



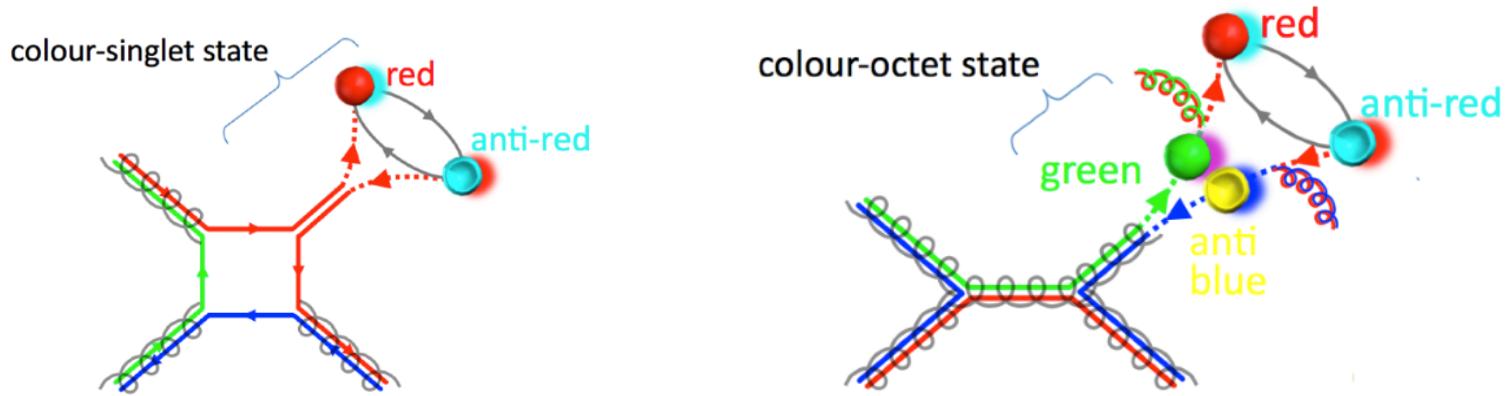
Charmonium production at ATLAS



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(on behalf of the ATLAS Collaboration)

Quakonium Production

- Study of heavy quarkonia probes hadron configuration and the non perturbative behaviour of QCD.
- Understanding of the production of P-wave charmonium states is a significant bottleneck in the understanding of charmonium production as a whole.
- Current theoretical calculations are limited in their ability to model the production and decay of these states. The Colour Singlet (CS) mechanism alone is insufficient to account for experimental measurements.



- In the CS model only those states with the same quantum numbers as the resulting charmonium contribute to the formation of the bound state.
- Non-Relativistic QCD (Colour Octet model), in addition to CS production, allows for possibility of heavy quark formation in a coloured state, which subsequently decays into a physical singlet quarkonium bound state through non-perturbative emission of soft gluons.
- High yields of quarkonia available at the LHC will enable stringent tests of existing theoretical models across a large range of momentum transfer.

Recent results on charmonium from ATLAS

Results in this presentation:

Measurement of the χ_{c1} and χ_{c2} production with $\sqrt{s}=7$ TeV pp collisions at ATLAS

[arXiv:1404.7035](https://arxiv.org/abs/1404.7035)

Cross-section measurement of $\Psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ in $\sqrt{s}=7$ TeV pp collisions at ATLAS

ATLAS-CONF-2013-094, paper in preparation

Measurement of the production cross section of prompt J/ψ mesons in association with a W boson in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector

[arXiv:1401.2831](https://arxiv.org/abs/1401.2831)

See talks from Andy Chisholm and Hannah Arnold

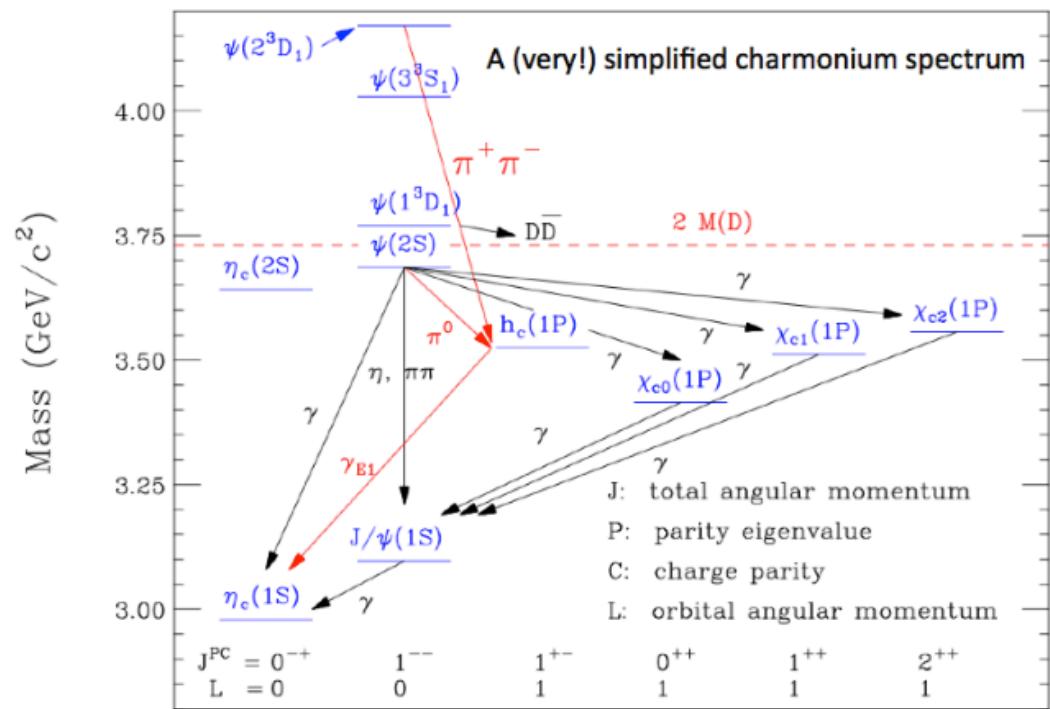
Theoretical Approaches

The measurements in this presentation are compared with predictions from

- Leading-order (LO) colour-singlet model (CSM) [<http://superchic.hepforge.org/chigen.html>]
- Leading-order (LO) non-relativistic QCD (NRQCD) [[arXiv:1009.3655](#)]
- Next-to-leading-order (NLO) NRQCD [[Phys. Rev.D83\(2011\) 111503, arXiv:1212.5293, arXiv:1009.3655](#)]
- kt-factorisation approach [[Phys. Rev.D83\(2011\) 034035, arXiv:1108.2856](#)]
- Fixed order next-to-leading-logarithm (FONLL) for b-hadron production [[arXiv:1205.6344, hep-ph/9803400](#)]

Measurement of the χ_{c1} and χ_{c2} production

- Inclusive production rate of prompt J/ ψ is the most experimentally accessible charmonium production observable at the LHC.
- Comparisons of experimental measurements with theoretical predictions are complicated by the large feed-down contributions from χ_c and $\psi(2S)$ decays.
- An understanding of χ_c production is a crucial component of any general description of charmonium production at the LHC.
- Prompt χ_c states are produced directly in $p\bar{p}$ collisions or through the decay of higher mass quarkonium states.
- Decay chains of b-hadrons can also produce χ_c states. Non-prompt production.
- The $\chi_{cJ}(1P)$ states (with $J = 0, 1, 2$) are the only triplet of P-wave states below the open-charm threshold.

