$J/\psi \to \mu^+\mu^-$ Production in pp Collisions at 7 TeV in ATLAS

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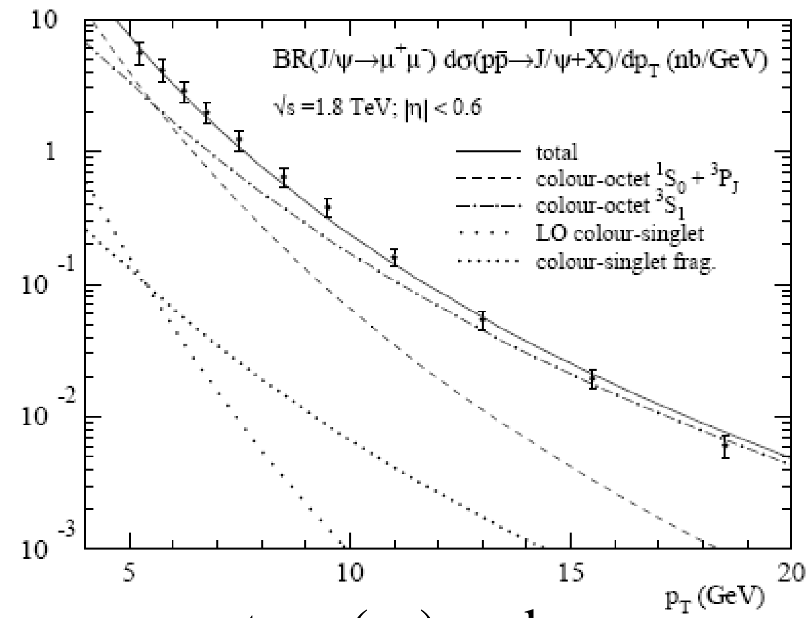
Introduction

- Tevatron previously obtained excellent agreement between data and Monte Carlo



- ATLAS can probe J/ψ production mechanisms in a new energy regime, providing a test of several QCD predictions

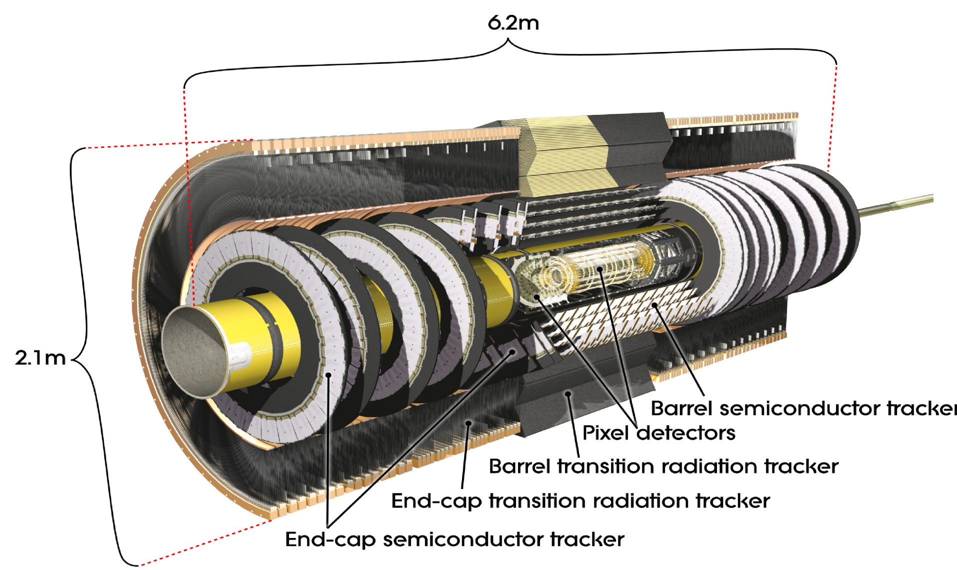
- Present two related first measurements:
  - Differential cross section of J/ψ vs. transverse momentum (p_T) and rapidity (y)
  - Ratio of non-prompt to prompt produced J/ψ:

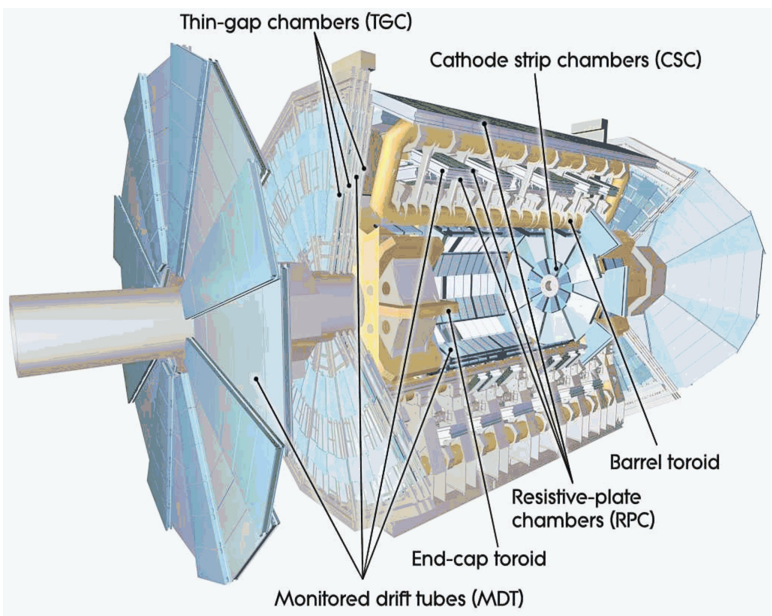
$$R \equiv \frac{d\sigma(pp \Rightarrow b\bar{b}X \Rightarrow J/\psi X')}{d\sigma(pp \Rightarrow J/\psi X'')_{prompt}}$$

- Non-prompt J/ψ's (produced in decay of long-lived b-hadrons
- Prompt J/ψ's (produced in QCD processes or in the decay of excited charmonium states)

