# ATLAS results on charmonium production

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# Outline

- **Measurement of the production cross-section of $J/\Psi$ and $\Psi(2S)$ mesons at high transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ATLAS-CONF-2019-047**

- **Measurement of $J/\Psi$ production in association with a W boson with pp data at 8 TeV JHEP 01 (2020) 095**

# Measurement of $J/\Psi$ and $\Psi(2S)$ Production

- In high energy hadronic collisions, charmonium states can be produced either in the initial hard interaction (prompt), or from decays of beauty hadrons (non-prompt).

  - Distinguished by measuring the distance between the production and decay vertices.

- Most of previous ATLAS measurement about $J/\Psi$ production exploited a dimuon trigger with the high-pT reach limited mainly by the trigger performance to about 100 GeV. Run1 result: Eur. Phys. J. C 76 (2016) 283

- New measurements of the $J/\Psi$ ( $\Psi(2S)$ ) meson production with $60 < p_T < 360$ GeV ($60 < p_T < 140$ GeV) have been performed by ATLAS in $\sqrt{s} = 13$ TeV pp collision.

**ATLAS-CONF-2019-047**

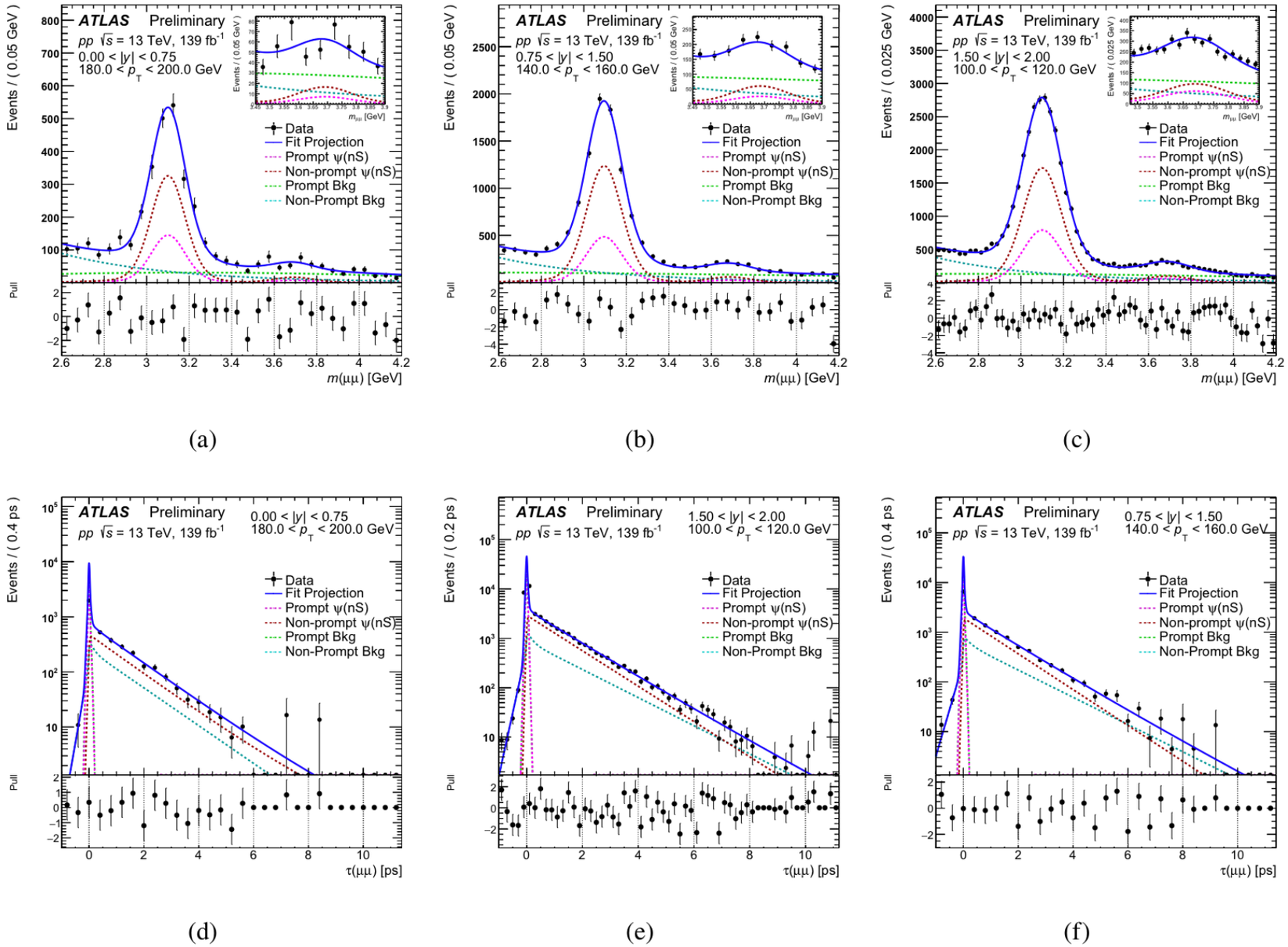
# $J/\Psi$ and $\Psi(2S)$ Measurement: Fit Model

- The fit model PDF is described by a sum of seven terms, corresponding to the prompt and non-prompt components for the two charmonium states and background processes:

$$PDF(m,\tau) = \sum_{i=1}^{7} k_i P_i(m,\tau),\ P_i(m,\tau) = f_i(m) \cdot (h_i(\tau) \otimes R(\tau))$$

Pseudo-proper decay time: $\tau = \frac{m}{p_T}\frac{L_{xy}}{c}$

- Different function f are used for different processes:
  - $J/\Psi(\Psi(2S))$: Gaussian and Crystal Ball
  - Prompt background: Bernstein polynomials
  - Non-prompt background: Exponential

