Quarkonium Working Group
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Charmonium and bottomonium production at ATLAS

Elisa Guido
INFN Torino
[previously with Università degli Studi di Genova & INFN]
(on behalf of the ATLAS Collaboration)

Interest in Quarkonia

- Quarkonium is a unique possibility for testing multi-scale QCD calculations at the boundary of the perturbative and non-perturbative regimes
- Feeding theoretical speculation, that still aims to provide a coherent picture able to explain all measurements simultaneously
- *Inclusive production of heavy flavour is a significant background for measurements in the electroweak and Higgs sectors*

Outline of contents

- Charmonium
- Bottomonium
- Also results from p+Pb collisions

- Study of **J/ψ and ψ(2S)** production in **5.02 TeV p+Pb** and **2.76 TeV pp** collisions (ATLAS-CONF-2015-023)
- Measurement of the production cross-section of **ψ(2S)—> J/ψ(—>$\mu^+\mu^-$)$\pi^+\pi^-$** in **pp** collisions at **7 TeV** at ATLAS (JHEP09 (2014) 079)
- Prompt and non-prompt **J/ψ and ψ(2S)** at **7 and 8 TeV** (arXiv:1512.03657, accepted by EPJC)
- Prompt and non-prompt **J/ψ** at **13 TeV** (ATLAS-CONF-2015-030)

- Measurement of **ϒ(nS)** production with **p+Pb** collisions at **5.02 TeV** and **pp** collisions at **2.76 TeV** (ATLAS-CONF-2015-050)

- Measurement of **ϒ** production in **7 TeV pp** collisions (Phys. Rev. D 87, 052004 (2013))

General strategy & datasets

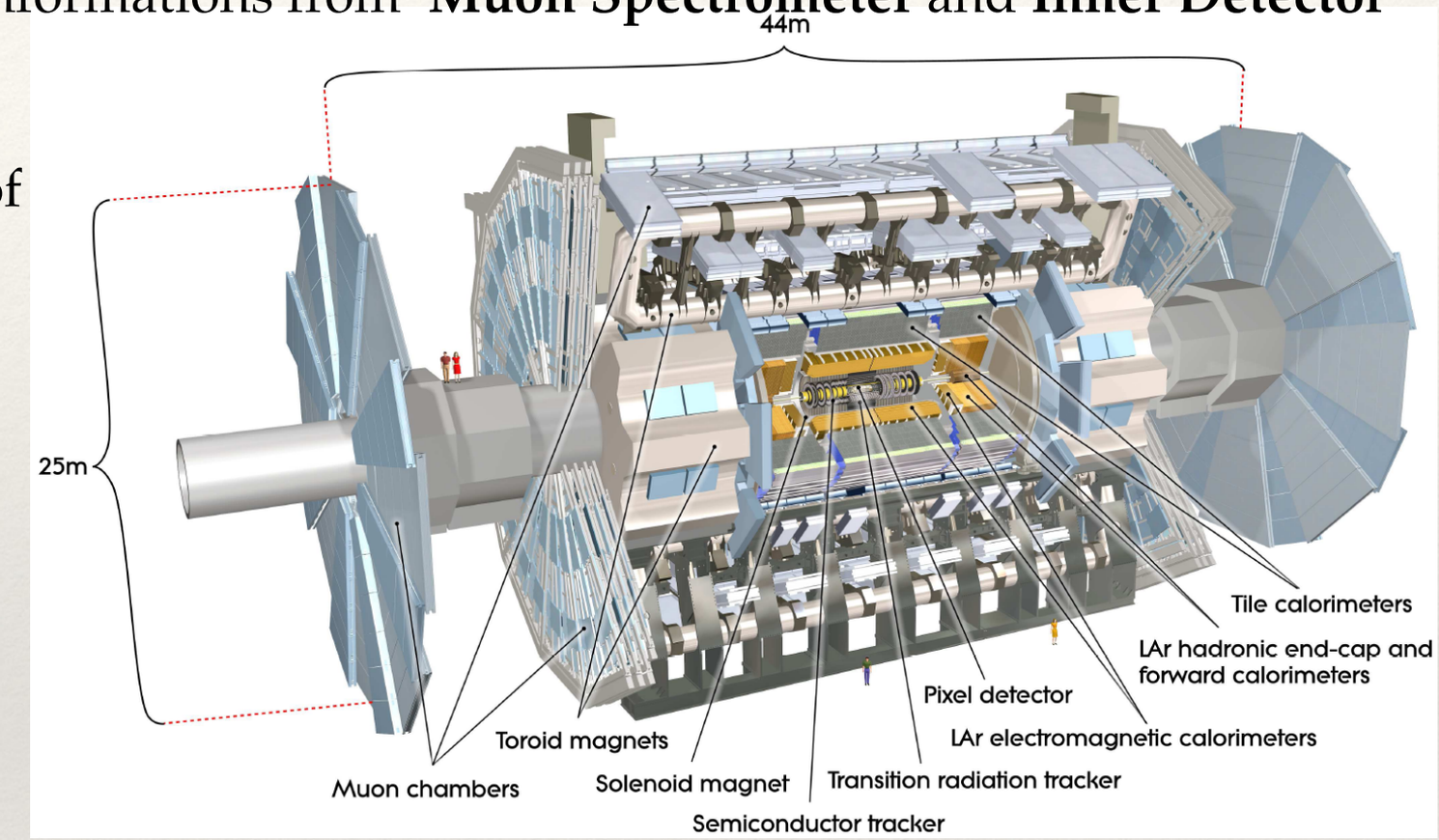
- Measurements at different √s will be presented

Energy	Collisions	Int. lumi used	Year
√s=7 TeV	**pp**	2.1 fb^{-1}	2011
√s=8 TeV	**pp**	11.4 fb^{-1}	2012
√s=13 TeV	**pp**	6.4 pb^{-1}	2015
√s=2.76 TeV	**pp**	4.0 pb^{-1}	2013
$\sqrt{s_{NN}}$=5.02 TeV	**p+Pb**	28.1 nb^{-1}	2013

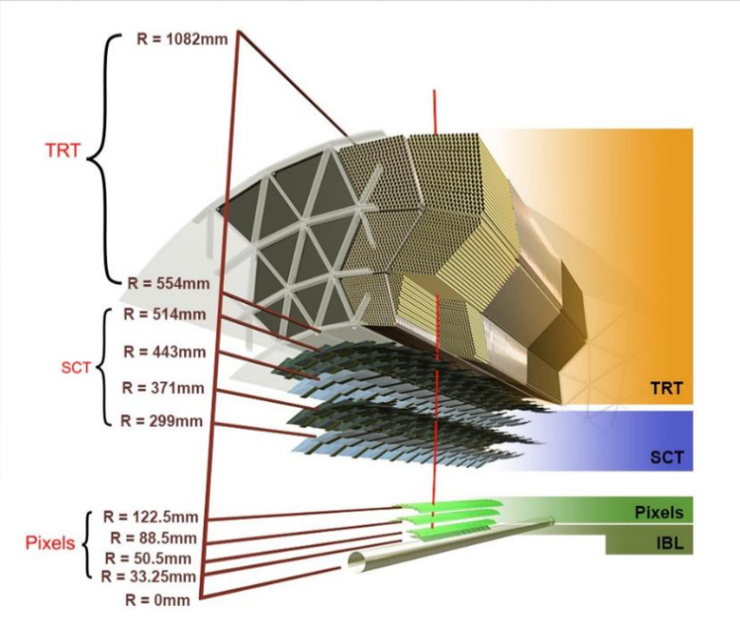
- Basic strategy common to all of them:
  - use of di-muon decays (easy reconstruction and trigger)

The ATLAS detector

- Muon identification from combined informations from **Muon Spectrometer** and **Inner Detector**
- Providing precise momentum and lifetime measurements for the range of momenta considered here



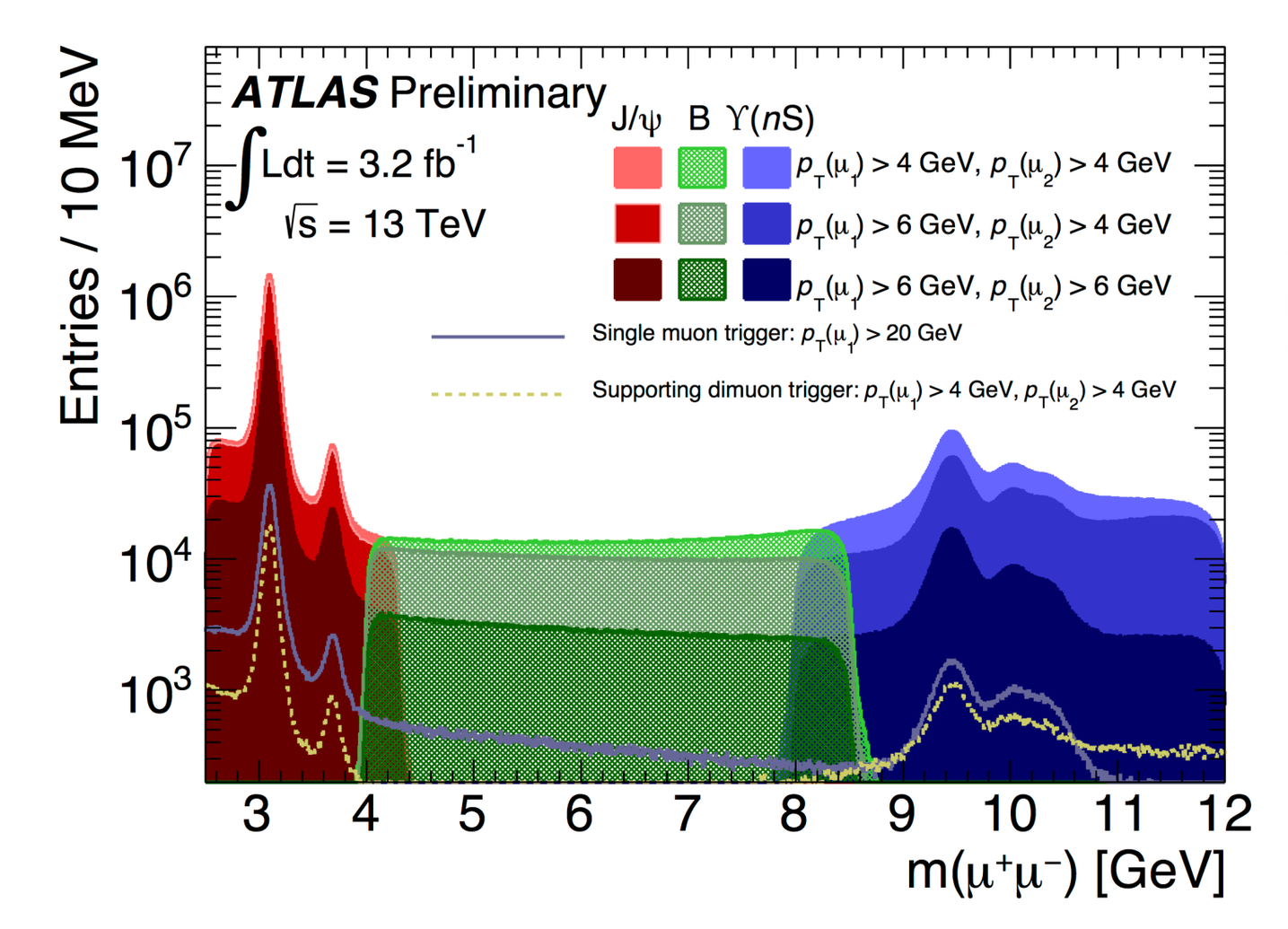
- Combined μ performances
  - $\sigma_p/p < 10\%$ up to 1 TeV
  - Resolution in $m_{\mu^+\mu^-}$: ~50 MeV at J/ψ, ~150 MeV at $\Upsilon(nS)$
  - Resolution in *b*-hadrons proper decay time ~100 fs (before IBL installation)



- Since 2015, the ID has one more layer (**Insertable B-Layer**), close to the beam pipe
- Designed to improve track and vertex resolutions
- Factor 2 improvement in impact parameter resolution for low-p_T tracks (contributes to a significant improvement in b-tagging)

Triggering

- 3-level system (2-level for Run2):
  - Level 1 - hardware
  - Level 2 and Event Filter (HLT for Run2) - software-based, offline-like reconstruction
- Primary B-physics triggers:
  - two muons at L1, $p_T(\mu) > 4{,}6$ GeV
  - confirmed at L2/EF with vertexing and invariant mass criteria applied depending on the state to be selected



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysicsTriggerPublicResults

Strategy successfully used through all Run1 and re-optmized for Run2

Typical event selection

- Muon selection:
  - muons with $\mathbf{p_T(\mu) > 4\ GeV}$, and $\mathbf{|\eta(\mu)| < 2.3}$
  - must be **oppositely charged tracks**
  - must come from a **common vertex**
  - the μ-pair must lie in a fiducial region within the geometrical acceptance of the detector

For instance pp collisions @ 7,8&13 TeV: $\mathbf{p_T(\mu\mu) > 8\ GeV}$ **and** $\mathbf{|y(\mu\mu)| < 2}$

Prompt and non-prompt J/ψ and ψ(2S) - method

- **Prompt production**: produced directly in the interaction or through feed-down decays from higher states
- **Non-prompt production**: produced by decaying B-hadrons (decay vertex can be displaced from primary vertex)
- Separate prompt and non-prompt, signal and background, with simultaneous fits to **mass** and **decay time**
- Displacement from PV for discriminating between prompt and non-prompt components

pseudo-proper decay time:

Transverse displacement from PV — Invariant mass

$$\tau(\mu\mu) = \frac{L_{xy} \cdot m(\mu\mu)}{p_T(\mu\mu)}$$

Transverse momentum

- Isotropic spin-alignment hypothesis is assumed (other tested as systematics)
  - Invariant mass distributions described by Crystal Ball and Gaussian functions (for 7-8 TeV analysis)

- prompt decays are modelled by a Dirac function

$$\delta(\tau) \otimes R(\tau)$$

- non-prompt decays are modelled by an exponential function

$$1/\tau_\psi \cdot \exp(\tau/\tau_\psi) \otimes R(\tau)$$

- R is a resolution function (Gaussian)

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- Displacement from PV for d… n-prompt components

The bulk of the method is the same for all the repetitions of the analysis: pp and p+Pb collisions, at different √s values

pseudo-proper decay time:

$p_T(\mu\mu)$

Transverse momentum

- Isotropic spin-alignment hypothesis is assumed (other tested as systematics)
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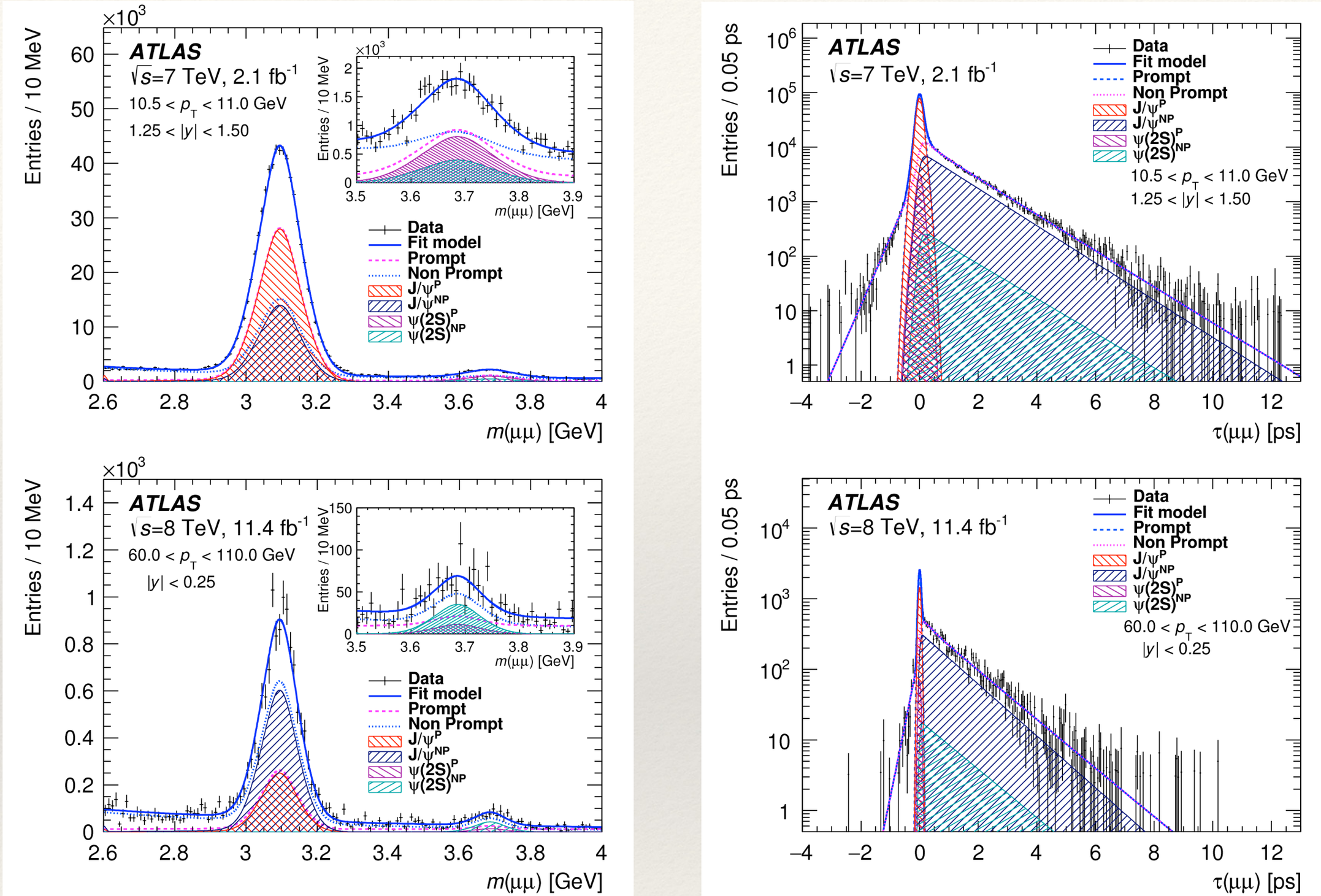
$$1/\tau_\psi \cdot \exp(\tau/\tau_\psi) \otimes R(\tau)$$

- R is a resolution function (Gaussian)

