Heavy flavour production at the ATLAS experiment

Onia and open flavour hadrons

Beauty 2014

14-18 July, Edinburgh, UK

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on behalf of the

ATLAS Collaboration

Overview of ATLAS results on heavy-flavour production

Via observation of charmonium and bottomonium

- **χ_{c1}, χ_{c2}, B—> χ_c + X** arXiv:1404.7035, Accepted by JHEP NEW
- **ψ', B—> ψ' + X** ATLAS-CONF-2013-094 NEW *(in this presentation)*
- W + J/ψ JHEP 04 (2014) 172 NEW *(see talk by M. Watson)*
- Υ(nS) Phys. Rev. D 87 (2013) 052004
- J/ψ, B—> J/ψ + X Nucl. Phys. B 850 (2011) 387-344

Via observation of b-hadrons and jets

- V+b-jets arXiv:1404.7042, JHEP 06 (2013) 084 NEW
- B^+—> J/ψ K^+ JHEP 10 (2013) 042
- B—> μ + X Phys. Lett. B 707 (2012) 438-458
- B—> D^{*+} μ^- + X Nucl. Phys. B864 (2012) 341-381
- b-jets Eur.Phys.J.C 71 (2011) 1846

NEW

see talk by R. Henderson (Spectroscopy of Onia and hadrons)

Observation of an **excited B_c meson state** with the ATLAS detector

arXiv:1407.1032

Heavy-flavour production studies at the LHC

Motivation

- Chance to test pertubative QCD calculations for quarkonium and b-production at a new energy regime, higher p_T and wider rapidity range than before

Prompt quarkonium (cc, bb) production

- Of great theoretical interest, production mechanisms not clearly understood

  - Cross-section and spin-alignment measurements are needed to test existing models (Colour-Singlet Model, Colour-Octet Model / NRQCD, Colour-Evaporation Model, k_T factorization)

  - Results from Tevatron experiments not conclusive

Open heavy-quark pair (cc, bb) production

- Put NLO QCD predictions to the test (MC@NLO, POWHEG, FONLL)

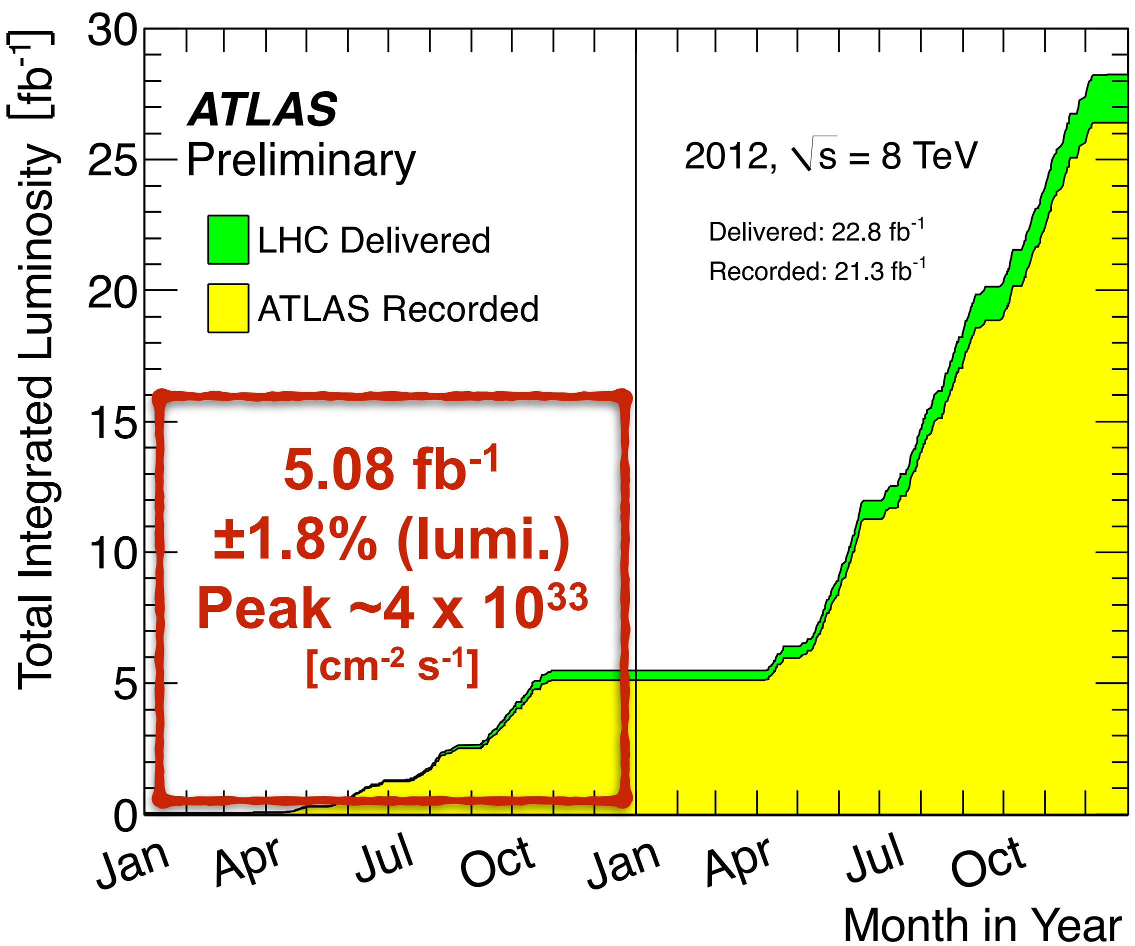
  - Large theoretical uncertainties due to factorisation/renormalisation scales, mainly

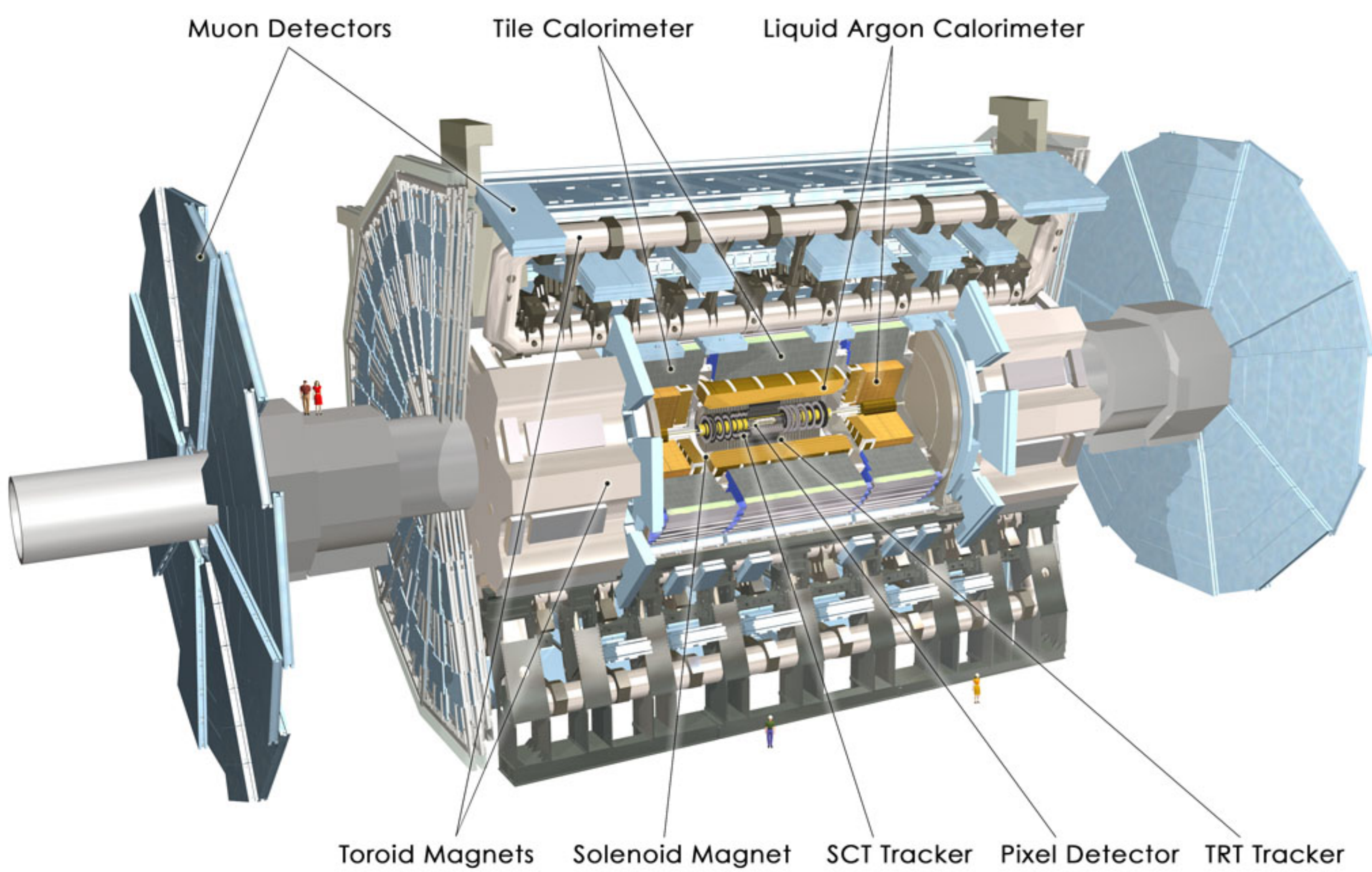
  - Experimental measurements can achieve better precision

- Prerequisite to searches for rare processes where bb production is a background ($B \to \mu^+\mu^-$, $H \to bb$)

The ATLAS detector at the LHC

- General-purpose detector designed for p-p (and Pb-Pb) collisions at the LHC
- Optimized for high-p_T discovery of physics up to 10^{34} $cm^{-2}s^{-1}$ of instantaneous luminosity
- Acceptance in pseudo-rapidity (η) up to 2.5 for inner tracker, up to 2.7 for muon spectrometer, up to 4.9 for the calorimeter system
- Recorded 26 fb^{-1} of p-p collision data at 7 & 8 TeV (also p-Pb, Pb-Pb)



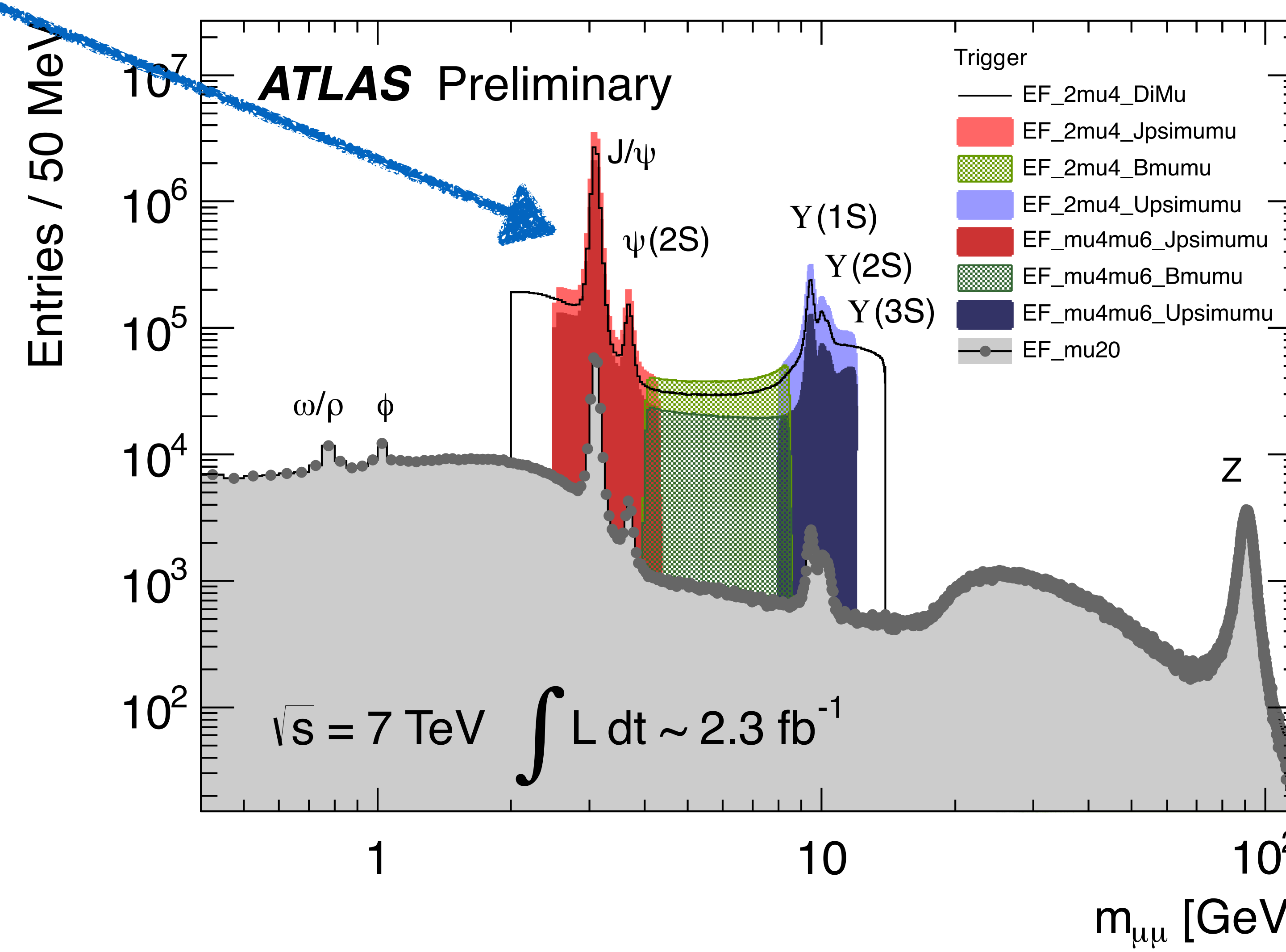


B-Physics strategy at ATLAS

B-hadron decays

- Exploit the ability of the ATLAS muon spectrometer to reconstruct muons with good efficiency
- Single-muon triggers were effective for the low luminosity period in 2010
- During 2011-2012 dimuon triggers become effective, allowing studies of:

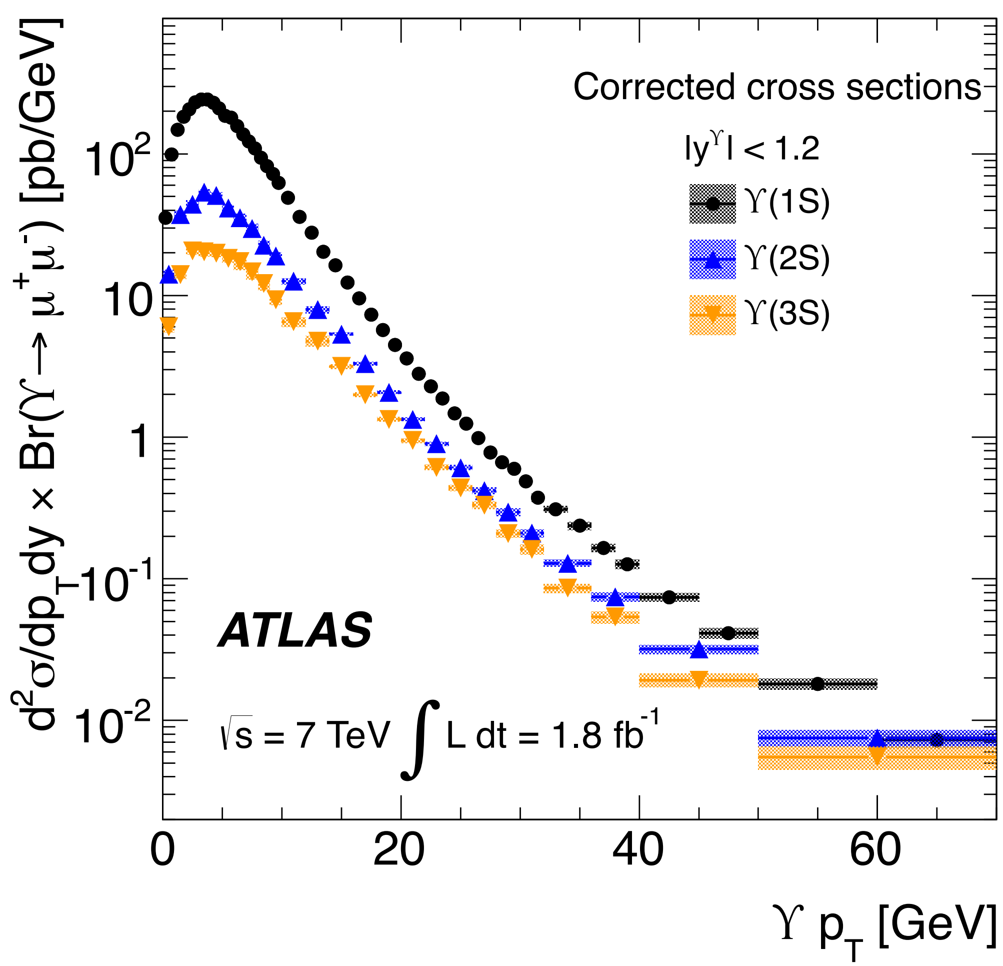
  - prompt quarkonia production
  - B-production in $B \to J/\psi\ X$ decays
  - rare and very rare decays ($B \to \mu^+\mu^- X$, $B \to \mu^+\mu^-$)

