



MEASUREMENT OF CROSS SECTIONS OF J/PSI AND UPSILON IN ATLAS

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Heavy Quarkonium 2011, GSI, Darmstadt, Oct 4-7th, 2011

Introduction

2

- No conclusive coherent theoretical picture of J/ψ and Υ hadro-production
- the production of heavy quarkonium at LHC provides the opportunity for insight the quarkonium and b-production in a new regime at higher transverse momenta and in a wider rapidity range then before

- The measurements presented in this talk are:

Inclusive J/ψ production cross-section

Non-prompt J/ψ fraction

Prompt/non prompt J/ψ production cross-section

Υ production cross-section

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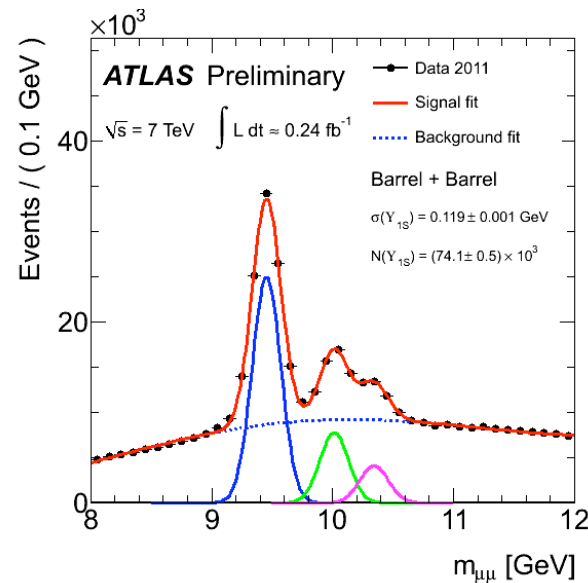
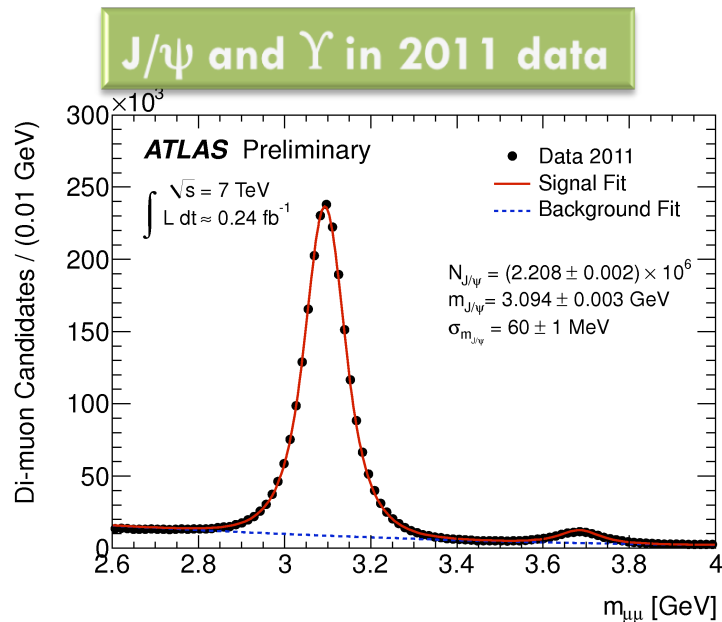
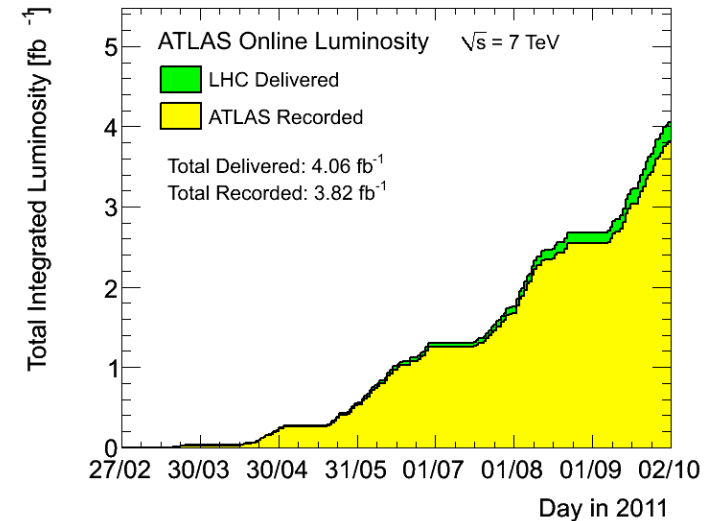
e-Print: [arXiv:1104.3038 \[hep-ex\]](#)

e-Print: [arXiv:1106.5325 \[hep-ex\]](#)

➤ These results were obtained using ATLAS 2010 data corresponding to an integrated luminosity of **$2.2 \text{ pb}^{-1}(J/\psi)$** and **$1.13 \text{ pb}^{-1}(\Upsilon)$**

3

- LHC Peak luminosity $\sim 3.31 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
 - Luminosity measured with 3.4% uncertainty
- ATLAS data taking efficiency 94%
- All subsystem operational fraction of channels $> 96\%$
- Similar performances in 2010



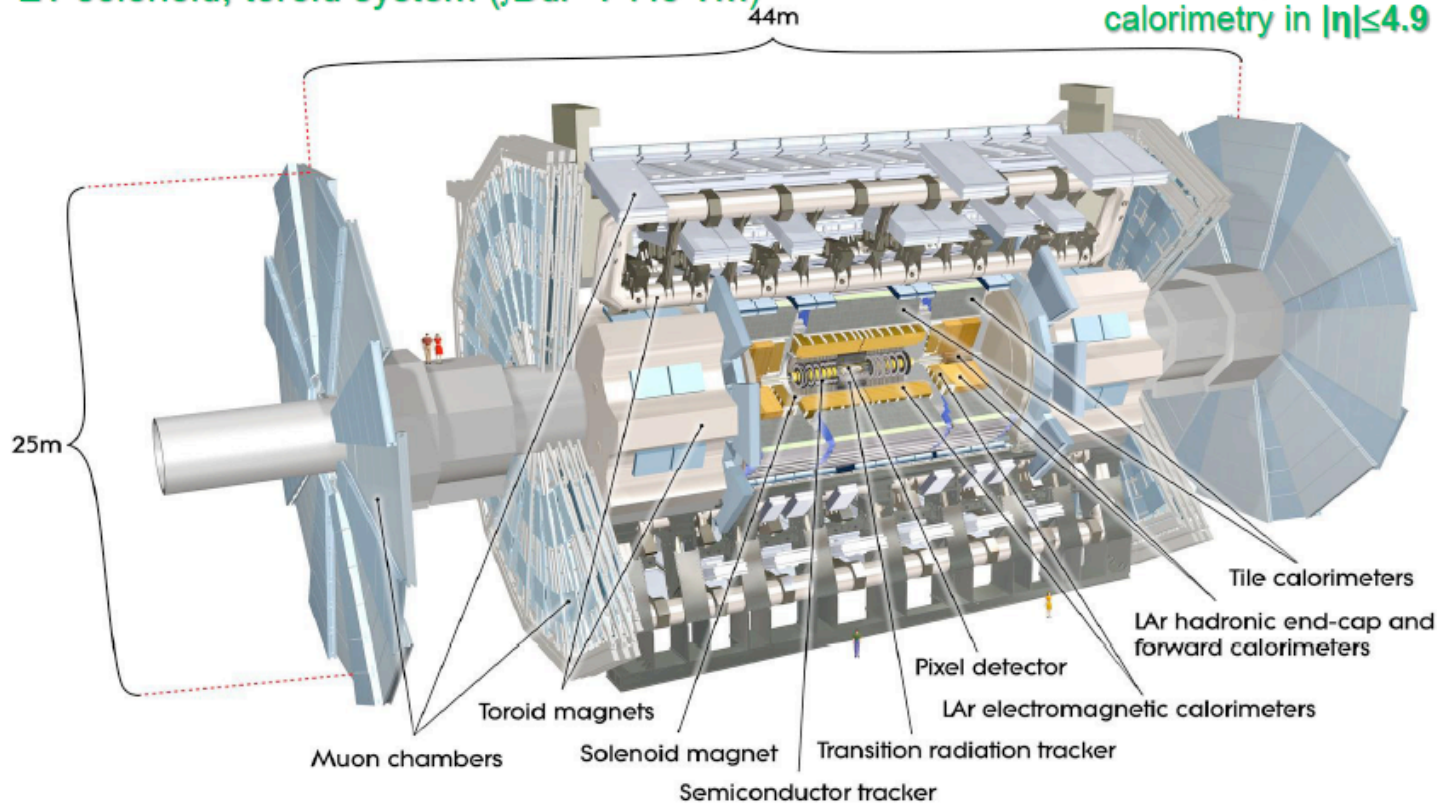
Quarkonia studies are mostly driven by the excellent Trigger, muon systems and inner tracker performances

