ATLAS results on quarkonia and associated production

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Outline

J/ψ and $\psi(2S)$ production cross sections at high p_T at 13 TeV
ATLAS-CONF-2019-047

J/ψ production in association with a W boson at 8 TeV
JHEP 01 (2020) 095

Measurements of quarkonia states provide insight into QCD near boundary of perturbative and non-perturbative regimes

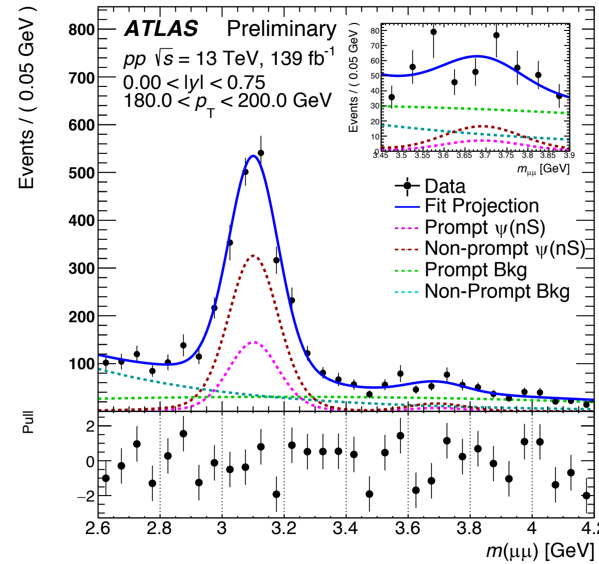
Previous measurements of cross sections used dimuon triggers with low thresholds

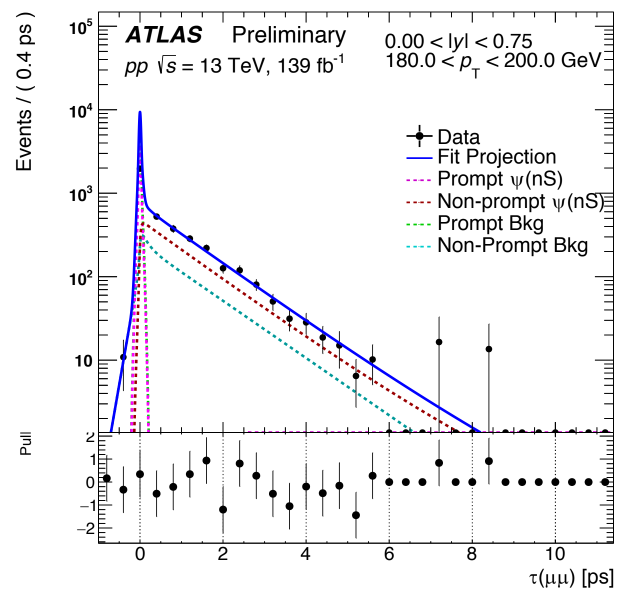
Dimuon triggers could not reach beyond p_T of ~ 100 GeV

Measuring high-p_T production of quarkonium states important because high p_T behavior may help discriminate various theoretical models

Previous measurements reached J/ψ p_T of 150 GeV
Phys. Lett. B **780** (2018) 251

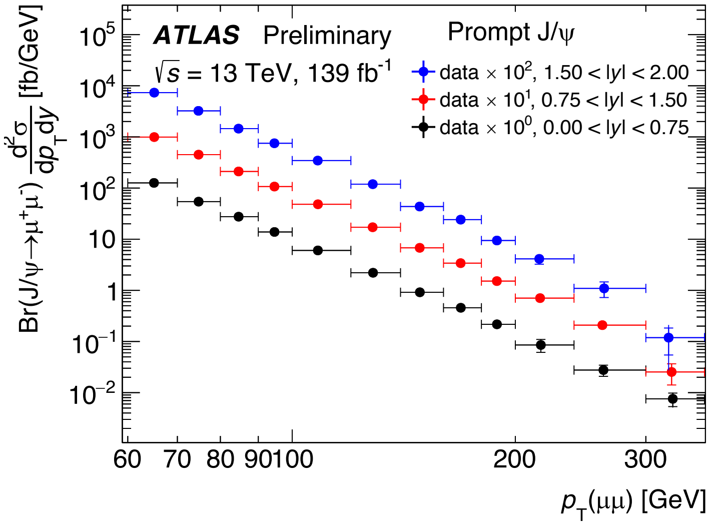
Single muon trigger (unprescaled) and full run-2 dataset allows measurement at high p_T (60-360 GeV) significantly expanding range