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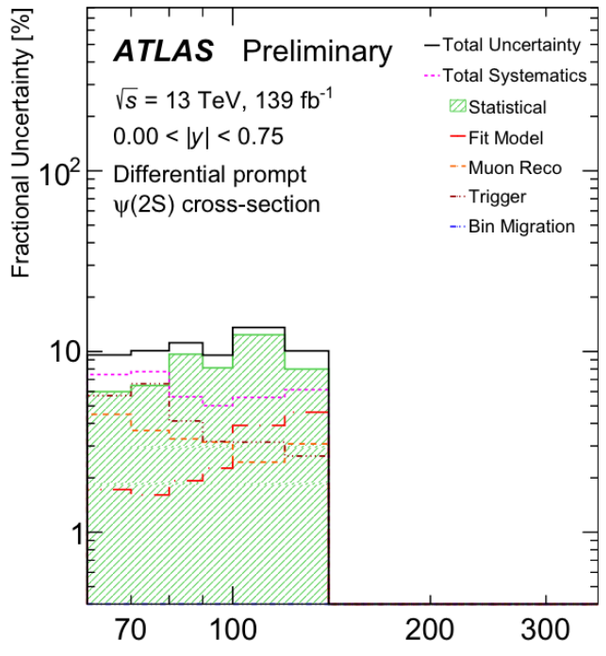
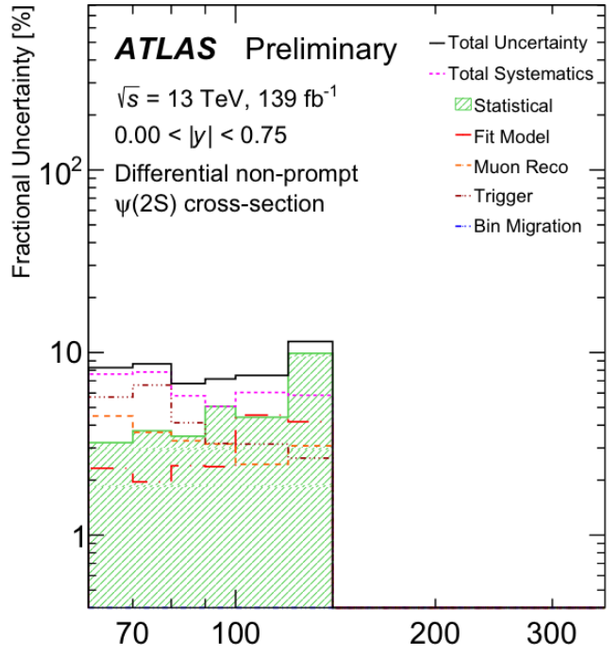
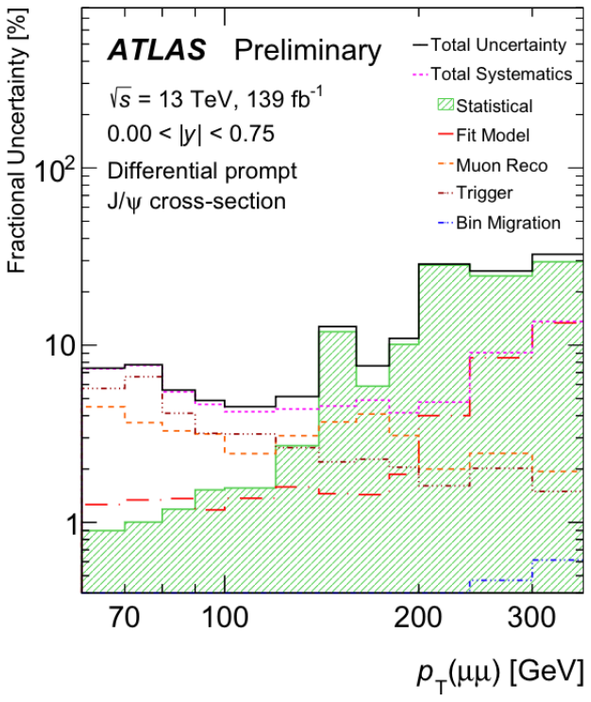
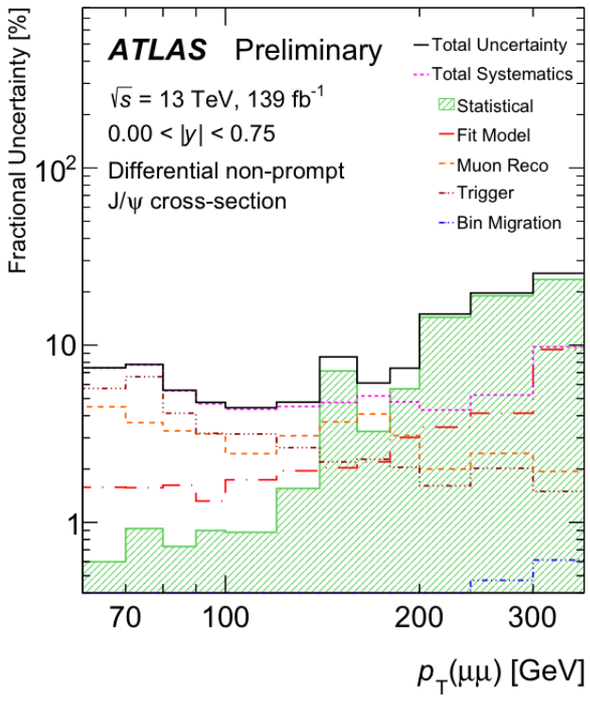
# $J/\Psi$ and $\Psi(2S)$ Measurement: Systematic Sources

- A variety of sources of systematic effects are studied:
  - Fit parameterisation
  - Muon reconstruction and trigger efficiencies
  - Bin migration corrections
  - Acceptance corrections




- The total, statistical, and systematic fractional uncertainties are shown for the central rapidty slice as a function of $p_T(\mu\mu)$
  - In low pT range, systematics on trigger and muon reconstruction have a larger impact
  - In high pT range, systematic from fit model dominates

