Quarkonium and heavy flavour production measurements at the ATLAS experiment

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Quarkonium and heavy flavour production measurements at ATLAS

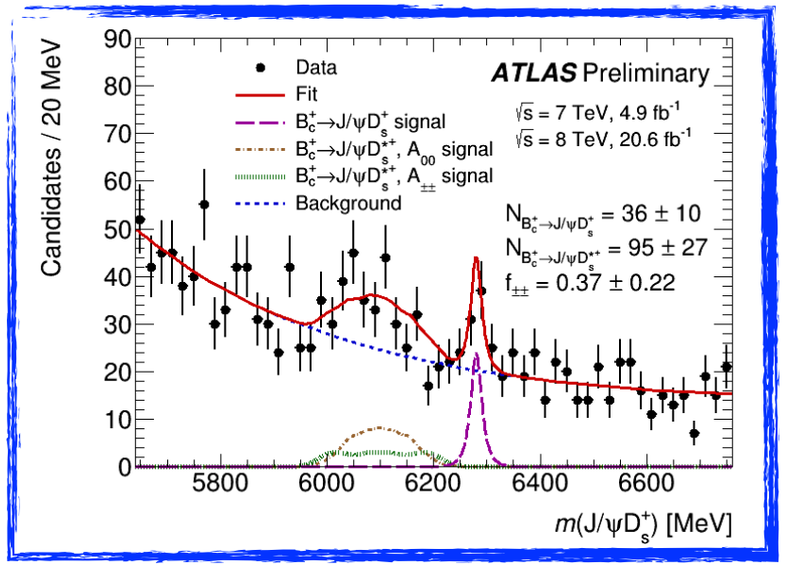
Introduction

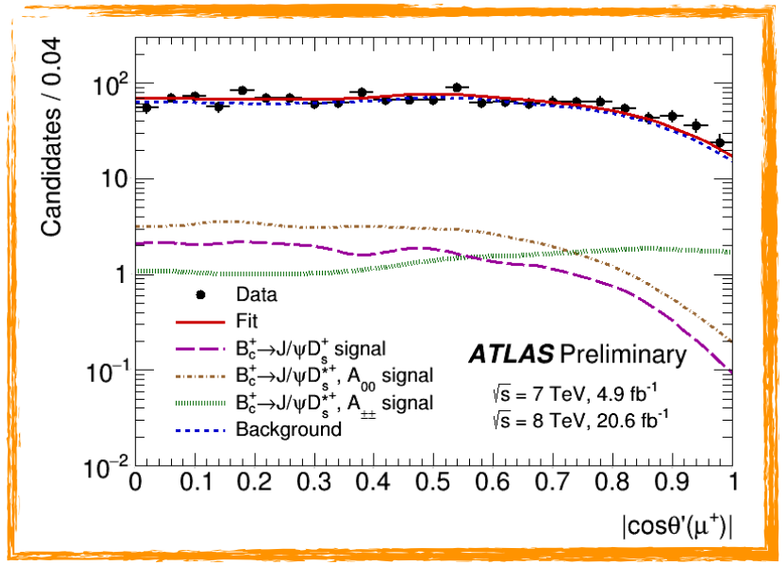
√	Associated production of prompt and non-prompt J/ψ mesons and Z boson at $\sqrt{s}$ = 8TeV	Eur. Phys. J. C75 (2015) 229
	Search for X_b and other hidden-beauty states using $\pi^+\pi^-\Upsilon(1S)$ channel	Phys. Lett. B 740 (2015) 199-217
	Cross-section measurement of ψ(2S) → J/ψ (→ $\mu^+\mu^-$) $\pi^+\pi^-$ at $\sqrt{s}$ = 7TeV	JHEP 09 (2014) 079
	ϕ_s and $\Delta\Gamma_s$ from flavour tagged time dependent angular analysis of $B^0_s \rightarrow J/\psi\,\phi$	Phys. Rev. D 90 (2014) 052007
	Observation of an excited $B^{\pm}_c$ meson state with the ATLAS detector	Phys. Rev. Lett. 113 (2014)
√	Branching fractions of $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ and transverse polarization fraction in the latter decay	ATLAS-CONF-2015-014
√	Study of J/ψ and ψ(2S) production in $\sqrt{s_{NN}}$ = 5.02 TeV p+Pb and $\sqrt{s}$ = 2.76 TeV pp collisions with the ATLAS detector	ATLAS-CONF-2015-023
√	Differential cross-sections of prompt and non-prompt J/ψ and ψ(2S) at $\sqrt{s}$ = 7 and 8 TeV	ATLAS-CONF-2015-024
√	Measurement of the differential non-prompt J/ψ production fraction in $\sqrt{s}$ = 13 TeV p p collisions at the ATLAS experiment	ATLAS-CONF-2015-030
√	Observation of Λ_b in the decay $\Lambda_b^0 \rightarrow \psi(2S)\,\Lambda^0$	

Quarkonium and heavy flavour production measurements at ATLAS

Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{+*}$ decays

- B_c^+ consists of a b and c quark $\bar{b} \to \bar{c}c\bar{s}$ processes occur via
  - colour-allowed and colour-suppressed spectator diagrams
  - weak annihilation diagrams
- Study B_c^+ decay to $J/\psi D_s^+$ and $J/\psi D_s^{+*}$
  - $D_s^+ \to \phi\pi^+$ ($\phi \to K^+K^-$)
  - $D_s^{+*} \to D_s^+ +$ soft photon or pion
- $B_c^+ \to J/\psi D_s^{+*}$
  - pseudoscalar meson to a pair of vector states transition
  - described by three helicity amplitudes
  - A_{++}, A_{--}, A_{00}





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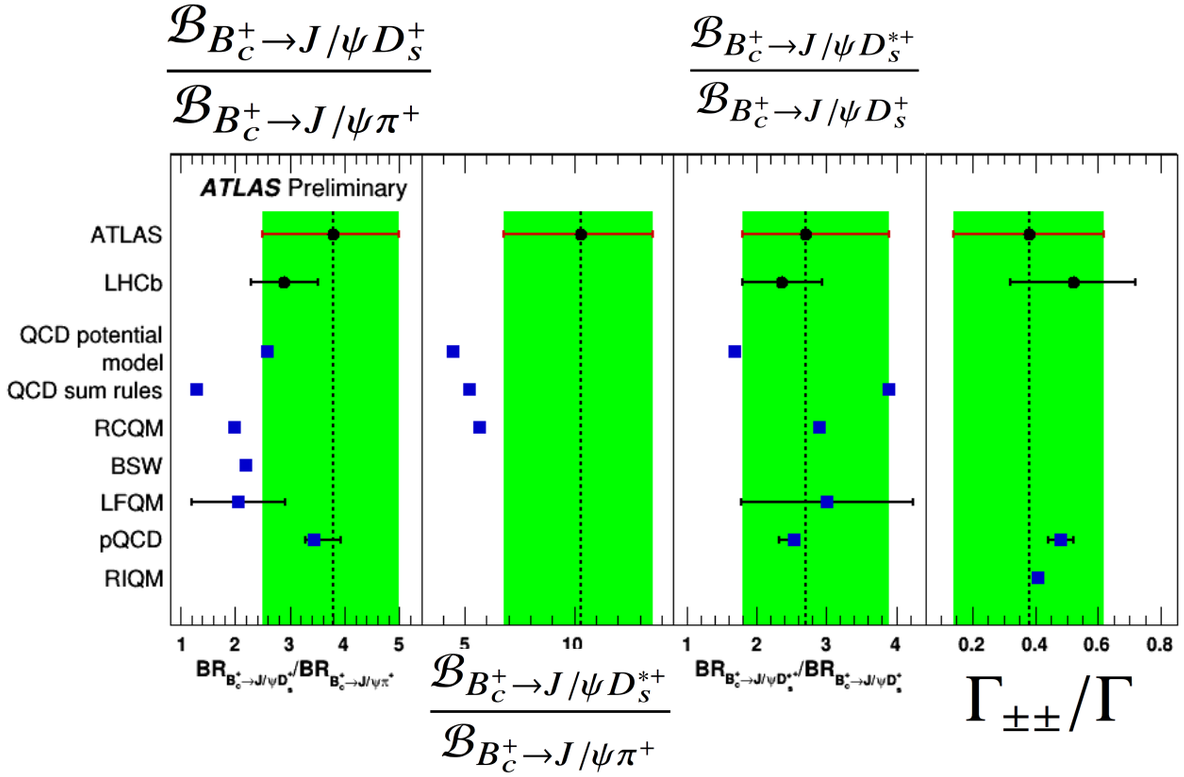
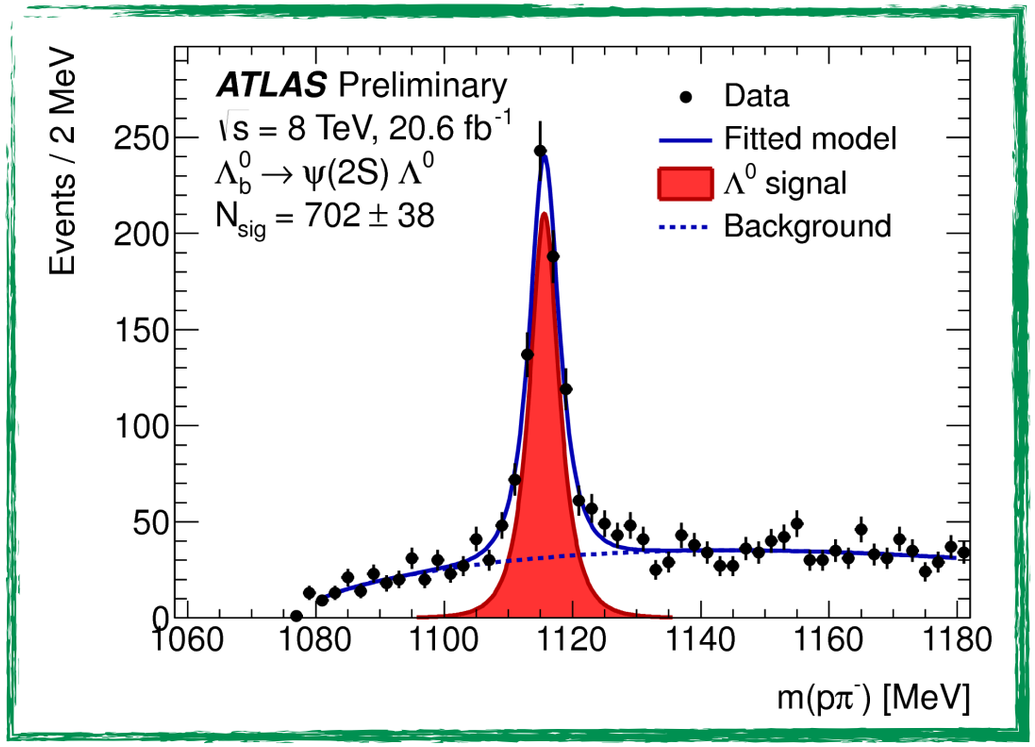


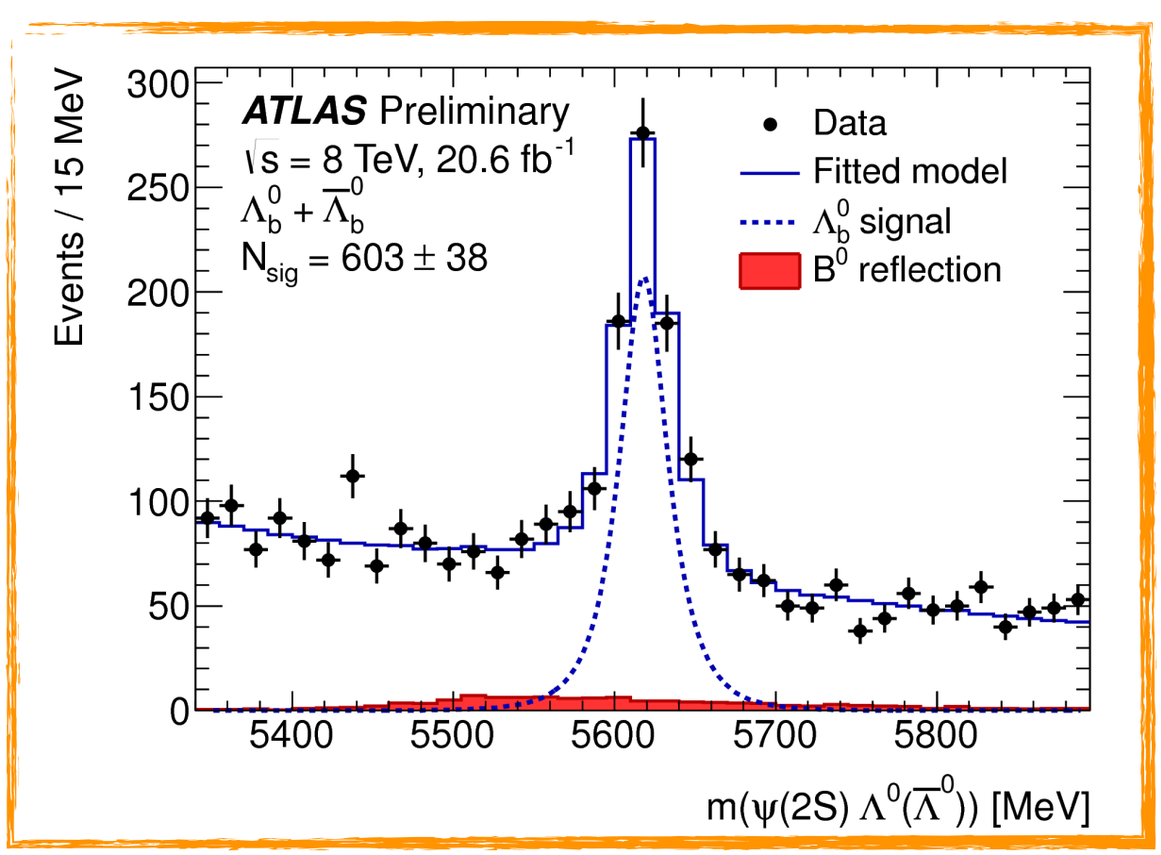
- Two dimensional extended unbinned ML fit
  - mass and helicity angle
- Both √s = 7 and 8 TeV data sets
  - 4.9 and 20.6 fb^{-1}
- Use an ensemble of single, di-muon and three-muon triggers

