Results on quarkonia and its associated production with ATLAS

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On behalf of the ATLAS Collaboration

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Quarkonium production in proton-proton, proton-lead and lead-lead collisions at 5.02 TeV

Measurement of quarkonium production in proton-lead and proton-proton collisions at 5.02 TeV with the ATLAS detector

Eur. Phys. J. C78 (2018) 171 arXiv:1709.03089

Prompt and non-prompt J/ψ and ψ(2S) suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment

submitted to Eur. Phys. J. C arXiv:1805.04077

Associated production with onia in pp collisions

Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

JHEP 04 (2014) 172 arXiv:1401.2831

Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV

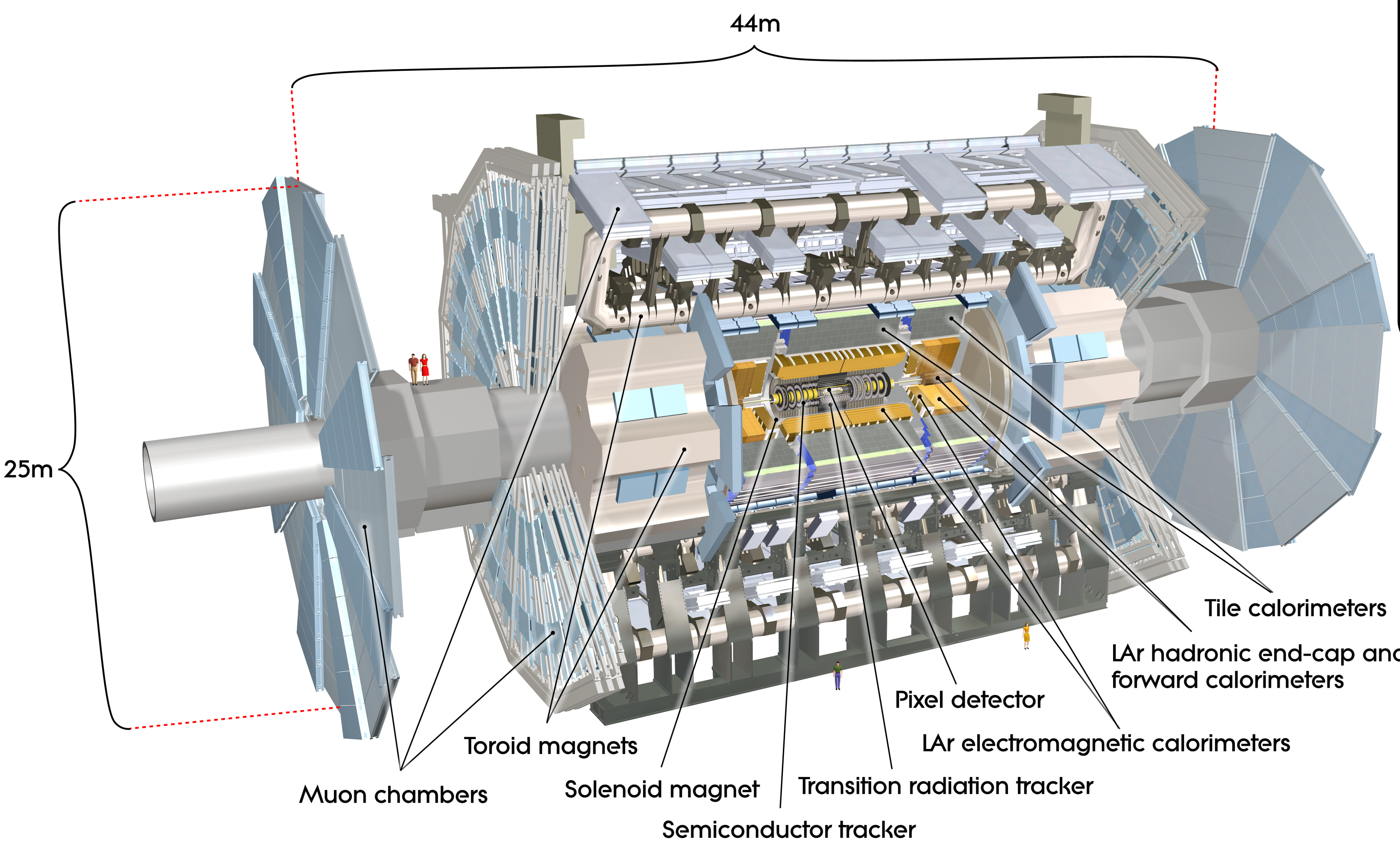
Eur. Phys. J. C75 (2015) 229 arXiv:1412.6428

Double onia production in pp collisions

Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

Eur. Phys. J. C77 (2017) 76 arXiv:1612.02950

The ATLAS Detector



Muon Spectrometer:
$|\eta| < 2.7$
air core toroids(average 0.5T)
gas-based muon chambers
Muon trigger and reconstruction
Momentum resolution < 10%
$up\ to\ E(\mu) \sim 1\ TeV$

3-level trigger, reducing the rate from 40 MHz to ~200 Hz

EM Calorimeter:
Pb-LAr accordion
e/γ trigger, identification and measurement
Resolution:
$\sigma/E \sim 10\%/\sqrt{E}$

Inner Detector:
Si Pixels, Si Strips, TRT straws
Precise tracking and vertexing
pT resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4}\ p_T(GeV) \oplus 0.015$
$|\eta| < 2.5,\ B = 2T$

HAD Calorimetry:
$|\eta| < 5$
Fe/scintillator tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and MET
Resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Quarkonium production in proton-proton, proton-lead and lead-lead collisions at 5.02 TeV

Heavy quarkonium bound states ($c\bar{c}$ and $b\bar{b}$) are a useful tool for studying the deconfined quark-gluon plasma (QGP) created in nucleus-nucleus (A+A) collisions and for disentangling the effects from cold nuclear matter (CNM) interactions, predominant in p+A collisions

Modification of quarkonium production w.r.t that in pp collisions quantified by the Nuclear modification factor

$$R_{p\mathrm{Pb}} = \frac{1}{208}\frac{\sigma^{O(nS)}_{p+\mathrm{Pb}}}{\sigma^{O(nS)}_{pp}}$$

$$R_{AA} = \frac{N_{AA}}{< T_{AA} > \times \sigma_{pp}}$$

$O(nS) = J/\psi,\ \psi(2S),\ \mathrm{and}\ \Upsilon(nS)\ (n = 1, 2, 3)$

$< T_{AA} >$: mean nuclear thickness function

$$\frac{\mathrm{d}^2\sigma^{O(nS)}}{\mathrm{d}p_T\mathrm{d}y^*} \times B(O(nS) \to \mu^+\mu^-) = \frac{N_{O(nS)}}{\Delta p_T \times \Delta y \times L}$$

$$N_{AA} = \frac{\mathrm{d}^2 N}{\mathrm{d}p_T\mathrm{d}y} \times B(\psi(nS) \to \mu^+\mu^-) = \frac{1}{\Delta p_T \times \Delta y}\frac{N_{\psi(nS)}}{N_{\mathrm{mb}}}$$

$N_{O(nS)}$: observed quarkonium yield in a kinematic interval, extracted from fits and corrected for acceptance, trigger and reconstruction efficiencies

per-event yield, N_{AA} : number of quarkonia produced per bin of transverse momentum, rapidity and centrality interval

(normalised to minimum-bias events)

CNM effects in excited quarkonium states w.r.t the ground state quantified by the double ratio

$$\rho^{O(nS)/O(1S)}_{p\mathrm{Pb}} = \frac{R_{p\mathrm{Pb}}(O(nS))}{R_{p\mathrm{Pb}}(O(1S))}$$

$$\rho^{\psi(2S)/J/\psi}_{\mathrm{PbPb}} = \frac{(N_{\psi(2S)}/N_{J/\psi})_{\mathrm{PbPb}}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}}$$

most sources of detector systematic uncertainty cancel out in the ratio

easier to compare to other experiments

initial-state effects expected to largely cancel out since partons are affected similarly before the formation of the quarkonium state => study final-state effects

Quarkonium production in proton-proton, proton-lead and lead-lead collisions at 5.02 TeV

$\mathcal{L} = 25\,\mathrm{pb}^{-1}\ (pp)$

$\mathcal{L} = 28\,\mathrm{nb}^{-1}\ (p+\mathrm{Pb})$

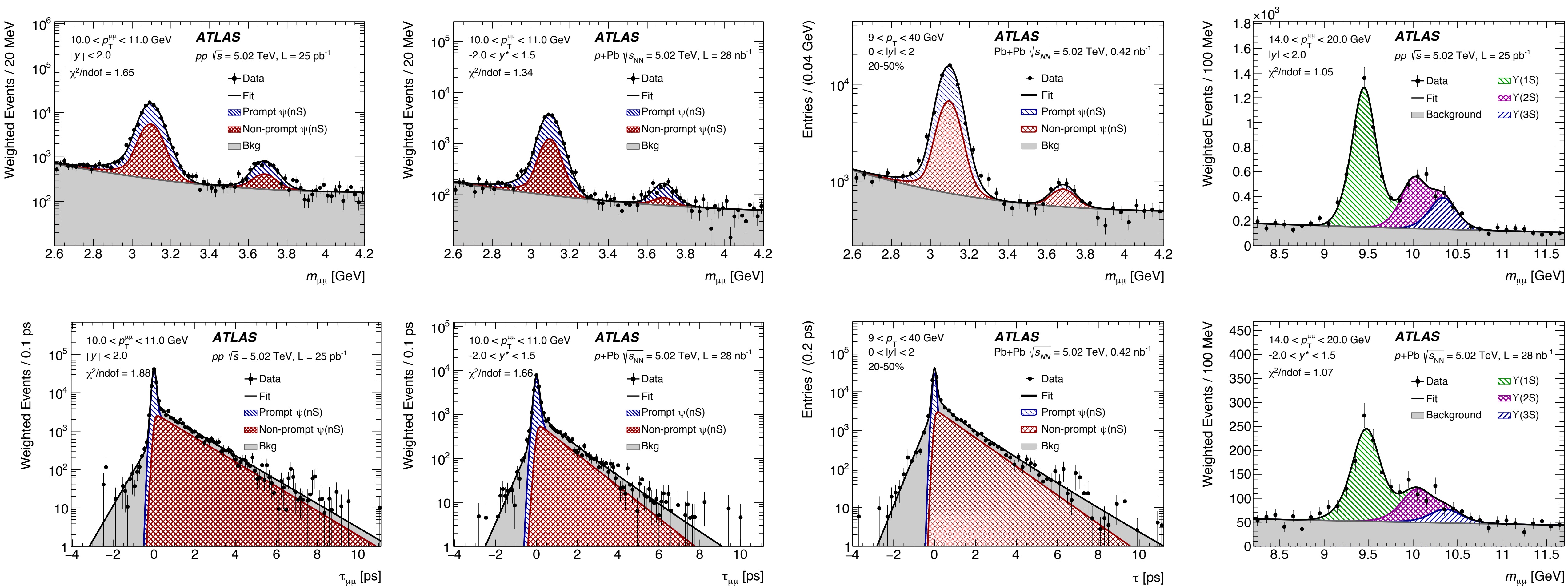
$\mathcal{L} = 0.42\,\mathrm{nb}^{-1}\ (\mathrm{Pb}+\mathrm{Pb})$

$\mathrm{O}(nS) \to \mu^+\mu^-$

$p_T^\mu > 4\,\mathrm{GeV} \quad |\eta^\mu| < 2.4$

unbinned maximum likelihood (ML) fits to the J/ψ and $\psi(2\mathrm{S})$ invariant mass and pseudo-proper time, τ to obtain yields for prompt and non-prompt J/ψ and $\psi(2\mathrm{S})$ and backgrounds

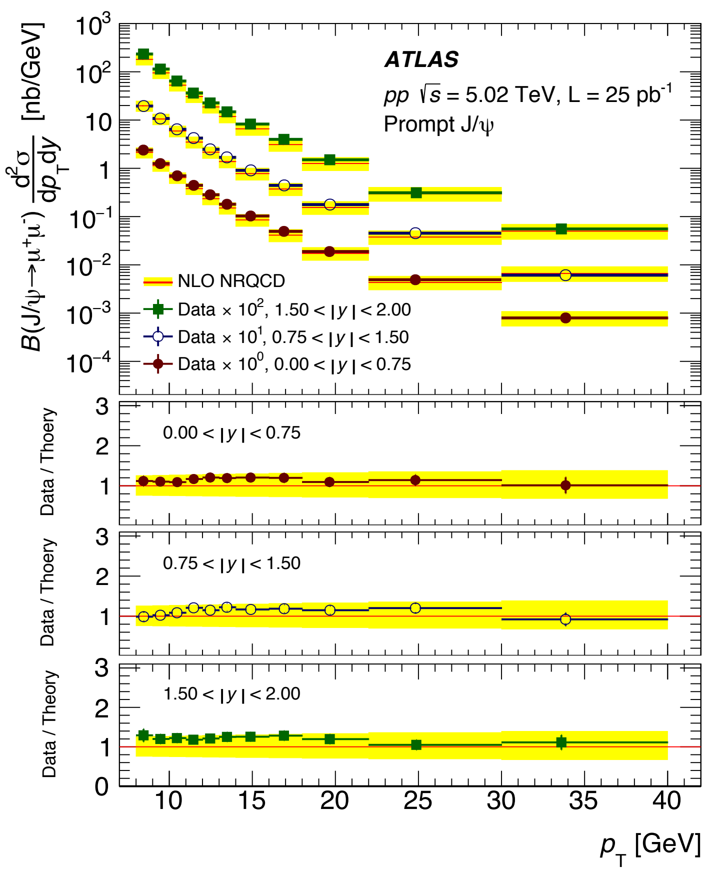
yields for the bottomonium states obtained from unbinned maximum likelihood fits to the invariant masses



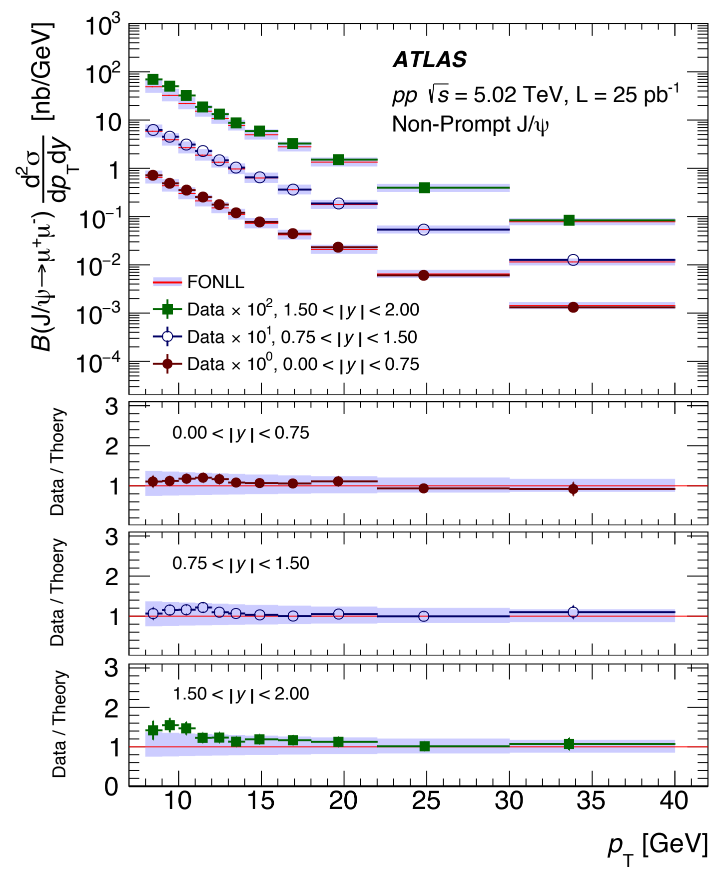
fits done in intervals of quarkonia transverse momenta, rapidity and centrality

