Production of Quarkonia and Heavy Flavor States in ATLAS

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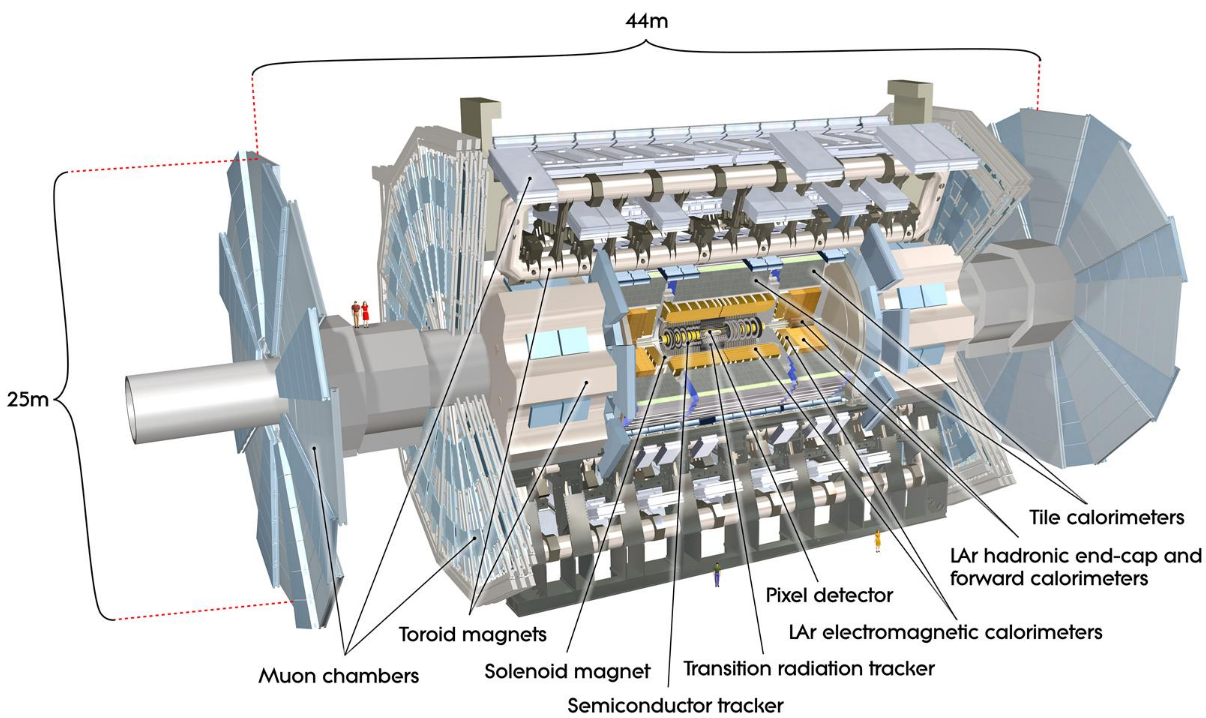
I. Introduction to ATLAS
II. b-Hadron Pair Production Cross-section at 8 TeV
III. Quarkonium Production in p-Pb and p-p at 5.02 TeV

Introduction

Two recent results in quarkonium and heavy flavors from ATLAS, using LHC pp and p-Pb data.



ATLAS from inside to out:

- Inner detector (pixel, silicon microstrips, straw-tube TRT) $|\eta| < 2.5$, surrounded by a 2T axial B field from the solenoid
- Sampling calorimeters (LAr EM $|\eta| < 3.2$; Scint tile HAD $|\eta| < 3.2$; LAr HAD $1.5 < |\eta| < 4.9$)
- Air core toroids provide B field for Muon drift tubes + cathode strip chambers (muon tracking to $|\eta| < 2.7$) and resistive plate + thin gap chambers (triggering to $|\eta| < 2.4$)

Measurement of b-hadron Pair Production Cross-section at 8 TeV*

***Message*:** This total cross section is measured: $\sigma\left(B\left(\to J/\psi\left[\to \mu^+\mu^-\right]+X\right)B\left(\to \mu+X\right)\right)$

Using it, 8 differential cross sections are obtained:

- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta R(J/\psi\mu)}$ separation between the J/ψ and the third μ in the azimuth-rapidity plane
- $\frac{1}{\sigma}\frac{d\sigma}{dm(J/\psi\mu)}[\mathrm{GeV}^{-1}]$ mass of the J/ψμ system
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi(J/\psi\mu)}[\mathrm{rad}^{-1}]$ azimuthal separation Δϕ between the J/ψ and the third μ
- $\frac{1}{\sigma}\frac{d\sigma}{dp_T(J/\psi\mu)}$ transverse momentum p_T of the 3-muon system
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta y(J/\psi\mu)}$ rapidity separation Δy between the J/ψ and the third μ

the list continues.....

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- $$\frac{1}{\sigma}\frac{d\sigma}{dy_{boost}(J/\psi\mu)}$$ magnitude y_{boost} of the avg. rapidity of the J/ψ and the third μ
- $$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{\mu\mu\mu}/m^{\mu\mu\mu}}$$ ratio of the p_T to the invariant mass of the 3-muon system,
- $$\frac{1}{\sigma}\frac{d\sigma}{dm^{\mu\mu\mu}/p_T^{\mu\mu\mu}}$$ and its inverse

These differential cross sections are compared to predictions from several event generators.

Motivation:

- Factorization of QCD calculations into parton distribution functions, hard matrix elements, and soft parton shower components allows the heavy (b) quark mass to be introduced at *different stages*.

- *Several schemes are possible* for inclusion of the heavy quark masses

- Previous analyses of heavy flavor production highlighted disagreements *among* theoretical predictions and *between* predictions and data. *This analysis constrains the options.*

- The region of small-angle $b\bar{b}$ production is *especially sensitive* to details of the calculations but has previously been *only loosely constrained* by data.

- Searches for Higgs produced in association with a vector boson (VH) and decaying to $b\bar{b}$ *rely on the modeling* of the background $b\bar{b}+V$

Details of the analysis (1)

- Trigger: 2 oppositely charged muons with a common vertex, $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.4$, $2.5 < m(\mu\mu) < 4.3$ GeV
- Integrated luminosity = 11.4 fb^{-1}
- Primary vertex: ≥ 2 tracks, each with $p_T > 400$ MeV, with largest summed p_T^2.
- Form the muon candidates:
  - use combined inner detector and muon spectrometer tracks
  - $p_T(\mu) > 6$ GeV, $|\eta(\mu)| < 2.5$
- J/ψ candidates:
  - opposite-sign muon pairs with $|\eta(\mu)| < 2.3$ and directional correspondence with the trigger-level candidate
  - $2.6 < m(\mu\mu) < 3.5$ GeV
  - If multiple candidates per event, choose the one with mass closest to J/ψ_{PDG}.
- Third muon: choose the highest-p_T one not included in the J/ψ reconstruction.
- The J/ψ and the third μ may come from feed-down or cascade.
- The data are first compared to these simulations:
  - Inclusive b-hadron pairs from PYTHIA8.186 (2->2 matrix element with parton shower); CTEQ6L1 pdf, AU2 tune; b quarks are massless in the pdf but the mass is reinstated during the shower; pile-up included with PYTHIA8 + MSTW2008 pdf + A2 tune.
  - $pp \to b\bar{b}$ simulated with HERWIG++, CTEQ6L1, UE-EE5 tune; b-quarks are massive in the matrix element and in the parton shower.
- 4-momenta of photons near muon ($\Delta R_\eta(\mu,\gamma) < 0.1$) added to muon

Analysis details (2)

Corrections:

- for trigger efficiency including vertex recon and spatial overlap of muons
- for muon reconstruction efficiency

- To collect the J/ψ's produced in decays of b-hadrons:
  - Define L_{xy}: transverse distance between primary vertex (PV) and dimuon vertex, signed positively for momentum pointing away from primary vertex.
  - Define pseudo-proper decay time:

$$\tau \equiv \frac{L_{xy} \cdot m\left(J/\psi_{PDG}\right)}{p_T\left(\mu^+\mu^-\right)}$$

  - J/ψ's from most b decays are non-prompt, so to optimize for signal events, require $\tau > 0.25$ mm/c.
  - simultaneous maximum likelihood fit to the distributions of dimuon mass and τ.

