MANCHESTER 1824
The University of Manchester

Production and spectroscopy of quarkonia states at the ATLAS experiment

Darren Price
on behalf of the ATLAS Collaboration

LHCP2014, New York, June 2nd—7th 2014

@darrenprice
Darren.Price@cern.ch

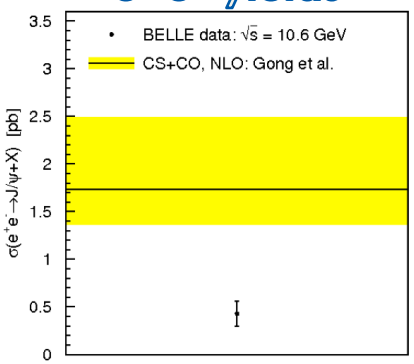
Quarkonium production

Naïvely a 'simple' system: quark and anti-quark of same flavour in a bound state:

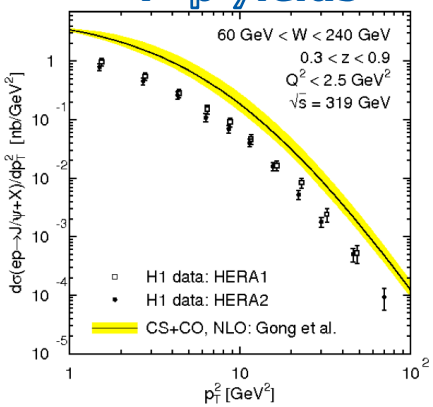
No calculational approach currently able to simultaneously describe production rates and other observables

Taken from slides by Mathias Butenschön, CHARM2013

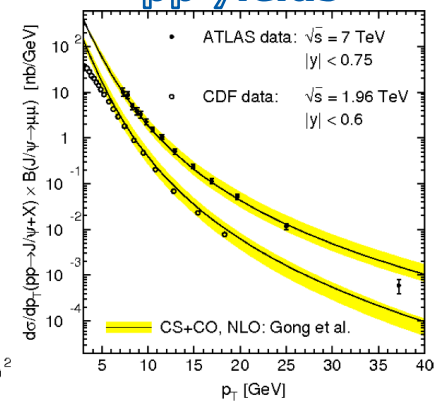
e+e- yields



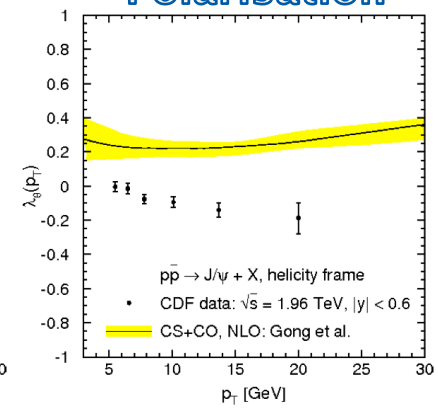
γ−p yields



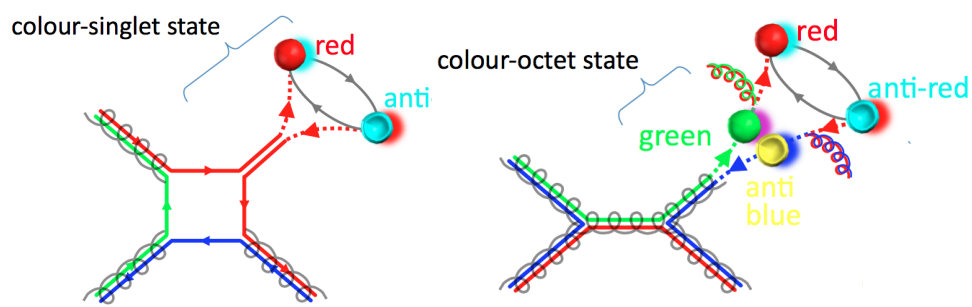
pp yields



Polarisation



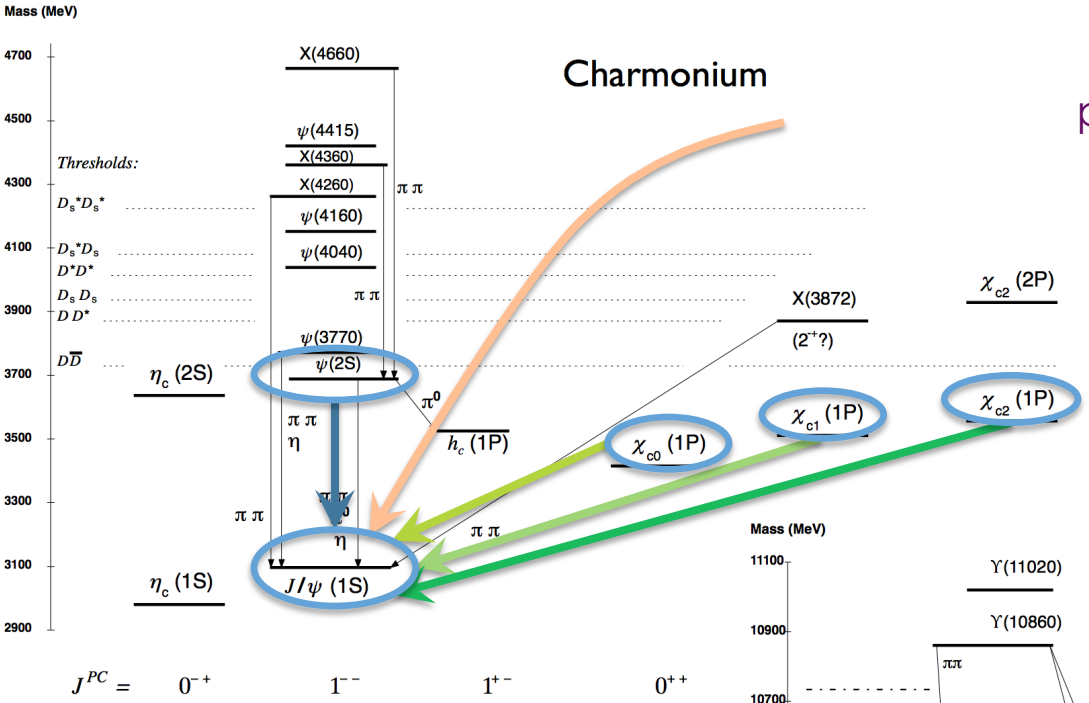
ATLAS data on quarkonium production provides additional precision data and new observables for:

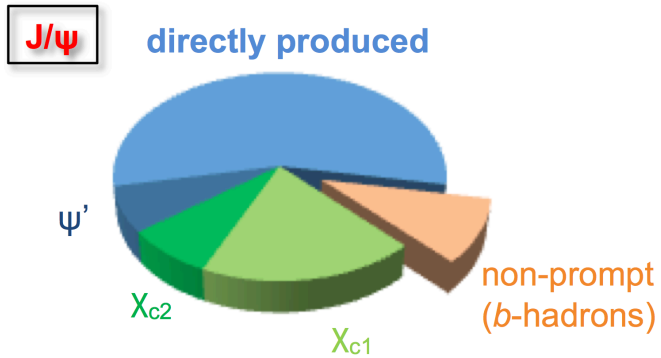


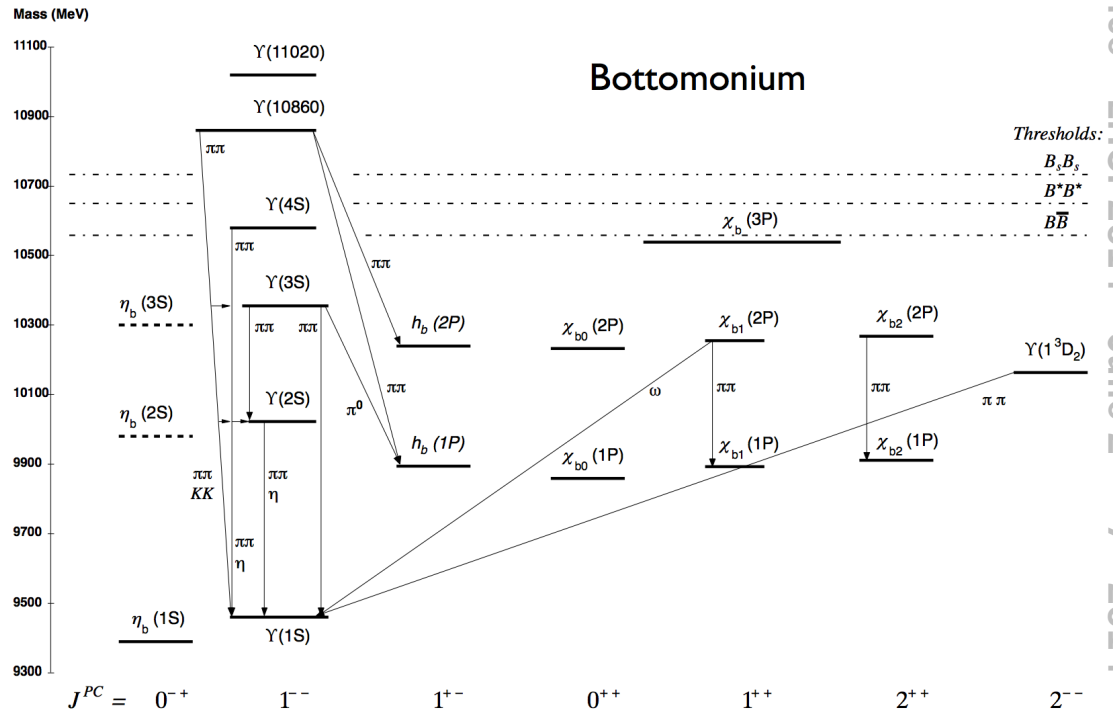
- Tests of **QCD calculations** at the perturbative / non-perturbative boundary
- **Standard candles** for Heavy Ions, B-meson production, backgrounds to SM/BSM processes
- Test **multiple parton scattering** effects, **parton density functions**
- Search for **rare decays** and probes of **new physics**

Not such a simple system…

Understanding of quarkonium production requires discrimination and understanding of the various modes of production







Latest results from ATLAS

Today, I will discuss three of the most recent quarkonium results from ATLAS:

- **Measurement of the production cross-section of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ in pp collisions at $\sqrt{s}$ = 7 TeV at ATLAS**
  ATLAS-CONF-2013-094, to be submitted to JHEP

- **Measurement of χ_{c1} and χ_{c2} production with $\sqrt{s}$=7 TeV pp collisions at ATLAS**
  Submitted to JHEP, arXiv:1404.7035

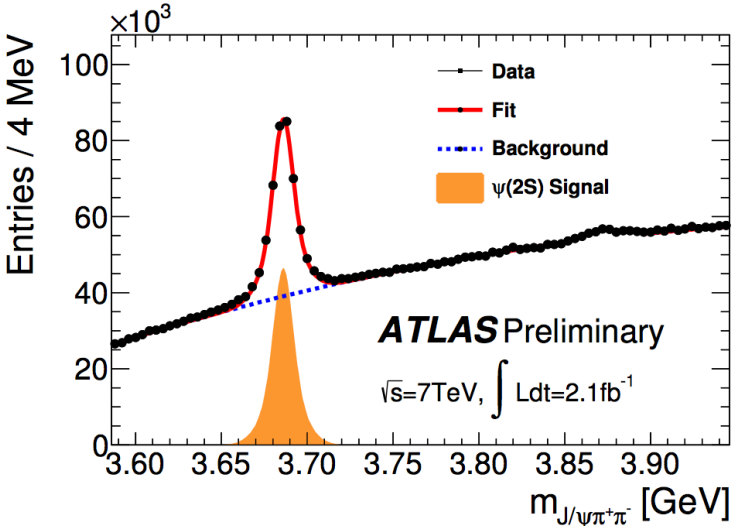
- **Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson in pp collisions at $\sqrt{s}$= 7 TeV with the ATLAS detector**
  JHEP 1404 (2014) 172, arXiv:1401.2831

