Production and spectroscopy of *b*-hadrons with ATLAS

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Introduction

Overview

Aim to give a summary of selected ATLAS results on the spectroscopy and production of b-hadrons at the LHC:

Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$

- Phys. Rev. Lett. **108** (2012) 152001 (arXiv:1112.5154)

Measurement of Υ production

- Phys. Rev. **D** 87, 052004 (2013) (arXiv:1211.7255)

Measurement of the B^+ meson production differential cross-section

- JHEP 10 (2013) 042 (arXiv:1307.0126)

All results presented are based upon the ATLAS 2011 pp dataset collected at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of up to $5\,\text{fb}^{-1}$

See also: Talks from Sue Cheatham, Tatjana Agatonovic-Jovin and Vladimir Nikolaenko on ATLAS charmonium, Λ_b and rare B meson decay measurements!

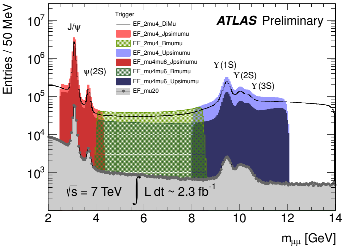
The ATLAS Detector

Relevant Components

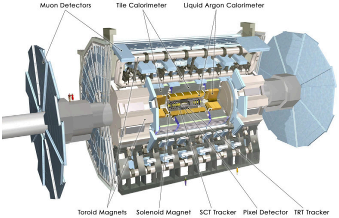
- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Muon Trigger:** Single and di-muon triggers - several p_T^{μ} thresholds (4–40 GeV)

Performance

- ID d_0 resolution $\sim 10\,\mu$m
- $m(\mu^+\mu^-)$ resolution: $\sim$ 60 MeV at J/ψ and $\sim$ 150 MeV at $\Upsilon(nS)$



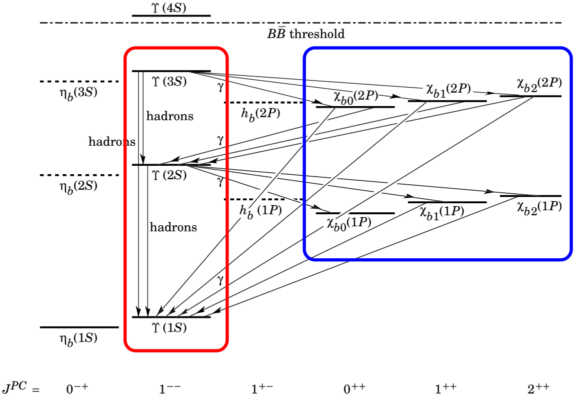
Dedicated di-muon triggers for quarkonium $\mathcal{Q} \rightarrow \mu^+\mu^-$ decays - huge gain in yields w.r.t. single muon trigger



General purpose detector, also well suited to *b*-hadron studies

The Υ and χ_b states represent the spin triplet ($S = 1$) S-wave and P-wave states of the bottomonium ($b\bar{b}$) spectrum:

- Each χ_b is a triplet of states with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ (splittings $\mathcal{O}$(10 MeV))
- Branching fractions for the radiative decays $\chi_b(mP) \to \Upsilon(nS)\,\gamma$ are large $\mathcal{O}(10\%)$
- $\Upsilon(nS) \to \mu^+\mu^-$ decays allow "simple" experimental reconstruction



A third χ_b triplet of states, $\chi_b(3P)$, is also expected below the $B\bar{B}$ threshold (around 10.525 GeV):

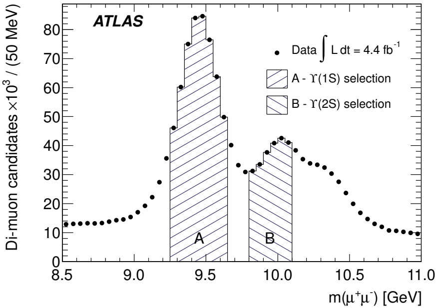
- Theoretical Predictions: Phys. Rev. D **36** 3401 (1987), Phys. Rev. D **38** 279 (1988), Eur. Phys. J. C. **4** 107 (1998)

Search for the $\chi_b(mP) \to \Upsilon(nS)\,\gamma$ decays with ATLAS...