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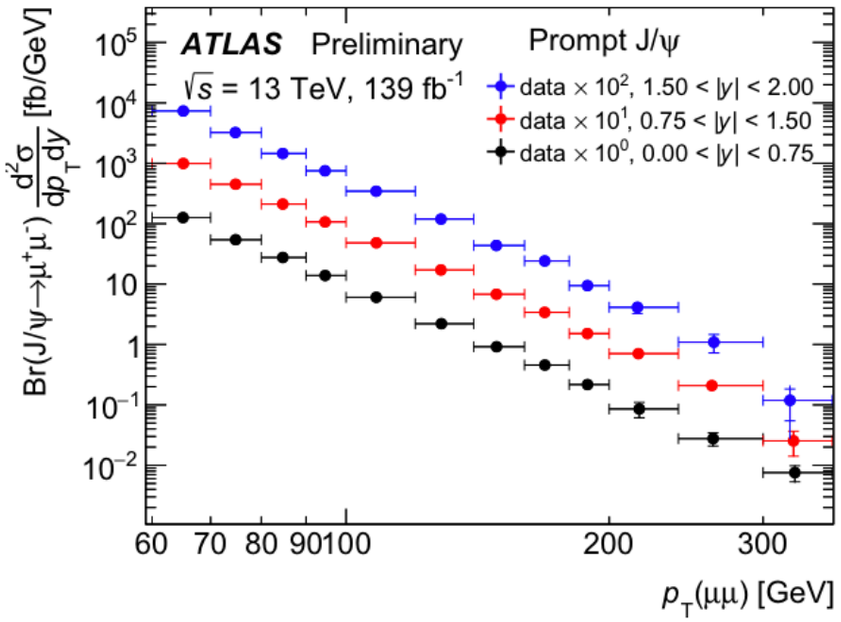
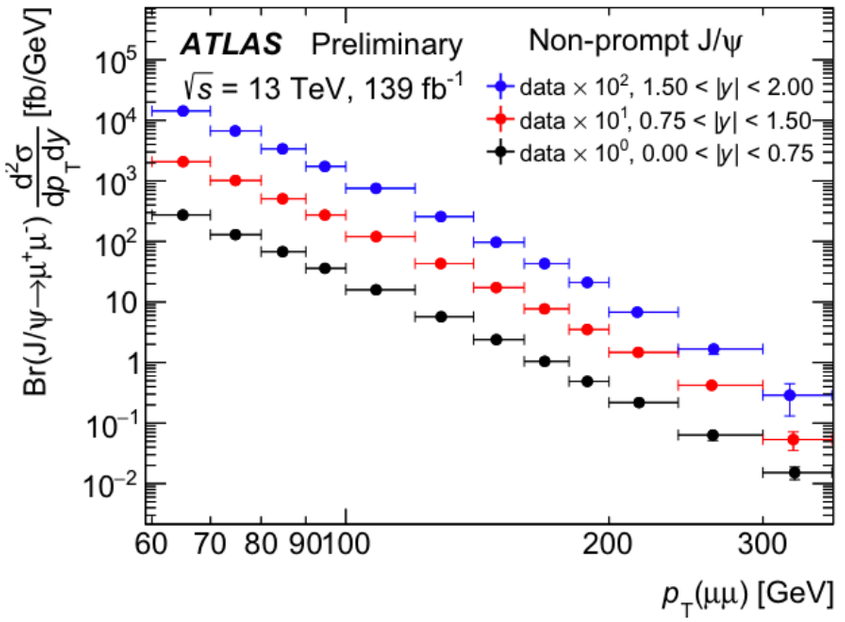
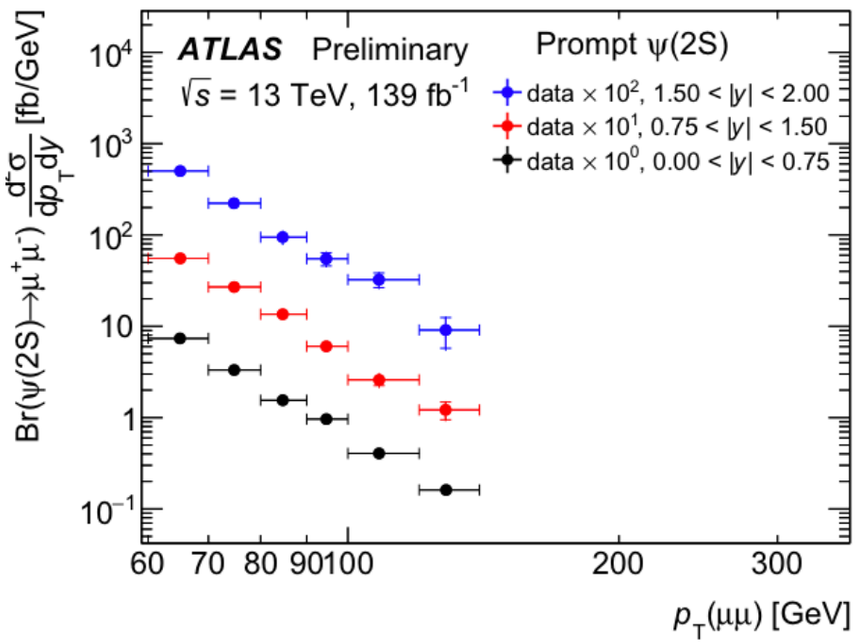
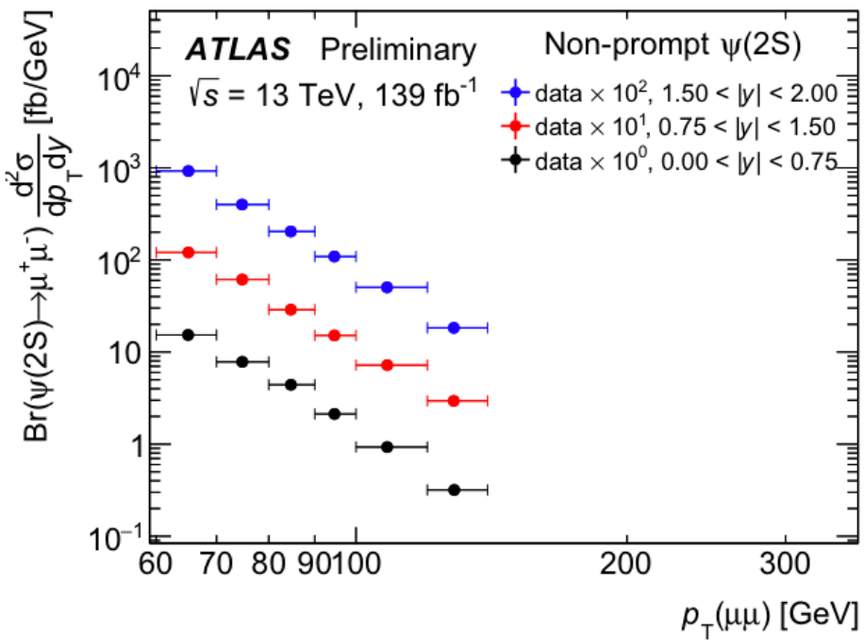
# $J/\Psi$ and $\Psi(2S)$ Measurement: Results

- The measured double-differential cross-sections of prompt and non-prompt $J/\Psi$ ( $\Psi(2S)$ ) production