J/ψ Production cross section results

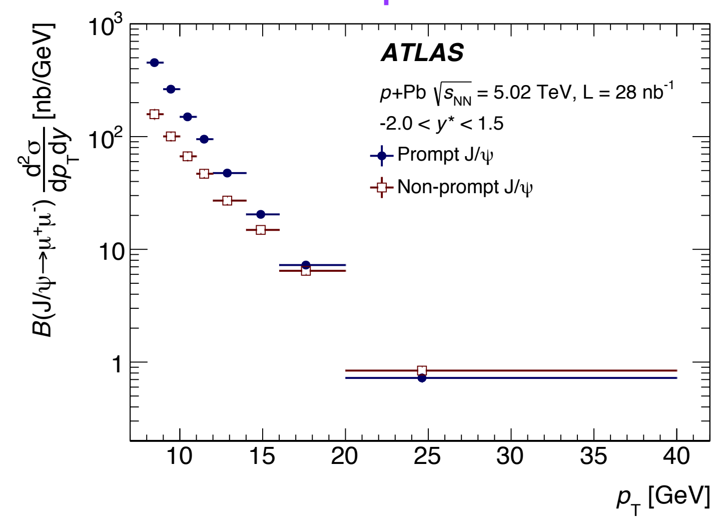
pp prompt: good agreement with NLO NRQCD over full p_T range

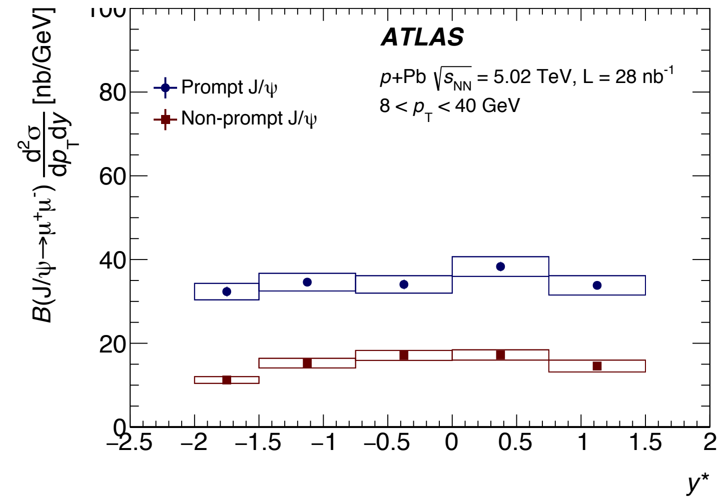


pp non-prompt: good agreement with FONLL over full p_T range

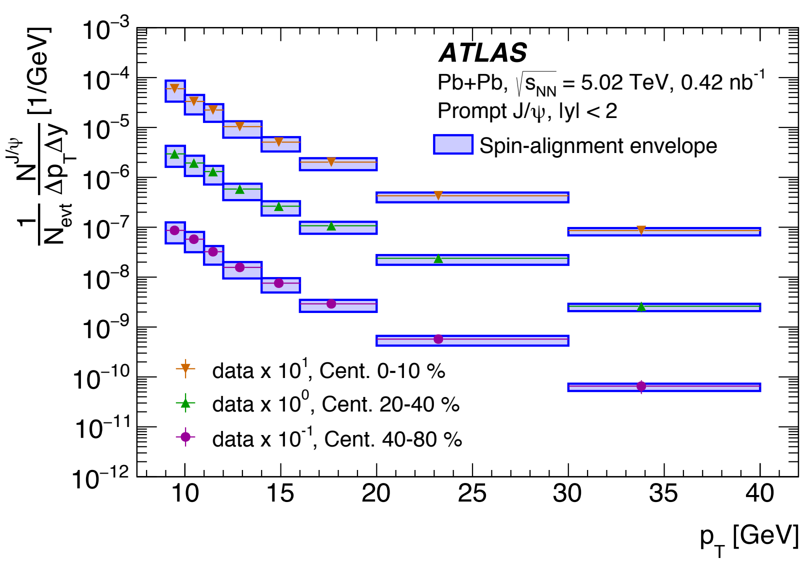


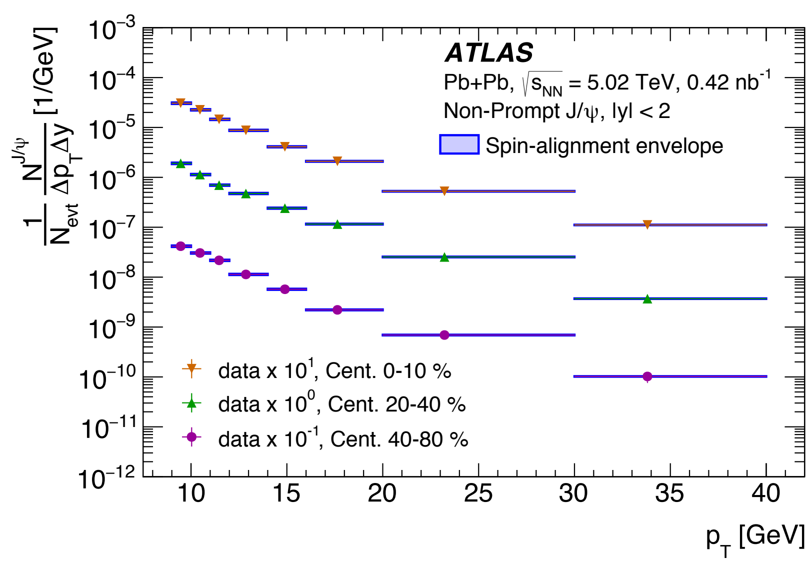
p+Pb: improved measurement, consistent with previous results



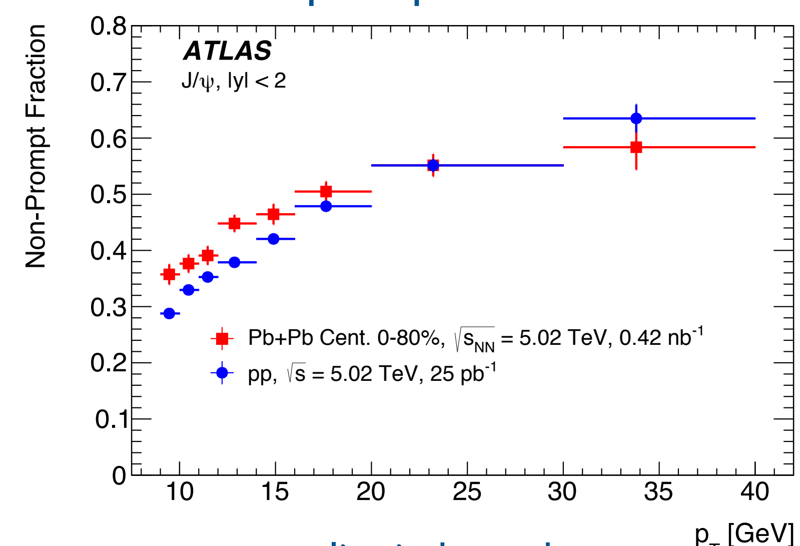


Pb+Pb per-event yields





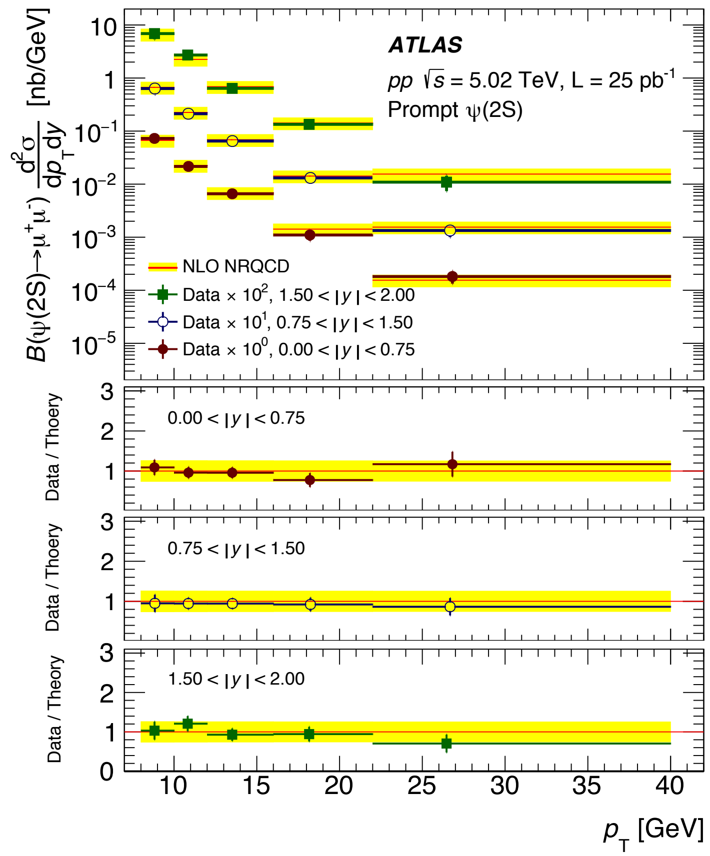
non-prompt fraction



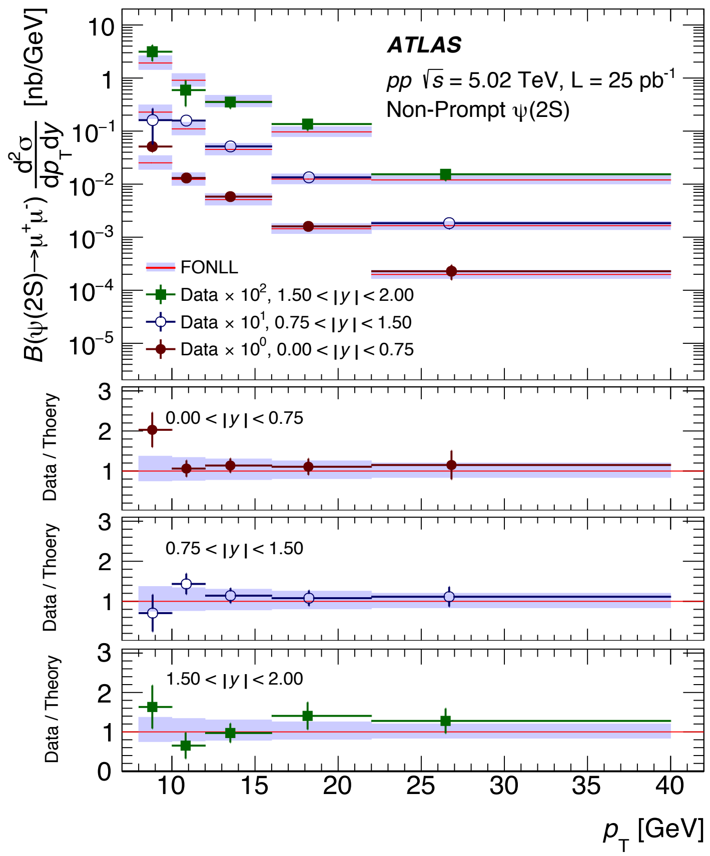
centrality-independent, slightly different slope from that found in pp collisions

$\psi(2S)$ Production cross section results

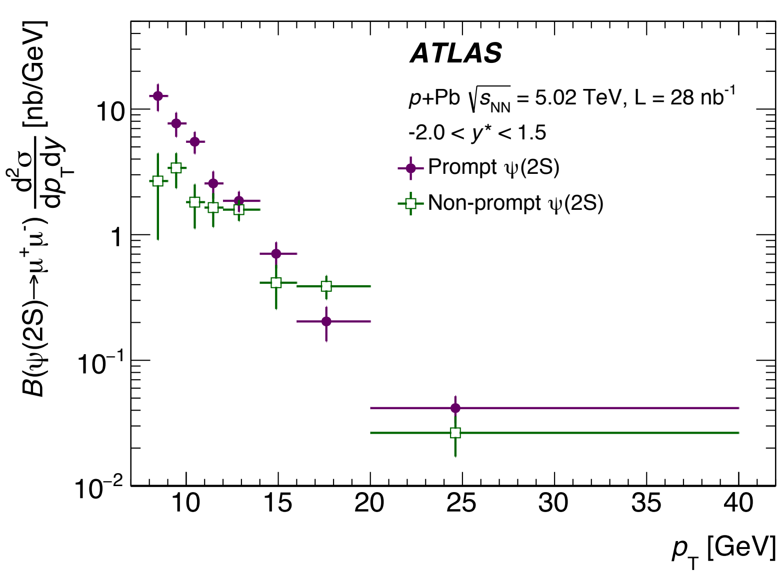
pp prompt: good agreement with NLO NRQCD over full p_T range

