

Quarkonium Production

Physics at the LHC and Beyond

Quy-Nhon 2014

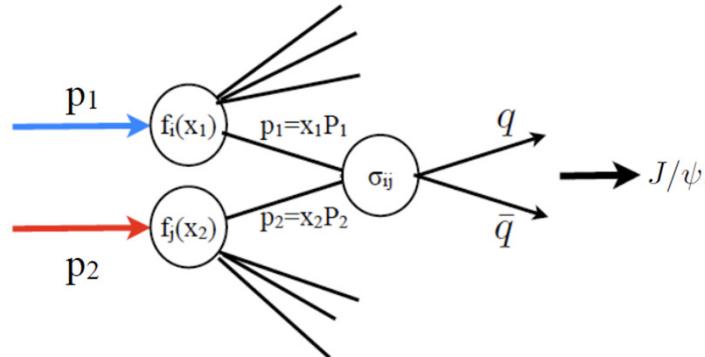


Chris Hawkes

UNIVERSITY OF
BIRMINGHAM

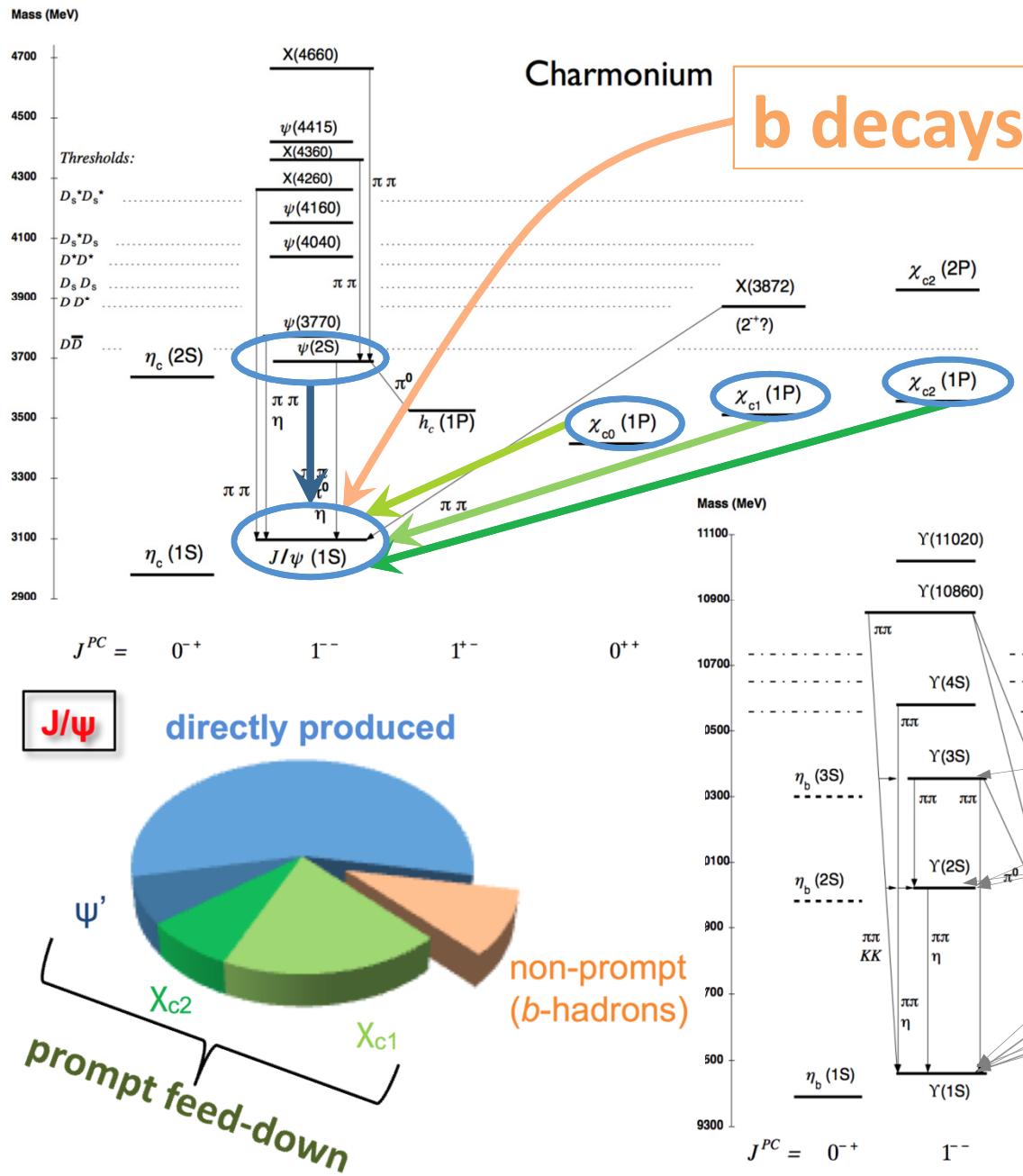
on behalf of the LHC Collaborations

Why Measure Quarkonia at LHC ?



- No single hadro-production model describes all quarkonium data
- Early models failed to predict quarkonium cross sections and polarization at Tevatron
- High-statistics, high- p_T samples from LHC allow more detailed tests of current QCD models
- Quarkonia also important as signals and backgrounds in searches for rare decays and new physics

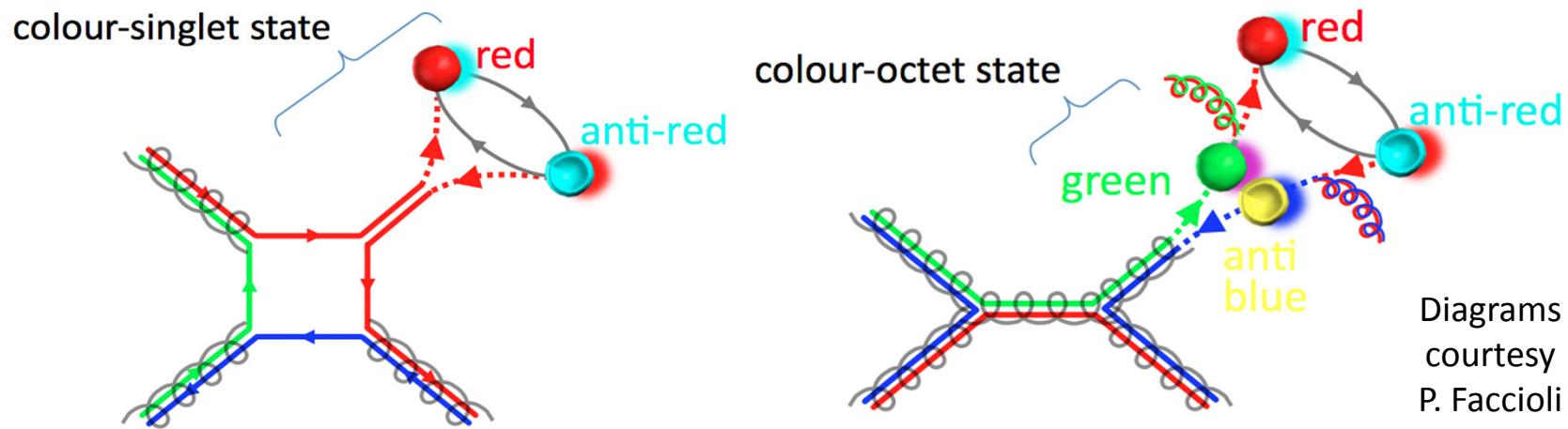
Quarkonium Spectra



Prompt feed-down contributions significant for J/ψ and $\Upsilon(1,2,3S)$, but not for $\psi(2S)$

Hadro-Production Models

- Initial $Q\bar{Q}$ state evolves into final quarkonium meson
 - range of energy scales involved
 - crosses perturbative/non-perturbative QCD boundary
- Colour-singlet model (CSM)
 - initial $Q\bar{Q}$ has identical quantum numbers to final quarkonium
- Non-relativistic QCD (NRQCD)
 - includes colour-octet $Q\bar{Q}$ states and long-range interactions
 - intermediate transitions change quantum numbers
 - long-distance matrix elements must be fitted to independent data