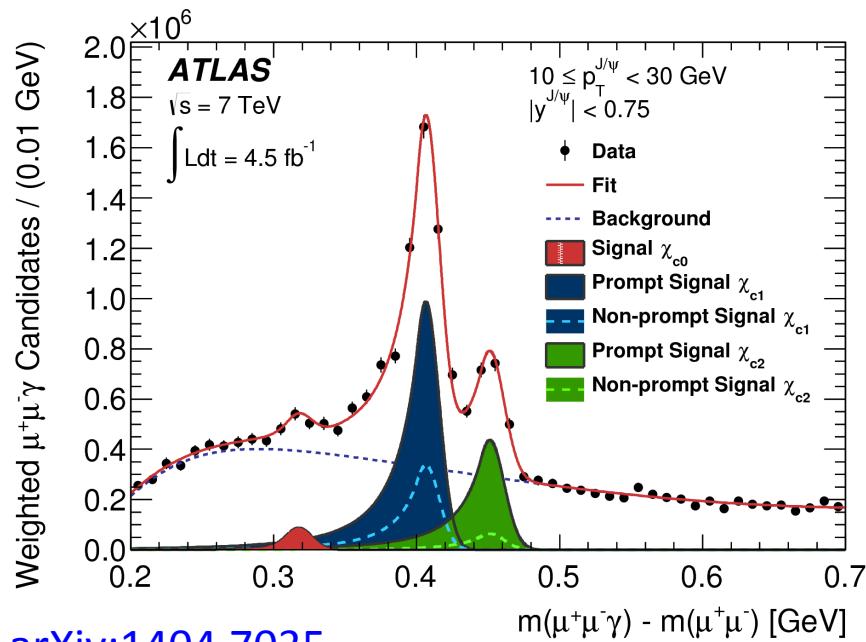


Measurement of the χ_{c1} and χ_{c2} production

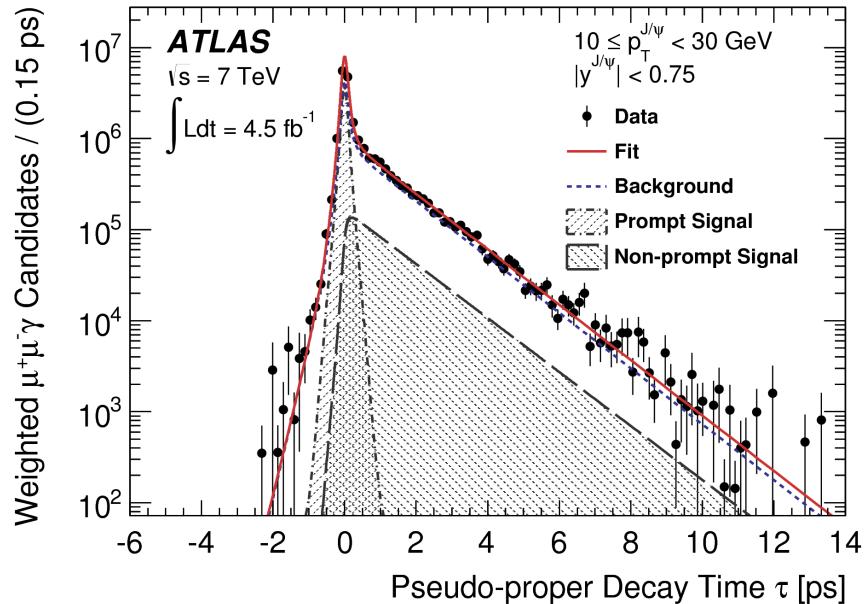
- Reconstructed $\chi_c \rightarrow J/\psi \gamma \rightarrow \mu^+ \mu^- \gamma$ with photon conversions ($\gamma \rightarrow e^+ e^-$)
- Main challenge: precise reconstruction of the soft γ .
- The mass difference $\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$ distribution distinguishes between χ_c candidates.
- Simultaneous fit to mass and pseudo-proper lifetime distributions.
- Pseudo-proper time, τ , distinguishes between prompt and non-prompt contributions.

$$\tau = \frac{L_{xy} \cdot m_{J/\psi}^{PDG}}{|\vec{p_T}|}$$

where L_{xy} is displacement of J/ψ decay vertex from primary vertex

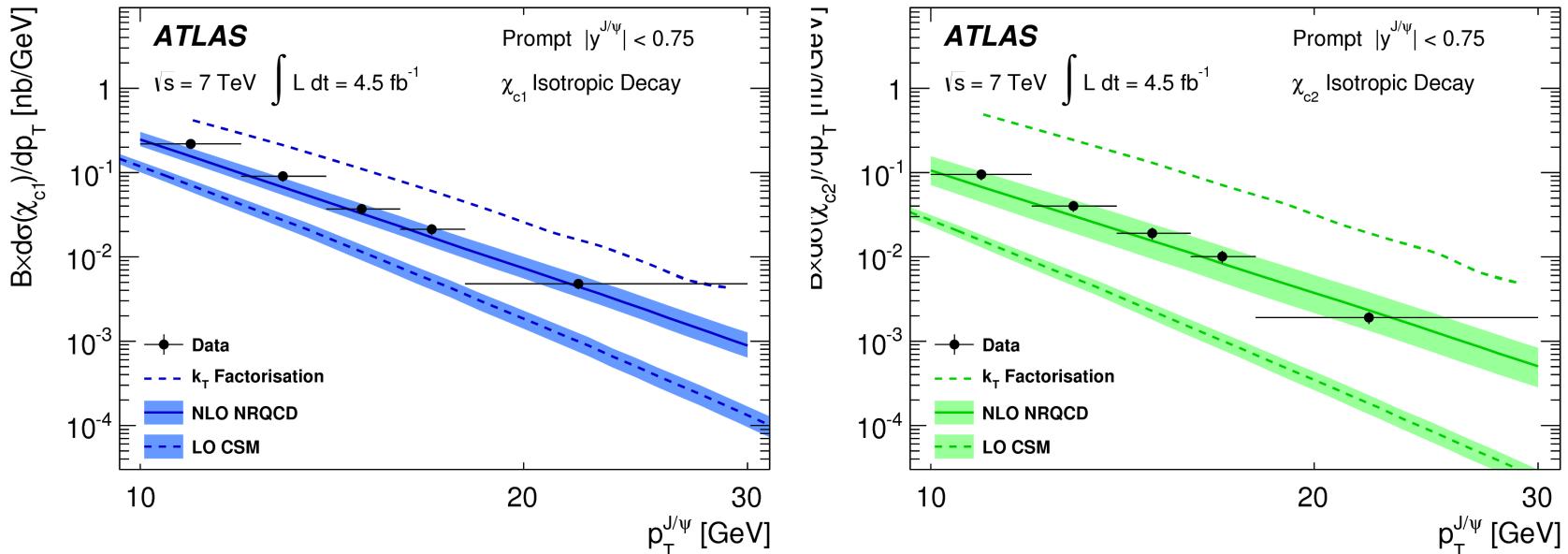


[arXiv:1404.7035](https://arxiv.org/abs/1404.7035)



Prompt χ_{c1} and χ_{c2} production

[arXiv:1404.7035](https://arxiv.org/abs/1404.7035)



Differential cross sections for prompt χ_{c1} (left) and χ_{c2} (right) production as a function of $p_T^{J/\psi}$

Signal yields (N_{χ_c}) obtained from simultaneous fits, to mass and lifetime distributions, used to calculate the cross section