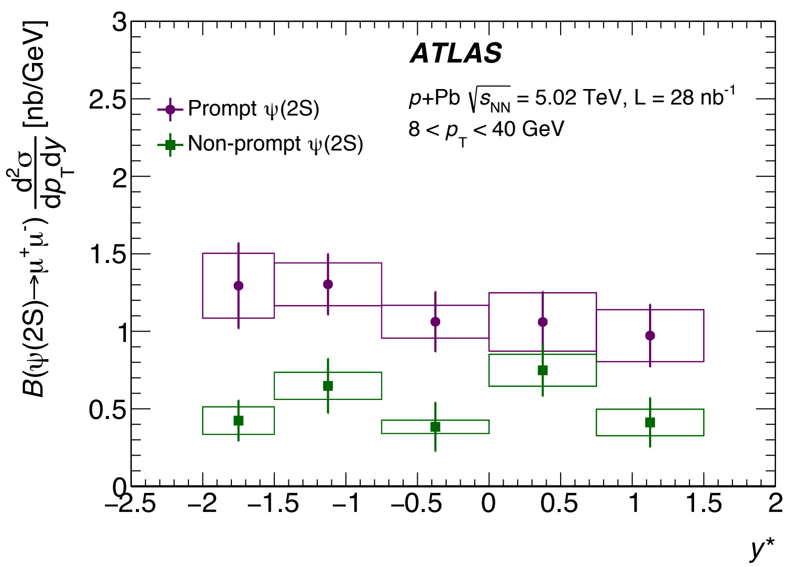


pp non-prompt: good agreement with FONLL over full p_T range



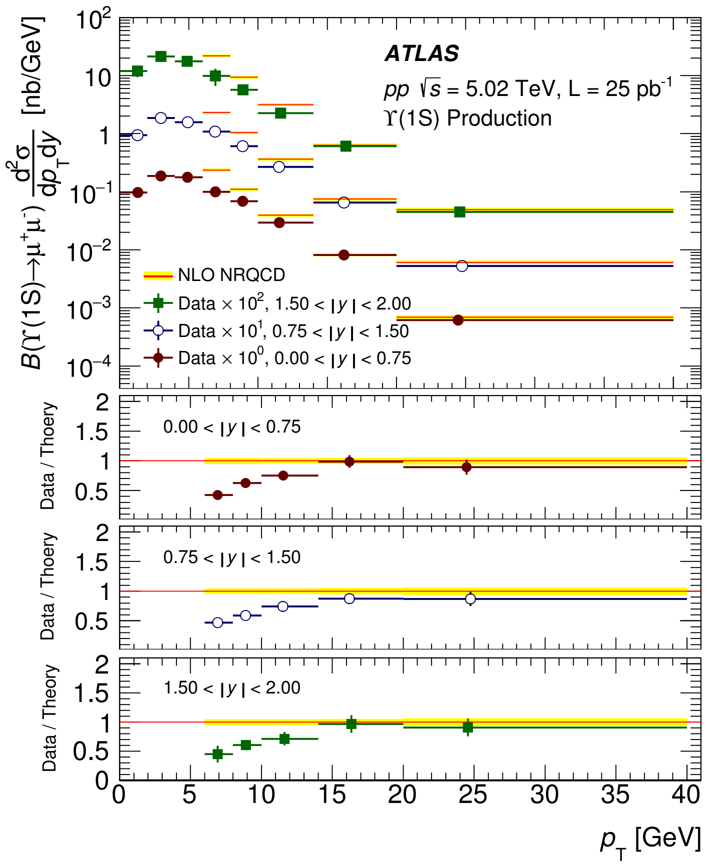
p+Pb

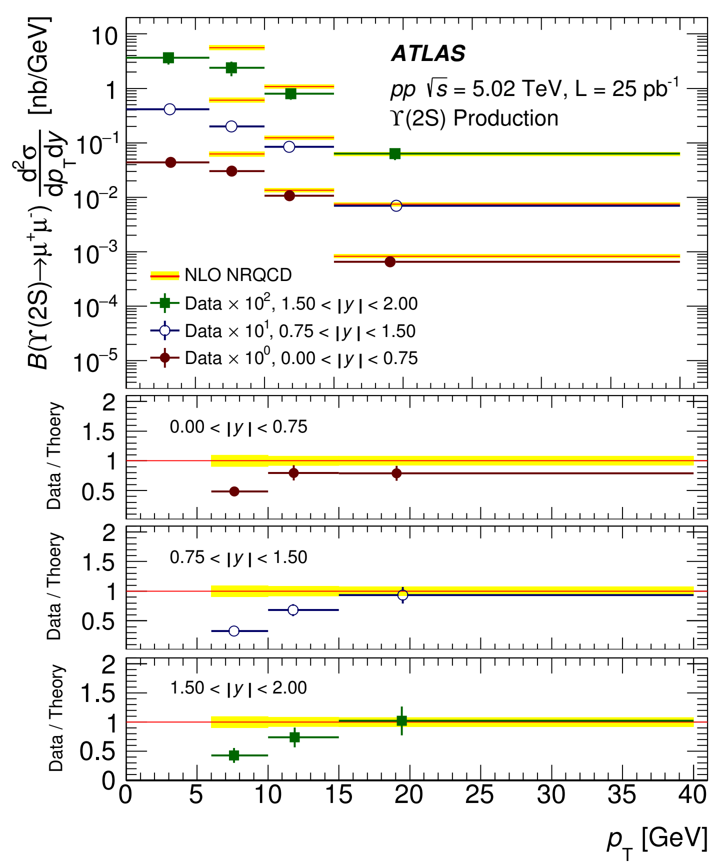


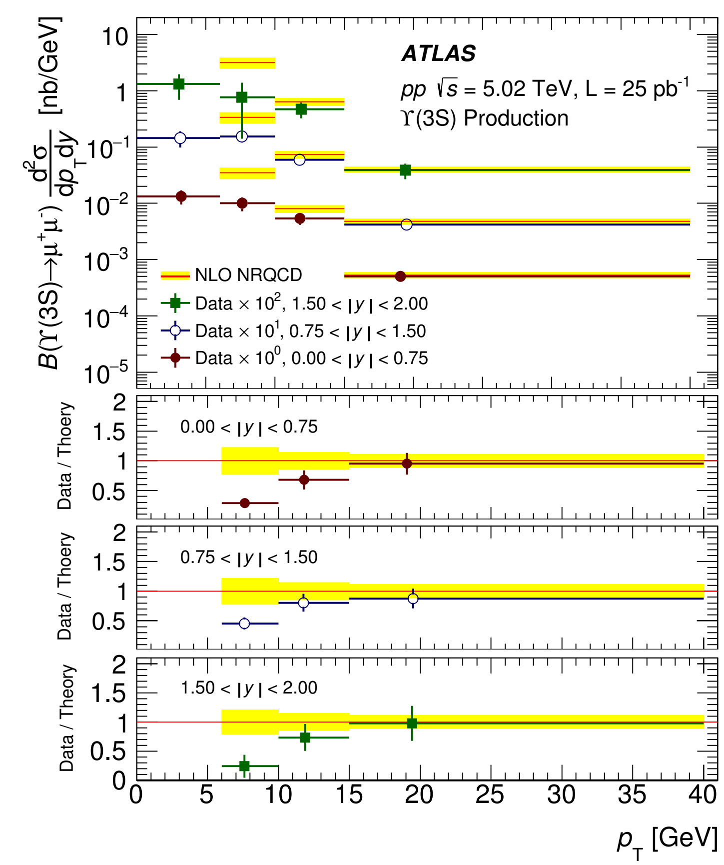


$\Upsilon(nS)$ Production cross section results

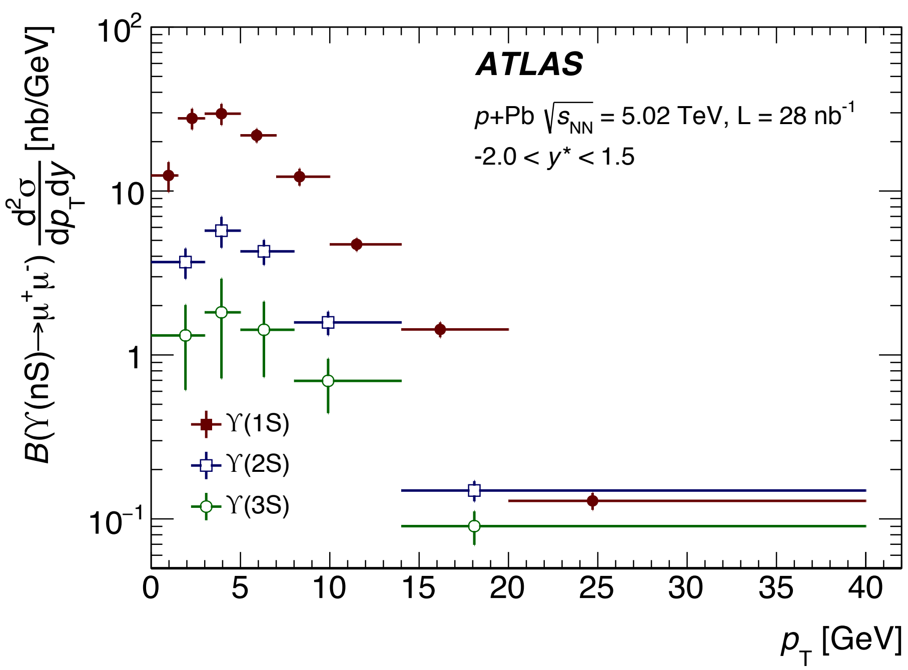
pp: NLO NRQCD gives a relatively good description for p_T > 15 GeV, but overestimates the cross section at lower p_T

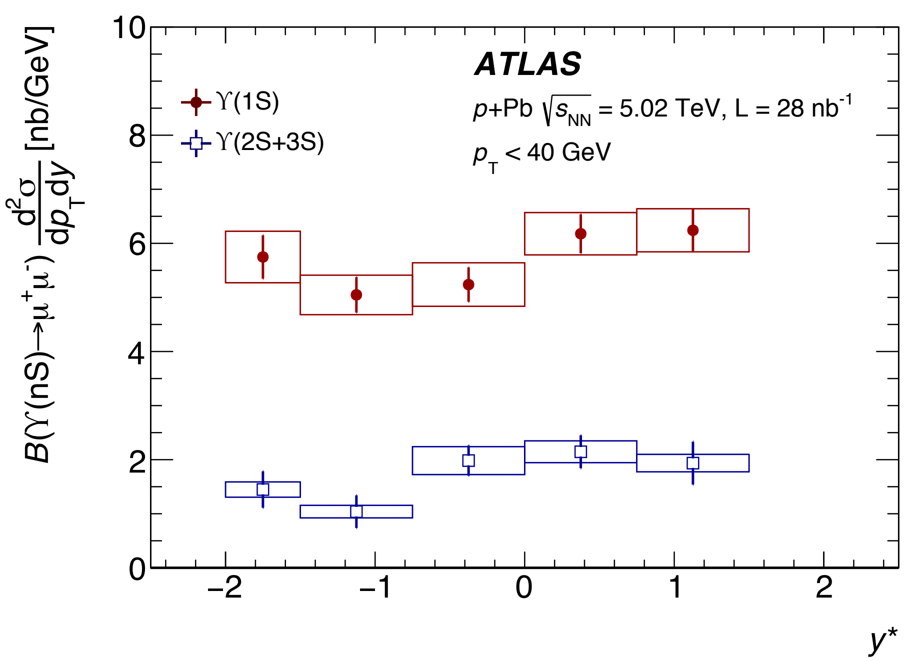




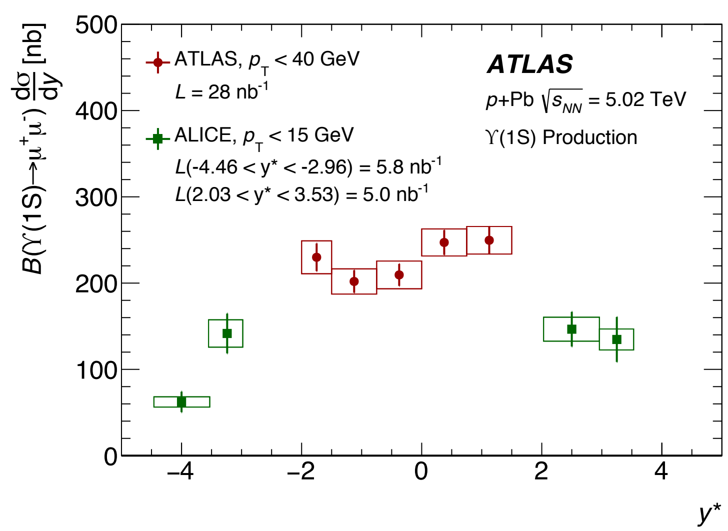


p+Pb





comparison with ALICE data

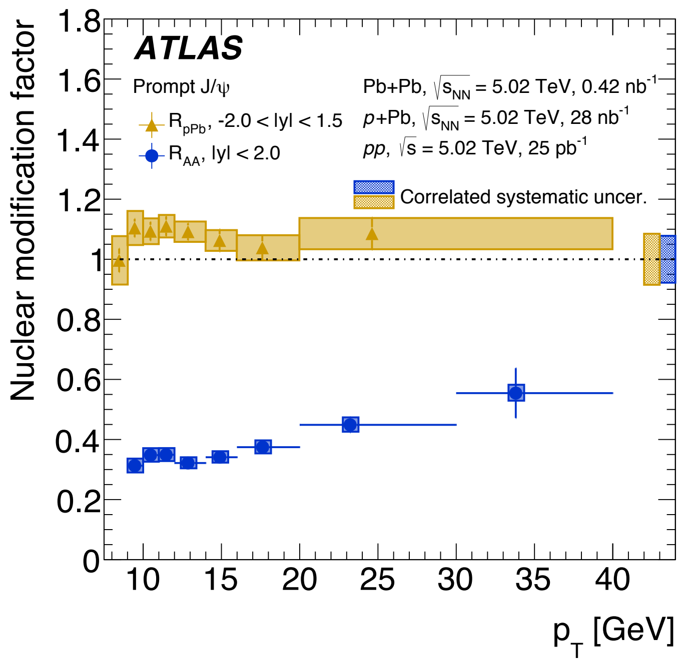


J/ψ Nuclear modification factor results

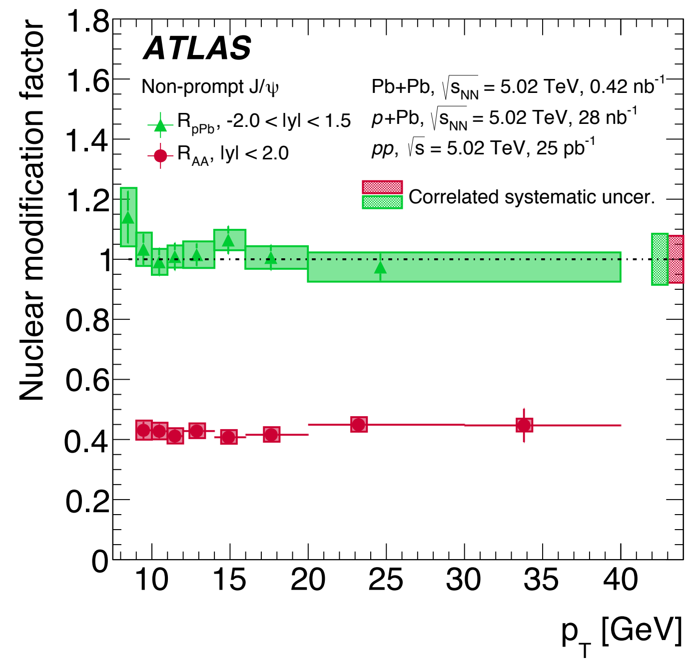
p+Pb: both prompt and non-prompt J/ψ $R_{p\mathrm{Pb}}$ consistent with unity across the entire p_T range and rapidity

Pb+Pb: production of J/ψ strongly suppressed in both prompt and non-prompt J/ψ production

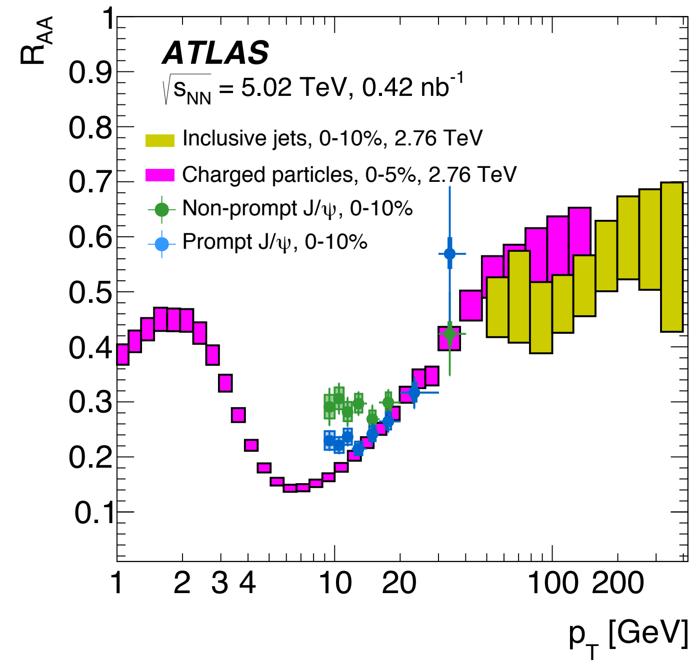
small increase in R_{AA} with increasing p_T in prompt J/ψ production



non-prompt J/ψ production approximately constant



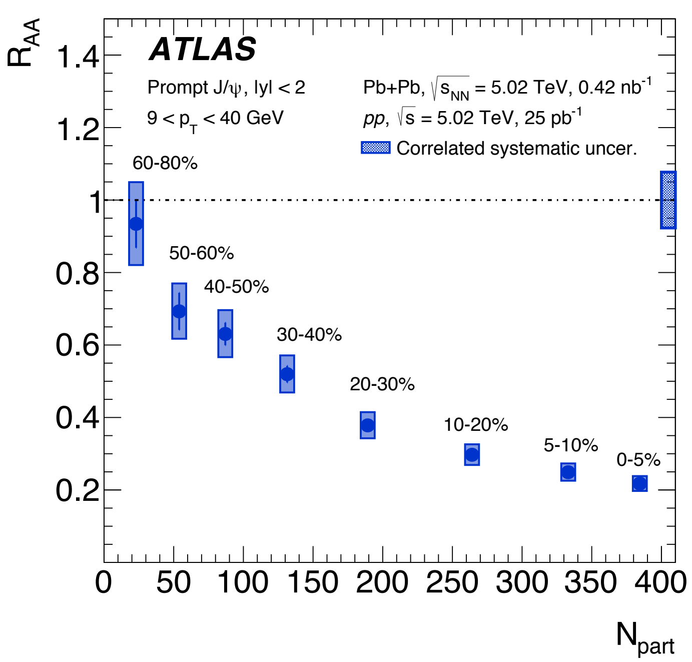
compared with R_{AA} in charged particles and D-mesons