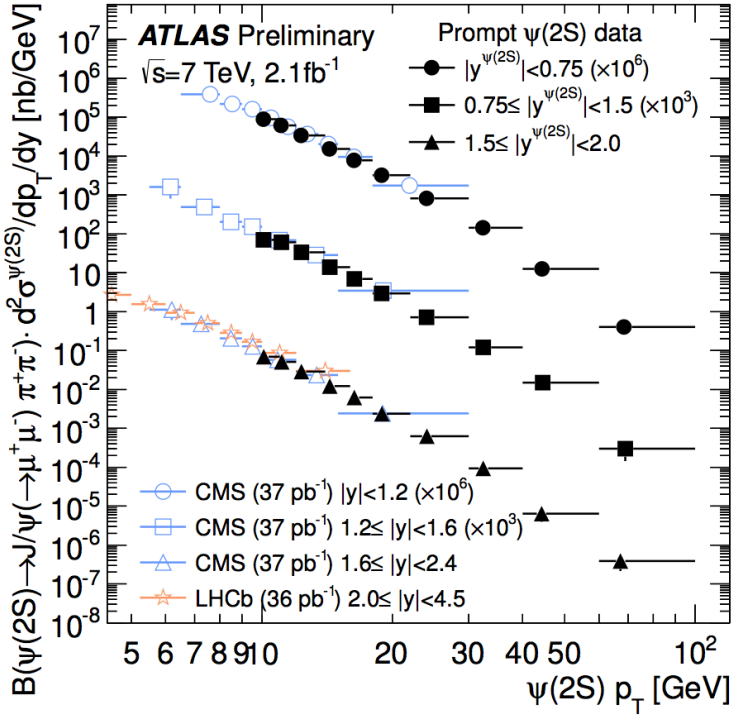
$\psi(2S) \rightarrow J/\psi(\rightarrow\mu^+\mu^-)\pi^+\pi^-$ production

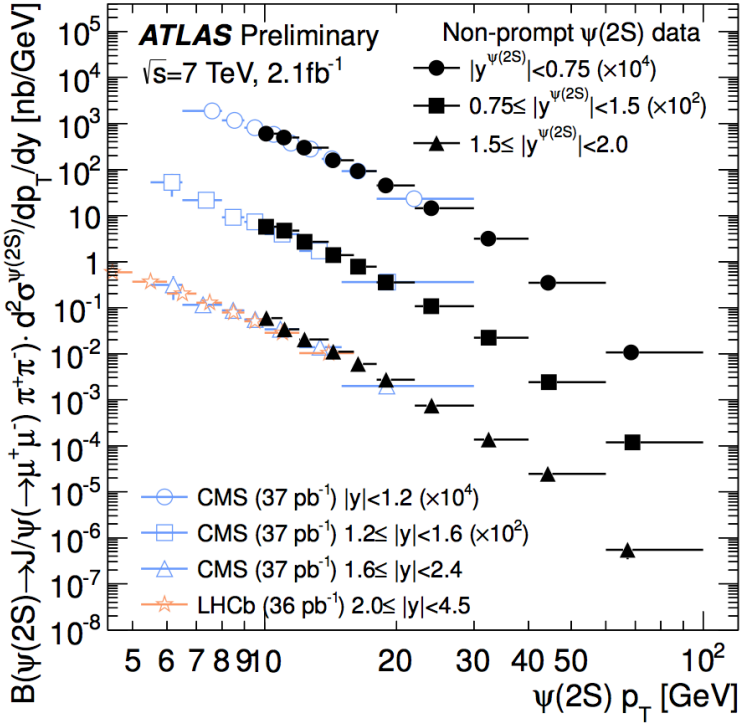
Measurement with 2.1 fb^{-1} pp data at 7 TeV

Muon p_T > 4 GeV, pion candidate tracks p_T> 0.5 GeV

- Use unbinned mass-lifetime maximum likelihood fit to separate prompt and non-prompt production sources
- Baseline channel for study of X(3872)
- Extend p_T range probed to 100 GeV



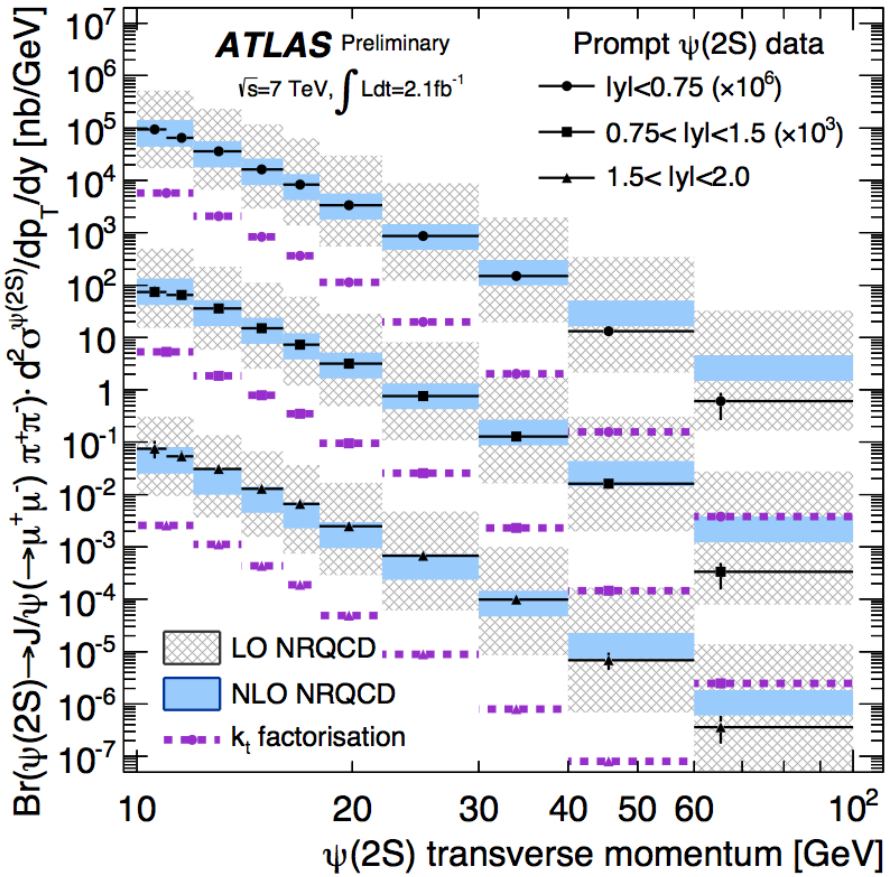


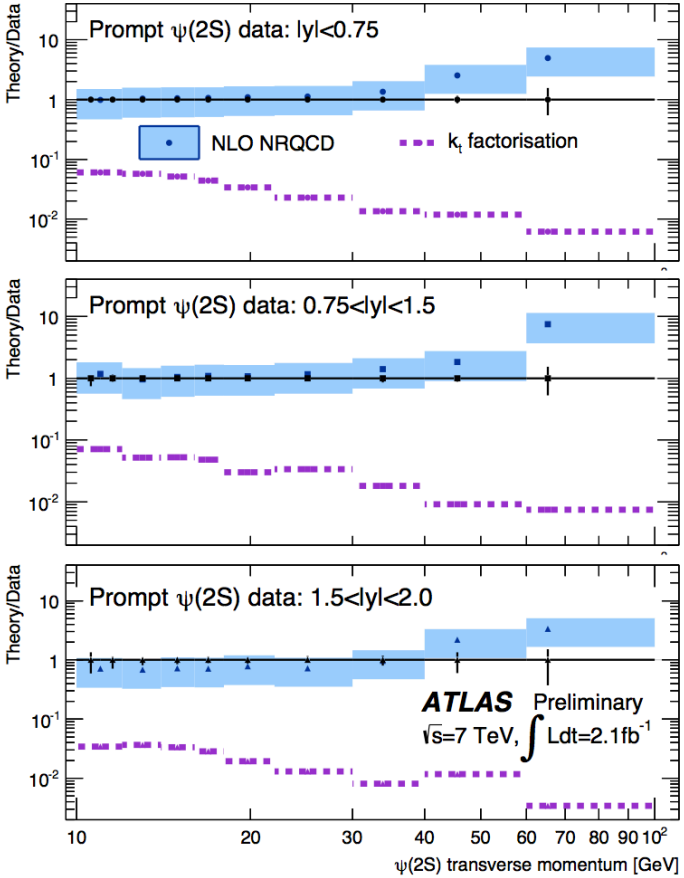


Prompt ψ(2S) → J/ψ π π production

High precision wide reach **prompt** production cross-section in ψ(2S)→J/ψππ.

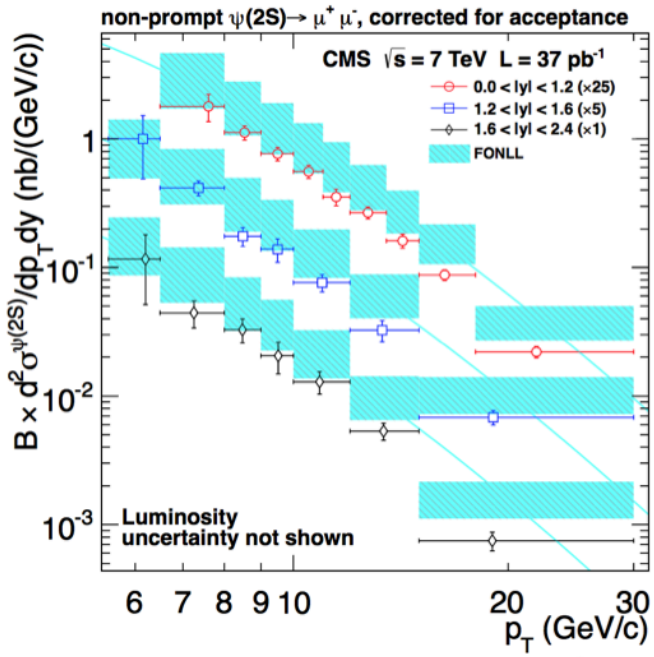
- Agreement with NRQCD, overestimate at highest p_T never before explored
- k_T-factorisation model does not describe data well
- Colour Singlet NNLO* predictions undershoot at highest scales

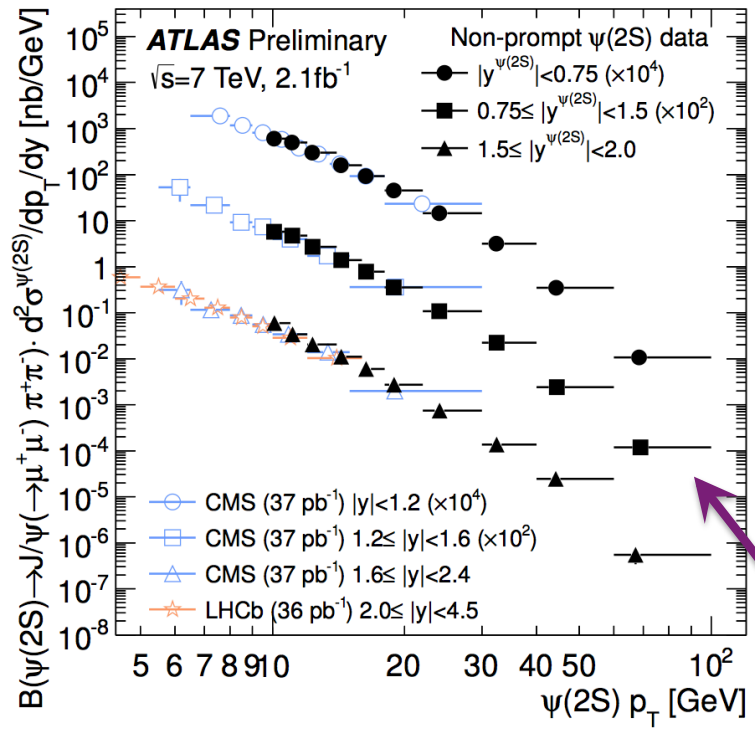




Non-prompt ψ(2S) → J/ψ π π production

Previous measurements by CMS hinted at tension with previously well-understood non-prompt production (a proxy for B-production)





