Quarkonium Production in ATLAS

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University of Colorado **Boulder**

ATLAS EXPERIMENT

- **Quarkonium production in pp collisions**
- **Quarkonium production in medium**

Focus on results since 2016

Quarkonium in pp collisions

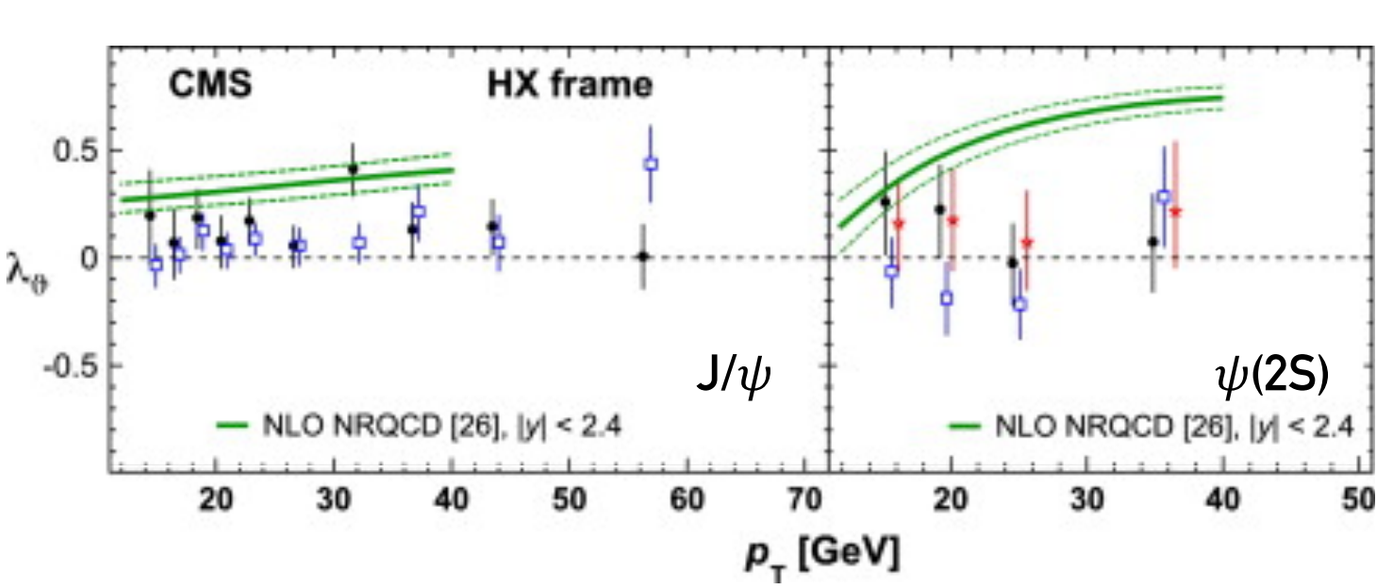
CEM (Color Evaporation Model)

CSM (Color Singlet Model)

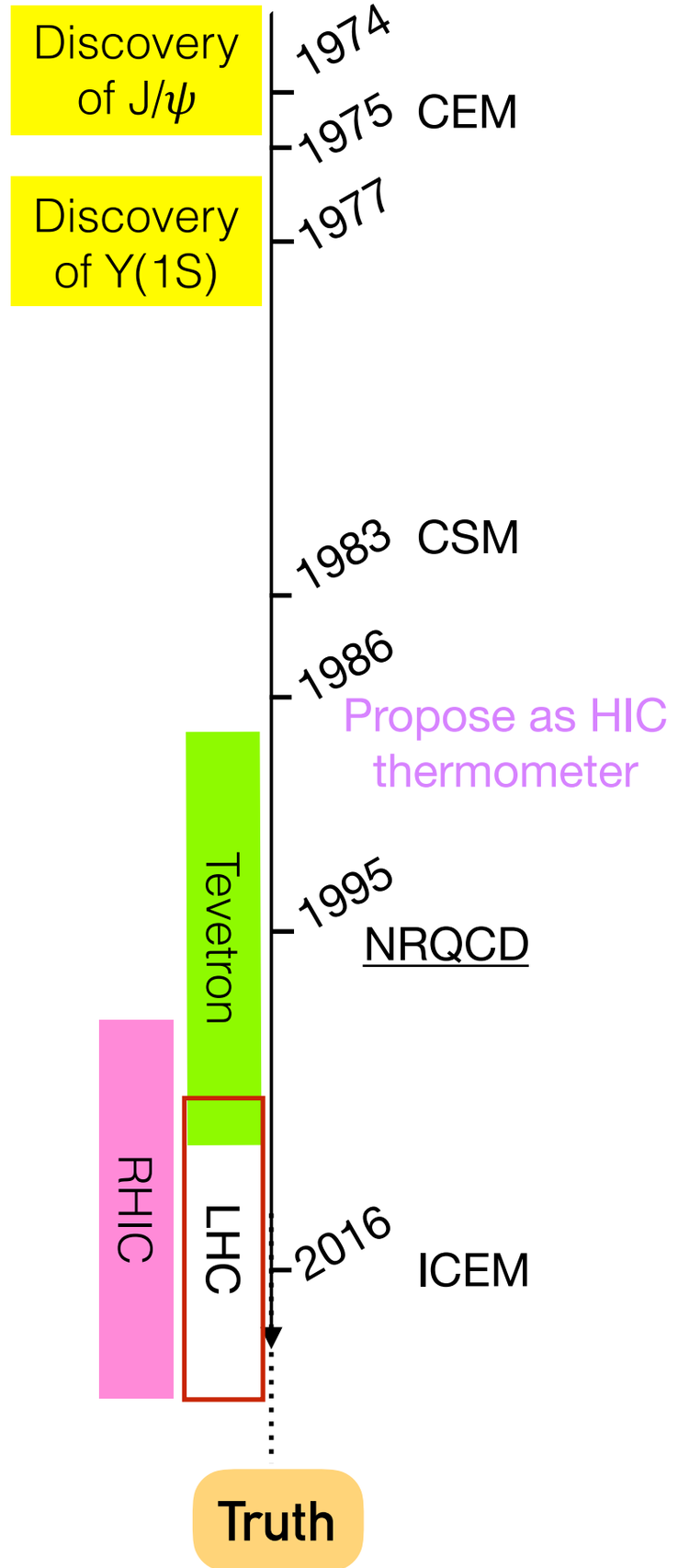
NRQCD (Nonrelativistic QCD)

ICEM (Improved Color Evaporation Model)

[Ma, Vogt 1609.06042]



- No consistency descriptions of cross section and polarization

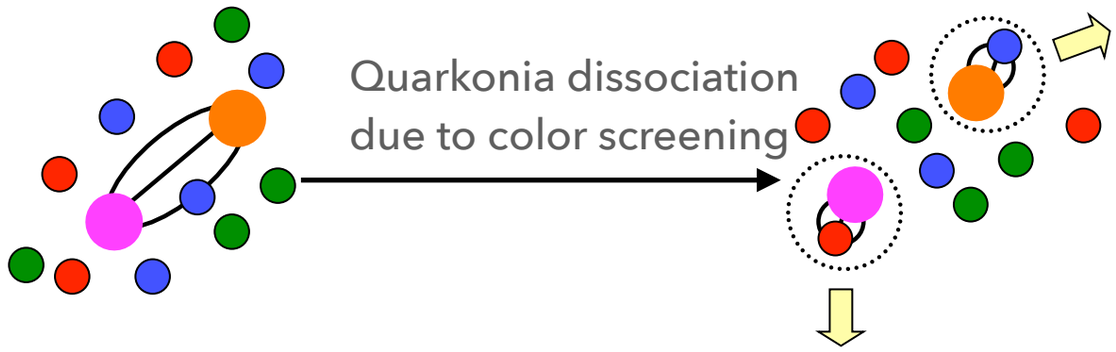


CMS: *PLB*, 727(2013)381
NRQCD: *PRL*, 110(2013)042002

Quarkonia in-medium

Quarkonium in hot & dense QGP:

- Color screening
- Sequential melting

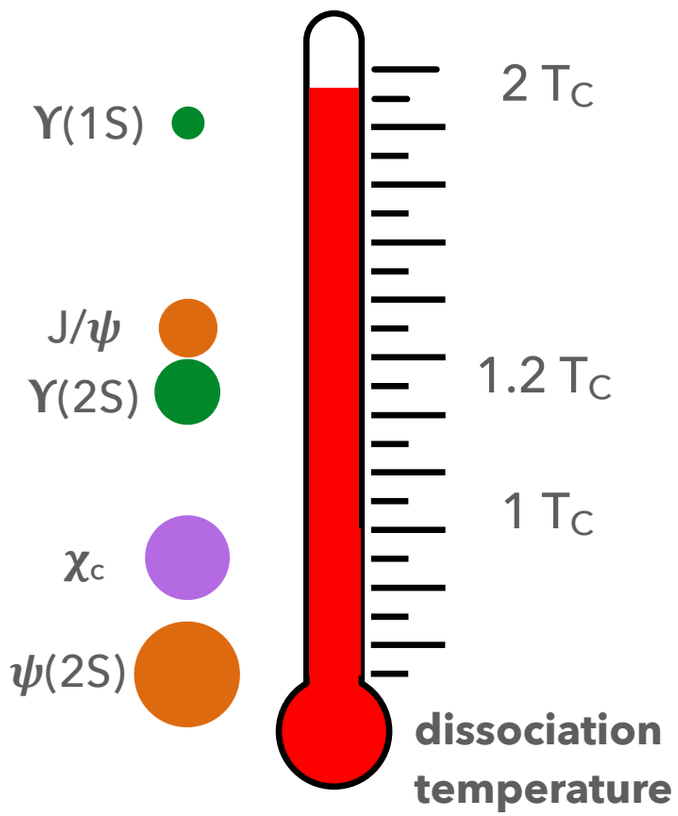


More effects that can impact the quarkonia yields:

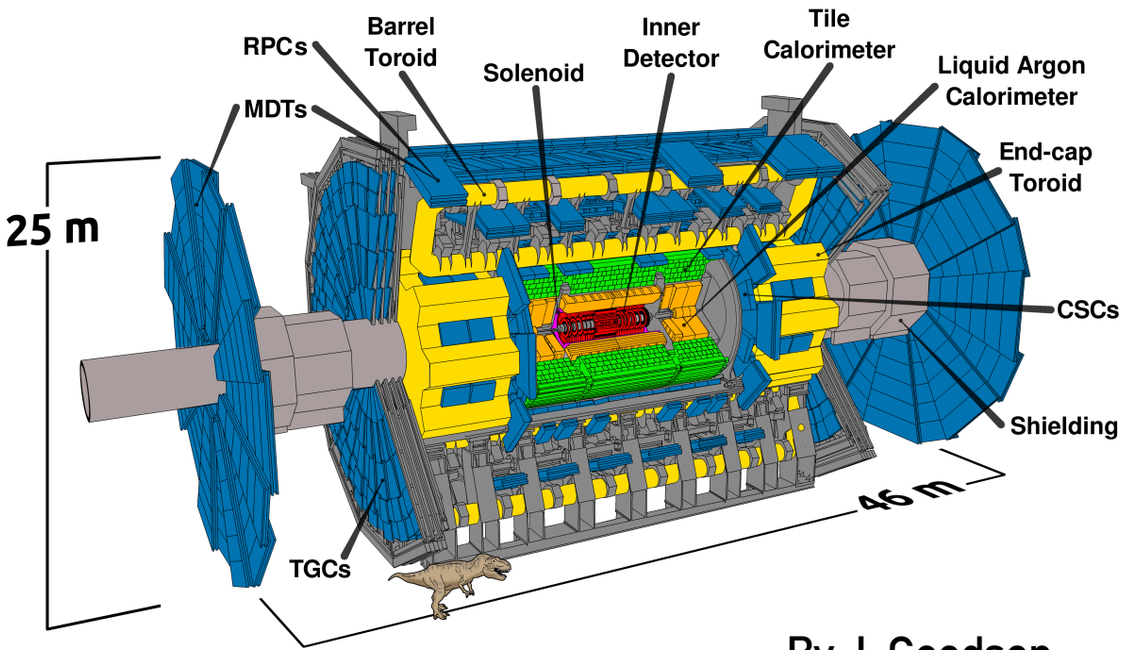
- Regeneration via statistical recombination
- Initial parton energy loss
- nPDF modification
- Final state interaction

hot effects
present only in A+A collisions

cold nuclear matter (CNM) effects
present in p+A and A+A collisions



ATLAS detector



By J. Goodson

Energy	Collision	Int. Lumi. [pb^{-1}]	Year
$\sqrt{s}$ = 7 TeV	***pp***	2100	2011
$\sqrt{s}$ = 8 TeV	***pp***	11400	2012
$\sqrt{s}$ = 13 TeV	***pp***	6400	2015
$\sqrt{s_{NN}}$ = 5.02 TeV	***p*+Pb**	0.028	2013
$\sqrt{s}$ = 5.02 TeV	***pp***	25	2015
$\sqrt{s_{NN}}$ = 5.02 TeV	**Pb+Pb**	0.0005	2015

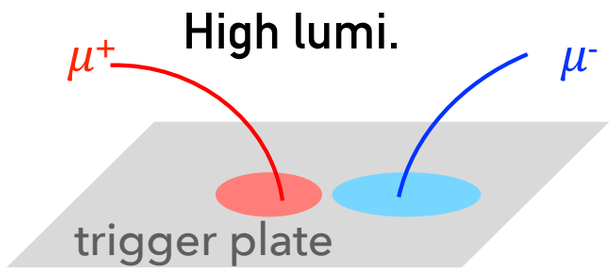
Inner Detector $|\eta| < 2.5$

Calorimeter $|\eta| < 4.9$

Muon Spectrometer $|\eta| < 2.7$

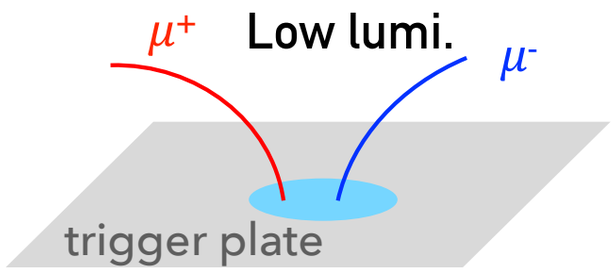
Precision muon reconstruction:
$p_T > 4$ GeV, $|\eta| < 2.4$