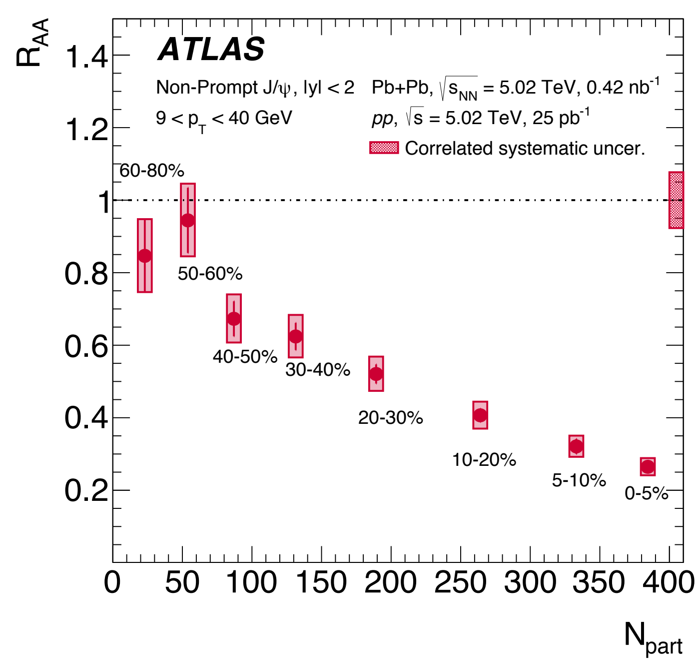


Pb+Pb: production of J/ψ has a modest dependancy on rapidity

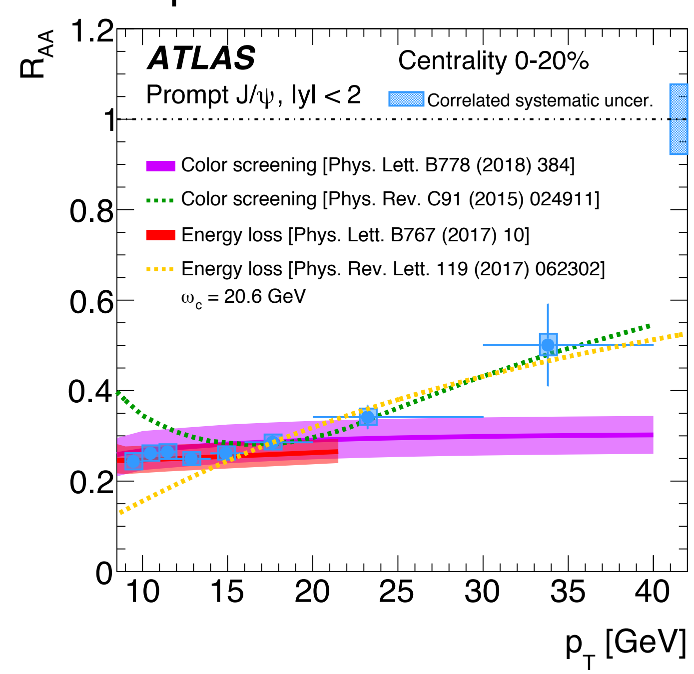
Pb+Pb: production of J/ψ as a function of centrality (number of participants)

strong suppression in central collisions





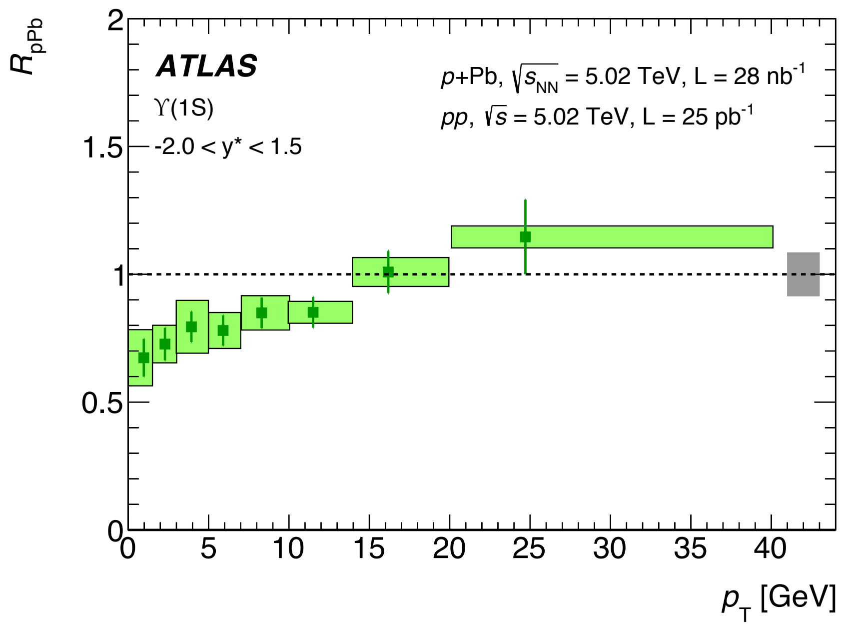
compared with theoretical models



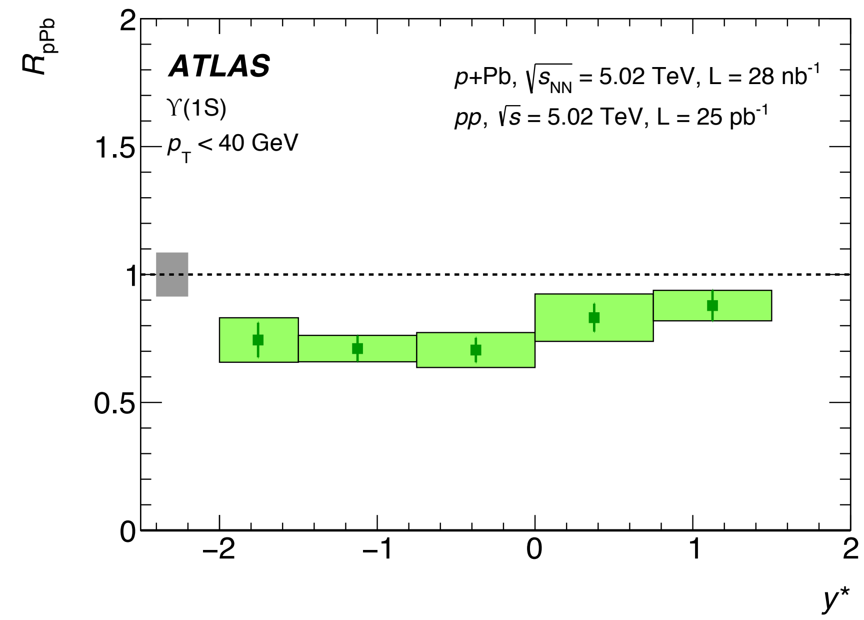
surprisingly similar pattern for prompt and non-prompt J/ψ in Pb+Pb

$\Upsilon(1S)$ Nuclear modification factor results

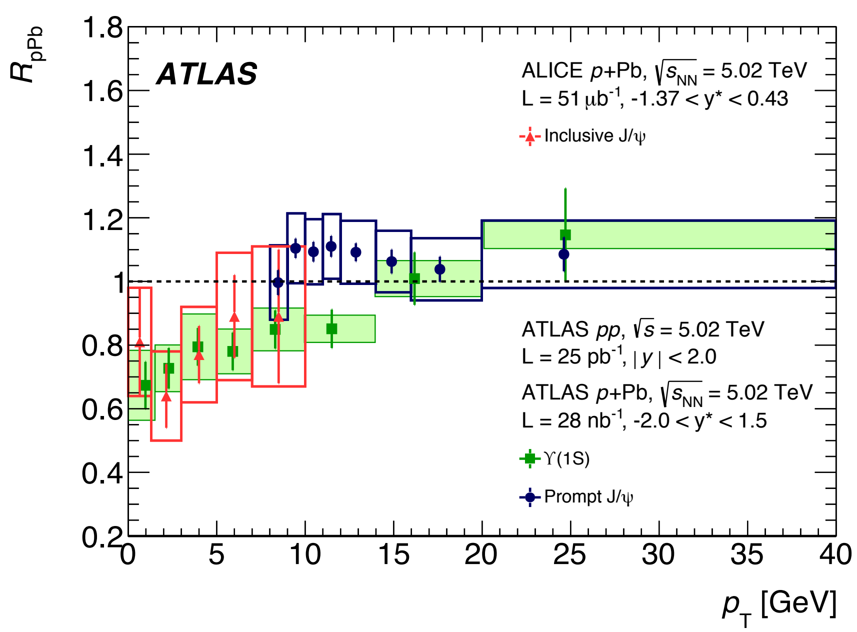
p+Pb: $\Upsilon(1S)$ production suppressed at low p_T (< 15 GeV) and increases with p_T



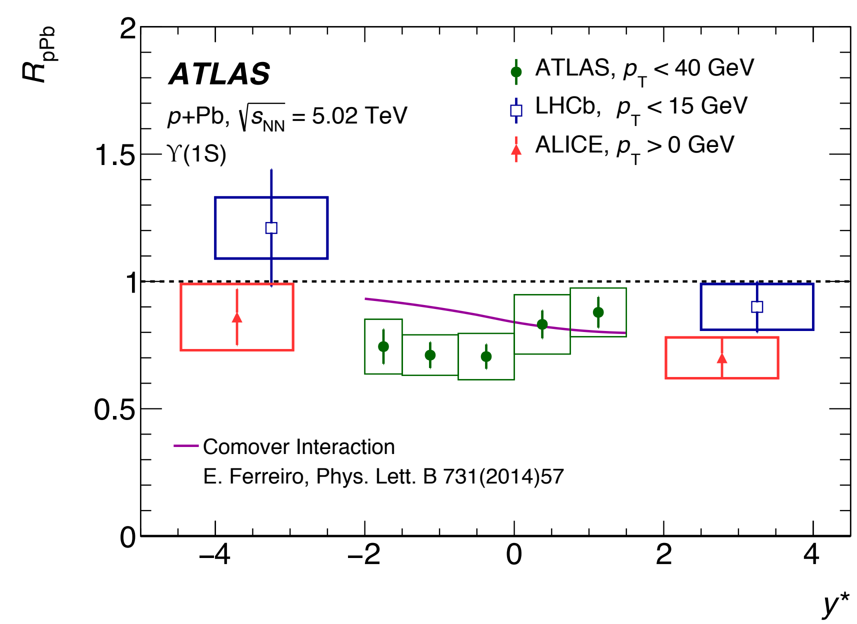
no significant rapidity dependence observed



comparison with ALICE data



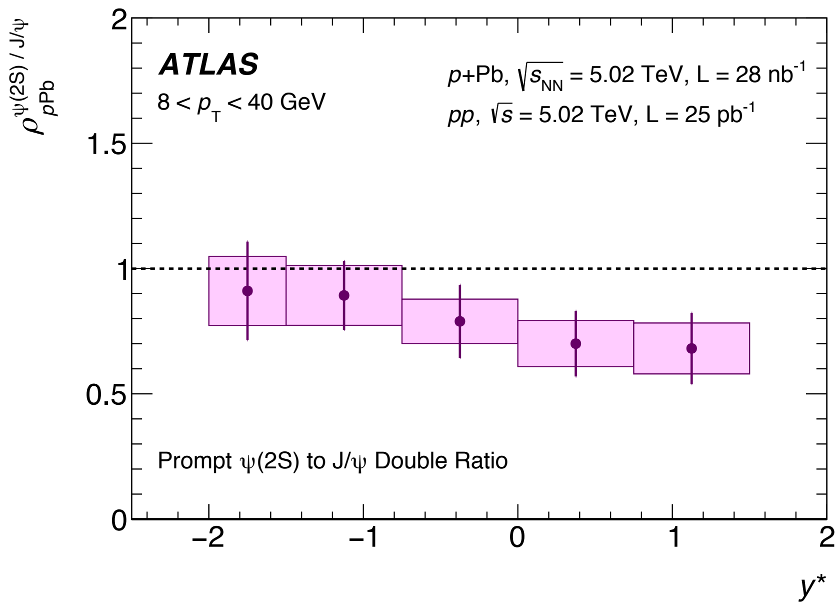
comparison with ALICE and LHCb data



Double ratio results

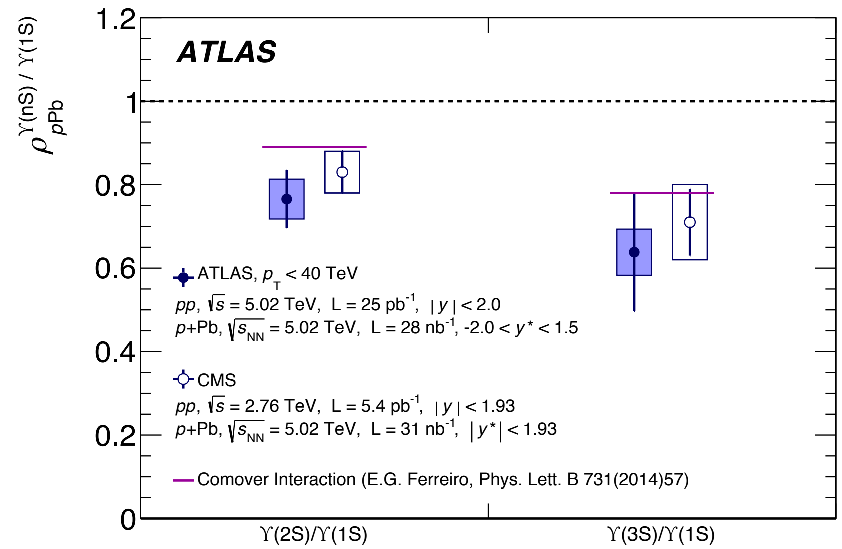
$\rho_{\mathrm{pPb}}^{\psi(2S)/J/\psi}$

decreasing trend $(1\,\sigma)$ from backward to forward centre-of-mass rapidity



$\rho_{\mathrm{pPb}}^{\Upsilon(nS)/\Upsilon(1S)}$

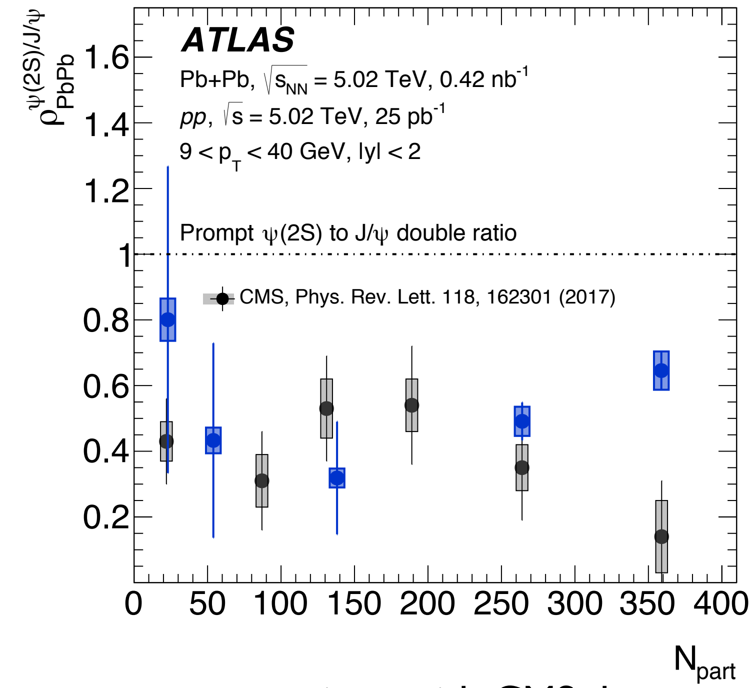
p_T and y^* integrated Υ double ratio: less than unity $(2\,\sigma)$



comparison with CMS data

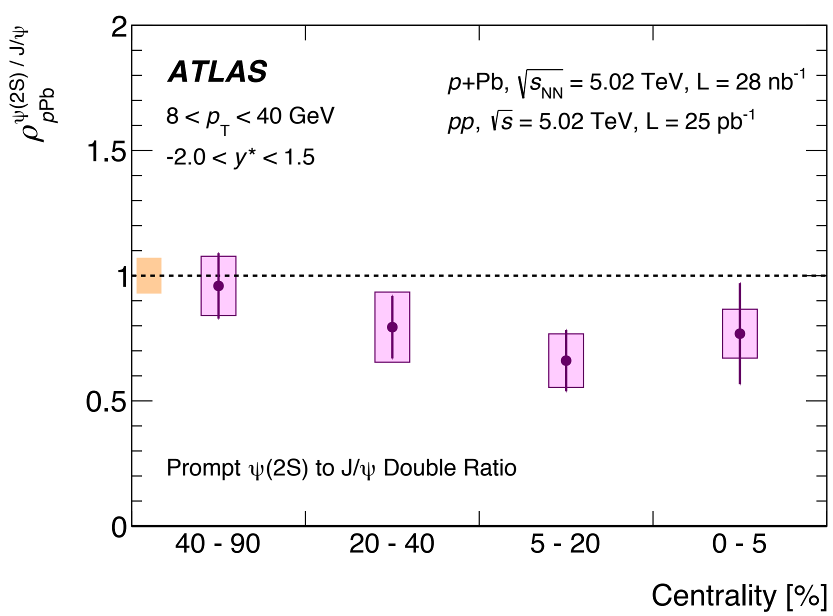
$\rho_{\mathrm{PbPb}}^{\psi(2S)/J/\psi}$

