Title

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Measurement of the branching ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$ with the ATLAS detector

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ABSTRACT

An observation of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay and a comparison of its branching fraction with that of the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay has been made with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV at the LHC using an integrated luminosity of 20.6 fb^{-1}. The J/ψ and $\psi(2S)$ mesons are reconstructed in their decays to a muon pair, while the $\Lambda^0 \to p\pi^-$ decay is exploited for the Λ^0 baryon reconstruction. The Λ_b^0 baryons are reconstructed with transverse momentum $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.1$. The measured branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays is $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0) = 0.501 \pm 0.033(\text{stat}) \pm 0.019(\text{syst})$, lower than the expectation from the covariant quark model.

1. Introduction

The Λ_b^0 baryon properties have been extensively studied at the Large Hadron Collider (LHC) [1–7]. The decay channel $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$[1] has been primarily used by the LHC experiments in these studies, although a number of other Λ_b^0 decay channels have been exploited by the LHCb experiment. In particular, a measurement of the differential branching fraction and angular analysis of the rare decay $\Lambda_b^0 \to \mu^+\mu^-\Lambda^0$ was performed by LHCb [8,9] following observation of this decay by the CDF experiment [10] at the Tevatron collider. However, no results for the decay mode $\Lambda_b^0 \to \psi(2S)\Lambda^0$ have yet been reported, although a measurement of the decay properties would be useful for verification of theoretical predictions [11].

The $\Lambda_b^0 \to \psi(2S)\Lambda^0$ branching fraction should be of the same order as that of the decay $\Lambda_b^0 \to J/\psi\Lambda^0$ as suggested by the branching fraction values of the B^0, B^+ and B_s^0 meson decays to $\psi(2S)/J/\psi$ and either a pseudoscalar (K^0, K^+, η) or vector (K^{*0}, K^{*+}, ϕ) meson. The branching ratios of such B meson decays to $\psi(2S)X$ and $J/\psi X$ are within the 0.5–0.8 range [12], and are generally reproduced by factorisation calculations [13]. The only available theoretical calculation of the branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays, performed in the framework of the covariant quark model [14], predicts 0.8 with an uncertainty of approximately 0.1 [11].

An observation of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay and a measurement of the branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays is reported in this Letter. The J/ψ and $\psi(2S)$ mesons are reconstructed in their decays to a muon pair, while the $\Lambda^0 \to p\pi^-$ decay is exploited for the Λ^0 baryon reconstruction. The Λ_b^0 baryons are reconstructed with transverse momentum $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.1$.

2. The ATLAS detector, data and Monte Carlo simulation samples

A detailed description of the ATLAS detector can be found elsewhere [15]. A brief outline of the components most relevant to this analysis is given below.

The ATLAS inner detector (ID) has full coverage[2] in ϕ, covers the pseudorapidity range $|\eta| < 2.5$ and operates inside an axial magnetic field of 2 T. It consists of a silicon pixel detector (Pixel), a silicon microstrip detector (semiconductor tracker, SCT) and a transition radiation tracker (TRT). The inner-detector barrel (end-cap) parts consist of 3 (2×3) Pixel layers, 4 (2×9) double-layers of single-sided SCT strips and 73 (2×160) layers of TRT straws. The ATLAS muon spectrometer (MS) covers the pseudorapidity range $|\eta| < 2.7$. It consists of precision tracking chambers, fast trigger detectors and a large toroidal magnet system generating an aver-

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[1] Hereafter, charge conjugation is implied, unless explicitly stated otherwise.

[2] The ATLAS coordinate system is a Cartesian right-handed system, with the coordinate origin at the nominal interaction point. The anti-clockwise beam direction defines the positive z-axis, with the x-axis pointing to the centre of the LHC ring. Polar (θ) and azimuthal (ϕ) angles are measured with respect to this reference system. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

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age field of 0.5 T in the barrel region ($|\eta| < 1.05$) and 1 T in the end-cap regions ($1.05 < |\eta| < 2.7$).

The ATLAS detector has a three-level trigger system [16]: the hardware-based Level-1 system and the two-stage High Level Trigger (HLT). For this measurement, dimuon triggers are used. At Level-1, the dimuon triggers search for patterns of MS hits corresponding to dimuons passing various p_T thresholds. Since the rate from the low-p_T dimuon triggers was too high, prescale factors were applied to reduce their output rates. The data sample used in this analysis was collected using three dimuon triggers with p_T thresholds of 4 GeV for both muons, 4 GeV and 6 GeV for the two muons, and 6 GeV for both muons. At the HLT, the dimuon triggers used require muons with opposite charges and dimuon mass in the range $2.5 < m(\mu^+\mu^-) < 4.3$ GeV.

