# Review of ATLAS Heavy Quark and Quarkonium Results

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UNIVERSITY OF BIRMINGHAM


THE ROYAL SOCIETY

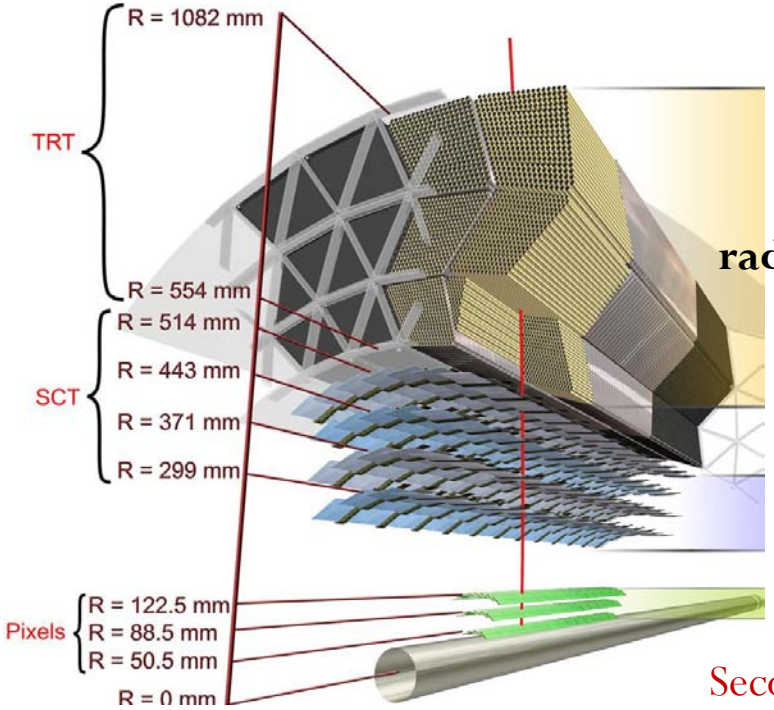
# Overview

- The ATLAS detector and performance
- Heavy flavour production measurements
  - b-hadron cross section from $D^{*+}\,\mu^-\,X$
  - B+ meson differential cross-section
- Quarkonium physics
  - Measurement of Upsilon production
  - $\chi_b(3P)$ observation
  - Associated production of prompt $J/\psi$ and W
- Summary

I will concentrate on recent results
Full details at https://twiki.cern.ch/twiki/bin/view/AtlasPublic
Also talks by J. Baines, J. Schieck in Flavour Physics sessions

# The ATLAS detector for B physics

## Inner detector




**Transition radiation tracker**
Particle ID, pattern recognition

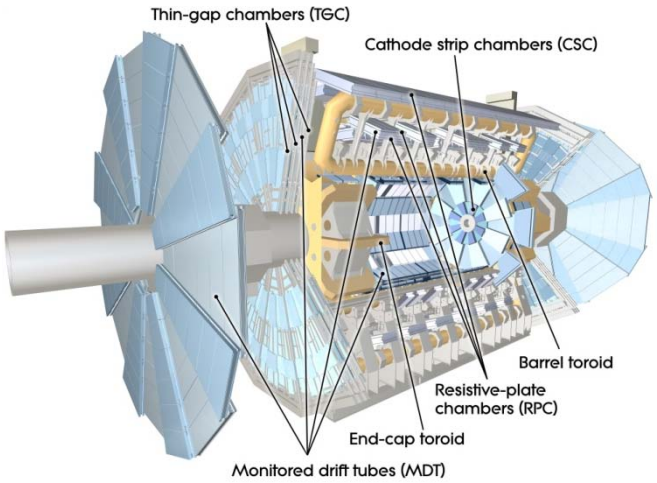
**Silicon strips**
Momenta

**Silicon pixels**
Secondary vertices

- Covers $|\eta|<2.5$
- Solenoidal B-field, 2T

## Muon system

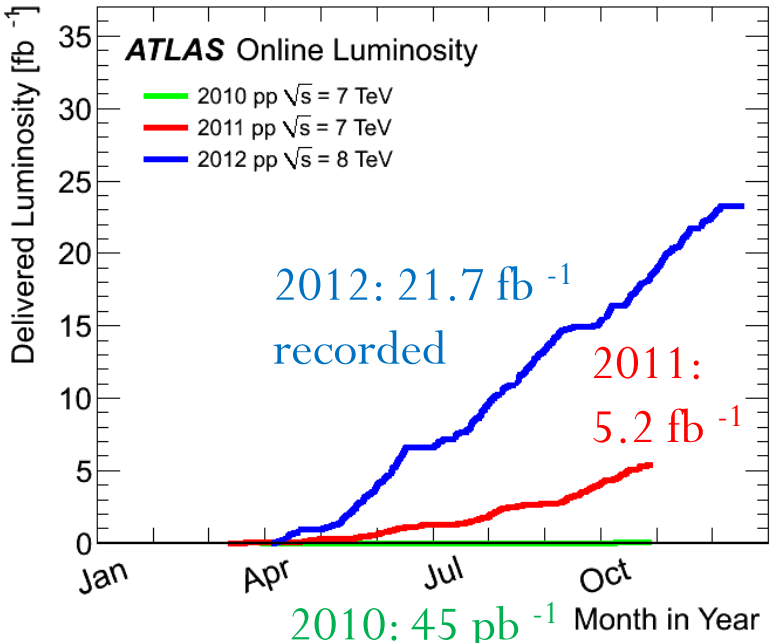
- Precise tracking chambers and trigger chambers
- $|\eta|<2.7$
- Toroidal B-field, ~0.5T

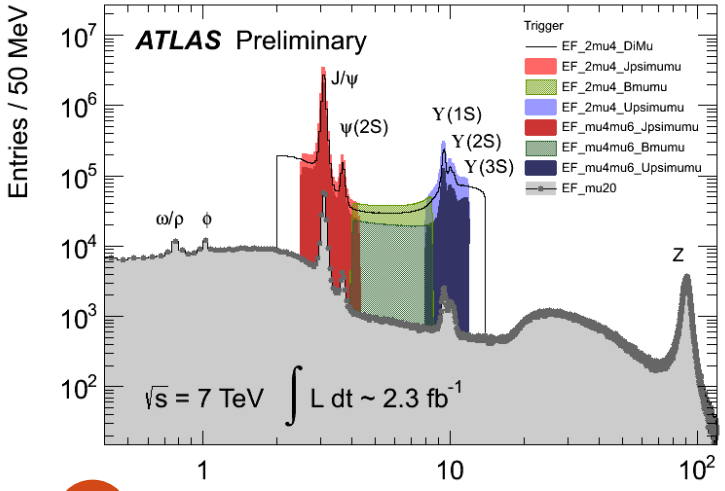



**Calorimeters:** for photons, missing $E_T$

# Performance

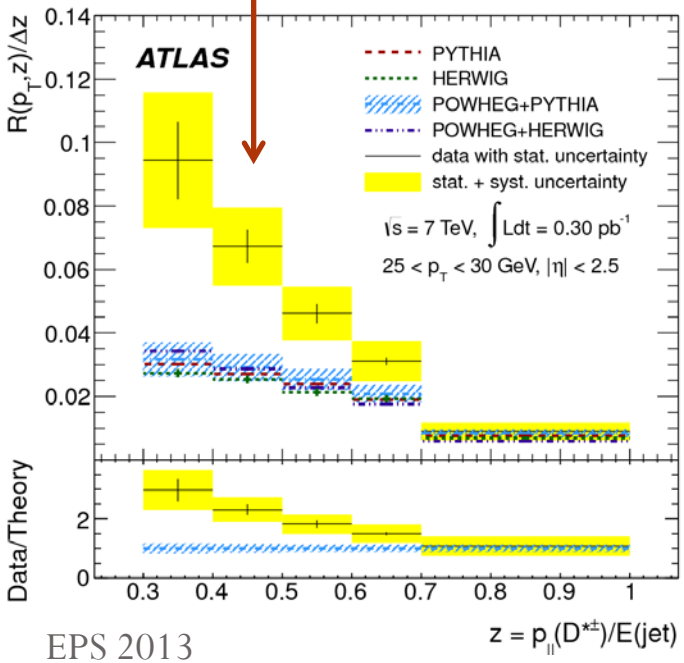
- Most analyses presented today use 2011 data; 2012 analyses in preparation
- Events predominantly selected in muon or di-muon decay channels (e.g. J/ψ or Υ)
- Single-muon triggers supplemented by di-muon triggers:
  - invariant mass windows in the regions of the J/ψ, B and Υ
  - largely unprescaled