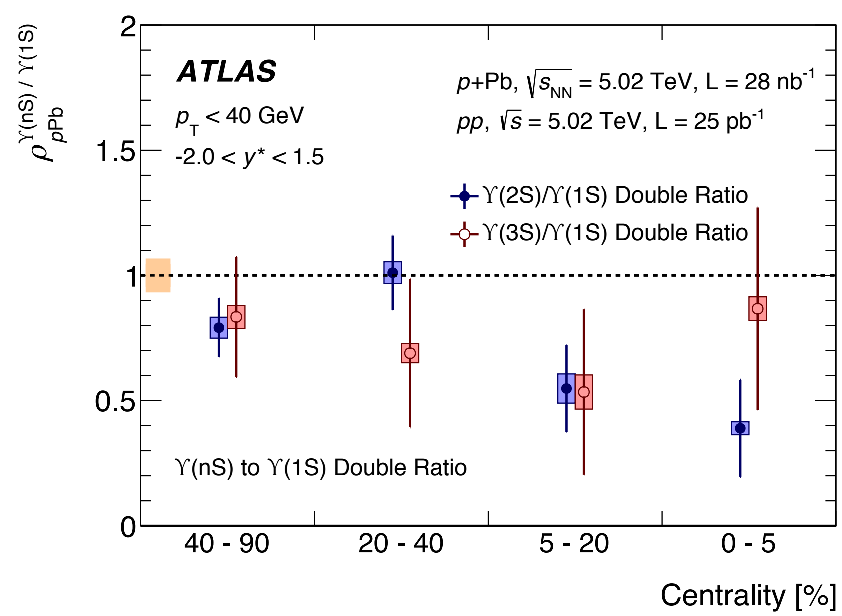
prompt: enhanced suppression



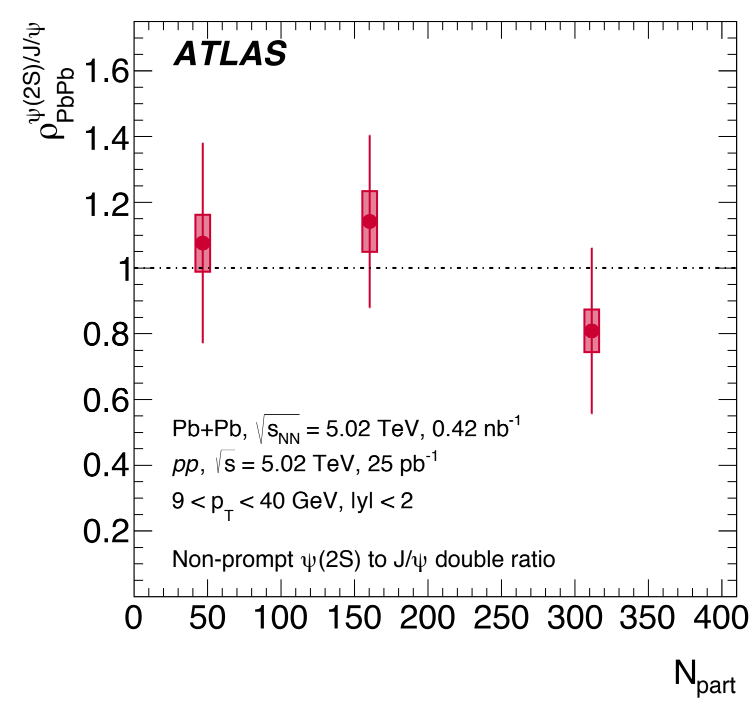
comparison with CMS data

slight decrease $(1\,\sigma)$ in pPb double ratios with increasing centrality





non-prompt: consistent with unity



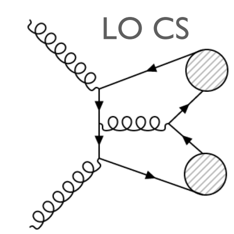
Associated production with onia in pp collisions

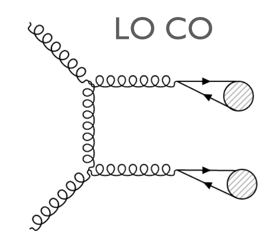
The study of double onia and associated onia production offers new tests of Quantum Chromodynamics (QCD)

Distinguish between production of a heavy quark system in colour-singlet (CS) and colour-octet (CO) states

The production of two objects in the same pp collision can be due to

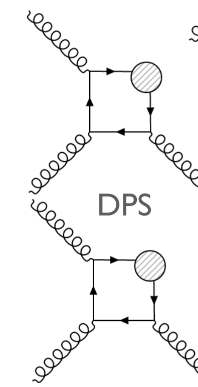
Single Parton Scattering (SPS): the two objects are produced by some process in a single interaction of two partons





Double Parton Scattering (DPS): simultaneous interaction of two pairs of partons, each producing one of the two objects

independent and uncorrelated



$$\sigma^{\mathrm{DPS}}_{A+B} = \frac{1}{1+\delta_{AB}}\frac{\sigma_A\sigma_B}{\sigma_{\mathrm{eff}}} \qquad \delta_{AB} = \begin{cases} 1, & A = B \\ 0, & A \neq B \end{cases}$$

σ_{eff} *effective cross section* ~(2 — 20) mb

assumed to be independent of the scattering process and $\sqrt{s}$

DPS not distinguishable on an event-by-event basis from SPS but expected to differ in overall kinematic features, such as angular correlations

Large uncertainties due to possible higher-order SPS contributions, feed-down and limited knowledge of the proton's transverse profile

$\sqrt{s} = 7\ \mathrm{TeV}$

$\mathcal{L} = 4.51\ \mathrm{fb}^{-1}$

$J/\psi \to \mu^+\mu^-$

$W^\pm \to \mu\nu_\mu$

Prompt J/ψ in association with a $W^\pm$

fiducial phase space $8.5 < p_T^{J/\psi} < 30\ \mathrm{GeV}$ $|y^{J/\psi}| < 2.1$

arXiv:1401.2831

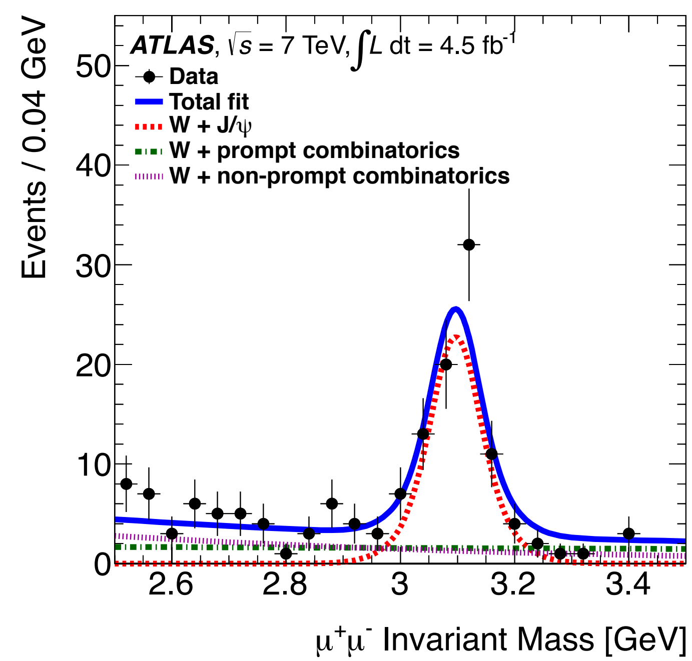
$p_T^\mu > 3.5\ \mathrm{GeV}$ $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$ at least one $p_T^\mu > 4\ \mathrm{GeV}$

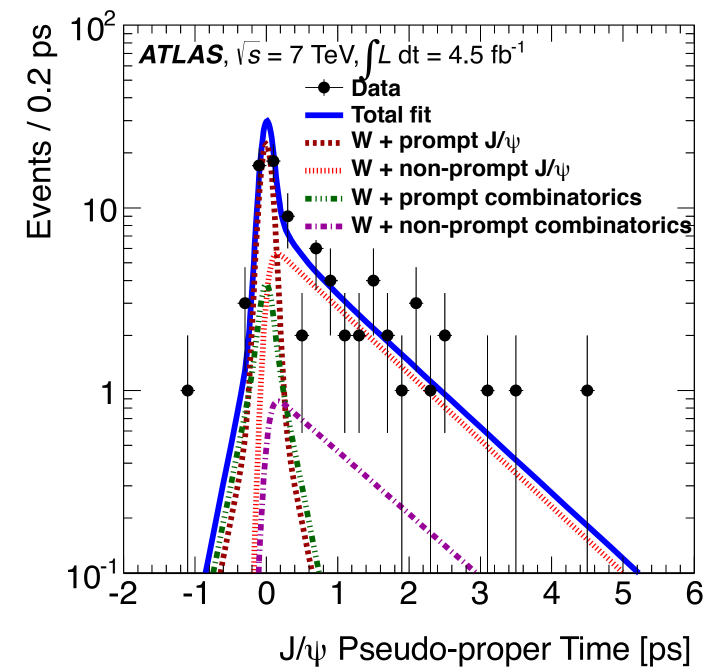
$p_T^\mu > 2.5\ \mathrm{GeV}$ $|\eta^\mu| > 1.3$ $p_T^{\mu(W)} > 25\ \mathrm{GeV}$ $|\eta^{\mu(W)}| < 2.4$

unbinned maximum likelihood (ML) fit in the J/ψ invariant mass and pseudo-proper time τ to obtain yields for prompt and non-prompt J/ψ and backgrounds

assign weights with sPlot arXiv:physics/0402083

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





fit to the weighted W boson transverse mass using templates to extract

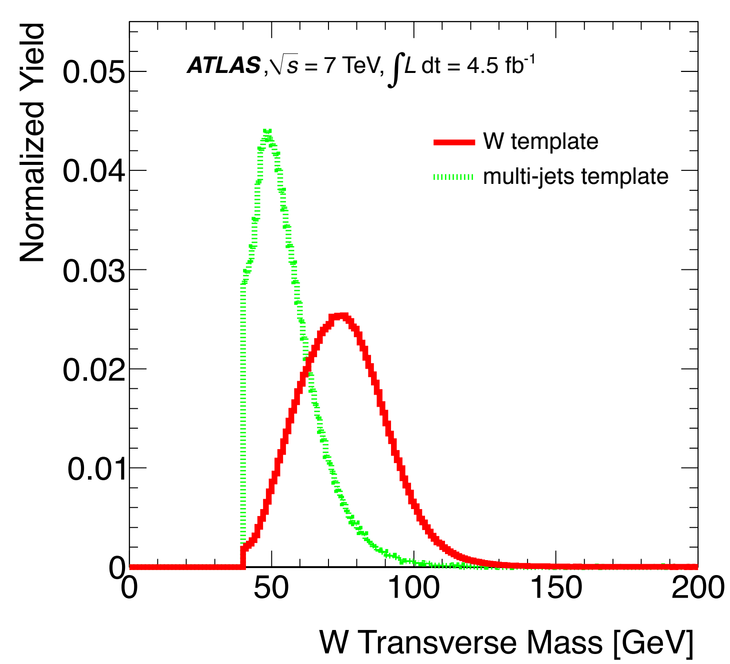
signal yield: $29.2^{+7.5}_{-6.5}$ 5.1σ

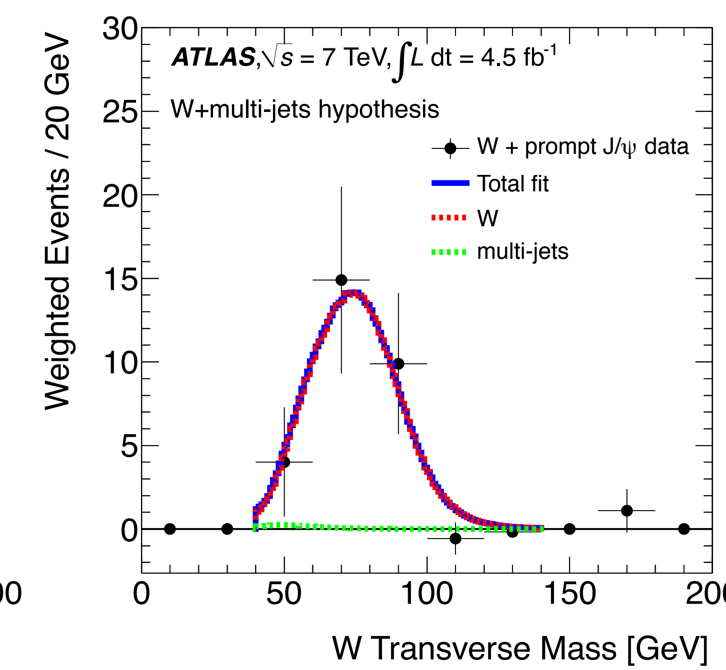
including 1.8 ± 0.2 from pile-up:

assuming $\sigma_{\mathrm{eff}} = 15 \pm 3\ (\mathrm{stat})\ ^{+5}_{-3}\ (\mathrm{syst})\ \mathrm{mb}$ arXiv:1301.6872

and $\sigma_{J/\psi}$ from arXiv:1104.3038

DPS yield: 10.8 ± 4.2





Prompt J/ψ in association with a $W^{\pm}$

arXiv:1401.2831

Ratios of the $W^{\pm}$+ prompt J/ψ cross section to the inclusive $W^{\pm}$ cross section

