# Inclusive production of quarkonium in ATLAS

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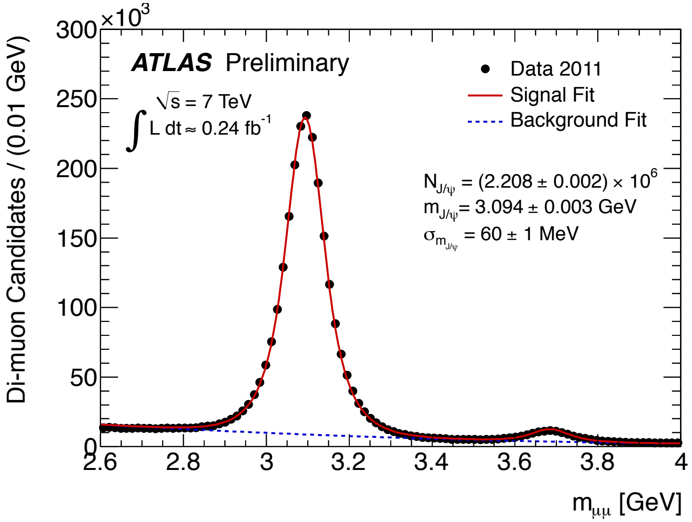
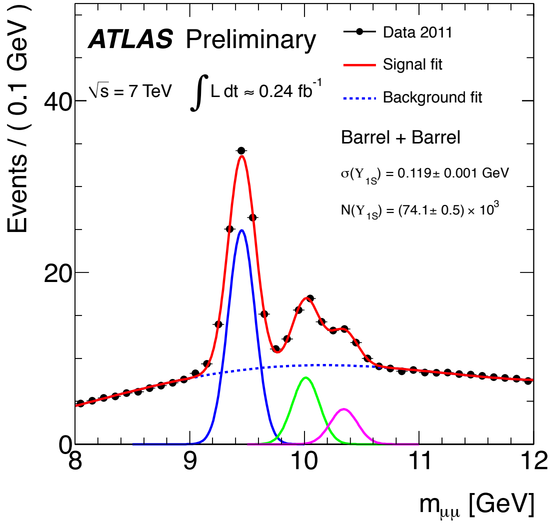
# Outline

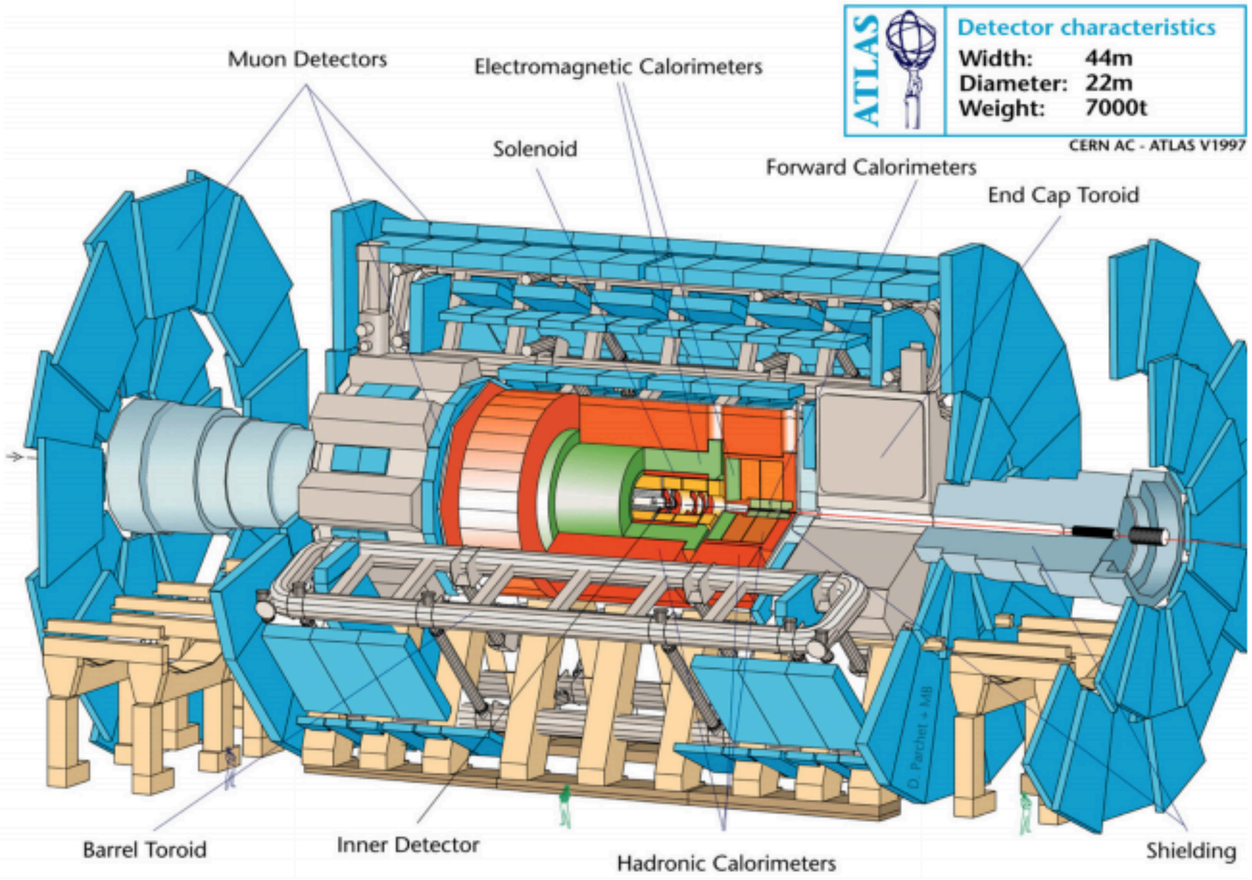
- The ATLAS detector @ LHC
- Recent ATLAS results covered in this talk:
  - b-hadron pair production cross-section @ 8 TeV
  - quarkonium production in p-Pb and pp @ 5.02 TeV
- Conclusions

# The ATLAS detector @ LHC

- Subsystems essential for B-physics: Inner detector and Muon spectrometer.
- Inner detector: tracking, momentum and vertexing, $|\eta|<2.5$, $d_0$ resolution ~10μm.
- Muon spectrometer: trigger and muon identification, $|\eta|<2.7$.
- J/ψ mass resolution: 60±1 MeV, ϒ(1S): 119±1 MeV (depend on η).