The ATLAS Detector

4

2T solenoid, toroid system ($\int B dl = 1-7.5 \text{ Tm}$)

Tracking in $|\eta| \leq 2.5$
calorimetry in $|\eta| \leq 4.9$



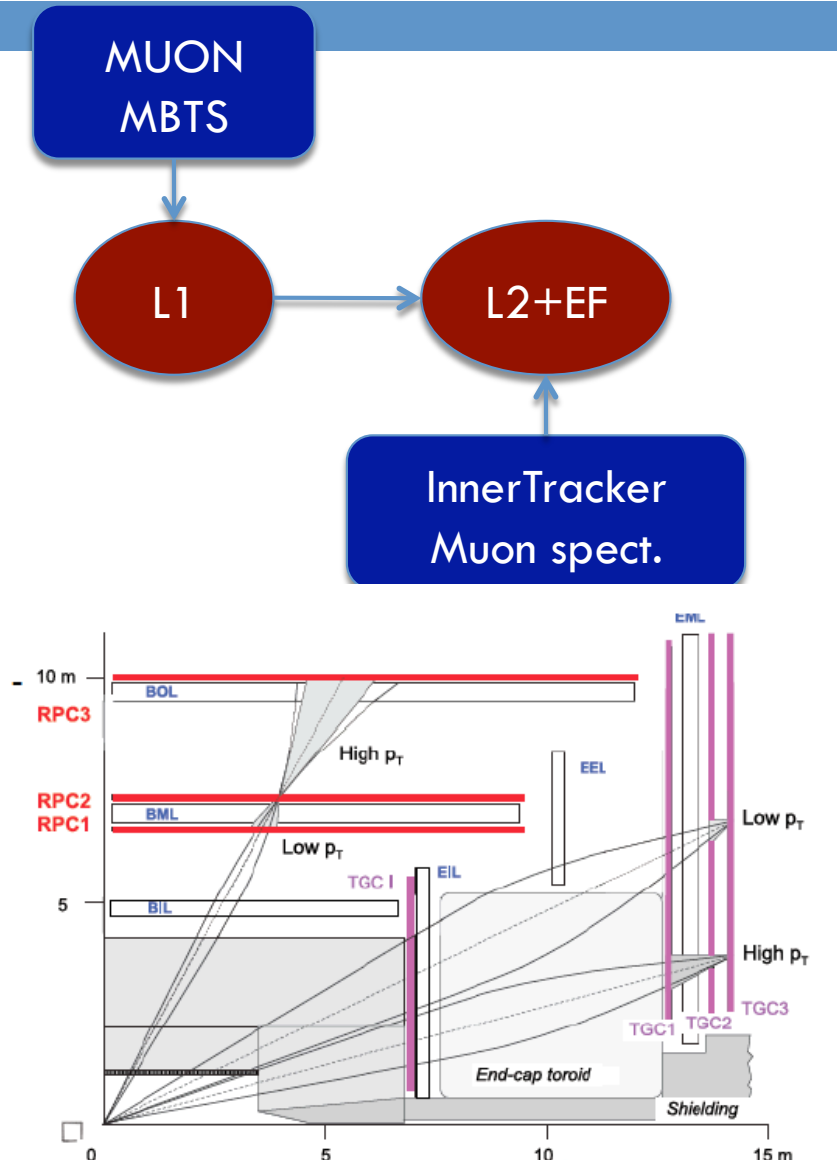
dimuon event
selection based on
inner detector
tracking devices
and the muon
spectrometer

- Inner Detector (ID) Momentum resolution: $\sigma / pT = 3.8 \times 10^{-4} (\text{GeV}) \oplus 0.015$
- ID coverage $|\eta| < 2.5$
- Primary vertex resolution: $\sim 30 \mu\text{m}$ transverse, $\sim 50 \mu\text{m}$ longitudinal
- Muon Spectrometer (MS) Momentum resolution $< 10\%$ for muons with energy $< 1 \text{ TeV}$
- MS coverage $|\eta| < 2.7$

Trigger Selection

5

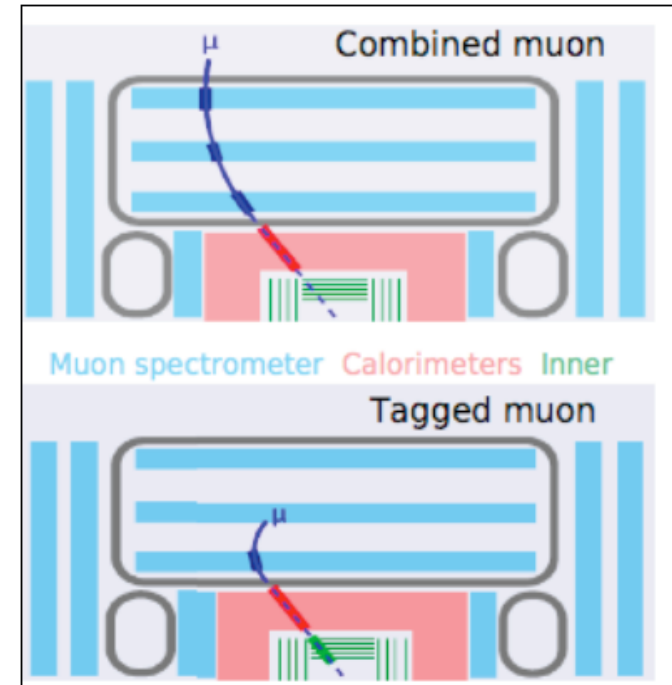
- Minimum Bias Trigger Scintillators for earliest data taking
- Muon Trigger system :
 - ▣ Single muon seeded trigger with thresholds of
 - lowest possible (simple time coincidence, no explicit cut on transverse momentum) based only on L1
 - Event Filter (EF) $p_T > 4 \text{ GeV} \rightarrow p_T > 6 \text{ GeV}$ (for Υ only 4 GeV) at EF stage
 - ▣ with each step in threshold necessitated by increases in instantaneous luminosity
 - ▣ Also EF $p_T > 10 \text{ GeV}$ for non prompt fraction measurements
 - ▣ di-muon trigger exploited in more recent analysis



