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Observation of a New χ_b State in Radiative Transitions to Υ(1S) and Υ(2S) at ATLAS

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The $\chi_b(n\text{P})$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider (LHC) at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. Using a data sample corresponding to an integrated luminosity of 4.4 fb^{-1}, these states are reconstructed through their radiative decays to $\Upsilon(1\text{S}, 2\text{S})$ with $\Upsilon \to \mu^+\mu^-$. In addition to the mass peaks corresponding to the decay modes $\chi_b(1\text{P}, 2\text{P}) \to \Upsilon(1\text{S})\,\gamma$, a new structure centered at a mass of 10.539±0.004 (stat.)±0.008 (syst.) GeV is also observed, in both the $\Upsilon(1\text{S})\,\gamma$ and $\Upsilon(2\text{S})\,\gamma$ decay modes. This structure is interpreted as the $\chi_b(3\text{P})$ system.

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Measurements of the properties of heavy quark-antiquark bound states, or quarkonia, provide a unique insight into the nature of Quantum Chromodynamics close to the strong decay threshold. For the $b\bar{b}$ system, the quarkonium states with parallel quark spins ($s = 1$) include the S-wave Υ and the P-wave χ_b states, where the latter each comprise a closely spaced triplet of $J = 0, 1, 2$ spin states: χ_{b0}, χ_{b1} and χ_{b2}. The χ_b(1P) and χ_b(2P), with spin-weighted mass barycenters of 9.90 and 10.26 GeV, respectively, can be readily produced in the radiative decays of Υ(2S) and Υ(3S) and have been studied experimentally [1].

In this letter, χ_b quarkonium states are reconstructed with the ATLAS detector through the radiative decay modes $\chi_b(n\text{P}) \to \Upsilon(1\text{S})\,\gamma$ and $\chi_b(n\text{P}) \to \Upsilon(2\text{S})\,\gamma$, in which $\Upsilon(1\text{S}, 2\text{S}) \to \mu^+\mu^-$ and the photon is reconstructed either through conversion to e^+e^- or by direct calorimetric measurement. Previous experiments have measured the χ_b(1P) and χ_b(2P) through these decay modes [2]. The χ_b(3P) state has not previously been observed. It is predicted to have an average mass of approximately 10.52 GeV, with hyperfine mass splitting between the triplet states of 10–20 MeV [3, 4].

The ATLAS detector [5] is a general-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic (EM) calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The endcap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of a system of precision tracking chambers and detectors for triggering, inside a toroidal magnetic field.

The data sample used for this measurement was recorded by the ATLAS experiment during the 2011 LHC proton-proton collision run at a center-of-mass energy $\sqrt{s} = 7$ TeV. The integrated luminosity of the data sample, which includes only data-taking periods where all relevant detector sub-systems were operational, is 4.4 fb^{-1}. A set of muon triggers designed to select events containing muon pairs or single high transverse momentum muons was used to collect the data sample.

In this analysis each muon candidate must satisfy standard muon quality requirements [6]. It must have a track, reconstructed in the MS, combined with a track reconstructed in the ID with transverse momentum $p_T >$ 4 GeV and pseudorapidity $|\eta| < 2.3$. The di-muon selection requires a pair of oppositely charged muons, which are fitted to a common vertex. A very loose vertex quality requirement (χ^2 per degree of freedom [d.o.f.] < 20) is used and no mass or momentum constraints are applied to the fit. The di-muon candidate is also required to have $p_T > 12$ GeV and $|\eta| < 2.0$. The invariant mass distribution, $m_{\mu\mu}$, of di-muon candidates is shown in Fig. 1. Those candidates with masses in the ranges $9.25 < m_{\mu\mu} < 9.65$ GeV and $9.80 < m_{\mu\mu} < 10.10$ GeV are selected as $\Upsilon(1\text{S}) \to \mu^+\mu^-$ and $\Upsilon(2\text{S}) \to \mu^+\mu^-$ candidates respectively. The asymmetric mass window (evident from Fig. 1) for Υ(2S) candidates is chosen in order to reduce contamination from the Υ(3S) peak and continuum background contributions.

The reconstruction of photons in ATLAS is described in Ref. [7]. Further details related to this particular analysis are described below.