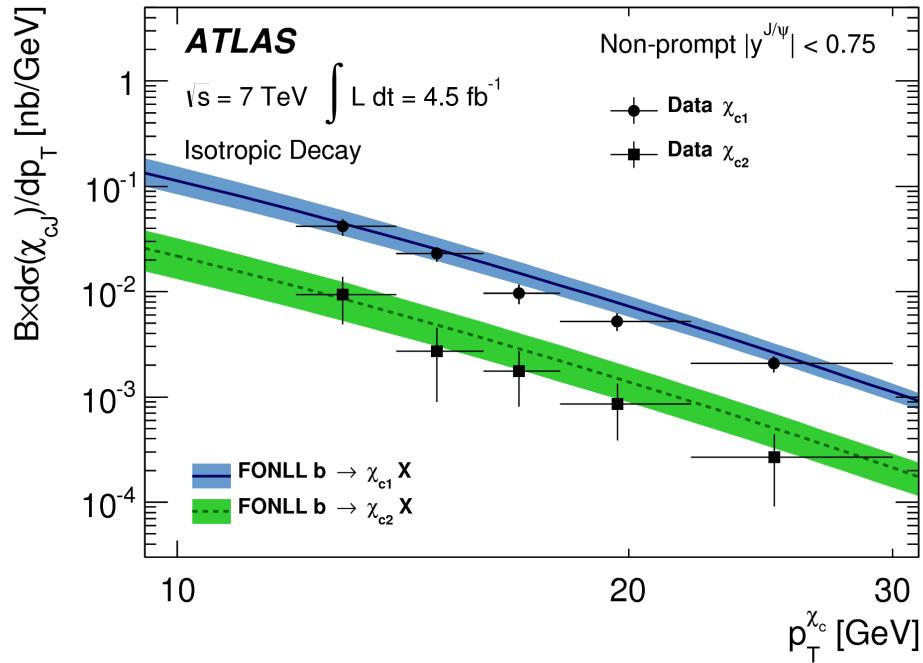
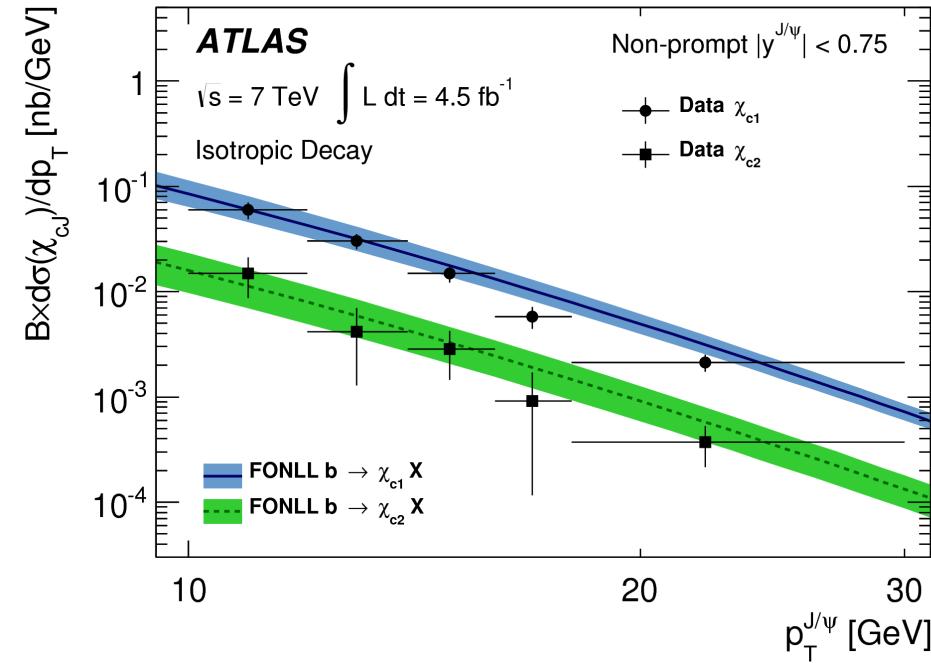
$$B \times \frac{d\sigma(\chi_c)}{dp_T} = \frac{N_{\chi_c}}{\mathcal{L} \Delta p_T}$$

Where the factor B denotes the product of branching fractions: $B=B(\chi_c \rightarrow J/\psi \gamma) \cdot B(J/\psi \rightarrow \mu^+ \mu^-)$

- NLO NRQCD prediction in good agreement with data
- k_T factorisation predicts that majority of J/ψ produced from χ_c at high p_T . Overestimate w.r.t data
- LO CSM significantly lower cross section than data. Higher order corrections known to be large

Non-prompt χ_{c1} and χ_{c2} production

[arXiv:1404.7035](https://arxiv.org/abs/1404.7035)

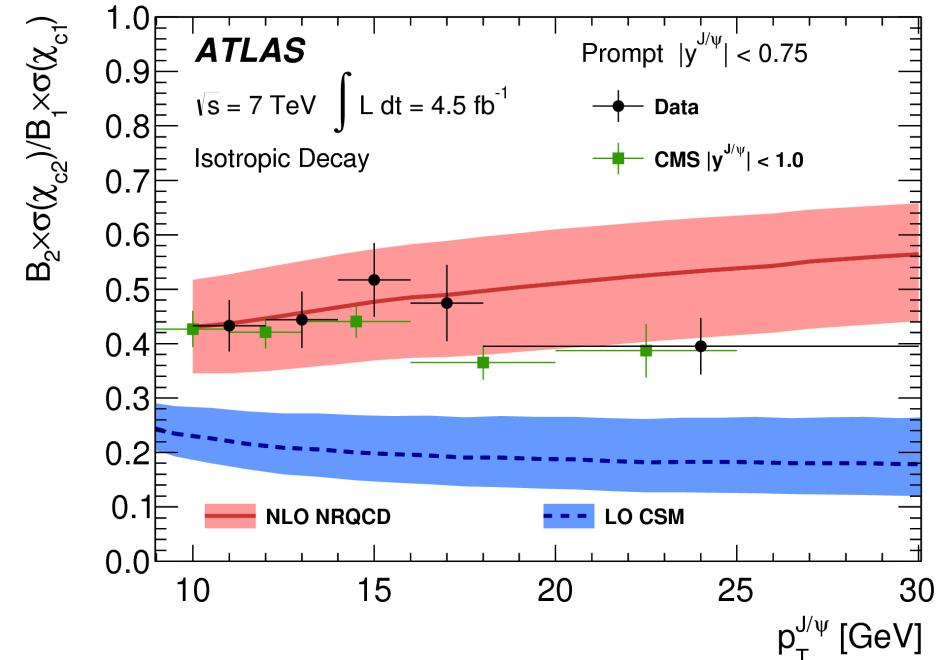


Differential cross sections for non-prompt χ_{c1} and χ_{c2} production as a function of $p_T^{J/\psi}$ (left) and $p_T^{\chi_c}$ (right)

- Polarisation of the χ_c mesons produced at the LHC is unknown. Both prompt and non-prompt measurement assumes unpolarised production.
- First measurement of non-prompt χ_c production at the LHC.
- Measurements generally well described by the fixed order next-to-leading logarithm (FONLL) prediction.