Inner Detector and Muon Spectrometer

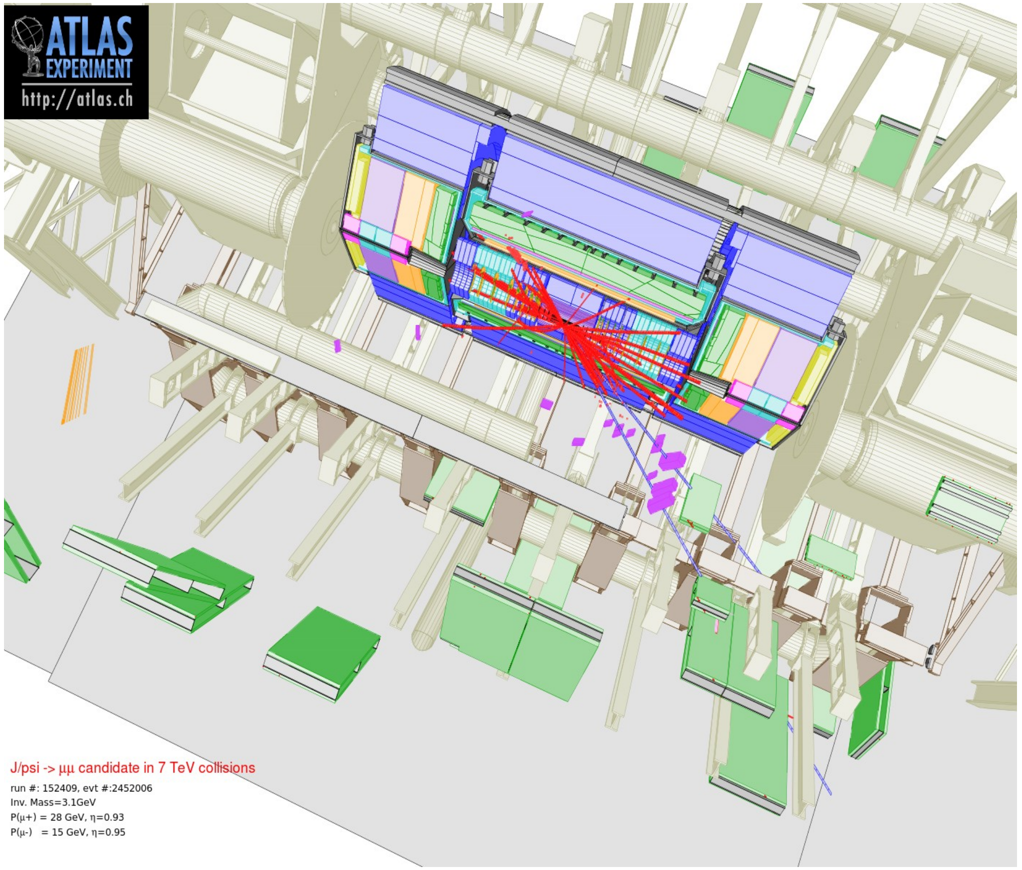
- Inner Detector:
  - Solenoidal magnetic field of 2 Tesla
  - Track parameters measured from the ID are used to calculate J/ψ kinematic properties
  - Pixel (|η|<2.5)
    - Resolution: 10/115μm in Rφ/z
  - Silicon Strip (SCT) (|η|<2.5)
    - Resolution: 17/580μm in Rφ/z
  - Transition Radiation Tracker (|η|<2)
    - Resolution: 130μm in Rφ
- Muon Spectrometer:
  - Average toroidal magnetic field of 0.5 Tesla
  - Only used to identify which inner detector tracks come from muons
- Trigger system:
  - Minimum Bias Trigger Scintillator (MBTS)
  - L1 Muon Trigger





Event Selection

- Trigger:
  - For cross section analysis ($L=9.5 nb^{-1}$), use the Minimum Bias Trigger Scintillators (MBTS)
  - For the ratio measurement ($L=17.5\ nb^{-1}$), the trigger efficiencies play no role, so the L1 muon trigger is included
- Vertex Requirements:
  - To veto cosmics, require ≥3 tracks from the same primary vertex
  - Tracks must pass quality cuts: ≥1 pixel hit, and ≥6 SCT hits
- Track Requirements:
  - Tracks must come from a muon
  - Tracks must pass the same quality cuts
- Opposite sign inner detector tracks are then fit to a common vertex



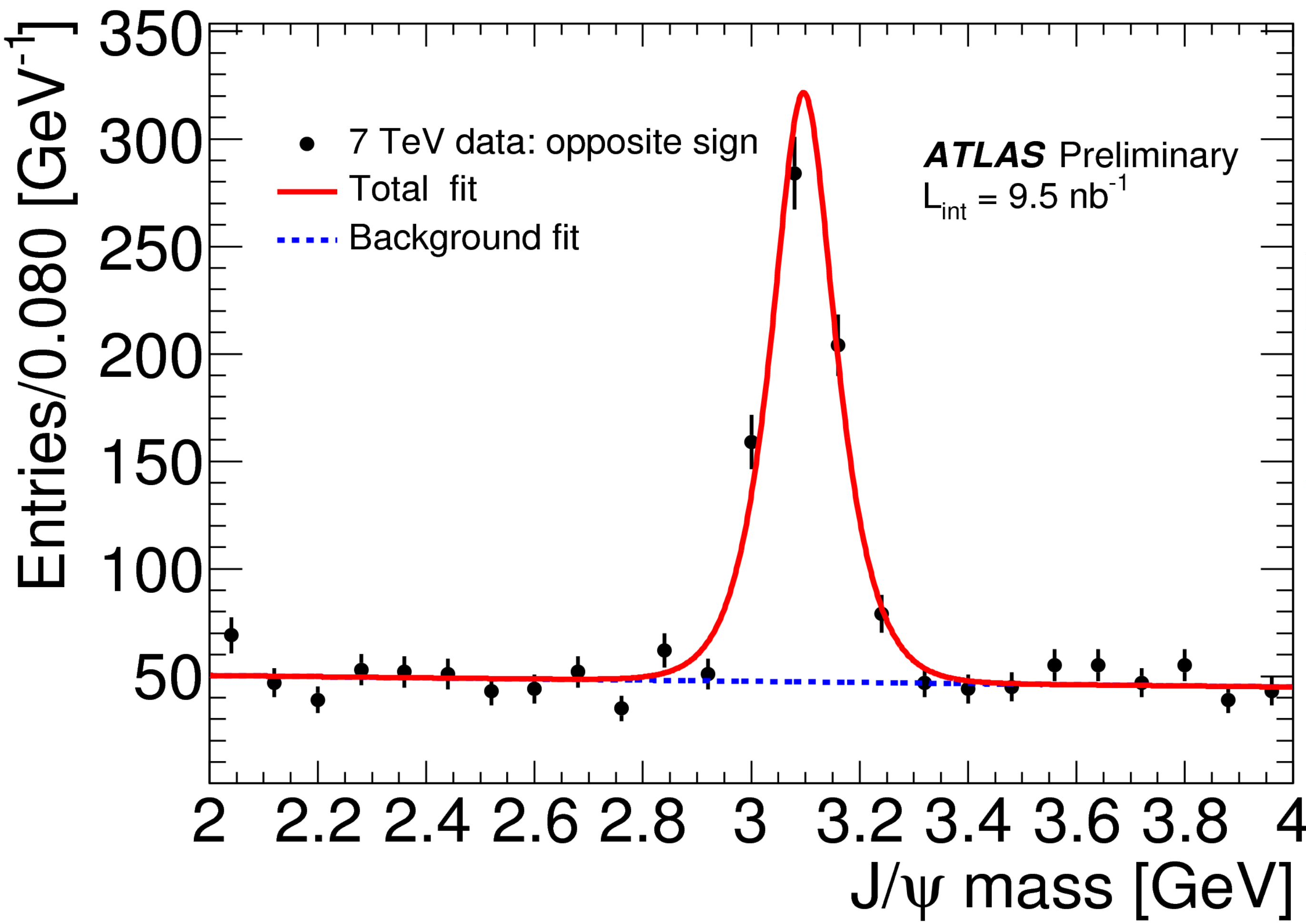
Differential Cross Section

- Measure the cross section of the J/ψ in bins of transverse momentum (p_T) and rapidity (y)
- Event-by-event maximum likelihood fit of m(J/ψ) is performed in each bin to determine the J/ψ yield
- To recover the number of produced $J/\psi \rightarrow \mu^+\mu^-$ decays, the acceptance, offline reconstruction, and trigger efficiency are needed
- Weight each event with the acceptance and efficiency