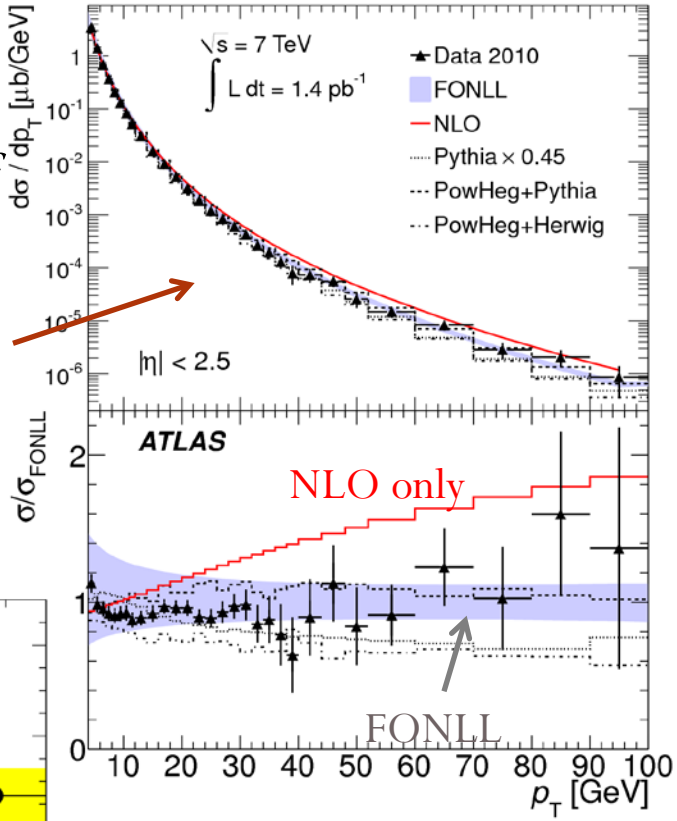



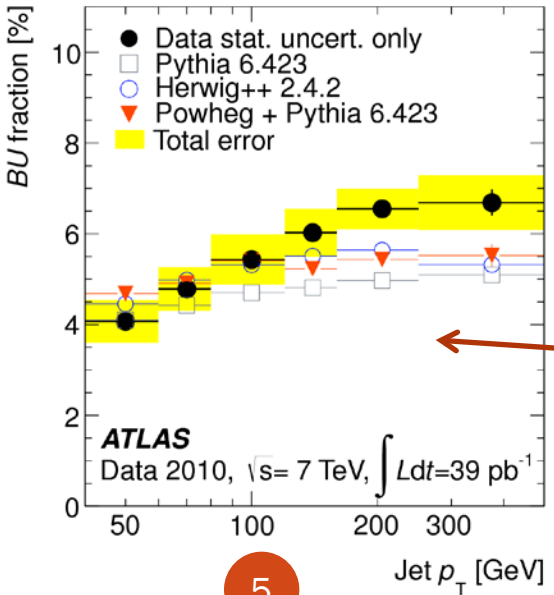
# Heavy flavour production measurements

- $D^{(*)}$ meson production cross sections ATLAS-CONF-2011-017
- Inclusive and dijet cross-sections of b-jets Eur.Phys.J.C 71 (2011) 1846
- $D^{*+/-}$ production in jets Phys. Rev. D85 (2012) 052005




- Inclusive production of electrons and muons (b/c cross section) Phys.Lett.B 707 (2012) 438



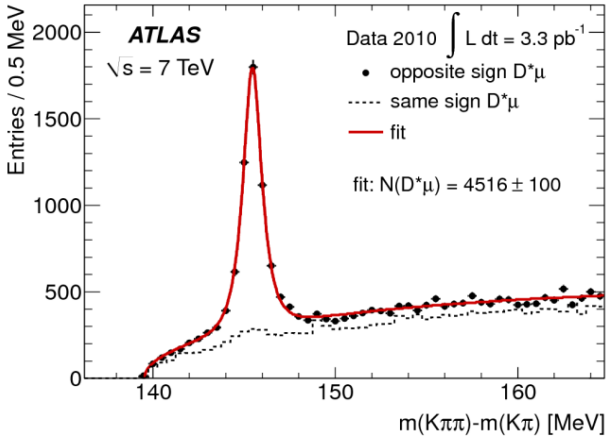



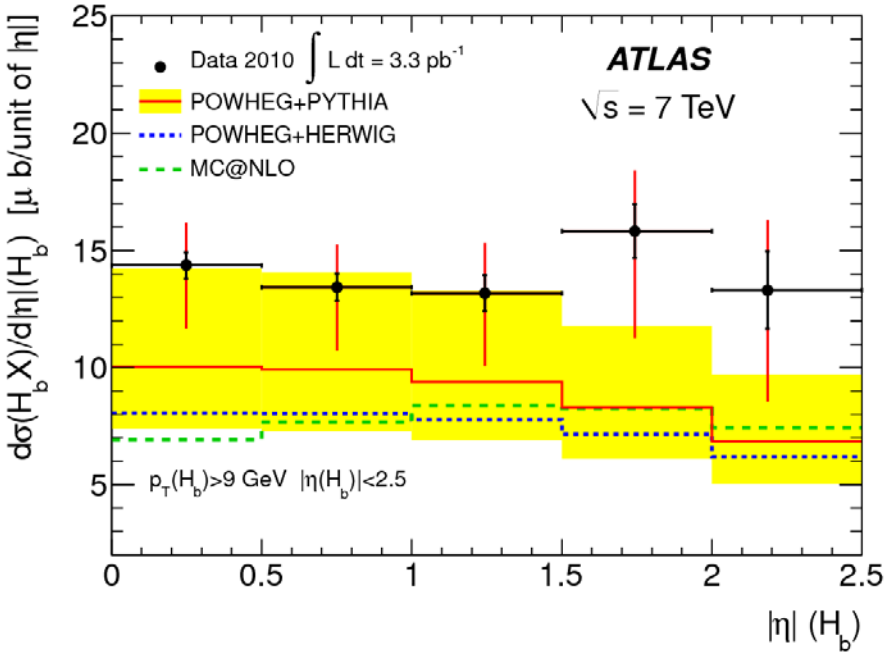

- Flavour composition of dijet events Eur. Phys. J. C (2013) 73:2301

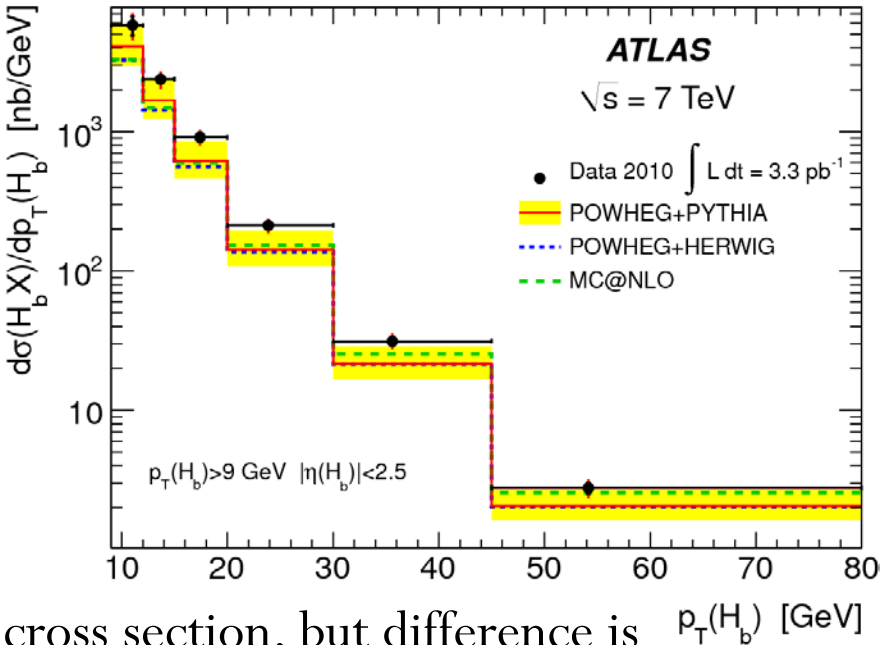
# b-hadron cross section from $D^{*+}\,\mu^-\,X$