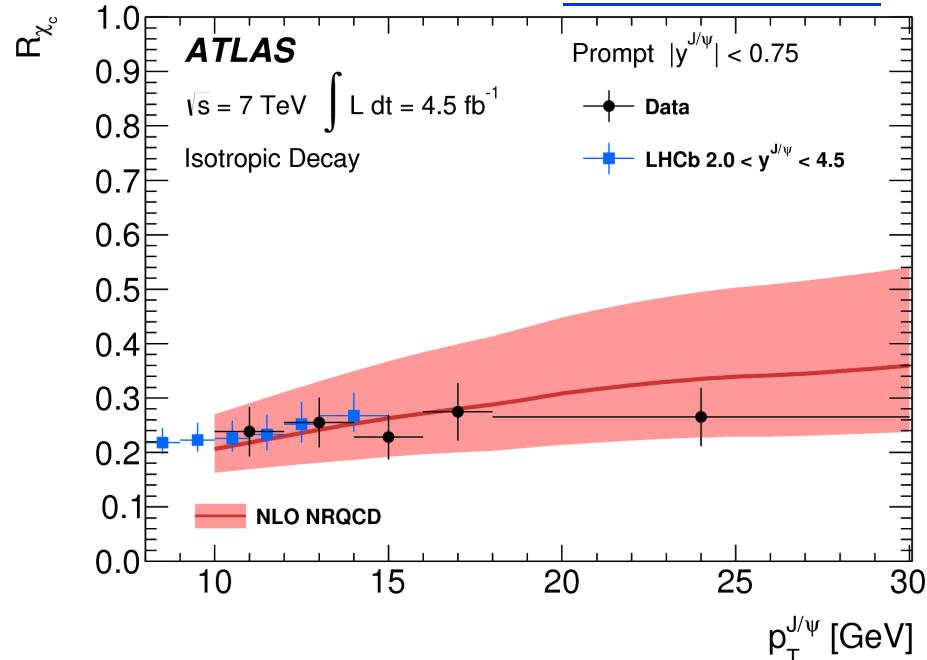
Measurement of the χ_{c1} and χ_{c2} production

[arXiv:1404.7035](https://arxiv.org/abs/1404.7035)



The production cross section of prompt χ_{c2} relative to prompt χ_{c1} measured as a function of $p_T^{J/\psi}$

- Prompt cross section ratio is a long standing puzzle. Much more χ_{c1} than χ_{c2} !
- NLO NRQCD in general agreement with data (due to NLO correction).
- LO CSM underestimates the data – suggest that CO or NLO terms important.



The fraction of prompt J/ ψ produced in χ_c decays as a function of $p_T^{J/\psi}$.

- Prompt χ_c cross section divided by existing ATLAS prompt J/ ψ result [arXiv:1106.5325]
- Around 25% of prompt J/ ψ are produced in χ_c feed-down.
- NLO NRQCD describes this fraction well.

Branching fraction $B(B^\pm \rightarrow \chi_{c1} K^\pm)$

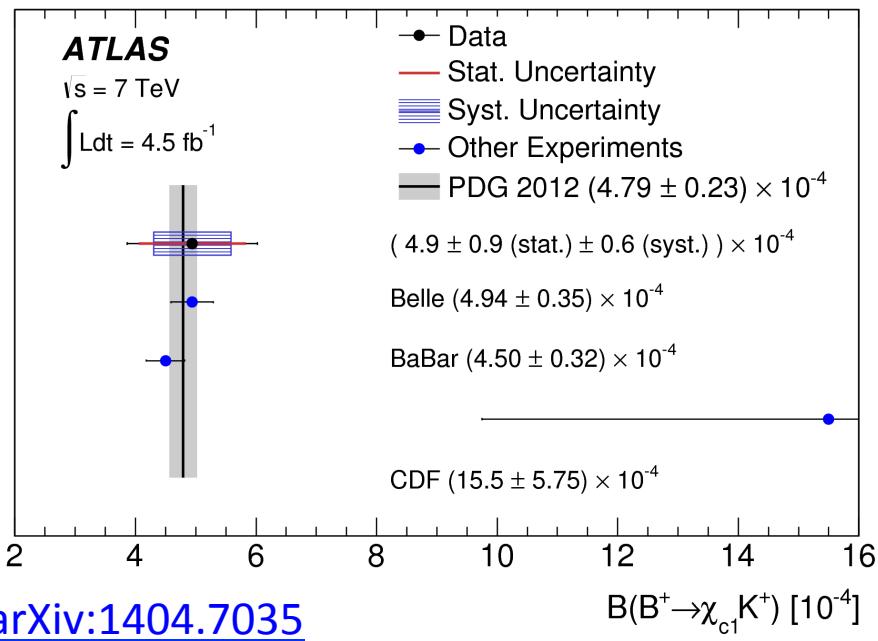
Signal: $B^\pm \rightarrow \chi_{c1} K^\pm \rightarrow \mu^+ \mu^- K^\pm$

Reference: $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$

NB. photon

$$\mathcal{B}(B^\pm \rightarrow \chi_{c1} K^\pm) = \mathcal{A} \cdot \frac{N_{\chi_{c1}}^{\mathcal{B}}}{N_{J/\psi}^{\mathcal{B}}} \cdot \frac{\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)}{\mathcal{B}(B^\pm \rightarrow J/\psi \gamma)}$$

Where A_B is a factor to correct for the different detector acceptances of the two decays,
 $N_{\chi_{c1}}^{\mathcal{B}}$ and $N_{J/\psi}^{\mathcal{B}}$ are the corrected yields for the signal and reference decay channels,
 Current world average values are used for the branching fractions.



$$B(B^\pm \rightarrow \chi_{c1} K^\pm) = (4.8 \pm 0.6 \text{ (stat.)} \pm 0.6 \text{ (syst.)}) \times 10^{-4}$$

Good agreement with current world average value of $(4.79 \pm 0.23) \times 10^{-4}$

Same event selection criteria as the χ_c measurement.

Cross-section measurement of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

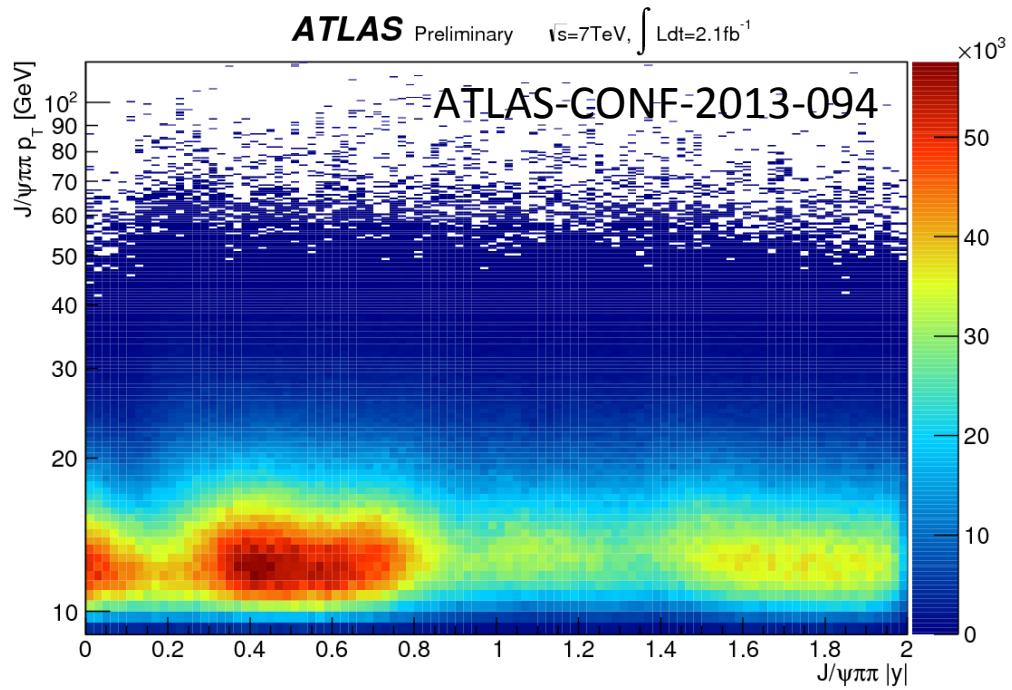
- Non-prompt J/ψ and $\psi(2S)$ production arises from weak decays of b -hadrons.
- Prompt J/ψ production can occur through either direct QCD production of J/ψ or the production of excited P-wave χ_{cJ} states that subsequently decay into $J/\psi + X$ final states.
- Prompt $\psi(2S)$ ONLY proceeds through direct QCD production.