- Extract # non-prompt J/ψ's.

Analysis details (3)

- To select the third muon, reject bkgs: prompt muons, muons from charged π/K decay, fake muons from decay in flight and hadron shower leakage, muons combined with continuum (false) J/ψ, and muons in pile-up.
- Discriminate third-muon signal from bkg with a simultaneous fit on 2 observables:
  - transverse impact parameter significance

$$S_{d_0} \equiv d_0 / \sigma_{d_0}$$

    (d_0 is distance of closest approach of the muon track to the PV in the r-ϕ projection, with sign given by the sign of the angular momentum of the track around the beam at point of closest approach)
  - Output of a boosted decision tree using kinematic variables related to track deflection significance, momentum balance, and |η|.

- Subtract 3 remaining irreducible bkgs from fitted yields:
  - $B_c \rightarrow J/\psi + \mu + X$ (very small, taken from simulation)
  - Semileptonic decays of c-hadrons not resulting from b-hadron feed-down
  - "Sail through" charged π/K: traverses the detector to the muon spectrometer without interacting or decaying (mimics a muon, taken from simulation)

Analysis details (4)

Corrections:

- for the τ requirement: extrapolate to full range
- for detector resolution on momentum and η of muons. Issue: migration between bins and in/out of fiducial volume.

Repeat for every kinematic bin for each differential cross section.

Systematic uncertainties:

- Muon efficiency corrections to data
- J/ψ model
- Background components in the fits

Statistical uncertainties:

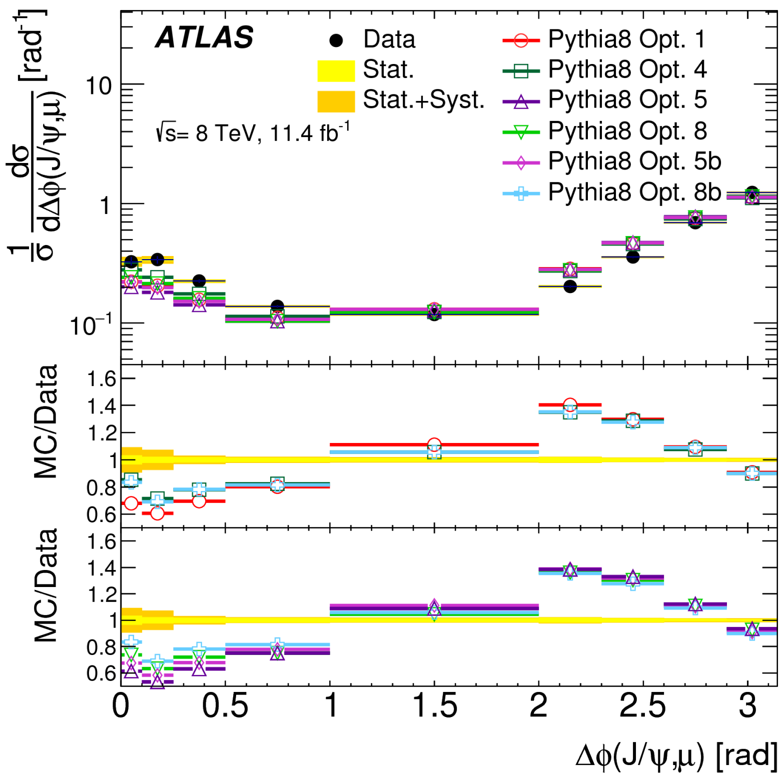
- On the data statistics
- On the third-muon templates taken from simulation

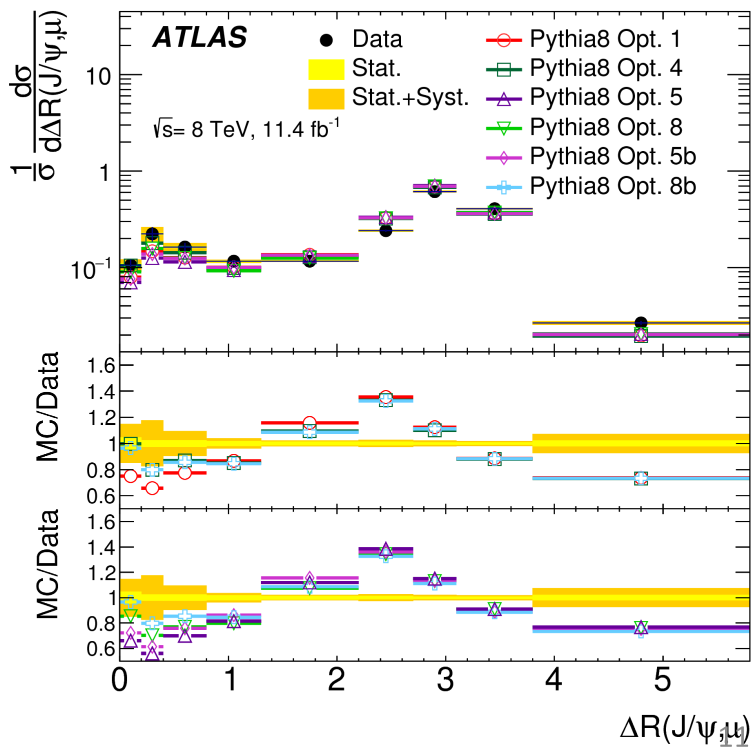
Luminosity uncertainty: 1.9%

Result 1: $\sigma\left(B\left(\to J/\psi\left[\to \mu^+\mu^-\right]+X\right)B\left(\to \mu+X\right)\right) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst})$ nb.

Result 2: Is the scale of α_s during splitting set by *relative* p_T or by *mass*?
Compare differential cross sections using 6 options in PYTHIA8 for the $g \to b\bar{b}$ splitting kernel (dominates small angle b-hadron production).

PYTHIA8 does not reproduce the shape of the angular distributions for any of the 6 options.