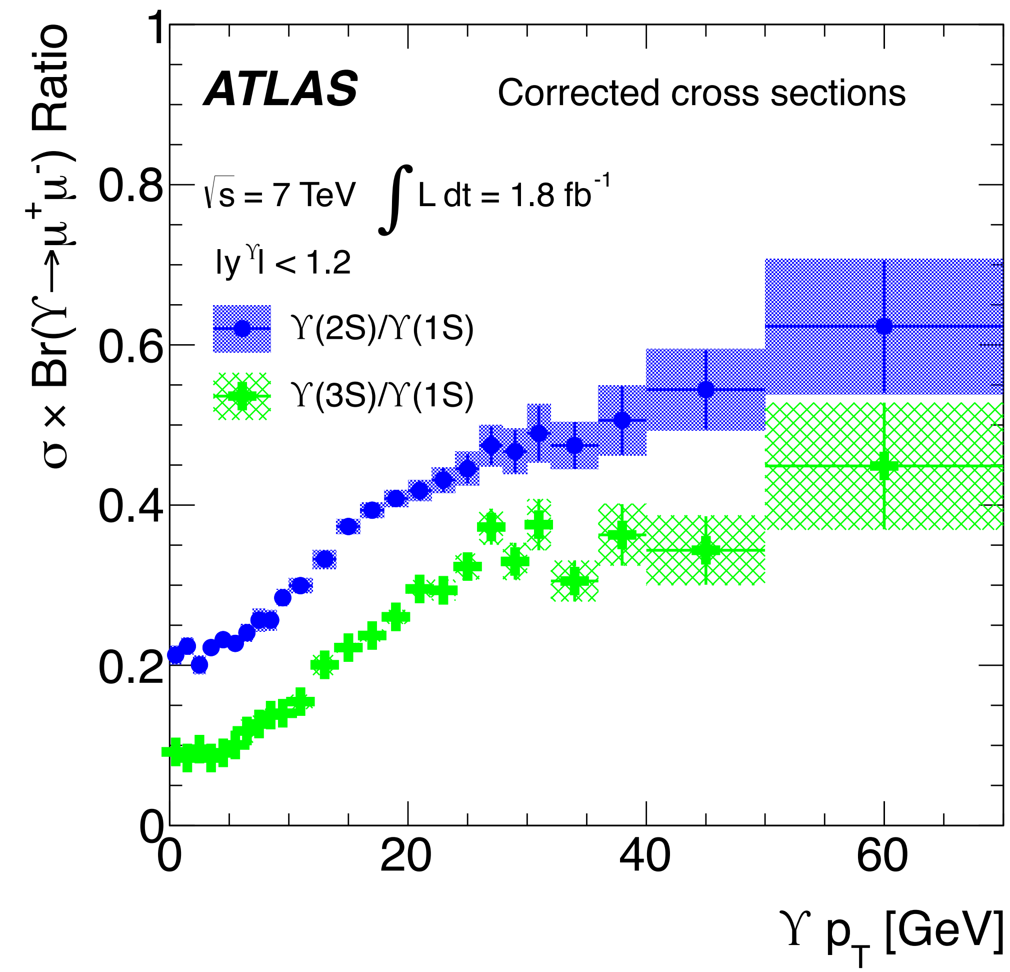


Quarkonium production… previously by ATLAS

Results for bottomonium states

- Complete study of inclusive production of Υ(1S), Υ(2S), Υ(3S) Phys. Rev. D 87 (2013) 052004



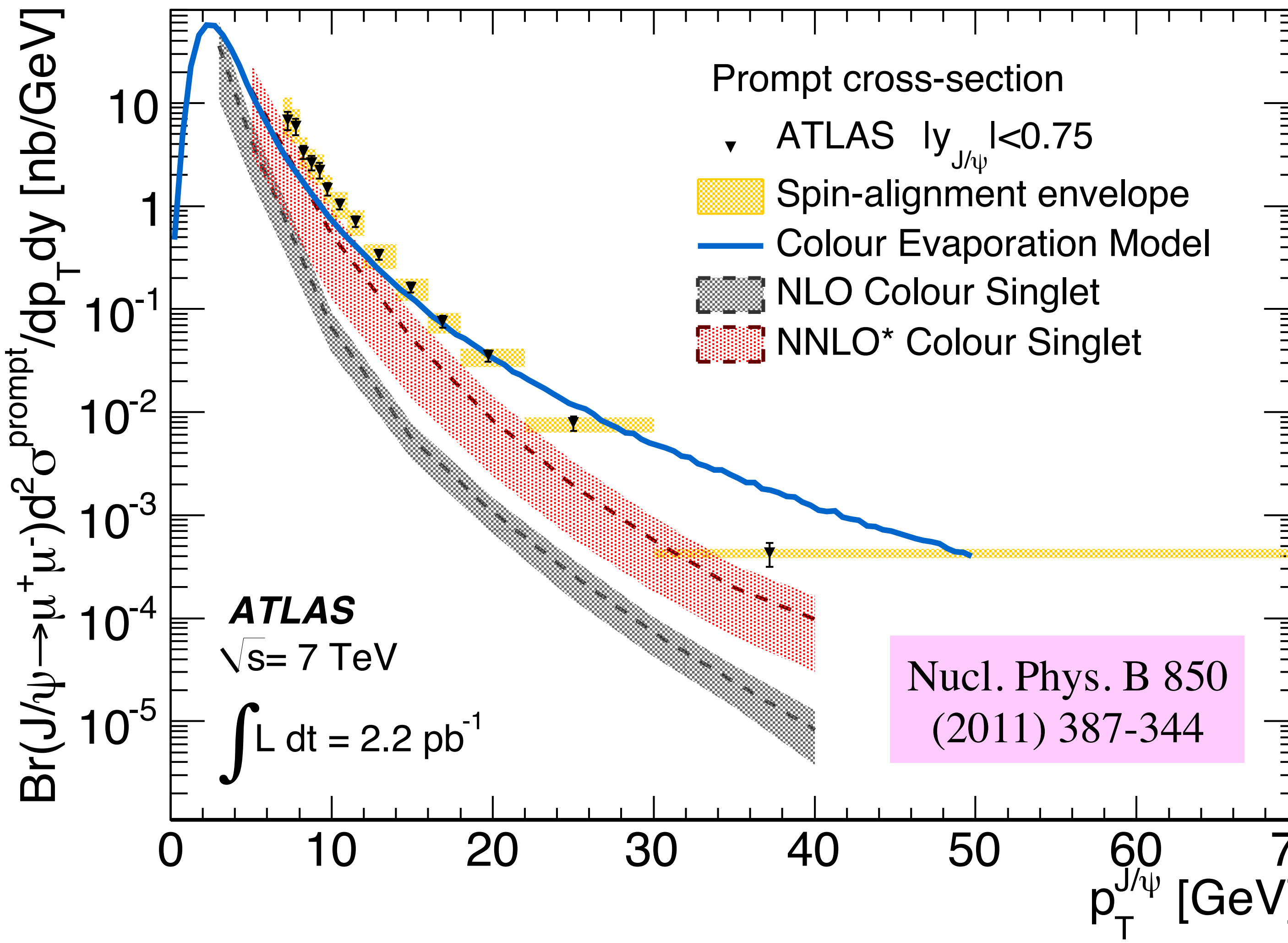


- Cross-section vs p_T in two rapidity regions ($|y|<1.2$ and $1.2<|y|<2$)
- Measurements of the relative production (2S/1S and 3S/1S)

Quarkonium production… previously by ATLAS

Results for J/ψ production

Sizeable contributions from higher charmonium states ("feed-down") complicate the theoretical interpretation



- Need estimation of contribution of the χ_c production to the J/ψ prompt cross-section
- Need another test: ψ' production is a good probe because it is feed-down free (just below the open charm threshold, so higher charmonium states decay to DD instead)

- *The new ATLAS results on χ_c and ψ' production complement the measurement of prompt J/ψ cross-section*

Analysis procedure for quarkonium production

At the LHC, charmonium resonances (J/ψ, ψ′, χ_c) can be produced:

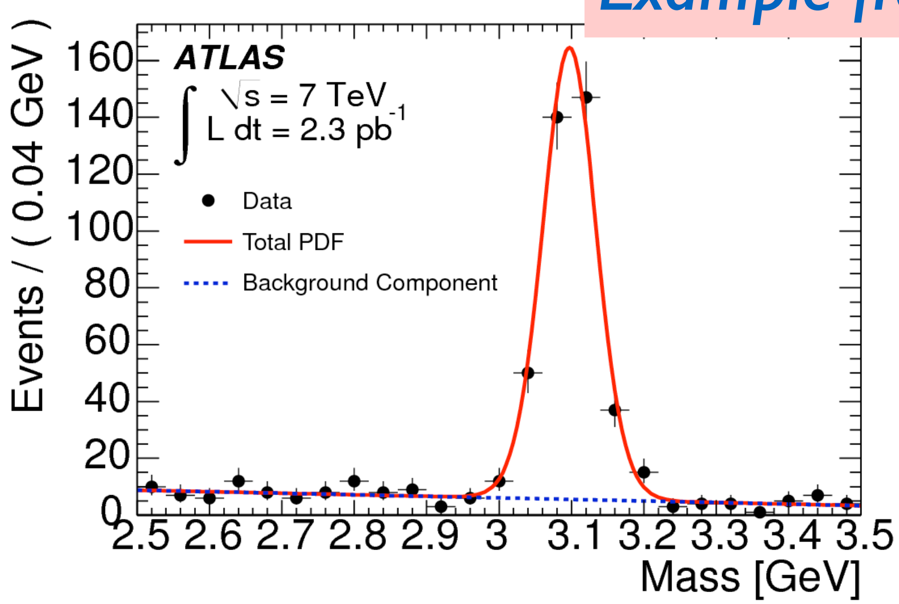
- via direct QCD mechanisms in pp collisions
- via decays of higher charmonium states

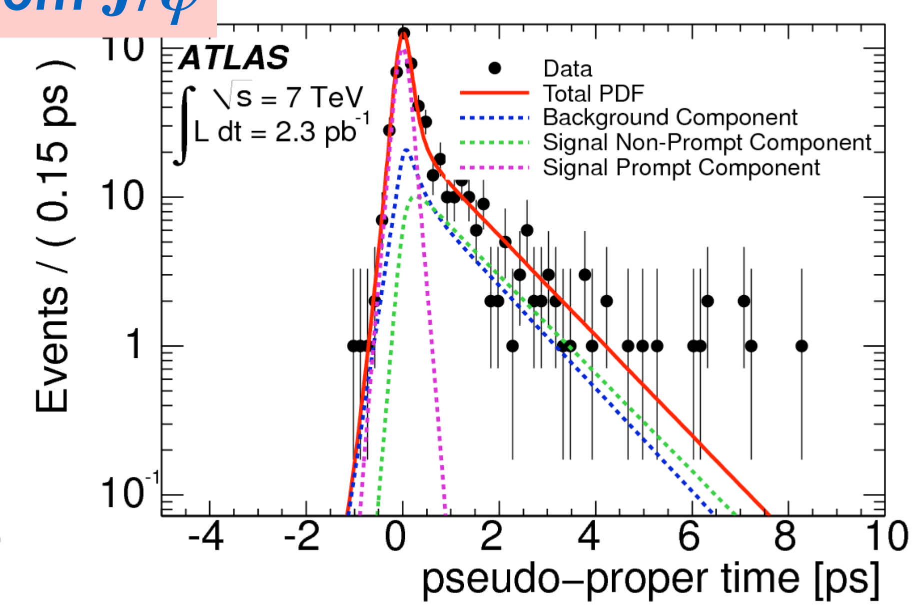
} *'prompt' production*

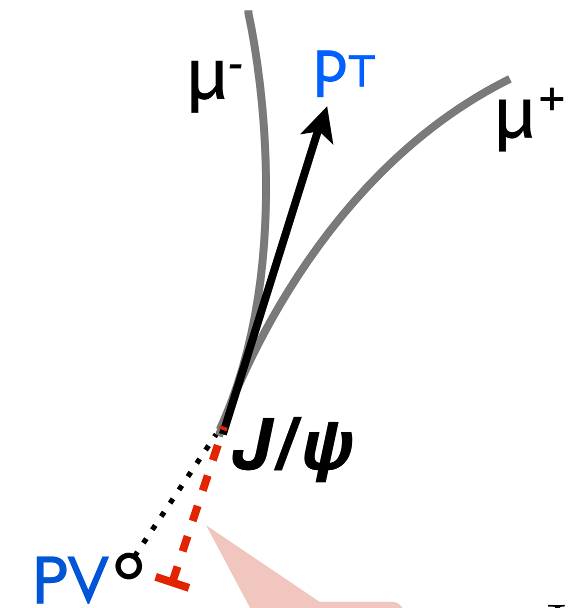
- via weak interactions in decays of b-hadrons *'non-prompt' production*

- Components are distinguished by exploiting the displaced vertex of charmonium originating from a b-hadron decay —> 2D ML fit on mass - proper time

Example from J/ψ







$$\tau = \frac{L_{xy} \cdot m^{J/\psi}}{p_T}$$

- Two measurements in one go: $\sigma\left(pp \to J/\psi + X\right)_{prompt}$

$\sigma\left(pp \to B + X' \to J/\psi + X''\right)$ **=> indirect b-production measurement**

Analysis procedure for quarkonium production

Cross-section calculation

Signal yield corrected for detector effects & acceptance

$$\frac{d^2\sigma(pp \to Q + X)}{dp_T dy} \cdot Br(Q \to \mu\mu) = \frac{N_{corr}^{Q\to\mu\mu}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}$$

integrated luminosity ($\mathcal{L}$) *bin interval* ($\Delta p_T \cdot \Delta y$)

Extracted from fit to data, after applying a ***weight*** to each candidate event to account for reconstruction efficiency and detector acceptance

$$w^{-1} = (\mathcal{A} \cdot \prod_i \varepsilon_i)^{-1}$$

: weight applied to each candidate in the likelihood fit

various efficiencies (trigger, muon reconstruction), estimated with data

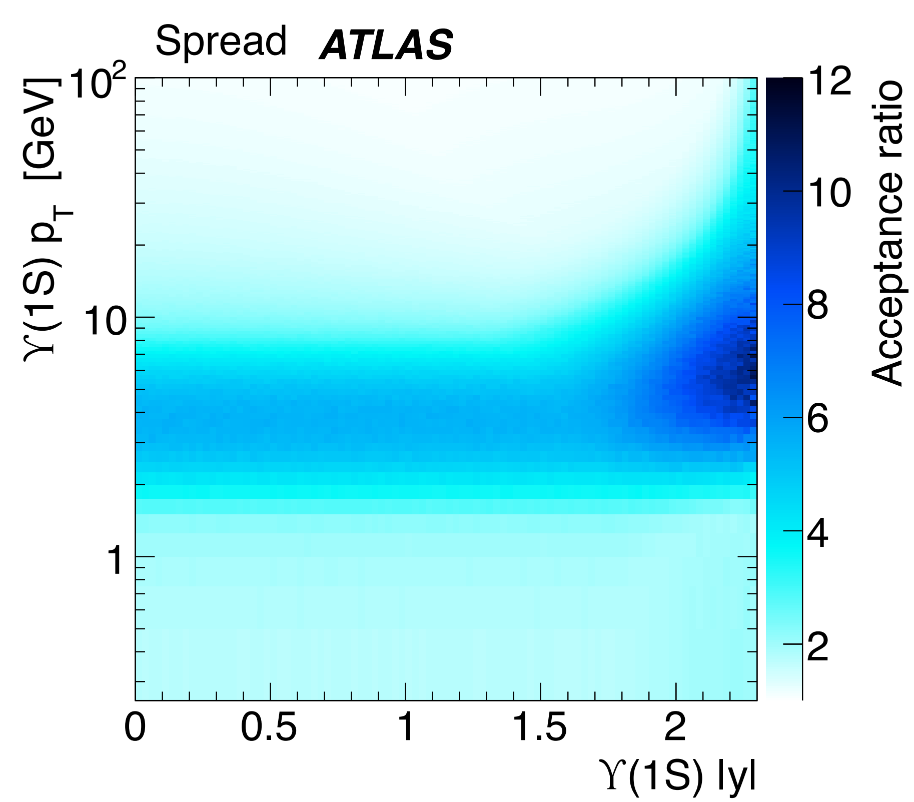
Acceptance

Depends on spin-momentum alignment which is unknown, in principle

- Use the isotropic decay scenario and consider the envelope of maximum variations in case of different polarization states

This is the largest systematic in all direct onia production studies; however, becomes small at high p_T.

Other systematics are ~10%.