Event Selection

6

- Primary vertex with >2 tracks
- OS di-muon events
 - ▣ $p > 3.0 \text{ GeV}$, $p_T > 1.0 \text{ GeV}$ (4 GeV , Υ)
 - ▣ $|\eta| < 2.5$
 - ▣ Track quality cuts
 - # Pixel Hits ≥ 1
 - # SCT Hits ≥ 6
 - ▣ Υ prompt production : $|d_0| < 150 \text{ mm}$ and $|z_0| \sin\theta < 1.5 \text{ mm}$ [impact parameters with respect to the event vertex in the transverse/longitudinal direction]
- Require at least one muon to be Combined
- Require at least one muon to have triggered the event



2 classes of muons :

Combined: full track segments in both the muon spectrometer and the inner detector

Tagged: full track segment in the inner detector associated with at least 1 hit in the muon system

Inclusive $J/\psi \rightarrow \mu^+ \mu^-$ Differential Production Cross-Section

7

$$\frac{d^2\sigma(J/\psi)}{dp_T dy} Br(J/\psi \rightarrow \mu^+ \mu^-) = \frac{N_{corr}^{J/\psi}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

yields in a given p_T - y bin after continuum background subtraction and correction for detector efficiency, bin migration and acceptance effects

Correction per candidate:

$$w^{-1} = \boxed{\mathcal{A}} \cdot \boxed{\mathcal{M}} \cdot \boxed{\mathcal{E}_{\text{trk}}^2} \cdot \boxed{\mathcal{E}_{\mu}^+(p_T^+, \eta^+) \cdot \mathcal{E}_{\mu}^-(p_T^-, \eta^-)} \cdot \boxed{\mathcal{E}_{\text{trig}}}$$

bin migration (orange box above \mathcal{M})

acceptance (red box below \mathcal{A})

ID track efficiency (green box below $\mathcal{E}_{\text{trk}}^2$)

Muon reconstruction efficiency (charge dependent) (blue box above the muon efficiency product)

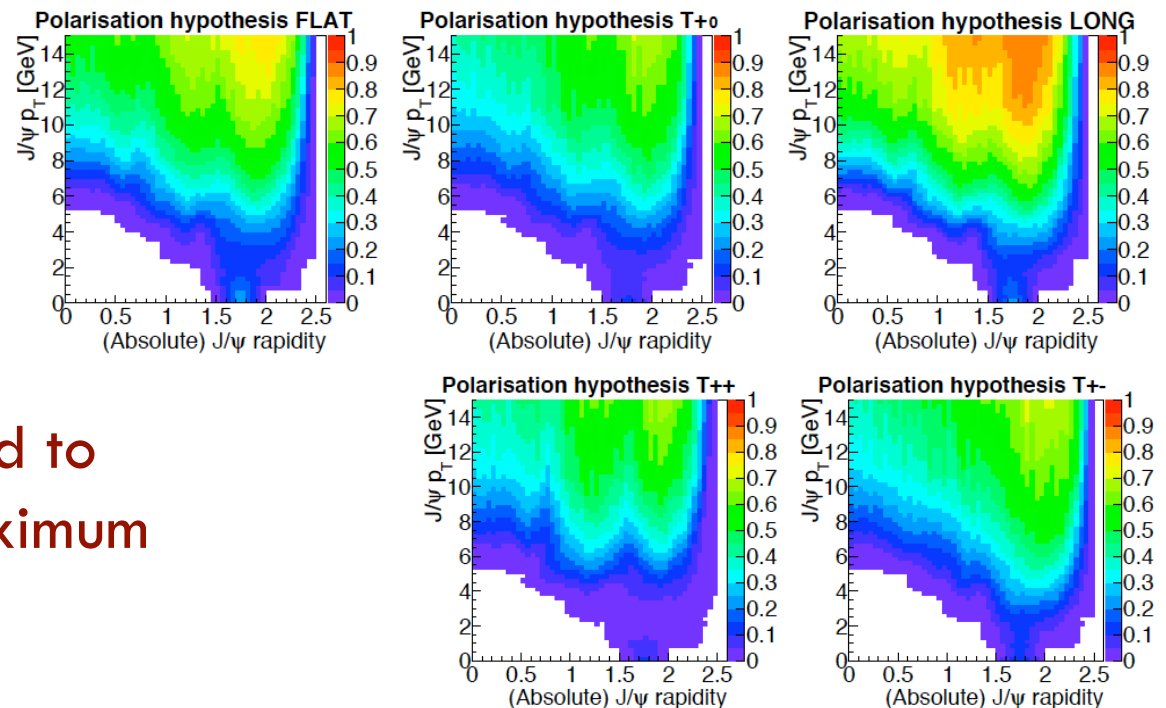
trigger efficiency (blue box below $\mathcal{E}_{\text{trig}}$)

The resultant weighted invariant mass peak is then fitted to extract N_{corr}

Acceptance

8

- probability that $J/\psi(p_T, \eta)$ decays into muons which fall in the detector active region
- calculated using generator-level Monte Carlo
- function of the not known J/ψ spin alignment, so enters as a theoretical uncertainty
- Five extreme cases that lead to the biggest variation of acceptance within the kinematics of the ATLAS detector

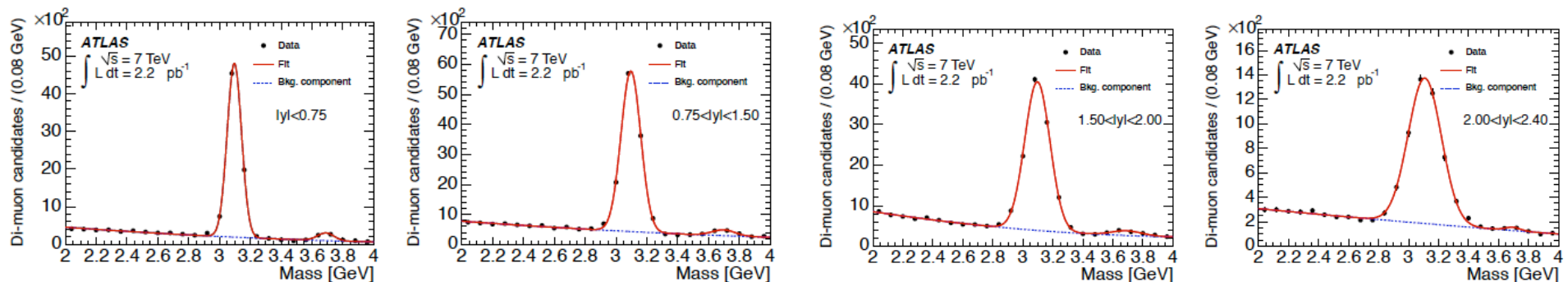


the measurement is repeated to
provide an envelope of maximum
variation

Signal Extraction

9

- Efficiency correction
 - ▣ Trigger : evaluated with Monte Carlo to obtain a fine granularity, and then corrected by data (tag and probe, charge dependent)
 - ▣ Reconstruction
 - muon : evaluated with data (tag and probe) using J/ψ for lower p_T muons and Z at higher p_T
 - ID : constant efficiency for muon tracks of $99.5 \pm 0.5 \%$
- The inclusive production cross-section is determined in bins of J/ψ p_T and y

