ATLAS Quarkonium Production Measurements

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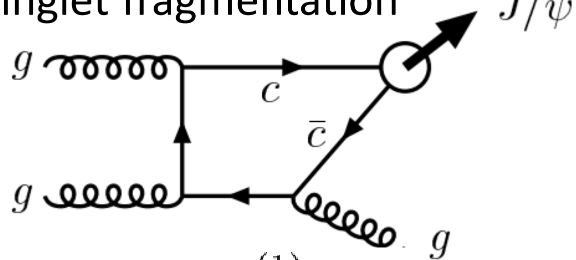
Overview

Motivation

- Quarkonium production at the LHC provides a unique window on QCD
- Comparisons of measurements and theoretical predictions provide additional input toward an improved understanding of quarkonium hadroproduction

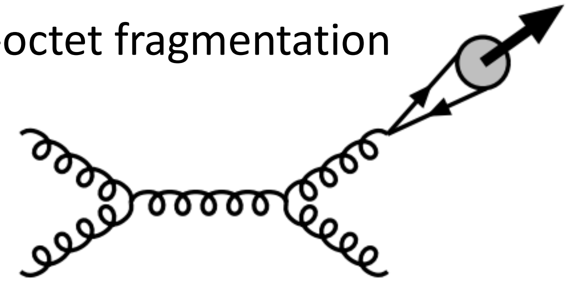
Quarkonium production

colour-singlet fragmentation



$$g + g \to c\bar{c}[^3S_1^{(1)}] + g$$

colour-octet fragmentation



$$g + g \to c\bar{c}[^3S_1^{(8)}] + g$$

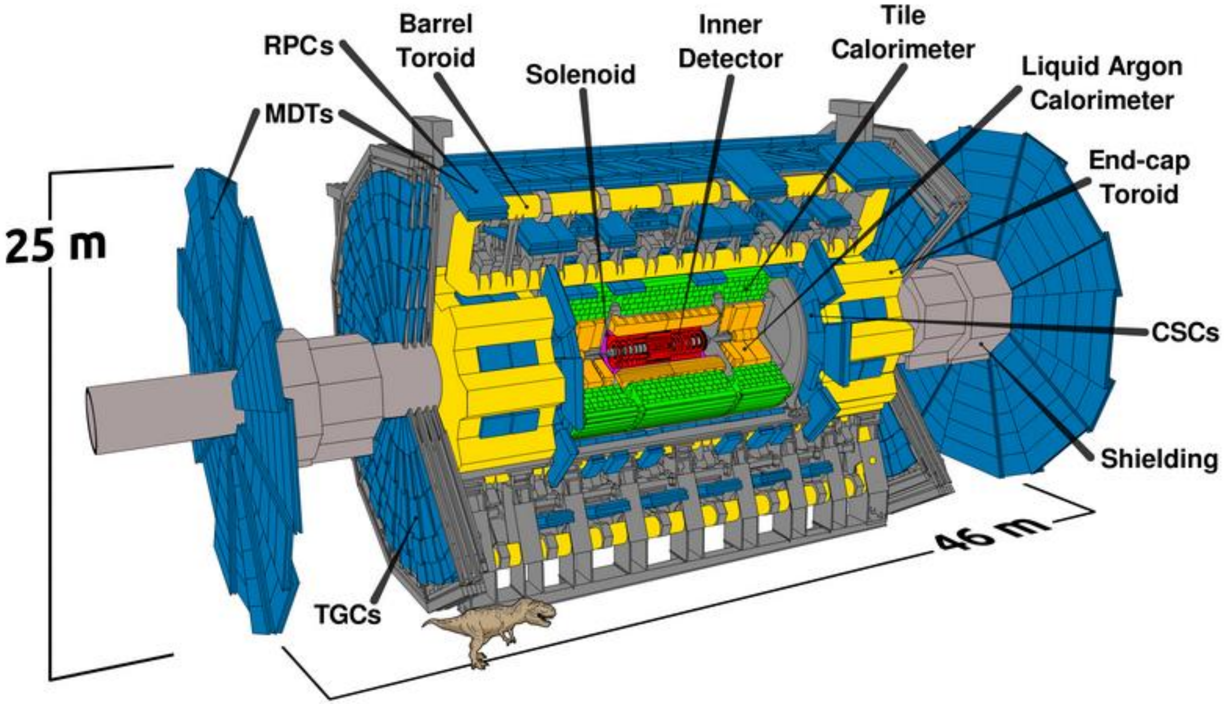
- charmonium production：

prompt and non-prompt production of J /ψ and ψ(2S) (Eur.Phys.J. C76 (2016) 5, 283)

- bottomonium production：

Upsilon production (Phys. Rev. D 87 (2013) 052004)

The ATLAS Detector



The inner detector (ID)
A silicon pixel detector, a silicon microstrip and a transition radiation tracker, $|\eta|< 2.5$

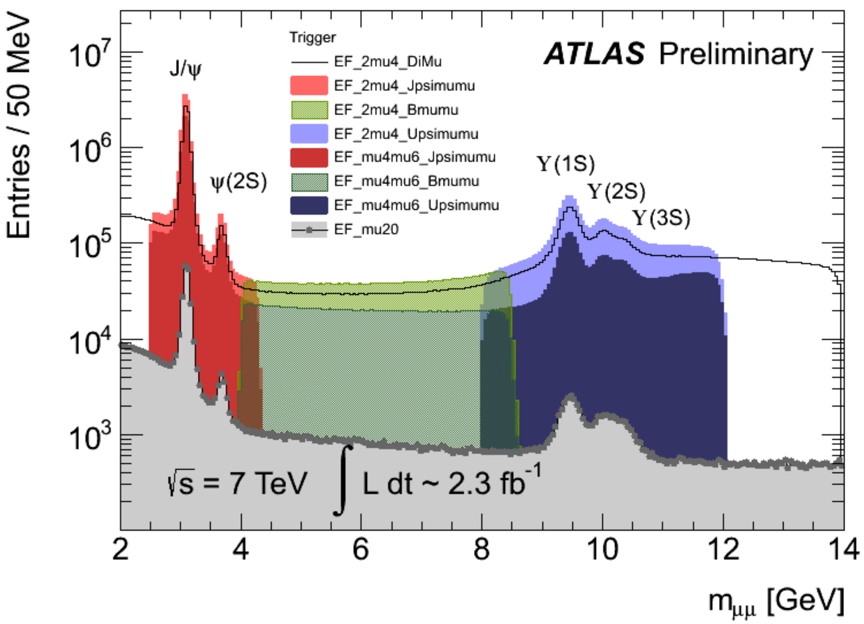
Calorimeters
electromagnetic and hadronic sections

Muon Spectrometer (MS)
Triggering $|\eta|< 2.4$ and Precision Tracking $|\eta|< 2.7$

Candidate selection

Selections

- Di-muon trigger
- $p_T^{\mu} > 4$ GeV and $|\eta^{\mu}| < 2.3$
- Both muons reconstructed from track in ID combined with MS track
- Two oppositely charged muon
- A common vertex

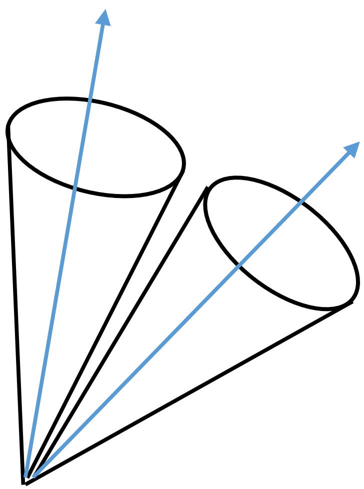


Dedicated di-muon triggers for quarkonium

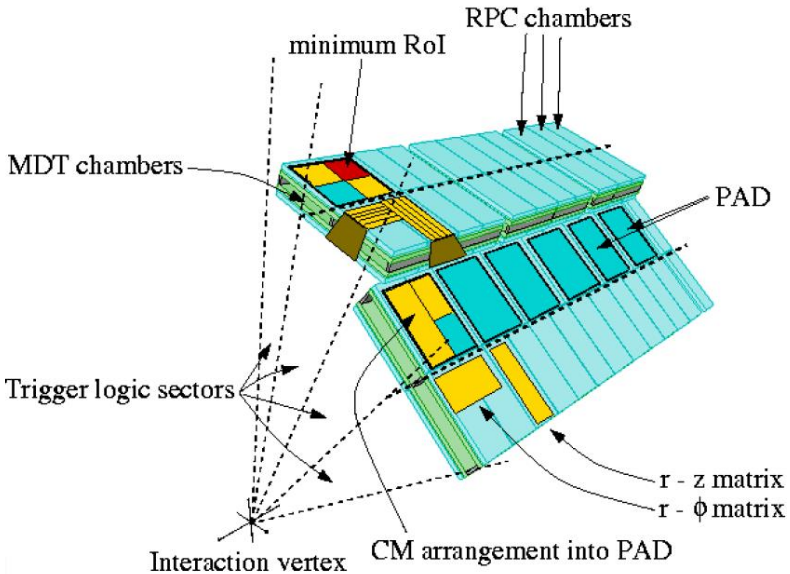
Trigger

- Jpsimumu, Bmumu, Upsimumu and DiMu denote coarse invariant mass windows in different regions