Converted photons are reconstructed from two oppositely charged ID tracks intersecting at a conversion vertex, with a constraint of a zero-degree opening angle between the two tracks at this vertex. For tracks with signals in the TRT, the transition radiation should be consistent with an electron hypothesis. In order to be reliably reconstructed, each conversion electron track must have a minimum transverse momentum of 500 MeV. It is also required to have at least four silicon detector hits and not to be associated to either of the two muon candidates. To reduce background contamination, the conversion candidate vertex is required to be at least 40 mm

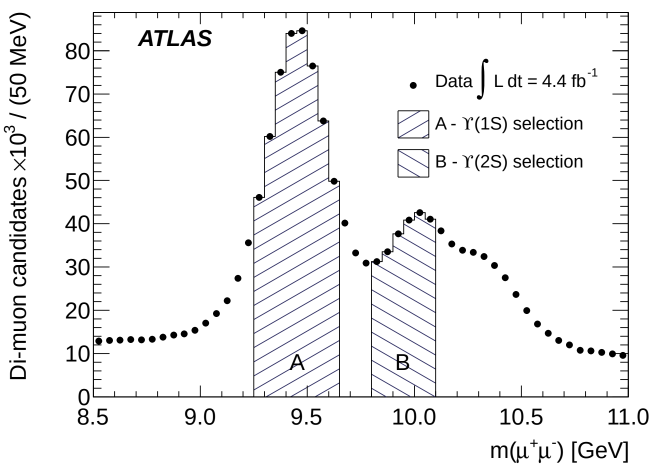


FIG. 1: The invariant mass of selected di-muon candidates. The shaded regions A and B show the selections for Υ(1S) and Υ(2S) candidates respectively.

from the beam axis and have a vertex χ^2 probability of greater than 0.01. The converted photon impact parameter with respect to the di-muon vertex is required to be less than 2 mm.

Electromagnetic calorimeter energy deposits not matched to any track are classified as unconverted photons. This analysis uses the "loose" photon selection described in Ref. [7], with a minimum photon energy of 2.5 GeV. The loose photon selection includes a limit on the fraction of the energy deposit in the hadronic calorimeter as well as a requirement that the transverse width of the shower be consistent with the narrow shape expected for an EM shower.

To check that an unconverted photon originates from the same vertex as the Υ, and to improve the mass resolution of the reconstructed χ_b, the polar angle of the photon is corrected using the procedure described in Ref. [8]. The corrected polar angle is determined using the measurement of the photon direction from the longitudinal segmentation of the calorimeter and the constraint from the di-muon vertex position. Photons incompatible with having originated from the di-muon vertex are rejected by means of a loose cut on the fit result (χ^2 per d.o.f. < 200).

The converted (unconverted) photon candidates are required to be within $|\eta| < 2.30\,(2.37)$. Unconverted photons must also be outside the transition region between the barrel and the endcap calorimeters, $1.37 < |\eta| < 1.52$.

The χ_b candidates are formed by associating a reconstructed $\Upsilon \to \mu^+\mu^-$ candidate with a reconstructed photon. The invariant mass difference $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ is calculated to minimize the effect of $\Upsilon \to \mu^+\mu^-$ mass resolution. In order to compare the Δm distributions of both $\chi_b(n\text{P}) \to \Upsilon(1\text{S})\gamma$ and $\chi_b(n\text{P}) \to \Upsilon(2\text{S})\gamma$ decays, the variable $\tilde{m}_k = \Delta m + m_{\Upsilon(k\text{S})}$ is defined, where $m_{\Upsilon(k\text{S})}$ are the world average masses [9] of the $\Upsilon(k\text{S})$ states. Requirements of $p_{\text{T}}(\mu^+\mu^-) > 20$ GeV and $p_{\text{T}}(\mu^+\mu^-) > 12$ GeV are applied to Υ candidates with unconverted and converted photon candidates respectively. These thresholds are chosen in order to optimize signal significance in the χ_b(1P,2P) peaks.

