PROCEEDINGS OF SCIENCE

Spectroscopy of excited states at ATLAS

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Spectroscopic studies using up to 4.9 fb^{-1} of data, collected by the ATLAS detector during 2011 at the LHC, are reviewed. This includes the measurement of the mass and lifetime of the Λ_b^0, the observation of the B_c, and the first observation of the $\chi_b(3P)$ states.

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1. Introduction

The LHC is an ideal environment for the production and study of heavy flavour states, including not only those well-known ($J/\psi, \Upsilon$ etc.), but also states that have not previously been seen. The following is a review of some recent studies performed using the ATLAS detector [1] with data collected in 2011. We begin by presenting the performance of the dimuon trigger, which forms the basis for each of these analyses.

2. Dimuon Trigger Performance and $\Upsilon(1,2,3S)$ Cross-section

At ATLAS, reconstruction of heavy flavour states is commonly performed using their transition to lower-lying quarkonia, which can then be efficiently and cleanly triggered through their decay to two muons. In 2011-2012, a rich *B*-physics trigger menu was employed for this purpose, including low threshold, un-prescaled triggers specifically dedicated to the J/ψ, $\psi(2S)$ and $\Upsilon(1,2,3S)$ mass regions. A summary of the yields of these triggers as a function of dimuon mass, for a 2.3 fb^{-1} subset of the 2011 dataset, is shown in Figure 1.

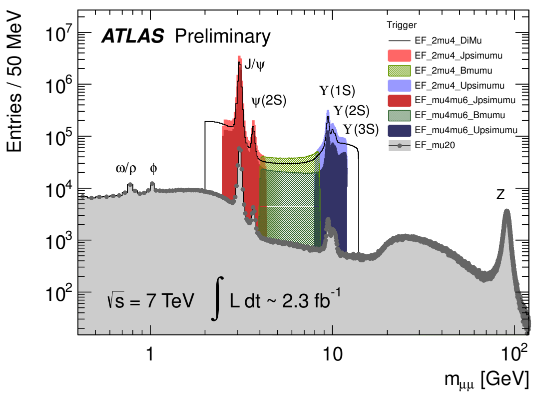


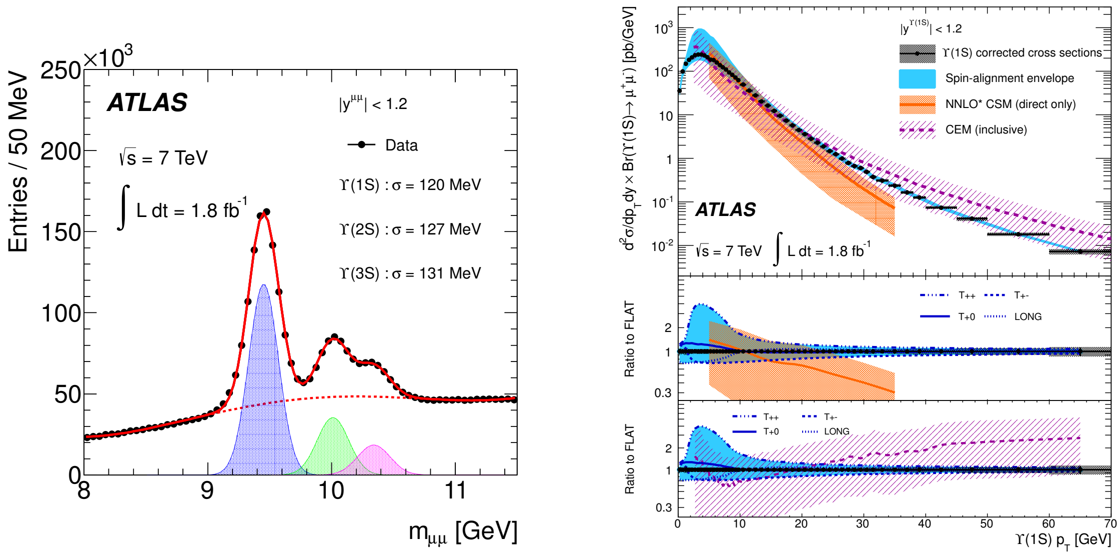
Figure 1: The dimuon invariant mass distributon resulting from the dedicated *B*-physics trigger menu used for 2011 data taking in a 2.3 fb^{-1} subset [2].