Triggering strategy



2 hardware level muons
with $p_T > 4$ GeV

Zero efficiency when
two muons are close-by

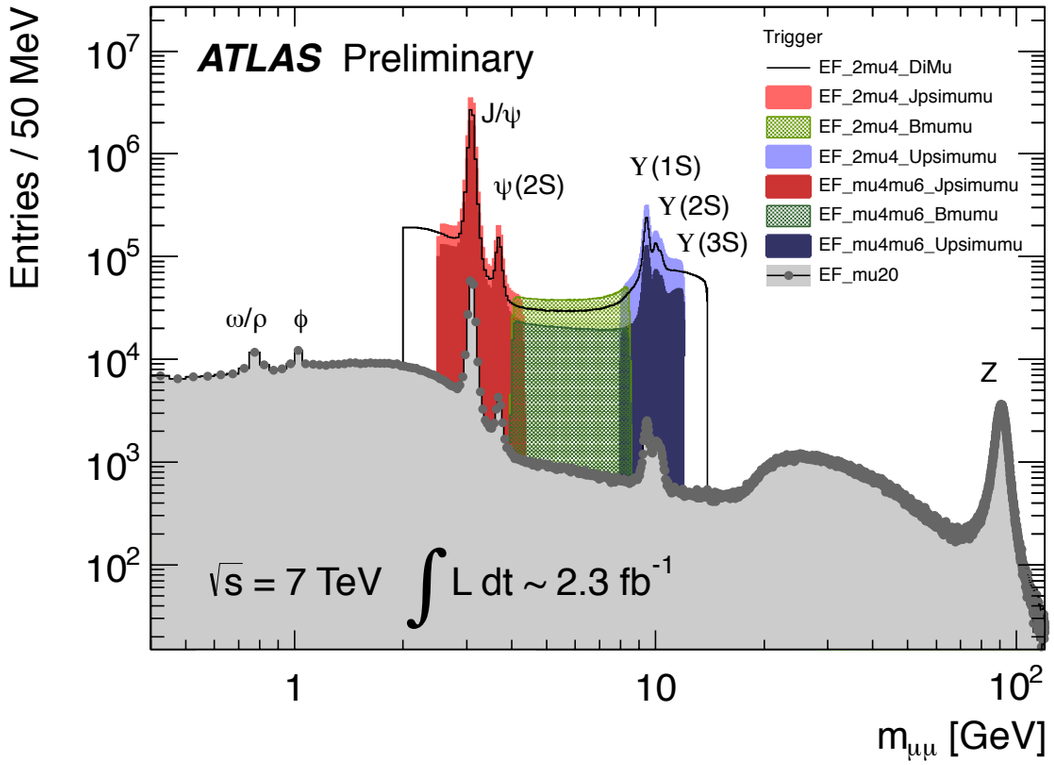


1 hardware level muon +
1 software level track/muon

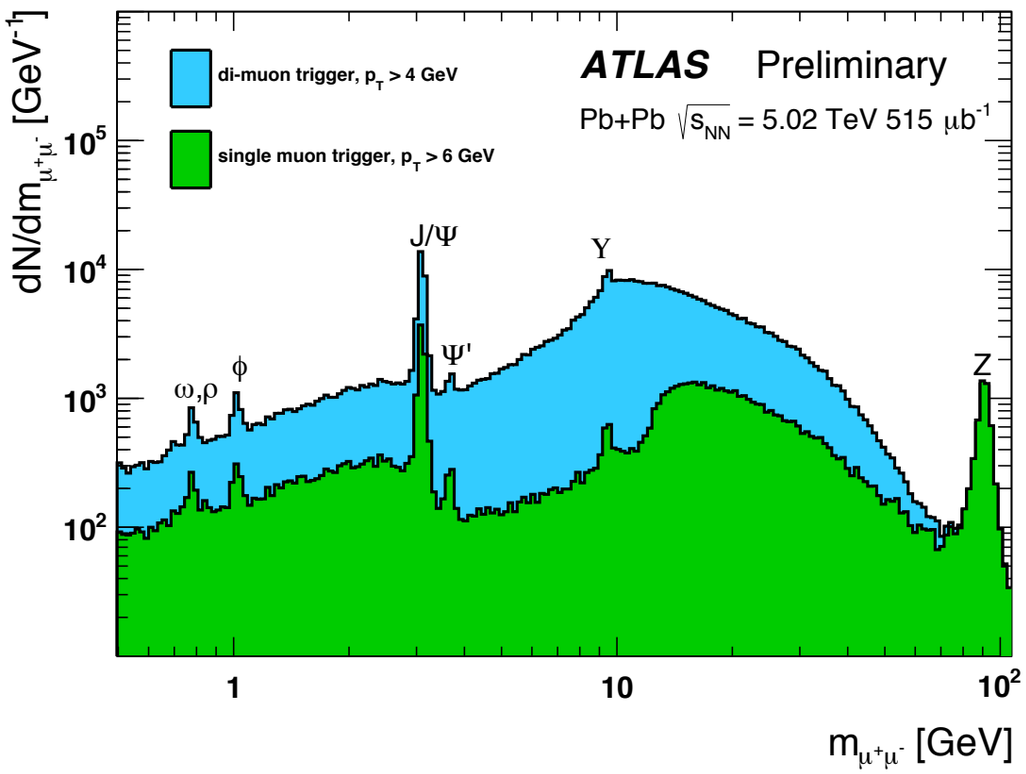
high efficiency
CPU/bandwidth consuming

Triggered events

pp



Pb+Pb



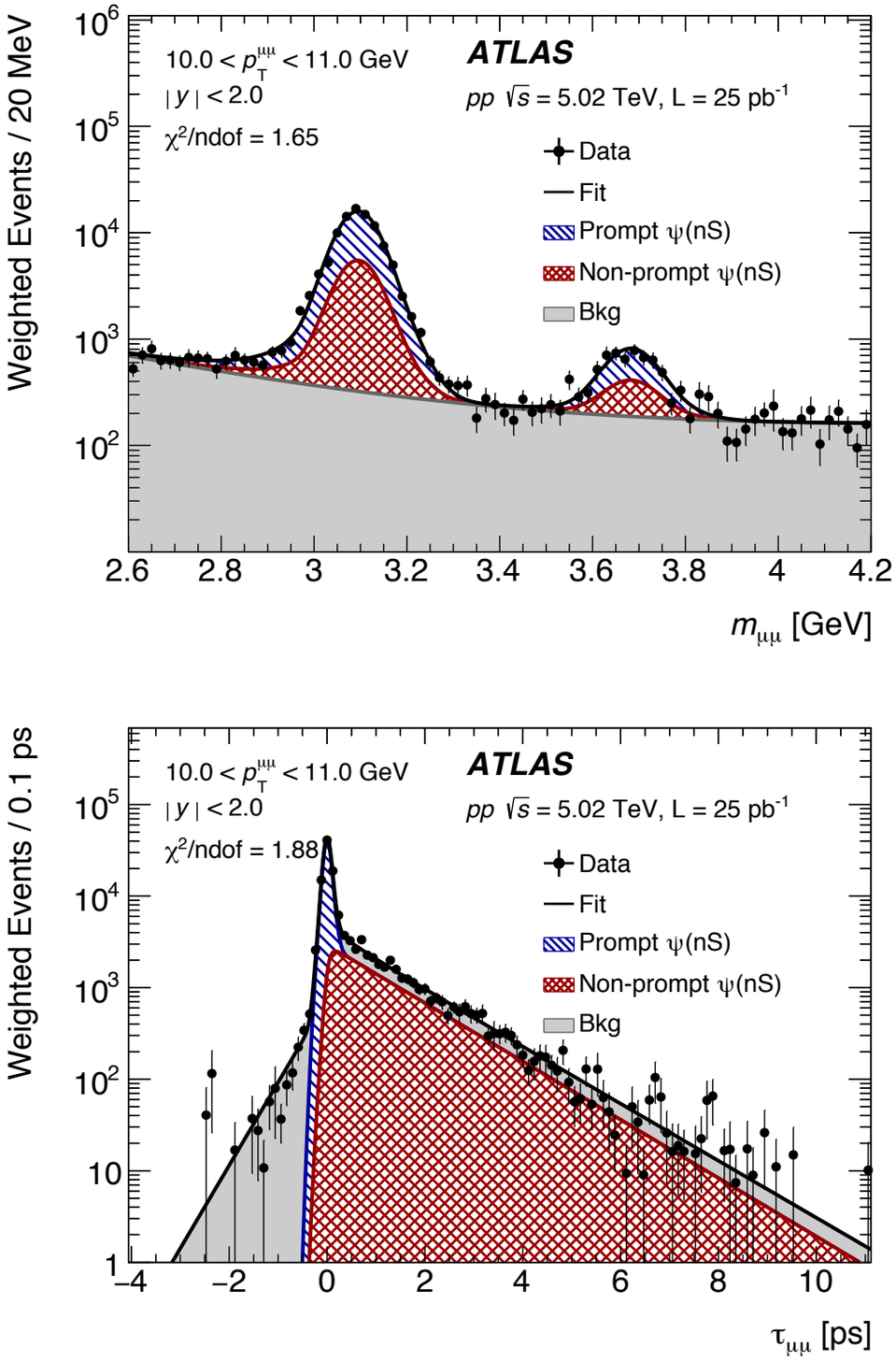
Topological cuts (invariant mass, charge, angle) applied online to reduce rate

Still able to collect p_T > 4 GeV without additional cuts.

Working on muon+track trigger to access to $p_T(\psi)$ < 8 GeV

- **Quarkonium production in pp collisions**
- **Quarkonium production in medium**

J/ψ, ψ(2S) ⟶ μ⁺μ⁻

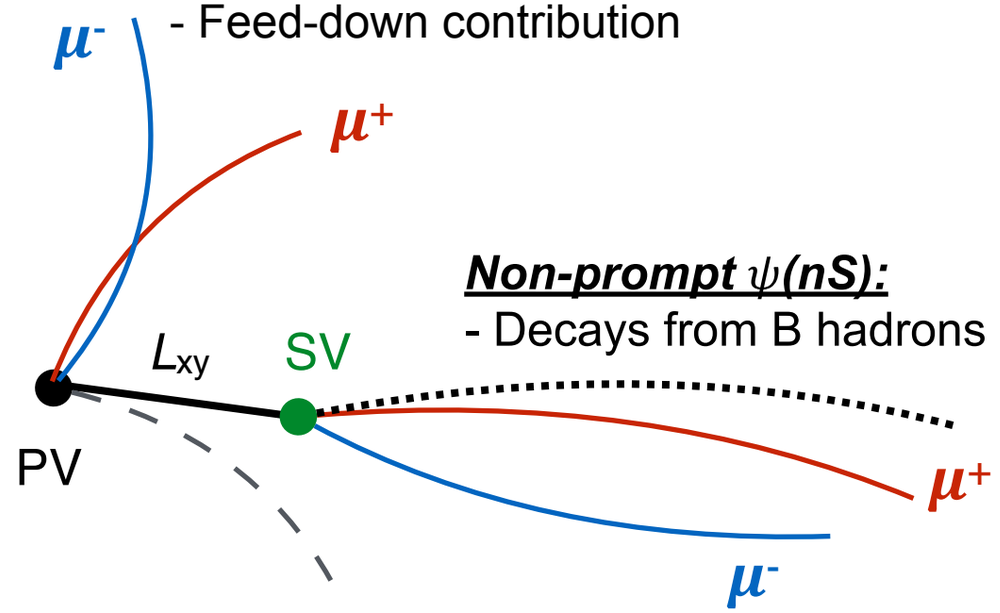


pseudo-proper lifetime:

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}}$$

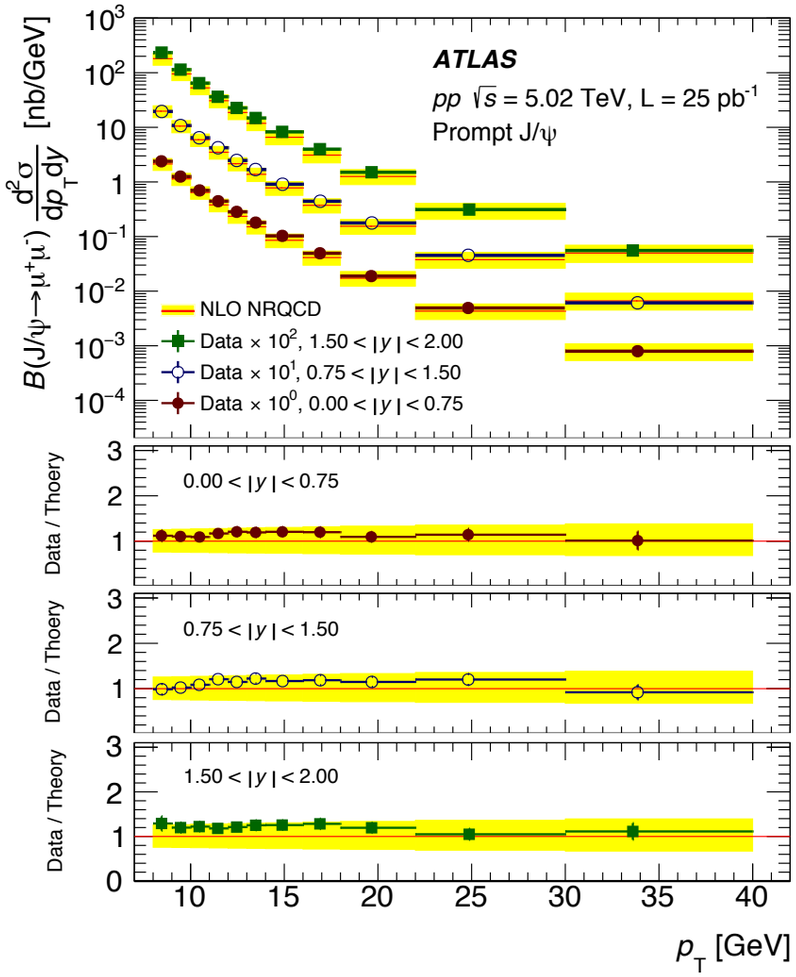
Prompt ψ(nS):
- Direct production
- Feed-down contribution

Non-prompt ψ(nS):
- Decays from B hadrons

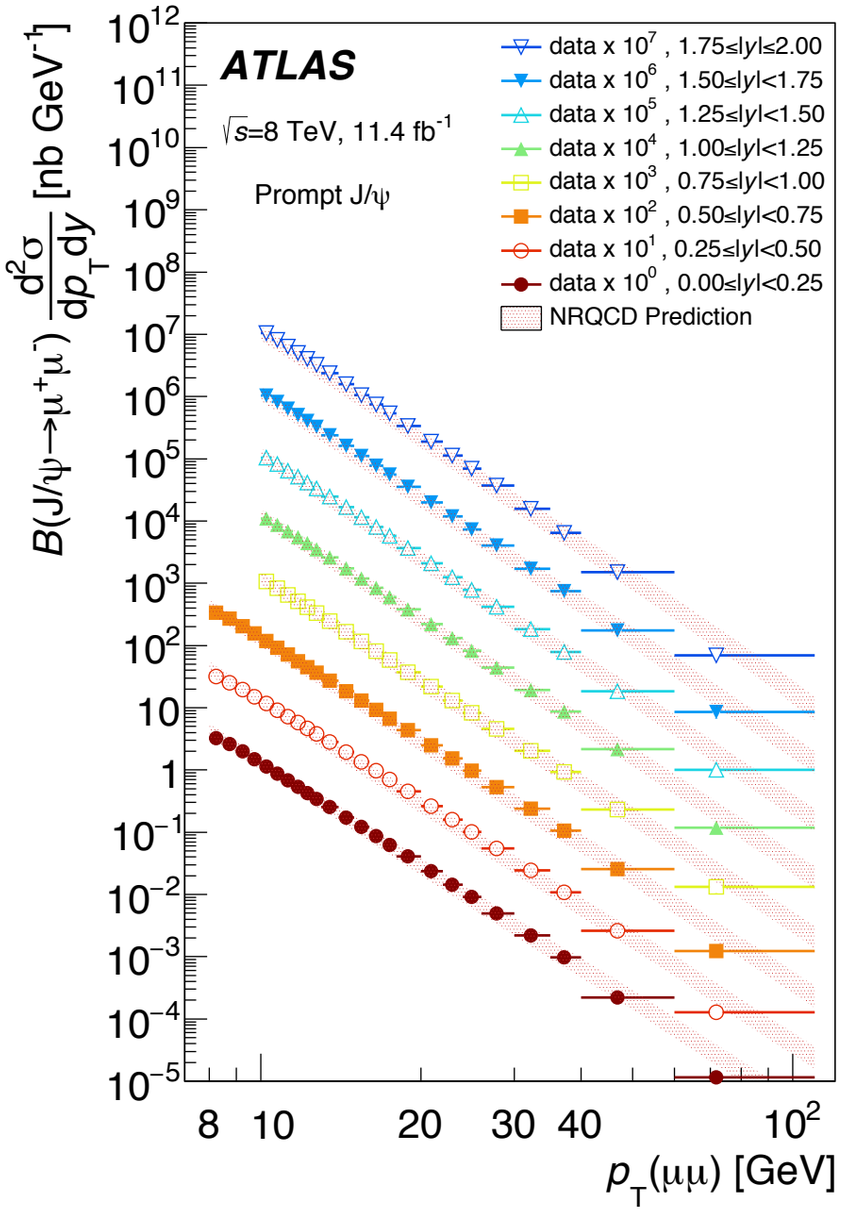


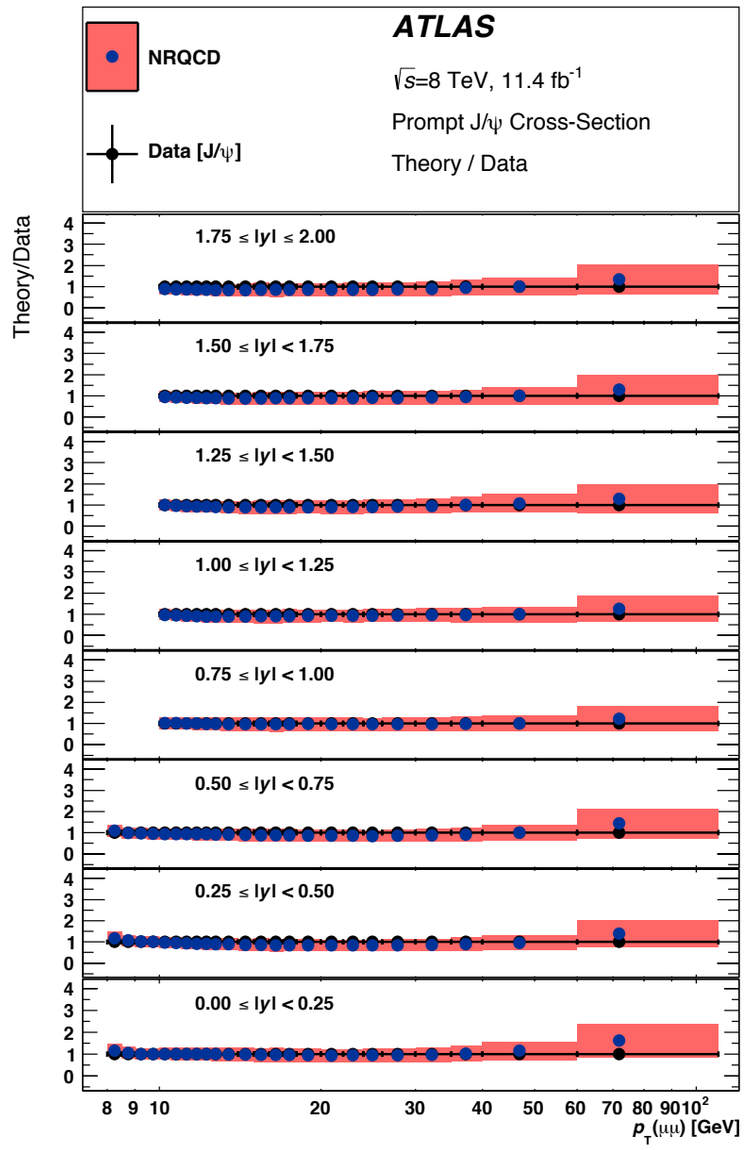
- Per-event weight to account for **trigger**, **reconstruction** efficiency and fiducial volume **acceptance**
- Weighted fit with physics motivated line-shapes performed to subtract background.

