Quarkonium Production at ATLAS

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Representing the ATLAS Experiment

Outline

- Introduction and Motivation
- The ATLAS Detector
- J/ψ production
  - J/ψ production cross section
  - prompt and non-prompt J/ψ
- **ϒ(nS) production**
  - ArXiv:1211.7255, Phys. Rev. D87 (2013) 052004
- **Observation of prompt J/ψ associated with the $W^{\pm}$**
  - ATLAS-CONF-2013-042
- Summary

Introduction and Motivation

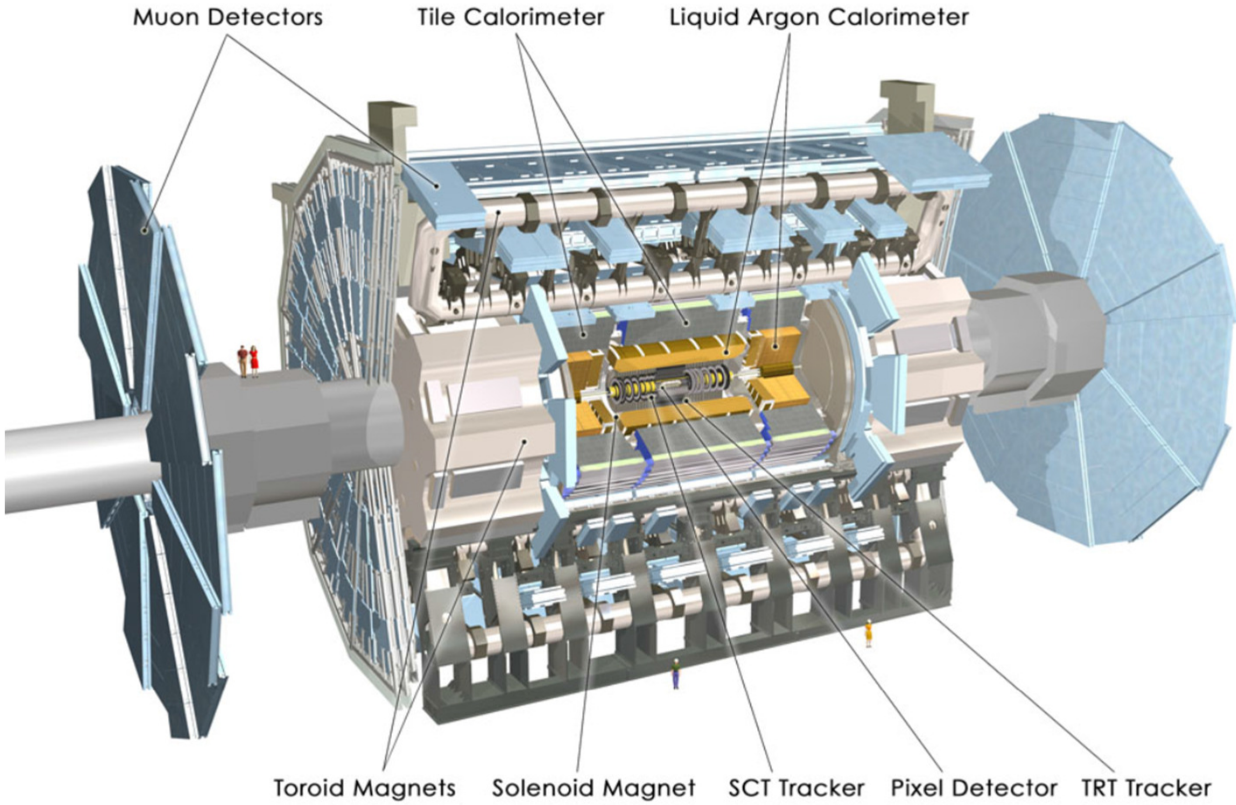
- The production of heavy quarkonium states in pp collision has been measured at various CM energies
- The production mechanism has not been well understood; color singlet (CS) and color octet (CO) schemes describe p_T spectrum measured at Tevatron, but not spin-alignment
- Quarkonia are produced via

  Prompt production: direct production or from decays of higher mass quarkonium states. No pseudo-life time tail

  Non-prompt production: from decays of B hadrons (to J/ψ), leaving a long pseudo-proper time tail

  fractions determined from a fit to the pseudo-proper time distribution
- LHC provides a new energy region to test and improve QCD calculations

The ATLAS Detector



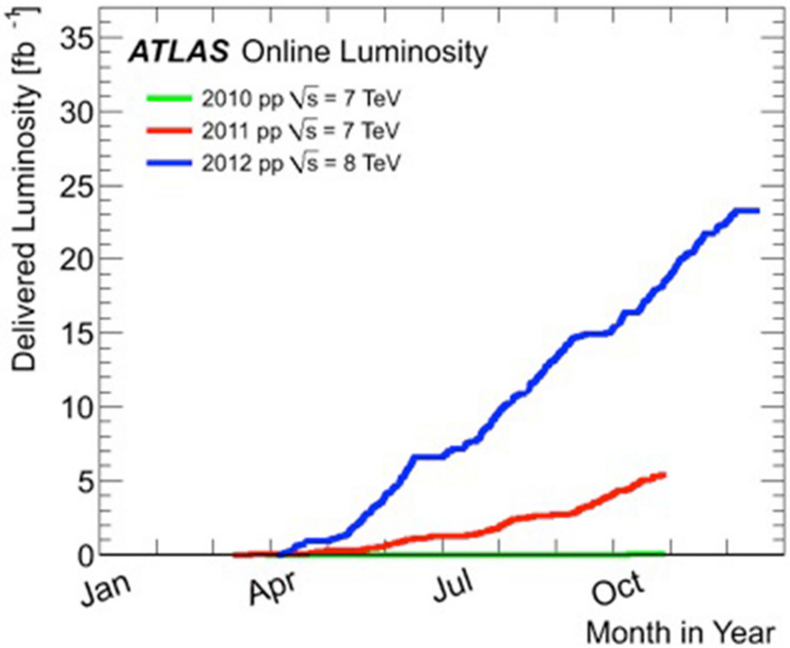
<u>Inner Detector</u>
Tracking with Silicon and Transition Radiation Trackers
Pseudorapidity range $|\eta|<2.5$
Solenoidal B-field 2T

<u>Liquid Argon and Tile Calorimeters</u>
Highly granular and longitudinally segmented in 3-4 layers

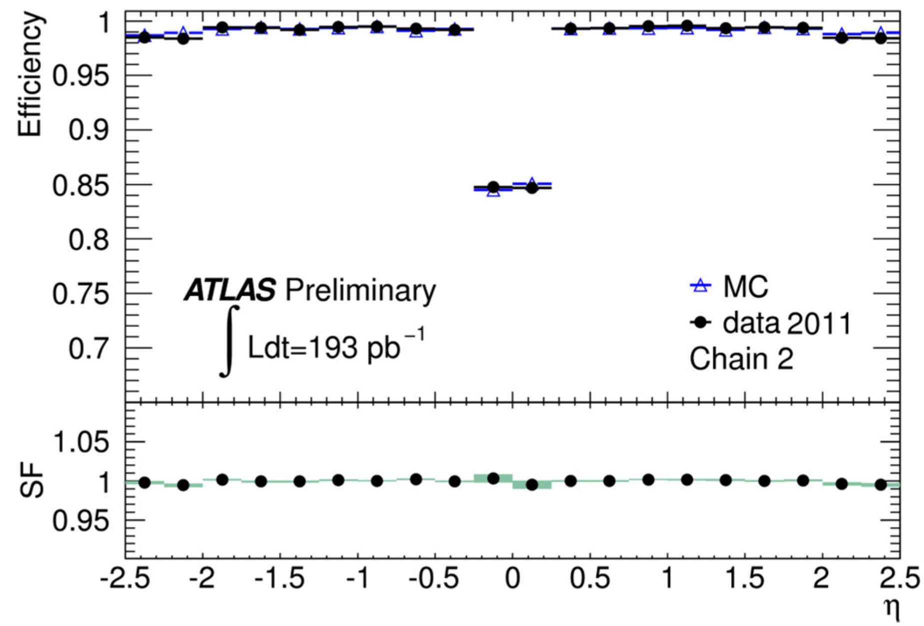
<u>Muon Spectrometer</u>
Dedicated muon chambers in pseudorapidity $|\eta|<2.7$ (trigger $|\eta|<2.4$)
Toroidal B-field 0.5 T