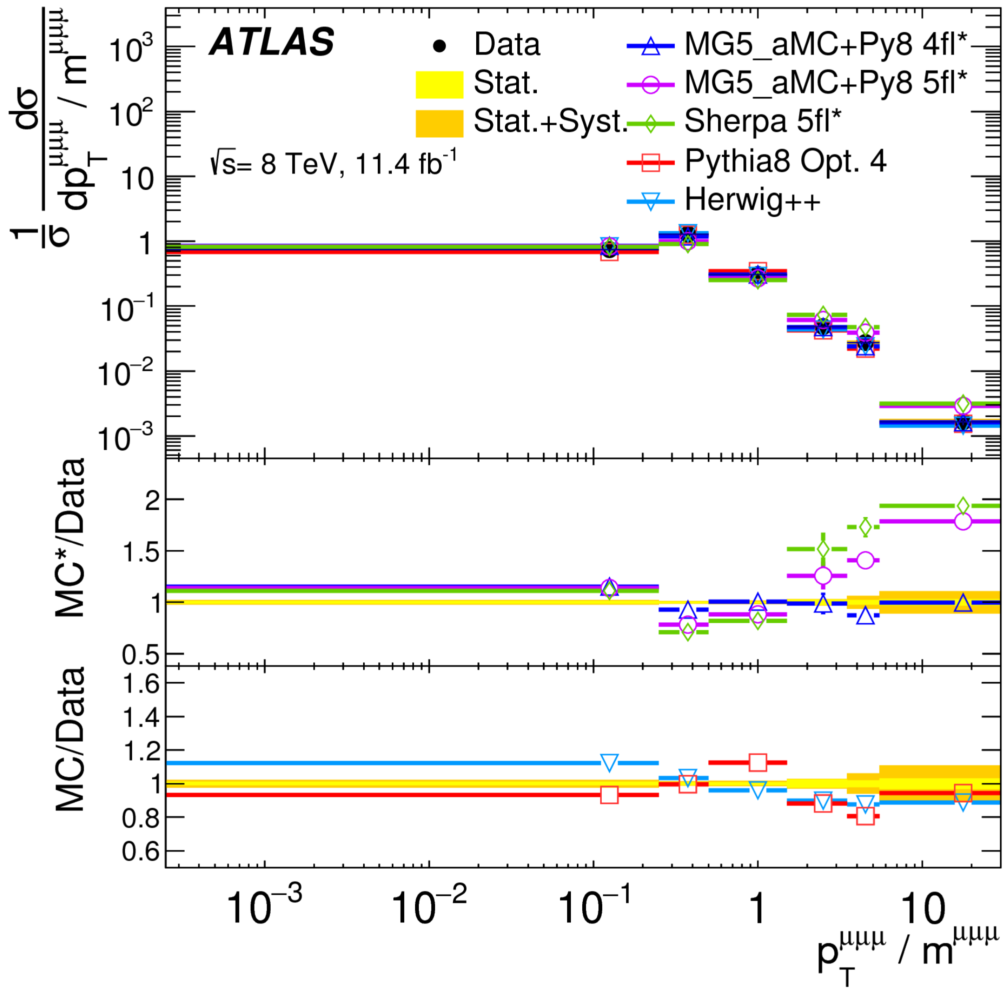
Result 3:

Extend the comparison of data to HERWIG++, SHERPA, and MADGraph5_AMC@NLOv2.2.2 + PYTHIA8.186 parton shower model.

These cover a range of matrix element calculations and parton shower models.

Consider options with 4 or 5 massless flavors. Compare all of these to PYTHIA8.

- HERWIG++ reproduces the ΔR and $\Delta\phi$ graphs best.
- 4-massless flavors models ΔR and $\Delta\phi$ better than 5.
- Δy spectrum is well modeled by MadGraph and SHERPA
- All models reproduce y_{boost} well.
- 5-massless flavor MadGraph models low mass distribution better than 4,
- but 4-massless flavor MadGraph models high p_T/m best.



Conclusions:

- Considering all distributions, the 4-massless flavor prediction from MadGraph5_AMC@NLO+PYTHIA8 best describes the data.
- Predictions of PYTHIA8 and HERWIG++ are comparable.
- Among PYTHIA8 options studied, the p_T-based splitting kernel is best, but none of the PYTHIA8 options fully describe the data.

Measurement of quarkonium production in p-Pb and p-p collisions at 5.02 TeV*

***Message*:**

- Production of J/ψ, ψ(2S), and Υ(nS) [n = 1,2,3] in p-Pb collisions is compared to production in p-p collisions

- Intent: understand effects of normal (cold) nuclear matter on suppression of quarkonium production in an environment where quark-gluon-plasma (QGP) is not expected.

- Ultimate goal is to better understand the backgrounds to effects associated with QGP.

*Eur. Phys. J C (2018) 78:171

Motivation:

Suppression of quarkonium has been observed previously. The goal here is to *understand well suppression caused by normal (cold) nuclear matter (CNM) so that this can be distinguished from suppression due to QGP.*

Significant formation of QGP is not expected in either p-p or p-Pb collisions, so effects observed here should be largely attributable to CNM.

CNM effects include:

Initial state effects, which impact quarks before the formation of quarkonium	- modification of nuclear pdf - parton saturation effects in the nucleus - parton energy loss due to interaction with the nuclear medium
Final state effect, depends on the quarkonium	- absorption of the quarkonium pair through interactions with the nuclear medium

Goal**:** select for final state effects, then see whether they match NRQCD predictions. *Use the results to constrain CNM models.*

- Define the *nuclear modification factor*: $$R_{pPb} = \frac{1}{208} \frac{\sigma_{p+Pb}^{O(nS)}}{\sigma_{p+p}^{O(nS)}}$$
- *O(nS)* is the quarkonium state (excitation *n*) and 208 is the # nucleons in lead.
- Define the *double ratio:* $$\rho_{pPb}^{O(nS)/O(1S)} = \frac{R_{pPb}(O(nS))}{R_{pPb}(O(1S))}$$
- *Initial state effects are expected to be canceled in the double ratio.*

Analysis details (1):

- Using integrated luminosities L = 28 nb^{-1} (p-Pb) and 25 pb^{-1} (p-p)
- COM energy 5.02 TeV per nucleon pair
  - proton beam 4 TeV, Pb beam 1.58 TeV per nucleon
  - In p-Pb collisions, COM rapidity y* is shifted by 0.465 wrt laboratory frame
  - data are recorded for p, Pb beams in both directions
- Trigger: dimuon candidate
- Selection: ≥ 1 primary vertex with ≥ 4 tracks, at least 2 muons with a common vertex
- All muons within pseudorapidity $|\eta| \leq 2.4$
- All muon pairs with opposite charges are quarkonium candidates
- Events arising from p-Pb are assigned "centrality class": more participating nucleons leads to more transverse energy: more central event.

- Define the cross section × branching ratio for number of observed quarkonia N in bins of p_T and y:

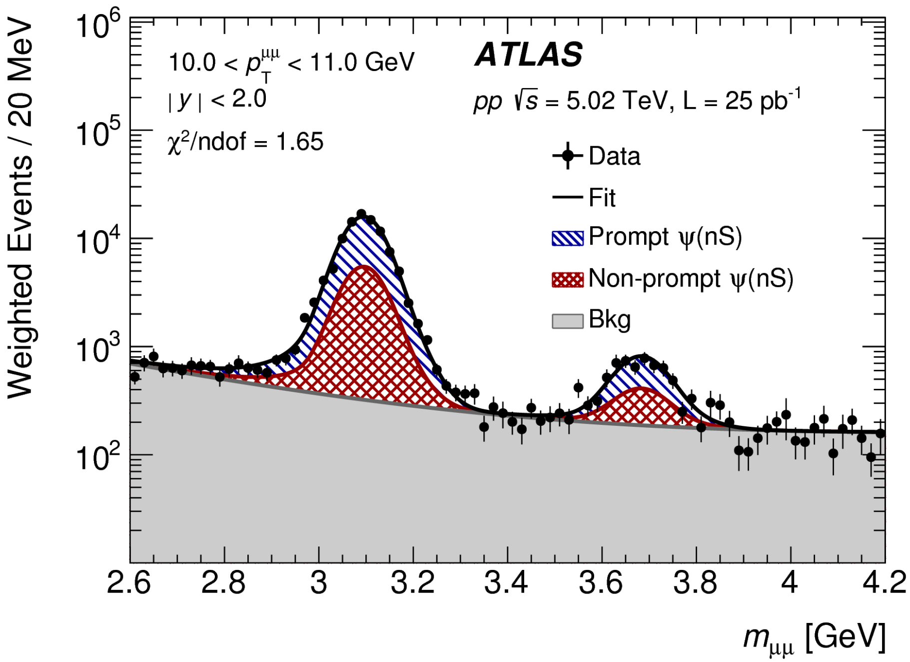
$$\frac{d^2\sigma_{O(nS)}}{dp_T dy^*} \times B(O(nS) \rightarrow \mu^+\mu^-) = \frac{N_{O(nS)}}{\Delta p_T \times \Delta y \times L}$$