arXiv:1709.03089



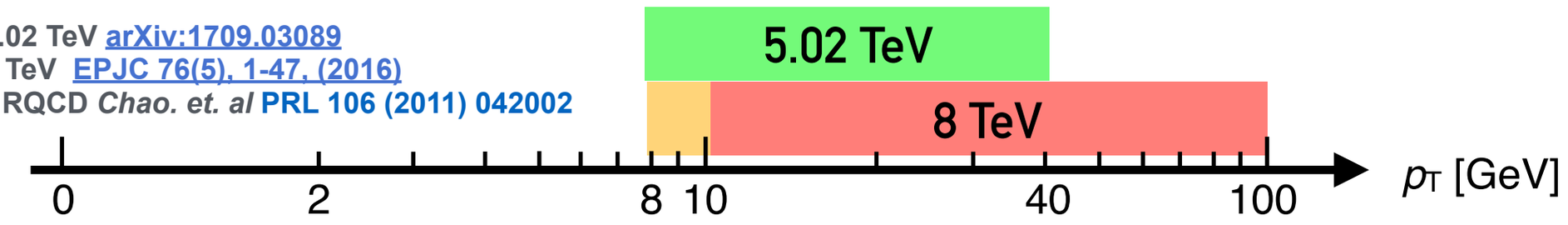
5.02 TeV

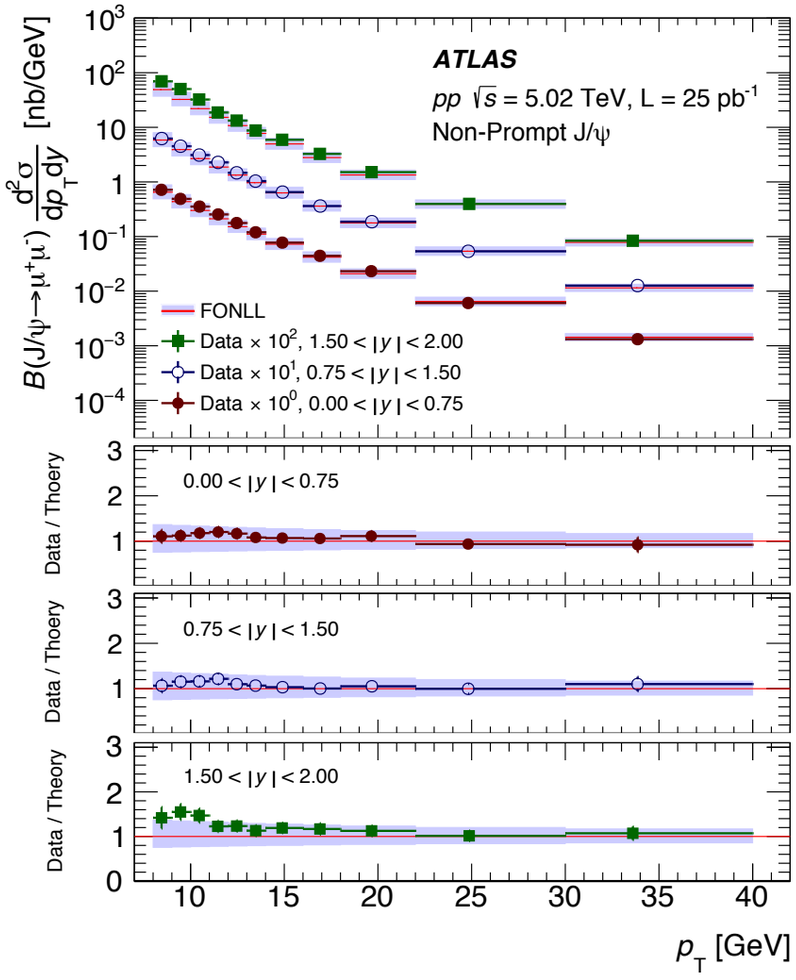




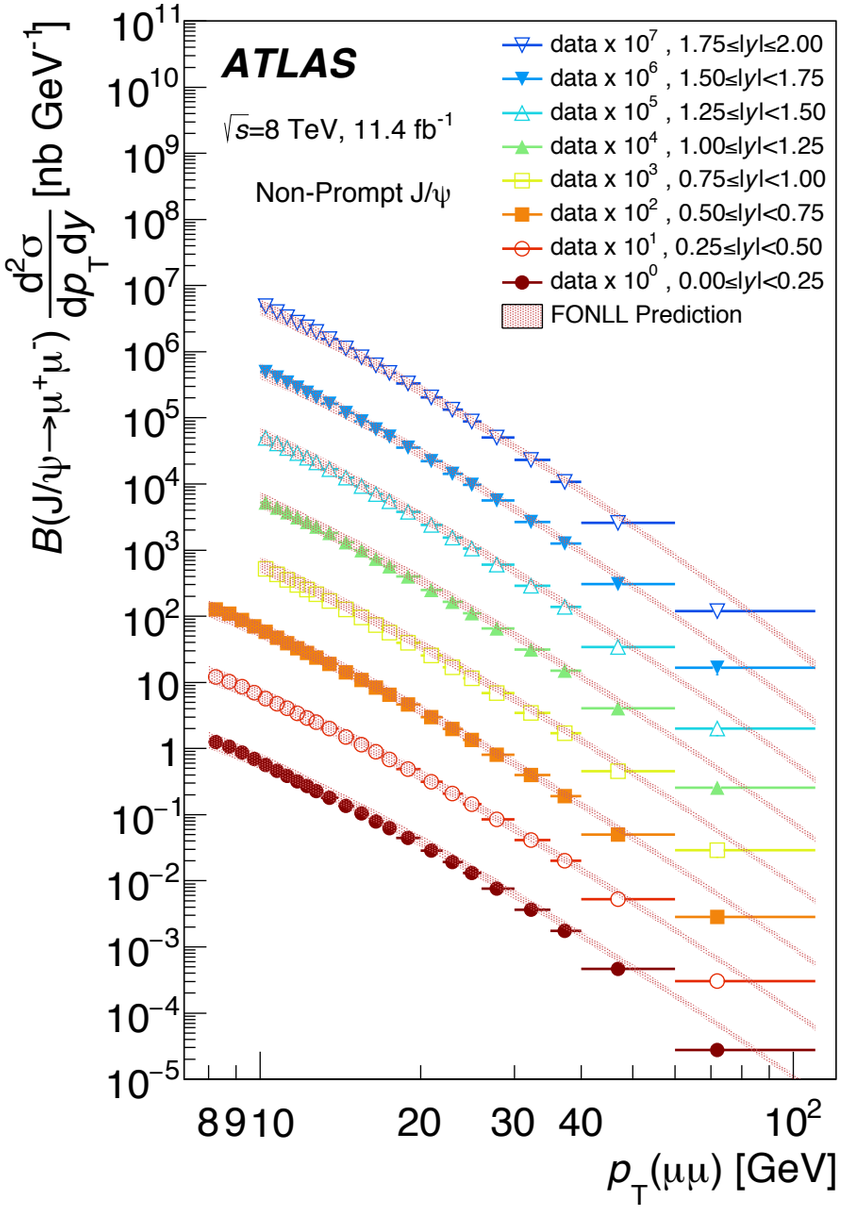
8 TeV

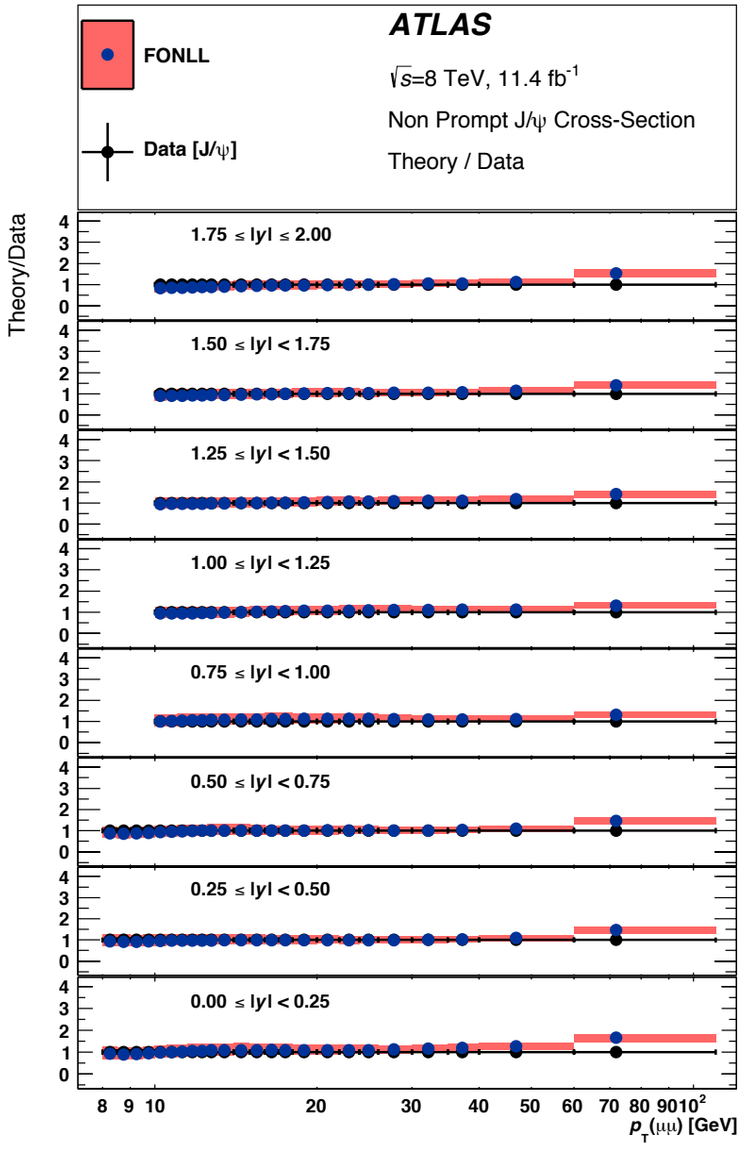
5.02 TeV arXiv:1709.03089
8 TeV EPJC 76(5), 1-47, (2016)
NRQCD *Chao. et. al* PRL 106 (2011) 042002





5.02 TeV





8 TeV

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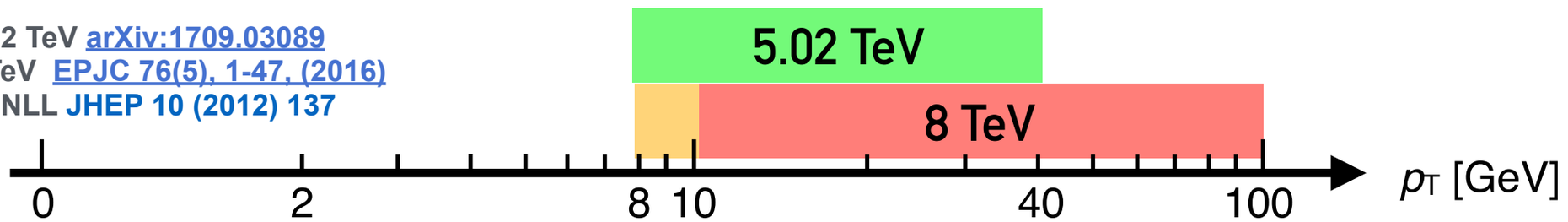
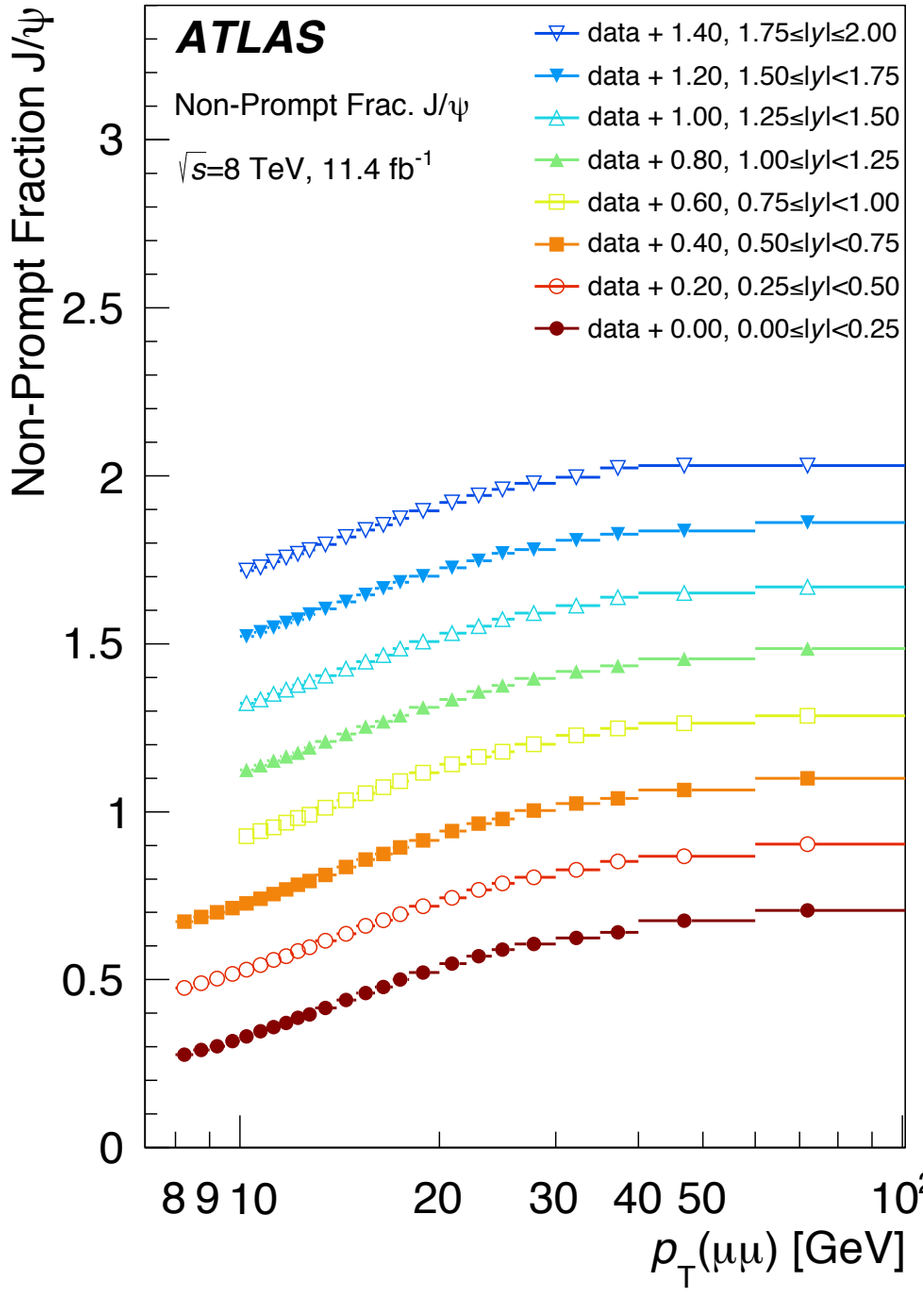
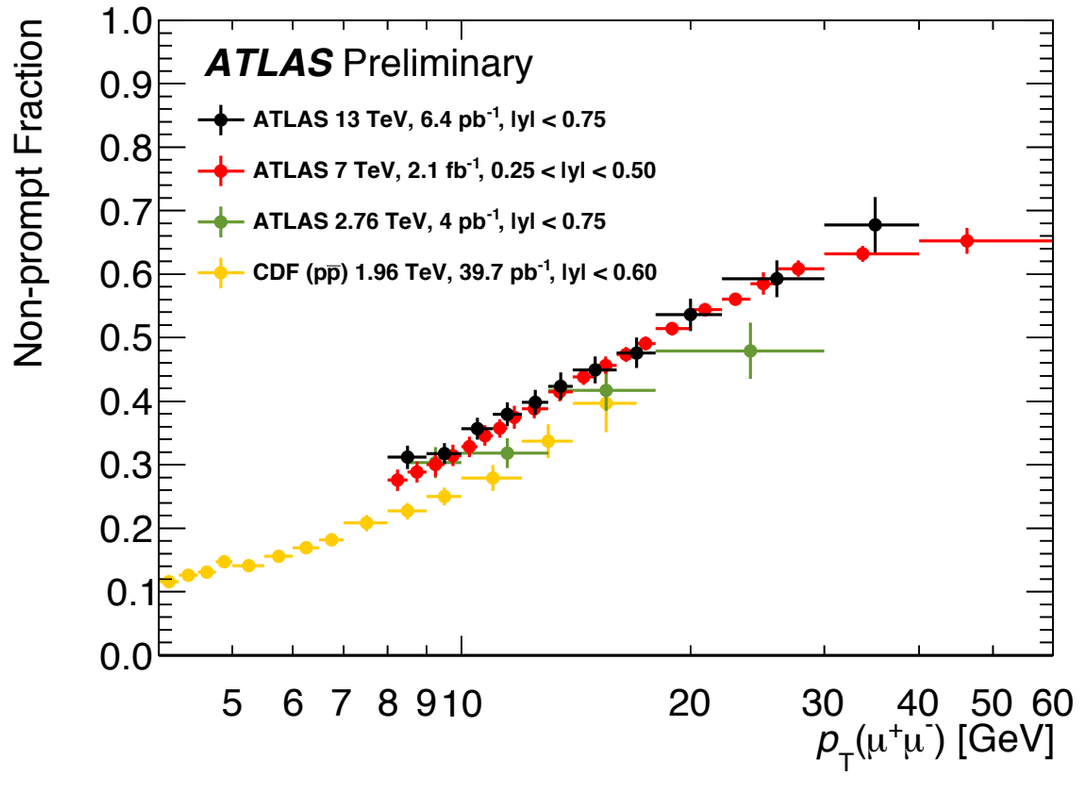
8 TeV EPJC 76(5), 1-47, (2016)
FONLL JHEP 10 (2012) 137



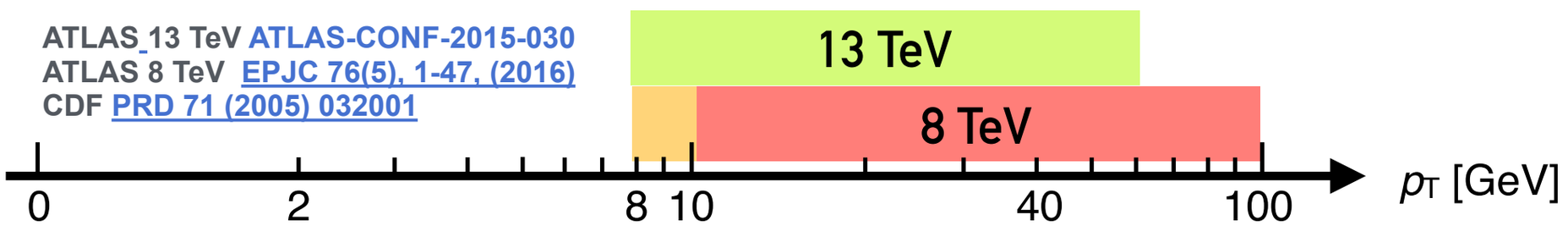




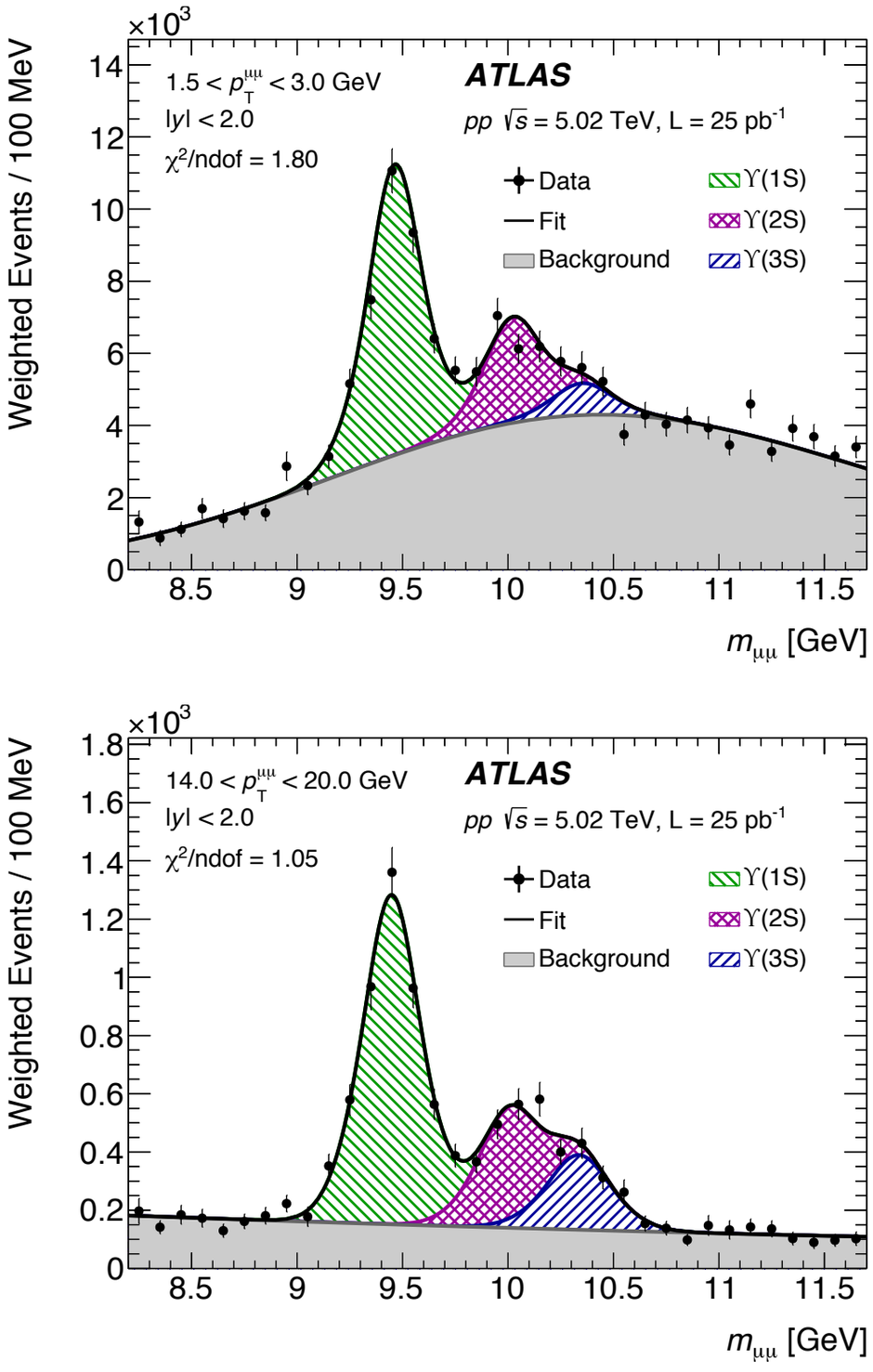
$N_{\text{non-prompt}} / (N_{\text{prompt}} + N_{\text{non-prompt}})$