Overview

**Latest proton-proton collision results from the
LHC Collaborations on:**

Quarkonium production cross sections

Quarkonium polarization

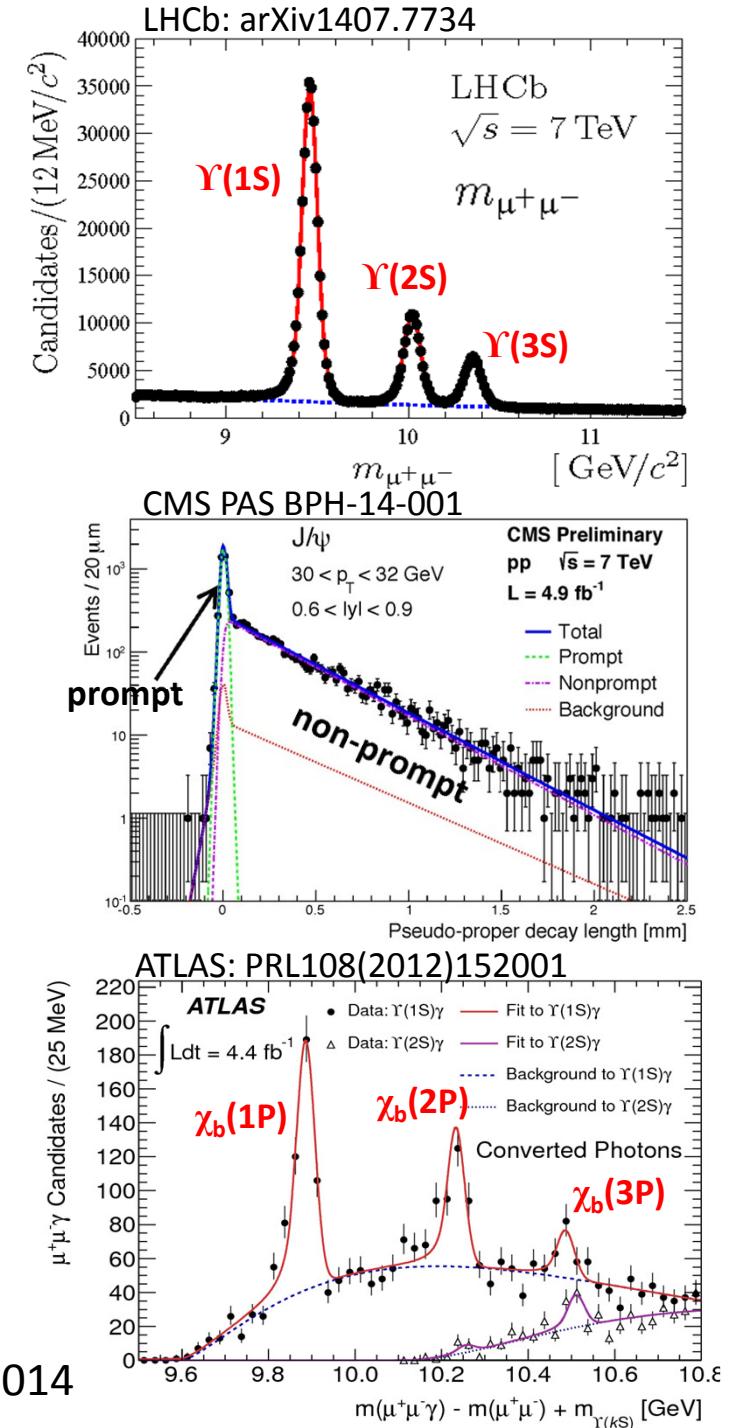
Associated production of quarkonium

Only a selection of results can be included in the limited time available.
Apologies for those that are not mentioned.

Experimental Techniques

- Events triggered on (di)muons
- Reconstruct J/ψ , $\psi(2S)$, $\Upsilon(1,2,3S)$, usually from $\mu^+\mu^-$
- Non-prompt charmonium from b-hadron decays identified using pseudo-proper decay length

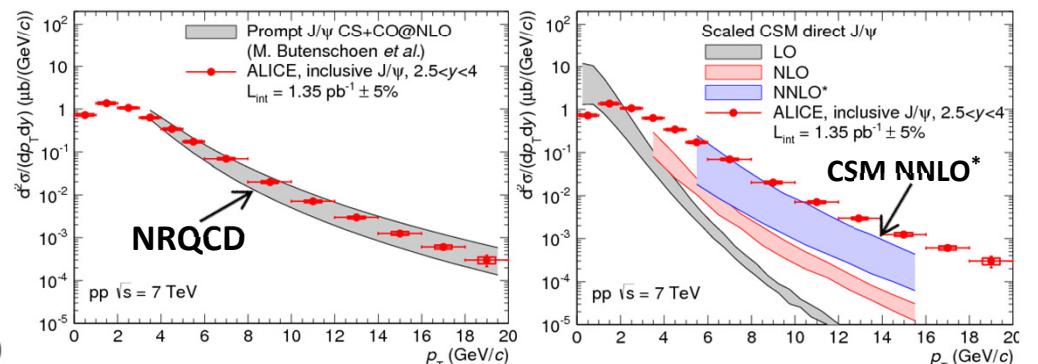
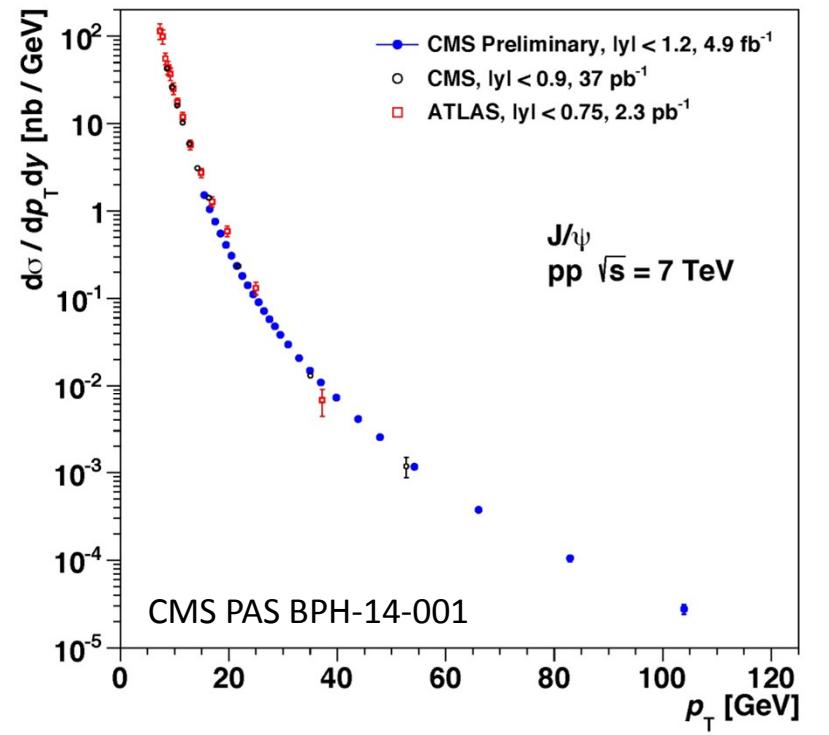
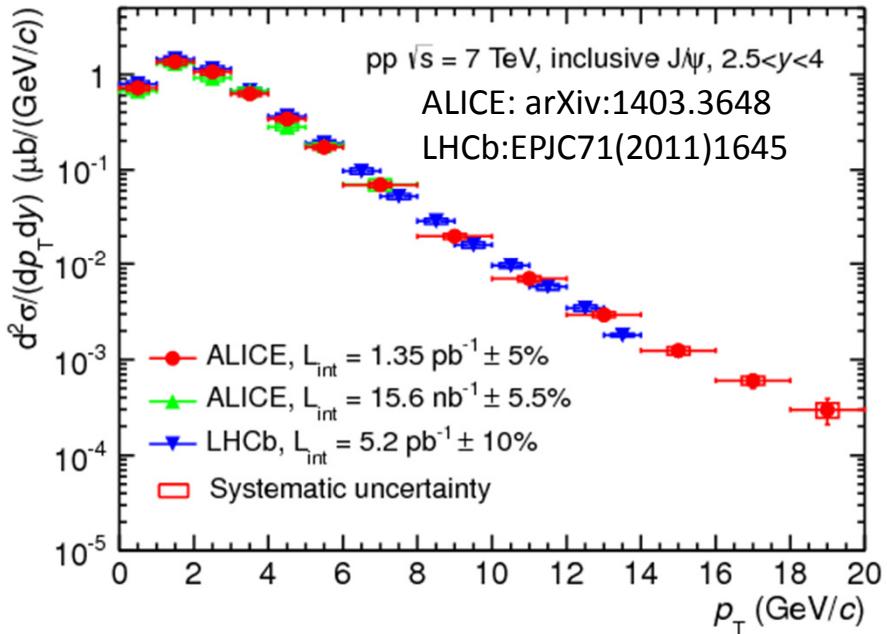
$$L_{xy} \cdot m_\psi / p_T$$
- Combine with (converted) photon to reconstruct $\chi_b \rightarrow \Upsilon\gamma$ or $\chi_c \rightarrow J/\psi\gamma$