Quarkonium production

New ATLAS results for higher charmonium states

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

  arXiv:1404.7035, to appear in JHEP

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

  ATLAS-CONF-2013-094

Onia production: χ_{c1}, χ_{c2}

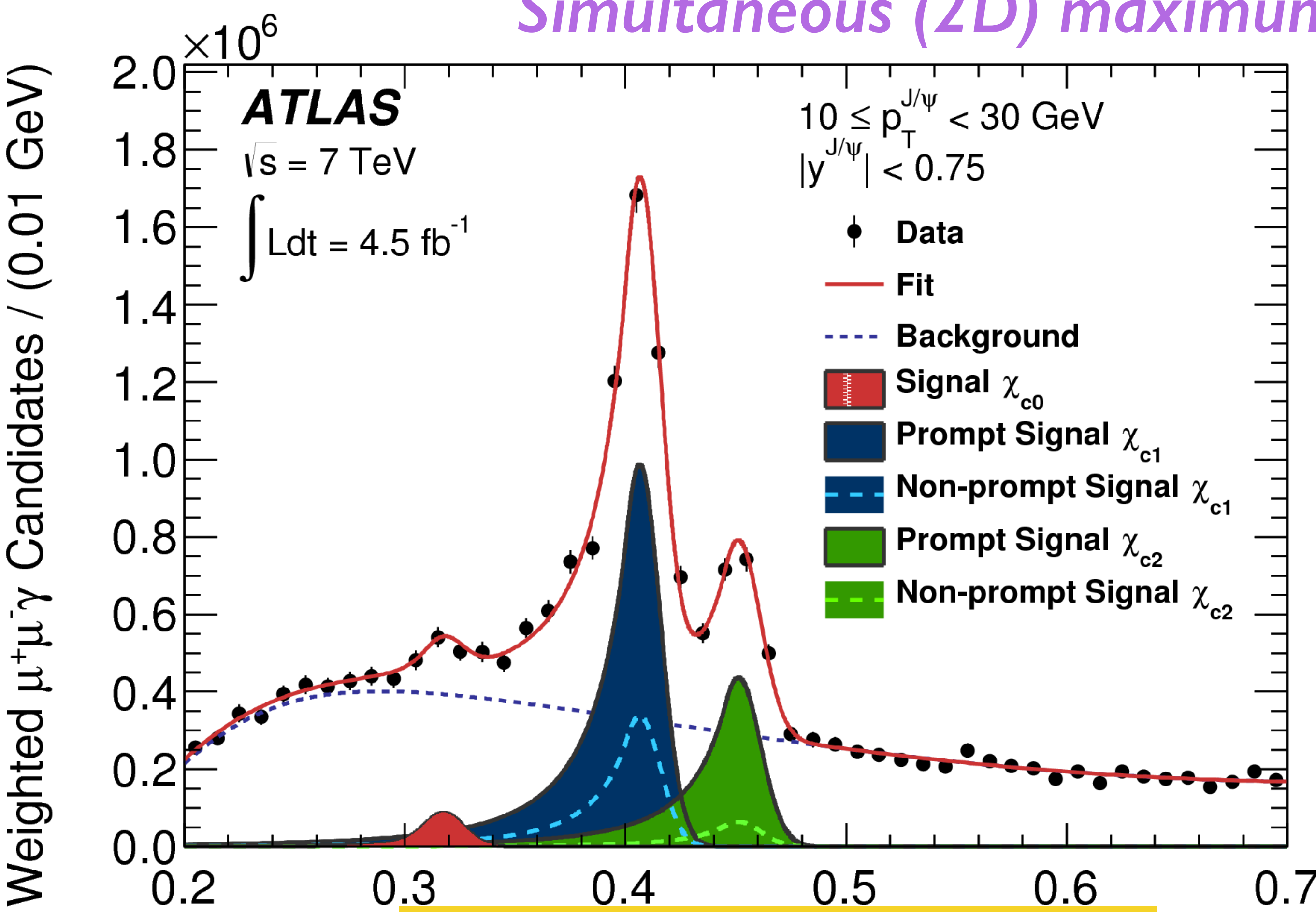
Analysis details

- Reconstructed in the decay: $\chi_{c(1,2)} \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\ \gamma\ (\rightarrow e^+e^-)$

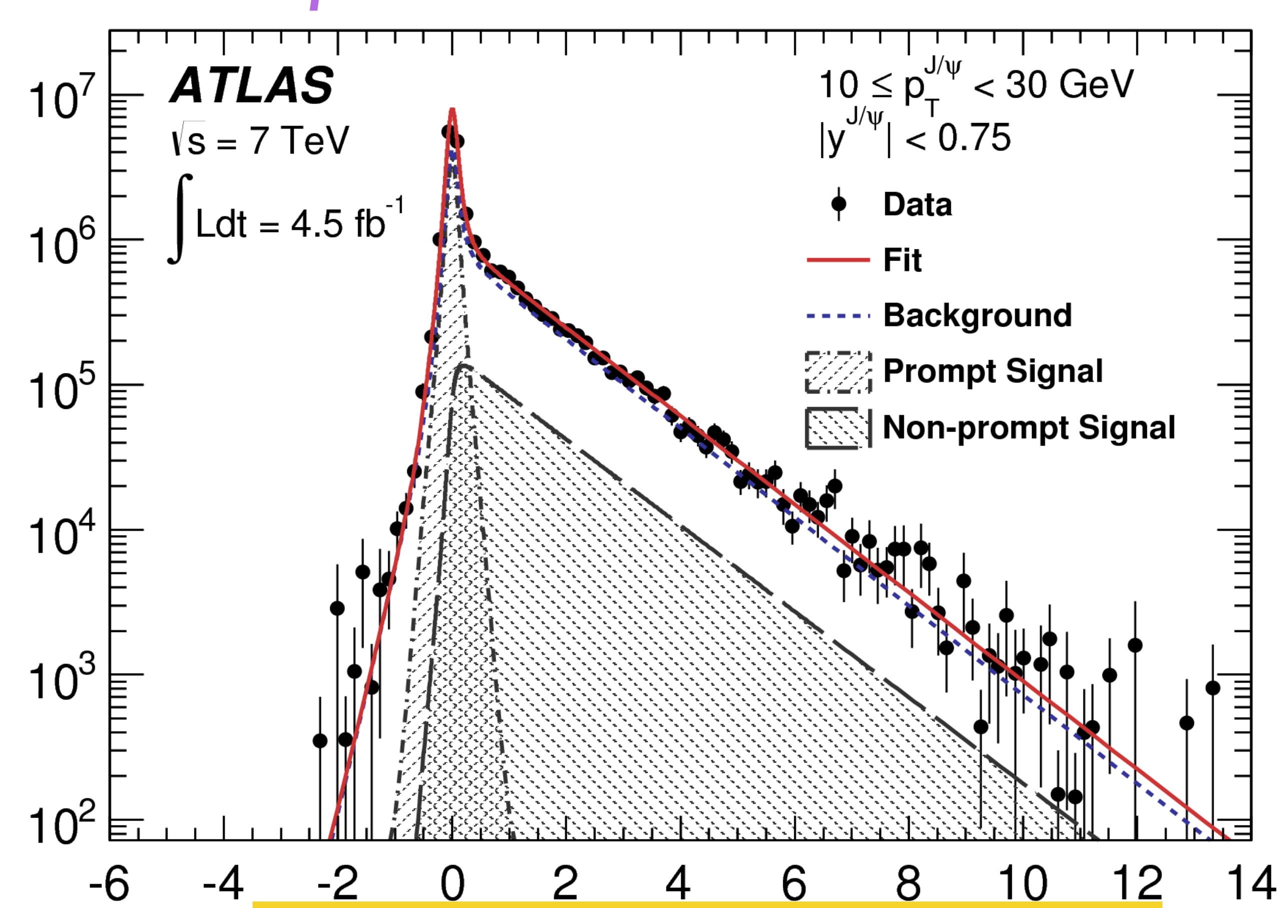
Need good mass resolution to have well-separated χ_{c1}, χ_{c2} states

Distinguish the χ_{c1} / χ_{c2} and prompt / non-prompt components with the fit

Simultaneous (2D) maximum likelihood fit to Δm and τ



$\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$

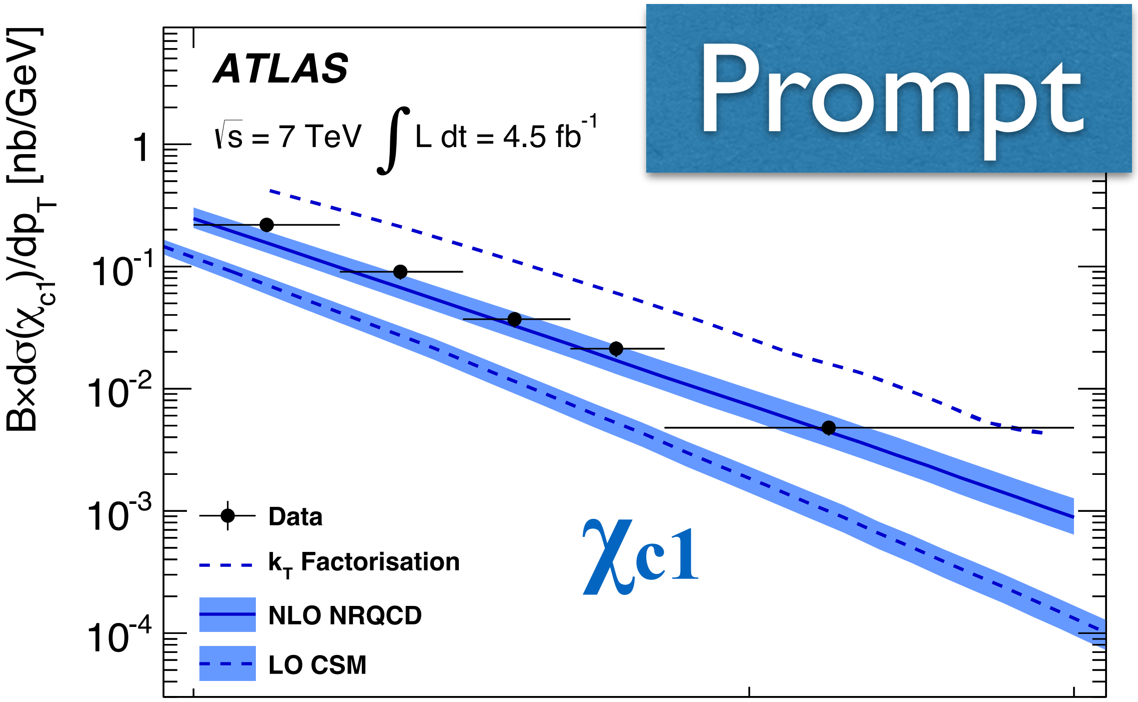


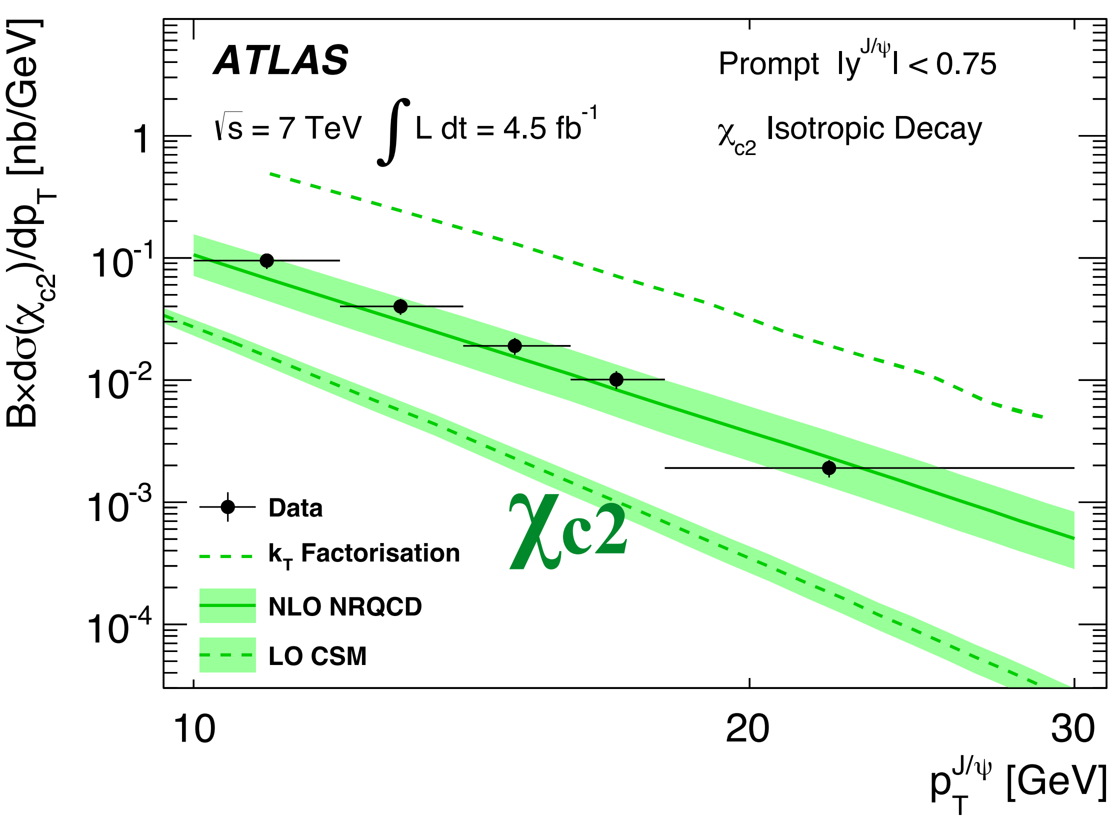
$\tau = L_{xy}(\mu\mu)\ m^{J/\psi} / p_T(\mu\mu)$

Onia production: χ_{c1}, χ_{c2}

Results for $d\sigma/dp_T^{J/\psi}$

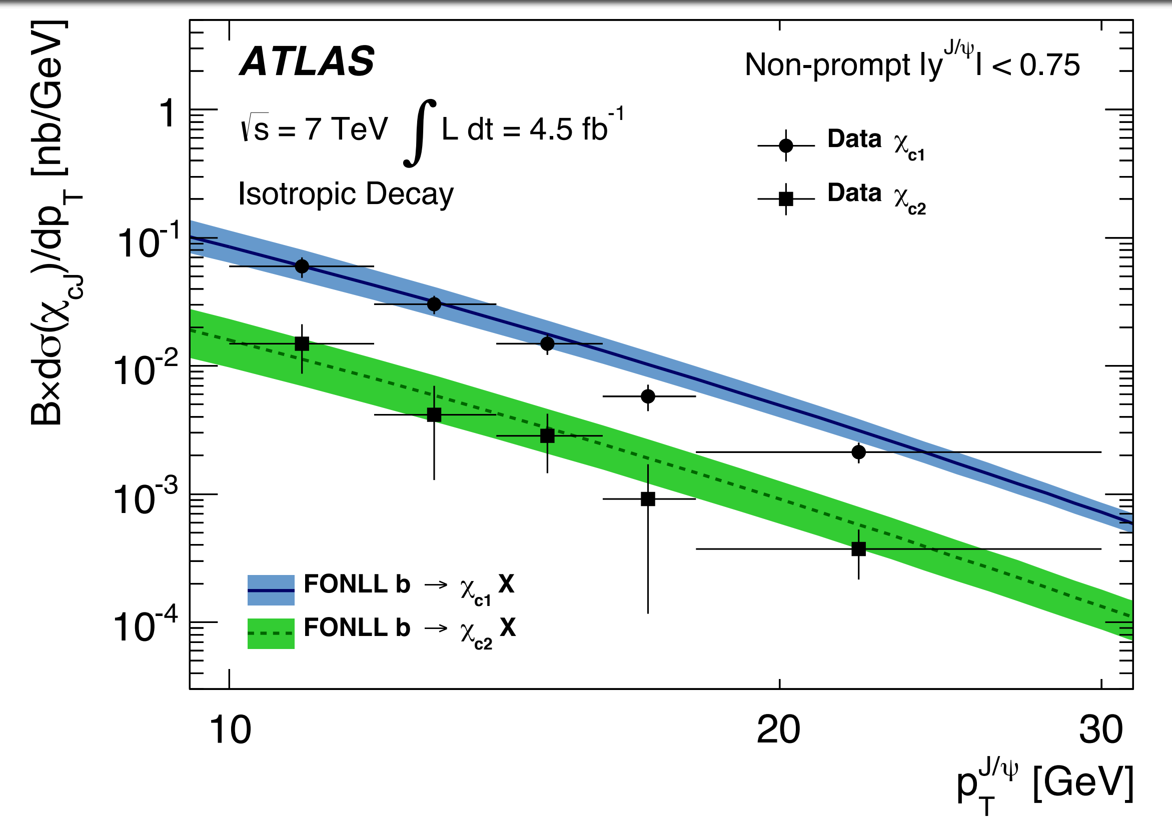
Prompt





- *Good agreement with NRQCD*
- *Similar plots for $d\sigma/dp_T^{\chi_c}$ show good understanding of χ_c kinematics*

Non-prompt ($H_b \rightarrow \chi_c X$)



- *Reasonable agreement with FONLL*
- *Tendency to overshoot the data at high p_T*

Onia production: χ_{c1}, χ_{c2}

Results for relative prompt production

- Contribution of J/ψ from decays of prompt χ_c to the inclusive prompt J/ψ cross-section

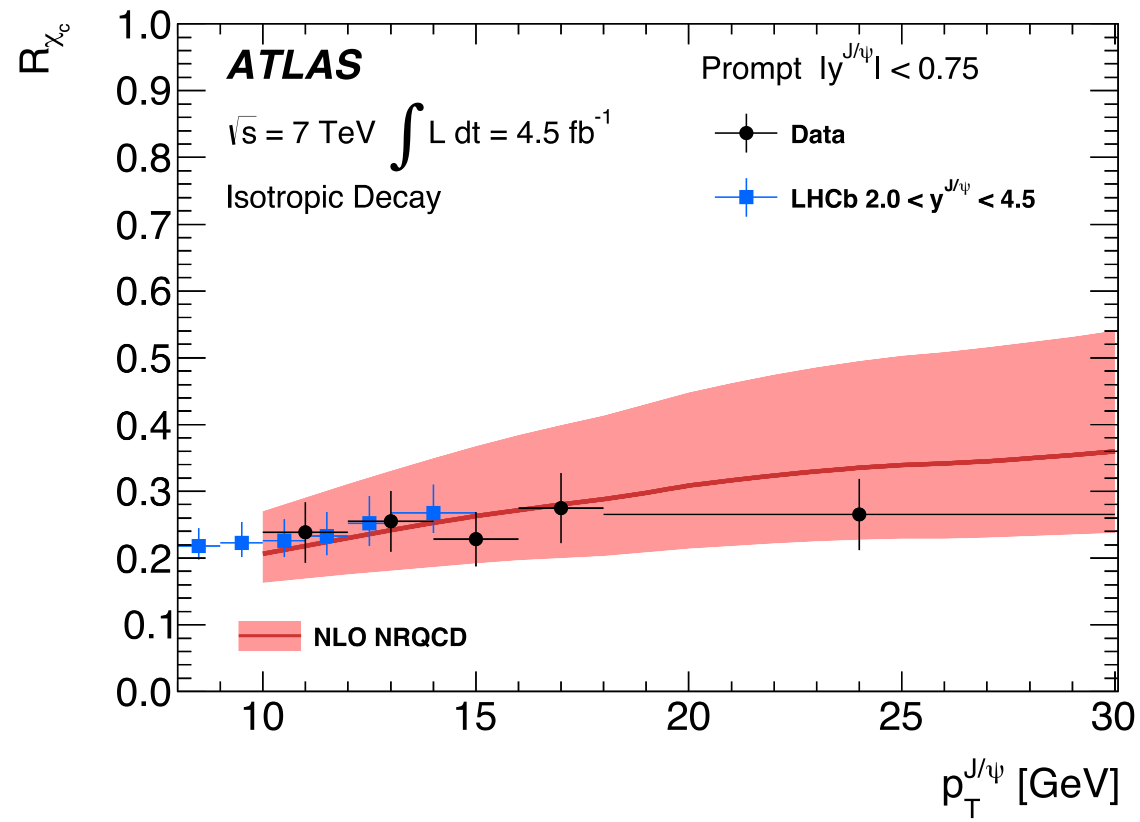
$$R_{\chi_c} = \frac{\sigma(pp \to \chi_{c(1,2)} \to J/\psi\,\gamma)}{\sigma(pp \to J/\psi + X)}$$