To provide an accurate picture of charmonium production it is necessary to study prompt and non-prompt production of $\psi(2S)$ as well as χ_{cJ} (nP) states and J/ψ .

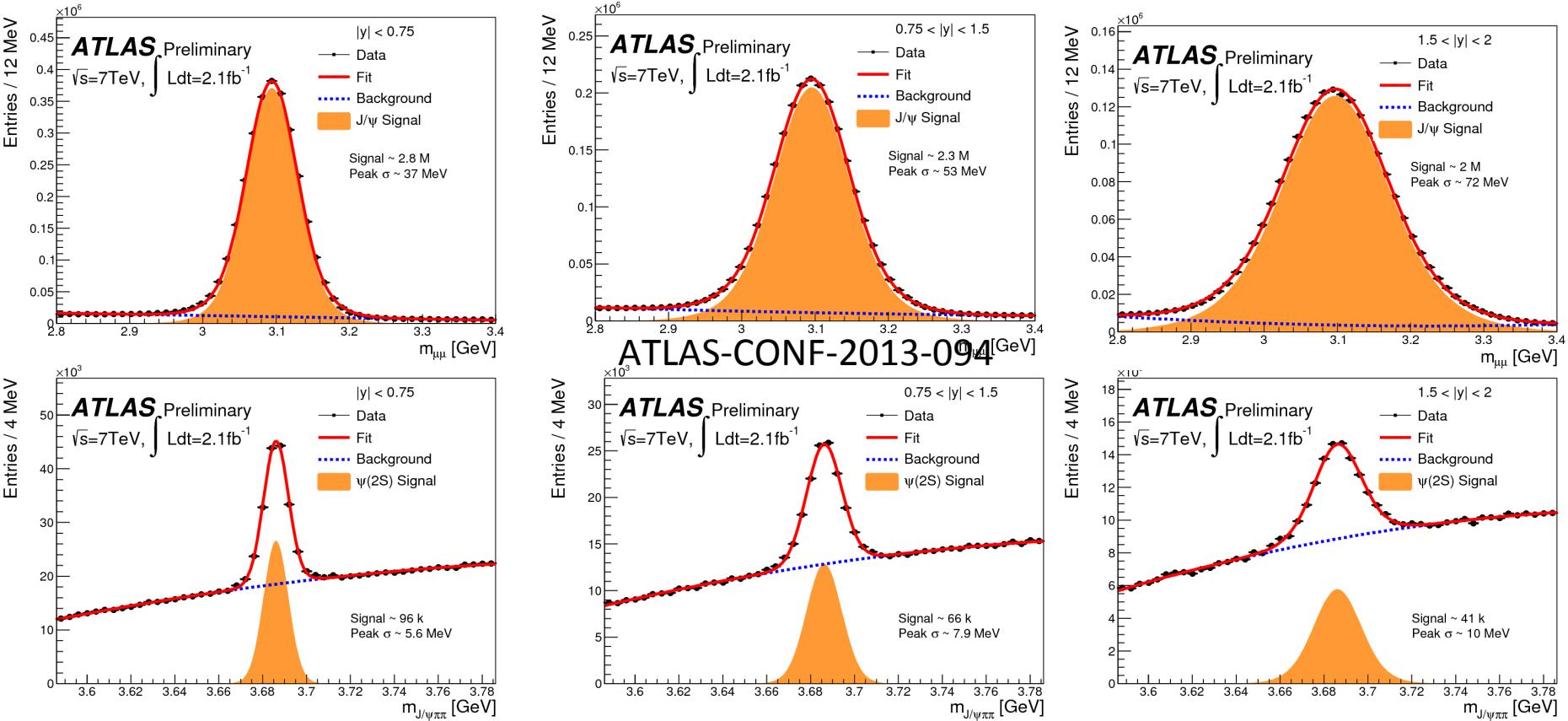
Cross-section measurement

- 2.1 fb^{-1} of pp collision data at 7TeV
- $\psi(2S) p_T = 10 - 100 \text{ GeV}$
- Three $\psi(2S)$ rapidity ranges :
 $|y| < 0.75, 0.75 < |y| < 1.5, 1.5 < |y| < 2.0$

Distribution of $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ candidates.
Before corrections.



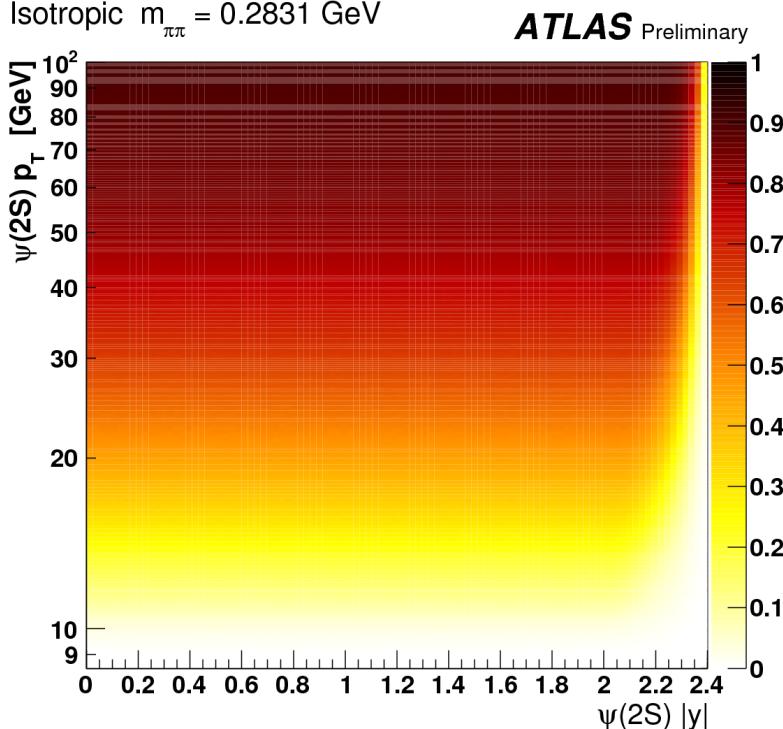
$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$



- Uncorrected yields and the invariant mass resolutions for the di-muon (top) and $J/\psi \pi^+\pi^-$ system (bottom) in the three rapidity ranges of the measurement.
- The data distributions are fitted with a combination of two Gaussians (for the signal peak) and second order polynomials (for backgrounds).