Dimuon trigger efficiency



Coincidence Matrix (CM):
η-CM: r-z matrix
ϕ-CM: r-ϕ matrix
Trigger PAD:
A PAD corresponds to 2 η-CM and 2 ϕ-CM
Region of Interest (RoI):
A RoI is defined by the overlap of an η-CM and a ϕ-CM

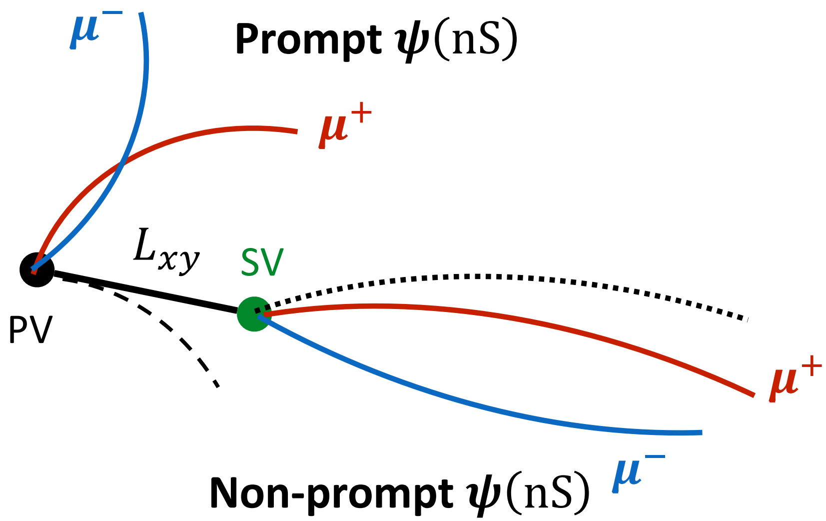


Dimuon trigger efficiency

$$\epsilon_{dimuon} = \epsilon_{trigger}(P_T^1, q, \eta_\mu^1) \times \epsilon_{trigger}(P_T^2, q, \eta_\mu^2) \times C(\Delta R_{\mu\mu}, |y^{\mu\mu}|)$$

$\epsilon_{trigger}$ is the trigger efficiency between muon and trigger object(L1 RoI, EF element etc.) .
$C(\Delta R_{\mu\mu}, |y^{\mu\mu}|)$ is used to correct dimuon trigger inefficiency when two muons are in the same RoI.

Methodology



Prompt

Produced from short-lived QCD decays (including feed-down from other charmonium states)

Non-prompt

Produced in the decays of long lived b-hadrons - displaced decay vertex

Pseudo-proper decay time

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

Corrected cross section

Ncorr is corrected by acceptance, trigger and reconstruction efficiencies event by event

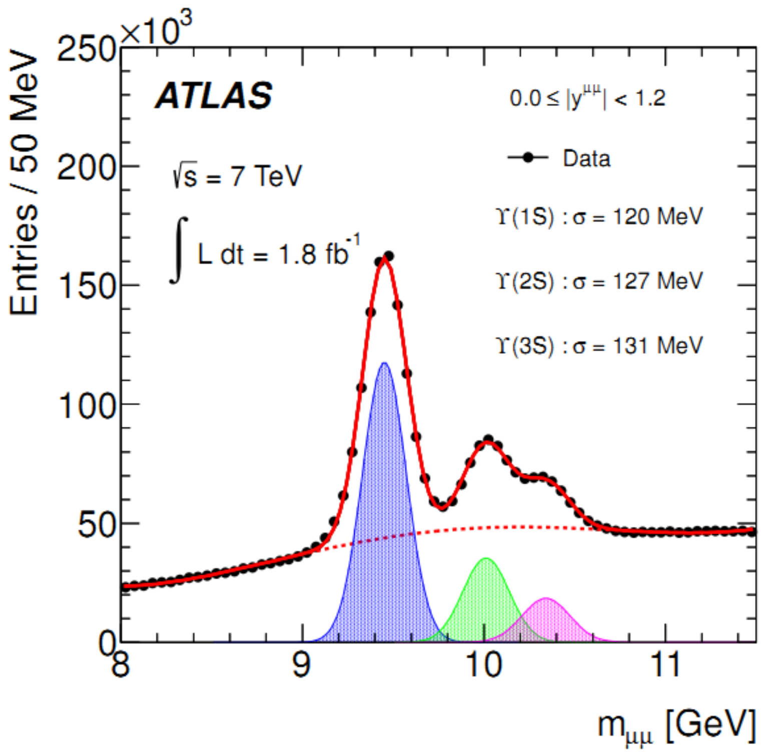
$$\frac{d^2\sigma(pp \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{Ncorr_\psi^p}{\Delta p_T \Delta y \times \int \mathcal{L}dt}$$

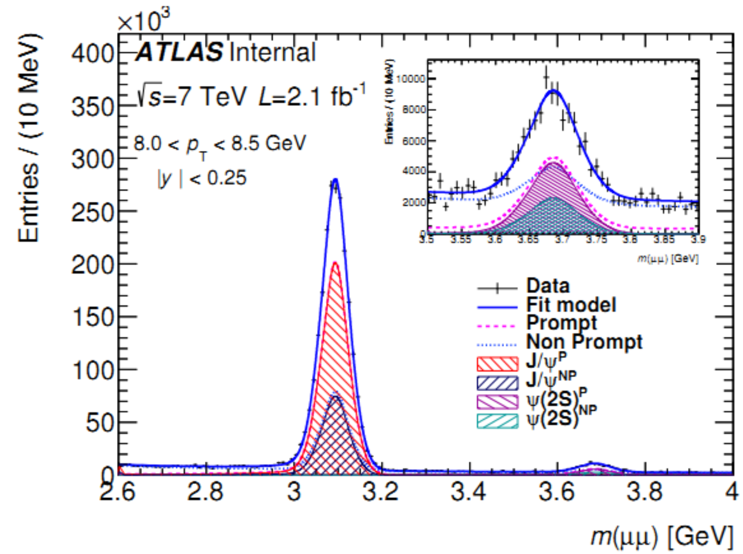
$$\frac{d^2\sigma(pp \to b\bar{b} \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{Ncorr_\psi^{np}}{\Delta p_T \Delta y \times \int \mathcal{L}dt}$$

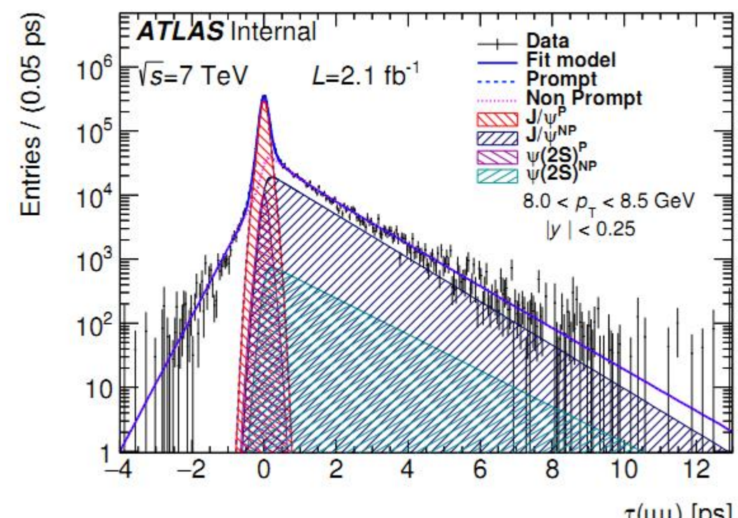
$$Ncorr_\psi^{p(np)} = \frac{N_\psi^{p(np)}}{\mathcal{A} \cdot \epsilon_{trig} \cdot \epsilon_{reco}}$$

Extracting the number of mesons

The number of produced mesons used in our cross-section determination is found by fitting signal and background functions to the m (μμ) (τ(μμ)) spectrum of weighted candidates.