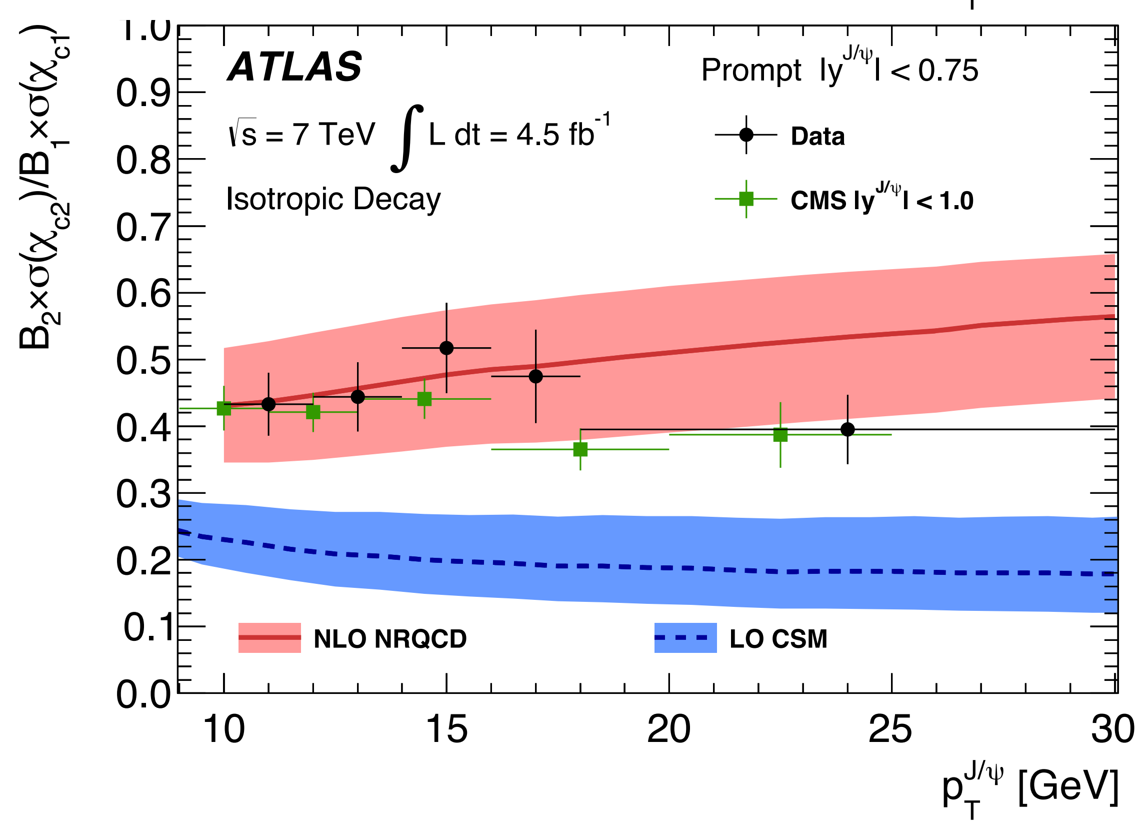
- Ratio of prompt χ_{c2}/χ_{c1} production

- CSM @ LO: good description of the p_T dependance but low in scale

- NRQCD @ NLO: agreement is good at low p_T, worse at high p_T

Results for relative non-prompt production and fraction of non-prompt production also available



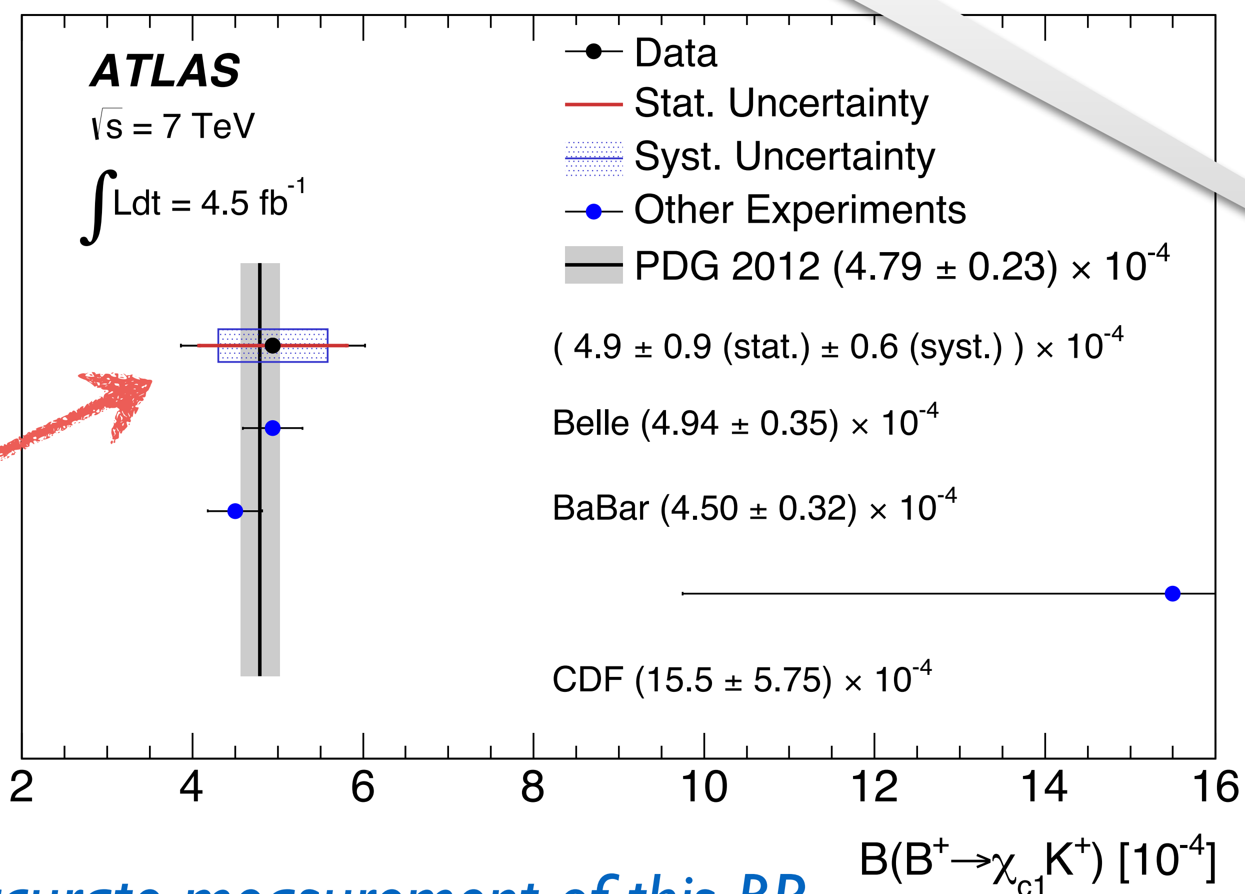


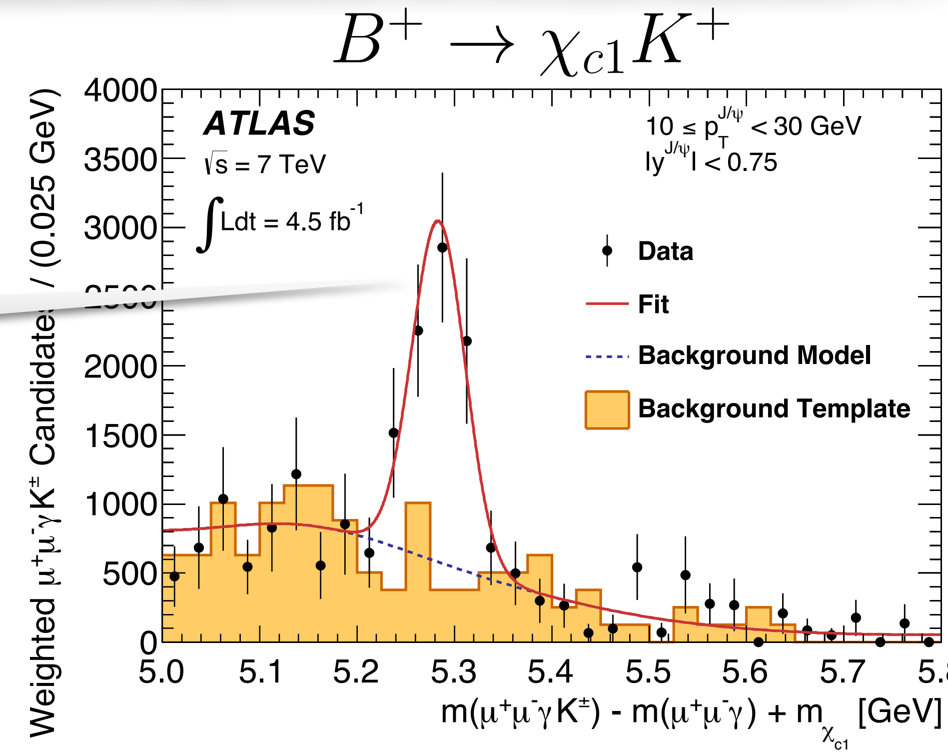
Onia production: χ_{c1}, χ_{c2}

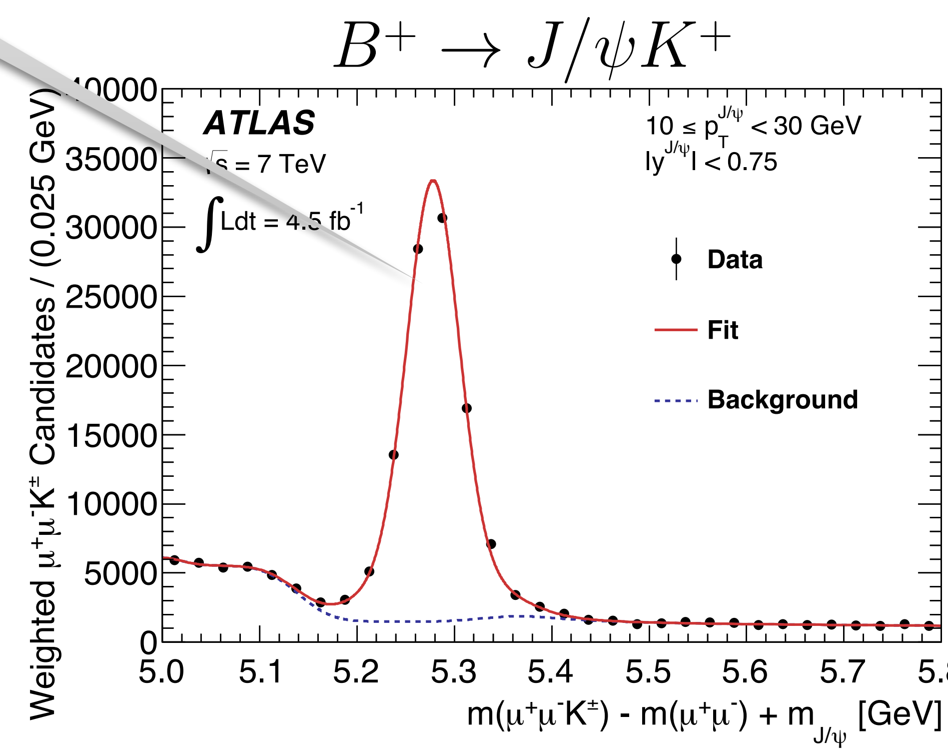
Results for relative <u>non-prompt</u> production

- Branching ratio measurement

$$\frac{BR(B^+ \to \chi_{c1} K^+)}{BR(B^+ \to J/\psi K^+)} = \alpha \cdot \frac{N^B_{\chi c1}}{N^B_{J/\psi}} \cdot \frac{1}{BR(\chi_{c1} \to J/\psi\,\gamma)}$$







- *Accurate measurement of this BR*
- *Excellent agreement with world-averaged value*
- *Good control of systematics (i.e. conversion reconstruction efficiency)*

Quarkonium production

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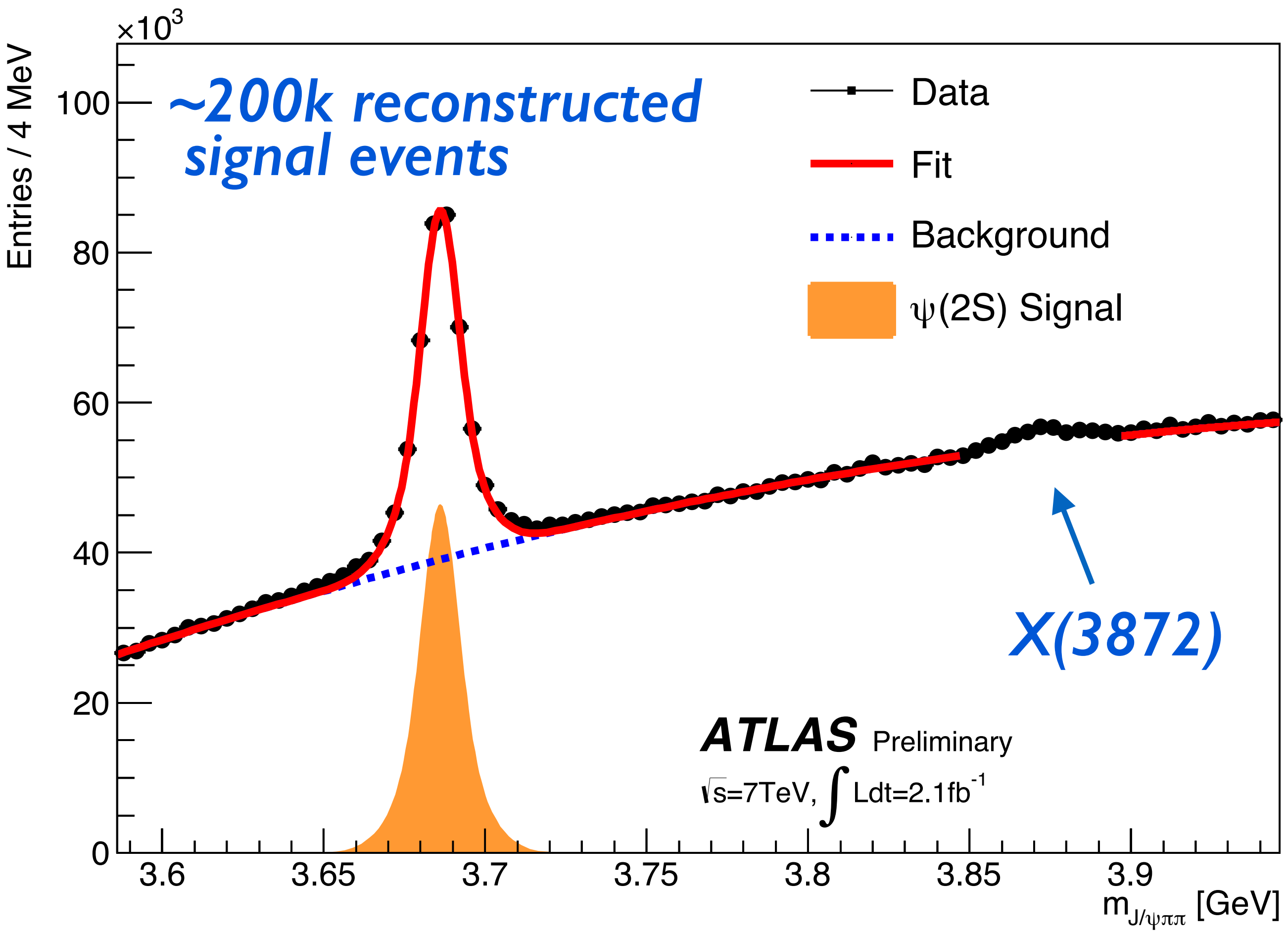
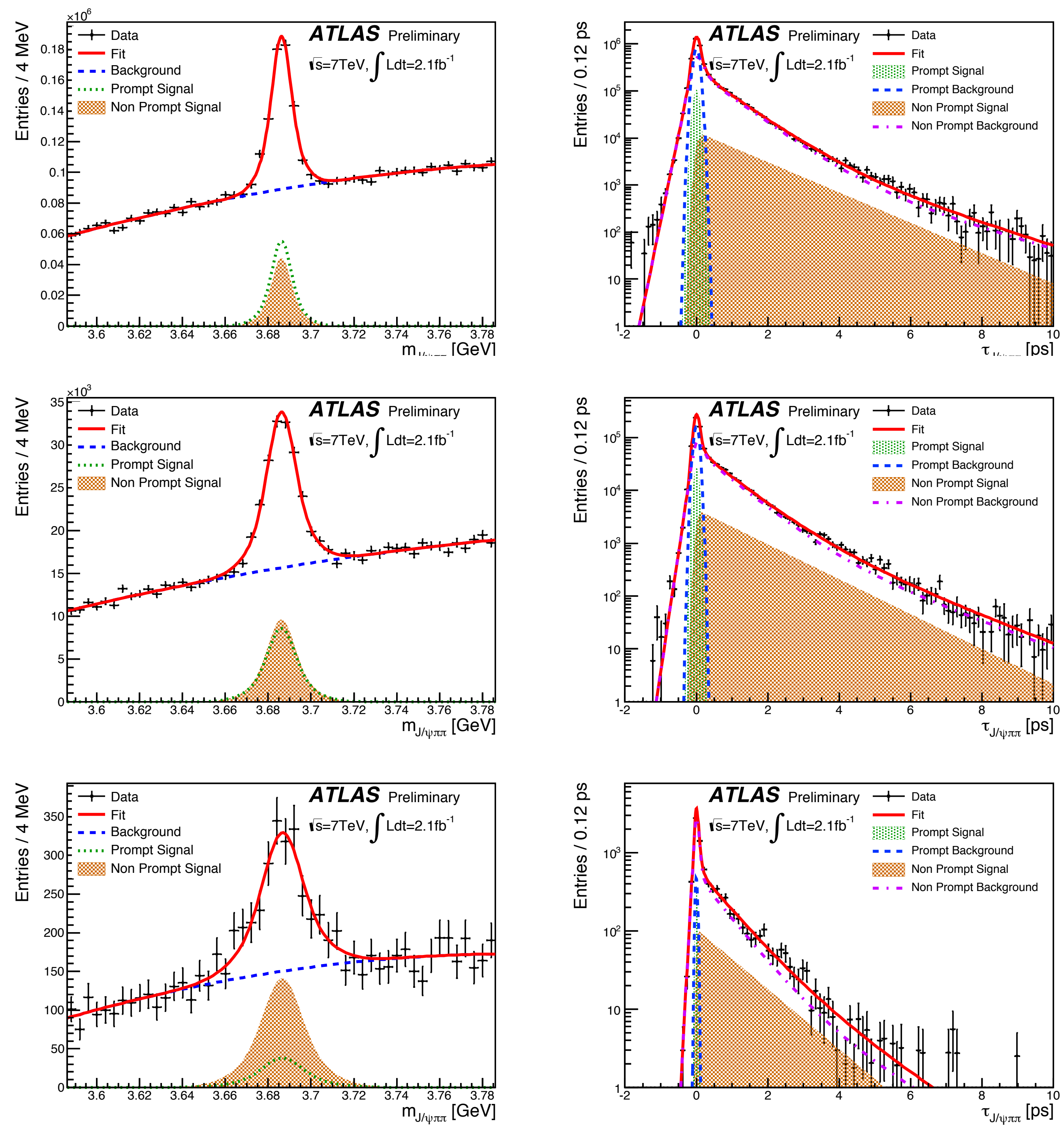
Onia production: ψ(2S)