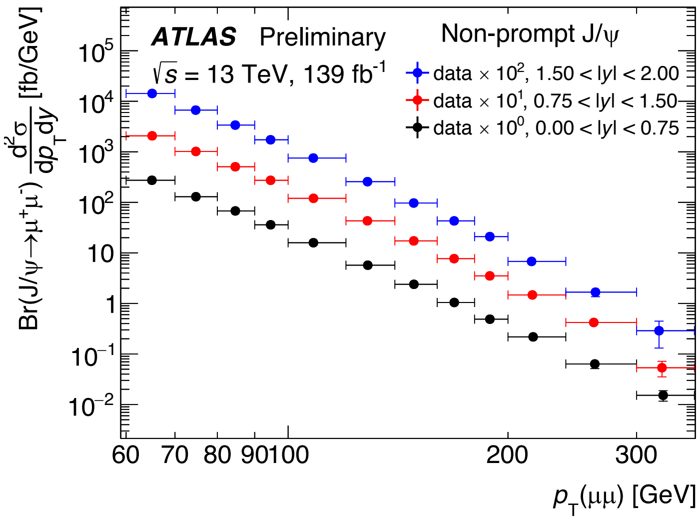




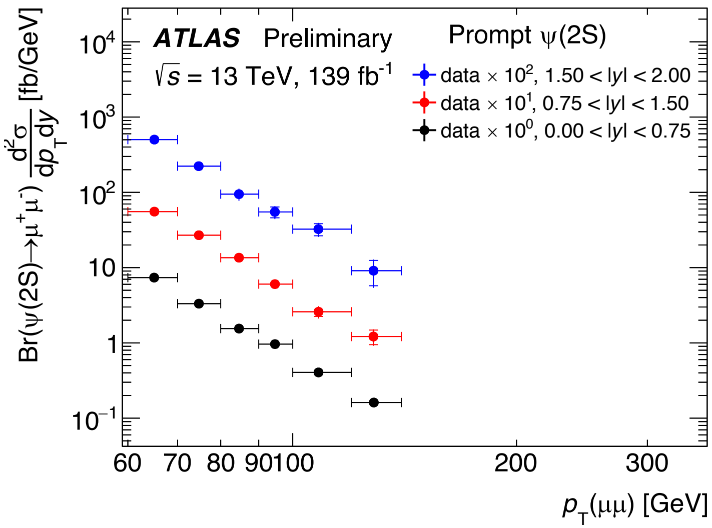
Differential Cross Sections

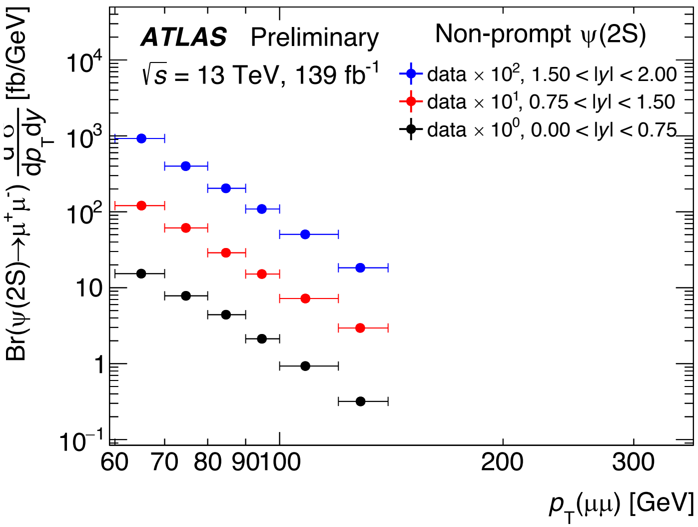
J/ψ prompt and non-prompt (From B-decays)





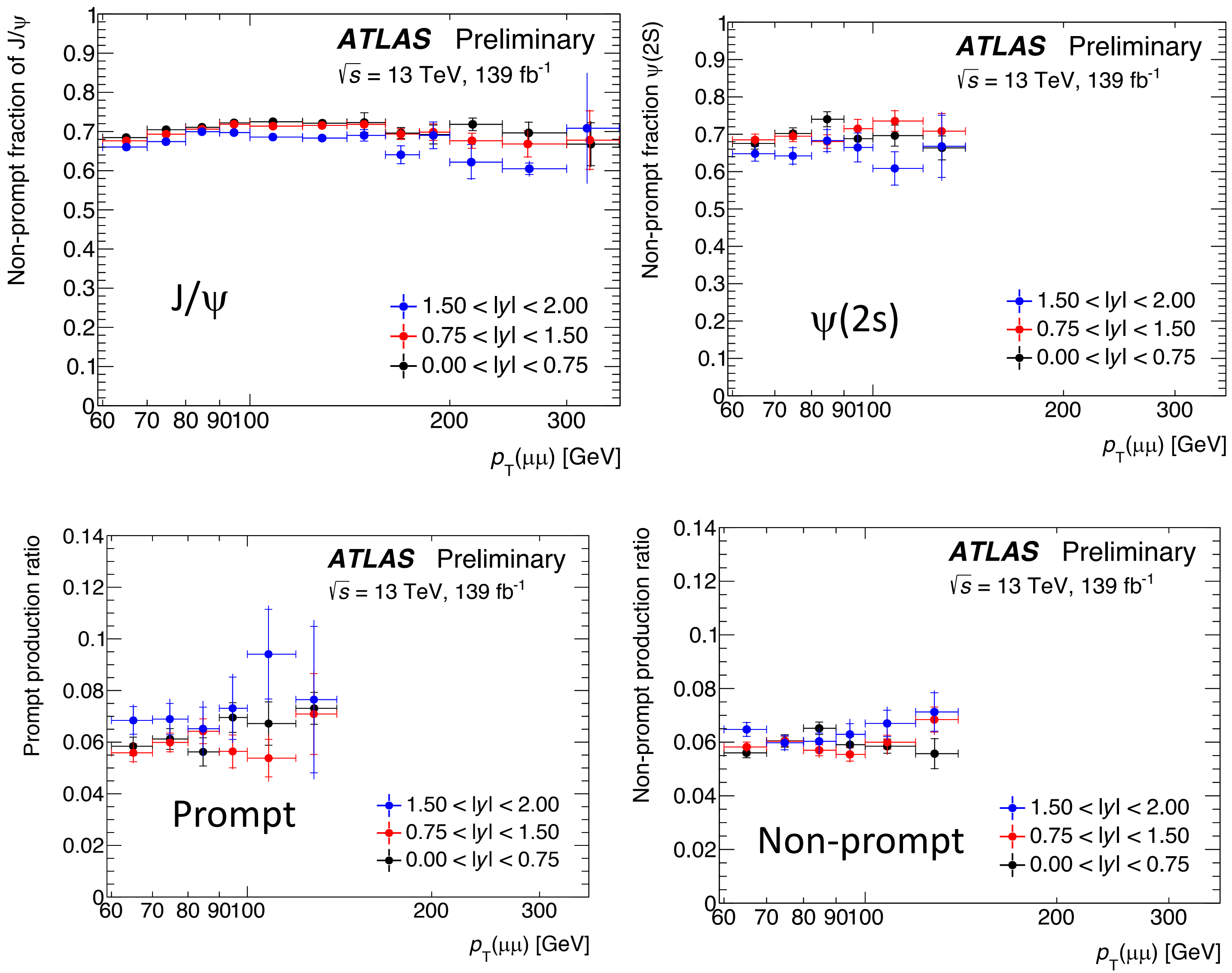
ψ(2S) prompt and non-prompt (From B-decays)





Non-prompt production fraction

Ratio of ψ(2s) to J/ψ



Acceptance

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

θ^*: Angle between μ^+ momentum in the ψ rest frame and ψ momentum in lab frame
ϕ^*: Angle between dimuon production and decay plans in lab frame

Polarization of the ψ state can affect acceptance so λ's chosen to define a range in which results may vary under any physically allowed spin-alignment assumptions