$$w^{-1} \equiv A(p_T, y, \lambda_i) \times \epsilon_\mu(\vec{p}_1) \times \epsilon_\mu(\vec{p}_2) \times \epsilon_{trig}(\vec{p}_1, \vec{p}_2)$$

  - Reconstruction efficiencies are calculated from simulation
  - Trigger efficiency is calculated from Minimum Bias triggered data

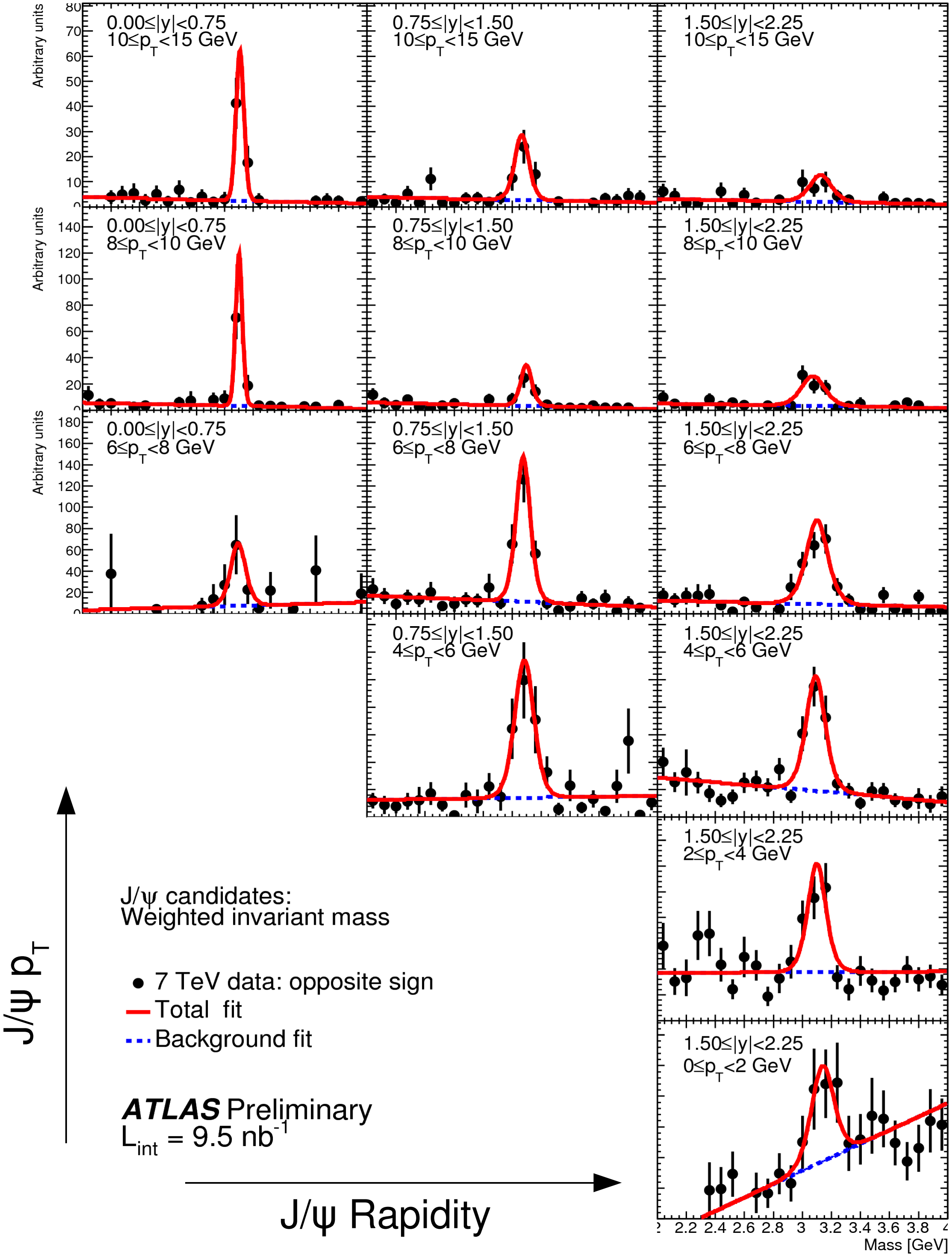
J/ψ→$\mu^+\mu^-$ Candidates Used in the Cross Section Analysis



No. Signal	592±30
Mass	3.095±0.003 GeV
Resolution	0.071±0.004 GeV

- Di-muon mass distribution for selected J/ψ→$\mu^+\mu^-$ candidates used in the cross section measurement

