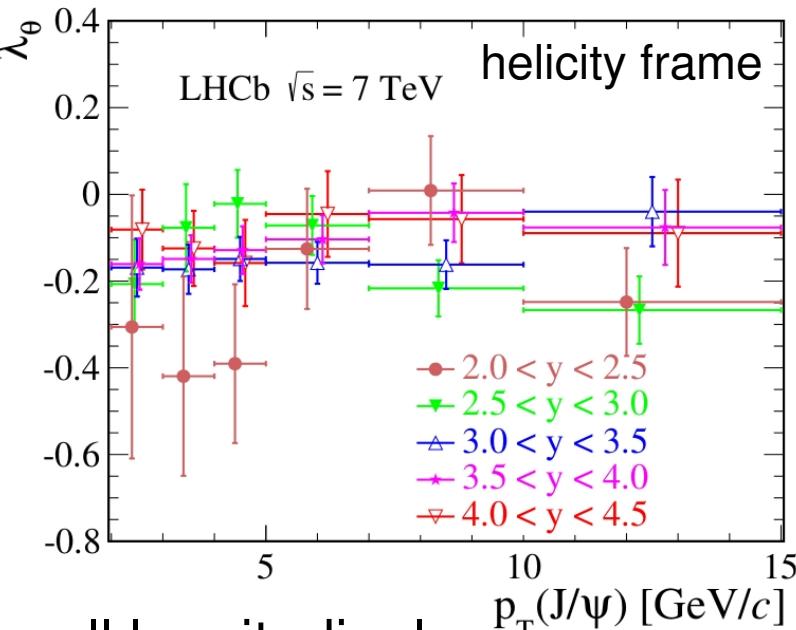


LHCb, arXiv:1403.1339

# J/ $\psi$ polarisation results

Prompt J/ $\psi$   
 $2 < p_T < 15 \text{ GeV}$   
 $2.0 < y < 4.5$

$B^+ \rightarrow J/\psi K^+$ :  
control sample  
to correct  
the simulation



$\lambda_\theta$  shows a small longitudinal  
polarisation  $\langle \lambda_\theta \rangle = 0.15 \pm 0.3$ ,  
 $\lambda_\phi, \lambda_{\theta\phi} \sim 0$

Theory predictions vary  
dramatically depending on the  
data used to determine the  
NRQCD matrix elements

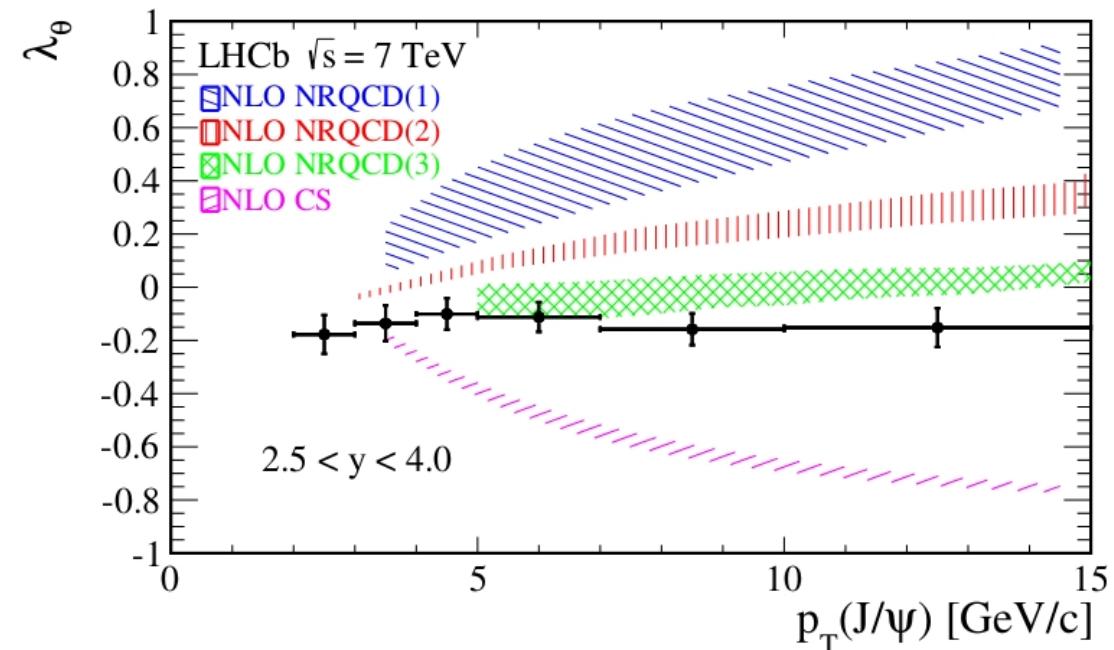
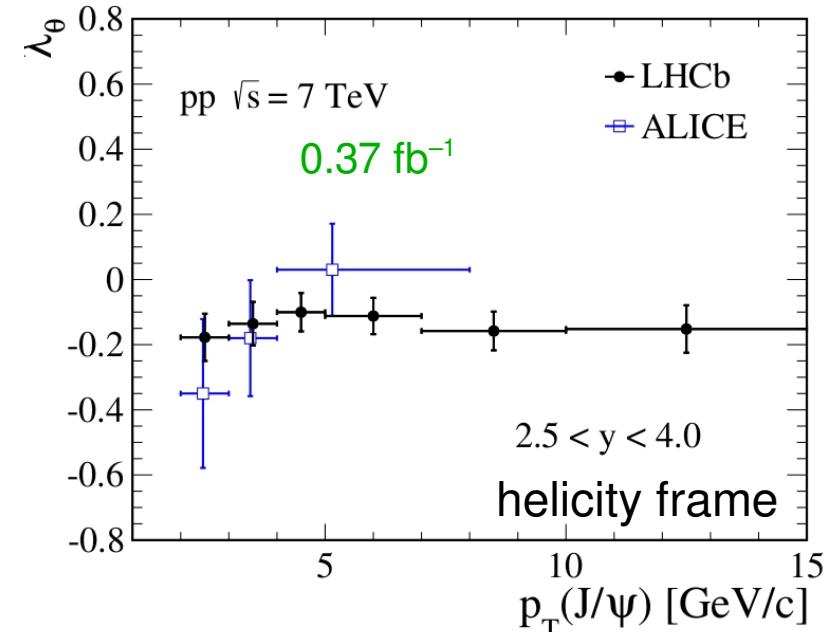
NLO NRQCD: Butenschoen, Kniehl

NLO NRQCD: Gong, Wan, J-X. Wang, H-F. Zhang

NLO NRQCD: Chao, MA, Shao, K. Wang, Y.-J. Zhang

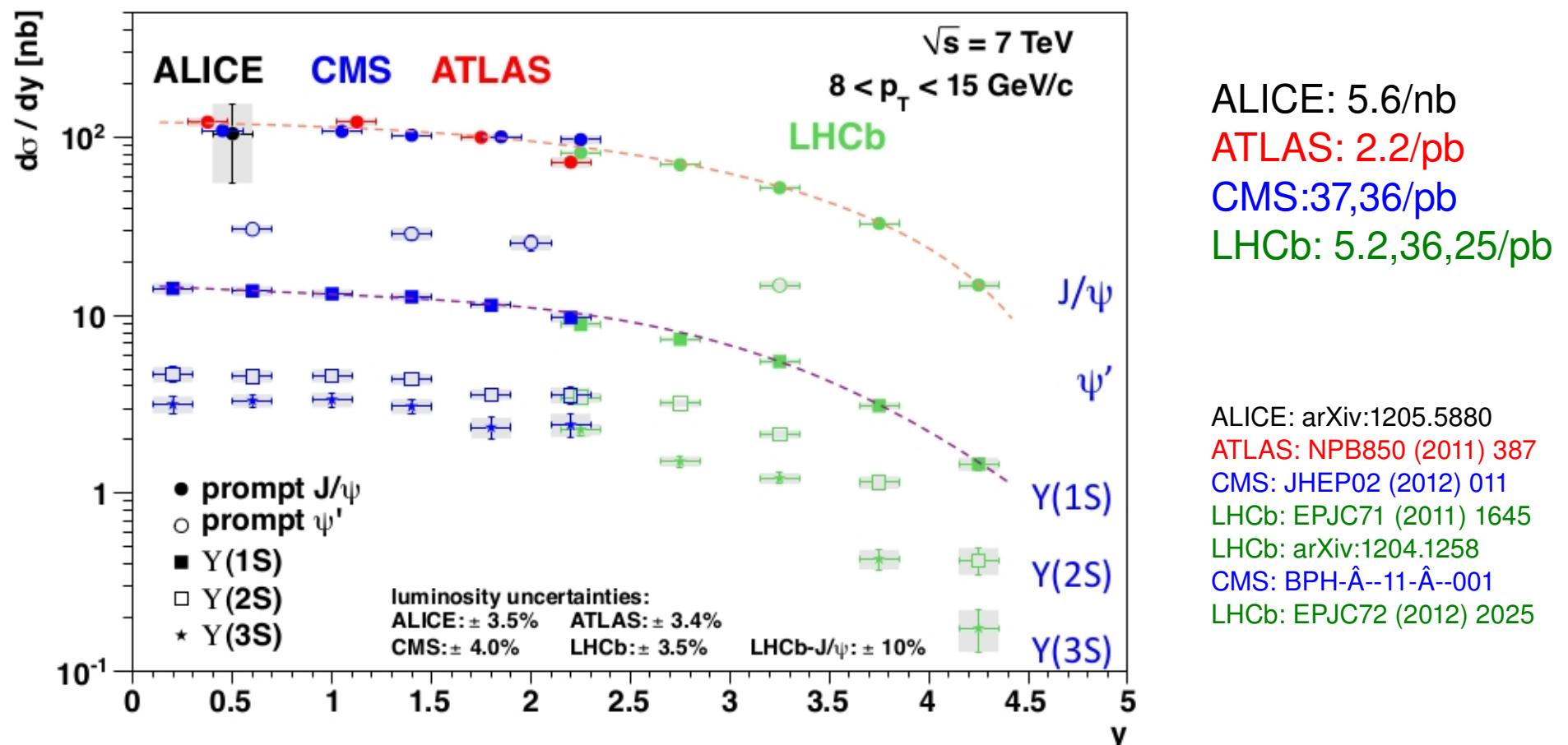
NLO CSM: Butenschoen, Kniehl

LHCb, Eur.Phys.J.C73 (2013) 2631



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

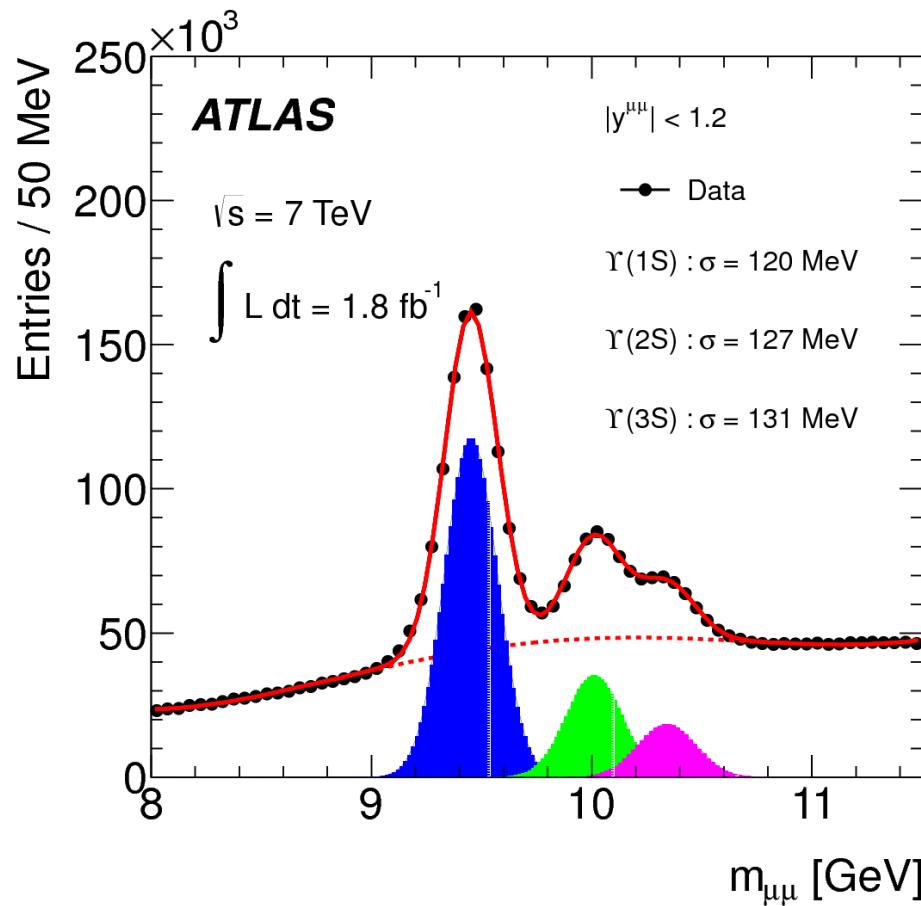
Prompt J/ $\psi$  production has been measured by four LHC experiments for  $p_T > 8 \text{ GeV}/c$ . Rapidity dependences (of ATLAS, CMS and LHCb) are similar but not perfectly overlapping. CMS and LHCb trends can also be compared for prompt  $\psi'$  and for the three Upsilon states.



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

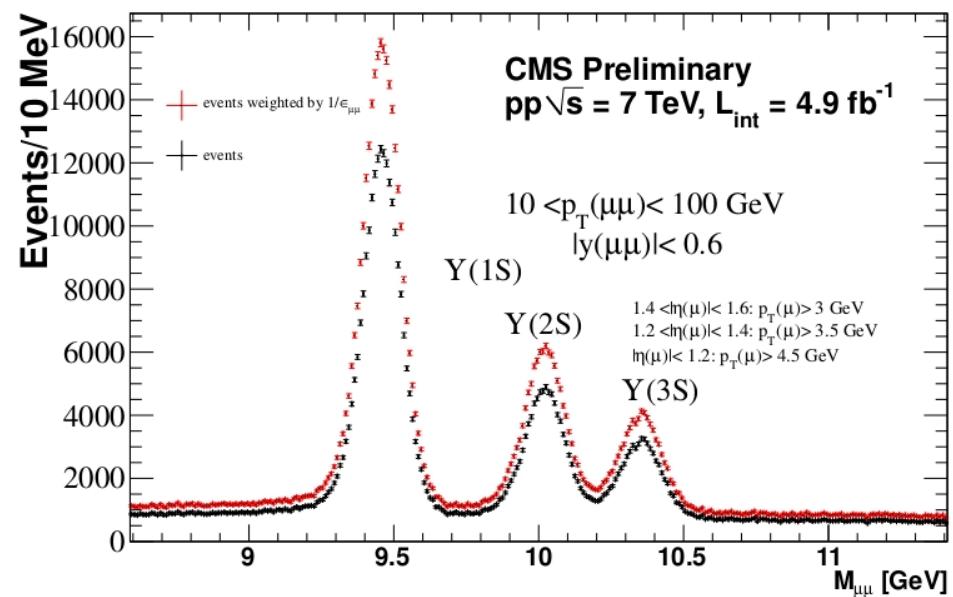
# Y(nS) production at $\sqrt{s} = 7 \text{ TeV}$ and mid-rapidity