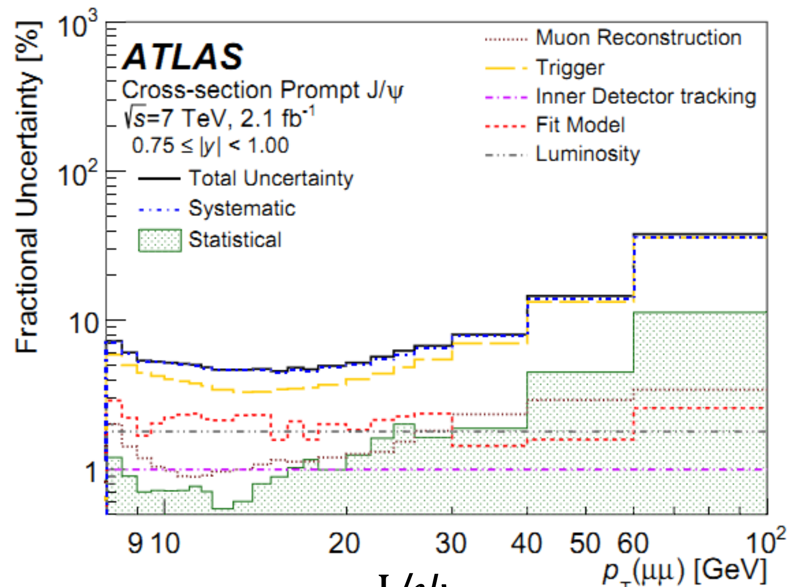




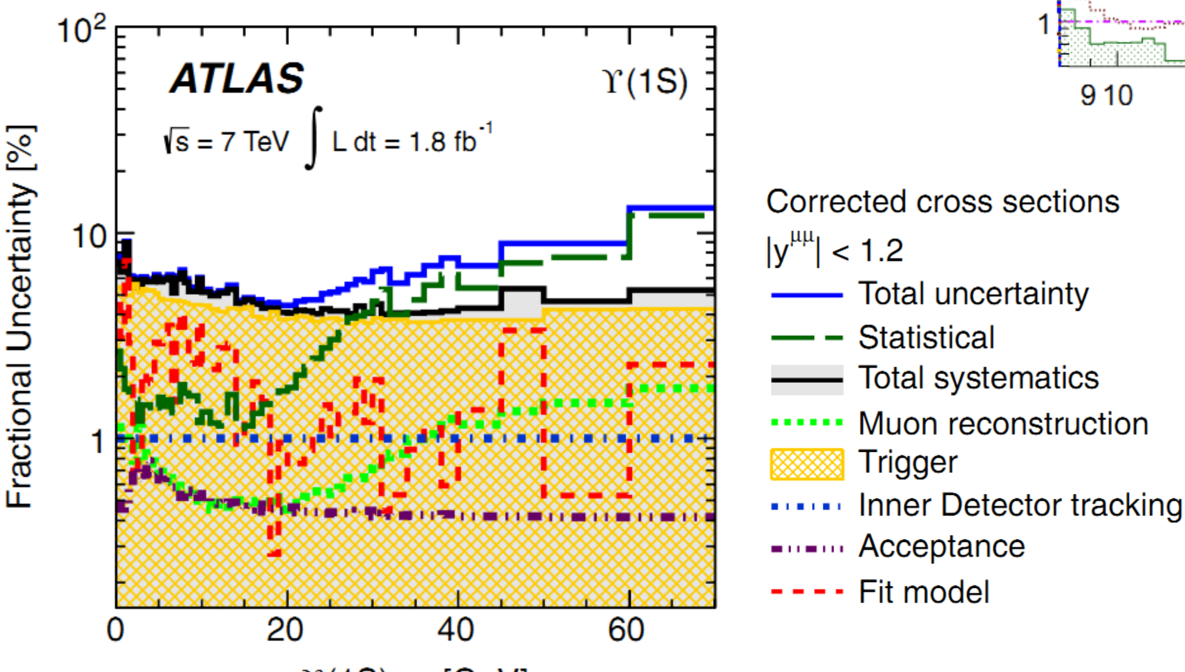
Systematic uncertainties

The largest contributions:

trigger uncertainties (limited statistics)

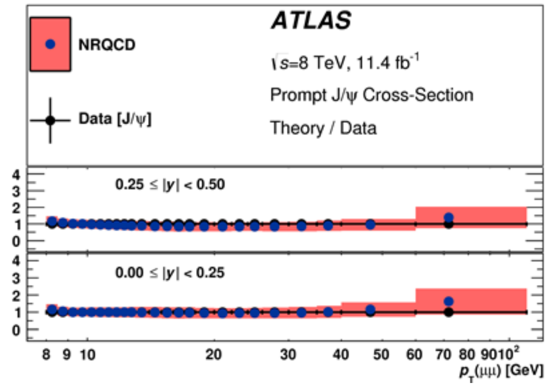


J/ψ



The uncertainties are valid bin by bin

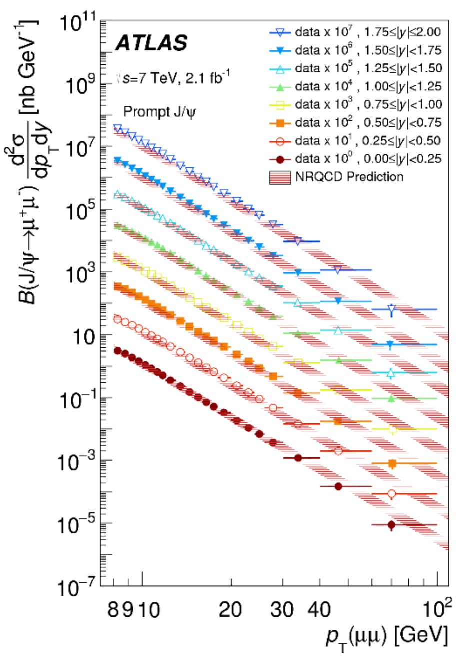
Prompt cross sections



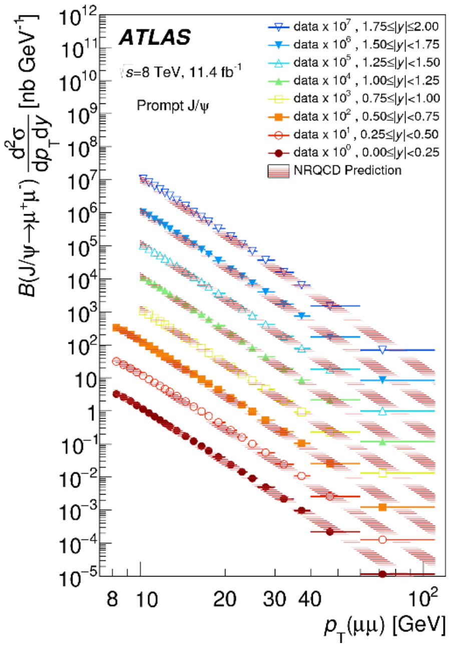
NRQCD (Non-relativistic QCD)

- parameters included, determined from fits to experimental data
- good description of cross-sections in low pt, overestimate in high pt

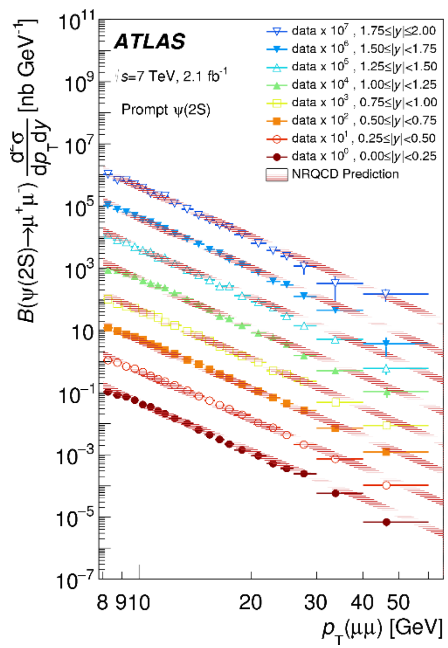
J/ψ 7TeV



J/ψ 8TeV



$\psi(2S)$ 7TeV



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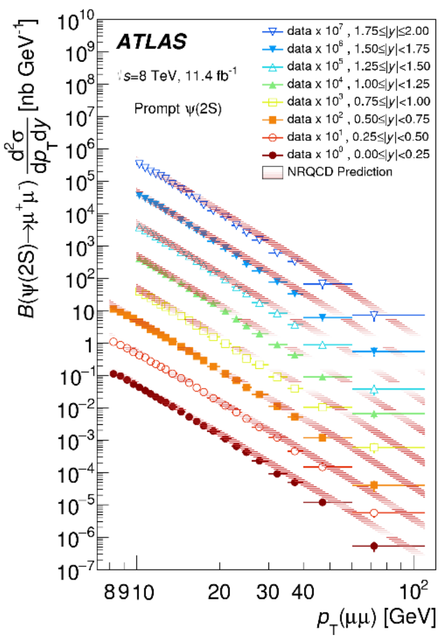
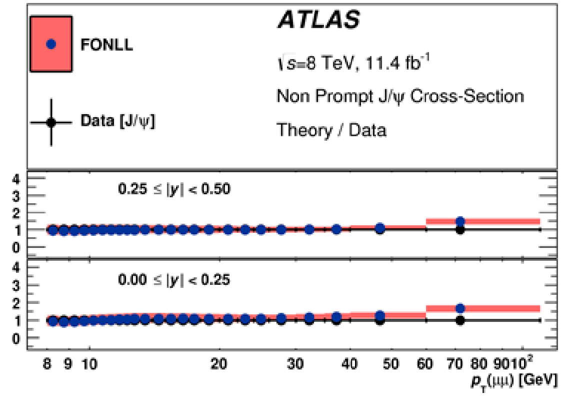