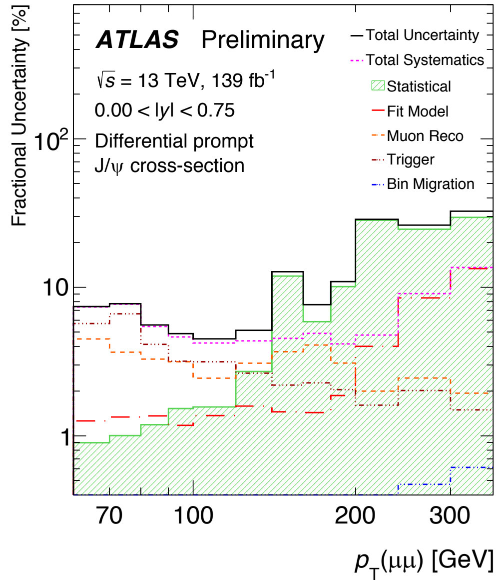
	Angular coefficients		
	λ_θ	λ_ϕ	$\lambda_{\theta\phi}$
Isotropic *(central value)*	0	0	0
Longitudinal	−1	0	0
Transverse positive	+1	+1	0
Transverse zero	+1	0	0
Transverse negative	+1	−1	0
Off-(λ_θ–λ_ϕ)-plane positive	0	0	+0.5
Off-(λ_θ–λ_ϕ)-plane negative	0	0	−0.5

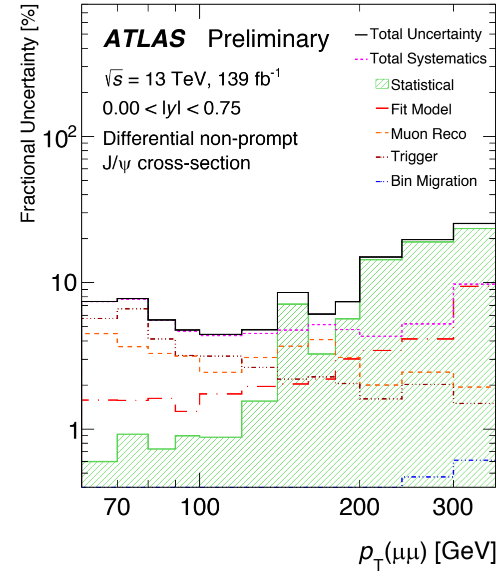
Systematics

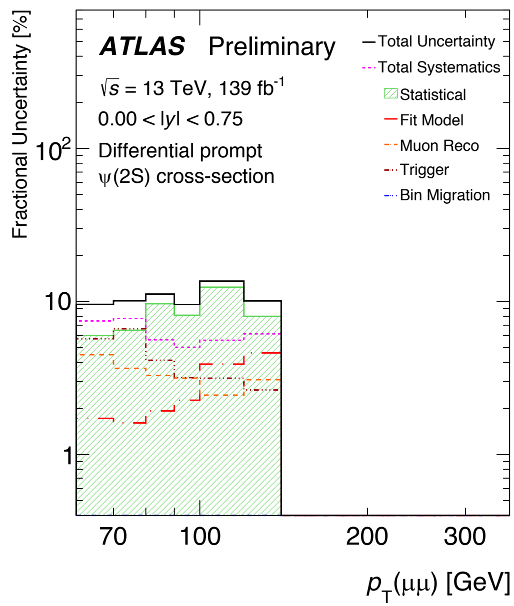
1. Trigger efficiency
2. Muon reco efficiency
3. Fit variations
4. Acceptance, bin migration, momentum scale, etc.
5. Luminosity

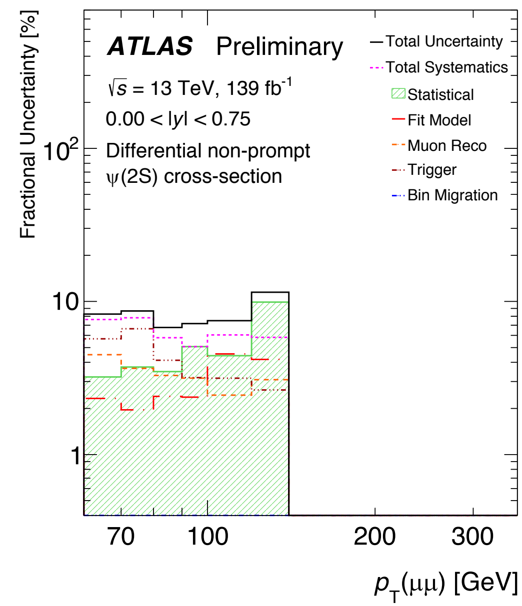
Dominated by statistical uncertainty at high p_T