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

Isotropic $m_{\pi\pi} = 0.2831$ GeV



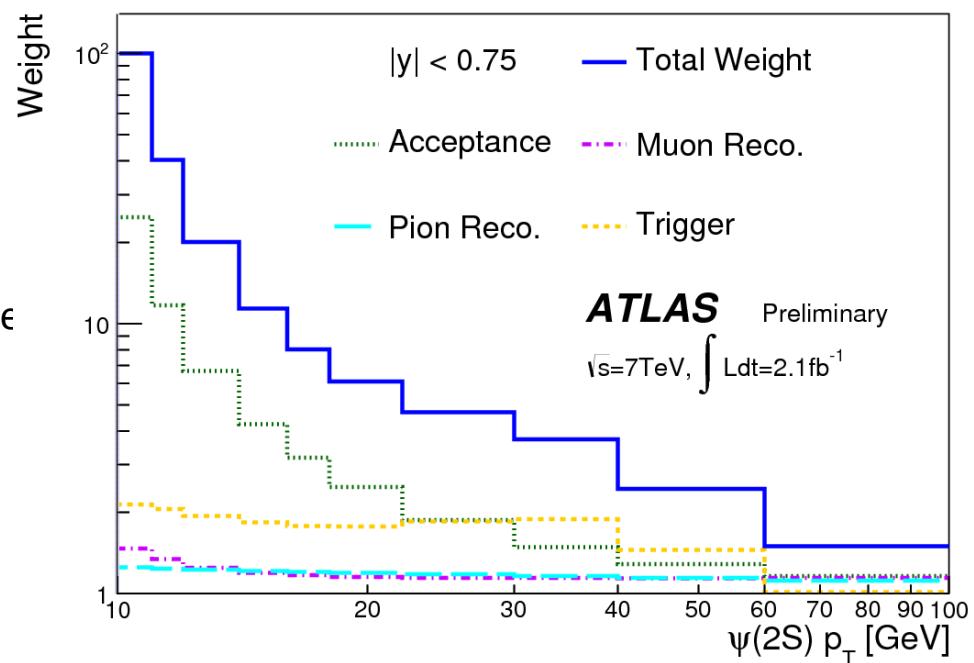
Each $\Psi(2S)$ candidate was weighted with the inverse product of:

- Acceptance
- Muon reconstruction efficiency
- Pion reconstruction efficiency
- Trigger efficiency

Spin-alignment:

- The spin-alignment state of the $\Psi(2S)$ is directly transferred to the J/ψ . Acceptance therefore depends on the spin-alignment of the $\Psi(2S)$.
- For the central results, the $\Psi(2S)$ is assumed to be isotropic.

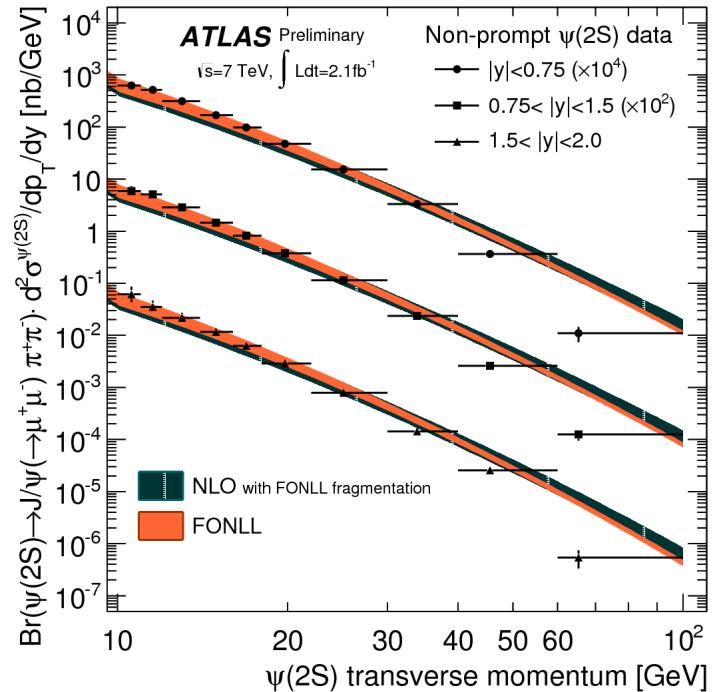
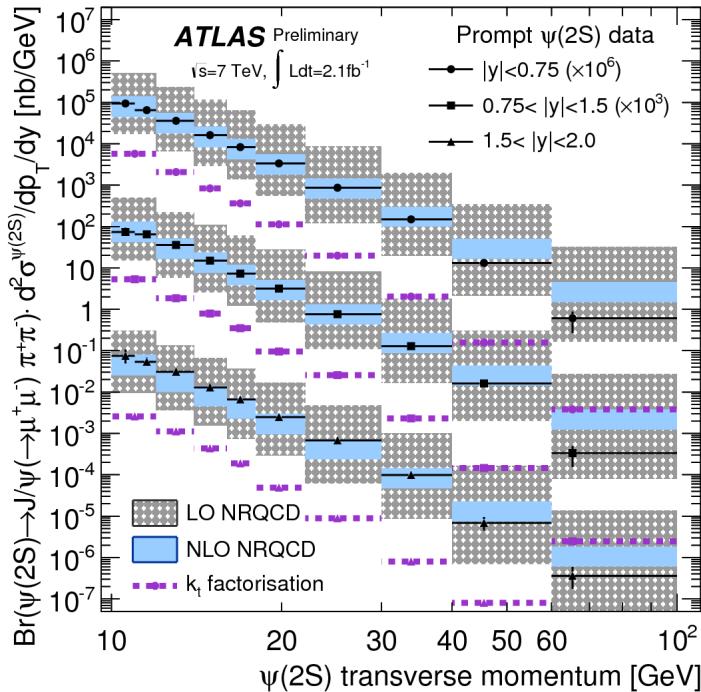
ATLAS-CONF-2013-094



Cross-section measurement of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

ATLAS-CONF-2013-094

Measured differential cross-sections for prompt and non-prompt $\psi(2S)$ production.



- LO predictions show agreement with data, albeit with large uncertainties.
- NLO NRQCD predictions describe data reasonably well. Potential to improve at high p_T with CO matrix element re-tune.
- k_T factorisation model clearly undershoots data.

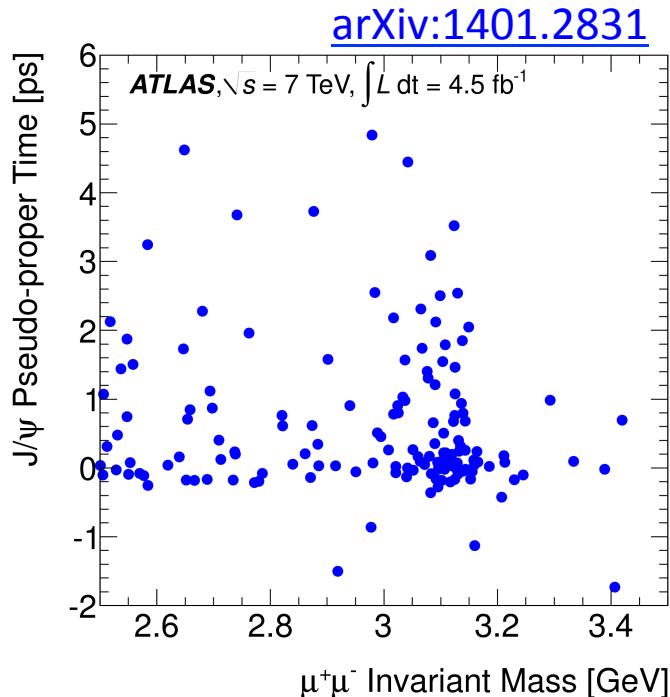
- Both NLO and FONLL calculations describe the data over a wide range of p_T .
- However both overestimate at high p_T and underestimate at low p_T .
- Important testing ground for different QCD approaches.

Associated W boson + prompt J/ψ production

- Offers new tests of QCD at the perturbative/ non-perturbative boundary.
- The relative contributions of CS and CO processes are expected to differ in $W^\pm + J/\psi$ and inclusive J/ψ .
- Sensitive to multiple parton interactions in the colliding proton.

Single parton scattering (SPS): the W^\pm and J/ψ originate from the same parton interaction.

Double parton scattering (DPS): the W^\pm and J/ψ originate from two different parton interactions in the same p-p collision.