Non-prompt charmonium fraction

- Significant cancellation of experimental uncertainties
- Might be a better observable to constrain models

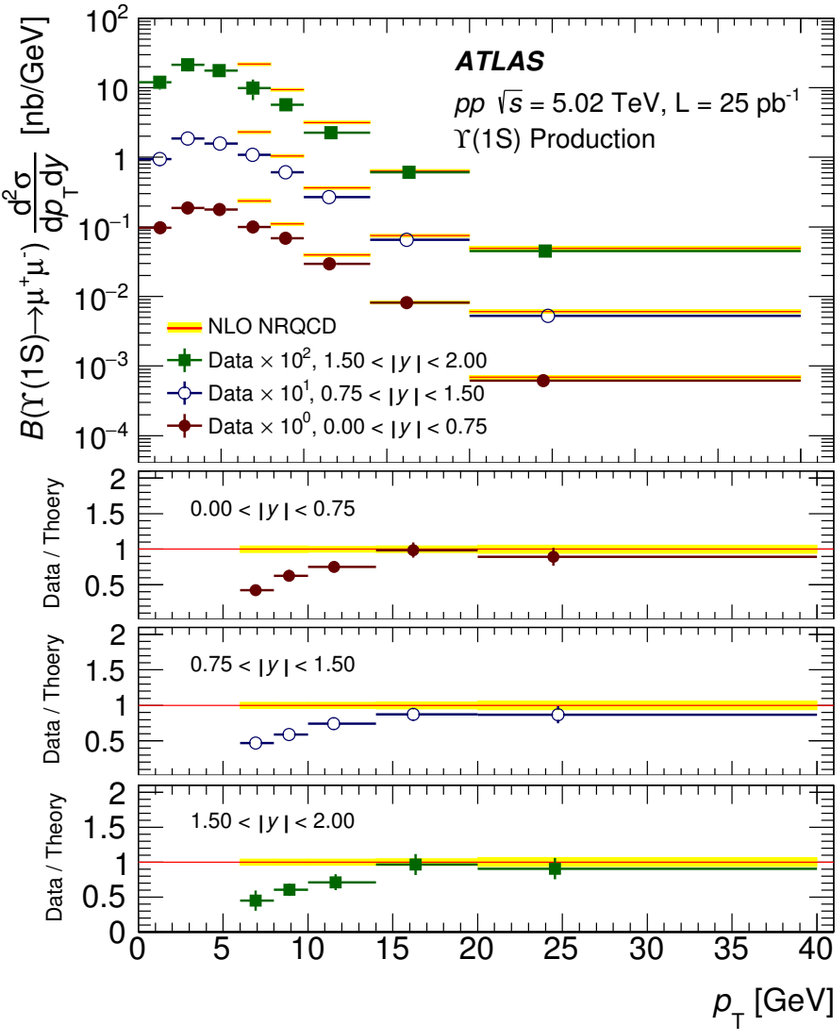


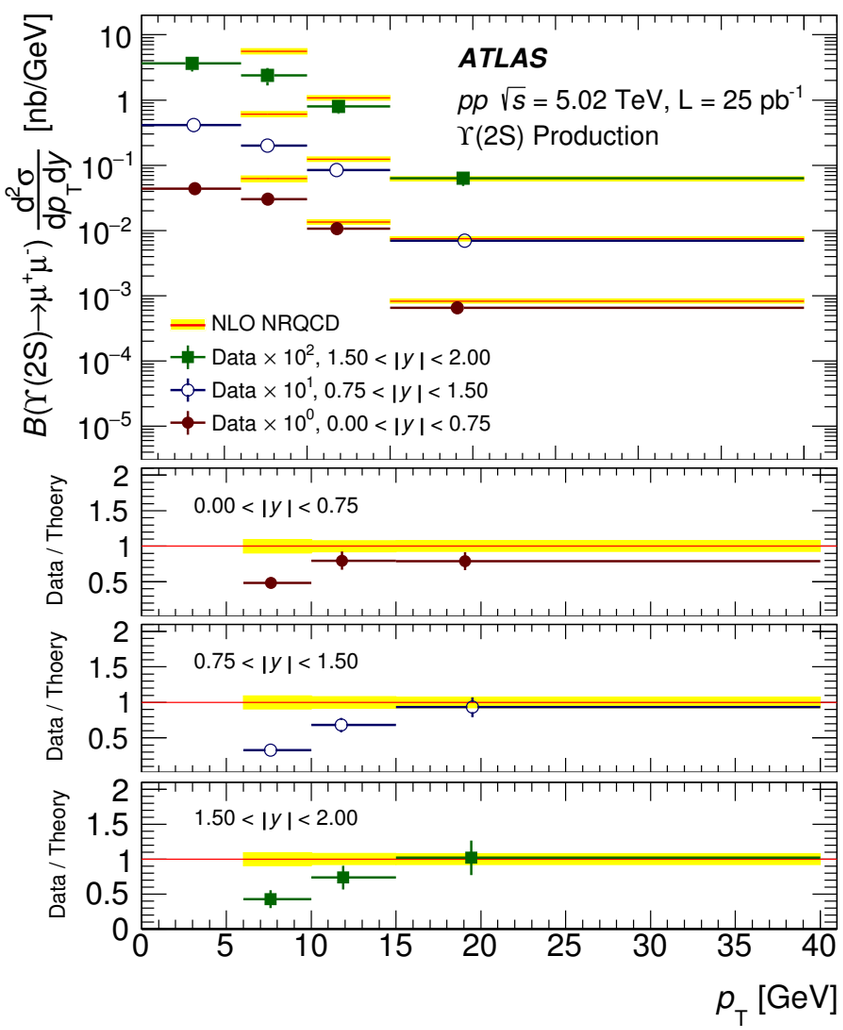
Υ(nS) $\longrightarrow \mu^+\mu^-$

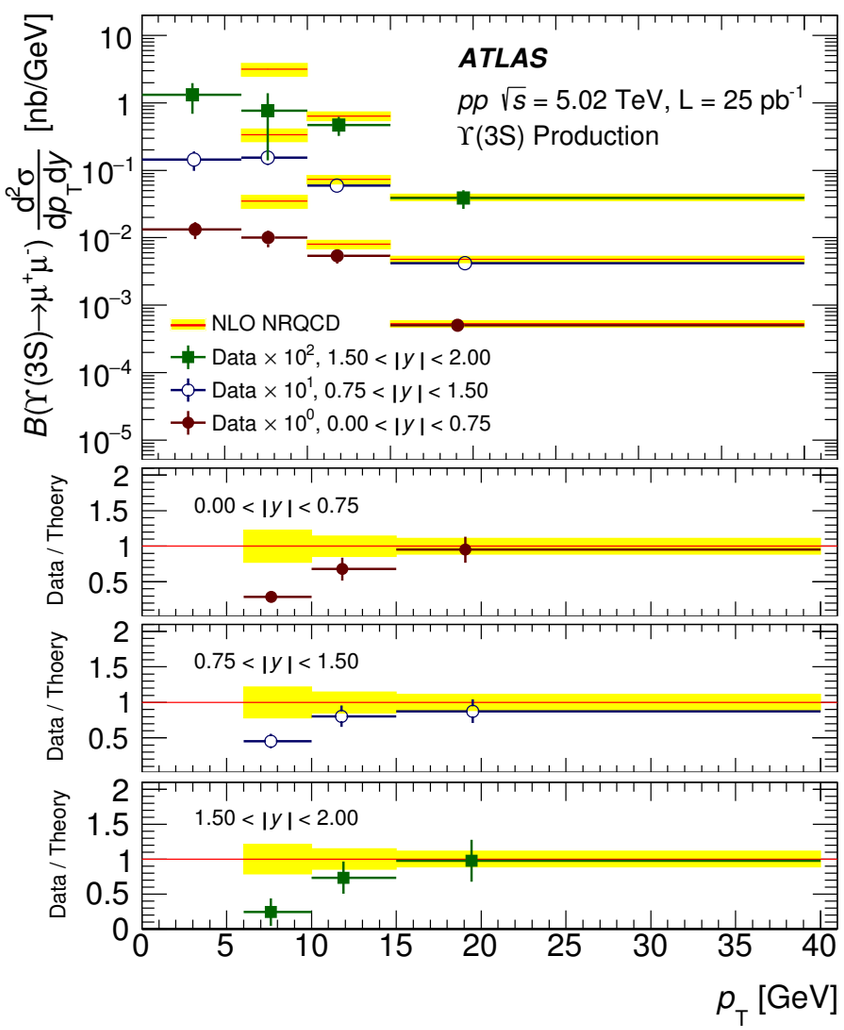


- Mass resolution ~ 150 MeV, not able to totally separate different states
- p_T (μ) > 4 GeV cause turn-on curve of bkg. at low p_T, constrained by same charge / displaced control sample

arXiv:1709.03089

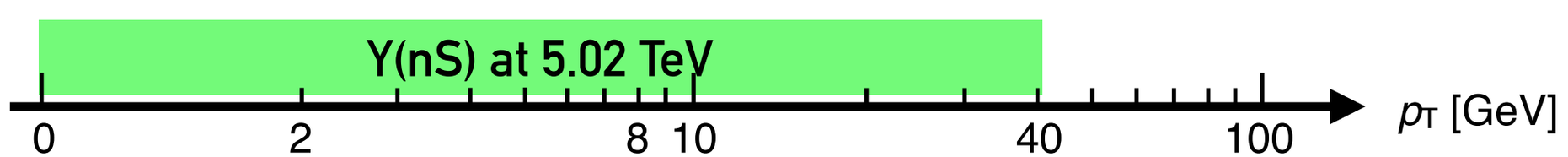




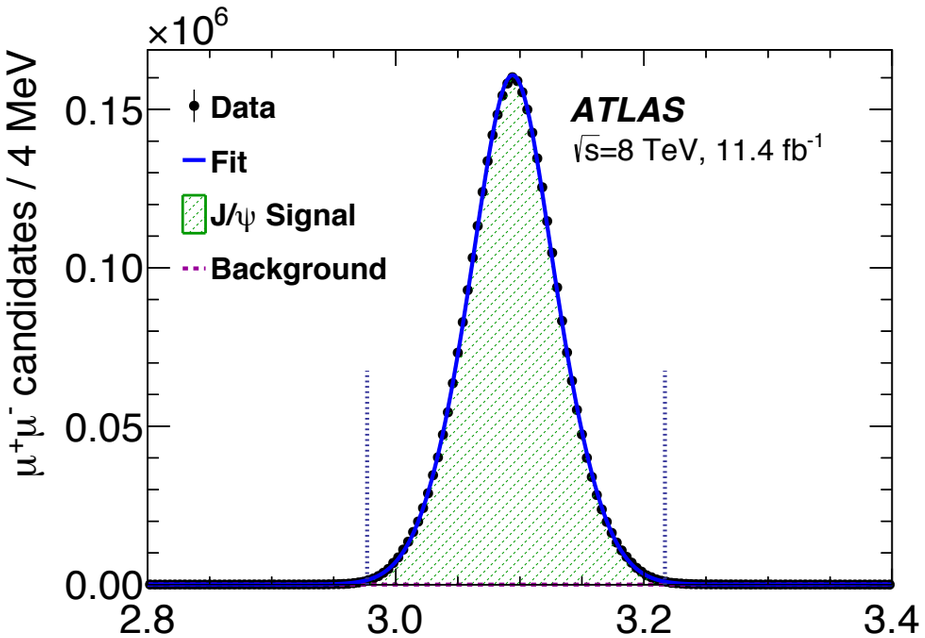


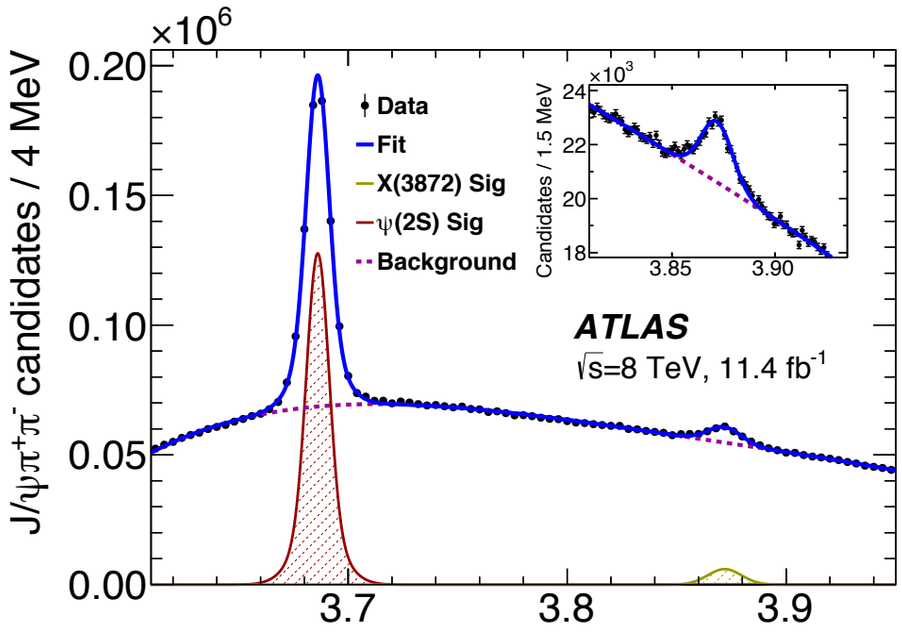
Good agreement between NLO NRQCD and 5.02 TeV data at p_T > 15 GeV as expected

ATLAS arXiv:1709.03089
NRQCD *Han. et. al* PRD 94 (2016) 014028



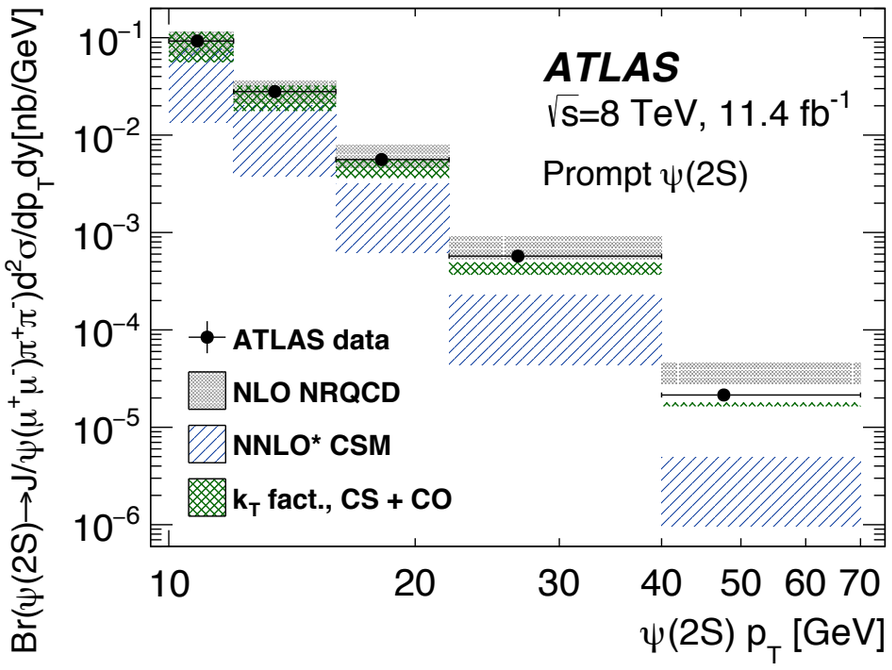
$\psi(2S), X(3872) \longrightarrow J/\psi\pi\pi$