A differential cross-section measurement was performed for the $\Upsilon(1,2,3S)$ states using 1.8 fb^{-1} of data provided by these triggers (an analogous measurement exists for the J/ψ based on 2010 data [3]). The size of the sample (more than 10^6 $\Upsilon(1S)$, and a significant fraction thereof for the other two states), and the comprehensive acceptance of the ATLAS detector, allowed for the measurement to be made out to a rapidity of $|y| < 2.25$ and up to a p_T of 70 GeV. Figure 2a shows the invariant mass of the dimuon candidates in central rapidities, alongside the corresponding differential cross-section (Figure 2b). Details of the analysis are given in [4].

This Υ sample underpins the $\chi_b(nP)$ analysis, as does the analogous J/ψ sample for those in Sections 3 and 4.

3. Λ_b^0 Mass and Lifetime

Hadron colliders are currently the only places available to study the properties of *b*-baryons. The Λ_b^0 is the lightest of these, and although its lifetime has been measured by several experiments,



(a) (b)

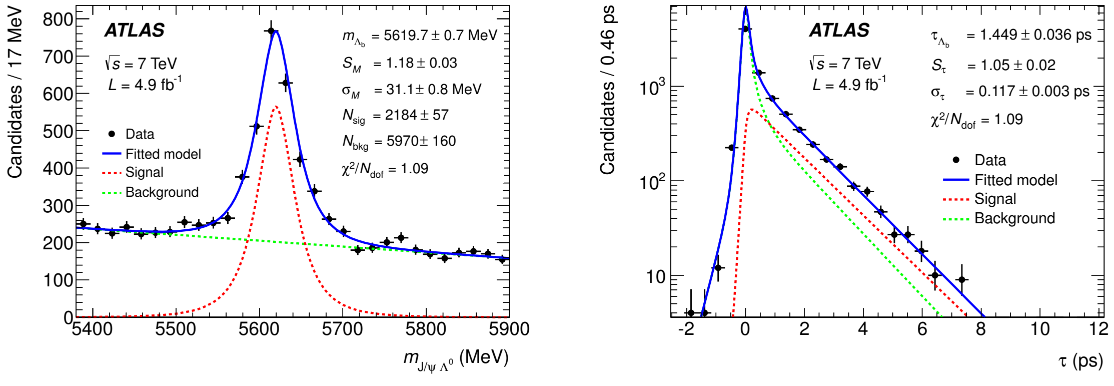
Figure 2: A subset of the results from the Υ cross-section analysis. On the left is the invariant mass distribution of dimuon candidates in the region surrounding the $\Upsilon(1,2,3S)$, with the fit showing the contribution from each state. The resultant differential cross-section is displayed as a function of p_T on the right. The theoretical uncertainty associated with the polarisation of the Υ is overlayed along with predictions from the Colour Siglet (CSM) and Colour Evaporation Models (CEM). In both cases, the results are for the central rapidity region, $|y| < 1.2$ [4].

its uncertainty remains large [5]. This is mostly due to tension between the measurements of $\tau_{\Lambda_b^0} = 1.303 \pm 0.075(\text{stat.}) \pm 0.035(\text{syst.})$ ps and $\tau_{\Lambda_b^0} = 1.537 \pm 0.045(\text{stat.}) \pm 0.014(\text{syst.})$ ps from *DØ* [6] and CDF [7], respectively.

