ATLAS RESULTS ON QUARKONIA AND ITS ASSOCIATED PRODUCTION

Cesare Bini

Sapienza Università and INFN Roma
On behalf of the ATLAS collaboration

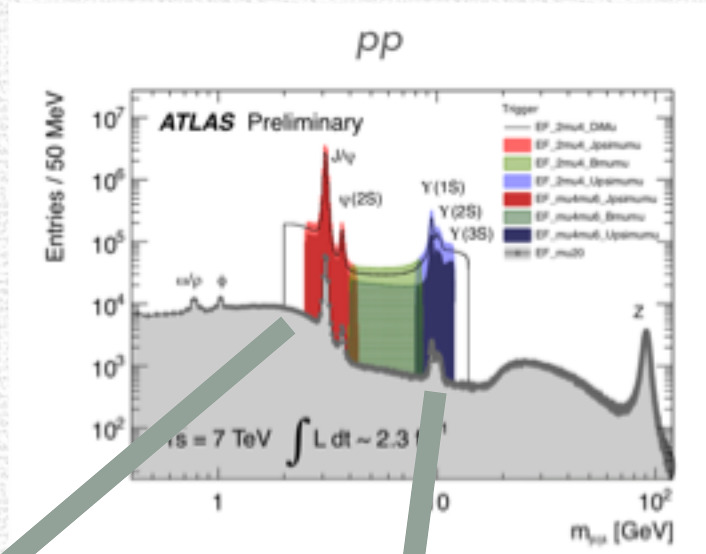
Outline

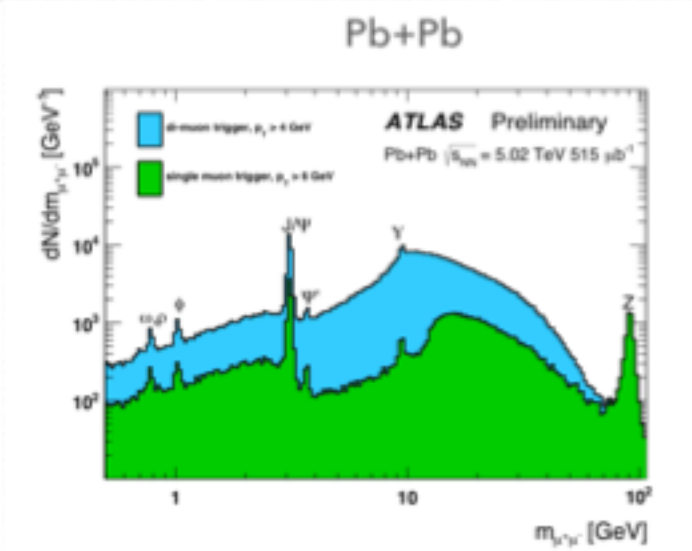
- *Study of Quarkonia with the ATLAS experiment*
- *Quarkonia production in pp, pPb and PbPb collisions*
  - *Motivations*
  - *Quarkonia production in pp and pPb collisions at 5.02 TeV*
  - *Prompt and non-prompt J/ψ and $\psi(2S)$ suppression in PbPb collisions at 5.02 TeV*
- *Quarkonia associated production*
  - *Motivations*
  - *di-J/ψ production at 8 TeV*
  - *DPS vs. SPS production and comparison with other results*
- *Summary*

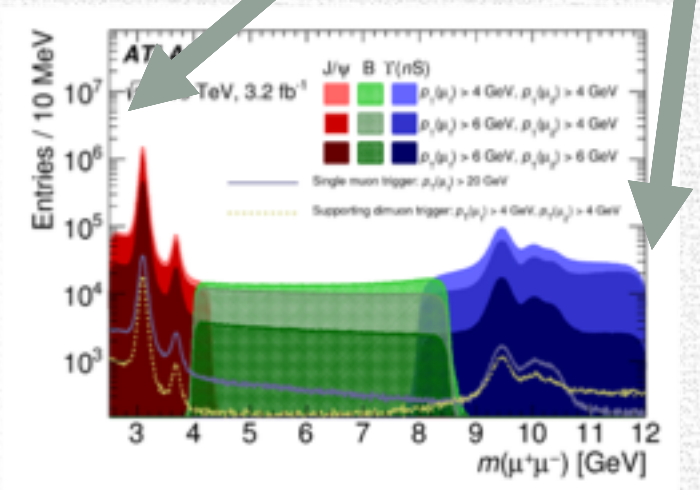
Papers:
ATLAS Collaboration Eur.Phys.J. C 78 (2018) 171
ATLAS Collaboration Eur.Phys.J. C 77 (2017) 76
ATLAS Collaboration arXiv:1805.04077 [nucl-ex]

Study of Quarkonia with the ATLAS experiment - I

Quarkonia physics in ATLAS is mostly based on low p_T muon triggers and track reconstruction in the Inner Detector





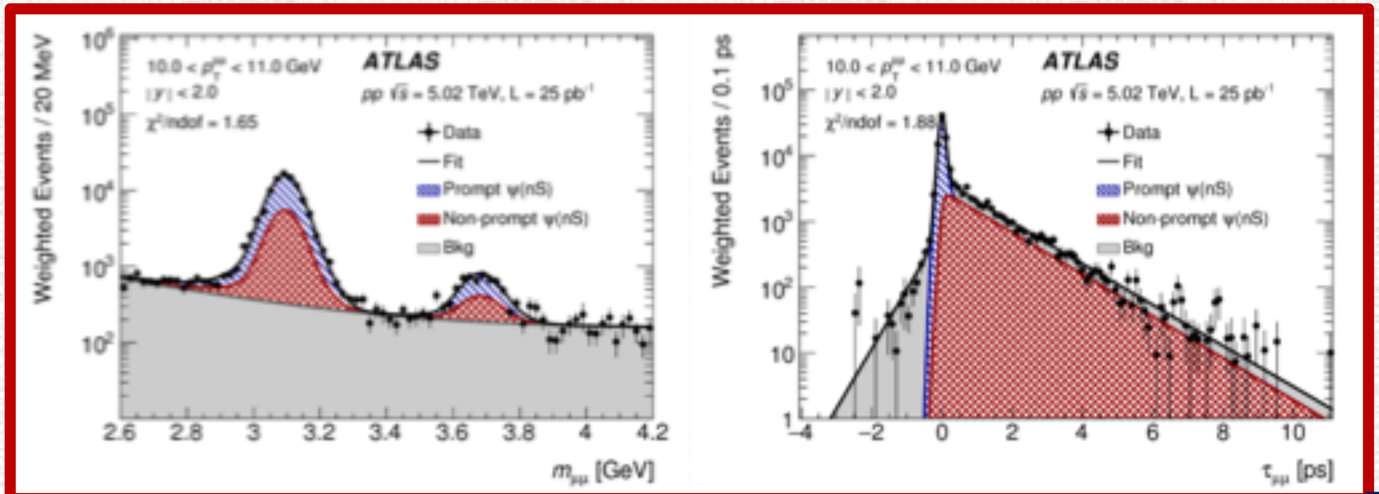


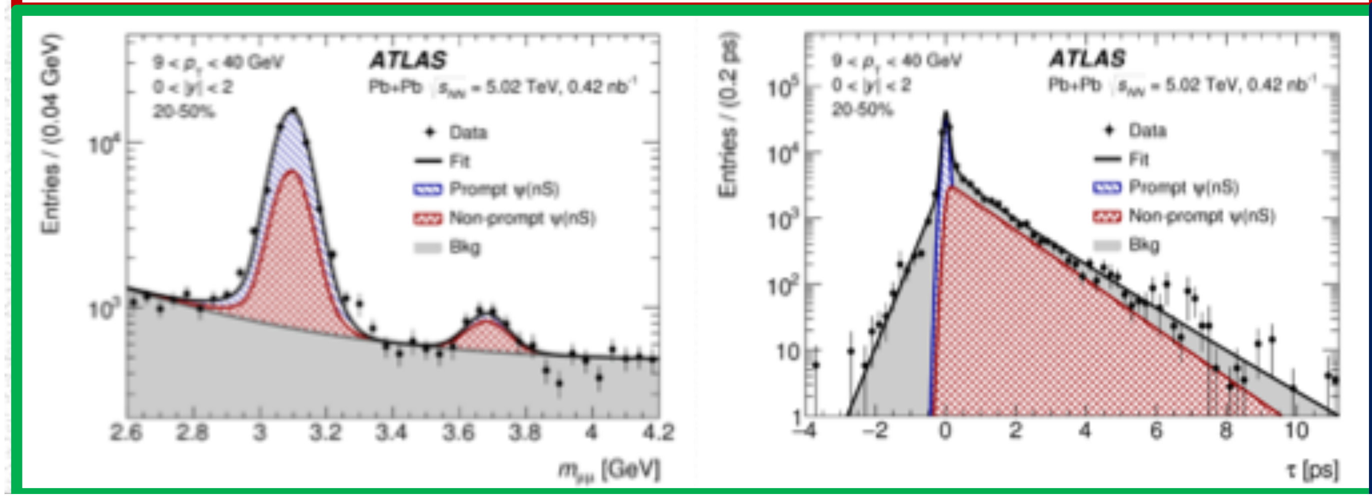
Datasets used

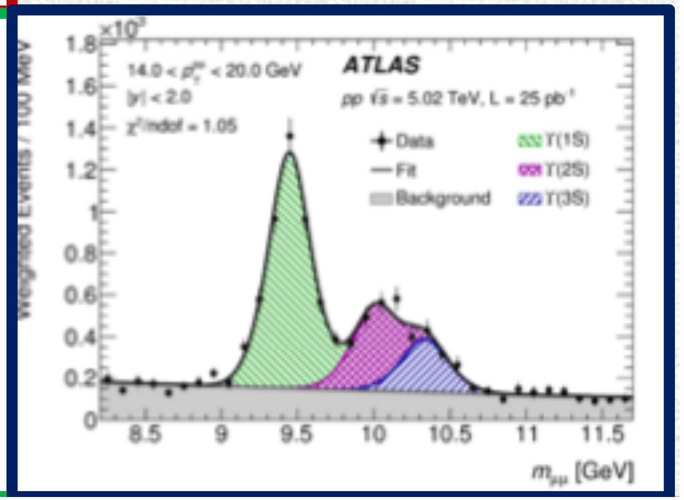
Run		Year	√SNN (TeV)	Lint (fb^{-1})
Run1	pp	2012	8	11.4
Run2	pPb	2013	5.02	0.028
Run2	pp	2015	5.02	25
Run2	PbPb	2015	5.02	0.0042

Study of Quarkonia with the ATLAS experiment - II

1. M(μμ) and τ(μμ) variables to characterize quarkonia production
2. ➔ 2D fit in these two variables
3. Prompt vs. Non-Prompt (mainly due to B decays in flight) prodction







J/ψ – ψ(2S) in pp

J/ψ – ψ(2S) in PbPb

Υ (1S-2S-3S) in pp

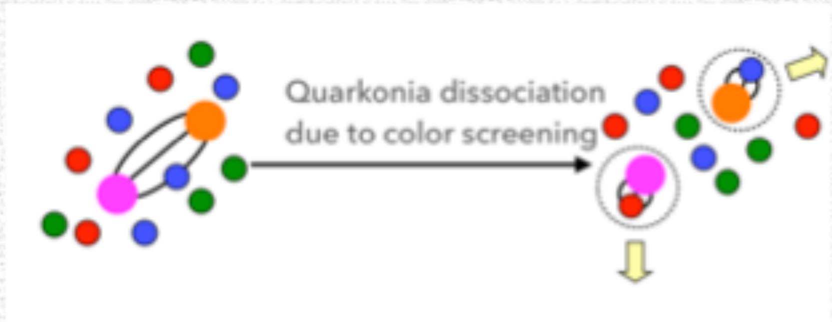
QUARKONIA PRODUCTION IN P+P P+PB AND PB+PB AT 5.02 TEV

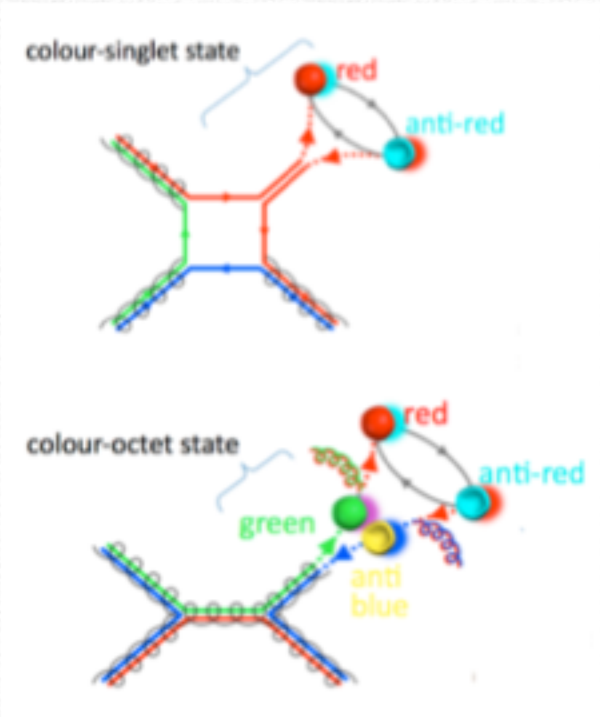
Quarkonia production in hadron collisions: Motivations

Quarkonia inclusive production in pp, pPb and PbPb collisions at E_{CM} (NN) = 5.02 TeV

→Comparison with NRQCD (prompt production) and FONNL (non-prompt production) models

→Disentangling of CNM effects (in pPb) and QGP effects (in PbPb)





Main observable quantities:

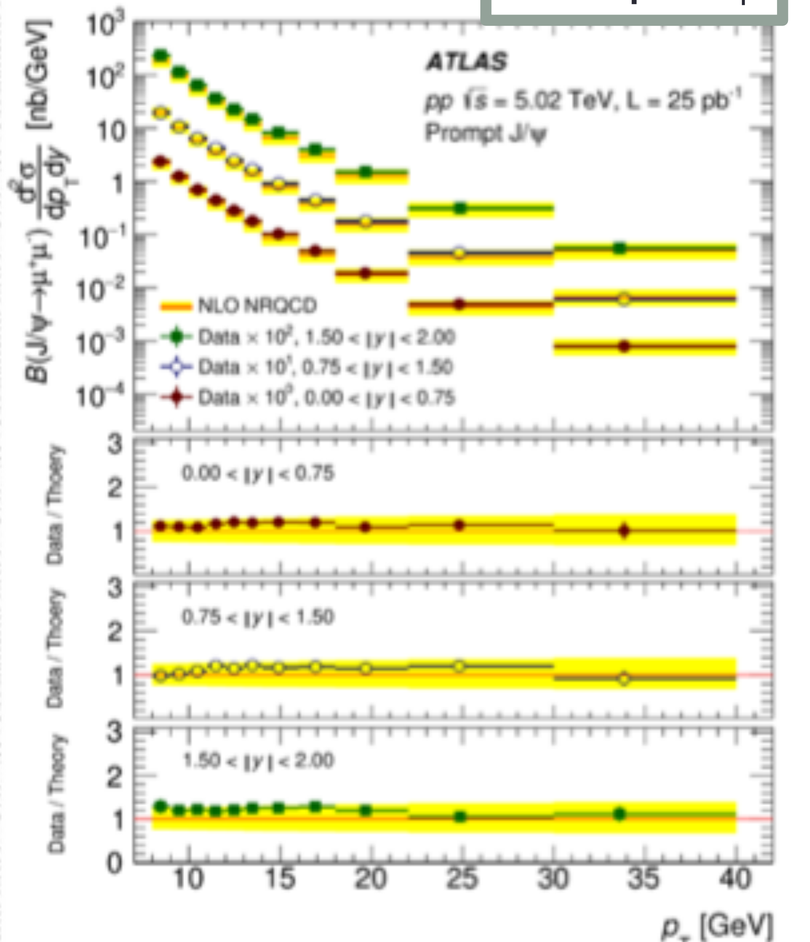
differential cross-section $\frac{d^2\sigma^{O(nS)}}{dp_T dy^*} BF(O(nS) \rightarrow \mu^+\mu^-)$

nuclear modification factor (pA) $R_{pPb} = \frac{1}{208}\frac{\sigma^{O(nS)}_{p+Pb}}{\sigma^{O(nS)}_{pp}}$

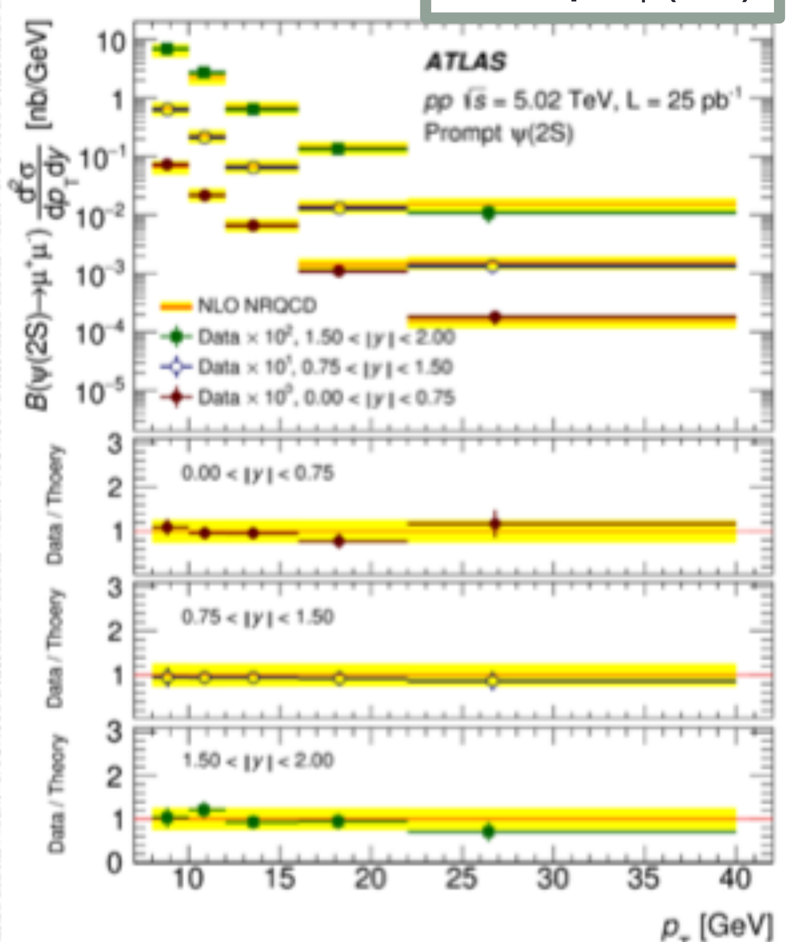
nuclear modification factor (AA) $R_{PbPb} = \frac{N_{PbPb}}{<T_{PbPb}> \times \sigma_{pp}}$