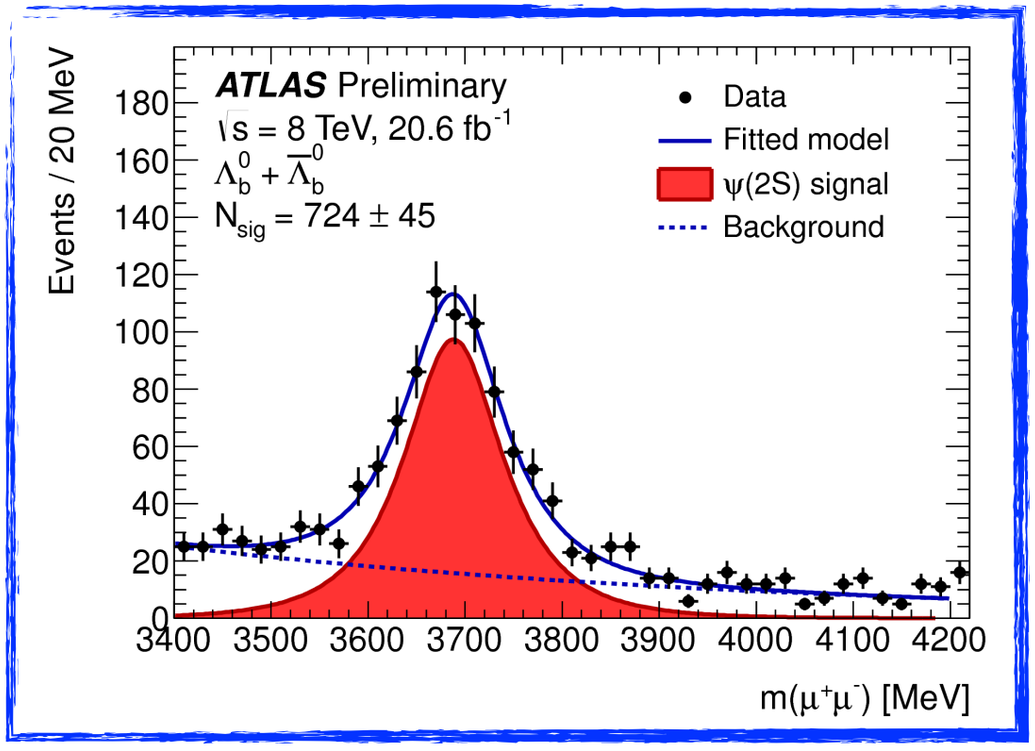
Quarkonium and heavy flavour production measurements at ATLAS

Observation of Λ_b in the decay $\Lambda_b^0 \rightarrow \psi(2S)\,\Lambda^0$

- First observation of $\Lambda_b^0 \rightarrow \psi(2S)\,\Lambda^0$
- Measurement of branching ratio $\Gamma(\Lambda_b^0 \rightarrow \psi(2S)\,\Lambda^0)/\Gamma(\Lambda_b^0 \rightarrow J/\psi\,\Lambda^0)$
  - onia reconstructed in the di-muon mode
  - $\Lambda^0 \rightarrow p^-\pi^+$
  - $= 0.501 \pm 0.033$ (stat.) ± 0.016 (syst.) ± 0.011 (B)
  - theory prediction: 0.8 ± 0.1
- $\sqrt{s}$ = 8 TeV data set
  - 20.6 fb^{-1}







arXiv: link IF AVAILABLE

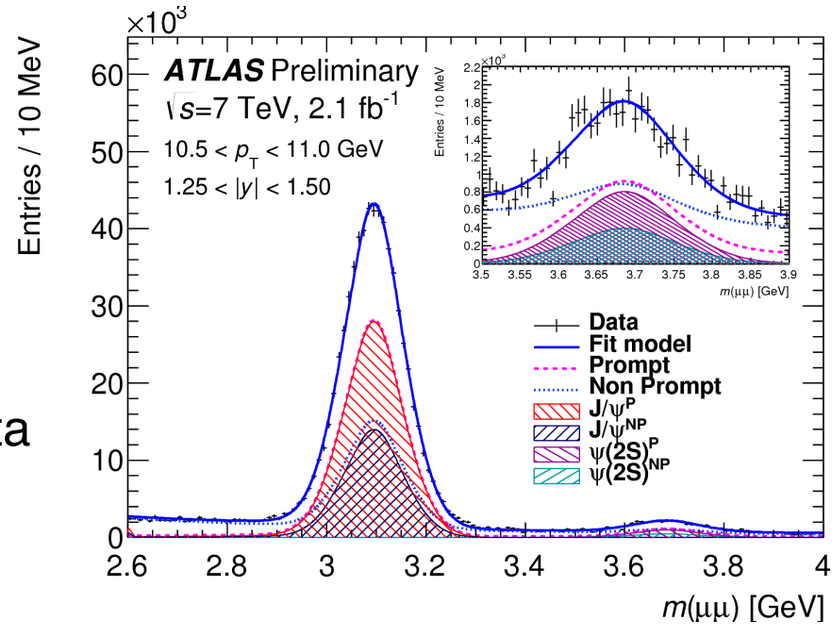
Quarkonium and heavy flavour production measurements at ATLAS

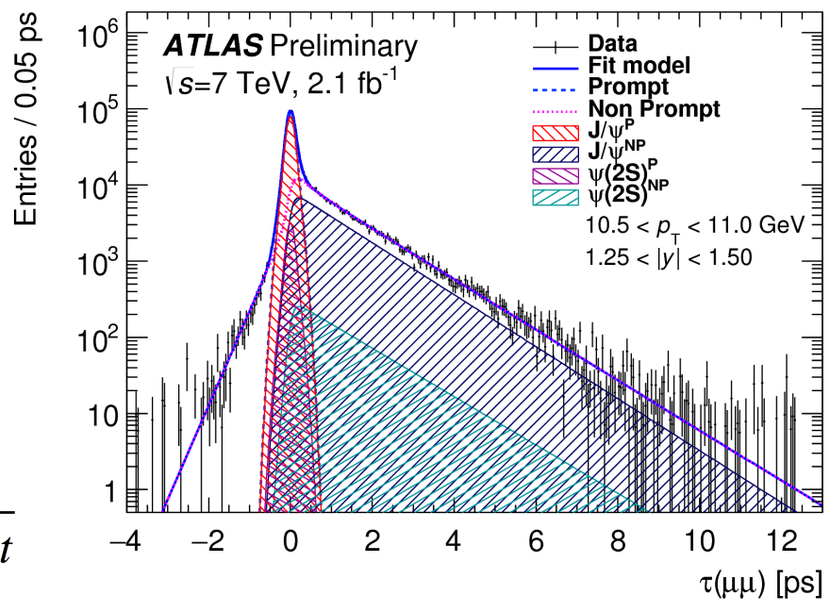
Prompt and non-prompt *J/ψ* and *ψ(2S)* production at $\sqrt{s}$ = 2.76, 7 and 8 TeV

- Quarkonia provide a unique opportunity to study QCD
- Hidden flavour presents significant challenges
  - theory and experiment
- Many theoretical models available
  - Colour Singlet Model
    - NNLO contributions calculated without introducing new phenomenological parameters
    - impossible to extend the calculation to P-wave states
  - Non-relativistic QCD (NRQCD)
    - parameters included, determined from fits to experimental data
    - good description of cross-sections - fail on polarisation
  - excuse me if your favourite one is not listed here
- Quarkonia are produced
  - QCD sources (prompt)
  - subsequent decays of *b*-hadrons (non-prompt)
    - ψ(2S) has no significant feed-down from higher states
- 4 pb^{-1} of $\sqrt{s}$=2.76 TeV, 2.1 fb^{-1} of $\sqrt{s}$=7 TeV and 11.4 fb^{-1} of $\sqrt{s}$=8 TeV
- J/ψ and ψ(2S) to di-muon final state
  - di-muon trigger
- Differential cross-section

$$\frac{\mathrm{d}^2\sigma(pp \to \psi)}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{N_\psi^\mathrm{p}}{\Delta p_\mathrm{T} \Delta y \times \int \mathcal{L}\mathrm{d}t}$$

Two dimensional unbinned maximum likelihood fit to separate prompt and non-prompt component





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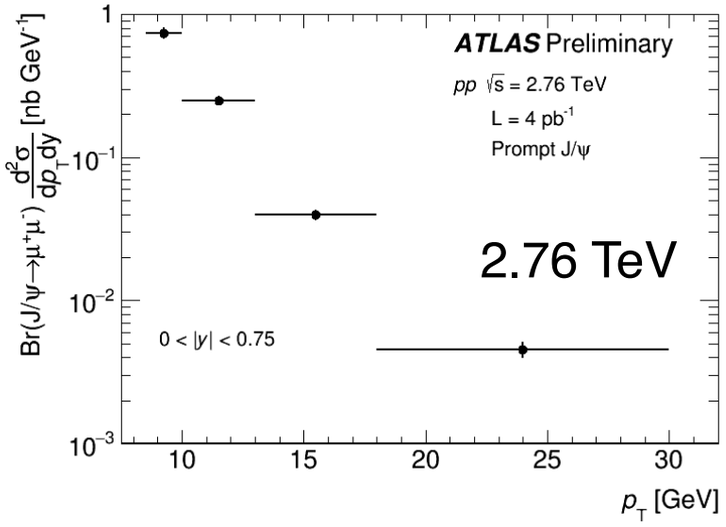
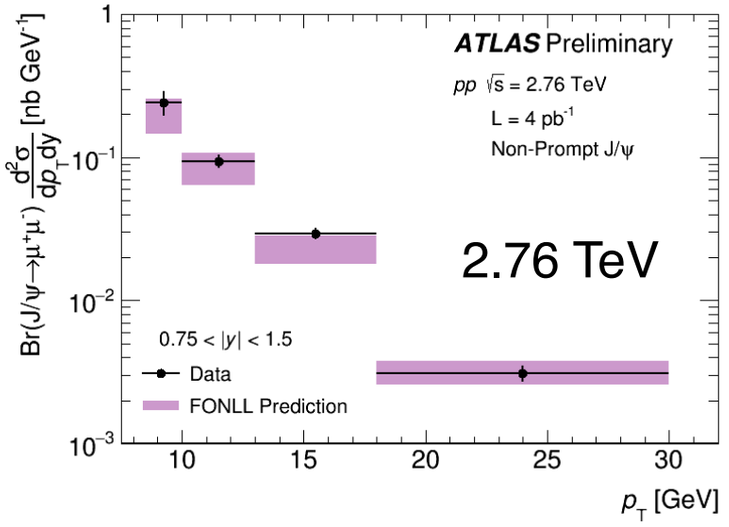
Quarkonium and heavy flavour production measurements at ATLAS

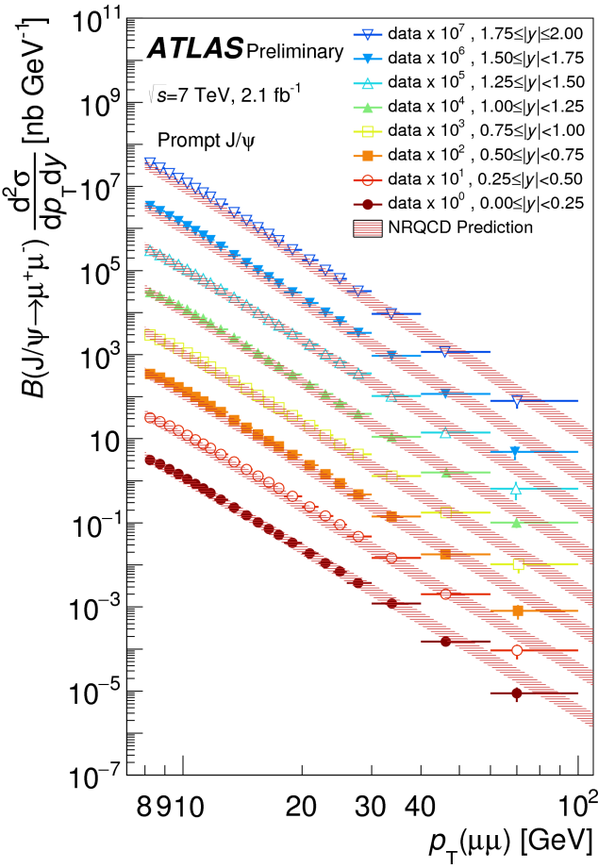
Prompt and non-prompt ***J/ψ*** and *ψ(2S)* production at $\sqrt{s}$ = 2.76, 7 and 8 TeV