Nucl.Phys. B864 (2012) 341

- Partially reconstructed final state $D^{*+}\mu X$; $D^{*+}\to\pi D^0\,(\to K^-\pi^+)$ 2010 data
- $|\eta(D^*\mu)|<2.5$; $9<p_T(D^*\mu)<80$ GeV
- Unfold for missing decay products



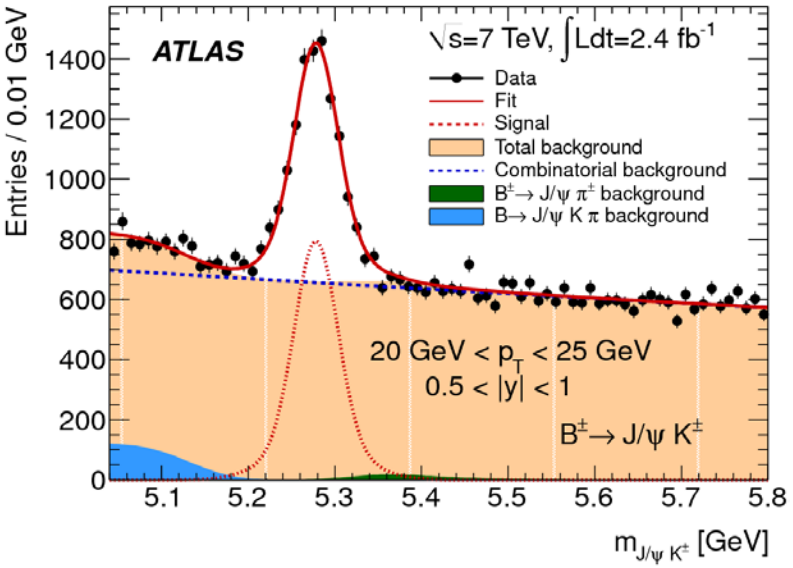



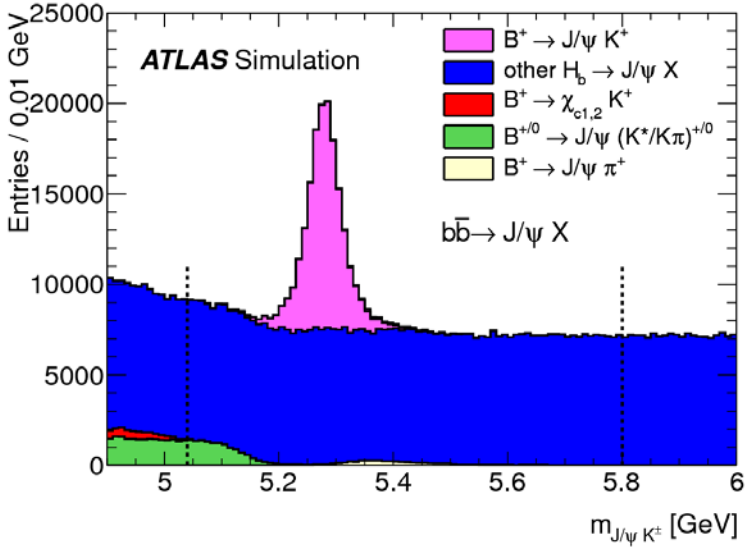

- NLO QCD predictions underestimate the cross section, but difference is within combined experimental and theoretical (e.g. scale) uncertainties

# $B^+$ cross-section

arXiv:1307.0126 [hep-ex], sub. JHEP

- 2.4 fb$^{-1}$ data at 7 TeV; select $B^{\pm} \rightarrow J/\psi\, K^{\pm}$
- Start from $J/\psi$ candidates in mass window [2.7,3.5] GeV
- Fit to common vertex with additional charged track of $p_T > 1$ GeV
- Retain $B^{\pm}$ candidates with $p_T > 9$ GeV and $|\eta| < 2.3$



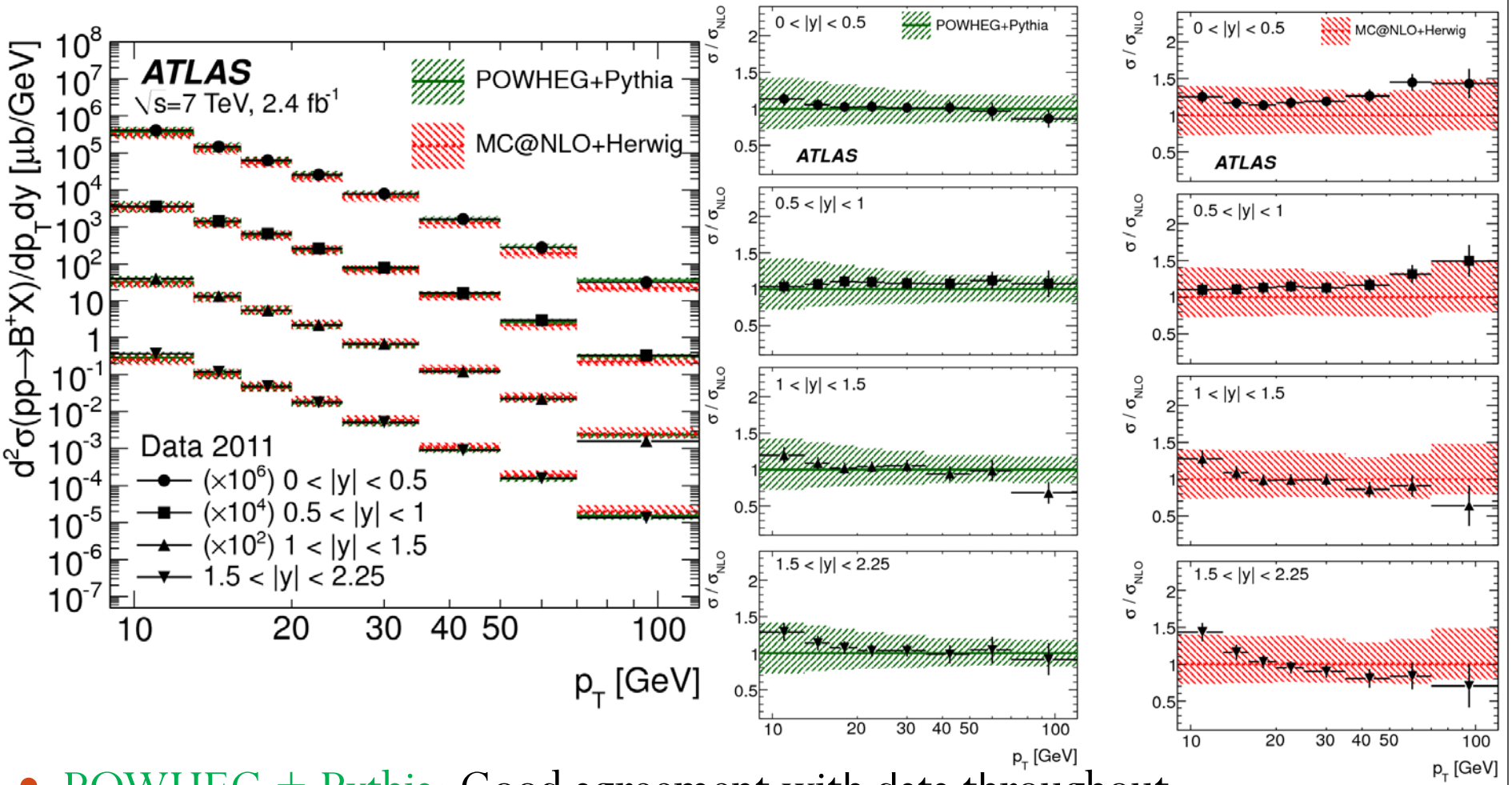

- Resonant backgrounds $J/\psi\, \pi$, $J/\psi\, K\pi$
- Combinatorial background $J/\psi$+X
- Extract differential cross-section:

$$\frac{\mathrm{d}^2\sigma(pp \rightarrow B^+X)}{\mathrm{d}p_T\mathrm{d}y} \cdot \mathscr{B} = \frac{N^{B^+}}{\mathscr{L} \cdot \Delta p_T \cdot \Delta y}$$

$$N^{B^+} = \frac{1}{A}\frac{N^{B^{\pm}}_{\mathrm{reco}}}{\varepsilon^{B^+} + \varepsilon^{B^-}}$$