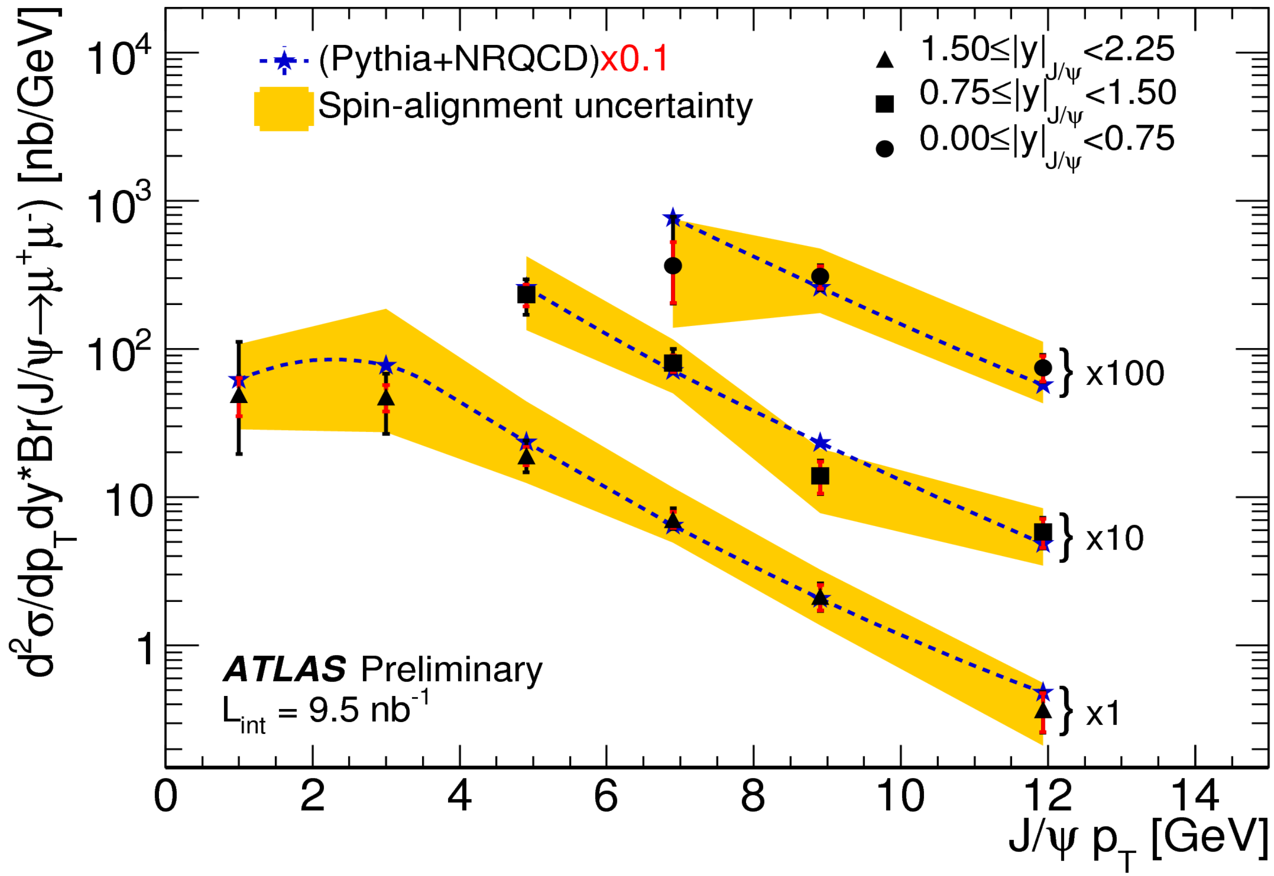
Di-Muon Mass in p_T and y Bins, after Weighting



- 6 bins in p_T: $0<p_T<15$
  - 0-2, 2-4, 4-6, 6-8,8-10, 10-15
- 3 bins in y: 0<y<2.25
  - 0-0.75, 0.75-1.5, 1.5-2.25
- Resolution decreases as y increases
  - As expected!

Differential Cross Section

- Differential J/ψ cross section vs. p_T and y
- Shape of of differential cross section agrees with Pythia Monte Carlo expectation
  - Significant absolute deviation

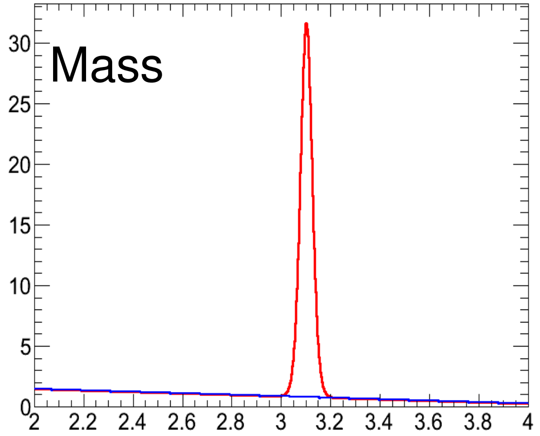


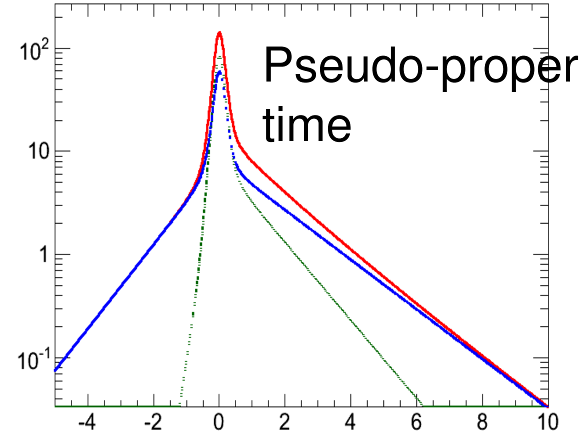
- Spin-alignment uncertainty the most significant systematic
- Other systematic sources:
  - Reconstruction and trigger efficiency uncertainty
  - Binning for acceptance and efficiency corrections

Fraction of J/ψ from b-Hadron Decays

- Distinguish between J/ψ's from prompt production and those produced in b-hadron decays by using the distance between the J/ψ decay vertex and the primary vertex

- Discriminating variable pseudo-proper decay time, τ:



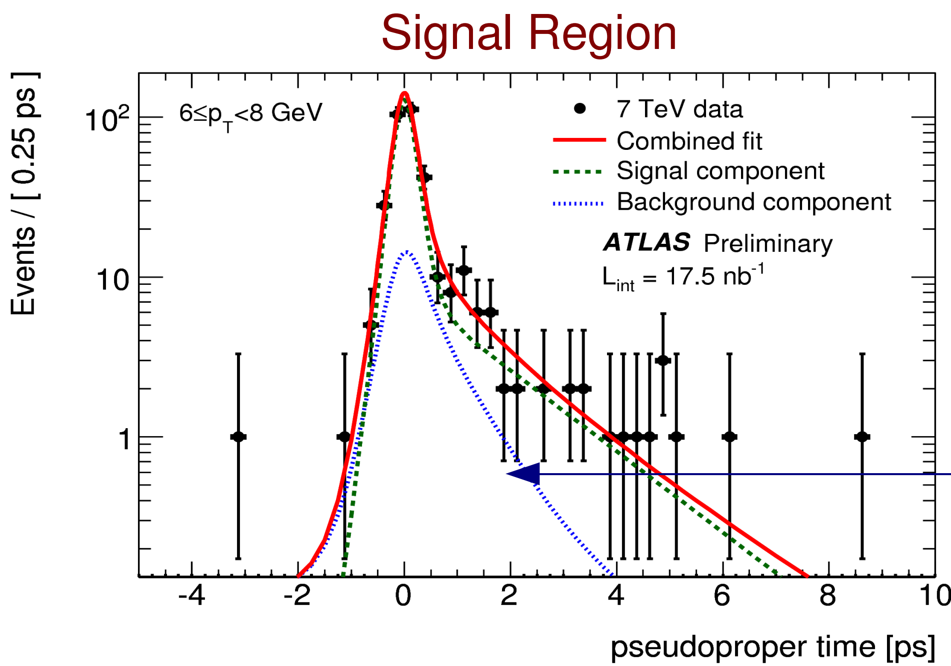


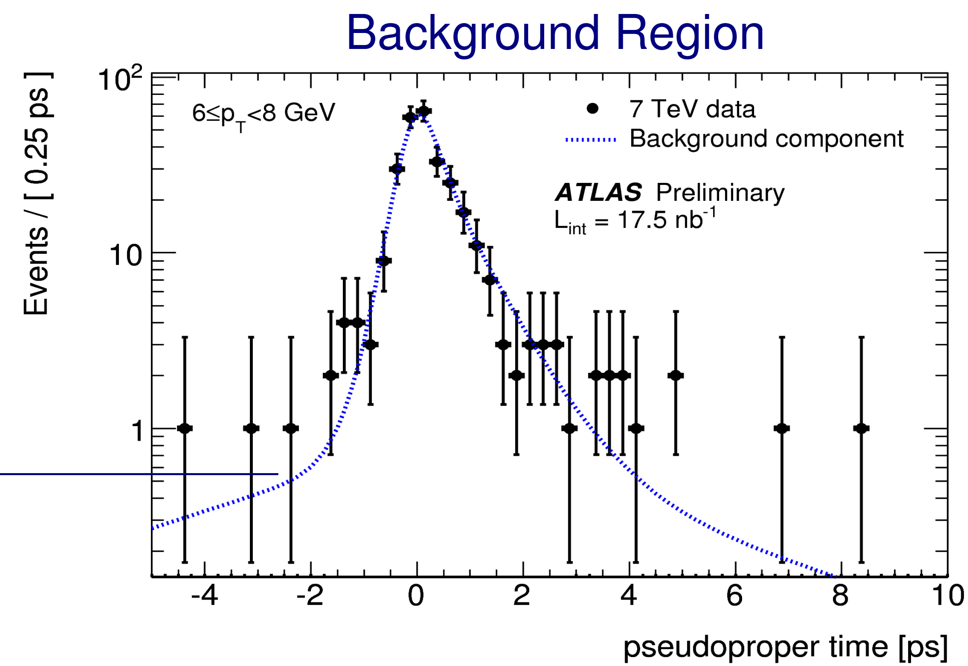
$$\tau \equiv \frac{L_{xy}\, m(J/\psi)}{p_T(J/\psi)}$$

L_{xy}=xy displacement of candidate from primary vertex projected on p_T

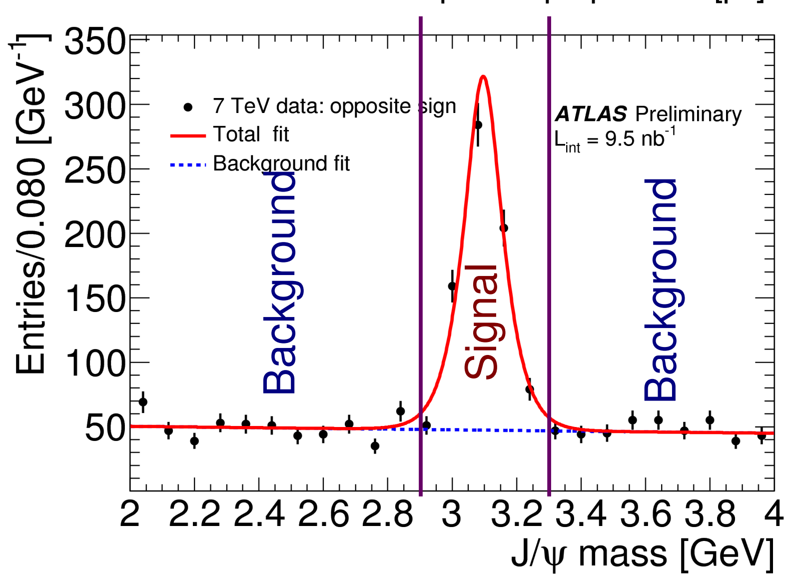
- Fit the mass and pseudo-proper time simultaneously in p_T bins from 1-15 GeV with an unbinned event-by-event maximum likelihood fit
  - Signal τ PDF: δ function plus exponential convolved with a Gaussian resolution function
  - Background τ PDF: δ function plus two exponentials convolved with a Gaussian resolution function (parameterization)

Example of Proper time Fit to Data

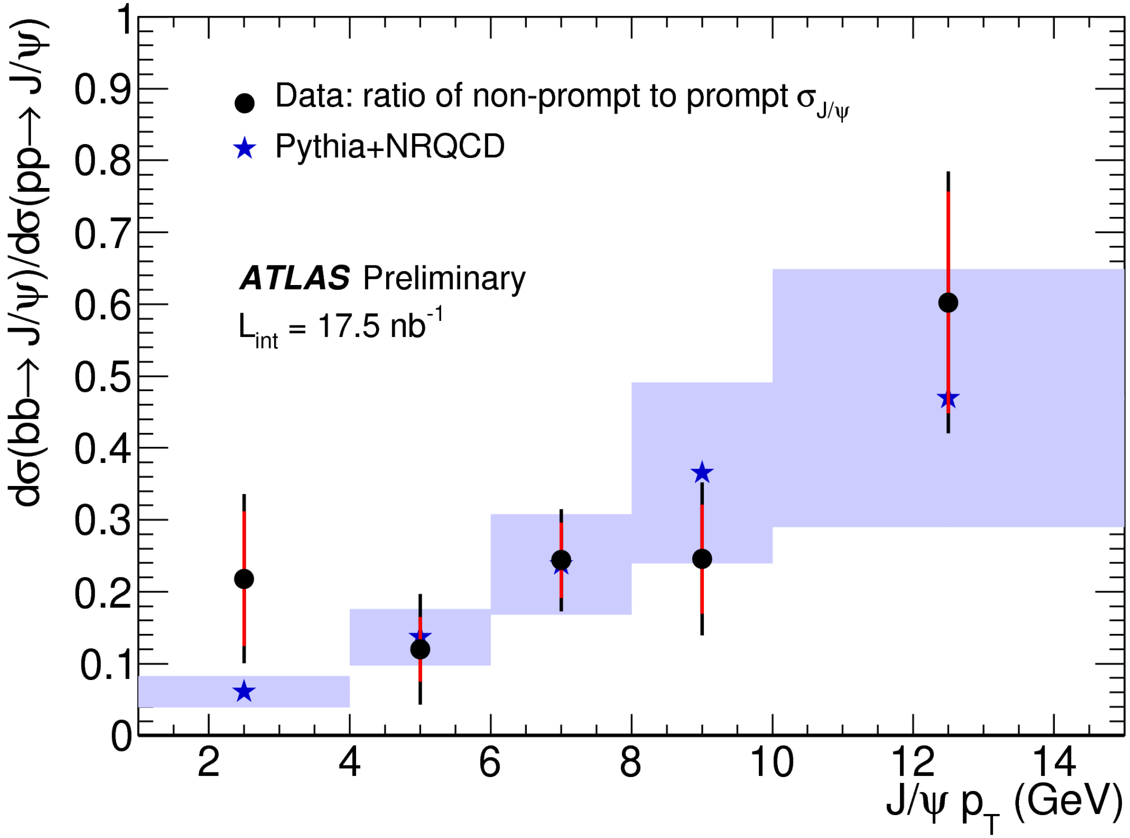




- Pseudo-proper time fit in the p_T bin $6 \leq p_T < 8$ GeV, projected into a signal and background region