normalised to unit rapidity

fiducial $R^{\rm fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$

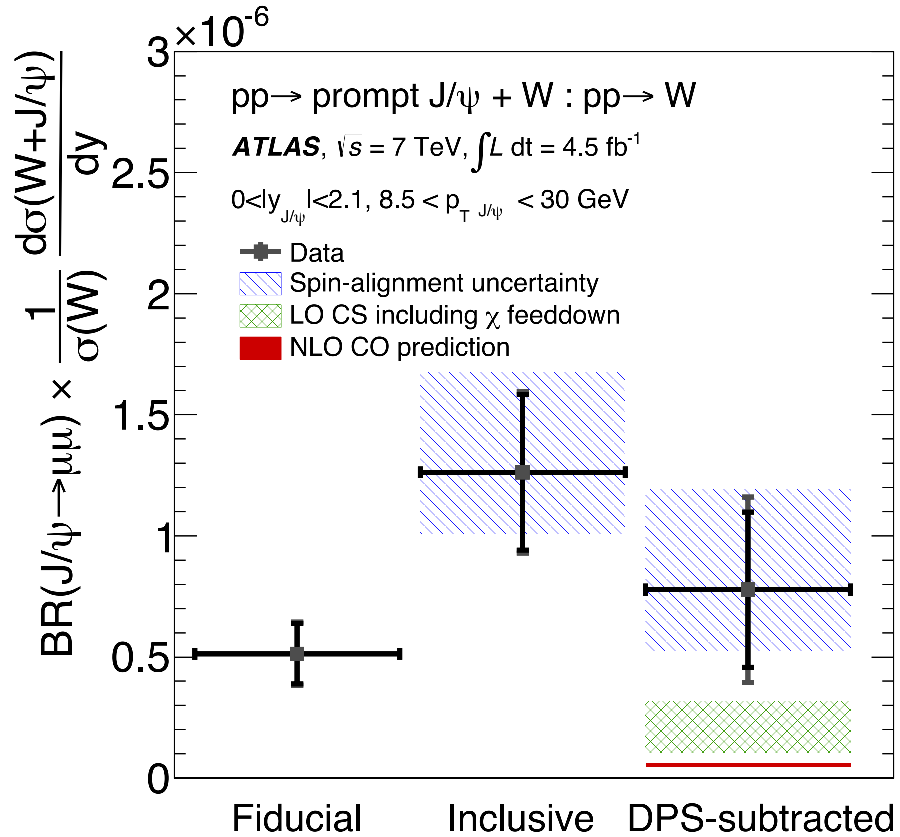
inclusive $R^{\rm incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$

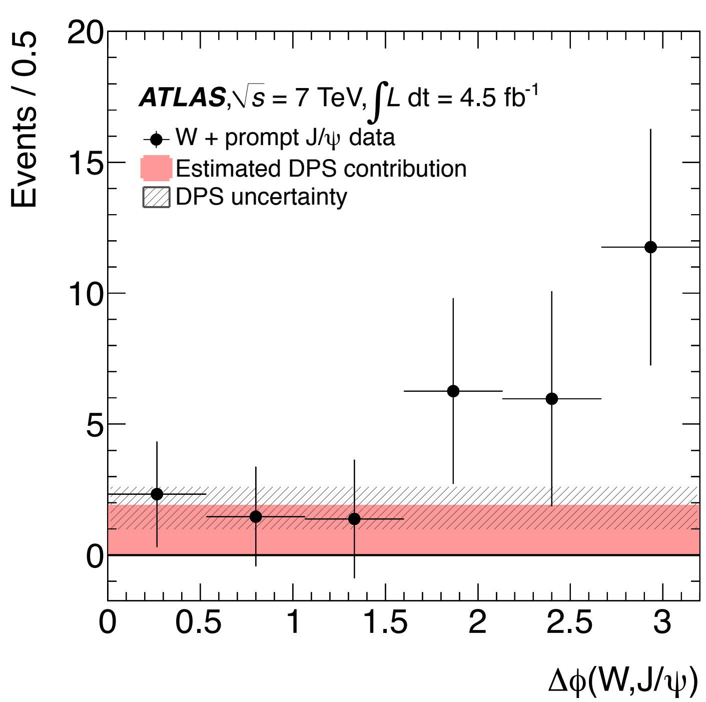
corrected for the fiducial acceptance of the muons from J/ψ
isotropic spin-alignment assumed
last uncertainty from variations with 5 extreme scenarios

DPS subtracted $R^{\rm DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

compared to LO CS and NLO CO predictions

$W + J/\psi$ dominated by CS production

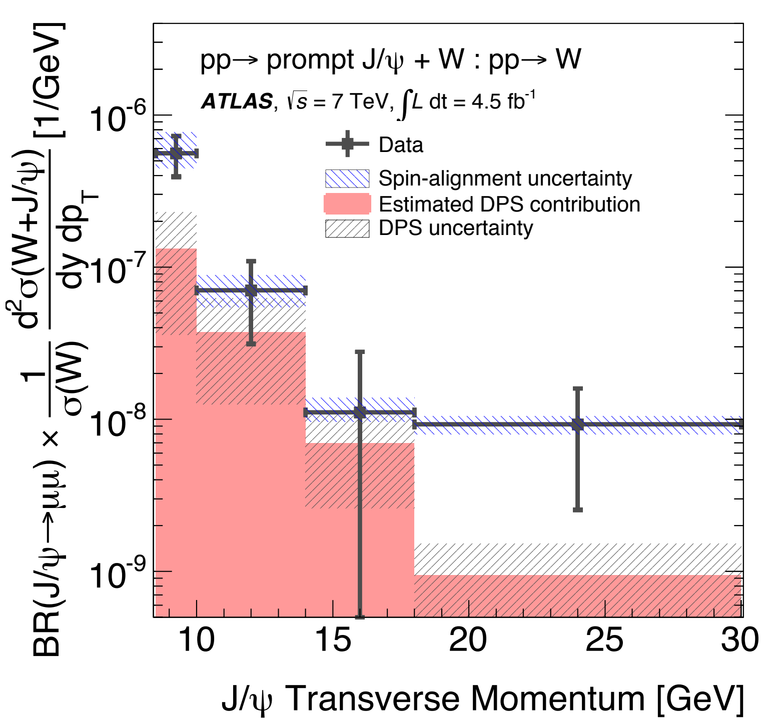




Presence of both SPS and DPS contributions

SPS is the dominant contribution to the total rate at low $p_T^{J/\psi}$

Inclusive differential cross section ratio



Prompt and non-prompt J/ψ in association with a Z

$\sqrt{s} = 8$ TeV

$\mathcal{L} = 20.3$ fb^{-1}

$J/\psi \to \mu^+\mu^-$

$Z \to \ell\ell,\ \ell = \mu, e$

fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV $|y^{J/\psi}| < 2.1$

arXiv:1412.6428

$p_T^{\mu} > 3.5$ GeV $|\eta^{\mu}| < 1.3$ $|\eta^{\mu}| < 2.5$

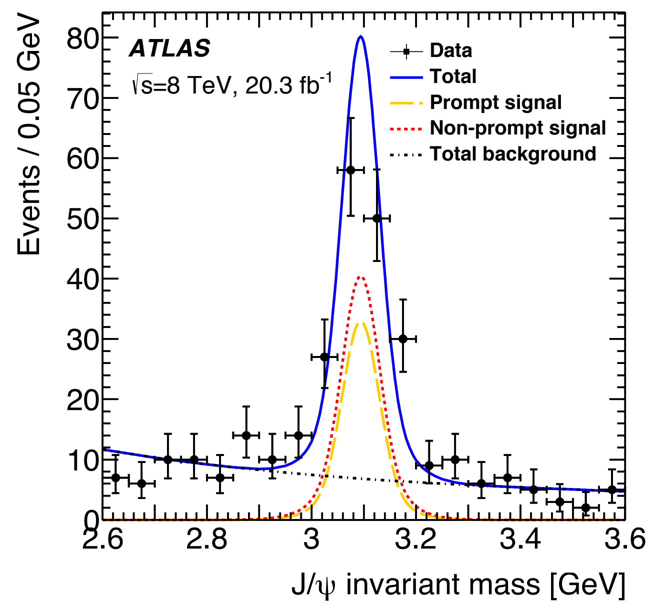
$p_T^{\mu} > 2.5$ GeV $|\eta^{\mu}| > 1.3$ at least one $p_T^{\mu} > 4$ GeV

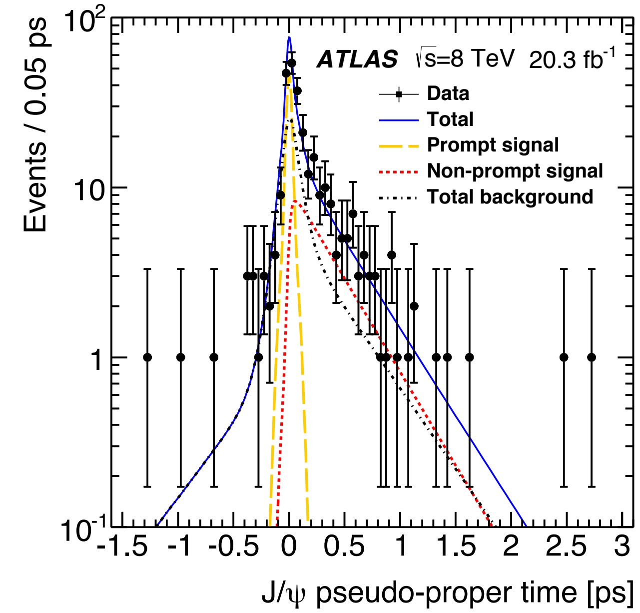
$p_T^{\mu(Z)} > 15$ GeV $|\eta^{\mu(Z)}| < 2.5$

$p_T^{e(Z)} > 15$ GeV $|\eta^{e(Z)}| < 2.47$

unbinned ML fit in J/ψ invariant mass and pseudo-proper time to obtain yields for prompt and non-prompt J/ψ and backgrounds

signal and multi-jet background templates for weighted Z mass used to extract signal yield separately for $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$



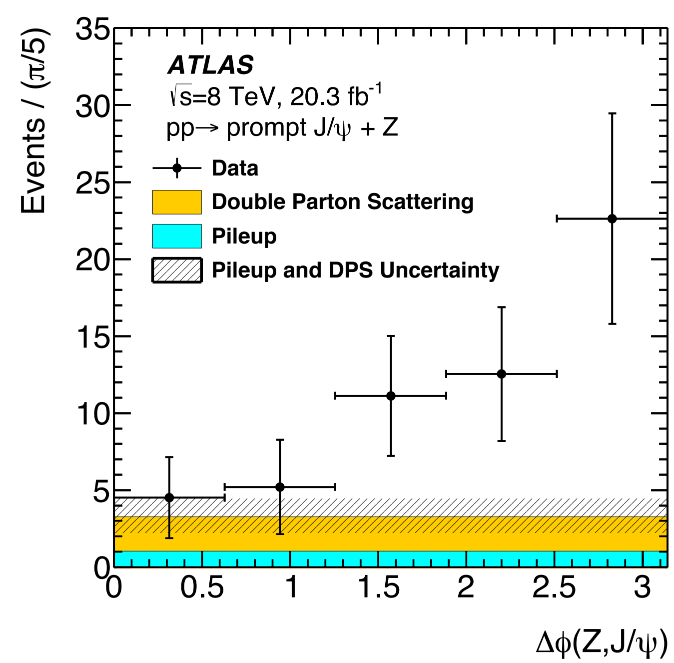


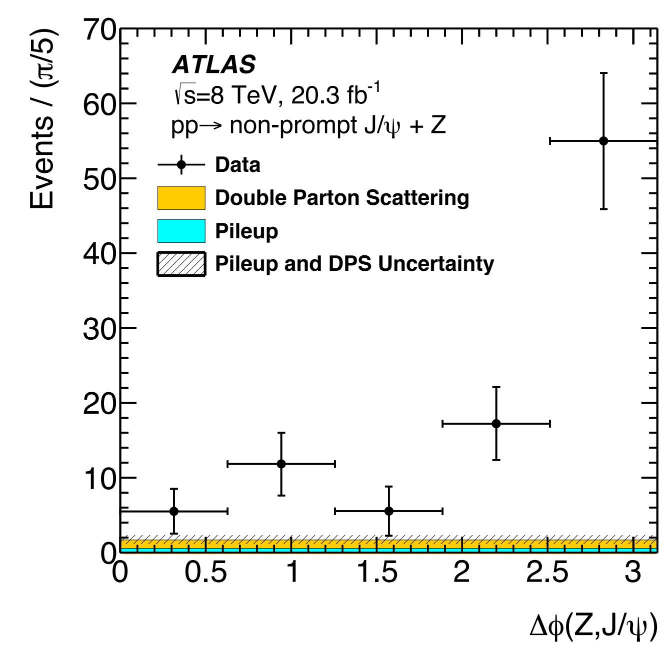
Yields:	prompt	non-prompt
	$56 \pm 10 \pm 5\ (5\sigma)$	$95 \pm 12 \pm 8\ (9\sigma)$
from DPS	$11.1^{+5.7}_{-5.0}$	$5.8^{+2.8}_{-2.6}$

assuming $\sigma_{\text{eff}} = 15 \pm 3\ (\text{stat})\ ^{+5}_{-3}\ (\text{syst})$ mb
arXiv:1301.6872

and $\sigma_{J/\psi}$ from arXiv:1104.3038

assuming all observed signal in the first bin $(< \frac{\pi}{5})$ is due to DPS, a lower limit is set on $\sigma_{\text{eff}} > 5.3$ mb





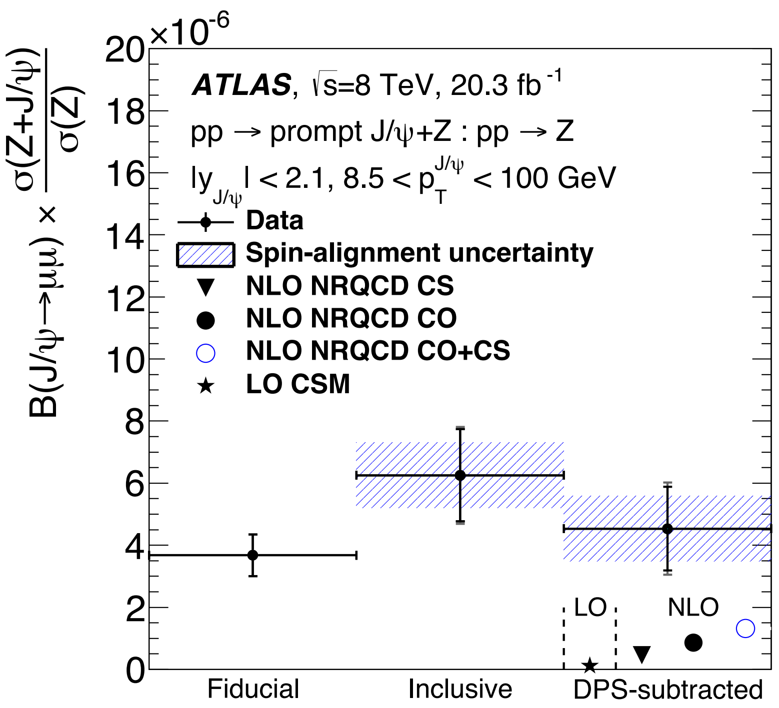
presence of both SPS and DPS contributions