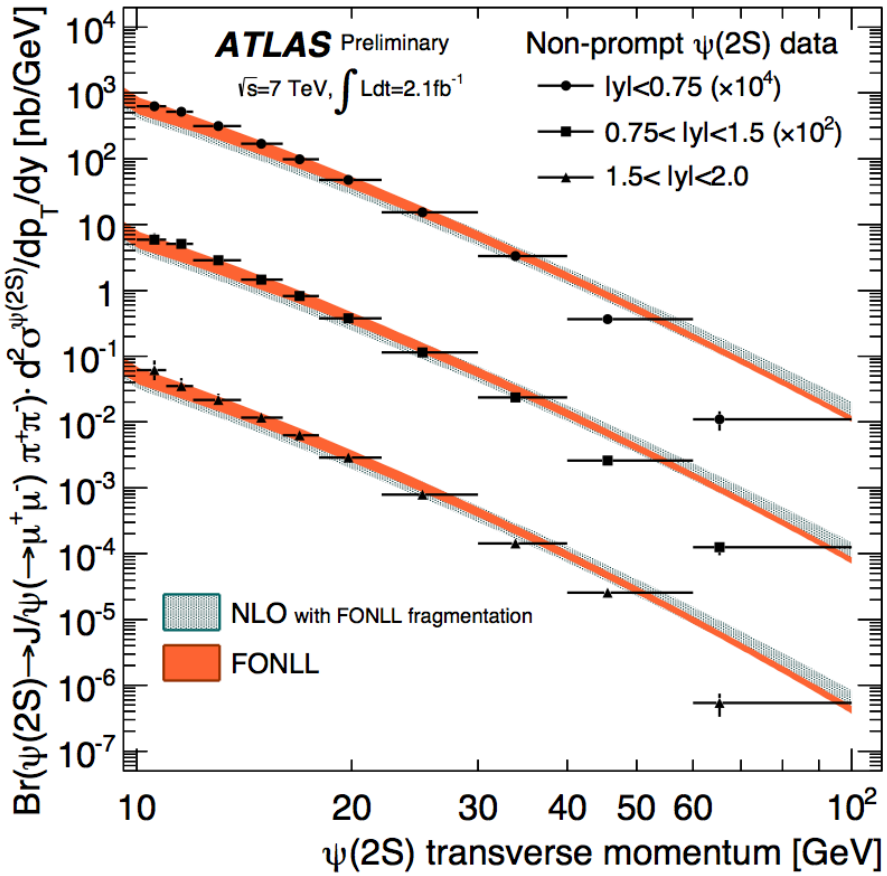
Cacciari et al. JHEP 1210 (2012) 137:

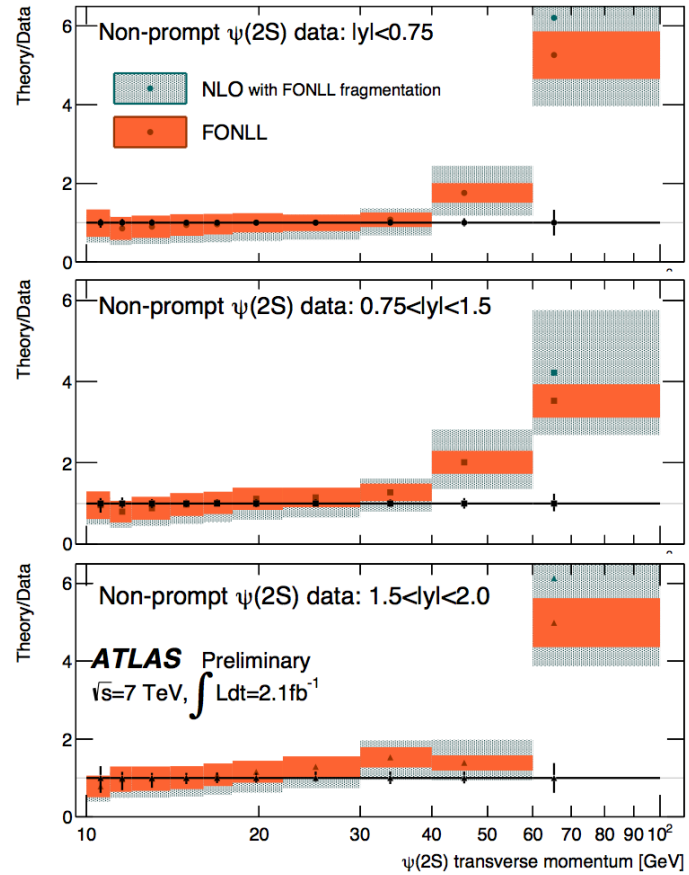
"A possible exception to the generally good agreement is the observation, made by CMS in [63], that the experimental cross section for non-prompt J/ψ and $\psi(2S)$ production tends to fall off at large transverse momentum slightly faster than the FONLL prediction. More data at even larger p_T will help clarify this issue."

Non-prompt ψ(2S) → J/ψ π π production

Good agreement with NLO and FONLL predictions at low p_T, but discrepancies observed in both at larger p_T (more prevalent for NLO, without resummation)

- High p_T B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.





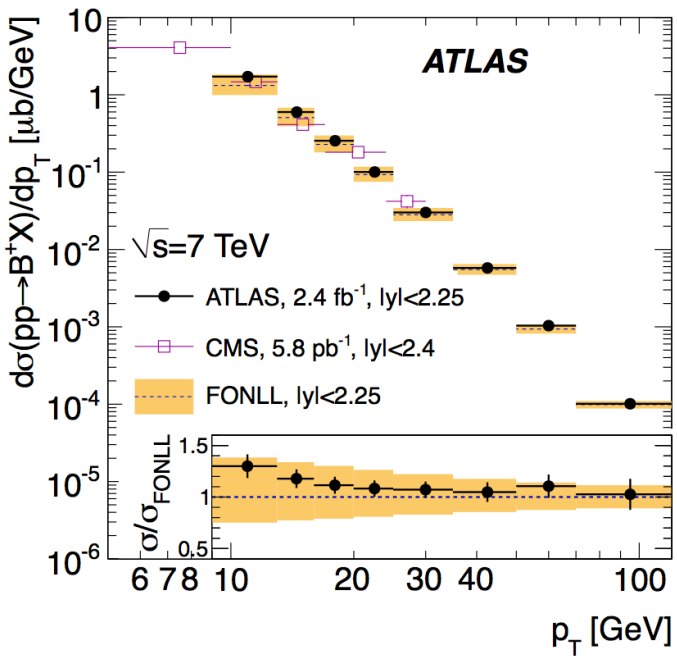
Non-prompt ψ(2S) → J/ψ π π production

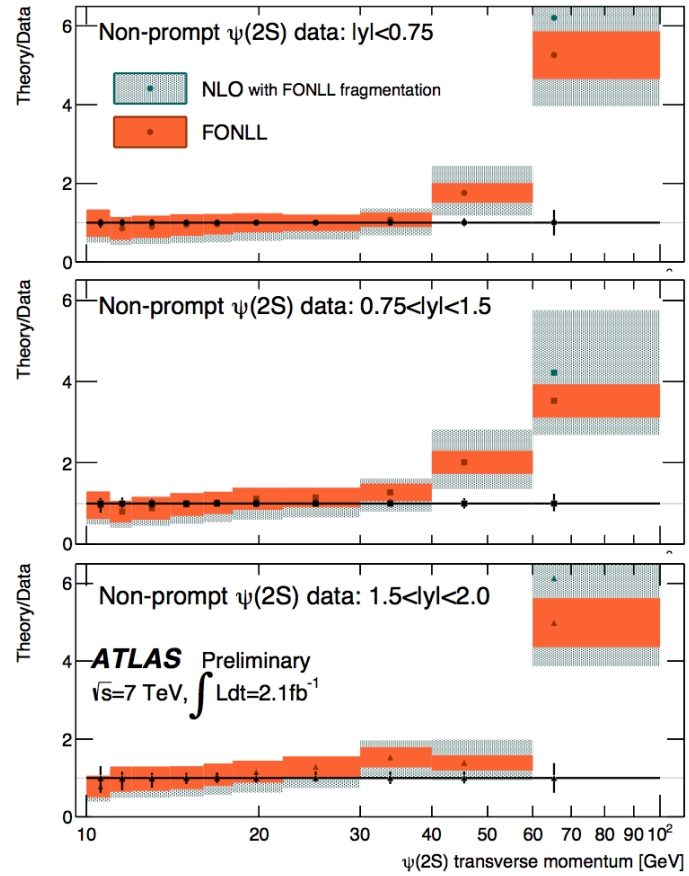
Good agreement with NLO and FONLL predictions at low p_T, but discrepancies observed in both at larger p_T (more prevalent for NLO, without resummation)

- High p_T B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.

Experimental issue?:

- CMS consistency
- Discrepancy not seen reconstruction of full B meson decay (using same efficiency corrections and methodology)





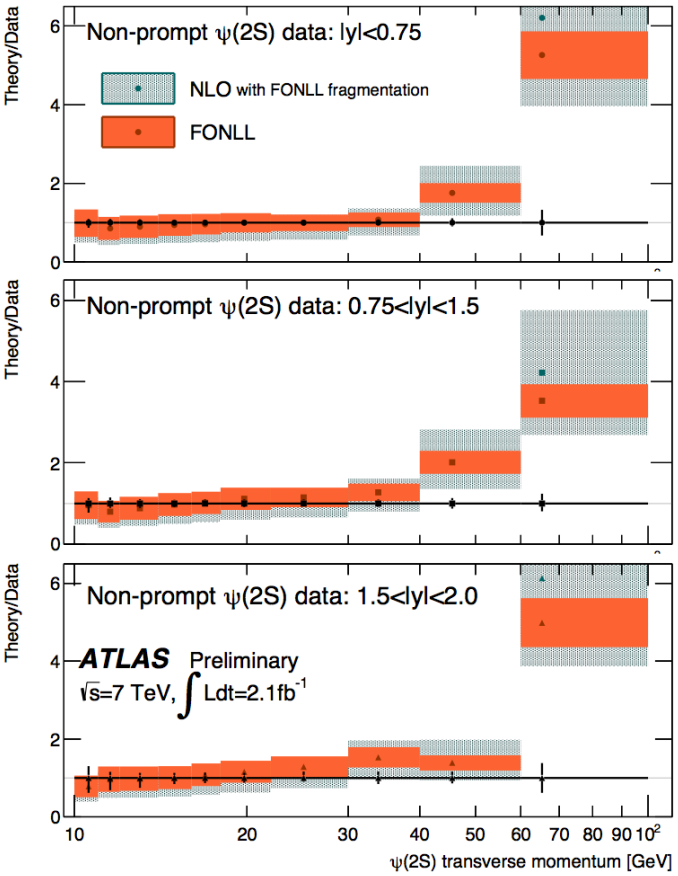
Non-prompt ψ(2S) → J/ψ π π production

Good agreement with NLO and FONLL predictions at low p_T, but discrepancies observed in both at larger p_T (more prevalent for NLO, without resummation)

- High p_T B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.