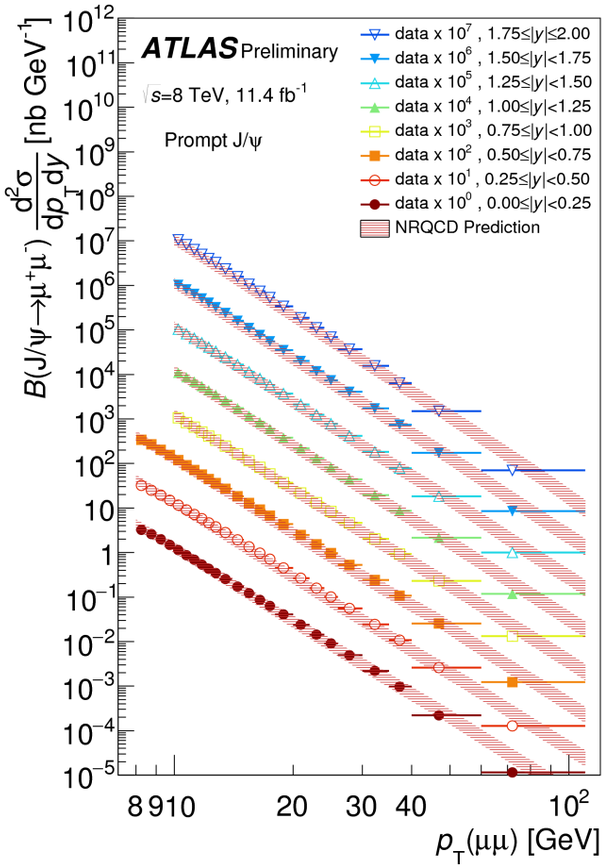
- Correcting for
  - trigger and reconstruction efficiencies
  - acceptance (depending on spin-alignment)
    - isotropic scenario considered for main result
- Double differential cross-section
  - 22 p_T bins: 8-110 GeV
  - 8 lyl bins: 0-2



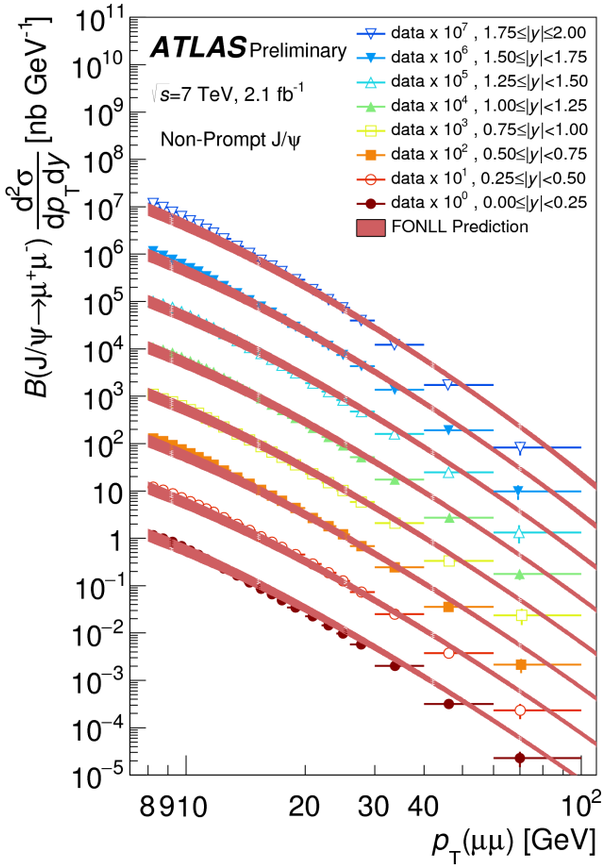


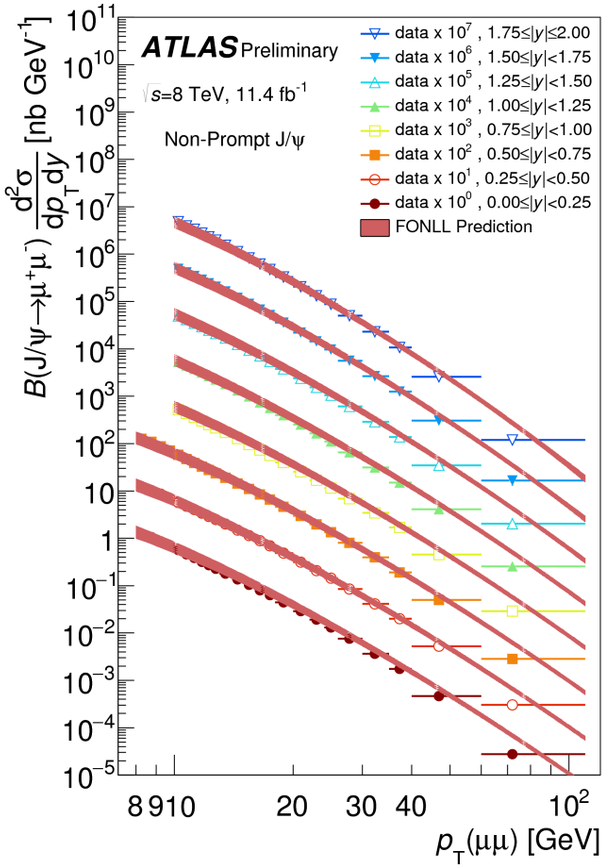
prompt





non-prompt





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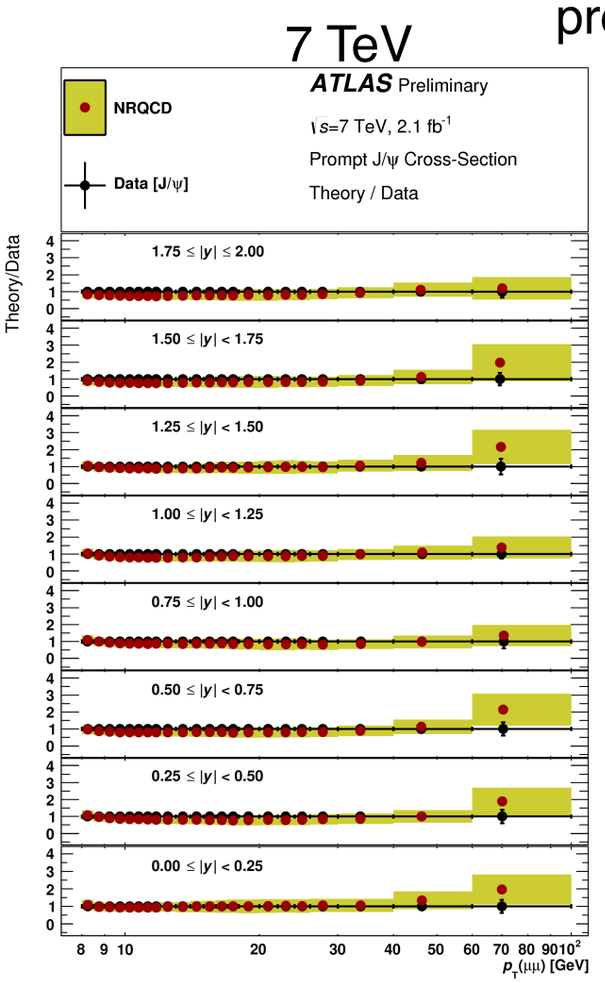
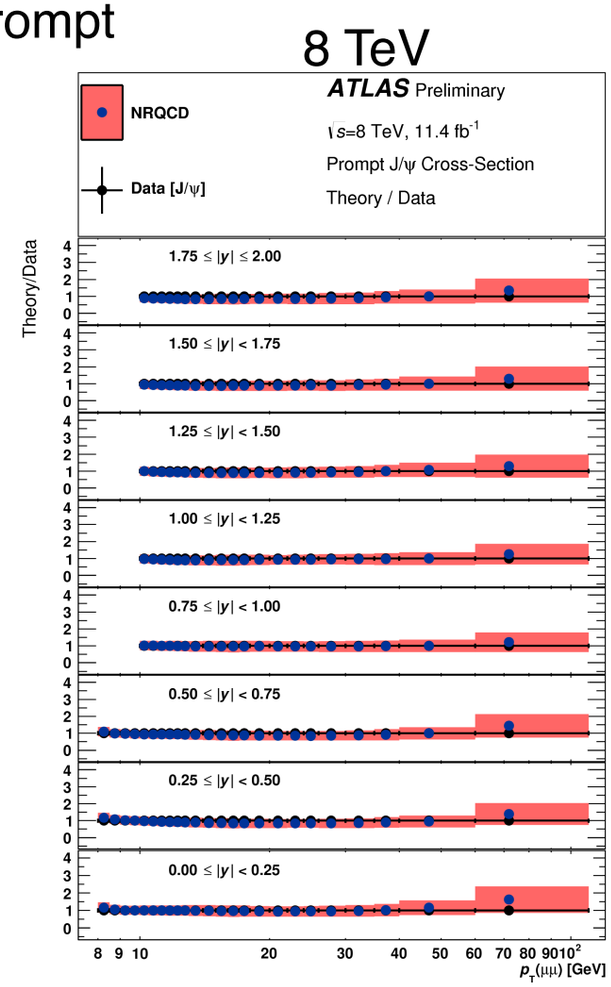
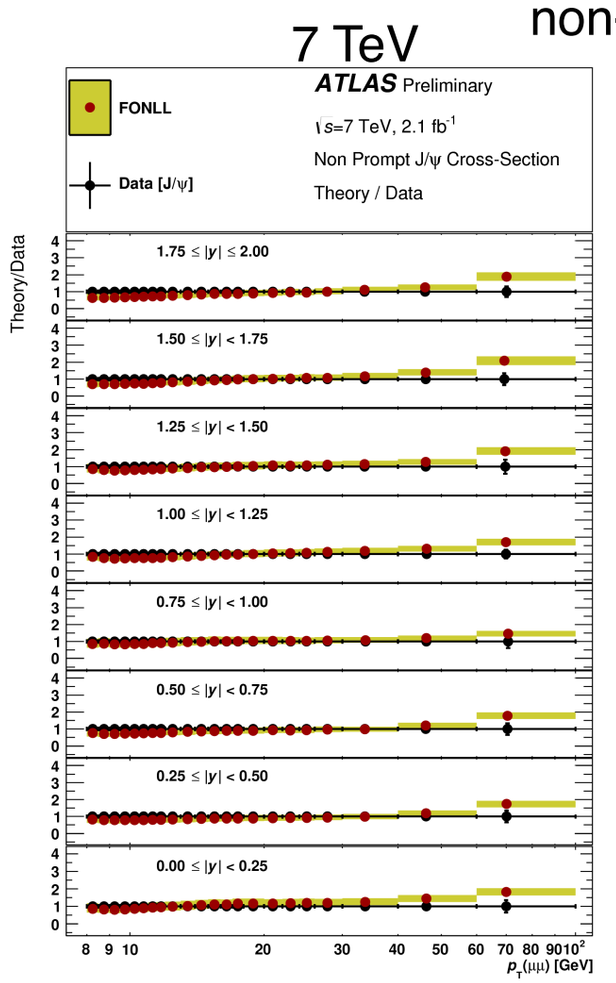
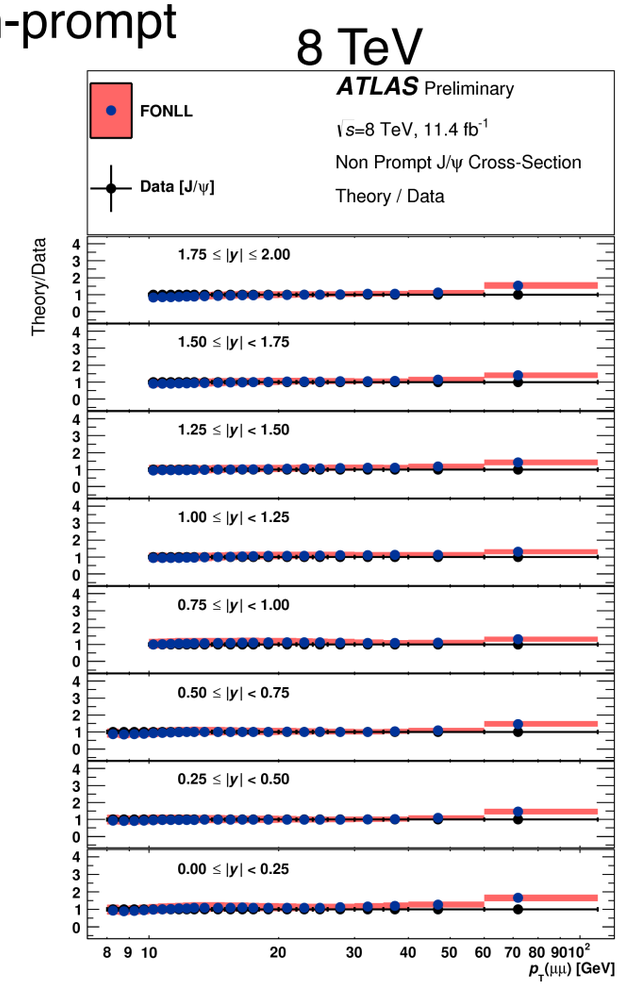