Figure 2(a) shows the $\tilde{m}_1$ distribution for unconverted photons and Fig. 2(b) the $\tilde{m}_1$ and $\tilde{m}_2$ distributions for converted photons. In addition to the expected peaks for $\chi_b(1\text{P},2\text{P}) \to \Upsilon(1\text{S},2\text{S})\gamma$, structures are observed at an invariant mass of approximately 10.5 GeV. These additional structures are interpreted as the radiative decays of the previously unobserved χ_b(3P) states, $\chi_b(3\text{P}) \to \Upsilon(1\text{S})\,\gamma$ and $\chi_b(3\text{P}) \to \Upsilon(2\text{S})\,\gamma$.

Separate fits are performed to the $\tilde{m}_k$ distributions of the selected $\mu^+\mu^-\gamma$ candidates reconstructed from converted and unconverted photons to extract mass information from the observed χ_b(3P) signals. The higher threshold for unconverted photons (2.5 GeV, versus 1 GeV for converted photons) prevents the reconstruction of the soft photons from χ_b(2P,3P) decays into Υ(2S).

An unbinned extended maximum likelihood fit is performed to the $\tilde{m}_1 = \Delta m + m_{\Upsilon(1\text{S})}$ distribution of the selected unconverted $\mu^+\mu^-\gamma$ candidates. The three peaks in the distribution are each modeled by a Gaussian probability density function (pdf) with independent normalization parameter, N_n, mean value, $\overline{m}_n$, and width parameter, σ_n. The background distribution is parameterized by the pdf $N_B \cdot \exp\left(A \cdot \Delta m + B \cdot \Delta m^{-2}\right)$ where N_B, A, and B are all free parameters. The three mean values $\overline{m}_{n=1,2,3}$ determined by the fit are shown in Table I. The mean value $\overline{m}_3$ is an estimate of the mass barycenter of the observed χ_b(3P) signal.

Likewise, the $\tilde{m}_1 = \Delta m + m_{\Upsilon(1\text{S})}$ and $\tilde{m}_2 = \Delta m + m_{\Upsilon(2\text{S})}$ distributions for the sample of $\mu^+\mu^-\gamma$ candidates reconstructed from converted photons are fitted using an unbinned extended maximum likelihood method. A simultaneous fit is performed on the $\tilde{m}_1$ and $\tilde{m}_2$ distributions for the $\chi_b(n\text{P}) \to \Upsilon(1\text{S})\gamma$ (for $n = 1, 2, 3$) and $\chi_b(n\text{P}) \to \Upsilon(2\text{S})\gamma$ (for $n = 2, 3$ only) signals, with the distributions modeled by three signal components (two of which are shared between the Υ(1S) and Υ(2S) distributions) and two background distributions.

In the Δm distribution for the converted photon candidates the mass resolution is of similar magnitude to the hyperfine splittings, motivating the need for multiple signal components for each of the $\chi_b(n\text{P})$ peaks. For $n = 1, 2$, the radiative transitions of the $J = 0$ states are suppressed with respect to the $J = 1, 2$ states [9] and therefore a $J = 0$ component is not included in the fit. Similar behavior is assumed for the $n = 3$ case. Each of the three peaks ($n = 1, 2, 3$) is therefore parameterized by a doublet of Crystal Ball (CB) [10] functions (corresponding to $J = 1, 2$ states) with resolution σ and radiative tail parameters common to all peaks. For $n = 1$ and

TABLE I: The fitted mass of the $\chi_b(n\text{P})$ signals for both converted and unconverted photons. The systematic uncertainty on the mass of candidates reconstructed with unconverted photons is determined in the same way for all three states. Also included are theoretical predictions [3, 4] for the spin-averaged masses of the χ_b states.

State	Model predictions [3, 4] [MeV]	Fitted masses [MeV] Unconverted Photons	Converted Photons
$\chi_b(1\text{P})$	9900	9910 ± 6 (stat.) ± 11 (syst.)	Fixed to χ_{b1} = 9892.78 & χ_{b2} = 9912.21 [9]
$\chi_b(2\text{P})$	10260	10246 ± 5 (stat.) ± 18 (syst.)	Fixed to χ_{b1} = 10255.46 & χ_{b2} = 10268.65 [9]
$\chi_b(3\text{P})$	10525	10541 ± 11 (stat.) ± 30 (syst.)	10539 ± 4 (stat.) ± 8 (syst.)