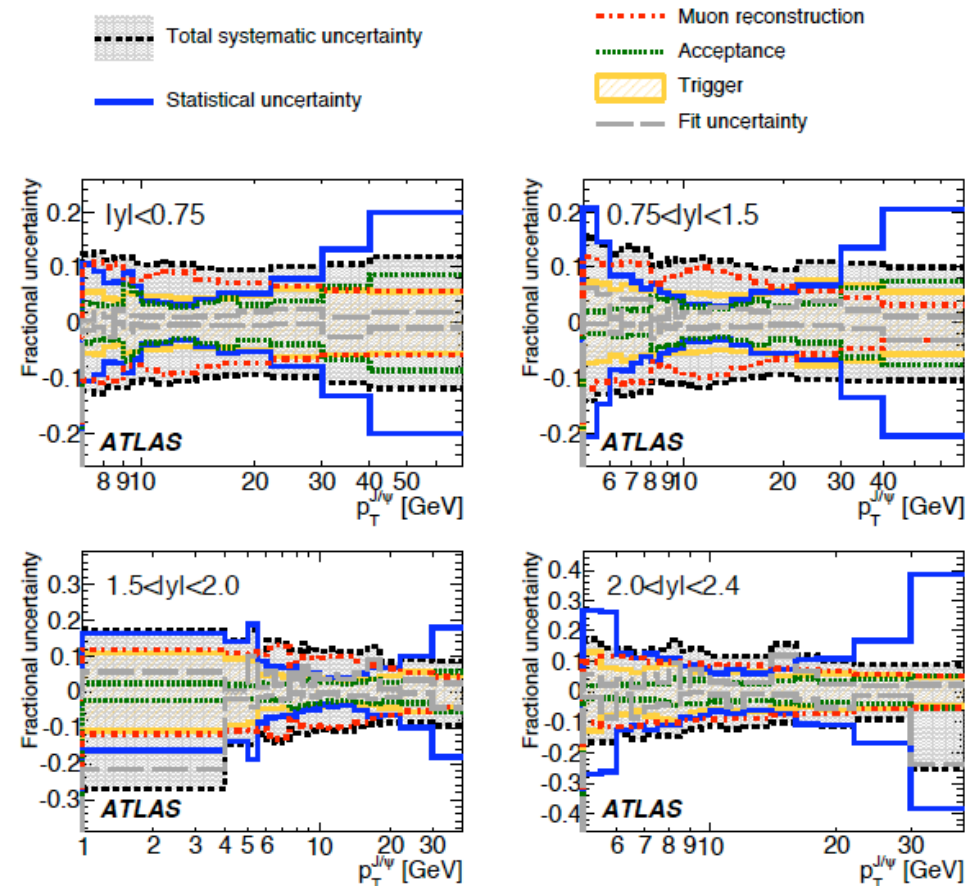


- Obtain weighted yields in each slice using a binned χ^2 fit to the corrected mass distribution
- Single Gaussian for the signal and linear background
- $\psi(2S)$ included in the fit but yield not extracted

Systematic Uncertainties

10

- Muon reconstruction and trigger
5 – 10 %
- Luminosity : 3.4%
- Acceptance : 1-2%
- Bin Migration
 - ▣ low p_T and $y \rightarrow 0.1\%$
 - ▣ high p_T and $y \rightarrow 3\%$
- Fit Procedure: 1-3%



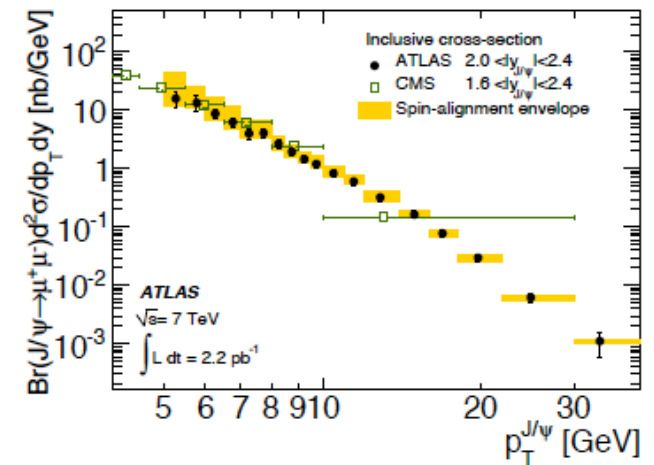
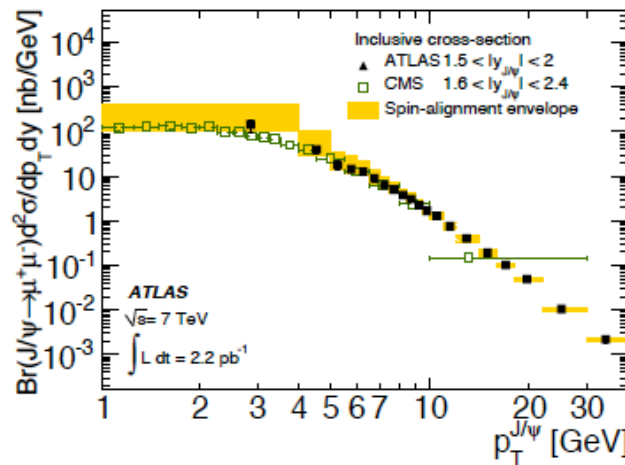
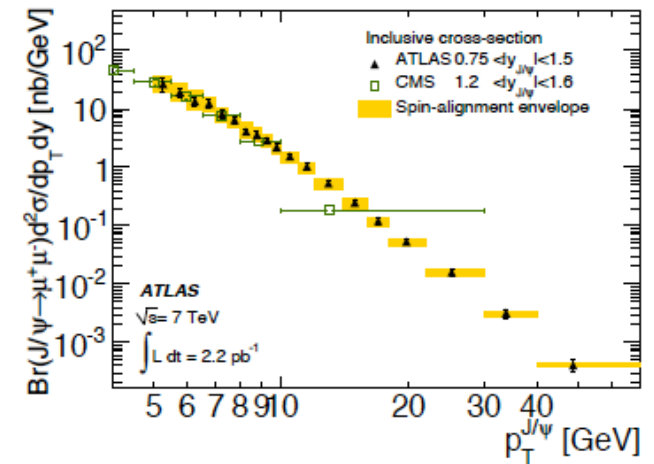
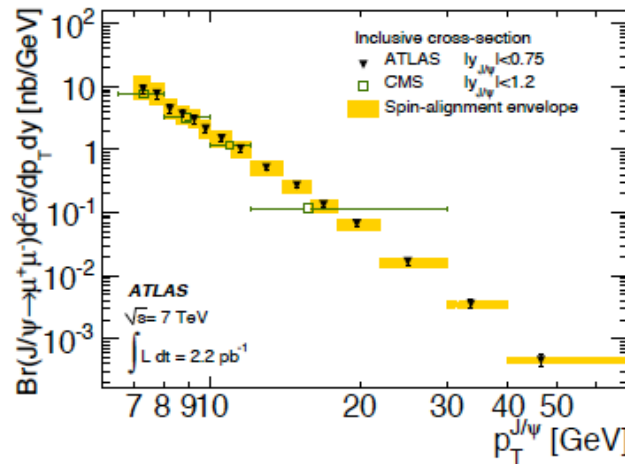
spin alignment not shown

Differential cross-section in rapidity bins

11

Compared to CMS [V.
Khachatryan et al.,
Eur.Phys.J. C71 (2011)
1575, [arXiv:1011.4193](https://arxiv.org/abs/1011.4193)
[hep-ex]]
for similar rapidity ranges.