This analysis uses 20.6 fb^{-1} of proton–proton collision data with a centre-of-mass energy of 8 TeV recorded by the ATLAS detector at the LHC in 2012. The uncertainty on the integrated luminosity is ±2.8%. It is derived following the same methodology as that detailed in [17]. The event sample is processed using the standard offline ATLAS detector calibration and event reconstruction code. There are typically a few primary vertex candidates in each event due to multiple collisions per bunch crossing. Only events with at least four reconstructed tracks with $p_T > 0.4$ GeV and at least one reconstructed primary vertex candidate are kept for further analysis.

To model inelastic pp events containing $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0$, $\Lambda_b^0 \to \psi(\mu^+\mu^-)\Lambda^0$, $B^0 \to J/\psi(\mu^+\mu^-)K_S^0$ or $B^0 \to \psi(\mu^+\mu^-)K_S^0$ decays,[3] four large samples of Monte Carlo (MC) simulated events are prepared using the PYTHIA 8.1 [18] MC generator. The B^0 MC samples are needed to control reflections from B^0 decays to the Λ_b^0 signal distributions. The generation is based on leading-order matrix elements for all $2 \to 2$ QCD processes. Initial- and final-state parton showering is used to simulate higher-order processes. Generated events with both muons from J/ψ or $\psi(2S)$ decays having transverse momenta above 3.5 GeV and pseudorapidities within ±2.5, and, for Λ_b^0 MC samples, with the Λ^0 transverse momentum above 1 GeV are passed through a full simulation of the detector using the ATLAS simulation framework [19] based on GEANT4 [20,21] and processed with the same reconstruction program as used for the data. An emulation of the three triggers used for the data collection is applied to the MC samples. The angular decay distributions of the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ decay are modelled using the helicity amplitudes measured by ATLAS [2]. For the $\Lambda_b^0 \to \psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ decay, the helicity amplitudes are set to the predicted values [11].

3. Event and Λ_b^0 candidate selection

3.1. Charmonium candidate selection

Events are required to contain at least two muons identified by the MS with tracks reconstructed in the ID. The reconstructed muons are required to match the muon candidates identified by the trigger. The muon track parameters are taken from the ID measurement alone, since the MS does not significantly improve the precision in the momentum range relevant for the charmonium measurements presented here. To ensure accurate measurements, each muon track must contain at least six SCT hits and at least one Pixel hit. Muon candidates satisfying these criteria are required to have opposite charges and a successful fit to a common vertex with $\chi^2/N_{\rm dof} < 10$, where χ^2 is the fit quality with the number of degrees of freedom $N_{\rm dof} = 1$. Events with $m(\mu^+\mu^-)$ values within ±200 MeV intervals around the J/ψ and $\psi(2S)$ world average masses [12] are used to search for $\Lambda^0 \to p\pi^-$ candidates.

3.2. Λ^0 and $\bar{\Lambda}^0$ candidate selection

In all events with J/ψ or $\psi(2S)$ candidates, pairs of tracks from particles with opposite charge are combined to form Λ^0 candidates. Each track is required to have at least one Pixel or SCT hit. Only pairs successfully fitted to a common vertex with $\chi^2/N_{\rm dof} < 5$ are kept. The track with larger momentum is assigned the proton mass hypothesis since the proton always has a larger momentum than the pion for Λ^0 baryons with momenta larger than 0.3 GeV. To suppress combinatorial background the following requirements are used:

- $p_T(p) > 1.7$ GeV.
- $|z_0(p)| < 25$ mm, where $z_0(p)$ is the proton longitudinal impact parameter with respect to the dimuon vertex. MC studies show the requirement produces no loss of signal.
- $L_{xy}^{\rm BL}(\Lambda^0) > 7$ mm, where $L_{xy}^{\rm BL}(\Lambda^0)$ is the transverse decay length[4] of the Λ^0 candidate measured from the beam line.

Events with $m(p\pi^-)$ values within an interval of ±20 MeV around the Λ^0 world average mass [12] are kept for further analysis.

3.3. Λ_b^0 reconstruction

Tracks of the selected charmonium and Λ^0 candidates are simultaneously refitted with the dimuon and dihadron masses constrained to the world average masses of J/ψ ($m_{J/\psi}$) or $\psi(2S)$ ($m_{\psi(2S)}$) and Λ^0 (m_{Λ^0}) [12], respectively. The combined momentum of the refitted Λ^0 track pair is required to point to the dimuon vertex. To control B^0 reflections to the Λ_b^0 signal distributions, a B^0 decay topology fit is also attempted for each track quadruplet successfully fitted to the Λ_b^0 topology, i.e. the pion mass is assigned to both hadron tracks and the dihadron mass is constrained to the world average mass of K_S^0 [12]. To suppress combinatorial and B^0 backgrounds the following requirements are used:

- $\chi^2(\Lambda_b^0)/N_{\rm dof} < 3$, where χ^2 is the quality of the fit to the Λ_b^0 topology with $N_{\rm dof} = 6$.
- $L_{xy}(\Lambda^0) > 10$ mm, where $L_{xy}(\Lambda^0)$ is the transverse decay length of the refitted Λ^0 vertex measured from the Λ_b^0 (dimuon) vertex.
- $p_T(\Lambda^0) > 2.5$ GeV.
- $p_T(\pi^-) > 0.45$ GeV.
- $\tau(\Lambda_b^0) > 0.35$ ps, where $\tau(\Lambda_b^0) = L_{xy}(\Lambda_b^0) \cdot m_{\Lambda_b^0}/p_T(\Lambda_b^0)$ is the Λ_b^0 proper decay time, $L_{xy}(\Lambda_b^0)$ is the transverse decay length of the Λ_b^0 vertex measured from the primary vertex and $m_{\Lambda_b^0}$ is the Λ_b^0 world average mass [12]. The primary vertex candidate with at least three tracks and the smallest value of the three-dimensional impact parameter of the Λ_b^0 candidate is selected as the actual primary vertex.
- $\mathcal{P}(\Lambda_b^0) > \mathcal{P}(B^0)$, where $\mathcal{P}(\Lambda_b^0)$ and $\mathcal{P}(B^0)$ are the χ^2 probabilities of the quadruplet fits with Λ_b^0 and B^0 topologies, respectively.

[3] In this Letter, $\psi(2S)$ is referred to as ψ when its decay channel is indicated.

[4] The transverse decay length of a particle is the transverse distance between the primary or production vertex and the particle decay vertex projected along the transverse momentum of the particle.

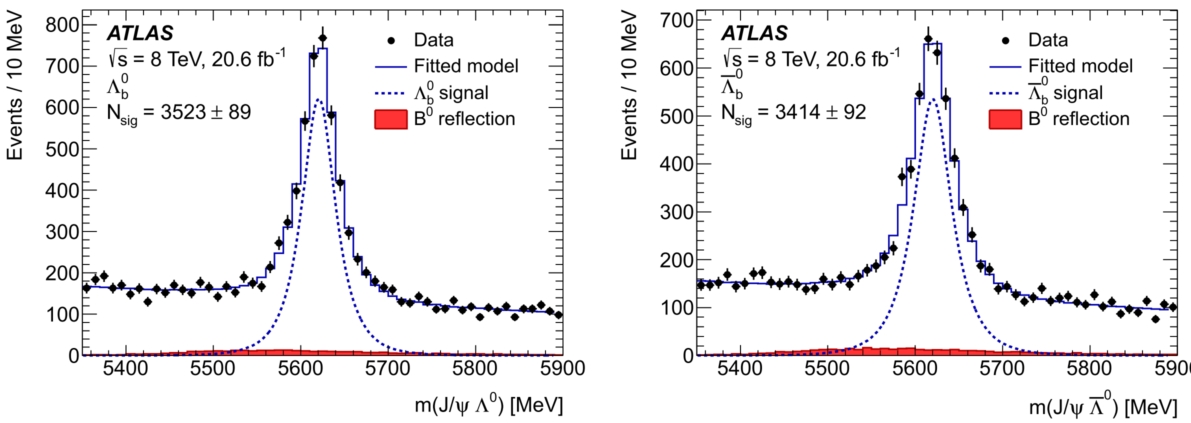

Fig. 1. The invariant mass distributions $m(J/\psi\Lambda^0)$ (left plot) and $m(J/\psi\bar{\Lambda}^0)$ (right plot) for selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates, respectively. The solid histograms represent the fit results (see text). The Λ_b^0 signals (dashed lines) and the B^0 reflections are also shown.