Muon reconstruction and Trigger dominant at low p_T



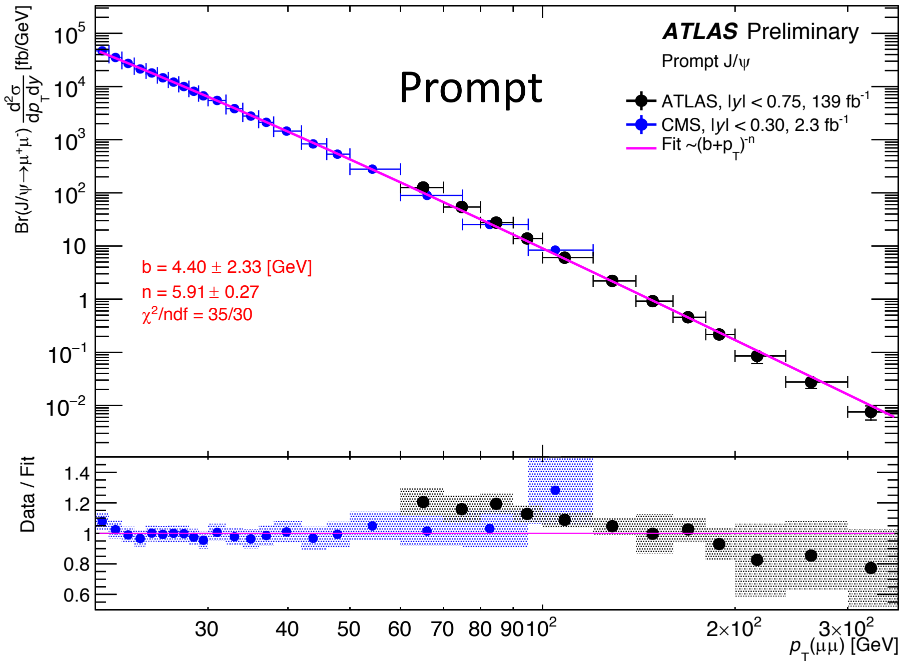






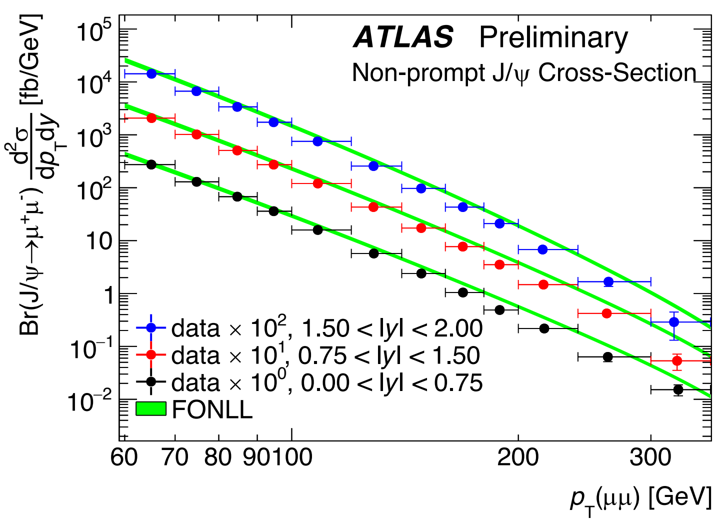
ATLAS and CMS results fit to a simple function $(b+p_T)^{-n}$

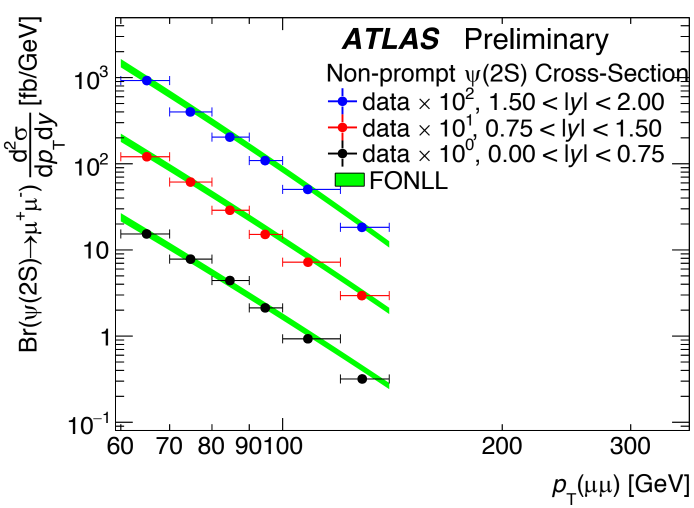
Consistent results with CMS in overlap region



Non Prompt

Comparison to FONLL

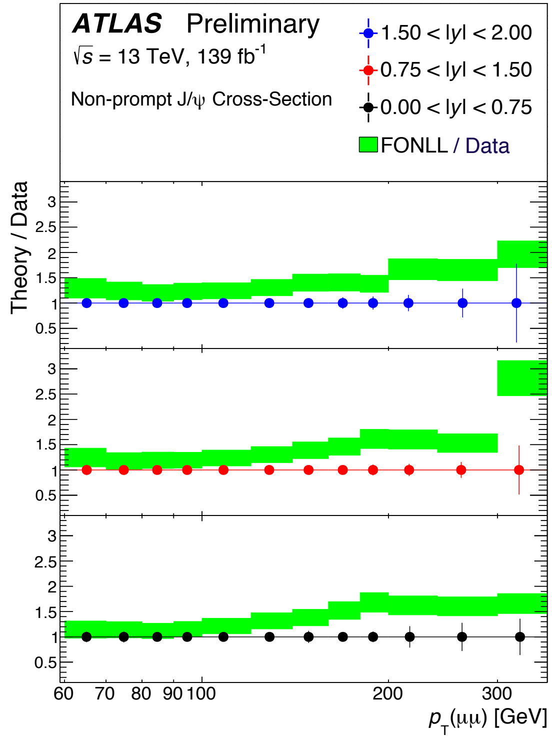


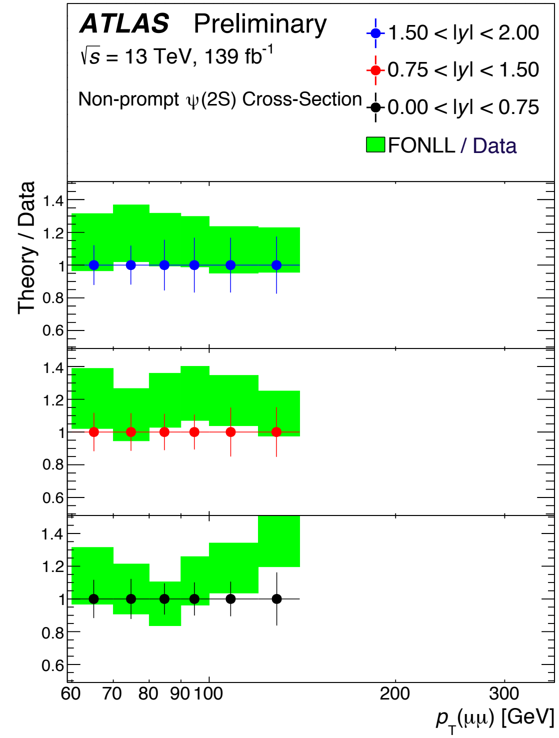


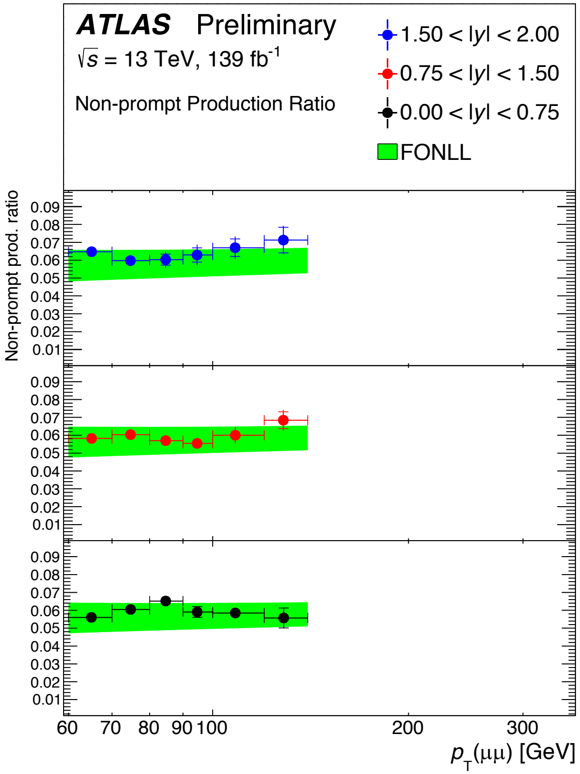
FONLL: JHEP **0103** (2001) 006, JHEP **1210** (2012) 137

Ratio of measurements to FONLL

Good agreement at lower end of p_T range, but FONLL predicting slightly larger cross sections at higher p_T for J/ψ







Non-prompt production ratio shows good agreement between data and FONLL

J/ψ production in association with a W boson at 8 TeV

- Production mechanism of charmonium in hadronic collisions is not fully understood
- Relative contribution of Color Singlet (CS) and Color Octet (CO) is unknown
- Including both CS and CO brings theory and experiment into better agreement
- Requiring an associated object ($W^{\pm}$) filters the possible CS/CO diagrams
- In addition contributions of double parton scattering vs single parton scattering processes unknown. $J/\psi + W^{\pm}$ can probe this using $\Delta\phi$ between the two particles.