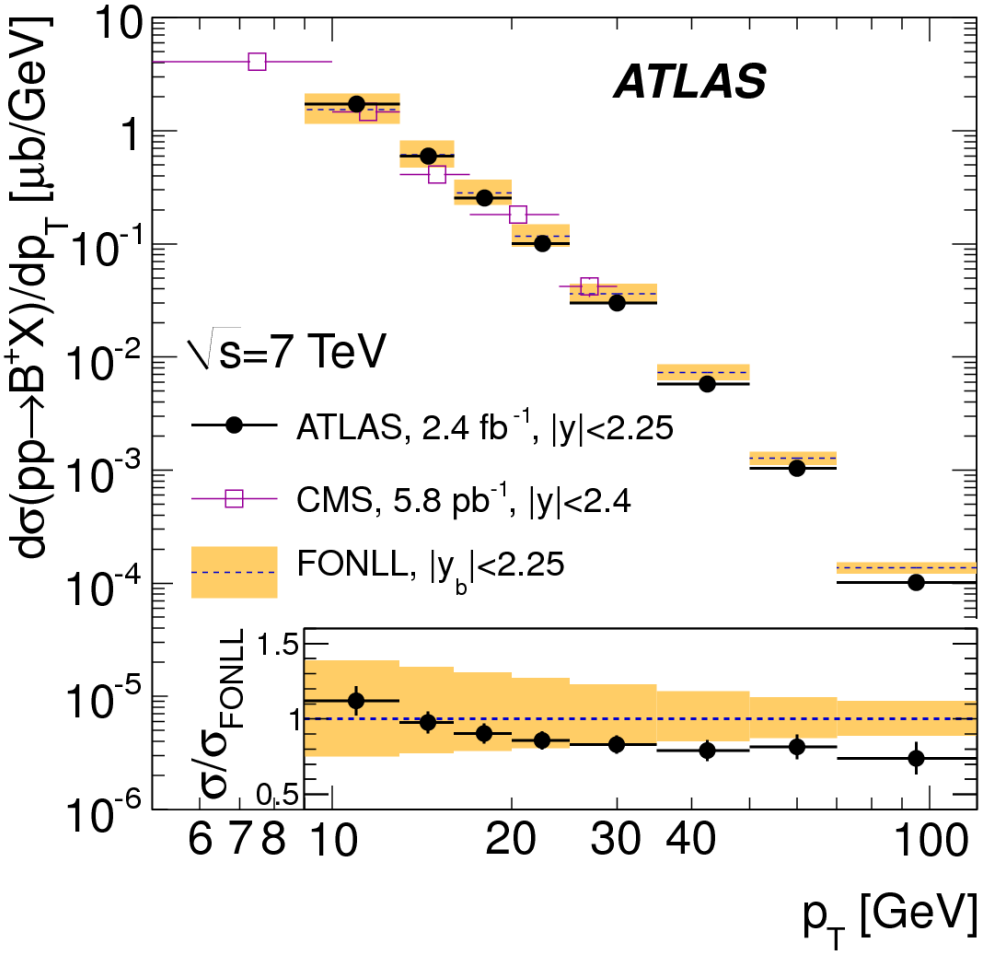
Luminosity
Branching ratio
Acceptance, efficiencies

# $B^+$ double differential cross-section




- POWHEG + Pythia: Good agreement with data throughout
- MC@NLO+Herwig: somewhat lower cross-section at low $p_T$, softer $p_T$ spectrum for $|y|<1$; harder for $|y|>1$

# $B^+$ cross-section vs. $p_T$




- Comparison with CMS and FONLL prediction with

$$f_{\bar{b}\to B^+} = 0.401 \pm 0.008$$

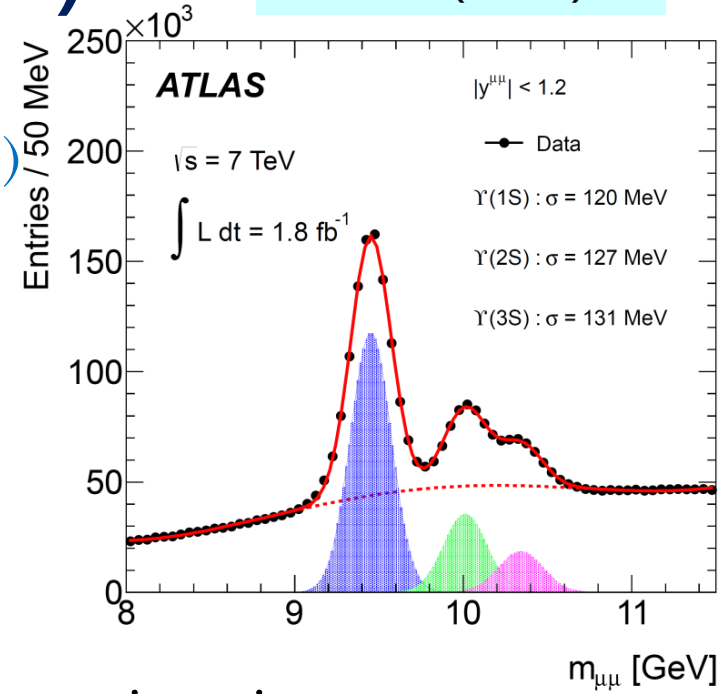
- FONLL (Fixed-Order-Next-to-Leading-Logarithm) describes dependence in $p_T$ and rapidity, especially for $p_T < 30$ GeV
- Theoretical uncertainties from scale and b-quark mass

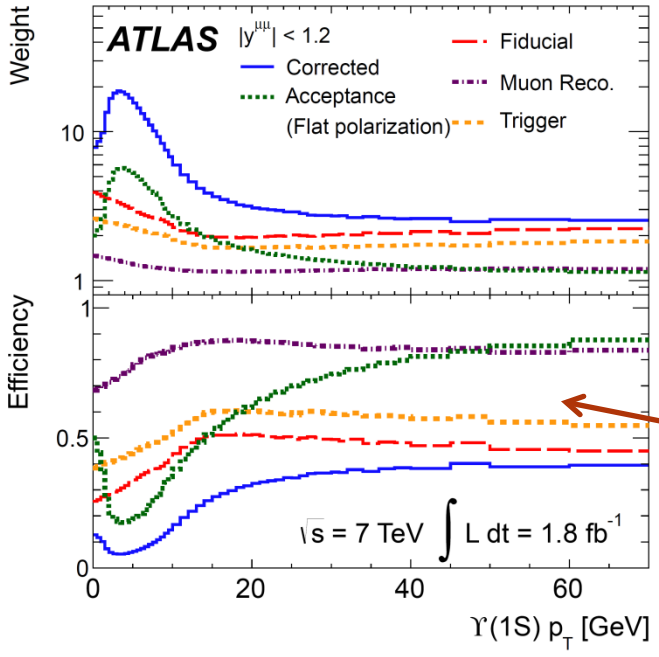
$$\sigma(pp \to B^+X) = 10.6 \pm 0.3\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.2\ (\text{lumi.}) \pm 0.4\ (\mathscr{B})\ \mu\text{b}$$

# Quarkonium physics: Υ(nS)

Phys. Rev. D 87, 052004 (2013)

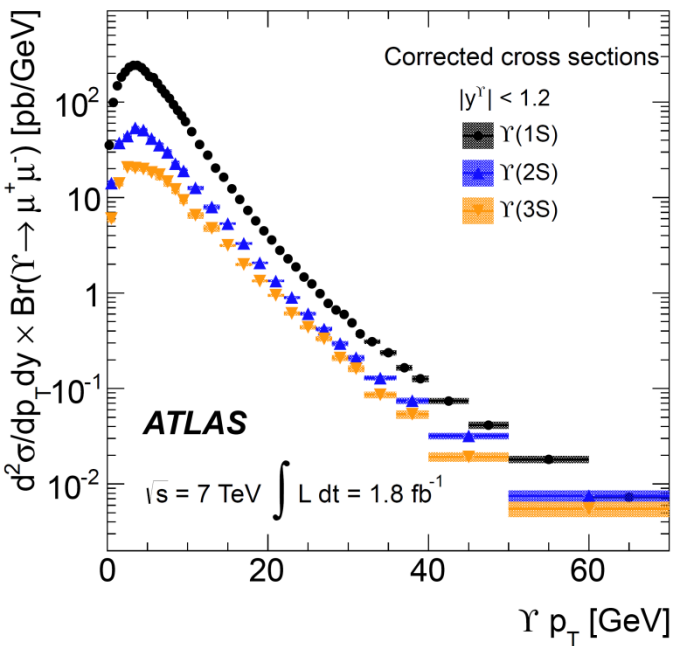
- Earlier results on J/ψ production and Υ(1S) fiducial cross-section: Nucl. Phys. B 850 (2011) 387, Phys.Lett.B 705 (2011) 9
- New: Υ(nS), n=1,3 using 1.8 fb$^{-1}$ at 7 TeV
- Test of perturbative QCD in a new energy regime: production mechanism not well understood (e.g. Colour Singlet vs Colour Octet)