$n = 2$, the peak mass values and hyperfine splittings are fixed to the world averages [9] for the respective χ_b states (see Table I). For $n = 3$, the hyperfine mass splitting is fixed to the theoretically predicted value of 12 MeV [4], while the average mass is left as a free parameter. The unknown relative normalization of the $J = 1$ and $J = 2$ CB peaks is taken to be equal and treated as a systematic uncertainty (for all doublets) for the baseline fit.

In order to take into account energy loss from the photon conversion electrons due to bremsstrahlung and other processes, the measured values of Δm in the $\tilde{m}_1$ and $\tilde{m}_2$ distributions are scaled by a common parameter $\lambda = 0.963 \pm 0.006$, which determines the energy scale and is derived from the fit to the $\chi_b(1\text{P}, 2\text{P})$ signals. The background components of the Δm distributions for the $\Upsilon(1\text{S})\gamma$ and $\Upsilon(2\text{S})\gamma$ final states are each modeled by the pdf $N_B^k \cdot \left(\Delta m - q_k^0\right)^{A_k} \cdot \exp\left[B_k \cdot \left(\Delta m - q_k^0\right)\right]$ for $\Delta m > q_k^0$, and zero otherwise, where N_B^k, q_k^0, A_k, and B_k ($k = 1, 2$) are all free parameters. The mean value $\overline{m}_3$ determined by the fit is shown in Table I.

In the fit using unconverted photons, the signal is refitted using an alternative (two Gaussians) model for each of the three χ_b states, resulting in a negligible change in the peak positions. Alternative fits to the background are also used, either including constraints on the Δm distribution using di-muon pairs from the low-mass (8.0 GeV $< m_{\mu\mu} <$ 8.8 GeV) sideband or different background pdfs. The systematic uncertainty on the $\chi_b(3\text{P})$ mass barycenter from modeling of the background distribution is determined to be ±21 MeV. The systematic uncertainty associated with the unconverted photon energy scale is estimated to be ±2% on the Δm position, corresponding to a systematic uncertainty on $\overline{m}_3$ of ±22 MeV. The uncertainties due to background modeling and photon energy scale comprise the dominant sources of systematic uncertainty.

For the fit using converted photons, alternative signal and background models are compared, as well as releasing various constraints in the fit model. The unknown relative normalizations of the $J = 1$ and $J = 2$ CB peaks are varied both coherently and incoherently between the 1P, 2P and 3P doublets by ±0.25, resulting in a maximum variation in $\overline{m}_3$ of ±5 MeV. Smaller variations are obtained if the common value of the relative normalization is allowed to be determined freely by the fit to the three doublets. Background modeling variations, decoupled fits to the $\tilde{m}_1$ and $\tilde{m}_2$ distributions, and individually released constraints on the mass position of the $n = 1, 2$ doublets each result in deviations of the order of ±3 MeV or smaller. The effect of symmetrizing the $\Upsilon(2\text{S})$ mass window is studied and found to have negligible effect on the fitted χ_b masses while increasing background contamination. The resulting shifts in $\overline{m}_3$ for these independent variations are added in quadrature to provide an estimate of the systematic uncertainty.

The $\chi_b(3\text{P})$ signal significance is assessed from $\log(L_{\max}/L_0)$, where $L_{\max}$ and L_0 are the likelihood values from the nominal fit and from a fit with no $\chi_b(3\text{P})$ signal included, respectively. The fit is repeated with each of the systematic variations in the model, as discussed above, and the likelihood ratio re-evaluated. Under conservative assumptions, the significance of the $\chi_b(3\text{P})$ signal is found to be in excess of six standard deviations in each of the unconverted and converted photon selections independently.