non-prompt





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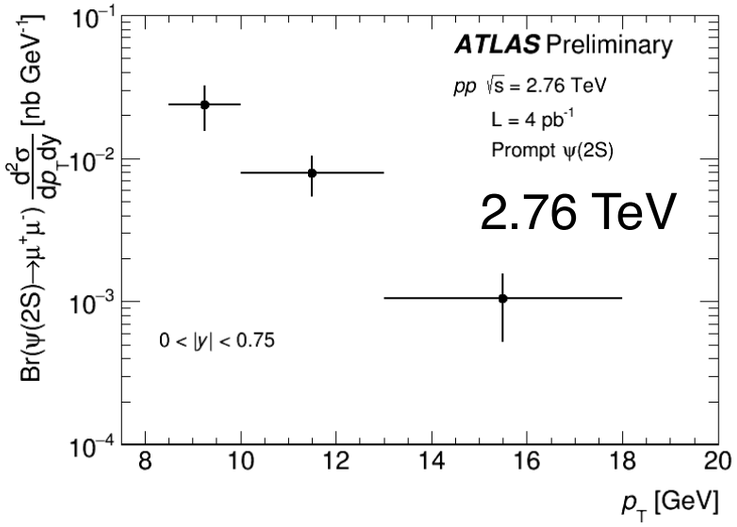
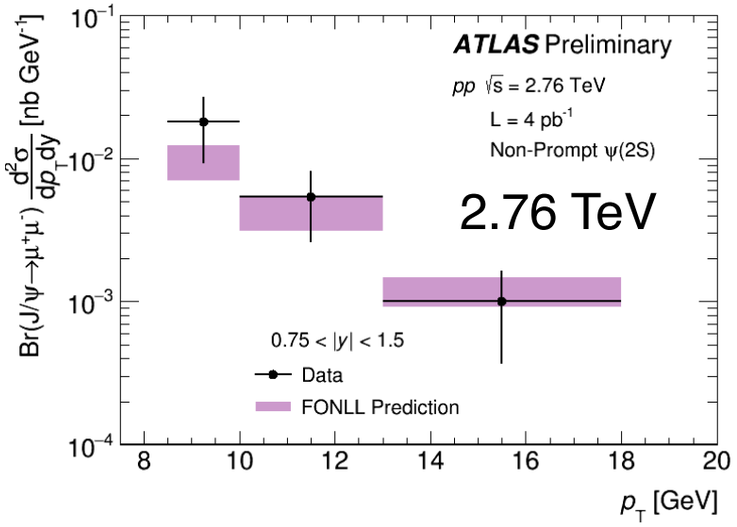
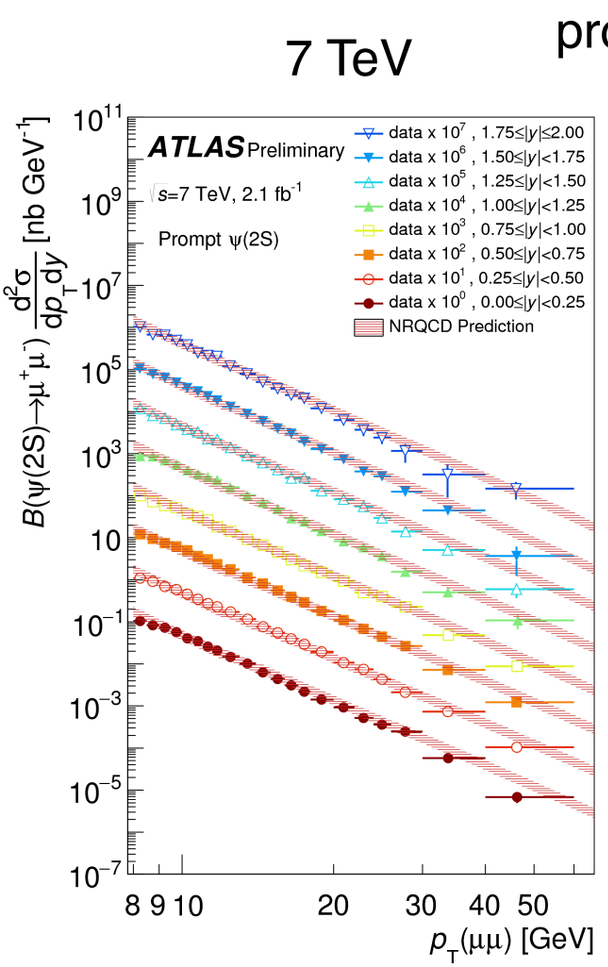
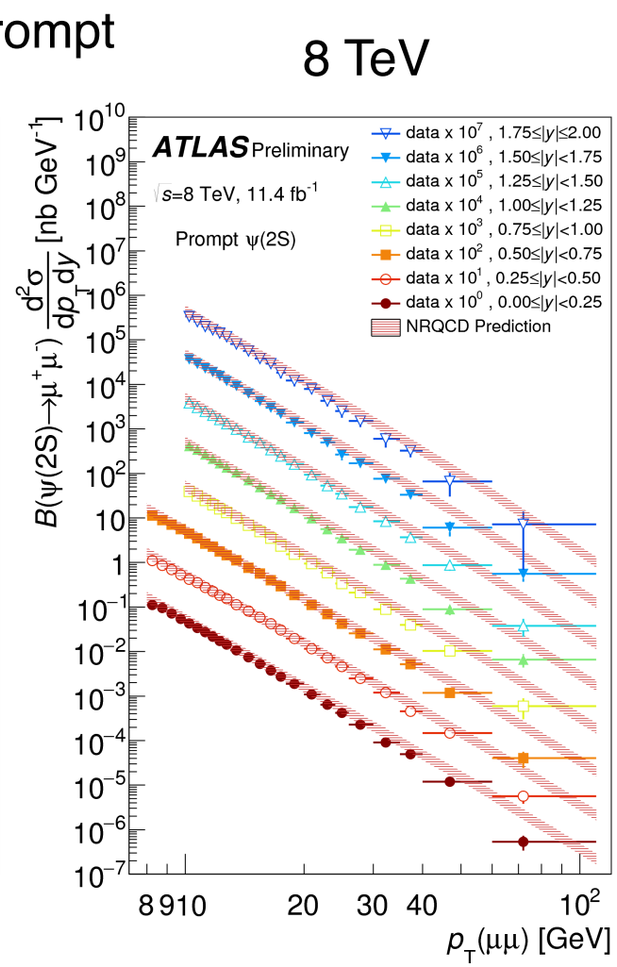
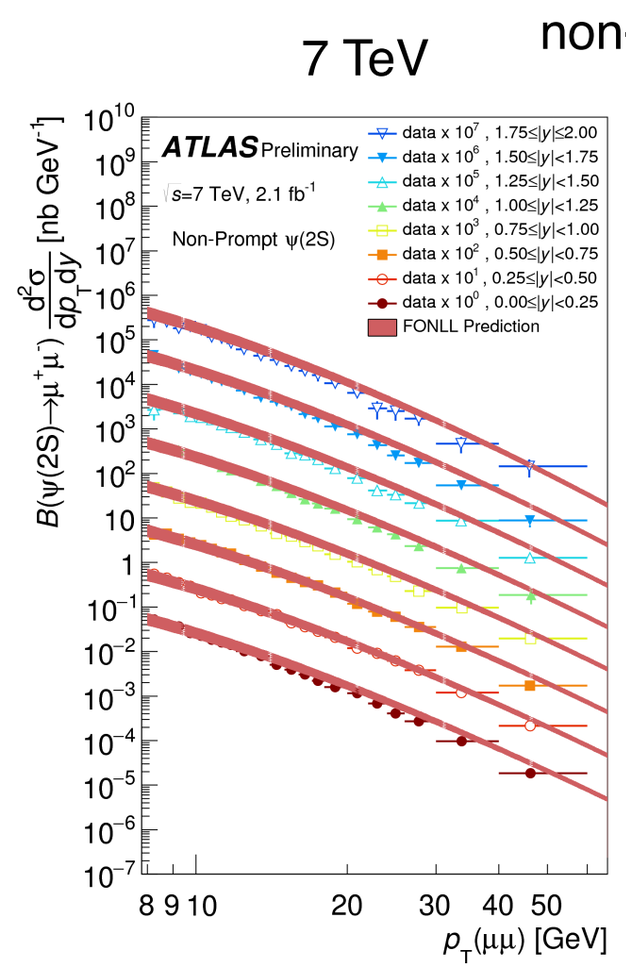
- Slight overestimation of non-prompt *ψ(2S)* production compared with *J/ψ* predictions

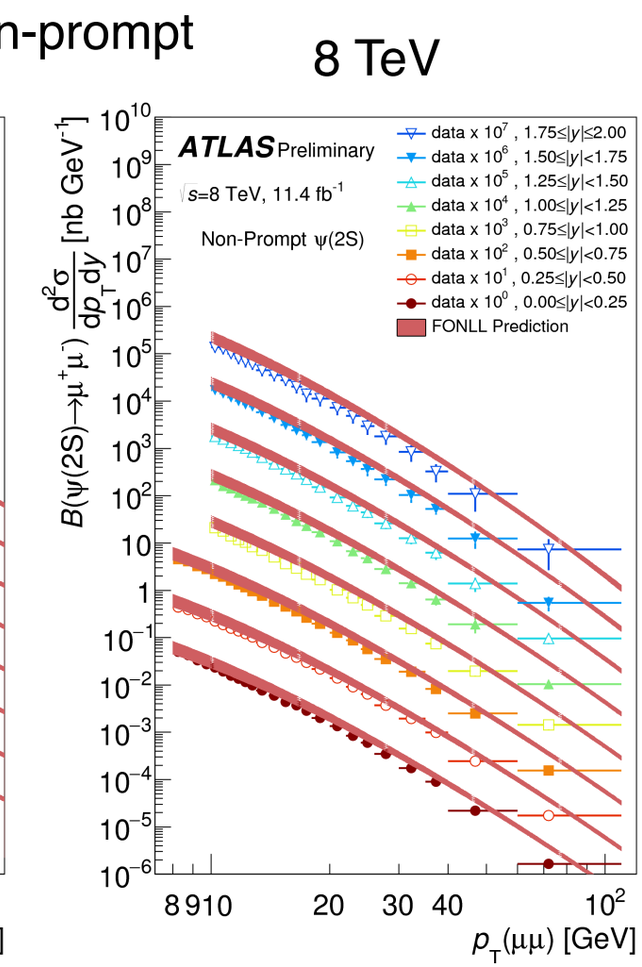












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- Good agreement across range of p_T
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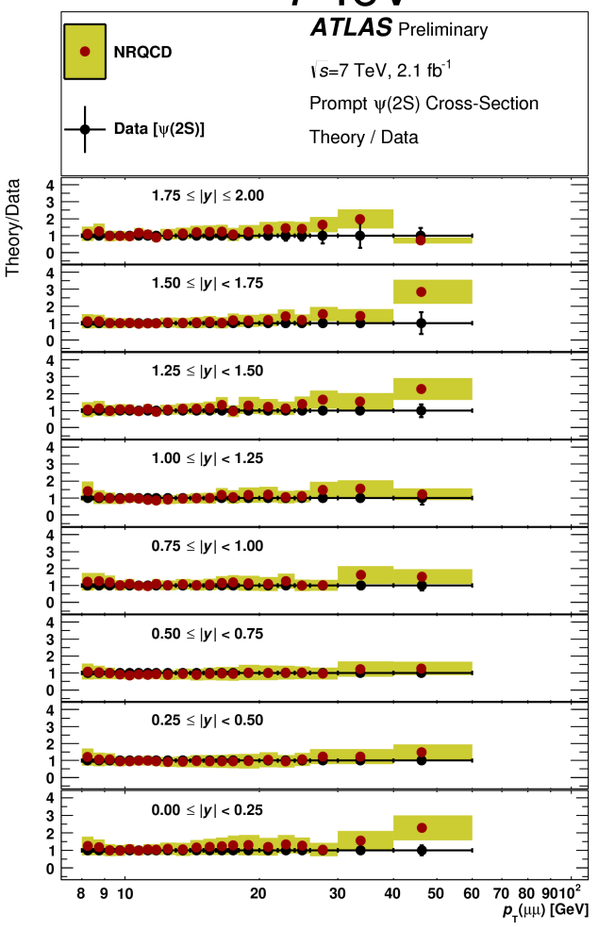
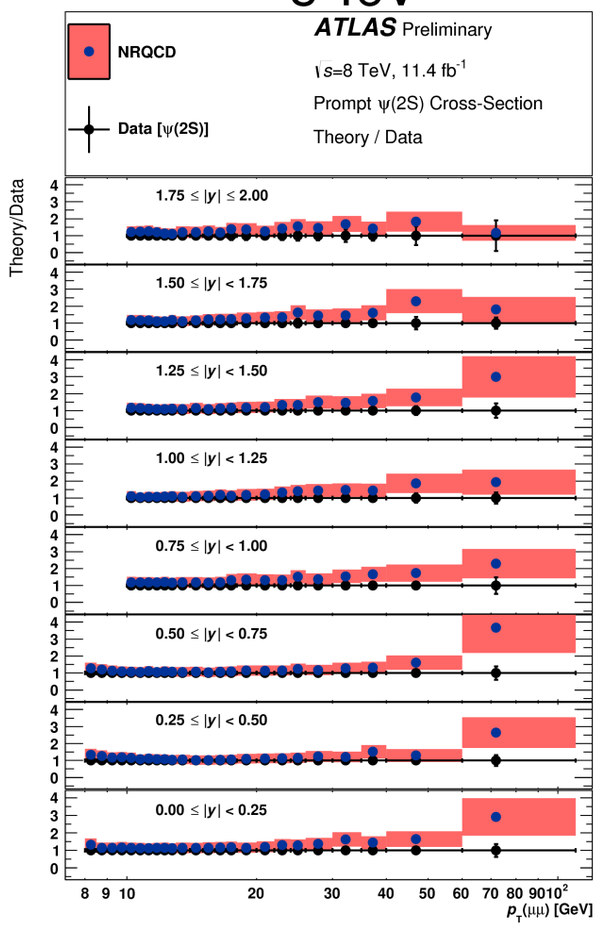
prompt