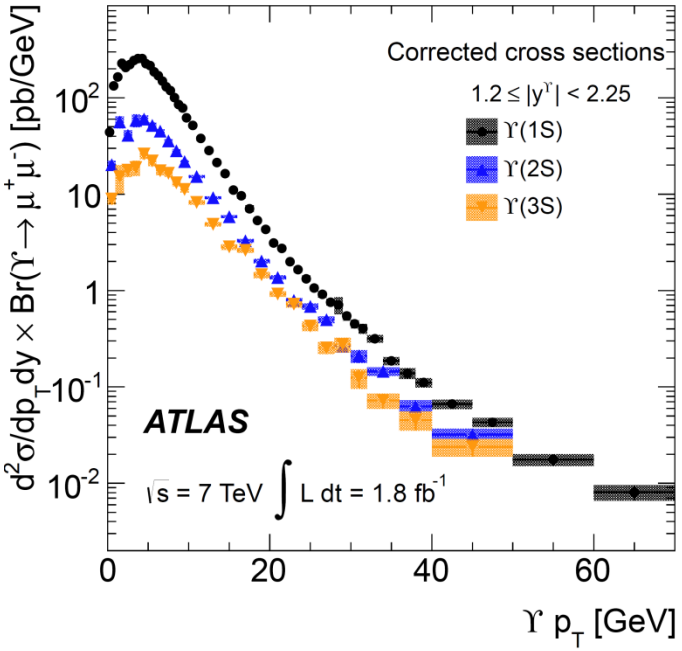


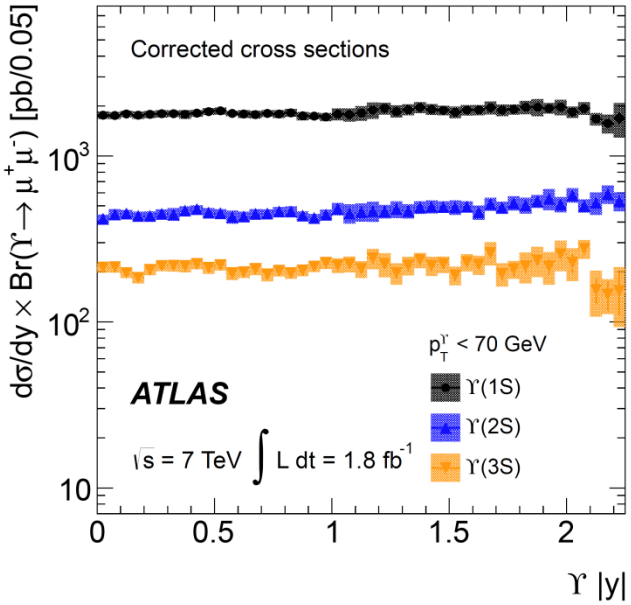

- Fit dimuon invariant mass spectra in finely binned $p_T$ and rapidity intervals
- Correct each event for detector efficiencies and acceptances: extract production cross-sections

# Corrected differential cross-sections



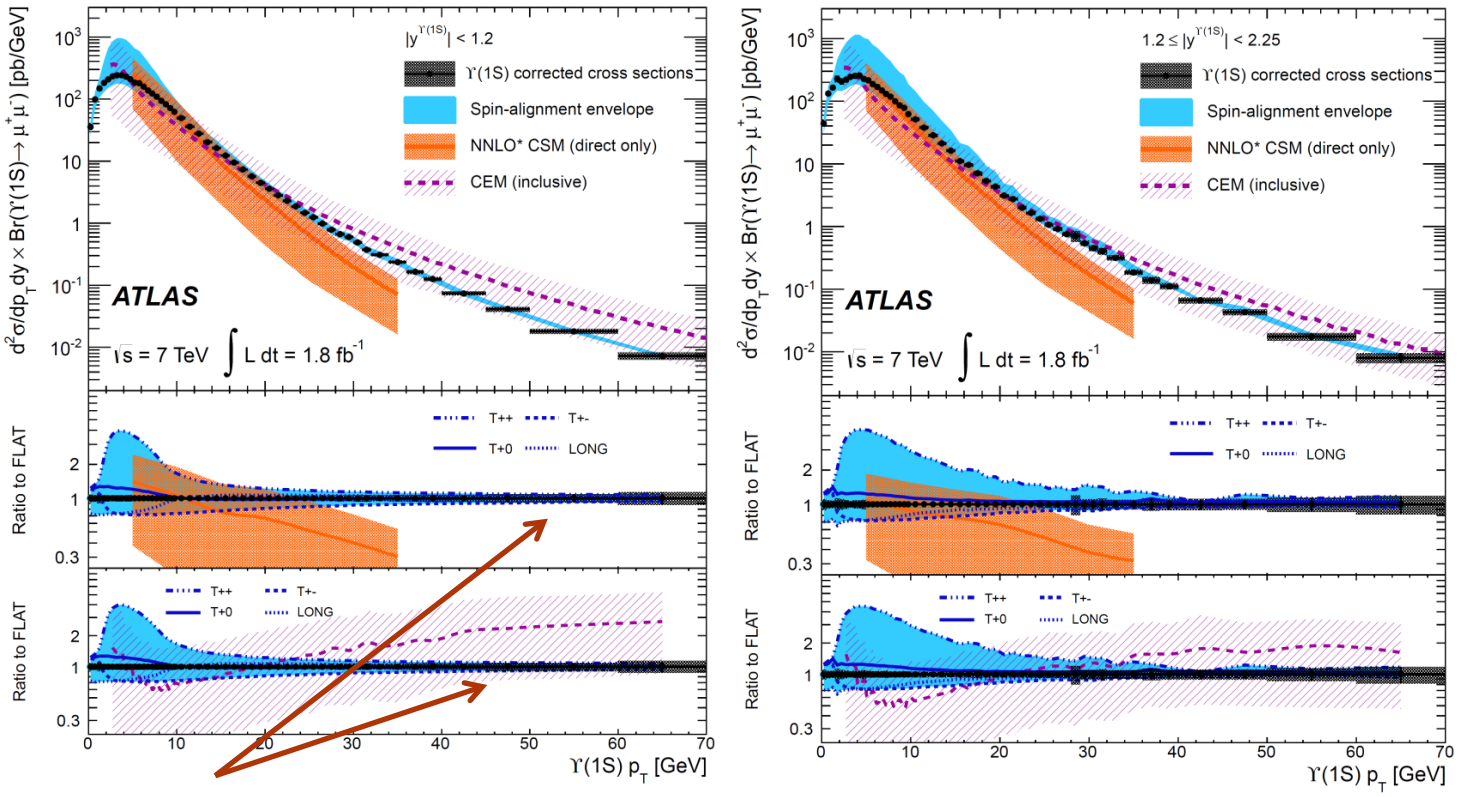

- Corrected for muon fiducial acceptance cuts
- $|y(\Upsilon)|<2.25$, $p_T(\Upsilon)<70$ GeV




- Acceptance depends on spin-alignment, i.e. angular distributions of muons
- Shown here for unpolarised (isotropic) muon angular distributions

# Comparison with theory: Υ(1S)

- Compare differential cross-sections with models:
  - NNLO* Colour Singlet Model (direct Υ production only)
  - Phenomenological Colour Evaporation Model (inclusive)




Note: high $p_T$ has **negligible spin-alignment uncertainty**→very precise measurements