Results: prompt J/ψ and ψ(2S) production in pp collisions at 5.02 TeV

Prompt J/ψ

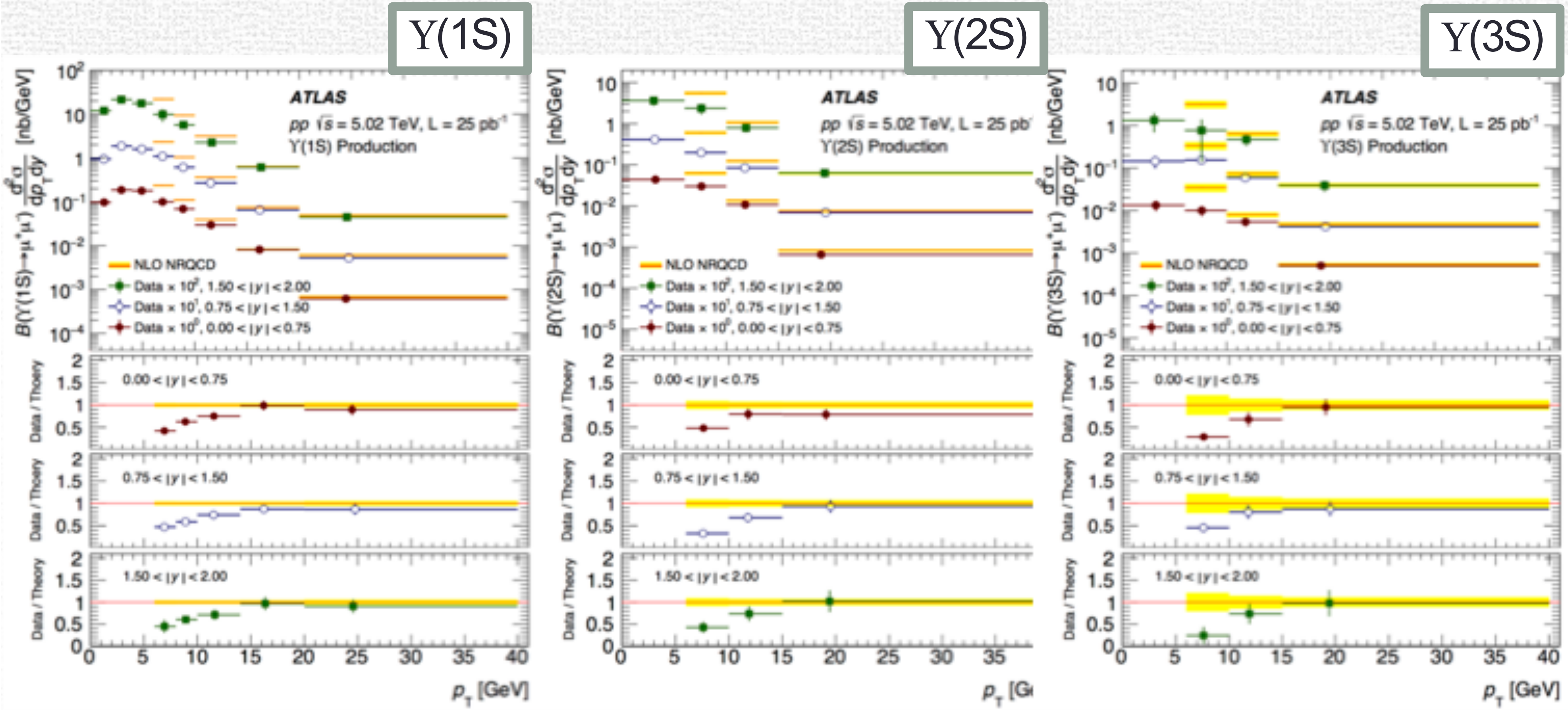


Prompt ψ(2S)



Good description of the data by NLO NRQCD calculations in the full p_T range (as it was for 7 and 8 TeV data)

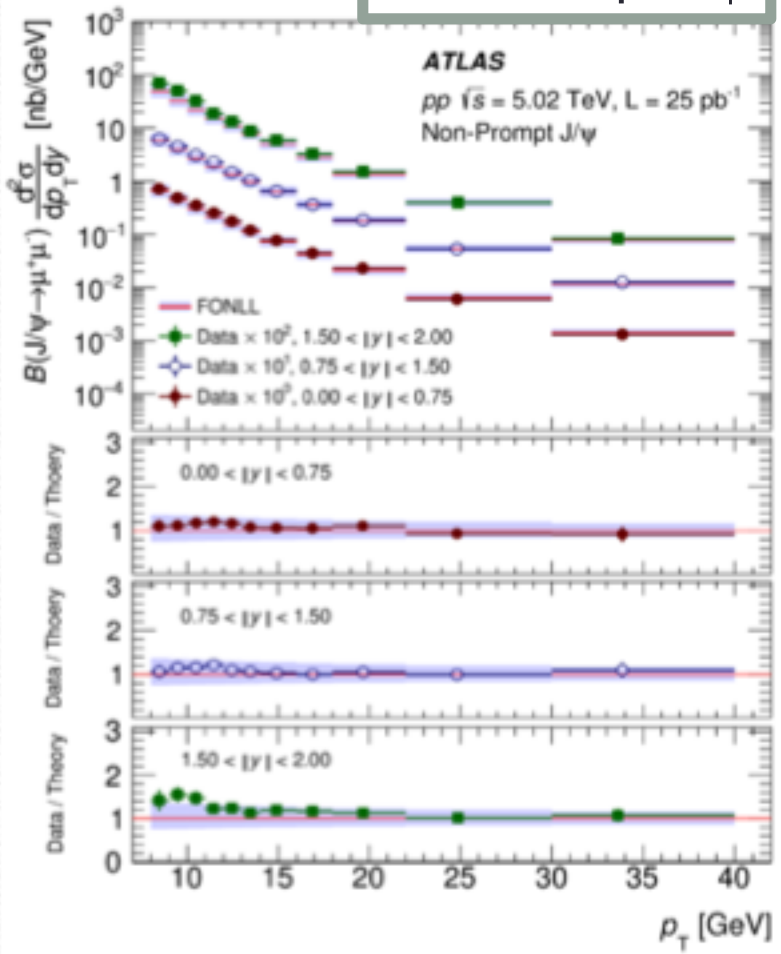
Results: Υ(1S-3S) production in pp collisions at 5.02 TeV



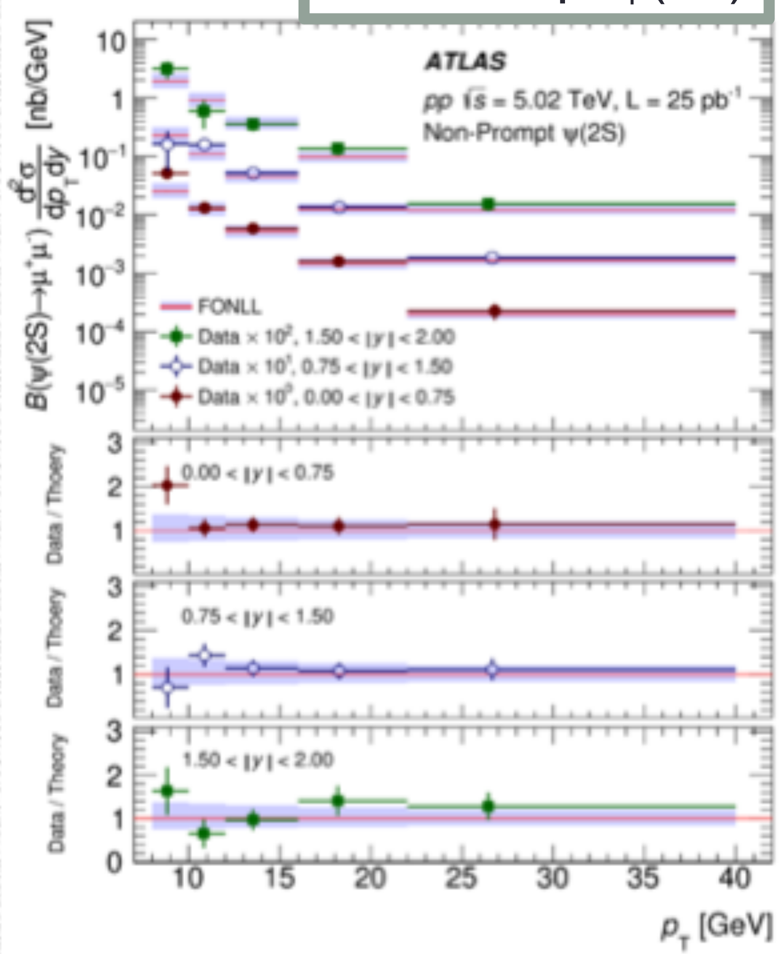
Significant discrepancies with NLO NRQCD calculations for p_T <15 GeV (agreement at higher p_T)

Results: non-prompt J/ψ and ψ(2S) production in pp collisions at 5.02 TeV

Non-Prompt J/ψ



Non-Prompt ψ(2S)

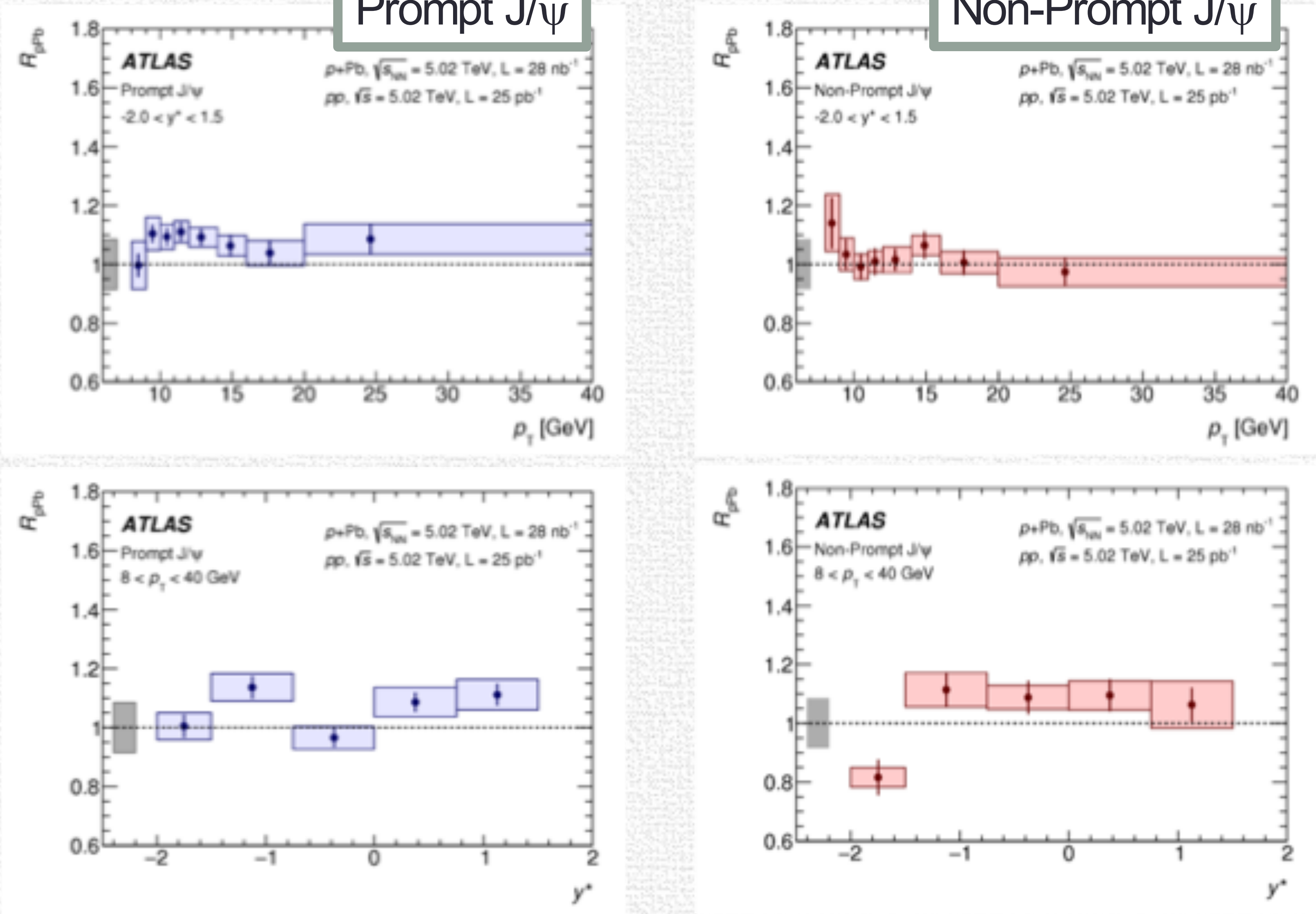


Good description of the data by FONLL calculations in the full p_T range
(better than 7 and 8 TeV data where some discrepancies were actually observed)

Results: nuclear modification factor R_{pPb} for J/ψ production

Prompt J/ψ

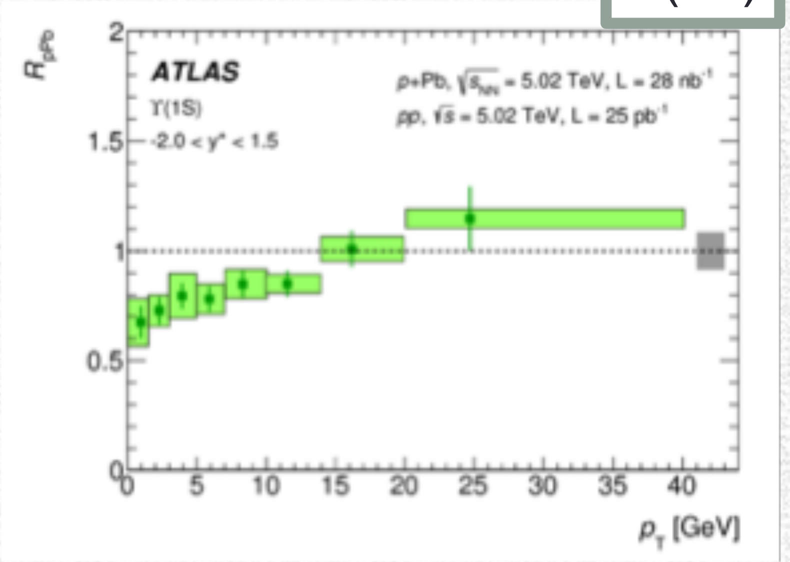
Non-Prompt J/ψ



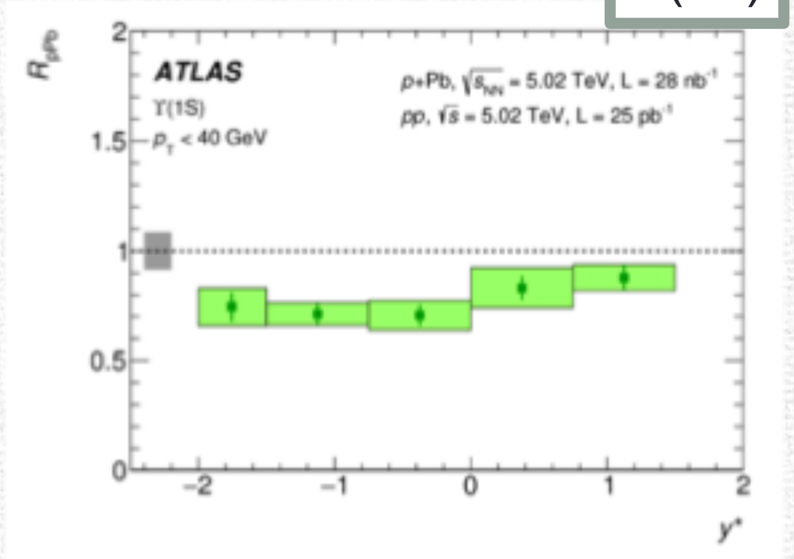
R_{pPb} ~ 1 in the full kinematic range → CNM effects are small for J/ψ production

Results: nuclear modification factor R_{pPb} for Υ(1S) production - I

Υ(1S)



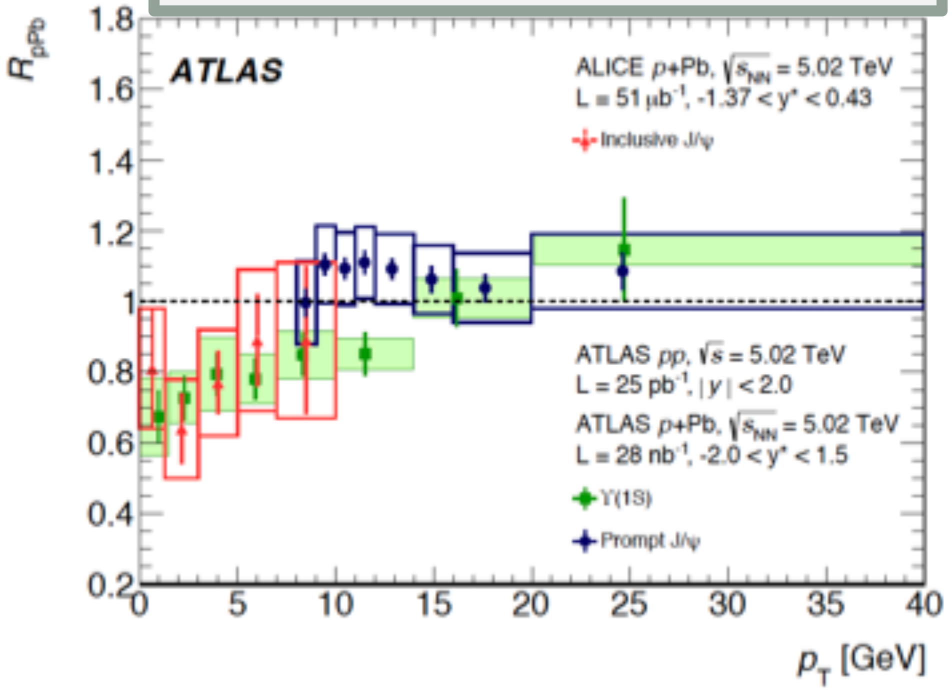
Υ(1S)