- Using **2.1 fb^{-1} at √s=7 TeV + 11.4 fb^{-1} at √s=8 TeV**

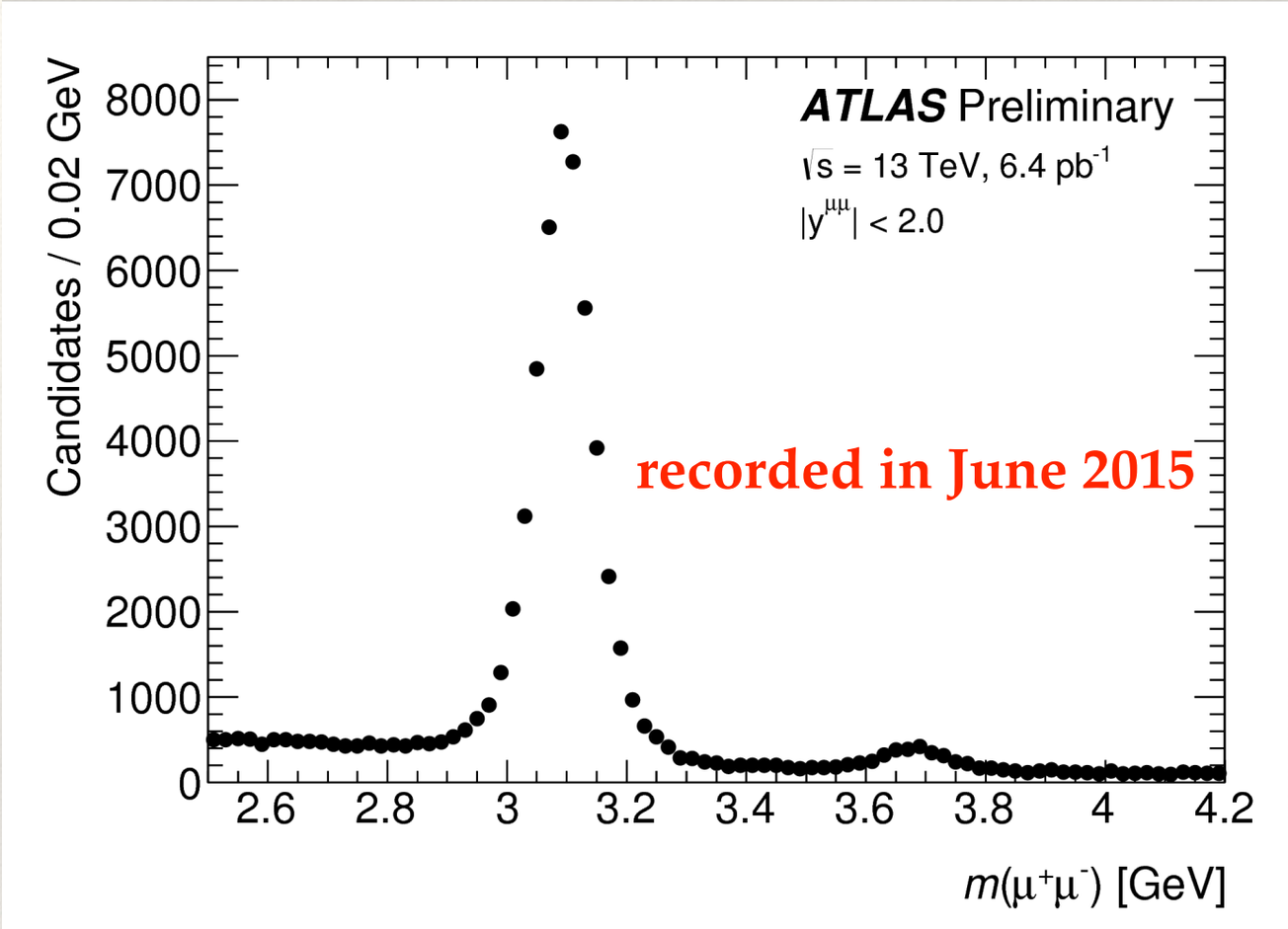
arXiv:1512.03657



- Various corrections applied for efficiencies and acceptance
- Main systematics from trigger efficiency corrections and fit model parameterisations

Prompt and non-prompt J/ψ at 13 TeV

- The first quarkonium analysis at 13 TeV!
- Invariant mass distribution of selected di-muon candidates
- **6.4 pb^{-1}** ~70,000 di-muon candidates
- ψ(2S) not considered due to limited statistics
- Same strategy as in the 7-8 TeV analysis: unbinned maximum likelihood fit and data projections onto the **invariant mass** and **pseudo-proper decay time** of the di-muon candidates

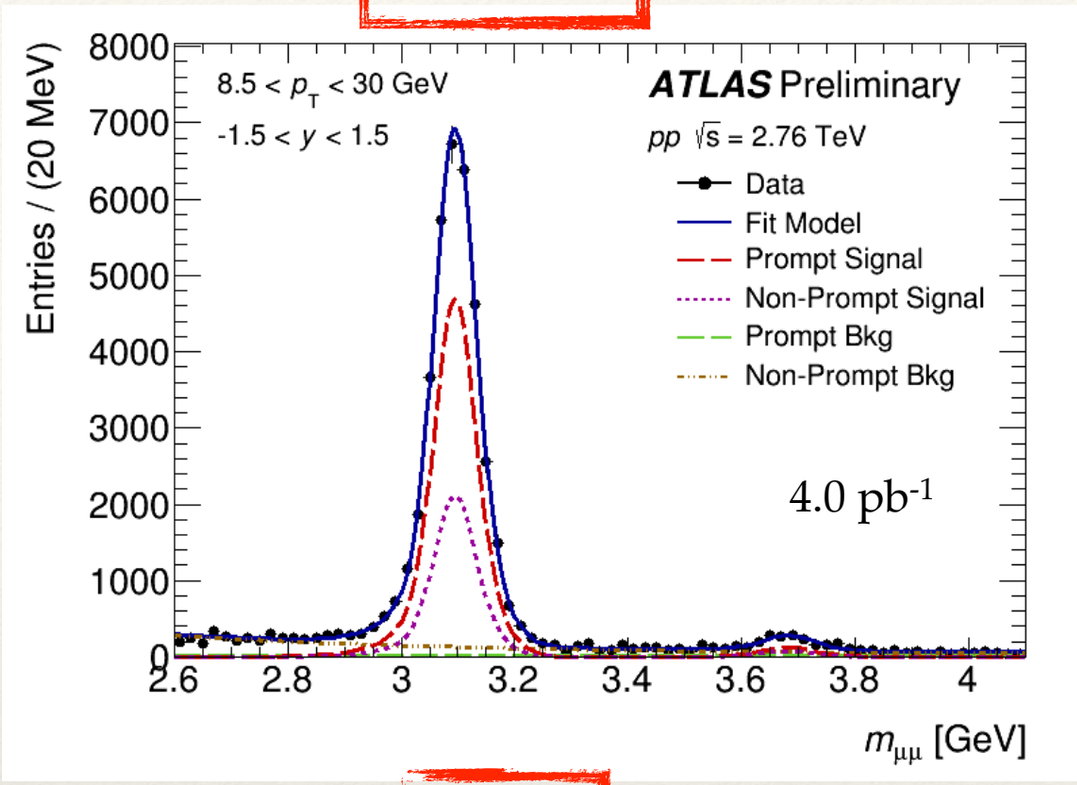


- Isotropic spin-alignment hypothesis is assumed
  - no geometric acceptance correction applied to the data
  - no spin-alignment uncertainty considered