Select events based on a variety of triggers which requiring either di-muon pairs or single high p_T muons...

Step 1: Common selection of $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decays

- Oppositely charged di-muon pair
- Both muons reconstructed from track in ID combined with MS track
- $\mu^+\mu^-$ common vertex fit $\chi^2/[d.o.f.] < 20$
- $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.3$
- $p_T^{\mu^+\mu^-} > 12$ GeV and $|y^{\mu^+\mu^-}| < 2.0$



Select $\Upsilon(1S)$ and $\Upsilon(2S)$ with $m(\mu^+\mu^-)$ regions A and B:

A $\Upsilon(1S)$ $9.25 < m(\mu^+\mu^-) < 9.65$ GeV

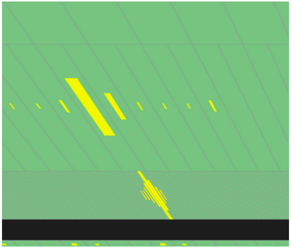
B $\Upsilon(2S)$ $9.80 < m(\mu^+\mu^-) < 10.10$ GeV

Aim to reconstruct $\chi_b(mP) \to \Upsilon(nS)\gamma$ decays using both converted and unconverted photons separately (different strengths and limitations)...

- **Converted** - Very good resolution ✓ Efficiency reduced by conversion probability ✗
- **Unconverted** - Poor resolution at low p_T^γ ✗ High efficiency ✓

Step 2: Photon Selection (Unconverted)

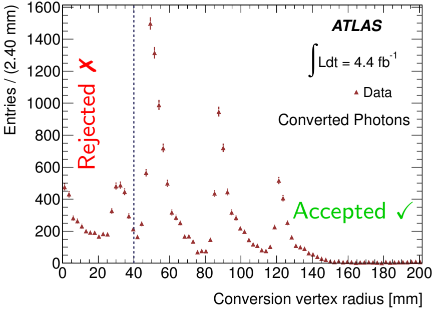
- Reconstruct from EM calorimeter energy deposits not matched to any track, require $E_T^\gamma > 2.5$ GeV
- $|\eta^\gamma| < 2.37$ (Barrel-Endcap transition region $1.37 < |\eta^\gamma| < 1.52$ excluded)
- "Loose" photon ID selection: Including limits on hadronic leakage and requirements on the EM shower shape (reject backgrounds from jets)



Photon Pointing Correction: η^γ is corrected to point back to $\mu^+\mu^-$ vertex significant resolution improvement!

Step 2: Photon Selection (Converted)

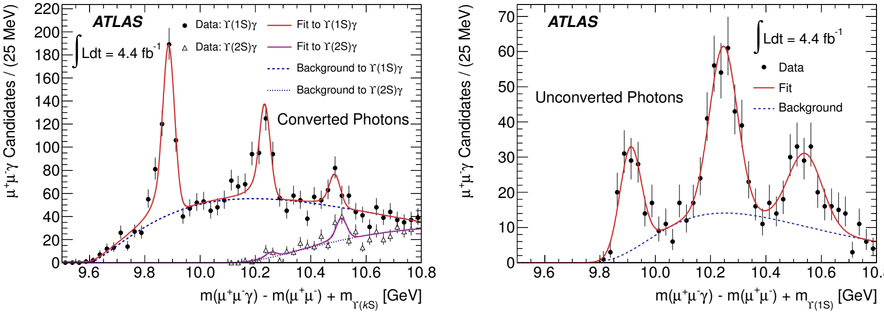
- Reconstruct from ID tracks alone
- Only two-track conversions are retained
- 4 silicon detector hits required for each electron track
- $p_T^\gamma > 1.0$ GeV and $|\eta^\gamma| < 2.0$
- Radius of conversion vertex $R > 40$ mm to reduce background contamination
- Require 3D impact parameter of conversion w.r.t. $\mu^+\mu^-$ vertex is less than 2 mm



Associate $\Upsilon(nS) \to \mu^+\mu^-$ and photon candidates and study $m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-) + m_{\Upsilon(kS)}$ distribution

Resolution better than $m(\mu^+\mu^-\gamma)$ alone!