Fraction of J/ψ from b-Hadron Decays



- Ratio of indirect to prompt J/ψ production cross sections as a function of J/ψ p_T
- Good agreement with MC expectation

- Systematic uncertainties determined by repeating fit under various assumptions
  - Effect from using different background models
  - Several detector resolution models were used for the fitting
  - Higher order polynomials were used in the mass fit for the background
  - Fit method varied: fit performed in three steps instead of simultaneously to test stability

Summary

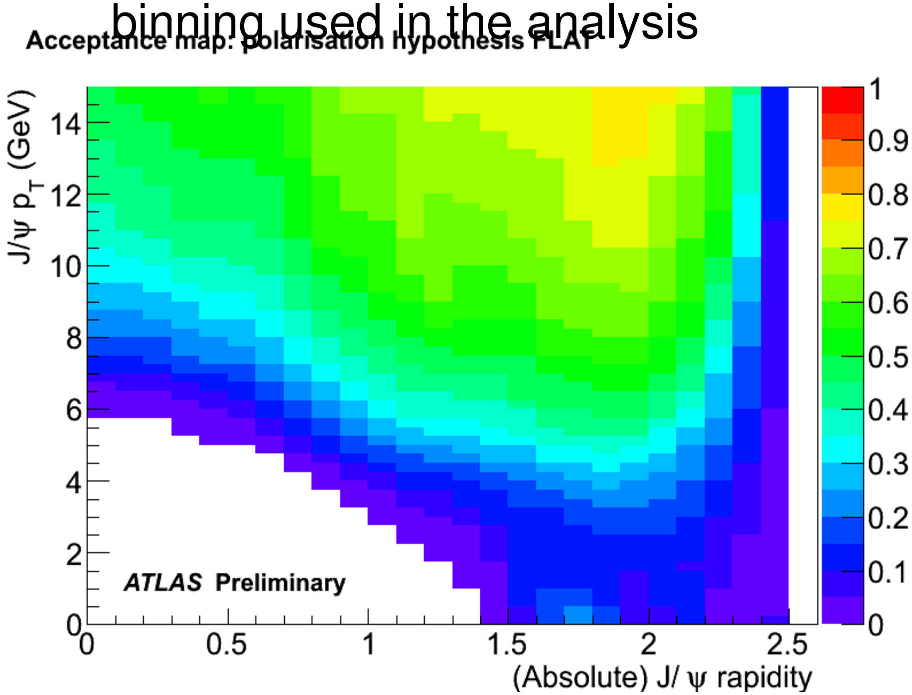
- Reported the first ATLAS measurement of the double differential cross section of $J/\psi \rightarrow \mu^+\mu^-$ in proton-proton collisions at 7 TeV in bins of p_T and rapidity
- Shape of the double differential cross section agrees well with the Monte Carlo expectation
  - Normalization of Monte Carlo is significantly larger
- Ratio of non-promptly to promptly produced J/ψ is also reported in bins of p_T
  - Compared against the Pythia Monte Carlo expectation: result is in good agreement across p_T bins

Bonus Slides

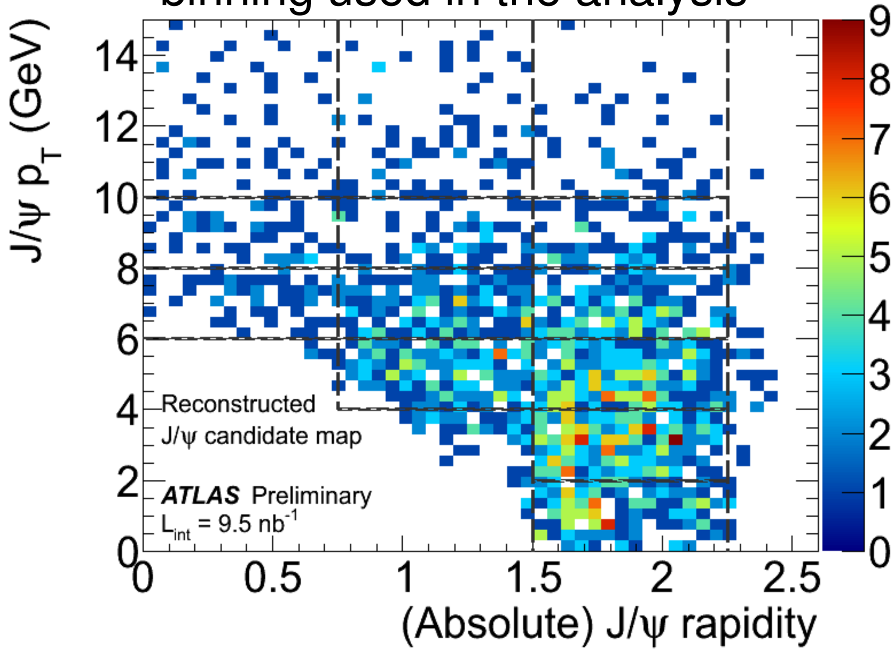
Acceptance

- Acceptance is the probability that the decay of a J/ψ with transverse momentum p_T and rapidity y happens in the fiducial volume of the detector
  - Momenta and pseudorapidity (η) of muons satisfy |p|>3.5 GeV |η|<2.5
- Depends strongly on J/psi spin alignment, which is not known, so this uncertainty is assigned as a systematic
  - Acceptance map is made using different spin alignment models

Example acceptance map with binning used in the analysis



Distribution of J/ψ candidates with binning used in the analysis



- Differential cross section for inclusive J/ψ production as a function of p_T and y