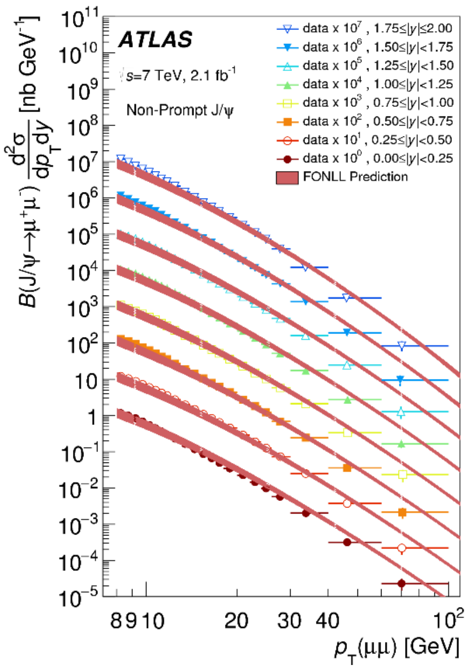
Non-prompt cross sections

FONLL(Fixed-Order with Next-to-Leading-Logarithm)

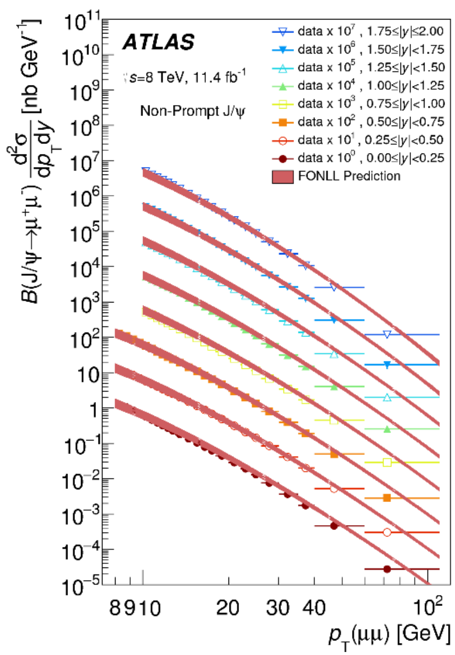
- perturbative QCD
- good description of non-prompt production of charmonium states



J/ψ 7TeV



J/ψ 8TeV



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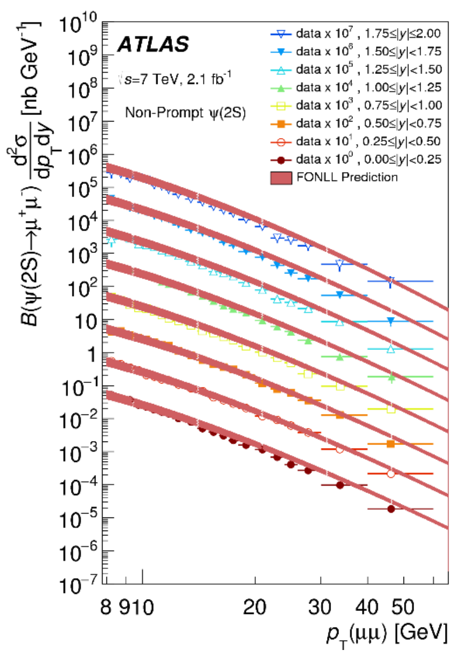
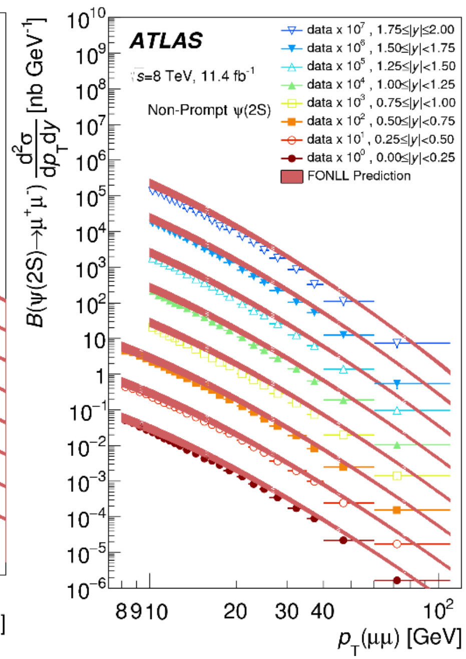
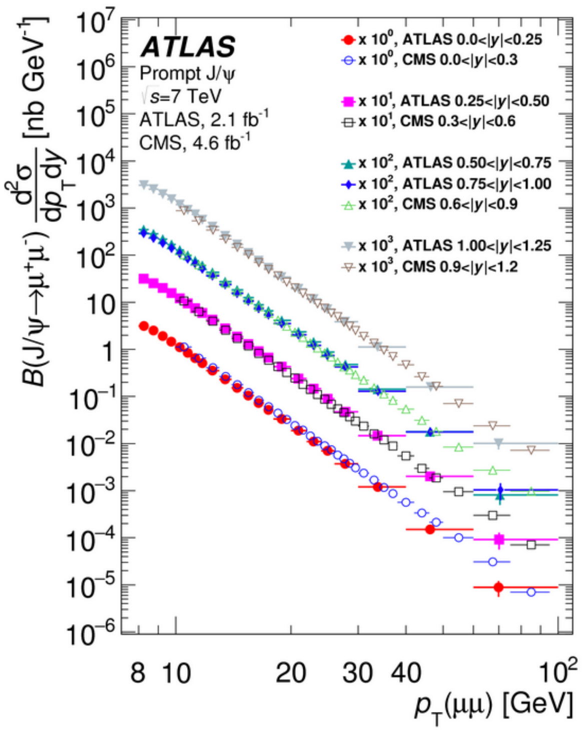
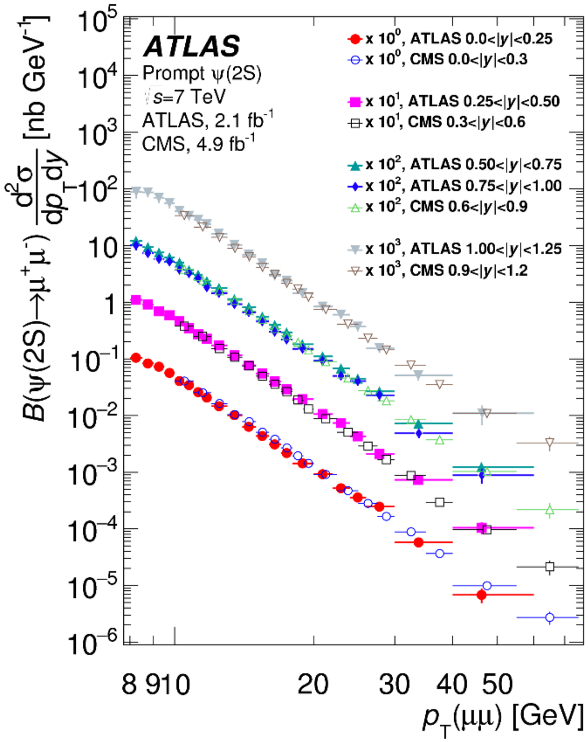