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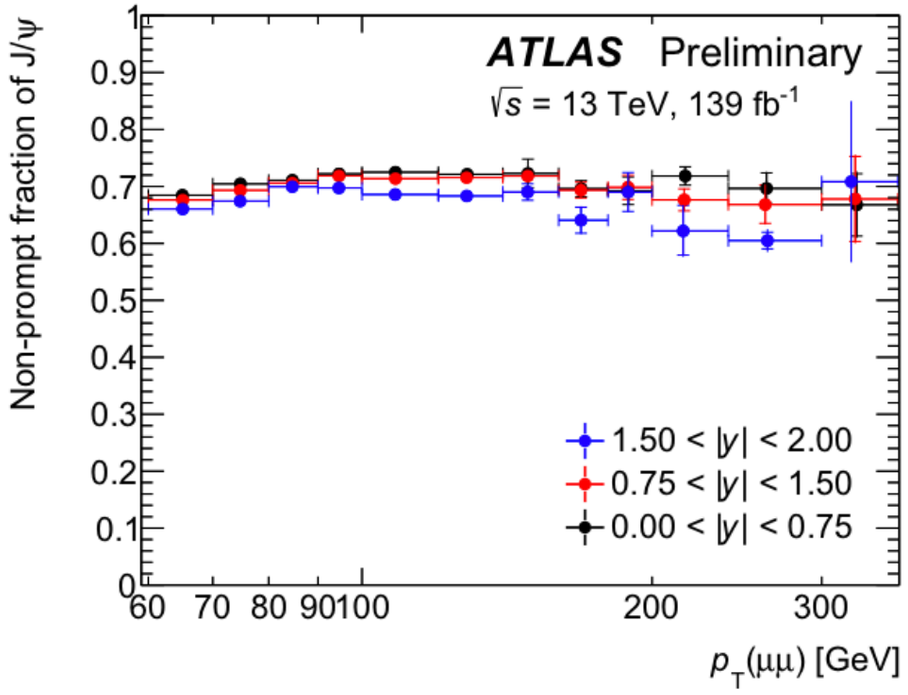
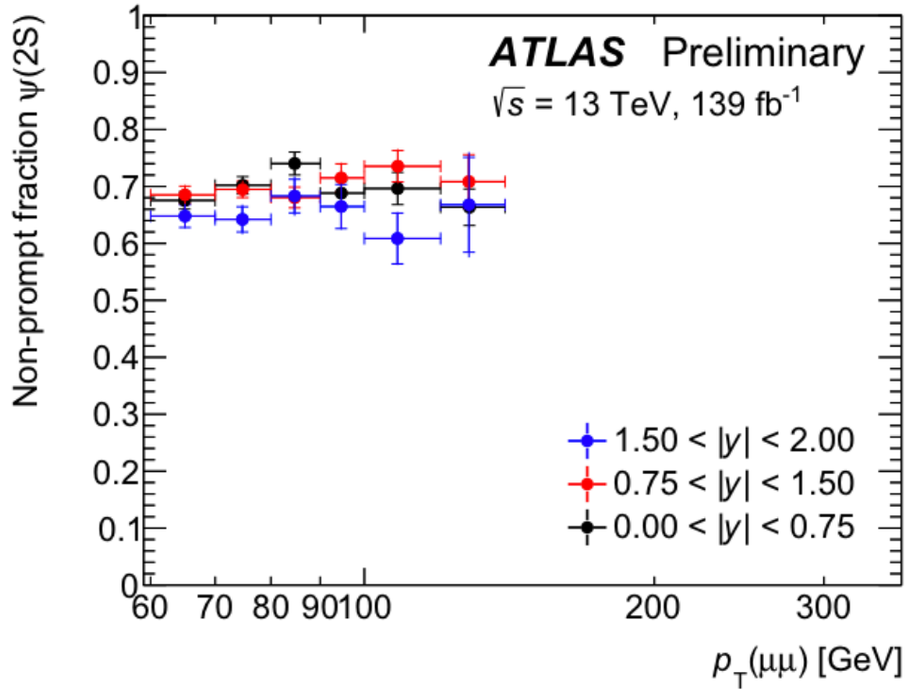
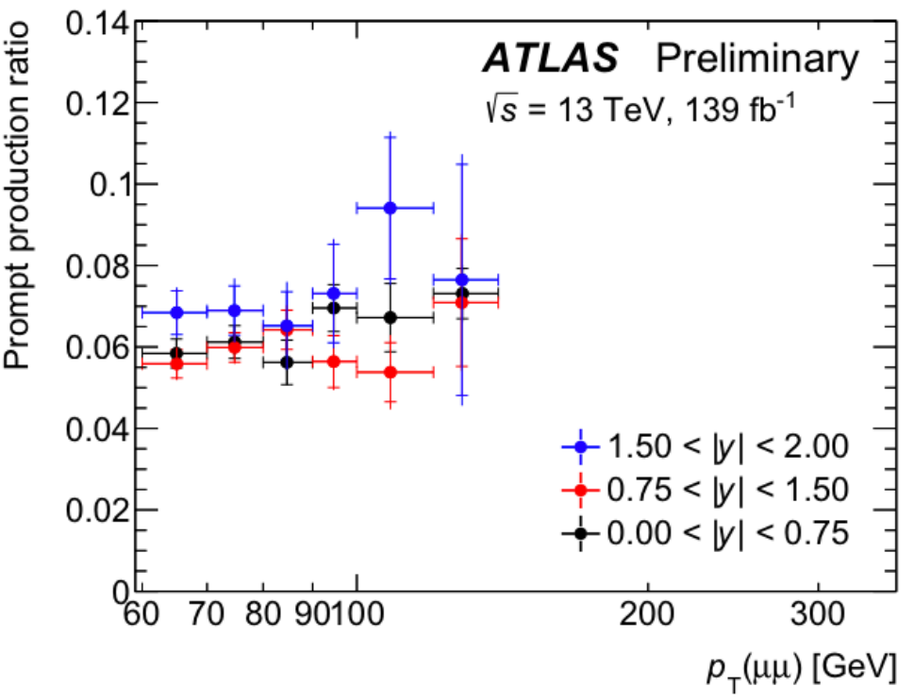
# $J/\Psi$ and $\Psi(2S)$ Measurement: Results

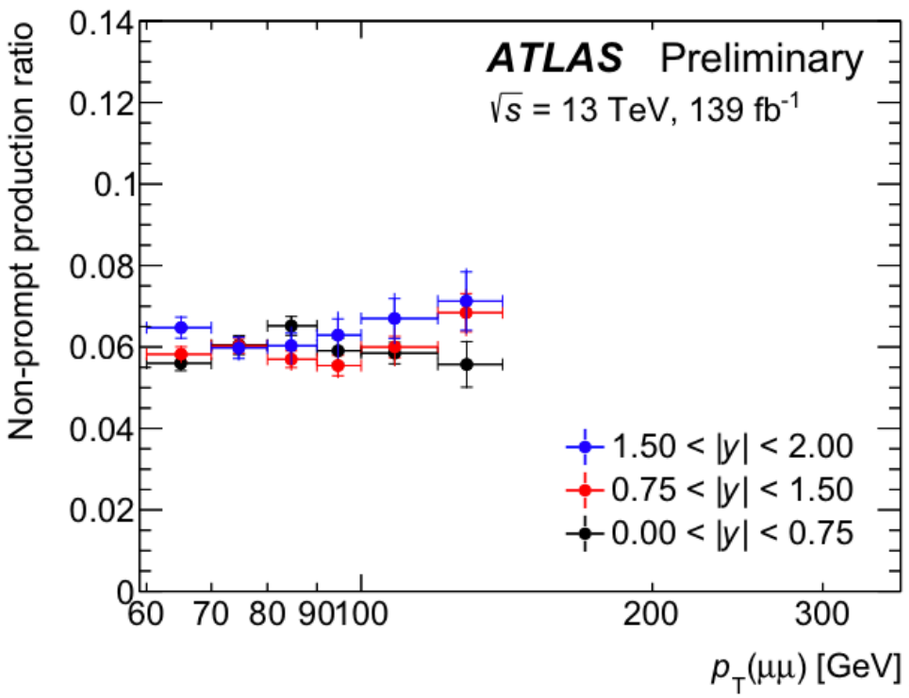
$$F_{\psi}^{\mathrm{NP}}(p_{\mathrm{T}}, y) = \frac{N_{\psi}^{\mathrm{NP}}}{N_{\psi}^{\mathrm{P}} + N_{\psi}^{\mathrm{NP}}}$$

- Non-prompt production fractions for $J/\Psi$ and $\Psi(2S)$
- The non-prompt fractions are in the plateau regime ~ 0.7




- The production ratios of $\Psi(2S)$ relative to $J/\Psi$

$$R^{\mathrm{P,NP}}(p_{\mathrm{T}}, y) = \left(\frac{\mathcal{A}(\psi(2S))}{\mathcal{A}(J/\psi)}\right)^{-1} \frac{N_{\psi(2S)}^{\mathrm{P,NP}}}{N_{J/\psi}^{\mathrm{P,NP}}}$$