Good agreement, provide
complementary
measurements at low (CMS)
and high (ATLAS) p_T



Non Prompt Fraction f_B

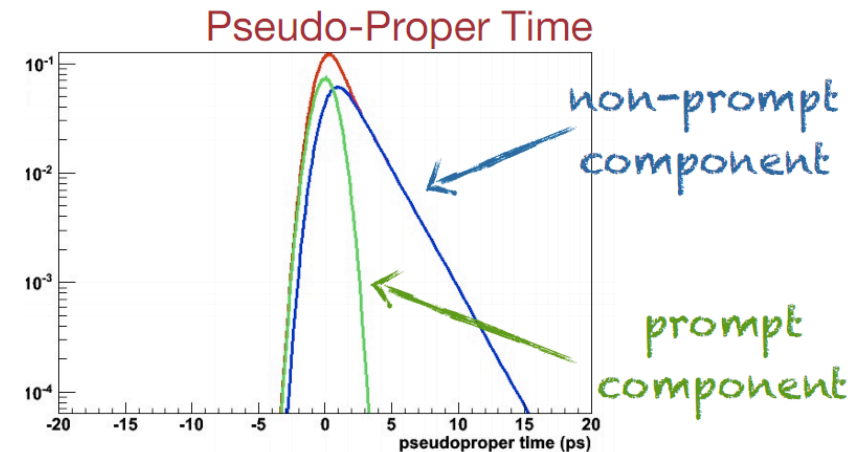
12

- possible to distinguish J/ψ from prompt production and decays of heavier charmonium states from the J/ψ produced in B-hadron decays (non-prompt production)
- from the measured distances between the primary vertices and corresponding J/ψ decay vertices
- Discriminating variable: **pseudo-proper lifetime**

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

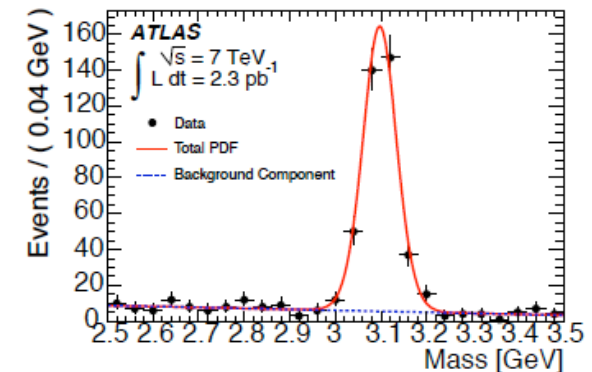
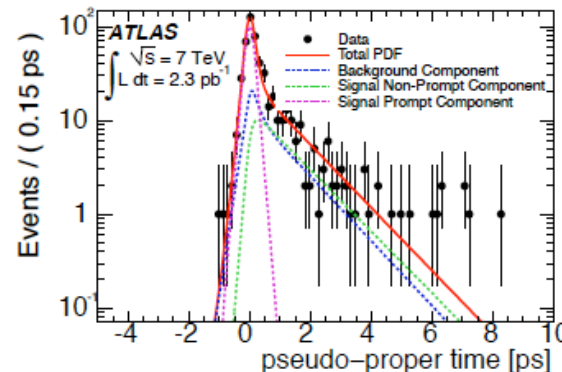
L_{xy} is the displacement of the J/ψ vertex in the transverse plane.

$$f_B \equiv \frac{\sigma(pp \rightarrow B + X \rightarrow J/\psi X')}{\sigma(pp \xrightarrow{\text{Inclusive}} J/\psi X'')}$$



- Perform simultaneous invariant mass and pseudoproper lifetime fits to extract the non-prompt fraction in each p_T - y slice

$|y_{J/\psi}| < 0.75$



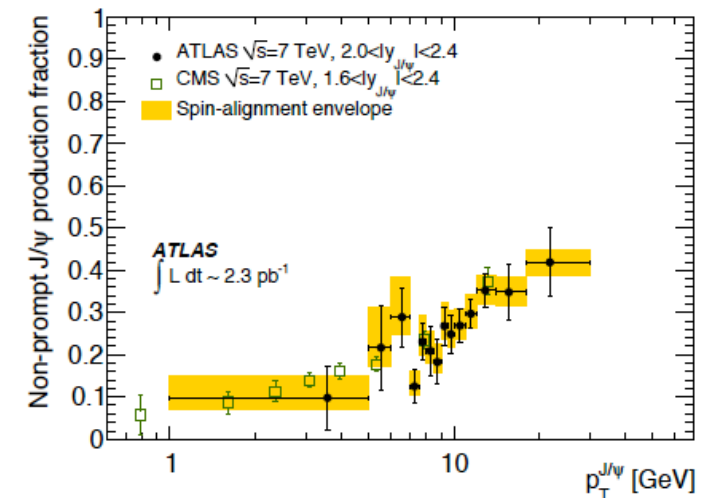
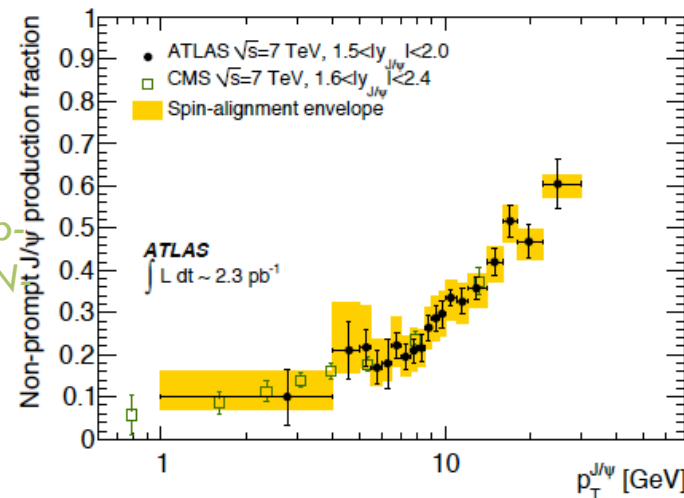
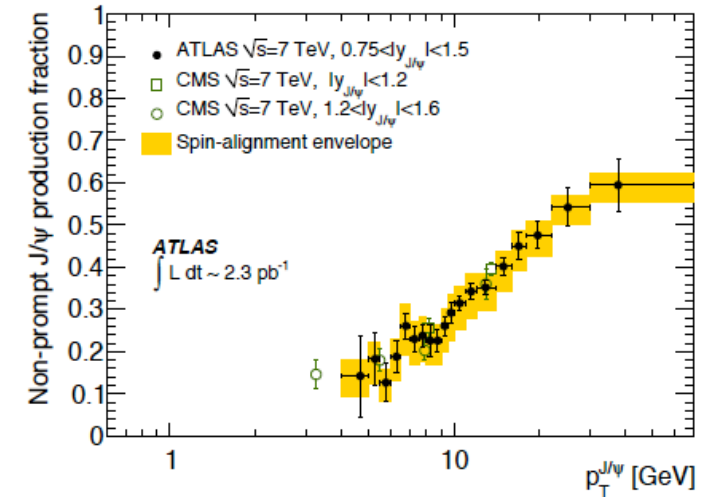
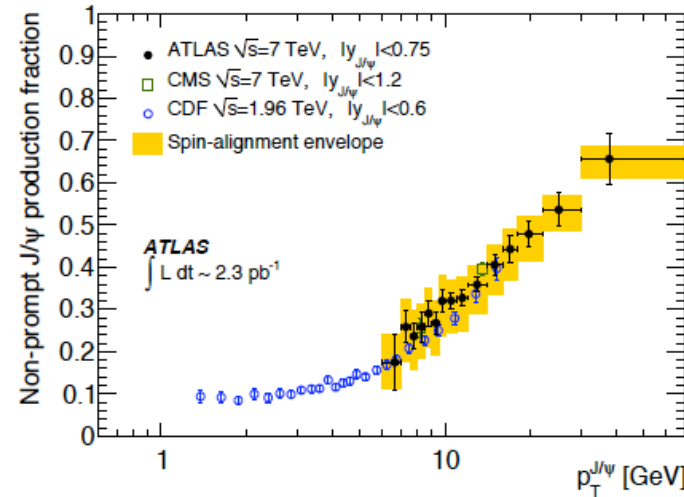
Non-prompt Fraction Results

13

Spin-alignment envelope covers variation from isotropic as measured by CDF [Phys. Rev. Lett. 99 (2007) 132001, arXiv: 0704.0638 [hep-ex]] sum $\sim 0.4\%$ uncertainty