7 TeV

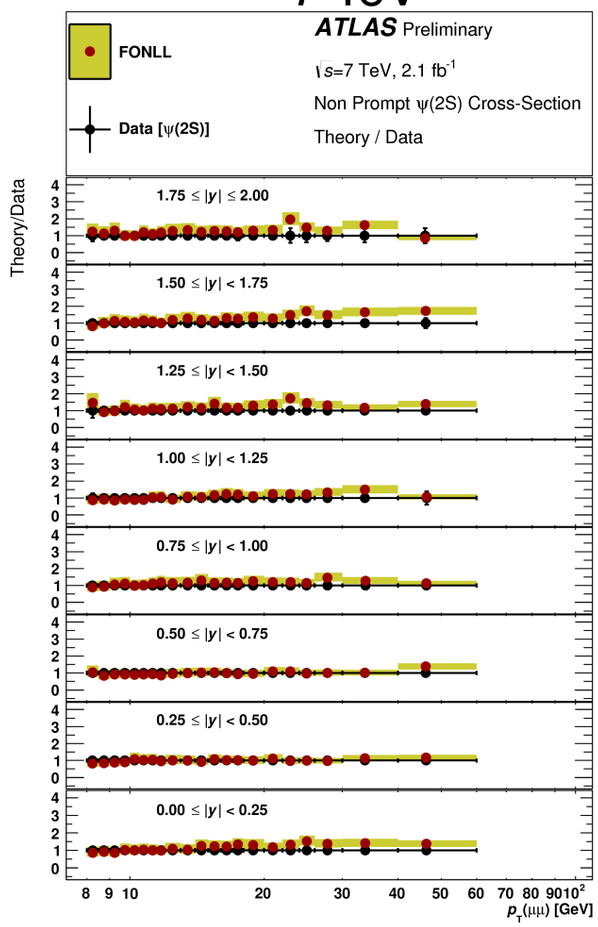


8 TeV

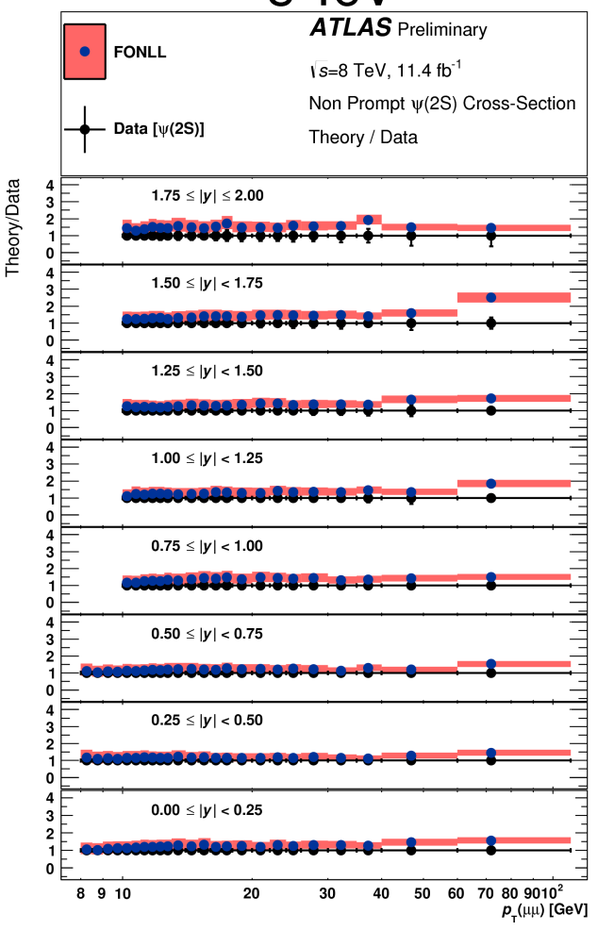


non-prompt

7 TeV



8 TeV



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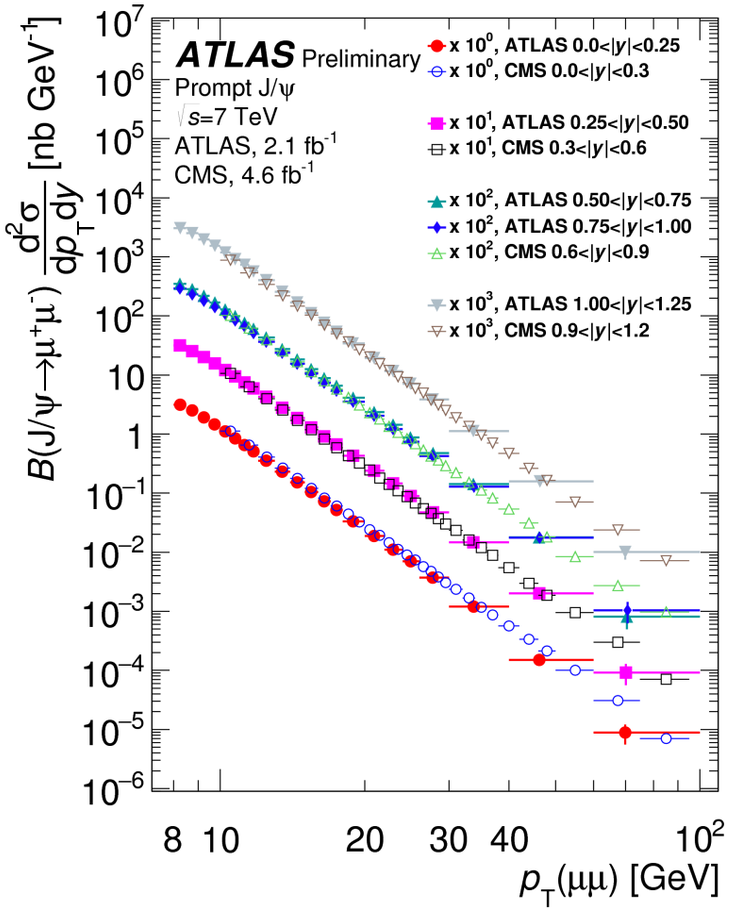
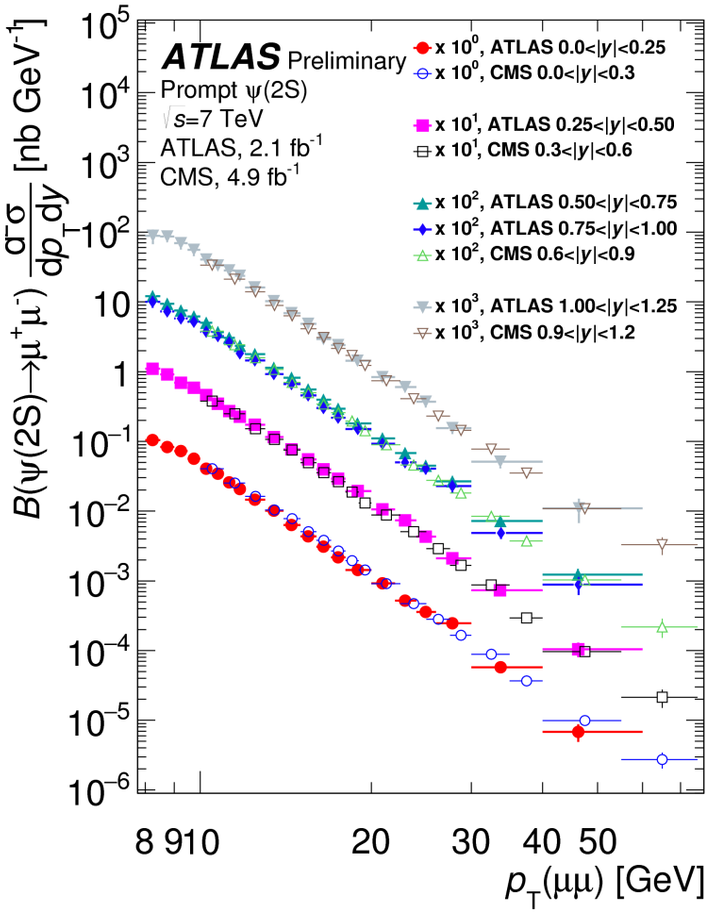
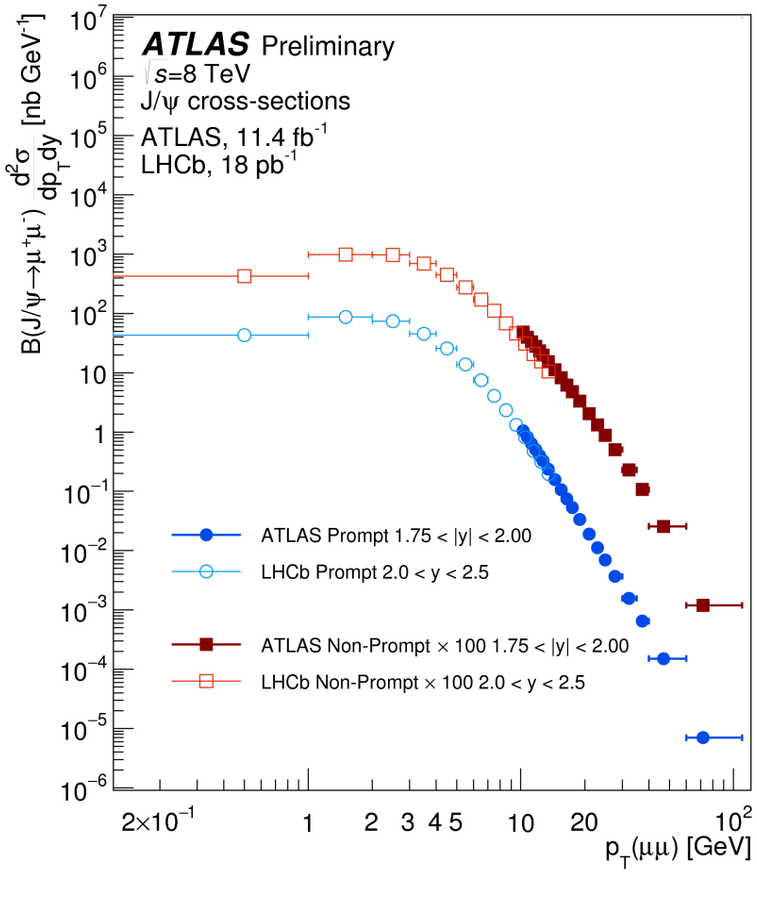
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt *J/ψ* and *ψ(2S)* production at $\sqrt{s}$ = 2.76, 7 and 8 TeV

- Comparison with CMS[1] and LHCb[2] results
  - overlapping regions of p_T and |y| shows good agreement
- Combination of LHC measurements provide a wide coverage on p_T and |y|







ATLAS-CONF-2015-024

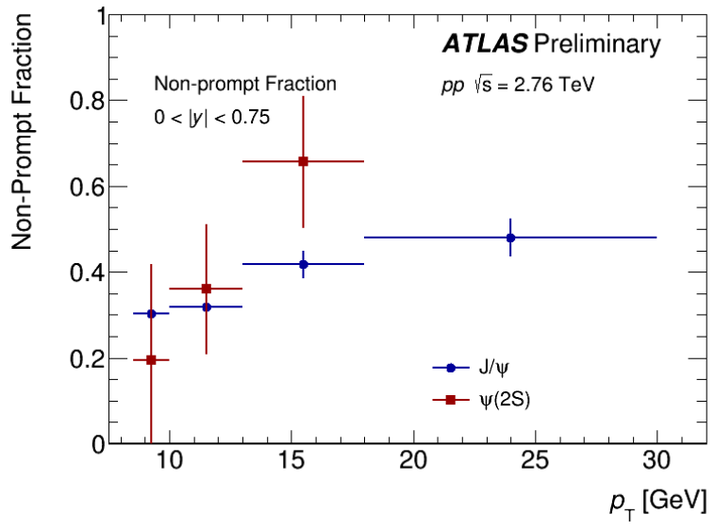
[1] Phys. Rev. Lett. 114.19 (2015) 191802
[2] JHEP 1306 (2013) 064

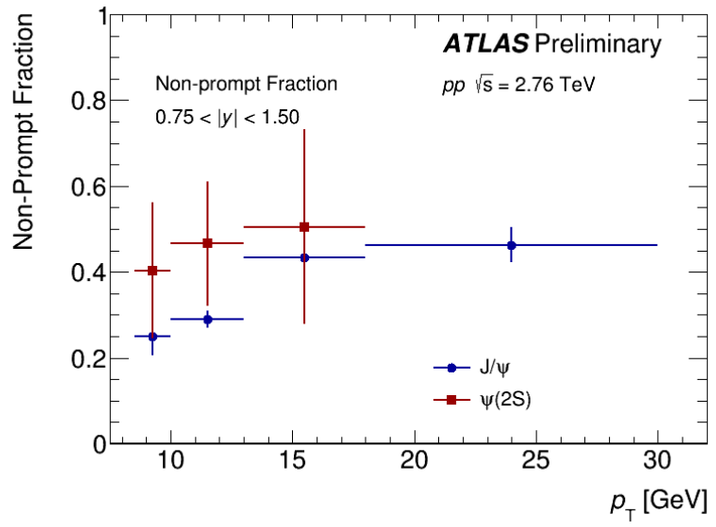
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt *J/ψ* and *ψ(2S)* production at $\sqrt{s}$ = 2.76, 7 and 8 TeV

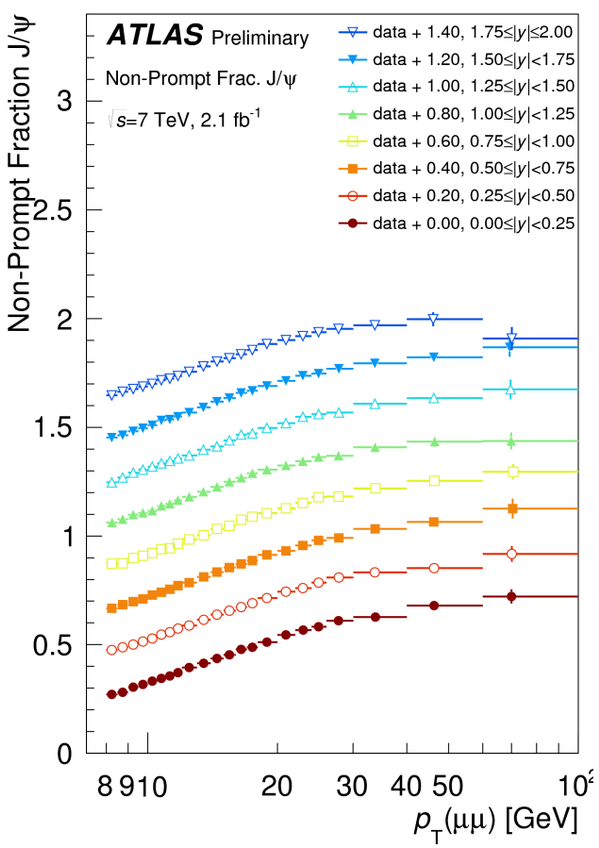
- Measurement of the non-prompt fraction
  - *J/ψ* and *ψ(2S)* at $\sqrt{s}$ = 7 and 8 TeV
  - cancellation of acceptance and efficiency corrections

$$f_b^{\psi} \equiv \frac{pp \to b + X \to \psi + X'}{pp \xrightarrow{\text{Inclusive}} \psi + X'} = \frac{N_{\psi}^{\text{np}}}{N_{\psi}^{\text{np}} + N_{\psi}^{\text{p}}}$$