The ATLAS Detector

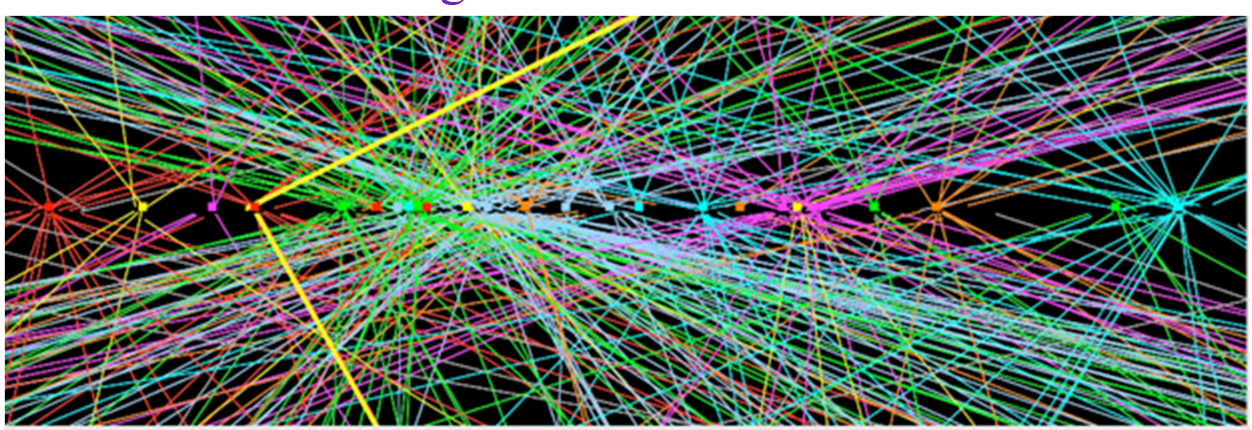
Data collection



Muon efficiency

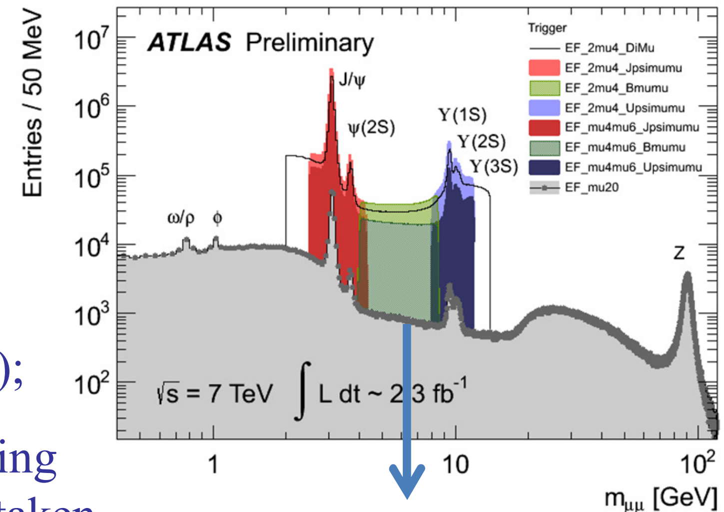


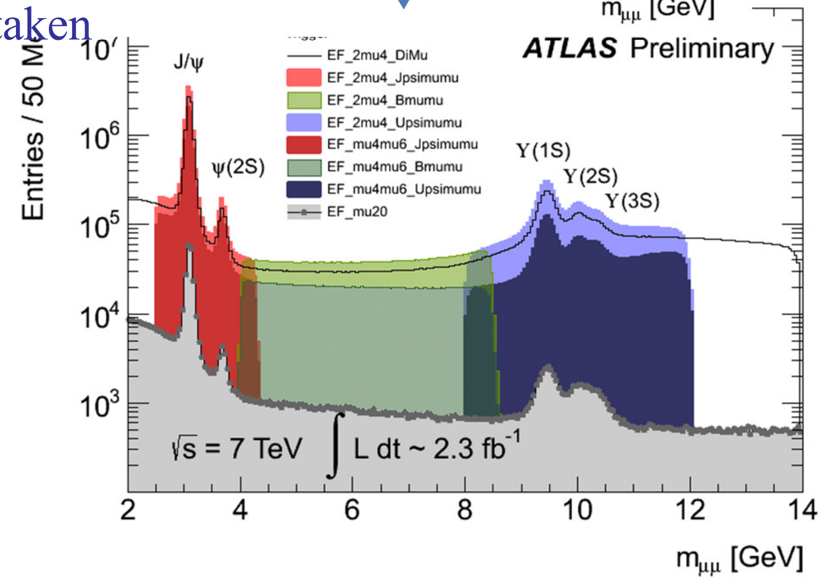
Tracking and vertex reconstruction

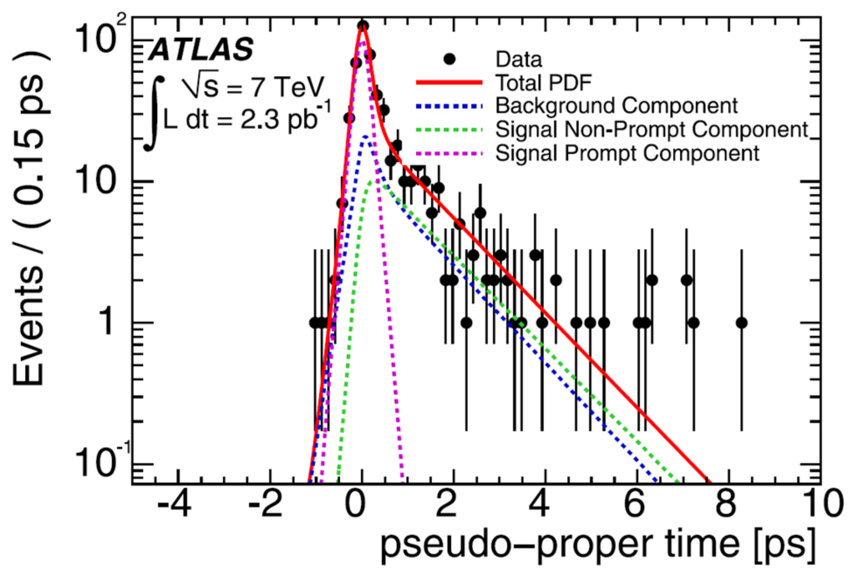


Trigger and Quarkonium Reconstruction

- Quarkonia are reconstructed through di-muons
- Sophisticated triggers are applied to select signal and reduce data rate
- Over time triggers are tightened to balance rate with increasing luminosity, affecting quarkonia: single muon trigger (2010); dimuon trigger (2011);
- pseudo-proper time measured with precision tracking (pixel + SCT and straw tracker); Data shown was taken in 2011







many onging analyses using 2012 data

Prompt and non-prompt J/ψ production (1)

- The LHC data can help test existing theoretical models of quarkonium and b hadron production in a new energy regime
- Measurements can be made at higher transverse momenta and wider rapidity ranges
- Help understand production & suppression mechanisms
- We can study new observables and processes in detail that was not possible, because of high production rates, large integrated luminosity, higher CM energies, excellent detector acceptance and detector performance at the LHC

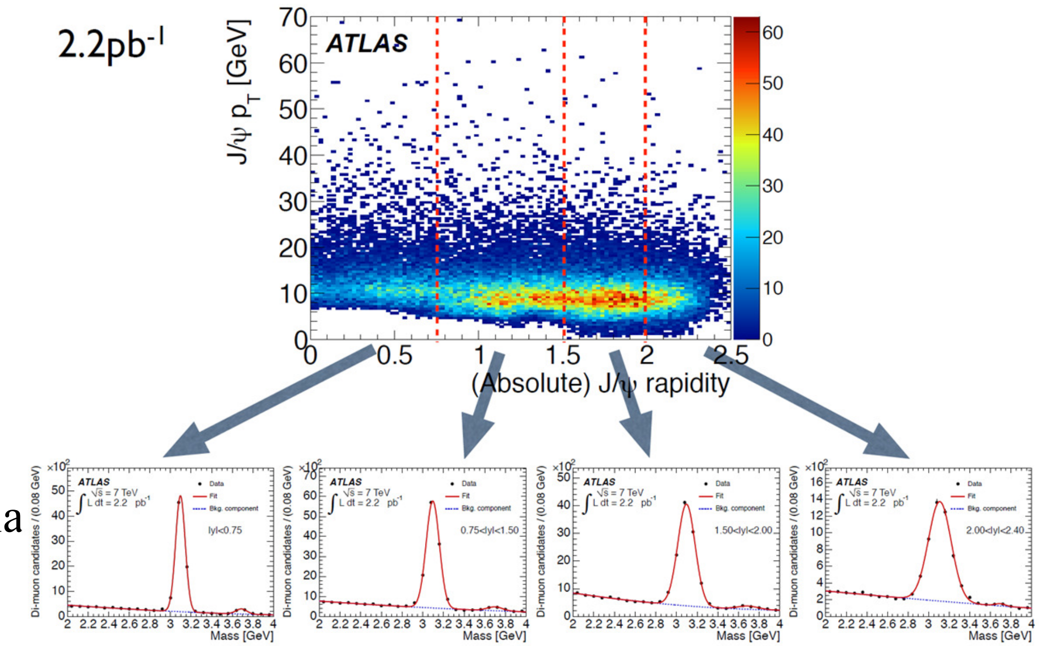
Prompt and non-prompt J/ψ production (2)

- Based on 2.2 pb^{-1} (2010) pp collision at 7 TeV
- Dimuon events with a vertex consisting of at least 3 tracks
- Events divided into 4 rapidity slices
- Binned χ^2 fit was applied
- Signal described with a single Gaussian
- Background ~ 2^{nd} order polynomial
- ψ(2S) included in the fit
- Differential cross sections determined via

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

- Luminosity error ~3.4%

Illustration of J/ψ signals



both J/ψ and ϒ(nS) measurements use same techniques

Nuclear Physics B 850 (2011) 387–444

Prompt and non-prompt J/ψ production (3)

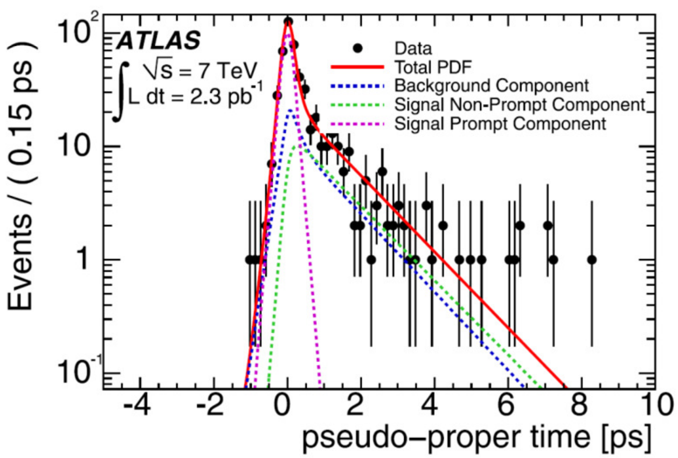
- Pseudo-proper lifetime

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

is used as a discriminator

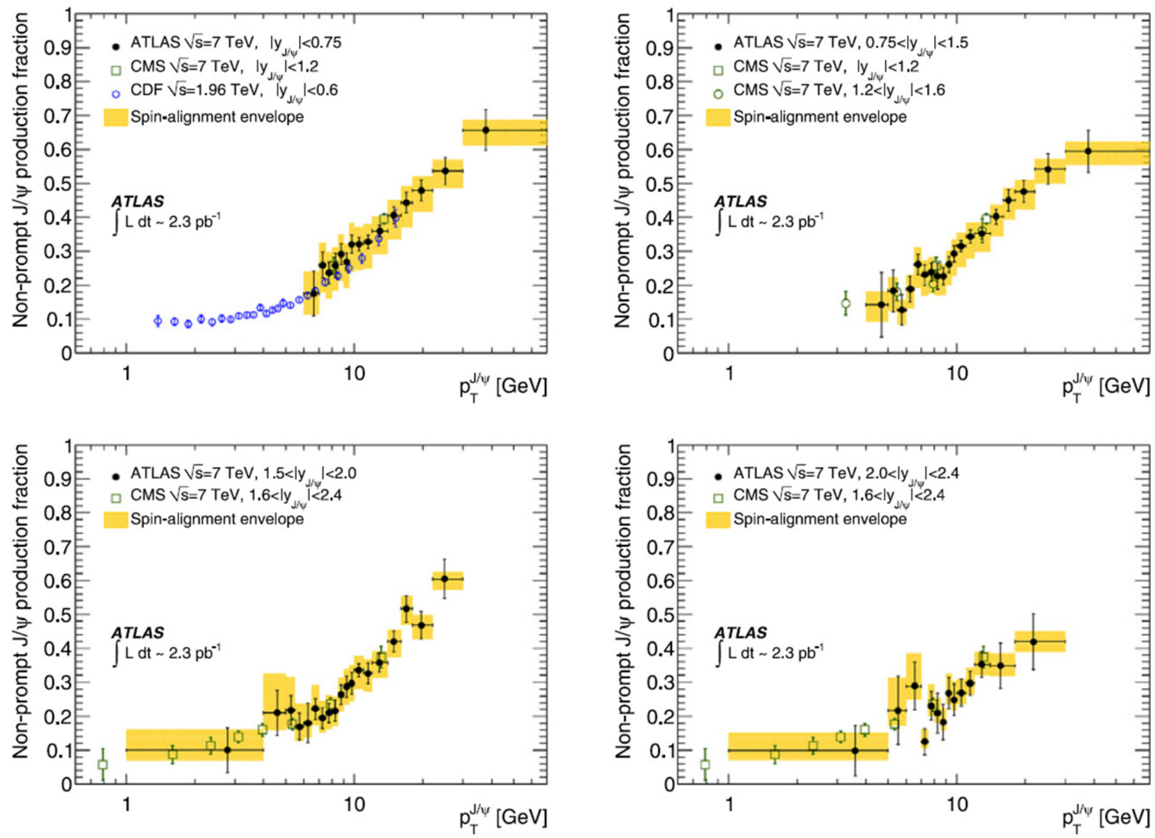
- Simultaneous mass-τ fit
- Non-prompt fraction:

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



ATLAS, CMS data consistent
LHC data merge well with CDF data
p_T trending independent of pp E_{cm}

non-prompt to inclusive fractions



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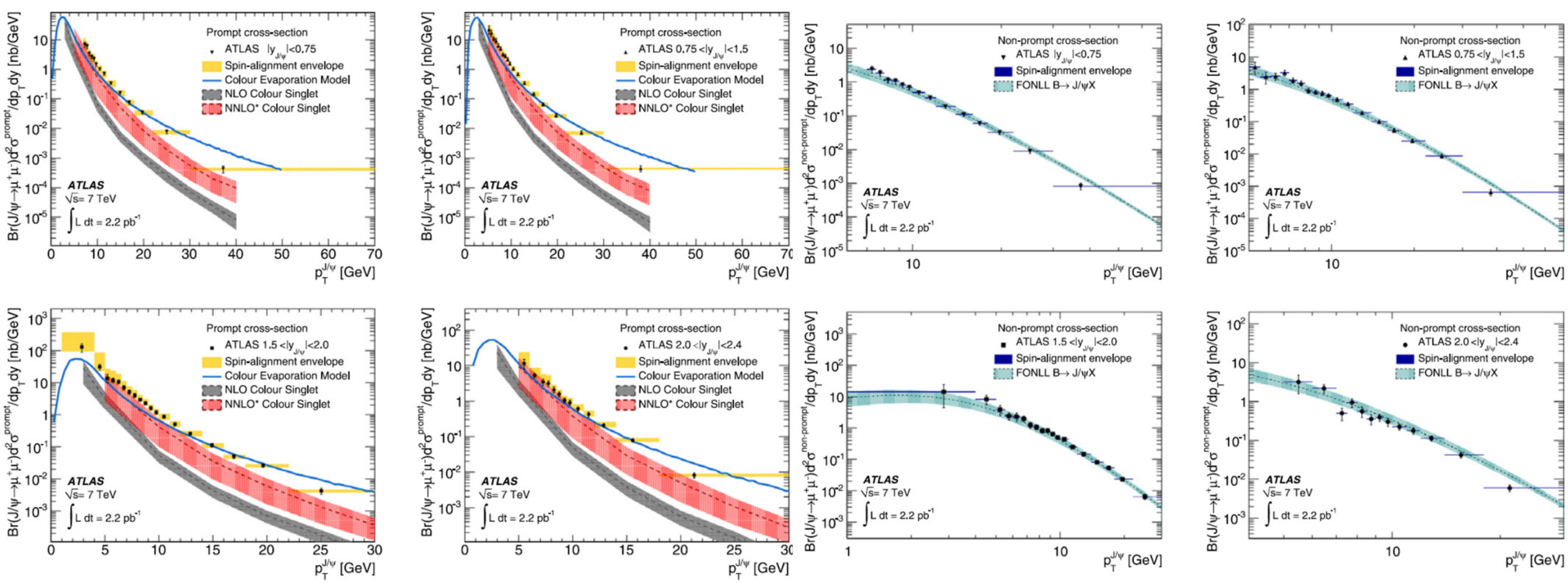
Prompt and non-prompt J/ψ production (4)

- Contributions from color singlet model: NNLO better than NLO
- NNLO Color singlet underestimates J/ψ rates
- CEM model underestimates J/ψ rates at low p_T
- Non-prompt cross-section well described by FONLL model



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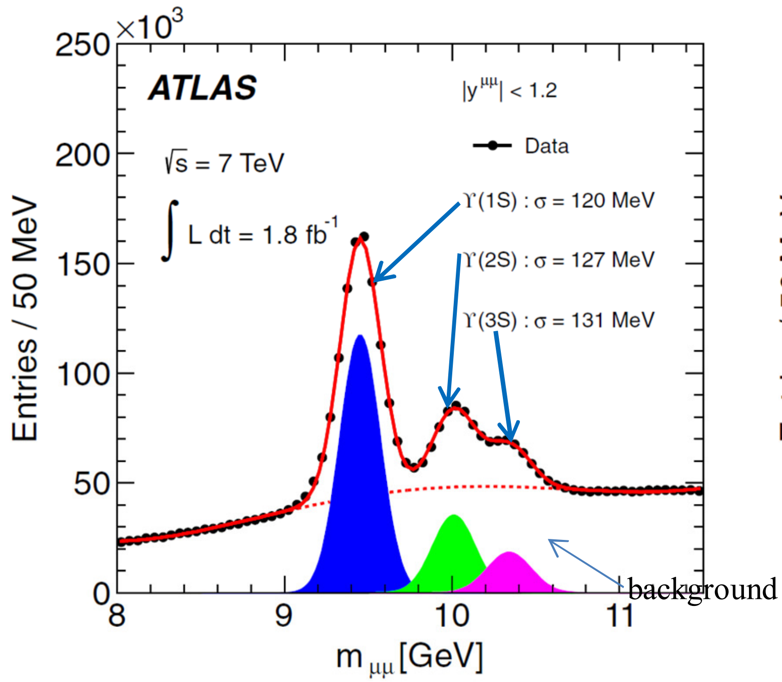
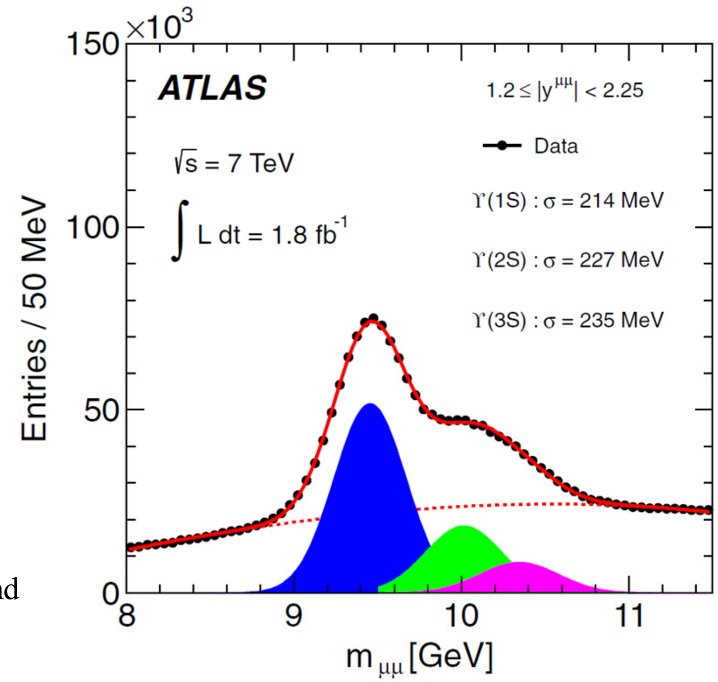
Υ(nS) Production (1)

- ATLAS measurement based on 1.8 fb^{-1} (2011) data; update from 1.13 pb^{-1}(2010)
- Υ(nS) (n=1,2,3) with p_T up to 70 GeV, $|\eta|<2.25$ (new p_T reach at LHC)





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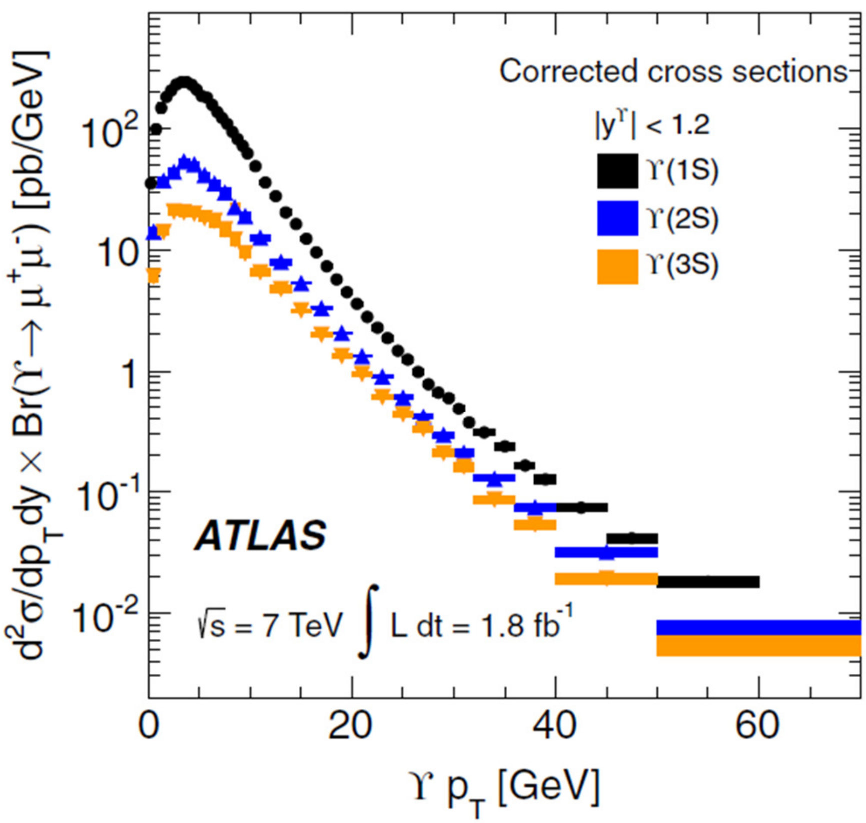
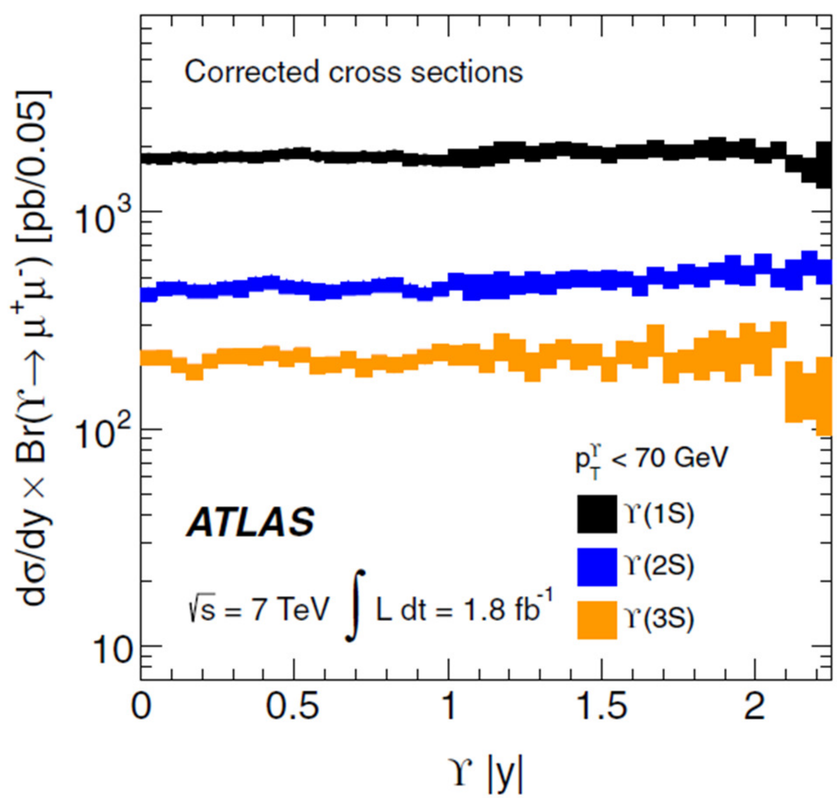
Υ(nS) Production (2)