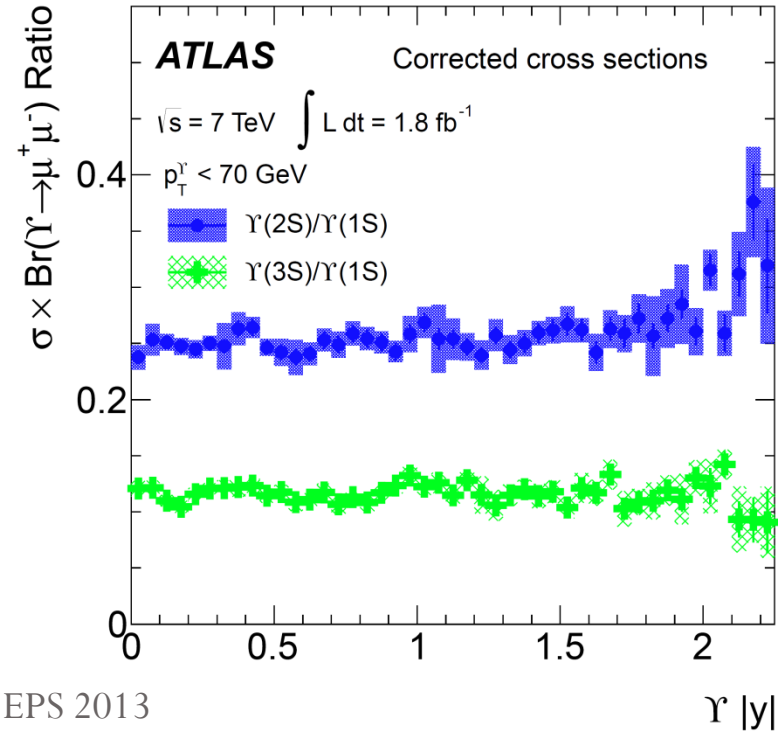
Models fail to describe shape & normalisation of data

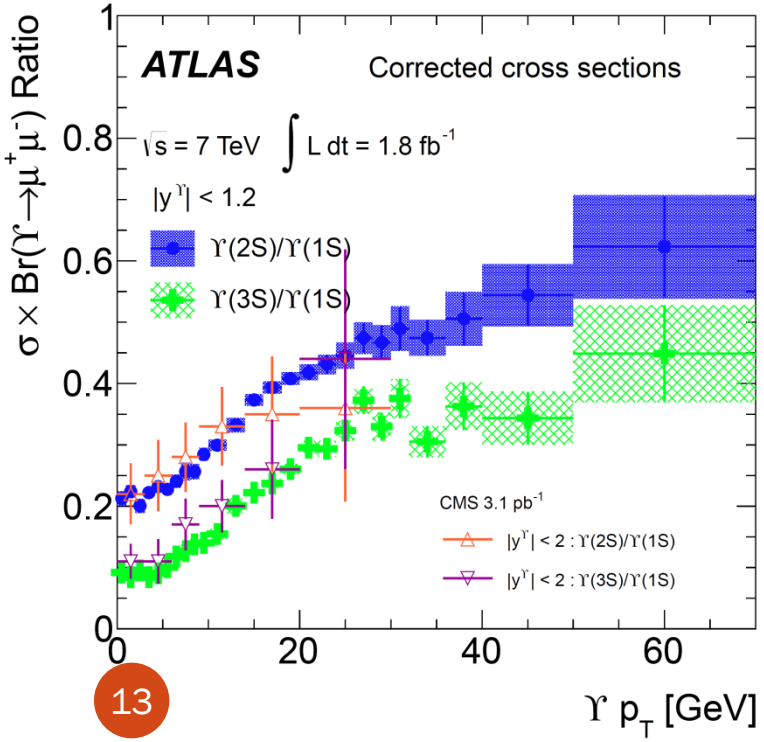
Better at $p_T$<20 GeV (Tevatron region), new contributions at high $p_T$ not accounted for by CSM

Also for Υ(2S,3S)

# Υ(3S)/Υ(1S) and Υ(2S)/Υ(1S)

- Production ratios sensitive to feed-down contributions
- Rise in production rates of higher Υ states as function of $p_T$ (c.f. CMS)
- Indication of saturation at 30-40 GeV: direct production dominates over decays of excited states?
- Ratio sensitive to $\chi_b$(nP) contributions

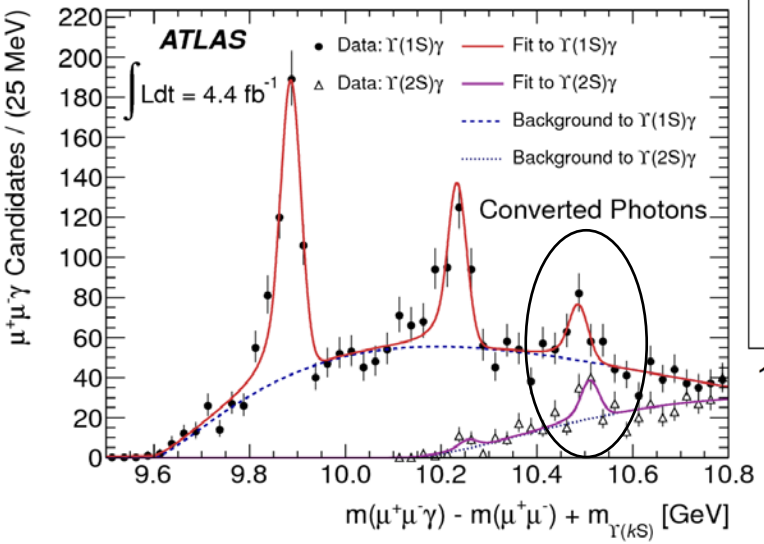


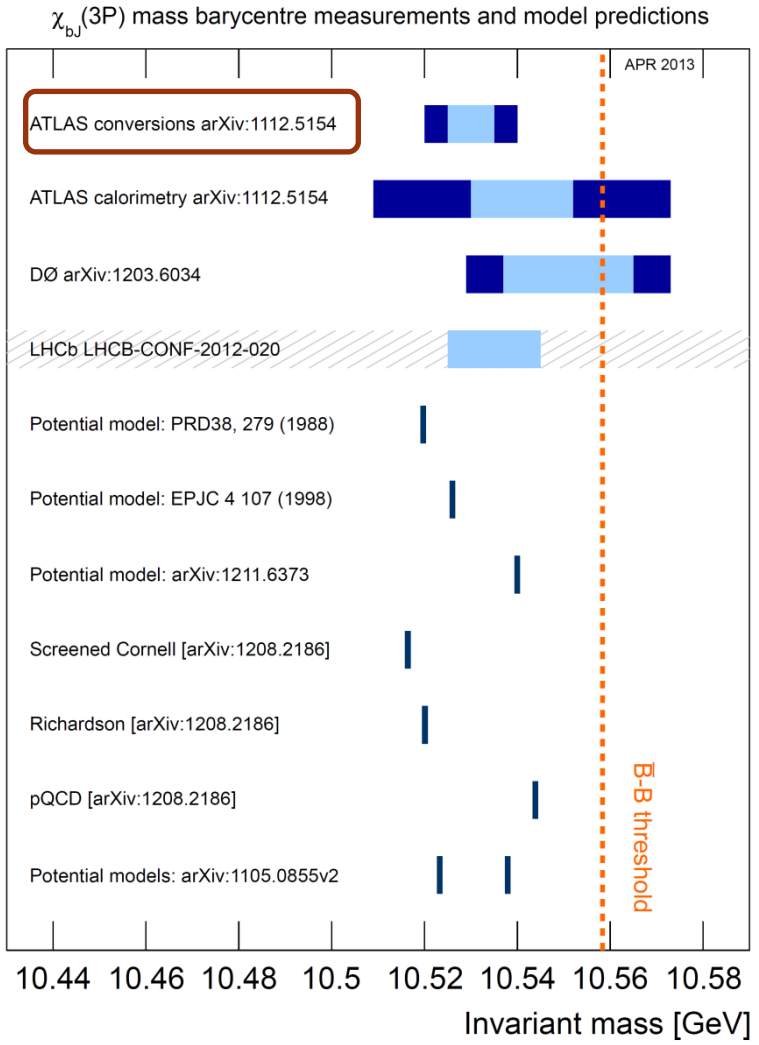



# $\chi_b(3P)$ observation

Phys. Rev. Lett. 108 (2012) 152001

- Production of states consistent with $\chi_b(3P)$ observed for the first time through radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$
- Observation confirmed by DØ and LHCb
- $\chi_b(3P)$ sits just below BB threshold; will affect feed-down contribution to $\Upsilon(nS)$ states
- Observation of $\chi_b(3P)$ has already led to modification of theoretical predictions, e.g. spin-alignment for $\Upsilon$