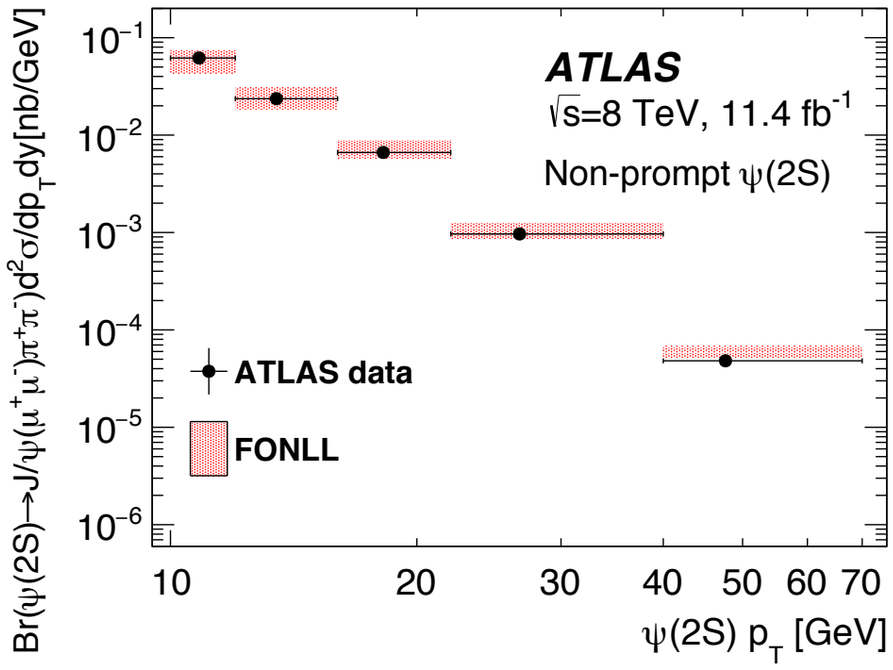


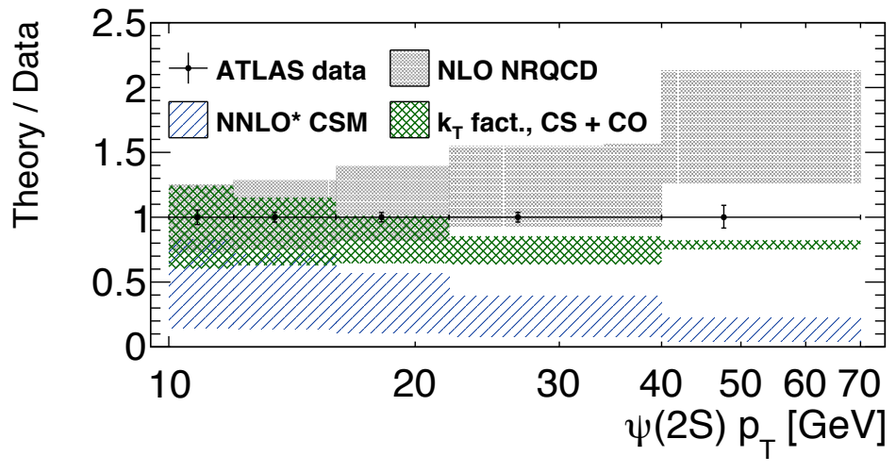


- Signal region around J/ψ $\longrightarrow$ $\mu^+\mu^-$ mass peak
- Better invariant mass resolution due constrained fit (fix dimuon mass at J/ψ mass)
- X(3872) is measured for the first time at ATLAS

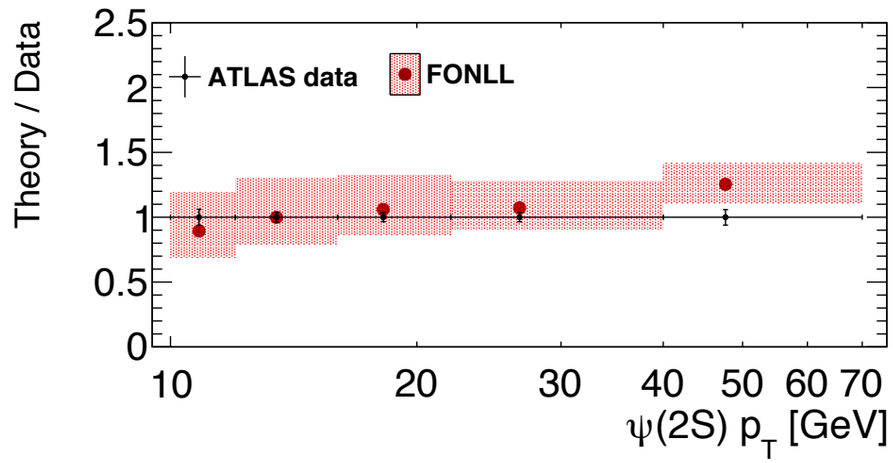
JHEP01(2017)117







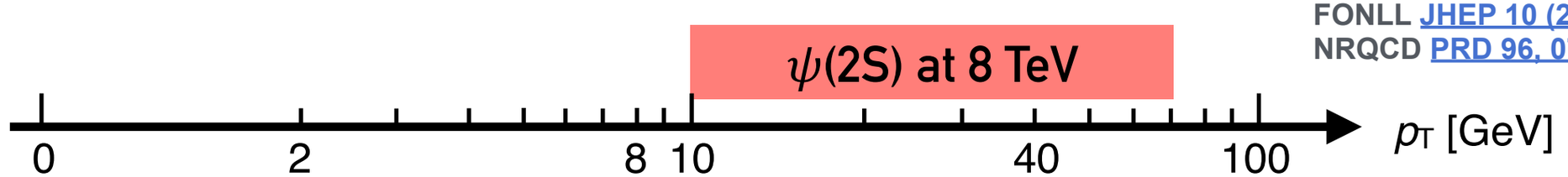
Prompt

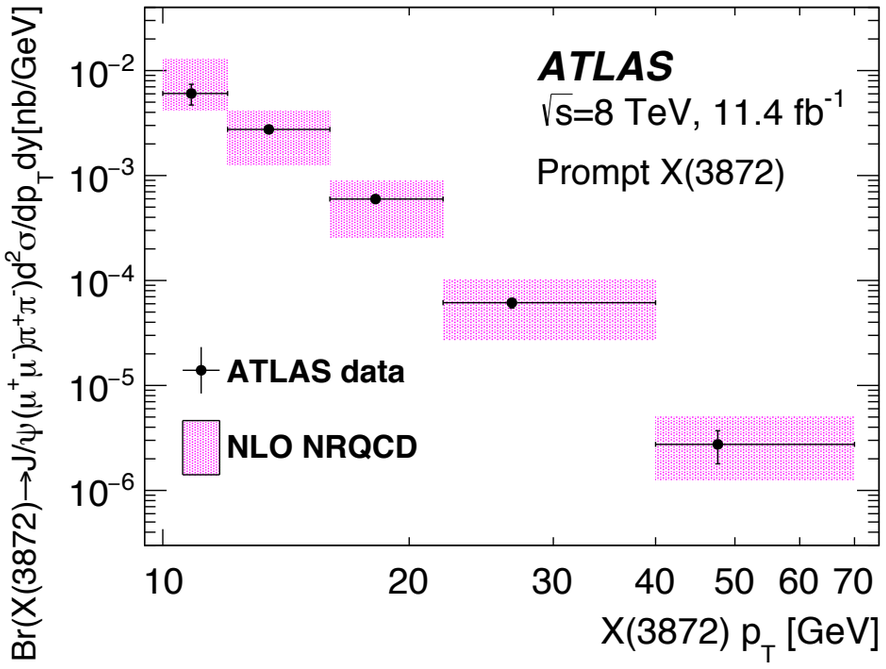


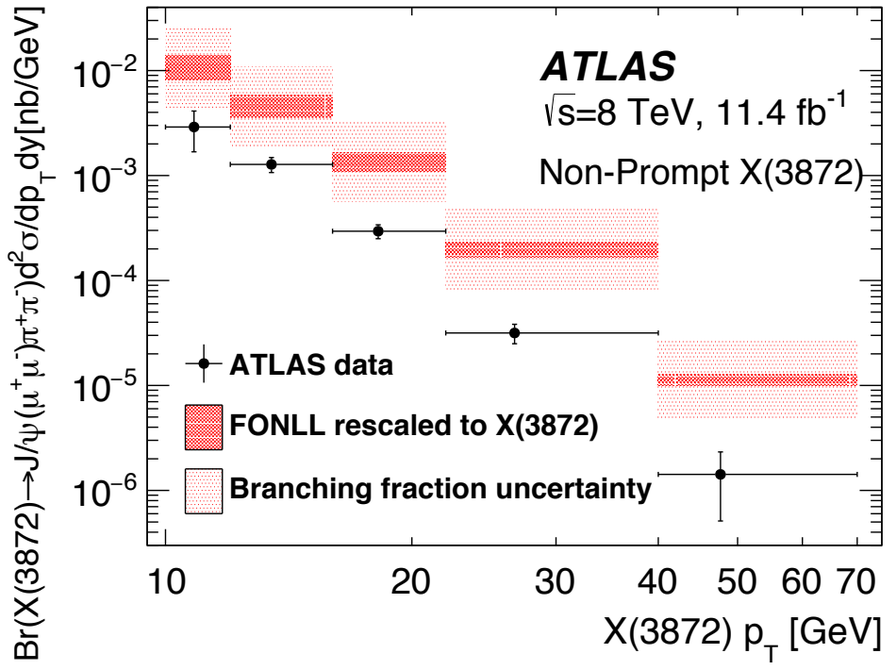
Non-prompt

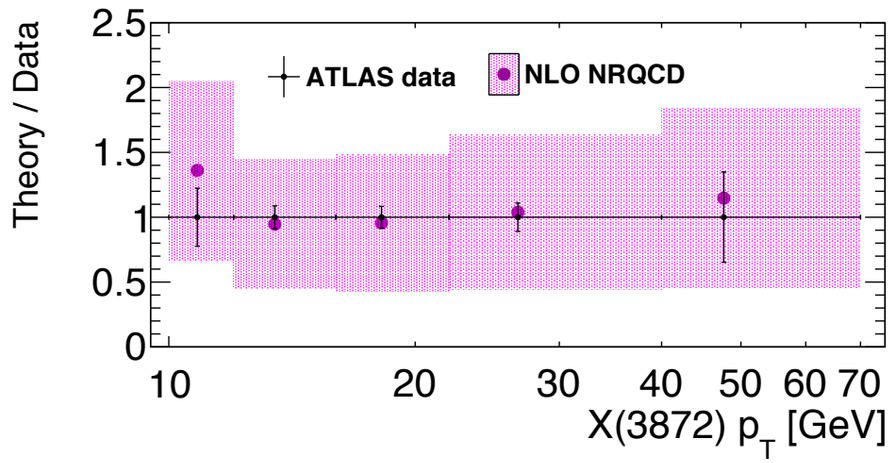
- Good agreements with NRQCD and FONLL at p_T < 40 GeV
- Both model overestimate data at high p_T

ATLAS JHEP01(2017)117
k_T fact. , EPJC 75 (2015) 455
CSM EPJC 61 (2009) 693–703
FONLL JHEP 10 (2012) 137
NRQCD PRD 96, 074014 (2017)

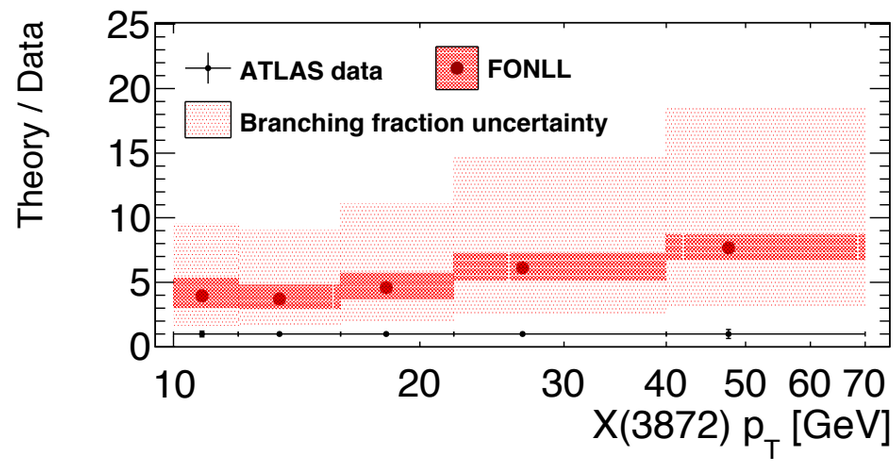






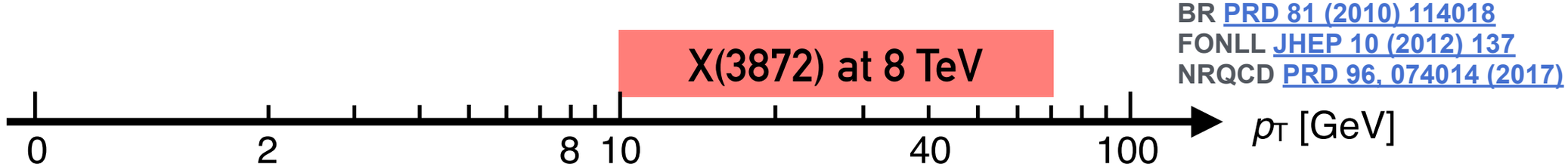


Prompt



Non-prompt

- NRQCD describe prompt X(3872) data well
- FONLL overestimate data mainly due to overestimation of BR



ATLAS JHEP01(2017)117
BR PRD 81 (2010) 114018
FONLL JHEP 10 (2012) 137
NRQCD PRD 96, 074014 (2017)

- Quarkonium production in pp collisions

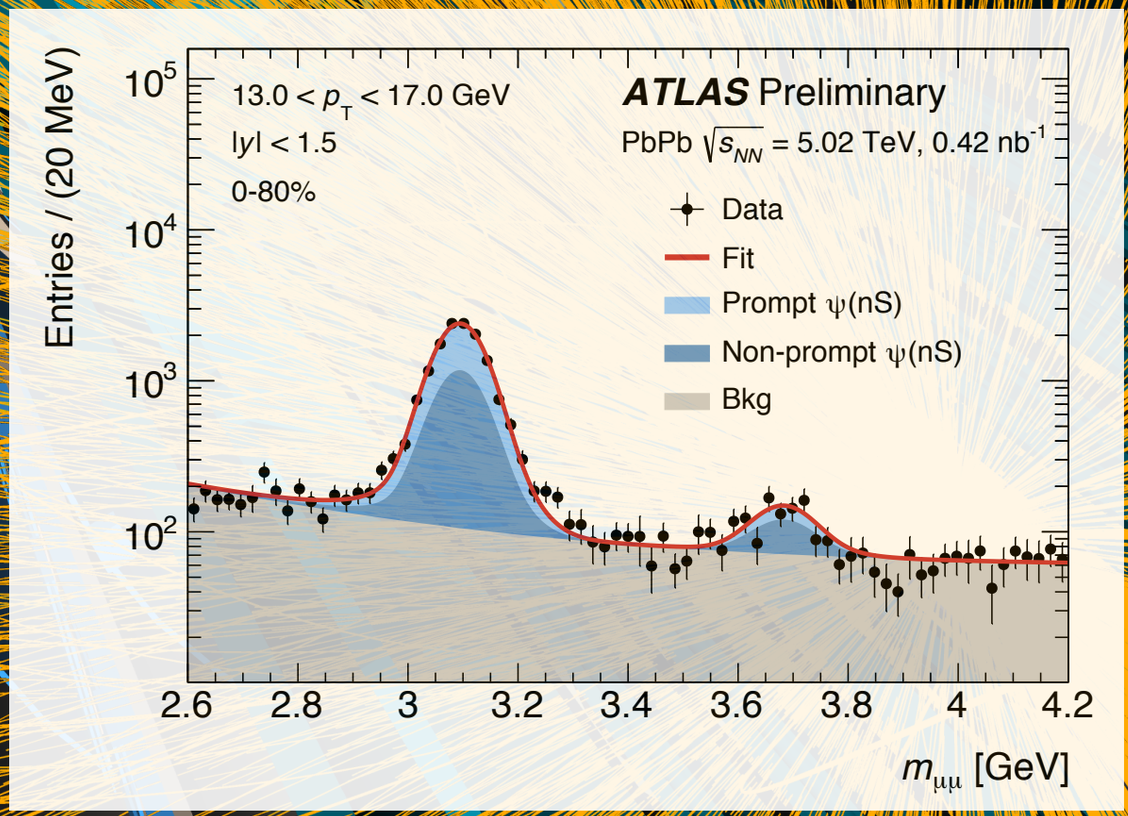
- Quarkonium production in medium

ATLAS
EXPERIMENT

Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST

first stable beams heavy-ion collisions

ATLAS
EXPERIMENT



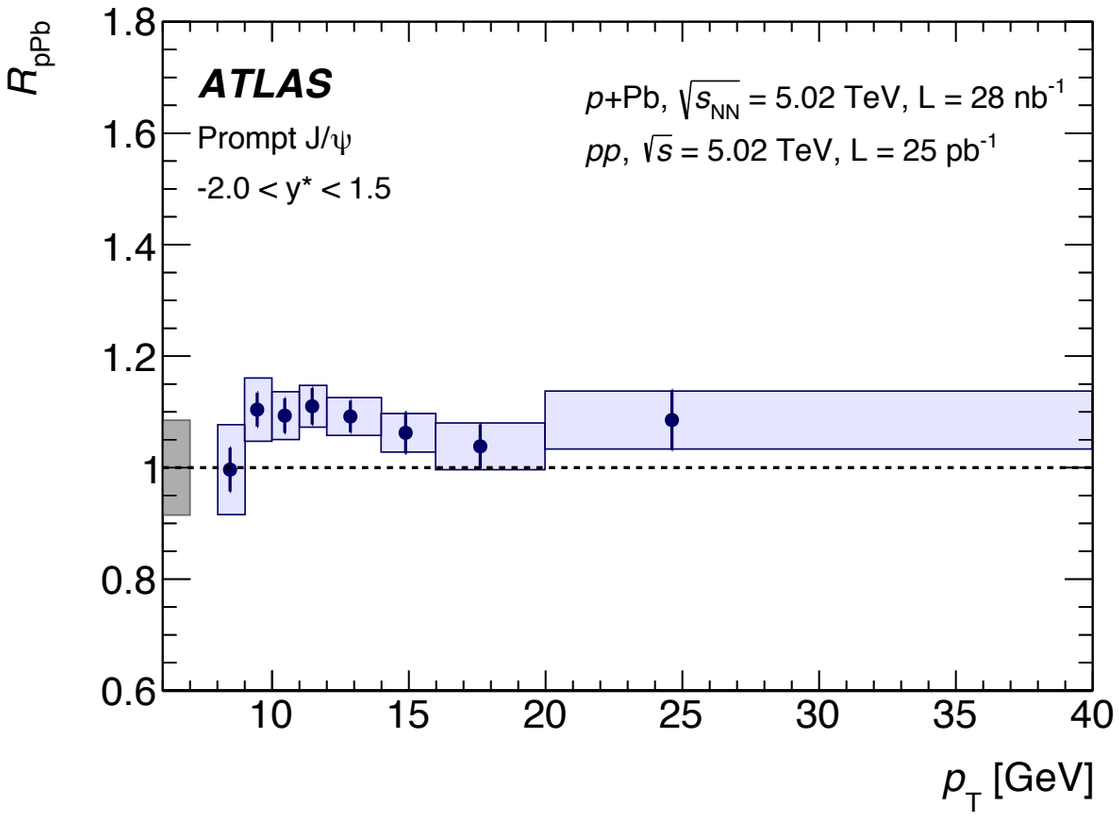
Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST

first stable beams heavy-ion collisions

Prompt J/ψ

$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

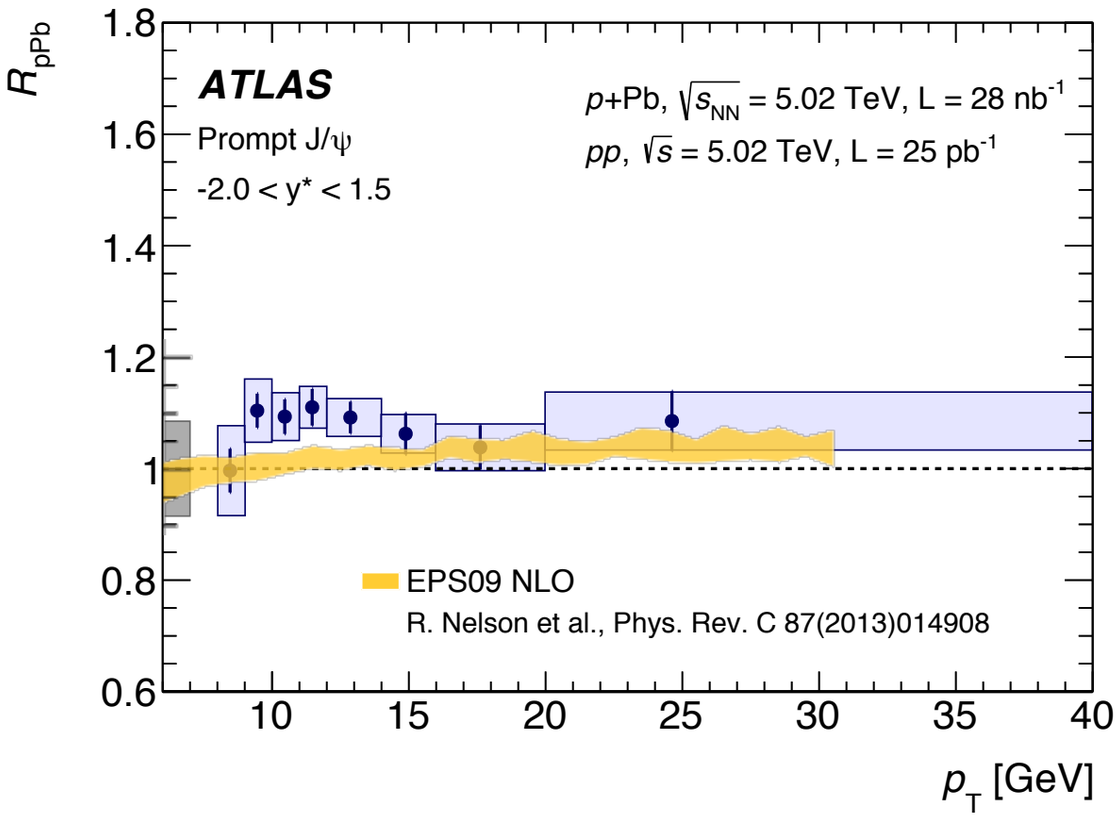
- $R_{\mathrm{pPb}} = 1$, no nuclear modification
- $R_{\mathrm{pPb}} \neq 1$, modification due to medium



- No obvious modification in p+Pb (no/small net CNM effect)

arXiv:1709.03089

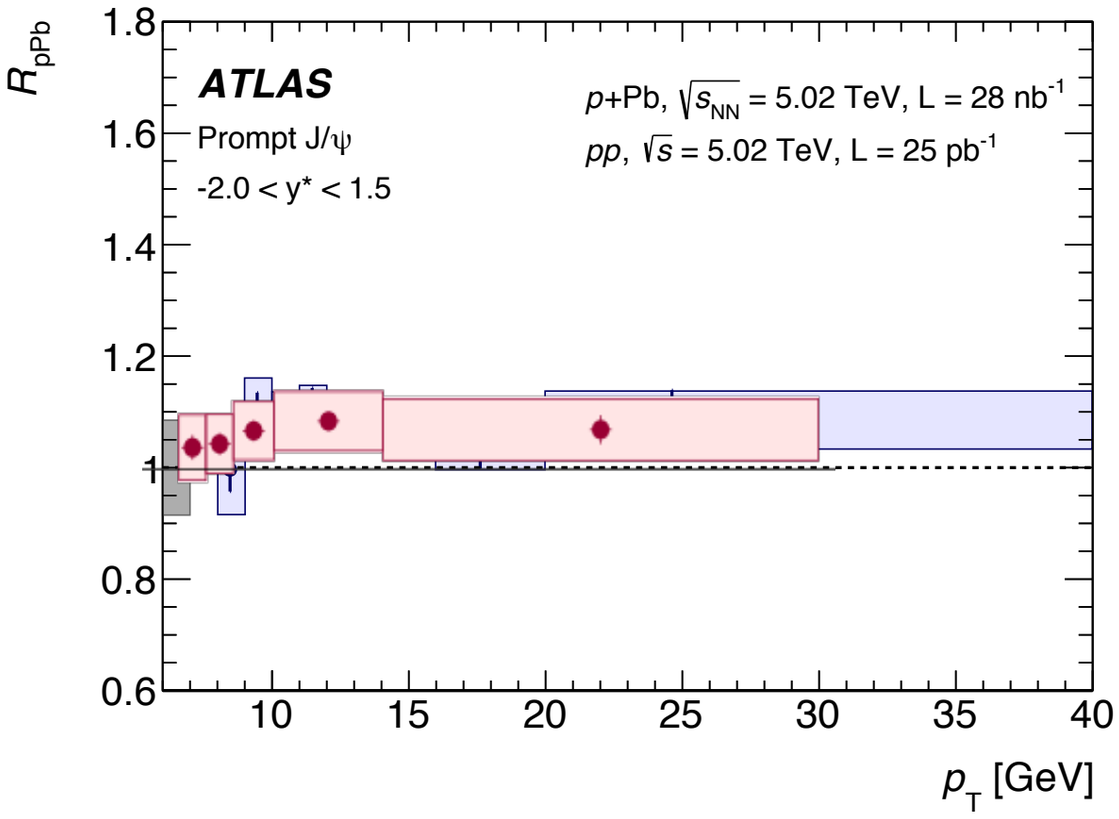
Prompt J/ψ



- No obvious modification in p+Pb (no/small net CNM effect)
- p+Pb results consistent with EPS09 calculation

arXiv:1709.03089

Prompt J/ψ

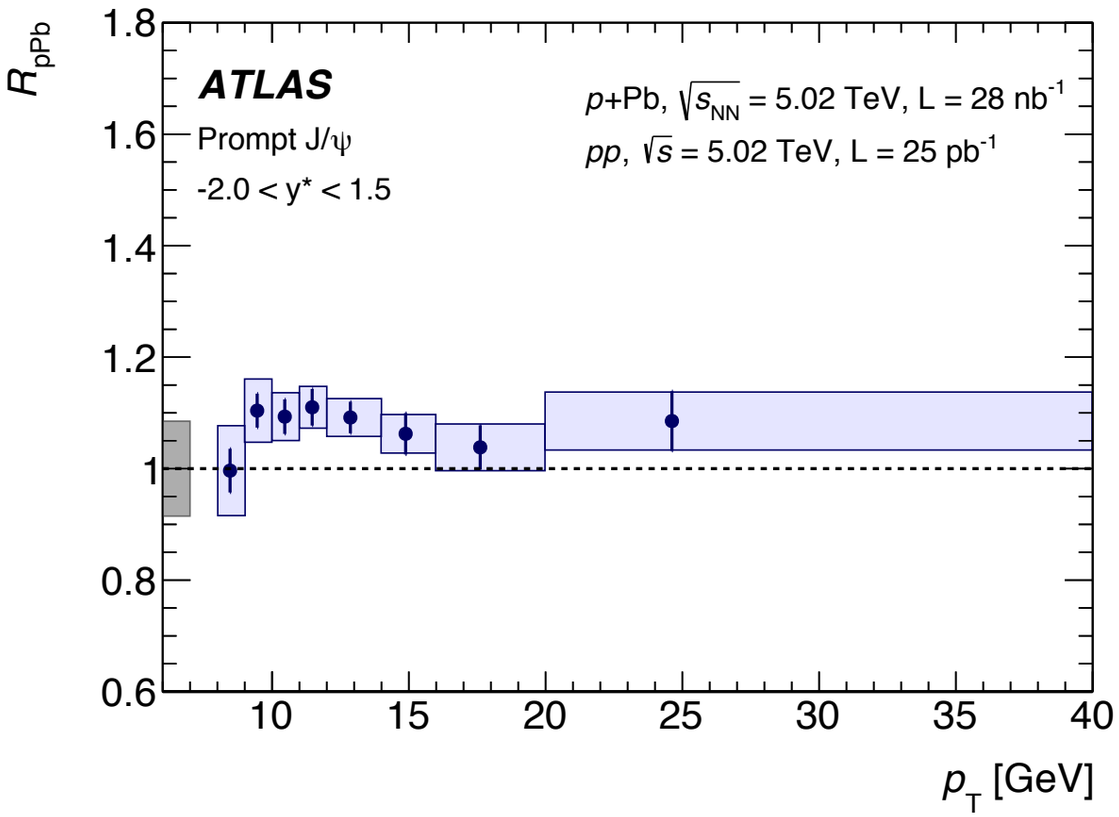


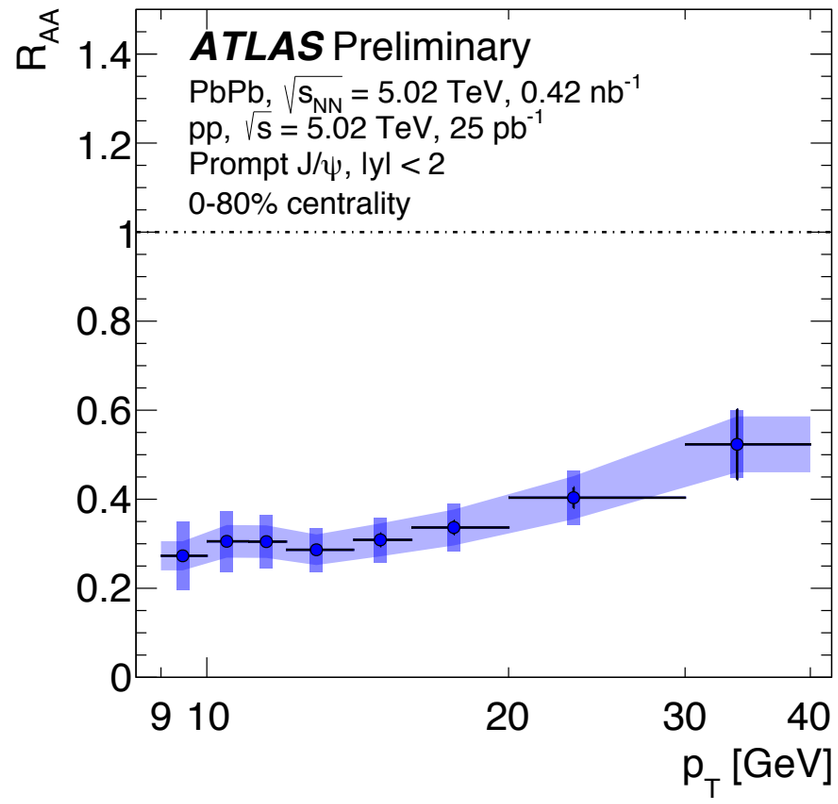
- No obvious modification in p+Pb (no/small net CNM effect)
- p+Pb results consistent with EPS09 calculation and CMS results

ATLAS: arXiv:1709.03089
CMS: EPJC 77 (2017) 269

Prompt J/ψ

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}}{< T_{\mathrm{AA}} > \sigma^{pp}}$$





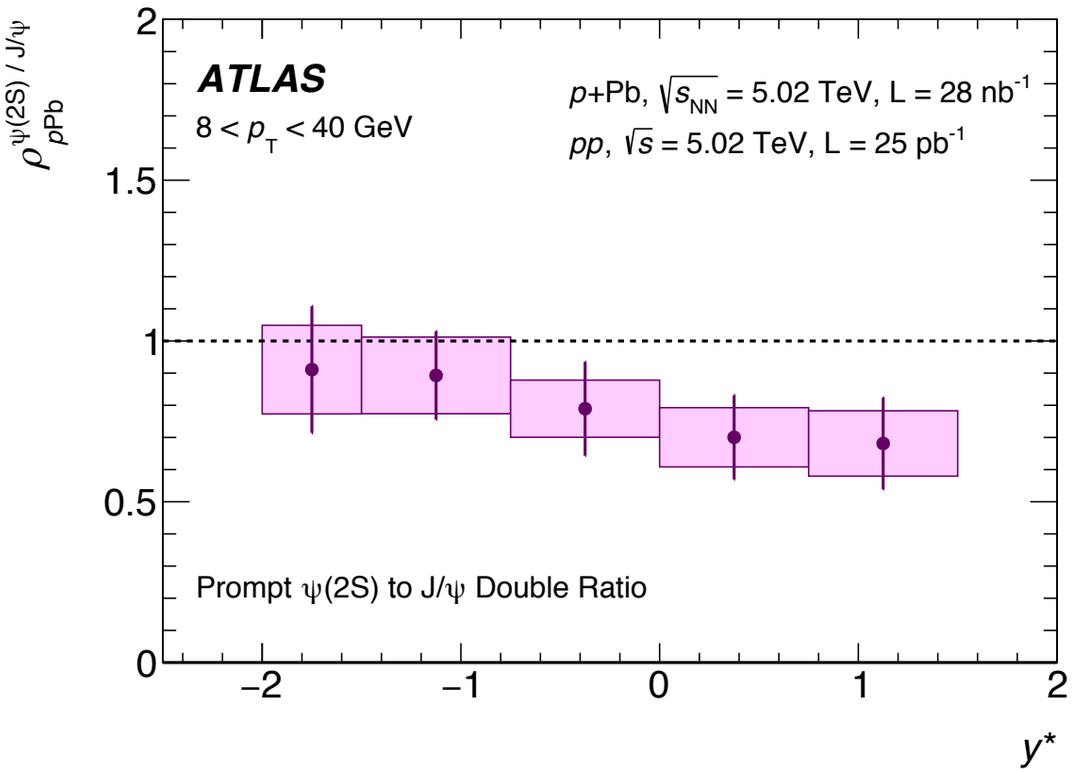
- No obvious modification in *p*+Pb (no/small net CNM effect)
- *p*+Pb results consistent with EPS09 calculation and CMS results
- Strong suppression in Pb+Pb dominated by QGP effects

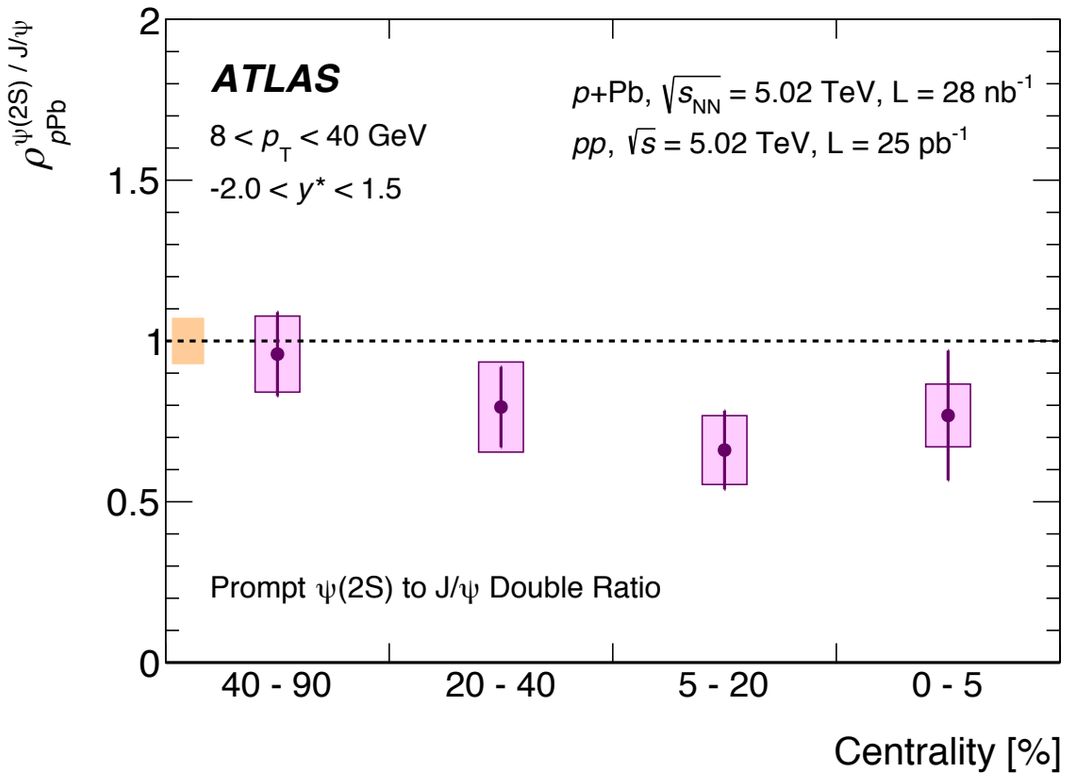
p+Pb arXiv:1709.03089
Pb+Pb ATLAS-CONF-2016-109

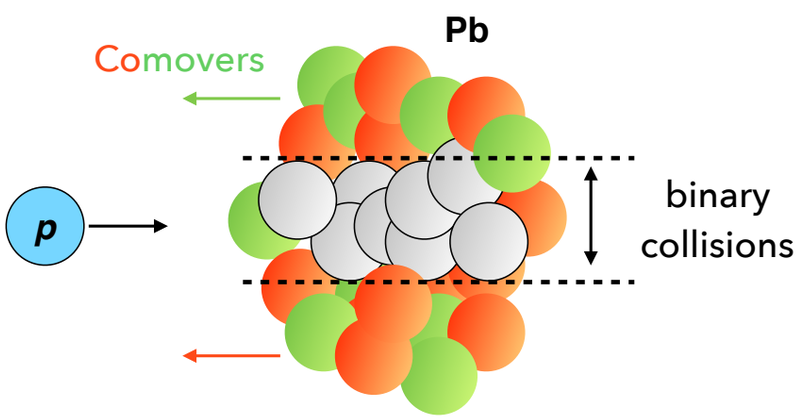
ψ(2S) in p+Pb

$$\rho_{p\mathrm{Pb}}^{\psi(2\mathrm{S})/J/\psi} = \frac{R_{p\mathrm{Pb}}(\psi(2\mathrm{S}))}{R_{p\mathrm{Pb}}(J/\psi)}$$