# b-hadron pair production cross-section

- JHEP 11 (2017) 062
- 11.4 fb-1 @ 8 TeV, luminosity uncertainty 1.9%
- Motivation:
  - test of QCD predictions
  - disagreements among theoretical predictions and between predictions and data
  - important background for Higgs production ($H \rightarrow b\bar{b}$) with association of a vector boson

# Analysis overview (1)

- Search for 1st b→J/ψ(μμ)+X, 2nd b→μ+X
- Dimuon trigger, $p_T(\mu_1,\mu_2)>4$ GeV, $2.5<m(\mu\mu)<4.3$ GeV
- Primary vertex of at least two tracks with $p_T>400$ MeV
- Muon candidates are "dressed" by adding a four-momentum of nearby photons ($\Delta R<0.1$)
- J/ψ candidates are formed from oppositely charged muons, $p_T(\mu)>6$ GeV, $|\eta|<2.3$, $2.6<m(J/\psi)<3.5$
- In case of multiple J/ψ candidates per event the one with the mass closest to the world average is chosen
- Third muon: the one with the highest $p_T$ which is not included in the J/ψ reconstruction
- The J/ψ and the third μ may come from feed-down or cascade decay

# Analysis overview (2)

- J/ψ candidates are required to be separated from the primary vertex
- Requirement on the pseudo-proper lifetime τ, $\tau>0.25$ mm/c ($\tau=L_{xy}m(J/\psi_{PDG})/p_T(\mu\mu)$)
- Simultaneous maximum likelihood fit is performed to the invariant mass of the muon pair and the pseudo-proper lifetime

- Various MC-based corrections:
  - trigger efficiency (including spatial resolution and vertexing)
  - muon reconstruction efficiency (including “fake” muons from kaon/pion decays/punch-throughs

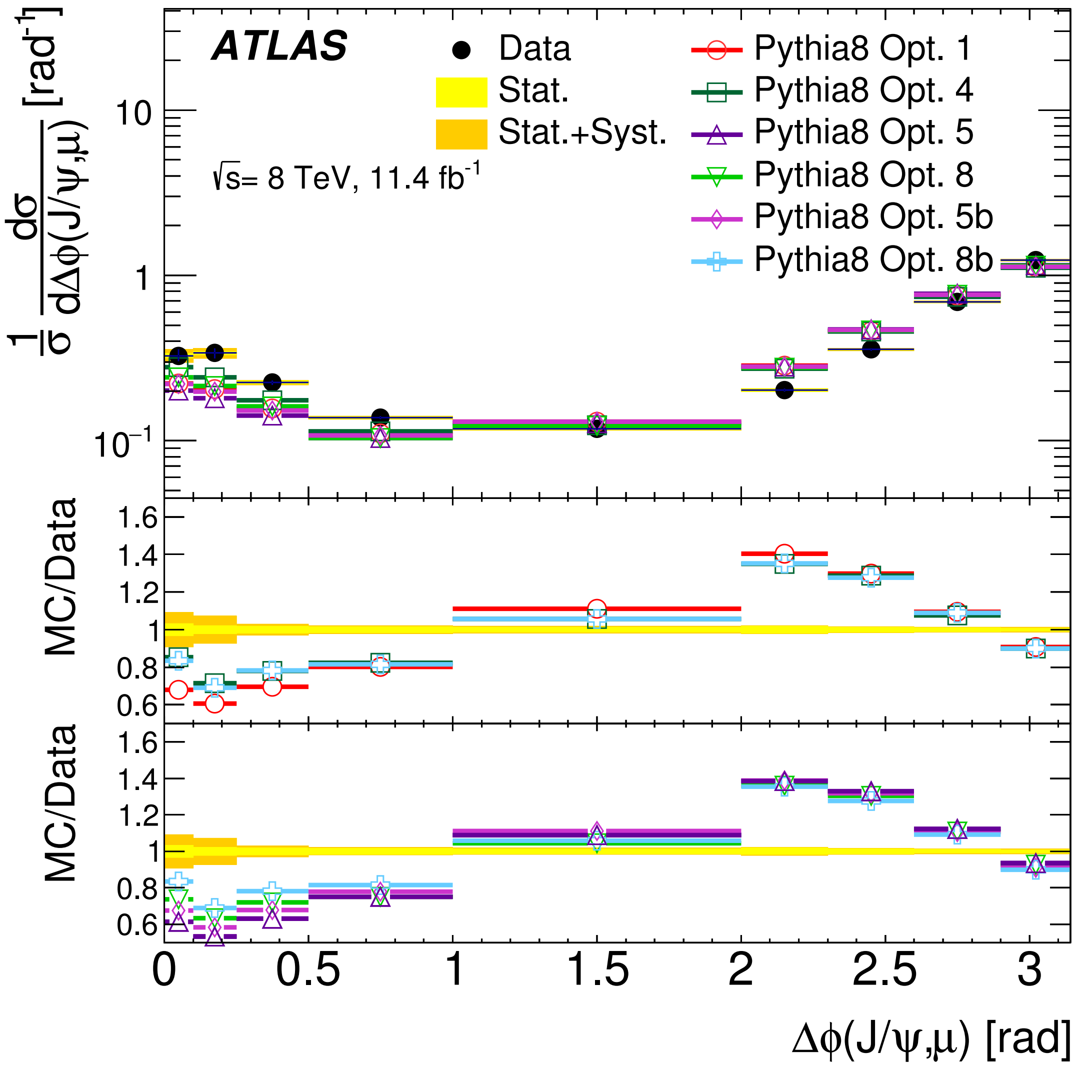
# Results (1)