Experimental issue?:

- ✓ CMS consistency
- ✓ Discrepancy not seen reconstruction of full B meson decay (using same efficiency corrections and methodology)
- Migration effects (~1%), larger migrations would point to *bigger* discrepancies



Non-prompt ψ(2S) → J/ψ π π production

Good agreement with NLO and FONLL predictions at low p_T, but discrepancies observed in both at larger p_T (more prevalent for NLO, without resummation)

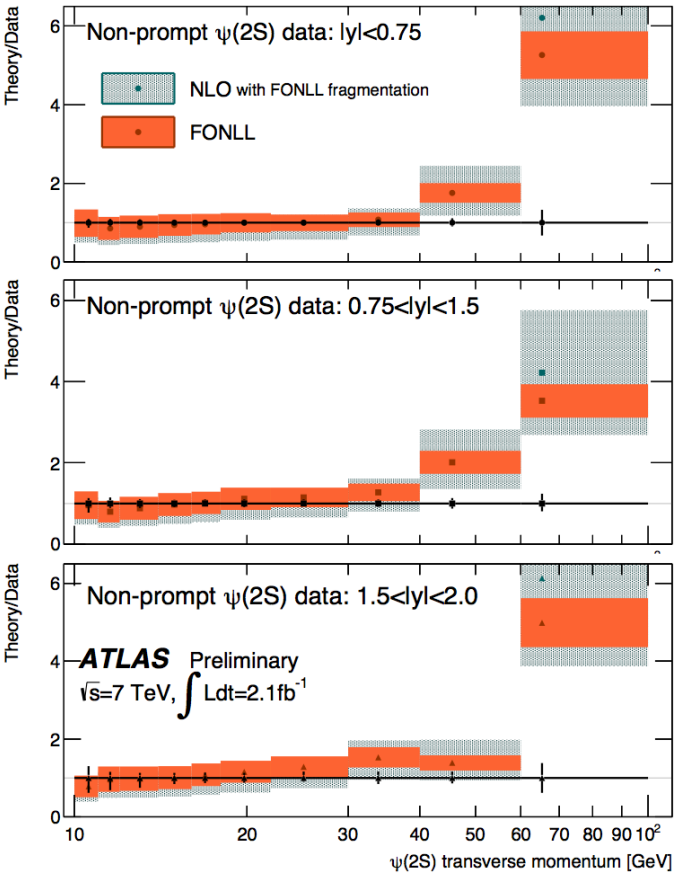
- High p_T B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.

Experimental issue?:

- ✓ CMS consistency
- ✓ Discrepancy not seen reconstruction of full B meson decay (using same efficiency corrections and methodology)
- ✓ Migration effects (~1%), larger migrations would point to *bigger* discrepancies

Theory issue?:

- Fragmentation functions a possibility, but B^+ consistency suggests otherwise…



Non-prompt ψ(2S) → J/ψ π π production

Good agreement with NLO and FONLL predictions at low p_T, but discrepancies observed in both at larger p_T (more prevalent for NLO, without resummation)

- High p_T B-meson production modelling issues had been hinted at by other production measurements. Now able to probe with high precision.

Experimental issue?:

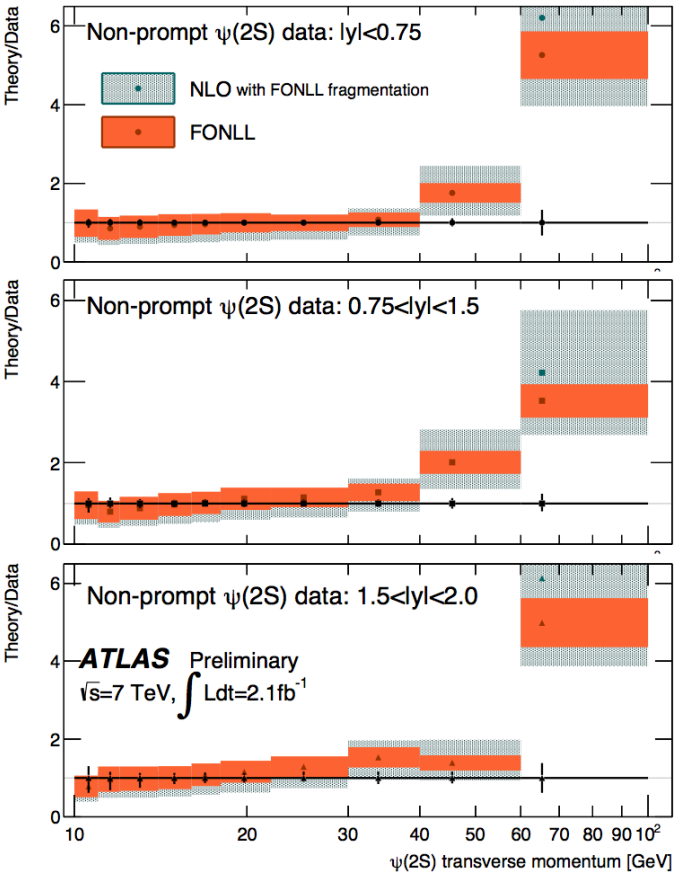
- CMS consistency
- Discrepancy not seen reconstruction of full B meson decay (using same efficiency corrections and methodology)
- Migration effects (~1%), larger migrations would point to *bigger* discrepancies

Theory issue?:

✓ Fragmentation functions a possibility, but B^+ consistency suggests otherwise…

- Energy fraction in decay of B→J/ψ (2S)+X not being appropriately shared.?

This is an input parameter for theory from B-factories (largely low p_T and different species)
… **a flaw in applicability revealed by this data?**



$\chi_c \rightarrow J/\psi(\rightarrow\mu\mu)\gamma(\rightarrow ee)$

Submitted to JHEP
arXiv:1404.7035

P-wave charmonium production theoretically and experimentally(!) tricky to determine.

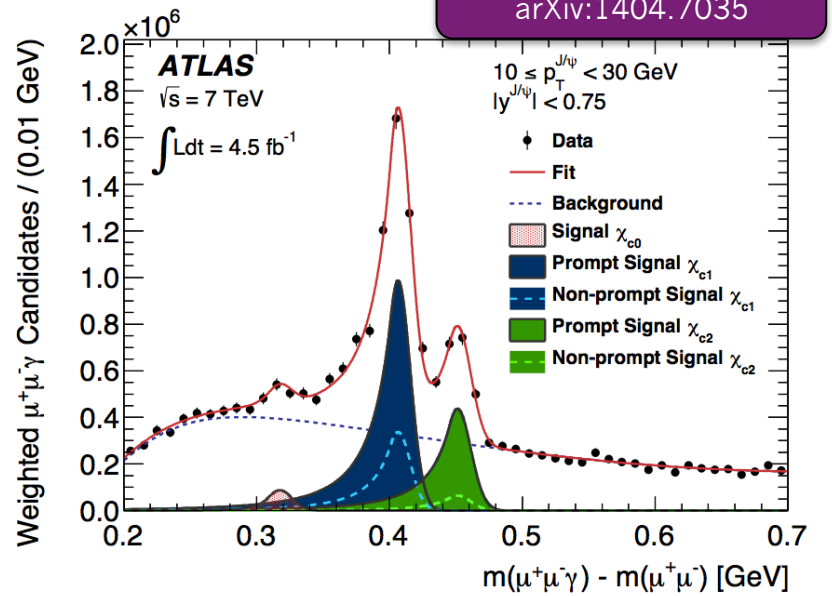
Important to understand this production channel to get a complete picture of quarkonium production.

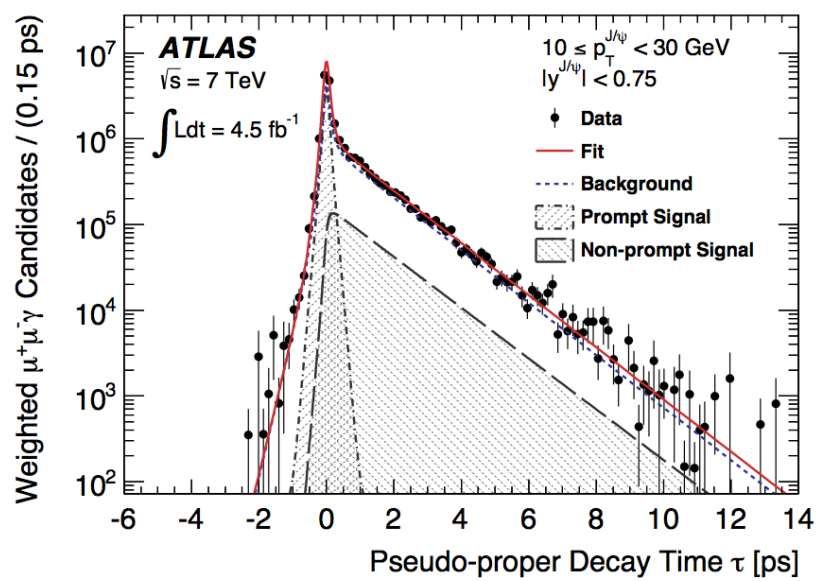
Experimentally challenging:

- low p_T muons
- precise reconstruction of soft (p_T~5 GeV) photon through conversions
  - low efficiencies

Perform unbinned maximum likelihood fit on acceptance and efficiency corrected mass and lifetime.

Extract prompt and non-prompt production of the χ_c states

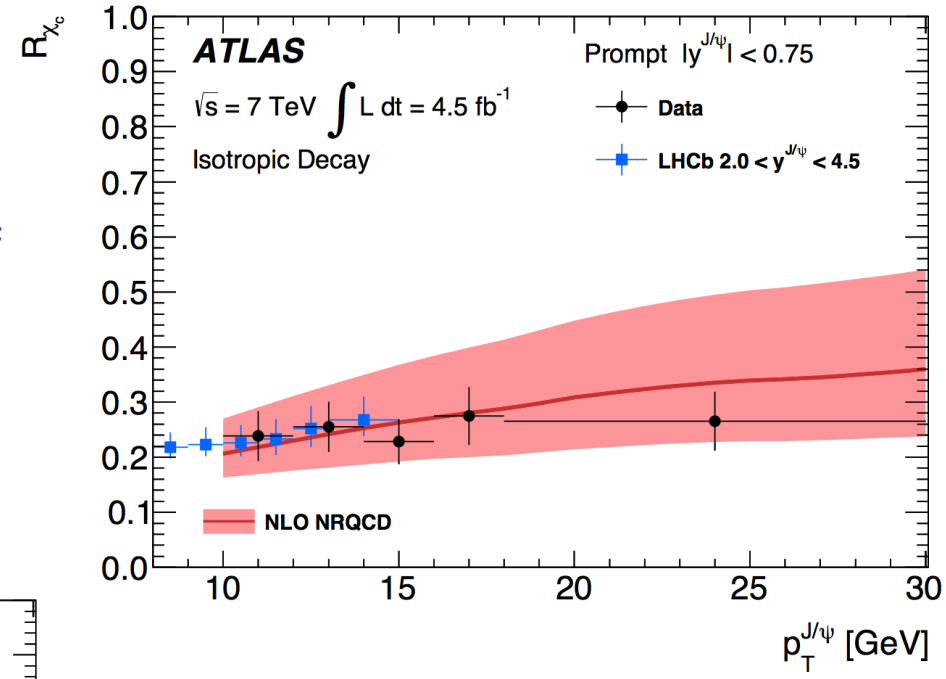


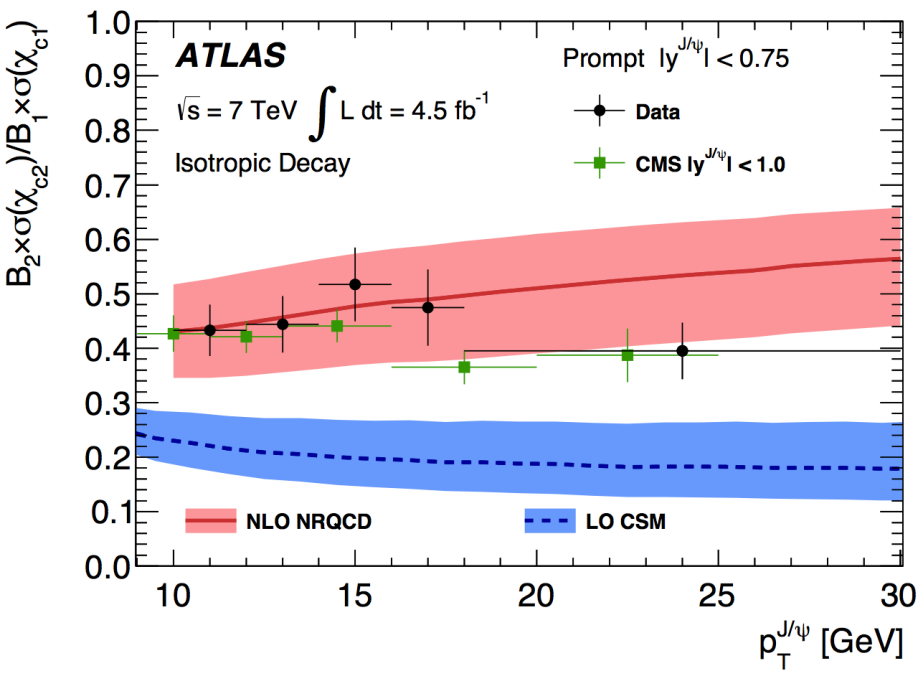


Prompt $\chi_c \rightarrow J/\psi\gamma$ and $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio

Fraction of prompt J/ψ produced in χ_c feed-down (right)→

Data show that between 20–30% of prompt J/ψ are produced in χ_c decays





Prompt χ_c cross-section ratio ← (left)

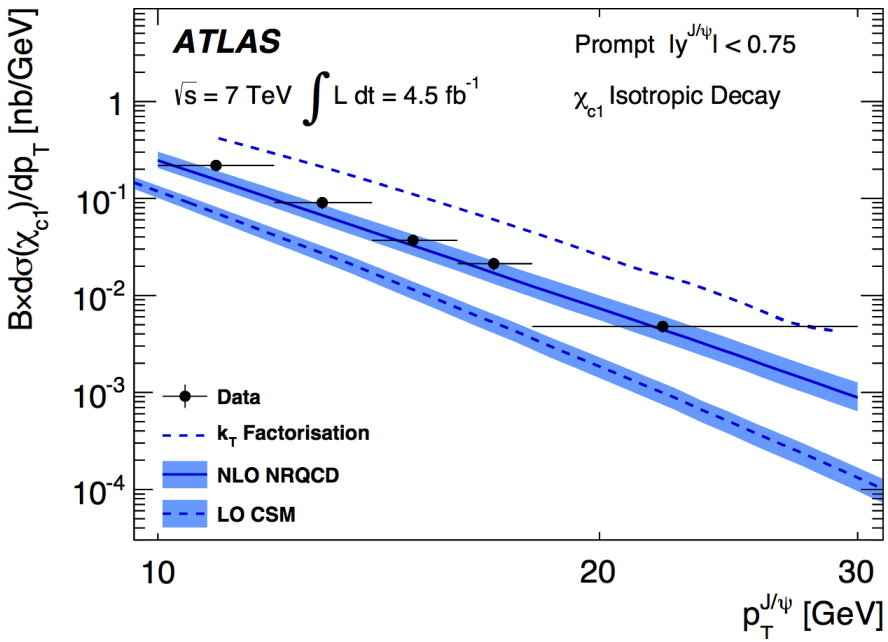
Data show more χ_{c1} than χ_{c2}

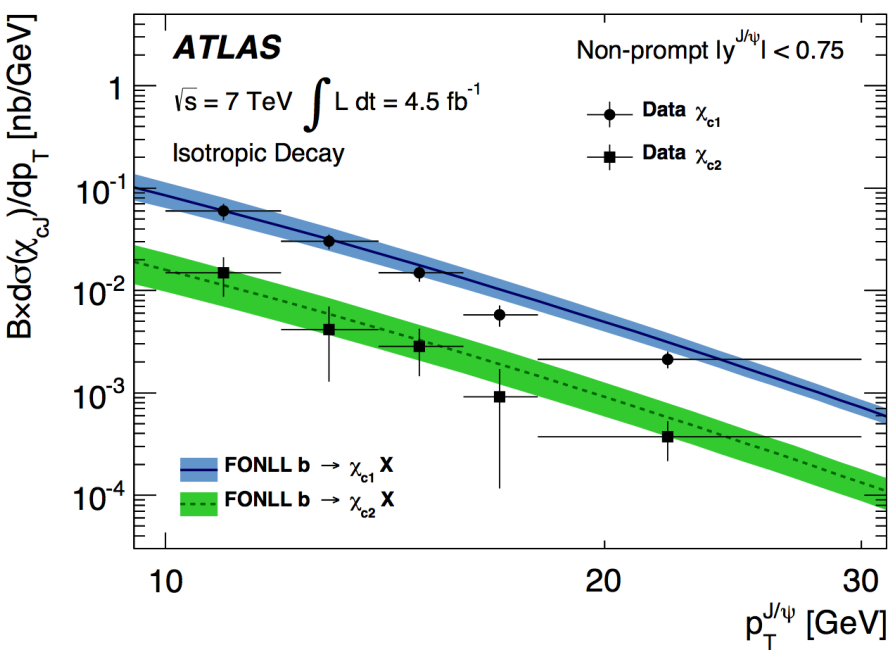
Ratio sensitive to presence of possible colour octet contributions in NRQCD

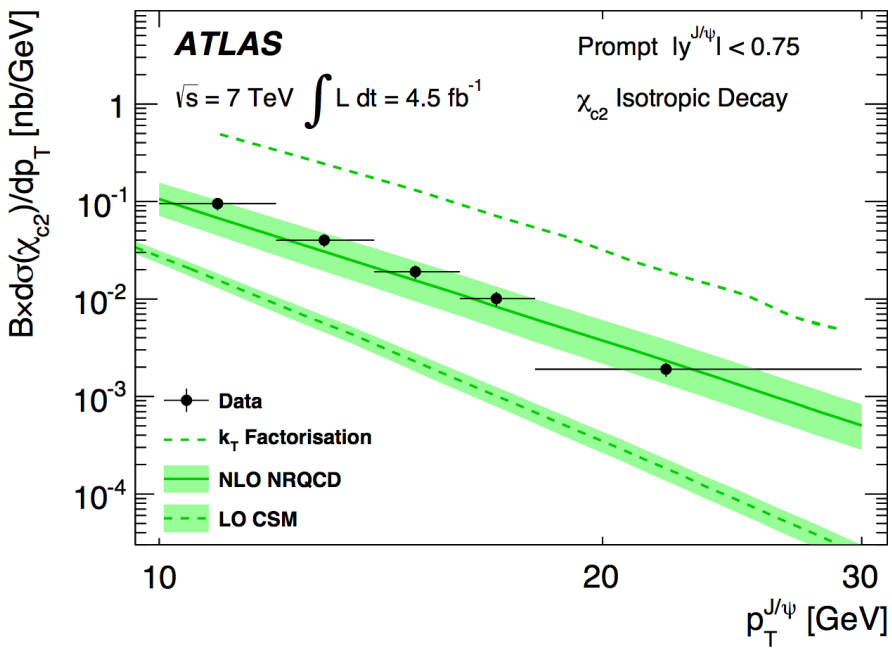
Absolute χ_c production rates

First absolute prompt (right) and non-prompt (below) χ_{c1} and χ_{c2} differential cross sections, compared to predictions

NRQCD / FONLL able to describe the data, hints at high-p_T excess in latter?







Measurement of Br($B^{\pm} \to \chi_{c1} K^{\pm}$)

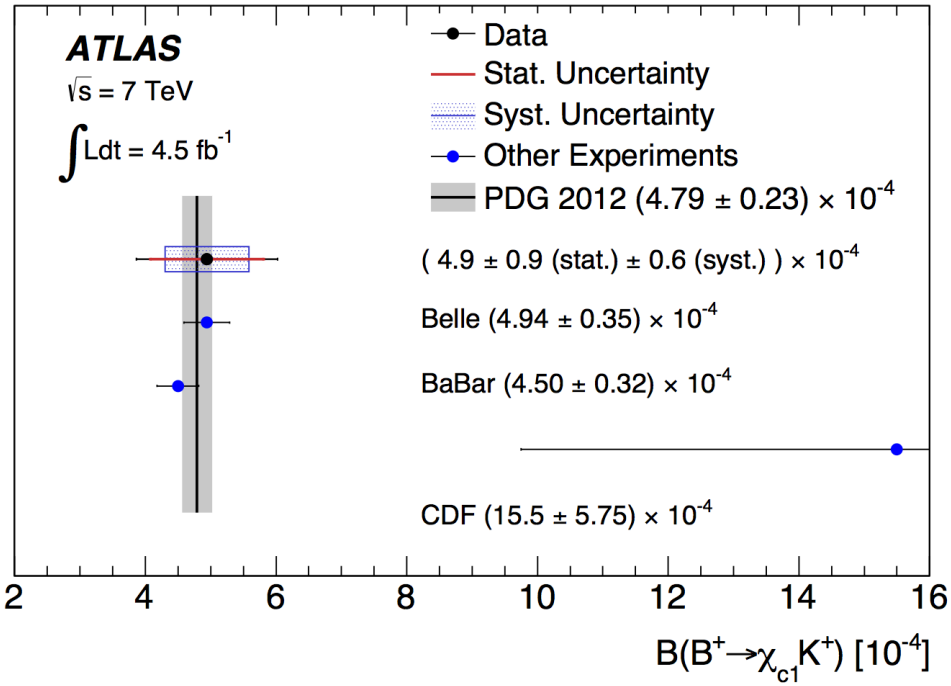
Branching fraction measurement

Using same χ_c data sample and selections, can extract measurement of Br($B^{\pm} \to \chi_{c1} K^{\pm}$)

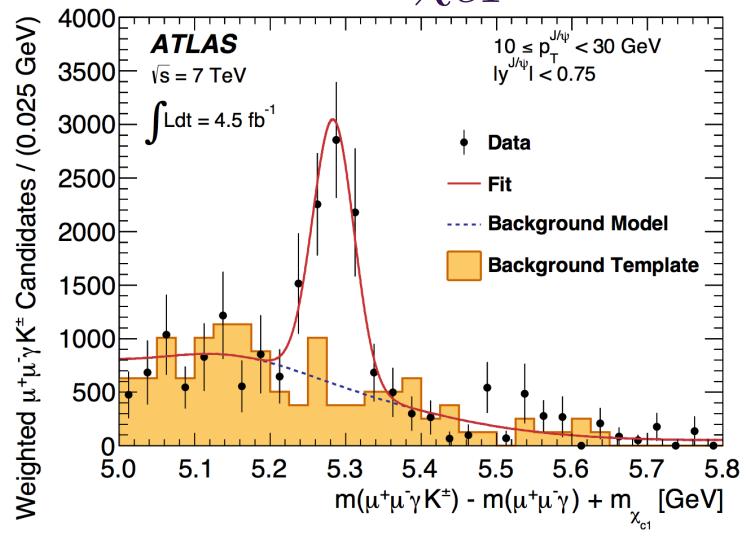
Use precisely-known $B^{\pm} \to J/\psi K^{\pm}$ decay as control.

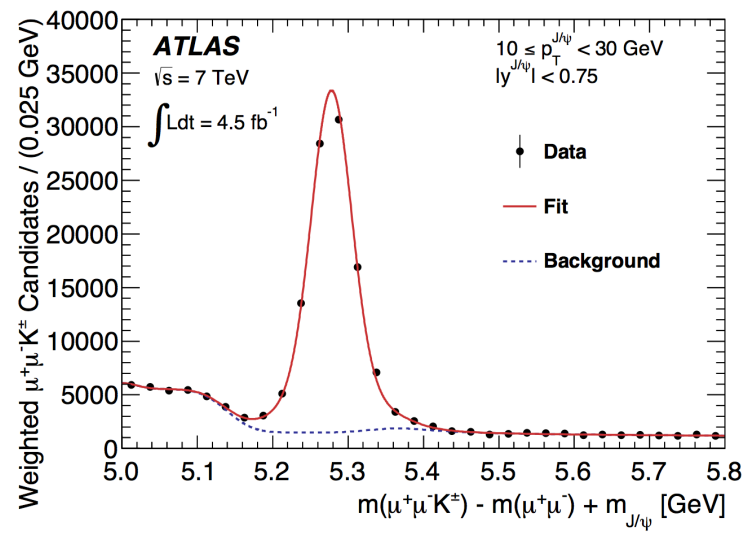
$$\mathcal{B}\left(B^{\pm} \to \chi_{c1} K^{\pm}\right) = \mathcal{A}_B \cdot \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \cdot \frac{\mathcal{B}\left(B^{\pm} \to J/\psi K^{\pm}\right)}{\mathcal{B}\left(\chi_{c1} \to J/\psi\,\gamma\right)}$$

Hadron collider measurement not far from best B-factory results; prospects for improvements!