$p_T(J/\psi)$ GeV	Mean p_T GeV	$\frac{d\sigma}{dp_T dy} \cdot Br[J/\psi \to \mu^+\mu^-]$ (nb/GeV)	
		$0.0 \le \lvert y \rvert < 0.75$	
		Data	PYTHIA
6 – 8	6.9	7.3 ± 3.2 (stat) $^{+7.7}_{-0.5}$ (syst) $^{+7.7}_{-4.5}$ (theory)	153 ± 3
8 – 10	8.9	6.1 ± 1.1 (stat) $^{+0.6}_{-0.4}$ (syst) $^{+3.4}_{-2.7}$ (theory)	52 ± 2
10 – 15	11.9	1.50 ± 0.29 (stat) $^{+0.16}_{-0.08}$ (syst) $^{+0.74}_{-0.64}$ (theory)	11.4 ± 0.6
		$0.75 \le \lvert y \rvert < 1.50$	
		Data	PYTHIA
4 – 6	4.9	46.5 ± 7.9 (stat) $^{+9.7}_{-9.6}$ (syst) $^{+37.8}_{-19.8}$ (theory)	519 ± 5
6 – 8	6.9	16.0 ± 2.0 (stat) $^{+3.4}_{-0.9}$ (syst) $^{+7.1}_{-6.0}$ (theory)	143 ± 3
8 – 10	8.9	2.79 ± 0.68 (stat) $^{+0.27}_{-0.16}$ (syst) $^{+1.45}_{-1.24}$ (theory)	46.5 ± 1.8
10 – 15	11.9	1.17 ± 0.26 (stat) $^{+0.14}_{-0.05}$ (syst) $^{+0.51}_{-0.47}$ (theory)	9.7 ± 0.5
		$1.50 \le \lvert y \rvert < 2.25$	
		Data	PYTHIA
0 – 2	1.0	99 ± 29 (stat) $^{+121}_{-52}$ (syst) $^{+115}_{-41}$ (theory)	1242 ± 5
2 – 4	3.0	95 ± 20 (stat) $^{+35}_{-36}$ (syst) $^{+277}_{-40}$ (theory)	1546 ± 6
4 – 6	4.9	38.2 ± 5.4 (stat) $^{+8.5}_{-6.7}$ (syst) $^{+50.2}_{-13.1}$ (theory)	469 ± 4
6 – 8	6.9	14.2 ± 1.8 (stat) $^{+2.0}_{-1.0}$ (syst) $^{+9.0}_{-4.3}$ (theory)	129 ± 3
8 – 10	8.9	4.3 ± 0.9 (stat) $^{+0.48}_{-0.18}$ (syst) $^{+2.2}_{-1.55}$ (theory)	41.3 ± 1.7
10 – 15	11.9	0.74 ± 0.22 (stat) $^{+0.09}_{-0.03}$ (syst) $^{+0.38}_{-0.31}$ (theory)	9.6 ± 0.6

Cross Section Systematics

p_T, GeV	$\langle p_T \rangle$, GeV	Value	Stat. error	Accept.	Reco.eff.	Trigger.eff	Tag-tag	Interpol.	Total syst.
$0.0 \leq \|y\| < 0.75$									
6 − 8	6.9	3.6	1.6	$^{+0.14}_{-0.13}$	$^{+0.42}_{-0.24}$	$^{+0.09}_{-0.09}$	$^{+3.84}_{0}$	$^{+0}_{-0.07}$	$^{+3.9}_{-0.3}$
8 − 10	8.9	3.08	0.66	$^{+0.08}_{-0.08}$	$^{+0.39}_{-0.16}$	$^{+0.02}_{-0.02}$	$^{+0}_{-0.12}$	$^{+0}_{-0.02}$	$^{+0.40}_{-0.22}$
10 − 15	11.9	0.75	0.18	$^{+0.03}_{-0.02}$	$^{+0.11}_{-0.04}$	$^{+0.01}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0.11}_{-0.05}$
$0.75 \leq \|y\| < 1.5$									
4 − 6	4.9	23.2	4.0	$^{+0.55}_{-0.53}$	$^{+2.5}_{-1.7}$	$^{+4.5}_{-4.5}$	$^{+0.08}_{0}$	$^{+0}_{-1.0}$	$^{+5.2}_{-4.9}$
6 − 8	6.9	8.0	1.0	$^{+0.14}_{-0.13}$	$^{+1.1}_{-0.4}$	$^{+0.4}_{-0.4}$	$^{+1.4}_{0}$	$^{+0.6}_{0}$	$^{+1.9}_{-0.6}$
8 − 10	8.9	1.40	0.34	$^{+0.02}_{-0.02}$	$^{+0.18}_{-0.05}$	$^{+0.02}_{-0.02}$	$^{+0}_{-0.06}$	$^{+0}_{-0.03}$	$^{+0.18}_{-0.09}$
10 − 15	11.9	0.58	0.13	$^{+0.01}_{-0.01}$	$^{+0.06}_{-0.03}$	$^{+0.01}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0.06}_{-0.04}$
$1.50 \leq \|y\| < 2.25$									
0 − 2	1.0	49	20	$^{+1.3}_{-1.2}$	$^{+12}_{-6}$	$^{+21}_{-21}$	$^{+56}_{0}$	$^{+0}_{-14}$	$^{+61}_{-26}$
2 − 4	3.0	48	10	$^{+0.8}_{-0.8}$	$^{+5}_{-3}$	$^{+17}_{-17}$	$^{+0}_{-3}$	$^{+0}_{-5}$	$^{+18}_{-18}$
4 − 6	4.9	19.1	2.7	$^{+0.4}_{-0.4}$	$^{+4.0}_{-1.6}$	$^{+3.1}_{-3.1}$	$^{+0}_{-0.4}$	$^{+0}_{-0.1}$	$^{+5.1}_{-3.5}$
6 − 8	6.9	7.10	0.88	$^{+0.10}_{-0.10}$	$^{+1.21}_{-0.41}$	$^{+0.39}_{-0.39}$	$^{+0.01}_{0}$	$^{+0.35}_{0}$	$^{+1.32}_{-0.57}$
8 − 10	8.9	2.14	0.43	$^{+0.03}_{-0.03}$	$^{+0.32}_{-0.07}$	$^{+0.07}_{-0.07}$	$^{+0}_{-0.01}$	$^{+0.01}_{0}$	$^{+0.33}_{-0.10}$
10 − 15	11.9	0.37	0.11	$^{+0.01}_{-0.01}$	$^{+0.06}_{-0.02}$	$^{+0.01}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0}_{-0.01}$	$^{+0.06}_{-0.03}$

Monte Carlo Predictions

- There is a significant deviation between the Monte Carlo expectation (using the ATLAS MC09 tuning) of differential cross section and what we see in data
- Heavy flavor production depends on a number of parameters in Pythia
- The ATLAS MC09 tuning is one of the higher Monte Carlo predictions
- For the mean value of y ~1.9, the differential cross section of p_T $\frac{d\sigma}{dp_T}$
  - ATLAS Data: 250^{+130}_{-80} nb
  - Pythia: 3450 nb
  - Color Singlet Model: 100-800 nb
  - Color Evaporation Model: 140-400 nb
  - Gluon Tower Model: ~300 nb

Pseudo-Proper Time Fitting

- Maximize the quantity, $\ln L = \sum \ln F(\tau, \delta_\tau, m_{\mu\mu}, \delta_m)$
- Pseudo-proper time and mass are fit with a simultaneous unbinned event-by-event maximum likelihood fit in the mass range 2-4 GeV, where the PDF is:

$$F \equiv F_{sig}(\tau, \delta_\tau) f_{sig}(m_{\mu\mu}, \delta m_{\mu\mu}) + F_{bkg}(\tau, \delta_\tau) f_{bkg}(m_{\mu\mu}, \delta m_{\mu\mu})$$