Good agreement with CMS [arXiv:1011.4193 [hep-ex], CMS-BPH-10-002, CERN PH-EP-2010-04] and CDF [Phys. Rev. D71 (2005) 032001, arXiv:hep-ex/0412071]

→ no strong dependence on the center of mass energy



Prompt/non-prompt cross sections can be extracted by combining the inclusive cross section and the non-prompt fraction

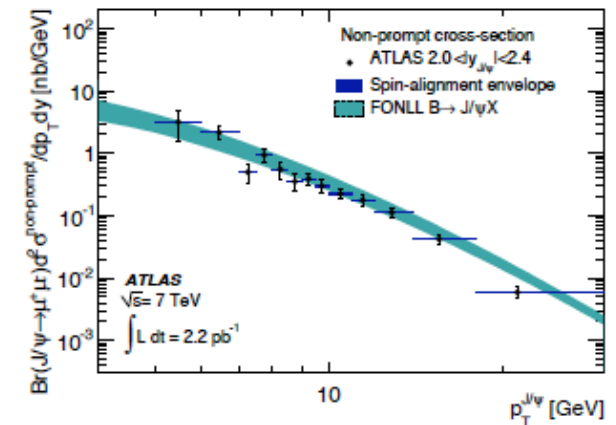
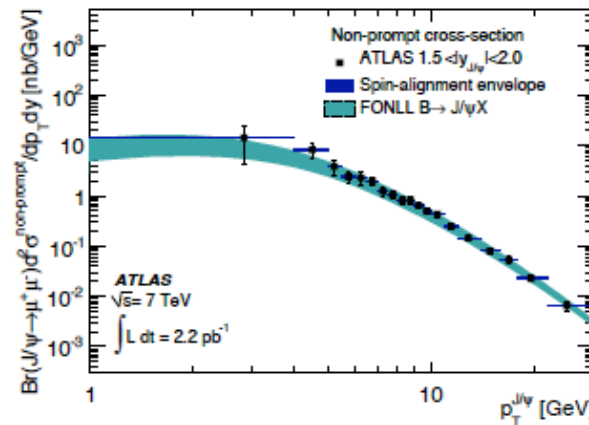
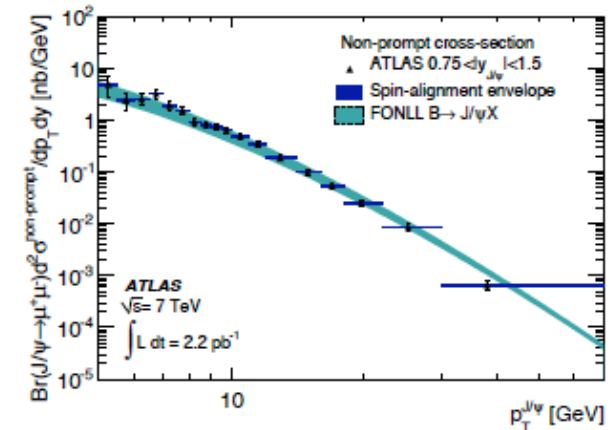
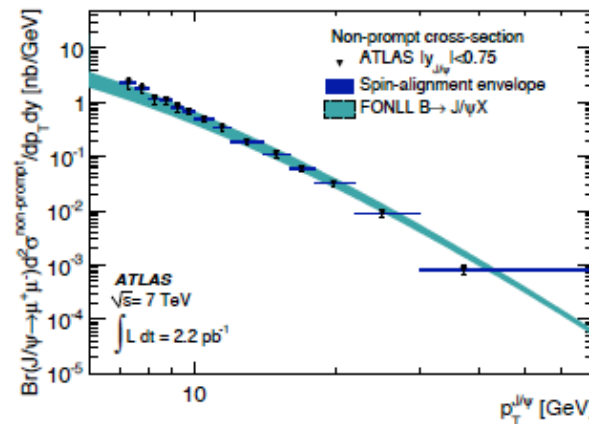
Non-Prompt Cross-Sections

14

- compared to Fixed Order Next-to-Leading Logarithm (FONLL) [M.

Cacciari, M. Greco and P. Nason, *JHEP* 9805 (1998) 007, [arXiv:hep-ph/9803400](https://arxiv.org/abs/hep-ph/9803400); *JHEP* 0103 (2001) 006, [arXiv:hep-ph/0102134](https://arxiv.org/abs/hep-ph/0102134)

- Good agreement between the experimental data and the theoretical prediction across the full range of rapidity and transverse momentum considered.



Prompt Cross-Sections

15

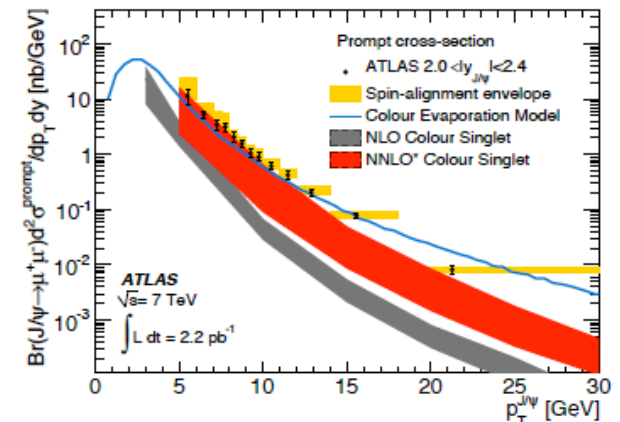
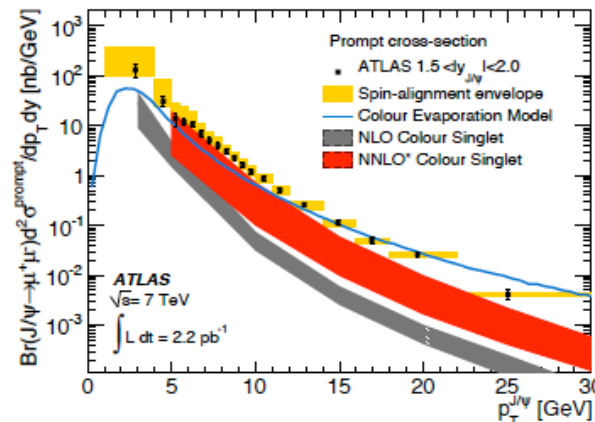
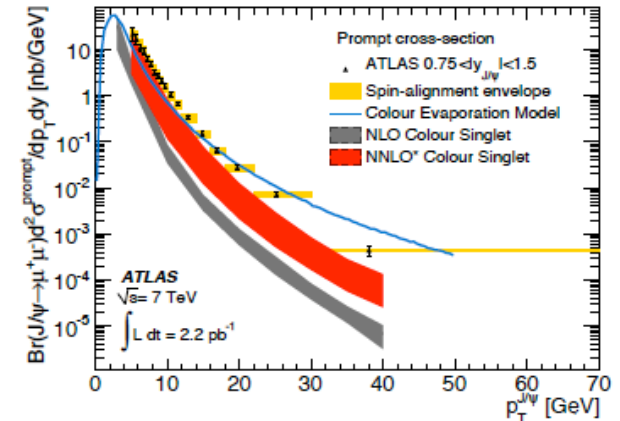
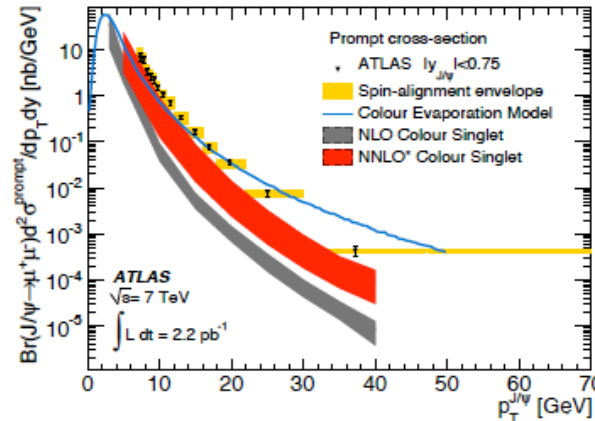
compared to

Colour Evaporation Model (CEM)

- *Phys. Rept.* 462 (2008) 125, *arXiv:0806.1013 [nucl-ex]*; *Phys. Lett. B* 91 (1980) 253; *Z. Phys. C* 6 (1980) 169

Colour Singlet Model (CSM) at NLO/ NNLO*

- *arXiv:1006.2750 [hep-ph]*; *Phys. Rev. D* 81 (2010) 051502; *Eur. Phys. J. C* 61 (2009) 693, *arXiv:0811.4005 [hep-ph]*.