J/ ψ Production Cross Section

- CMS measures J/ ψ in central rapidity ($|y| < 1.2$)
- Consistent with ATLAS data: NPB850(2011)387

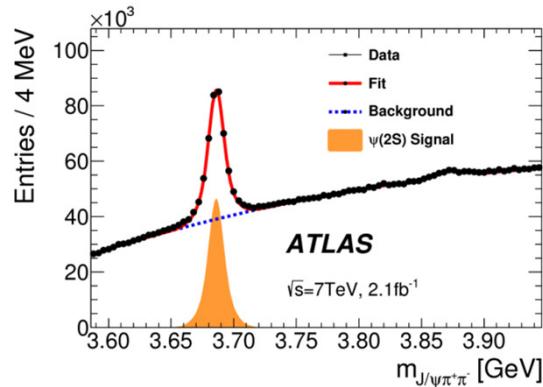
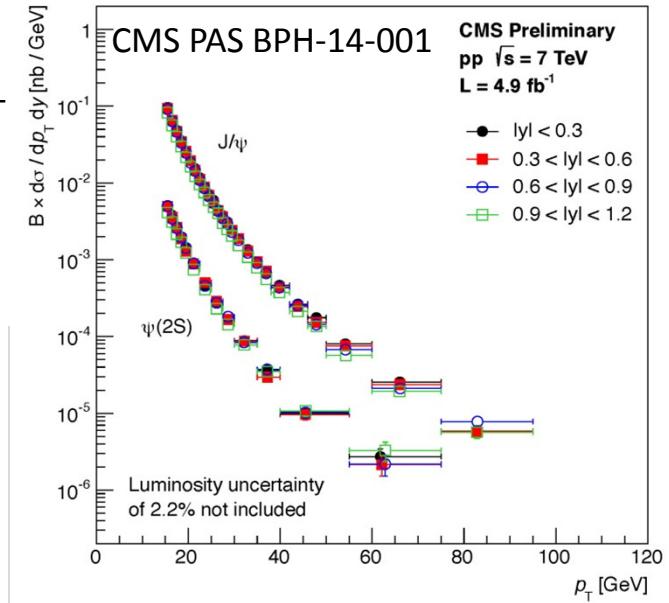
- ALICE measures J/ ψ at forward rapidity ($2.5 < y < 4$)
- Consistent with LHCb results
(see also LHCb:JHEP06(2013)064 at 8 TeV)
- NRQCD calculations consistent with data,
but CSM NNLO* underestimates data



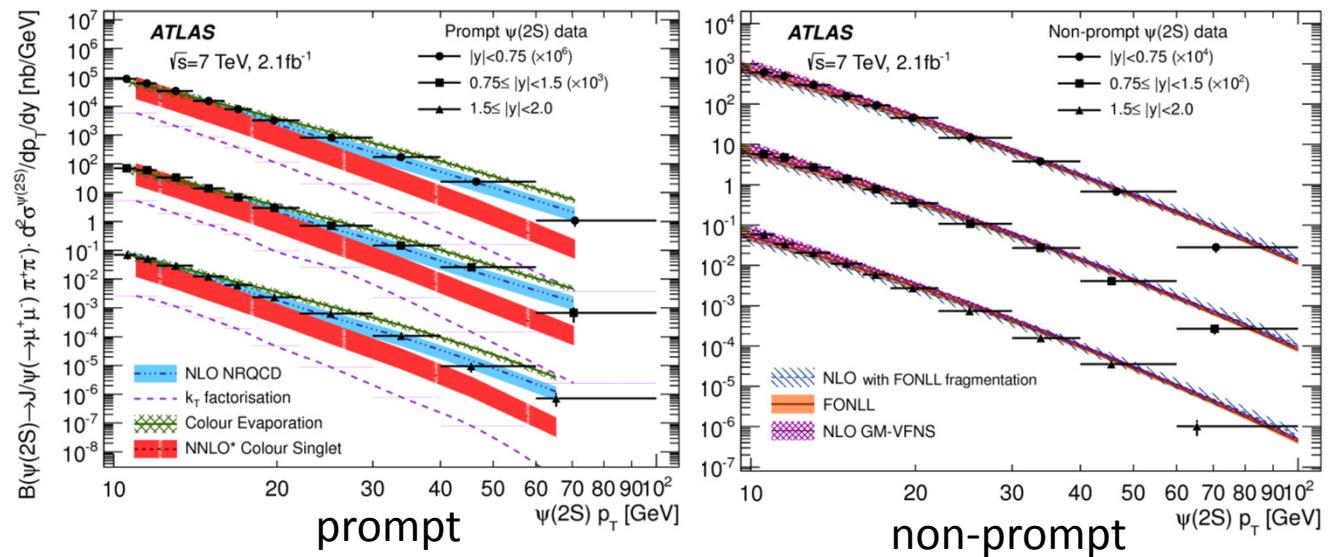
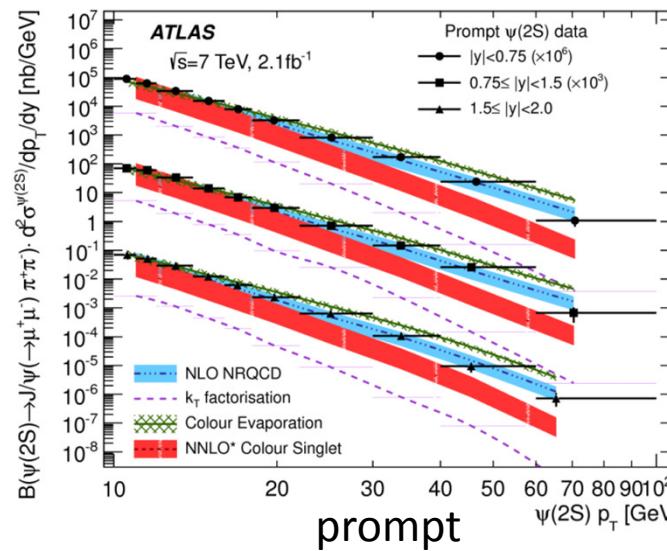
$\psi(2S)$ Production Cross Section

CMS reconstructs $\psi(2S) \rightarrow \mu^+\mu^-$ up to high p_T

- ATLAS reconstructs $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
- Prompt data consistent with NLO NRQCD to high p_T
 - free from feed-down contributions
- Models overestimate non-prompt data at high p_T
- Consistent with LHCb: EPJC72(2012)2100