Pseudo-proper time PDF for signal candidates

Mass PDF for signal

Pseudo-proper time PDF for background

Mass PDF for signal

- Pseudo-proper time PDF for signal candidatesis an exponential plus a delta function convolved with a Gaussian resolution function
- Mass PDF for signal is a Gaussian
- Pseudo-proper time PDF for background is an exponential plus a double sided exponential plus a delta function convolved with a Gaussian
- Mass PDF for background is linear function

Pseudo-Proper Time PDFs

- Signal J/ψ candidate pseudo-proper time PDF is

$$\mathcal{F}_{\rm sig}(\tau,\delta_\tau) = f_B\mathcal{F}_B(\tau,\delta_\tau) + (1-f_B)\mathcal{F}_P(\tau,\delta_\tau).$$

- Where the nonprompt and prompt components are, respectively

$$\mathcal{F}_B(\tau,\delta_\tau) = R(\tau'-\tau,\delta_\tau)\otimes E(\tau'). \qquad \mathcal{F}_P(\tau,\delta_\tau) = R(\tau'-\tau,\delta_\tau)\otimes\delta(\tau') = R(\tau,\delta_\tau).$$

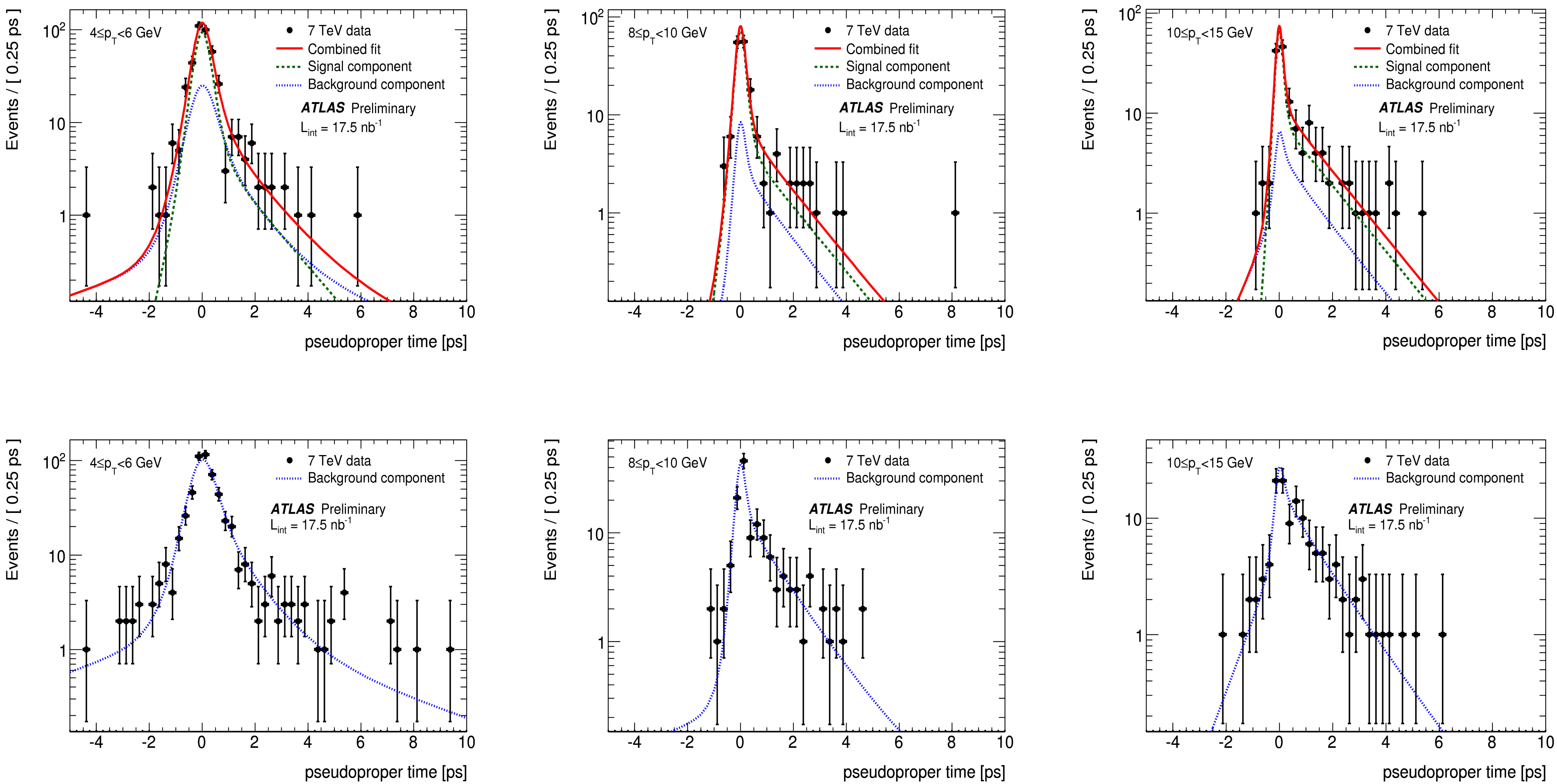
- Where R connotes the signal resolution function

- Background pseudo-proper time PDF is

$$\mathcal{F}_{\rm bkg}(\tau,\delta_\tau) = R_{\rm bkg}(\tau,\delta_\tau) + \exp\left(\frac{-\tau'}{\tau_{\rm eff1}}\right)\otimes R_{\rm bkg}(\tau'-\tau,\delta_\tau) + \exp\left(\frac{-|\tau'|}{\tau_{\rm eff2}}\right)\otimes R_{\rm bkg}(\tau'-\tau,\delta_\tau)$$

- R_{bkg} connotes the background resolution function

Pseudo-Proper time Fit to Data



Fraction Results

$p_T(J/\psi)$ GeV	$\mathcal{R} \equiv \sigma(pp \to b\bar{b}X \to J/\psi X')/\sigma(pp \to J/\psi X'')_{\text{prompt}}$		χ^2/DoF	p-value
	Data	MC		
1 – 4	$0.22 \pm 0.09(stat) \pm 0.07(syst)$	0.061 ± 0.022	33.5/34	0.49
4 – 6	$0.12 \pm 0.05(stat) \pm 0.06(syst)$	0.137 ± 0.039	23.2/25	0.57
6 – 8	$0.24 \pm 0.05(stat) \pm 0.05(syst)$	0.238 ± 0.070	22.0/20	0.34
8 – 10	$0.25 \pm 0.08(stat) \pm 0.07(syst)$	0.365 ± 0.126	10.1/15	0.81
10 – 15	$0.60 \pm 0.15(stat) \pm 0.10(syst)$	0.469 ± 0.180	6.9/16	0.97

- Ratio of indirect to direct J/ψ production cross sections as a function of J/ψ p_T