- Measured total cross-section in the fiducial region: $\sigma(B(\rightarrow J/\psi(\mu\mu)+X)B(\rightarrow \mu+X))=17.7\pm0.1_{stat}\pm0.2_{syst}$ nb
- Various differential cross-sections compared to MC-generators output
  - separation between the J/ψ and the third μ in the azimuth-rapidity plane (Δϕ(J/ψ, μ), see next slide)
  - mass of the J/ψμ system
  - azimuthal separation Δφ between the J/ψ and the third μ
  - transverse momentum $p_T$ of the 3-muon system
  - rapidity separation Δy between the J/ψ and the third μ
  - magnitude $y_{boost}$ of the average rapidity of the J/ψ and the third μ
  - ratio of the $p_T$ to the invariant mass of the 3-muon system
  - ratio of the invariant mass of the 3-muon system to its $p_T$

# Results (2)

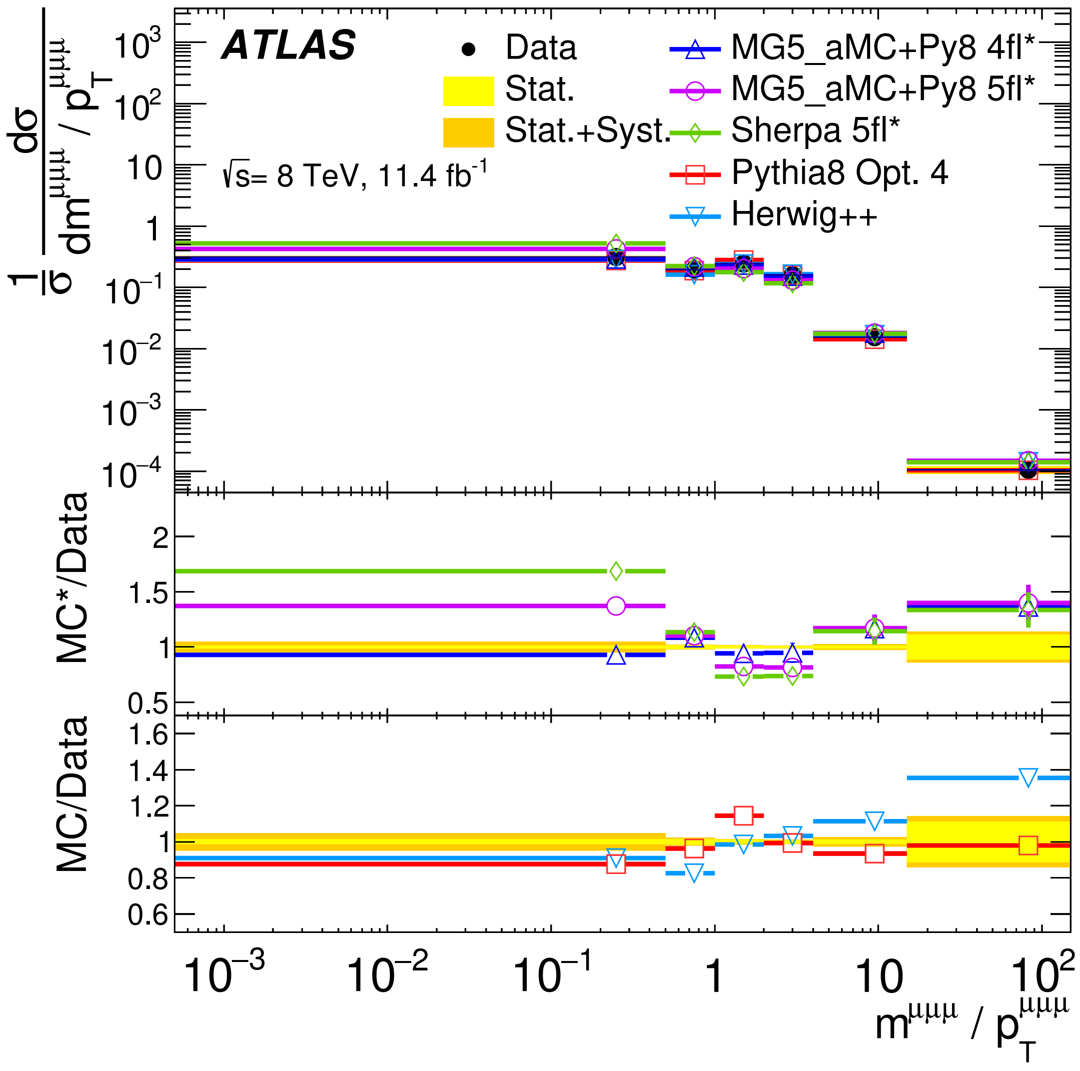
- Comparison with Pythia 8: a set of production options for the g→$b\bar{b}$ splitting kernel which dominates small-angle quarkonium production

- The shape of the angular distributions is not accurately predicted by any of the production options



# Results (3)

- Comparison with HERWIG++, SHERPA, and MadGraph5_aMC@NLOv2.2.2 + PYTHIA8.186 parton shower model
- HERWIG++ has the best correspondence with data for for ΔR and Δϕ
- 4 massless flavours model has a better correspondence than 5 one for ΔR and Δϕ
- Δy distribution is well described by MADGraph and Sherpa
- 5-massless flavor MadGraph models low mass distribution better than 4,
- But 4-massless flavor MadGraph models high $p_T$/m best.