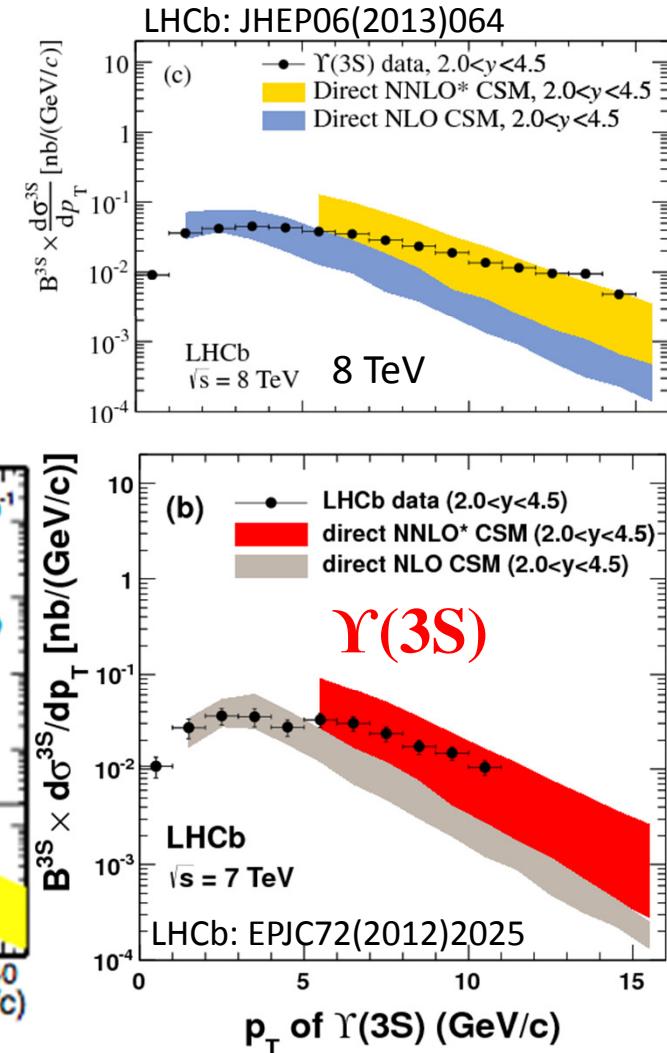
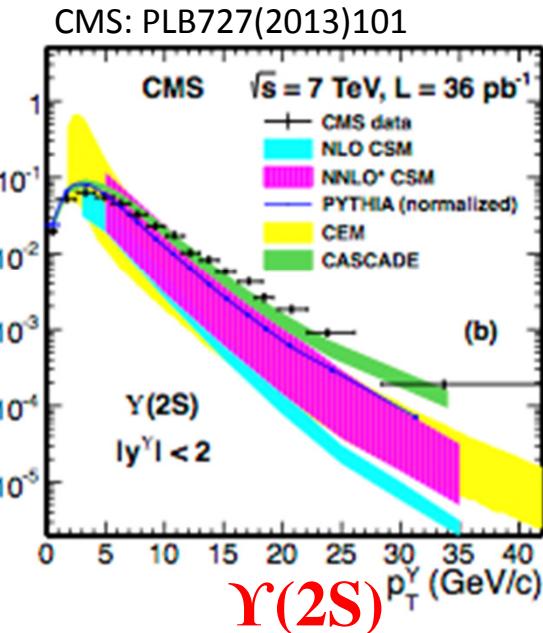
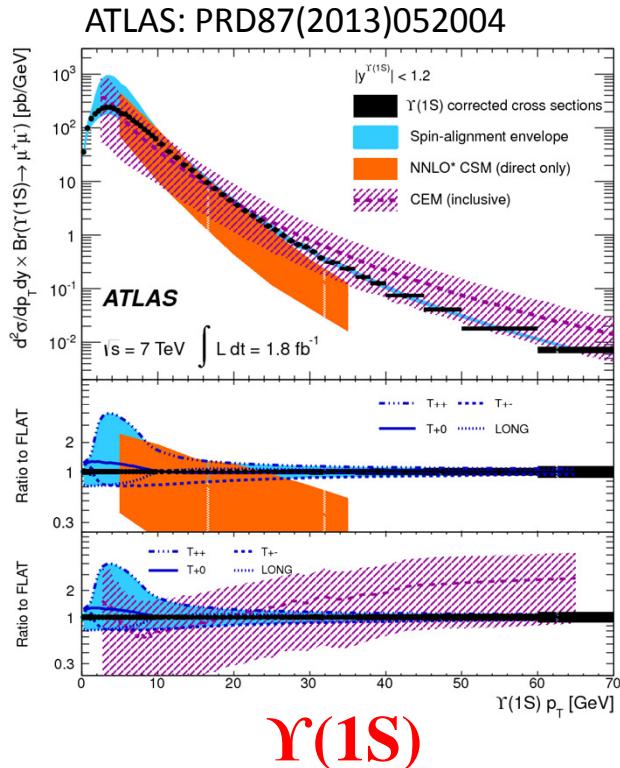


ATLAS: arXiv:1407.5532

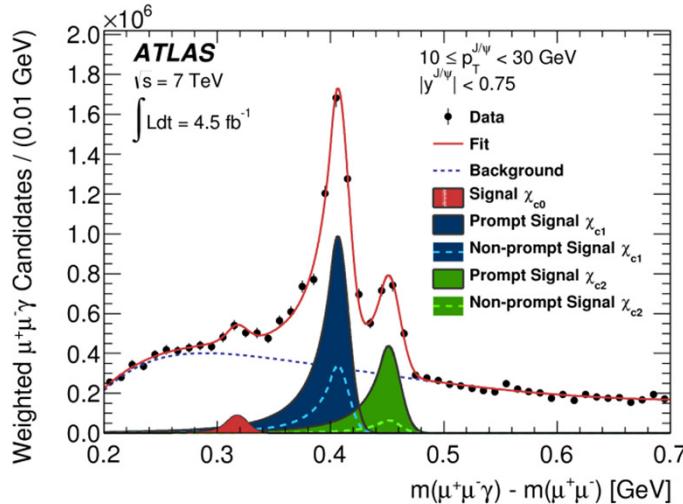


$\Upsilon(mS)$ Production Cross Sections

- ATLAS ($|y| < 1.2$), CMS ($|y| < 2$), LHCb ($2 < y < 4.5$) data consistent at 7 TeV
- Model descriptions disagree at high p_T
- Feed-down from χ_b significant for all Υ states
- Acceptance sensitive to Υ polarization



$\chi_{cJ}(1P)$ Production Cross Sections

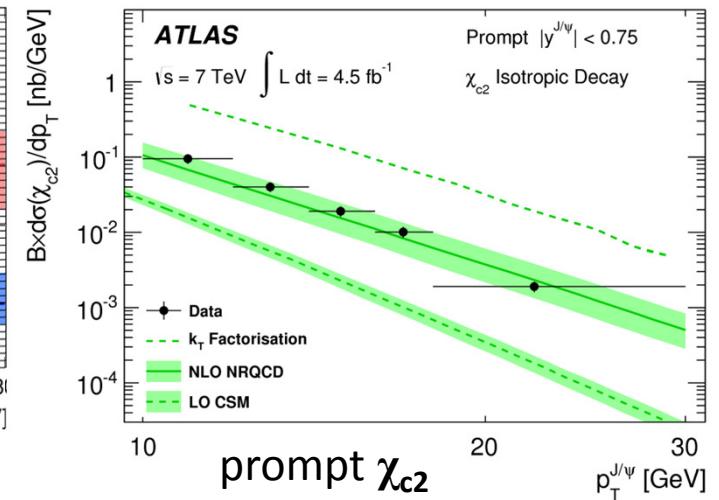
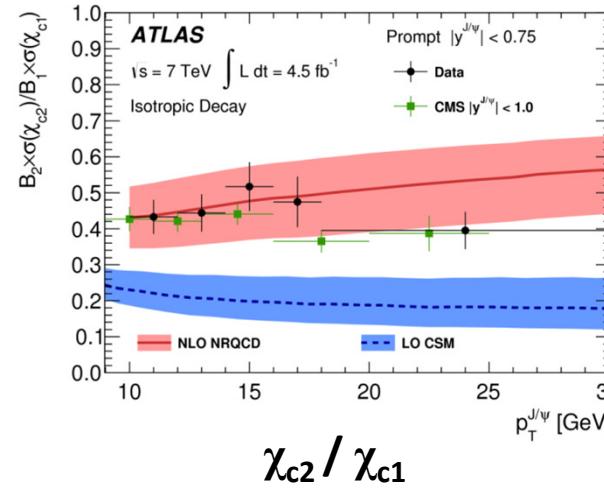
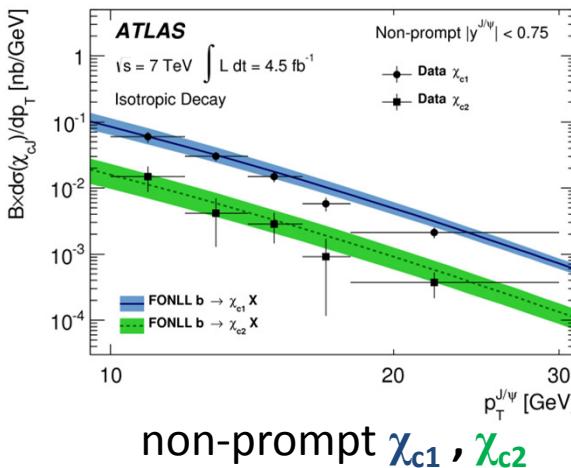
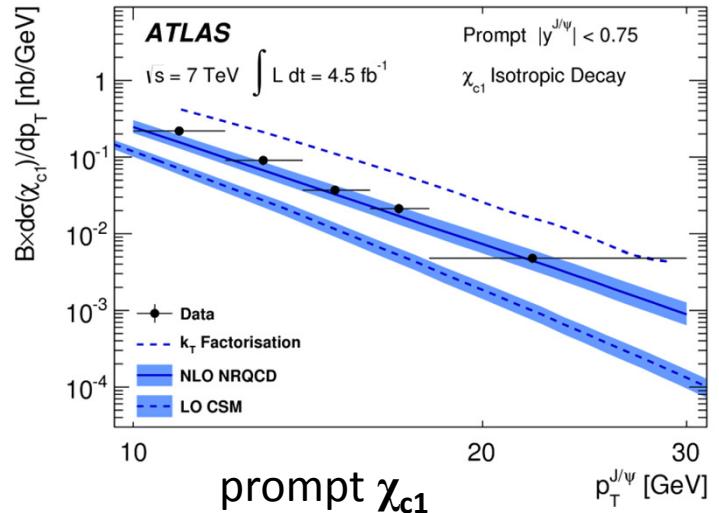