Measure $R_{J/\psi}$:

Cross section of associated prompt J/ψ +W production divided by cross section of inclusive W production

$$R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W} \equiv \frac{\dfrac{N_{W+J/\psi}}{\cancel{\mathcal{T}} \times \cancel{\mathcal{L}} \times \cancel{\epsilon_W} \times \cancel{\mathcal{A}_W} \times \epsilon_{J/\psi} \times \mathcal{A}_{J/\psi}}}{\dfrac{N_W}{\cancel{\mathcal{T}} \times \cancel{\mathcal{L}} \times \cancel{\epsilon_W} \times \cancel{\mathcal{A}_W}}} \equiv \frac{1}{N_W}\left[\frac{N_{W+J/\psi}}{\epsilon_{J/\psi} \times \mathcal{A}_{J/\psi}}\right]$$

Need

N_W: Background subtracted yield for inclusive W

$N_{W+J/\psi}$: Background subtracted yield of prompt $W+J/\psi$

$\varepsilon_{J/\psi}$, $A_{J/\psi}$: Efficiency and acceptance for J/ψ

Inclusive W sample

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

<u>Backgrounds:</u>

$W \rightarrow e\nu$

$W \rightarrow \tau\nu$

$Z \rightarrow ee, \mu\mu, \tau\tau$ → N_W

Single t

Diboson

ttbar

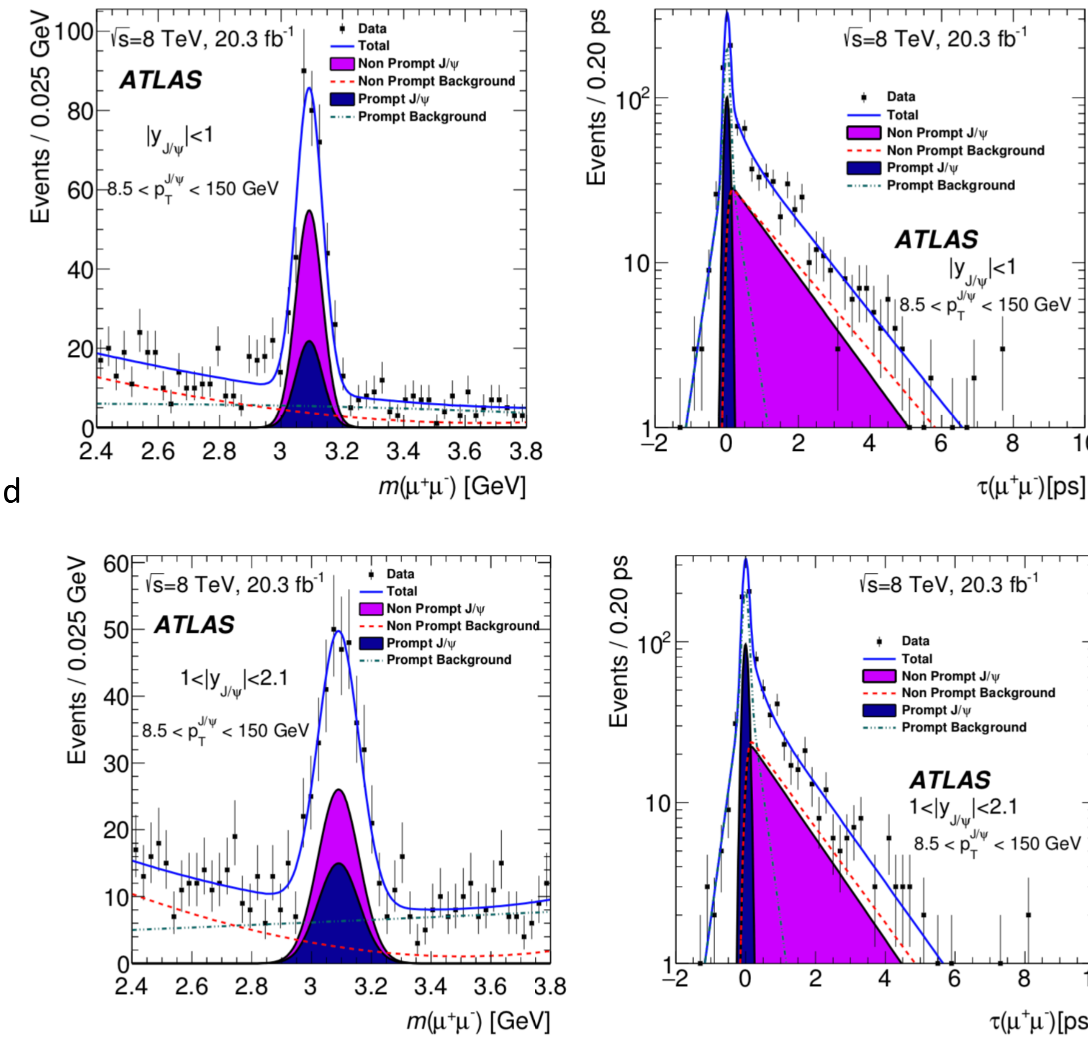
Multijet (QCD)

W + J/ψ sample

Associated J/ψ + W sample

J/ψ selection
$2.4 < m(\mu^+\mu^-) < 3.8$ GeV
$8.5 < p_T^{J/\psi} < 150$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$
$p_T^{\mu_1} > 4$ GeV, $\lvert\eta^{\mu_1}\rvert < 2.5$
$\left\{ \begin{array}{ll} \text{either } p_T^{\mu_2} > 2.5 \text{ GeV}, & 1.3 \leq \lvert\eta^{\mu_2}\rvert < 2.5 \\ \text{or } p_T^{\mu_2} > 3.5 \text{ GeV}, & \lvert\eta^{\mu_2}\rvert < 1.3 \end{array} \right\}$