Two-dimensional plot of $W^\pm + J/\psi$ candidates in pseudo-proper time versus $\mu^+\mu^-$ invariant mass.

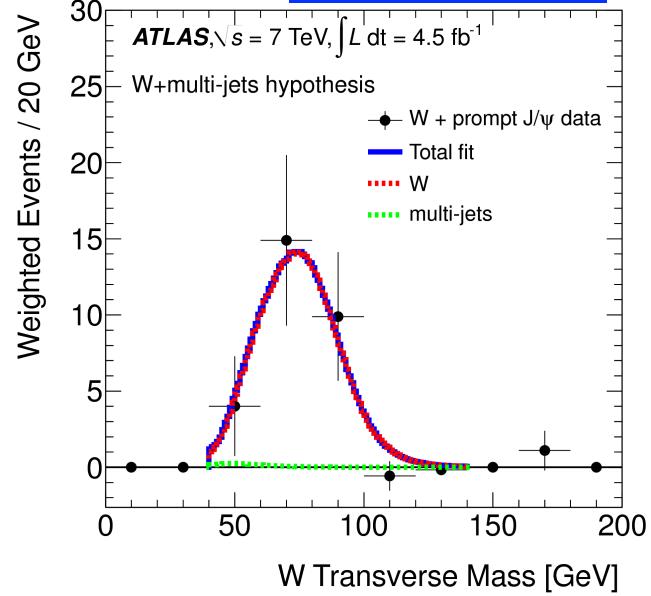
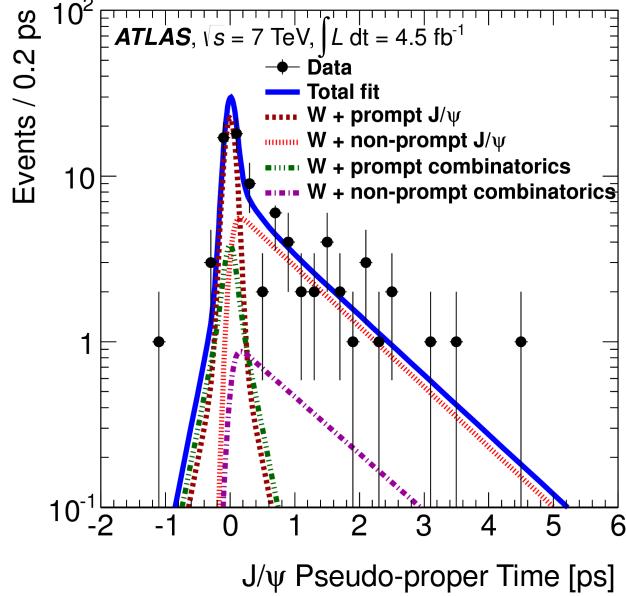
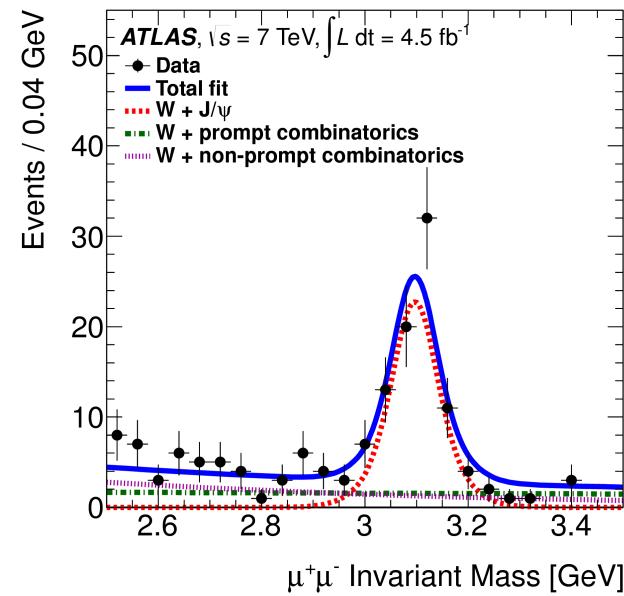
Many candidates fall near the J/ψ mass of 3.097 GeV and pseudo-proper time near 0 ps, as expected from prompt J/ψ production.

Background contributions assessed from:
Pileup, Z+jets, top pair production, $W+b$ -quark,
 $B_c \rightarrow J/\psi + \mu\nu + X$, heavy quark jets.

Associated W boson + prompt J/ ψ production

Unbinned maximum likelihood fit to J/ ψ mass and lifetime distributions used to extract prompt component from data.

[arXiv:1401.2831](https://arxiv.org/abs/1401.2831)



Yields from two-dimensional fit

Process	Barrel	Endcap	Total
Prompt J/ ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5} (*)$
Non-prompt J/ ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
<i>p</i> -value	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

(*) of which 1.8 ± 0.2 originate from pileup

DIS2014: 28 April- 2 May

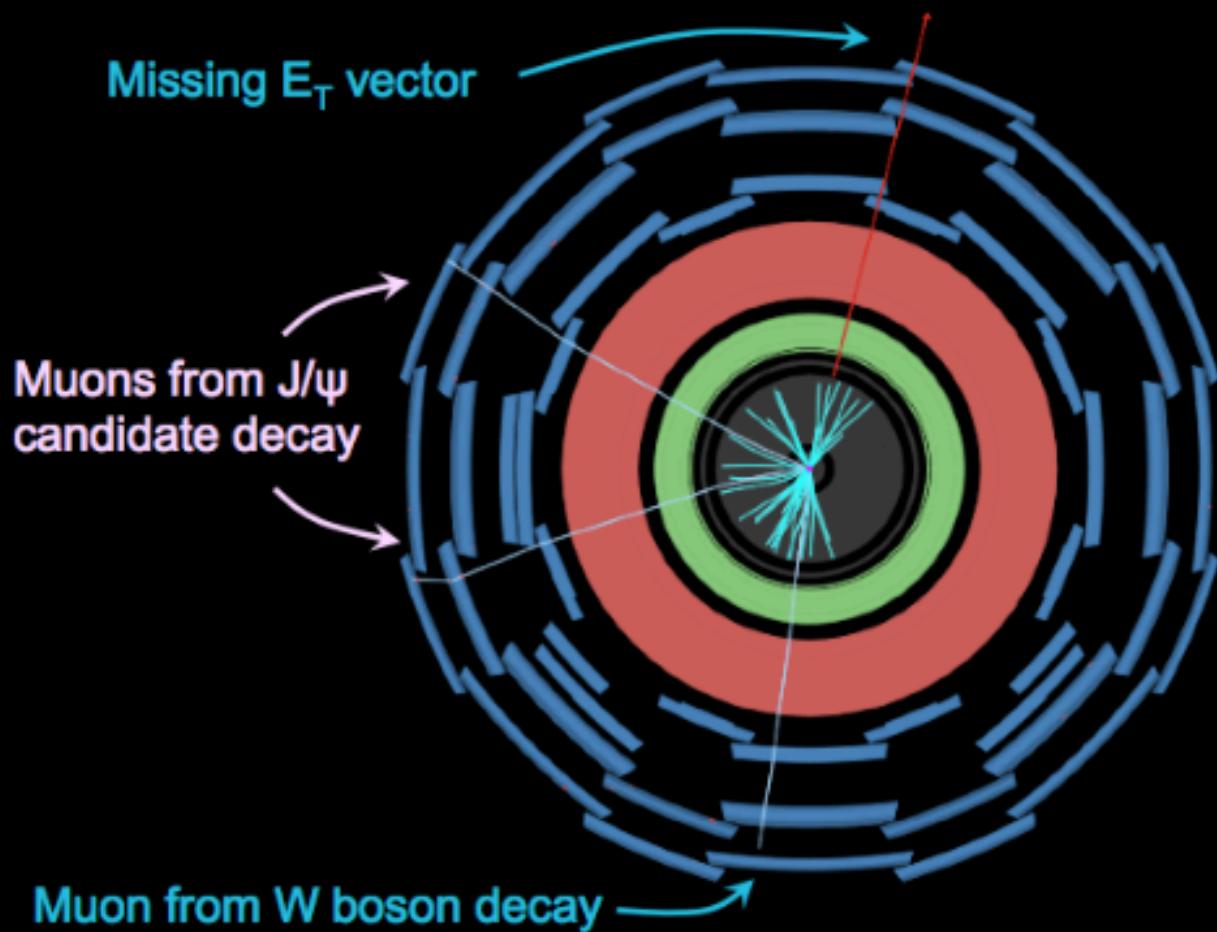
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A yield of $27.4^{+7.5}_{-6.5}$
 $W^\pm + \text{Prompt J}/\psi$ events is observed,
with a statistical significance of 5.1σ .