ATLAS, PRD87 (2013) 052004



Acceptance assumes unpolarized  $\Upsilon(nS)$

CMS-BPH-12-006



Acceptance from measured  
 $\Upsilon(nS)$  polarization

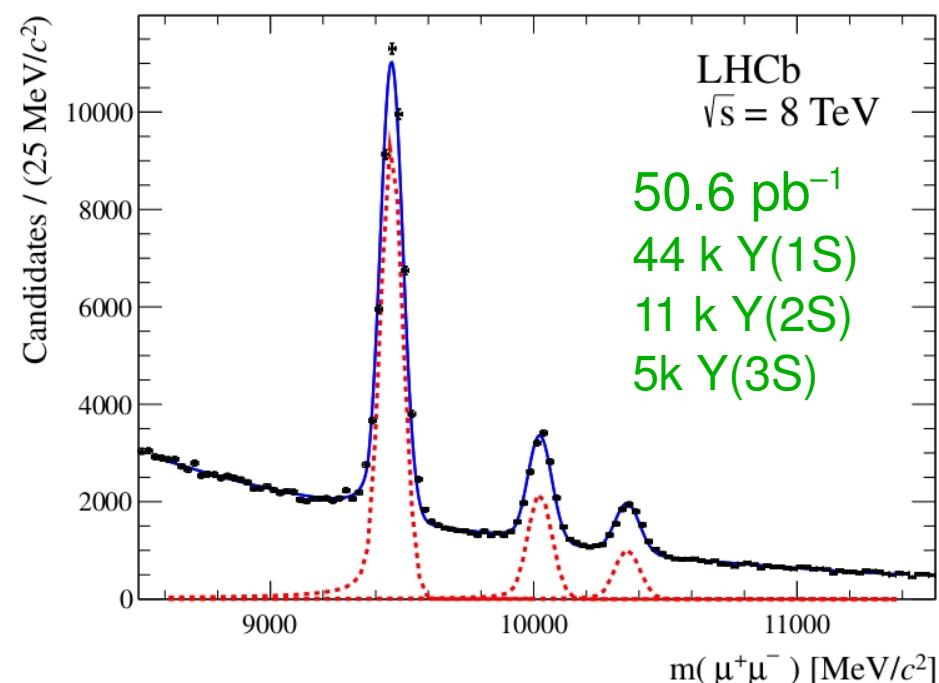
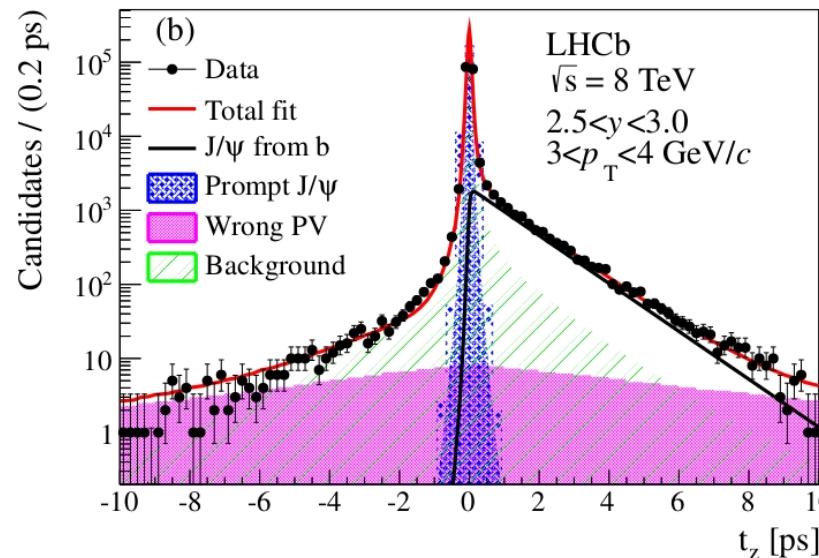
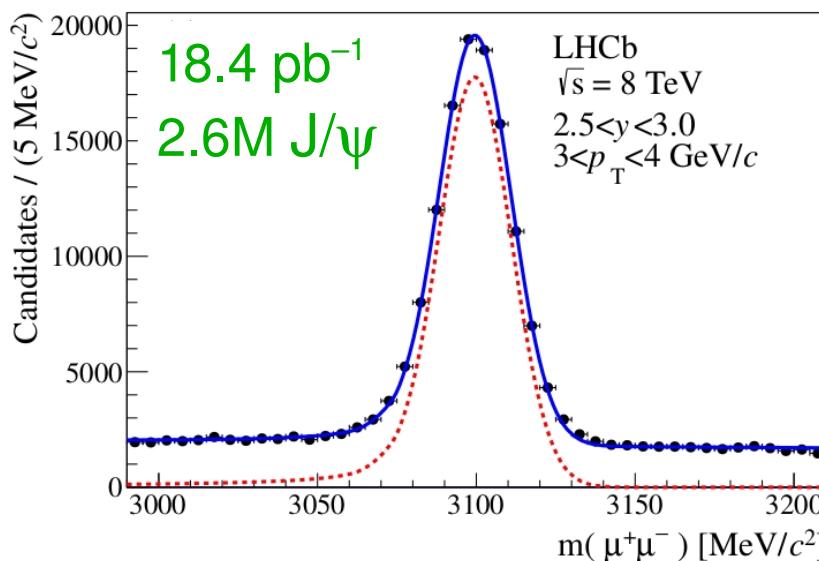
Both experiments evaluated the muon efficiencies from data-driven methods

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

LHCb, JHEP 06 (2013) 064

quarkonium double-differential cross sections in  $p_T$  and  $y$

$2.0 < y < 4.5$ ,  $0 < p_T < 14$  GeV for J/ $\psi$  and  $0 < p_T < 15$  GeV for Y



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

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

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

LHCb, JHEP 06 (2013) 064

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

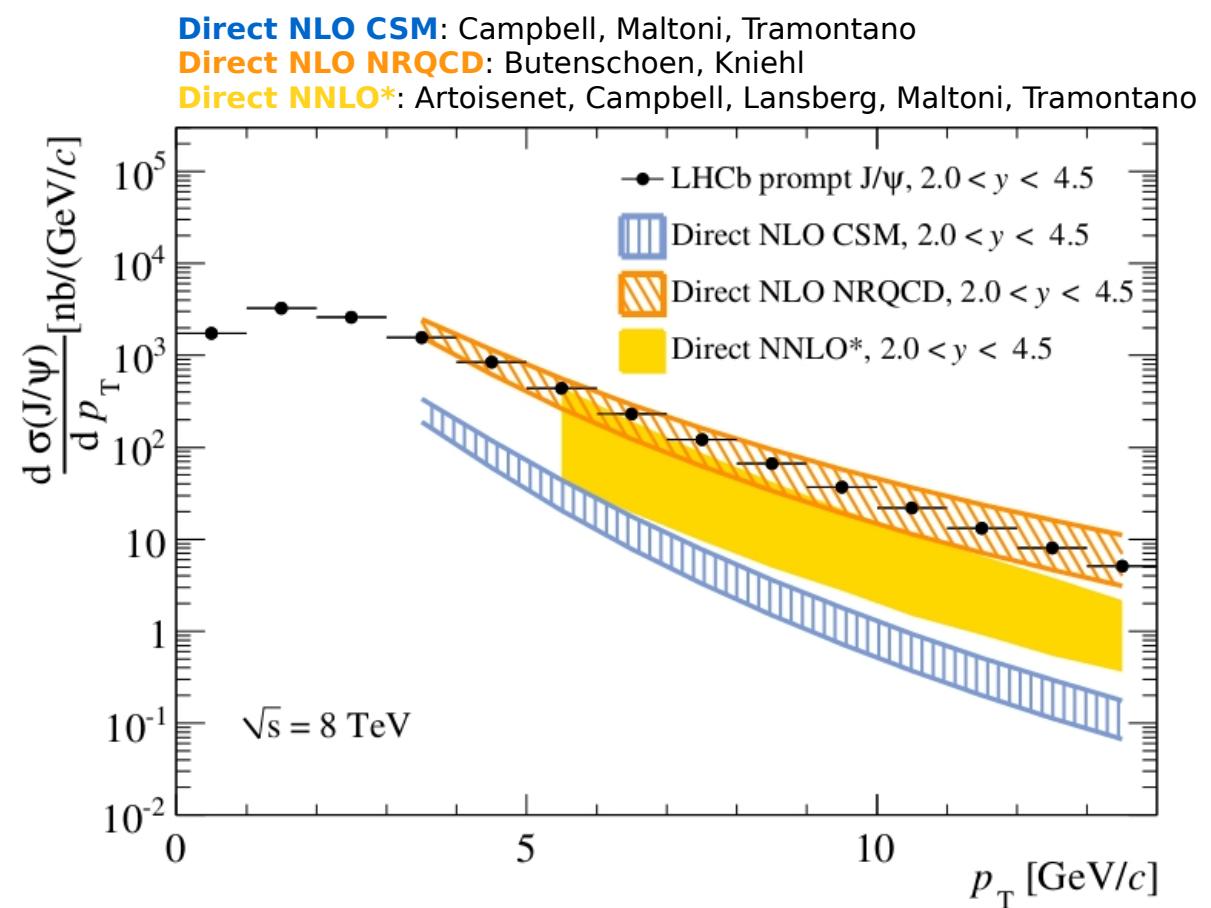
## Prompt J/ $\psi$ :

Large data samples: double differential cross-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



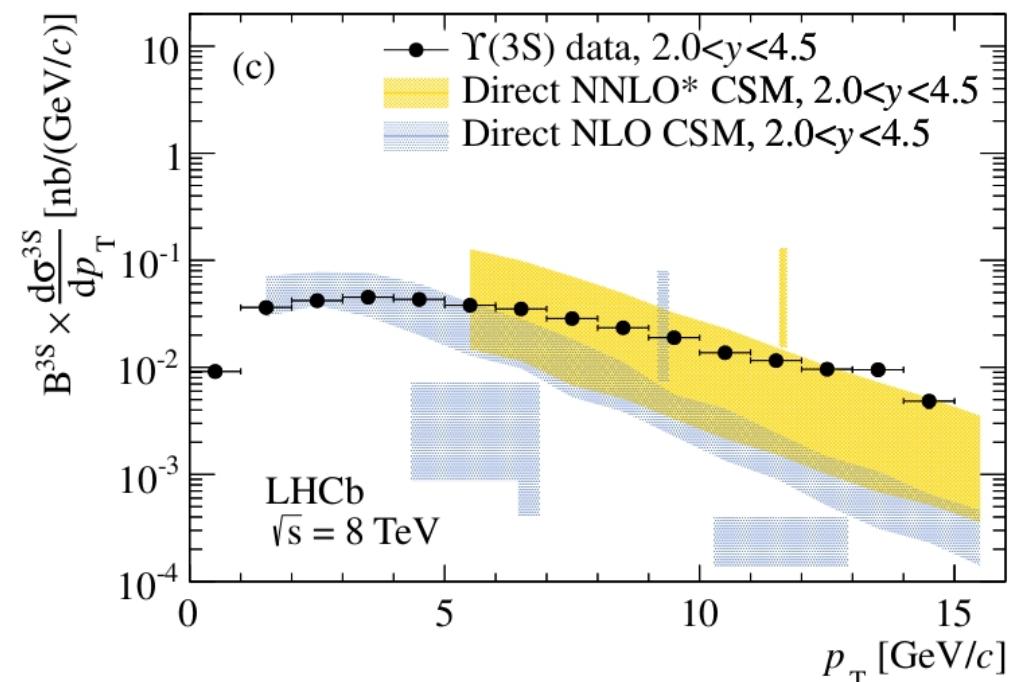
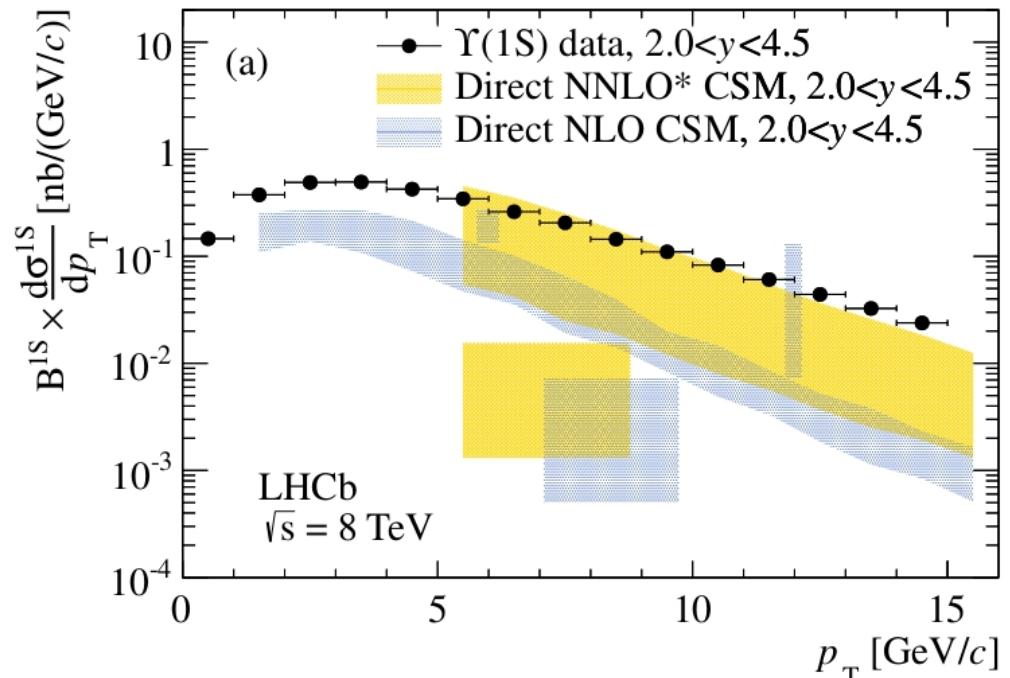
# J/ $\psi$ and Y production at $\sqrt{s} = 8$ TeV

LHCb, JHEP 06 (2013) 064

Y(nS) production:

Feed-down not included in  
calculations

NNLO\* CSM describes the data



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

LHCb, JHEP 06 (2013) 064

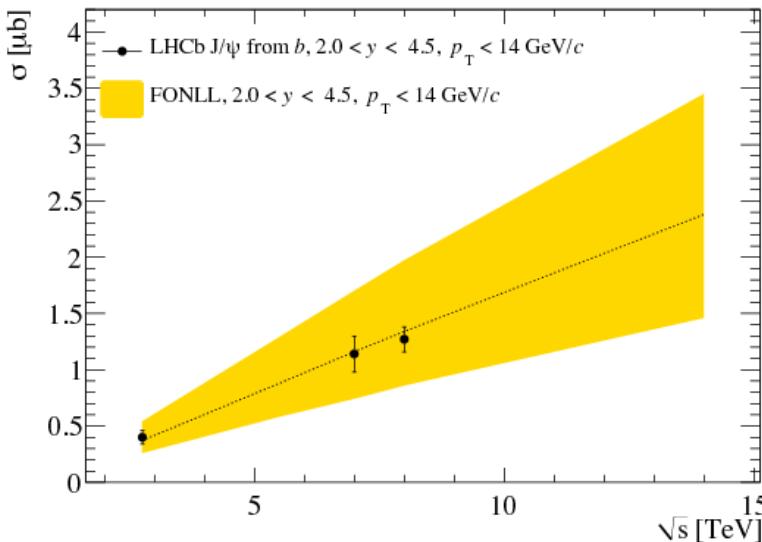
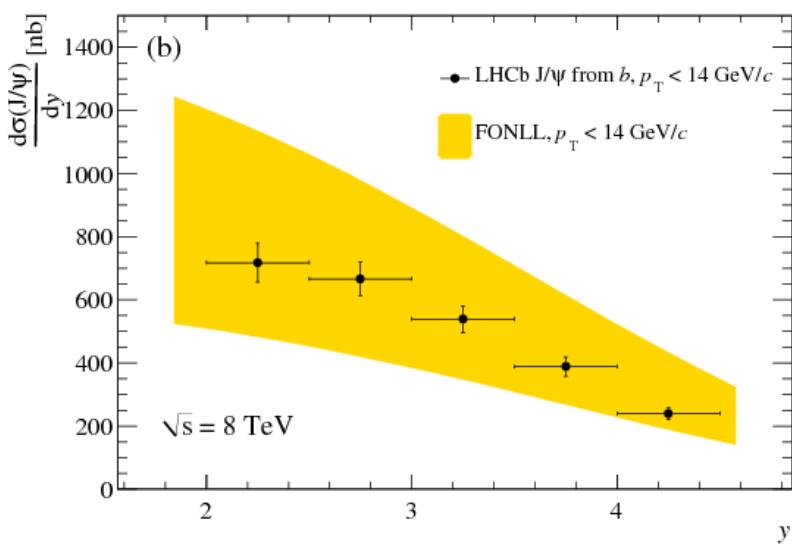
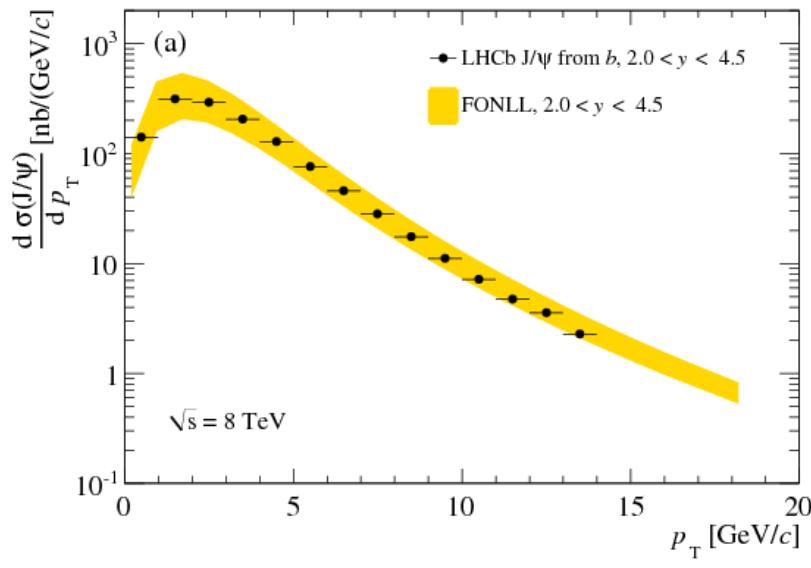
B cross section obtained through non-prompt  $J/\psi$ , performing a mass-lifetime fit

Measured cross section for  $2.0 < y(J/\psi) < 4.5$  and  $p_T(J/\psi) < 14$  GeV

$$\sigma = 1.28 \pm 0.01 \pm 0.11 \text{ } \mu\text{b}$$

Total  $b\bar{b}$  production cross section is thus

$$\sigma = 298 \pm 2 \pm 36 \text{ } \mu\text{b}$$



FONLL calculations reproduce the  $p_T$  and  $y$  dependence of  $J/\psi$ 's from  $B$  decays, and the total cross section

The  $\sqrt{s}$  dependence at LHC energies was established by LHCb from 2.76 to 8 TeV

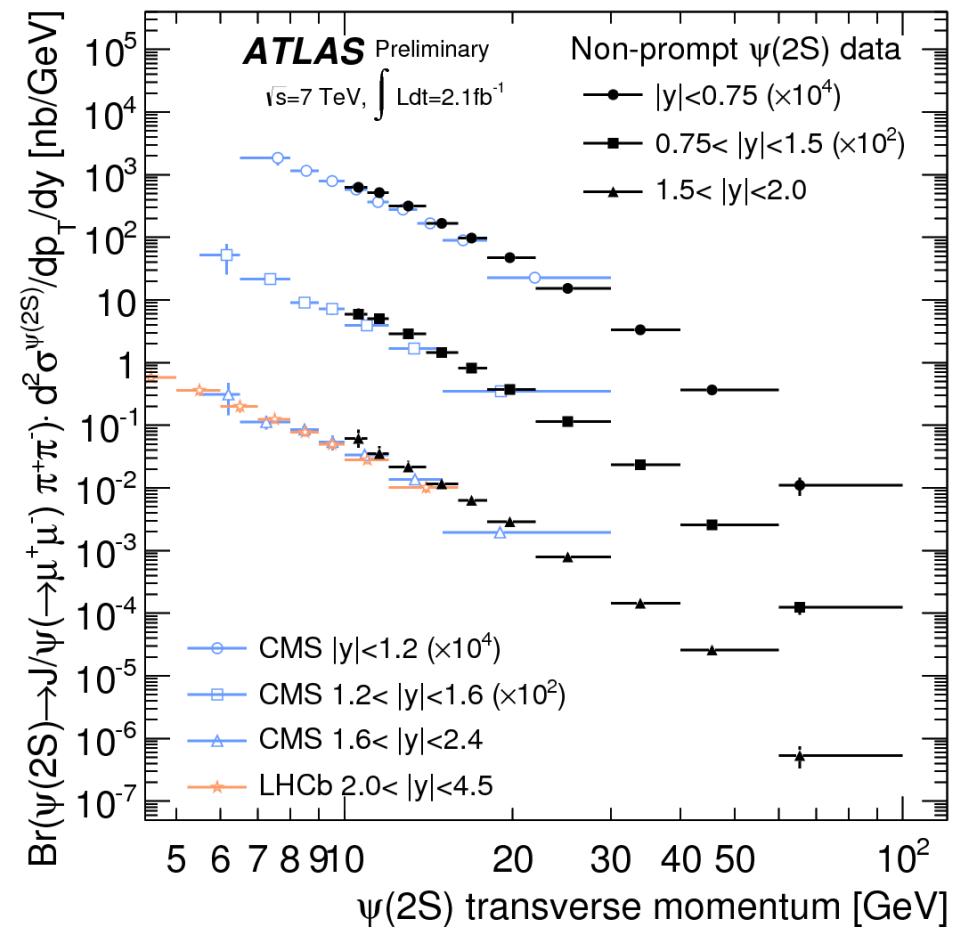
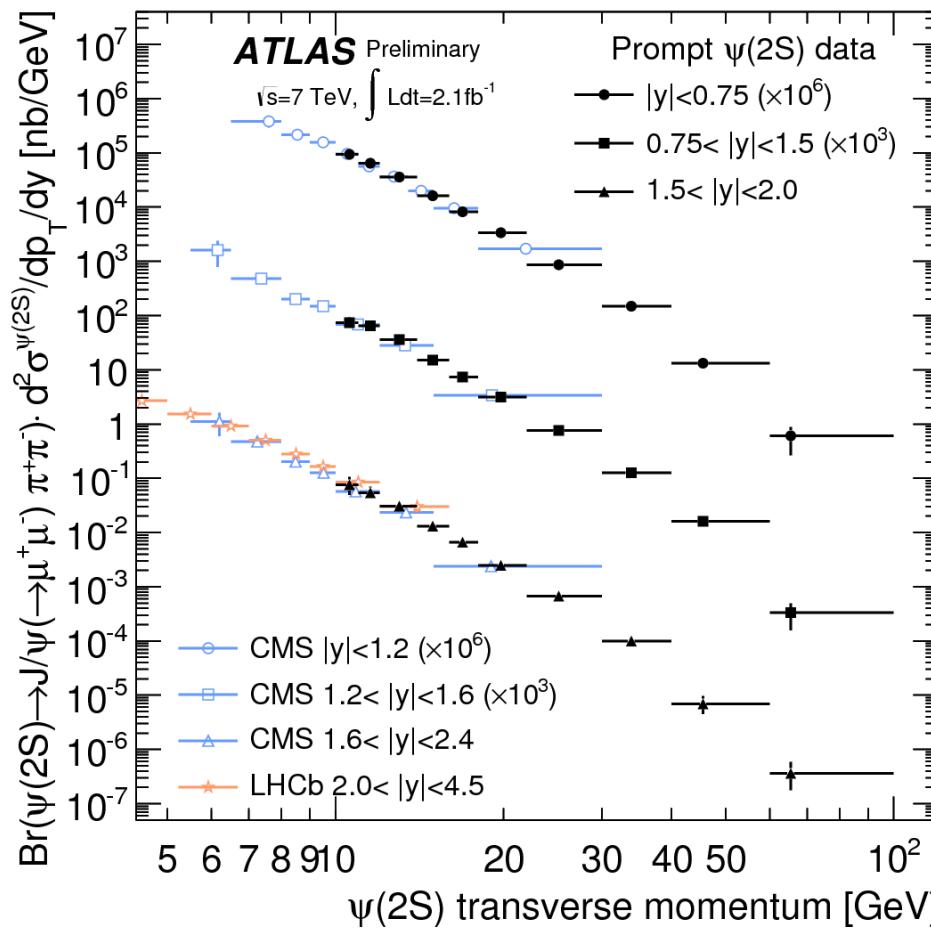
Increase is reproduced by FONLL

# Cross-section measurement of

$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-) \pi^+\pi^-$  at  $\sqrt{s} = 7$  TeV

ATLAS-CONF-2013-094

Fully-corrected differential prompt and non-prompt cross-sections  
 Assumed isotropically production of the  $\psi(2S)$   
 Compared to earlier results from LHCb and CMS in rapidity intervals



$10 < p_T < 100$  GeV and  $|y| < 2.0$

# Cross-section measurement of

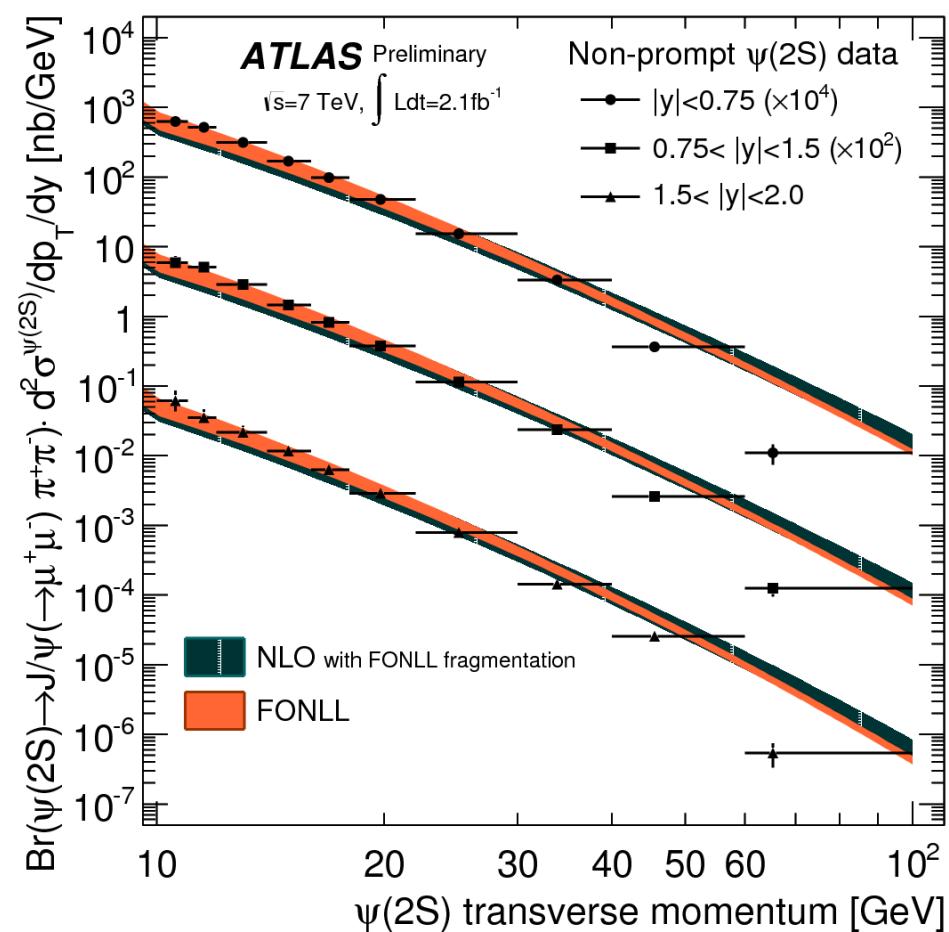
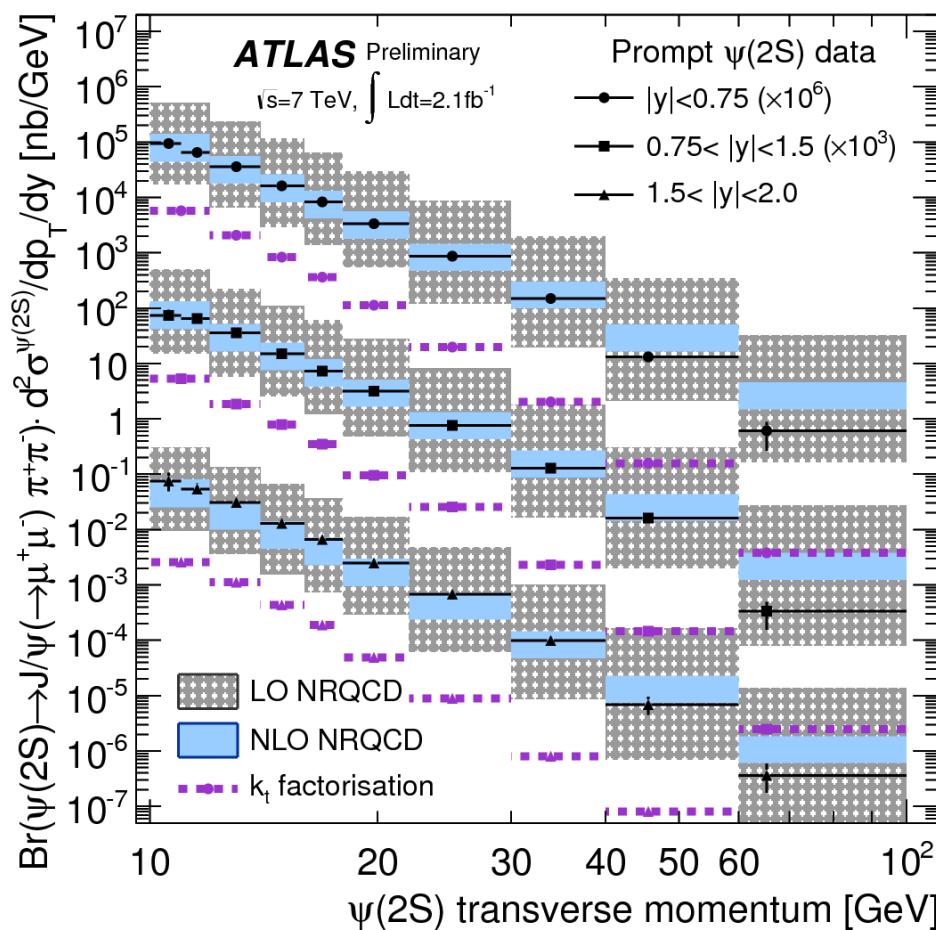
$$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-) \pi^+\pi^- \text{ at } \sqrt{s} = 7 \text{ TeV}$$

ATLAS-CONF-2013-094

NRQCD LO: agreement with data

NRQCD NLO: good shape and normalisation  
at high transverse momenta, NRQCD  
predicts a harder spectrum than observed.