Absolute cross sections
for $\chi_{c1}(1P)$ and $\chi_{c2}(1P)$

Also non-prompt cross
sections and relative
rates χ_{c2} / χ_{c1}

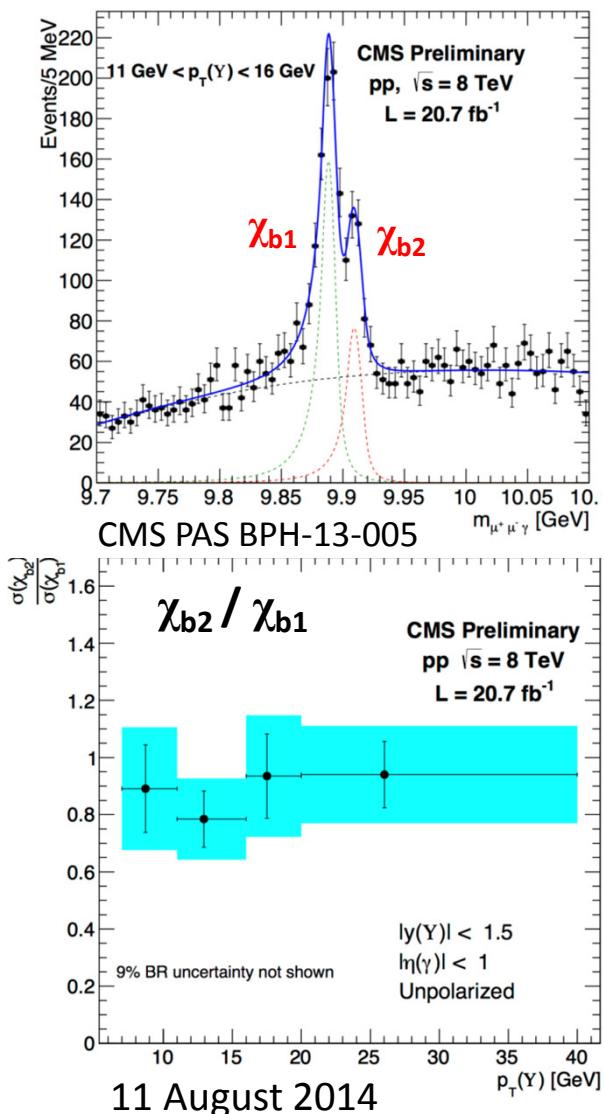
Consistent with NLO
NRQCD predictions

ATLAS: JHEP07(2014)154

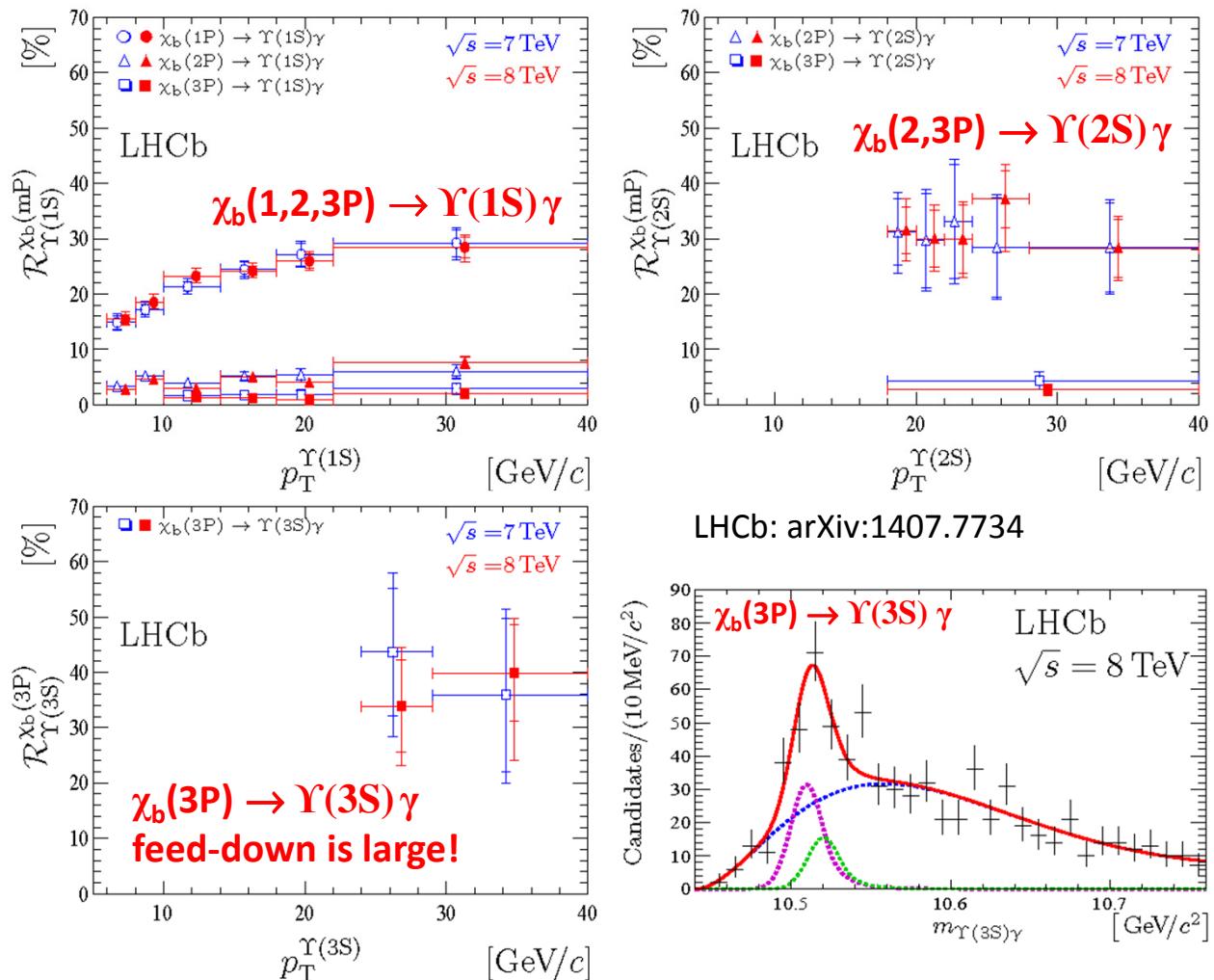


Consistent with results from CMS: EPJC72(2012)2251, and LHCb: PLB718(2012)431

CMS reconstructs
separate $\chi_{b1}(1P)$, $\chi_{b2}(1P)$
peaks and measures
relative cross sections