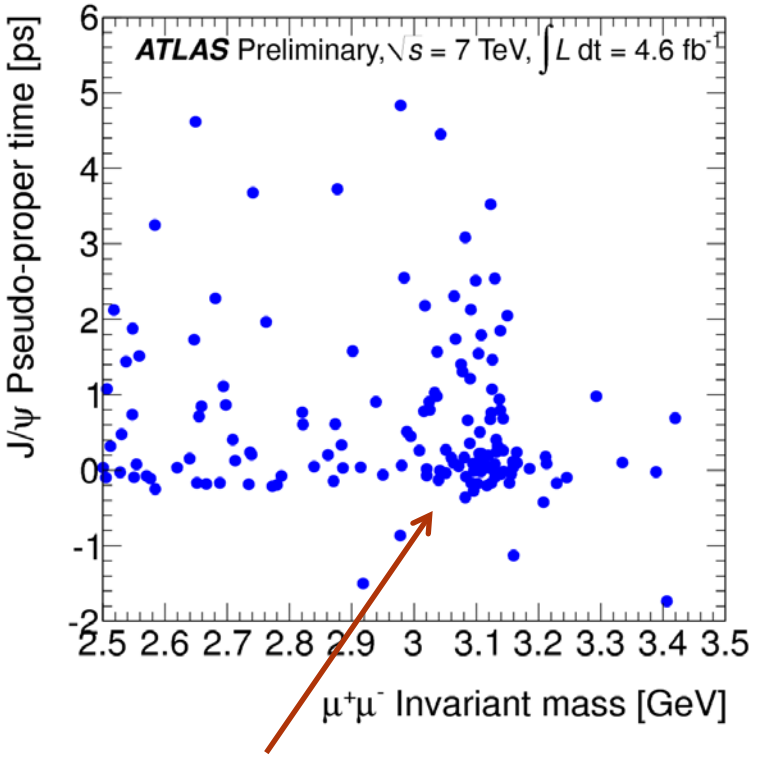


# W+prompt J/ψ measurement

ATLAS-CONF-2013-042

- Search for associated production of W(→μν) and prompt J/ψ (→μμ)
- Probes quarkonium production mechanism
- Sensitive to multiple parton interactions
- Use 4.6 $fb^{-1}$ at 7 TeV (2011)
- Include double parton scattering (DPS) in signal, and estimate contribution



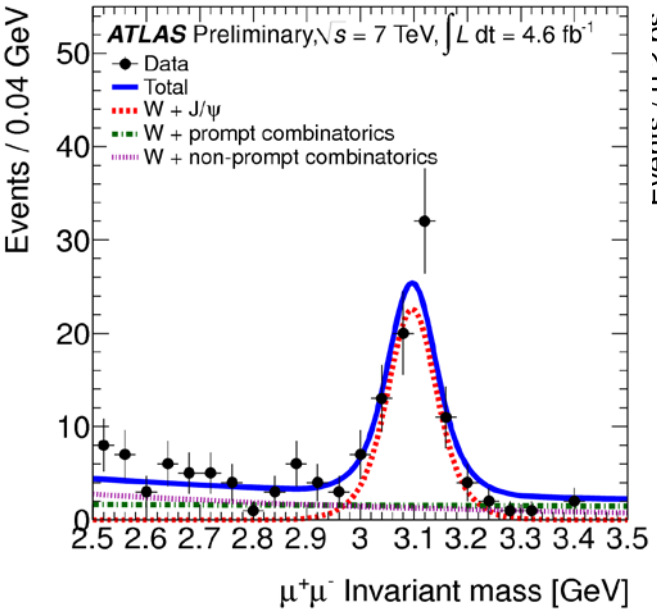

J/psi pseudo-proper time vs. mass

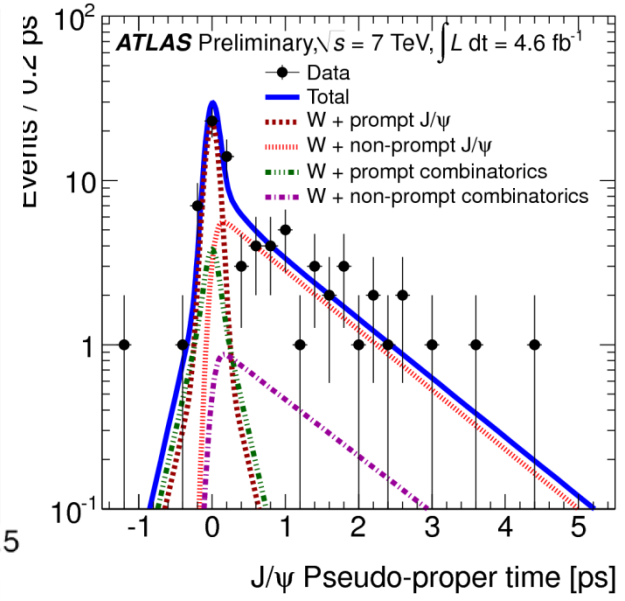
Events triggered on W muon (single lepton trigger)

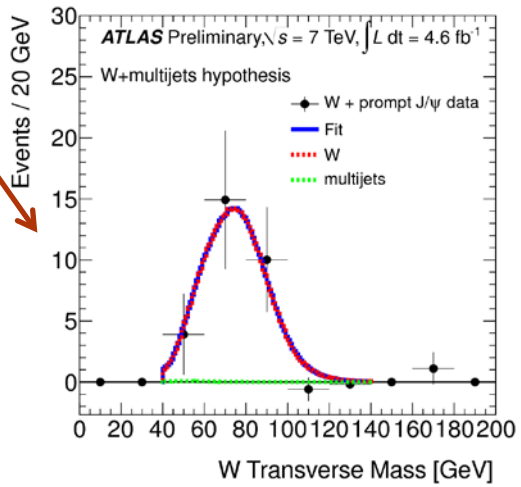
See also W+D production, B.Cooper in EWK/Top session

# Prompt J/ψ fits and W verification

- Unbinned maximum likelihood fit to J/ψ mass and pseudo-proper time → extract prompt signal
- Fit weighted $m_T(W)$ distribution for prompt candidates: W signal and multi-jet background
- Jet bkd. 0.1±4.6 events