Fixed-order next-to-leading-log (FONLL)  
good agreement  
slightly underestimation at low  $p_T$  and  
overestimation at the high  $p_T$  values,  
→ overall softer  $p_T$  distribution

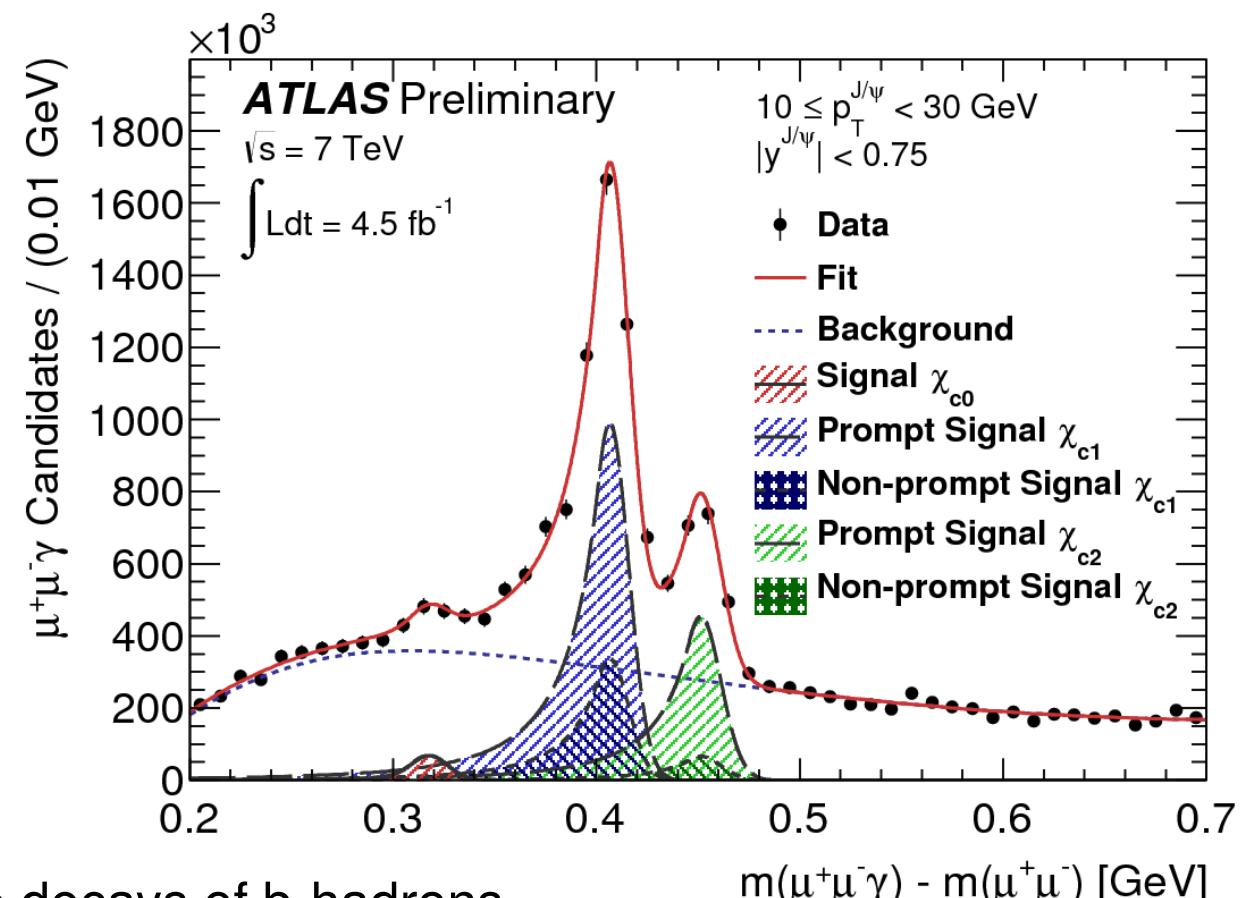


# Measurement of the $\chi_{c1}$ and $\chi_{c2}$ production at $\sqrt{s} = 7$ TeV

ATLAS-CONF-2013-095

Radiative decay  $\chi_c \rightarrow J/\psi \gamma$   
 with  $J/\psi \rightarrow \mu^+ \mu^-$   
 with converted photons.

Mass difference to distinguish  
 the  $\chi_{c1}$  and  $\chi_{c2}$  states.  
 Partial cancellations give  
 improved overall mass  
 resolution.



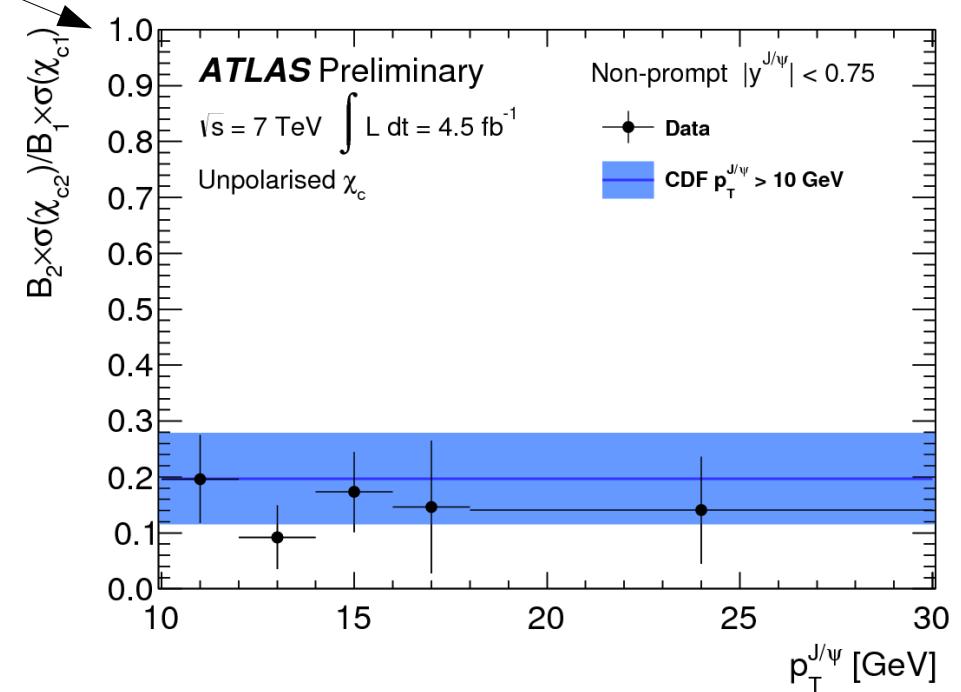
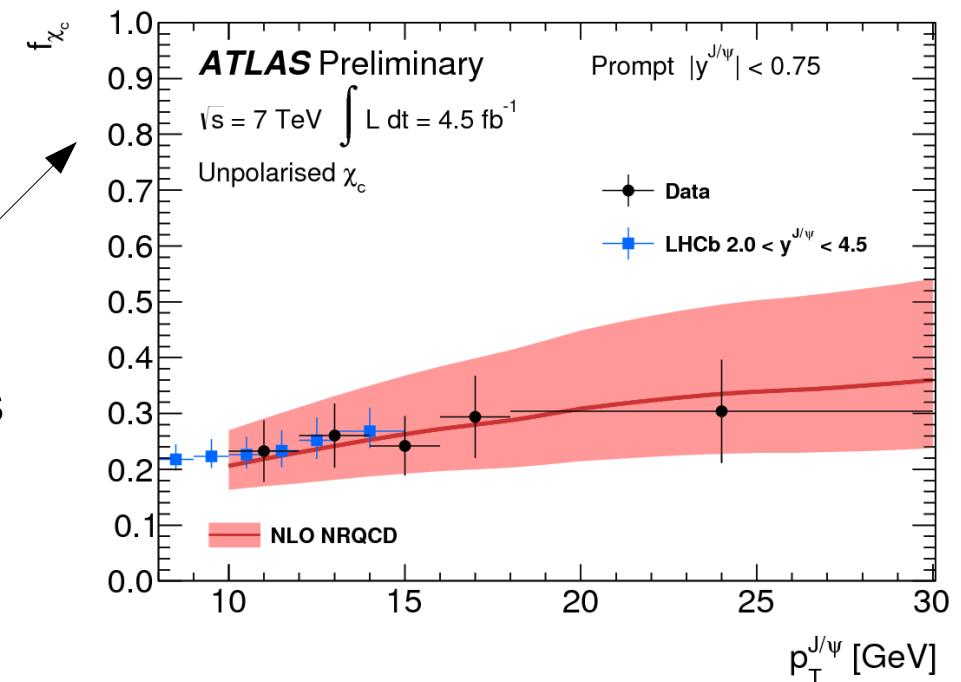
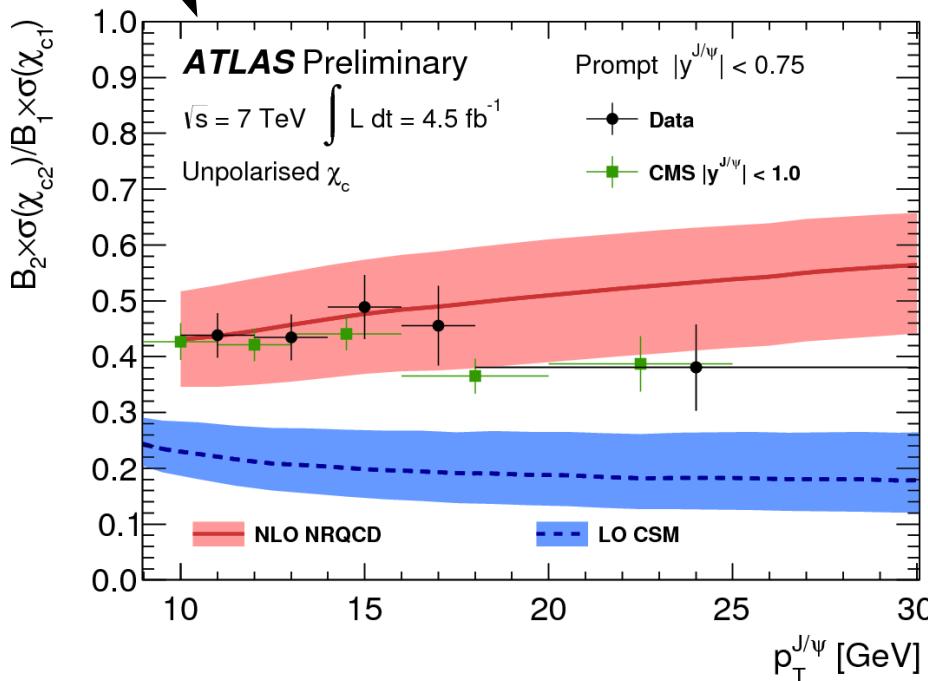
Non-prompt  $\chi_c$  produced in the decays of b-hadrons  
 distinguished from prompt  $\chi_c$  candidates (produced in the  
 primary pp interaction) with the pseudo-proper decay  
 time distribution

See also (on 7 TeV data):  
 CMS, EPJC 72 (2012) 2251

# Measurement of the $\chi_{c1}$ and $\chi_{c2}$ production at $\sqrt{s} = 7$ TeV

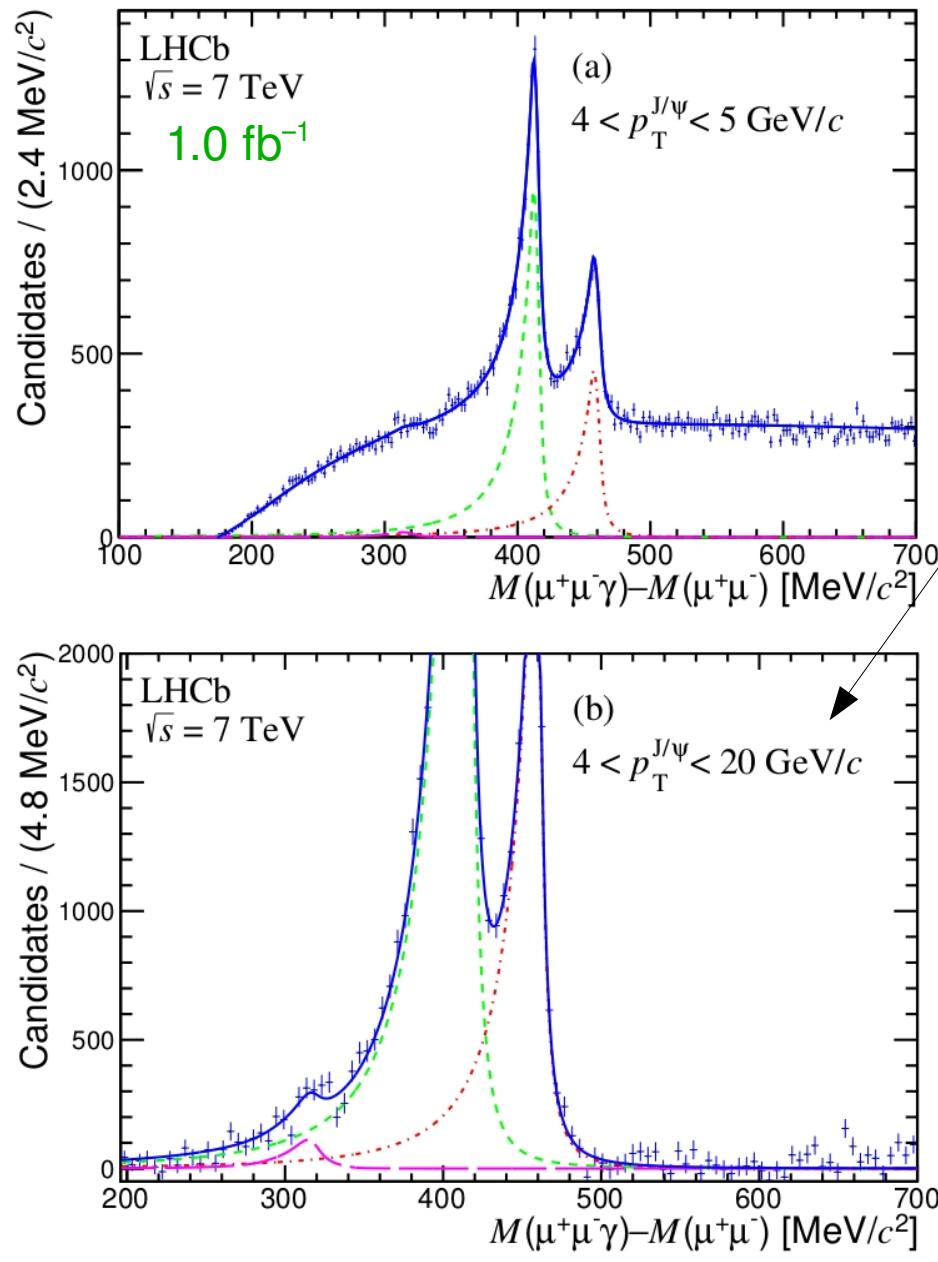
ATLAS-CONF-2013-095

The prompt  $\chi_c$  cross sections combined with prompt J/ $\psi$  production to obtain the fraction of prompt J/ $\psi$  produced in feed-down from  $\chi_c$  decays  $\chi_{c2}$  production rate relative to  $\chi_{c1}$  prompt and non-prompt  $\chi_c$  function of J/ $\psi$  transverse momentum.