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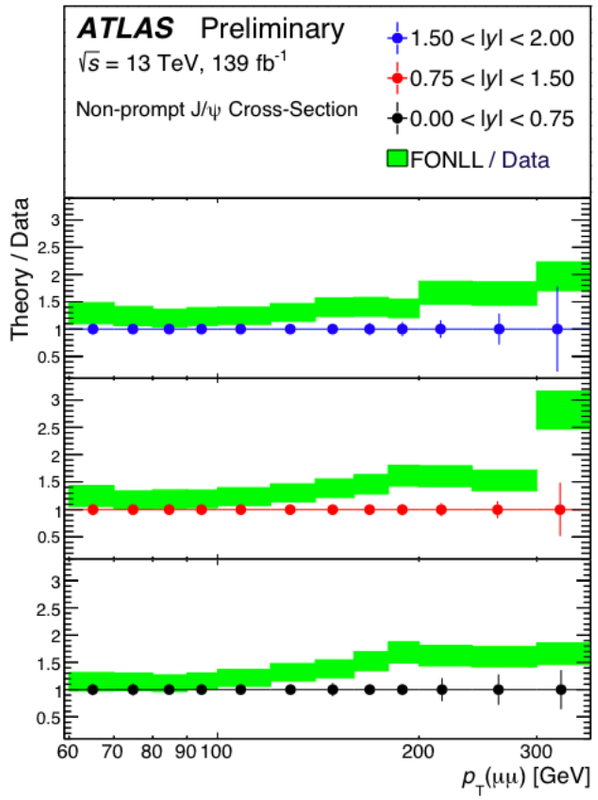
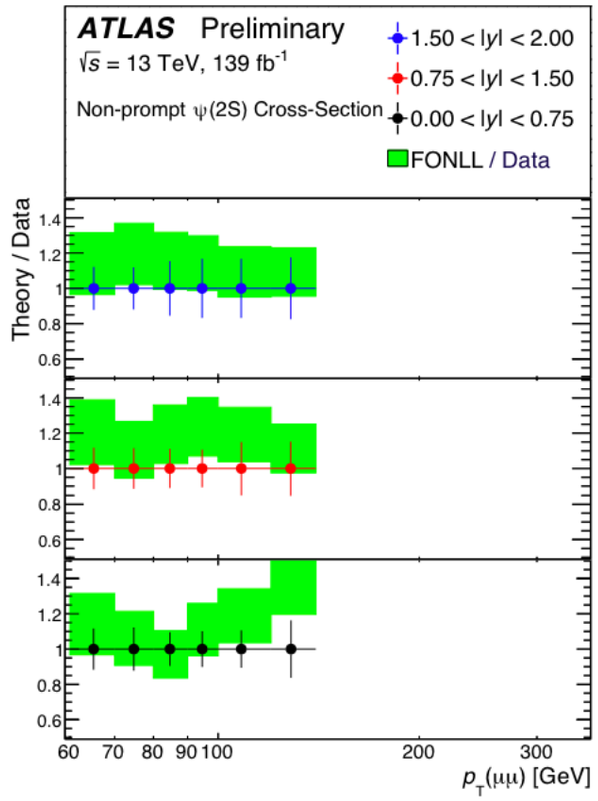
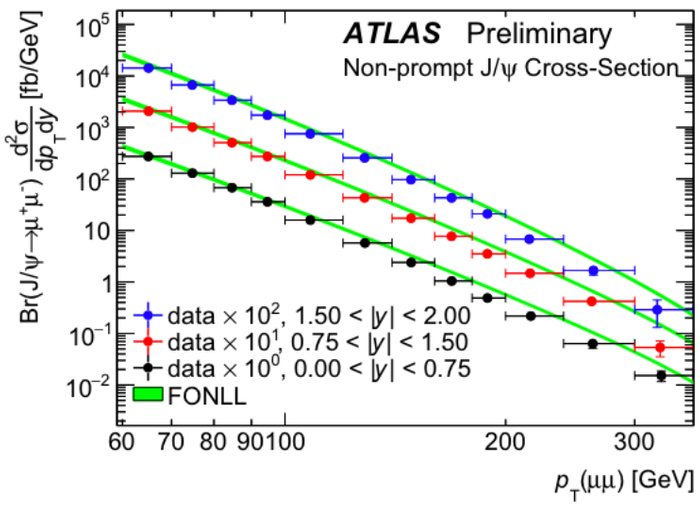
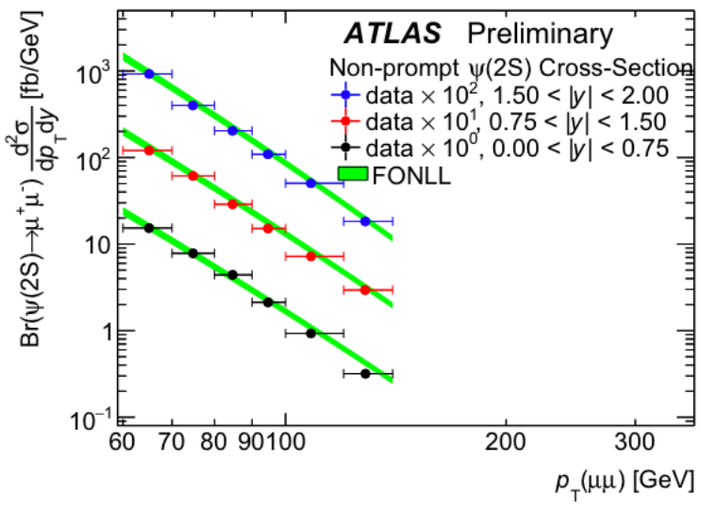
# $J/\Psi$ and $\Psi(2S)$ Measurement: Results

- Measurement of the non-prompt differential cross sections are compared to the FONLL calculations
- Good agreement at low pT range, but overestimation in FONLL at high pT range

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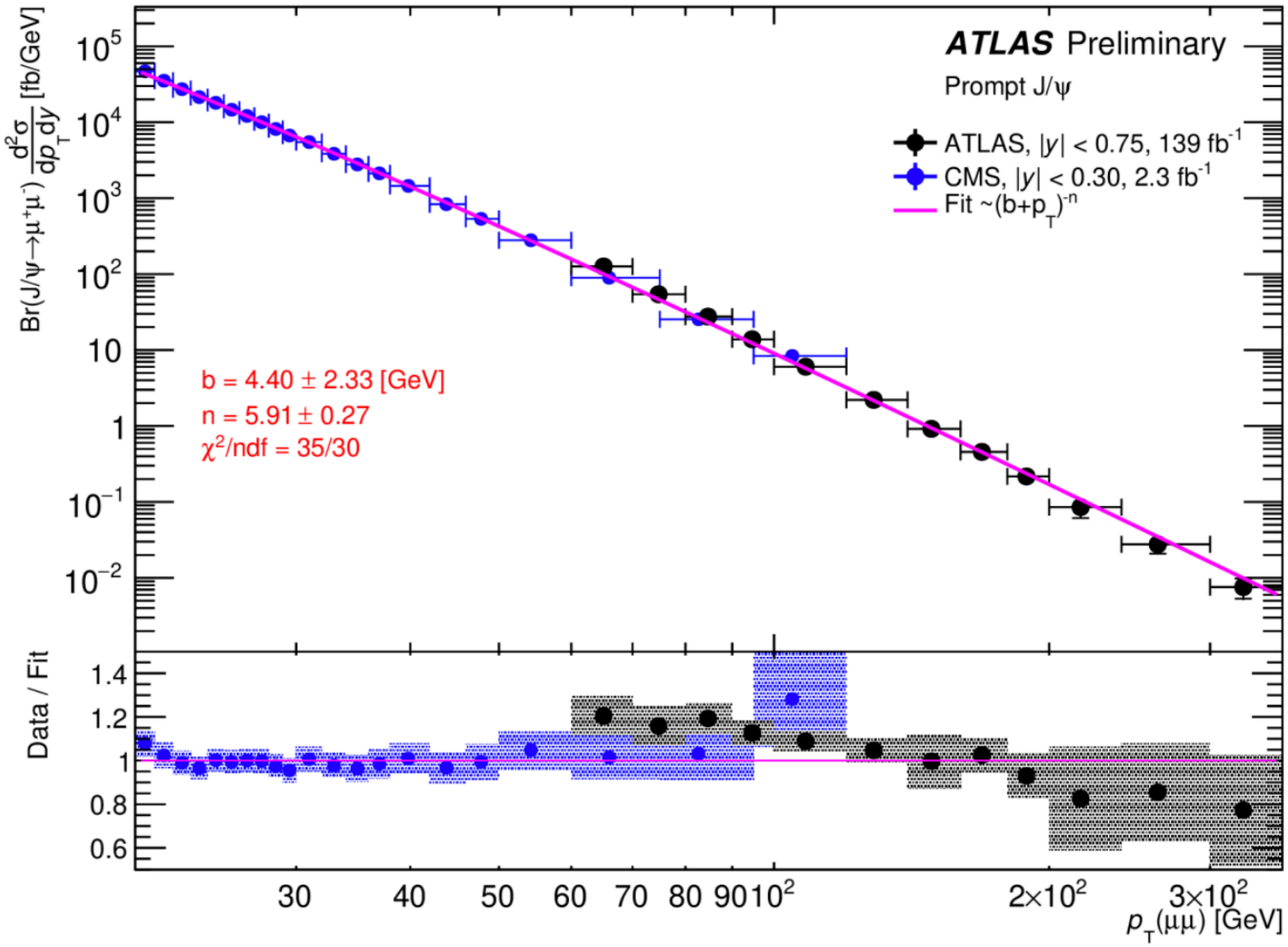
# $J/\Psi$ and $\Psi(2S)$ Measurement: Results