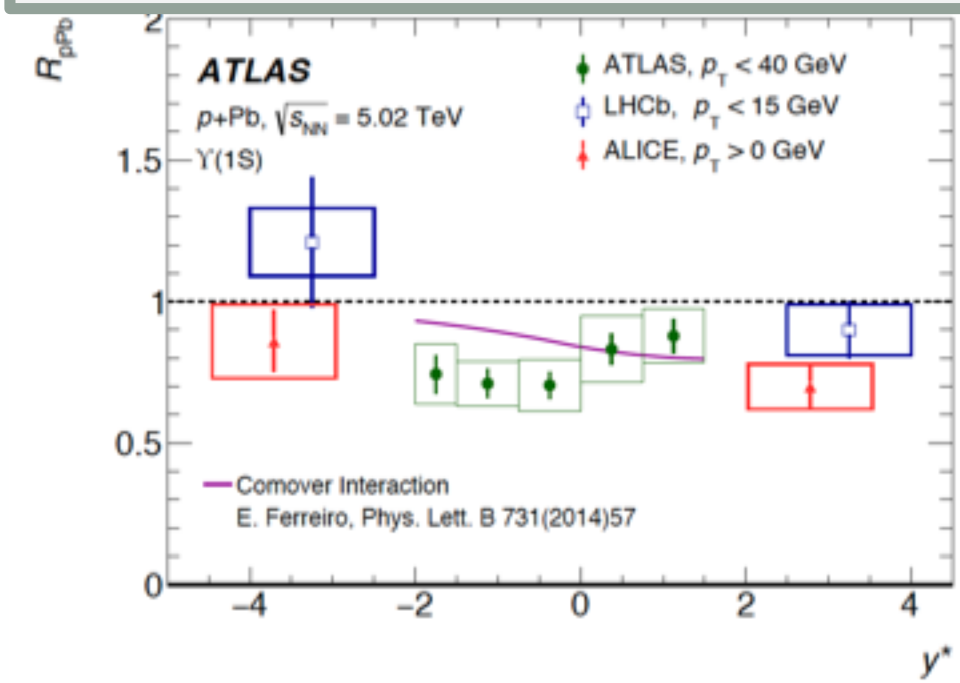
$R_{pPb} < 1$ at low p_T ➔ CNM effects are relevant in the case of Υ(1S)
Nuclear PDF are modified relative to those of the nucleon ?
This deserves additional investigations

Results: nuclear modification factor R_{pPb} for Υ(1S) production - II

Comparison with **J/ψ** ALICE data



Comparison with **Υ** ALICE and LHCb data

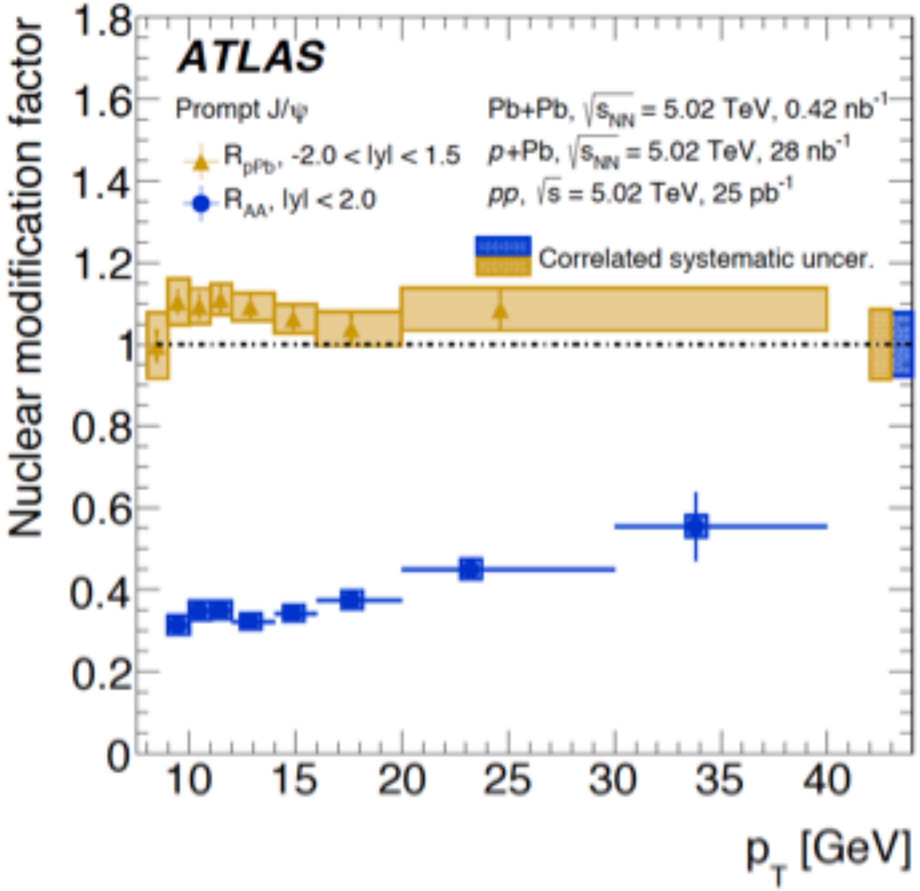


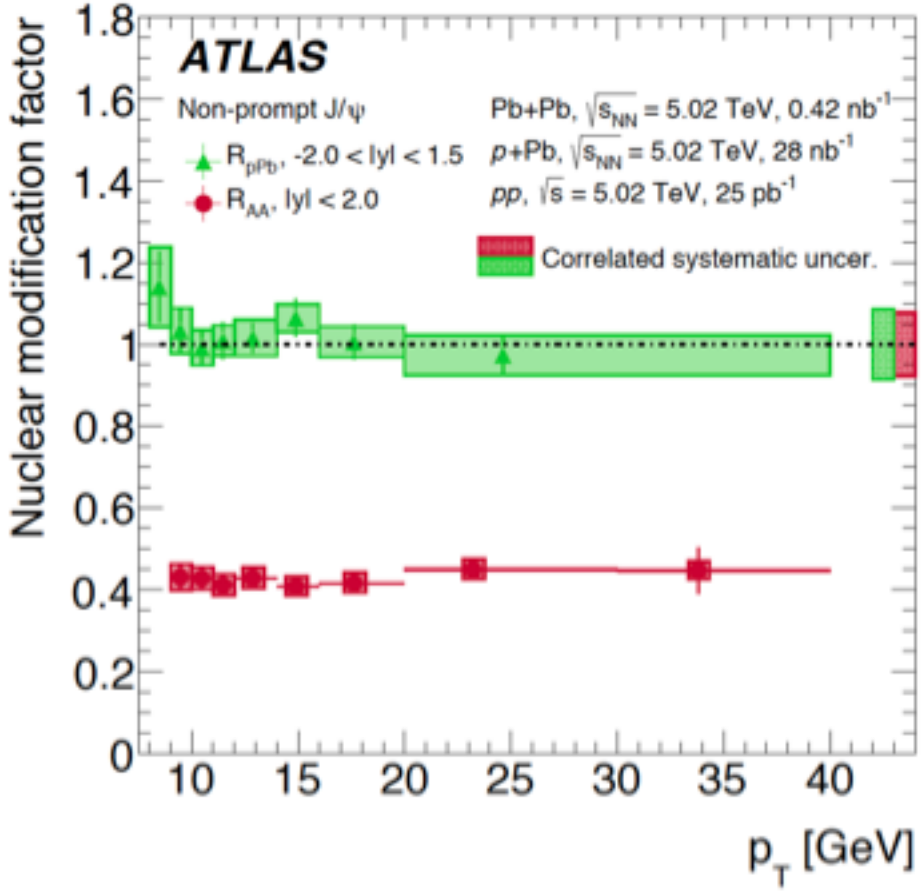
J/ψ and Υ R_{pPb} data vs. p_T compared with Alice data on Inclusive J/ψ (left)

Υ R_{pPb} data vs. y* compared to Alice and LHCb data (right) suggesting a common dependence on y*

Results: R_{pPb} compared to R_{PbPb} for J/ψ production

J/ψ: pA nuclear modification factors vs. AA nuclear modification factors

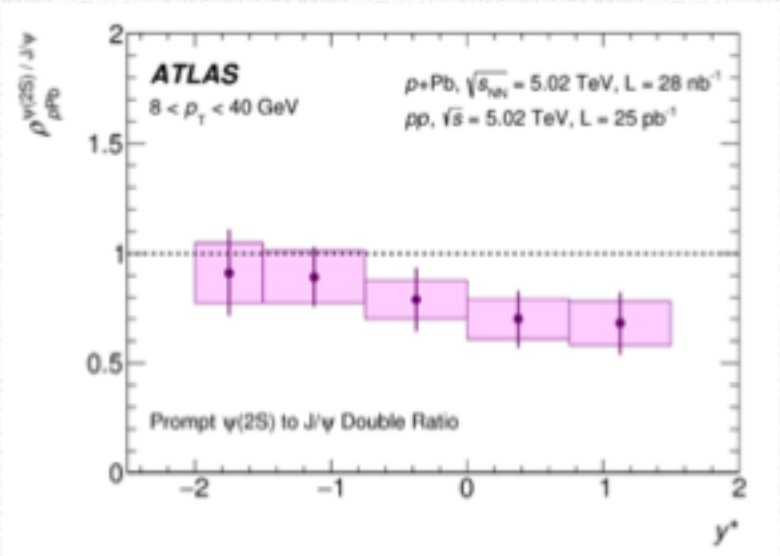


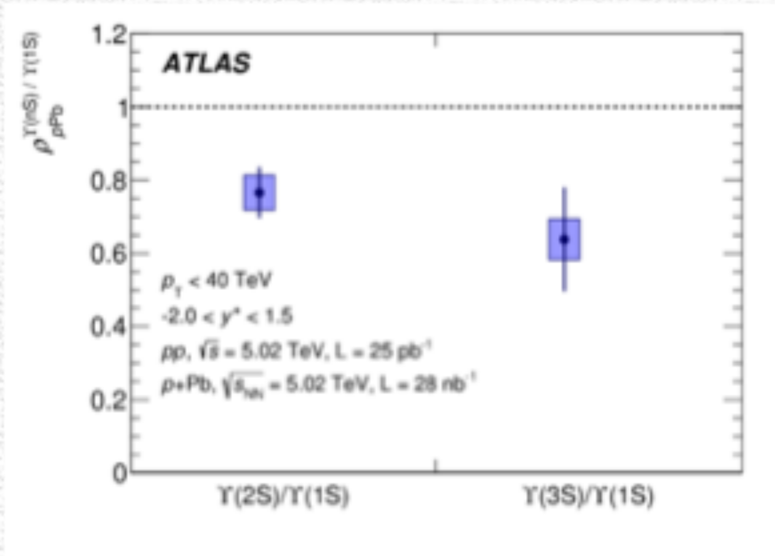


Results: prompt quarkonia double ratios

The double ratios allow to test the nuclear modification factors of excited states with respect to ground states

$$\rho_{pPb}^{O(nS)/O(1S)} = \frac{R_{pPb}(O(nS))}{R_{pPb}(O(1S))} = \frac{\sigma_{p+Pb}^{O(nS)}}{\sigma_{p+Pb}^{O(1S)}} \Big/ \frac{\sigma_{pp}^{O(nS)}}{\sigma_{pp}^{O(1S)}},$$





Significant differences from $\rho = 1$

- small effects on charmonium at y*>0
- significant effect for bottomonium excites states

DI-J/Ψ ASSOCIATED PRODUCTION

Quarkonia associated production in hadron collisions - Motivations

Quarkonia associated production → DPS vs. SPS production

DPS = Double Parton Scattering

SPS = Single Parton Scattering

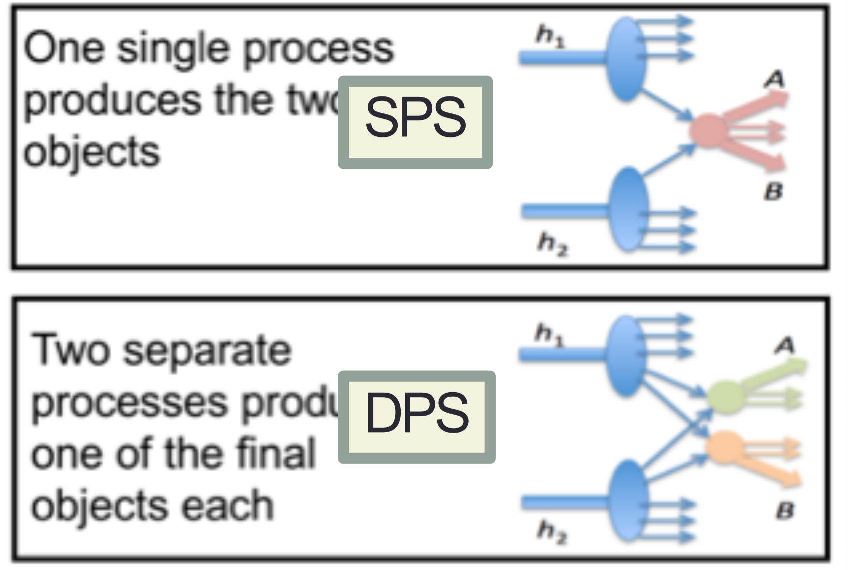
W+J/ψ and Z+J/ψ associated production

di-J/ψ production at 8 TeV

four-jets production

➔ Estimate of σ_{eff}

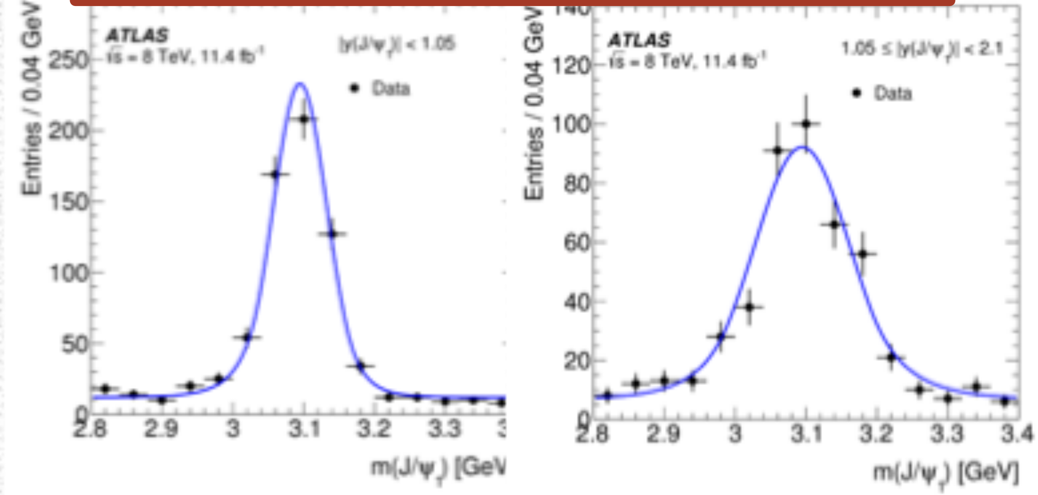
$$\sigma^{DPS}_{(hh' \to ab)} = \left(\frac{m}{2}\right) \frac{\sigma^{SPS}_{(hh' \to a)} \sigma^{SPS}_{(hh' \to b)}}{\sigma_{eff}}$$



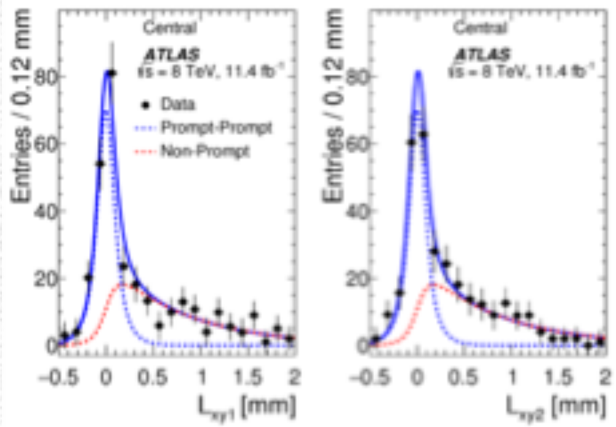
Results: di-J/ψ production at 8 TeV - I

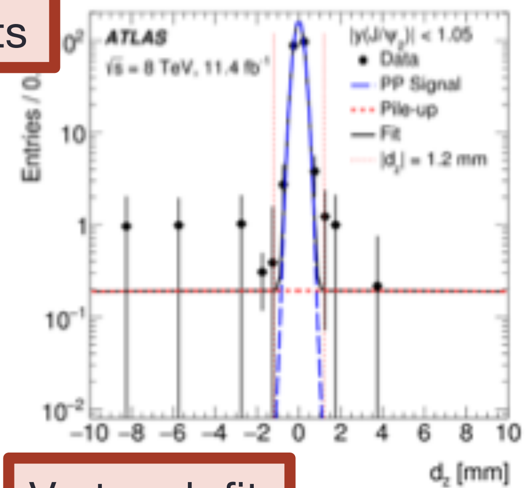
- Aim: select events with two prompt J/ψ → μμ decays from the same pp collision
- Step1) Select di-J/ψ events➔ *Invariant mass* fits
  J/ψ1 – leading, J/ψ2 – subleading
- Step2) Select Prompt-Prompt di-J/ψ ➔ *Pseudo-proper decay time* fits
- Step3) Select Prompt-Prompt di-J/ψ from same vertex ➔ *vertex d_z* fit (pile-up removal)
- ➔ 1170 events selected