- The cross section is measured within full ATLAS detector acceptance
- Product of BR and cross sections are shown





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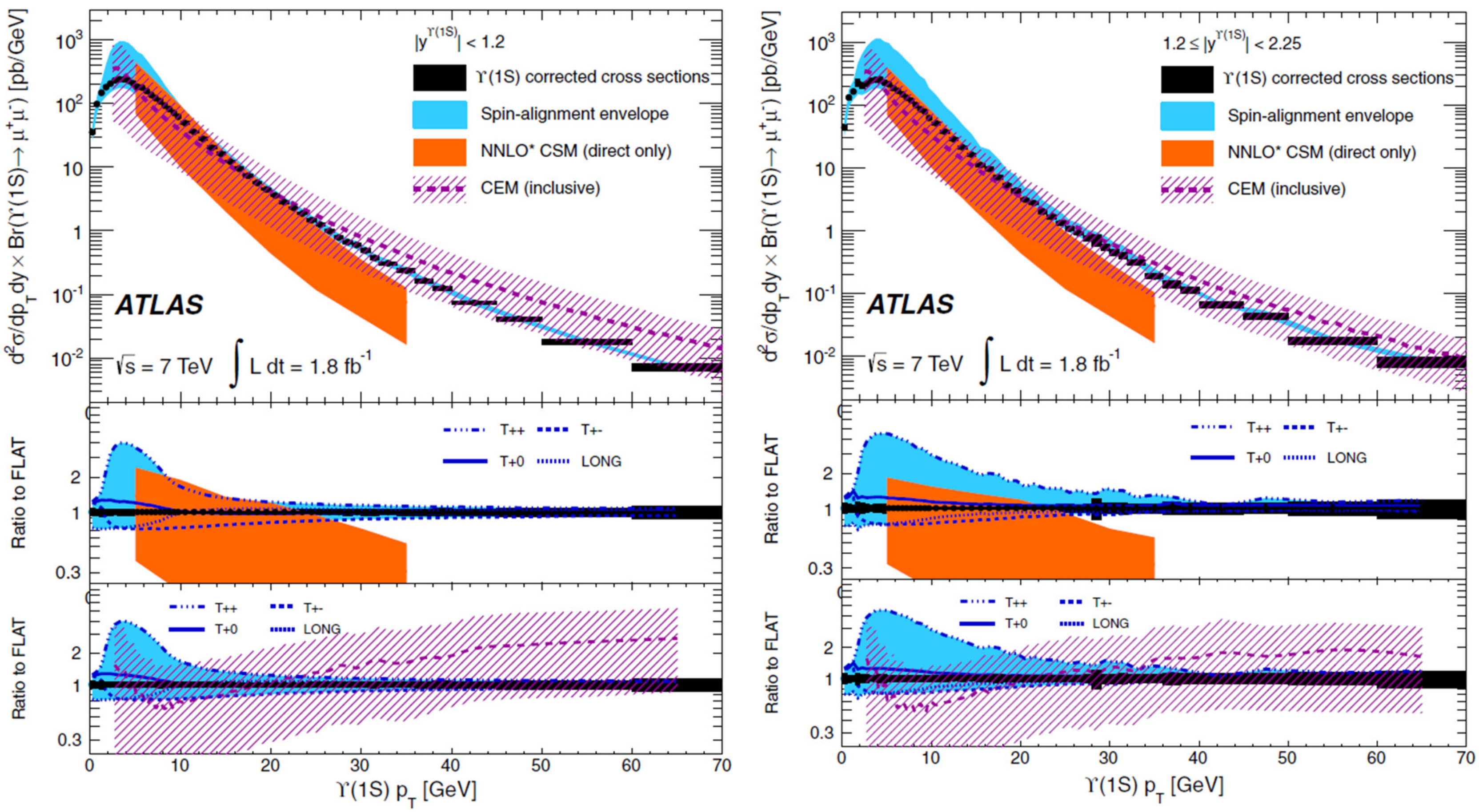
ϒ(nS) Production (3)

- The differential cross sections are compared with NNLO color singlet (CSM) predictions and Color Evaporation Model (CEM)
- CSM underestimates ϒ(1S) rate; large number of points, extends to p_T=70 GeV



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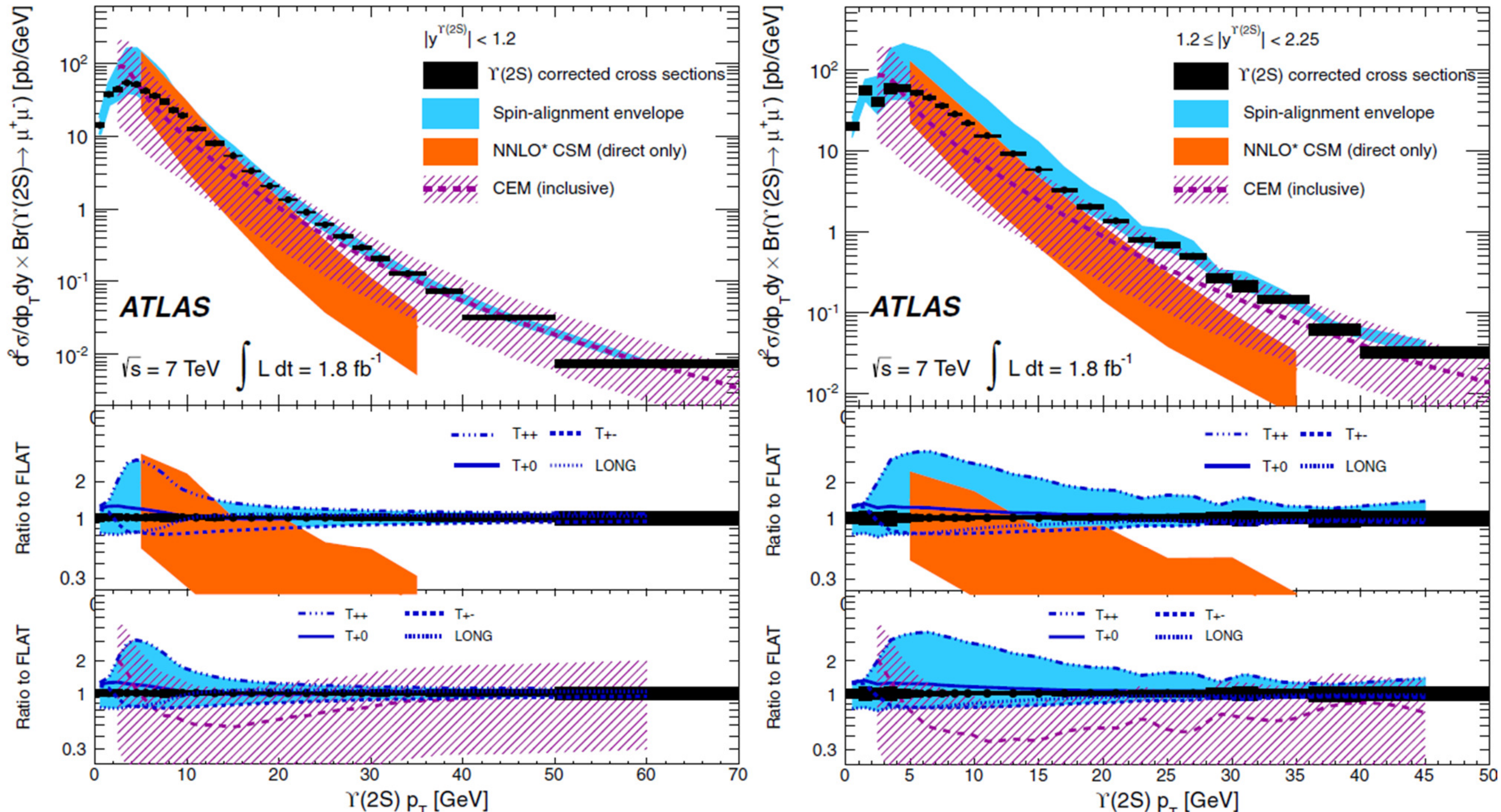
ϒ(nS) Production (4)

The differential cross sections are compared with NNLO color singlet predictions and Color Evaporation model