Prompt and non-prompt J/ψ in association with a Z

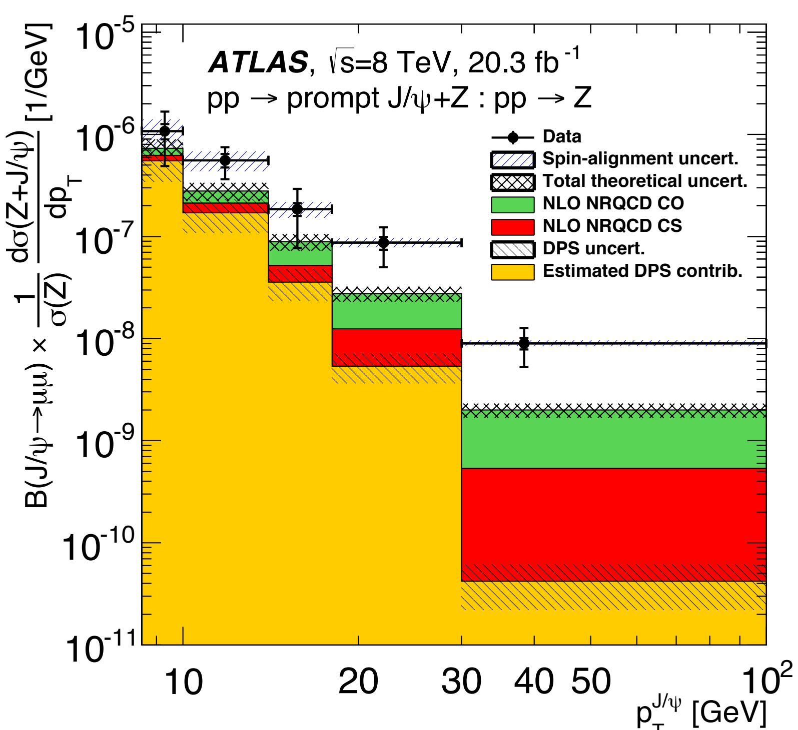
Ratios of the $Z + J/\psi$ cross section to the inclusive Z cross section

arXiv:1412.6428

	prompt	non-prompt
fiducial	${}^{\mathrm{p}}R^{\mathrm{fid}}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{fid}}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$
inclusive	${}^{\mathrm{p}}R^{\mathrm{incl}}_{Z+J/\psi} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{incl}}_{Z+J/\psi} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS subtracted	${}^{\mathrm{p}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (94 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS fraction	${}^{\mathrm{p}}f_{\mathrm{DPS}} = (29 \pm 9)\%$	${}^{\mathrm{np}}f_{\mathrm{DPS}} = (8 \pm 2)\%$



Inclusive differential cross section ratio



a higher production rate predicted through CO than through CS, CO dominant at high transverse momentum

The expected production rate from the sum of CO and CS is lower than the data by a factor of 2 to 5

discrepancy increasing with transverse momentum

$\sqrt{s} = 8\ \mathrm{TeV}$
$\mathcal{L} = 11.4\ \mathrm{fb}^{-1}$

Prompt J/ψ pair production

arXiv:1612.02950

fiducial phase space $p_T^{J/\psi} > 8.5\ \mathrm{GeV}$ $|y^{J/\psi}| < 2.1$

$p_T^{\mu} > 2.5\ \mathrm{GeV}$ $|\eta^{\mu}| < 2.3$

unbinned ML fit to the two invariant masses to extract di-J/ψ signal

signal used to create prompt-prompt event weights from a 2D fit to the transverse decay length distributions of the two J/ψ

cross sections reported for two rapidity regions based on the sub-leading J/ψ rapidity

$|y_{J/\psi_2}| < 1.05$

$N_{J/\psi J/\psi} = 3310 \pm 330$

$\sigma^{\mathrm{fid}}_{J/\psi J/\psi} = 15.6 \pm 1.3 \pm 1.2 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})\ \mathrm{pb}$

$1.05 < |y_{J/\psi_2}| < 2.1$

$N_{J/\psi J/\psi} = 3140 \pm 370$

$\sigma^{\mathrm{fid}}_{J/\psi J/\psi} = 13.5 \pm 1.3 \pm 1.1 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})\ \mathrm{pb}$

after correcting for muon acceptance and assuming unpolarised production

$\sigma_{J/\psi J/\psi} = 82.2 \pm 8.3 \pm 6.3 \pm 0.9\ (\mathcal{B}) \pm 1.6(\mathcal{L})\ \mathrm{pb}$

$\sigma_{J/\psi J/\psi} = 78.3 \pm 9.2 \pm 6.6 \pm 0.9\ (\mathcal{B}) \pm 1.5(\mathcal{L})\ \mathrm{pb}$

the fraction of DPS events is determined by fitting DPS and SPS templates to the data $|\Delta y|$ vs $|\Delta \phi|$

assign DPS and SPS event weights

$f_{\mathrm{DPS}} = (9.2 \pm 2.1 \pm 0.5)\%$ from $|\Delta y|$

$\sigma^{\mathrm{DPS}}_{J/\psi J/\psi} = 14.8 \pm 3.5 \pm 1.5 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})\ \mathrm{pb}$

$\sigma^{J/\psi J/\psi}_{\mathrm{eff}} = 6.3 \pm 1.6 \pm 1.0(\mathcal{B}) \pm 0.1(\mathcal{L})\ \mathrm{mb}$

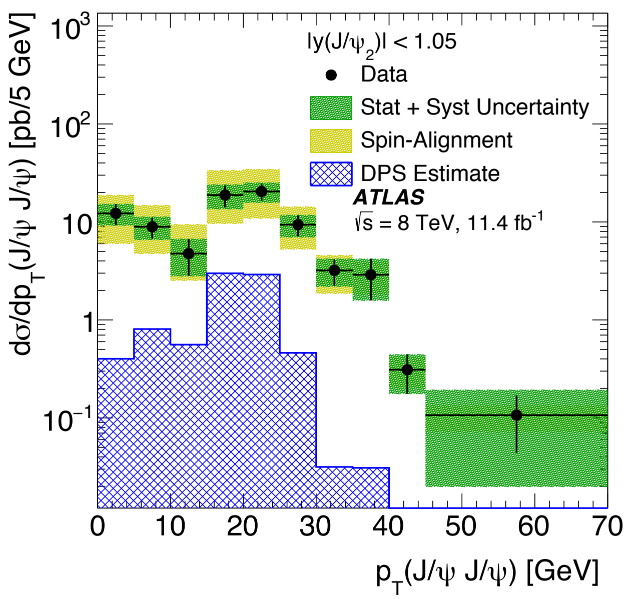
σ^{eff} measured from prompt di-J/ψ
consistent with other experiments
lower than from other final states

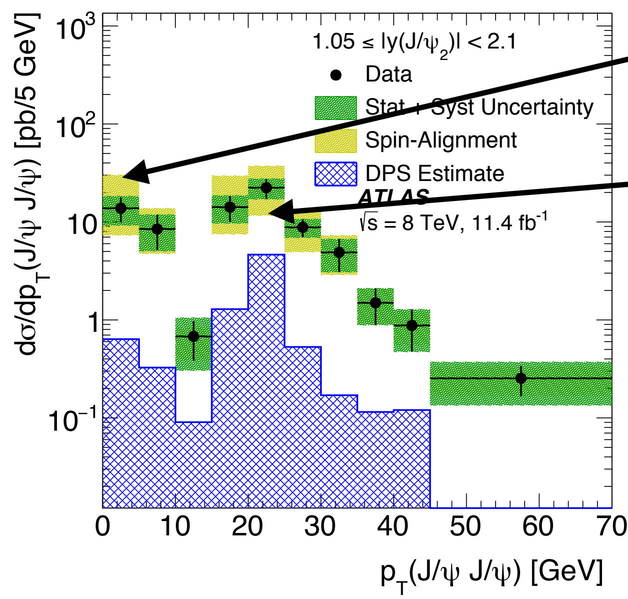
Prompt J/ψ pair production

Differential cross sections as a function of the sub-leading J/ψ p_T, the di-J/ψ p_T and invariant mass

arXiv:1612.02950

central and forward J/ψ_2 rapidity ranges





events produced back-to-back

events produced together
and back-to-back to a gluon

DPS estimate from data

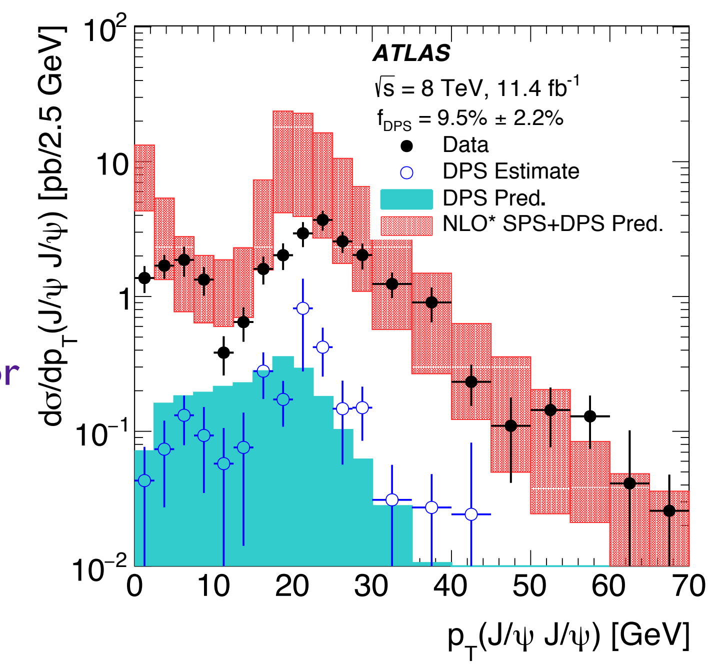
Total and DPS cross sections (full rapidity range) in the muon fiducial volume:

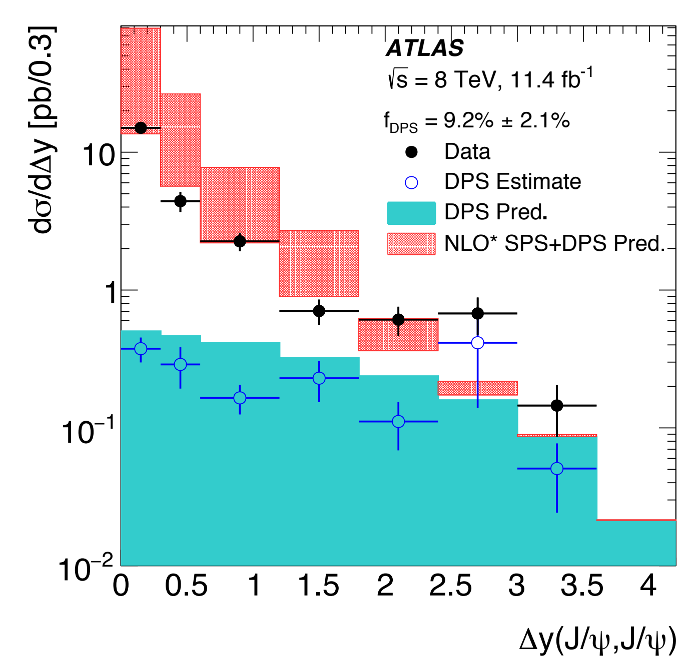
di-J/ψ p_T and invariant mass, Δy and $\Delta\phi$

compared to: NLO* SPS with a feed-down correction factor

LO DPS normalised to measured

disagreement for large invariant mass, large Δy
and in the low-p_T region





Data largely in agreement with NLO* SPS + LO DPS

contributions from feed-down and/or intrinsic parton transverse momentum needed

Summary

Quarkonia production:

p+Pb

data indicates weak modification of J/ψ production at central rapidity and high pt

the observed suppression of $\Upsilon(1S)$ at low pt suggests that the nuclear parton distribution functions are modified relative to those of the nucleon

a stronger cold nuclear matter effect observed in excited quarkonium states compared to that in ground states

Pb+Pb

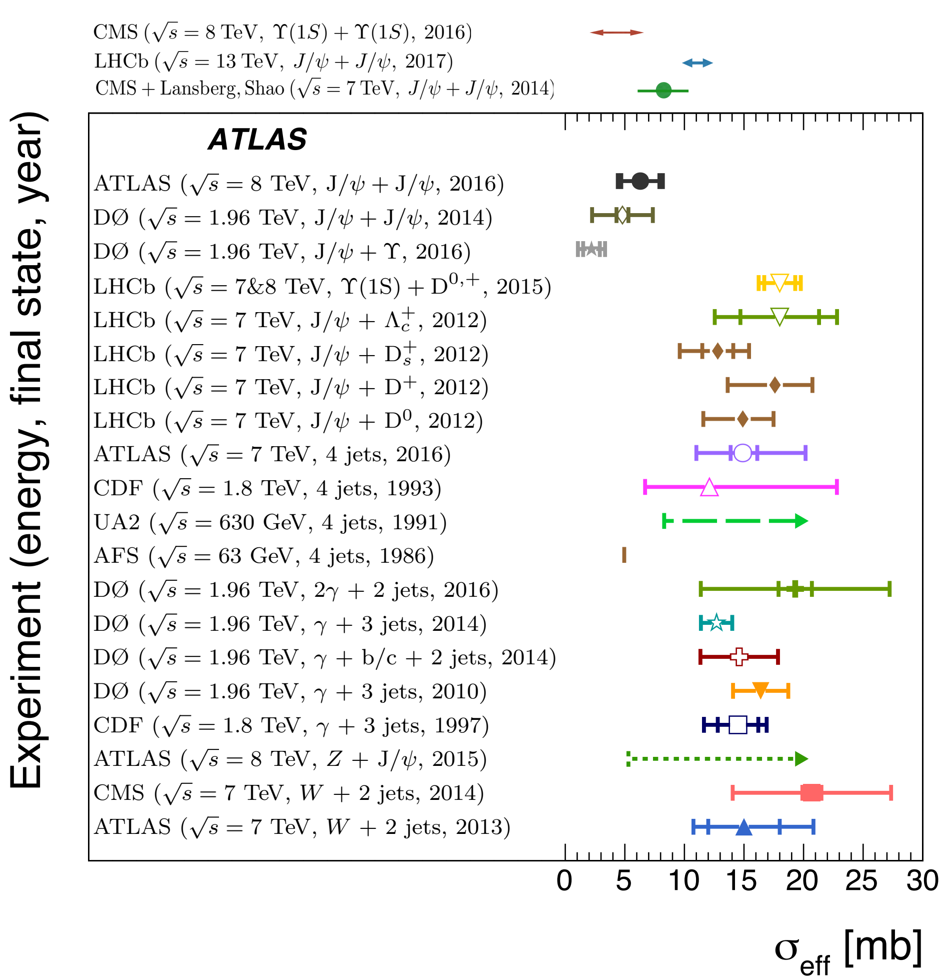
strong suppression of prompt and non-prompt J/ψ and $\psi(2S)$

similar dependence of the nuclear modification factor on centrality for prompt and non-prompt J/ψ

prompt J/ψ R_{AA} shows an increasing trend with pt, constant for non-prompt

$\psi(2S)/J/\psi$ production below (consistent) with unity for prompt (non-prompt) mesons

Double onia and associated onia production:



Several ATLAS measurements contributing to the understanding of the production of heavy quark systems have been performed, with new results expected soon

Presence of both SPS and DPS contributions observed in associated onia production

Data largely in agreement with NLO* SPS + LO DPS

contributions from feed-down and/or intrinsic parton transverse momentum may be needed