Mass peaks consistent with the known $\chi_b(1P)$ and $\chi_b(2P)$ states observed, in addition to a third peak, statistical significance $> 6\sigma$ in both channels...



Perform separate fits to measure mass barycentre of new state:

Converted (left): $\bar{m}_3 = 10.530 \pm 0.005$ (stat.) ± 0.009 (syst.) GeV

- Simultaneous fit to $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ distributions

Unconverted (right): $\bar{m}_3 = 10.541 \pm 0.011$ (stat.) ± 0.030 (syst.) GeV

- Larger systematic dominated by low p_T photon energy scale uncertainty

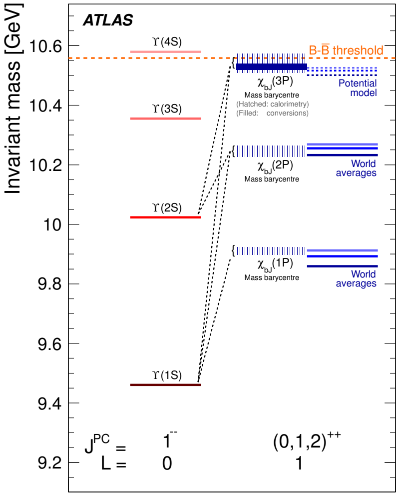
Summary

- Mass of new state consistent with theoretical expectations for $\chi_b(3P)$ states
- Now also confirmed by DØ (Phys. Rev. **D86** (2012) 031103
- and LHCb (LHCb-CONF-2012-020)

Implications

- Important "new" contribution to the phenomenology of bottomonium production
- In particular, $\Upsilon(3S)$ production previously thought to be free from significant feed-down contributions (clean probe of direct polarisation)
- $\chi_b(3P) \to \Upsilon(3S)\,\gamma$ potentially significant contribution that should be accounted for by theory!

Observed bottomonium radiative decays in ATLAS, L = 4.4 fb^{-1}



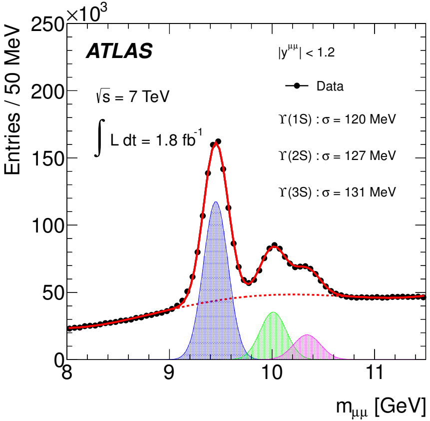
Measurement of Υ production (arXiv:1211.7255) - Analysis

$\Upsilon(nS) \to \mu^+\mu^-$ Selection

- Use $p_T^\mu > 4$ GeV di-muon trigger + simple offline di-muon selection
- Both muons reconstructed from track in ID combined with MS track
- Perform full $\mu^+\mu^-$ vertex fit
- $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.3$

Experimental Corrections

- Measure muon reconstruction and trigger efficiency with $J/\psi \to \mu^+\mu^-$ and $\Upsilon(nS) \to \mu^+\mu^-$ events in data
- Calculate acceptance with high statistics MC simulation for various $\Upsilon(nS)$ polarisation scenarios

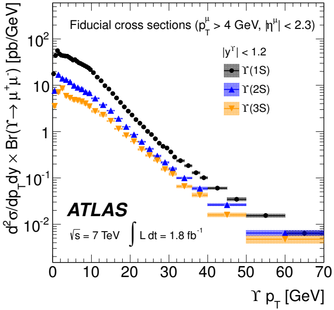


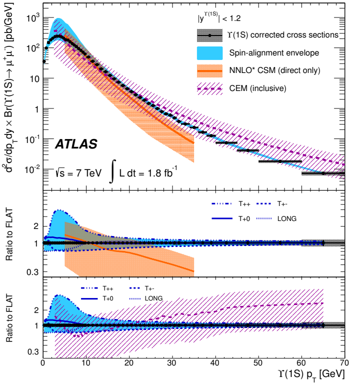
Measurement Procedure

- Weight each event to correct for experimental losses, extract $\Upsilon(nS)$ yields with a weighted binned χ^2 fit to the $m(\mu^+\mu^-)$ distribution in bins of Υ $|y|$ and p_T