CEM prediction is generally lower and diverges in shape from measured data, showing disagreement in the extended p_T range probed in this measurement

CSM corrected for feed-downs. The overall scale of the central prediction is low. NNLO* improves the p_T dependence and normalisation over NLO.

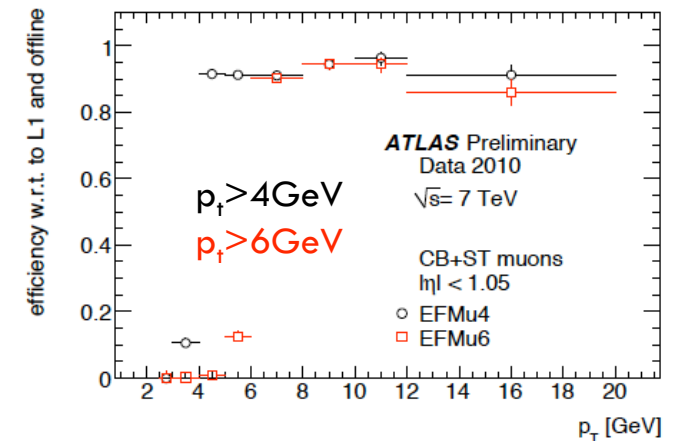
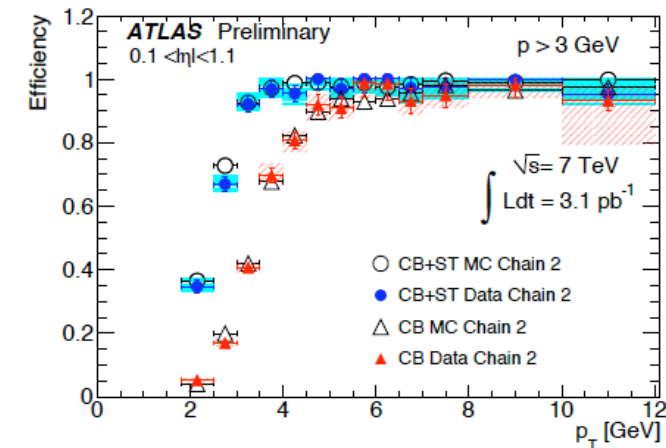
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- Measurement within fiducial cuts
 - ▣ $p_T > 4 \text{ GeV}$, $|\eta| < 2.5$
 - ▣ no uncertainties due to the spin alignment

$$\frac{d^2\sigma}{dp_T dy} \times \text{BR}(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = \frac{N_{\Upsilon(1S)}^*}{\int \mathcal{L} dt \times \Delta p_T \times \Delta y},$$

(*)corrected

- unbinned maximum likelihood fit to the dimuon mass distribution after correcting for the efficiency per event
 - ▣ Muon reconstruction efficiency
 - ▣ Muon trigger efficiency
 - ▣ Tracking efficiency
 - ▣ Efficiency of impact parameter selection
- all efficiency factors are determined directly from the data

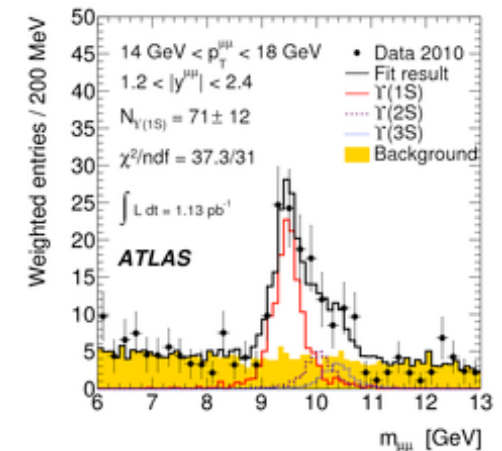
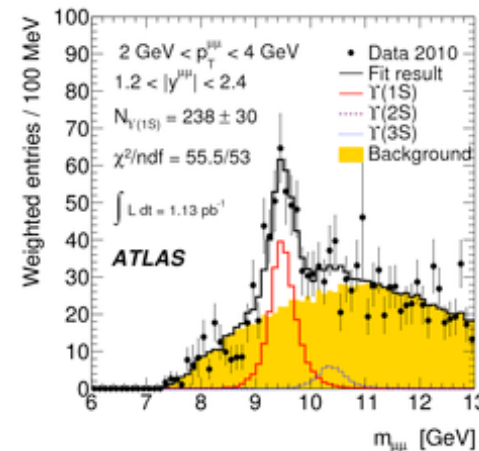
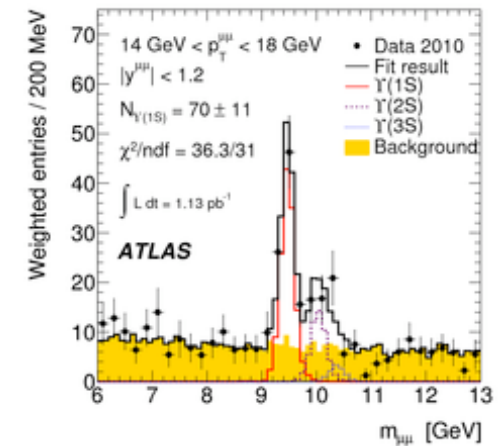
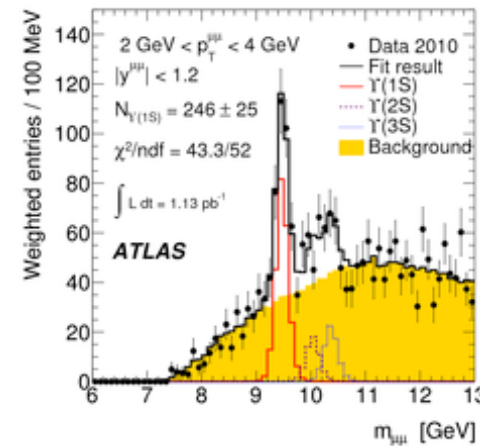


muon reconstruction and trigger
efficiency using J/ψ decays

Υ Yields and Background Determination

17

- background depends on the kinematic bin
- $\Upsilon(1S)$ is not well separated from $\Upsilon(2S)$ and $\Upsilon(3S)$
- Signal Model: templates from MC
 - Independent for each resonance peak
 - Adjust resolution to reflect data
 - Separation of mass peaks fixed to world average
- Background model from data
 - Template generated from μ + oppositely signed track
 - same track quality and kinematic selection applied
 - Alternative templates (μ +SS track, MC $b\bar{b}$) give results in agreement (systematic uncert.)
- 4 parameters are fitted independently in each kinematic bin: $N_{\Upsilon(1S)}$, $N_{\Upsilon(2S)}$, $N_{\Upsilon(3S)}$, N_{bkg}