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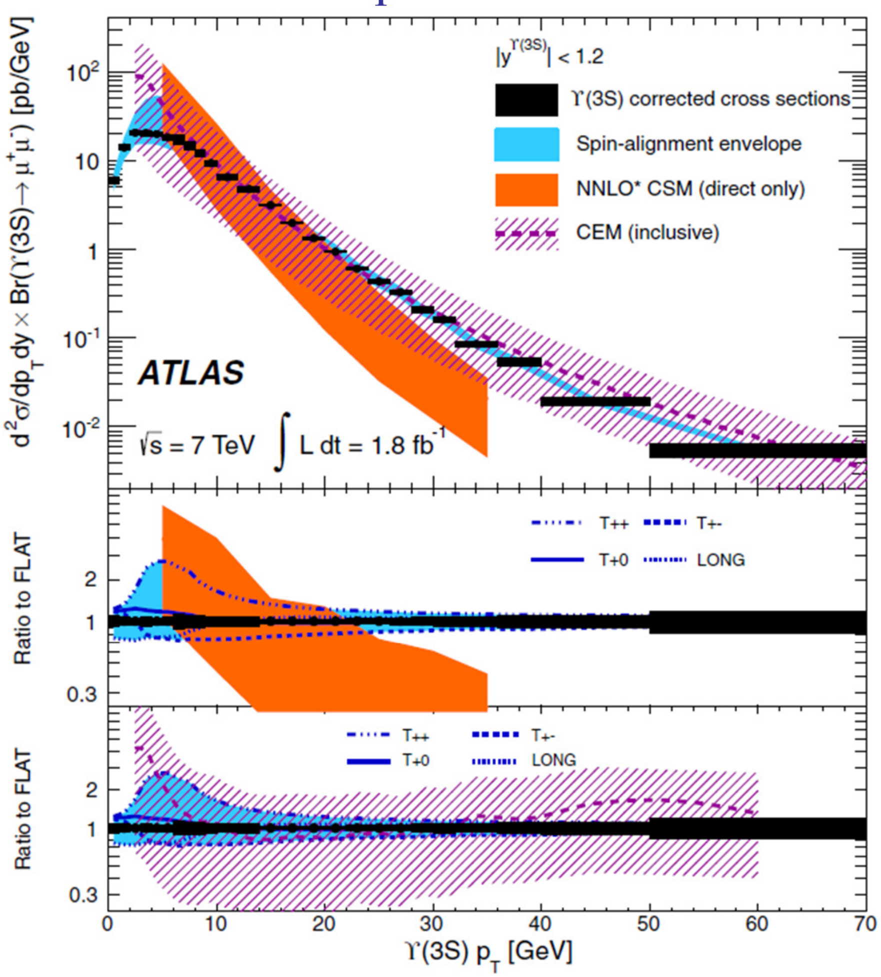
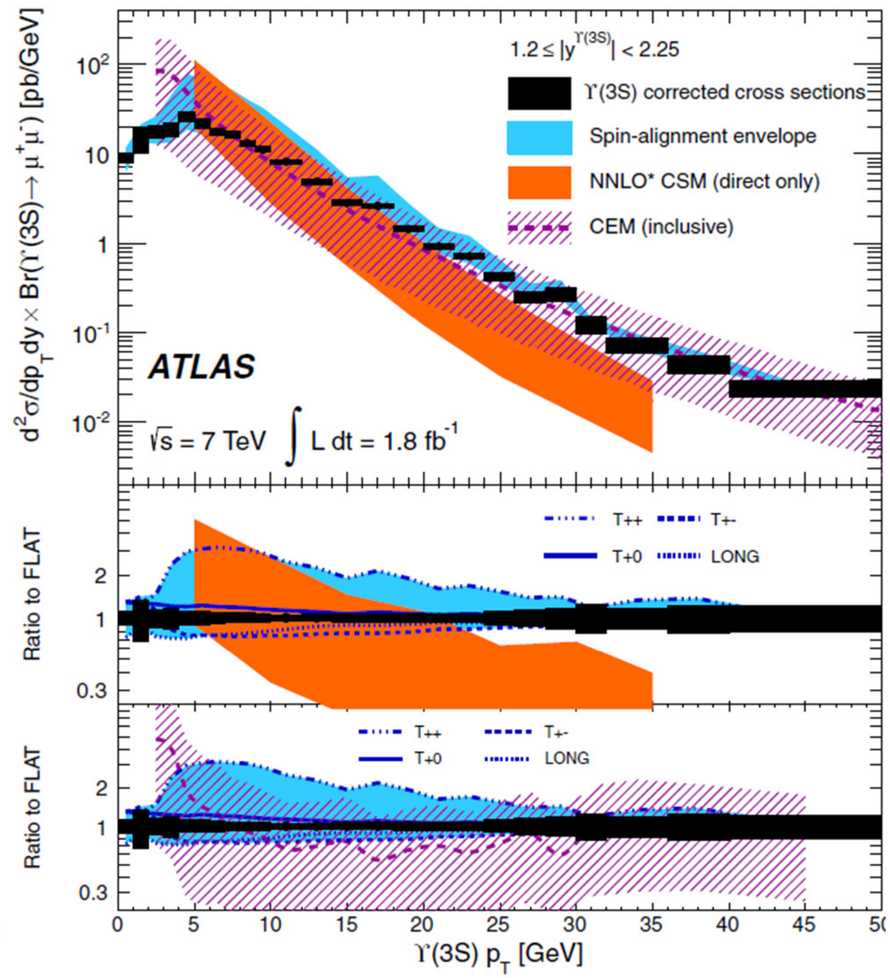
ϒ(nS) Production (5)

The differential cross sections are compared with NNLO color singlet predictions and Color Evaporation model





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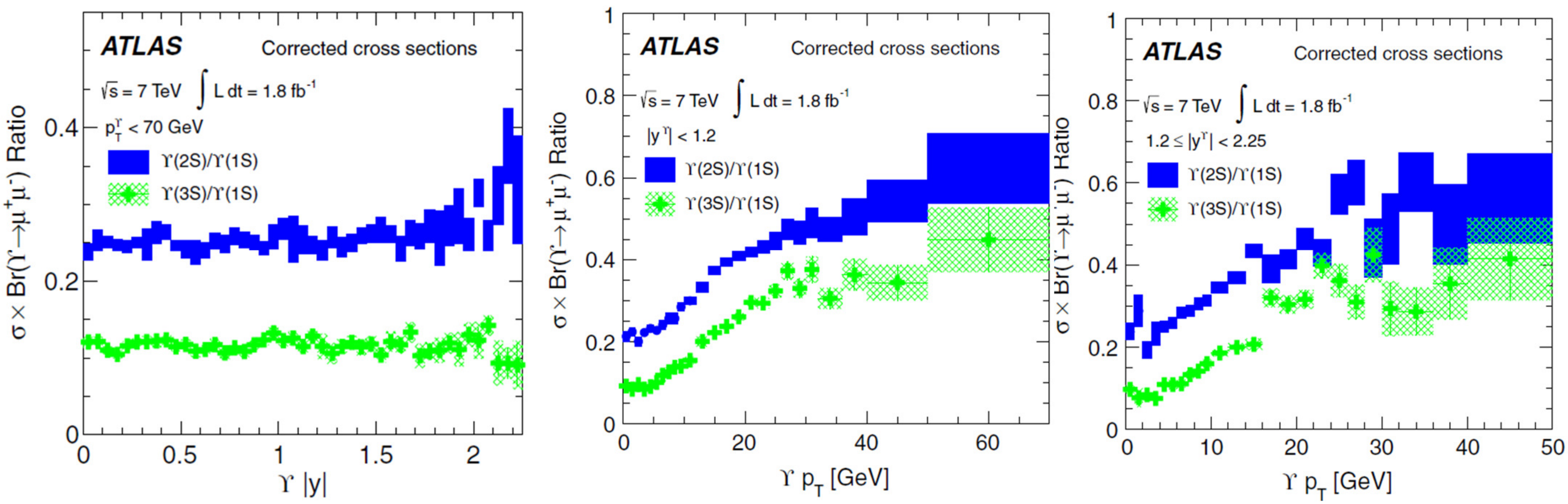
Υ(nS) Production (6)

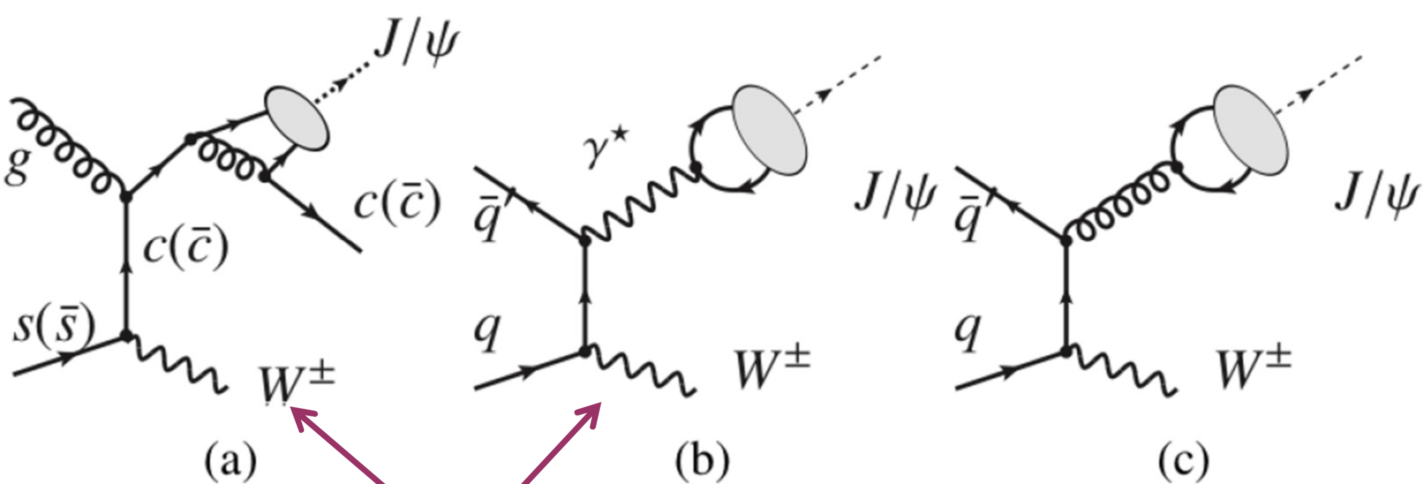
- Υ(1S) is sum of direct production and decays of higher mass states
- Flat over the full rapidity region
- Low values at low p_T are result of χ_b that preferentially decays to Υ(1S)



QWG 2013 Nuclear Physics B 850 (2011) 387–444

W + J/ψ Associated Production Analysis (1)

- The production mechanism for heavy quarkonium states in pp collision needs to be understood
- Measurement of W + prompt J/ψ production will offer insight; the test is accessible just now with the LHC data at 7 TeV
- W+ prompt J/ψ cross section helps determine the relative contribution of color octet and singlet production, as well as other possible contributions
- CDF searched for W+ϒ, Z+ ϒ (1.8 TeV), no evidence was found



color singlet production | color octet production

 ArXiv:1303.5327

W + J/ψ Associated Production Analysis (2)

ATLAS Analysis: The method and the analysis

ATLAS-CONF-2013-42

- $W \rightarrow \mu\nu_{\mu}$; $J/\psi \rightarrow \mu^{+}\mu^{-}$
- Use $\mu + \not{E}_T$ transverse mass to reject QCD multijet background
- Use pseudo-proper time to take out "W+ b-hadrons" events
- Allow J/ψ events from decays of higher mass charmonium states
- Present cross section ratio of inclusive W+inclusive J/ψ vs inclusive W
- Measure the single parton scattering W+prompt J/ψ production rate normalized to the inclusive W production
- Subtract estimated double parton scattering (W+2jets events) background

The data set

4.6 fb^{-1} of data collected in 2011 pp collision at CM energy 7 TeV

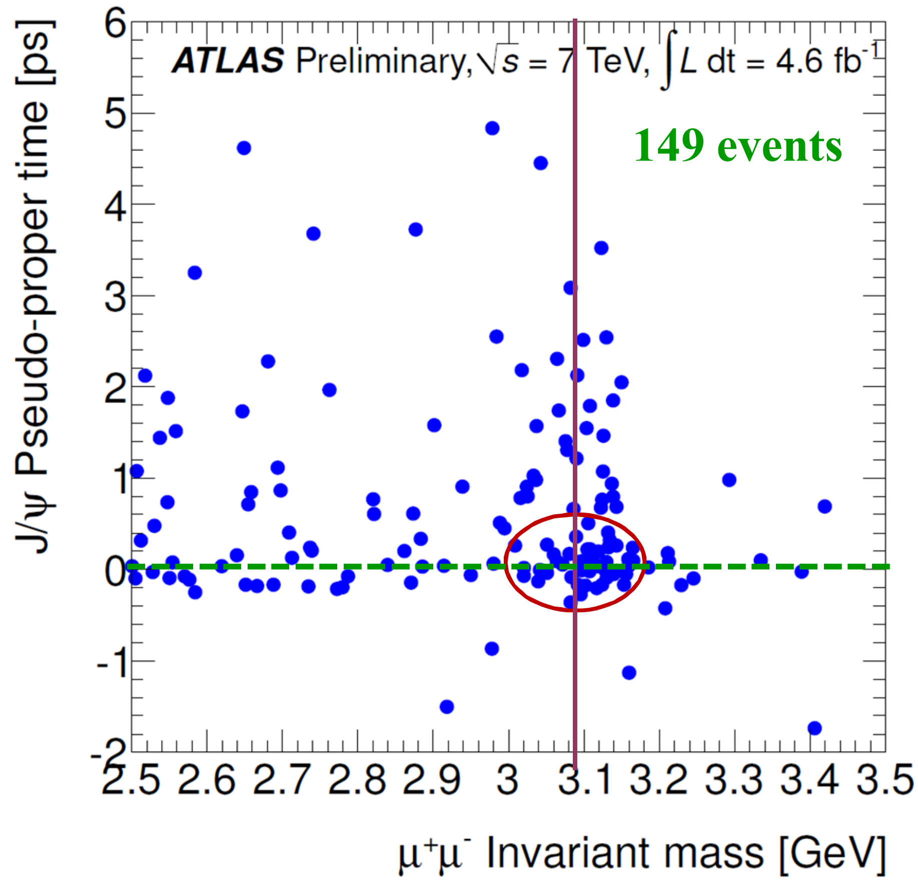
W + J/ψ Associated Production Analysis (3)