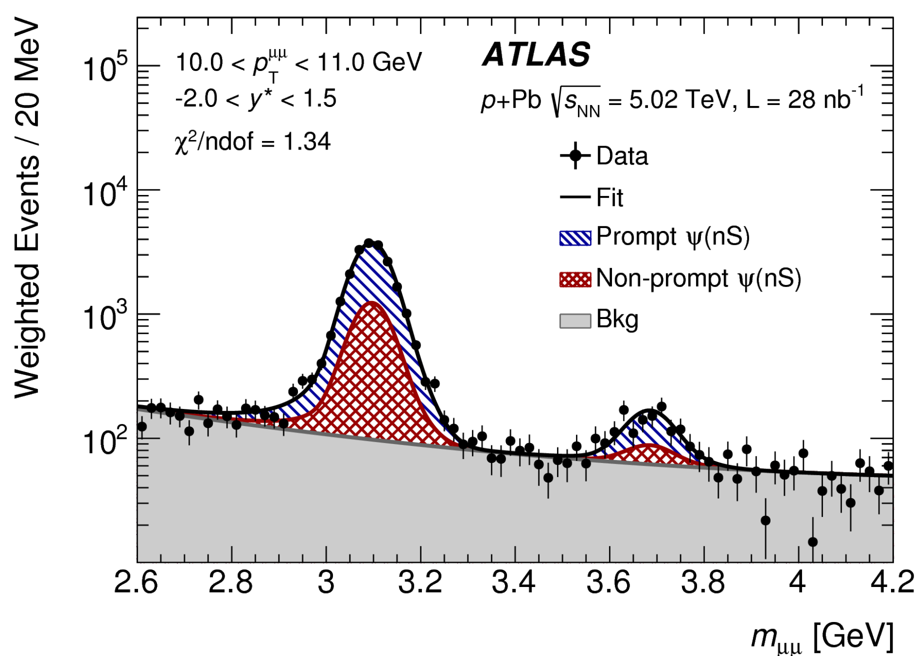
- For charmonium: MC-based corrections for acceptance (p_T, η, corrected for final-state radiation), trigger efficiency, and recon efficiency

Analysis details (2):

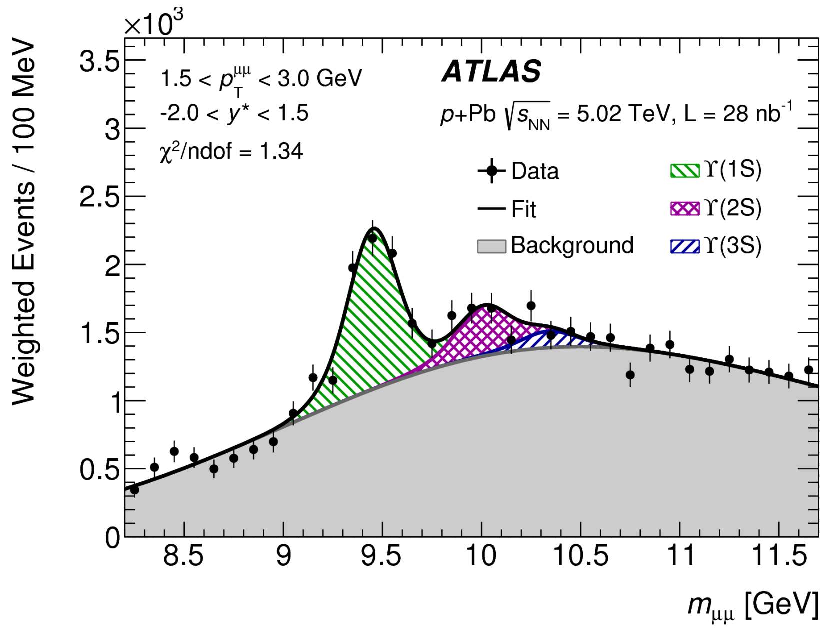
- reconstruction and trigger efficiencies from $J/\psi \to \mu^+\mu^-$ data
- Use pseudo-proper lifetime to divide charmonium sample into
  - prompt: strongly produced, including feeddown from excited charmonium states
  - non-prompt: from b-hadron weak decays
- Fit data in every $p_T^{\mu\mu}$, y, and centrality bin to a probability density function in $m_{\mu\mu}$ and $\tau_{\mu\mu}$

- Example result:





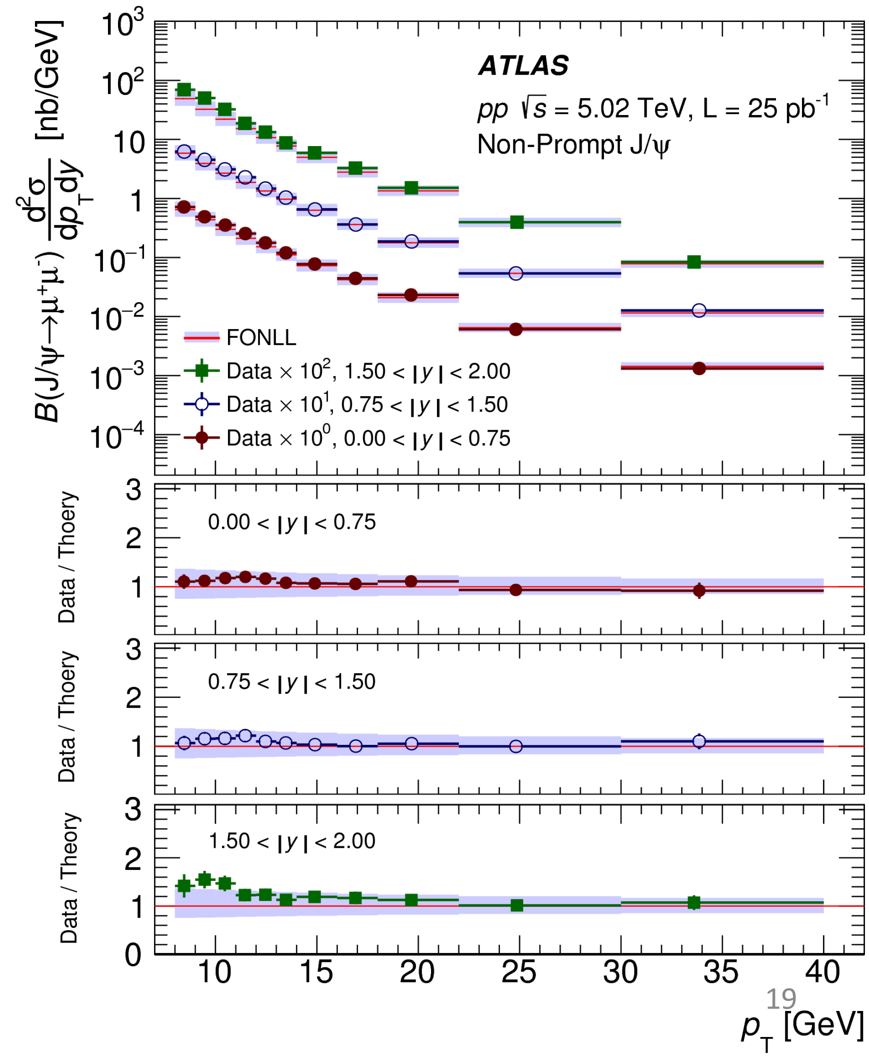
- Similar analysis for bottomonium, with acceptance estimate modified to accommodate overlapping mass peaks, example:



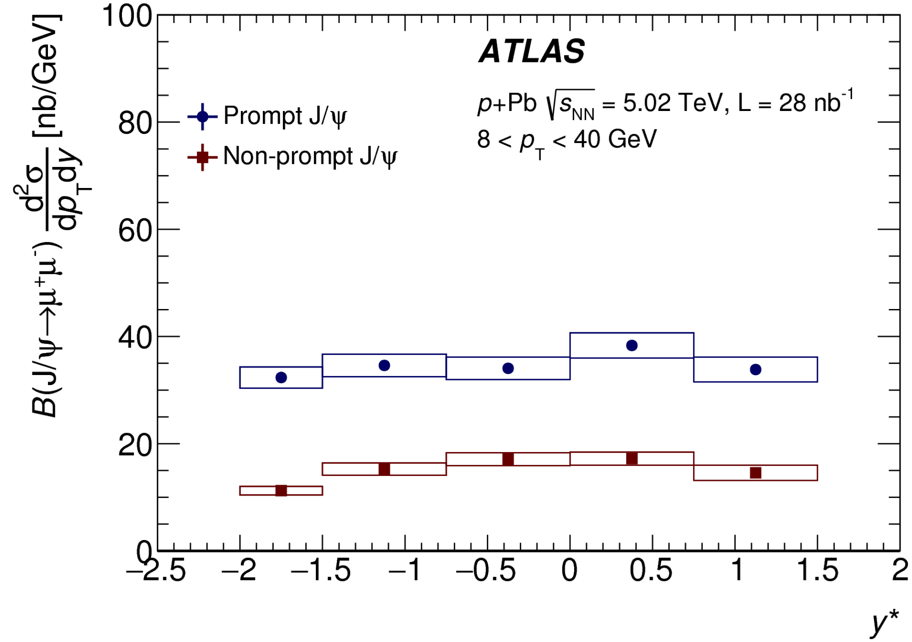
Systematic uncertainties:

- acceptance
- muon recon correction
- trigger eff correction
- fit model parameterization
- bin migrations
- luminosity

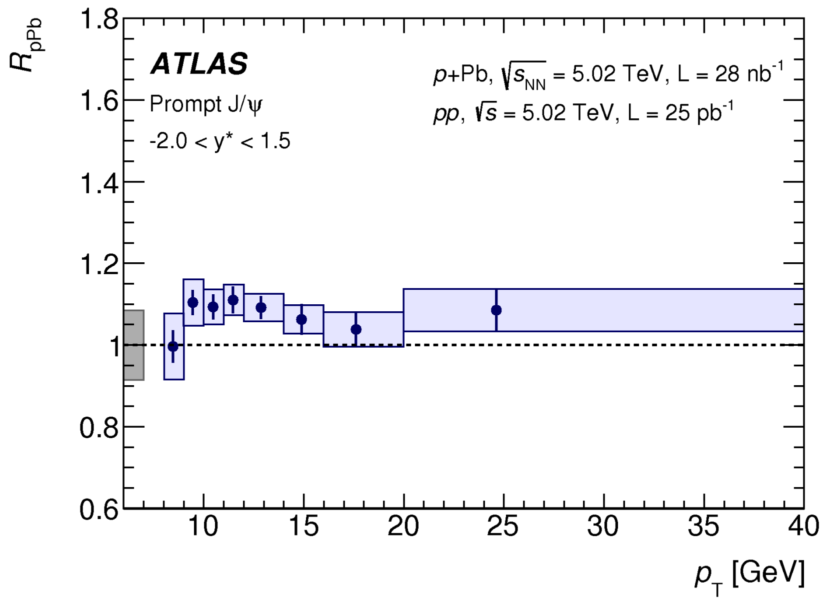
- Extract signal, calculate yield, compare cross sections to predictions. Example p-p results (bars are statistical ⊕ systematic) compared to FONLL model:

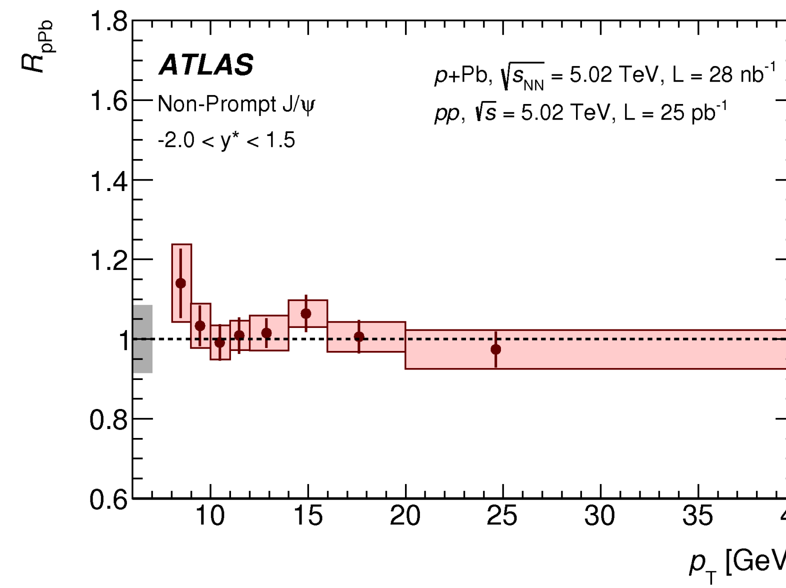


- An example result for p-Pb (bars are statistical, boxes are systematic):