Invariant mass fits in two rapidity regions



Pseudo-proper decay time fits





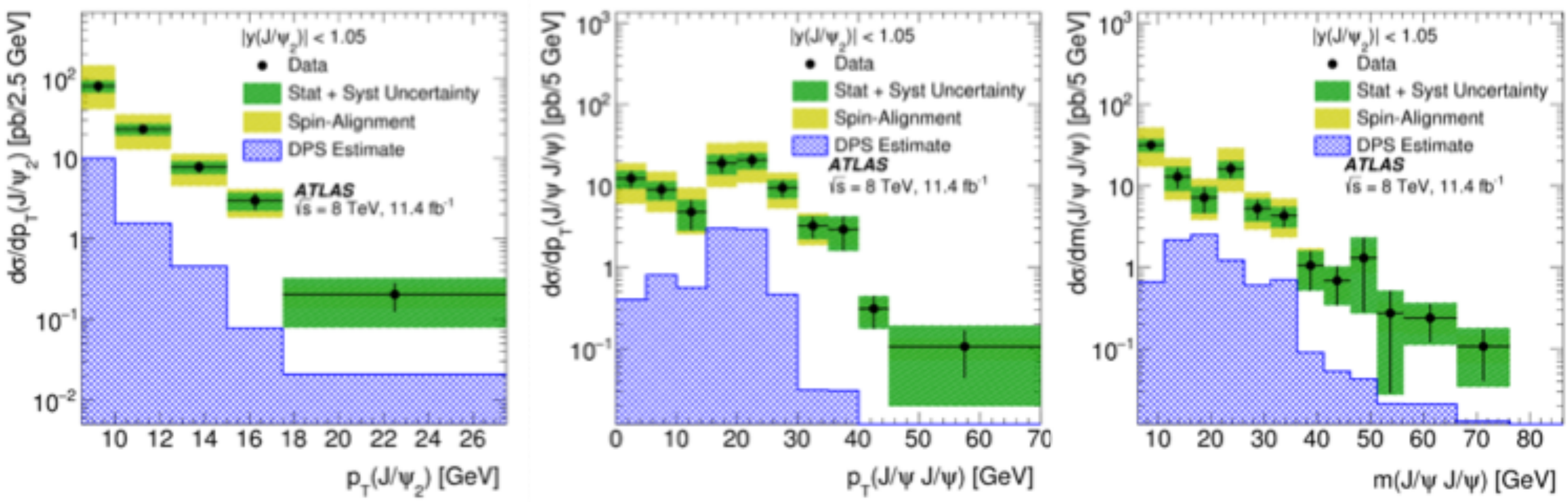
Vertex d_z fit

Results: di-J/ψ production at 8 TeV - II

Fiducial cross-section measurement in two rapidity regions of J/ψ_2

(Fiducial region = $p_T(J/\psi_2)>8.5$ GeV, $|y(J/\psi_2)|<2.1$, $p_T(\mu)>2.5$ GeV, $|\eta(\mu)|<2.3$)

$$\sigma_{\mathrm{Fid}}(pp \to J/\psi J/\psi + X) = \begin{cases} 15.6 \pm 1.3\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) \pm 0.2\,(\mathrm{BF}) \pm 0.3\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } |y| < 1.05, \\ 13.5 \pm 1.3\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst}) \pm 0.2\,(\mathrm{BF}) \pm 0.3\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } 1.05 \le |y| < 2.1. \end{cases}$$



Extrapolating to the full muon acceptance (assuming unpolarized J/ψ)

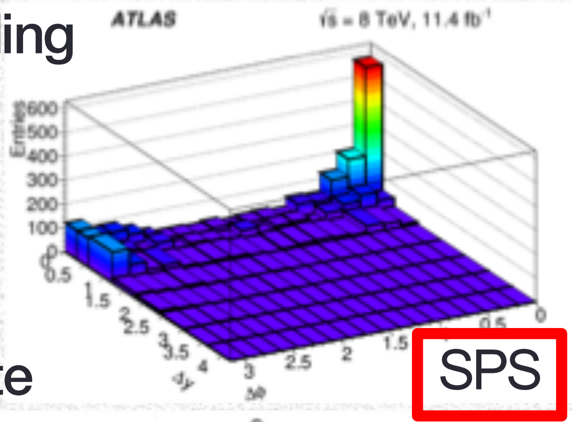
$$\sigma(pp \to J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3\,(\mathrm{stat}) \pm 6.3\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 1.6\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } |y| < 1.05, \\ 78.3 \pm 9.2\,(\mathrm{stat}) \pm 6.6\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{pb}, & \text{for } 1.05 \le |y| < 2.1. \end{cases}$$

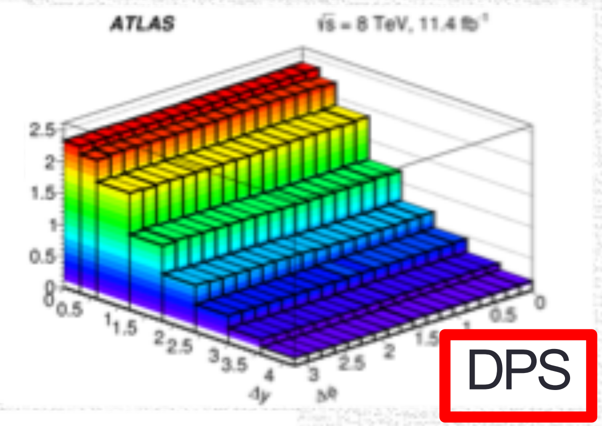
Results: di-J/ψ production at 8 TeV - III

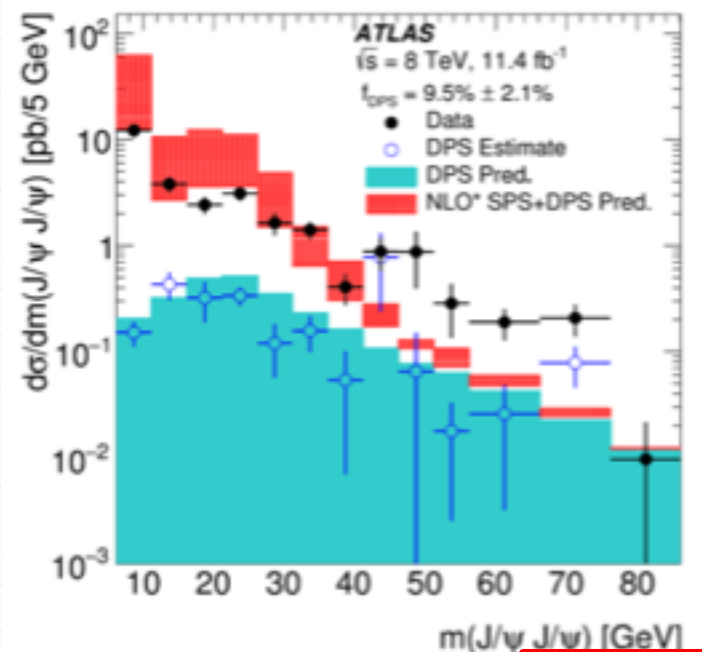
DPS vs. SPS disentangling is possible in the $\Delta y - \Delta\phi$ plane

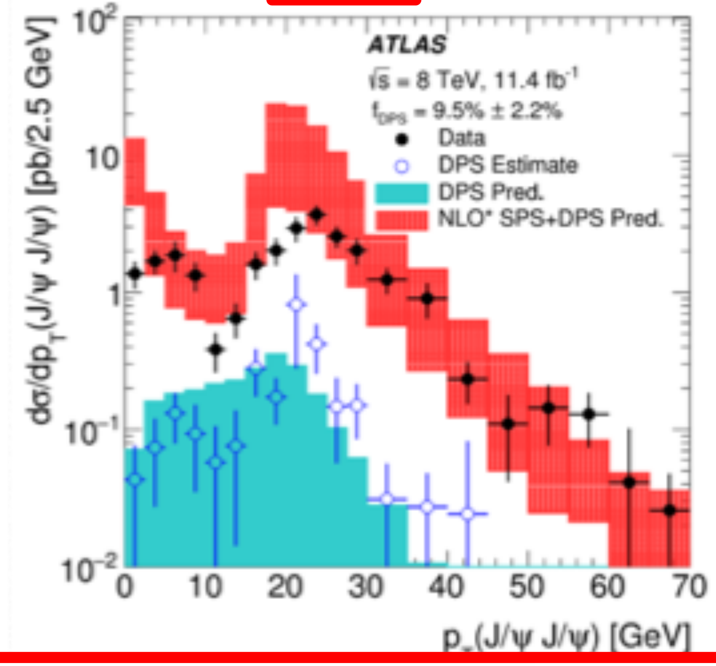
➔ Every event is weighted according to its position in the $\Delta y - \Delta\phi$ plane

Total cross-section and estimated DPS cross-section vs. m(J/ψJ/ψ) and p_T(J/ψJ/ψ) and comparison with NLO*estimate









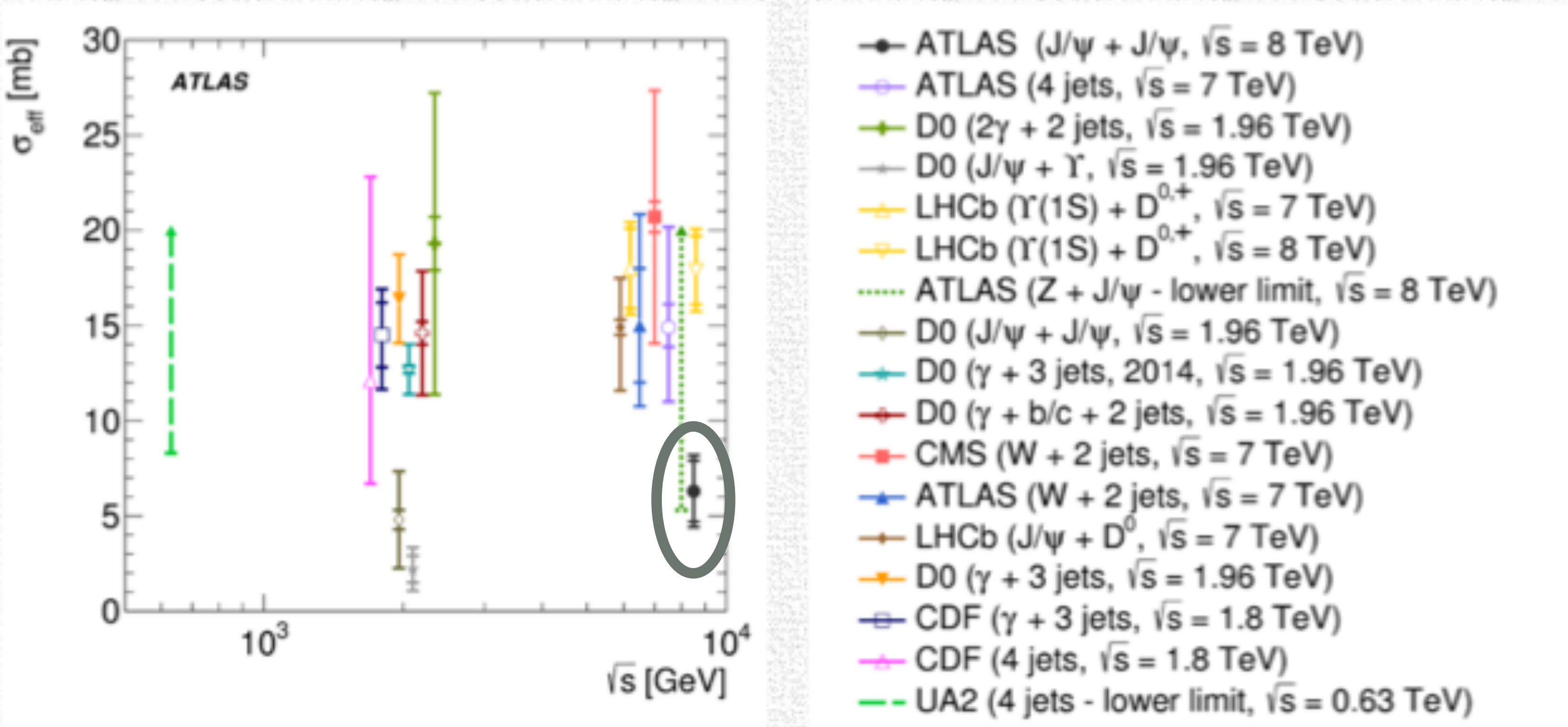
$f_{\mathrm{DPS}} = (9.2 \pm 2.1\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst}))\%.$

$\sigma^{J/\psi, J/\psi}_{\mathrm{DPS}} = 14.8 \pm 3.5\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}) \pm 0.2\ (\mathrm{BF}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb}.$

DPS vs. SPS – summary of σ_{eff} estimates

Estimate of σ_{eff} from this analysis and comparison with other estimates

$$\sigma_{eff} = 6.3 \pm 1.6\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 0.1\,(\text{BF}) \pm 0.1\,(\text{lumi})\ \text{mb.}$$



In general, results based on di-quarkonia production give lower values of σ_{eff}

Not included in the list:

CMS di-J/ψ : 8.2 mb

CMS di-ϒ : 2.2 – 6.6 mb

Summary

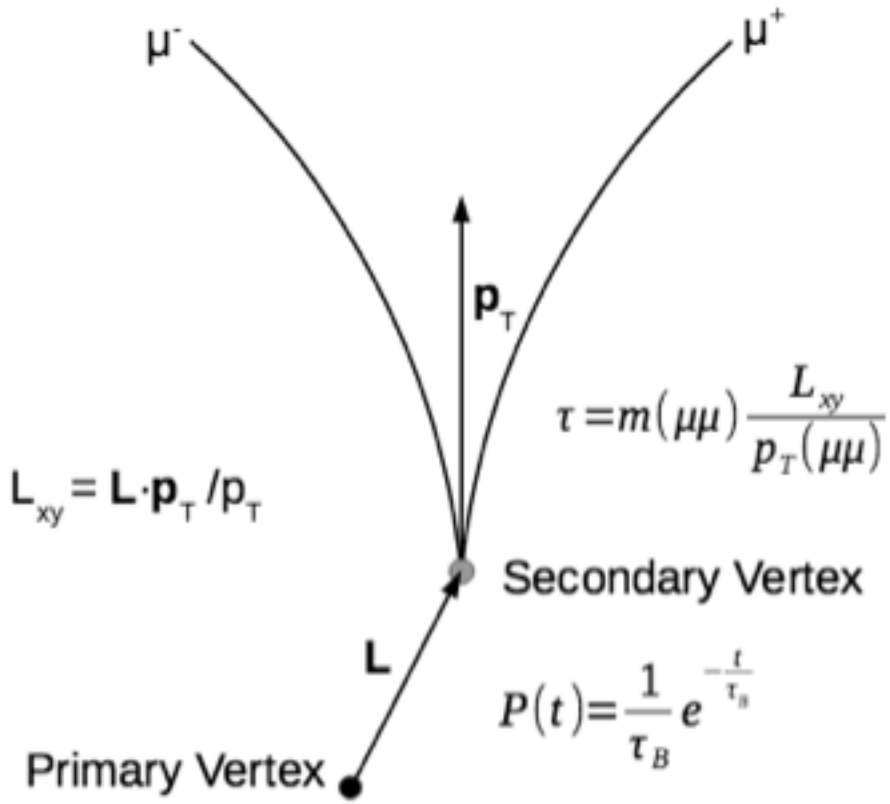
- Quarkonia production in pp, pPb and PbPb collisions
  - J/ψ, $\psi(2S)$ production well described by NLO NRQCD and FONNL
  - $\Upsilon(1S)$ below p_T<15 GeV deviates from NLO NRQCD
  - R_{pPb} ~ 1 for charmonium and < 1 for bottomonium (at low p_T)
  - Sizeable suppression in PbPb collisions is observed
- Prompt di-J/ψ production in pp collisions at 8 TeV:
  - Differential cross-section measured in a wide kinematic range
  - ~ 9% of the cross-section is estimated to be due to DPS
  - Good description by NLO* estimates (LO DPS + NLO (CS) SPS)
  - σ_{eff} below previous estimates