Analysis details

- Reconstructed in the decay: $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-)\,\pi^+\pi^-$



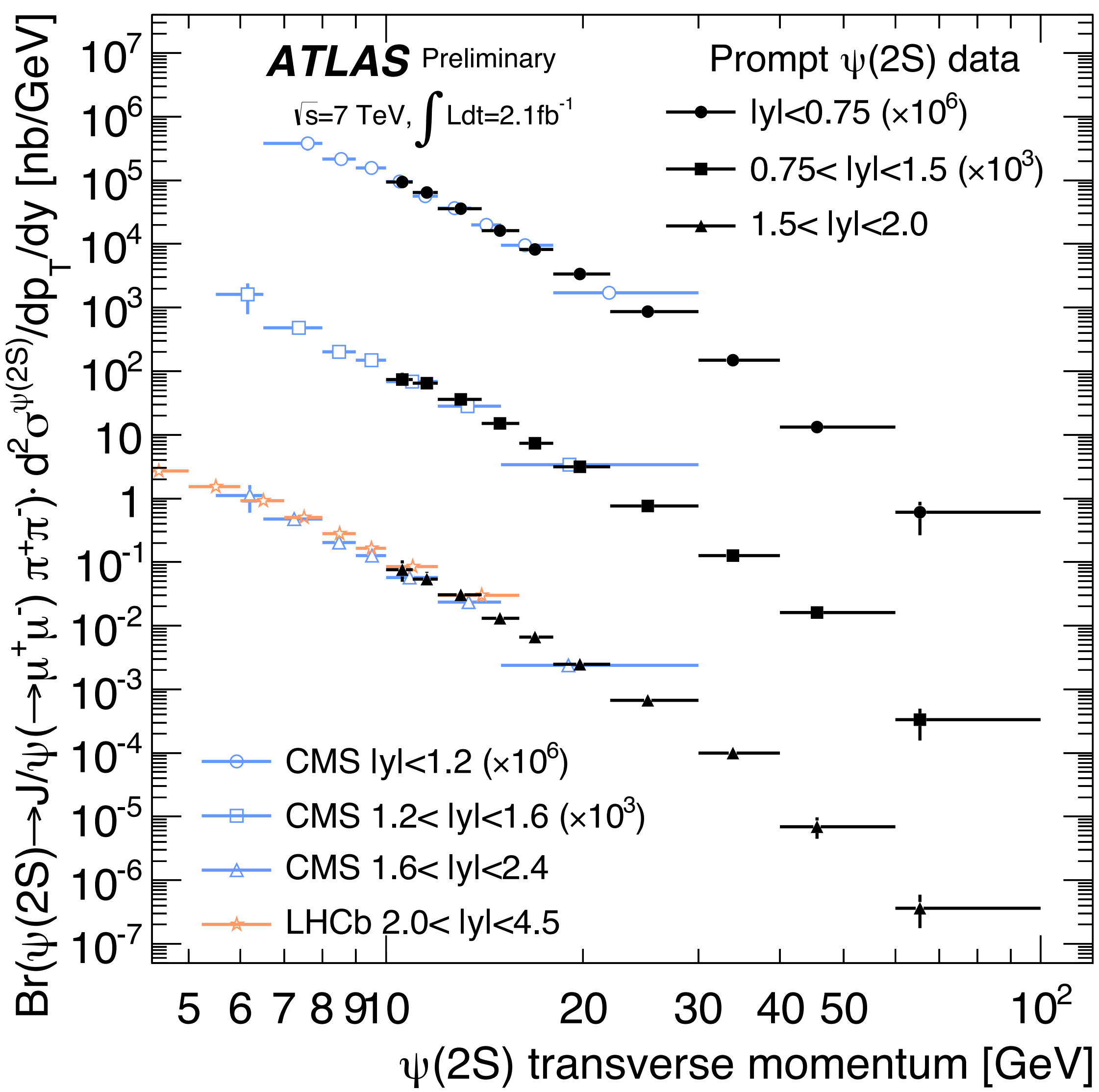


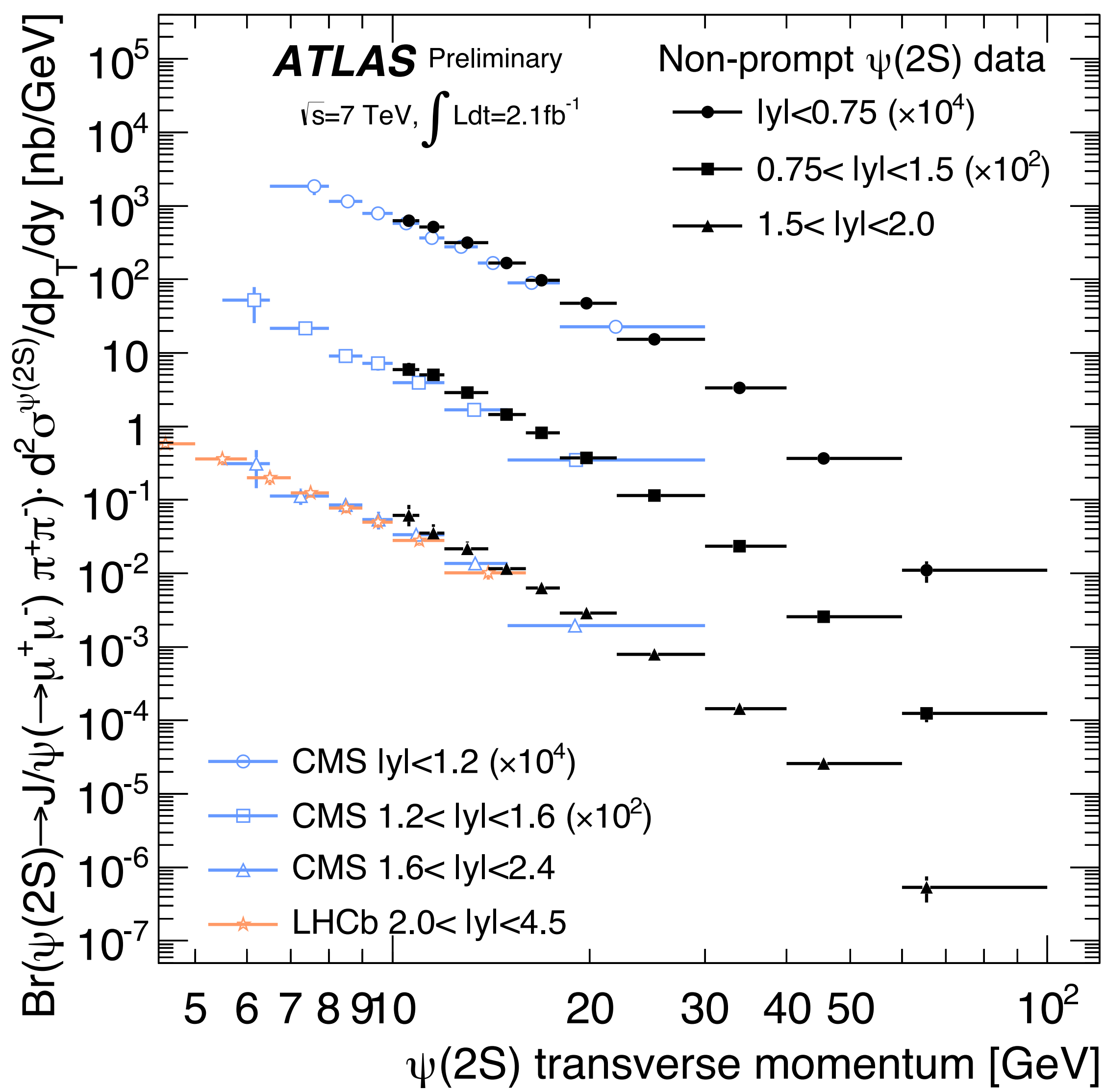
- *Half of the 2011 data sample (2.1 fb^{-1})*
- *Enough statistics to split in three rapidity regions covering |y|<2.0 and measure cross-section up to p_T~80 GeV*

Onia production: ψ(2S)

Results for prompt and non-prompt production

- Double-differential cross-section measurements ($d^2\sigma/dp_T dy$)



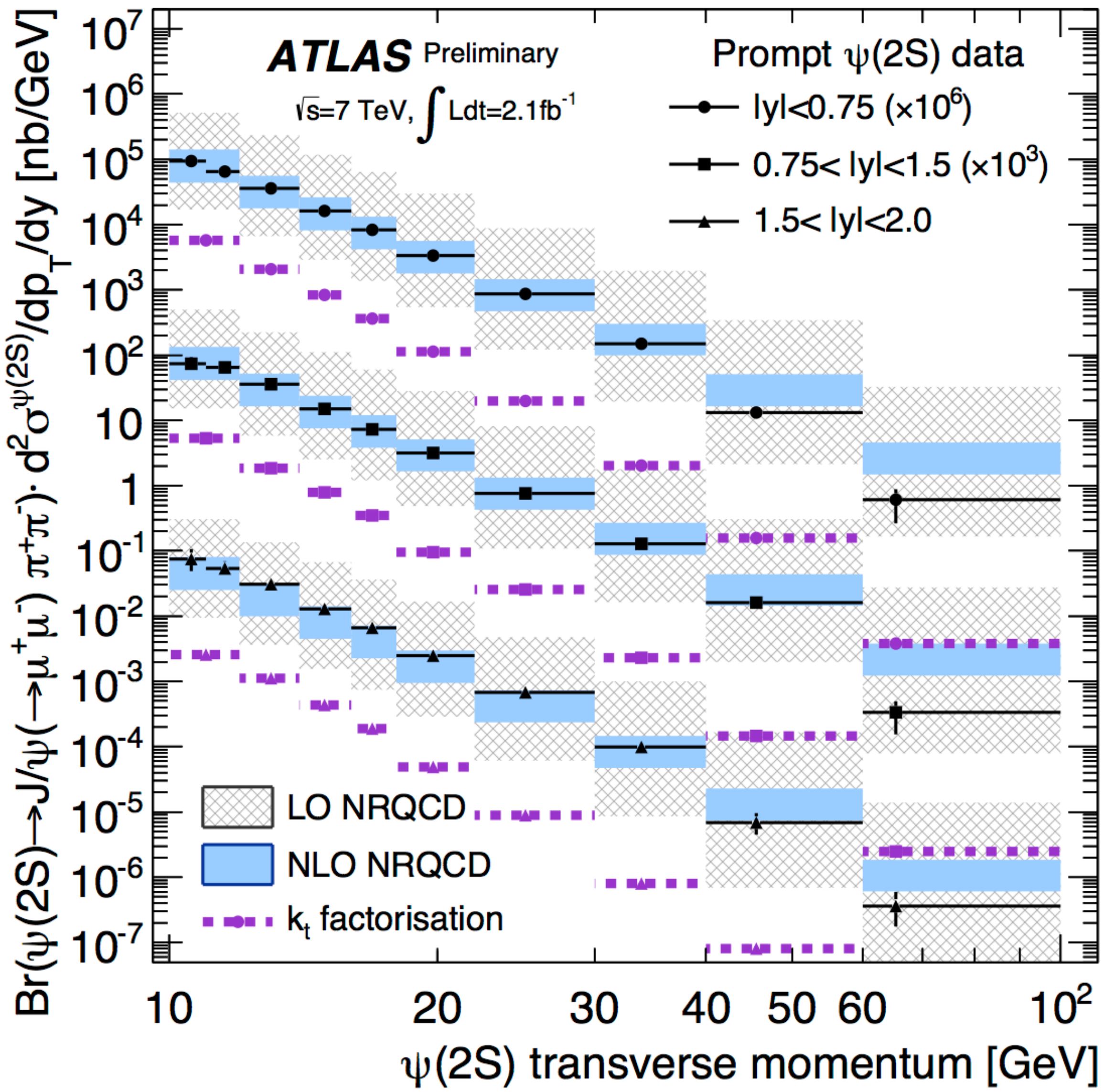


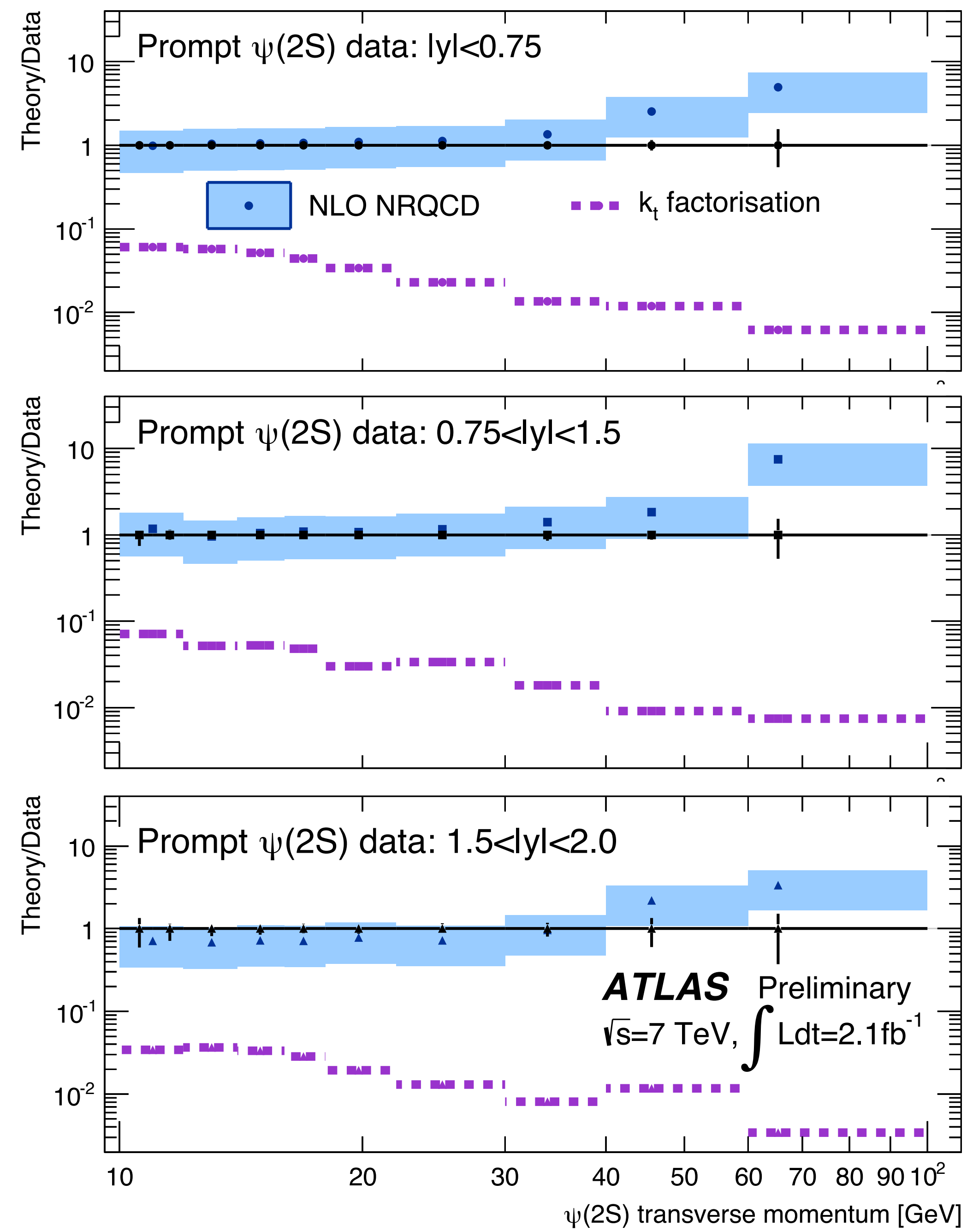
- *Comparison with CMS and LHCb data in the overlapping region yields good agreement*
- *ATLAS measurement extents measurements to the high-p_T region up to ~80 GeV*

Onia production: ψ(2S)

Results for prompt production

- Comparison with theory predictions





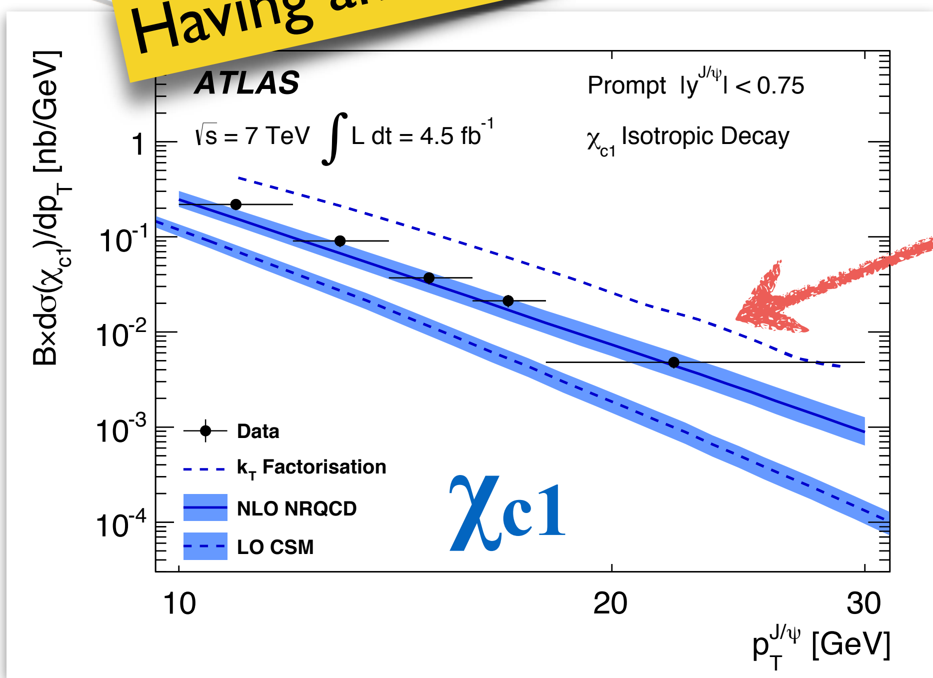
- *Agreement with NLO NRQCD, but disagreement appears at high p_T*
- *k_T factorisation model fails to describe data*