ATLAS performed a simultaneous measurement of the mass and lifetime of the Λ_b^0 through its decay to $J/\psi\Lambda^0$.[1] In events which pass a J/ψ trigger, the corresponding muons were fitted to a common vertex with a mass preselection of $2.8 < m < 3.4$ GeV to reduce background contamination. A similar pre-selection was applied to the $\Lambda^0 \to p\pi^-$ decay, ensuring the combined mass of the pion and proton tracks was close to the expected value (within the resolution of the detector). The four tracks were subsequently subjected to a cascade topology vertex fit; the dimuon vertex was constrained to give the (world-average value of the) J/ψ mass and the $p\pi^-$ vertex the Λ^0 mass, with the momentum associated with the latter constrained to point back to the former. The full details of this procedure are given in [8].

The result of each vertex fit provided a mass, m_i, proper time, τ_i, and their associated uncertainties. These were used as the inputs to an unbinned extended maximum likelihood simultaneous mass-lifetime fit, the projections of which are shown in Figure 3. The fitted value of the Λ_b mass, $m = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})$ MeV, compares well with the world average value, 5619.4 ± 0.7 MeV [5], and a recent measurement from LHCb of 5619.19 ± 0.70 MeV

[1]The charge conjugate decay was also utilised.



(a) (b)

Figure 3: The mass (left) and lifetime (right) distribution of Λ_b^0 candidates, with the projection of the simultaneous fit overlayed [8].

[9]. The lifetime value, $\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst.})$ ps, also agrees with the world average and is between the DØ [6] and CDF measurements [7]. The analysis was also applied to the $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ decay, which has a similar topology, and a lifetime ratio of $R = \tau_{\Lambda_b^0}/\tau_{B_d} = 0.960 \pm 0.025(\text{stat.}) \pm 0.016(\text{syst.})$ obtained. This ratio is an important quantity, as it gives insights into the difference in the dynamics of a $b-qq$ baryon system and a $b\bar{q}$ meson system (q here represents a light quark). The value measured here is consistent with expectations from heavy quark expansion calculations [10], and intermediate to that found by DØ and CDF.

4. B_c Observation

The $b\bar{c}$ (or charge-conjugate) system is a probe for heavy quark dynamics that is not accessible in the $b\bar{b}$ or $c\bar{c}$ states. The ground state is referred to as the B_c, and was first observed by CDF and then DØ (whose latest results are given in [11] and [12], respectively). ATLAS has added to this with an observation and preliminary mass measurement, utilising the full 2011 dataset.

$B_c^\pm$ decays to $J/\psi\pi^\pm$ were reconstructed in a similar fashion to the Λ_b^0 analysis – the J/ψ was used for triggering, with a pre-selection on the $\mu^+\mu^-$ vertex mass, p_T, transverse displacement (from the closest primary vertex) and fit quality. A subsequent vertex fit, incorporating an additional track for the pion, was then performed with the dimuon mass fixed to the J/ψ world average. Any such $\mu^+\mu^-\pi^\pm$ combinations with a $p_T > 15$ GeV and $\chi^2/n.d.o.f < 2$ were retained as B_c candidates. The reader interested in further details is referred to [13].

The mass distribution of the B_c candidates is given in Figure 4. The fitted mass was $m_{B_C} = 6282 \pm 7(\text{stat.})$ MeV, in line with the world average value of 6277 ± 6 MeV [5] and the previous determinations from CDF [11] and DØ [12]. It is also consistent with a recent measurement from CMS using a similar sample size [14], and another from LHCb [15]. No systematic uncertainty was calculated because, based on previous similar analyses (for example, the Λ_b^0 analyses described above [8]), it was assumed that the statistical uncertainty would be dominant. Extending the anal-

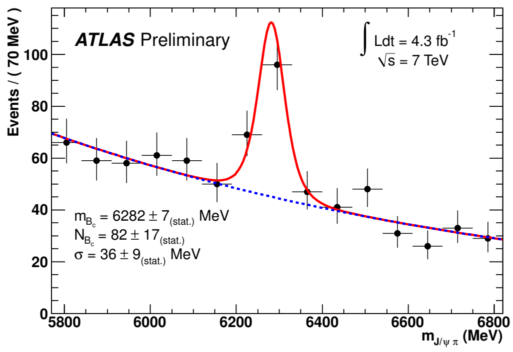


Figure 4: The mass of reconstructed B_c candidates, with a clear signal peak with a yield of 82 ± 17.

ysis to the full combined 2011-2012 dataset would increase the accuracy of the measurement, in which case a study of the systematic uncertainty would be essential.