- Comparison between results from ATLAS and from CMS shows a good agreement in the range of overlap




- Described by $\sim(b + p_T)^{-n}$ with b=4.4 and n=6

# Measurement of $J/\Psi + W^{\pm}$ Production

- Associated prompt $J/\Psi + W^{\pm}$ production allows tests of QCD at boundary between perturbative and non-perturbative regimes

- Two measurement about associated production of $J/\Psi$ with vector bosons have been presented in ATLAS:

  - Associated prompt $J/\Psi + W^{\pm}$ production in $\sqrt{s} = 7$ TeV data (modest statistics)

  - Associated $J/\Psi + Z$ production in $\sqrt{s} = 8$ TeV data

- This analysis measures the associated prompt $J/\Psi + W^{\pm}$ production in $\sqrt{s} = 8$ TeV data. The production is supposed to be a clear signature of colour octet (OC) state

  - Although other authors argue that higher-order colour singlet (CS) processes will dominate

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# $J/\Psi + W^{\pm}$ Measurement: $J/\Psi$ and $W$ Selection

- The W boson transverse mass is defined as:

$$m_{\mathrm{T}}(W^{\pm}) \equiv \sqrt{2p_{\mathrm{T}}(\mu)E_{\mathrm{T}}^{\mathrm{miss}}[1-\cos(\phi^{\mu}-\phi^{\nu})]}$$

- Require two additional muons to select $J/\Psi$ mesons

| $J/\psi$ selection |
|---|
| $2.4 < m(\mu^+\mu^-) < 3.8$ GeV |
| $8.5 < p_{\mathrm{T}}^{J/\psi} < 150$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$ |
| $p_{\mathrm{T}}^{\mu_1} > 4$ GeV, $\lvert\eta^{\mu_1}\rvert < 2.5$ |
| $\left\{\begin{array}{c}\text{either } p_{\mathrm{T}}^{\mu_2} > 2.5 \text{ GeV}, \quad 1.3 \le \lvert\eta^{\mu_2}\rvert < 2.5 \\ \text{or } p_{\mathrm{T}}^{\mu_2} > 3.5 \text{ GeV}, \quad \lvert\eta^{\mu_2}\rvert < 1.3\end{array}\right\}$ |

| $W^{\pm}$ boson selection |
|---|
| At least one isolated muon that originates $< 1$ mm from primary vertex along $z$-axis |
| $p_{\mathrm{T}}$ (trigger muon) $> 25\,\mathrm{GeV}$ |
| $\lvert\eta^{\mu}\rvert < 2.4$ |
| Missing transverse momentum $> 20\,\mathrm{GeV}$ |
| $m_{\mathrm{T}}(W^{\pm}) > 40\,\mathrm{GeV}$ |
| $\lvert d_0\rvert/\sigma_{d_0} < 3$ |

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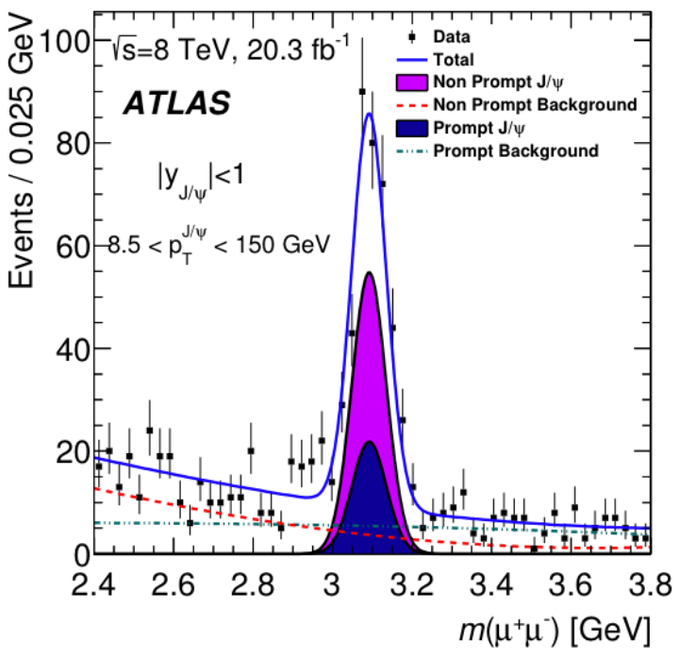
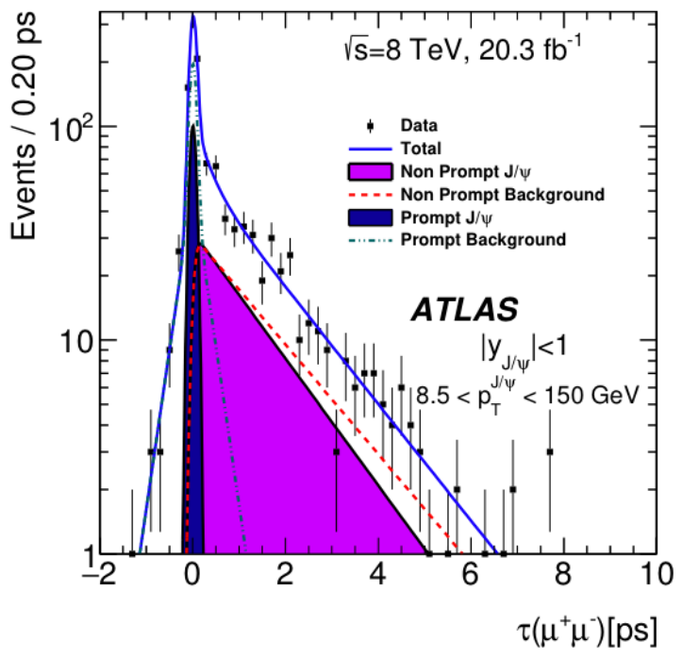
# $J/\Psi + W^{\pm}$ Measurement: Prompt and Non-Prompt $J/\Psi$