BACKUP

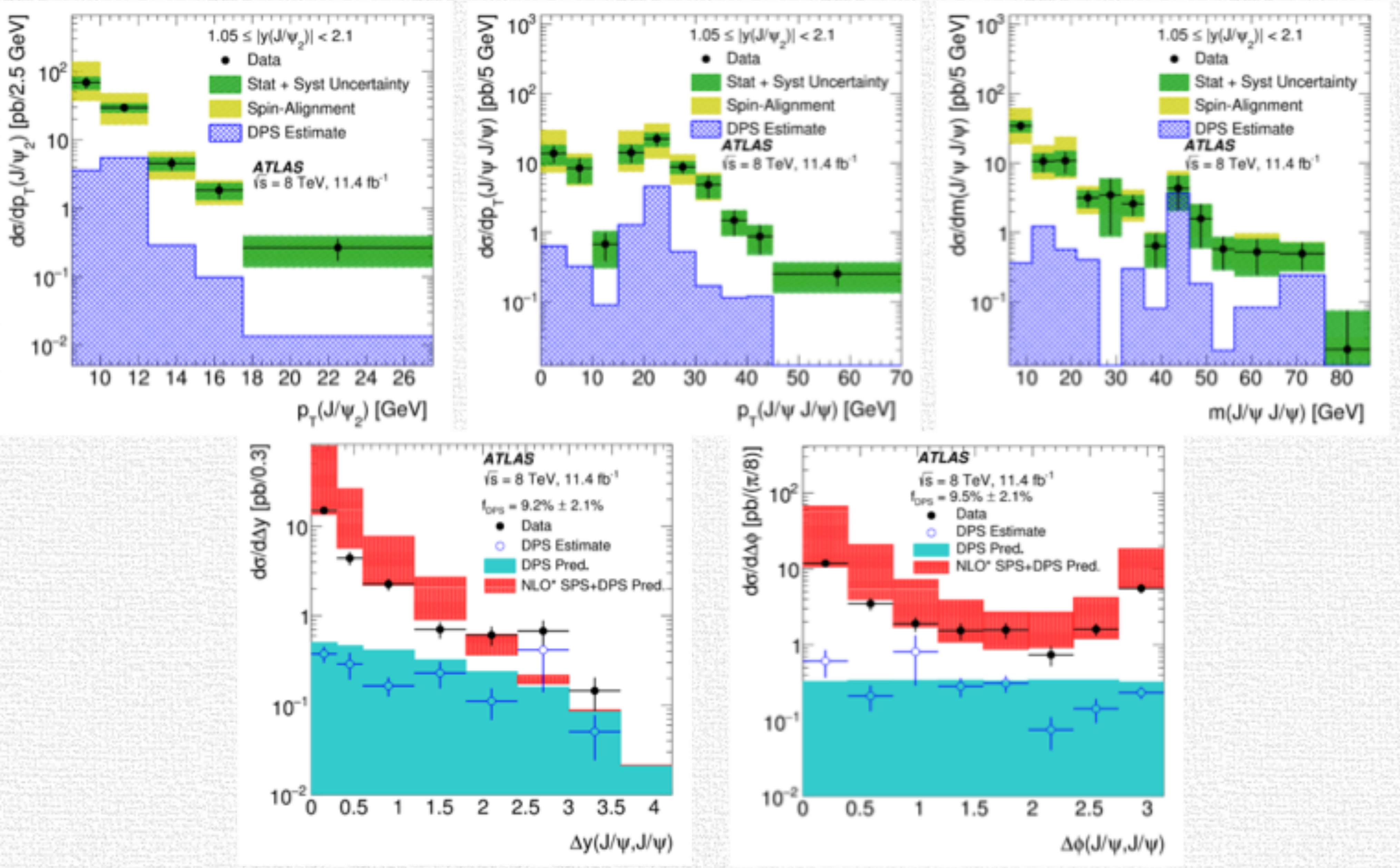
Measuring the Pseudo-proper Decay Time

Pseudo-proper Decay Time

- Distinguishes non-prompt and prompt sources
- **L**: distance from the primary vertex to the secondary vertex
- Use signed L_{xy} as a proxy for *b*-hadron decay length
- Good approximation when ψ momentum and *b*-hadron momentum are aligned



di-J/ψ measurement: additional plots



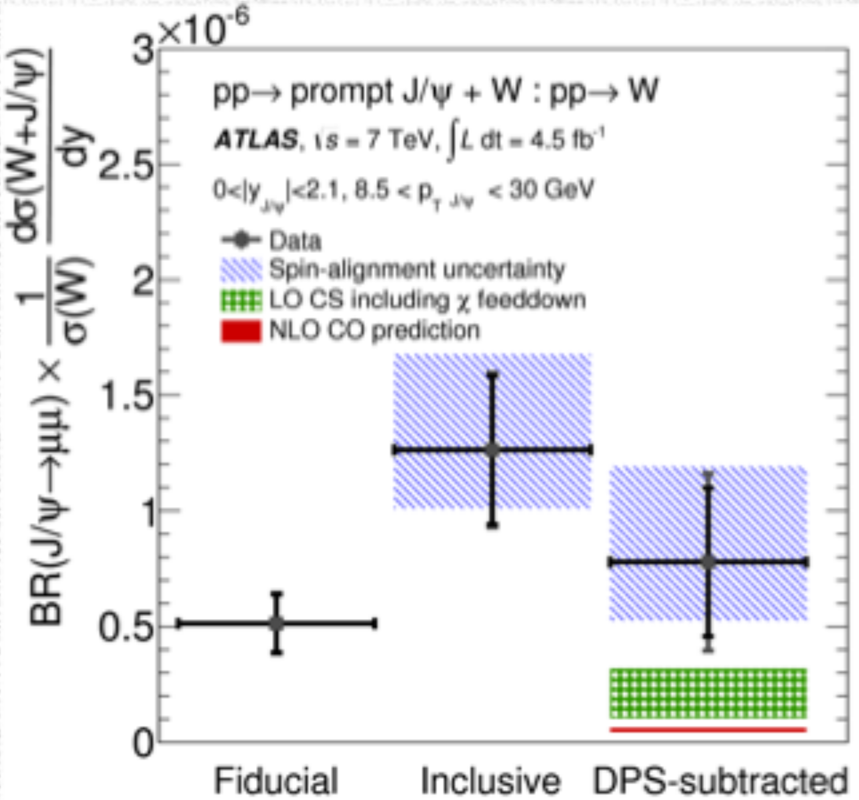
di-J/ψ measurement: systematic uncertainties

Systematic uncertainty: di-J/ψ cross-section [%]		
Source	$\lvert y(J/\psi_2)\rvert < 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Trigger	±7.5	±8.3
Muon reconstruction	±1.1	±1.3
Kinematic acceptance	±0.4	±1.1
Mass model	±0.1	±0.1
Mass bias	±0.2	±0.2
Prompt–prompt model	±0.2	±0.01
Differential f_{PP} corr.	±0.6	±0.3
Pile-up	±0.03	±0.4
Total	± 7.7	± 8.5
Branching fraction	±1.1	
Luminosity	±1.9	

Systematic uncertainty: f_{DPS} [%]	
Source	Relative uncertainty [%]
Trigger	±0.7
Muon reconstruction	±0.1
Mass model	±0.01
Mass bias	±0.02
Prompt–prompt model	±0.1
Differential f_{PP} corr.	±0.1
Pile-up	±0.8
DPS model	±5.6
Total	± 5.7

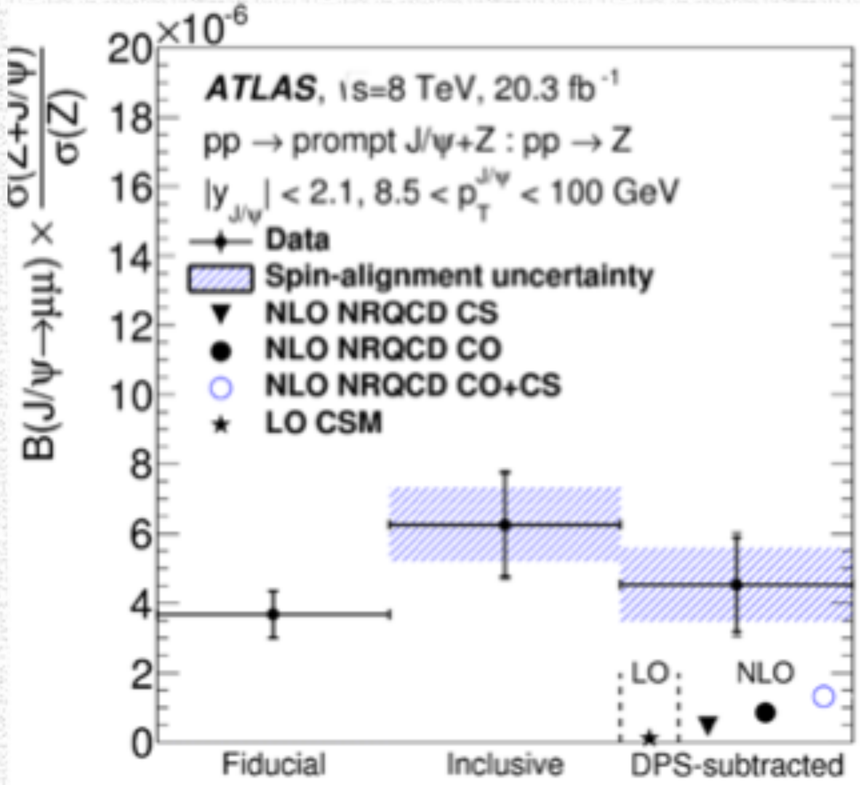
Measurement of associated production of the J/ψ with vector bosons W and Z

J/ψ +W: DPS-subtracted cross-section compared to CS and CO production models



See *JHEP 04 (2014) 172*

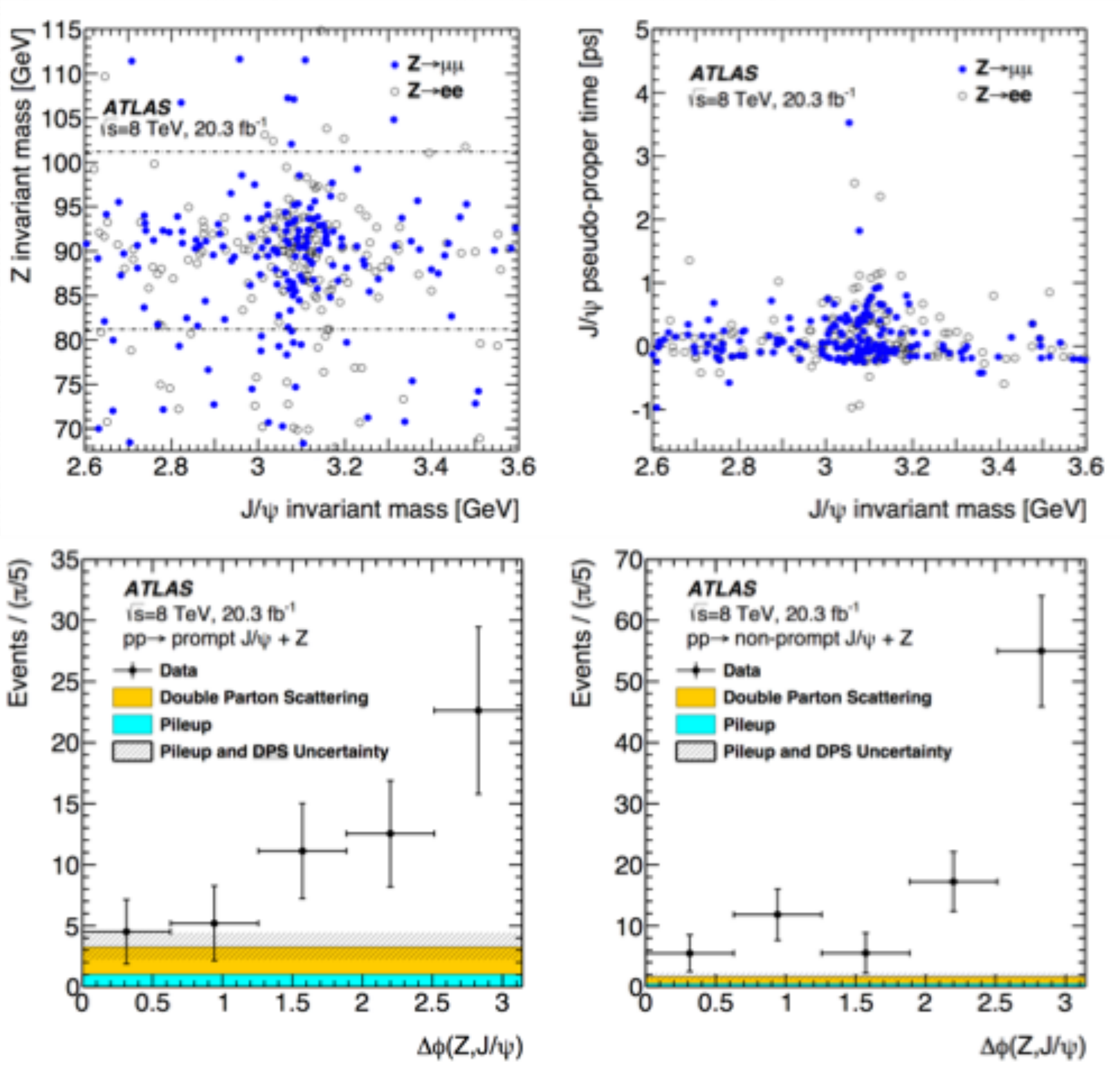
J/ψ +Z: DPS-subtracted cross-section compared to NLO NRQCD and LO CSM production models



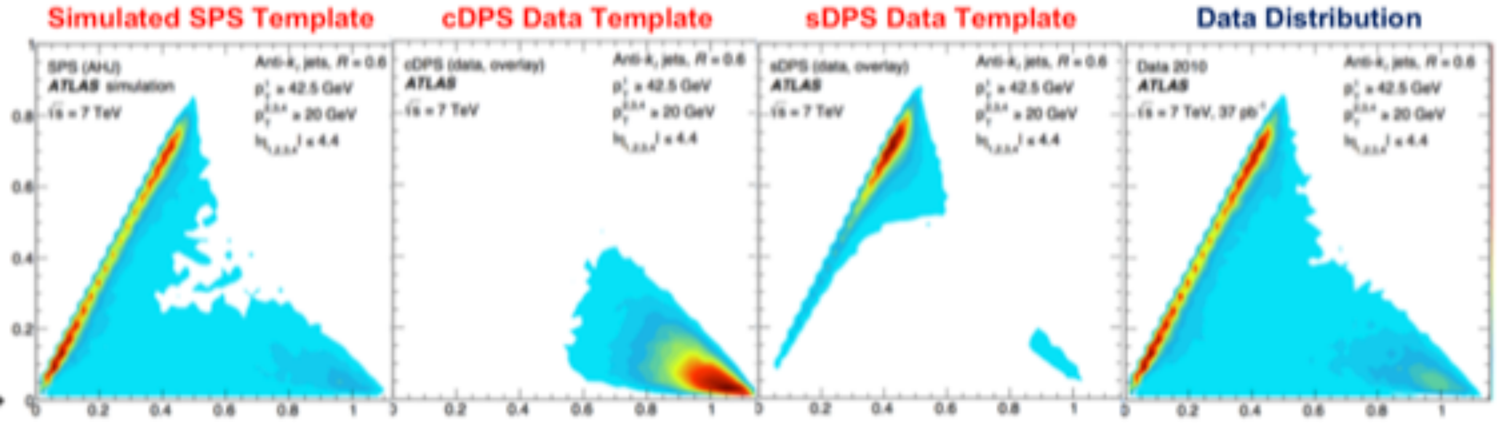
See *Eur. Phys. J. C75 (2015) 229*

No model describes the large values of the associated production

Z+J/ψ: selection and DPS estimate



Results: 4-jets analysis



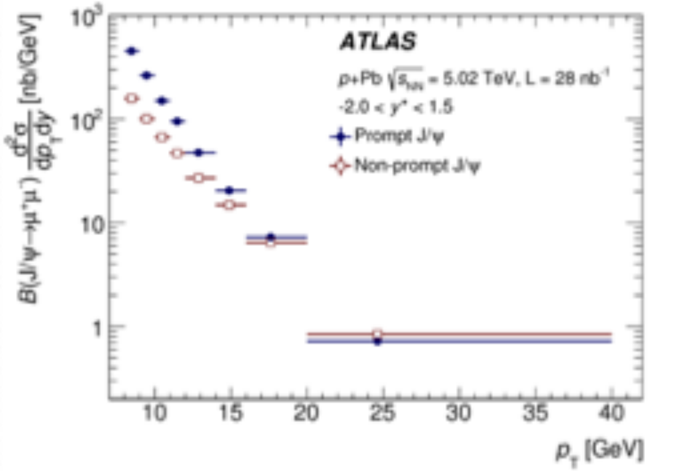
- Fit data using the three templates above:

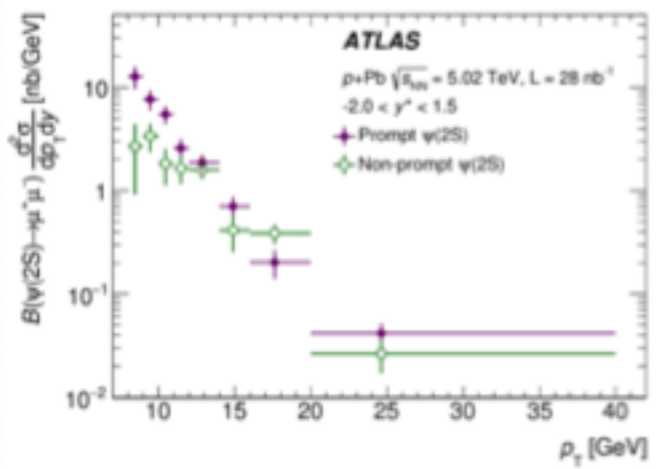
$$f_{\text{DPS}} = 0.092\ ^{+0.005}_{-0.011}\ (\text{stat.})\ ^{+0.033}_{-0.037}\ (\text{syst.})$$

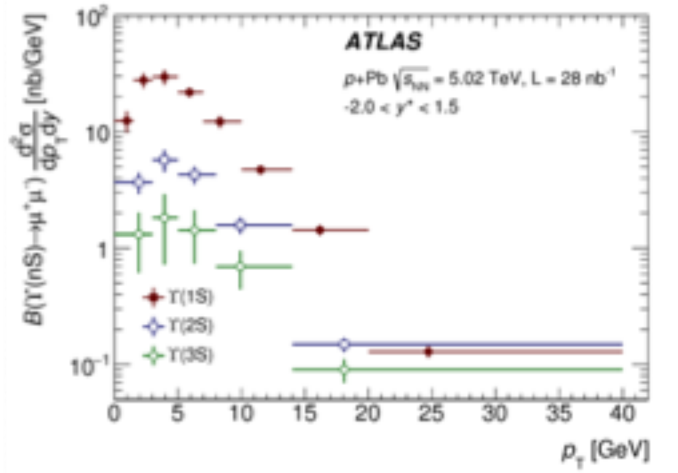
$$\sigma_{\text{eff}} = 14.9\ ^{+1.2}_{-1.0}\ (\text{stat.})\ ^{+5.1}_{-3.8}\ (\text{syst.})\ \text{mb}$$