Combined mass-lifetime fit to extract prompt J/ψ yield



Backgrounds:
$B_c \to J/\psi\, l\nu X$
Multijet (QCD)
J/ψ+Z
J/ψ+W (W→ τν)

Pileup:
J/ψ and W produced
in two different collisions

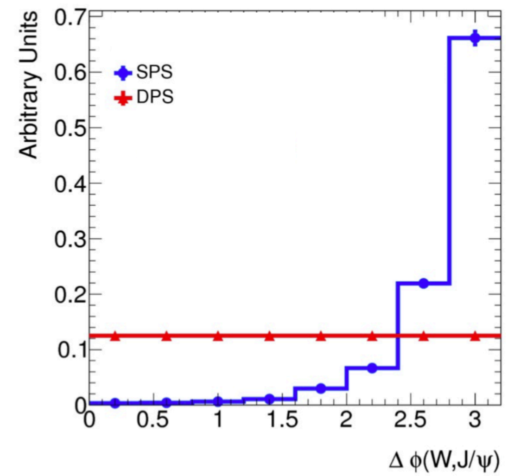
$N_{W+J/\psi}$

$\varepsilon_{J/\psi}$ and $A_{J/\psi}$ determined using p_T and rapidity dependent corrections

Double Parton Scattering

Probability that a J/ψ is produced by a second hard process

$$P^{ij}_{J/\psi|W^{\pm}} = \frac{\sigma^{ij}_{J/\psi}}{\sigma_{\text{eff}}}$$

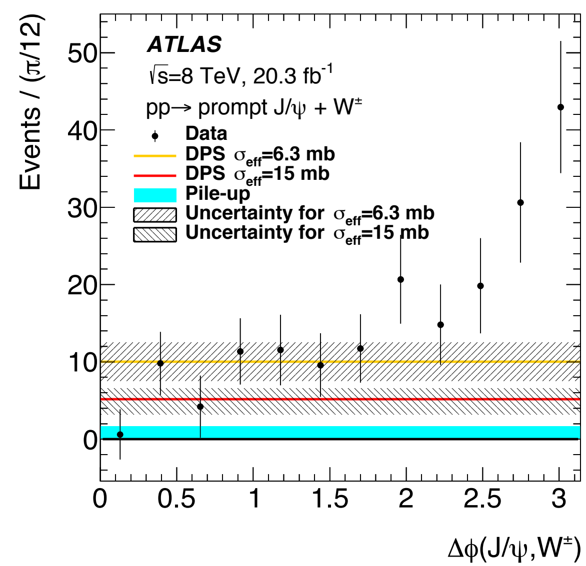


Exact shape of SPS unknown

Effective cross section σ_{eff} is unknown so choose two different values from previous ATLAS measurements

$$\sigma_{\text{eff}} = 15 \pm 3(\text{stat.})^{+5}_{-3}(\text{sys.}) \text{ mb from } W^{\pm} + 2\text{-jet events}$$

$$\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{sys.}) \text{ mb from prompt } J/\psi \text{ pair production}$$



Both values of σ_{eff} consistent with data at low $\Delta\phi$

Systematics:

Source of Uncertainty	Uncertainty [%]	
	$\lvert y_{J/\psi}\rvert < 1$	$1 < \lvert y_{J/\psi}\rvert < 2.1$
J/ψ mass fit	8.7	4.9
Vertex separation	12	15
$\mu_{J/\psi}$ efficiency	2.0	1.6
Pile-up	1.1	1.4
$J/\psi + Z$ and $J/\psi + W^{\pm}(\rightarrow \tau^{\pm}\nu)$	3.5	4.8
Efficiency correction	2.3	2.3
J/ψ spin alignment	34	28

Fiducial measurement: Independent of unknown spin-alignment of J/ψ

$$R^{\text{fid}}_{J/\psi} = \frac{\sigma_{\text{fid}}(pp \rightarrow J/\psi + W^{\pm})}{\sigma(pp \rightarrow W^{\pm})} \cdot \mathcal{B}(J/\psi \rightarrow \mu\mu) = \frac{1}{N(W^{\pm})} \sum_{p_{\text{T}}\text{ bins}} [N^{\text{eff}}(J/\psi + W^{\pm}) - N^{\text{fid}}_{\text{pile-up}}],$$

$$R^{\text{fid}}_{J/\psi} = (2.2 \pm 0.3 \pm 0.7) \times 10^{-6}$$

Inclusive measurement: Takes into account unknown J/ψ spin-alignment and J/ψ acceptance

$$R^{\text{incl}}_{J/\psi} = \frac{\sigma_{\text{incl}}(pp \rightarrow J/\psi + W^{\pm})}{\sigma(pp \rightarrow W^{\pm})} \cdot \mathcal{B}(J/\psi \rightarrow \mu\mu) = \frac{1}{N(W^{\pm})} \sum_{p_{\text{T}}\text{ bins}} [N^{\text{eff+acc}}(J/\psi + W^{\pm}) - N_{\text{pile-up}}],$$

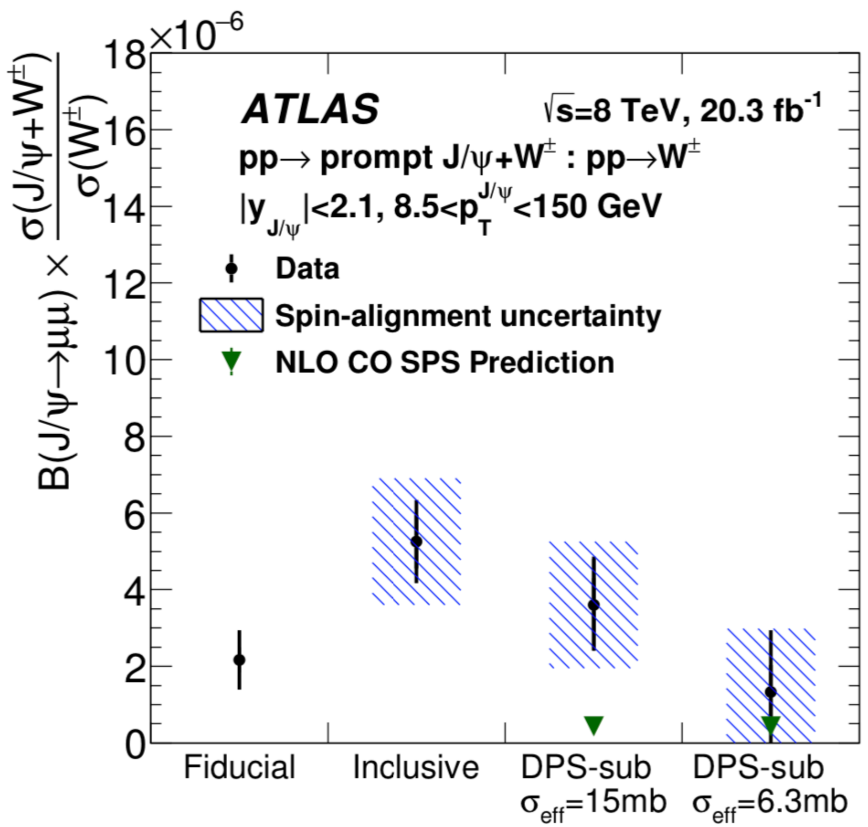
$$R^{\text{incl}}_{J/\psi} = (5.3 \pm 0.7 \pm 0.8 \pm 1.7) \times 10^{-6}$$