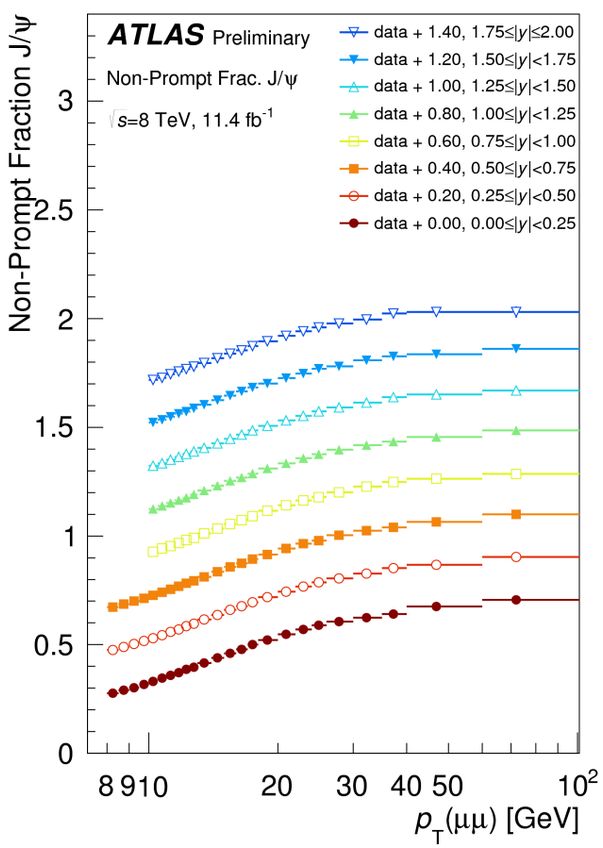




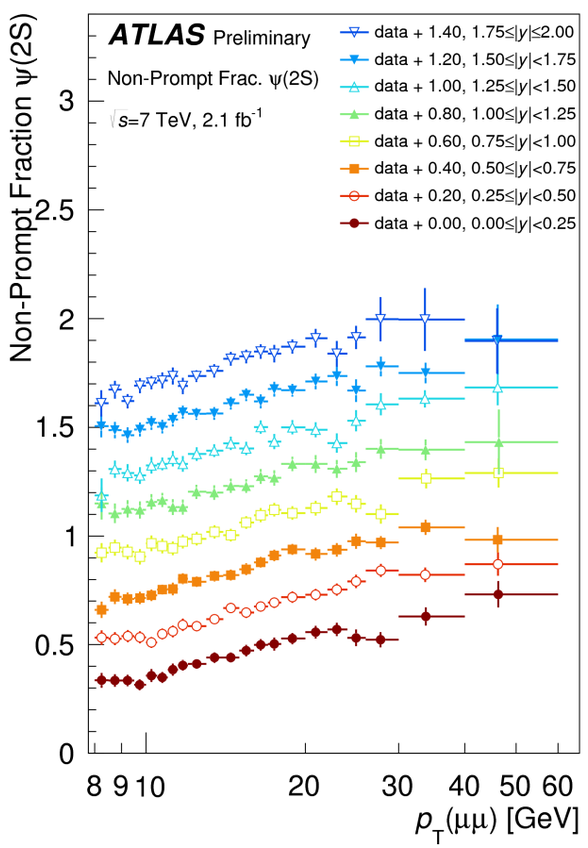
J/ψ 7 TeV



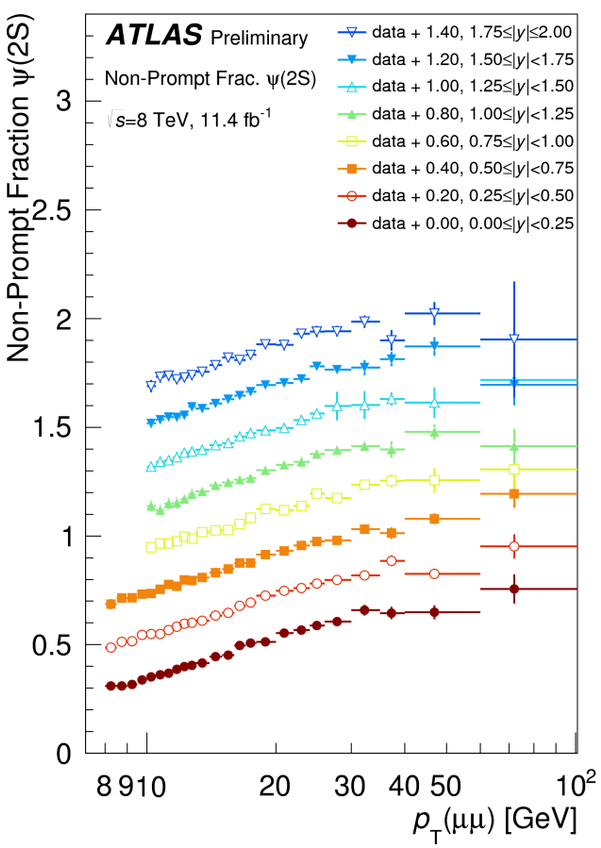
J/ψ 8 TeV



ψ(2S) 7 TeV



ψ(2S) 8 TeV



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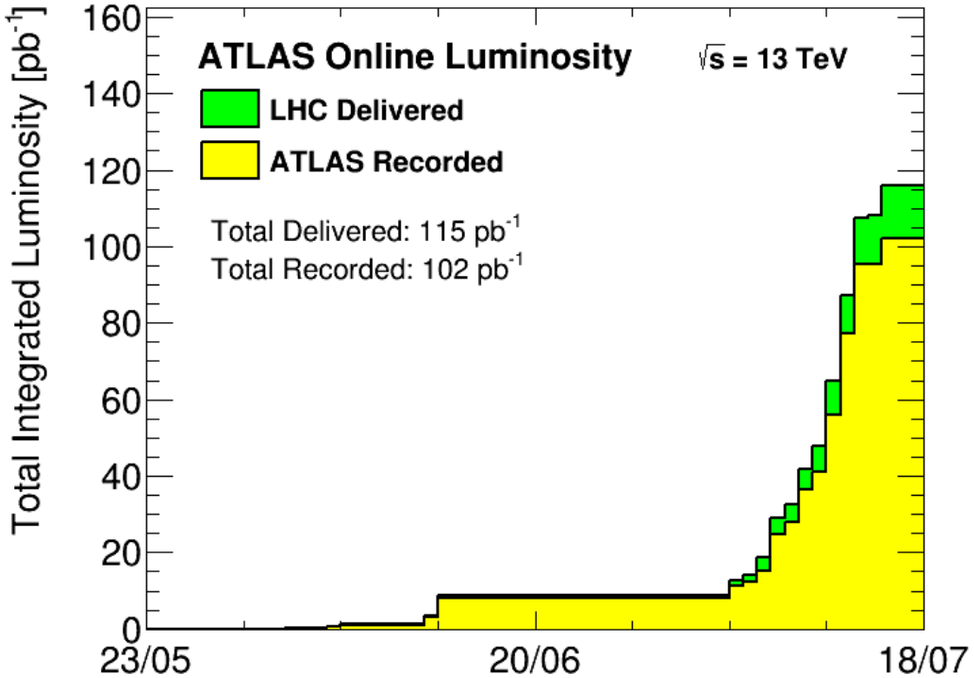
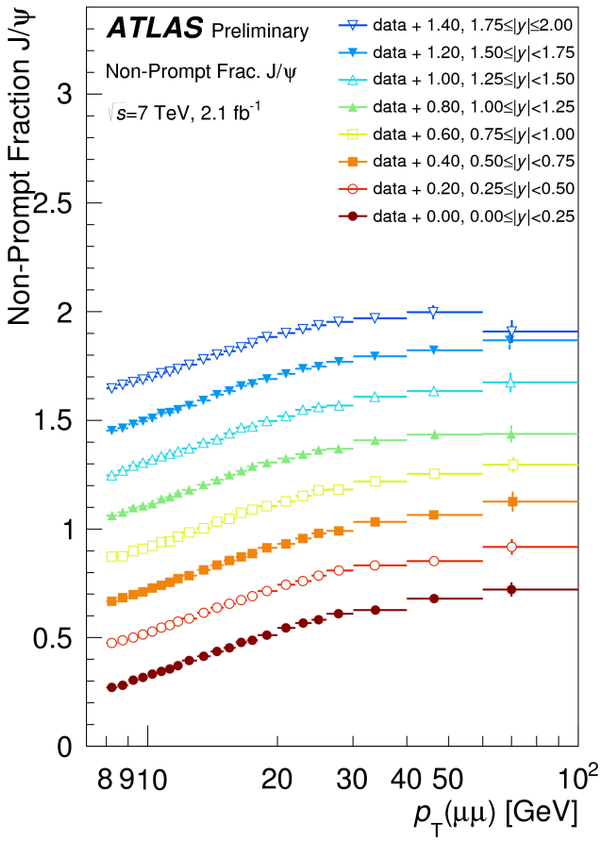
Quarkonium and heavy flavour production measurements at ATLAS

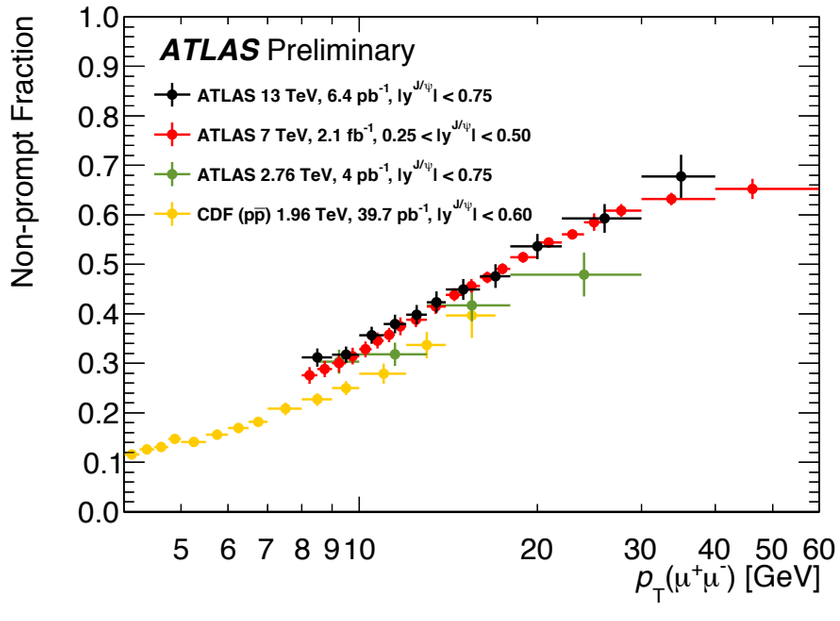
Prompt and non-prompt *J/ψ* and *ψ(2S)* production at $\sqrt{s}$ = 2.76, 7 and 8 TeV and **13 TeV**

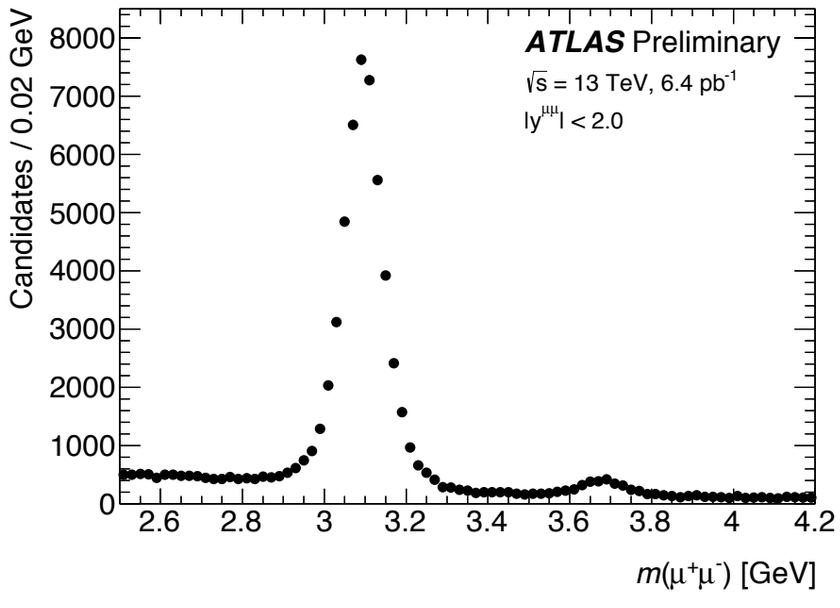
- Measurement of the non-prompt fraction
  - *J/ψ* and *ψ(2S)* at $\sqrt{s}$ = 7 and 8 TeV **+ 13 TeV**
  - low p_T (4 GeV) di-muon or higher p_T (14 GeV) single muon trigger requirement
  - integrated luminosity of 6 pb^{-1}

$$f_b^{\psi} \equiv \frac{pp \to b + X \to \psi + X'}{pp \xrightarrow{\text{Inclusive}} \psi + X'} = \frac{N_{\psi}^{\text{np}}}{N_{\psi}^{\text{np}} + N_{\psi}^{\text{p}}}$$