χ_b Production



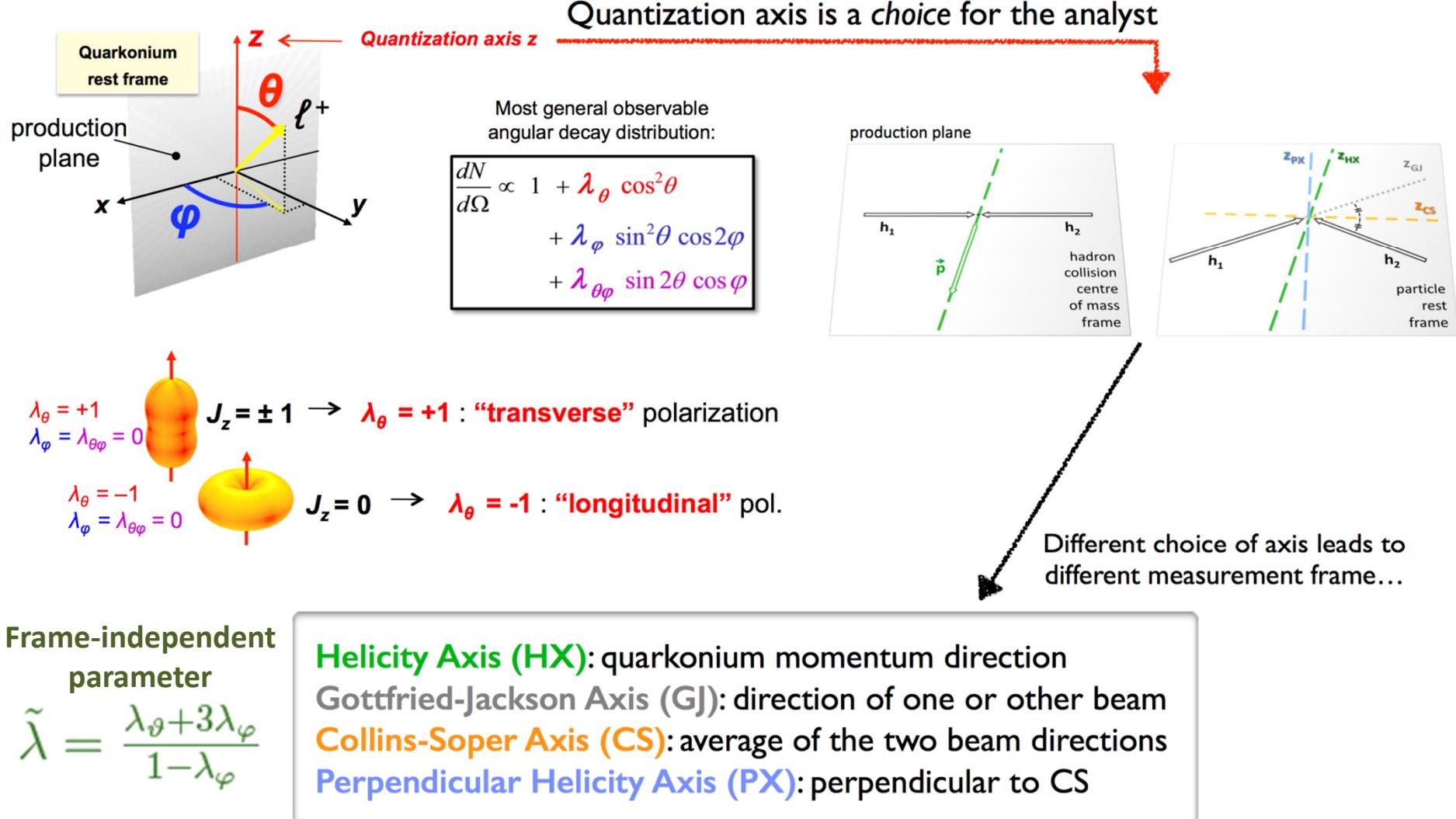
LHCb confirms $\chi_b(3P)$: $m(\chi_{b1}(3P)) = 10511.3 \pm 1.7 \pm 2.5 \text{ MeV}/c^2$
Large feed-down from all $\chi_b(1,2,3P)$ into $\Upsilon(1,2,3S)$ states

Cross Section Summary

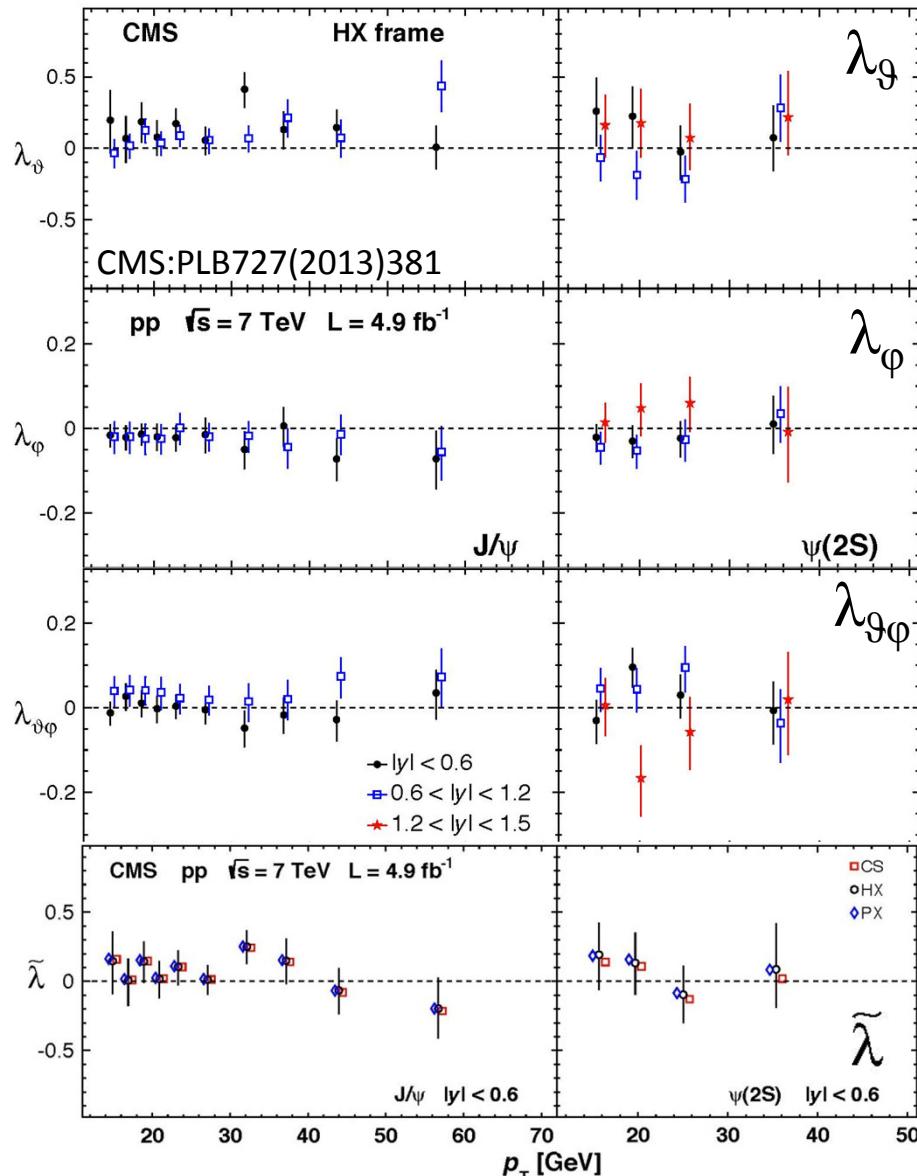
- J/ψ , $\psi(2S)$, $\Upsilon(1,2,3S)$, χ_c , χ_b production cross sections measured over wide kinematic ranges
- Generally consistent with NLO NRQCD, but
 - feed-down contributions large for J/ψ , $\Upsilon(1,2,3S)$
 - acceptance corrections depend on polarization (usually assumed to be isotropic production)
- Need to study polarization of quarkonium states produced

Polarization (spin alignment)

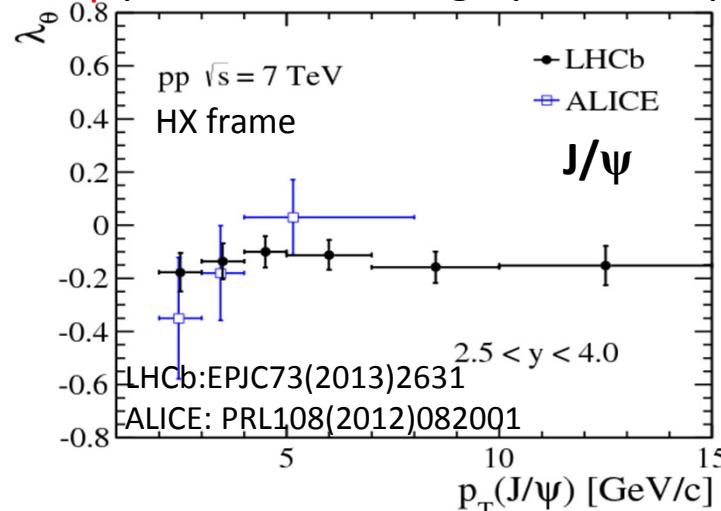
with thanks to Pietro Faccioli and James Catmore