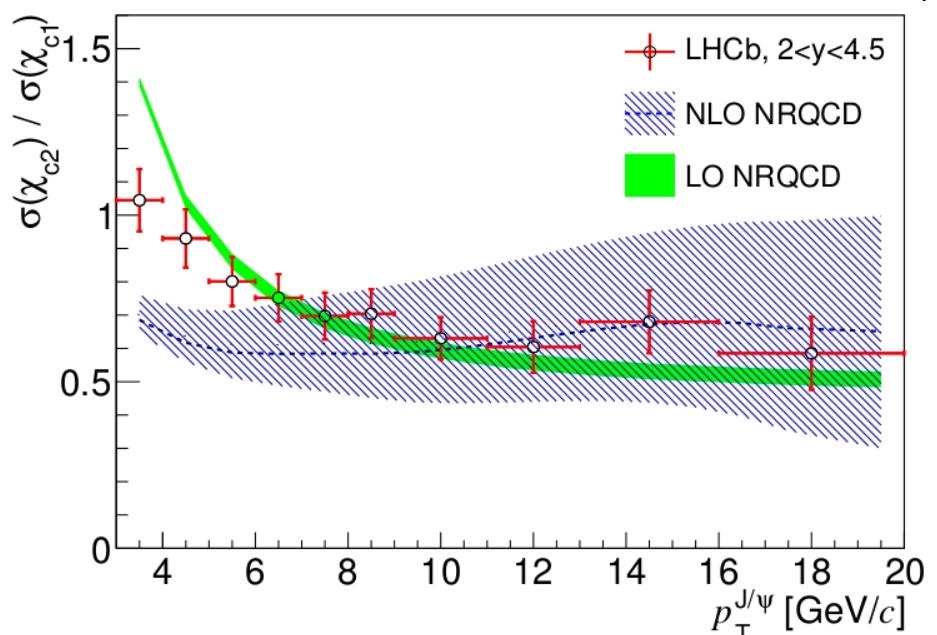
# Measurement of the $\chi_{c1}$ and $\chi_{c2}$ production at $\sqrt{s} = 7$ TeV

LHCb, JHEP 10 (2013) 115



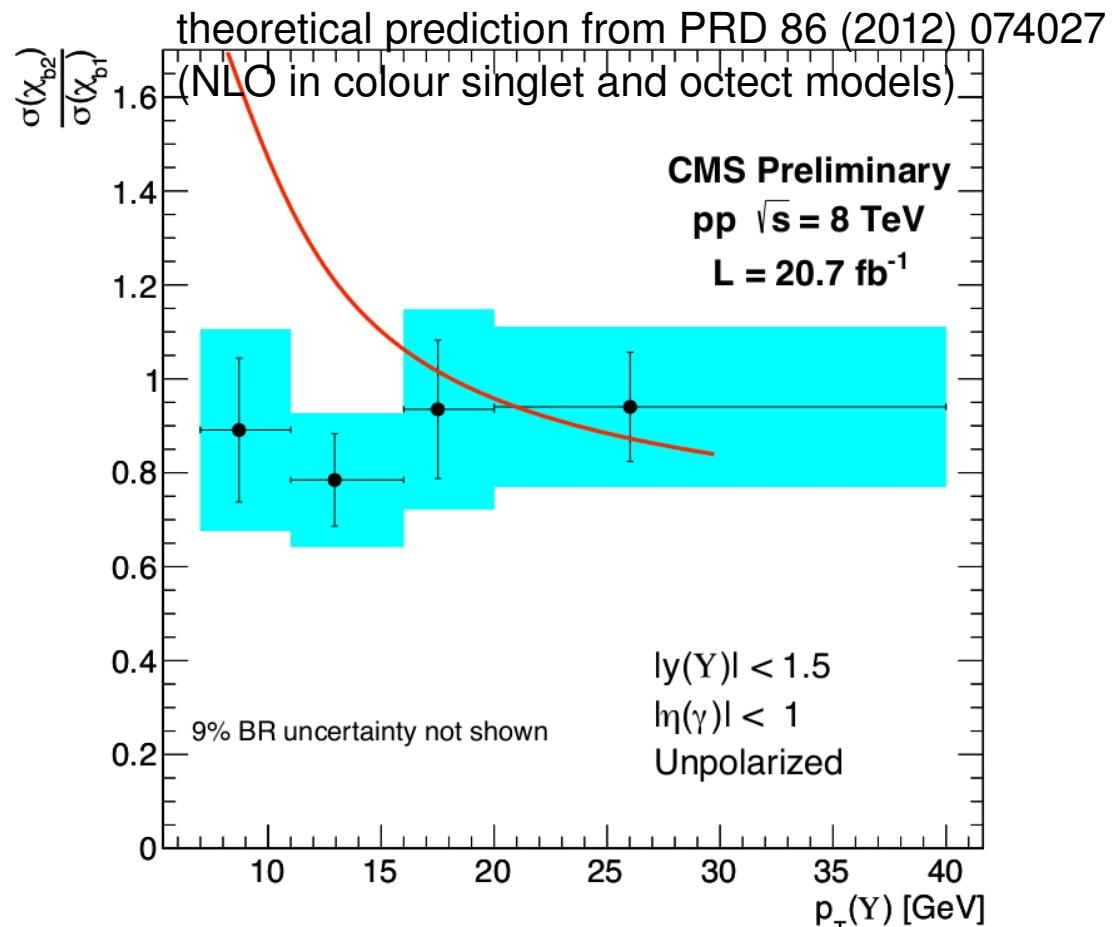
Prompt production of  $\chi_{c0}$ ,  $\chi_{c1}$  and  $\chi_{c2}$   
Radiative decay  $\chi_c \rightarrow \text{J}/\psi \gamma$   
with  $\text{J}/\psi \rightarrow \mu^+\mu^-$   
with converted photons.  
Rapidity range  $2.0 < y < 4.5$   
Transverse momentum  $3 < p_T < 20 \text{ GeV}/c$ .  
First evidence for  $\chi_{c0}$  at the LHC

Relative prompt production rate of  
 $\chi_{c1}$  and  $\chi_{c2}$  as function of the  $\text{J}/\psi p_T$

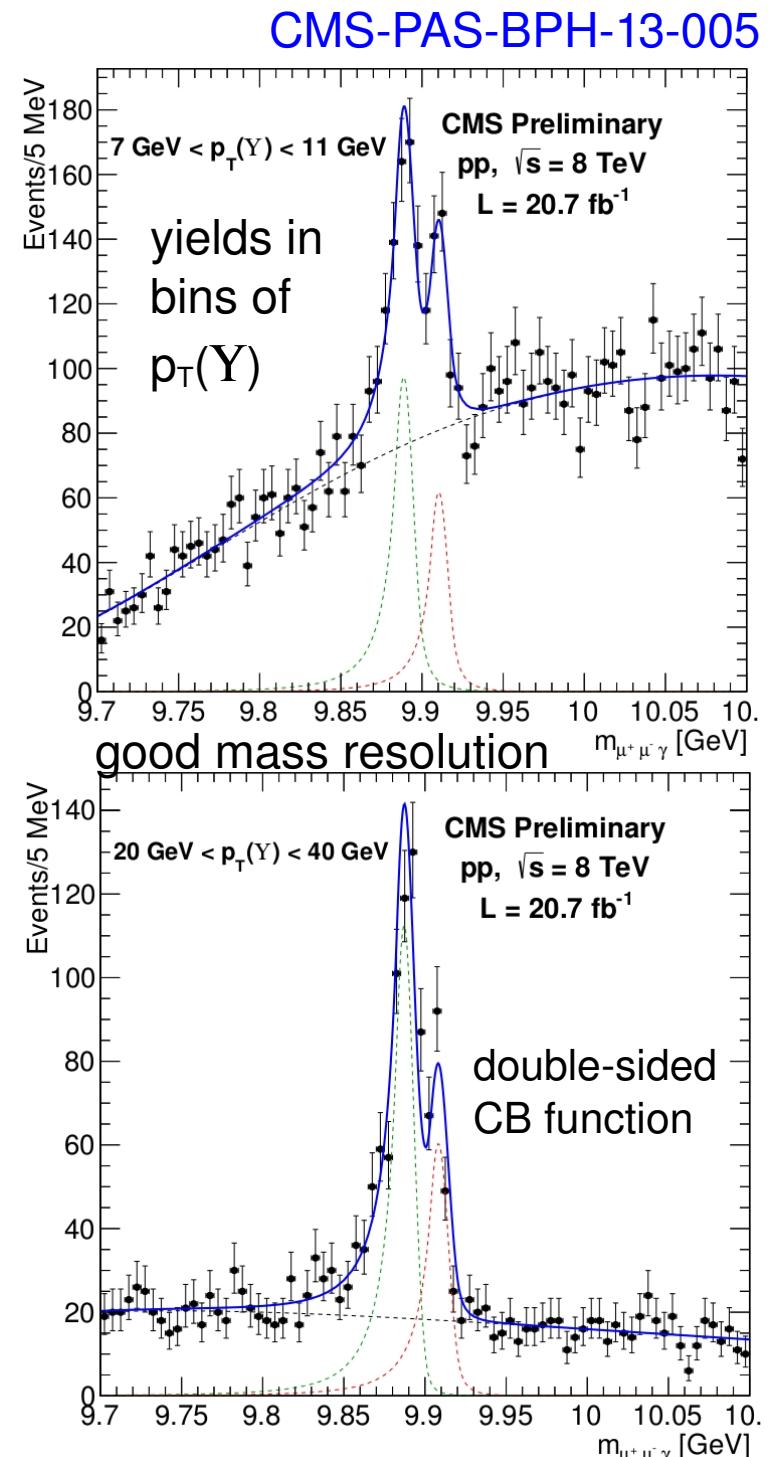


# Measurement of the $\chi_{b1}$ and $\chi_{b2}$ cross section ratio at $\sqrt{s} = 8\text{TeV}$

The ratio of cross sections of  $\chi_{b2}(1P)$  and  $\chi_{b1}(1P)$  radiative decays  $\chi_{b1}(1P) \rightarrow Y(1S) + \gamma$  (converted)

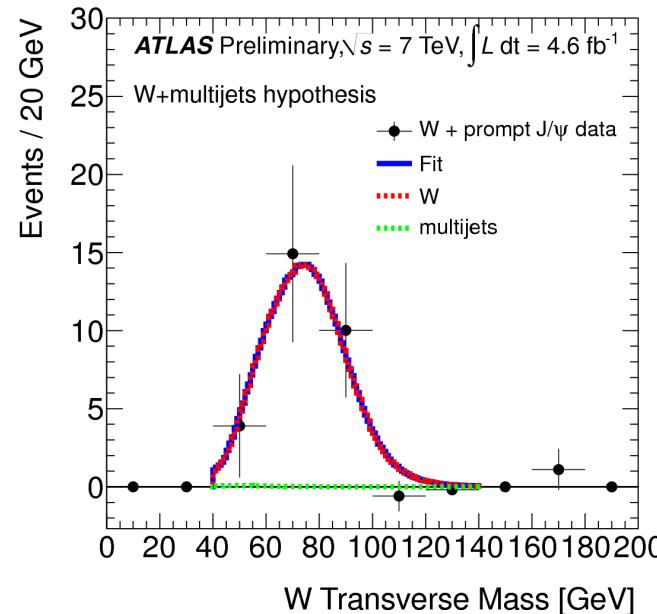
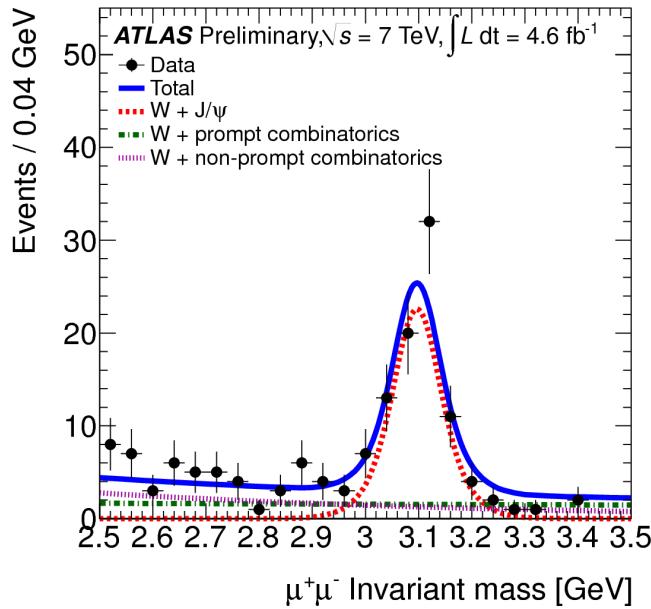


Measured cross-section ratio is around 0.9, with no significant dependence on  $p_T(Y)$ .

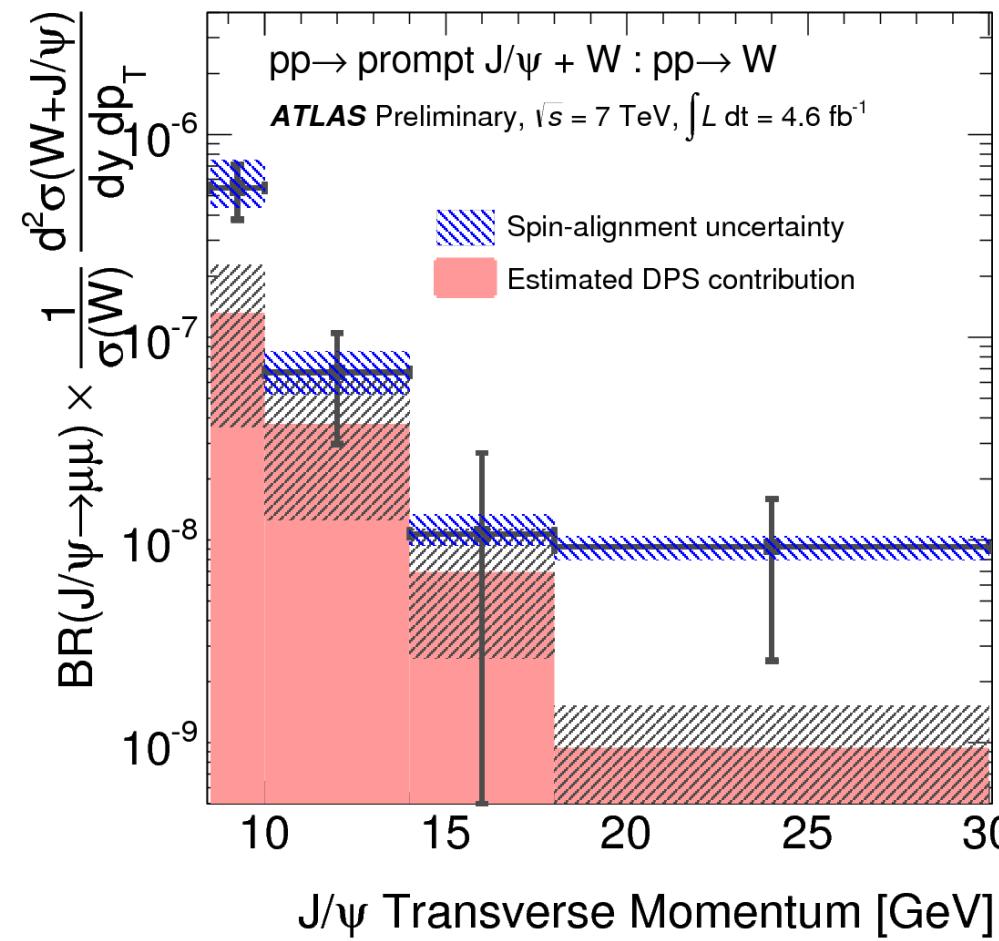


# Associated $J/\psi$ and $W^\pm$ production at $\sqrt{s} = 7$ TeV

ATLAS, arXiv:1401.2831



Another measurement to test quarkonium production  
UML fit to  $J/\psi$  mass and lifetime  
gives  $\sim 30$  prompt  $J/\psi$  with a  $W^\pm$   
includes  $1.8 \pm 0.2$  from pile-up and  
 $10.8 \pm 4.2$  from double parton scattering (DPS)