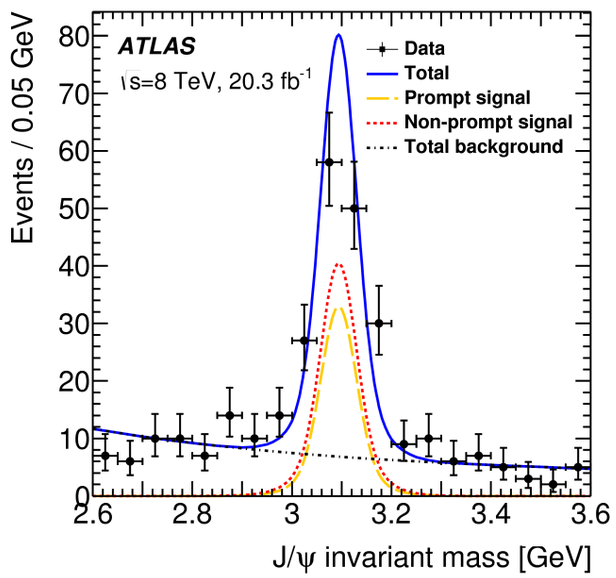


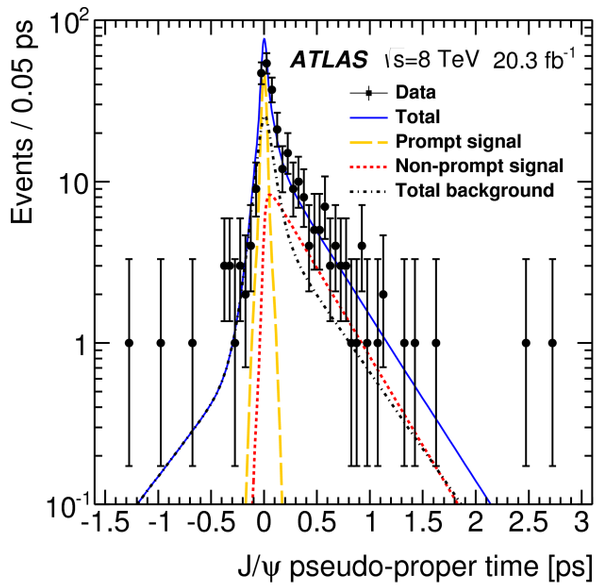
ATLAS-CONF-2015-030

Quarkonium and heavy flavour production measurements at ATLAS

Associated production of Z bosons with prompt and non-prompt J/ψ mesons

- J/ψ + Z can occur
  - single parton scattering (SPS)
  - double parton scattering (DPS)
- J/ψ can be produced
  - prompt
  - non-prompt
- Additional observables and new final states provides further constraints on the contributions from colour-singlet and colour-octet production processes





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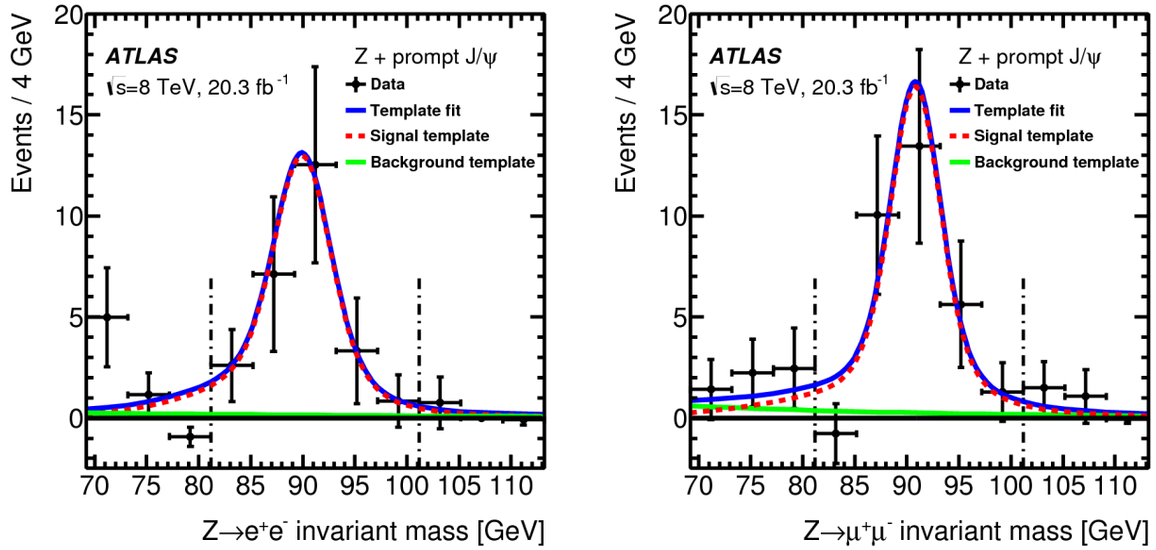
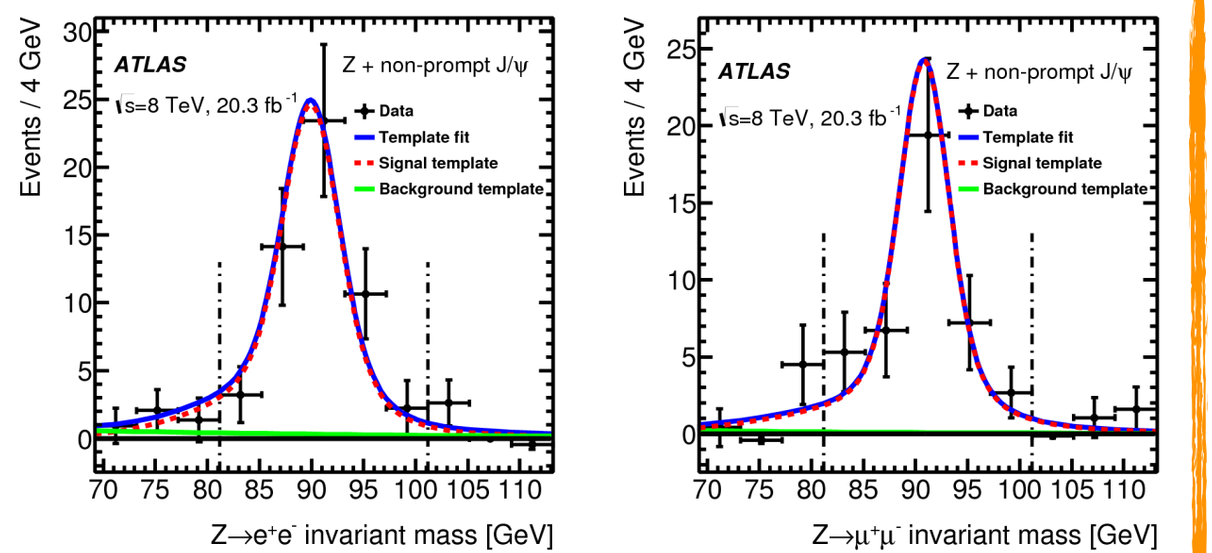
- Using 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV data
  - high-p_T single muon trigger
- Two dimensional unbinned maximum likelihood fit to separate prompt and non-prompt component

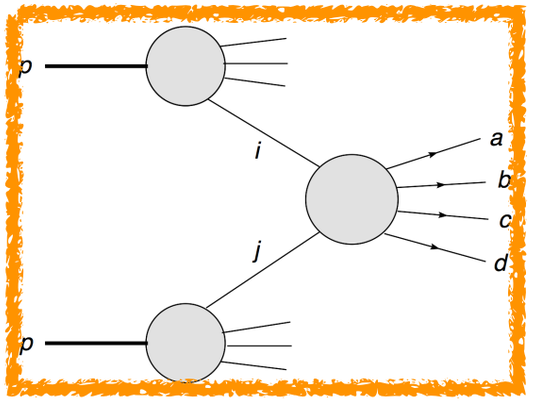


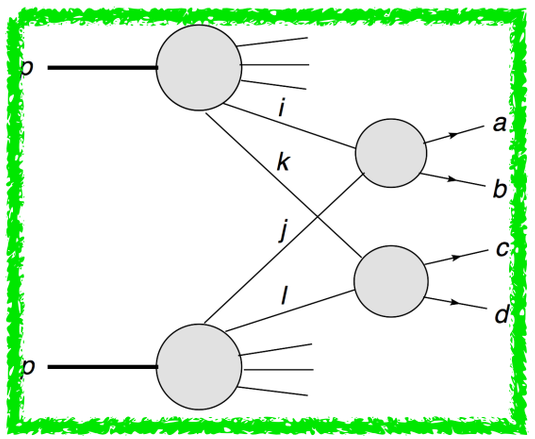


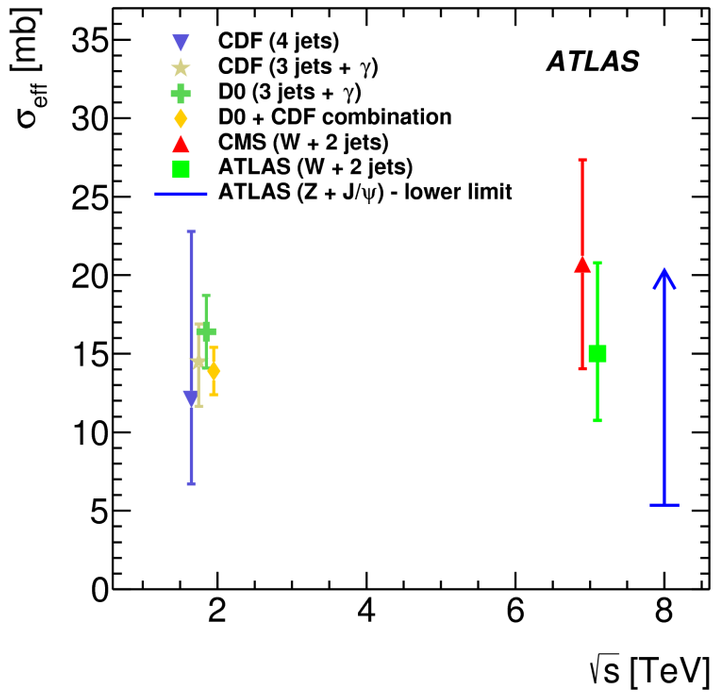
Quarkonium and heavy flavour production measurements at ATLAS

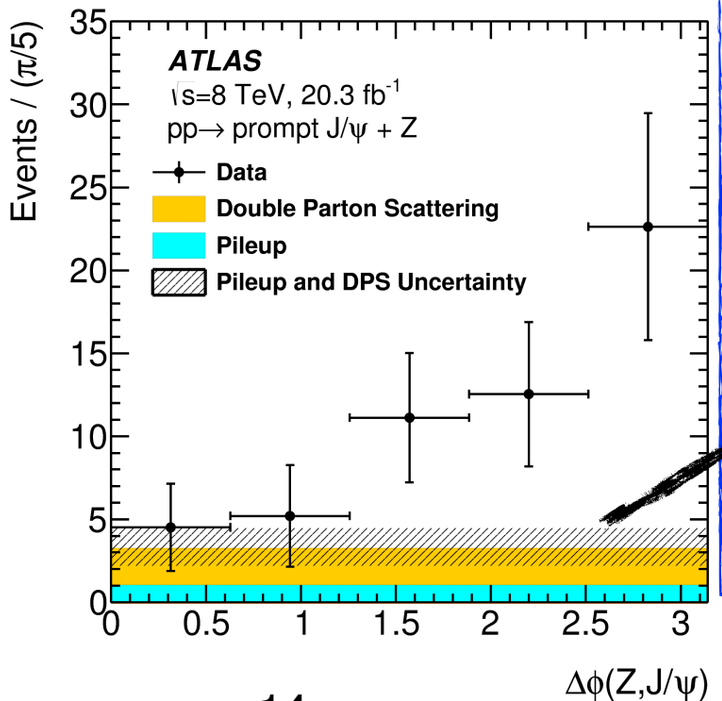
Associated production of Z bosons with prompt and non-prompt J/ψ mesons

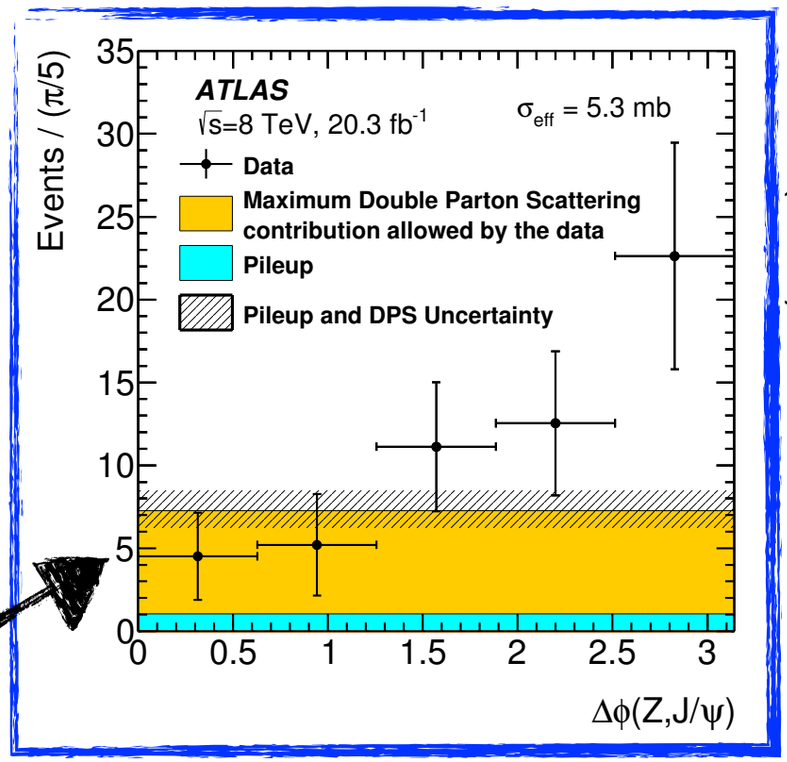
- Single parton scattering
  - both objects from the same interaction
- Double parton scattering
  - each object from independent scatter
- Indistinguishable on an event-by-event basis
- Use of discriminating variables
  - azimuthal angle between the two particles [$\Delta\phi(Z,J/\psi)$]
  - flat contribution from DPS
  - peak at $\Delta\phi=\pi$, from SPS back-to-back production
    - smeared due to detector effects
- DPS governed by a "universal" effective cross-section, σ_{eff}
- Estimation follows:
  - $N_{DPS}=P_{DPS}^{J/\psi}\, N_{fid}^{Z}$
  - $P_{DPS}^{J/\psi} = \sigma_{bin}^{J/\psi} / \sigma_{eff}$
  - σ_{eff} taken from ATLAS W+2jets measurement
- Prompt: $11.1^{+5.7}_{-5.0}$
- Non prompt: $5.8^{+2.8}_{-2.6}$
- Extraction of lower limit on $\sigma_{eff}>5.3$ mb