# Results (4)

- Among all of the distributions, the 4-massless flavour model gives the best correspondence with the data (MadGraph5_aMC@NLO +Pythia8)
- HERWIG++ and Pythia8 demonstrate compatible agreement with the data
- Among the various Pythia8 production options the $p_T$-based splitting kernel is the best one (option 4b)

# Quarkonium production in p-Pb and pp

- Eur. Phys. J C (2018) 171
- 28 $\mathrm{nb}^{-1}$ (p-Pb) and 25 $\mathrm{pb}^{-1}$ (pp) @ 5.02 TeV
- Motivation:
  - QGP (quark-gluon plasma) is not expected to occur in p-Pb collisions, so one can study the effects of CNM (cold nuclear matter)
  - compare the production of $J/\psi$, $\psi(2S)$, $\Upsilon(1S,2S,3S)$
  - understand the background to QGP effects

# Analysis overview (1)

- The double-differential cross section multiplied by the dimuon decay branching fraction is calculated for each measurement interval as:

$$\frac{\mathrm{d}^2\sigma_{\Upsilon(n\mathrm{S})}}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y^*} \times B(\Upsilon(n\mathrm{S}) \rightarrow \mu^+\mu^-) = \frac{N_{\Upsilon(n\mathrm{S})}}{\Delta p_{\mathrm{T}} \times \Delta y \times L}$$

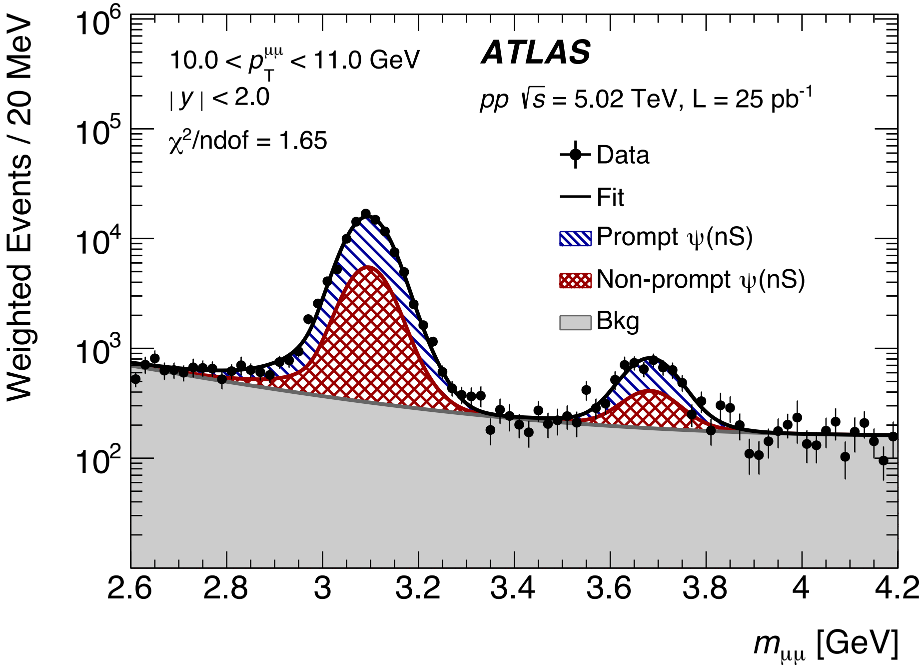
- The y* here is the center-of-mass p-Pb rapidity, which is shifted by Δy=0.465 with respect to y in the laboratory rest frame

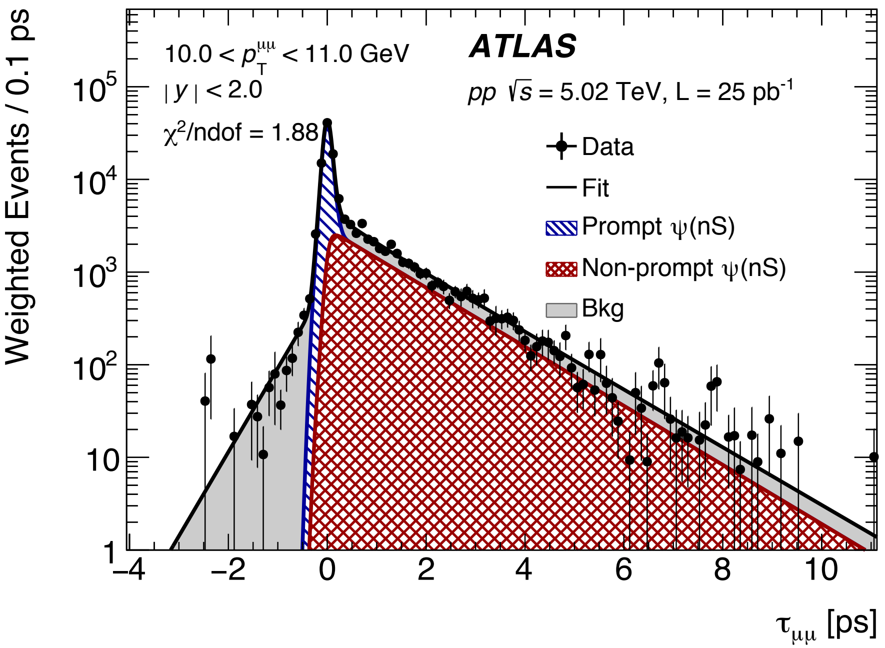
# Analysis overview (2)

- Dimuon trigger: $p_T(\mu_1,\mu_2)>4$ GeV
- Primary vertex is formed with at least 4 tracks, at least 2 muons with common vertex
- All muons with $|\eta|<2.4$ are considered as quarkonium candidates
- p-Pb events are divided into “centrality class” – more participating nucleons leads to more transverse energy
- MC corrections for acceptance calculation: final state radiation, $p_T$, $\eta$, trigger and reconstruction efficiency