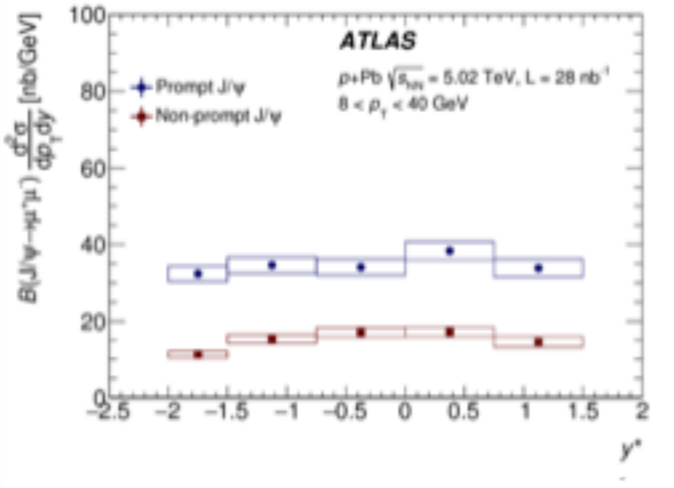
Source of systematic uncertainty	Δf_{DPS}	$\Delta\alpha^{4j}_{2j}$	$\Delta\sigma_{\text{eff}}$
Luminosity			±3.5 %
Model dependence for detector corrections		±2 %	±2 %
Reweighting of AHJ	±6 %		±6 %
Jet reconstruction efficiency			±0.1 %
Single-vertex events selection			±0.1 %
Jet energy and angular resolution	±15 %	±3 %	±15 %
JES uncertainty	$^{+32}_{-37}$ %	±12 %	$^{+31}_{-19}$ %
Total systematic uncertainty	$^{+36}_{-40}$ %	±13 %	$^{+35}_{-25}$ %

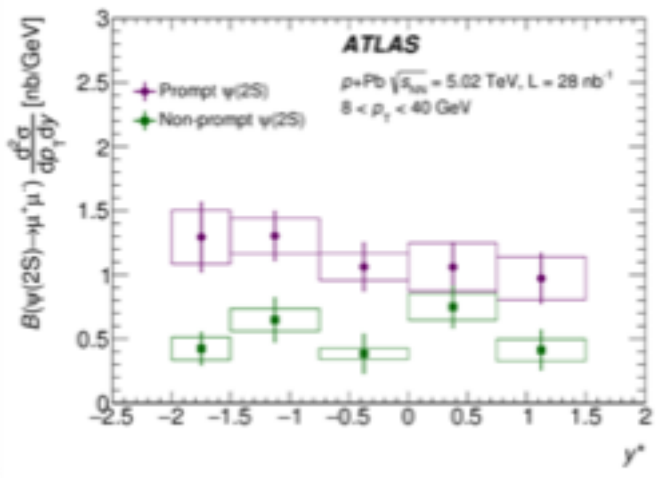
Quarkonia production on pPb collisions: additional plots - I

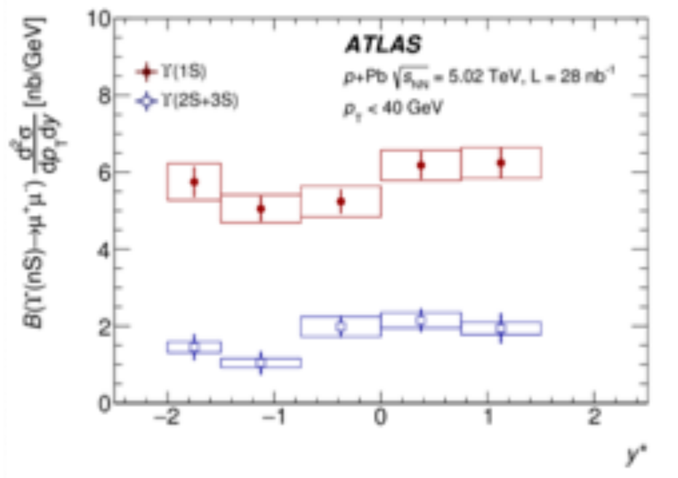




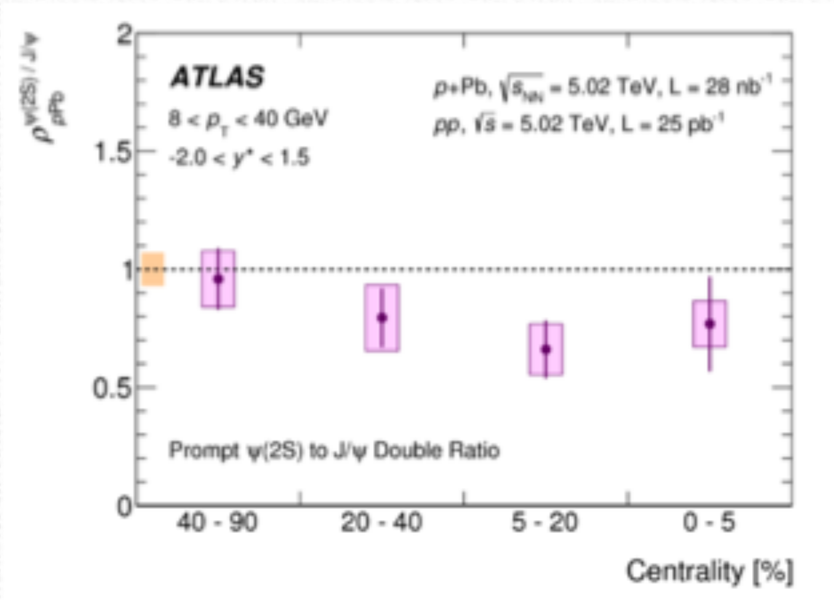


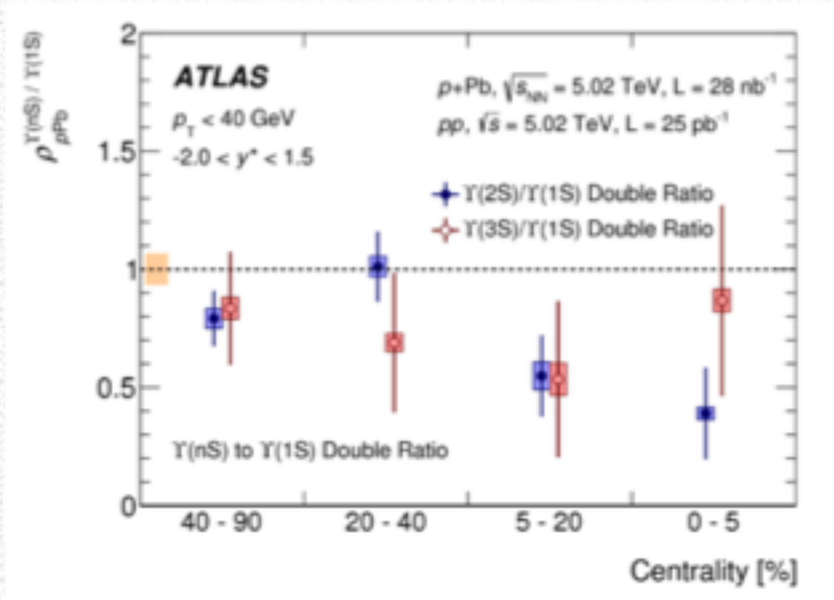






Quarkonia production on pPb collisions: additional plots - II



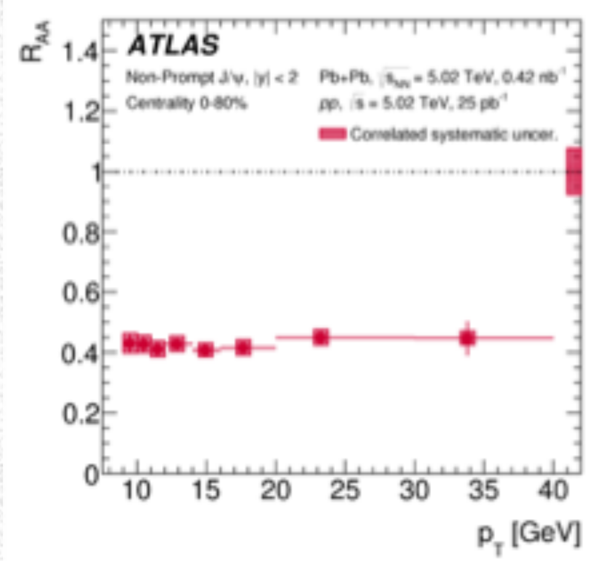


Quarkonia production on pPb collisions: systematics

Collision type	Source	Ground-state yield [%]	Excited-state yield [%]	Ratio [%]
collisions	Luminosity	2.7	2.7	–
	Acceptance	1–4	1–4	–
	Muon reco.	1–2	1–2	<1
	Muon trigger	4–5	4–5	<1
	Charmonium fit	2–5	4–10	7–15
	Bottomonium fit	2–15	2–15	5–12
pp collisions	Luminosity	5.4	5.4	–
	Acceptance	1–4	1–4	–
	Muon reco.	1–5	1–5	<1
	Muon trigger	5–7	5–7	<1
	Charmonium fit	2–7	4–10	7–11
	Bottomonium fit	1–15	2–15	5–12

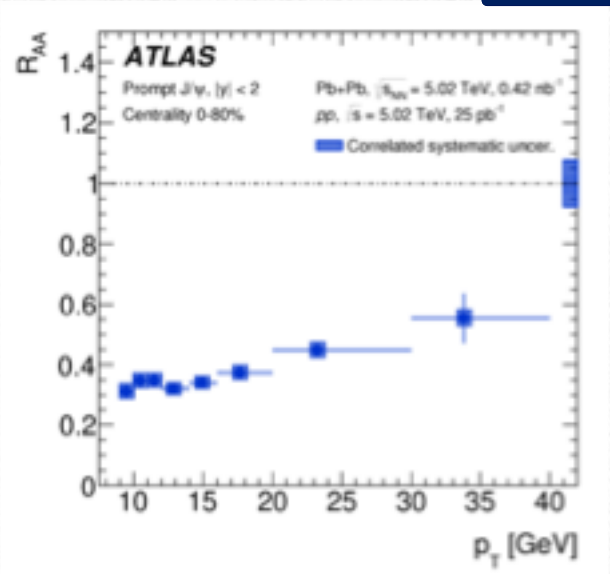
Results: nuclear modification factor R_{PbPb} for J/ψ production

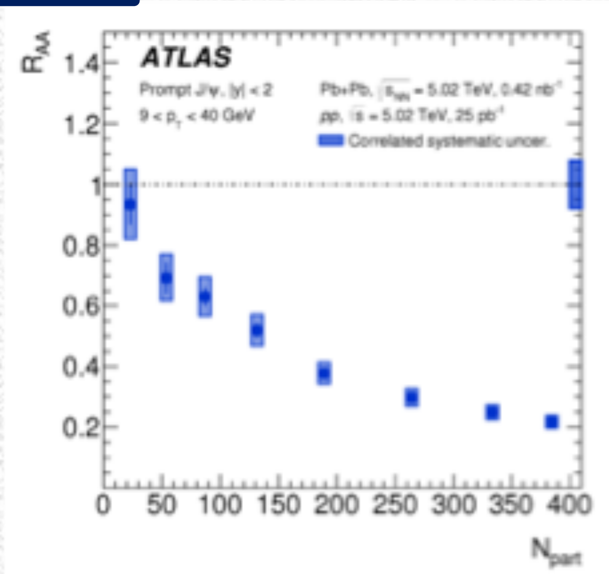
Non-Prompt J/ψ

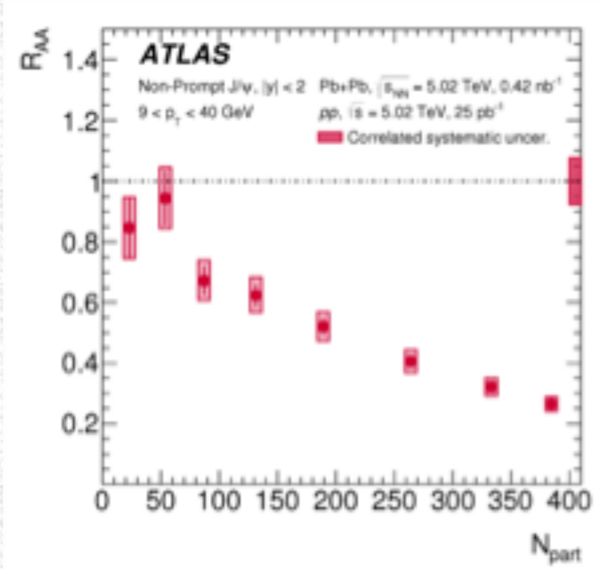


- Strong suppression of prompt and non-prompt J/ψ and ψ(2S) observed in Pb+Pb data.
- Maximal suppression for the most central collisions.
- Same R_{AA} vs centrality dependence for prompt and non-prompt J/ψ.