pp collisions results

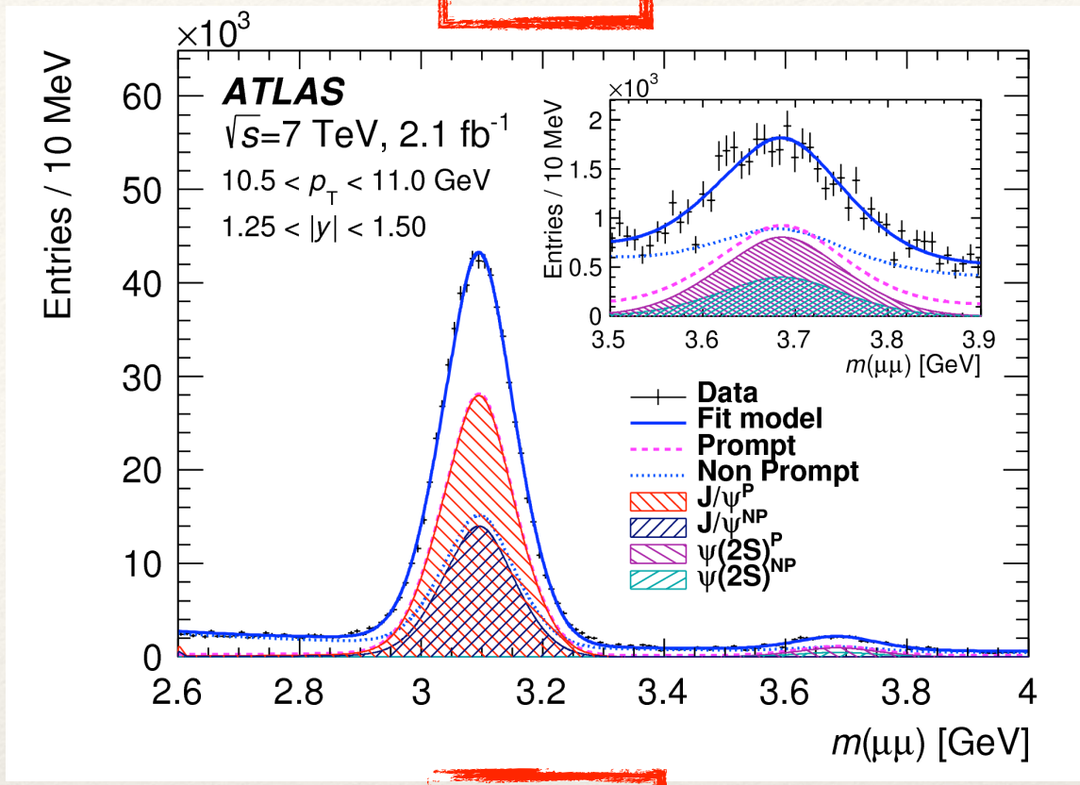
2.76 TeV

ATLAS-CONF-2015-023



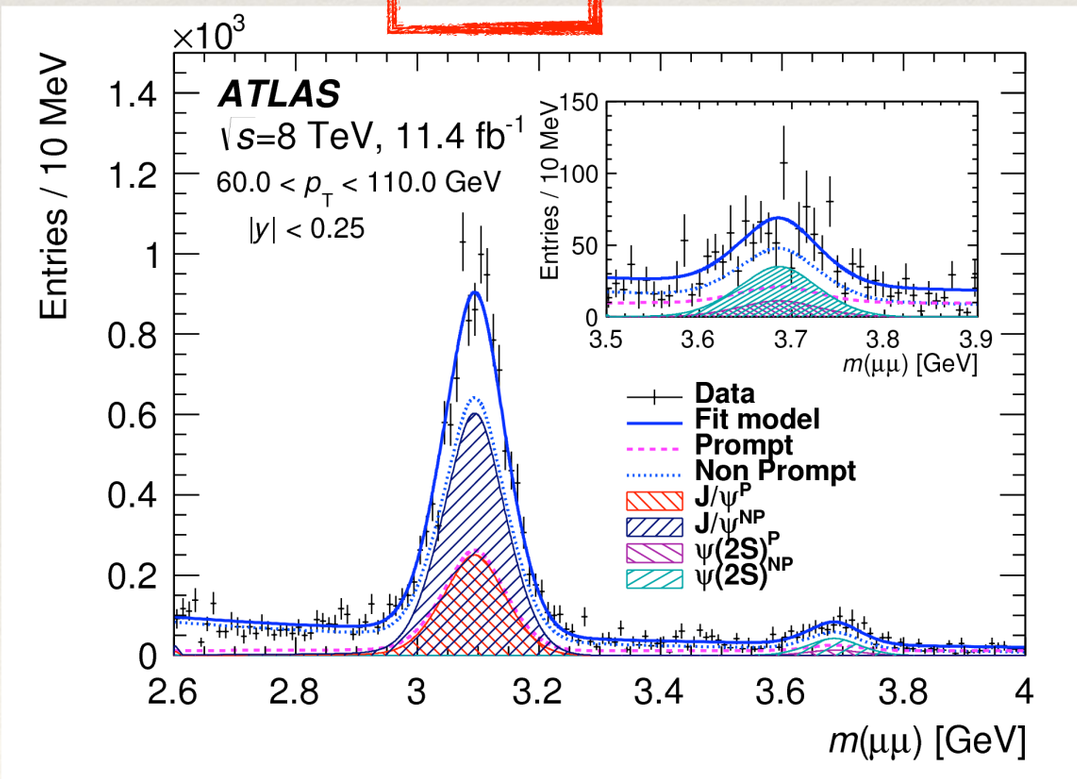
7 TeV

arXiv:1512.03657



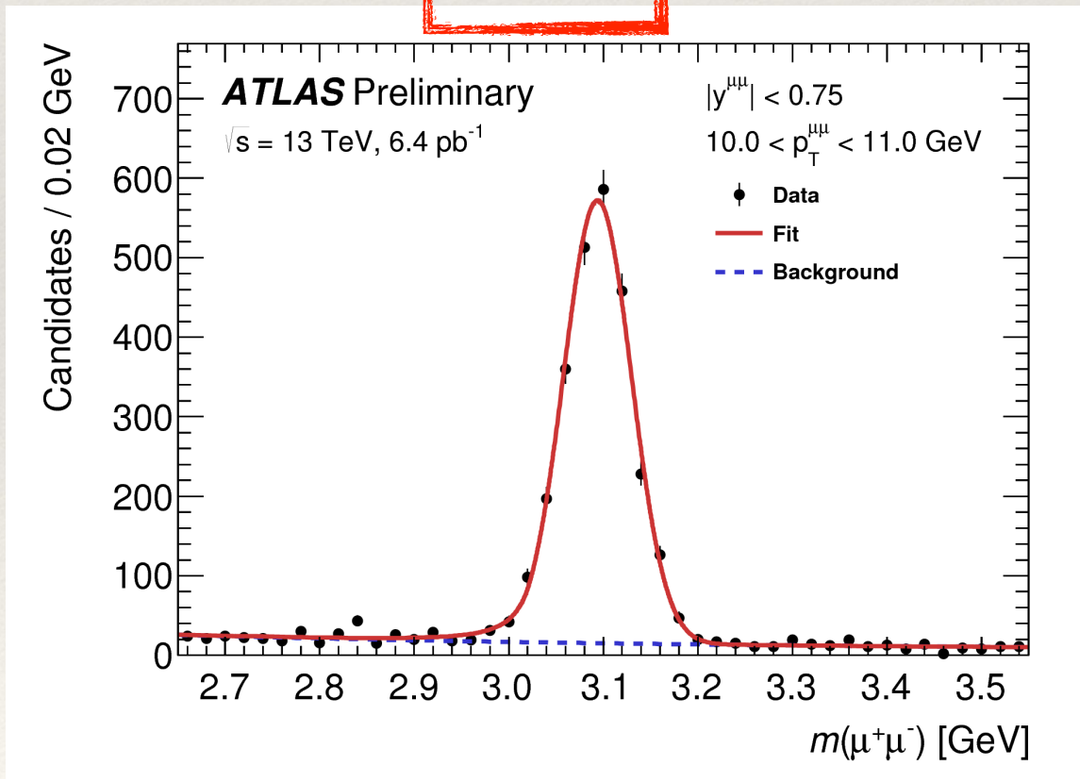
8 TeV

arXiv:1512.03657



13 TeV

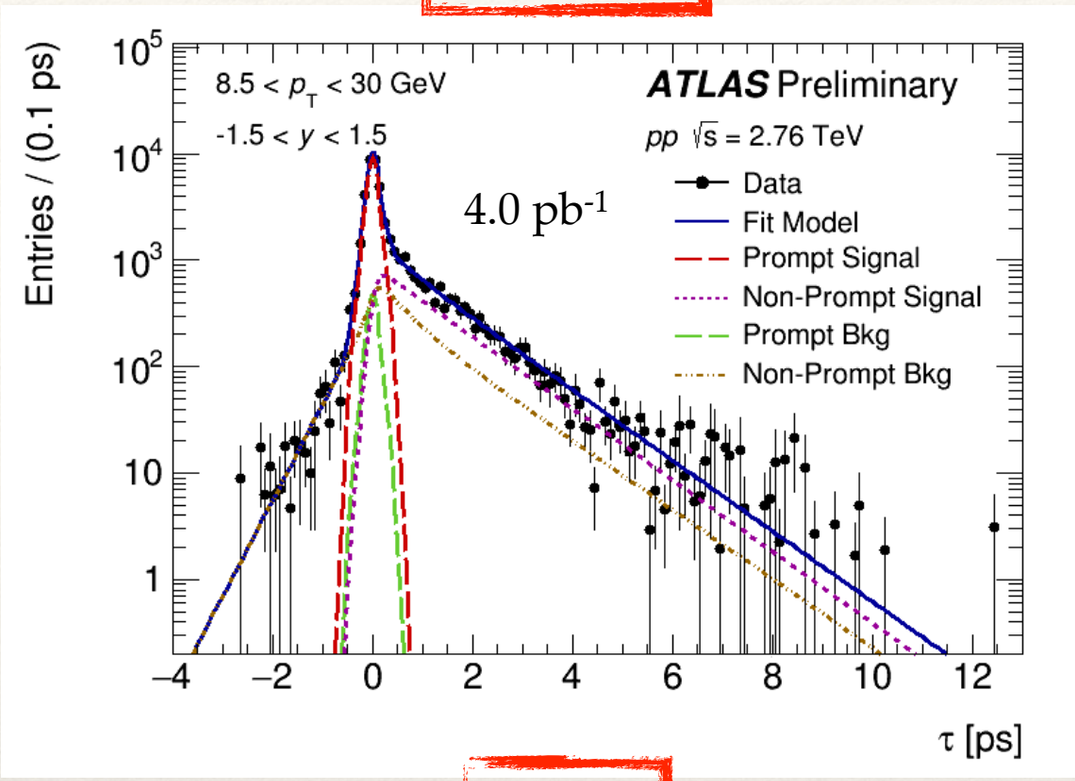
ATLAS-CONF-2015-030



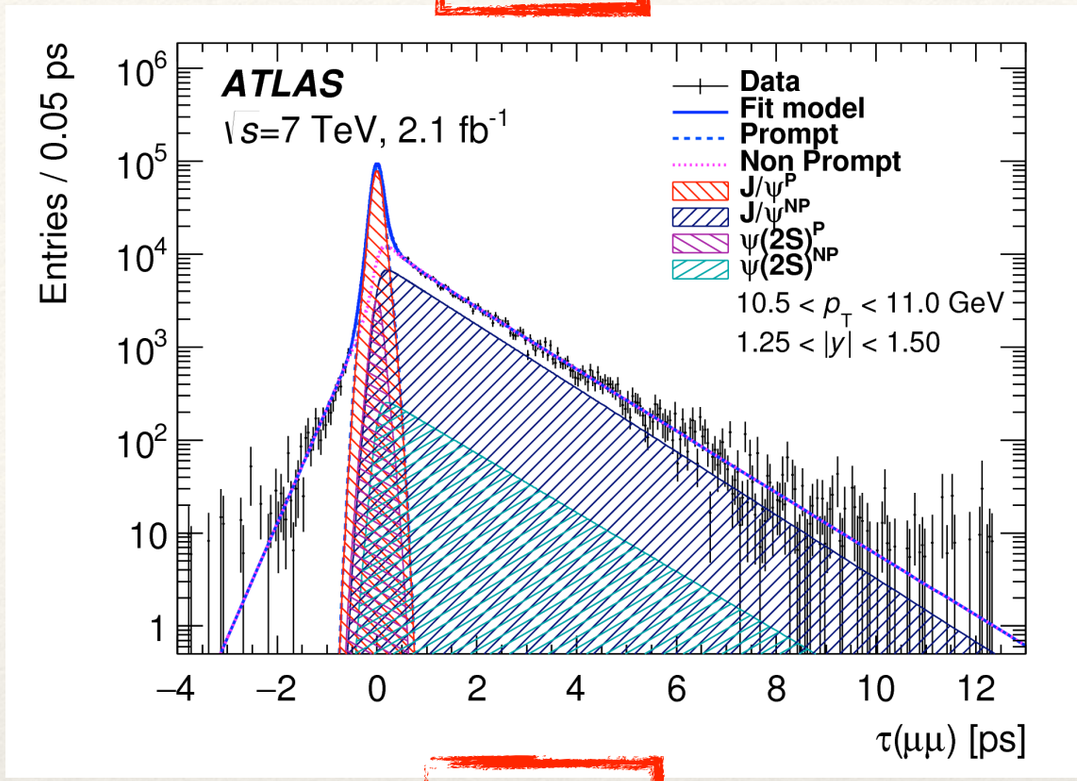
pp collisions results

2.76 TeV

ATLAS-CONF-2015-023



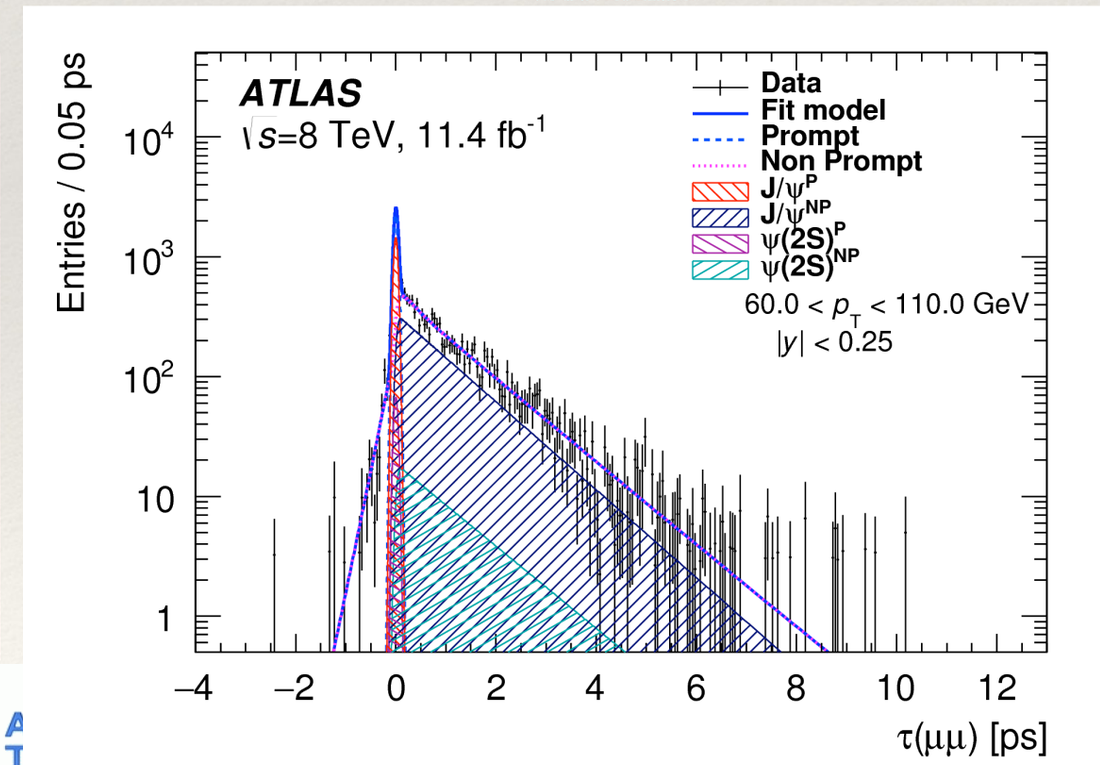
7 TeV



arXiv:1512.03657

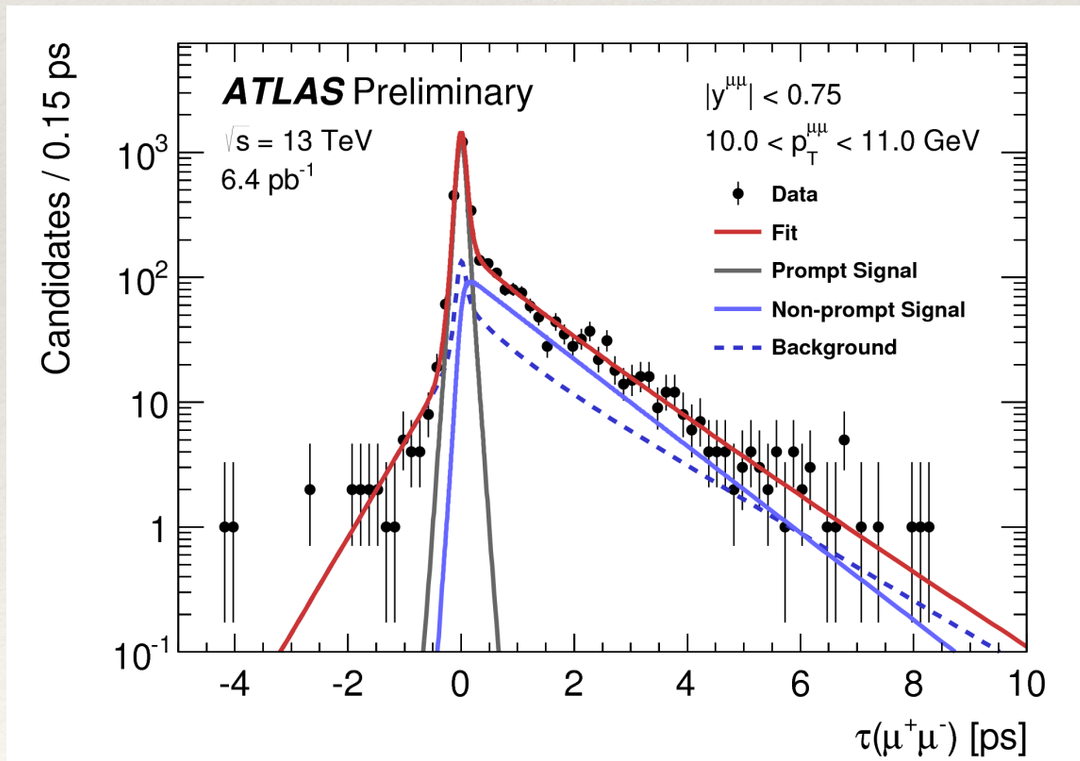
8 TeV

arXiv:1512.03657



13 TeV

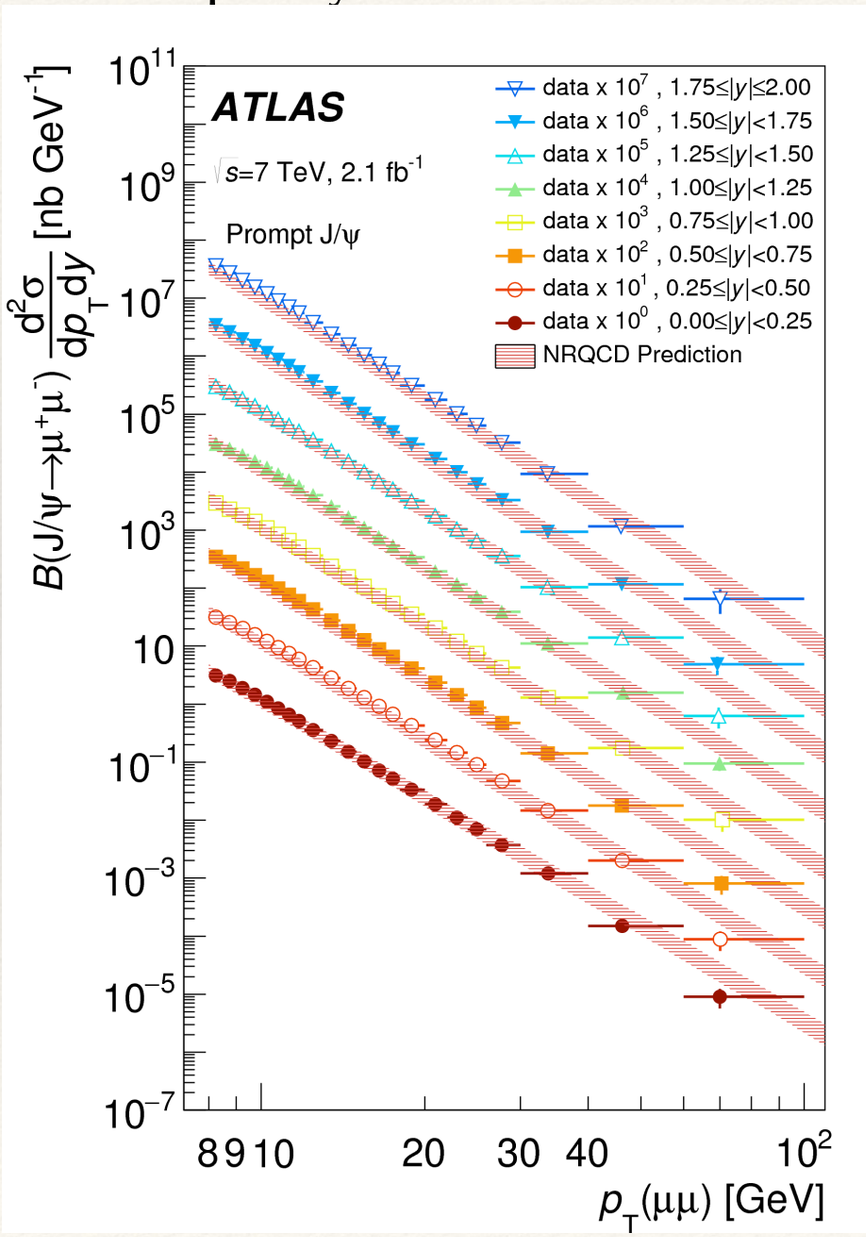
ATLAS-CONF-2015-030

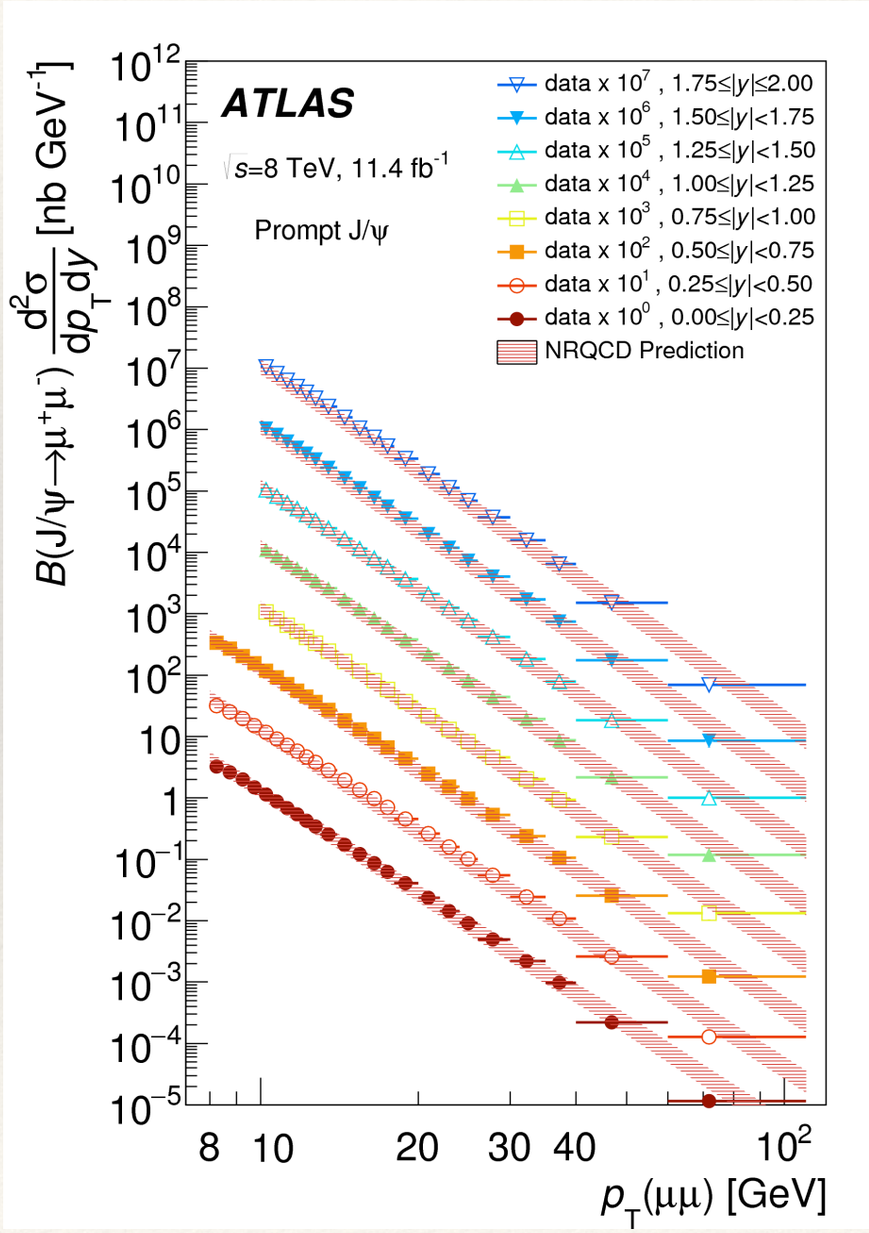


arXiv:1512.03657

Double-differential J/ψ cross-section

- Differential prompt and non-prompt cross-sections times di-muon branching fraction of J/ψ as a function of di-muon p_T for 8 rapidity slices
- Powerful tool to validate theoretical models of production
- **Prompt** cross-sections compared to NLO Non-relativistic QCD (**NRQCD**) theory calculations
  - Theory uncertainties from scale, charm quark mass and long-distance matrix elements
  - **Reasonable agreement between calculation and data**





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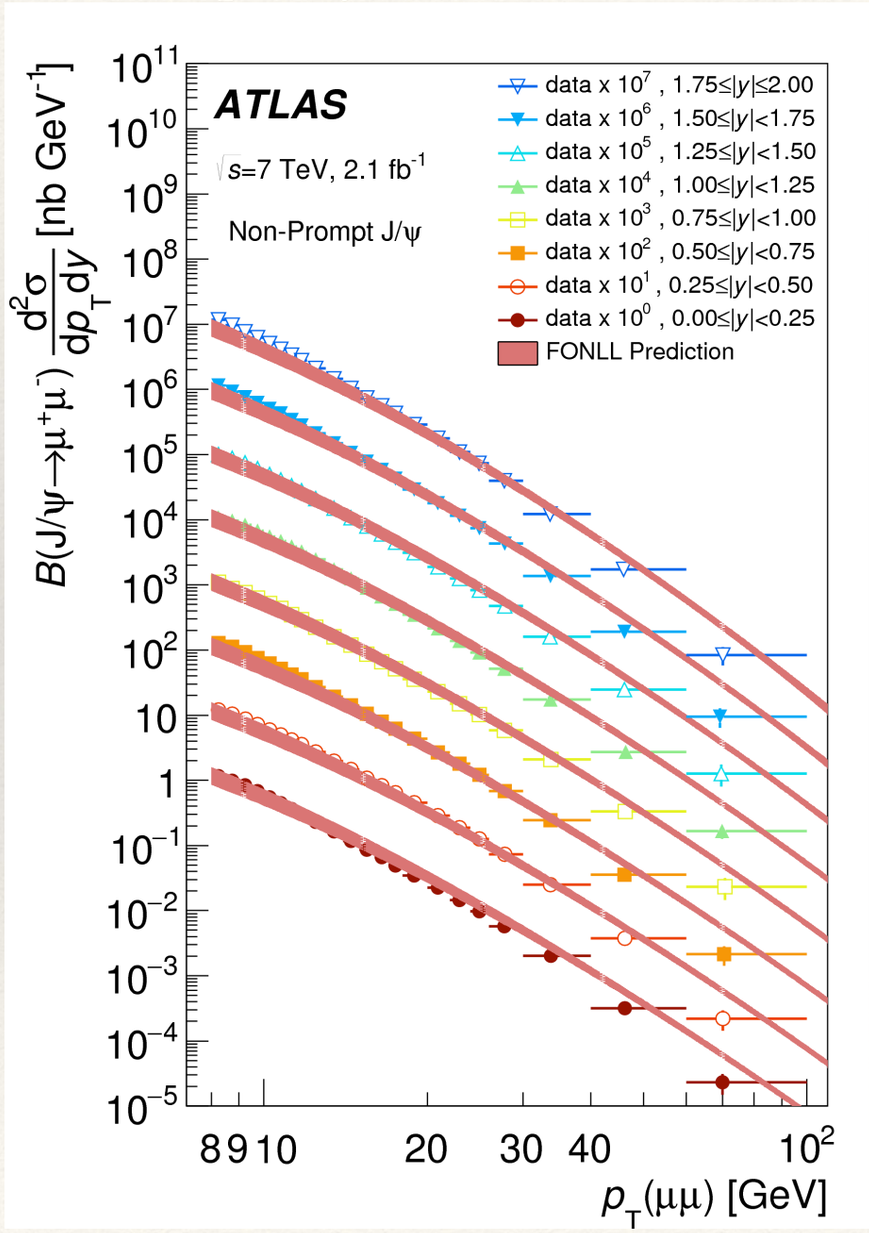
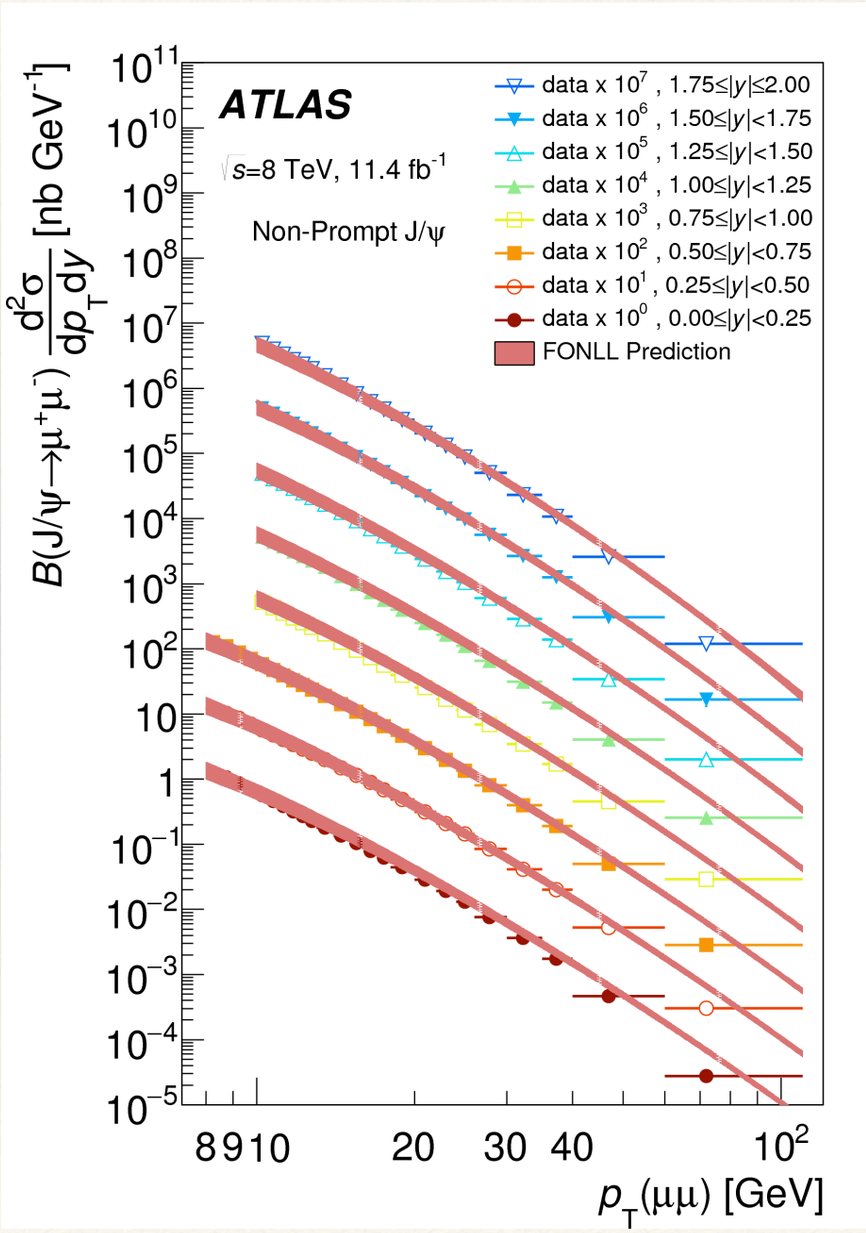
Double-differential J/ψ cross-section