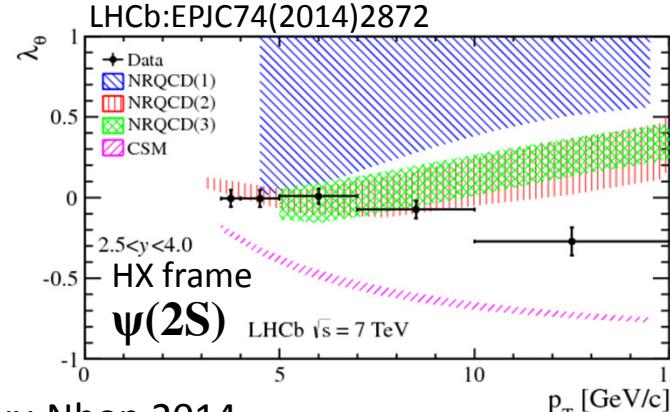
J/ ψ and $\psi(2S)$ Polarization



- CMS measures no strong polarizations over a wide range of p_T
- LHCb & ALICE measure small negative J/ψ polarization at high y and low p_T

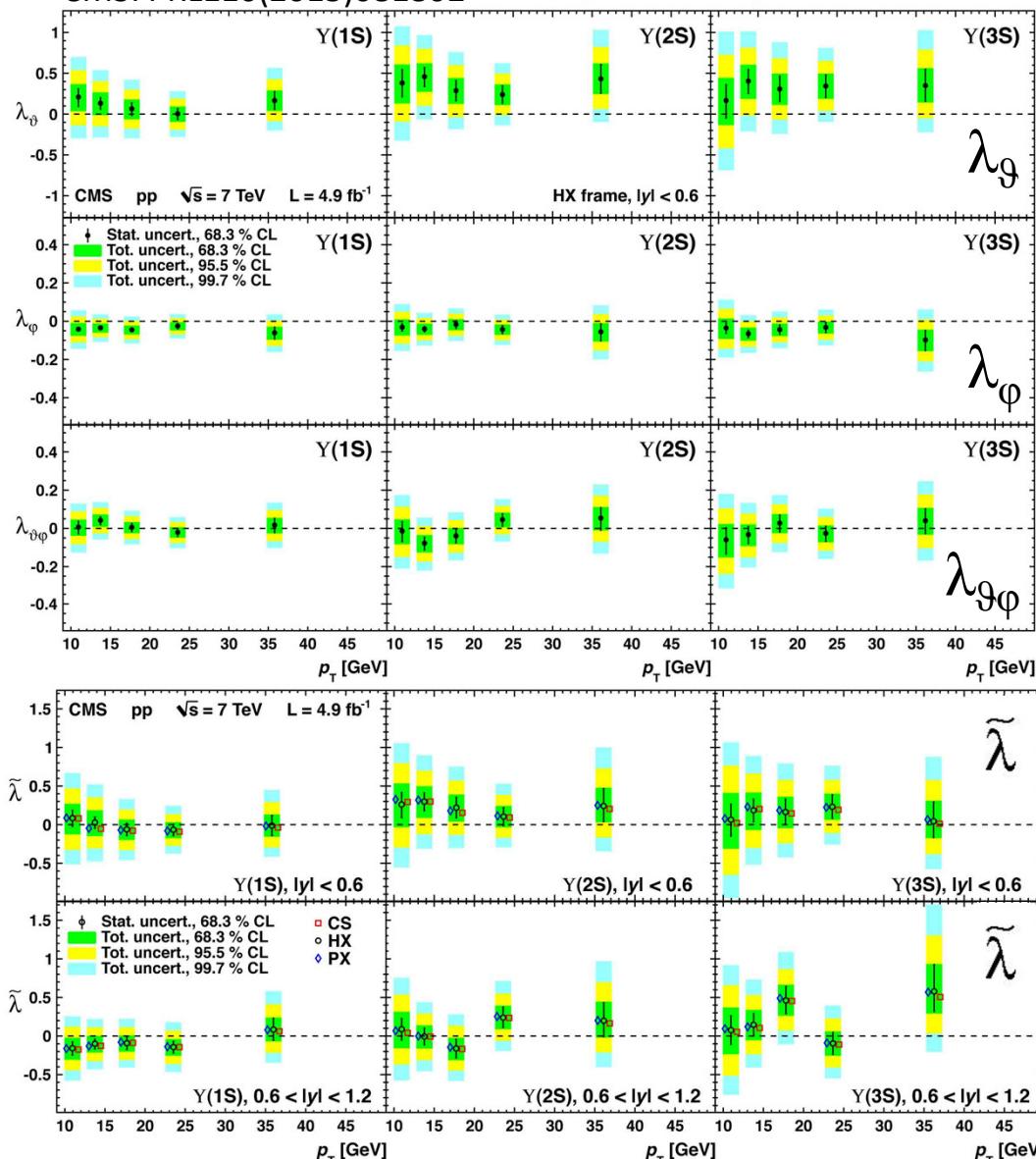


LHCb measures small negative $\psi(2S)$ pol'n



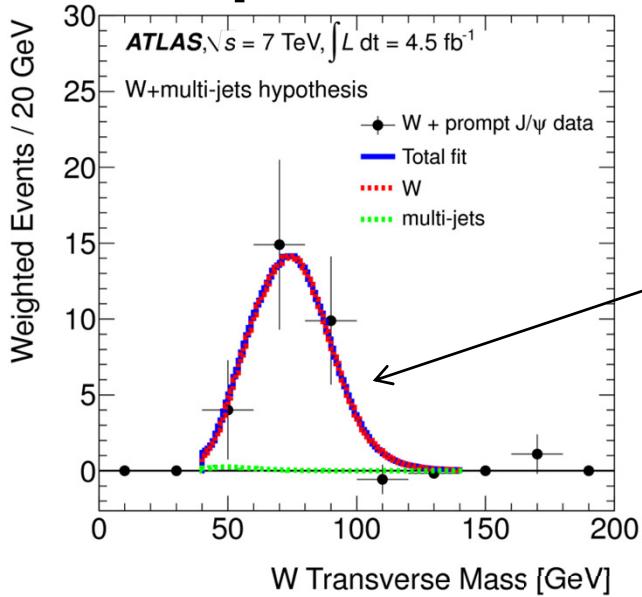
$\Upsilon(mS)$ Polarization

CMS: PRL110(2013)081802

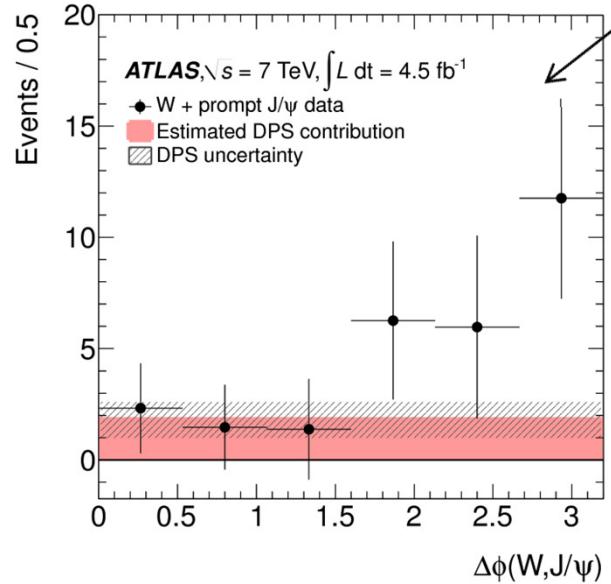


- CMS measures no strong Υ polarizations over range of p_T
- All are affected by significant feed-down from $\chi_b(mP)$ decays
 - $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma$ is large
- Models predict polarization to increase with p_T , not supported by charmonium or bottomonium measurements
- See **P.Faccioli et al., PLB736 (2014) 98** for a review and new perspective on quarkonium production and polarization measurements