W + prompt J/ψ candidate event



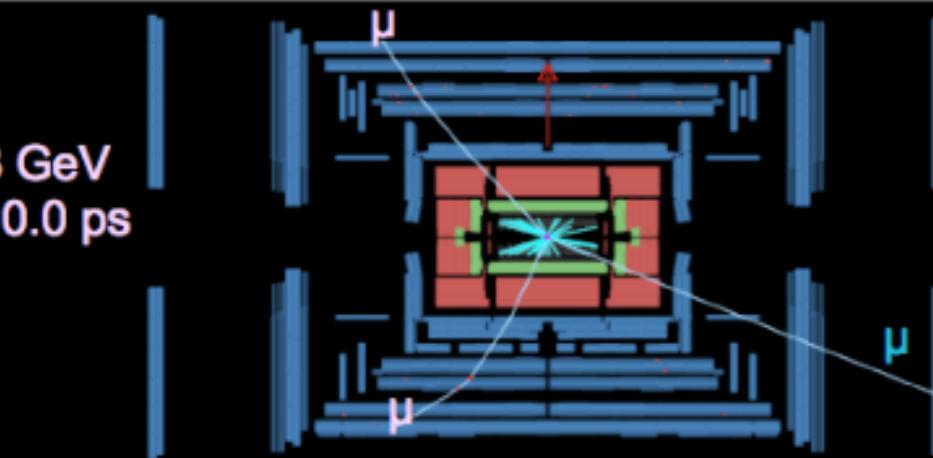
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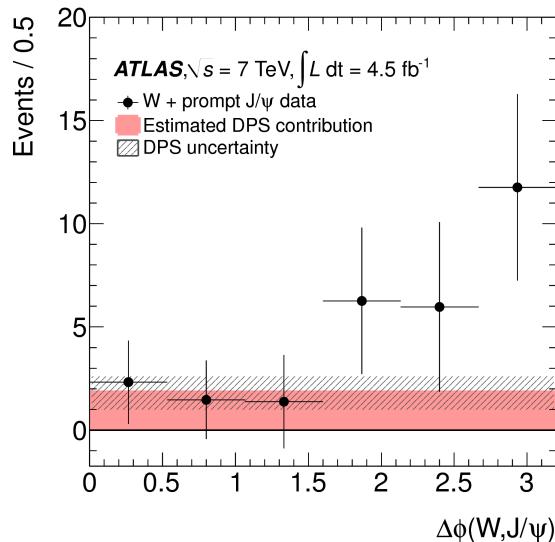
J/ψ candidate $p_T = 9.3$ GeV
Pseudo proper time = 0.0 ps

W boson $p_T = 39$ GeV

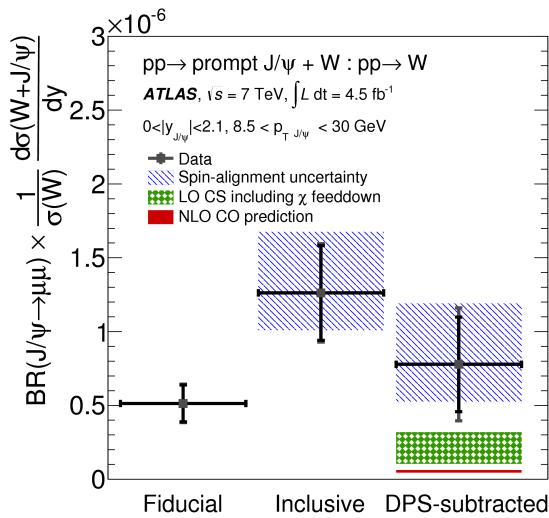


Associated W boson + prompt J/ ψ production

The Probability of an additional distinguishable process (J/ ψ production) for a collision in which a hard process occurs (W^\pm production), is taken from $W^\pm \rightarrow \ell v + 2$ jet measurement [arXiv:1301.6872].
 The total number of DPS events in the $W^\pm +$ prompt J/ ψ signal yield is estimated to be $10.8 +/- 4.2$.

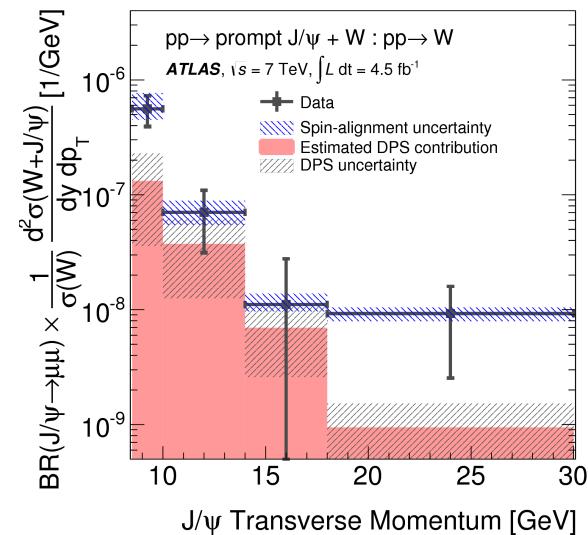


Flat DPS contribution expected since independent interactions.
 CO + CS models both predict SPS contribution peak at $\Delta\phi = \pi$



The $W^\pm +$ prompt J/ ψ : W production differential cross-section ratio

- in the J/ ψ fiducial region,
- after correction for J/ ψ acceptance,
- after subtraction of the DPS.



The inclusive (SPS+DPS) cross-section ratio.

[arXiv:1401.2831](https://arxiv.org/abs/1401.2831)

- The LO CS mechanism makes the dominant contribution to the single parton scattering cross section.
- Data suggests single parton scattering is the dominant contribution to the total rate at low J/ ψ p_T

Summary

Measurement of the χ_{c1} and χ_{c2} production

- Wide range of measurements made, some for the first time at the LHC.
- Prompt and non-prompt cross section measurements for χ_{c1} and χ_{c2}
- The fraction of prompt J/ ψ produced in χ_c decays.
- Branching fraction $B(B^\pm \rightarrow \chi_{c1} K^\pm)$

Cross-section measurement of $\Psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

- Prompt and non-prompt production cross section measurements.
- Expanded on the precision and reach of previous measurements.
- Provides useful input to theoretical calculations, since $\Psi(2S)$ is the only charmonium state without any significant feed-down contributions to complicate the theoretical framework.

Associated W boson + prompt J/ ψ production

- The first observation of W^\pm + prompt J/ ψ events with a 5.1σ significance.
- Novel double parton scattering study environment: Further ongoing studies at 8 TeV in W/Z+onia and in double quarkonium production.