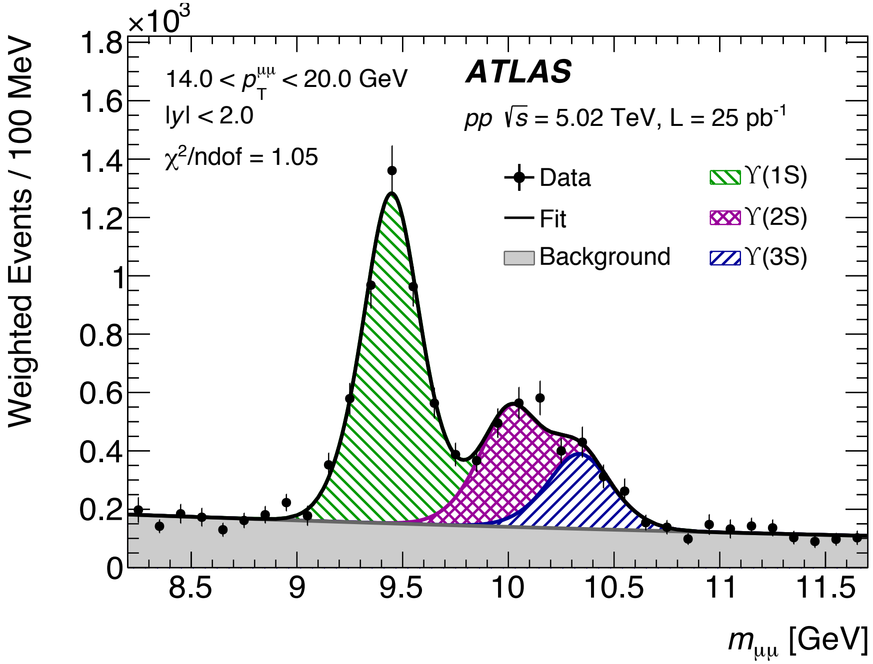
# Analysis overview (3)

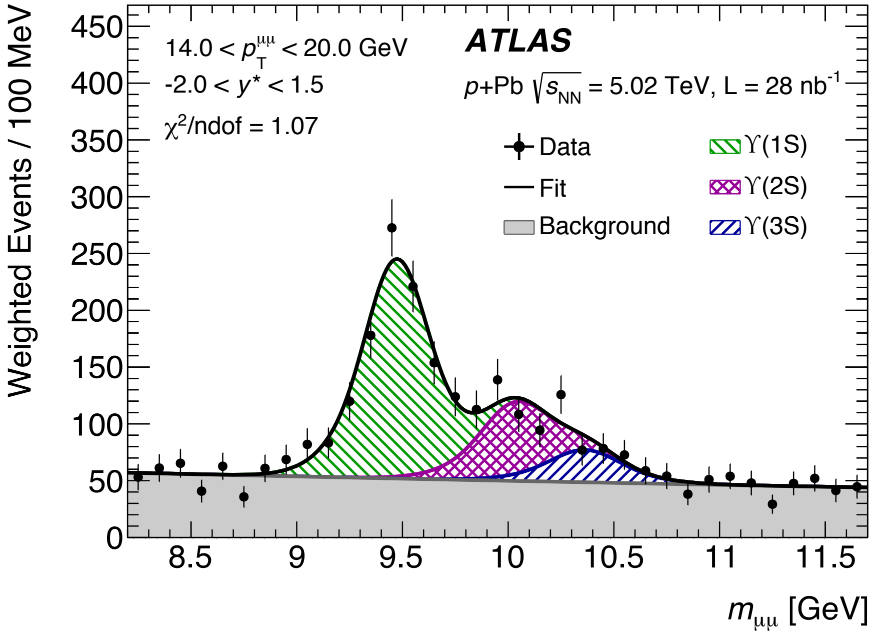
- Reconstruction and trigger efficiencies are taken from J/ψ→μμ data
- Pseudo-proper lifetime is used to separate prompt and non-prompt quarkonium candidates
- Simultaneous maximum likelihood fit to the μμ invariant mass and pseudo-proper lifetime is performed to extract the number of charmonium candidates
- Separate fits in every pT, rapidity, and centrality bins