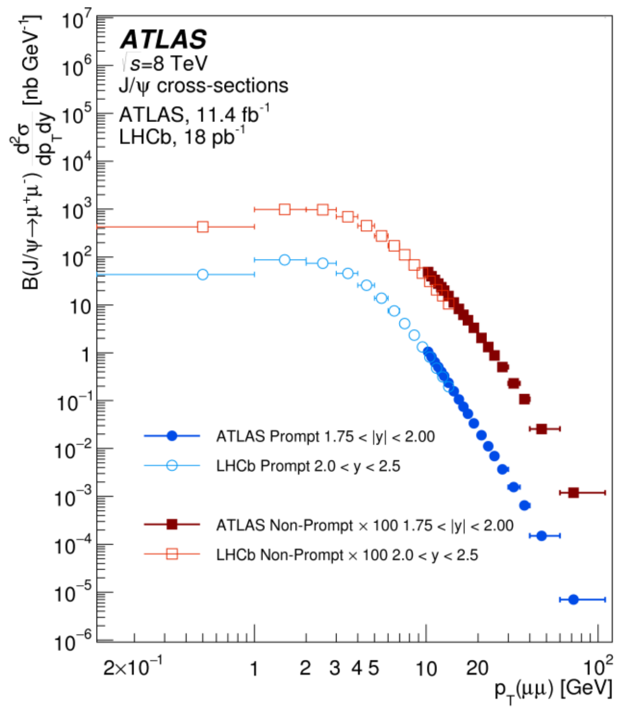
$\psi(2S)$ 8TeV



Comparison



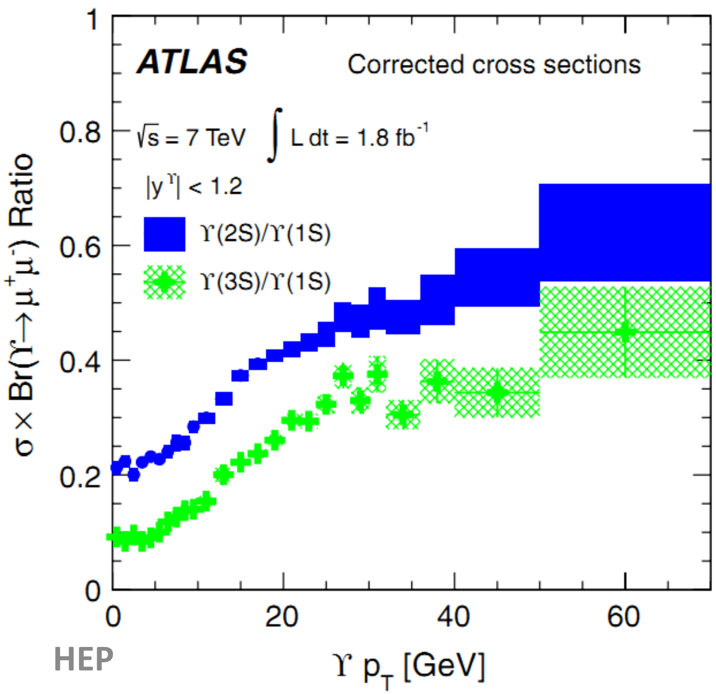


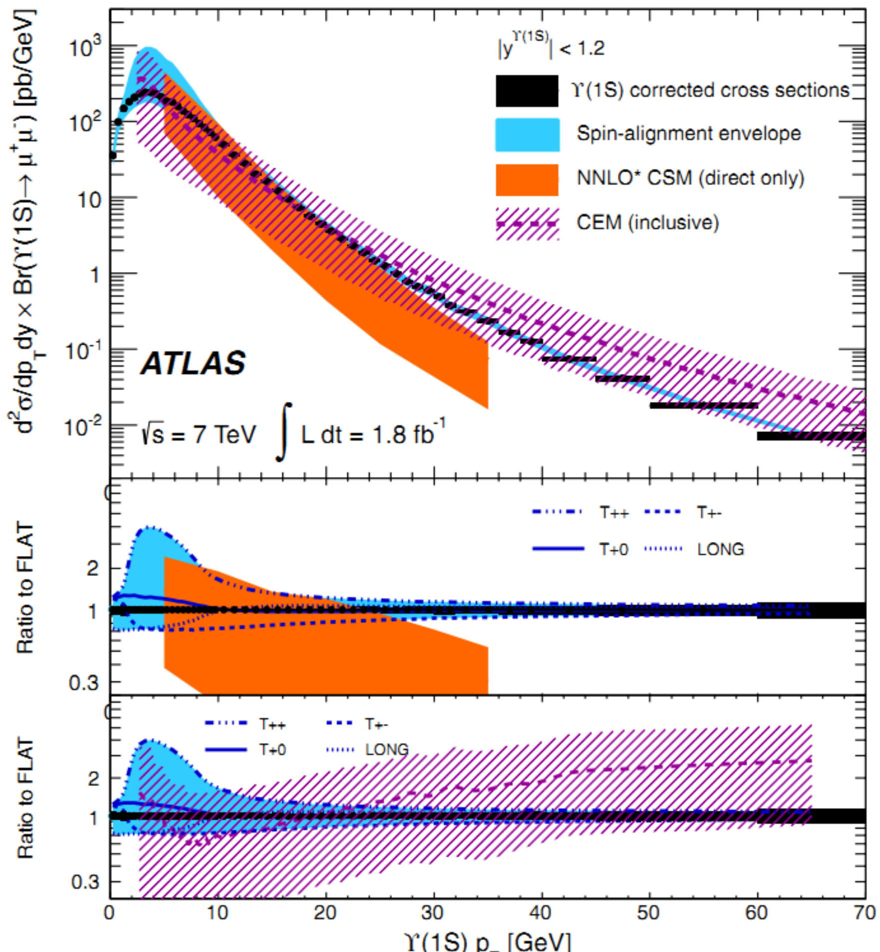


ATLAS results are in good agreement with CMS and LHCb

ϒ(nS) cross sections

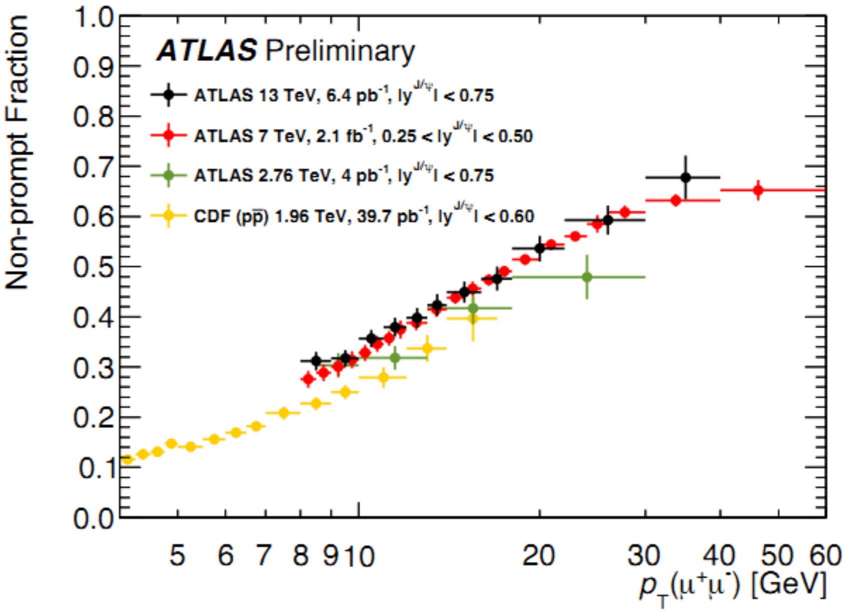
- spin-alignment envelope shows acceptance sensitive to polarization
- NNLO* CSM (next-to-next-to-leading-order*colour-singlet model) generally underestimates data
- CEM(color evaporation model) does not reproduce shape of data well

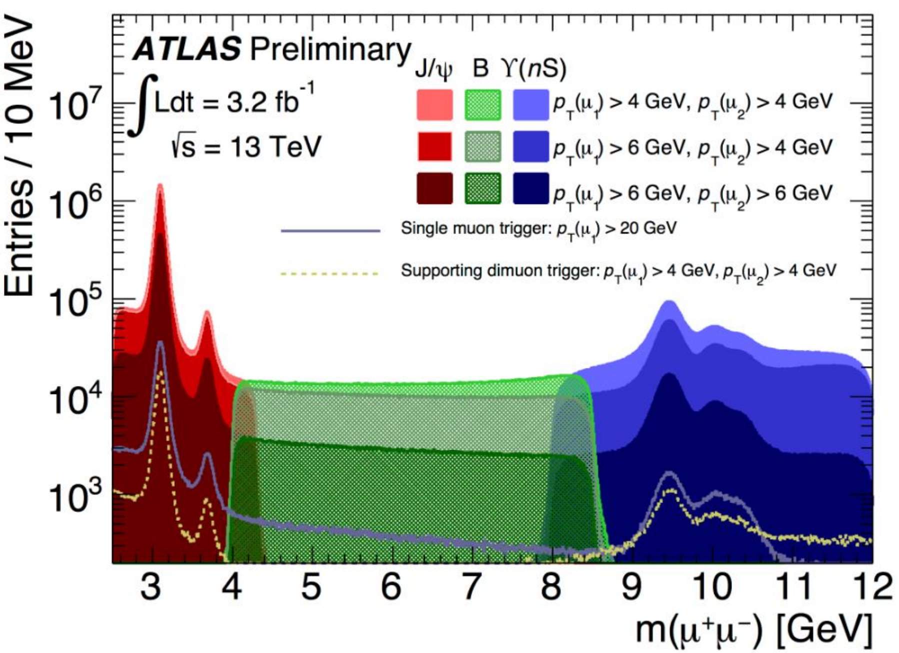




Quarkonium at 13 TeV

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





Summary

Charmonium Production

- The prompt and non-prompt production cross-sections were measured in the rapidity range |y| < 2.0 for transverse momenta between 8 and 110 GeV.
- Both the NRQCD model and the FONLL are found to be in good agreement with the observed data.

Bottomonium Production

- We have measured differential production cross sections and relative production rates for ϒ(nS) mesons in pp collisions at $\sqrt{s}$ = 7 TeV at the LHC up to p_T^{Υ} < 70 GeV in the rapidity interval $|y^{\Upsilon}|$ < 2.25.
- Our measurements find both the NNLO* CSM and the CEM predictions have some problems in describing the normalization and shape of the differential spectra.