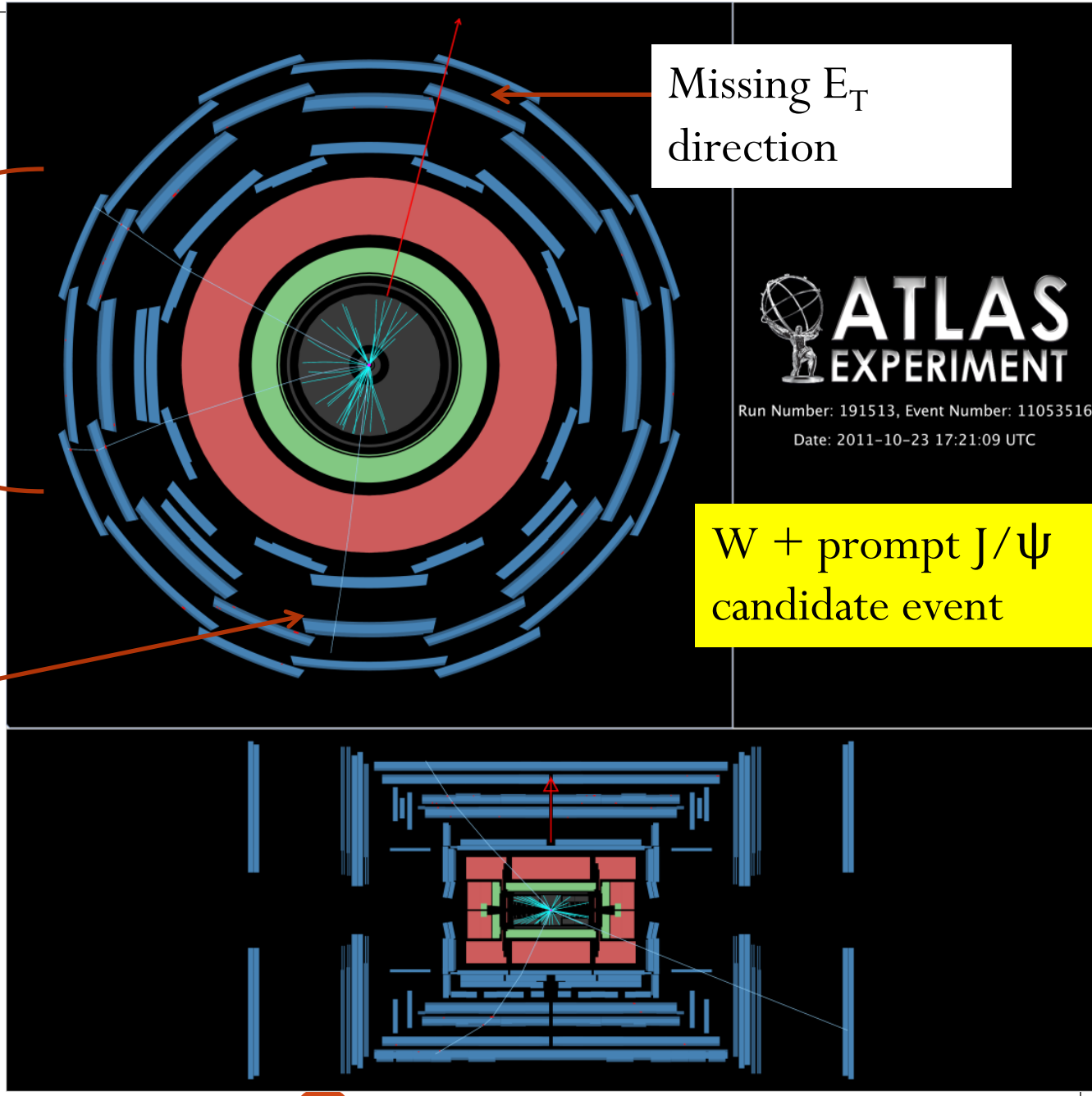




Observe ~29 W+prompt J/ψ events

Background-only hypothesis rejected at 5.3σ level

Muons from J/ψ candidate

$p_T$ (J/ψ) = 9.3 GeV, pseudo-proper time = 0.0 ps




Muon from W candidate

$p_T$ (μ) = 39 GeV

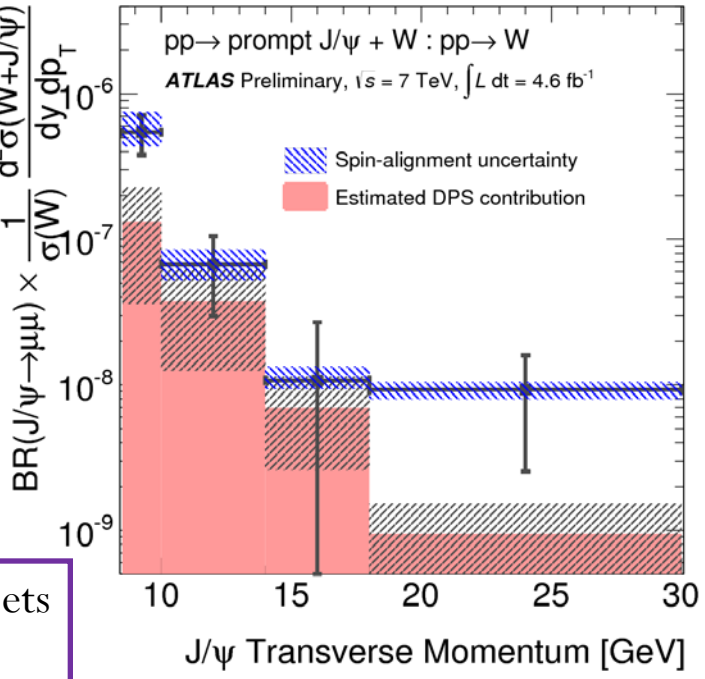
# SPS and DPS contributions

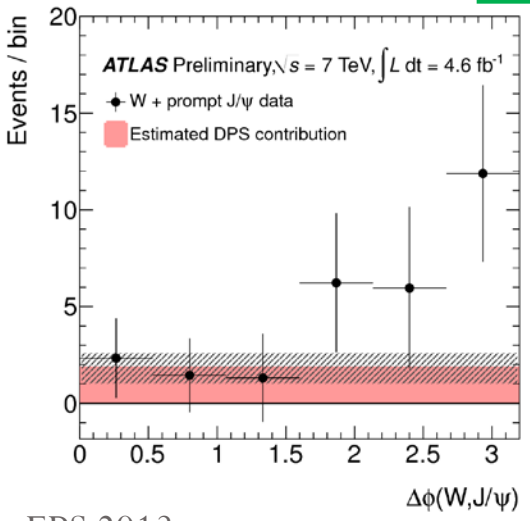
- Measure $(W^{\pm} + J/\psi)$ production cross-section relative to inclusive $W^{\pm}$ cross-section
- Estimate DPS contribution from:
  - $d\sigma(W+J/\psi) = d\sigma(W) \otimes d\sigma(J/\psi) / \sigma_{eff}$

Measured in this analysis

From ATLAS prompt $J/\psi$ arXiv:1104.3038

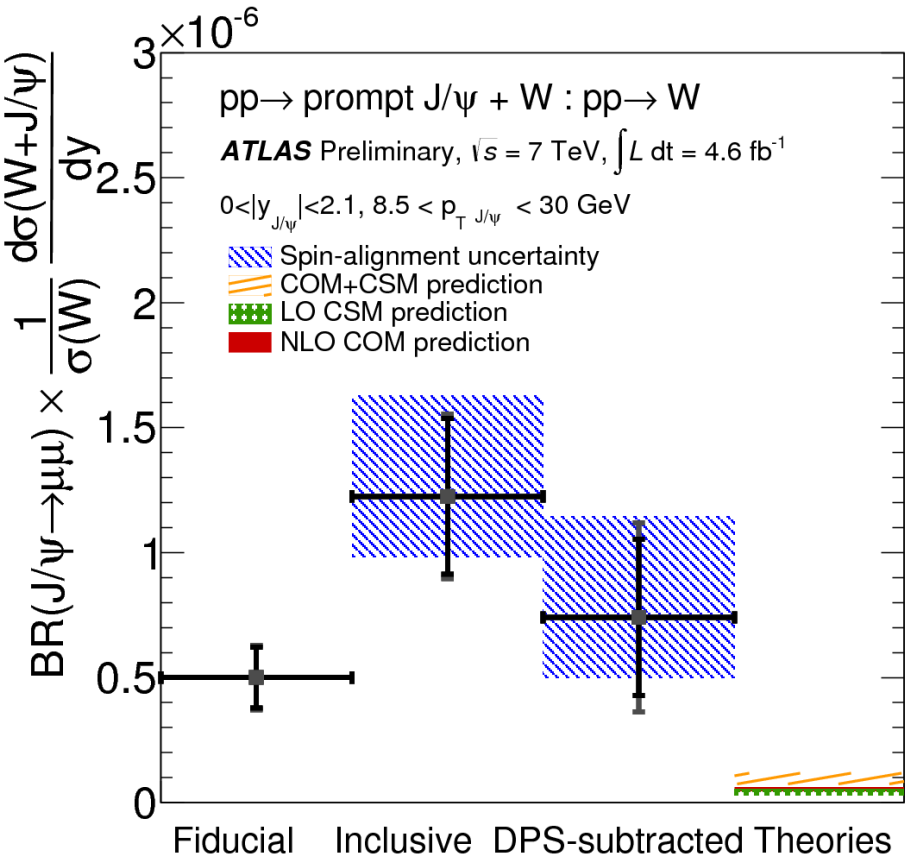
From ATLAS W+2jets arXiv:1301.6872




- Note: this is a phenomenological approximation
- DPS estimate ~40%

# Prompt J/ψ+W compared to theory




- Summary of fiducial, corrected and DPS-subtracted cross-section ratios
- Compare to LO colour singlet (CSM) and NLO colour octet (COM) models, plus sum
- Measured rate underestimated by order of magnitude (but large uncertainties on data)
- Modified calculations expected soon

CSM: arXiv:1303.5327
COM:arXiv:1012.3798

# Summary

- Many interesting results from the first years of ATLAS
  - Heavy flavour production measurements
    - Absolute cross-section measurements
    - Detailed comparisons with NLO and NLO+NLL predictions
  - Quarkonium physics
    - Production of charmonium and bottomonium; comparison with theory
    - Discovery of new $\chi_b(3P)$ state
    - First observation of associated W+ prompt $J/\psi$
    - Confronting data with colour-singlet, -octet and -evaporation models
    - Future vector boson+onia measurements will provide input to multiple parton scattering studies
  - Details on https://twiki.cern.ch/twiki/bin/view/AtlasPublic

- Updates and new analyses with more data are in progress