# Analysis overview (4)

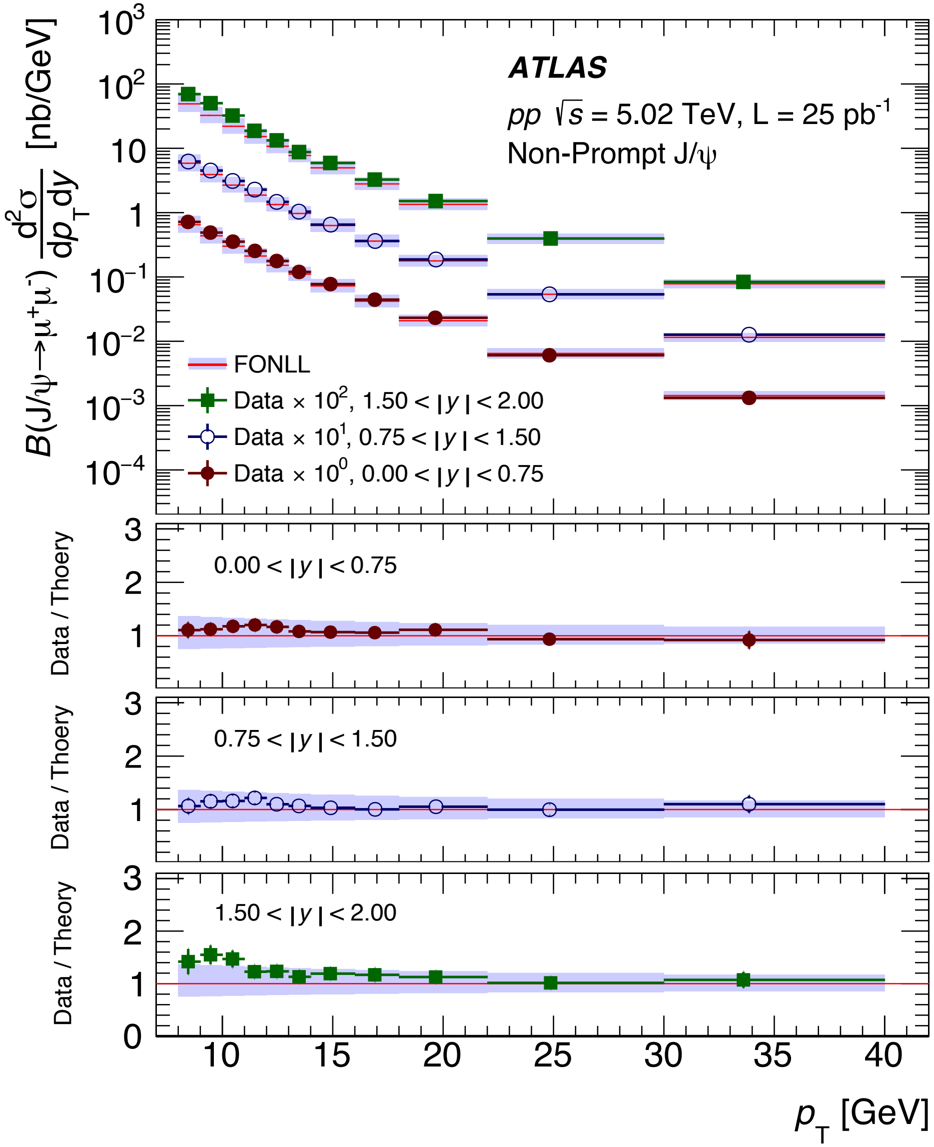




- For the bottomonium the acceptance is recalculated in order to take into account peak overlaps
- Systematics include: acceptance, muon reconstruction efficiency, trigger effects, fit model, bin-to-bin migration, luminosity

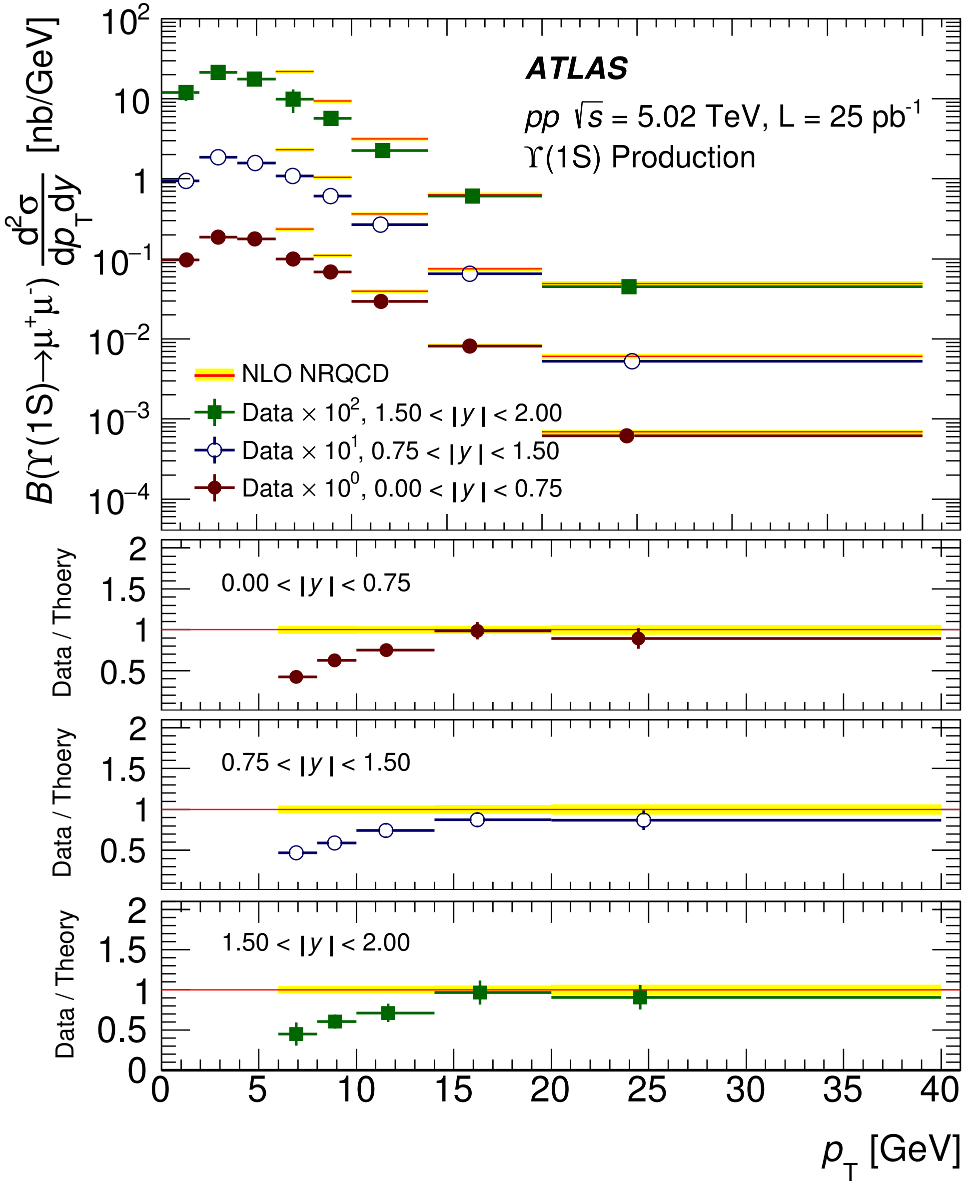
# Results (1)

- The differential non-prompt J/ψ and ψ(2S) production cross-section is compared to FONLL theory predictions for three intervals of rapidity
- Non-prompt J/ψ and ψ(2S) production in pp is in a good agreement with FONLL
- Prompt charmonium production is compatible with NRQCD
- The error bands in the prediction correspond to the combined factorisation scale, quark mass and parton distribution functions uncertainties.