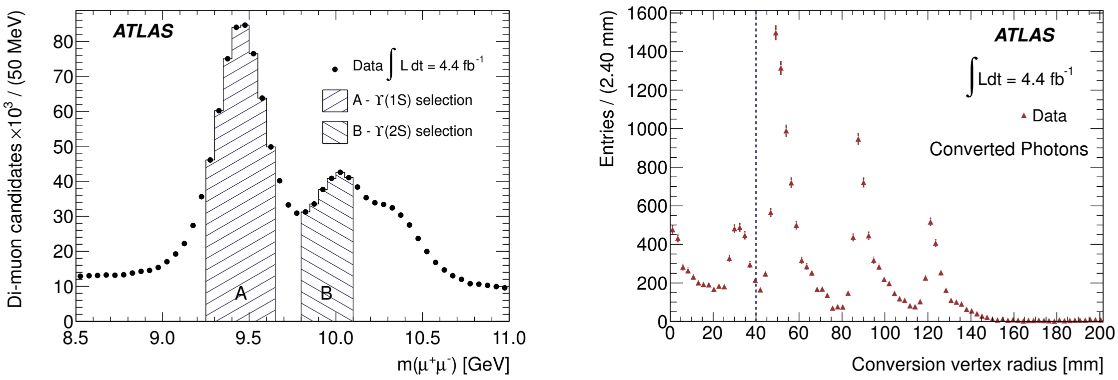
5. First Observation of the $\chi_{bJ}(3P)$

The $\chi_{bJ}(nP)$ are the spin 1 $L = 1$ bottomonium states. The ground and first excited states have both been studied extensively in their radiative transitions to the lower lying upsilon states, and have a (barycentre) mass of 9.90 and 10.26 GeV, respectively. The $n = 3$ state has long been predicted (see, e.g. [16]) to lie just below the $B\overline{B}$ threshold, and participate in the similar radiative decays.

ATLAS performed a search for the $\chi_{bJ}(3P) \to \gamma\Upsilon(1,2S)$ decay using the full 2011 dataset [17]. Dimuon pairs again provided the objects used for triggering, and were retained as potential Υ candidates if their combined mass fell within a region surrounding the 1S or 2S mass (Figure 5a). In the case of the 2S, an asymmetric window was used to avoid contamination from 3S decays[2]. These were then combined with a photon, detected directly by the electromagnetic calorimeter or through its conversion to e^+e^-. The latter is an important category, due to the large amount of material in the ATLAS tracking system (the distribution of the conversion radius, Figure 5b, demonstrates this), and, in fact, leads to a better resolution on the photon four-momentum than direct detection.