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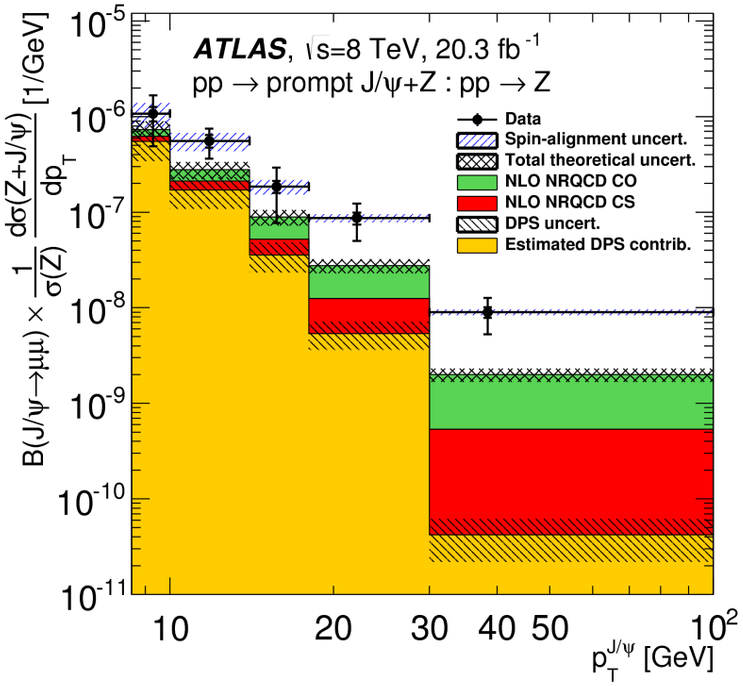
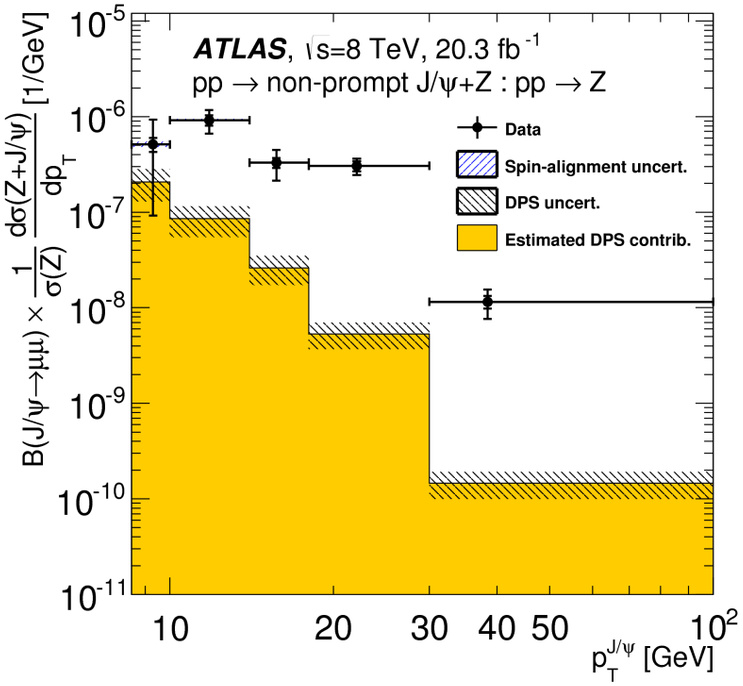
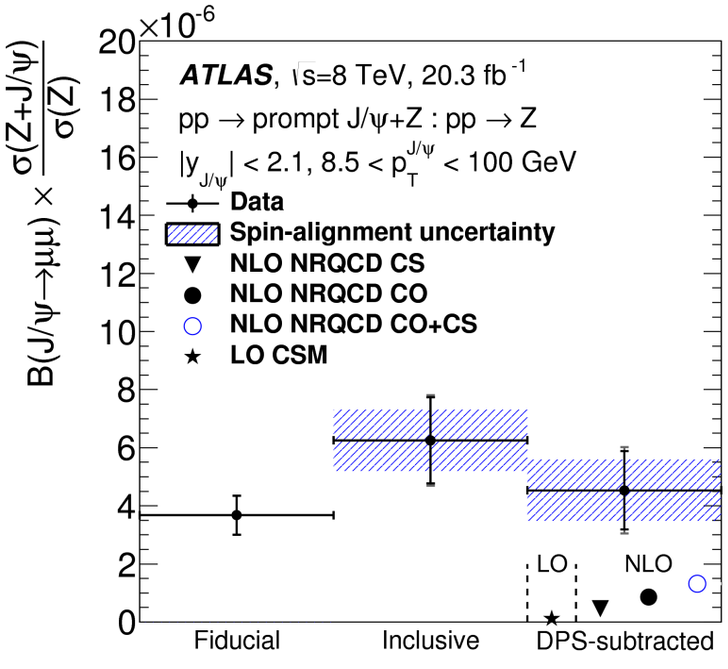
Quarkonium and heavy flavour production measurements at ATLAS

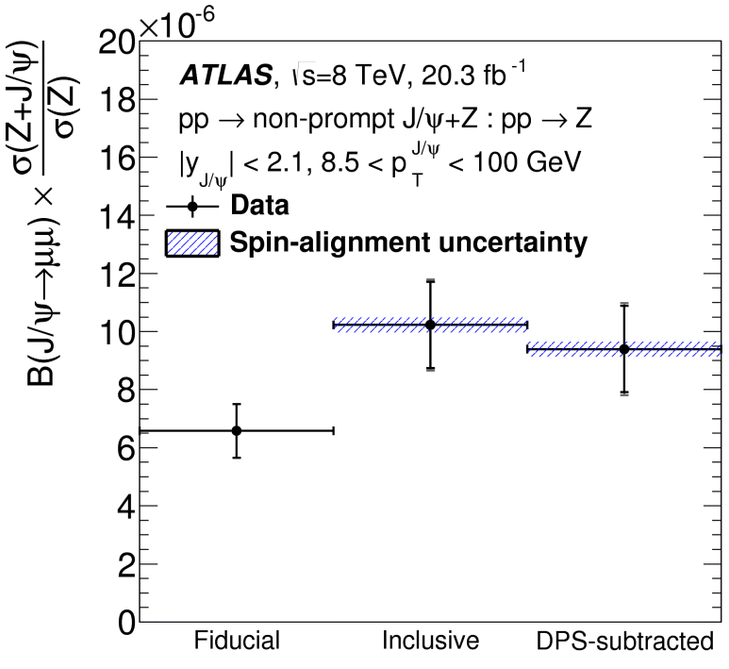
Associated production of *Z* bosons with prompt and non-prompt *J/ψ* mesons

- First observation of *Z+J/ψ*
  - prompt 5σ significance
  - non-prompt 9σ significance
- One of the most rare processes
  - occurs 10 times every million *Z* bosons
- Total cross sections
  - theory is underestimating the SPS production
- Differential cross sections
  - low p_T dominated by DPS
  - SPS drops off less steeply with p_T than DPS
  - Theory discrepancy more pronounced with higher p_T
- DPS fraction is
  - 29% for the prompt *J/ψ + Z*
  - 8% for the non-prompt *J/ψ + Z*









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Quarkonium and heavy flavour production measurements at ATLAS

Conclusions

√	Associated production of prompt and non-prompt J/ψ mesons and Z boson at √s = 8TeV	Eur. Phys. J. C75 (2015) 229
	Search for X_b and other hidden-beauty states using $\pi^+\pi^-\Upsilon(1S)$ channel	Phys. Lett. B 740 (2015) 199-217
	Cross-section measurement of ψ(2S) → J/ψ (→ $\mu^+\mu^-$) $\pi^+\pi^-$ at √s = 7TeV	JHEP 09 (2014) 079
	ϕ_s and $\Delta\Gamma_s$ from flavour tagged time dependent angular analysis of $B^0_s \to J/\psi\ \phi$	Phys. Rev. D 90 (2014) 052007
	Observation of an excited $B^{\pm}_c$ meson state with the ATLAS detector	Phys. Rev. Lett. 113 (2014)
√	Branching fractions of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ and transverse polarization fraction in the latter decay	ATLAS-CONF-2015-014
√	Study of J/ψ and ψ(2S) production in $\sqrt{s_{NN}}$ = 5.02 TeV p+Pb and √s = 2.76 TeV pp collisions with the ATLAS detector	ATLAS-CONF-2015-023
√	Differential cross-sections of prompt and non-prompt J/ψ and ψ(2S) at √s = 7 and 8 TeV	ATLAS-CONF-2015-024
√	Measurement of the differential non-prompt J/ψ production fraction in √ s = 13 TeV p p collisions at the ATLAS experiment	ATLAS-CONF-2015-XXX
√	Observation of Λ_b in the decay $\Lambda_b^0 \to$ ψ(2S) Λ^0	ATLAS-CONF-2015-030
	https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults	

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Quarkonium and heavy flavour production measurements at ATLAS

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√	Branch	ATLAS-NF-2015-014
√	Study d	ATLAS-NF-2015-023
√	Different	ATLAS-NF-2015-024
√	Measurer collisions at the ATLAS experiment	ATLAS-CONF-2015-XXX
√	Observation of Λ_b in the decay $\Lambda_b^0 \rightarrow \psi(2S)\, \Lambda^0$	ATLAS-CONF-2015-030
	https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults	

- Don't miss the talks from
  - Cristiano Alpigiani
    - New physics searches with heavy flavour observables at ATLAS
  - James Walder
    - Measurements of production and decay of exotic mesons at the ATLAS and CMS experiments

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BACKUP

Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt J/ψ and $\psi(2S)$ production at $\sqrt{s}$ = 7 and 8 TeV

Systematics

	7 TeV [%]			8 TeV [%]		
Systematic Type	Min	Median	Max	Min	Median	Max
Luminosity	1.8	1.8	1.8	2.8	2.8	2.8
Inner Detector tracking efficiency	1.0	1.0	1.0	1.0	1.0	1.0
Muon reconstruction efficiency	0.7	1.2	4.7	0.3	0.7	6.0
Muon trigger efficiency	3.2	4.7	35.9	2.9	7.0	23.4
Fit model parameterizations	0.9	3.7	39.1	0.9	3.7	86.2
Bin migrations	0.01	0.1	1.4	0.01	0.3	1.5
Total	4.3	7.4	43.2	5.2	9.1	87.1

ATLAS-CONF-2015-024

Quarkonium and heavy flavour production measurements at ATLAS

Associated production of Z bosons with prompt and non-prompt J/ψ mesons

Systematics

Source	Prompt		Non-prompt	
	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$
Fit procedure	3 %	3 %	4%	8%
Z boson kinematics	1%	1%	1%	1%
$\mu_{J/\psi}$ efficiency	1%	1%	1%	1%
Vertex separation	7%	16%	2%	15%

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Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{+*}$ decays

Systematics

Source	Uncertainty [%]			
	$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$
Simulated $p_{\mathrm{T}}(B_c^+)$ spectrum	$^{+0.4}_{-0.4}$	$^{+0.9}_{-0.9}$	$^{+0.4}_{-0.5}$	$^{+0.4}_{-0.4}$
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	$^{+1.8}_{-1.8}$	$^{+2.4}_{-2.3}$	$^{+0.6}_{-0.5}$	$^{+0.2}_{-0.1}$
Tracking efficiency	±5.0	±4.9	–	–
B_c^+ lifetime	$^{+1.1}_{-1.2}$	$^{+1.2}_{-1.3}$	–	–
D_s^+ lifetime	±0.3	±0.3	±0.1	±0.1
$B_c^+ \to J/\psi D_s^{(*)+}$ signal extraction	$^{+1.7}_{-13.5}$	$^{+3.9}_{-10.7}$	$^{+12.8}_{-10.1}$	$^{+15.2}_{-17.8}$
$B_c^+ \to J/\psi \pi^+$ signal extraction	$^{+1.5}_{-7.4}$	$^{+1.5}_{-7.4}$	–	–
D_s^{*+} branching fractions	–	$^{+0.2}_{-0.0}$	$^{+0.2}_{-0.3}$	$^{+0.8}_{-1.1}$
MC statistics	±2.3	±2.4	±2.7	±2.2
Total	$^{+6.3}_{-16.5}$	$^{+7.5}_{-14.3}$	$^{+13.1}_{-10.4}$	$^{+15.4}_{-17.9}$
$\mathcal{B}_{D_s^+ \to \phi(K^+K^-)\pi^+}$	±5.9	±5.9	–	–

ATLAS-CONF-2015-014