We stay tuned for measurements at 13 TeV!

backup

Fit model

G_i : Gaussian functions
B_i : Crystal Ball distributions
E_i : exponential functions
C_1 first-order Chebyshev polynomial
ω : fractional contribution of the B and G mass signal functions
$\delta(\tau)$: pseudo-proper decay time distribution of the prompt candidates

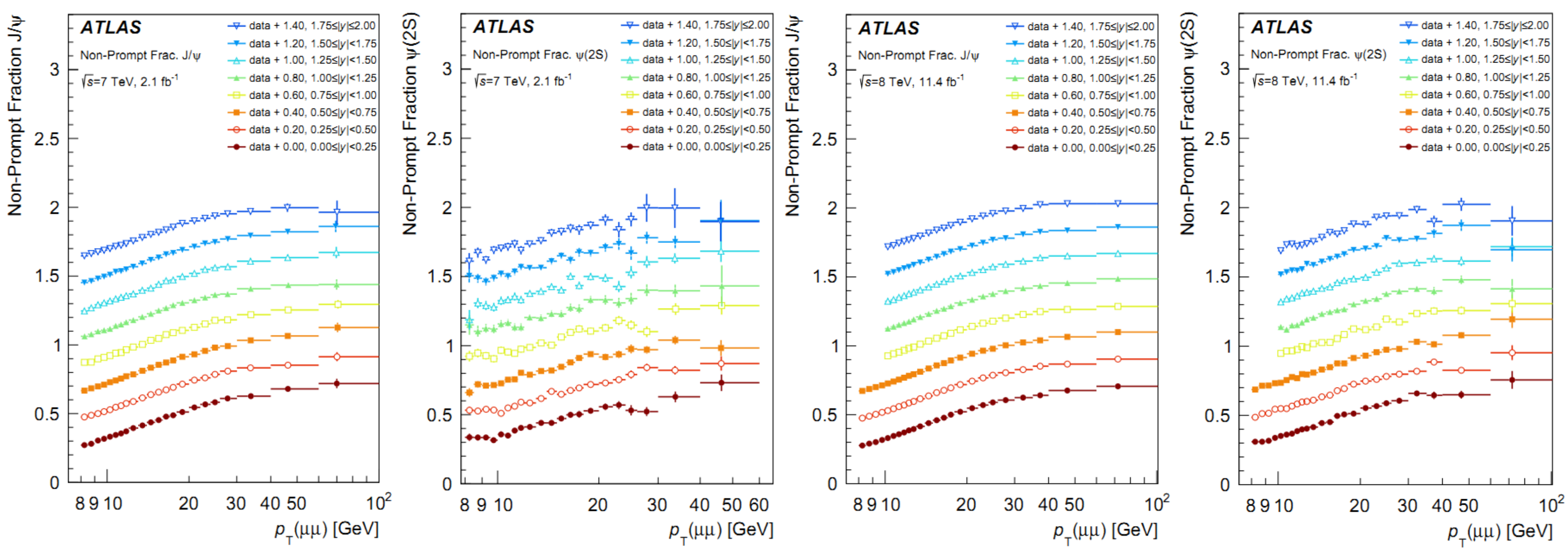
i	Type	Source	$f_i(m)$	$h_i(\tau)$
1	J/ψ S	P	$\omega_i B_1(m) + (1-\omega_i)G_1(m)$	$\delta(\tau)$
2	J/ψ S	NP	$\omega_i B_1(m) + (1-\omega_i)G_1(m)$	$E_1(\tau)$
3	$\psi(2S)$ S	P	$\omega_i B_2(m) + (1-\omega_i)G_2(m)$	$\delta(\tau)$
4	$\psi(2S)$ S	NP	$\omega_i B_2(m) + (1-\omega_i)G_2(m)$	$E_2(\tau)$
5	Bkg	P	$F(m)$	$\delta(\tau)$
6	Bkg	NP	$C_1(m)$	$E_3(\tau)$
7	Bkg	NP	$E_4(m)$	$E_5(\|\tau\|)$

Table 2: Fit model PDF. Components of the probability density function used to extract the prompt (P) and non-prompt (NP) contributions for J/ψ and $\psi(2S)$ signal (S) and background (Bkg).

Non-prompt fraction

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

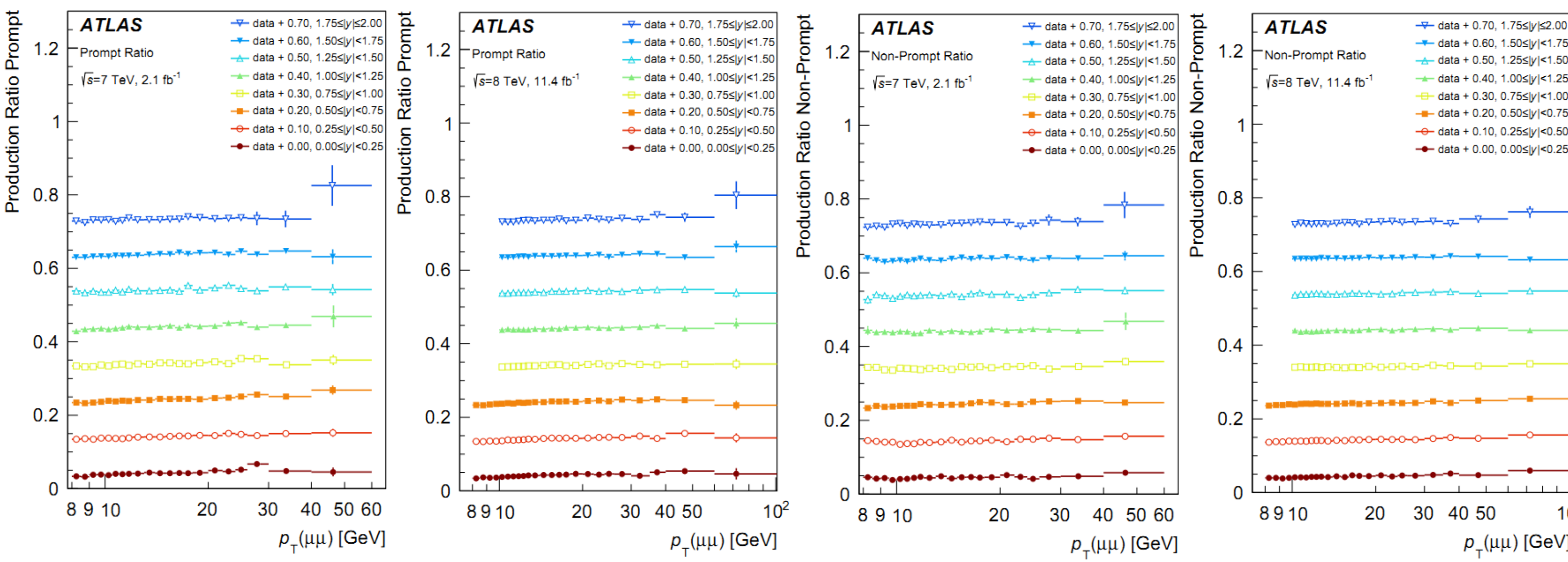
Determining the fraction from this ratio is advanta-geous since acceptance and efficiencies largely cancel and the systematic uncertainty is reduced.



Ratio of ψ(2S) to J /ψ production

$$R^{p(np)} = \frac{N_{\psi(2S)}^{p(np)}}{N_{J/\psi}^{p(np)}}$$

- corrected for selection efficiencies and acceptance
- the acceptance and efficiency corrections largely cancel, thus allowing a more precise measurement. The theoretical uncertainties on such ratios are also smaller, as several dependencies, such as parton distribution functions and b-hadron production spectra, largely cancel in the ratio.