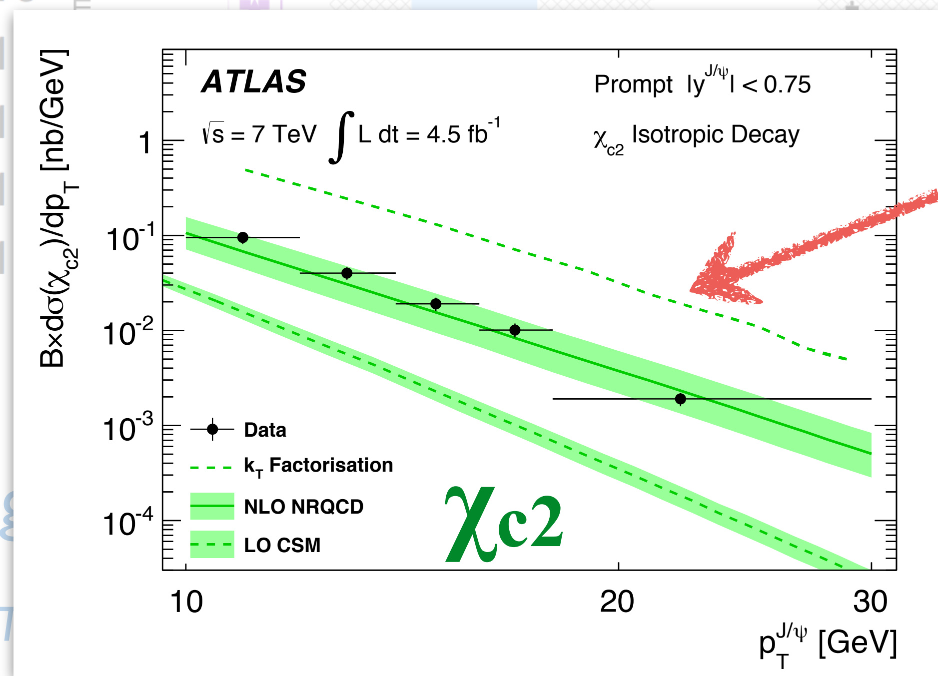
Onia production: ψ(2S)

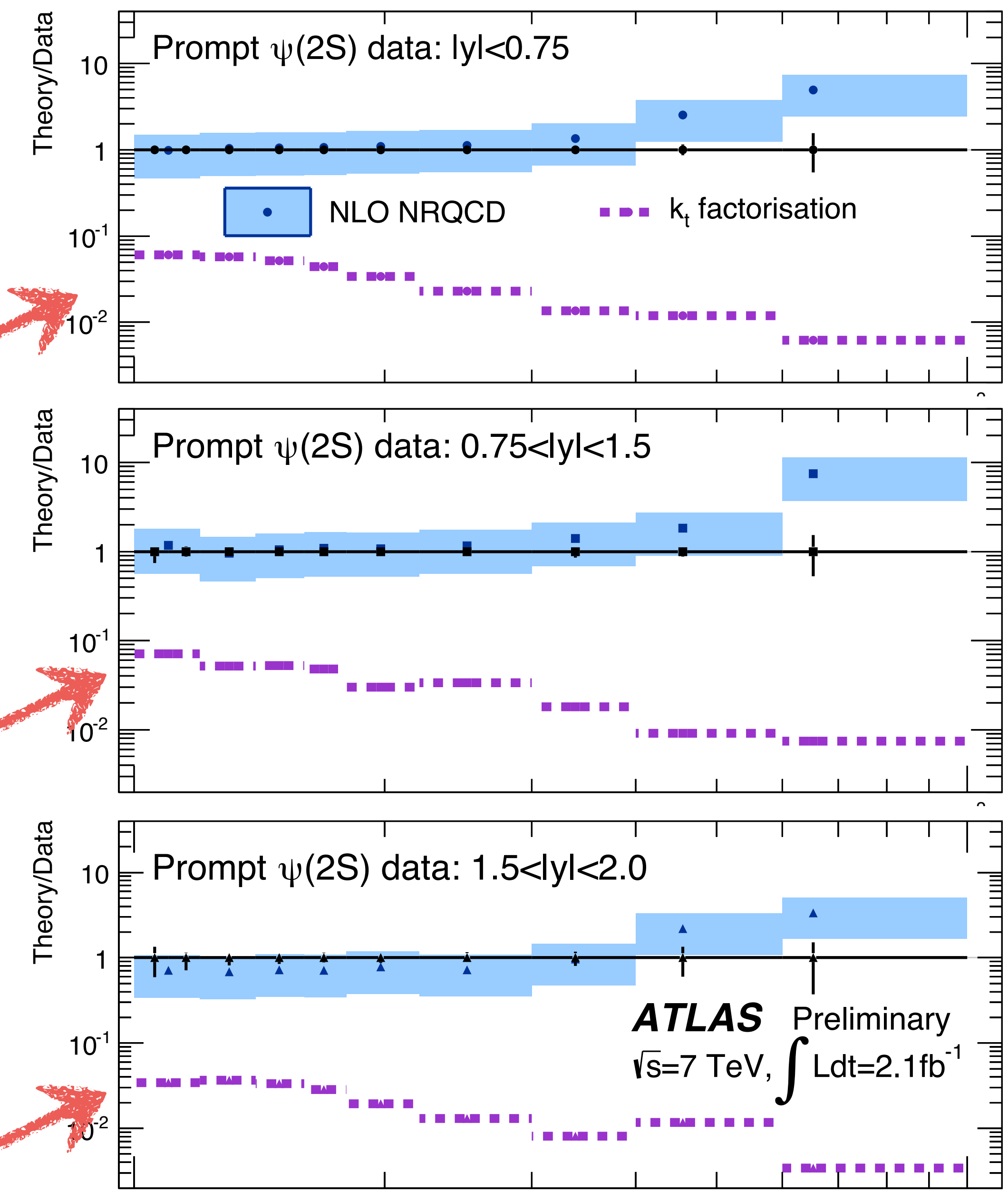
Results for ______

- Compariso... predictions

Having another look at the $\chi_{c1,2}$ results…







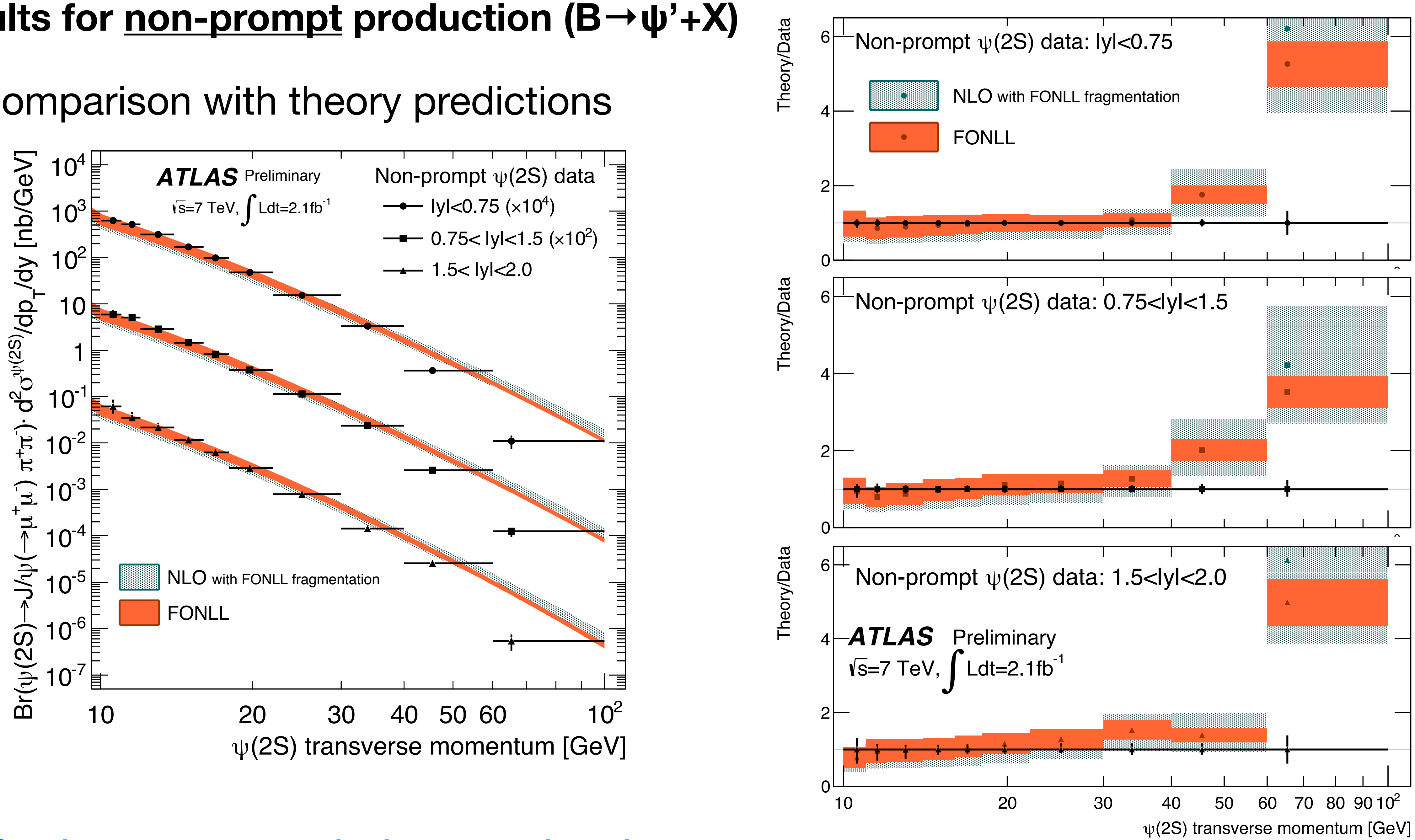
- Ag... diverg...
- k_T ... ibe d...

k_T factorisation approach overestimates χc production while underestimating ψ(2S) production

Onia production: ψ(2S)

Results for <u>non-prompt</u> production (B→ψ'+X)

- Comparison with theory predictions

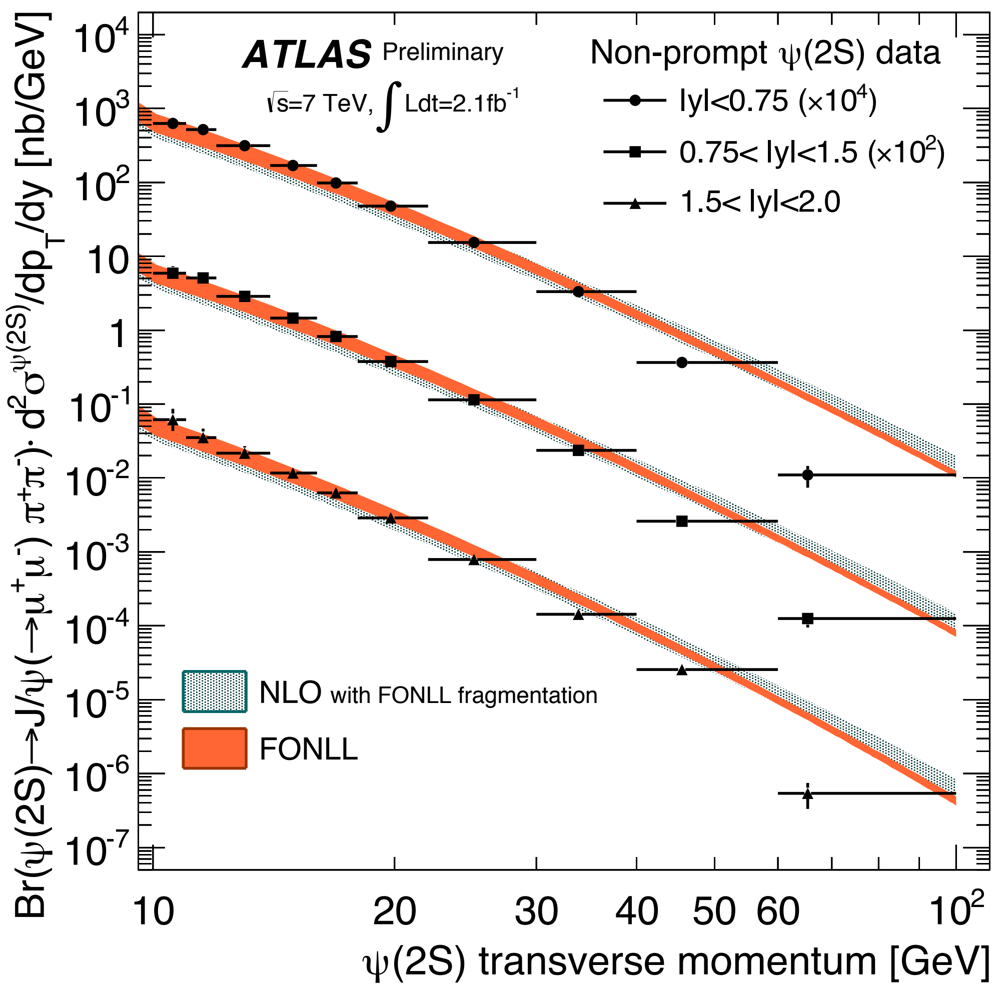


- *Good agreement with theory within the uncertainties*
- *Trend of underestimating the data at low p_T, overestimation shows up at high p_T*

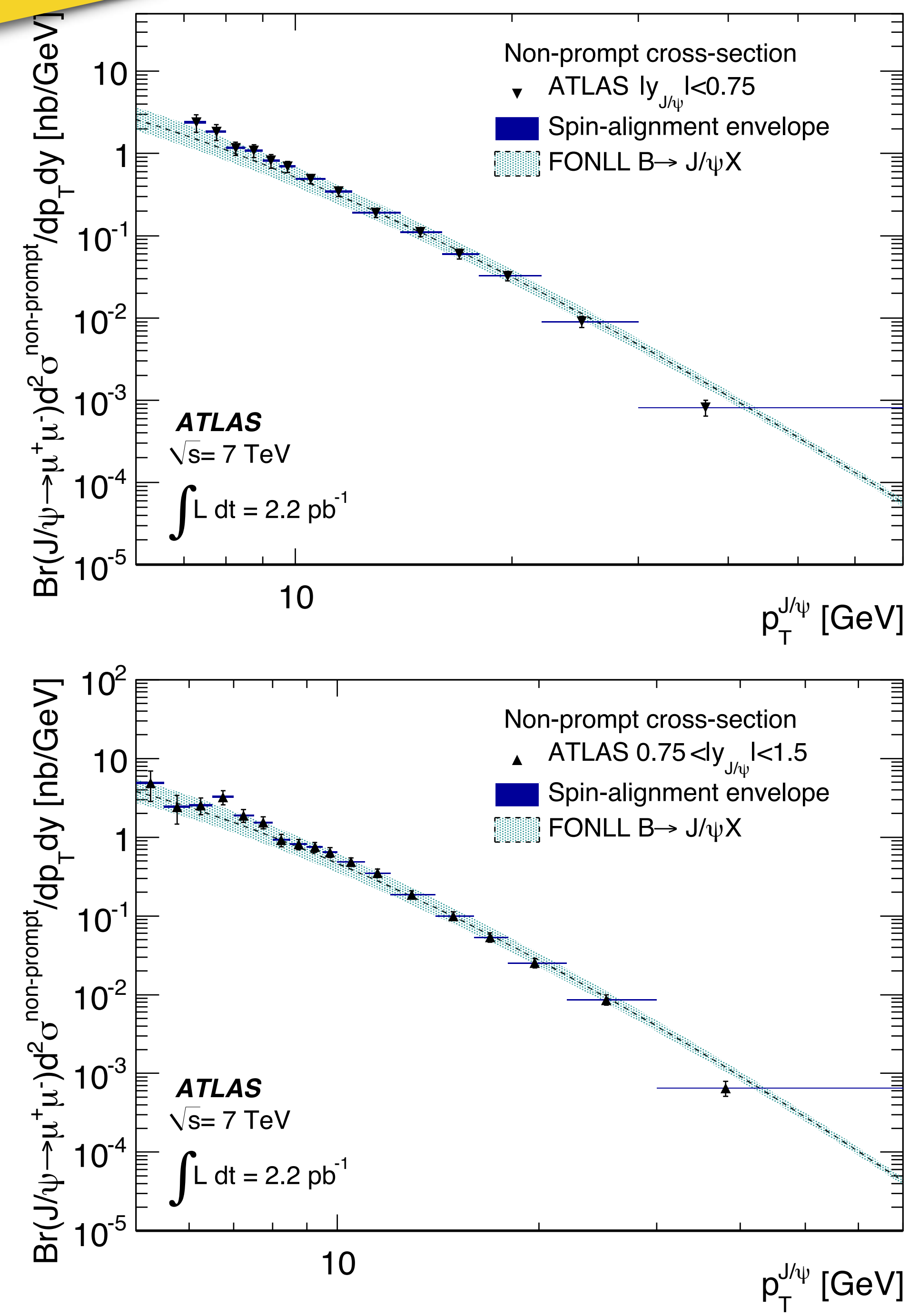
Onia production: ψ(2S)

Results for <u>non-prompt</u> production (B→ψ'+X)