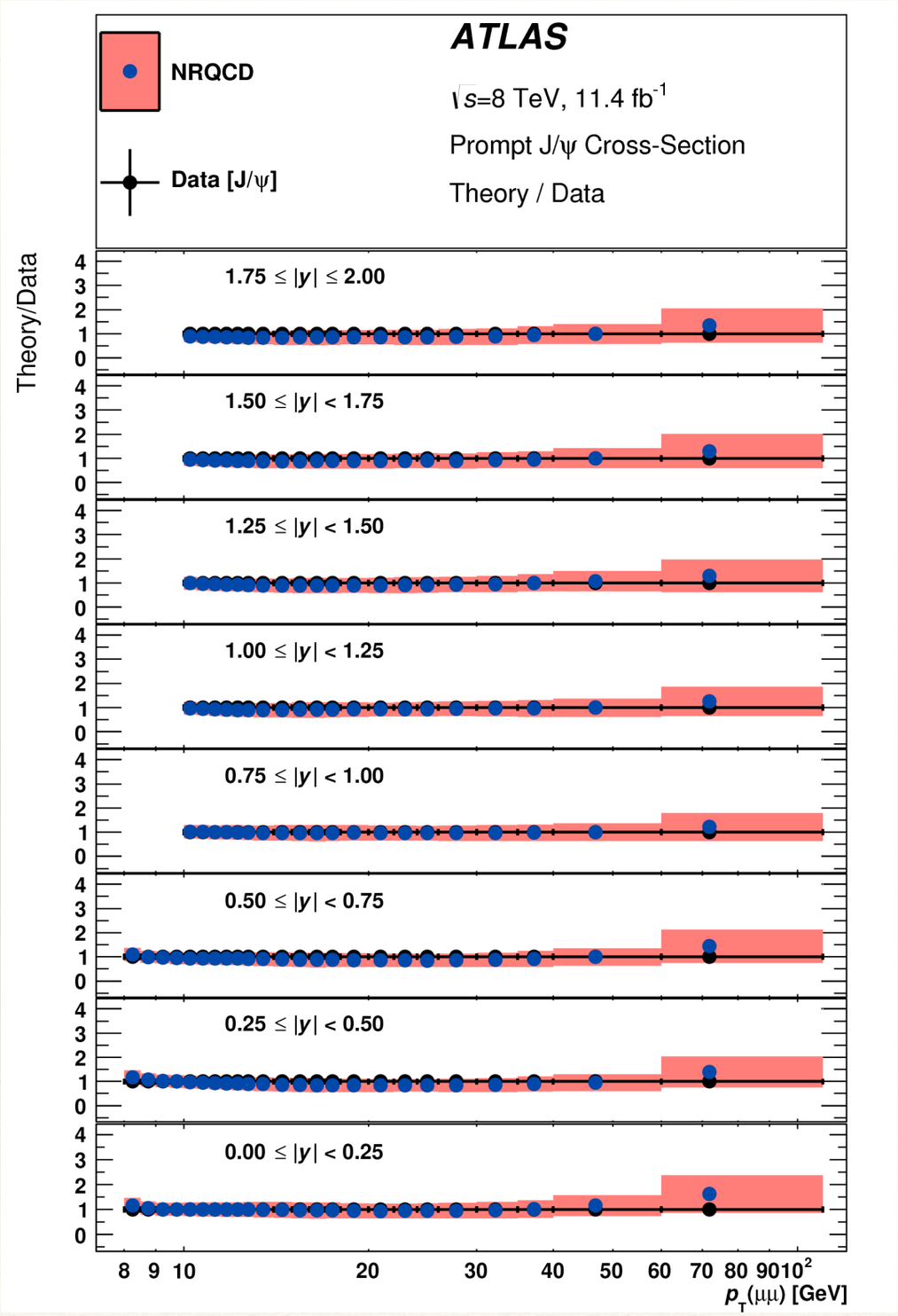
- Differential prompt and non-prompt cross-sections times di-muon branching fraction of J/ψ as a function of di-muon p_T for 8 rapidity slices
- Powerful tool to validate theoretical models of production
- **Non-prompt** cross-sections compared to Fixed-Order with Next-to-Leading-Log (**FONLL**) theory calculations
  - Theory uncertainties from scale and quark masses
  - **Theory predicts slightly harder p_T for J/ψ**

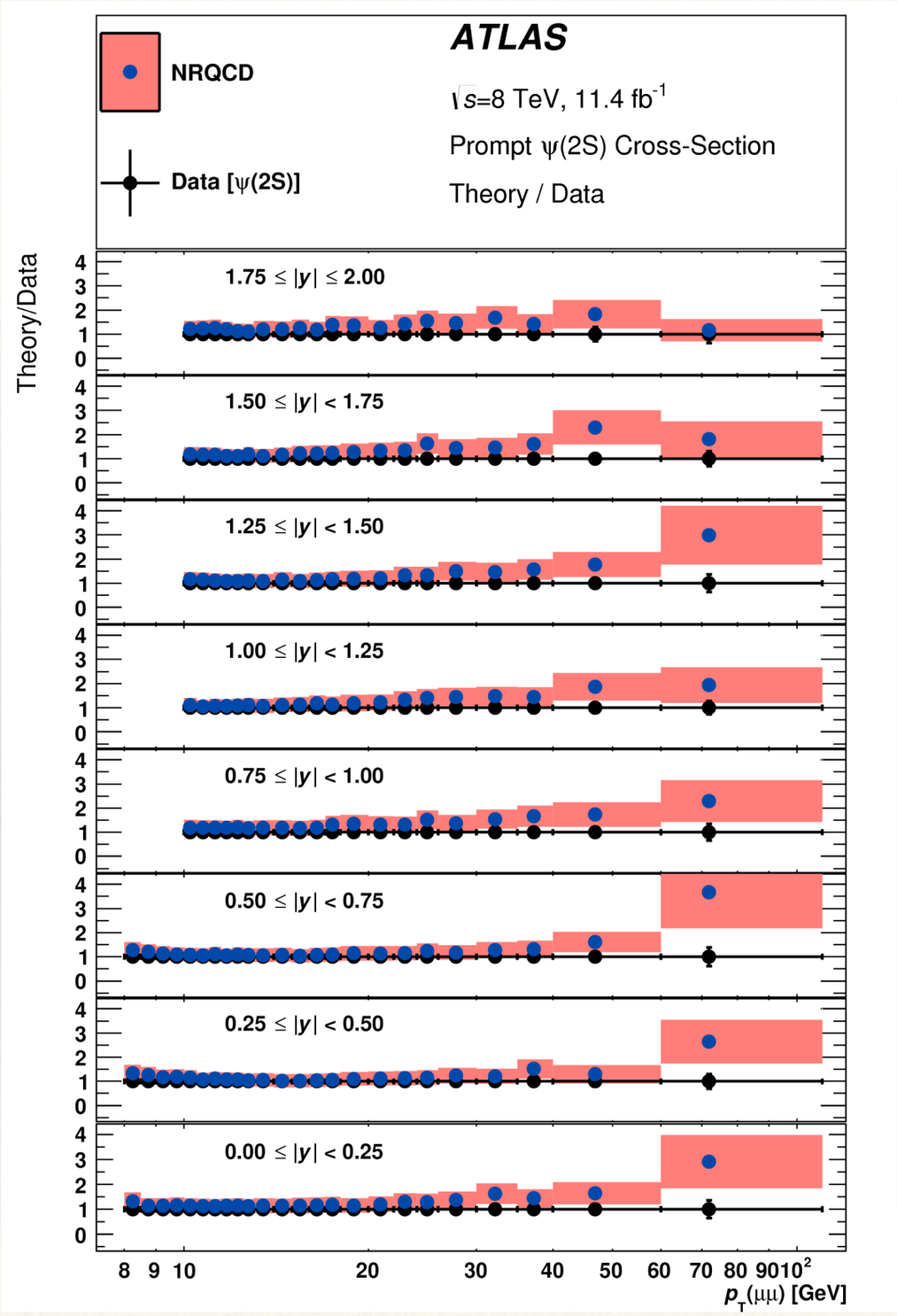




arXiv:1512.03657

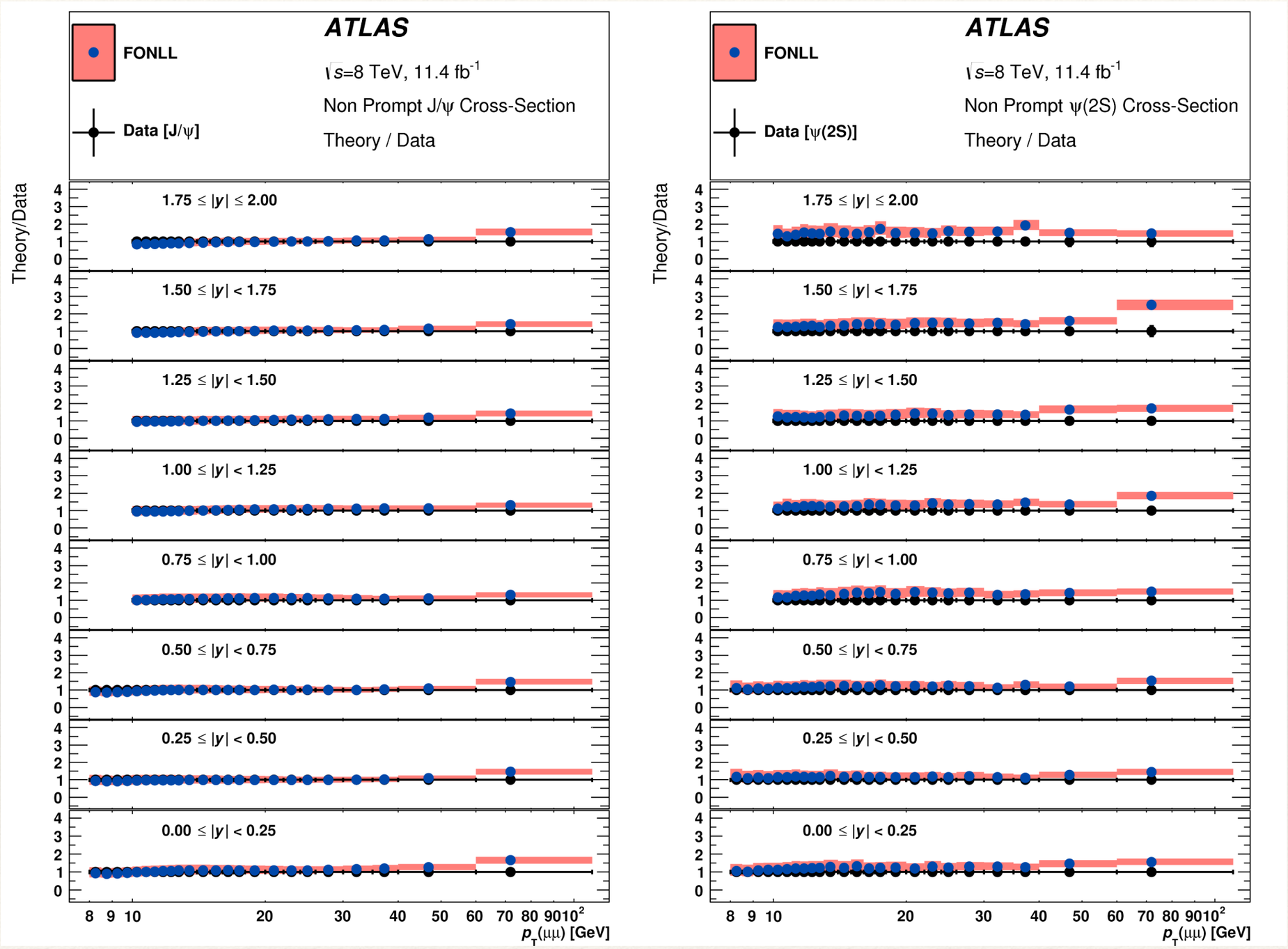
- Theory / data @ 8TeV, for J/ψ and ψ(2S) prompt cross sections:





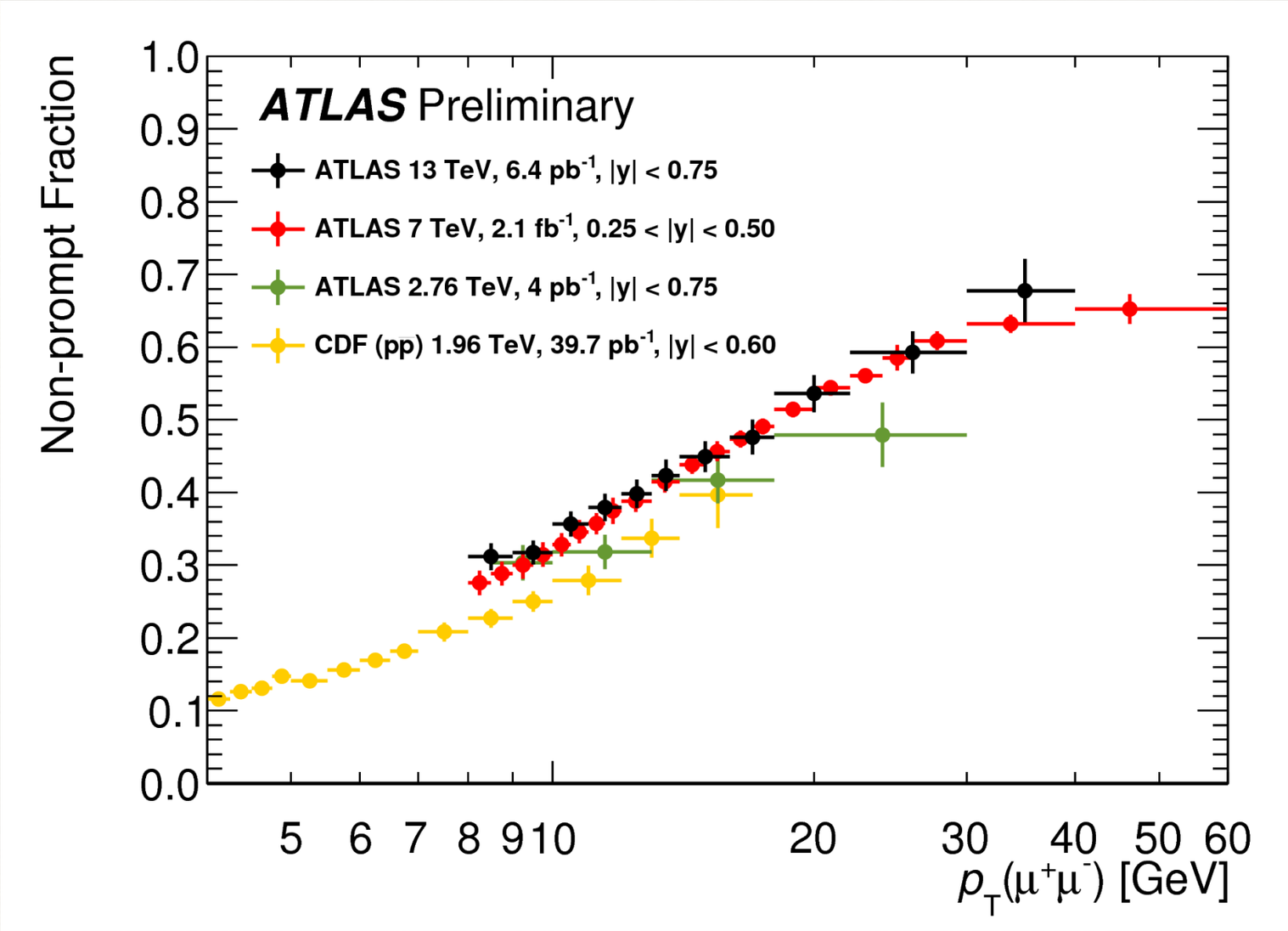
arXiv:1512.03657

- Theory / data @ 8TeV, for J/ψ and ψ(2S) non-prompt cross sections:



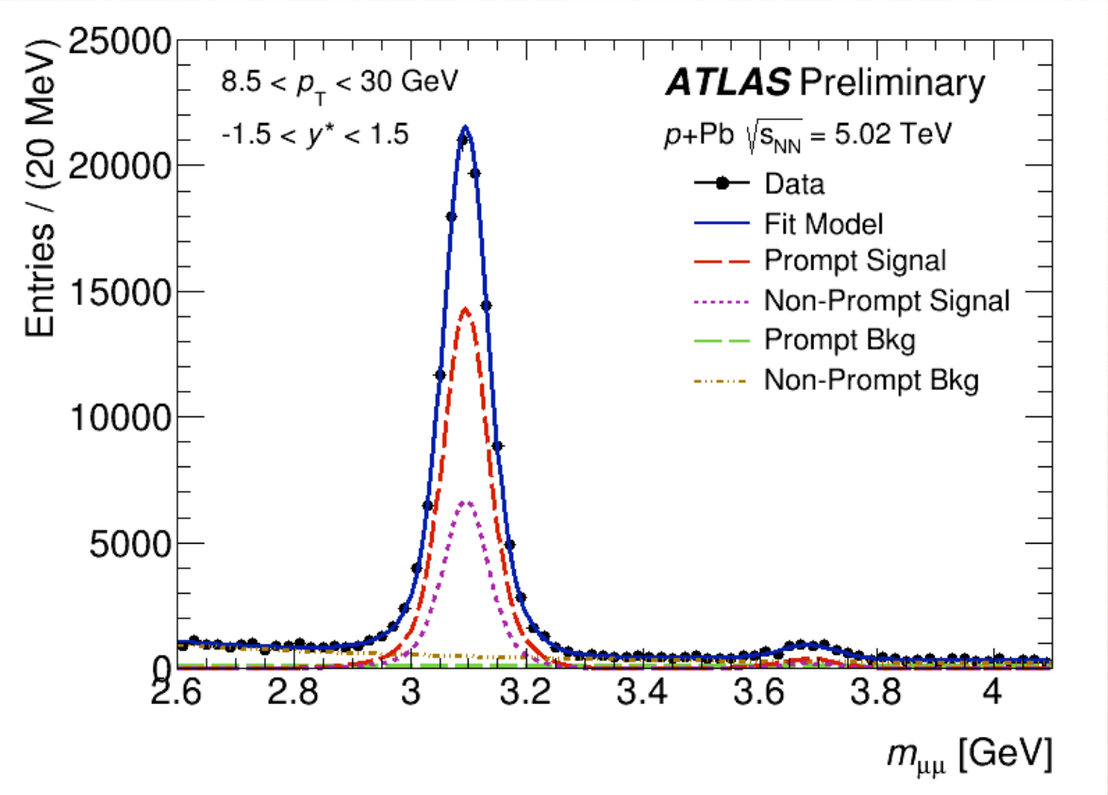
Non-prompt J/ψ fraction

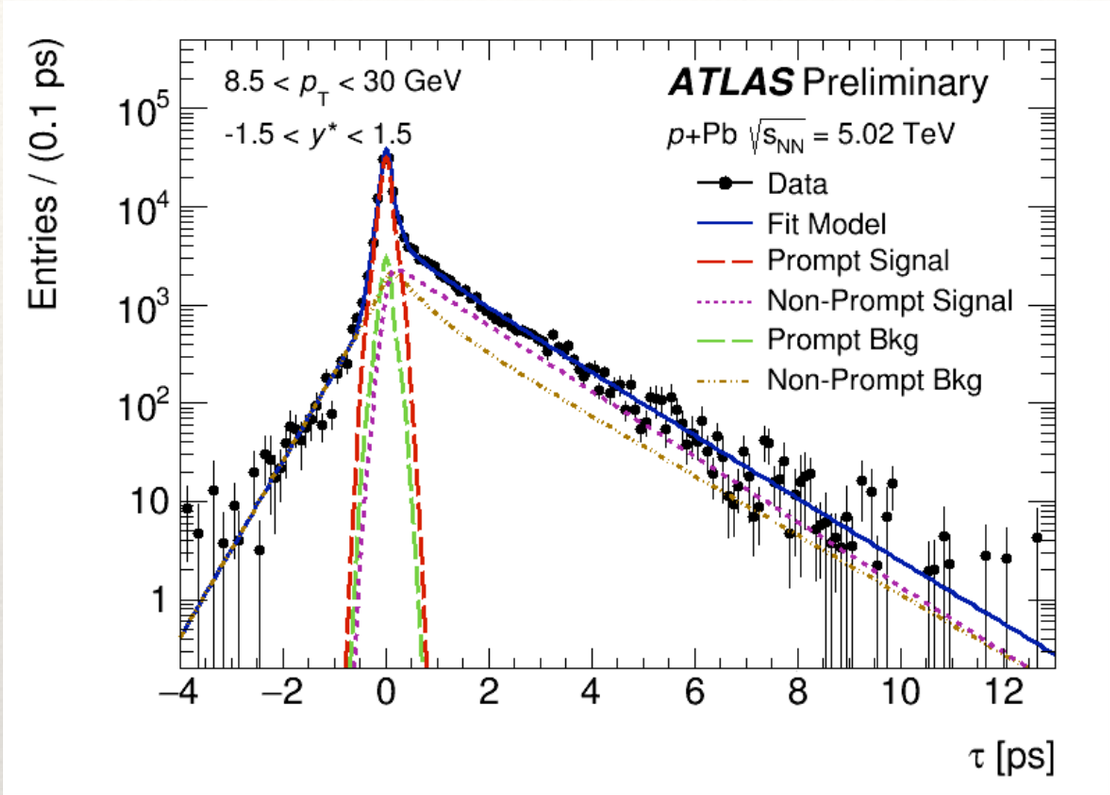
- Measuring a fraction
  —> reduced systematics
- Strong dependence on p_T
- No dependence on |y|
  (already seen in Run1)
  - 3 |y| bins 0,0.75–0.75,1.5–1.5,2.0 (see backup)



- Prompt fraction dominates at low p_T, non-prompt exceeds prompt at ~20 GeV
- Very similar behaviour between 7 and 13 TeV; larger differences at lower energies

Prompt and non-prompt J/ψ in p+Pb

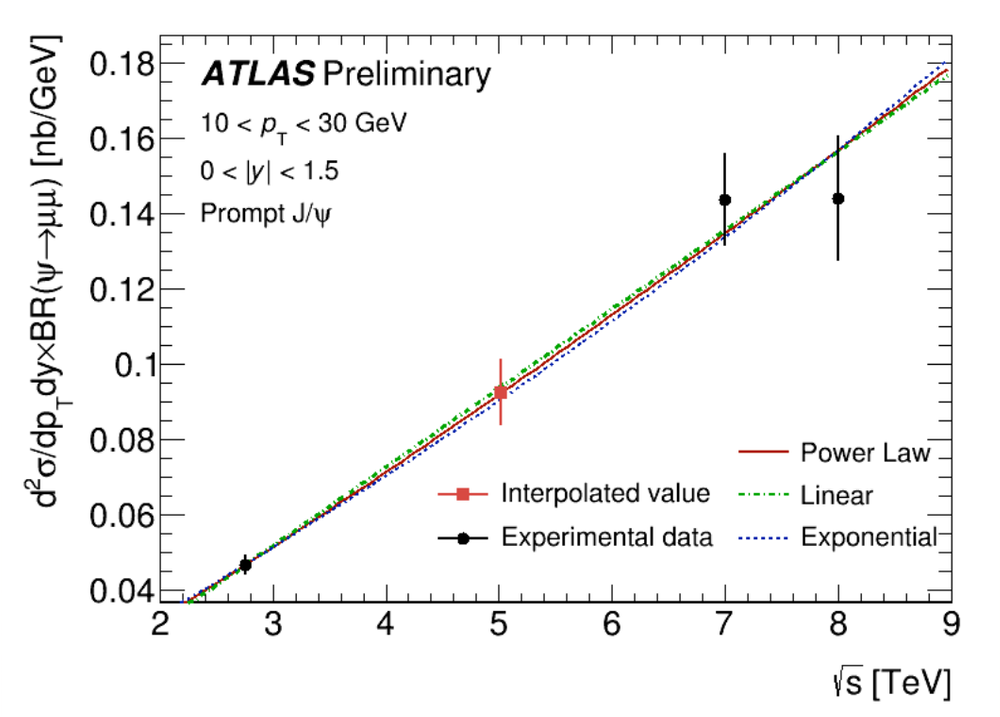




- The method remains the same
- y* is the CM rapidity of the pA system, defined to be always positive in the p direction: **$y^* = y_{lab}$ - 0.465** (the CM of the pA system is shifted in the direction of the p beam relative to the lab frame, due to energy asymmetry of the LHC beams: 4 TeV p + 1.57 TeV per A Pb beam)

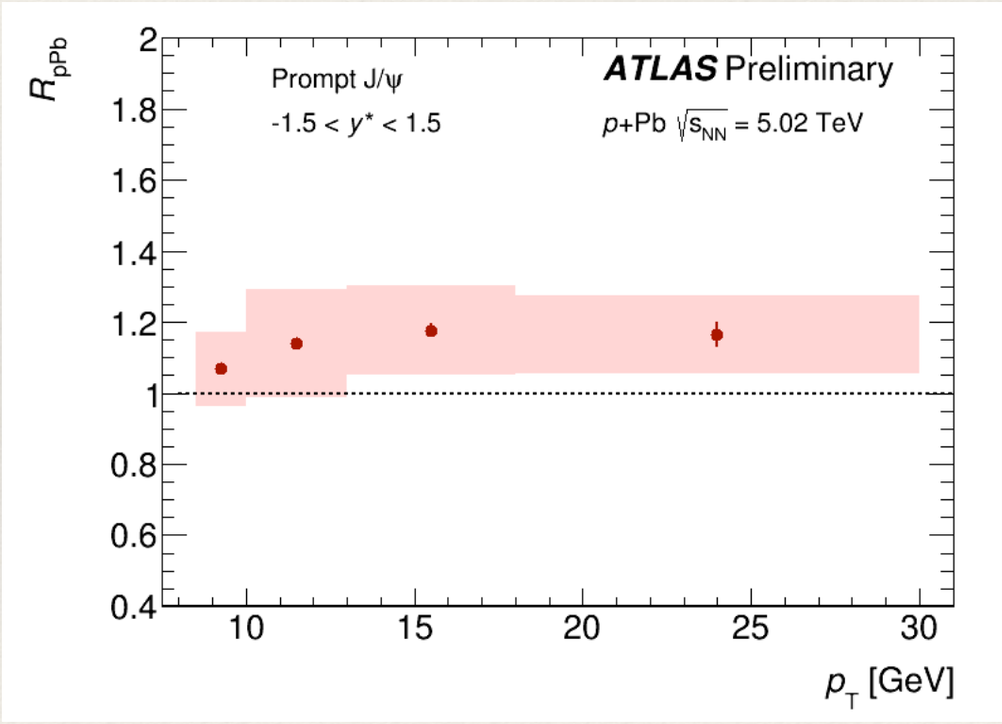
ATLAS-CONF-2015-023

- Cross section for pp collisions at 5.02 TeV interpolated and used as a reference for the nuclear modification factor $\mathbf{R_{pPb}}$

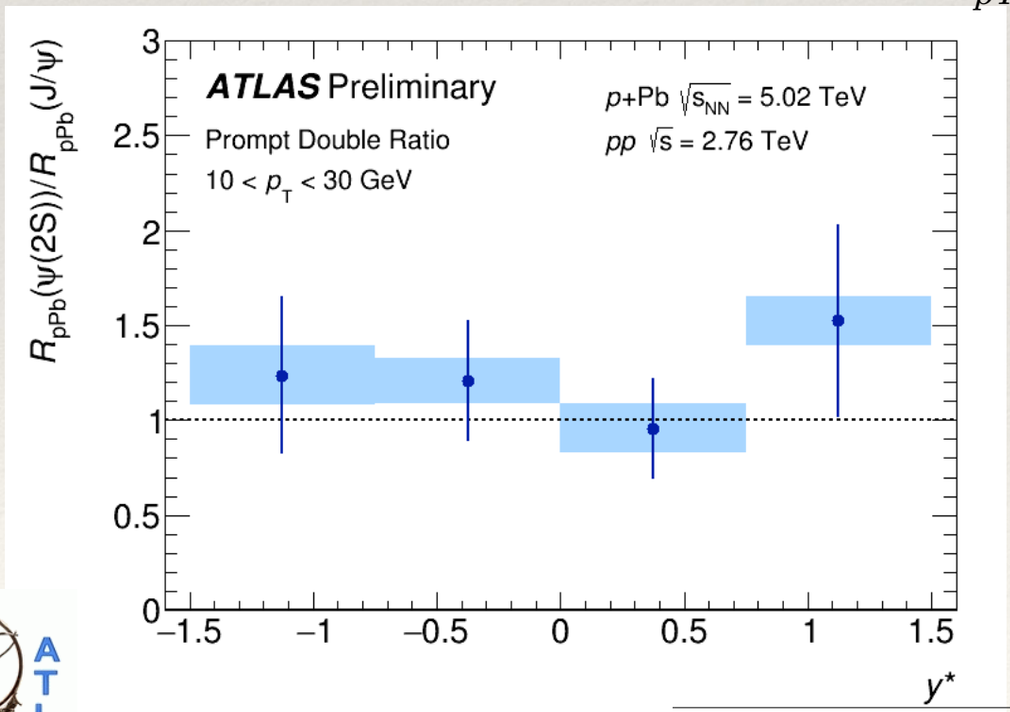


$$R_{p\mathrm{Pb}} = \frac{1}{A^{\mathrm{Pb}}} \frac{d^2\sigma_\psi^{p+\mathrm{Pb}}/dy^* dp_T}{d^2\sigma_\psi^{pp}/dy dp_T}$$

- J/ψ (prompt and non-prompt): above unity and independent of p_T and y* (and of number of participant nucleons after centrality bias correction due to hard scattering processes)
- non-prompt ψ(2S) results limited by uncertainties



- For comparison with other experiments, **prompt double ratio** is also given: $\frac{R_{pPb}(\psi(2S))}{R_{pPb}(J/\psi)}$



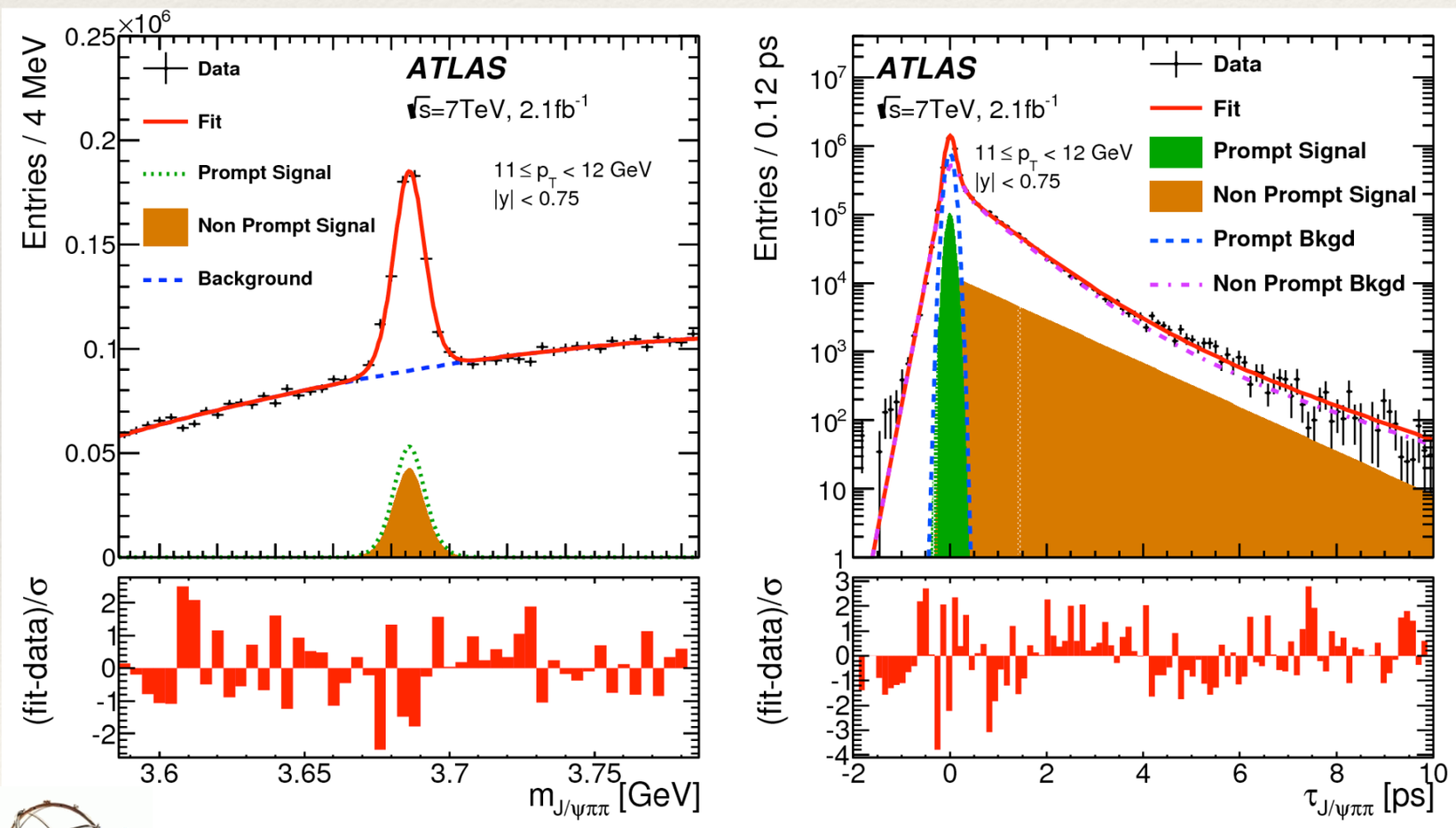
- no rapidity dependence
- decreasing trend with increasing event activity

JHEP09(2014)079

$\psi(2S) \longrightarrow J/\psi\pi^+\pi^-$ at 7 TeV

- Measurement of prompt and non-prompt production cross-sections
  - Proves the range $10 < p_T(\psi(2S)) < 100$ GeV and $|y| < 2.0$
  - Same technique (mass and decay time fits, in bins of p_T)