J/ ψ + W Production Cross Section

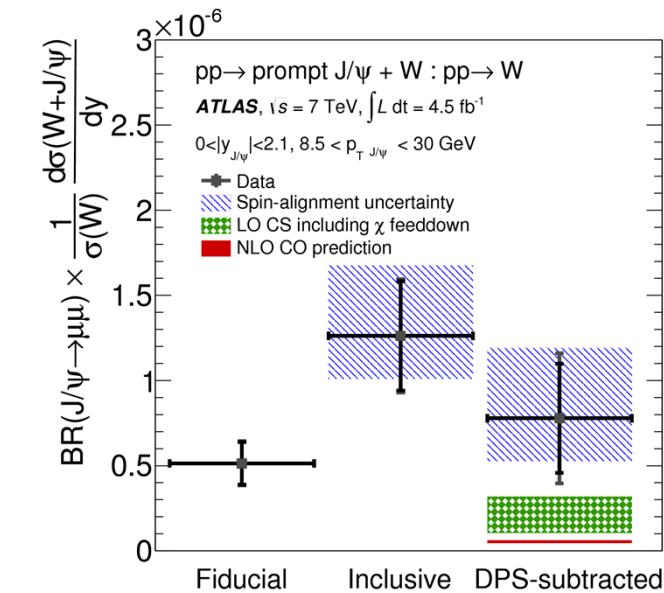
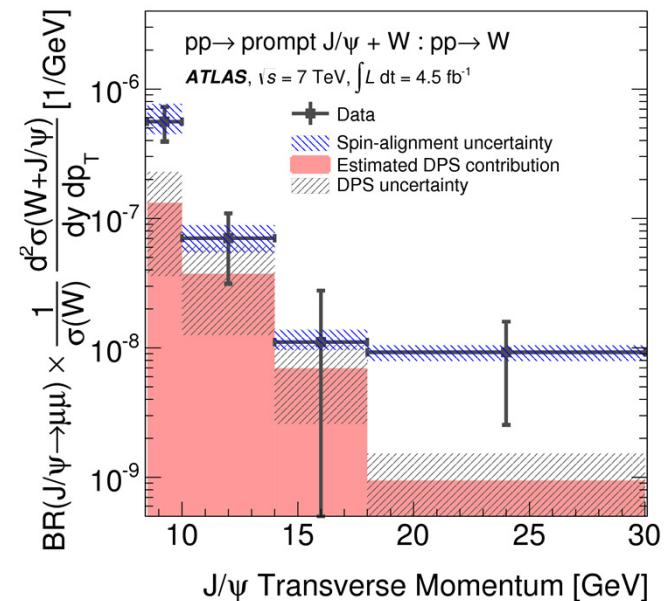


Provides new tests of production models



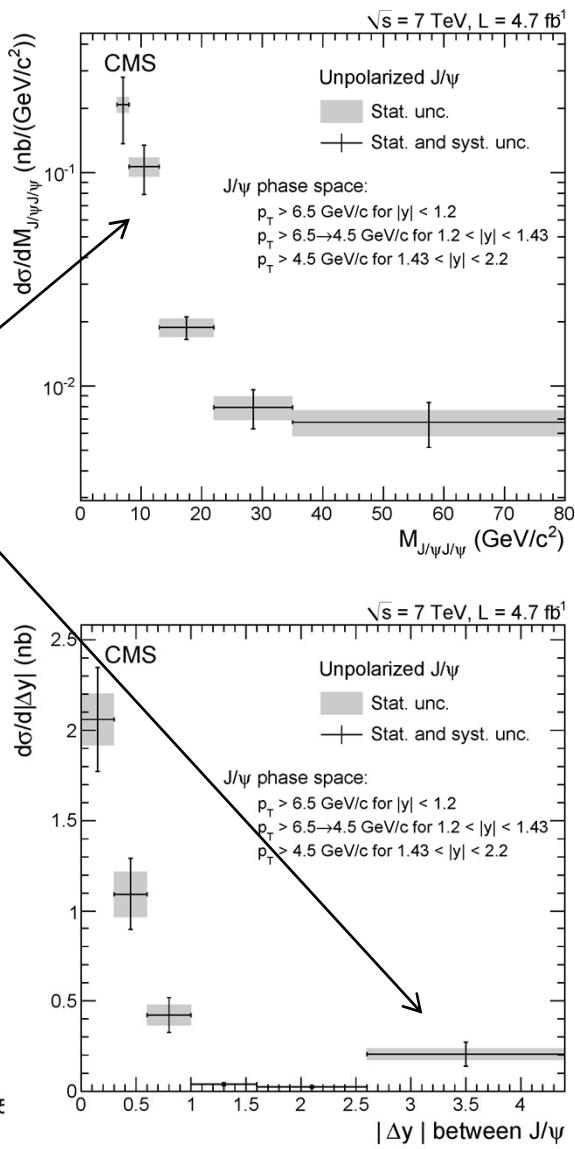
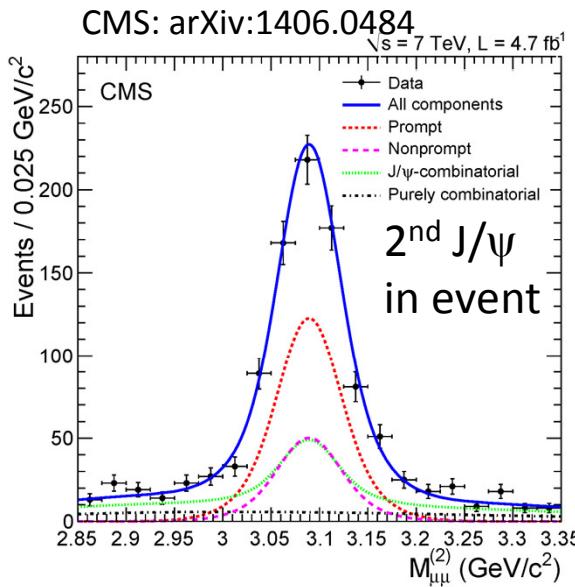
Will be important for future measurements of Higgs+VB production and rare Higgs decays

ATLAS: JHEP04(2014)172

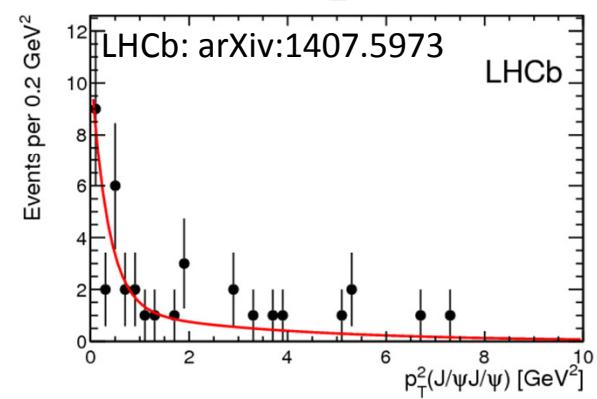
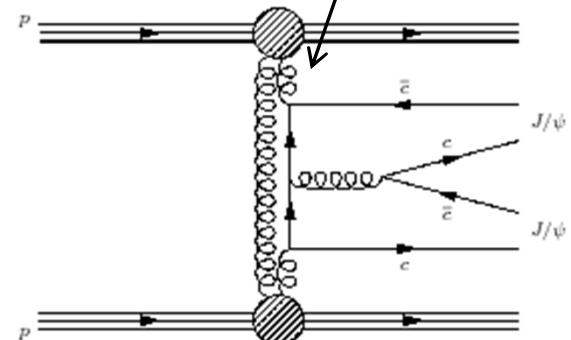


Charmonium Pair Production

- CMS measures inclusive production of two prompt J/ψ decays in the same event
- No evidence for resonant production (e.g. $\eta_b \rightarrow J/\psi J/\psi$)
- Sensitive to double-parton scattering



- LHCb measures central exclusive production of $J/\psi J/\psi$ and $J/\psi \psi(2S)$ pairs, and searches for $\psi(2S) \psi(2S)$ and $\chi_c \chi_c$
- Sensitive to double-pomeron exchange



Summary

- LHC measurements of several quarkonium states over wide ranges of momentum and rapidity
- Cross sections are consistent with NLO NRQCD model calculations
- No strong quarkonium polarization measured, not increasing with p_T , in disagreement with models
- Associated production of quarkonium observed

Outlook

- LHC Run-II will provide higher statistics and broader p_T range to study quarkonium production
- Important to measure χ_c and χ_b – interesting in their own right and define feed-down into the Ψ and Υ channels
- Polarization and cross sections must be measured and understood together
- Associated quarkonium production provides signal and backgrounds for new searches and rare decay channels