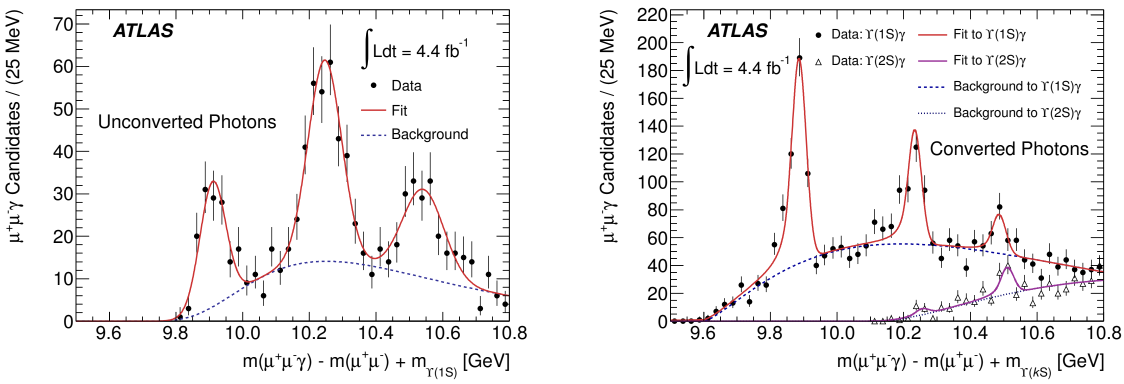
To minimise the effect of the muon resolution on the invariant mass of the $\gamma\mu^+\mu^-$, an alternative variable, $\tilde{m}_{1,2} = m_{\gamma\mu^+\mu^-} - m_{\mu^+\mu^-} + m_{\Upsilon(1,2S)\mathrm{PDG}}$, was constructed. Its distribution is shown for the unconverted (left) and converted (right) candidates in Figure 6, where, in the latter case, the electron tracks allowed for the reconstruction of soft photons from transitions to the $\Upsilon(2S)$. In each case, an unbinned maximum likelihood fit was performed to extract the relevant information. For the unconverted photons, Gaussians were used to model each of the signal states, with independent mass, width and normalisation parameters. In the case of converted photons, the resolution was of the same order as the mass splitting between the individual angular momentum states, and so

[2] Any possible bias this may have introduced was explored in the systematic studies, and found to be negligible.



(a) (b)

Figure 5: The invariant mass of the dimuons used in the $\chi_{bJ}(nP)$ analysis is shown on the left, with the pre-selection mass windows around the $\Upsilon(1S)$ and $\Upsilon(2S)$ shaded. In the converted photon analysis, these are then combined with an e^+e^- vertex, the radius of which is shown on the left [17]. The beam pipe and 3 layers of the pixel detector are evident.



(a) Unconverted photons (b) Converted photons

Figure 6: The distribution of the mass variable $\tilde{m}_{1,2} = m_{\gamma\mu^+\mu^-} - m_{\mu^+\mu^-} + m_{\Upsilon(1,2S)\mathrm{PDG}}$ in the unconverted (left) and converted (right) categories of the $\chi_{bJ}(3P) \to \gamma\Upsilon(1,2S)$ analysis [17].

each J state was modelled separately. In fact, the $J = 0$ state is known to have a supressed radiative transition rate with respect to $J = 1$ and $J = 2$, and so was omitted from the fit. Furthermore, bremsstrahlung (and other energy loss mechanisms) necessitated the use of Crystal Ball line-shapes to describe the longer tail on the lower mass side of the peaks. To accomodate the additional parameters this introduced, the world average values for the mass and mass splittings of the $n = 1$ and $n = 2$ states, as well as the theoretical mass splitting for the $\chi_b J(3P)$ triplet, were incorportated into the fitting model.

In both analysis categories, the signal peaks from the $n = 1$ and $n = 2$ states are clearly visible, along with an addition structure at a higher mass, which ATLAS claims as the $\chi_{bJ}(3P)$. The signal significance, as determined from $-2\sqrt{\log L_{max}/L_0}$, was found to be in excess of 6σ for both categories under all considered systematic variations. The fitted (barycentre) mass for this structure was determined to be $\tilde{m} = 10541 \pm 11(\text{stat.}) \pm 30(\text{syst.})$ MeV and $\tilde{m} = 10530 \pm 5(\text{stat.}) \pm 9(\text{syst.})$ MeV in the uncoverted and converted analyses, respectively. Due to the substantially smaller systematic undertainty of the latter, this value alone is quoted as the mass of the $\chi_{bJ}(3P)$.

The DØ and LHCb collaborations have since confirmed the observation of this structure [18, 19].