The Event Selection

- $W \to \mu\nu$ selection
  $p_T>25$ GeV, $|\eta|<2.4$,
  track isolation, calo. energy isolation
  $E\!\!\!/_T>20$ GeV, $M_T(W)>40$ GeV

- J/ψ selection
  $p_T>2.5+|\eta|<1.3$ or $p_T>3.5+|\eta|>1.3$

- Dimuon requirements
  opposite charges
  at least one muon with $p_T>4$ GeV
  vertex constraint
  $8.5<p_T(J/\psi)<30$ GeV, $|\eta_\psi|<2.1$
  $Z\to\mu^+\mu^-$ veto (outside [81,101] GeV)



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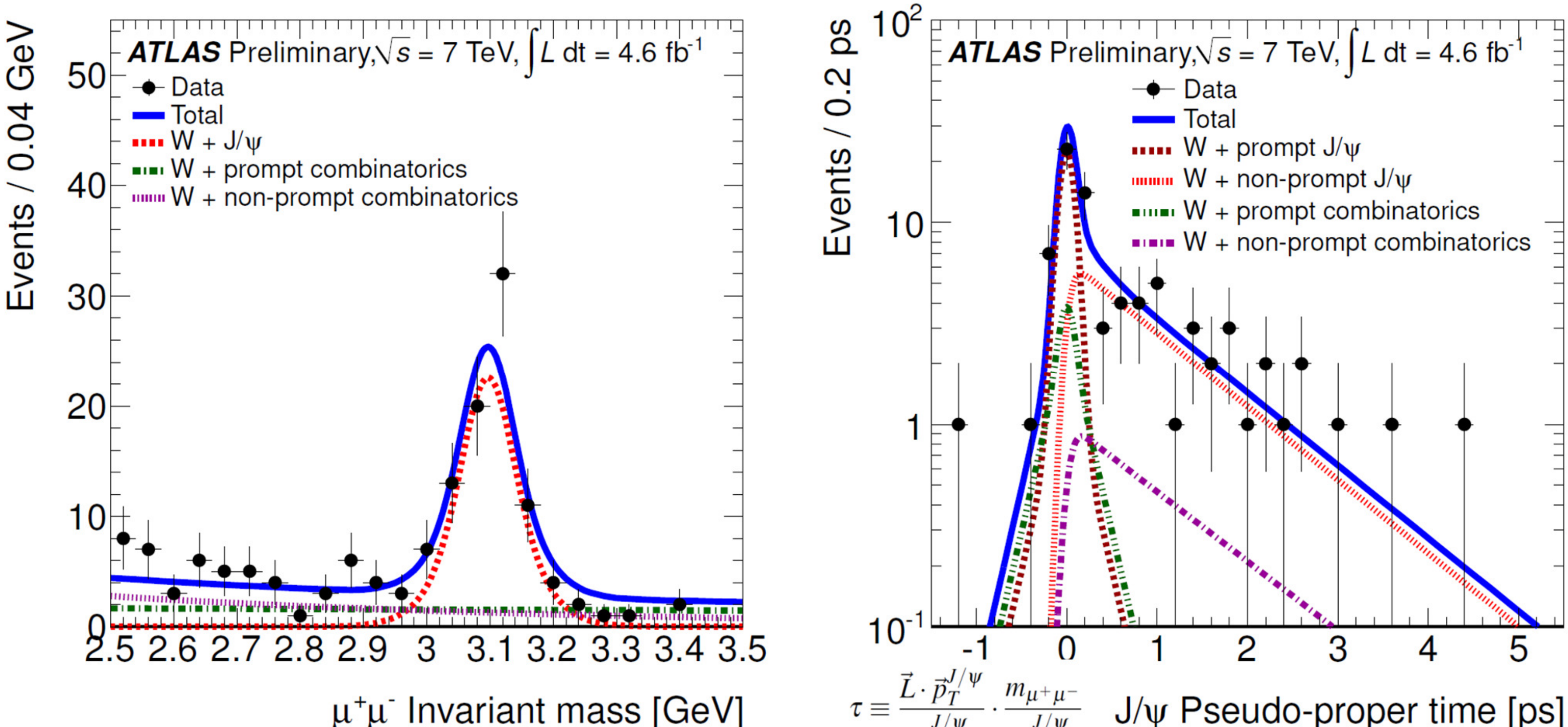
W + J/ψ Associated Production Analysis (4)

Signal extraction

Number of W+prompt J/ψ events is determined from an un-binned maximum likelihood fit to the J/ψ candidate invariant mass and pseudo-proper time distributions



$$\tau \equiv \frac{\vec{L}\cdot\vec{p}_T^{\,J/\psi}}{p_T^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_T^{J/\psi}}$$

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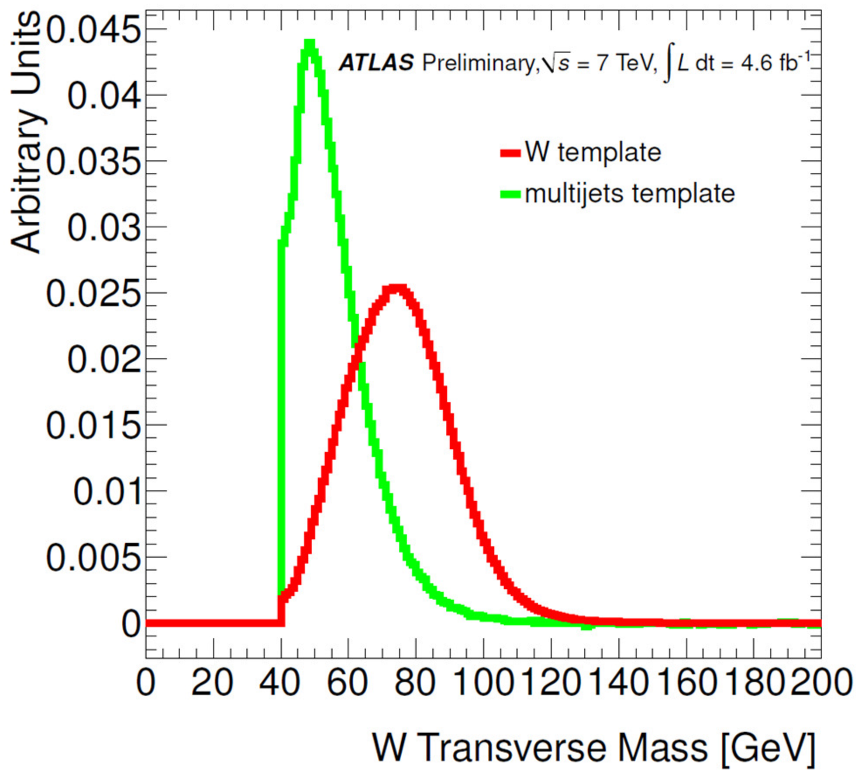
W + J/ψ Associated Production Analysis (5)

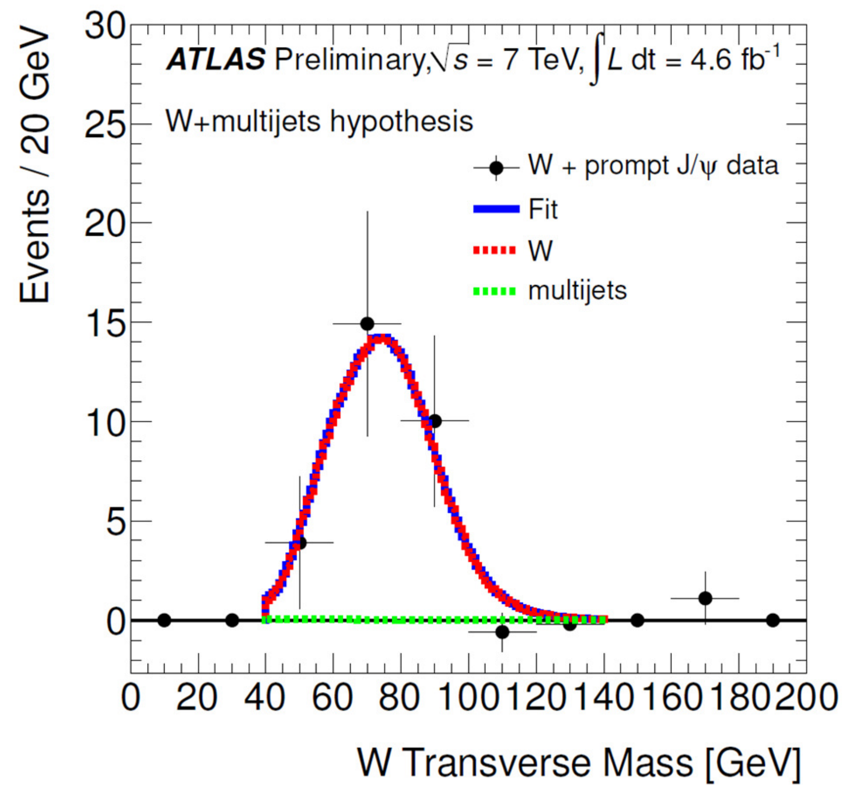
First observation of **W+prompt J/ψ** production in pp collision

prompt $J/\psi = 29^{+7.5}_{-6.5}$, 5.3σ
p(background only)~ 4.4×10^{-8}

Unit-normalized templates for W boson M_T for signal and multijet background



Fit to data including signal and multijet background

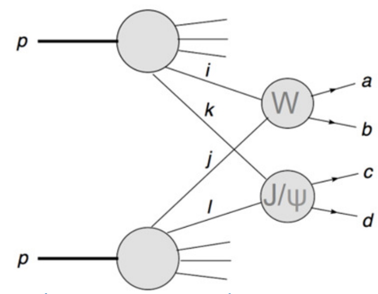


W + J/ψ Associated Production Analysis (6)