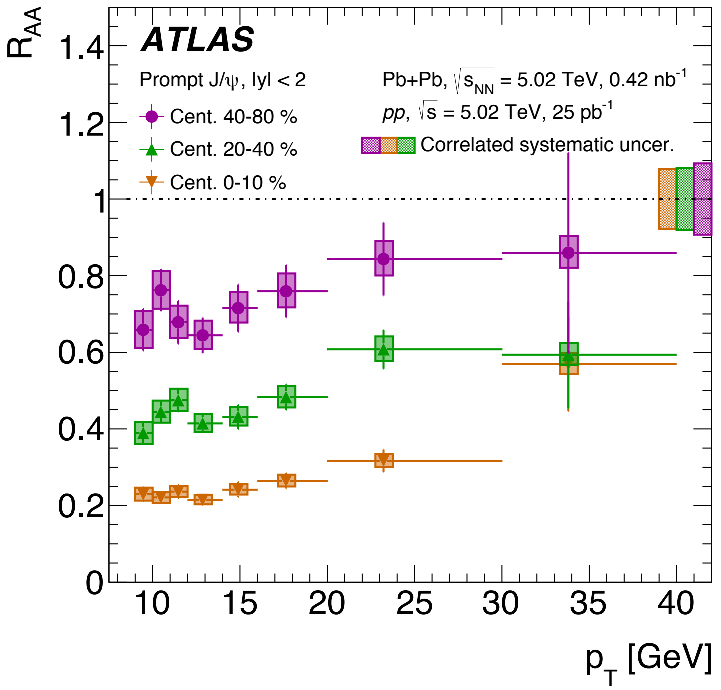
$\sigma_{\rm eff}$ measured from prompt di-J/ψ generally lower than from other final states

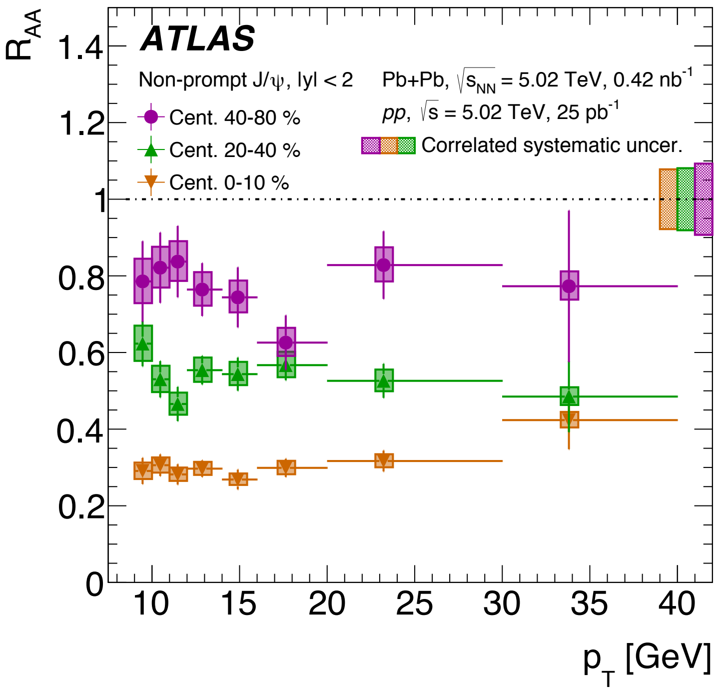
Theoretical predictions of the dependence of $\sigma_{\rm eff}$ on the process and the centre-of-mass energy are needed

Backup slides

Nuclear modification factor results

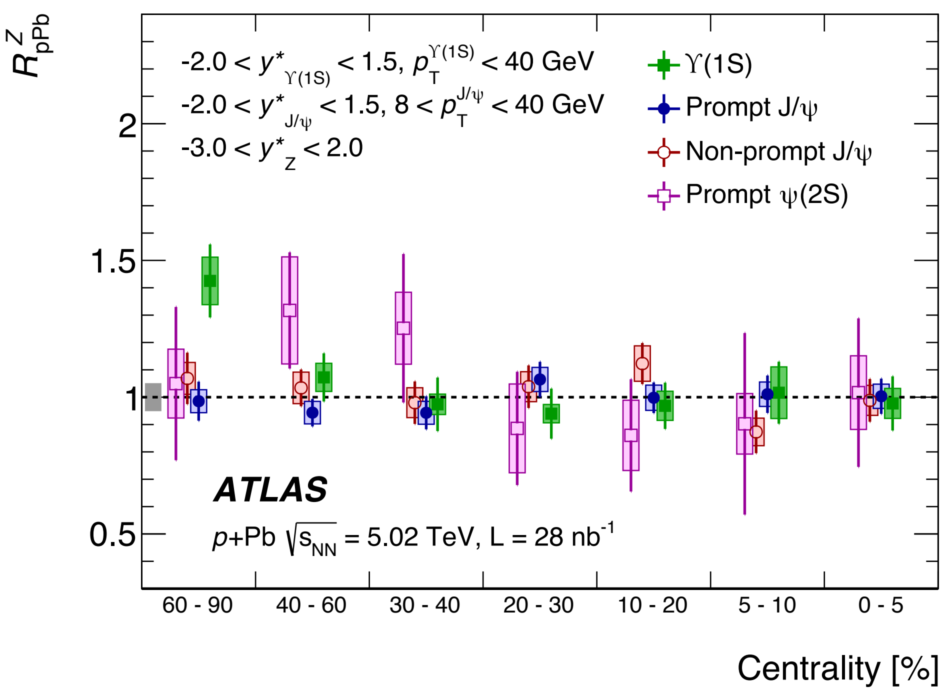
arXiv:1805.04077



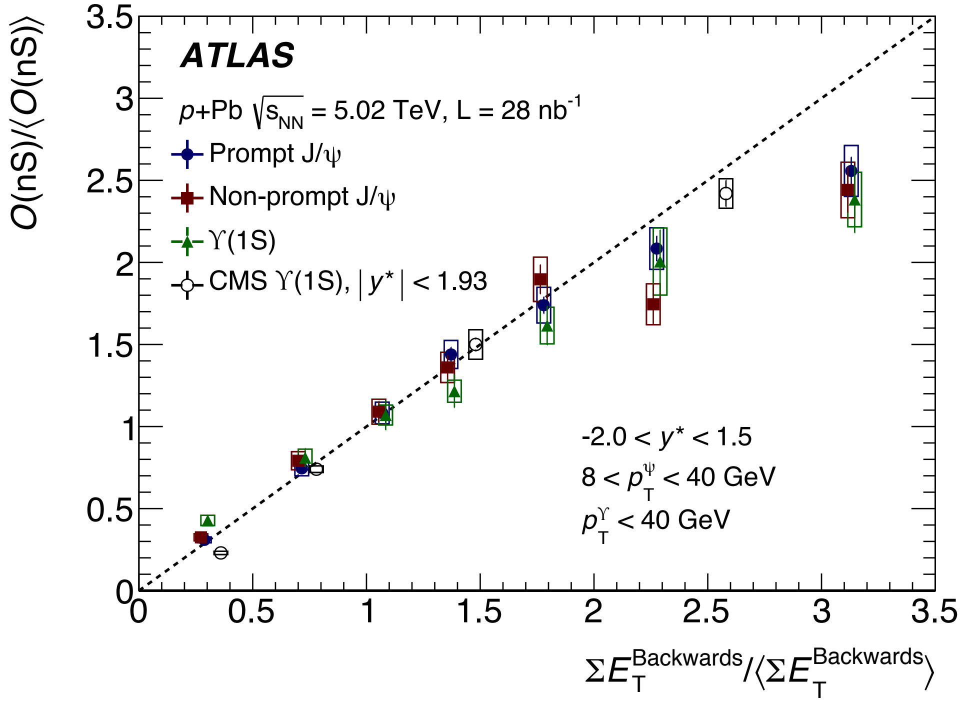


arXiv:1709.03089

p+Pb: ratios to Z boson production
(normalised to the ratio in 0-90% centrality)



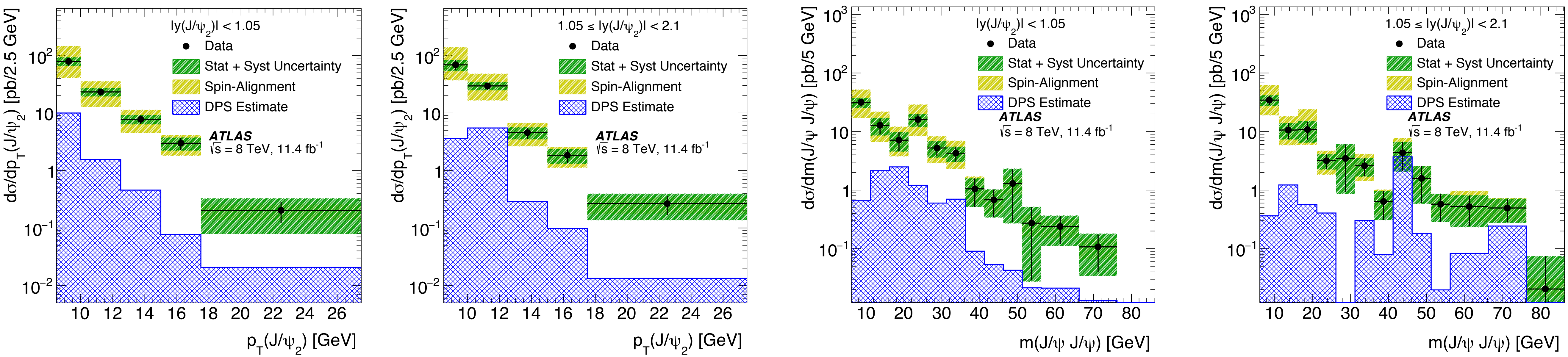
p+Pb: quarkonium self-normalised yields
(normalised to the yields in 0-90% centrality)



Prompt J/ψ pair production

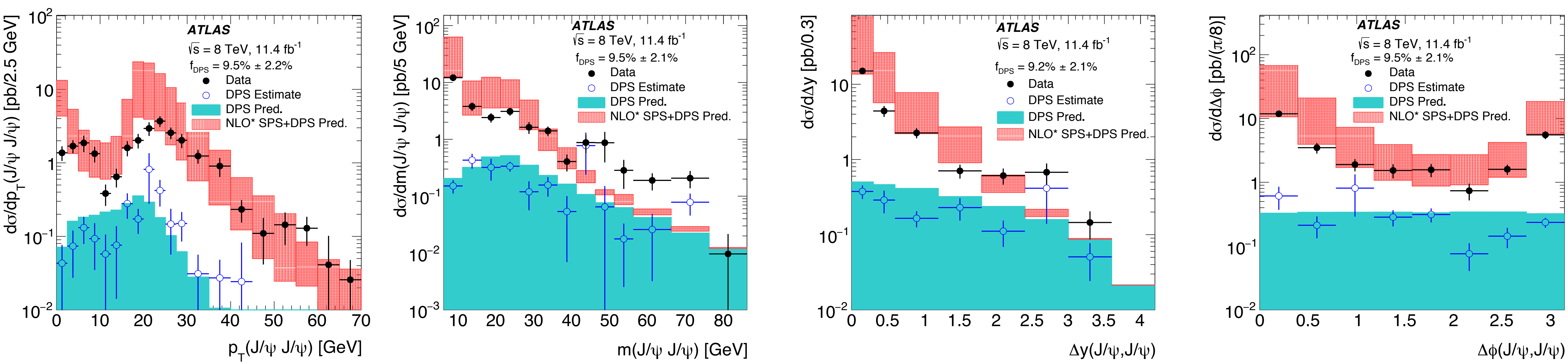
arXiv:1612.02950

Differential cross sections as a function of the sub-leading $J/\psi\ p_T$ and the invariant mass



Total and DPS cross sections (full rapidity range) in the muon fiducial volume:

di-$J/\psi\ p_T$ and invariant mass, Δy and $\Delta\phi$

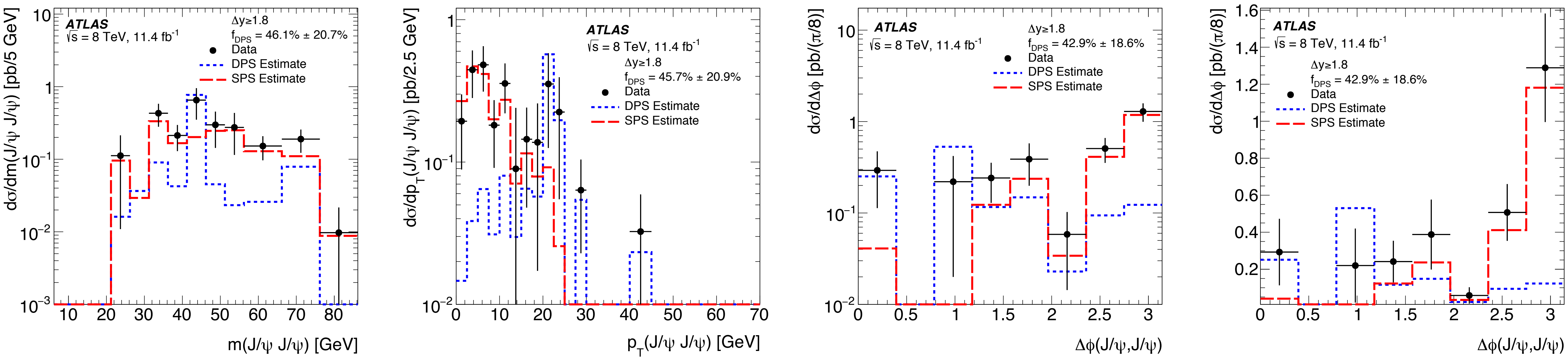


arXiv:1612.02950

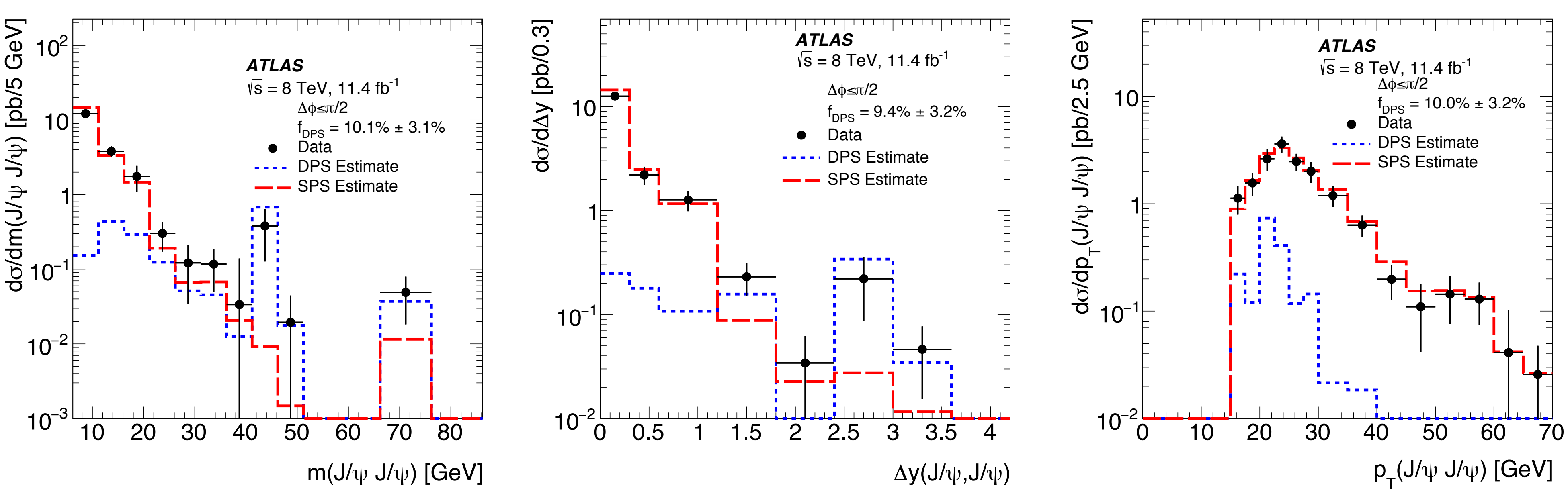
Prompt J/ψ pair production

arXiv:1612.02950

$\Delta y \geq 1.8$



$\Delta \phi \leq \pi/2$



arXiv:1612.02950