$B^{\pm} \to \chi_{c1} K^{\pm}$





$B^{\pm} \to J/\psi K^{\pm}$

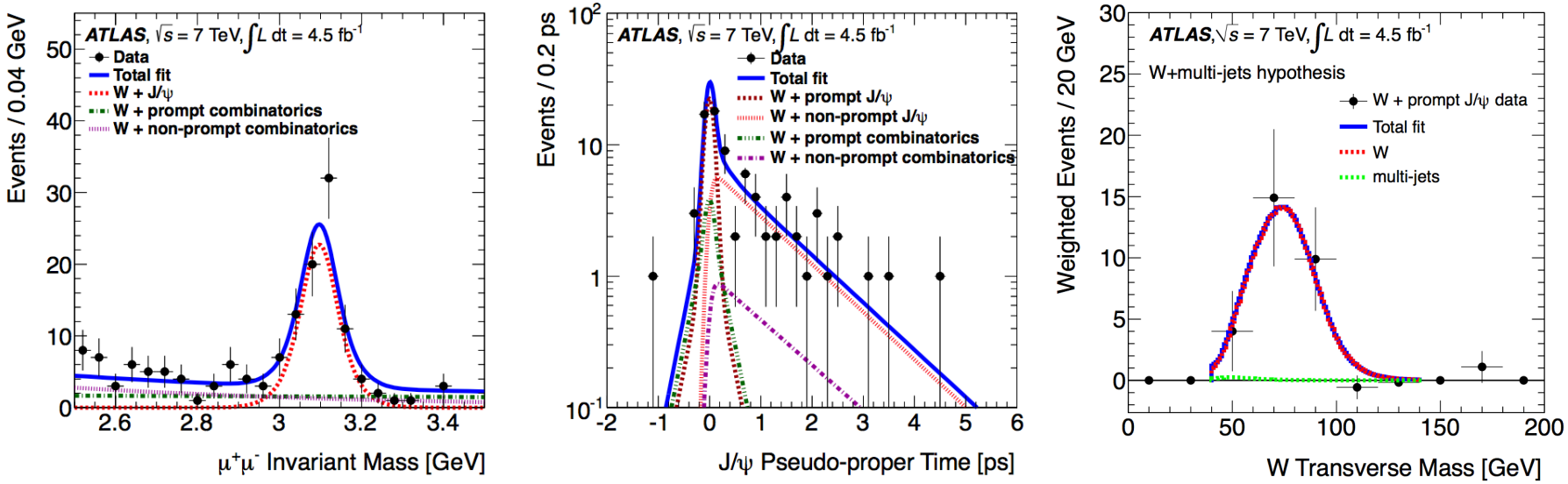
Associated W boson + prompt J/ψ production

JHEP 1404 (2014) 172
arXiv:1401.2831

Extend quarkonium studies into new horizons:

Search for associated production of a W boson and *prompt* J/ψ production for first time (7 TeV, 4.6 fb^{-1} data)

- **Probe new production modes of quarkonium, new ways to test theory**
- **Background to SM processes like WW scattering, H→WW**
- **Search channel for new physics phenomena**



Unbinned maximum likelihood fit to J/ψ mass and lifetime, extract prompt component from data – background-only hypothesis rejected at 5.1 σ level

Background contributions assessed from: pileup (multiple pp collisions in bunch crossing), Z+jets, top pair production, W+b-quark, $B_c \rightarrow J/\psi + \mu\ \nu$ +X, heavy quark jets.

W+prompt J/ψ production cross-section

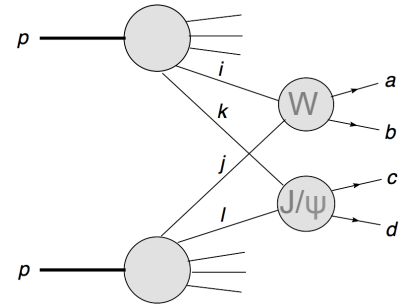
Double parton scattering can contribute to prompt signal cross-section.
Estimate using the following standard/simple ansatz:

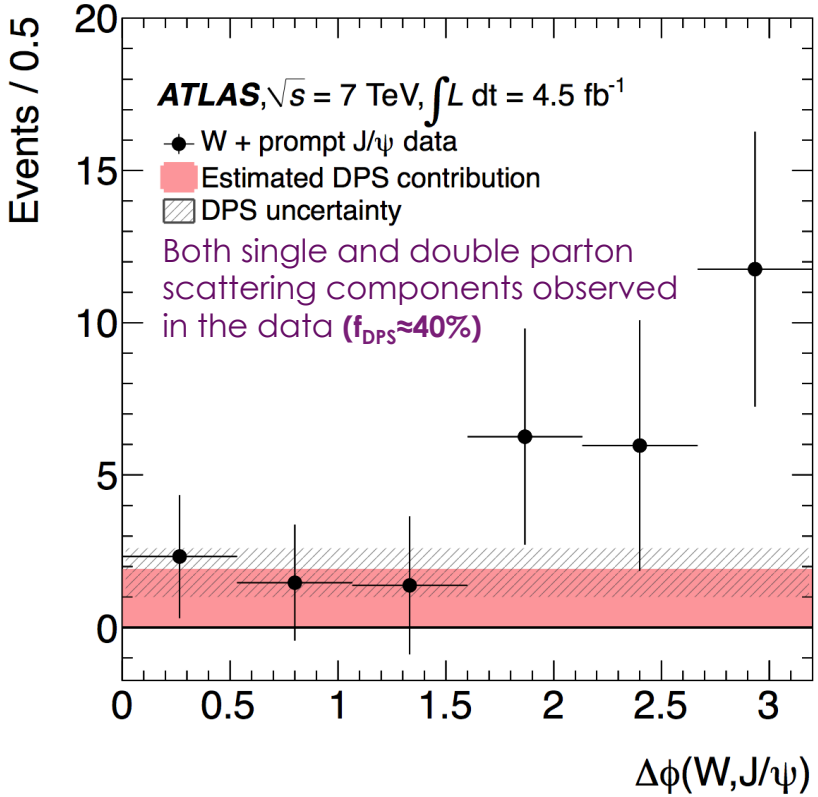
Measured directly in this analysis

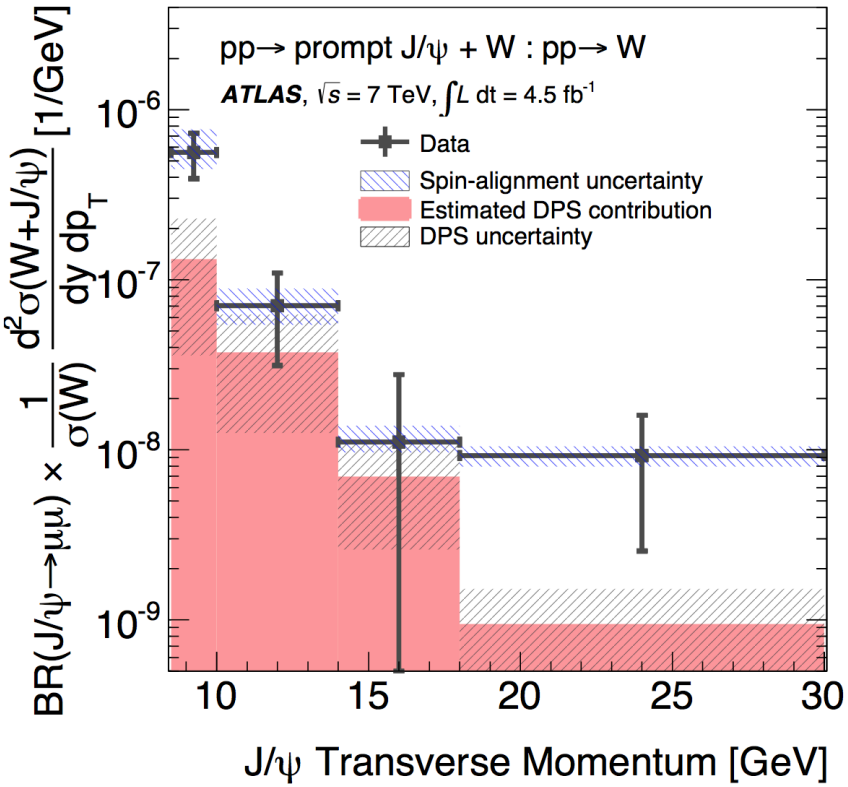
From ATLAS measurement prompt J/ψ arXiv:1104.3038

$$d\sigma^{\mathrm{DPS}}_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{\mathrm{eff}}}$$

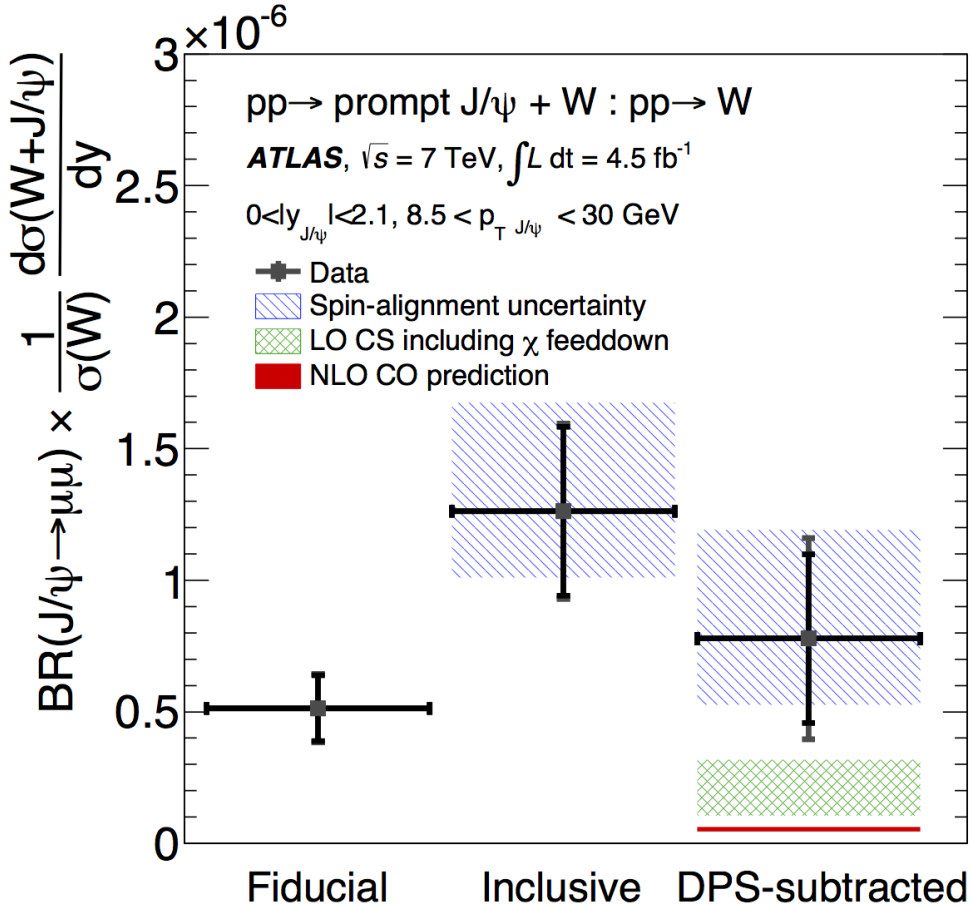
From ATLAS measurement W+2jets arXiv:1301.6872