(a)

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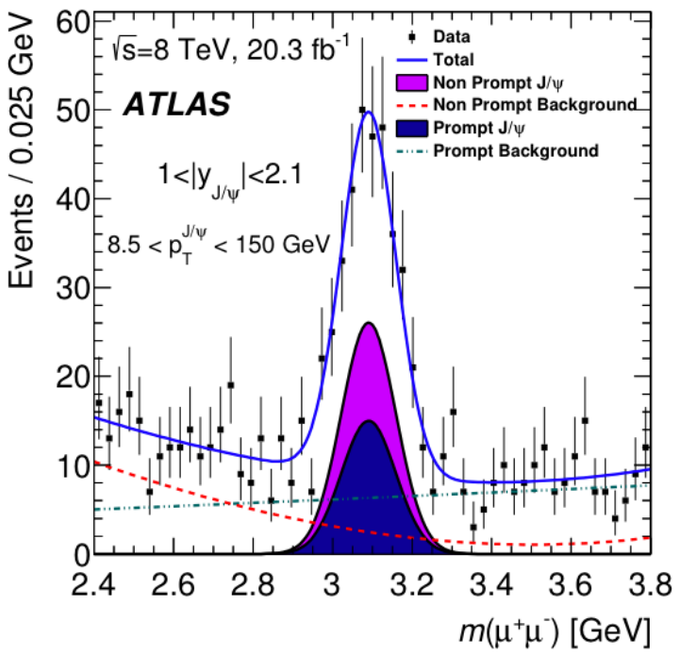
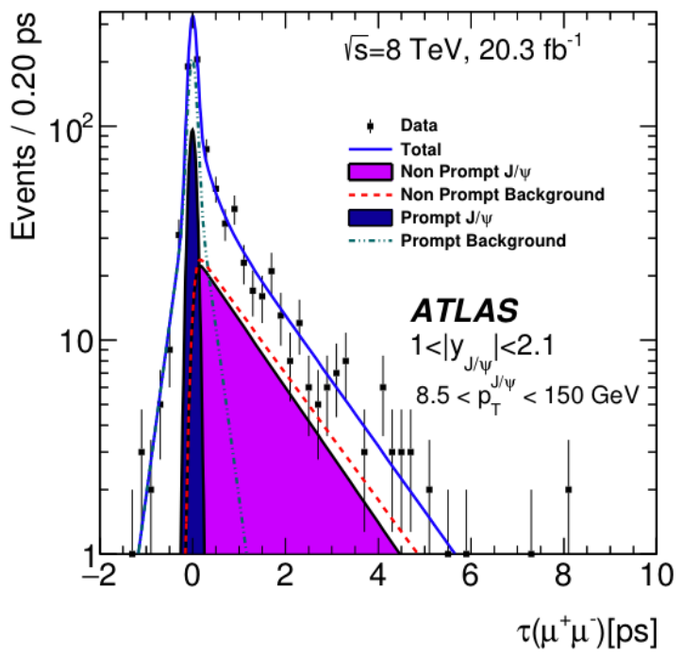



(c)




(d)

- The pseudo proper decay time ( $\tau(\mu^+\mu^-)$ ) is used to distinguish prompt $J/\Psi$ and non-prompt $J/\Psi$ from b-hadron decay
- Two dimensional mass and decay time fit is applied in the region with
  - $2.4 < m(\mu^+\mu^-) < 3.8$ GeV
  - $-2 < \tau(\mu^+\mu^-) < 10$ ps

$$\tau(\mu^+\mu^-) \equiv \frac{\vec{L} \cdot \vec{p}_{\mathrm{T}}^{J/\psi}}{p_{\mathrm{T}}^{J/\psi}} \cdot \frac{m(\mu^+\mu^-)}{p_{\mathrm{T}}^{J/\psi}}$$

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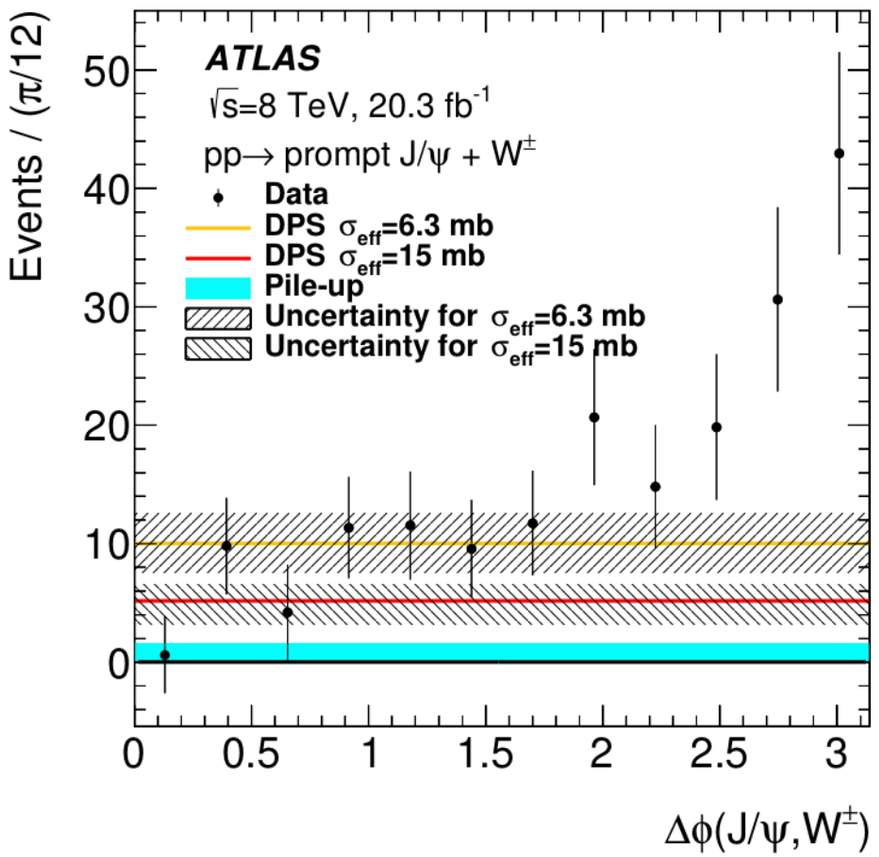
# $J/\Psi + W^{\pm}$ Measurement: DPS

- The double parton scattering (DPS) contribution is estimated using the effective cross-section ( $\sigma_{eff}$ ) measured by the ATLAS.
  - $\sigma_{eff}$ is the effective transverse overlap area of the interacting partons
- With the assumption that two hard scatters are uncorrelated, the probability that a $J/\Psi$ is produced by the second hard process in event containing a W boson is defined as:

$$P^{ij}_{J/\Psi \backslash W^{\pm}} = \frac{\sigma^{ij}_{J/\Psi}}{\sigma_{eff}}$$