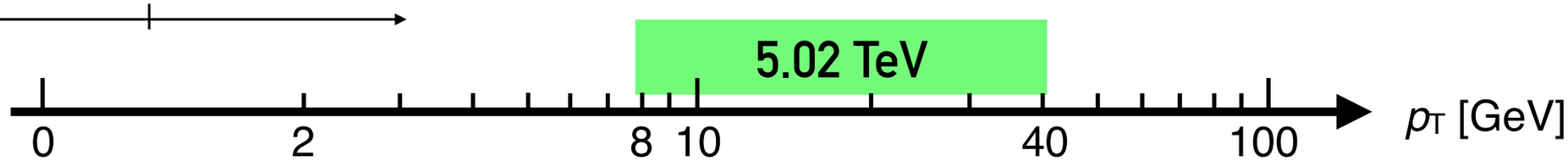
- Initial state effects are largely cancelled
- Sensitive to final state effects





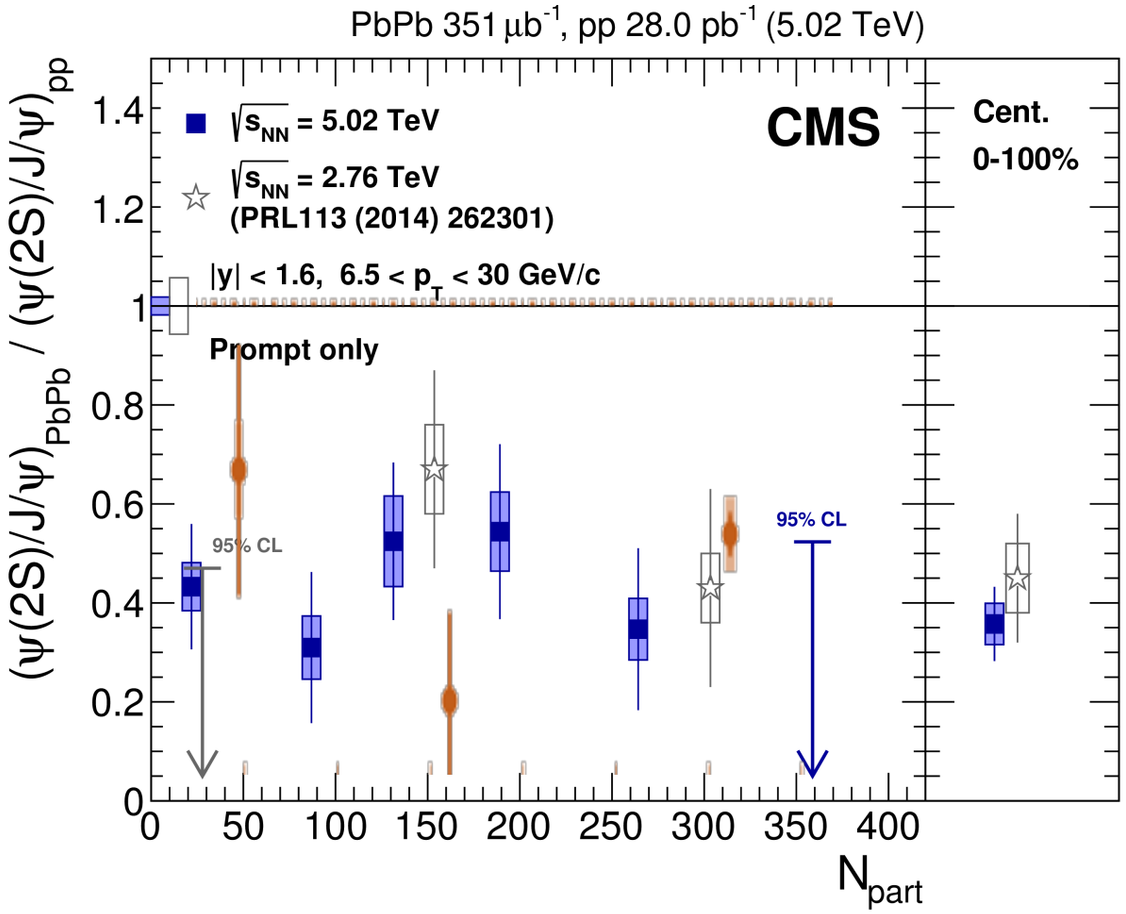


- Prompt ψ(2S) is more suppressed wrt. prompt J/ψ in both p+Pb
- Slight stronger suppression in forward and in more central p+Pb collisions
- Need more data



arXiv:1709.03089

ψ(2S) in Pb+Pb

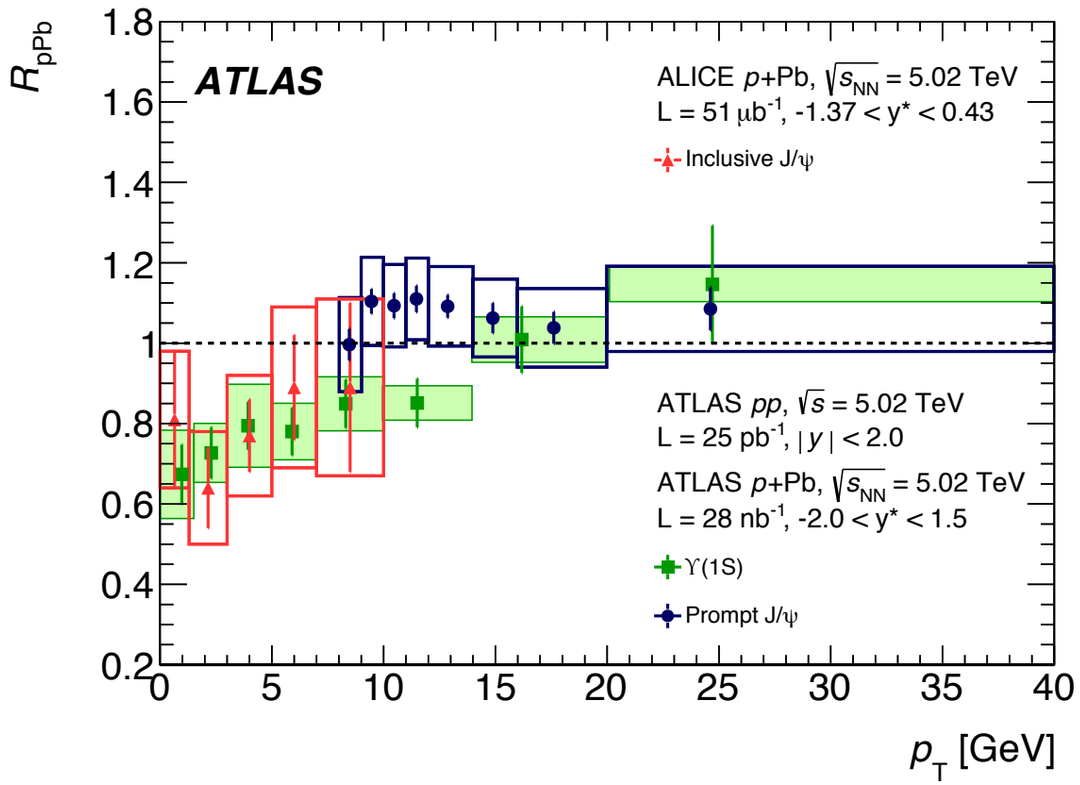


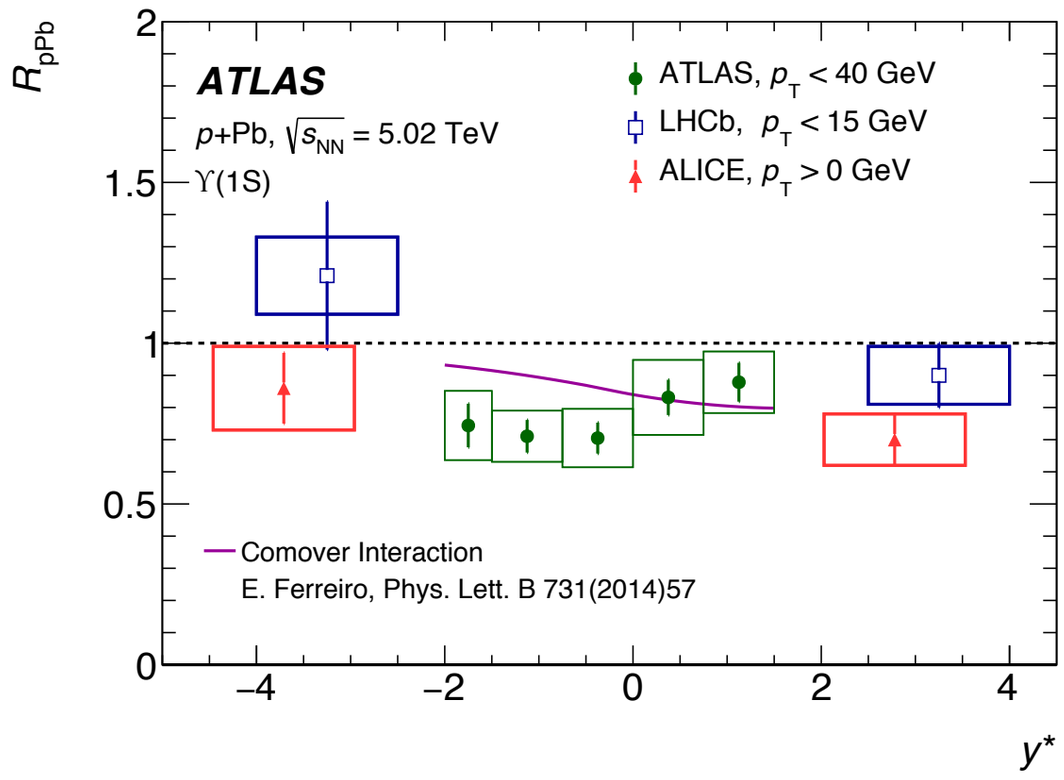
ATLAS
$|y| < 2.0$, $9 < p_T < 40$ GeV

- Stronger suppression of prompt ψ(2S) wrt. J/ψ
- Large statistical errors prevent concluding centrality dependence
- Good consistency with CMS measurements at similar kinematics

ATLAS arXiv:1709.03089
CMS PRL 118, 162301 (2017)

Υ(1S) in p+Pb

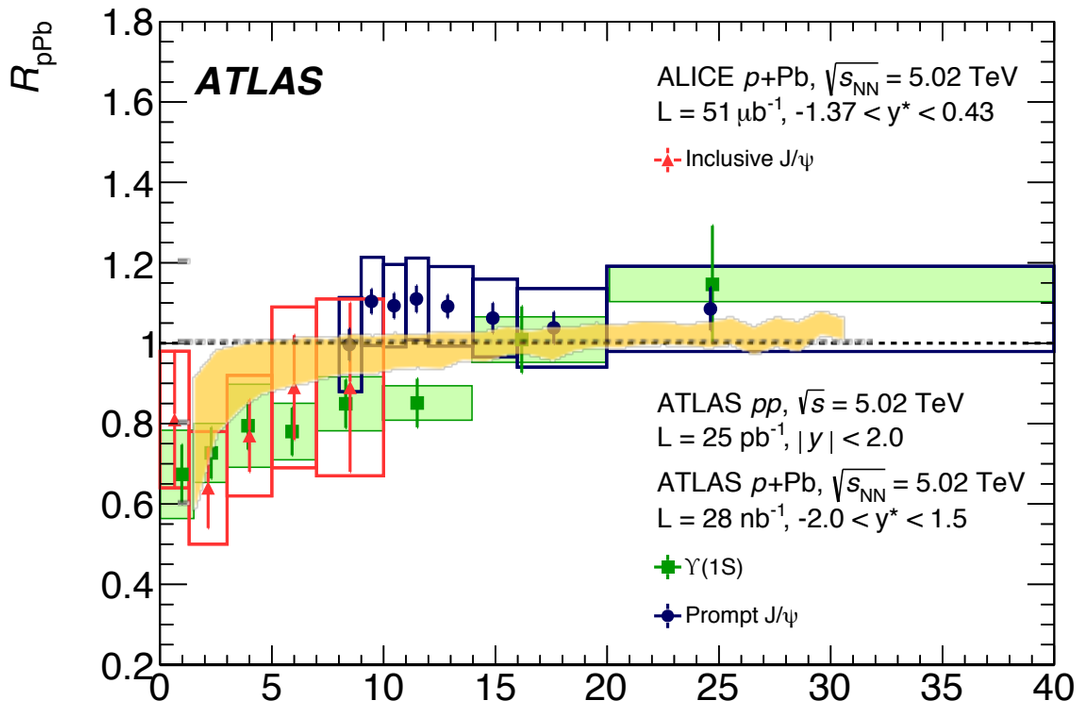


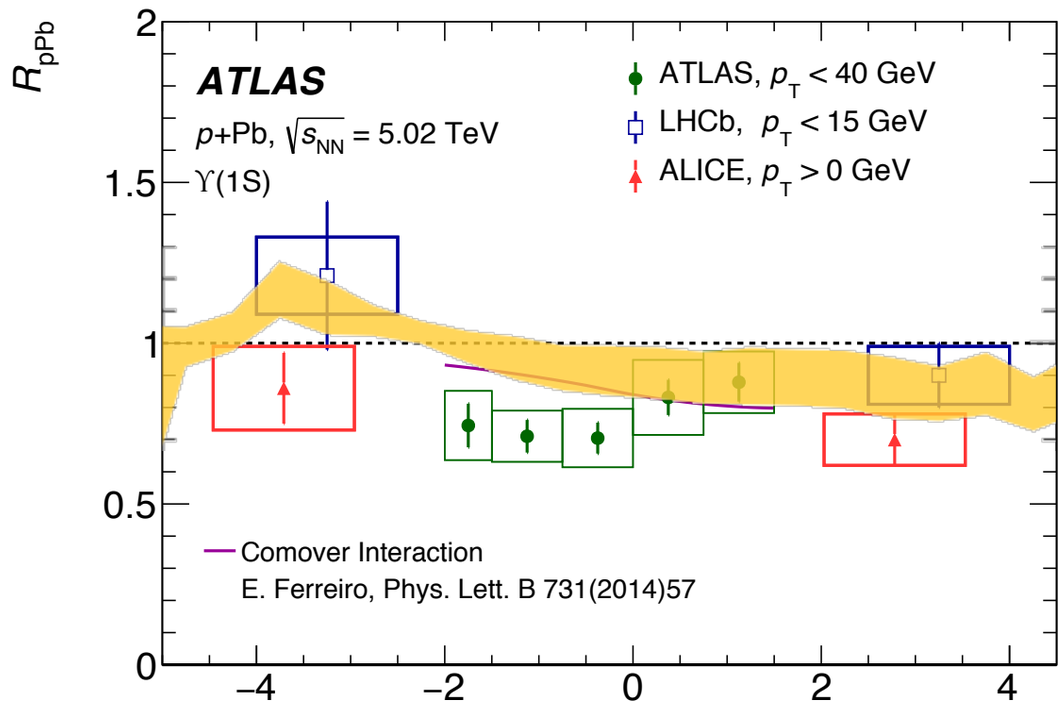


- **ϒ**(1S) is found to be suppressed at low p_T
- Difference between **ϒ**(1S) and J/ψ R_{pPb} at $10 < p_T < 15$ GeV
- Co-mover interaction gives a rough interpretation of the observables.

ATLAS arXiv:1709.03089
LHCb JHEP 02 (2014) 072
ALICE JHEP 06 (2015) 055
ALICE JHEP 02 (2014) 073

Υ(1S) in p+Pb

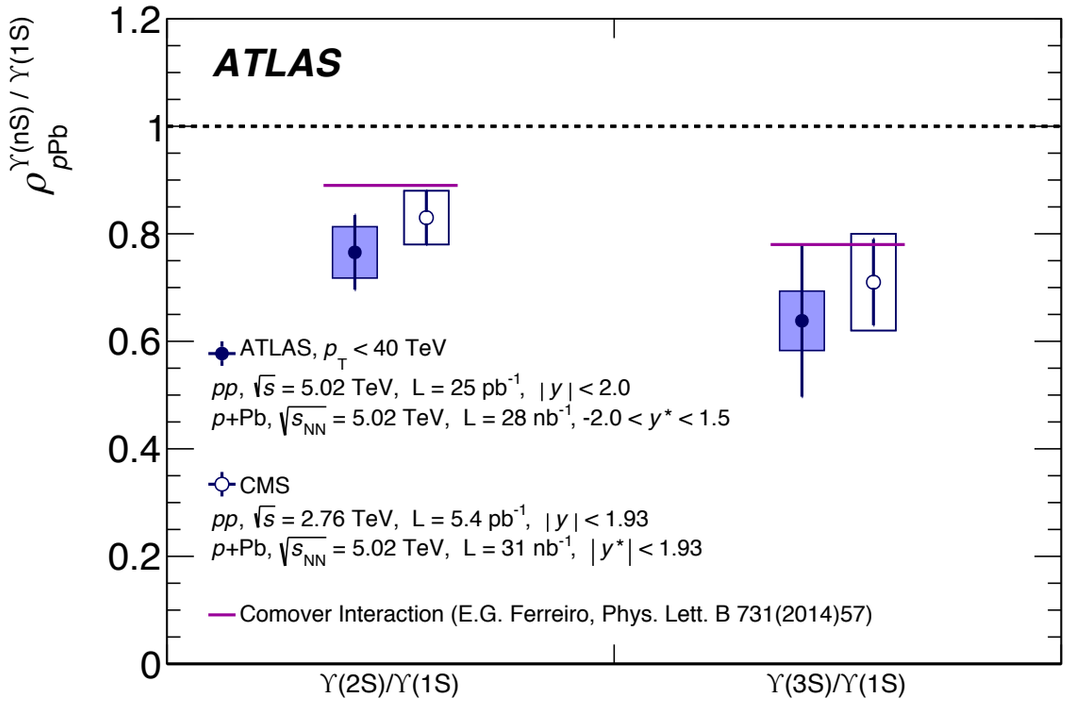


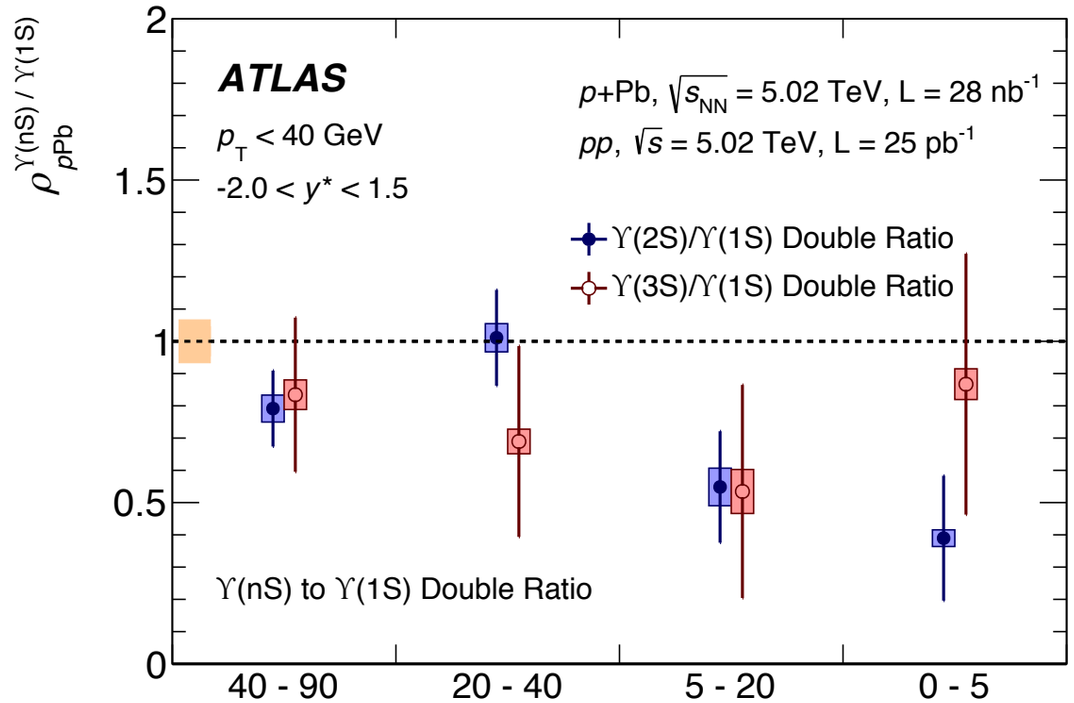


- ϒ(1S) is found to be suppressed at low p_T
- Difference between ϒ(1S) and J/ψ R_{pPb} at $10 < p_T < 15$ GeV
- Co-mover interaction gives a rough interpretation of the observables. So does EPS09