- Observed W+prompt J/ψ signal contains both SPS and DPS

SPS – Single Parton Scattering
The W and J/ψ originate from the same hard parton in pp collision

DPS –Double Parton Scattering
The W and the J/ψ originate from two different partons in the same pp collision



The DPS contribution to W and prompt J/ψ, treated as independent and unrelated, is estimated using the Atlas rate of W+2jets, and factorization of the double parton distribution function, and experimental inputs, to be 10.8±4.2 events

$$d\sigma_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{eff}}$$

ATLAS measurement
This work

ATLAS measurement
arXic:1104.3038

ATLAS measurement
arXic:1301.68728

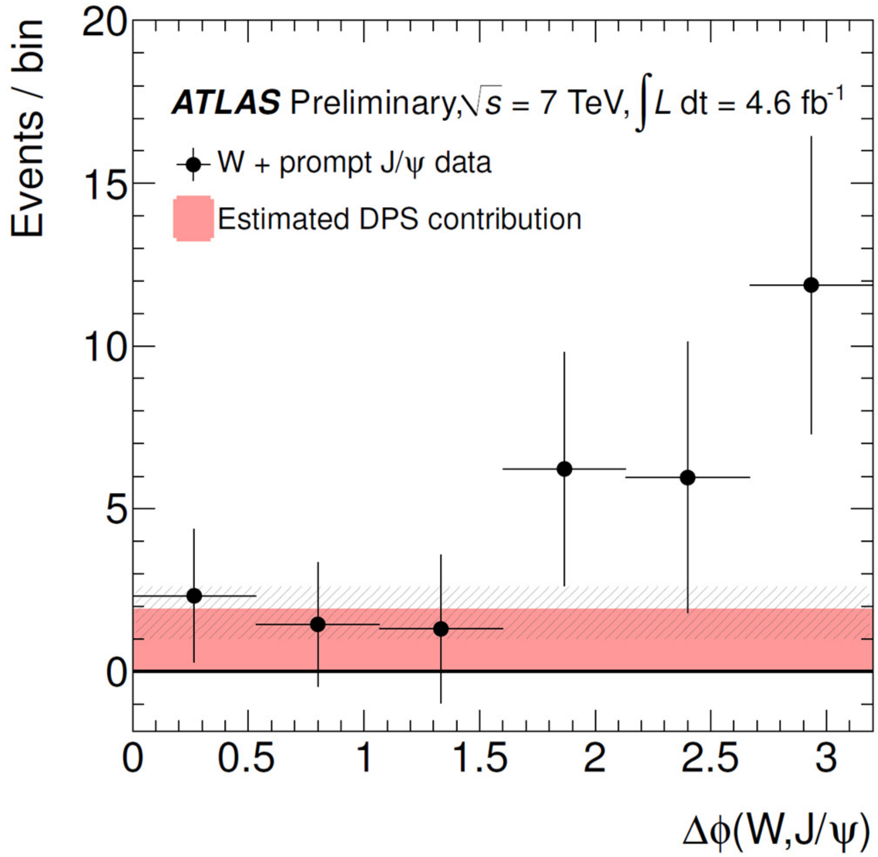
- Other sources of background considered:
  Pileup (1.8±0.2 events), Z+jets(0), multijets (0.1±4.6)
  top pair production, W+b-quark, $B_c \rightarrow J/\psi + \mu\nu + X$, heavy quark jets

W + J/ψ Associated Production Analysis (7)

DPS contribution is flat

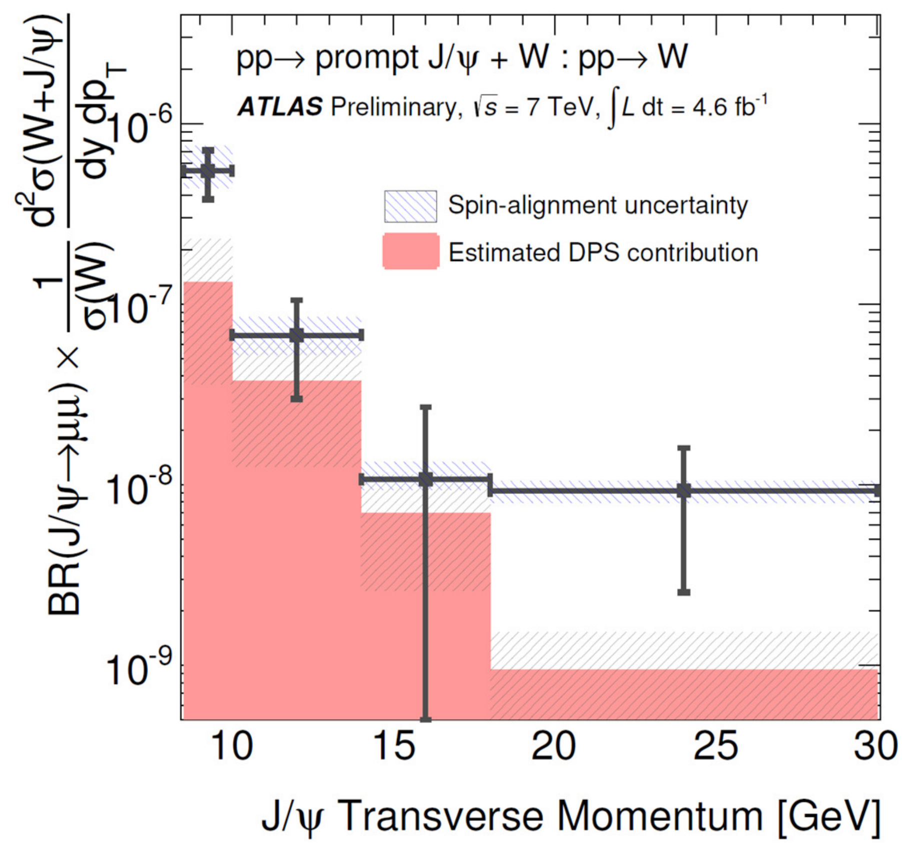
Excess is evidence for SPS

W+prompt J/ψ events at high Δφ



Apply event-by-event efficiency correction to determine the cross section ratio

Inclusive cross section ratio vs. $p_T(J/\psi)$, excess above DPS at low p_T is observed



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W + J/ψ Associated Production Analysis (8)

Assume isotropic scenario, include maximum difference in the systematic error

Values of three ratios measured:

(1) $R^{fid}_{J/\psi} = (50 \pm 12 \pm 4) \times 10^{-8}$

(2) $R^{incl}_{J/\psi} = (123 \pm 31^{+40}_{-24}) \times 10^{-8}$

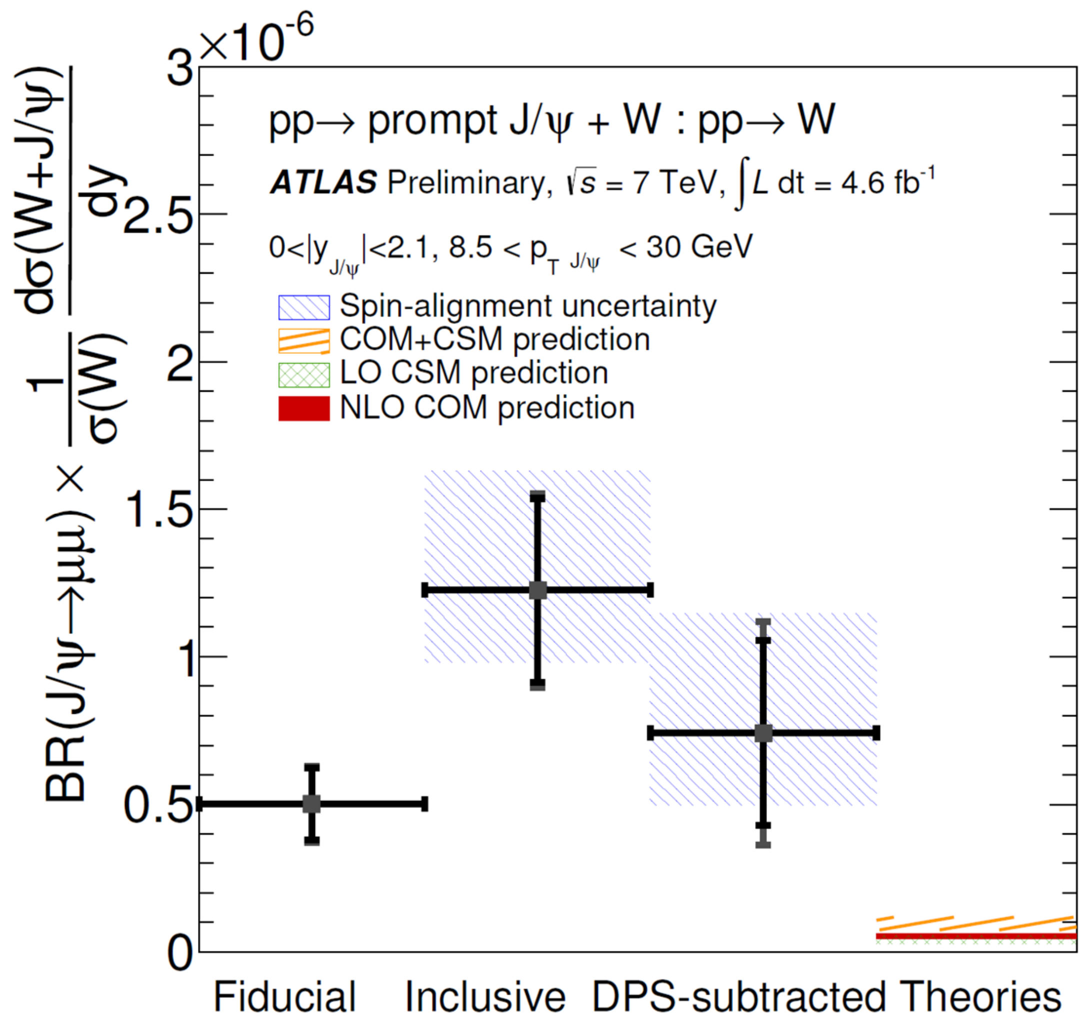
(3) $R^{DPS\ sub}_{J/\psi} = (74 \pm 31 \pm 21^{+40}_{-24}) \times 10^{-8}$

$(4.6\text{-}6.2) \times 10^{-8}$ NLO color octet
$(5.3\text{-}10.7) \times 10^{-8}$ LO color singlet