- From W+2jet events,
  $\sigma_{eff} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{sys.})$ mb
- From prompt $J/\Psi$ pair production,
  $\sigma_{eff} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{sys.})$ mb

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# $J/\Psi + W^{\pm}$ Measurement: Results

- The final prompt $J/\Psi + W^{\pm}$signal yields after the application of the $J/\Psi$ acceptance and muon efficiency weights are:
  - $222 \pm 27$ (stat) for central region
  - $195 \pm 33$ (stat) for forward region
- The fully corrected inclusive production cross-section ratio, in which the $J/\Psi$ acceptance and the unknown J/ψ spin-alignment are taken into account, is $(5.3 \pm 0.7 \pm 0.8^{+1.5}_{-0.7}) \times 10^{-6}$

$$R^{incl}_{J/\Psi} = \frac{\sigma_{incl}(pp \to J/\Psi + W^{\pm})}{\sigma(pp \to W^{\pm})} \cdot \mathcal{B}(J/\Psi \to \mu\mu)$$

$$= \frac{1}{N(W^{\pm})} \sum_{p_T bins} [N^{eff+acc}(J/\Psi + W^{\pm}) - N_{pile-up}]$$

- Subtraction of estimated DPS contribution:
  - $R^{DPSsub}_{J/\Psi} = (3.6 \pm 0.7^{+1.1+1.5}_{-1.0-0.7}) \times 10^{-6}$, $[\sigma_{eff} = 15^{5.8}_{-4.2} mb]$
  - $R^{DPSsub}_{J/\Psi} = (1.3 \pm 0.7 \pm 1.5^{+1.5}_{-0.7}) \times 10^{-6}$, $[\sigma_{eff} = 6.3 \pm 1.9 mb]$

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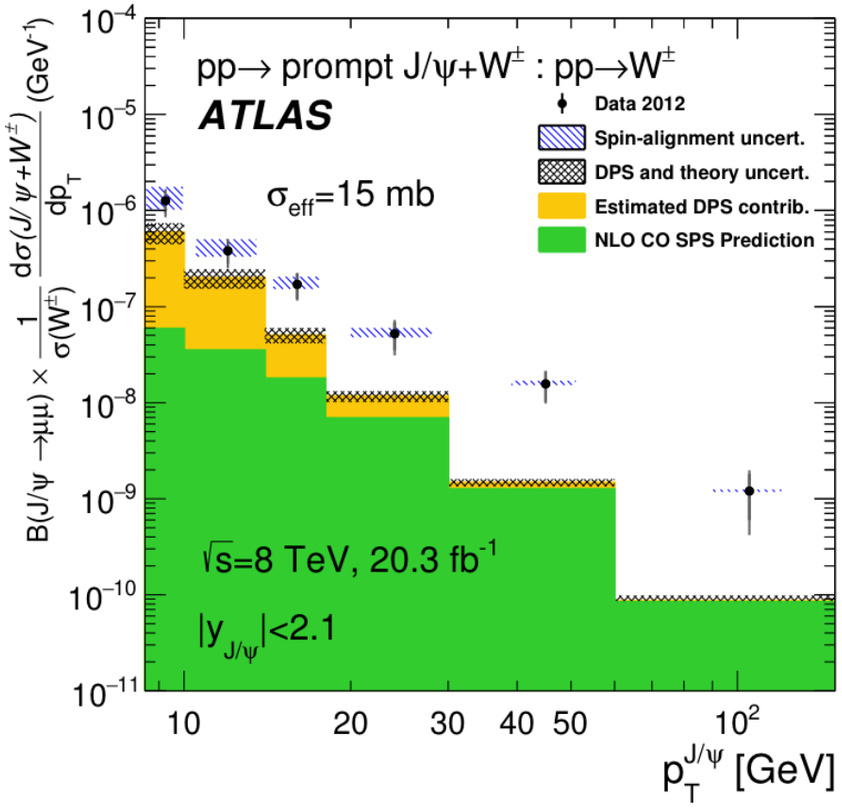
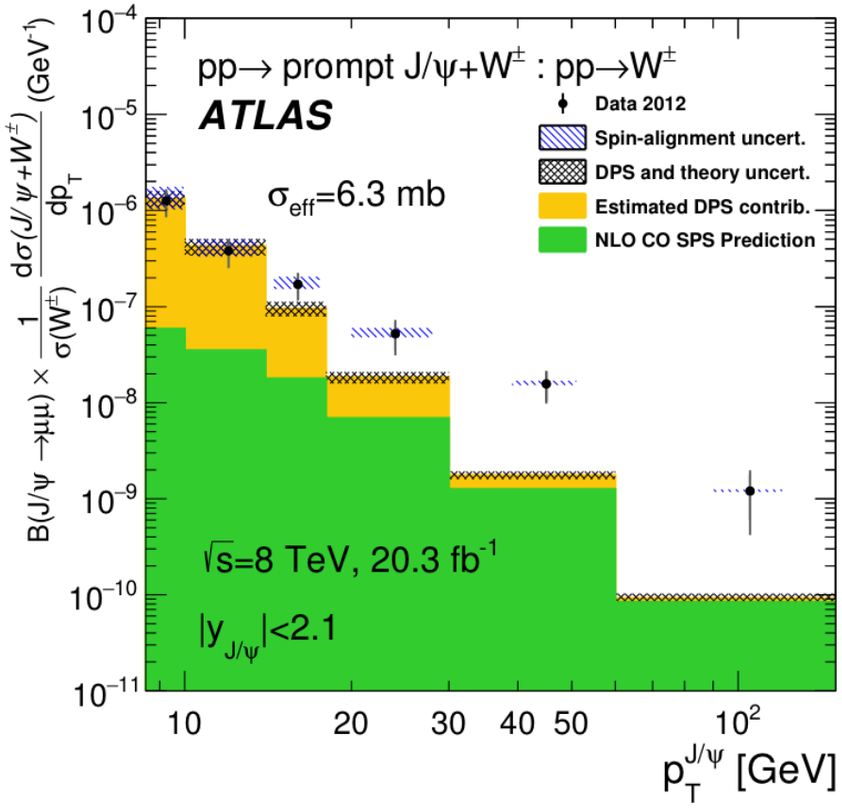
# $J/\Psi + W^{\pm}$ Measurement: Results




- The inclusive differential cross-section ratio is measured in six $J/\Psi$ transverse momentum intervals
- The combined prediction underestimates the measurement especially in high pT intervals
- The miss of contribution from SPS colour singlet mechanism may account for the underestimation

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# Summary

- Measurement on charmonium production provide a unique insight into the nature of QCD near the boundary of perturbative and non-perturbative regimes.

- In the measurement of $J/\Psi$ and $\Psi(2S)$ production, high $p_T$ range is covered, which may help discriminate various theoretical models.

- In the measurement of $J/\Psi + W^{\pm}$ production, the results are presented initially for muons from $J/\Psi$ decay in the fiducial volume of the ATLAS detector.

- More studies are on-going with Run 2 data

**Stay tuned!**

# Thanks