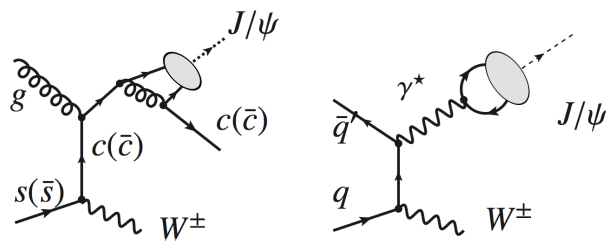


W+prompt J/ψ results and interpretation

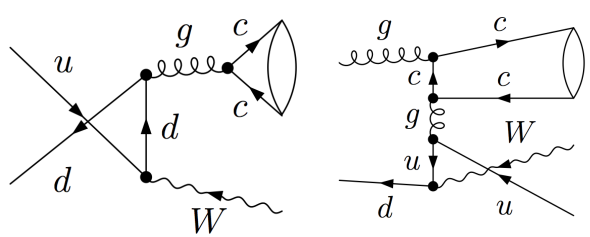


Present cross-sections ***before and after*** estimation of double parton scattering component

- DPS consistency with ATLAS W+2jet measurement
- DPS-subtracted data in disagreement with colour octet NLO, consistent with colour singlet



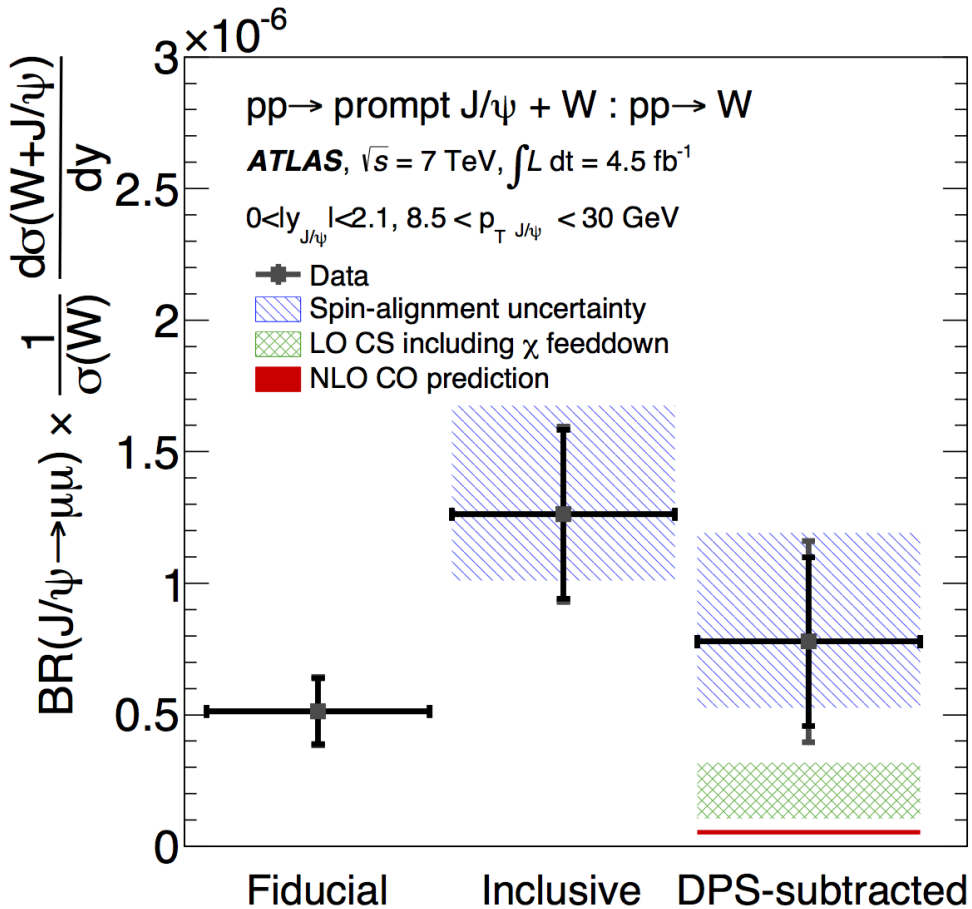
LO CSM (SINGLET) arXiv:1303.5327



NLO COM (OCTET) arXiv:1304.4670

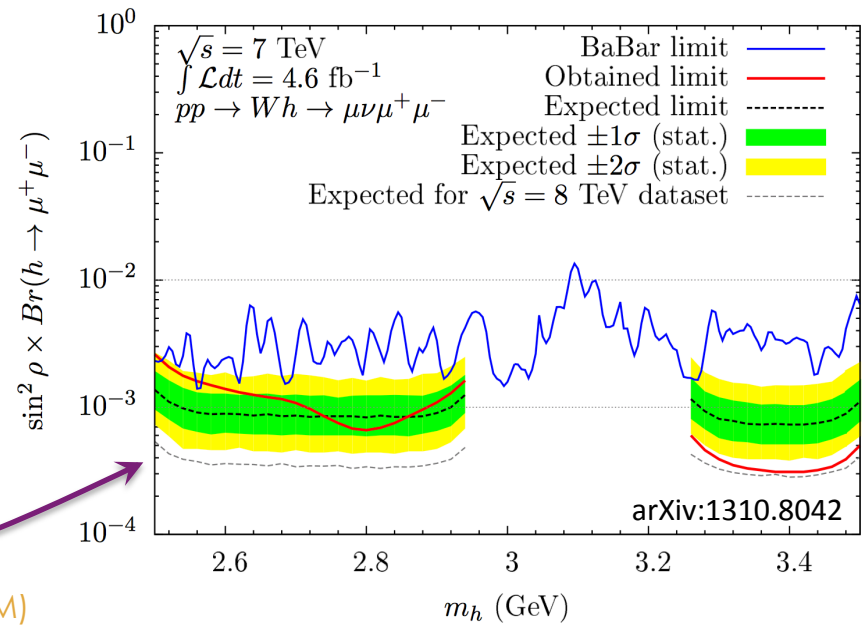
Measured relative to inclusive W production with rates below 10^{-6} – this is one of the rarest processes measured at the LHC!

W+prompt J/ψ comparison to theory



Present cross-sections ***before and after*** estimation of double parton scattering component

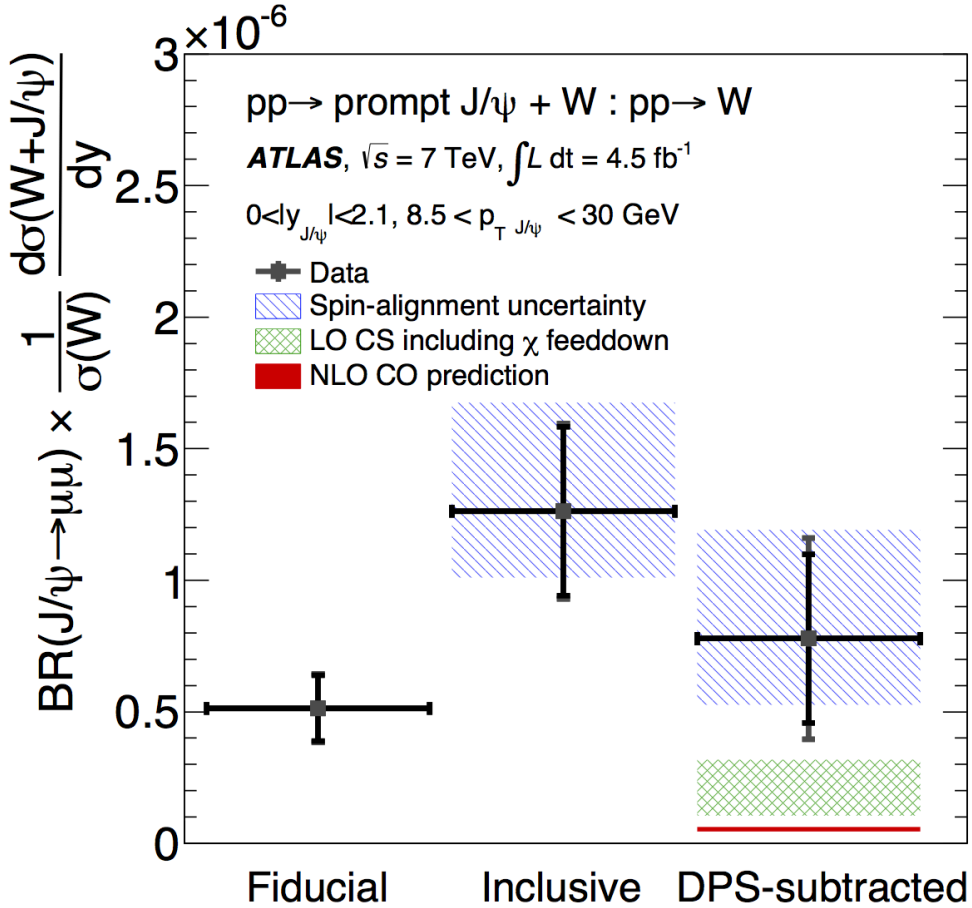
- DPS consistency with ATLAS W+2jet measurement
- DPS-subtracted data in disagreement with colour octet NLO, consistent with colour singlet



Extensions with 2012/Run-2 data:

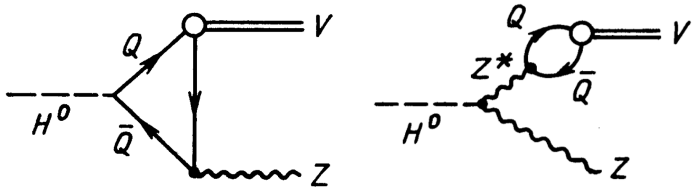
- DPS measurements
- Sensitivity to rare (unobserved) 3-body decay W→l+ν+J/ψ
- Light scalar mixing with SM Higgs
- Rare Higgs decay channel in Z (SM and BSM)

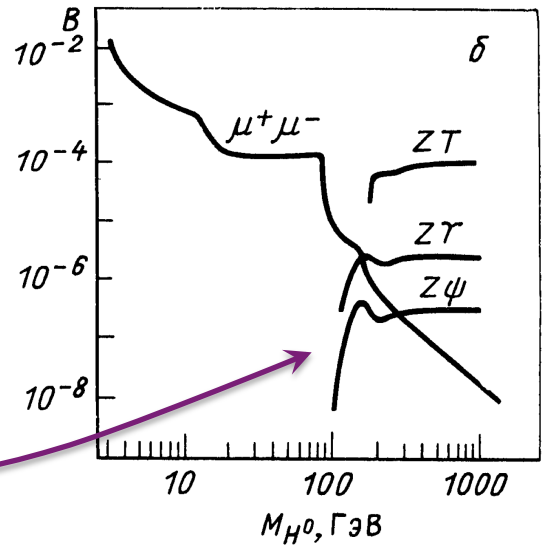
W+prompt J/ψ comparison to theory



Present cross-sections ***before and after*** estimation of double parton scattering component

- DPS consistency with ATLAS W+2jet measurement
- DPS-subtracted data in disagreement with colour octet NLO, consistent with colour singlet





Extensions with 2012/Run-2 data:

- DPS measurements
- Sensitivity to rare (unobserved) 3-body decay W→l+ν+J/ψ
- Light scalar mixing with SM Higgs
- Rare Higgs decay channel in Z (SM and BSM)

Summary

With the excellent performance of the LHC detectors and the large data samples we are able to make high precision measurements.
New discrepancies and puzzling results in both prompt and non-prompt production