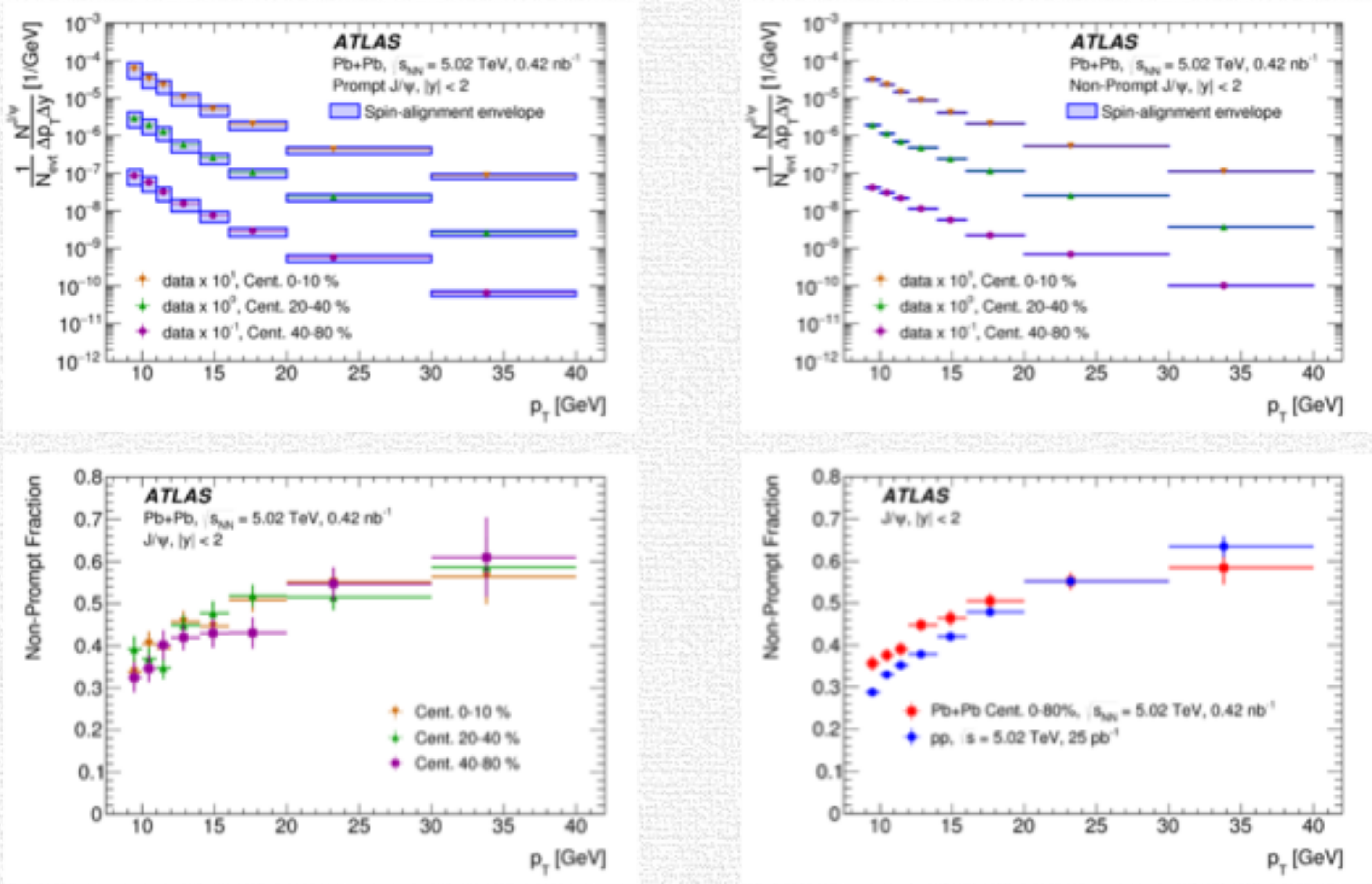
Prompt J/ψ



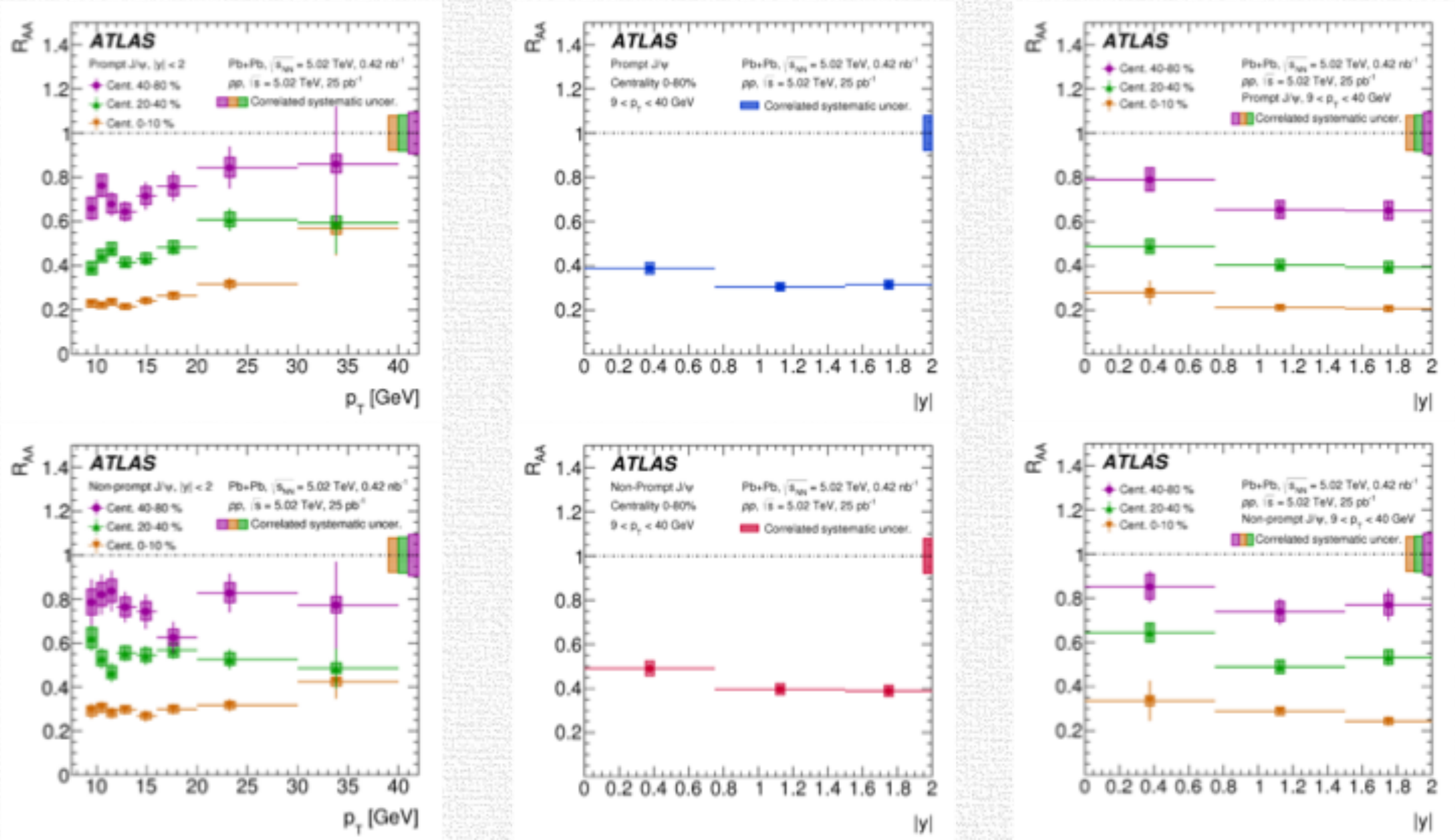




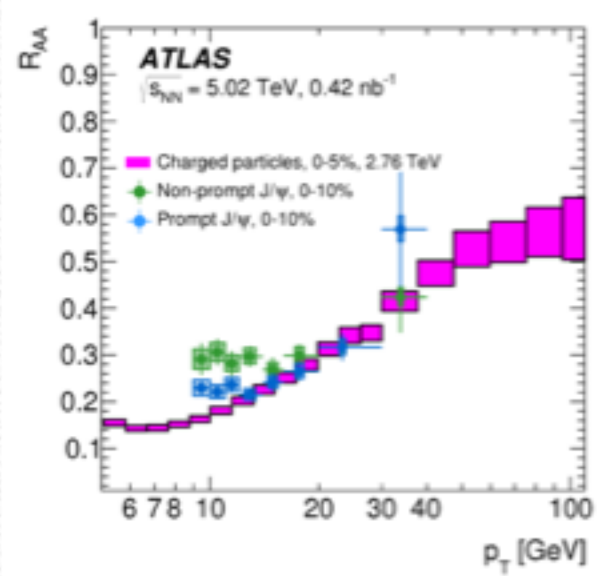
Quarkonia production in PbPb collisions: additional plots - I

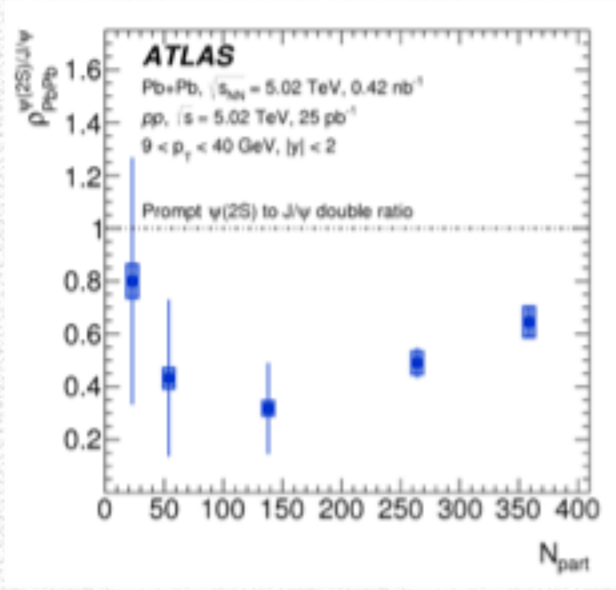


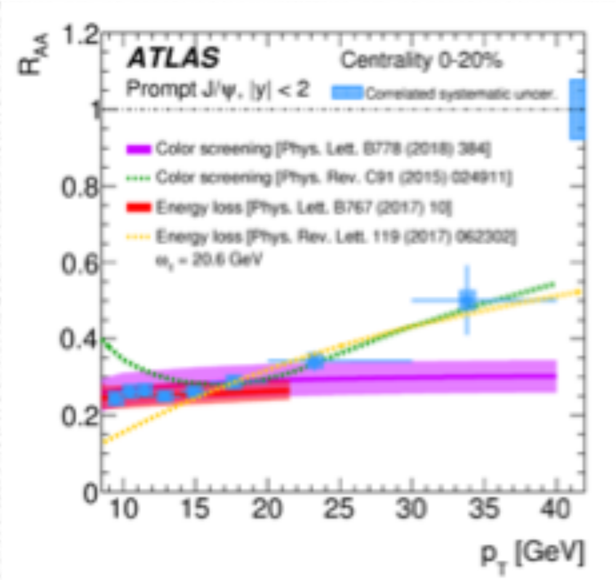
Quarkonia production in PbPb collisions: additional plots - II

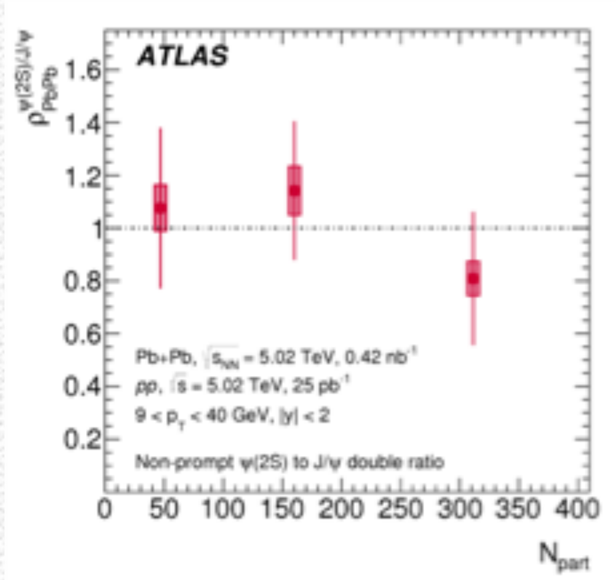


Quarkonia production in PbPb collisions: additional plots - III

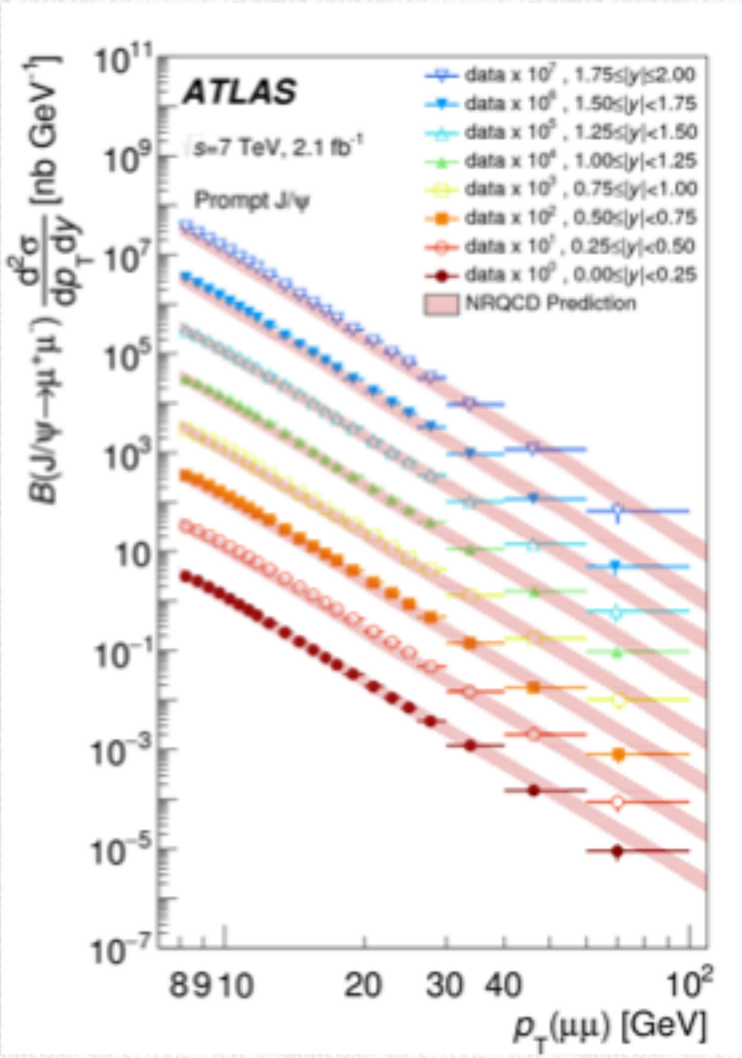


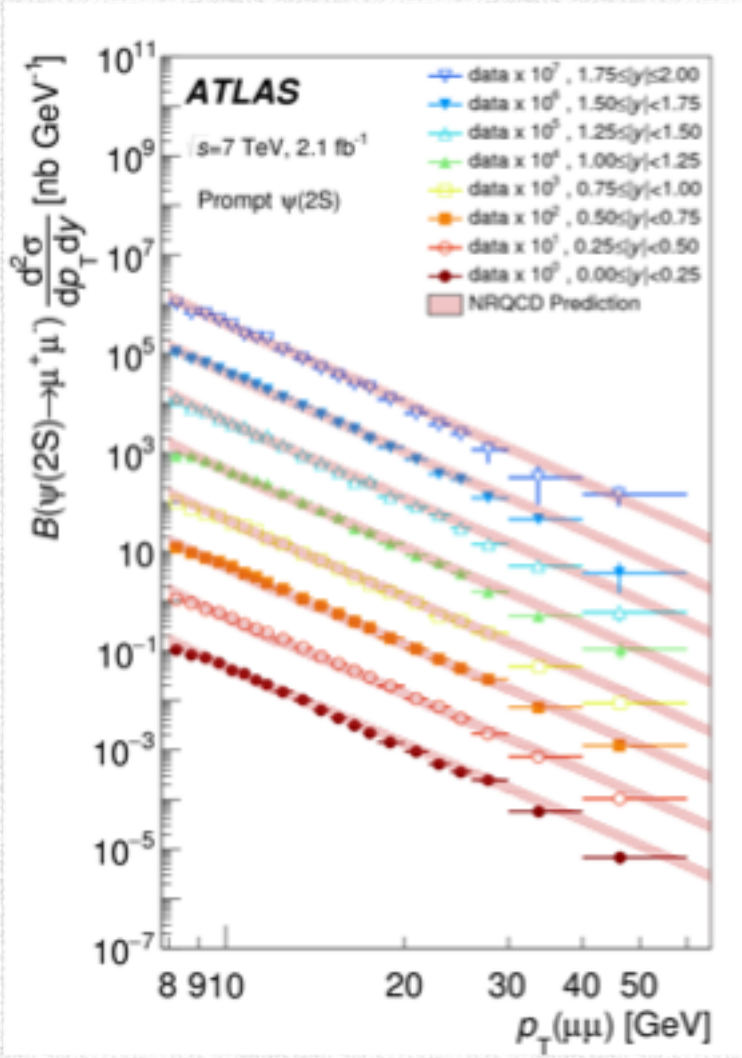






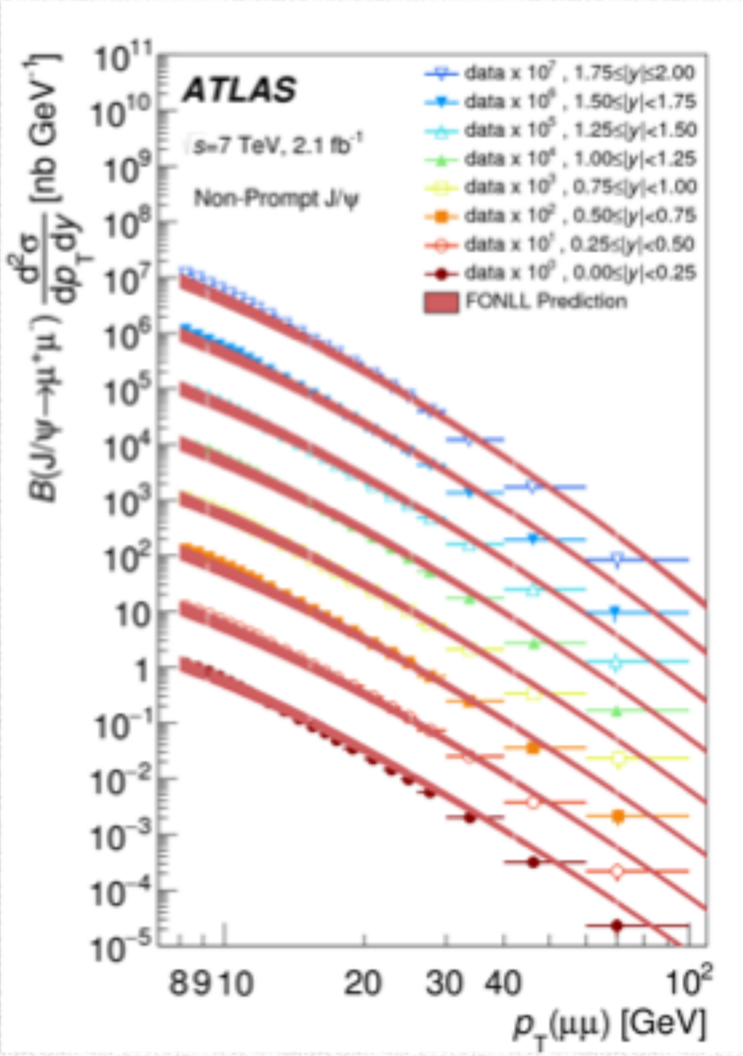
Results – I: prompt production cross-sections vs. $p_T(\mu\mu)$ and |y|. Comparison with NRQCD predictions

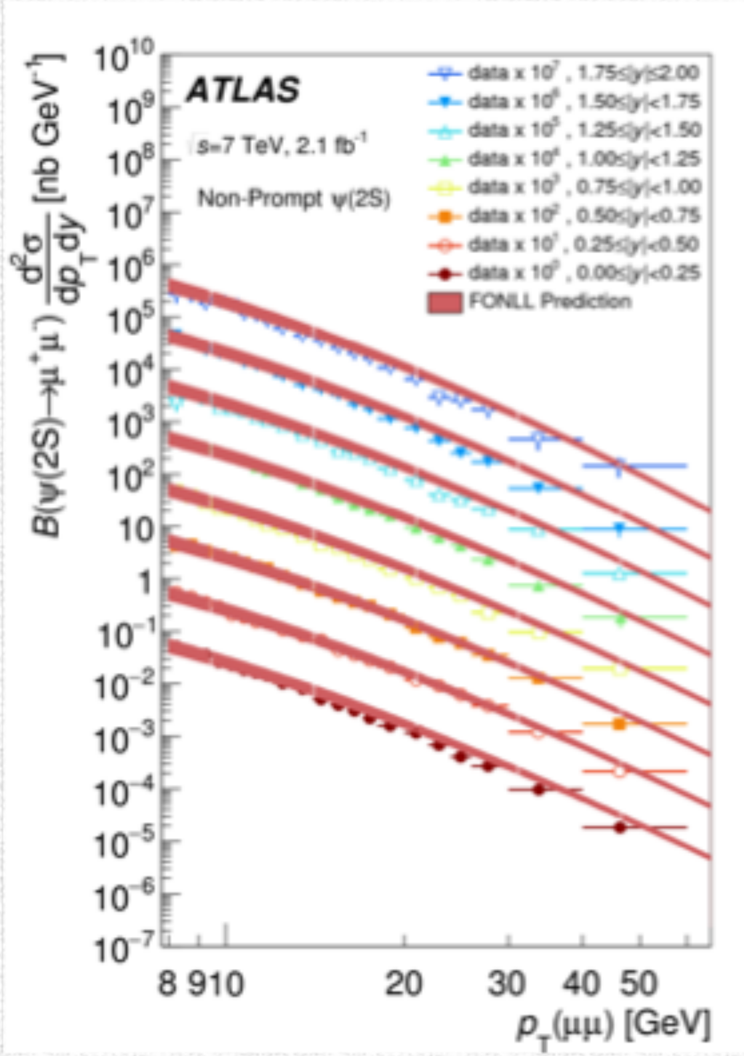




Fair agreement with NRQCD (based on LDMEs) in the whole p_T - |y| range.