(1) Established W+prompt J/ψ signal

(2) Efficiency corrected ratio

(3) DPS ~60% of total W+prompt J/ψ



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Summary

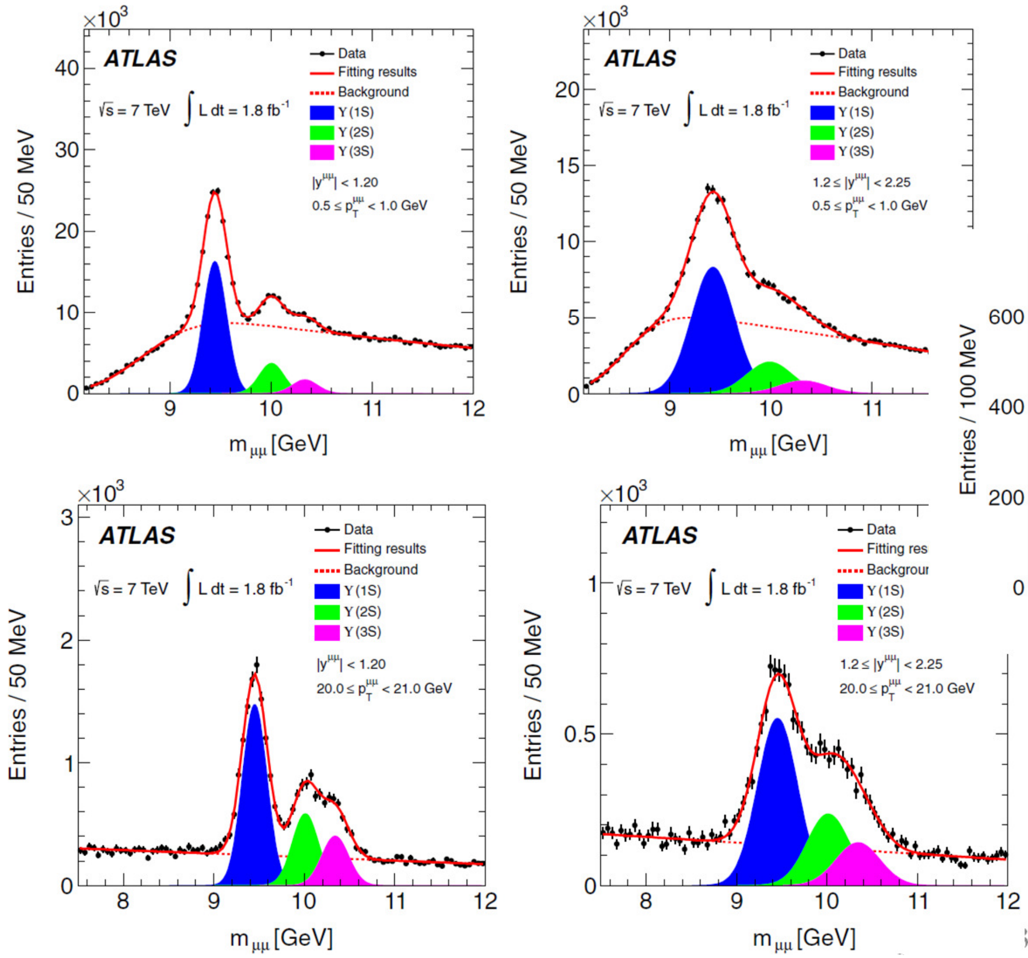
ATLAS experiment has produced high quality physics with quarkonia

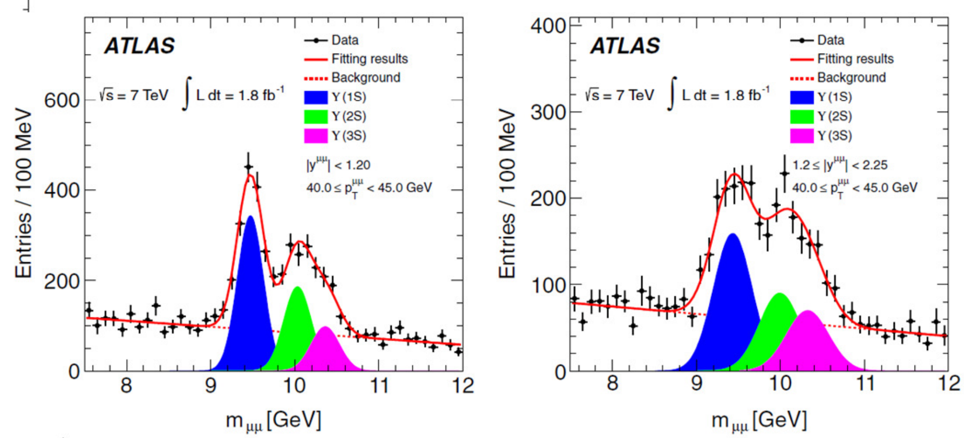
- Measurement of differential cross-sections of inclusive, prompt and non-prompt J/ψ production
- Published study of inclusive Upsilon production in pp collision at 7 TeV
- First observation (5.3σ) of J/ψ in association with $W^{\pm}$ in pp collision
- We measure the production cross-section of W+prompt J/psi and estimate the contribution to this signal from SPS and DPS
- We are analyzing 2012 data; further interesting results can be expected

Backup slide

ϒ(nS) Production

- Efficiency corrected mass distributions in p_T and rapidity slices
- Signal is modeled by a single Gaussian; background by 2nd or 1st order polynomial





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W + J/ψ Associated Production Analysis

$$M_{J/\psi}(m_{\mu^+\mu^-}) = G(m_{\mu^+\mu^-}; m_{J/\psi\ \mathrm{PDG}}, \sigma_m)$$

$$T_{\mathrm{prompt}\ J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left((1-a)\delta(\tau) + aN_0 e^{-|\tau|/\tau_0}\right)$$

$$T_{\mathrm{non\text{-}prompt}\ J/\psi}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left(N_1 \theta(\tau) e^{-\tau/\tau_1}\right)$$

$$M_{\mathrm{prompt\ bkg}}(m_{\mu^+\mu^-}) = N_2 e^{-m_{\mu^+\mu^-}/k_0}$$

$$M_{\mathrm{non\text{-}prompt\ bkg}}(m_{\mu^+\mu^-}) = N_3 e^{-m_{\mu^+\mu^-}/k_1}$$

$$T_{\mathrm{prompt\ bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left((1-b)\delta(\tau) + bN_4 e^{-|\tau|/\tau_0}\right)$$

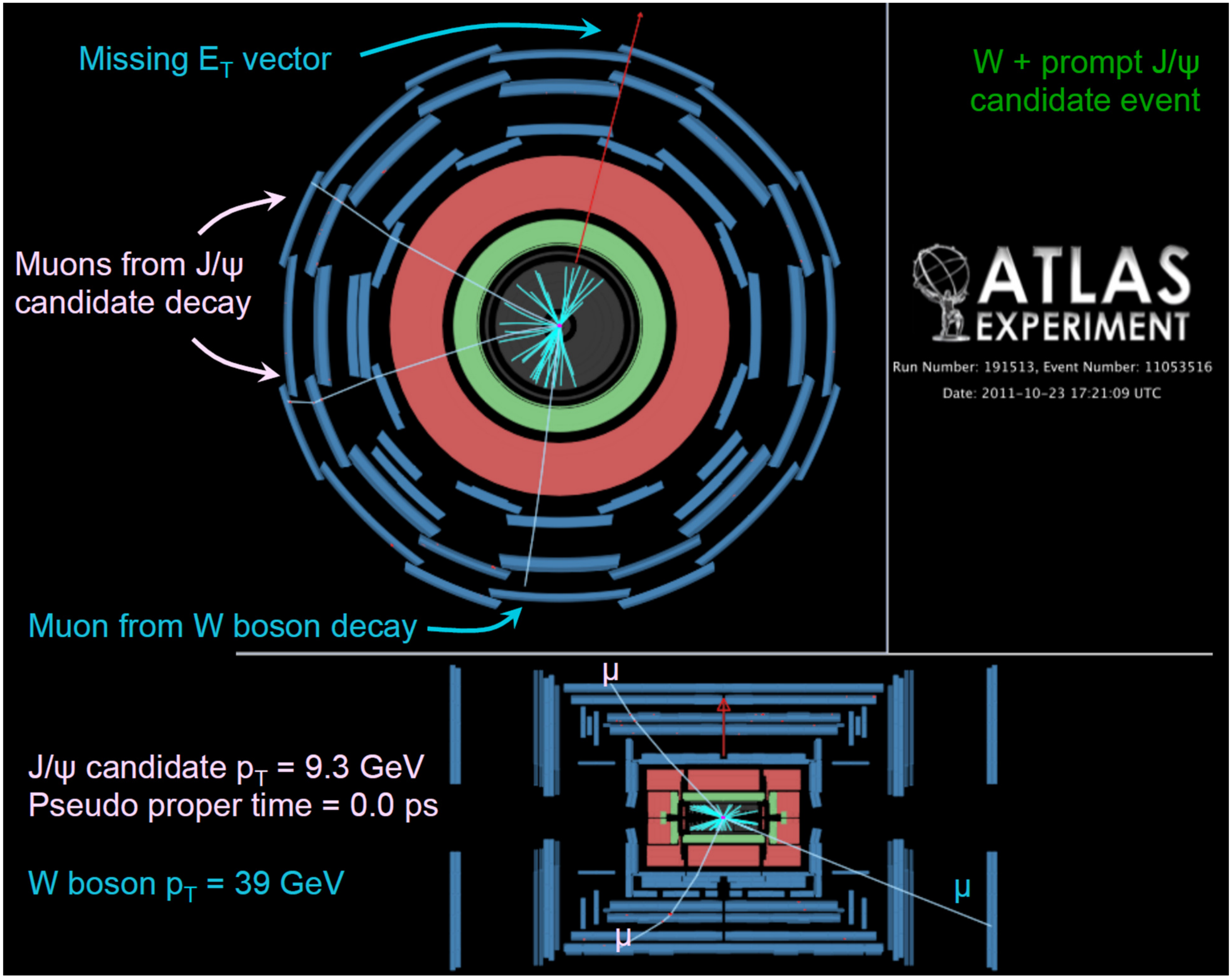
$$T_{\mathrm{non\text{-}prompt\ bkg}}(\tau) = G(\tau; 0, \sigma_\tau) \otimes \left(N_5 \theta(\tau) e^{-\tau/\tau_2}\right).$$

$$\begin{aligned} p \quad = \quad & N_{\mathrm{prompt}\ J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\mathrm{prompt}\ J/\psi}(\tau) \\ + \quad & N_{\mathrm{non\text{-}prompt}\ J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\mathrm{non\text{-}prompt}\ J/\psi}(\tau) \\ + \quad & N_{\mathrm{prompt\ bkg}} \times M_{\mathrm{prompt\ bkg}}(m_{\mu^+\mu^-}) \times T_{\mathrm{prompt\ bkg}}(\tau) \\ + \quad & N_{\mathrm{non\text{-}prompt\ bkg}} \times M_{\mathrm{non\text{-}prompt\ bkg}}(m_{\mu^+\mu^-}) \\ & \times T_{\mathrm{non\text{-}prompt\ bkg}}(\tau). \end{aligned}$$

backup

W + J/ψ Associated Production Analysis

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	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	1.5×10^{-3}	1.4×10^{-6}	4.4×10^{-8}
Significance	3.0	4.7	5.3


Missing E_T vector
W + prompt J/ψ candidate event
Muons from J/ψ candidate decay
ATLAS EXPERIMENT
Run Number: 191513, Event Number: 11053516
Date: 2011-10-23 17:21:09 UTC
Muon from W boson decay
μ
μ
μ
J/ψ candidate p_T = 9.3 GeV
Pseudo proper time = 0.0 ps
W boson p_T = 39 GeV