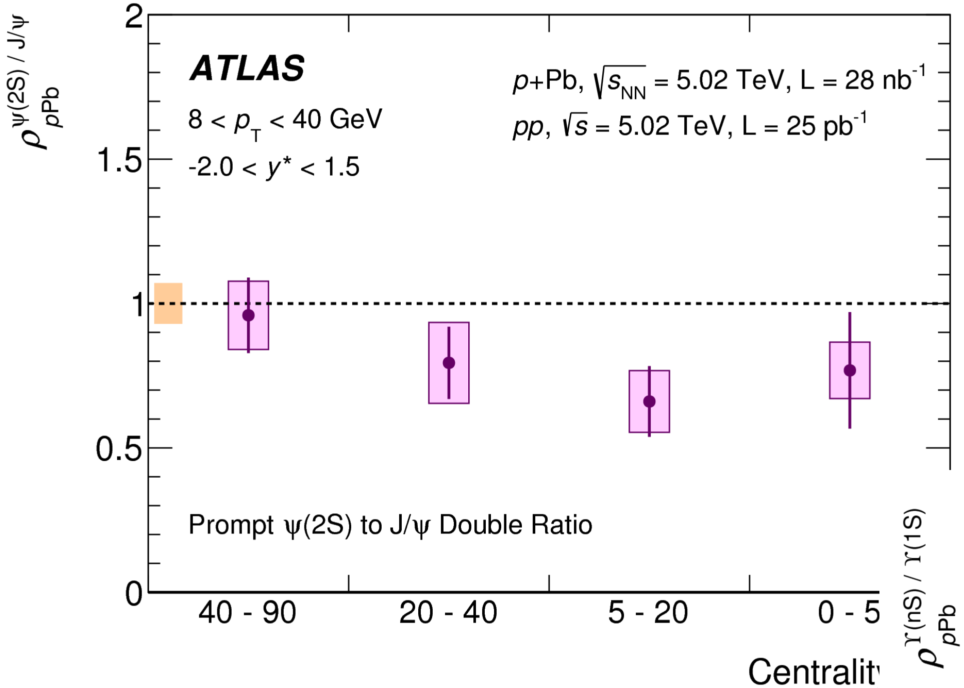


- Calculate nuclear modification factors $R_{pPb} = \dfrac{1}{208}\dfrac{\sigma^{O(nS)}_{p+Pb}}{\sigma^{O(nS)}_{p+p}}$, for example:

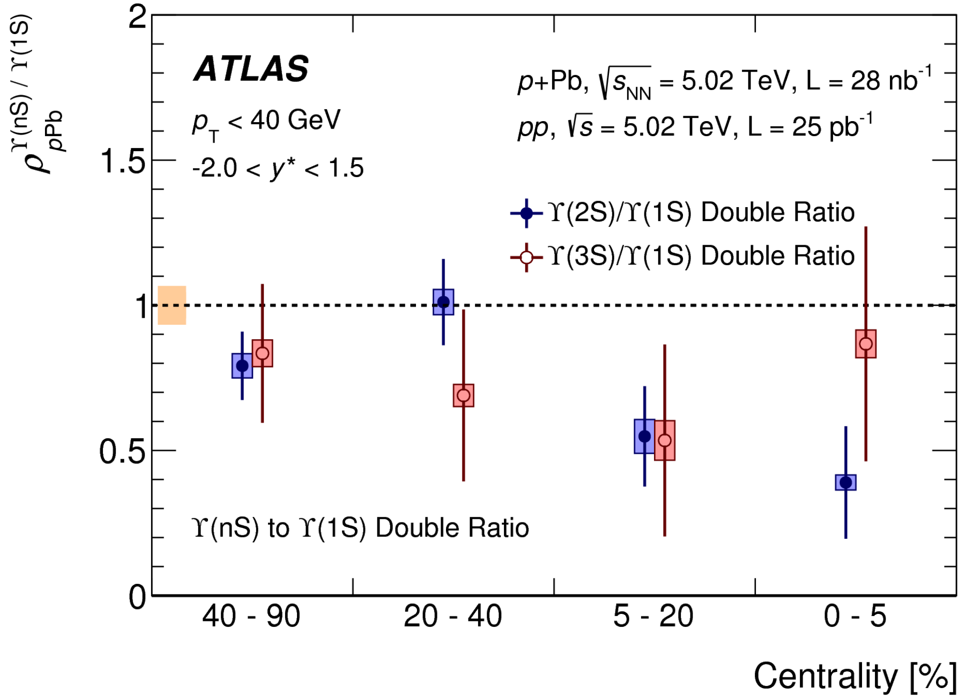




- Calculate double ratio of nuclear modification factors, versus centrality:



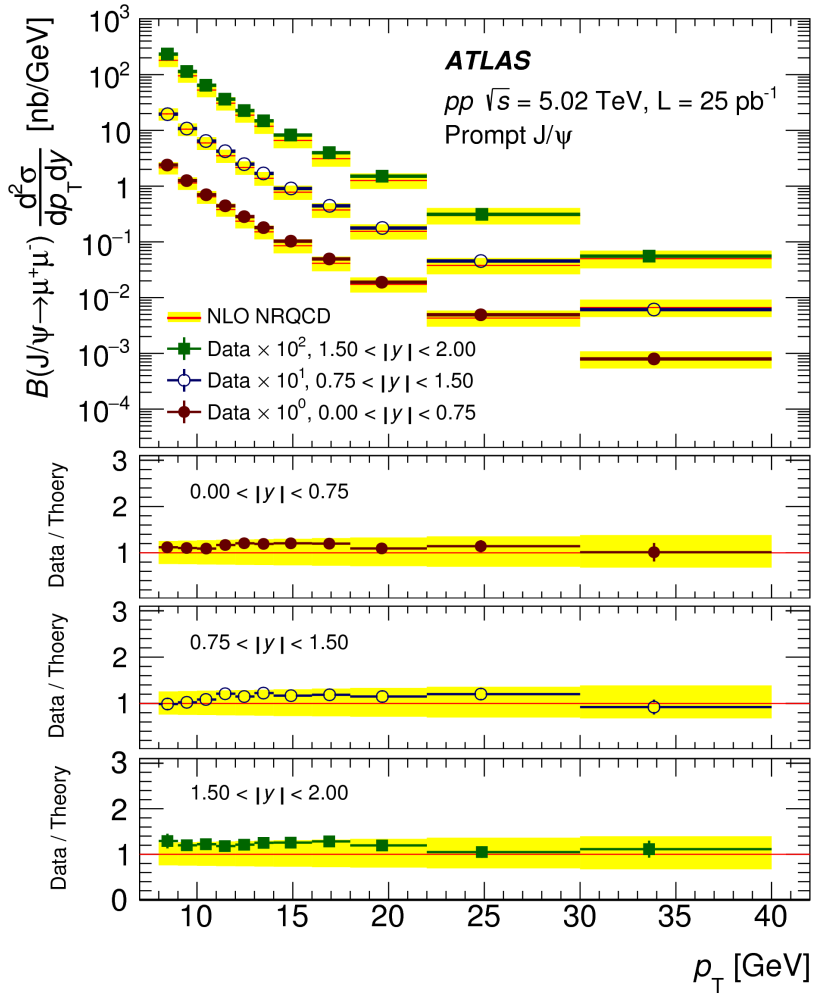
← *peripheral* *central* →

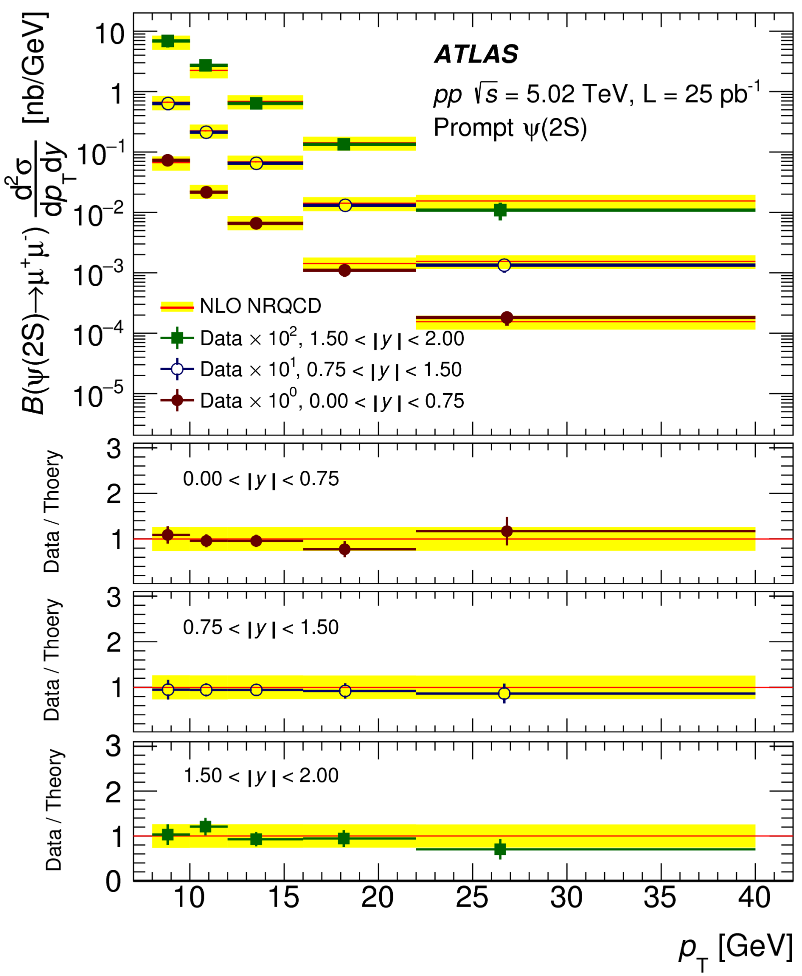


← *peripheral* *central* →

Results on production cross sections (1):

- Prompt charmonium production at $8 < p_T < 40$ GeV is compatible with NRQCD:

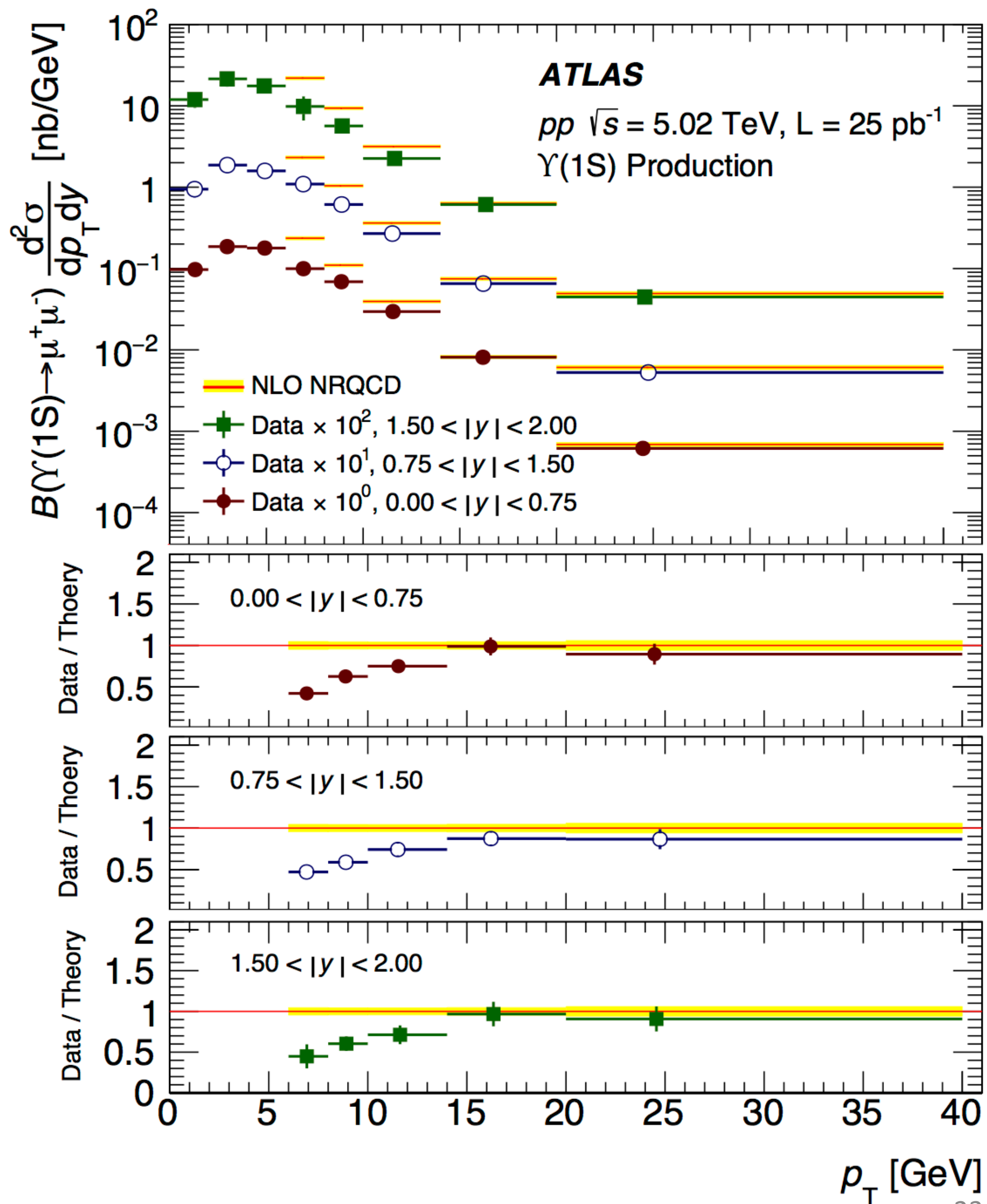




- and non-prompt J/ψ and non-prompt ψ(2S) production in p-p collisions are well described by FONLL