1st uncertainty: statistical
2nd uncertainty: systematic
3rd uncertainty: spin alignment

Subtract estimated DPS contribution to allow measurement to be compared to theory

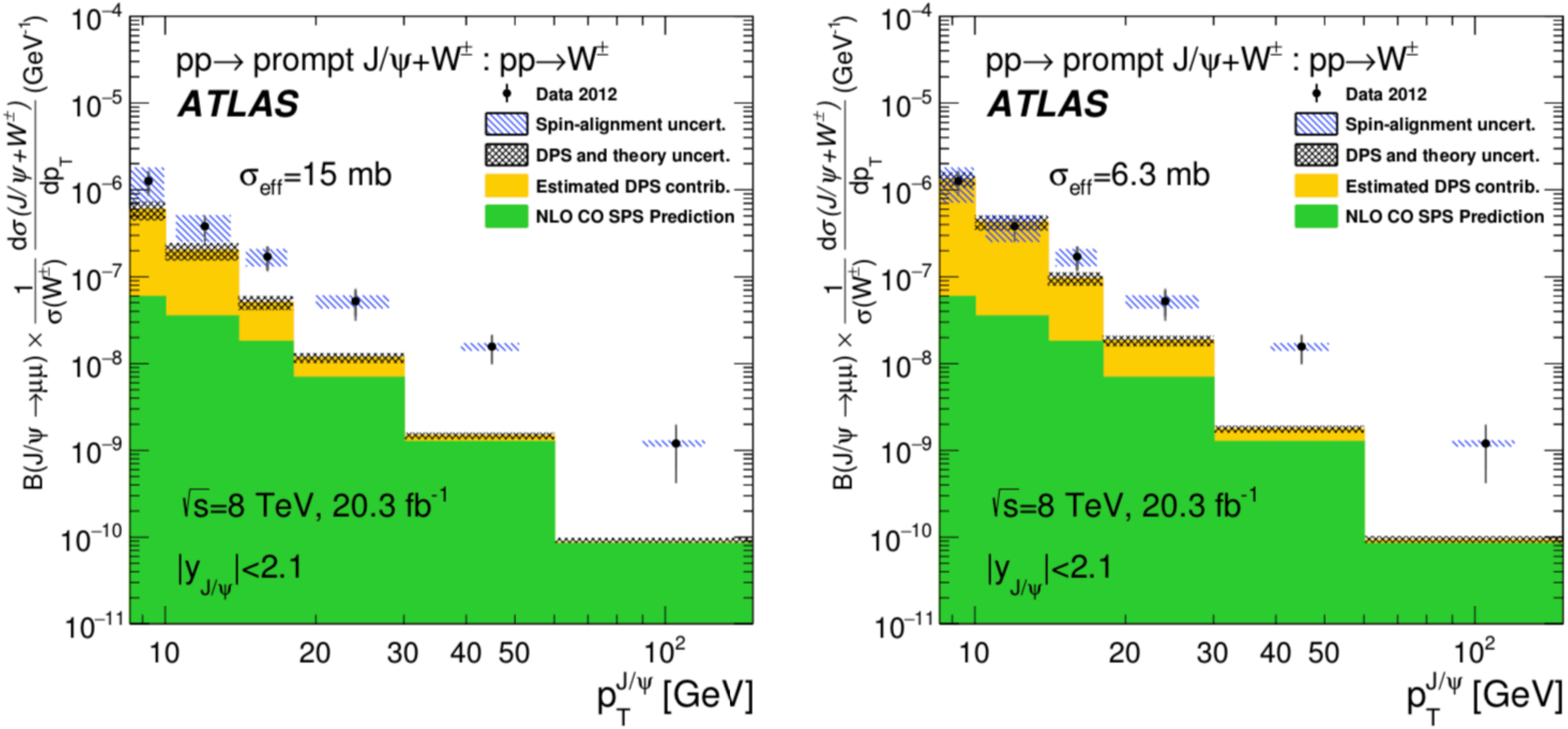
$$R_{J/\psi}^{\mathrm{DPSsub}} = (3.6 \pm 0.7^{+1.1}_{-1.0} \pm 1.7) \times 10^{-6}, \quad [\sigma_{\mathrm{eff}} = 15^{+5.8}_{-4.2}\ \mathrm{mb}]$$

$$R_{J/\psi}^{\mathrm{DPSsub}} = (1.3 \pm 0.7 \pm 1.5 \pm 1.7) \times 10^{-6}, \quad [\sigma_{\mathrm{eff}} = 6.3 \pm 1.9\ \mathrm{mb}]$$