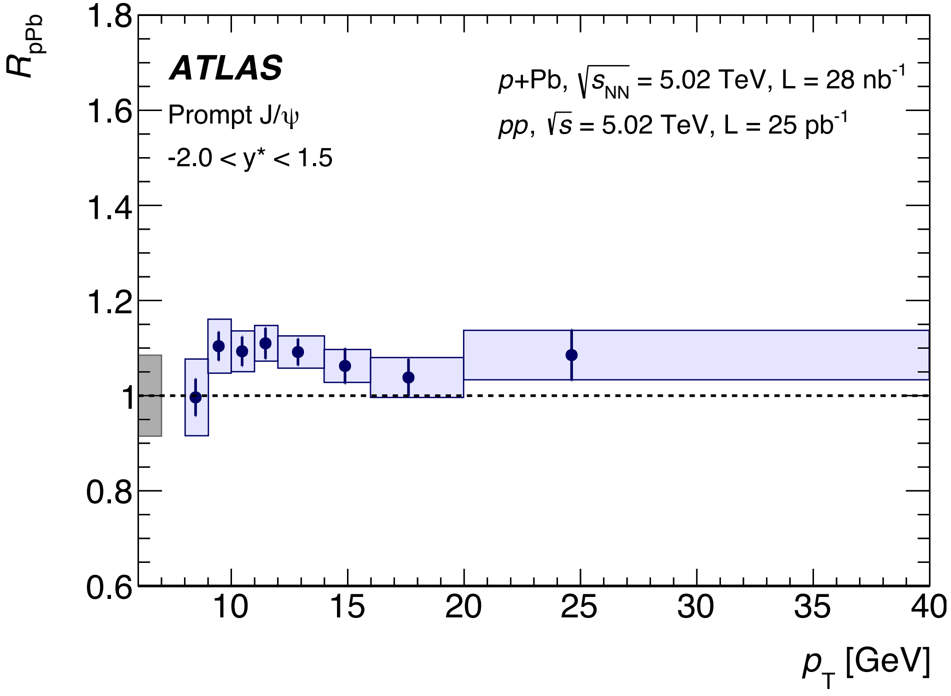
# Results (2)

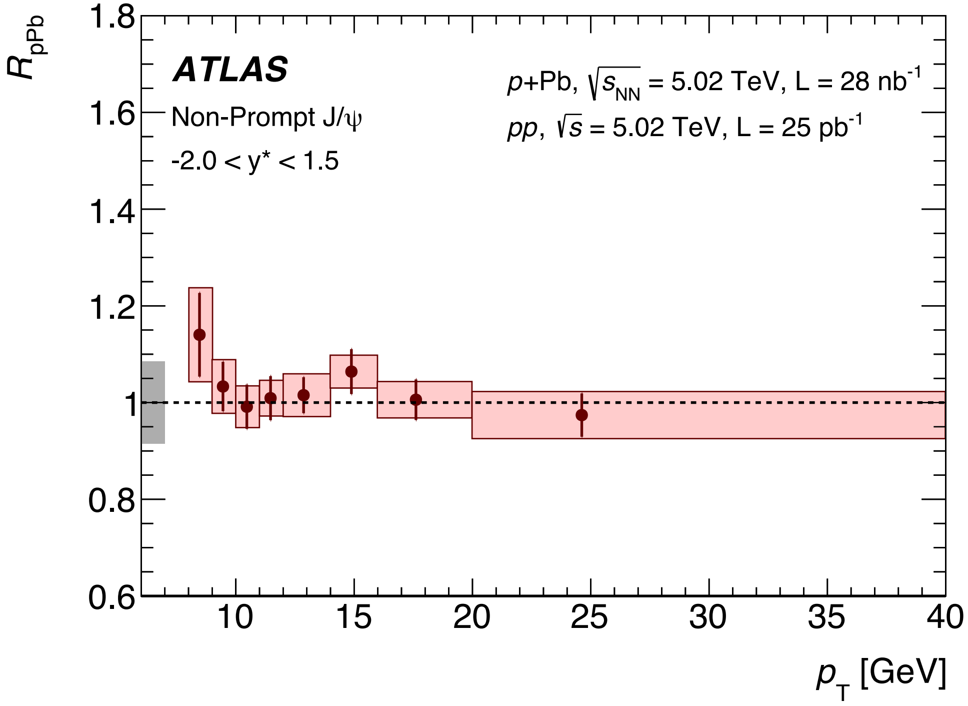
- Bottomonium production is not in a good agreement with NRQCD



# Results (3)

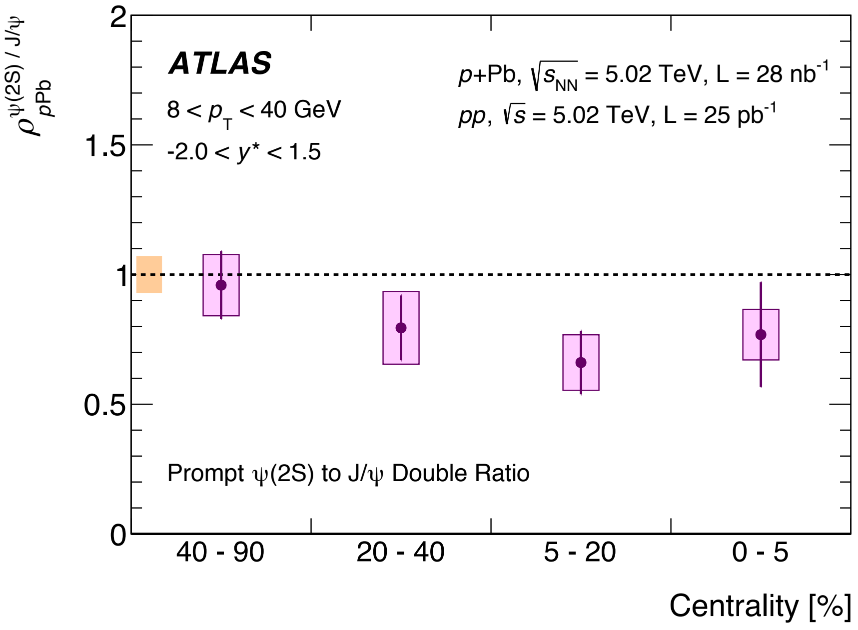
- Nuclear modification factors are calculated as functions of $p_T$ and rapidity for prompt and non-prompt production
- Bars on the plots represent statistical uncertainty, boxes – uncorrelated systematical ones, and the gray boxes – correlated systematics.