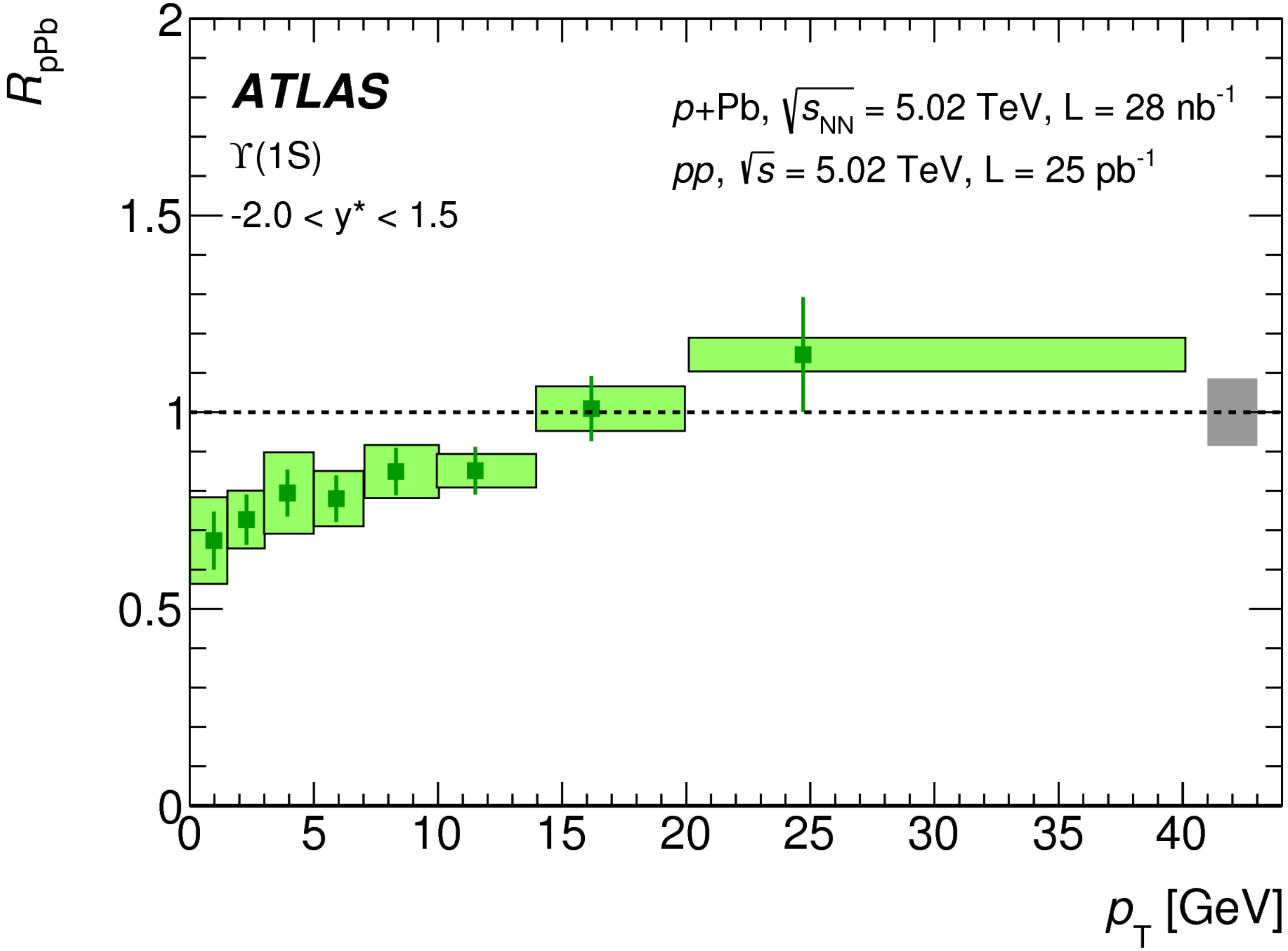
Results on production cross sections: (2)

- Bottomonium production cross sections at $p_T < 15$ GeV are NOT described by NRQCD. Example:



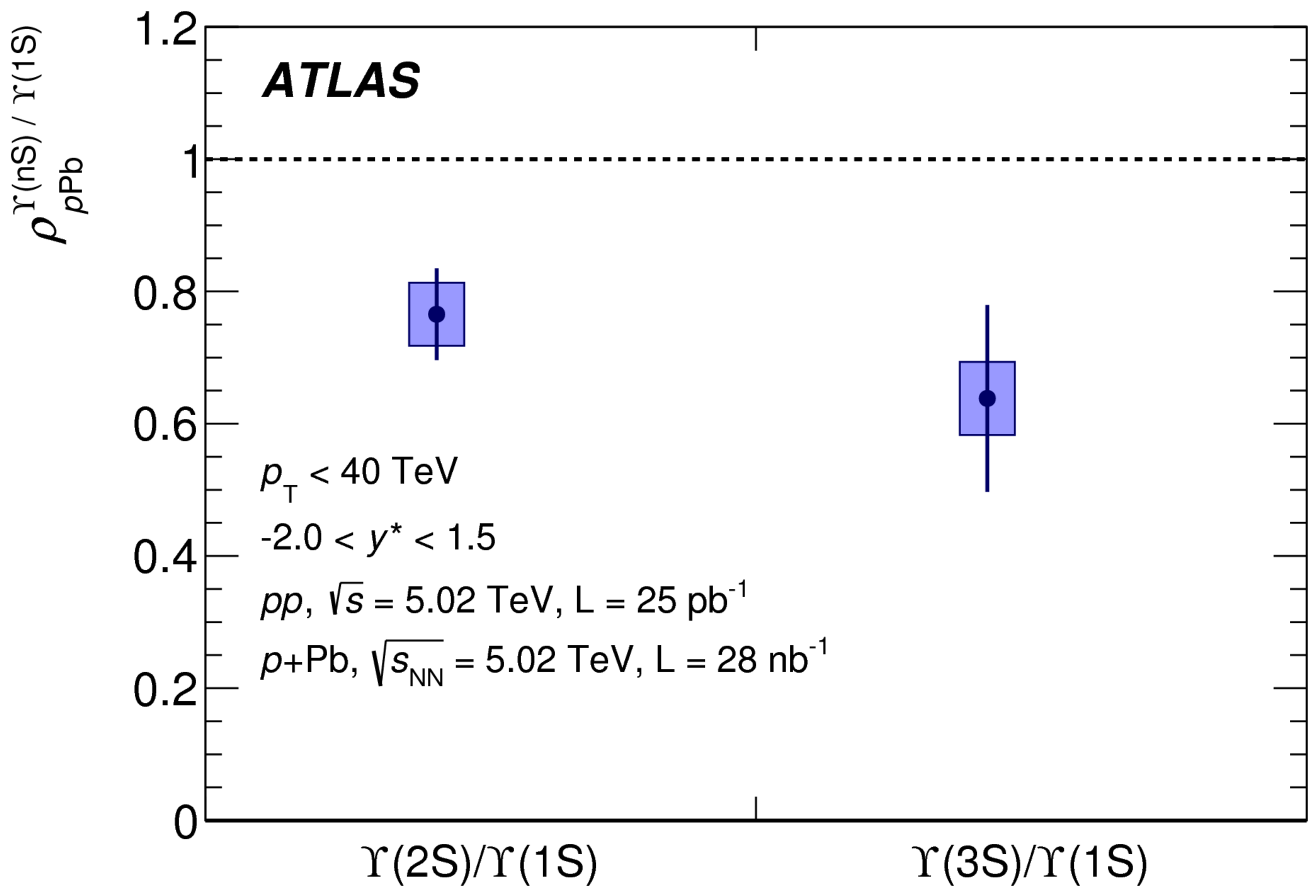
Results on nuclear modification factors R_{pPb} :

- R_{pPb} for prompt and non-prompt J/ψ production in p-Pb consistent with unity across p_T and y.
- R_{pPb} for Υ(1S) for p_T< 15 GeV is below unity: suggests that nuclear pdf's are modified relative to those of the nucleon:



Results on double ratio ρ:

- Prompt charmonium ρ decreases slightly from backward (Pb-side) to forward (p-side).
- Prompt ψ(2S) suppressed w.r.t. prompt J/ψ at the one-sigma level.
- Prompt ψ(2S):J/ψ and prompt ϒ(2S):ϒ(1S) are suppressed in central collisions at the one-sigma level.
- ϒ(nS):ϒ(1S) suppressed for $p_T < 40$ GeV and $-2 < y^* < 1.5$ at the two-sigma level:



Conclusion: These datasets will be used to constrain models of CNM.

Summary

ATLAS presents 2 recent results on quarkonium and heavy flavors:

- **Differential cross sections for b-hadron pair production** – *to improve the theoretical description of quarkonium production and to facilitate background subtractions for new physics searches.*

- **Quarkonium production in proton-lead and proton-proton collisions** – *using the quarkonium as a diagnostic to understand the effects of cold nuclear matter on final state suppression: to better understand this background to quarkonium suppression in QGP.*