The mass barycenter for the $\chi_b(3\text{P})$ signal, determined from the fit using unconverted photon candidates is:

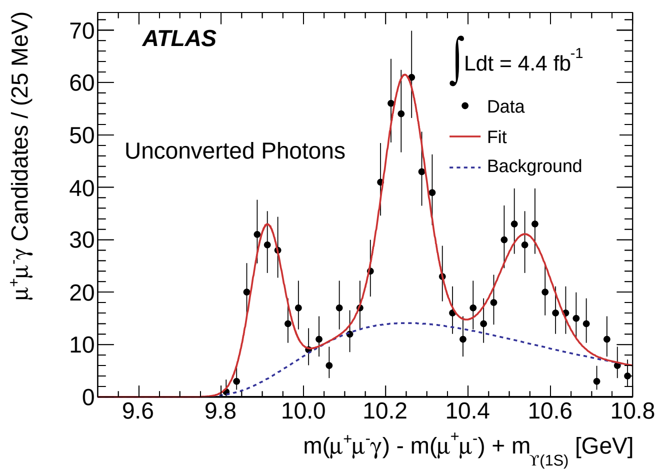
$$\overline{m}_3 = 10.541 \pm 0.011\ (\text{stat.}) \pm 0.030\ (\text{syst.})\ \text{GeV}.$$

The mass barycenter for the $\chi_b(3\text{P})$ signal, determined from the fit using converted photon candidates is:

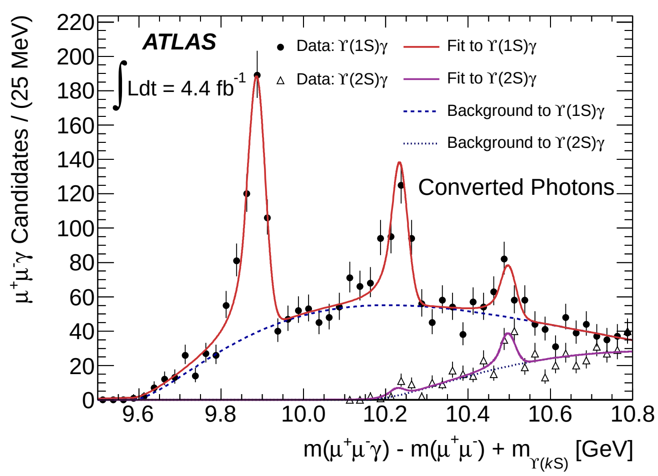
$$\overline{m}_3 = 10.539 \pm 0.004\ (\text{stat.}) \pm 0.008\ (\text{syst.})\ \text{GeV}.$$

The measured mass barycenters of the $\chi_b(1\text{P})$, $\chi_b(2\text{P})$ and $\chi_b(3\text{P})$ systems are summarized in Table I. The results of the converted and unconverted photon analyses for the $\chi_b(3\text{P})$ are found to be compatible. Given the substantially smaller systematic uncertainties in the conversion measurement, the final mass determination for $\overline{m}_3$ is quoted solely on the basis of this analysis.

In conclusion, the production of the heavy quarkonium states $\chi_b(n\text{P})$ in proton-proton collisions at $\sqrt{s} = 7$ TeV is observed through reconstruction of the radiative decay modes of $\chi_b(n\text{P}) \to \Upsilon(1\text{S},2\text{S})\,\gamma$. Mass peaks corresponding to $\chi_b(1\text{P},2\text{P})$ decays are observed, together with additional structures at higher mass, which are consistent with theoretical predictions for $\chi_b(3\text{P}) \to \Upsilon(1\text{S})\,\gamma$ and $\chi_b(3\text{P}) \to \Upsilon(2\text{S})\,\gamma$. These observations are interpreted as the $\chi_b(3\text{P})$ multiplet, the mass barycenter of which is measured to be $10.539 \pm 0.004\ (\text{stat.}) \pm 0.008\ (\text{syst.})$ GeV.



(a)



(b)

FIG. 2: (a) The mass distribution of $\chi_b \to \Upsilon(1\mathrm{S})\gamma$ candidates for unconverted photons reconstructed from energy deposits in the electromagnetic calorimeter (χ^2_{fit}/d.o.f. = 0.85). (b) The mass distributions of $\chi_b \to \Upsilon(k\mathrm{S})\gamma$ ($k = 1, 2$) candidates formed using photons which have converted and been reconstructed in the ID (χ^2_{fit}/d.o.f. = 1.3). Data are shown before the correction for the energy loss from the photon conversion electrons due to bremsstrahlung and other processes. The data for decays of $\chi_b \to \Upsilon(1\mathrm{S})\gamma$ and $\chi_b \to \Upsilon(2\mathrm{S})\gamma$ are plotted using circles and triangles respectively. Solid lines represent the total fit result for each mass window. The dashed lines represent the background components only.

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