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

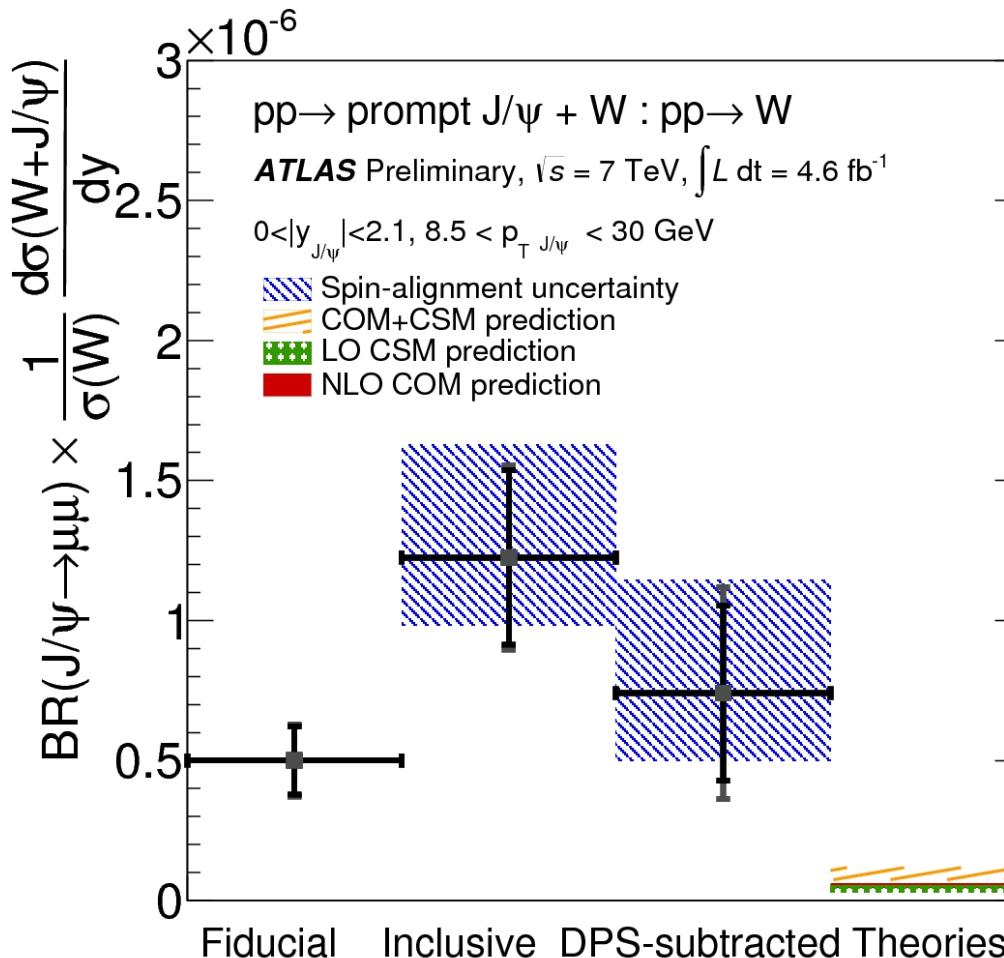
$(W^\pm + J/\psi)$  to inclusive  $W^\pm$  cross-section ratio ( $R$ )

ATLAS, arXiv:1401.2831

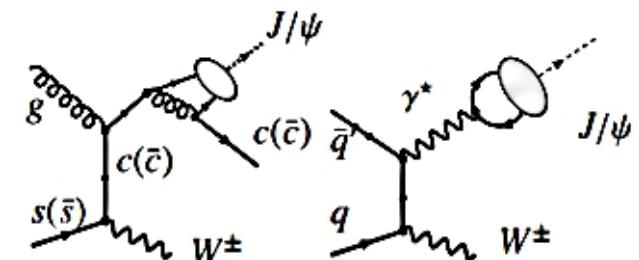
for  $|y(J/\psi)| < 2.1$  and  $8.5 < p_T(J/\psi) < 30$  GeV:

Comparison with quarkonium models after subtracting the DPS contribution:

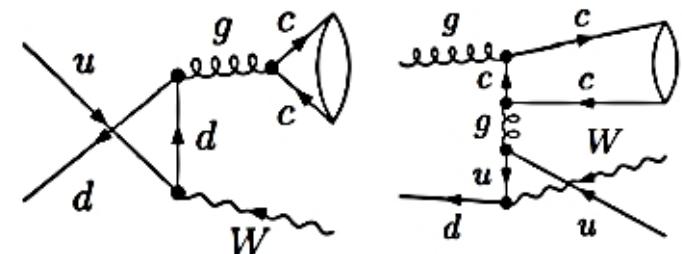
Data show roughly an order of magnitude larger cross section  
than theory predictions



LO  
CSM  
[arXiv:1303.5327]

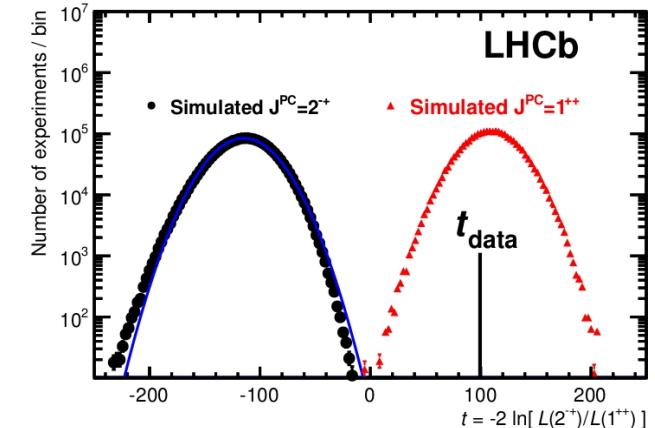


NLO  
NRQCD  
[arXiv:1304.4670]



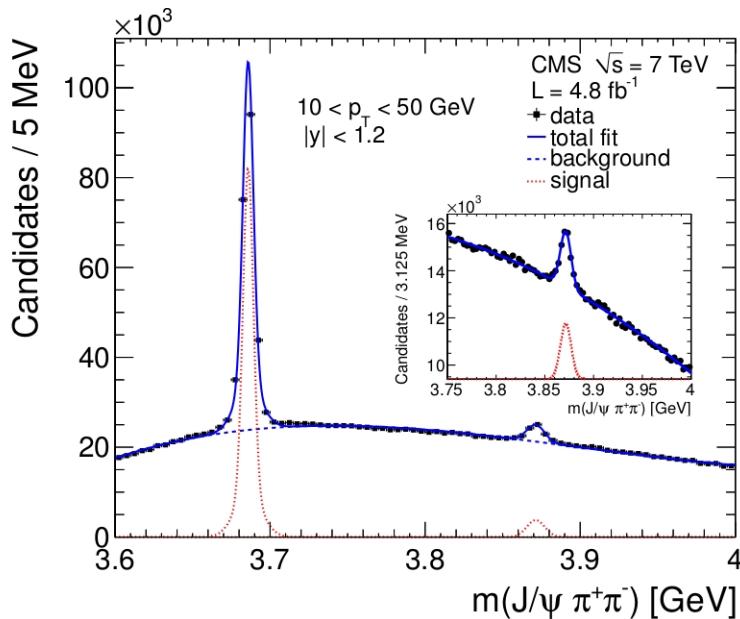
# Exotic X(3872) state

is it tetra-quark, c anti-c, DD\* molecule, ...  
 CDF previously ruled out all  $J^{PC}$  except  $1^{++}$  and  $2^{-+}$



CMS measures

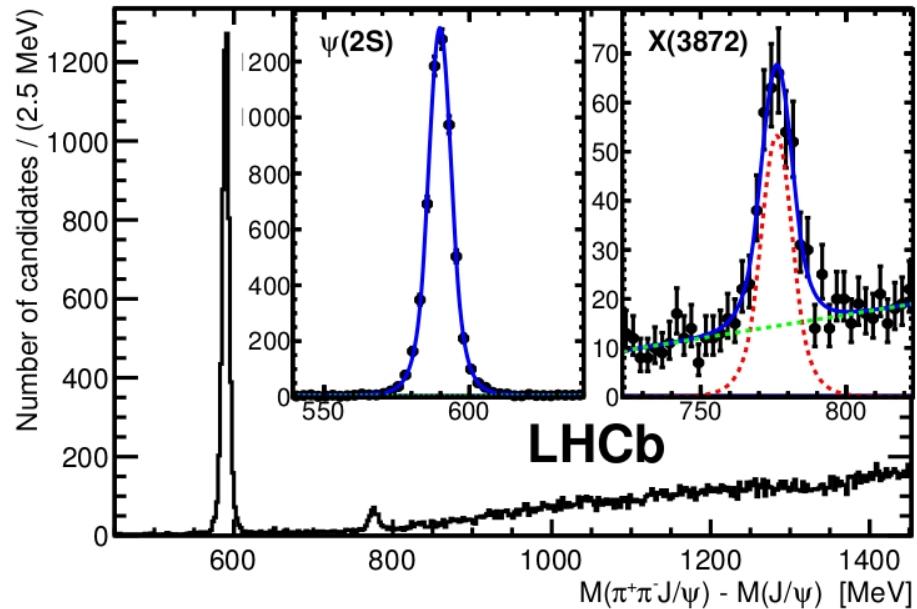
$X \rightarrow J/\psi \pi\pi$  decays  
 ~12.000 X candidates  
 with  $p_T(\mu) > 4$  GeV,  
 $p_T(\pi) > 600$  MeV



CMS, JHEP 04 (2013) 154

LHCb studies its quantum numbers

313 events in decay  $B \rightarrow X(3872)K^+$ ,  
 $X(3872) \rightarrow J/\psi \pi\pi$   
 angular analysis establishes  $J^{PC} = 1^{++}$



LHCb, PRL 110 (2013) 222001

# Exotic X(3872) state

LHCb, arXiv:1404.0275

is it tetra-quark, c anti-c, DD\* molecule, ...

X(3872) radiative decays

branching ratio sensitive to interpretation:

tetra-quark, c anti-c, DD\* molecule and mixtures

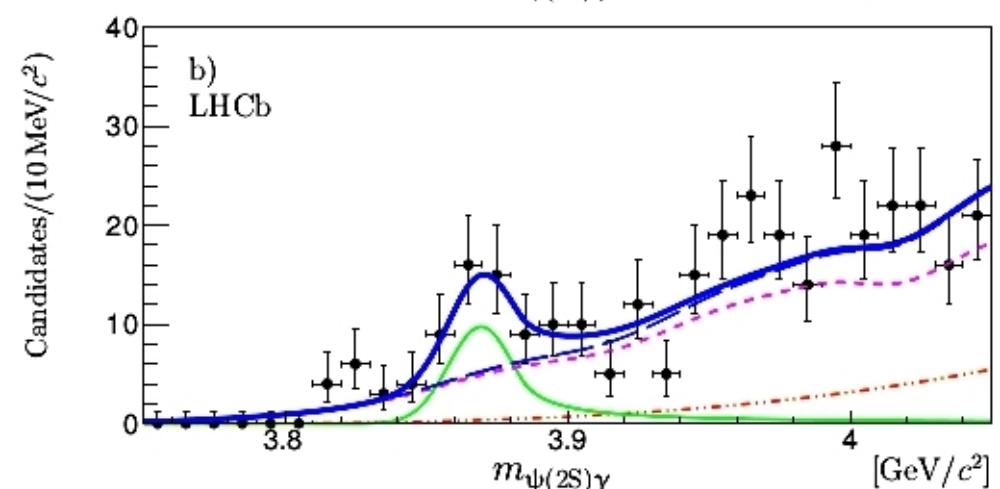
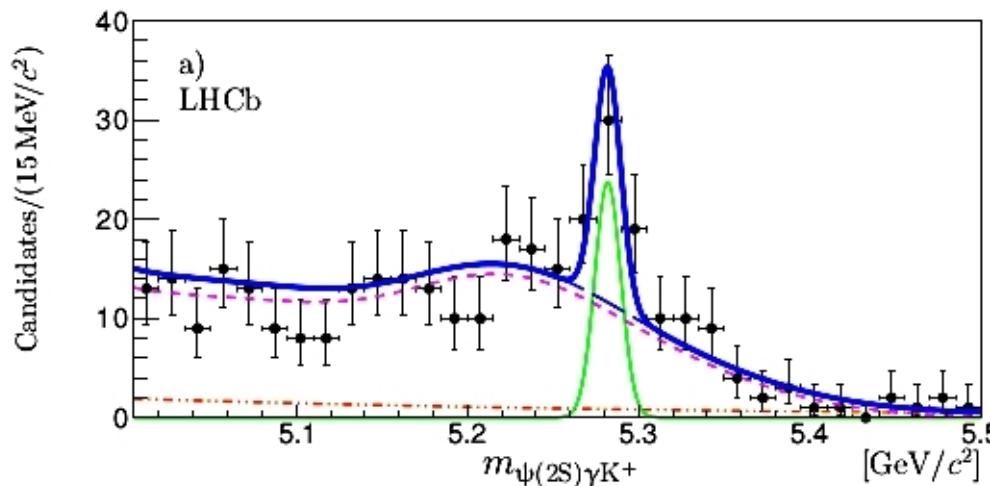
Babar evidence & Belle upper limit

LHCb measurement

$$R = 2.46 \pm 0.64 \pm 0.29 \pm 0.06$$

does not support a pure DD\* molecule interpretation

$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)}$$



evidence for the decay  $X(3872) \rightarrow \psi(2S)\gamma$  in  $B^+ \rightarrow X(3872)K^+$  decays is found with a significance of 4.4 standard deviations.

# Exotic Z(4430) state

$Z(4430)^- \rightarrow \psi(2S)\pi^-$  observed by Belle  
in  $B^0 \rightarrow \psi(2S) K^+\pi^-$  decays  
charged state, not described by  
quark model  
quark content  $\bar{c}c\bar{u}\bar{d}$ ?

Hot off the press!

“Observation of the resonant  
character of the  $Z(4430)^-$  state”

Resonant structure in

~25K events  $B^0 \rightarrow \psi(2S) K^+\pi^-$

Measurement based on 4D amplitude fit

Data cannot be described with

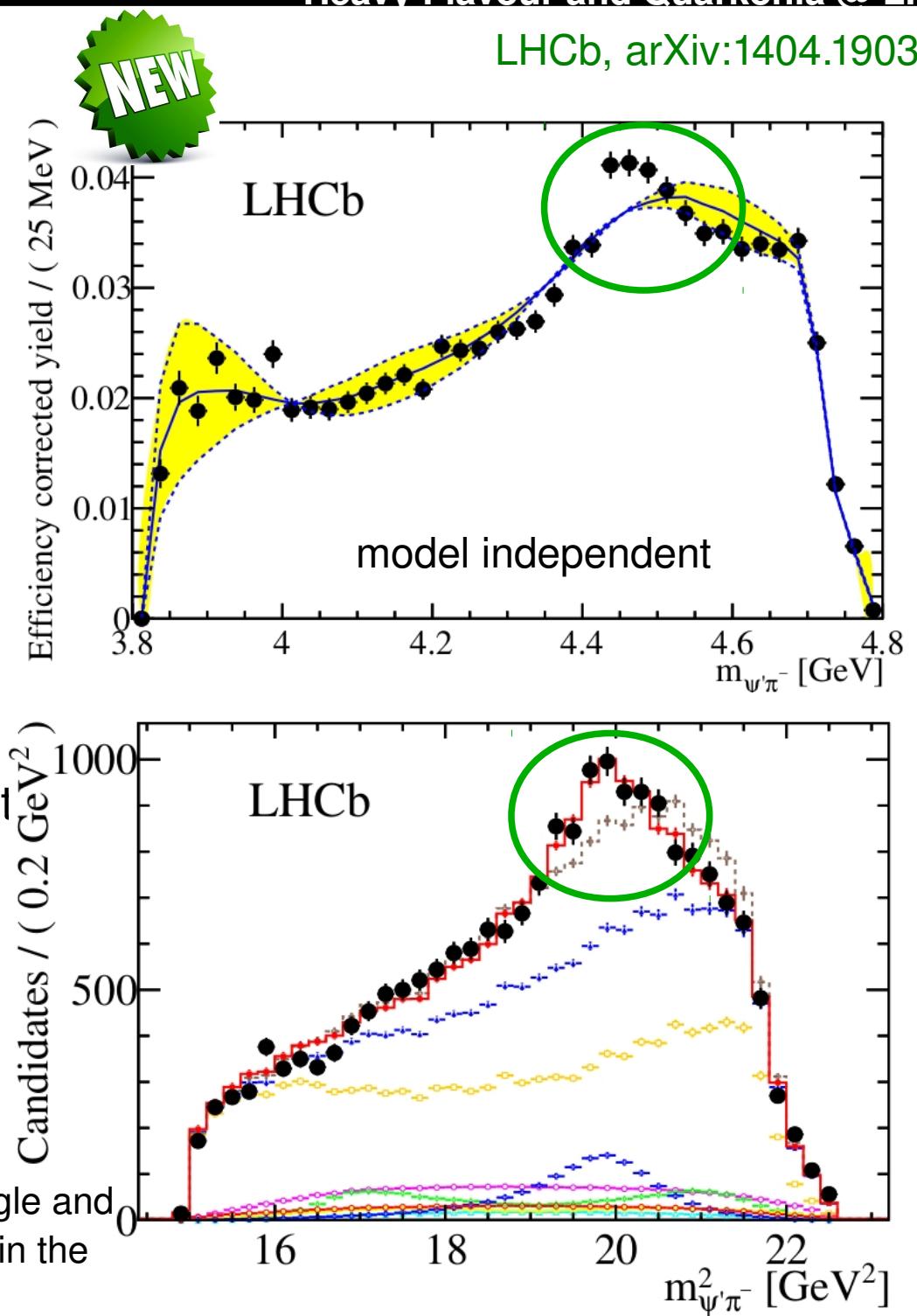
$K^+\pi^-$  resonances alone

need of a highly significant

$Z(4430) \rightarrow \psi(2S)\pi^-$  component

spin-parity is unambiguously  $1^+$

$(m_{K\pi}^2, m_{\psi\pi}^2, \cos \theta_\psi, \phi)$ , where  $\theta_\psi$  is the  $\psi$  helicity angle and  $\phi$  is the angle between the  $K^*$  and  $\psi$  decay planes in the  $B^0$  rest frame.