ATLAS arXiv:1709.03089
LHCb JHEP 02 (2014) 072
ALICE JHEP 06 (2015) 055
ALICE JHEP 02 (2014) 073

Υ(nS) in p+Pb





- Similar to prompt ψ(2S), excited states are suppressed wrt. ground state.
- Systematic size seems to play a role in both case
- More data would help

ATLAS arXiv:1709.03089
CMS JHEP 04 (2014) 103

Summary

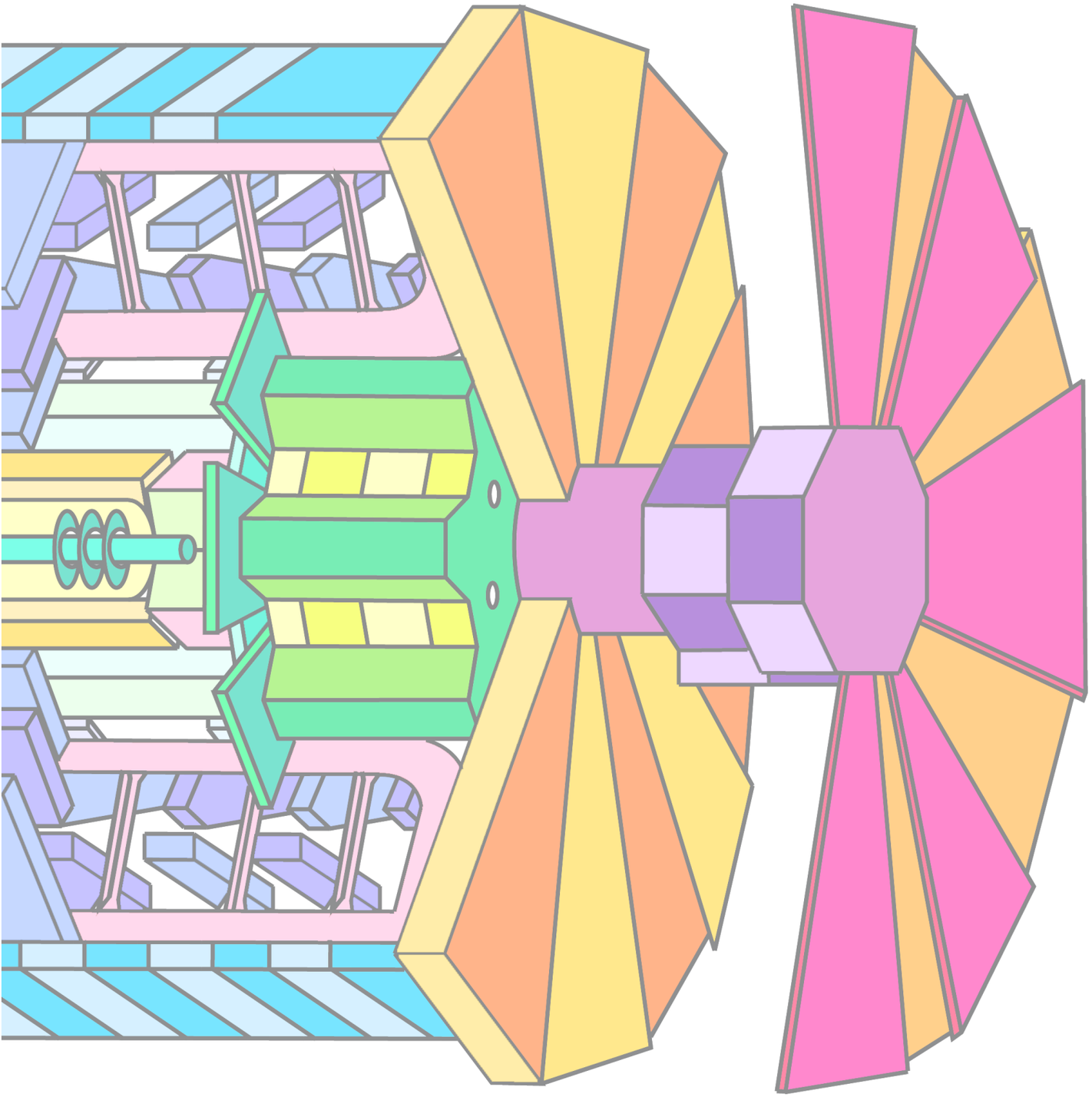
- Quarkonium production in pp

  Cross section measurements show good consistency with NLO NRQCD for prompt and FONLL non-prompt productions

- Quarkonium production in heavy ion collisions

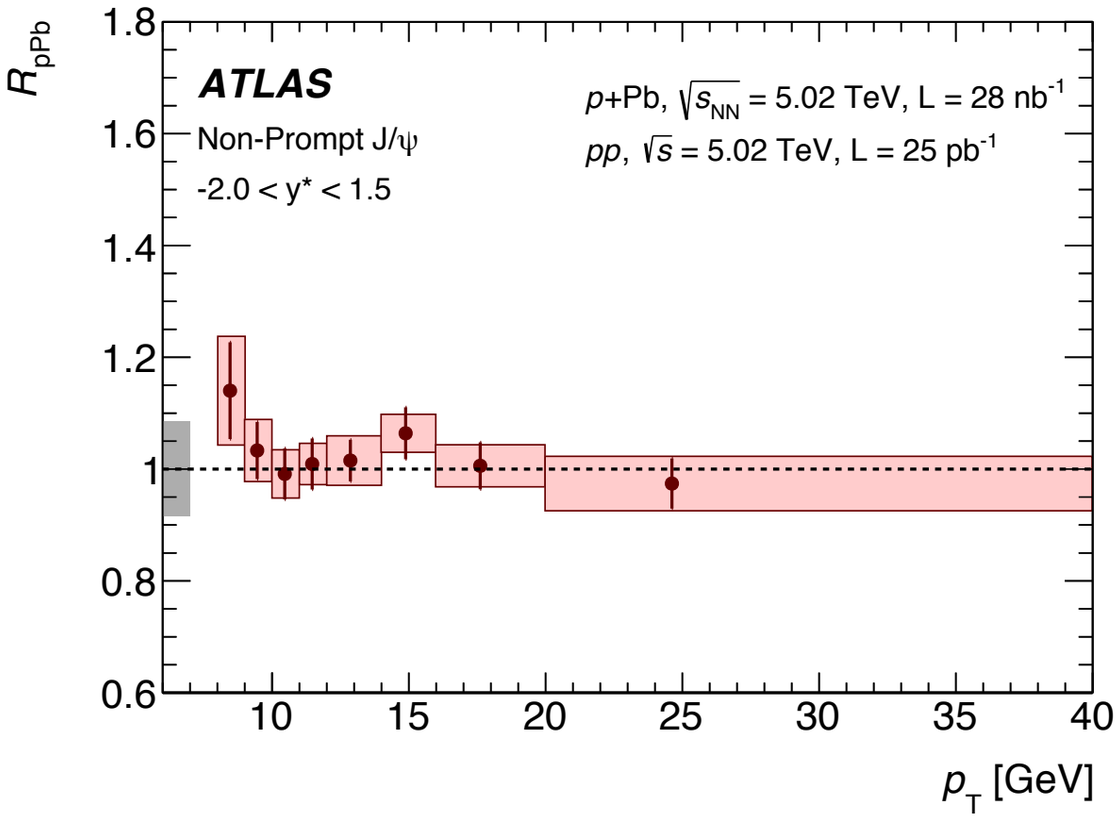
  Interesting suppression pattern of excited states in *p*+Pb collisions

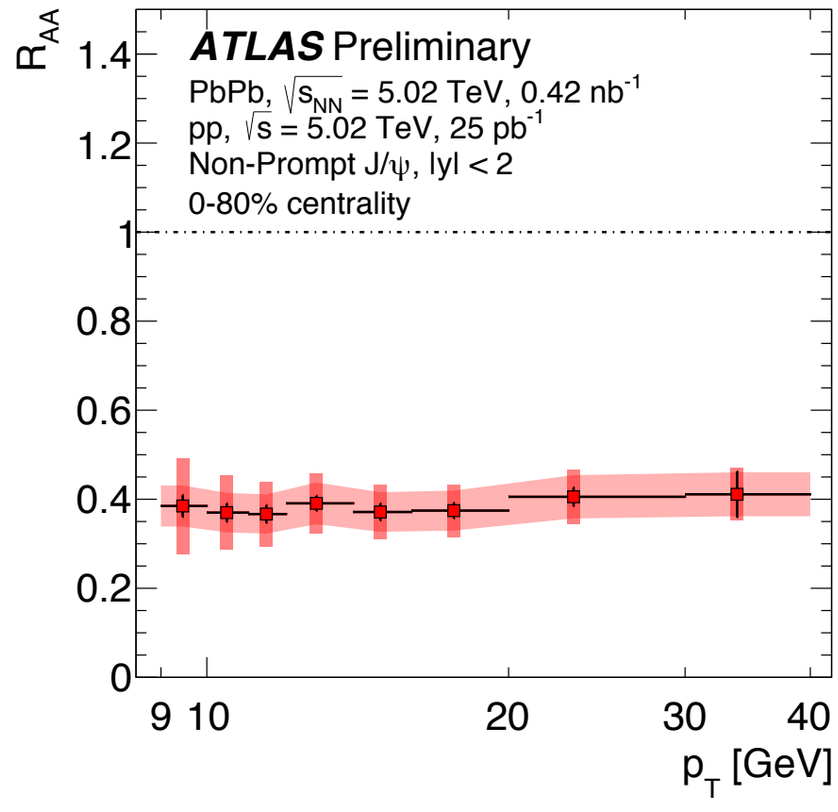
  Strong suppression of J/ψ and even strong suppression of ψ(2S) observed in Pb+Pb collisions



Backup

Non-prompt J/ψ

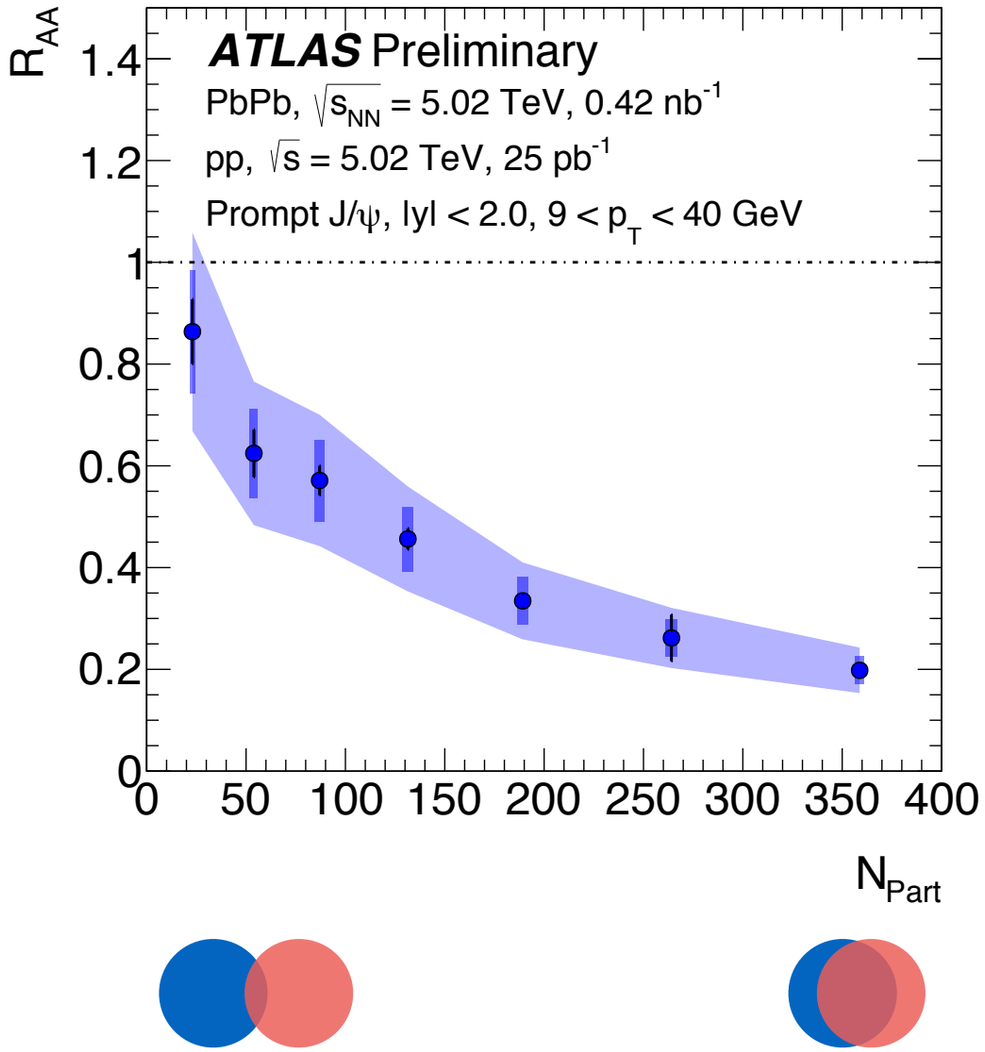


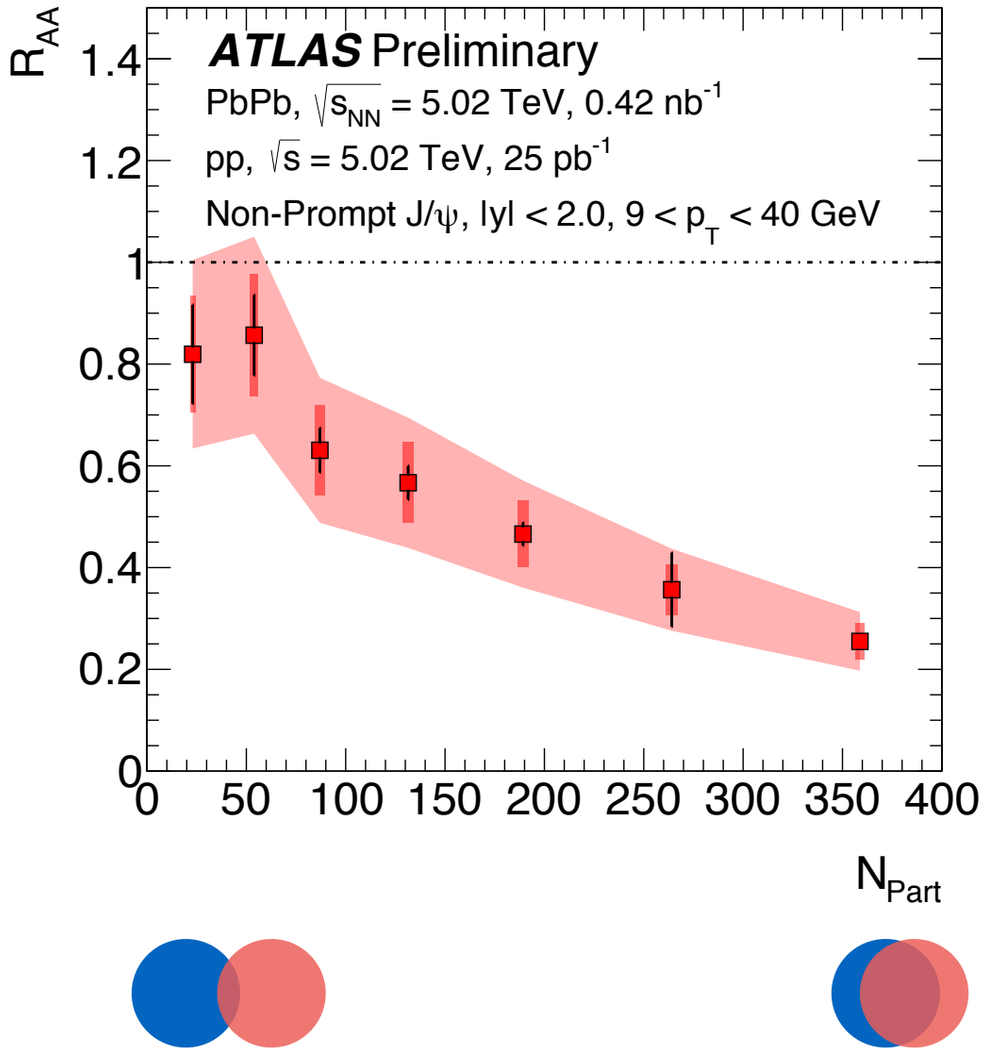


- No obvious modification in p+Pb (no/small net CNM effect)
- Significant suppression in Pb+Pb is dominate by QGP effects

p+Pb arXiv:1709.03089
Pb+Pb ATLAS-CONF-2016-109

Centrality dependence





- J/psi RAA in Pb+Pb shows very strong centrality dependence: more suppressed at central collisions (larger/hotter QGP medium)
- More peripheral collisions are comparable with *pp* collisions