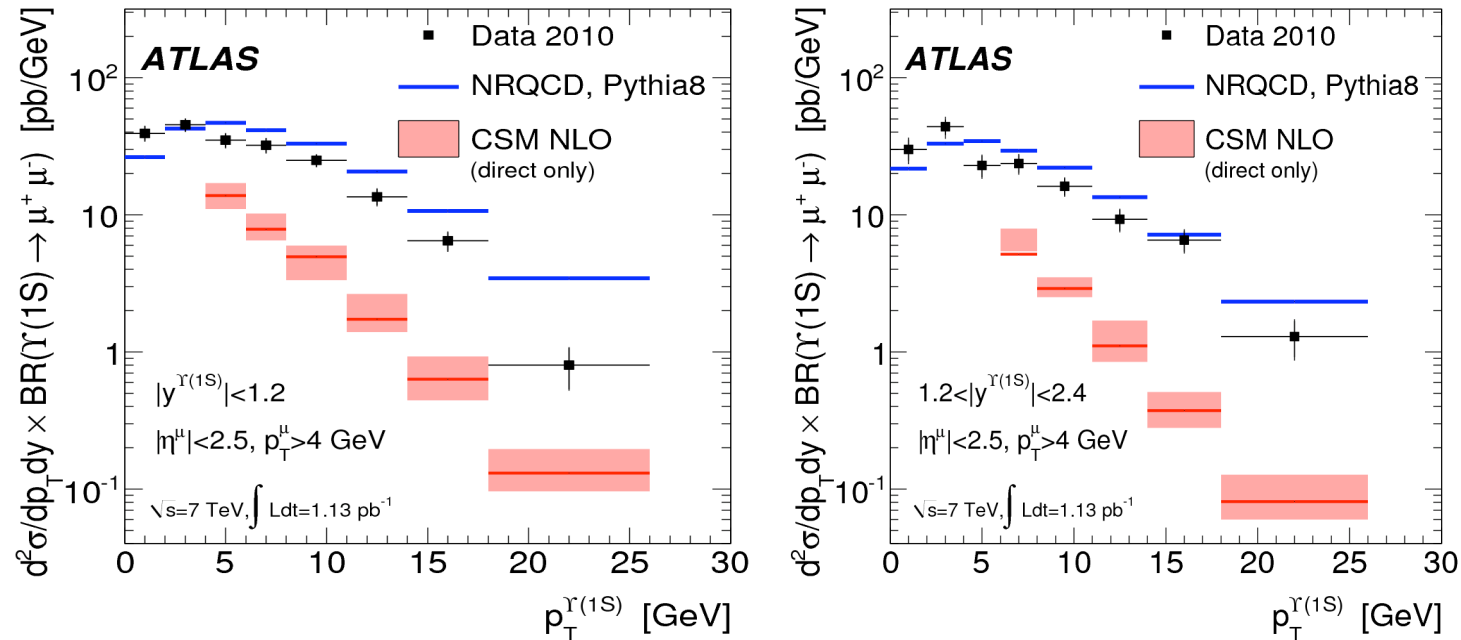
Systematic Uncertainties

18

- Luminosity calibration → 3.4%
- Muon reconstruction efficiency → 1%
- Muon trigger efficiency → 1%
- Efficiency of impact parameter selection → 1% - 3.5%
- bin migrations due to detector resolution and final state → 2%
- Fit model → 5%-10%
 - Signal
 - Pseudo-experiments with varied signal description
 - Mass scale (peak position & separation) & resolution
 - Background
 - Pseudo-experiments with varied templates:
 - same sign μ +track
 - bb, cc Monte Carlo

$\Upsilon(1S)$ Differential Cross Section

19



uncertainty
 $\sim 10\text{-}15\%$ at low p_T
 $\sim 35\%$ at high p_T
 dominated by the
 statistical precision of
 the data

- Compared to
 - ▣ PYTHIA8/Non Relativistic QCD : different p_T dependence, but normalization is reasonable
 - ▣ MCFM/Color Singlet Model NLO : cross section from data is higher
 - prediction does not include feed-down from higher mass states (factor ~ 2)
 - higher order corrections needed

Summary

20

- J/ψ inclusive cross section measured in four rapidity slices from p_T 1-70 GeV
 - ▣ non-prompt fraction also measured allowing the derivation of the non-prompt and prompt cross sections separately
 - ▣ reasonable agreement of the fraction with CDF :no strong dependence on the center of mass energy
 - ▣ FONLL describes the non-prompt cross section well; prompt production is more problematic
- Measurements of $\Upsilon(1S)$ cross section in fiducial cuts
 - ▣ two muons with $p_{T,\mu} > 4$ GeV and $|\eta| < 2.5$
- Both the J/ψ prompt component result and the $\Upsilon(1S)$ results suggest improvements of theoretical models needed
- The data presented here will be useful to further understand the complex mechanisms that govern quarkonium production
- Coming soon: $\chi_c \rightarrow J/\psi \gamma$ (public results available), inclusive $b \rightarrow J/\psi$ lifetime, $\psi(2S) \rightarrow \mu \mu \pi \pi$, 2.76 TeV J/ψ cross section, Υ cross section & polarization, J/ψ J/ψ production, $J/\psi / \psi(2S)$ ratio, J/ψ Polarization ...

Backup

21

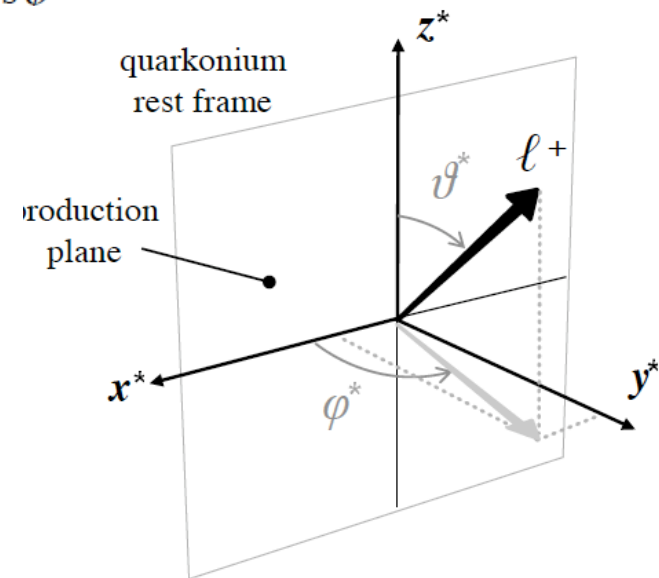


J/ψ Polarization Hypothesis

22

The general angular distribution for the decay $J/\psi \rightarrow \mu^+ \mu^-$ in the J/ψ decay frame

$$\frac{d^2N}{d\cos\theta^*d\phi^*} \propto 1 + \lambda_\theta \cos^2\theta^* + \lambda_\phi \sin^2\theta^* \cos 2\phi^* + \lambda_{\theta\phi} \sin 2\theta^* \cos \phi^*$$



Five extreme cases

1. Isotropic distribution, independent of θ^* and ϕ^* , with $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$, labelled as **"FLAT"**. Used as the main (central) hypothesis.
2. Full longitudinal alignment with $\lambda_\theta = -1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$, labelled as **"LONG"**.
3. Transverse alignment with $\lambda_\theta = +1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$, labelled as **T^{+0}** .
4. Transverse alignment with $\lambda_\theta = +1$, $\lambda_\phi = +1$, $\lambda_{\theta\phi} = 0$, labelled as **T^{++}** .
5. Transverse alignment with $\lambda_\theta = +1$, $\lambda_\phi = -1$, $\lambda_{\theta\phi} = 0$, labelled as **T^{+-}** .