# Summary

Many other results I could not cover

The LHC accelerator is a heavy quarkonia “factory”

The LHC detectors are very good to study beauty and quarkonium physics

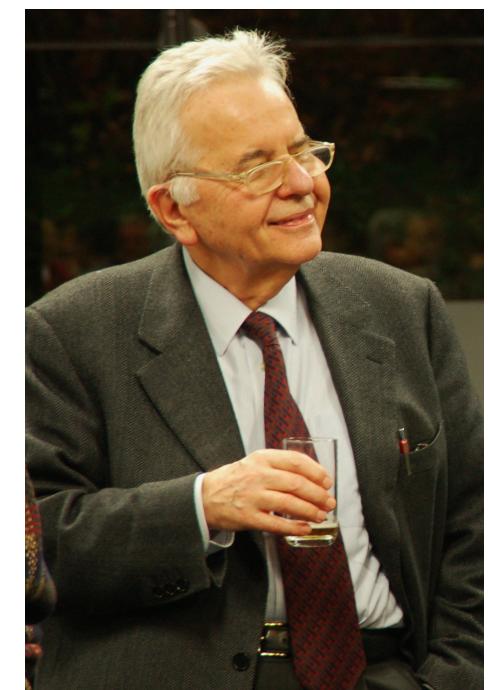
All experiments have ongoing efforts in this physics area

These results allow an in depth comparison with theoretical models

a simple CSM is disfavoured by the data,  
while a combination of CS and CO,  
as implemented in the NRQCD model,  
or CS improved by QCD corrections  
(NNLO\*) are more successful

More ongoing studies of the 8 TeV data will trigger further progress

ricordo di Nicola  
nel giorno del suo  
compleanno





10th and 11th July 2014

Queen Mary University of London (Mile End Campus)

On July 10th 1964 **Cronin**, Fitch, Christensen and Turlay submitted a paper to Phys. Rev. Lett. announcing the discovery of CP violation in the weak decays of neutral kaons. This was the start of our understanding of the implications of this broken improper symmetry, and the consequences this has for the existence of our Universe in its matter dominated state. The phenomenon of CP violation, even after 50 years of exploration, is still not well understood from first principles. However we thankfully have a good understanding of the **Kobayashi-Maskawa** ansatz that defines a three generation Standard Model, where CP violation is incorporated in the Cabibbo-Kobayashi-Maskawa matrix.

backup

# X(3872) production

CMS measures

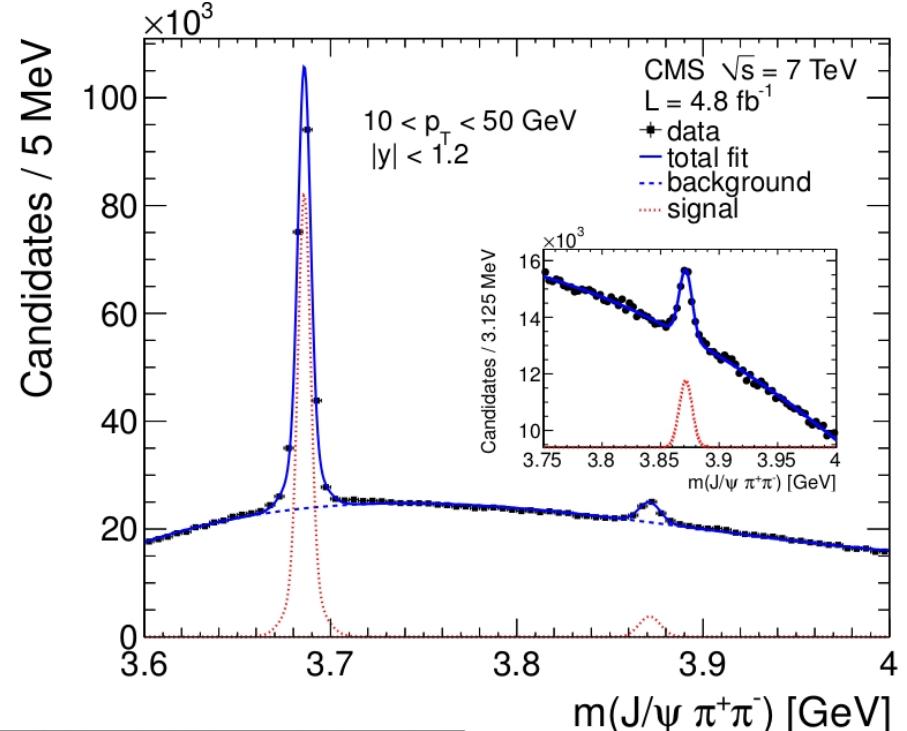
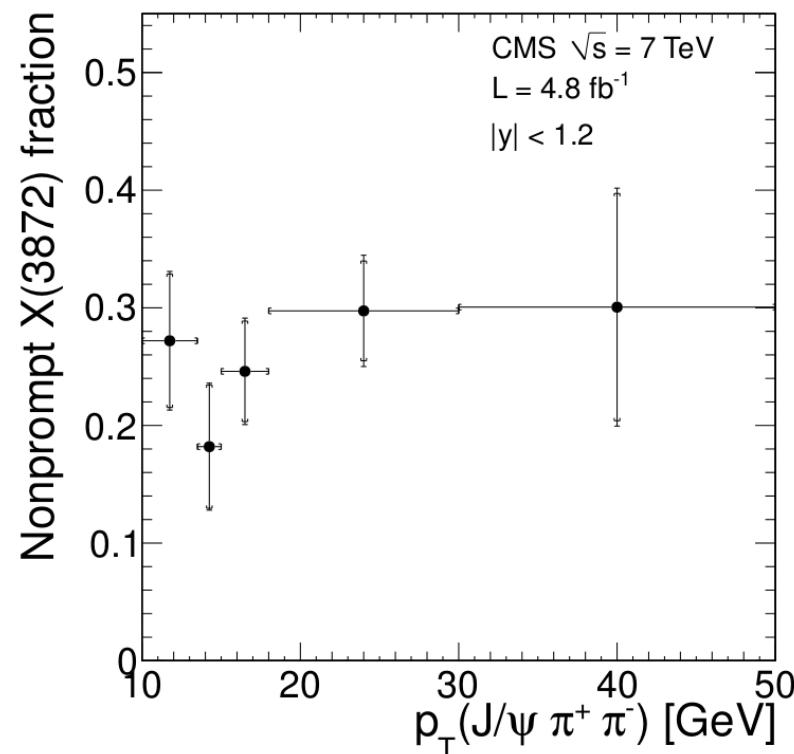
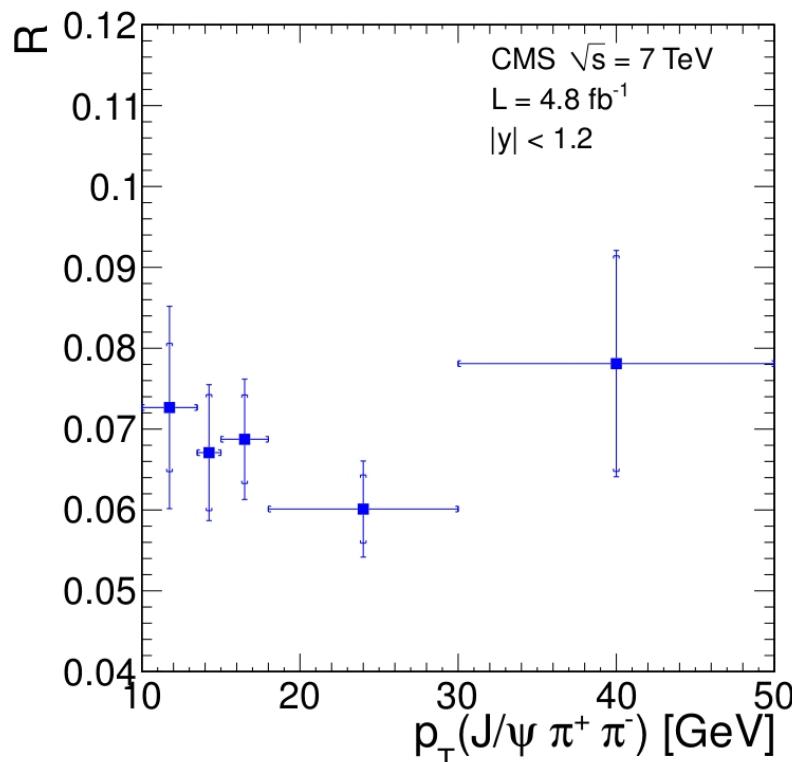
$X \rightarrow J/\psi \pi\pi$  decays within  
 $|y| < 1.2$ ,  $10 < p_T < 50$  GeV

Lint = 4.8 /fb:

~12.000 X candidates

with  $p_T \mu > 4$  GeV,  $p_T \pi > 600$  MeV

CMS, JHEP 04 (2013) 154



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

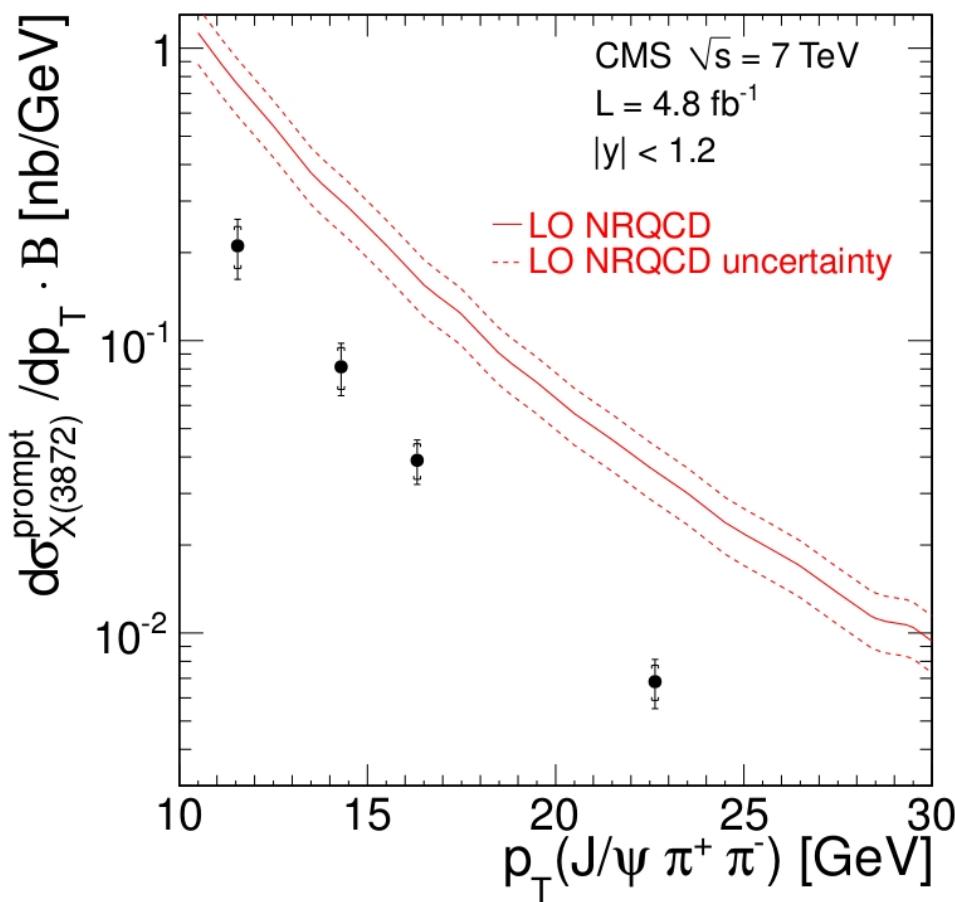
Discriminate prompt  $X$  from  $B \rightarrow X$  through transverse decay length