Acceptance Corrected $\Upsilon(1S)$ cross-section →

- Corrected cross sections also measured for $\Upsilon(2S)$ and $\Upsilon(3S)$
- Acceptance sensitive to Υ polarisation - blue uncertainty band
- Colour Evaporation Model does not reproduce shape of data well
- NNLO* Colour Singlet Model generally underestimates data, though doesn't include (large) feed-down contributions



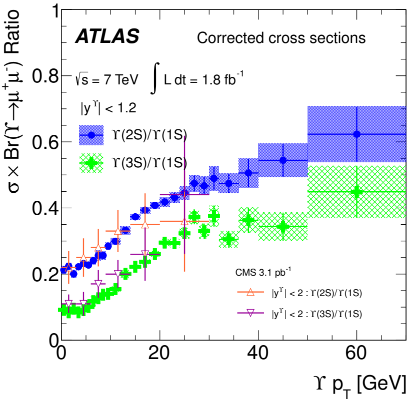


← Fiducial $\Upsilon(nS)$ cross-sections

- No sensitivity to Υ polarisation
- More precise test for predictions calculated within fiducial volume

Measurement of Υ production (arXiv:1211.7255) - Results + Summary

Υ(3S) and Υ(2S) production relative to Υ(1S)



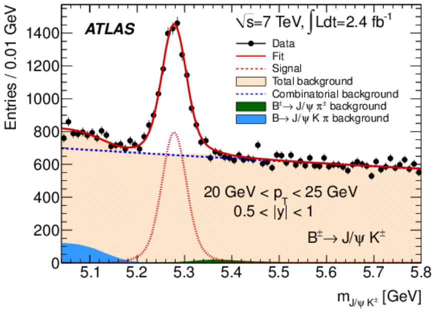
Summary

- Many precise measurements!
- Total cross sections and differential measurements in $|y|$ also made!
- Can provide stringent constrains on theoretical predictions of bottomonium production
- All measurements can be found in HEPDATA: `hepdata.cedar.ac.uk`

- Evidence for beginning of plateau at high p_T?

Introduction

- Measurements of B^+ meson production provide an important test of our understanding of *b*-quark production and fragmentation
- The high $pp \to b\bar{b}X$ cross section at the LHC provides large data samples for high precision measurements
- Measurement uses *pp* data sample of 2.4 fb^{-1} collected at $\sqrt{s} = 7$ TeV



B^+ meson reconstruction

- Utilise $B^+ \to J/\psi\, K^+$ channel, experimentally clean with large branching fraction $\approx 1.03 \times 10^{-3}$
- Trigger with $J/\psi \to \mu^+\mu^-$ and reconstruct $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.3$
- Add track with $p_T > 1$ GeV, assign K^+ mass
- Perform $\mu^+\mu^-K^+$ vertex fit, require $\chi^2/[d.o.f.] < 6$
- Retain candidates with $5.04 < m(\mu^+\mu^-K^+) < 5.8$ GeV and $p_T^B > 9$ GeV

Cross-section Measurement

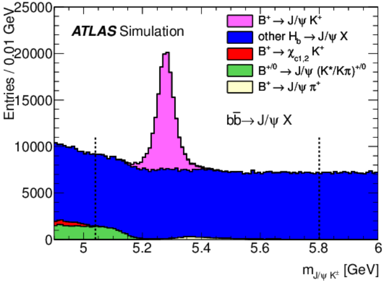
Determine differential cross-section from:

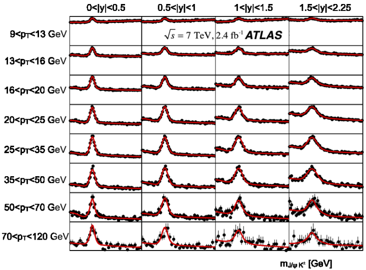
$$\mathcal{B} \cdot \frac{d\sigma(pp \to B^+ X)}{dp_T dy} = \frac{N^{B^+}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}$$

- Assume equal production of $B^\pm$ and measure together
- N^{B^+} is fitted number of B^+ candidates, corrected for efficiency and acceptance
- Use mixture of MC and data-driven efficiency corrections

Fitting Procedure

- Un-binned maximum likelihood fit
- Model reflections with MC samples





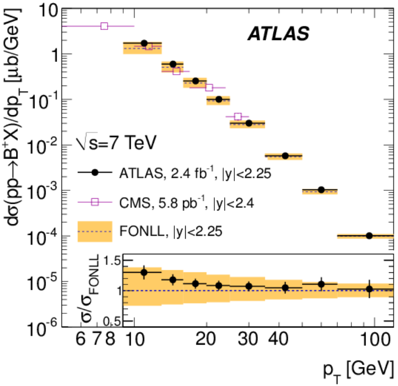
Differential Cross-section

- Measured differentially in $|y|$ and p_T
- Good agreement between ATLAS and CMS

FONLL prediction (arXiv:1205.6344)

- *b*-quark production calculated in fixed order next-to-leading logarithm (FONLL) approach
- *b* fragmentation function fitted from LEP data
- Use world average value $f_{\bar{b}\to B^+} = (40.1 \pm 0.8)\%$
- Good agreement with data!

Integrated over $|y| < 2.25$



Total Cross-section

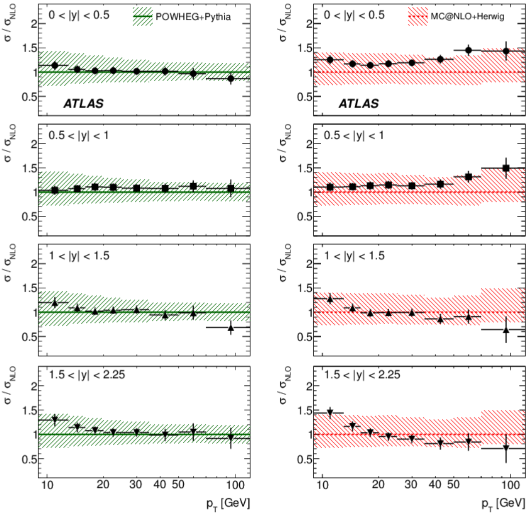
$$\sigma(pp \to B^+ + X) = 10.6 \pm 0.3\,(\text{stat.}) \pm 0.7\,(\text{syst.}) \pm 0.2\,(\mathcal{L}) \pm 0.4\,(\mathcal{B})\,\mu\text{b}$$
$$\sigma^{FONLL}(pp \to b + X) \cdot f_{\bar{b}\to B^+} = 8.6^{+3.0}_{-1.9}\,(\text{scale}) \pm 0.6\,(m_b)\,\mu\text{b}$$

Comparisons to MC generators

- Compare to two combinations of MC *b*-quark production (POWHEG and MC@NLO) + parton showering (Pythia and Herwig)
- Good agreement in both cases - though both tend to underestimate data at low p_T
- Systematic change in Data w.r.t. MC@NLO+Herwig as a function of $|y|$

Summary

- Wealth of precise data can help inform modelling of *b*-quark production and fragmentation!



POWHEG+Pythia MC@NLO+Herwig

Conclusion

Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$

- "New" contribution to bottomonium production phenomenology

Measurement of Υ production in 7 TeV *pp* collisions at ATLAS

- Many measurements to provide very stringent constraints on models of bottomonium production

Measurement of the B^+ meson production differential cross-section

- Detailed measurements to test *b*-quark production and fragmentation models

Further interesting ATLAS results on *b*-hadrons:

- *b*-hadron production cross-section from $D^*\mu X$ final states

  Nucl. Phys. B 864 (2012) 341 (arXiv:1206.3122)

Expect new results on excited *b*-hadrons, new decay modes and exotic state searches soon!