2.1 fb^{-1} at 7 TeV

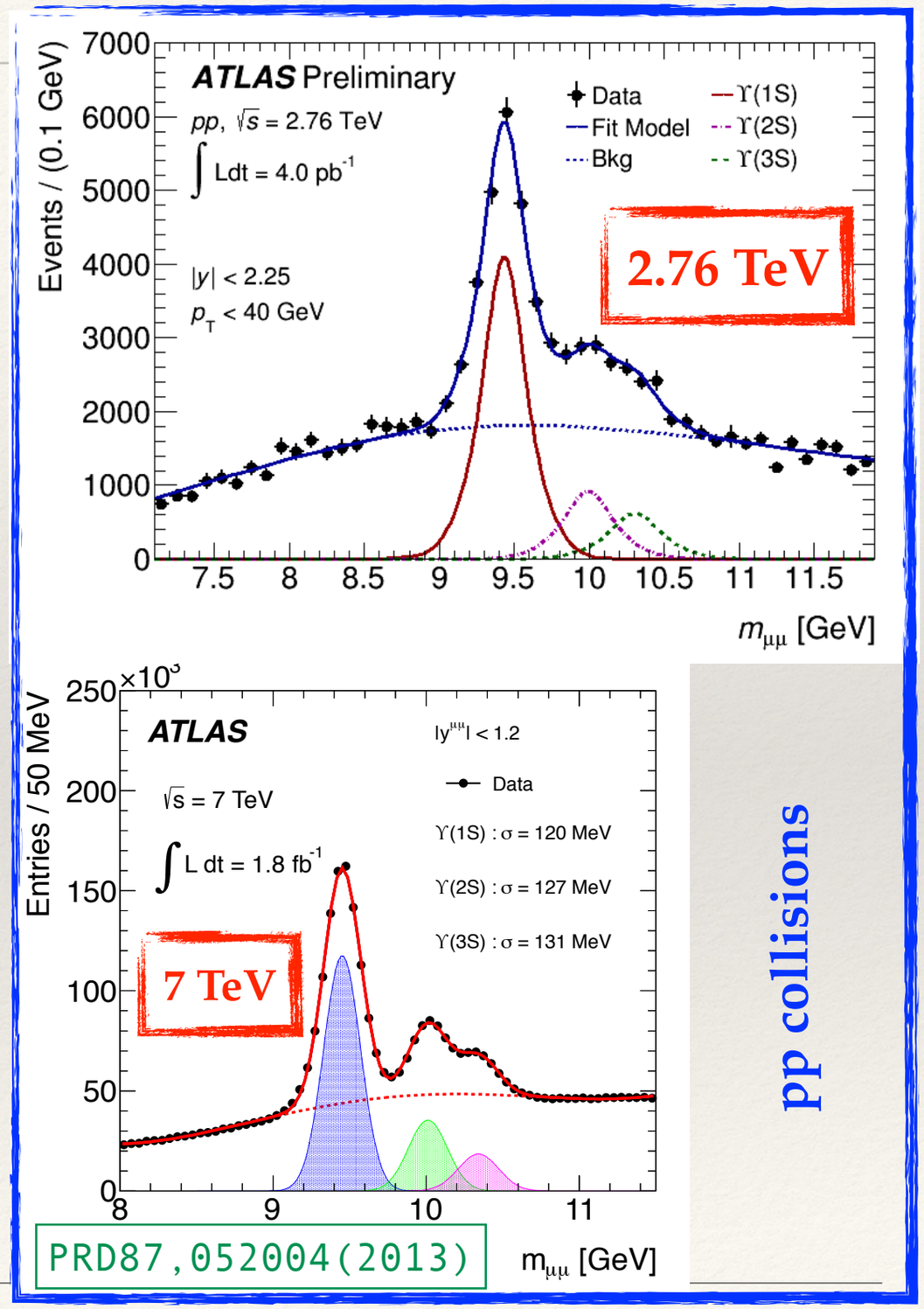


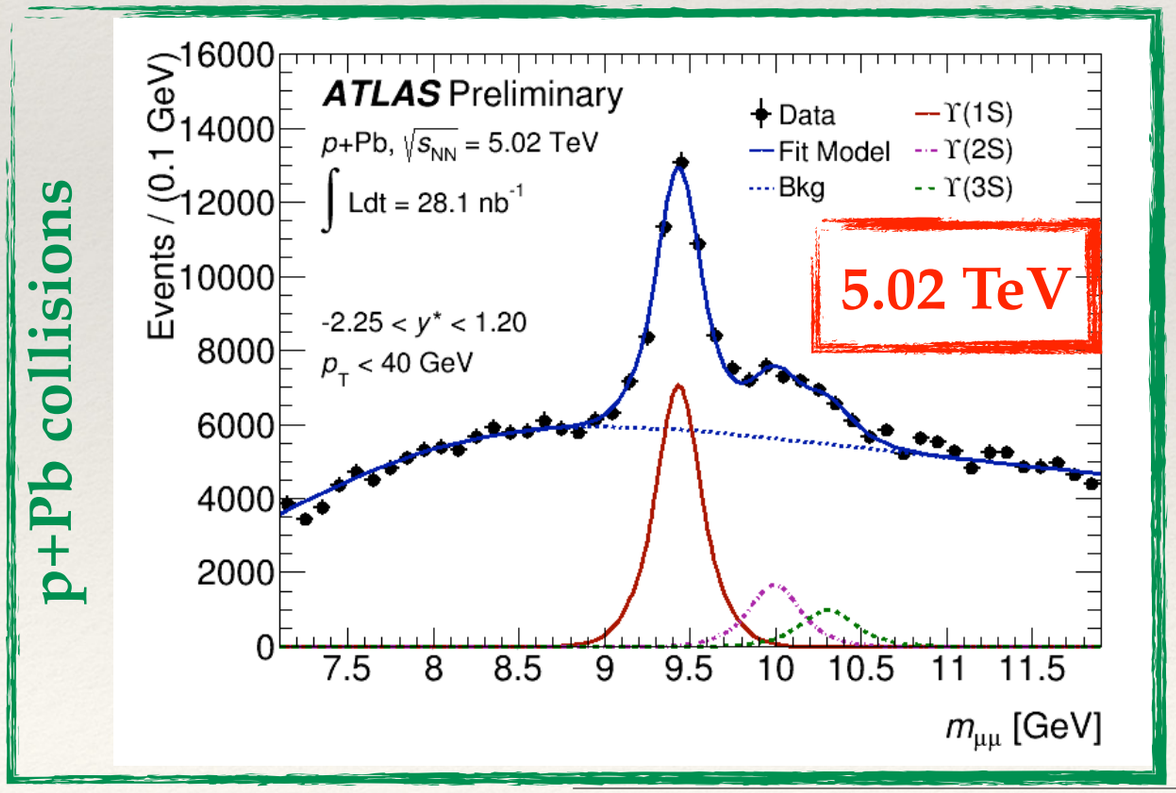
- Comparison of prompt and non-prompt cross sections with various theoretical models:
  - Prompt well described by NLO NRQCD
  - Non-prompt by FONLL, with deviations at high momenta (slightly higher spectrum than in data)

ATLAS-CONF-2015-050

Υ(nS) production

- Analysis of **4.0 pb^{-1}** of **pp collisions** at **√s=2.76 TeV** and **28.1 nb^{-1}** of **p+Pb collisions** at **√s$_{NN}$=5.02 TeV**
  - Previous result on **1.8 fb^{-1}** of **pp collisions** at **√s=7 TeV**
- Measurement of Υ(1S) and Υ(2S)+Υ(3S) production cross sections

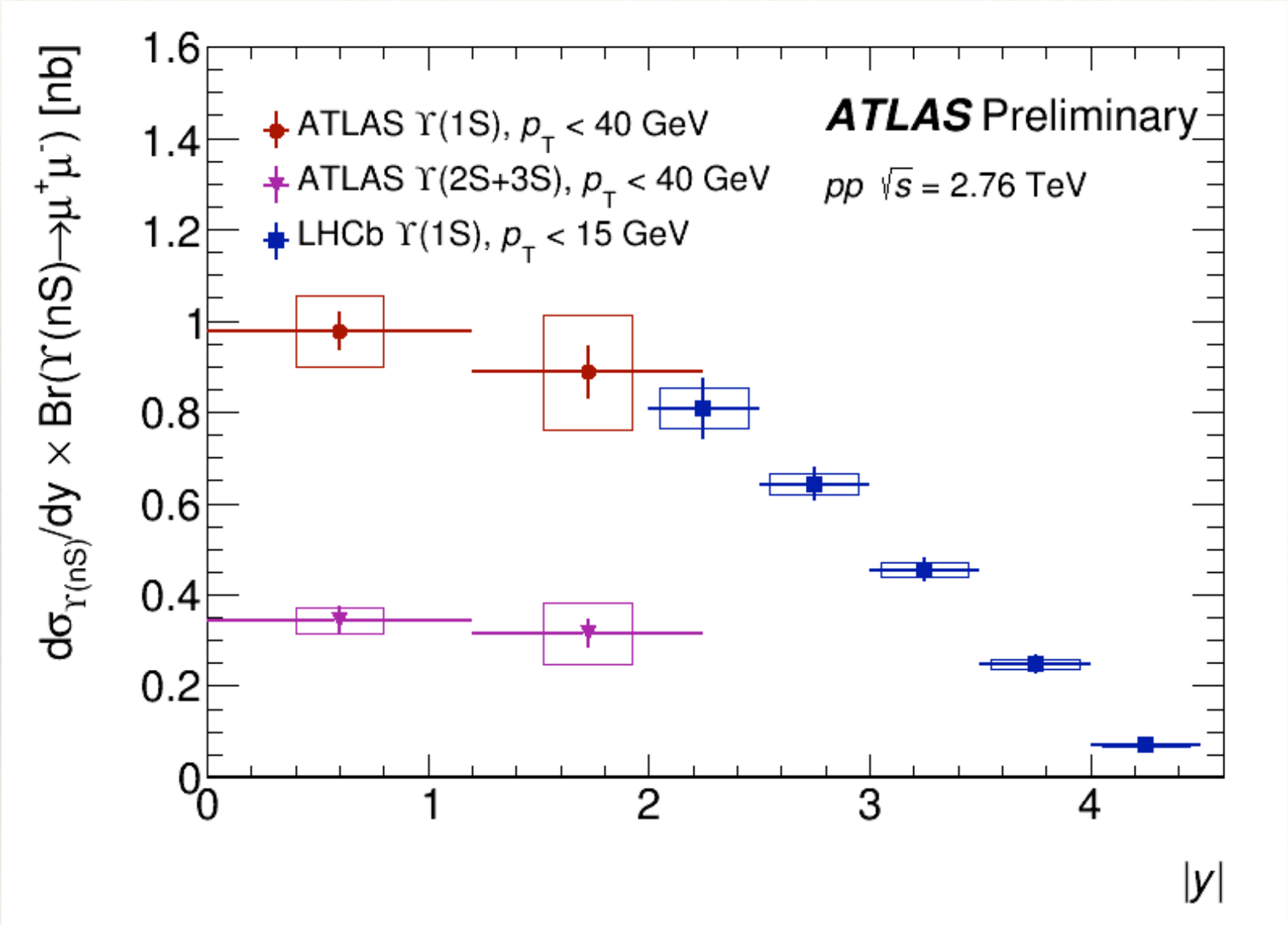




ATLAS-CONF-2015-050

pp collisions results

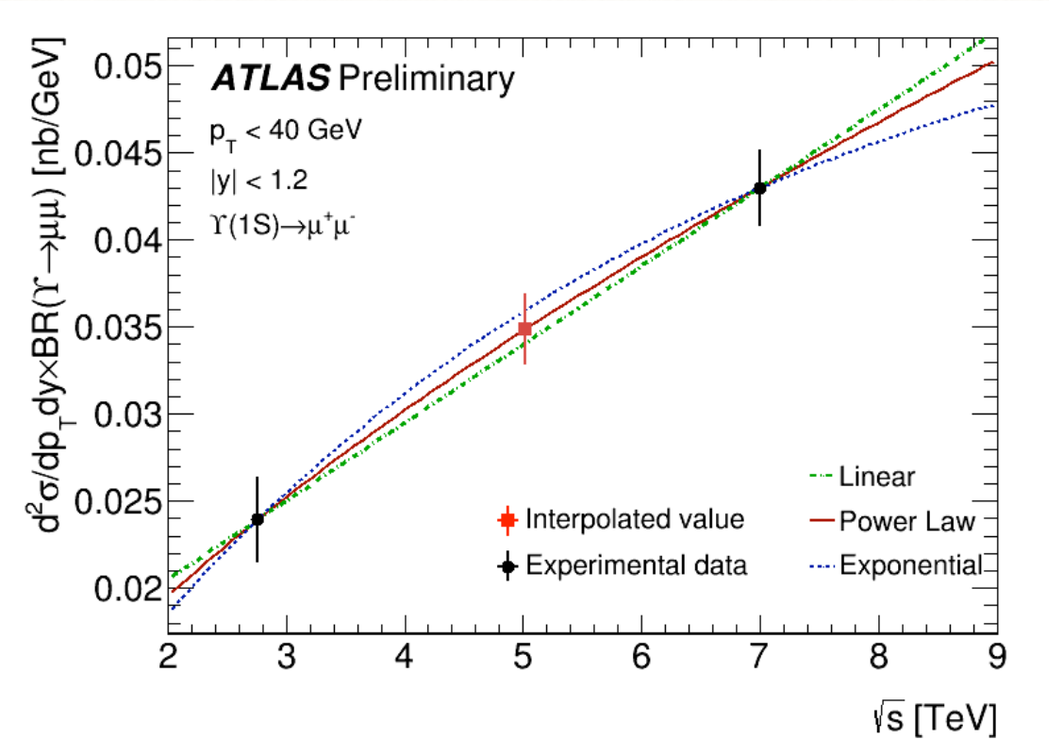
- **Cross section results:**
- single differential cross sections as a function of |y|
- here in comparison with LHCb results



p+Pb collisions results

ATLAS-CONF-2015-050

- **Interpolation of ϒ(1S) cross section** in pp collisions, to get a reference at 5.02 TeV
- different interpolation functions are tested



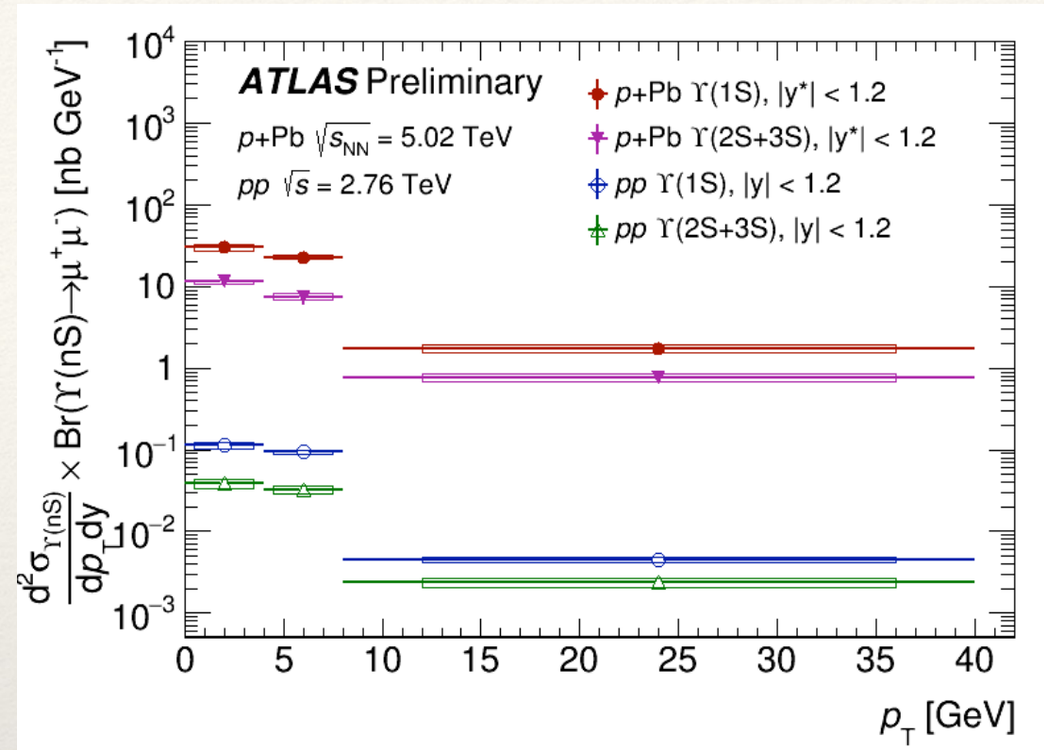
- Nuclear modification factor $\mathbf{R_{pPb}}$

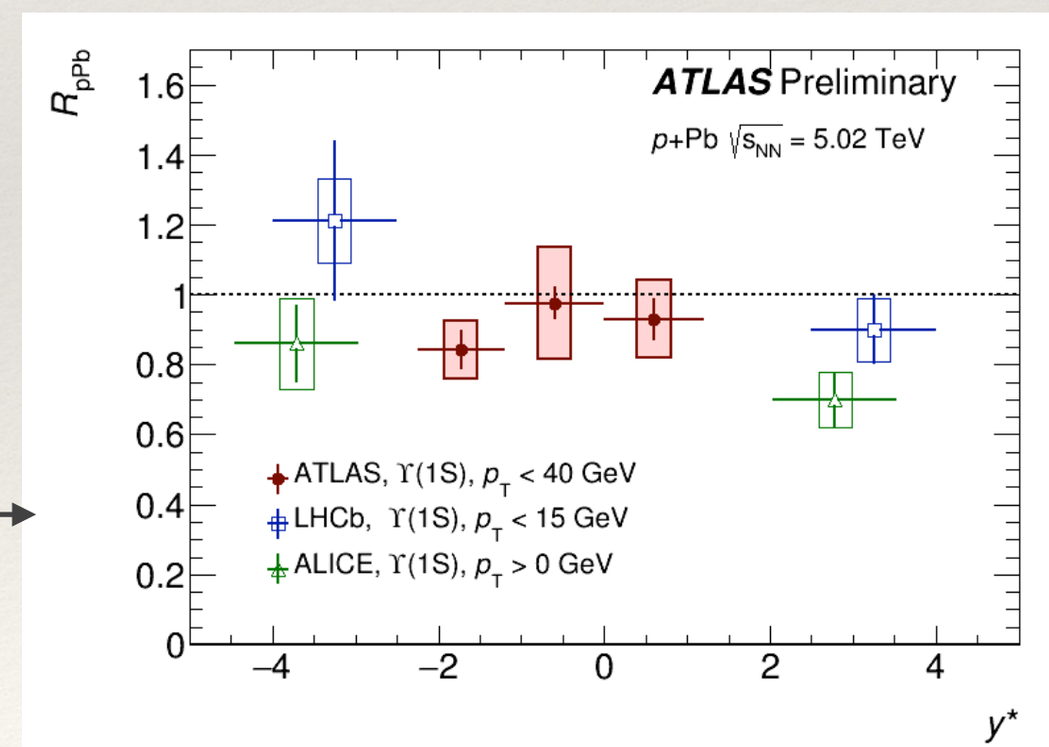
$$R_{p\mathrm{Pb}} = \frac{1}{A^{\mathrm{Pb}}} \frac{d^2\sigma_{\psi}^{p+\mathrm{Pb}}/dy^* dp_{\mathrm{T}}}{d^2\sigma_{\psi}^{pp}/dy dp_{\mathrm{T}}}$$