6. Future Outlook

Each of these analyses utilised data which was collected during 2011. In 2012, the running conditions of the LHC changed to $\sqrt{s} = 8$ TeV, and the total integrated luminosity for the detector was increased by more than 22 fb^{-1}. This provides an excellent opportunity for a number of different studies – in particular, searches for new states or rare decays – and should lead to some interesting new results in the near future.

References

[1] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instrumentation*, 3(08):S08003, 2008.

[2] ATLAS Collaboration. *B*-physics public results `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/BPHYSICS/PUBLIC/DiMu_mas_diff_Triggers.png`. Accessed: 2013-04-12.

[3] ATLAS Collaboration. Measurement of the differential cross-sections of inclusive, prompt and non-prompt production in protonproton collisions at ATLAS. *Nuclear Physics B*, 850(3):387 – 444, 2011.

[4] ATLAS Collaboration. Measurement of upsilon production in 7 TeV *pp* collisions at ATLAS. *Phys. Rev. D*, 87:052004, Mar 2013.

[5] K. Nakamura et al. Review of Particle Physics. *Physical Review D*, 86:010001, 2012.

[6] DØ Collaboration. Measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \to J/\psi\Lambda^0$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Rev. D*, 85:112003, Jun 2012.

[7] CDF Collaboration. Measurement of *b* Hadron Lifetimes in Exclusive Decays Containing a J/ψ in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$TeV. *Phys. Rev. Lett.*, 106:121804, Mar 2011.

[8] ATLAS Collaboration. Measurement of the Λ_b^0 lifetime and mass in the ATLAS experiment. *Phys. Rev. D*, 87:032002, Feb 2013.

[9] LHCb Collaboration. Measurement of b-hadron masses. *Physics Letters B*, 708:241 – 248, 2012.

[10] N.G Uraltsev. On the problem of boosting non-leptonic b baryon decays. *Physics Letters B*, 376(4):303 – 308, 1996.

[11] CDF Collaboration. Observation of the decay $B_c^\pm \to J/\psi\pi^\pm$ and measurement of the $B_c^\pm$ mass. *Phys. Rev. Lett.*, 100:182002, May 2008.

[12] DØ Collaboration. Observation of the B_c meson in the exclusive decay $B_c \to J/\psi\pi$. *Phys. Rev. Lett.*, 101:012001, Jul 2008.

[13] ATLAS Collaboration. Observation of the $B_c^\pm$ meson in the decay $B_c^\pm \to J/\psi(\mu^+\mu^-)\pi^\pm$ with the ATLAS detector at the LHC `https://cds.cern.ch/record/1430737/`. Technical Report ATLAS-CONF-2012-028, CERN, Geneva, Mar 2012.

[14] CMS Collaboration. Observation of the decays $B_c \to J/\psi\pi$ and $B_c \to J/\psi\pi\pi\pi$ in pp collisions at $\sqrt{s} = 7$ TeV `https://cds.cern.ch/record/1461944`. Technical Report CMS-PAS-BPH-11-003, CERN, Geneva, 2012.

[15] G Manca. b and c spectroscopy at LHCb `https://cds.cern.ch/record/1525947?ln=en`. Mar 2013.

[16] L. Motyka and K. Zalewski. Mass spectra and leptonic decay widths of heavy quarkonia. *The European Physical Journal C - Particles and Fields*, 4(1):107–114, 1998.

[17] ATLAS Collaboration. Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at atlas. *Phys. Rev. Lett.*, 108:152001, Apr 2012.

[18] DØ Collaboration. Observation of a narrow mass state decaying into $\Upsilon(1S) + \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys.Rev.*, D86:031103, 2012.

[19] LHCb Collaboration. Observation of the $\chi_b(3P)$ state at LHCb in pp collisions at $\sqrt{s} = 7$ TeV `https://cds.cern.ch/record/1456078`. Jul 2012.

PoS(Beauty 2013)046