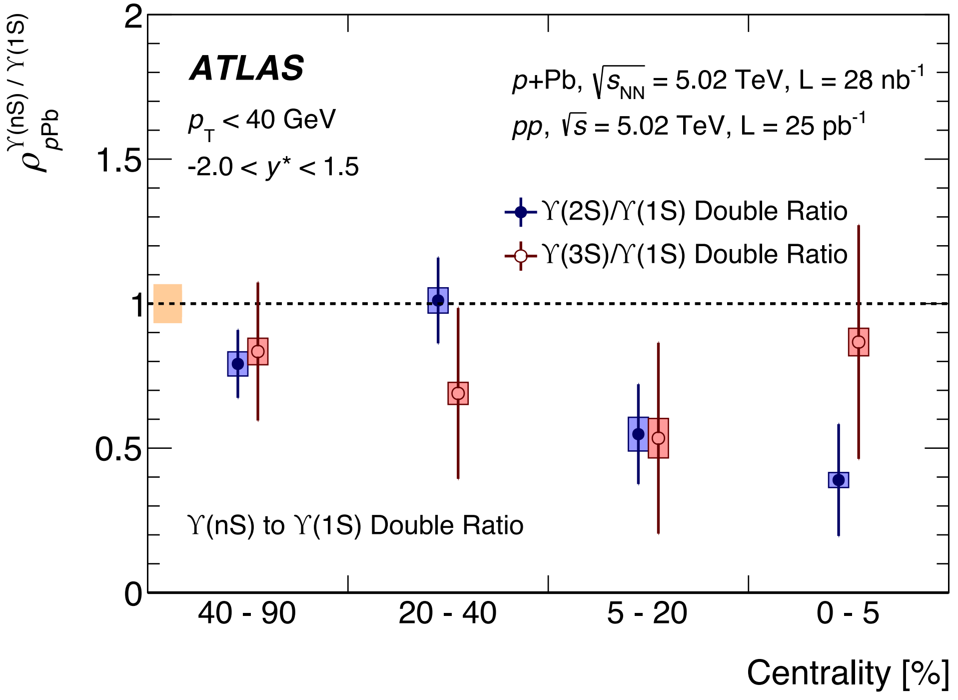




# Results (4)

- Double ratio of nuclear modifications factors versus centrality:





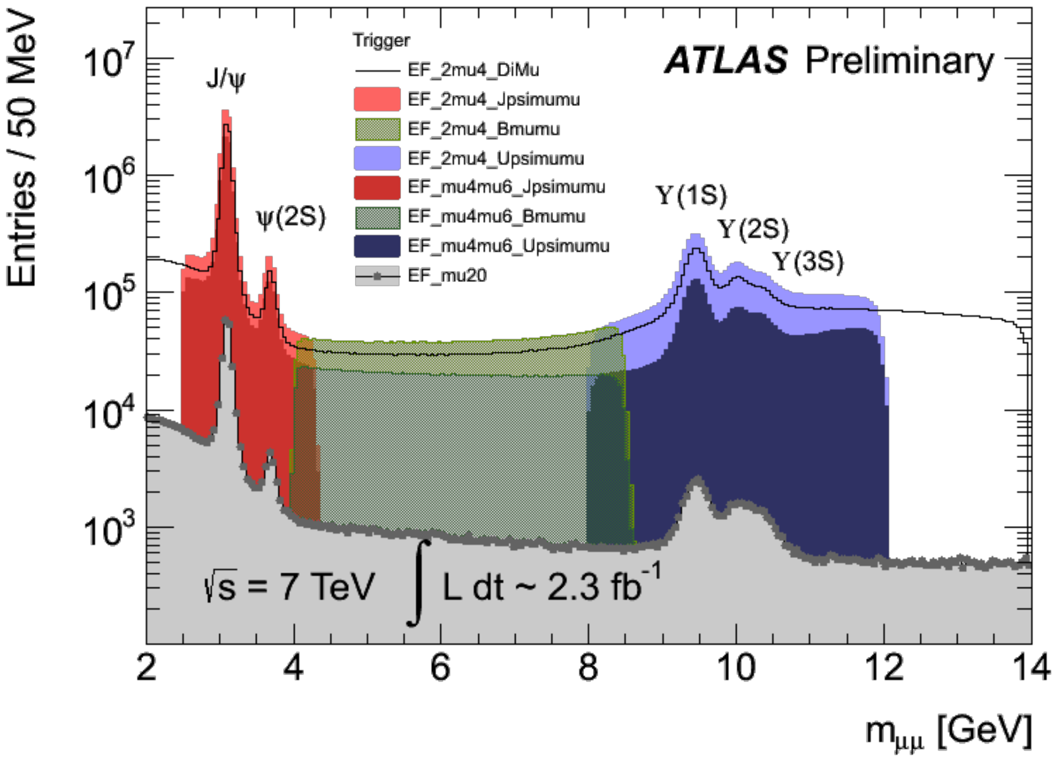
# Conclusions

- ATLAS has studied b-hadron pair production with 8 TeV pp collisions data
  - Various production options of several MC generators are compared to the data
  - Allowing better tuning of the corresponding underlying models
- ATLAS has performed a study of quarkonium production in p-Pb and pp collisions data
  - Number of observations on the production of prompt and non-prompt quarkonium, comparison with theoretical predictions
  - Constraints on CNM models

# BACKUP

# Trigger and datasets

- B-physics starts with single or di-muon triggers with various thresholds:
  - $p_T(\mu) > 6$ GeV
  - $p_T(\mu) > 18$ GeV
  - $p_T(\mu_1) > 4$ GeV & $p_T(\mu_2) > 4$ GeV
  - $p_T(\mu_1) > 6$ GeV & $p_T(\mu_2) > 4$ GeV
  - $p_T(\mu_1) > 6$ GeV & $p_T(\mu_2) > 6$ GeV



- Di-muon mass range: m(μμ)∈[2.5; 4.3] GeV (final states containing J/ψ) and m(μμ)∈[4.0; 8.5] GeV (B to μ transitions).