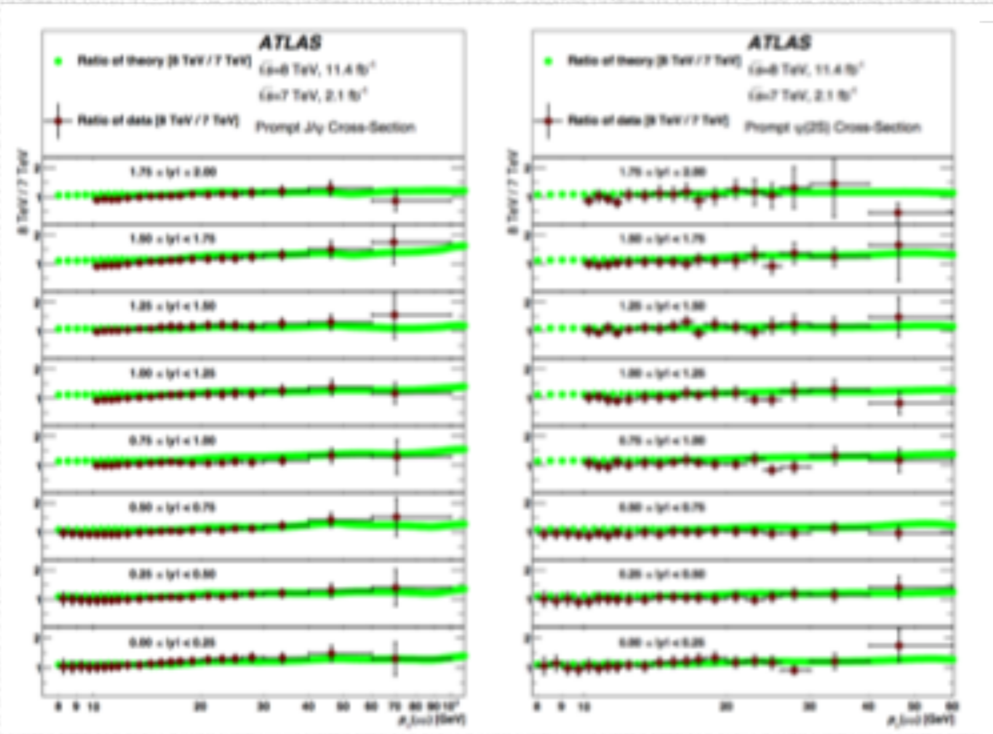
Results – II: non-prompt production cross-section vs. $p_T(\mu\mu)$ and $|y|$. Comparison with FONLL predictions

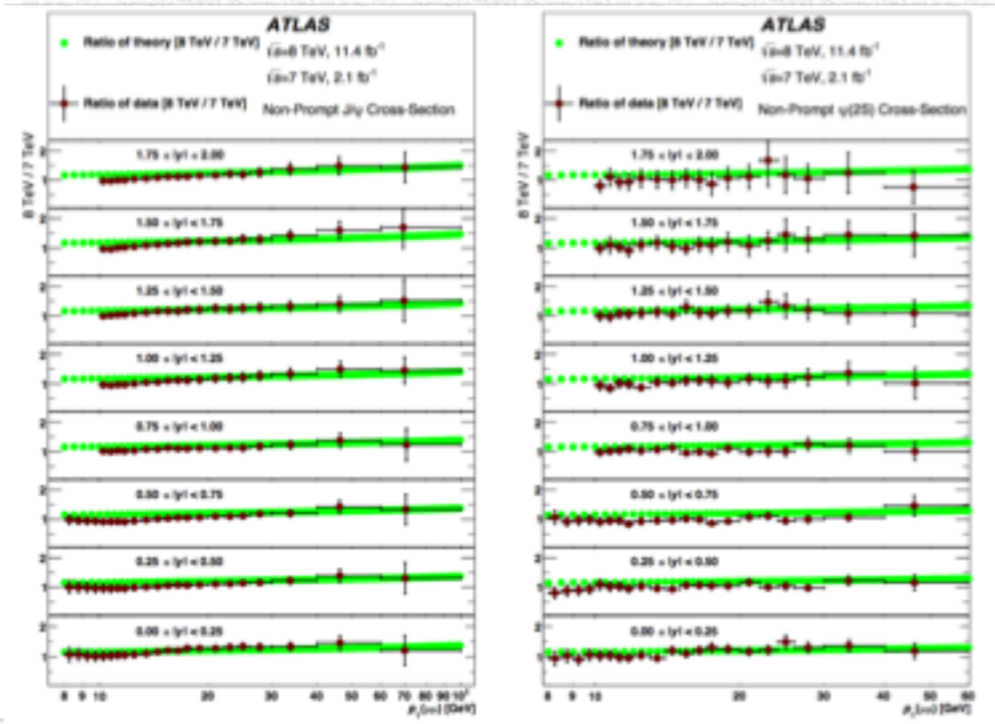




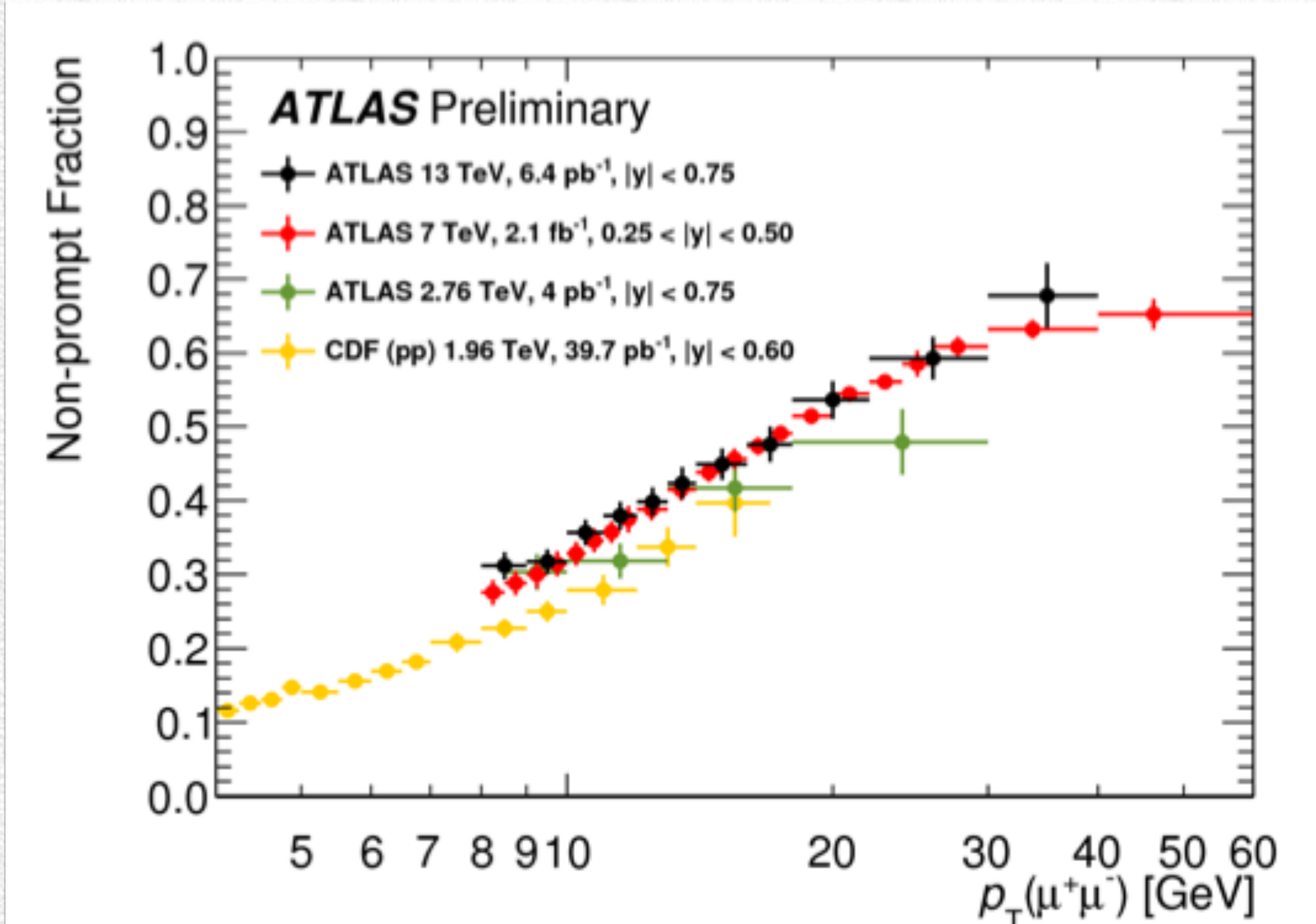
Theory predicts: for J/ψ a slightly harder p_T spectrum; for ψ(2S) higher yields wrt data

Results: scaling 7-8 TeV





Results: non-prompt J/ψ fraction vs. $p_T(\mu\mu)$ from $\sqrt{s}$ = 2.76 to 13 TeV compared with CDF at $\sqrt{s}$=1.96 TeV

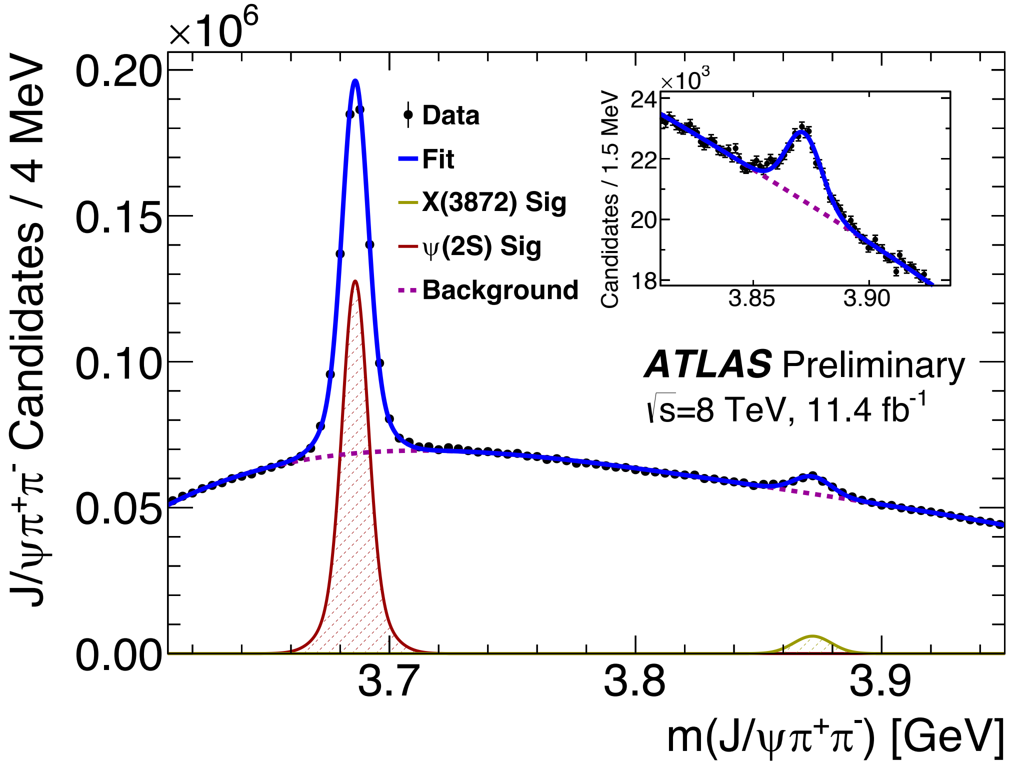


No significant difference btw $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 13 TeV data.
Significant difference btw the $\sqrt{s}$ = 7 TeV data and lower $\sqrt{s}$ data.

Production measurements of $\psi(2S)$ and X(3872) decaying to $J/\psi\, \pi^+\pi^-$ at $\sqrt{s}$ = 8 TeV

- Data sample
  - 11.4 fb^{-1} @ 8 TeV
- Search in the $J/\psi\, \pi^+\pi^-$ with $J/\psi \rightarrow \mu\mu$ channel:
  - Dimuon trigger (p_T>4GeV)
  - Measurement of proper decay time ➔ prompt/non-prompt discrimination
  - Attempt to discriminate short and long lifetime components for X(3872)
  - Analysis of $m(\pi\pi)$ spectra
- Analysis vs. p_T and y in the range |y|<0.75 and $10<p_T<70$ GeV

See **ATLAS-CONF-2016-028**.

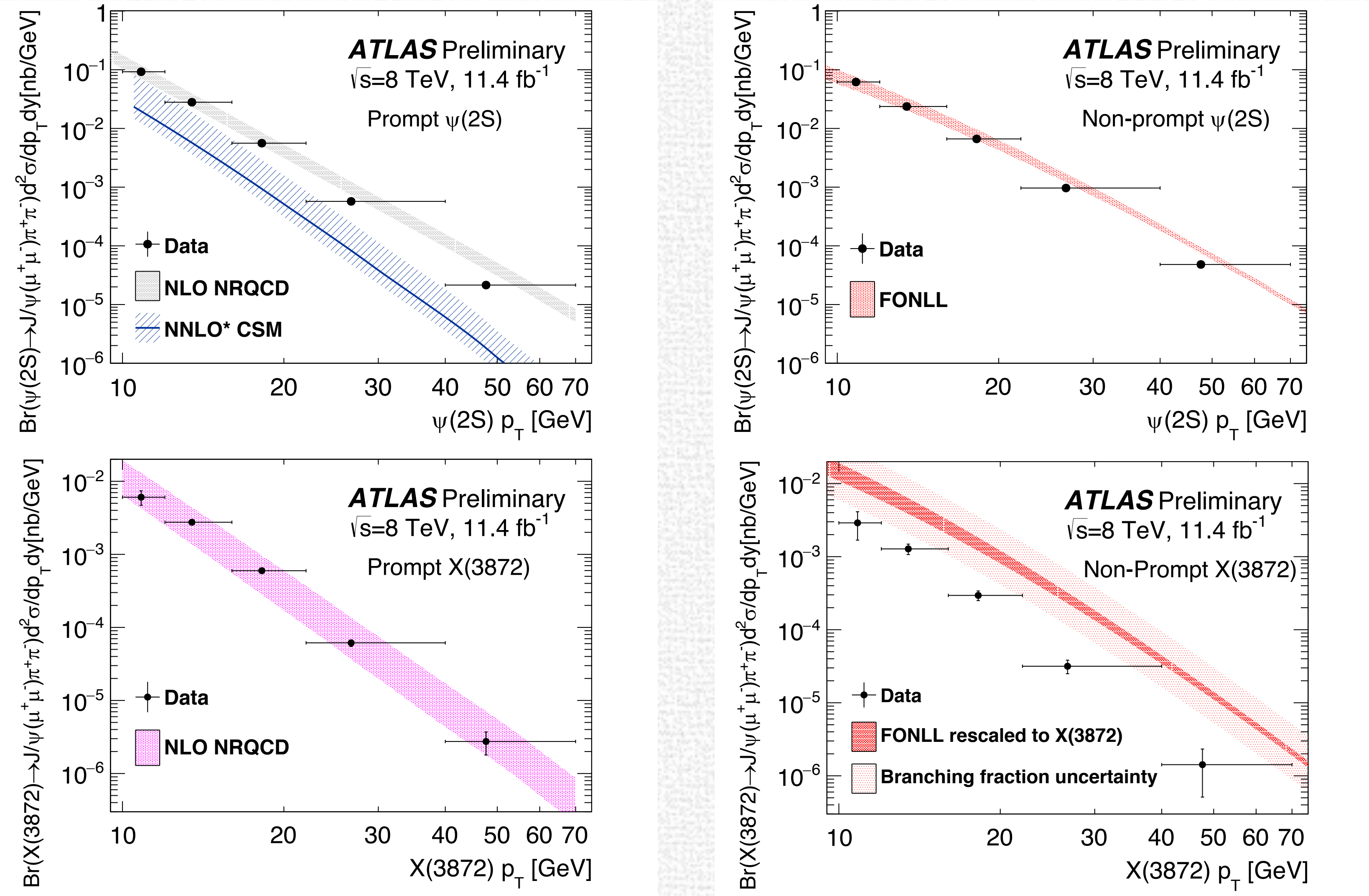


X(3872) "exotic" candidate:
CMS data disagrees with D^0D^{0*} molecule hypothesys

$X(3872) = D^0D^{0*} + \chi_{c1}(2P)$

NRQCD incorporates this recipe CMS ok

Results – I: prompt and non-prompt ψ(2S) and X(3872) production vs. p_T: comparison with theory



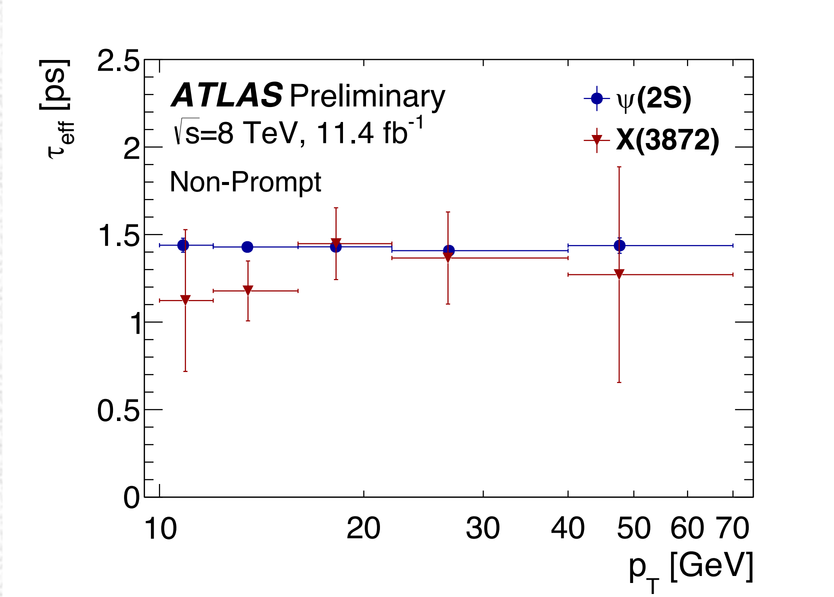
ψ(2S): well described by NLO NRQCD (prompt) and FONLL (non-prompt)

X(3872): well described by CMS-like mixing (prompt) not by FONLL (non-prompt)

Results – II: short vs. long-lived X(3872) non-prompt production; m(ππ) spectra

Double-exponential non-prompt time distributions tried for X non-prompt:
→ **ψ(2S)**: a single-exponential is ok
→ **X(3872)**: short-lived (due to B_c) and long-lived (due to B, B*, Bs)

R = (SL)/(LL) = (25±10(stat)±2(syst)±5(spin))%



Analysis of m(ππ) spectra:

→ **ψ(2S)**: good agreement with Voloshin-Zakharov formula **λ=4.16±0.08**
→ **X(3872)** evidence of ***ρ-dominance*** in the decay