for ϒ(1S) as a function of y*

- Consistent with 1, no strong kinematic dependence

- **Double differential cross sections:**



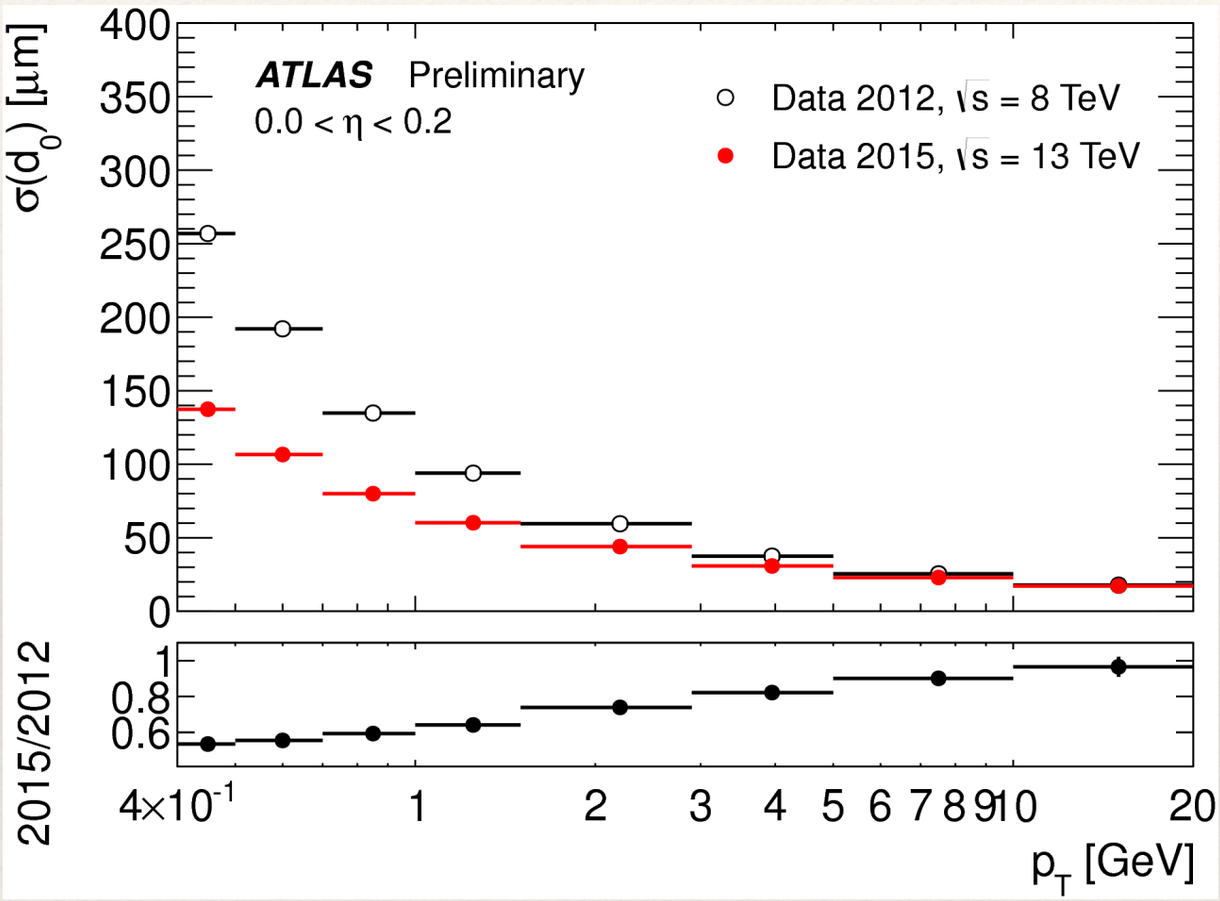


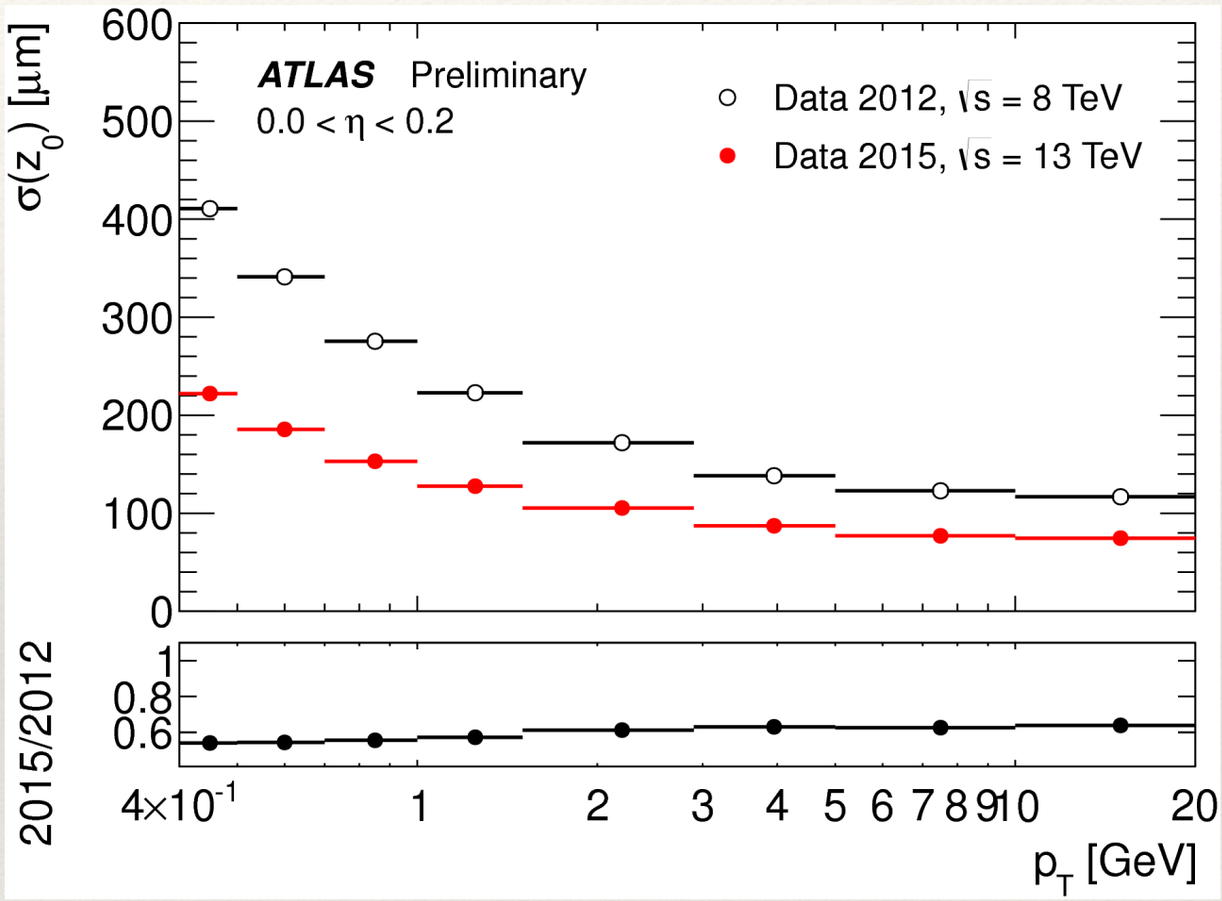
Summary

- Large quarkonium sample from Run 1 allows detailed tests of QCD (even "in media" through the analysis of p+Pb collisions)
- Run 2 measurements just started, will open a new energy regime to study
- Full details of published results at:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