- Comparison with theory predictions



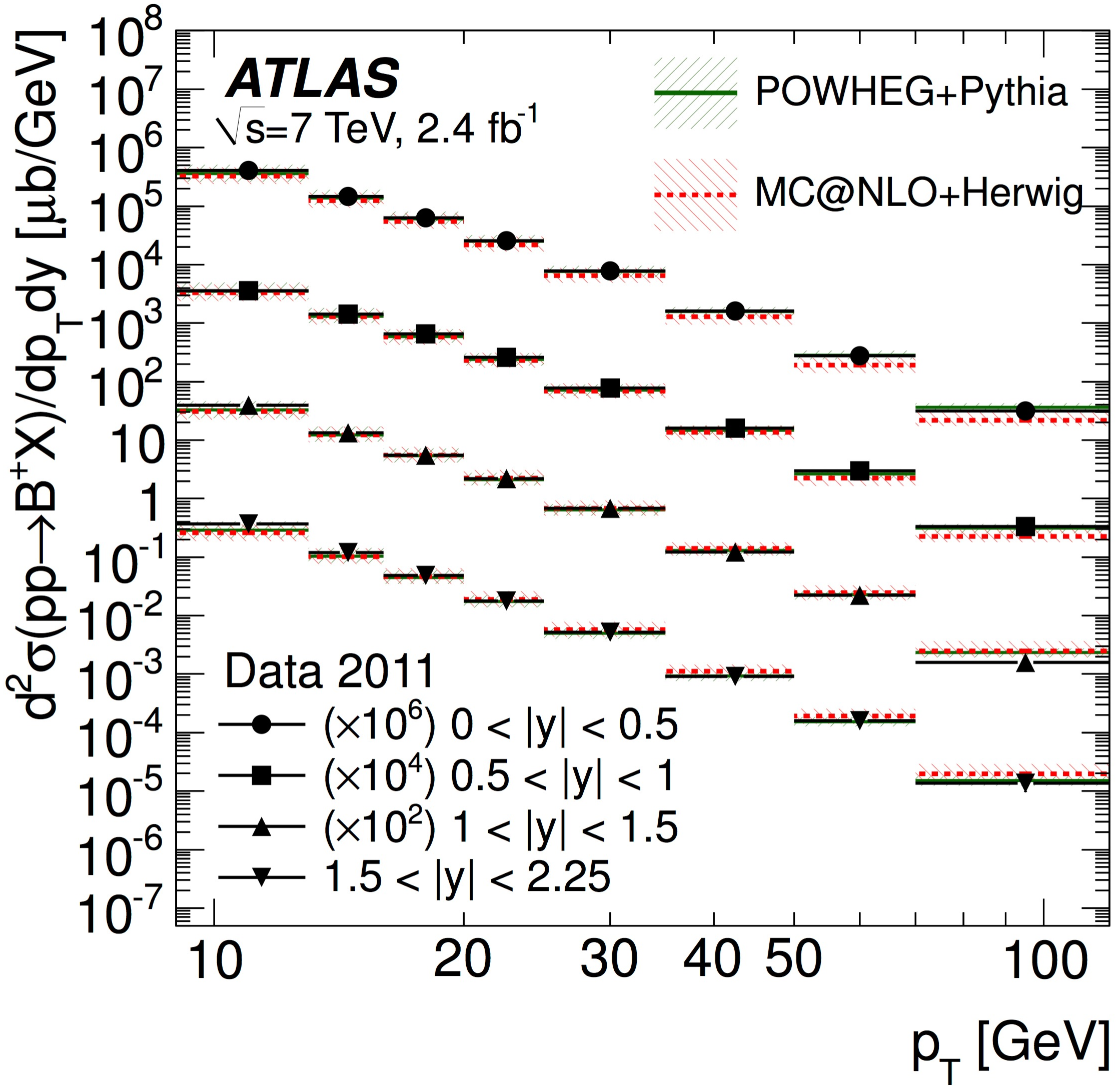
Compare with the B→J/ψ+X results…

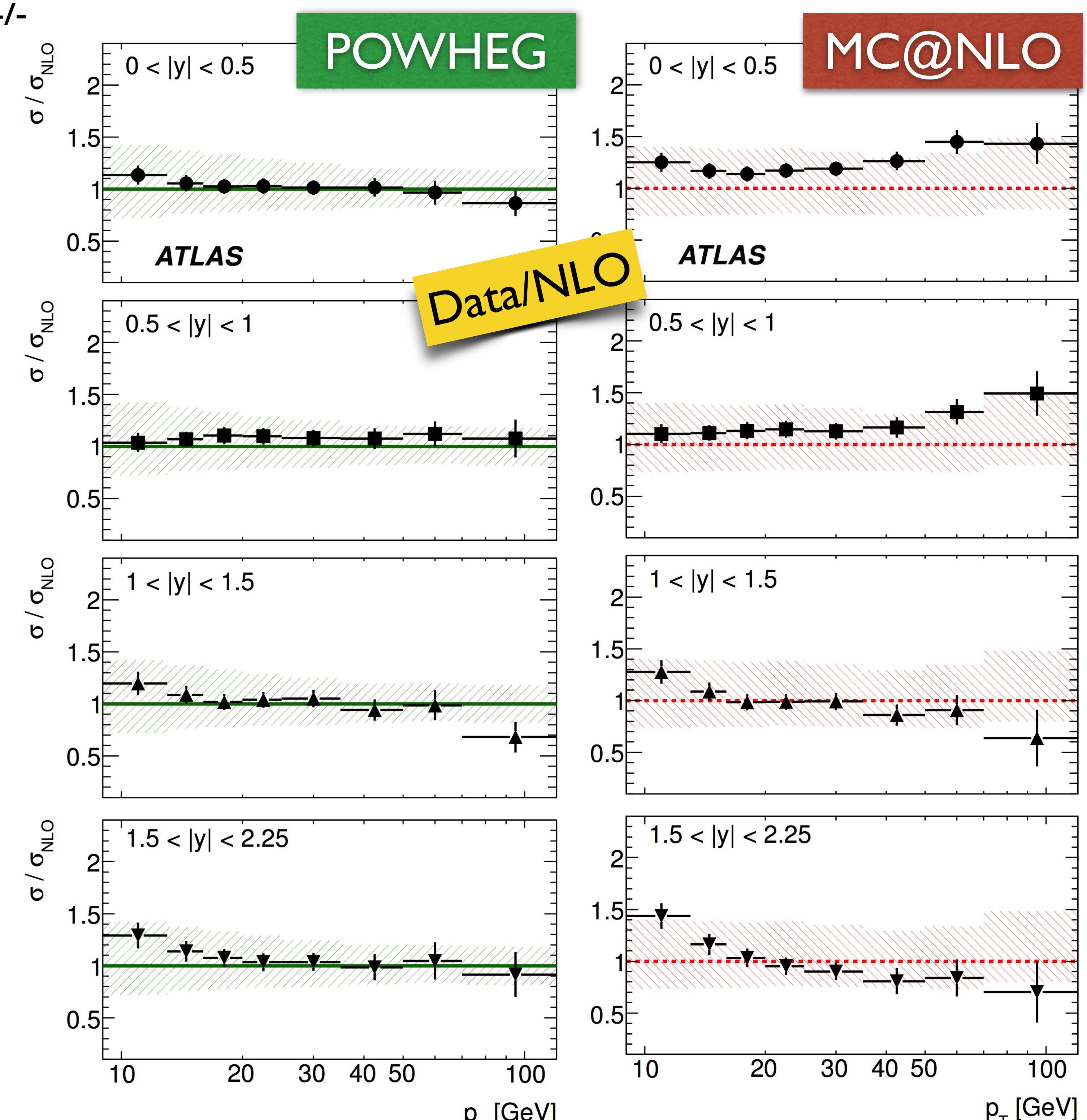


Good agreement of FONLL predictions with the data within the uncertainties. Trend in the predictions to over(under) shoot the data at high(low) pt.

More results on b-hadron production

Exclusive decay channel $B^{+/-} \to J/\psi K^{+/-}$

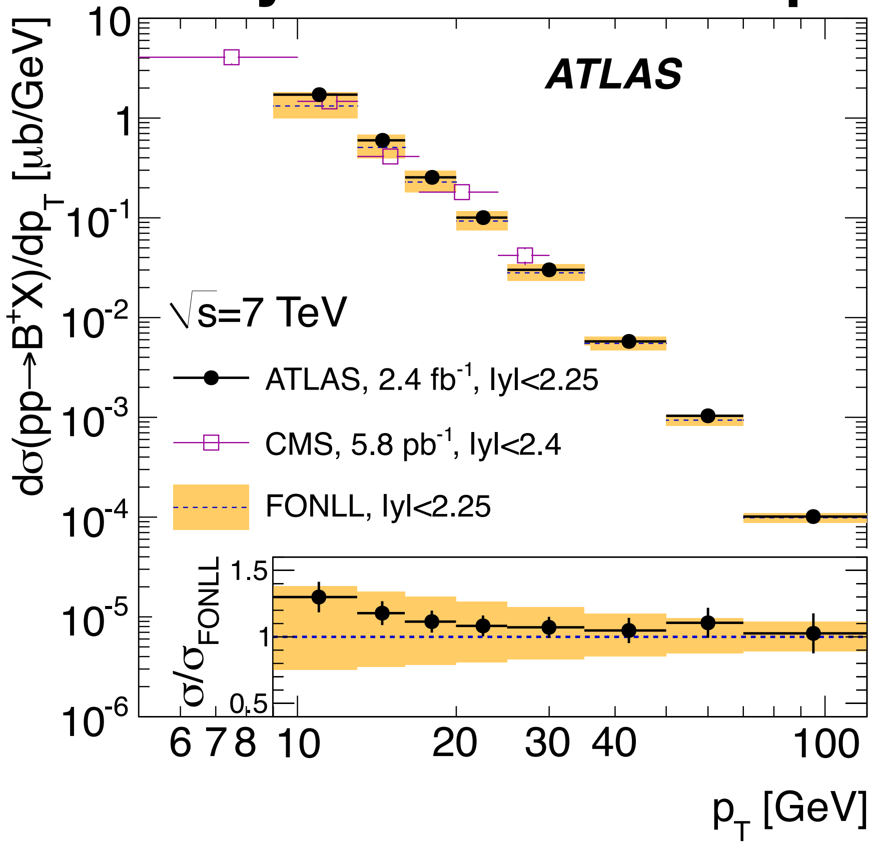


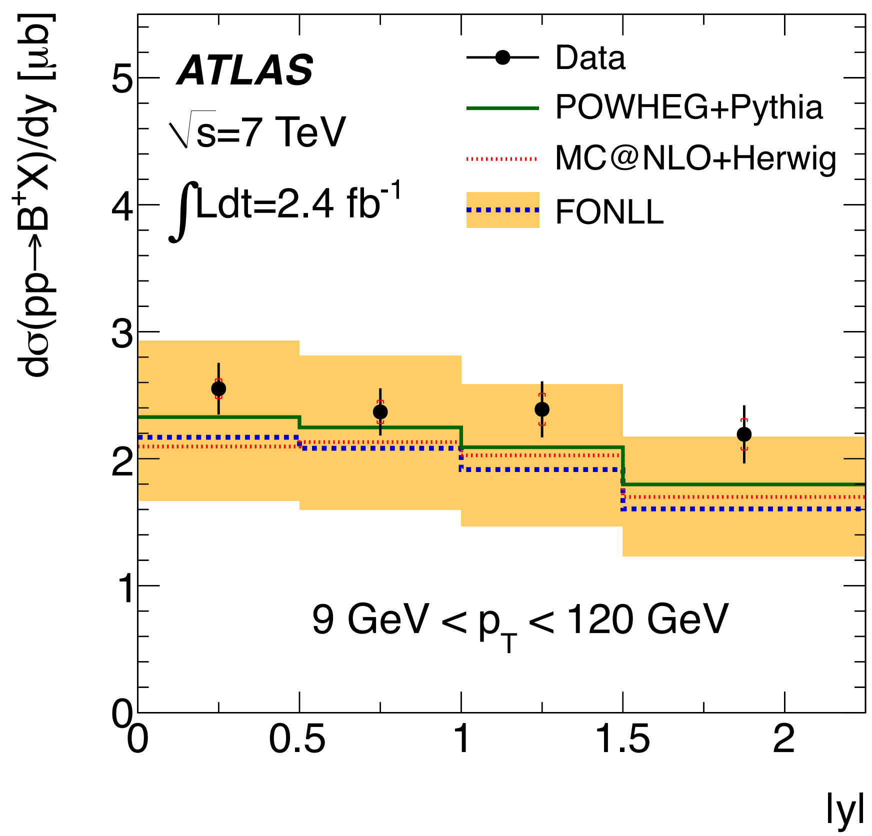


- $d^2\sigma/dp_T\,dy$ measurement
- Comparisons with NLO+parton-shower approaches and FONLL (next slide)
- *The picture is consistent with $B \to cc+X$ results*

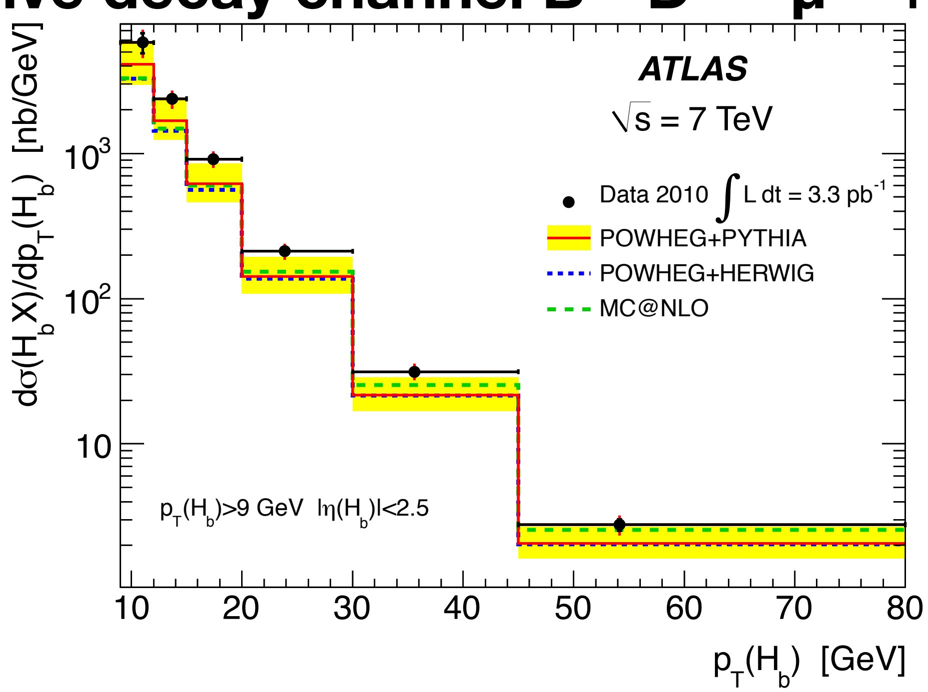
More results on b-hadron production

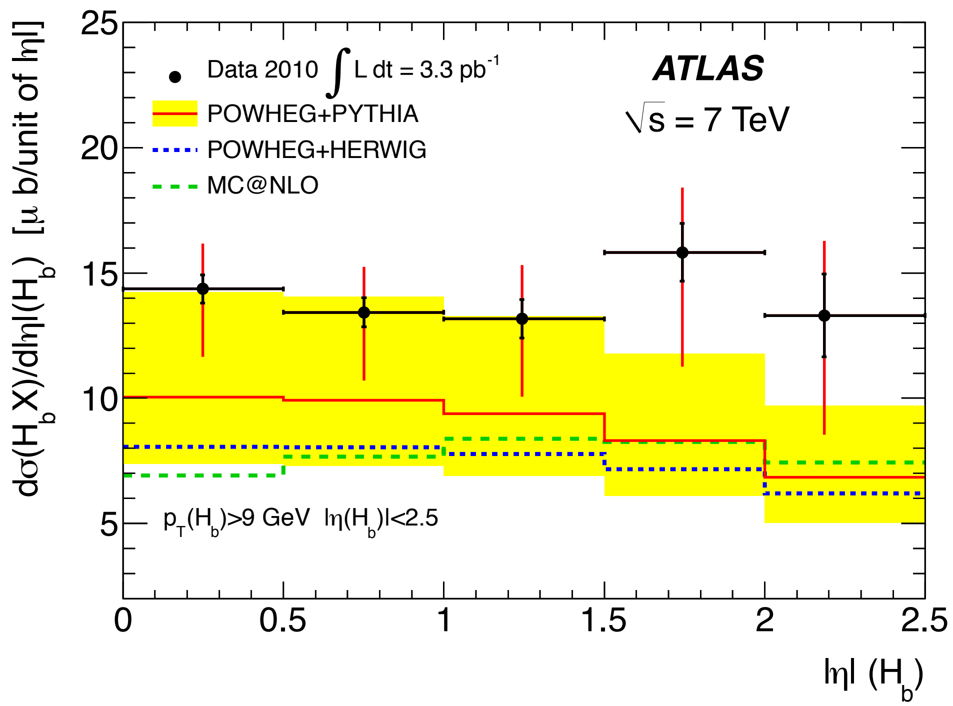
Exclusive decay channel $B^{+/-} \rightarrow J/\psi\ K^{+/-}$





Inclusive decay channel $B \rightarrow D^{*+/-}\ \mu^{-/+} + X$





Conclusions

- ATLAS has provided interesting studies on heavy-flavour production
- High-p_T regions are becoming available and are important for comparisons with the predictions of QCD calculations regarding:
  - **production of b-hadrons ($B \to ccX$, $B \to D^* \mu X$, $B^+ \to J/\psi K^+$)**

Calculations at NLO from different approaches (NLO+PS, FONLL) for b-hadron production describe data well but within large uncertainties from factorisation and renormalisation scales, mainly.

Measurements achieve better precision — time for NNLO.

  - **production of prompt quarkonia (Υ, J/ψ, ψ', χ_{c1}, χ_{c2})**

NRQCD (Colour-Octet) in reasonable agreement with data, divergences appear at high-p_T. The k_T-factorisation approach needs improvements and can benefit from the results presented here.

Anticipating ATLAS spin-alignment measurements, essential for a conclusive picture towards understanding the quarkonium production mechanism.