NLO:Phys. Rev. D **53**(1996) 150, 6203

Differential Measurement



Neither value of σ_{eff} can correctly model J/ψ p_T dependence

Conclusions

Two selected measurements in ATLAS heavy flavor production shown

Quarkonia allowing probes of QCD at the perturbative/non-perturbative boundary

For 13 TeV measurement

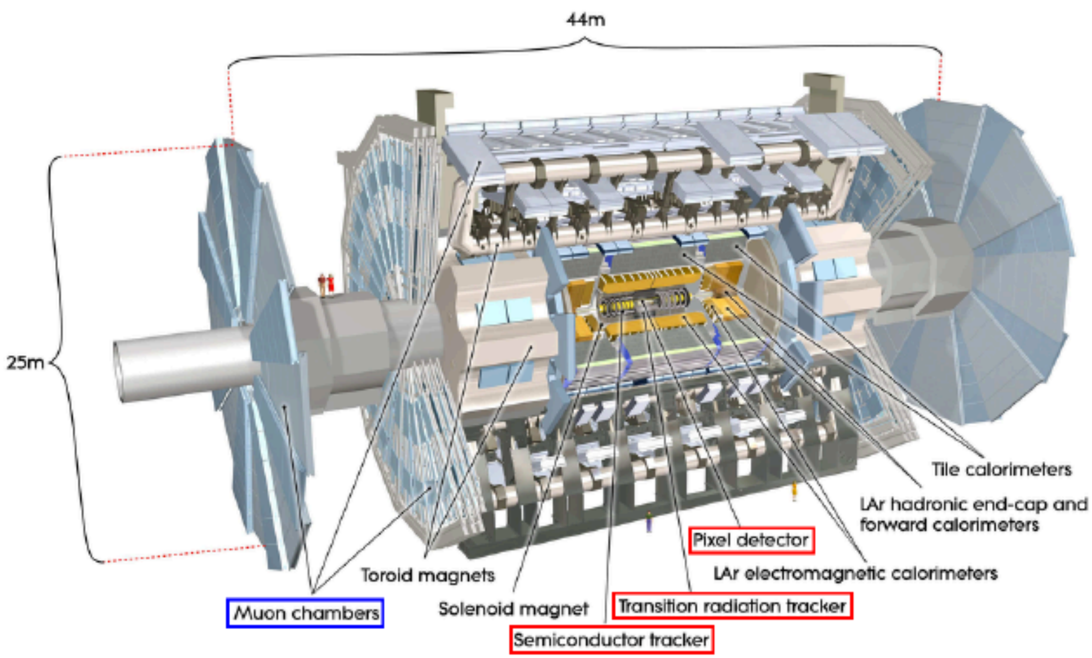
> Good agreement with previous measurement from CMS
> p_T reach greatly extended to ~360 GeV
> Non-prompt production of J/ψ consistent with FONLL at low p_T
> FONLL overestimates non-prompt J/ψ cross section at high p_T
> Plan to extend p_T range down to ~ 8 GeV

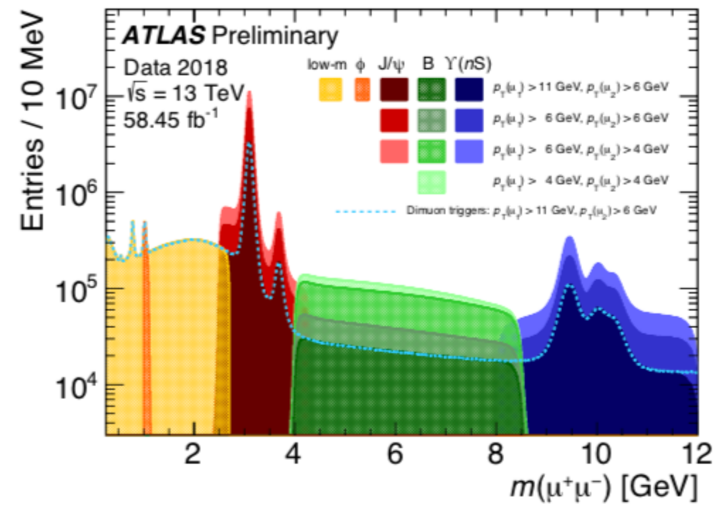
Prompt J/ψ + W

> Measurement of $\Delta\phi$ distribution indicates that both SPS and DPS contributions are present in data
> Smaller value of σ_{eff} is preferred
> Neither value of σ_{eff} can describe J/ψ p_T dependence

Additional Material

ATLAS detector and triggers





Fit Model

$$\mathrm{PDF}(m,\tau) = \sum_{i=1}^{7} \kappa_i f_i(m) \cdot (h_i(\tau) \otimes R(\tau)) \cdot C_i(m,\tau).$$

i	Type	P/NP	$f_i(m)$	$h_i(\tau)$	$C_i(m,\tau)$
1	J/ψ	P	$\omega G_1(m) + (1-\omega)CB_1(m)$	$\delta(\tau)$	$BV(m,\tau,\rho)$
2	J/ψ	NP	$\omega G_1(m) + (1-\omega)CB_1(m)$	$E_1(\tau)$	1
3	ψ(2S)	P	$\omega G_2(m) + (1-\omega)CB_2(m)$	$\delta(\tau)$	1
4	ψ(2S)	NP	$\omega G_2(m) + (1-\omega)CB_2(m)$	$E_2(\tau)$	1
5	Bkg	P	B	$\delta(\tau)$	1
6	Bkg	NP	$E_4(m)$	$E_5(\tau)$	1
7	Bkg	NP	$E_6(m)$	$E_7(\|\tau\|)$	1

Notation	Function
G	Gaussian
CB	Crystal Ball
E	Exponential
B	Bernstein polynomials
BV	Correlation term of the bivariate Gaussian dist.

R(τ): Resolution Function

$$BV \sim \exp\left[\frac{1}{2(1-\rho^2)}\left(\frac{(m-\mu_m)^2}{\sigma_m^2} - \frac{2\rho(m-\mu_m)(\tau-\mu_\tau)}{\sigma_m\sigma_\tau} + \frac{(\tau-\mu_\tau)^2}{\sigma_\tau^2}\right)\right]$$

J/ψ and ψ(2S) production cross sections at high p_T at 13 TeV

Each event weighted by product of reconstructed efficiency:

$$w_{reco} = \frac{1}{\epsilon_{reco}(\mu^+)\epsilon_{reco}(\mu^-)}$$

Trigger:

$$w_{trig} = \frac{1}{1-(1-\epsilon_{trig}(\mu^+))(1-\epsilon_{trig}(\mu^-))}$$

And decay length

$$w_{dec} = \frac{1}{\epsilon_{dec}}$$

Reconstruction efficiencies for W+J/ψ and inclusive W samples do not exactly cancel so correction applied

Acceptance depends on the unknown polarization of the J/ψ

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

1. Isotropic (nominal): $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$
2. Longitudinal: $\lambda_\theta = -1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$
3. Transverse-0: $\lambda_\theta = +1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$
4. Transverse-M: $\lambda_\theta = +1$, $\lambda_\phi = -1$, $\lambda_{\theta\phi} = 0$
5. Transverse-P: $\lambda_\theta = \lambda_\phi = +1$, $\lambda_{\theta\phi} = 0$

Largest systematic uncertainty in measurement