Backup

IBL performance

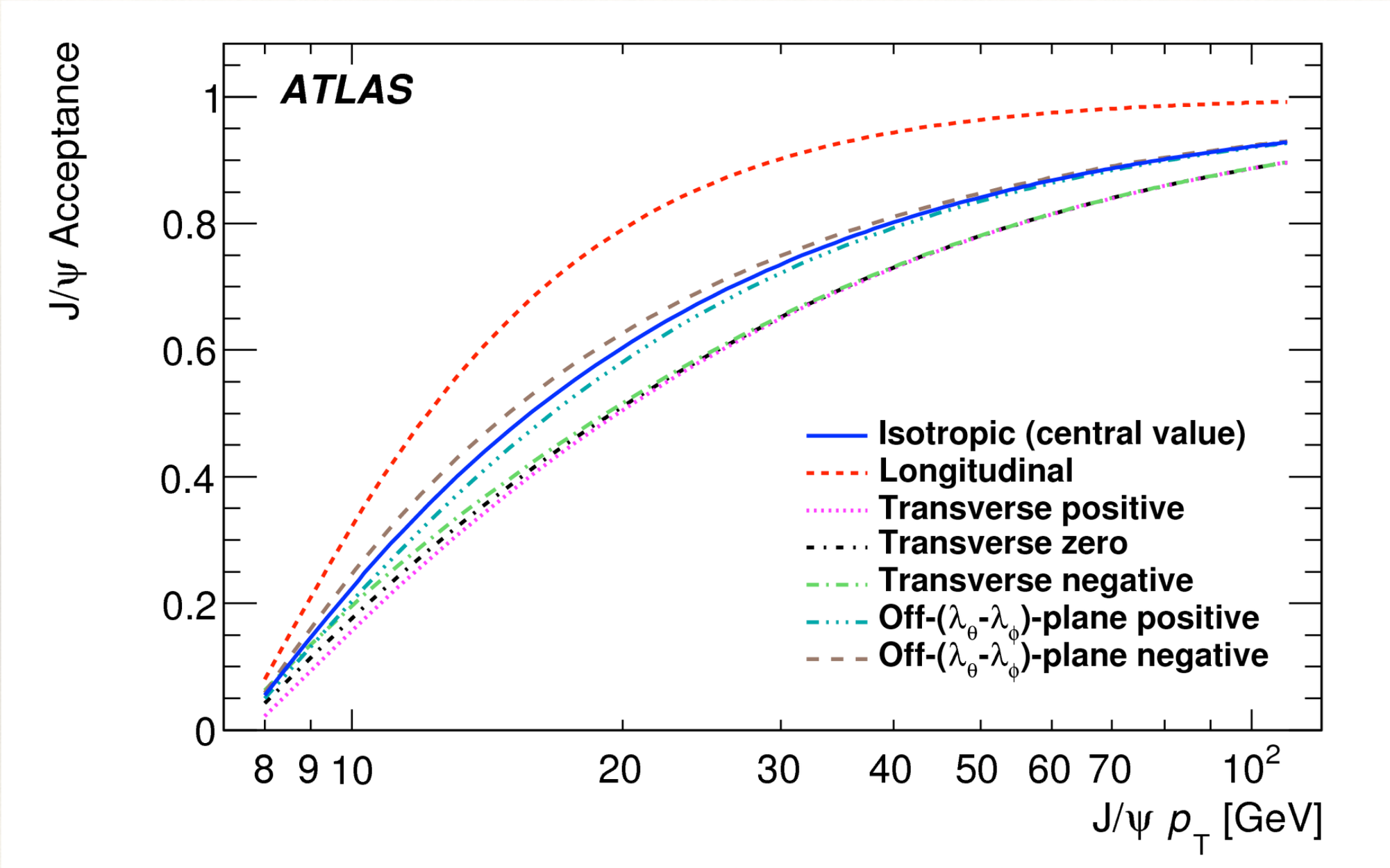




ATLAS Public Results - Inner Detector Tracking Performance

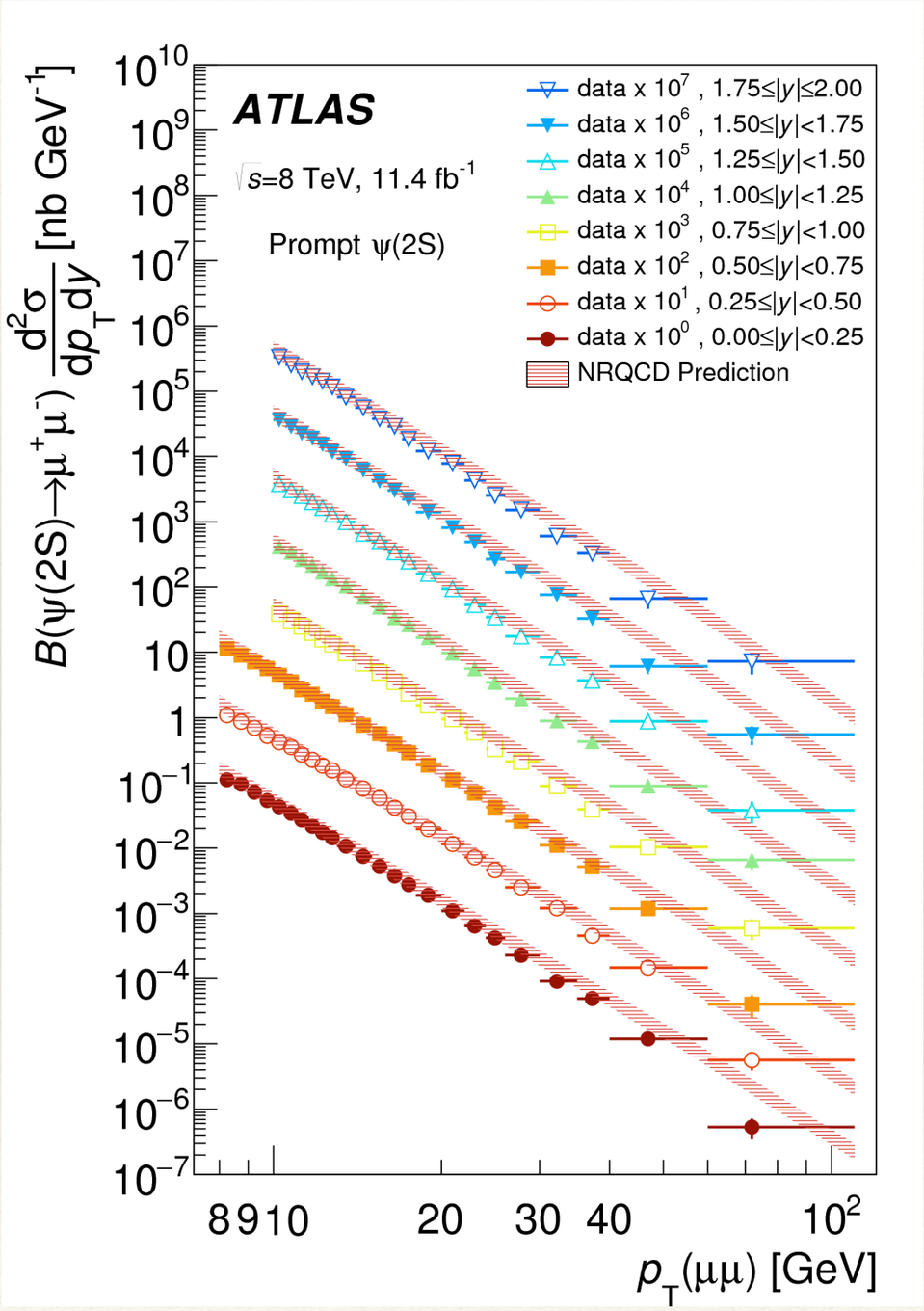
arXiv:1512.03657

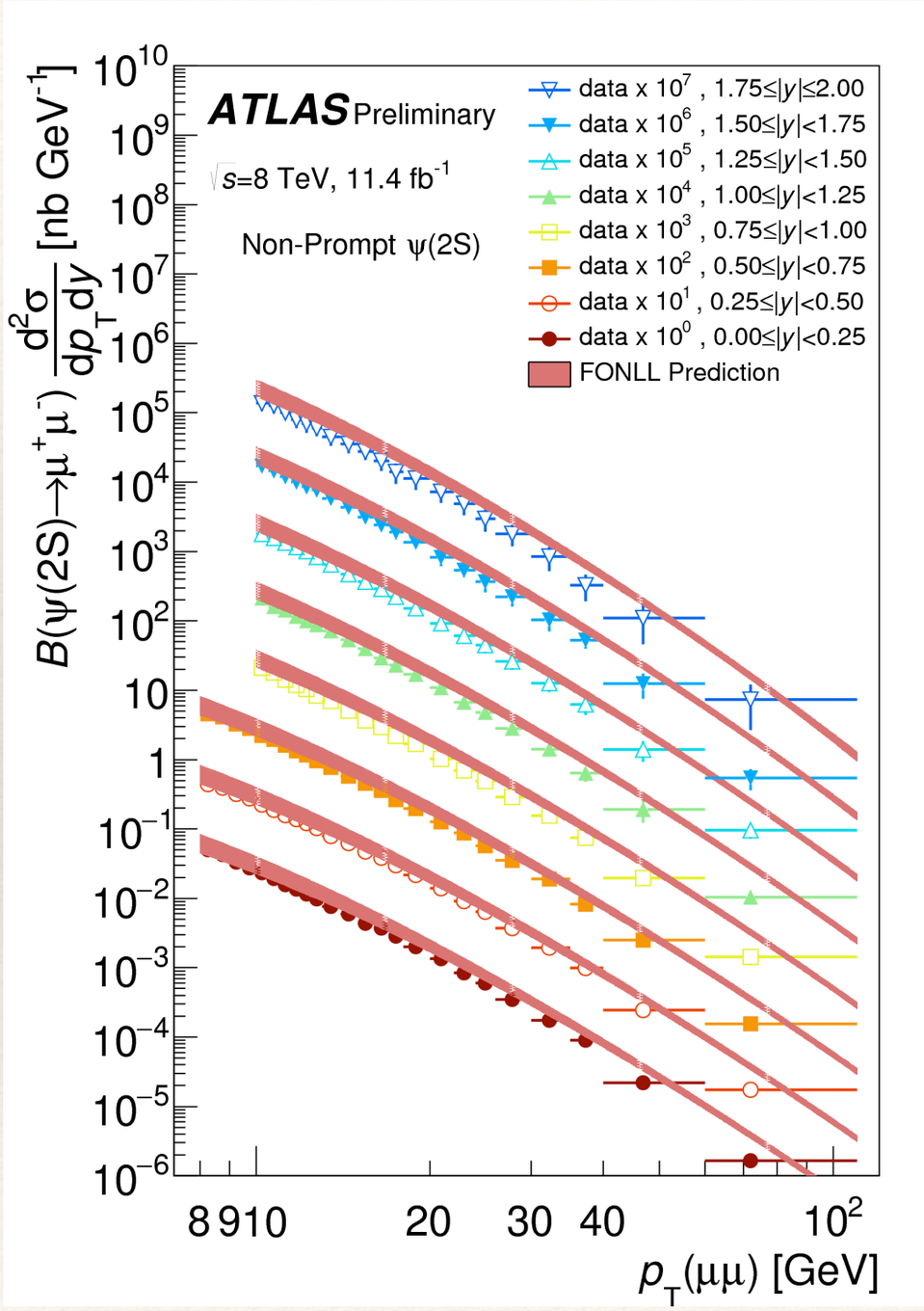
Non-isotropic spin alignment



arXiv:1512.03657

Double-differential ψ(2S) cross-section

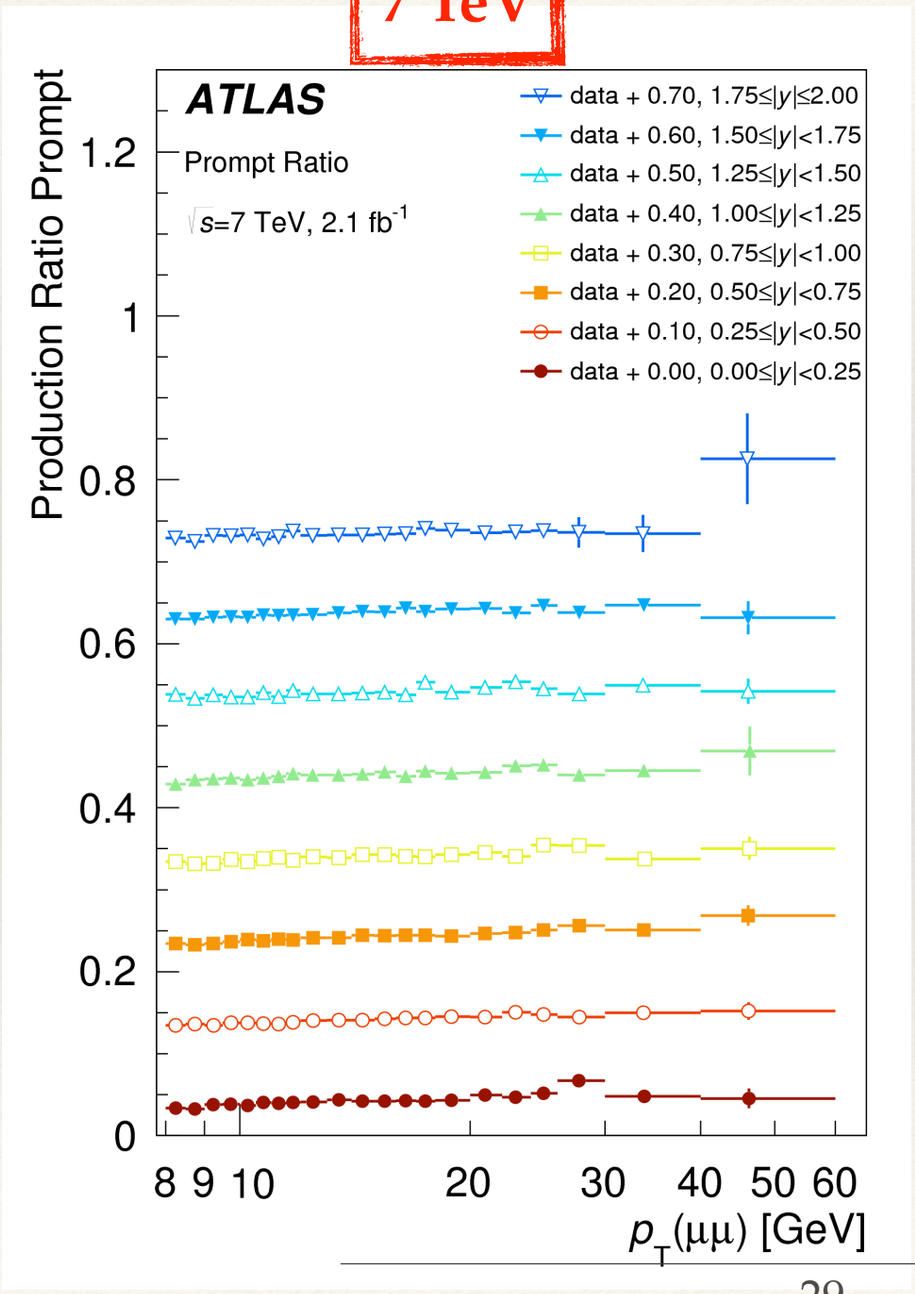




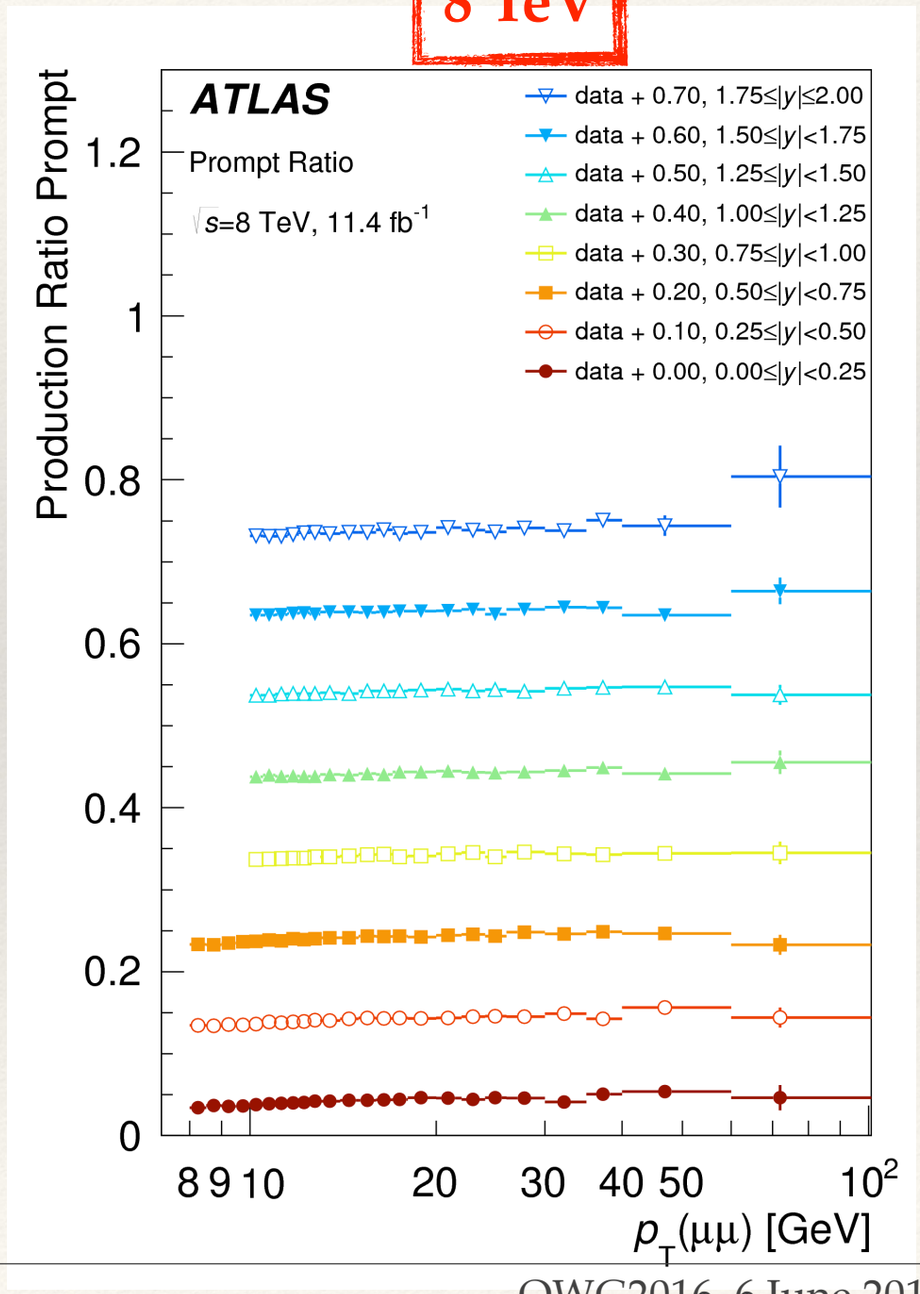
Prompt ratio

- **Production ratio** of prompt $\psi(2S)/J/\psi$ (consistent with flat across the whole p_T range analyzed)

7 TeV

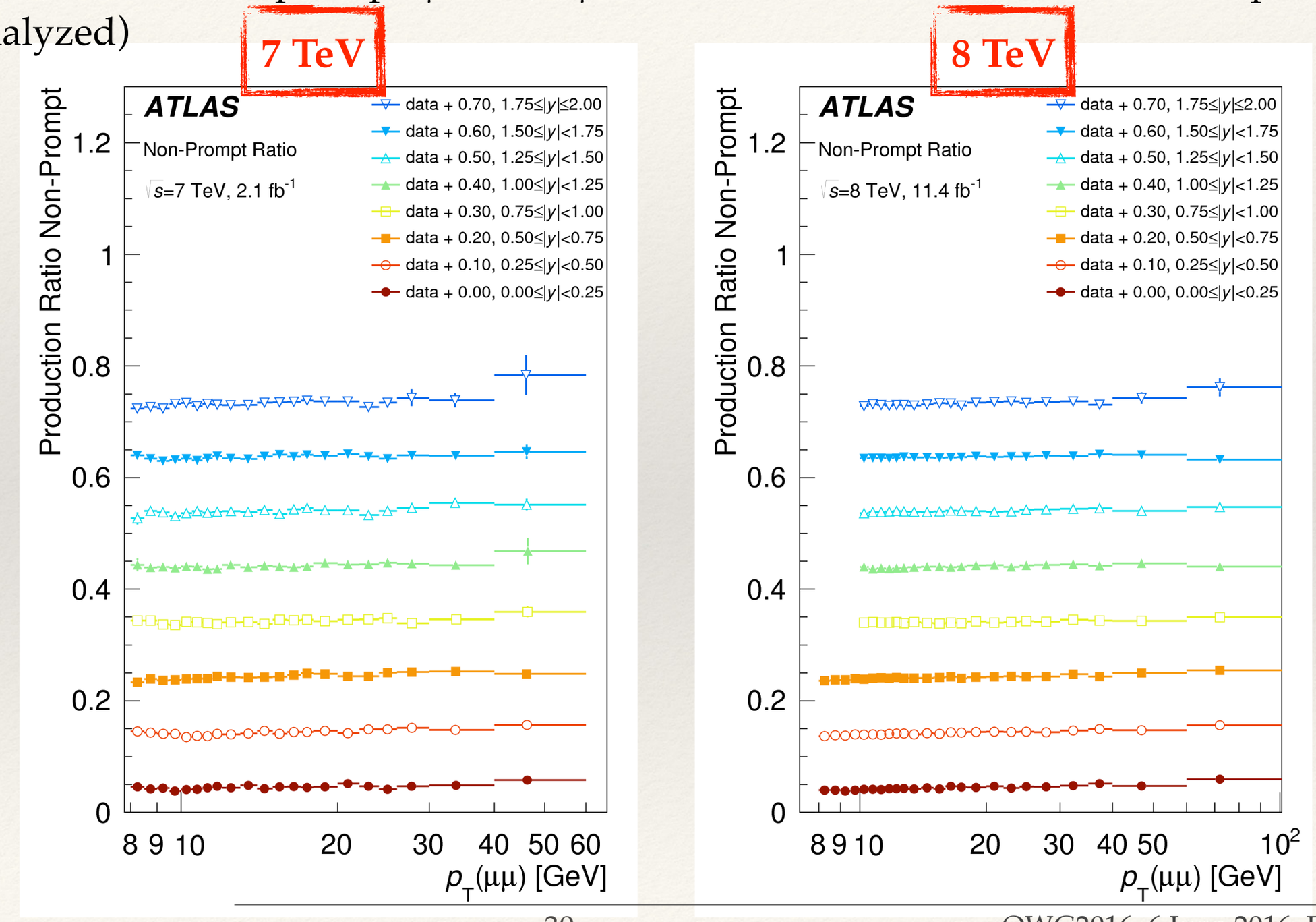


8 TeV



Non-prompt ratio

- **Production ratio** of non-prompt ψ(2S)/J/ψ (consistent with flat across the whole p_T range analyzed)



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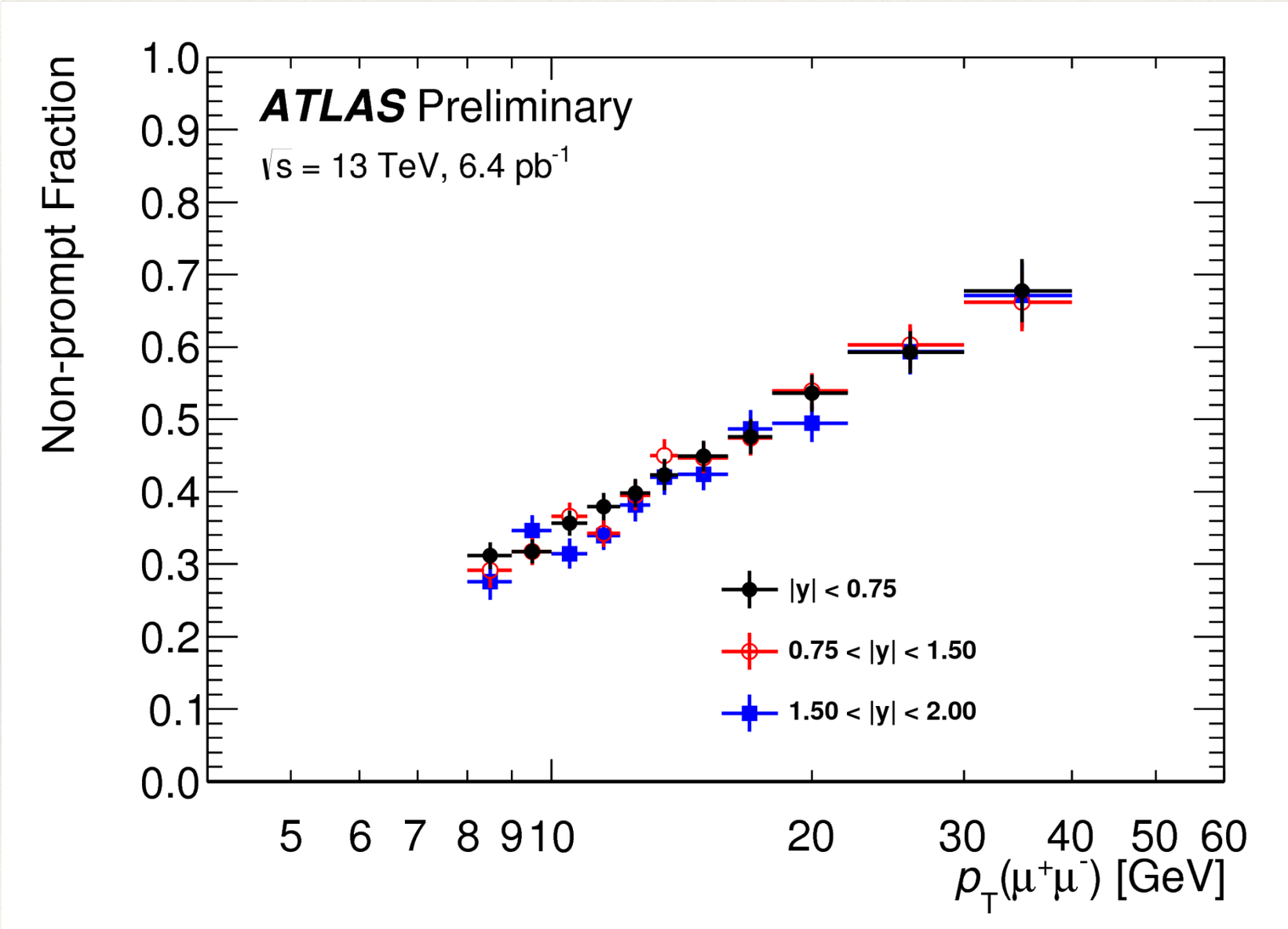
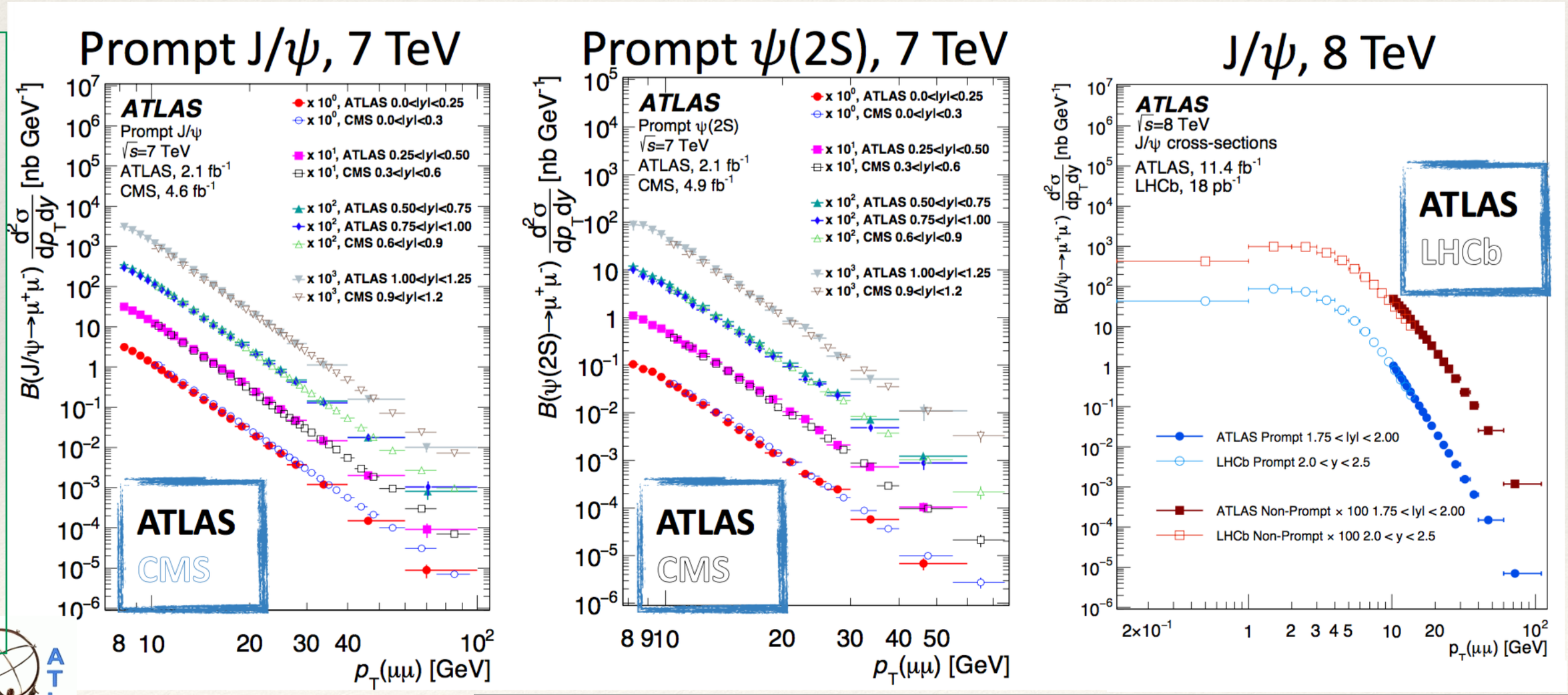
Non-prompt fraction vs. |y|



LHC comparisons

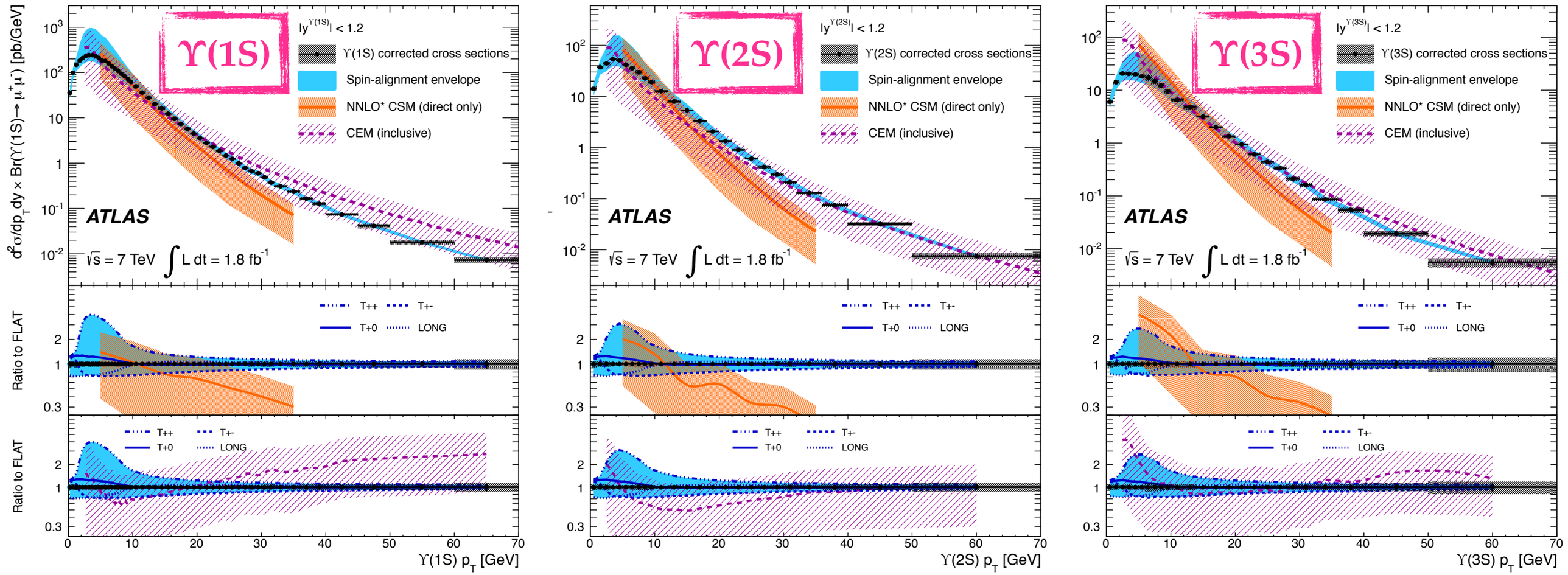
- Comparison of ATLAS to other LHC experiments
- Good agreement with CMS for overlapping rapidity and p_T (at 7 TeV)
- Comparison with LHCb in overlapping p_T, but adjoining slices of rapidity)at 8 TeV)



CMS, PRL114 (2015) 191802

LHCb, JHEP 1306 (2013) 064

PRD87,052004(2013)



- Comparison to theoretical predictions:
  - **NNLO* Color Singlet Model (CSM)**
  - **Color Evaporation Model (CEM)**
- Both have problems in describing the normalisation and shape of the differential spectra
- **CSM** underestimates the rate at high transverse momenta, where data agree better with **CEM**
  - Lack of a model able to describe data over the full range of ϒ transverse momenta accessible with the 7 TeV dataset