Backup

Event selections

$\chi_{c1,2}$ -> J/ψ γ

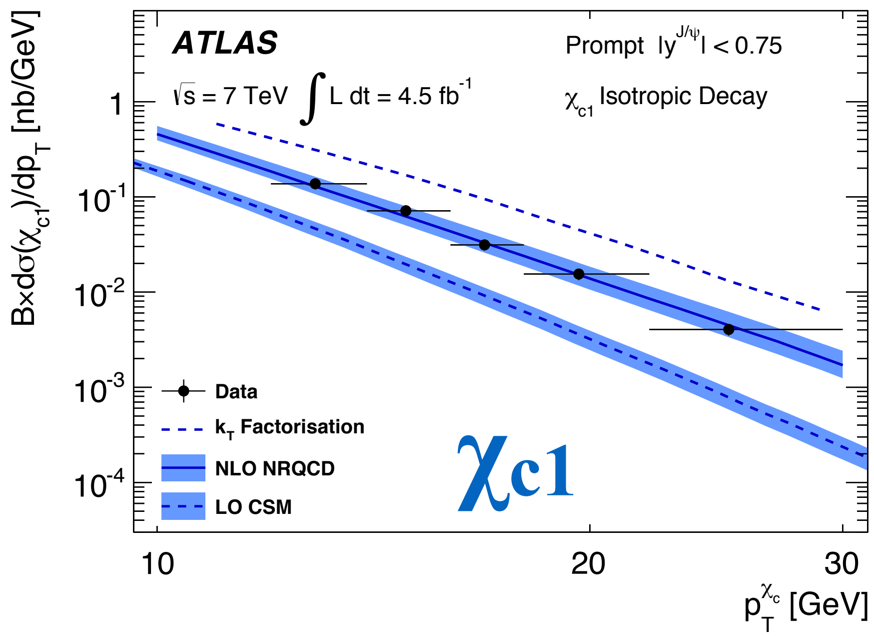
- Muons: $p_T^{\mu}>4$ GeV , $|\eta^{\mu}|<2.3$
- Dimuons: vertex fit -> $m^{\mu\mu}$ ~ (2.95, 3.25) GeV , $|y^{\mu\mu}|<0.75$
- Electrons: $p_T^{e}>0.4$ GeV, $|\eta^{e}|<2.3$ (no calo information)
- Photons (e^+e^-): vertex fit->$m^{ee}=0$, $p_T^{\gamma}>1.5$ GeV, $|\eta^{\gamma}|<2.0$, r^{γ} ~ (40,150) mm
- χ_c candidates: d(J/ψ, γ) < 5 mm

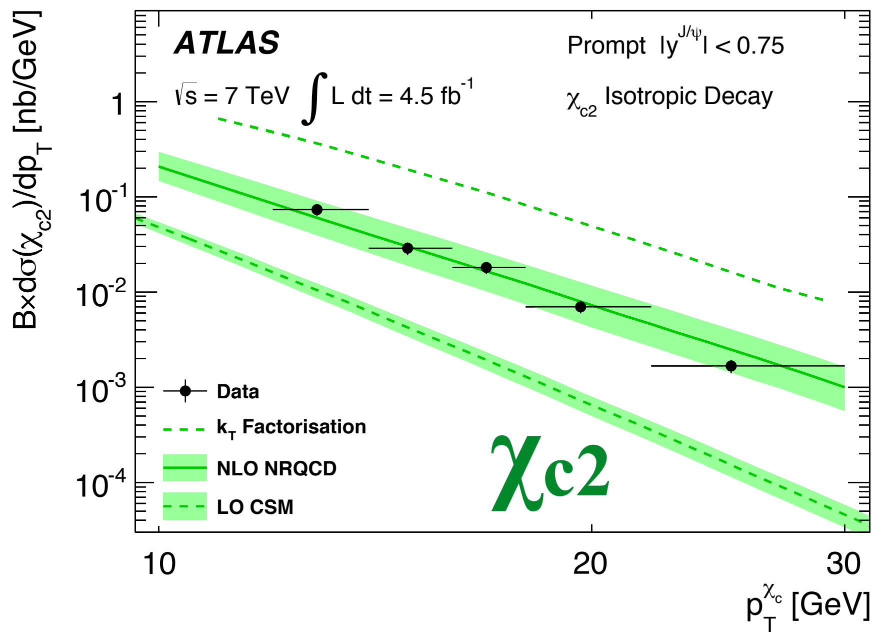
ψ' -> J/ψ $\pi^+ \pi^-$

- Muons: $p_T^{\mu}>4$ GeV , $|\eta^{\mu}|<2.3$
- Dimuons: vertex fit->$m^{\mu\mu}$ ~ (2.8, 3.4) GeV , $p_T^{\mu\mu}>8$ GeV , $|y^{\mu\mu}|<2.0$
- ψ' candidates: vertex - χ^2 probablility > 0.005

Onia production: χ_{c1}, χ_{c2}

Results for $d\sigma/dp_T^{\chi_c}$



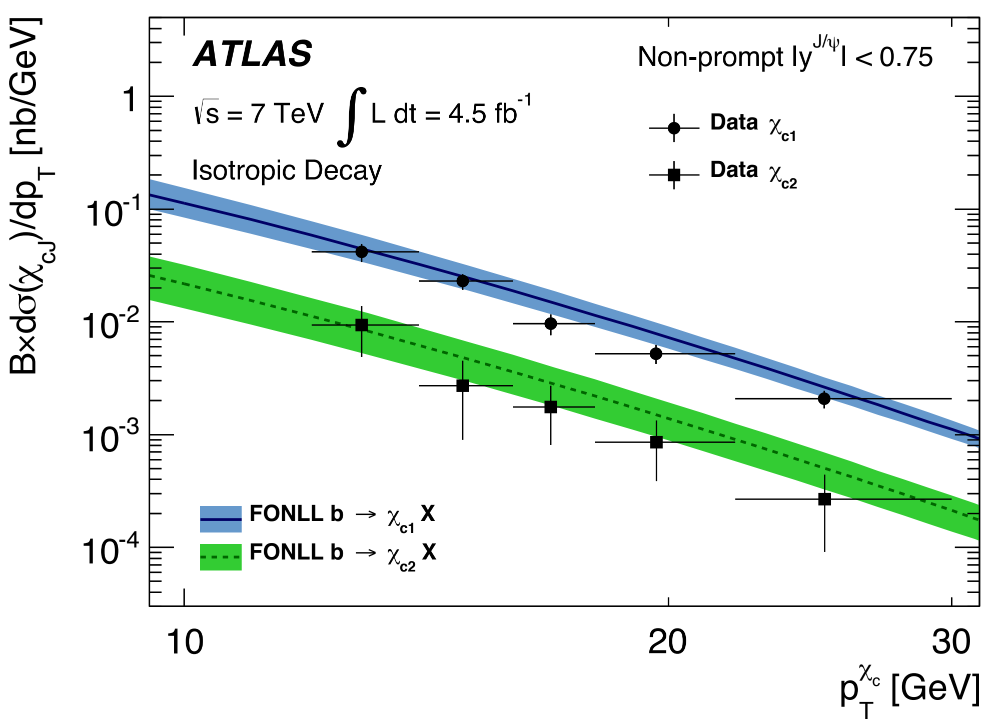


Prompt production:

- Comparison with NRQCD —> good agreement

Non-prompt production ($H_b \rightarrow \chi_c X$):

- Comparison with FONLL —> reasonable, tendency of predictions to overshoot the data at high p_T

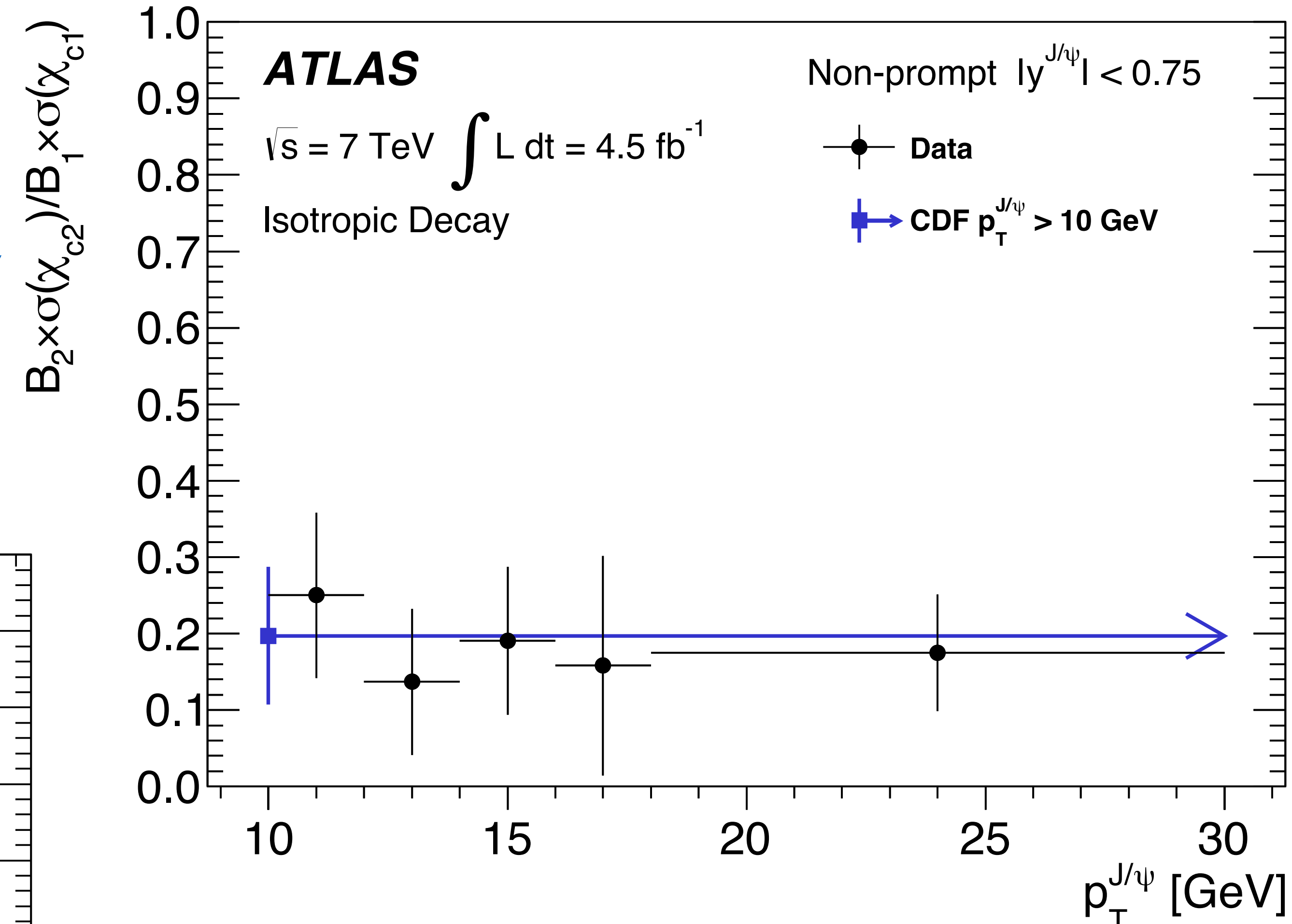


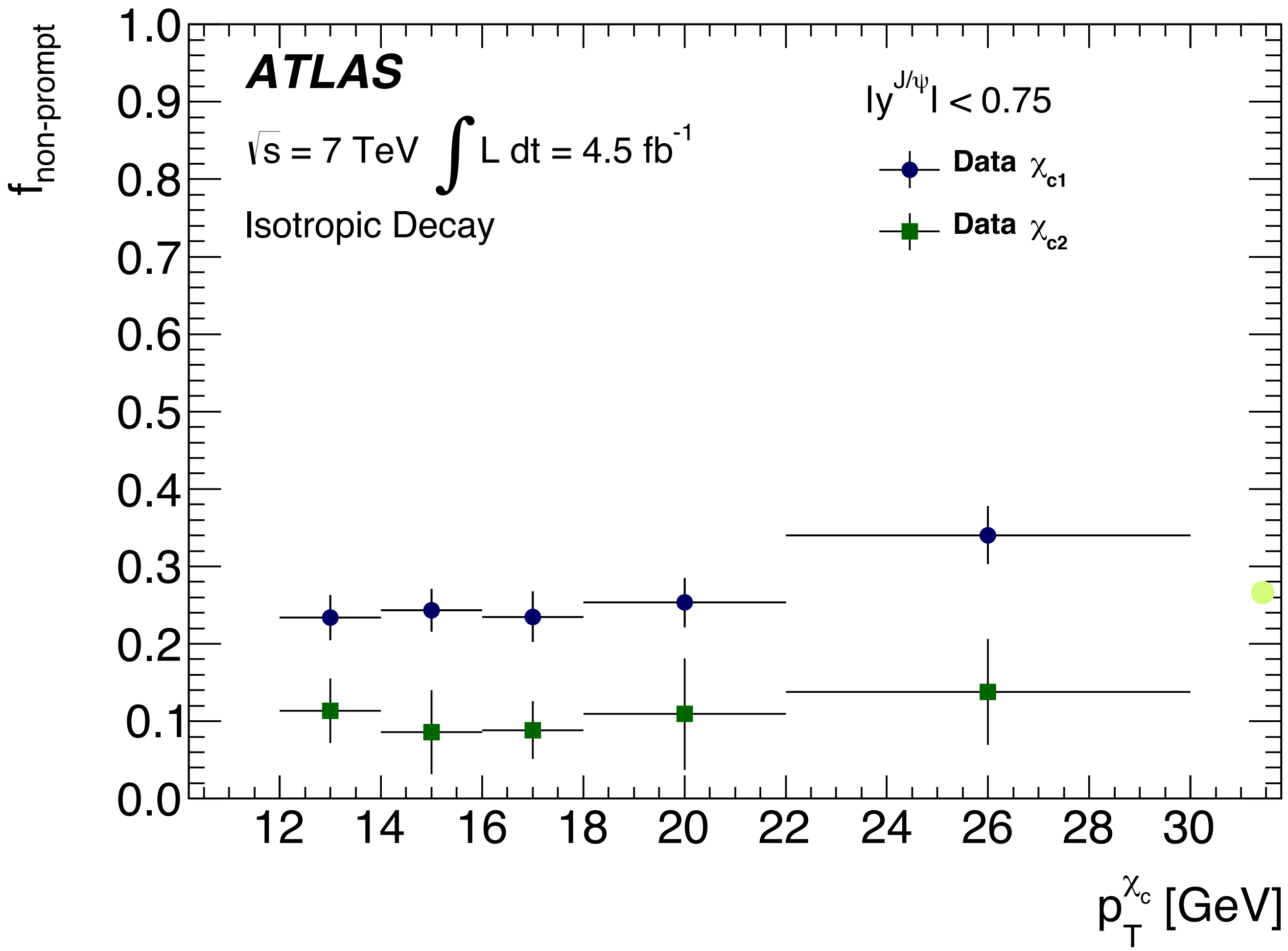
Onia production: χ_{c1}, χ_{c2}

Results for relative non-prompt production ($B \rightarrow \chi_c + X$)

- Ratio of non-prompt χ_{c2}/χ_{c1} production
  - *stable with p_T and center-of-mass energy*

⇒





⇐

- Fraction of non-prompt χ_{c1},χ_{c2} production
  - *only small increase at this range of p_T*

Quarkonium production… previously by ATLAS

Results for bottomonium states

- Complete study of inclusive production of Υ(1S), Υ(2S), Υ(3S)

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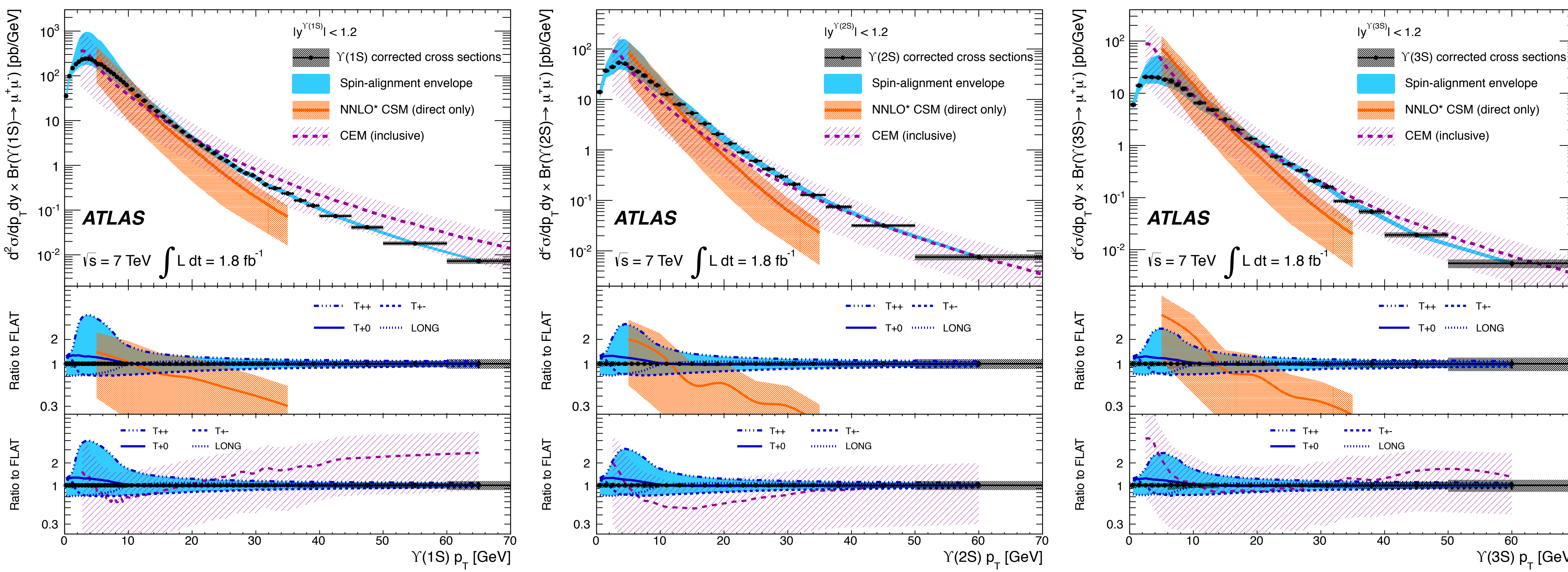

Comparison with theoretical predictions