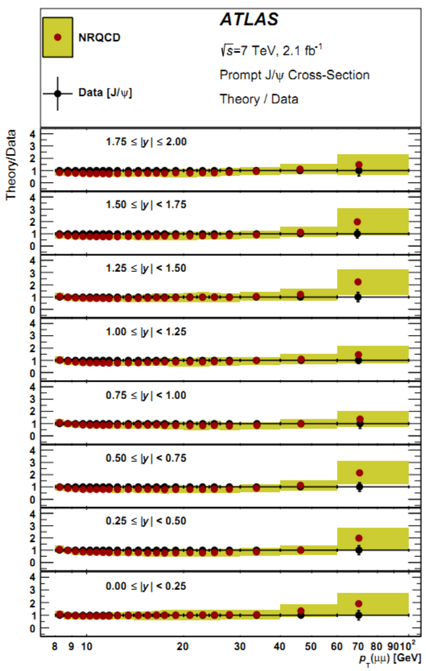


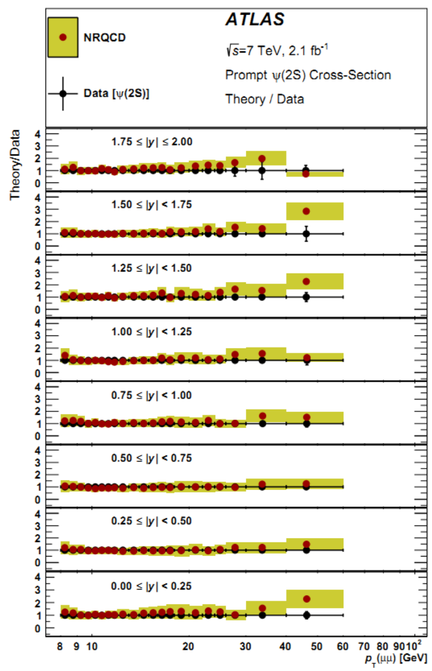
Theoretical predictions/data

prompt production:
NRQCD model

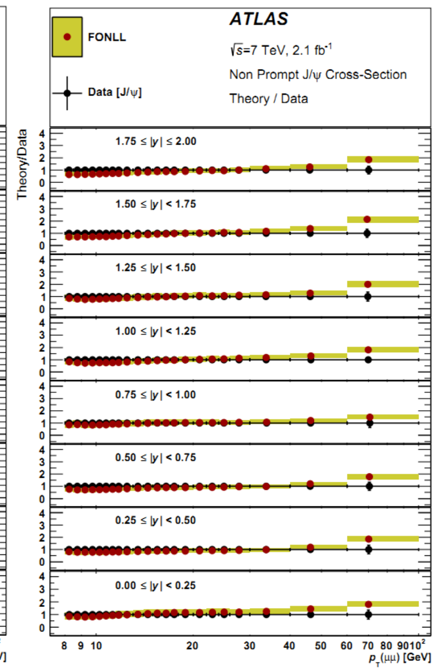
non-prompt production:
FONLL model

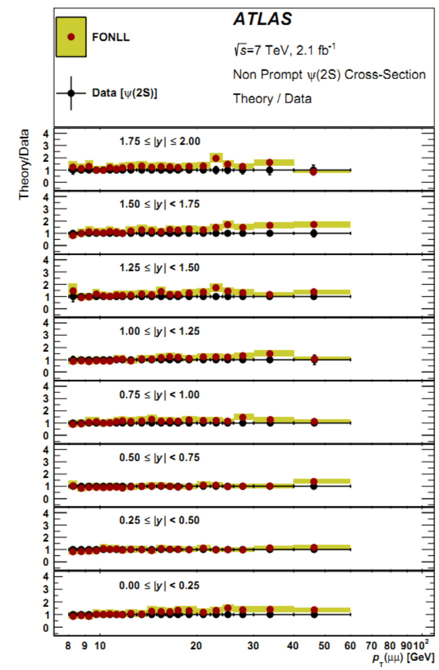
prompt 7TeV





non-prompt 7TeV



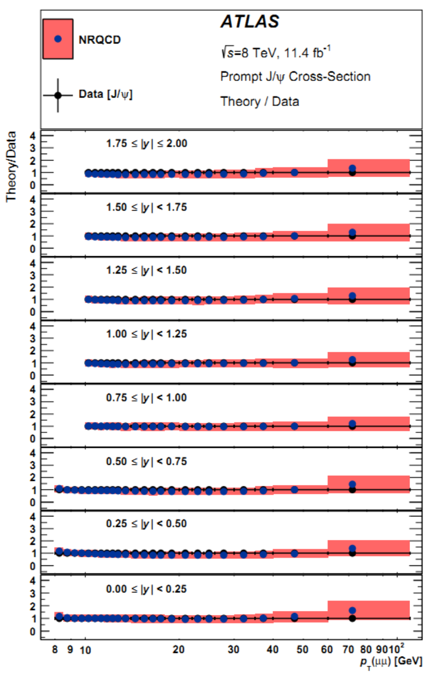


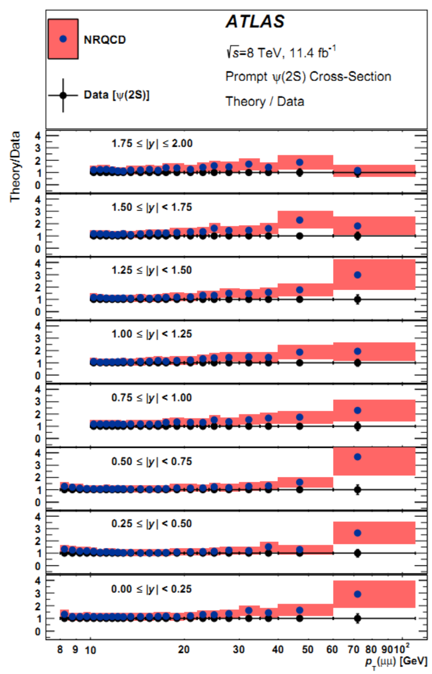
Theoretical predictions/data

prompt production:
NRQCD model

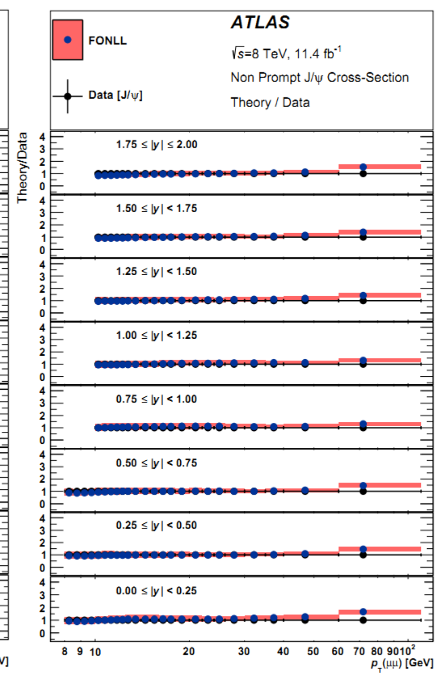
non-prompt production:
FONLL model

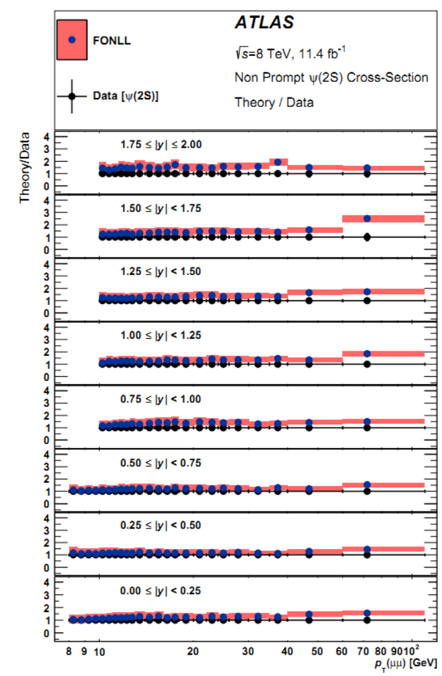
prompt 8TeV





non-prompt 8TeV





Bottomonium

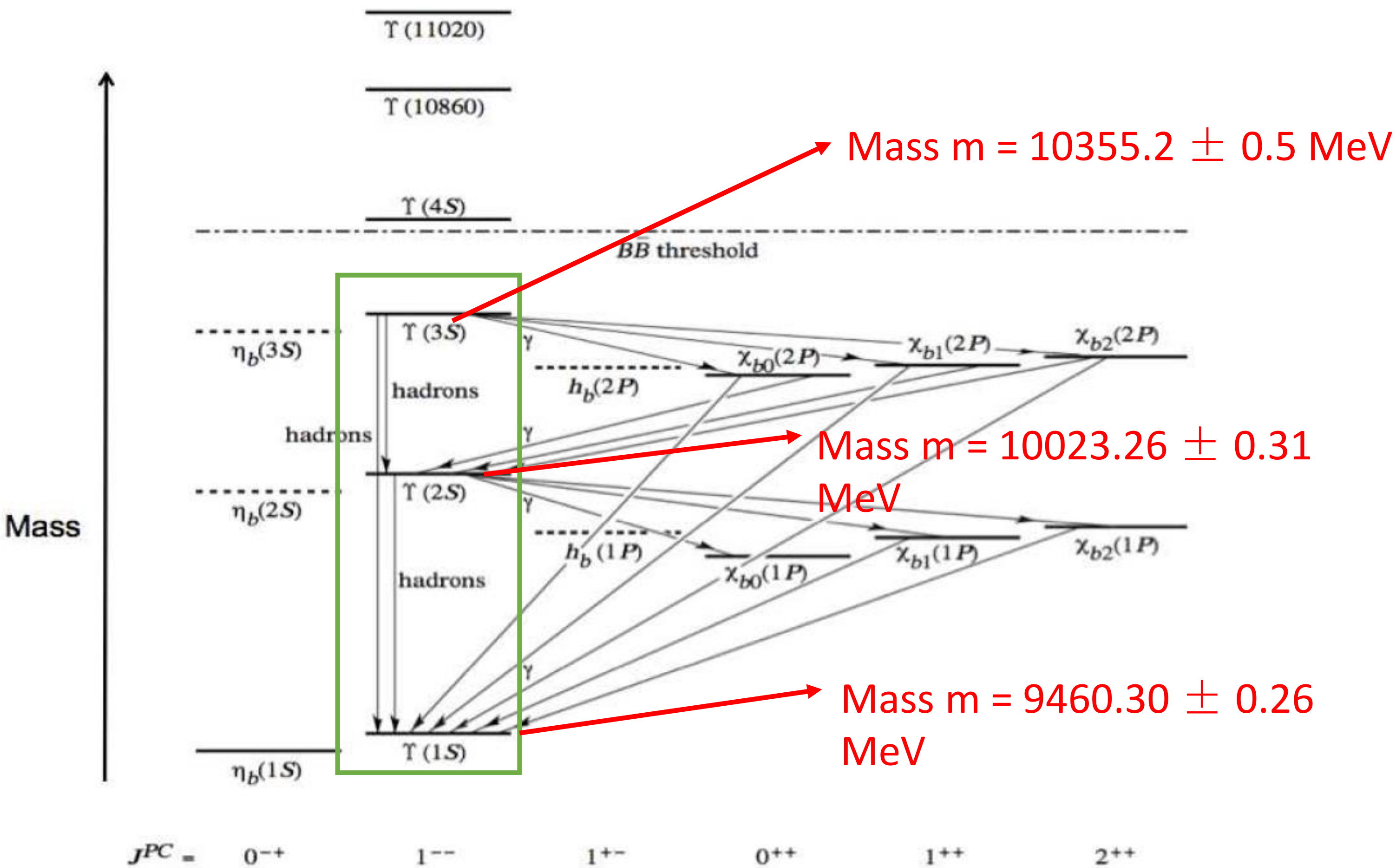


Figure 2.7: Mass levels of the bottomonium $b\bar{b}$ system.