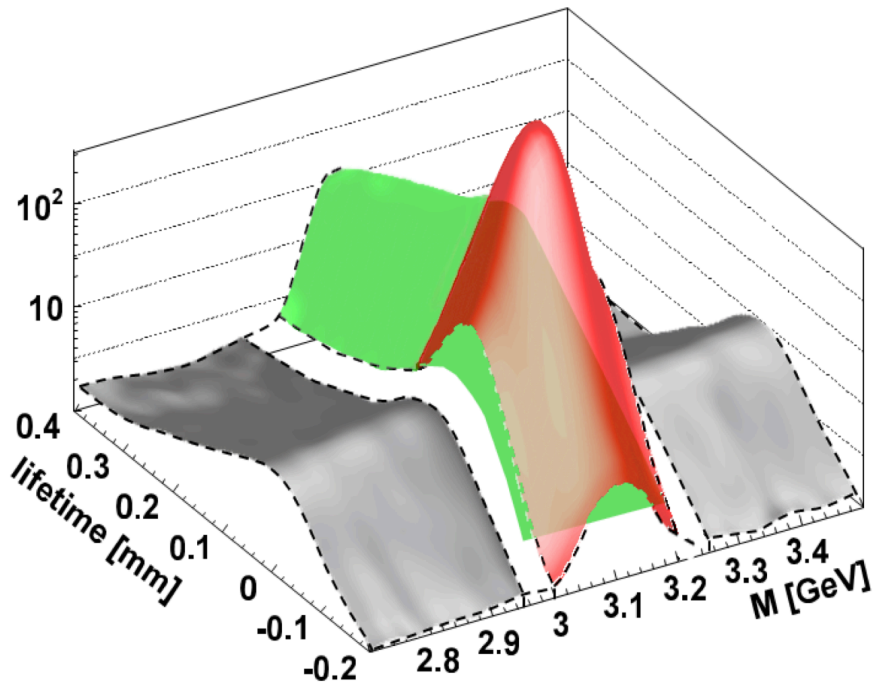
Quarkonia measurements can provide input to wide range of physics:

- Tests of QCD modelling at perturbative/non-perturbative boundary
- Searches for exotic quarkonium states
- Competitive branching fraction measurements
- Probe the proton structure through numerous final states (DPS, k_T-dependent PDFs)
- Sensitivity to rare W boson decays

Unique opportunities to study rare Higgs decays / couplings and searches for extensions to the Standard Model in novel final states.

Thanks for your attention! ☺

Reconstructing and separating quarkonia

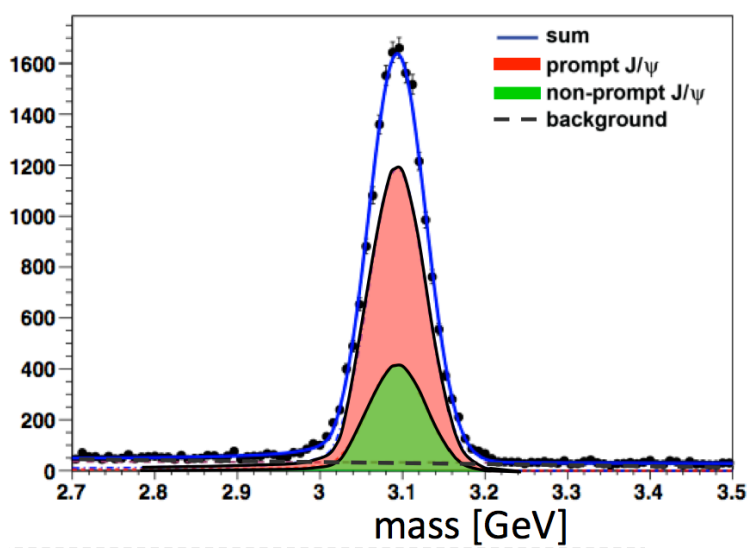


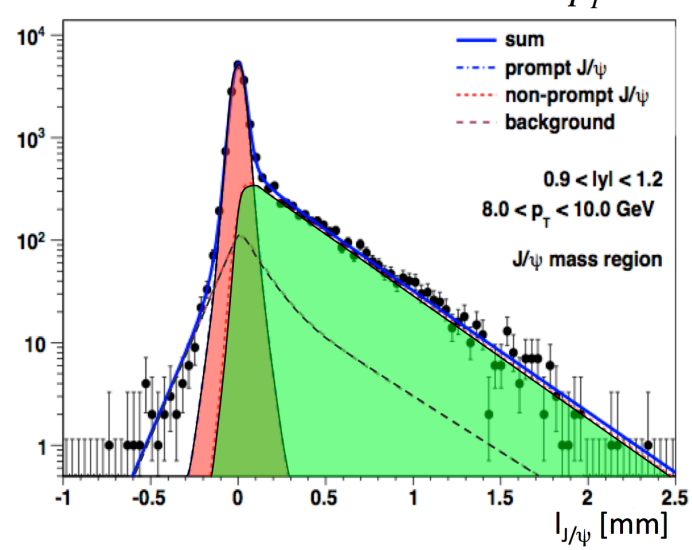
Separate two classes of production:

1) **From B-decays "non-prompt"**
2) **Direct QCD production "prompt"**

Use lifetime of B hadrons to distinguish

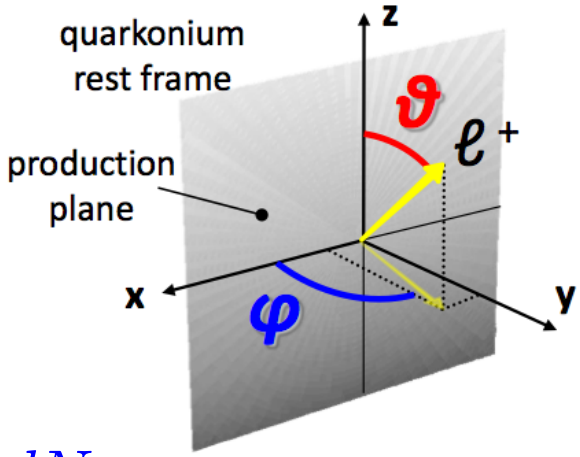
$$l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T}$$

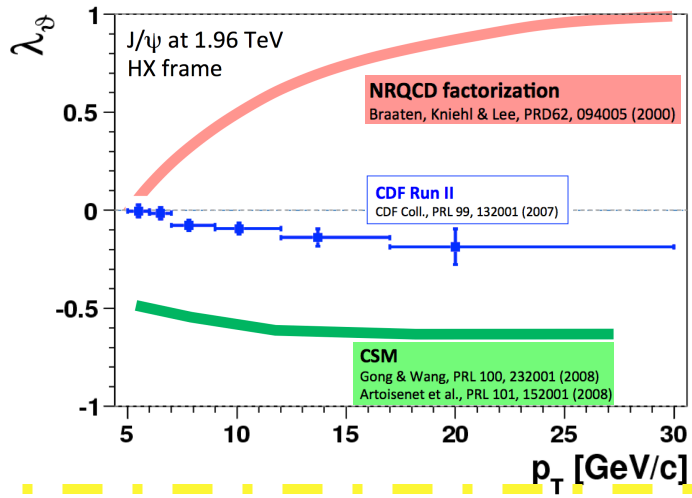


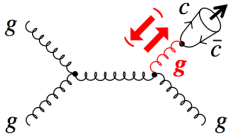


Spin-alignment measurements

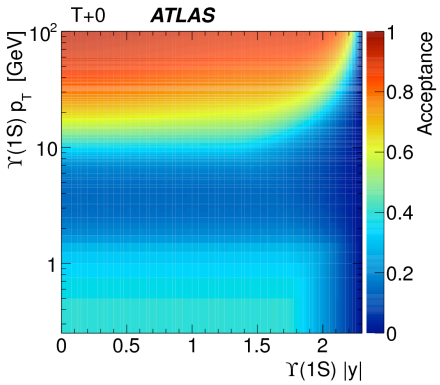
Measurement of spin-alignment (or 'polarisation') of quarkonia has historically proven to be a challenging observable to correctly predict

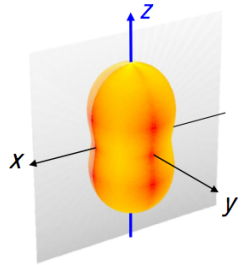






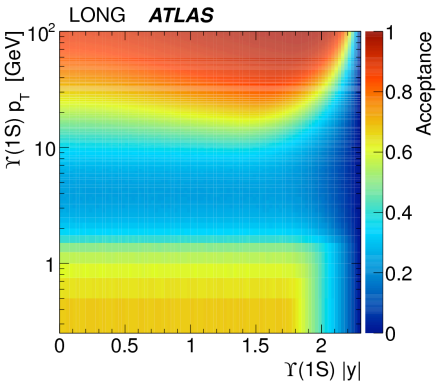
$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star}\cos^2\theta^\star + \lambda_{\phi^\star}\sin^2\theta^\star\cos 2\phi^\star + \lambda_{\theta^\star\phi^\star}\sin 2\theta^\star\cos\phi^\star$$

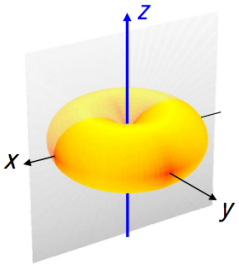




Transverse polarisation

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta^\star$$





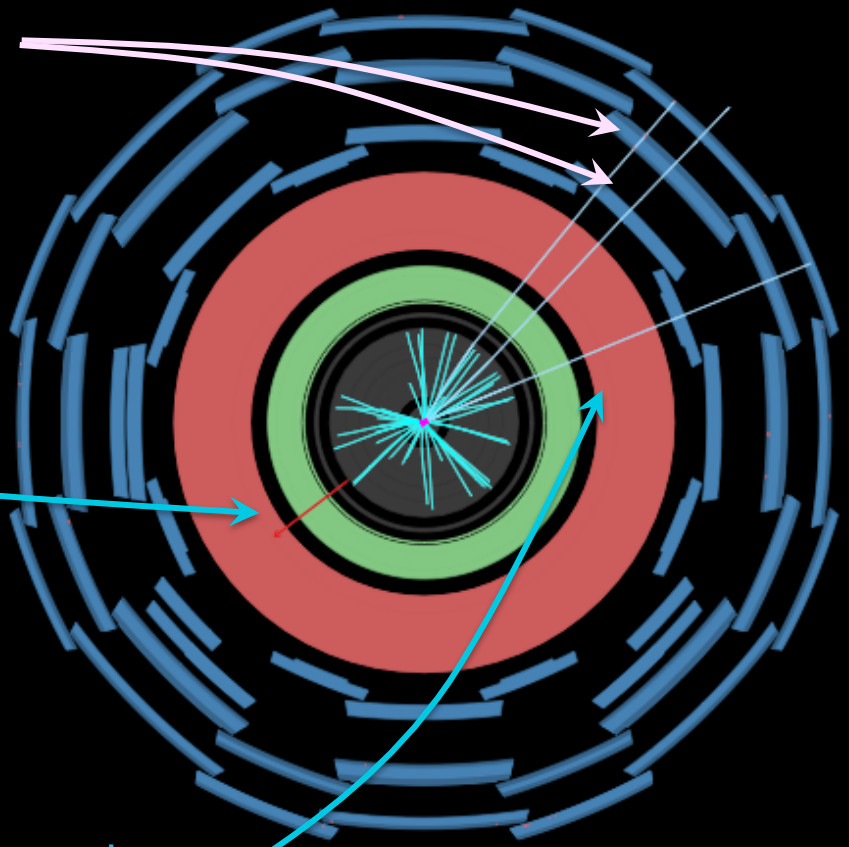
Longitudinal polarisation

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta^\star$$

Muons from J/ψ candidate decay

Missing E_T vector

Muon from W boson decay



W + prompt J/ψ candidate event

ATLAS EXPERIMENT

Run Number: 189421, Event Number: 32188372

Date: 2011-09-16 18:30:08 UTC

J/ψ candidate p_T = 9.4 GeV
Pseudo proper time = -0.1 ps

W boson p_T = 42 GeV