# X(3872) production

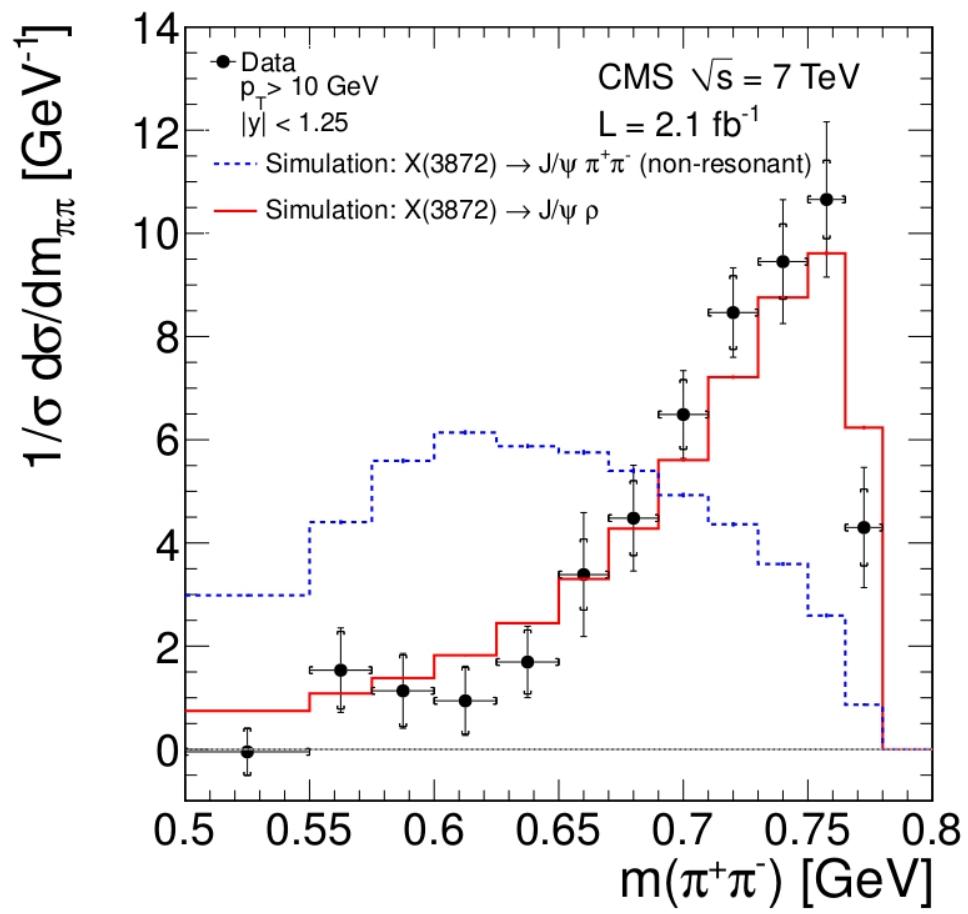
CMS, JHEP 04 (2013) 154

Compute prompt X cross section

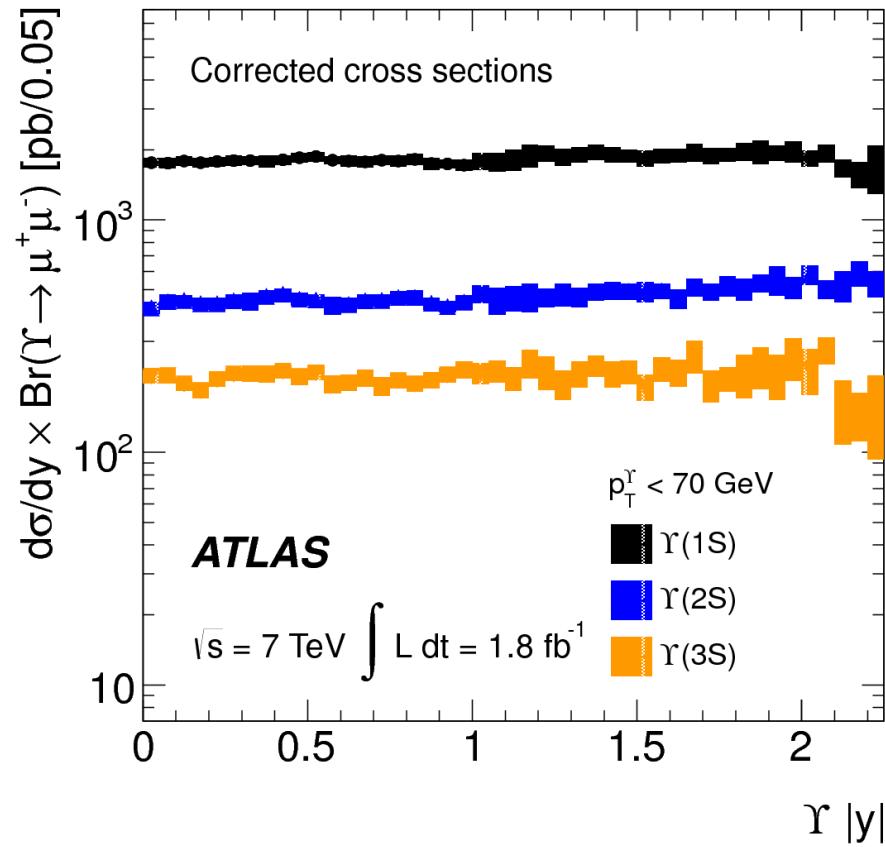
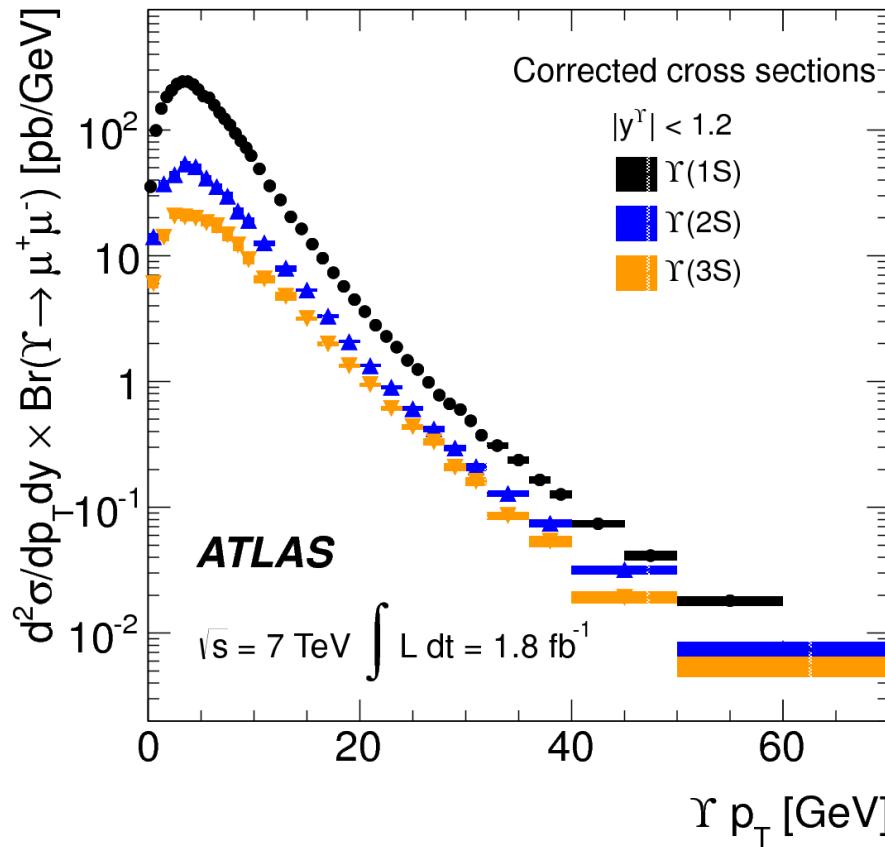
$\sigma \cdot \text{BR} = 1.06 \pm 0.11(\text{stat}) \pm 0.15(\text{syst}) \text{ nb}$   
using the CMS  $\psi(2S)$  data  
[JHEP 02 (2012) 011]



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



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

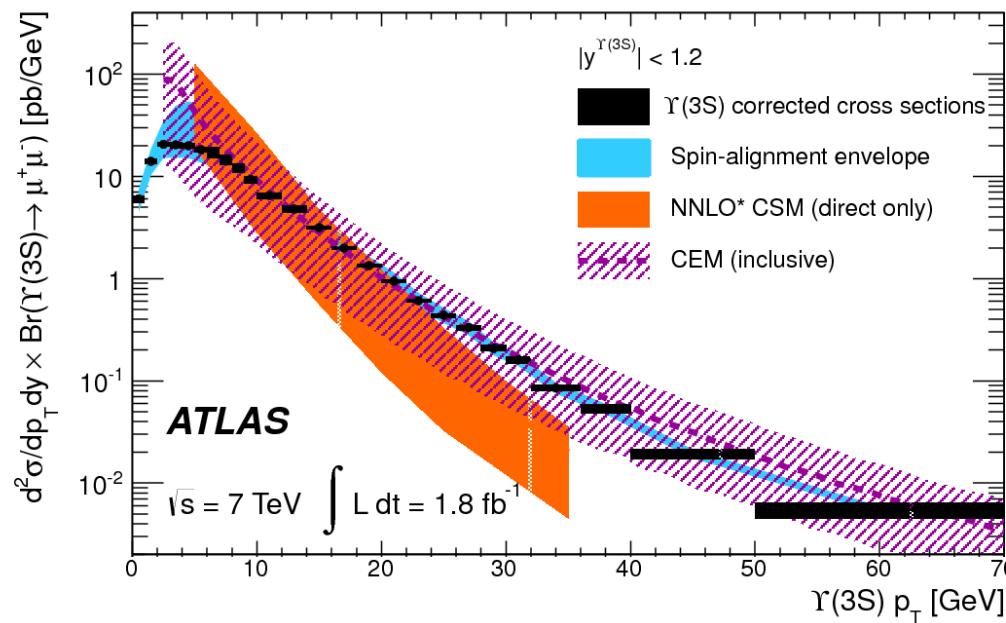
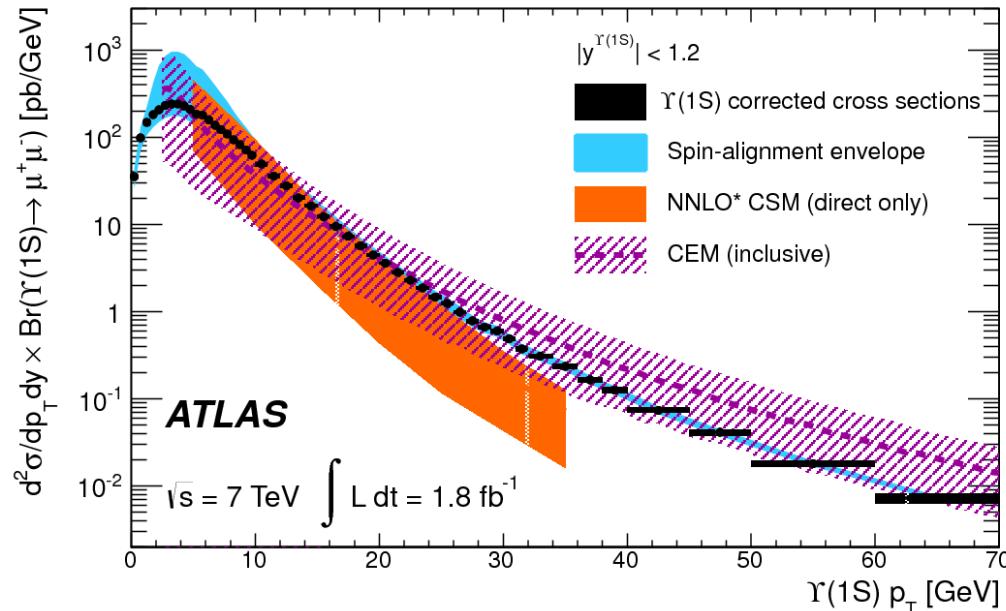


Cross sections measured up to very large  $pT$  ( $pT \gg m$ )  
 $\rightarrow$  stringent QCD test

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

ATLAS, PRD87 (2013) 052004

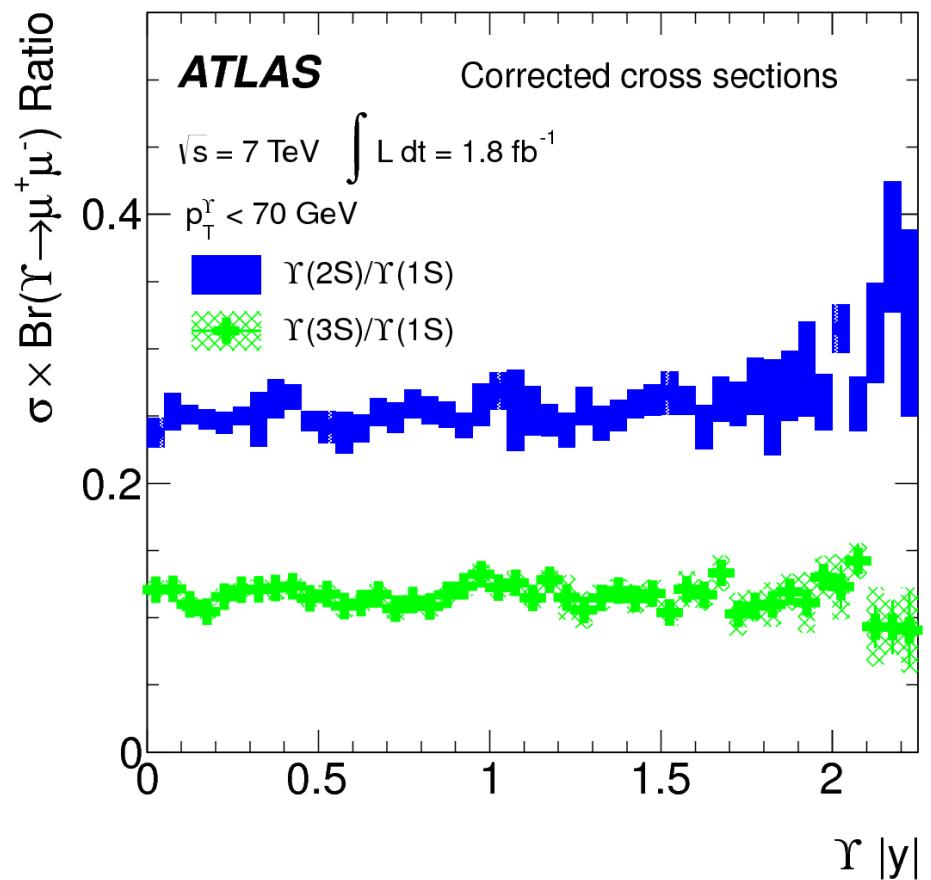
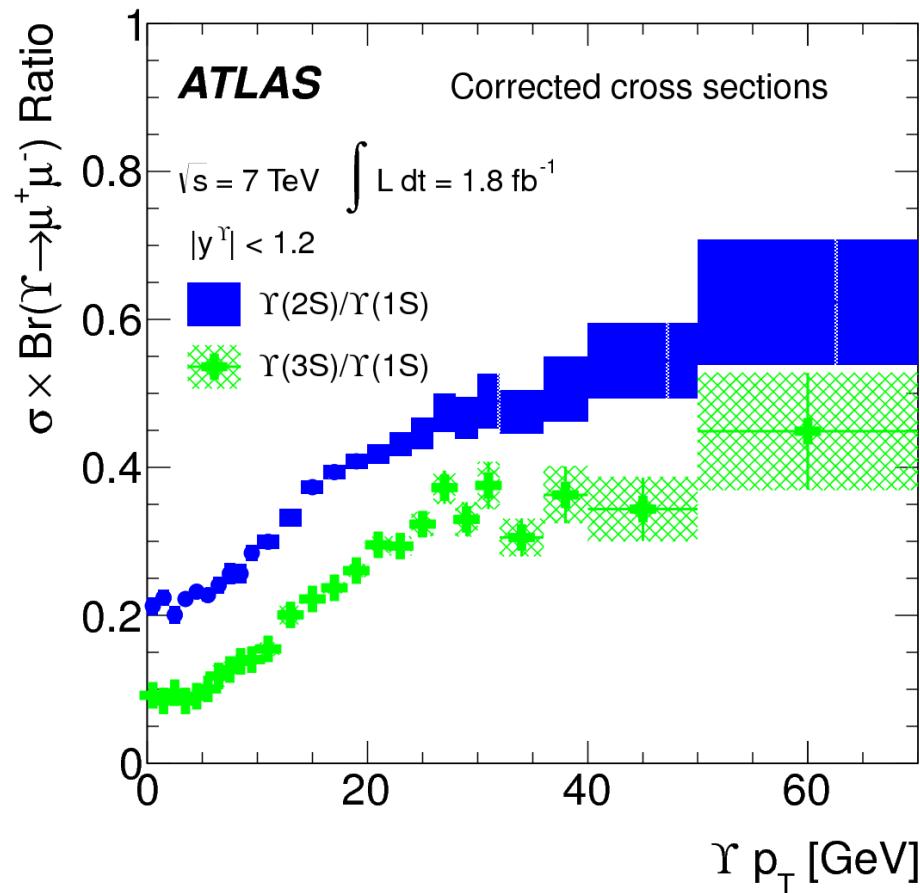
# Y(nS) production at $\sqrt{s} = 7$ TeV and mid-rapidity



$\gamma(3S)$  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  $p_T > 8$  GeV

ATLAS, PRD87 (2013) 052004

# Y(3S,2S) / Y(1S) production ratios



ATLAS, PRD87 (2013) 052004

# Observation of structures in $J/\psi \phi$ spectrum in exclusive $B^+ \rightarrow J/\psi \phi K^+$ decays at 7 TeV

CMS, arXiv:1309:6920