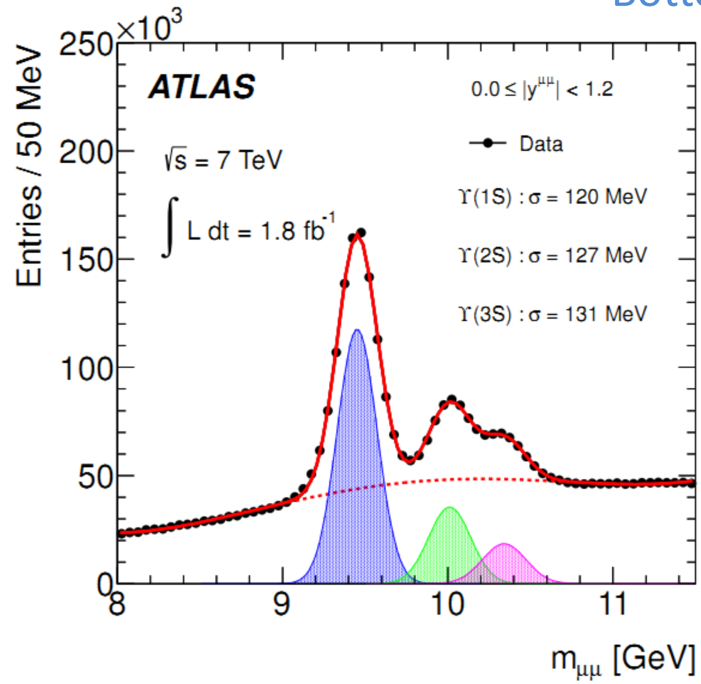
$\Upsilon(nS) \to \mu^+\mu^-$

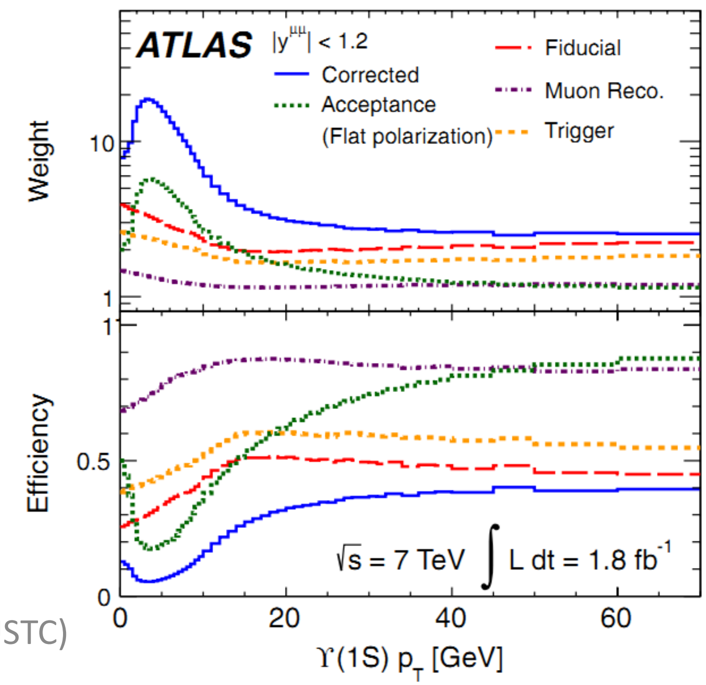
Selections

- Dimuon trigger
- Both muons reconstructed from track in ID combined with MS track
- two oppositely charged muon
- $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.3$
- a common vertex

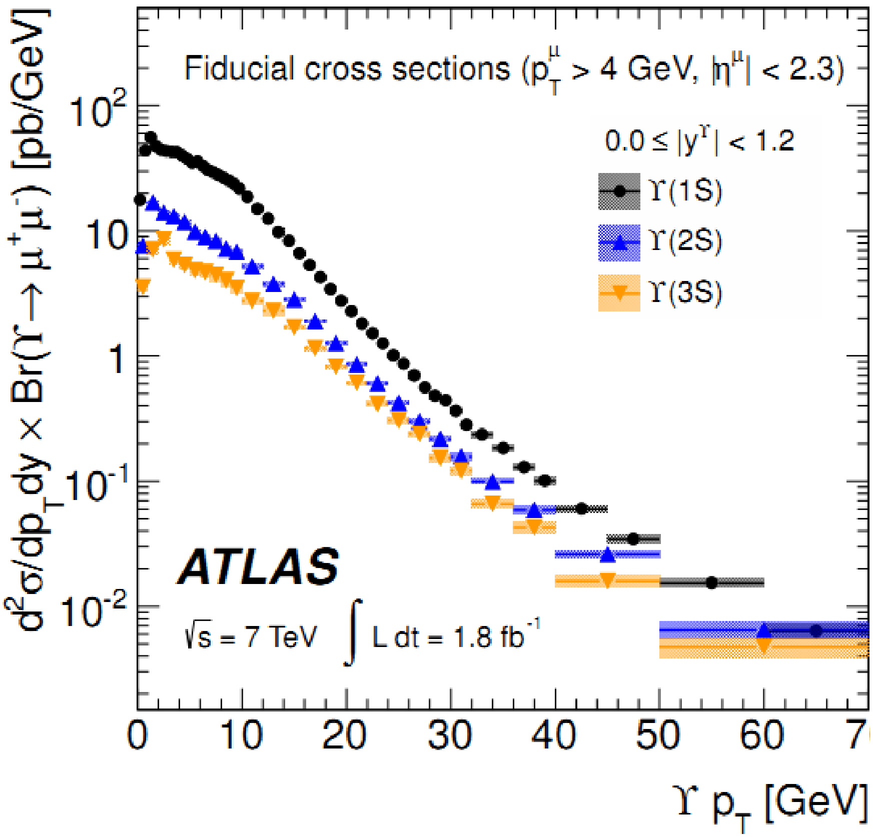
Corrections

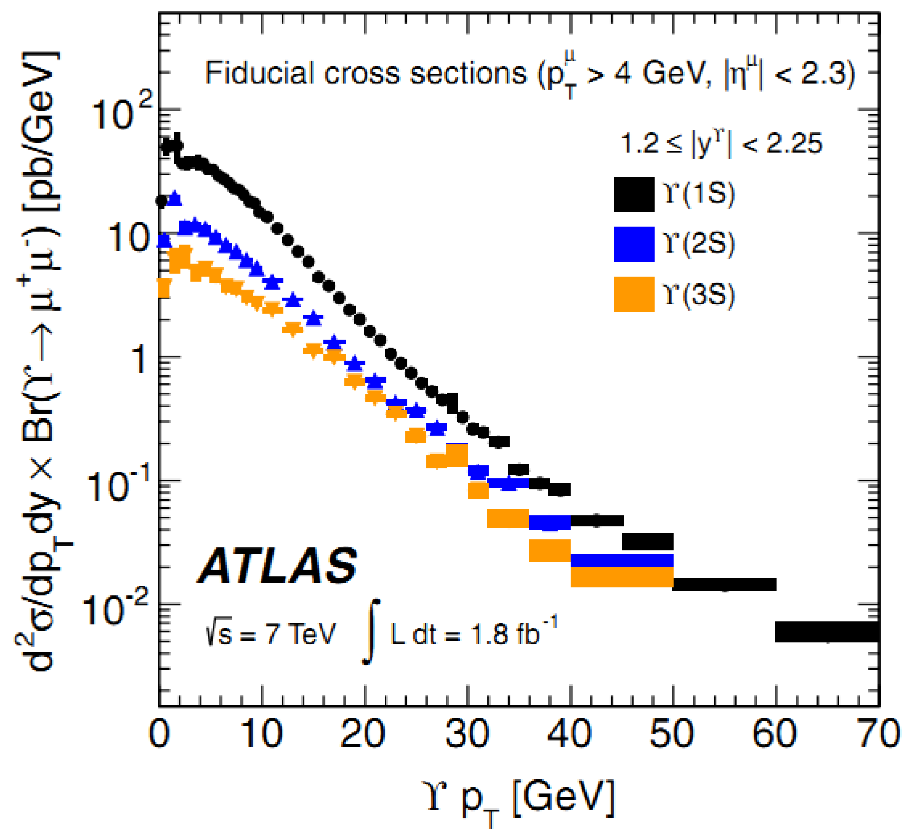
- Measure muon reconstruction and trigger efficiency with $J/\psi \to \mu^+\mu^-$ and $\Upsilon(nS) \to \mu^+\mu^-$ events in data
- There are various ϒ(nS) polarisation scenarios, the unpolarized (FLAT) acceptance scenario used in the correction





Fiducial cross section





Corrected cross section