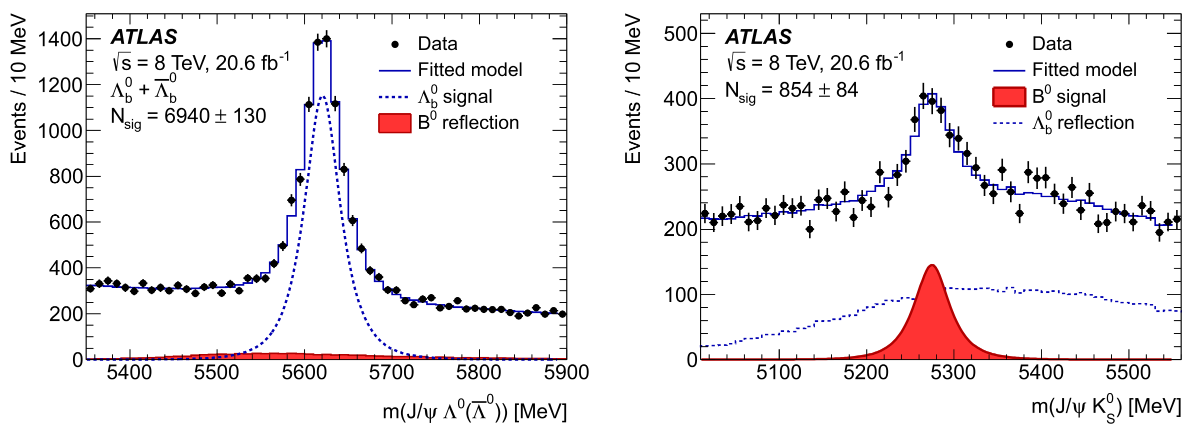

Fig. 2. The invariant mass distributions for the combined sample of the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates obtained after their fits to the $\Lambda_b^0 \to J/\psi\Lambda^0$ (left plot) and $B^0 \to J/\psi K_S^0$ (right plot) topologies. The solid histograms represent fit results (see text). The Λ_b^0 and B^0 signals and their mutual reflections are also shown.

The muon transverse momenta and pseudorapidities are required to be in the ranges with high values of the trigger and reconstruction acceptances:

$$p_T(\mu^\pm) > 4\,\text{GeV},\ |\eta(\mu^\pm)| < 2.3.$$

The kinematic range of the Λ_b^0 measurement is fixed to

$$p_T(\Lambda_b^0) > 10\,\text{GeV},\ |\eta(\Lambda_b^0)| < 2.1.$$

The invariant mass distribution $m(J/\psi\Lambda^0)$, calculated using track parameters from the Λ_b^0 topology fits, is shown in Fig. 1 separately for the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates. Clear signals with similar size are seen in the two distributions around the world average mass of the Λ_b^0 baryon. Figs. 2 and 3 show the $m(J/\psi\Lambda^0)$ and $m(\psi(2S)\Lambda^0)$ distributions for the combined sample of the Λ_b^0 and $\bar{\Lambda}_b^0$ candidates. The invariant mass distributions $m(J/\psi K_S^0)$ and $m(\psi(2S)K_S^0)$ from the B^0 topology fits are also shown. Clear signals are seen in the $m(J/\psi\Lambda^0)$ and $m(\psi(2S)\Lambda^0)$ distributions[5] around the world average mass of the Λ_b^0 baryon. There are also signals in the $m(J/\psi K_S^0)$ and $m(\psi(2S)K_S^0)$ distributions near the world average mass of the B^0 meson [12]. The B^0 signals are smaller than the Λ_b^0 signals due to the selection requirements.

The $m(J/\psi\Lambda^0)$ and $m(J/\psi K_S^0)$ distributions are simultaneously fitted to sums of signal and two-component background distributions. The signals are described by modified Gaussian functions [22]. The modified Gaussian function is defined as

$$\text{Gauss}^{\text{mod}} \propto \exp[-0.5 \cdot x^{1+1/(1+0.5\cdot x)}],$$

where $x = |(m - m_0)/\sigma|$. This functional form, introduced to take into account the non-Gaussian tails of resonant signals, describes both data and MC signals well. The signal position, m_0, and width, σ, as well as the number of the signal events are free parameters of the fit. The non-resonant backgrounds in the distributions are described by independent exponential functions. The mutual B^0 and Λ_b^0 reflections are described by MC templates normalised to the numbers of B^0 and Λ_b^0 hadrons obtained in the fit. The reflection normalisations are corrected for small losses (2–6%) of Λ_b^0 and B^0 hadrons that passed the Λ_b^0 reconstruction but failed the B^0 reconstruction. The corrections are obtained using MC simulation. A similar fit is performed for the $m(\psi(2S)\Lambda^0)$ and $m(\psi(2S)K_S^0)$ distributions. In the analysis of the combined Λ_b^0 and $\bar{\Lambda}_b^0$ samples, the ratio of the MC Λ_b^0 and $\bar{\Lambda}_b^0$ events is set to the data ratio obtained in the separate $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\bar{\Lambda}_b^0 \to J/\psi\bar{\Lambda}^0$ fits (Fig. 1). The Λ_b^0 and $\bar{\Lambda}_b^0$ fitted yields are 3523 ± 89 and 3414 ± 92, respectively, providing the ratio $1.03 \pm 0.04(\text{stat})$.

The results of the fits for the combined Λ_b^0 and $\bar{\Lambda}_b^0$ samples are summarised in Table 1. The Λ_b^0 mass values obtained from the fits of the $m(J/\psi\Lambda^0)$ and $m(\psi(2S)\Lambda^0)$ distributions agree with

[5] Studies with MC simulated events show that the fraction of reconstructed $\Lambda_b^0 \to J/\psi\Lambda^0$ decays which can contribute to the reconstructed $\Lambda_b^0 \to \psi(2S)\Lambda^0$ signal is $\sim 10^{-5}$.

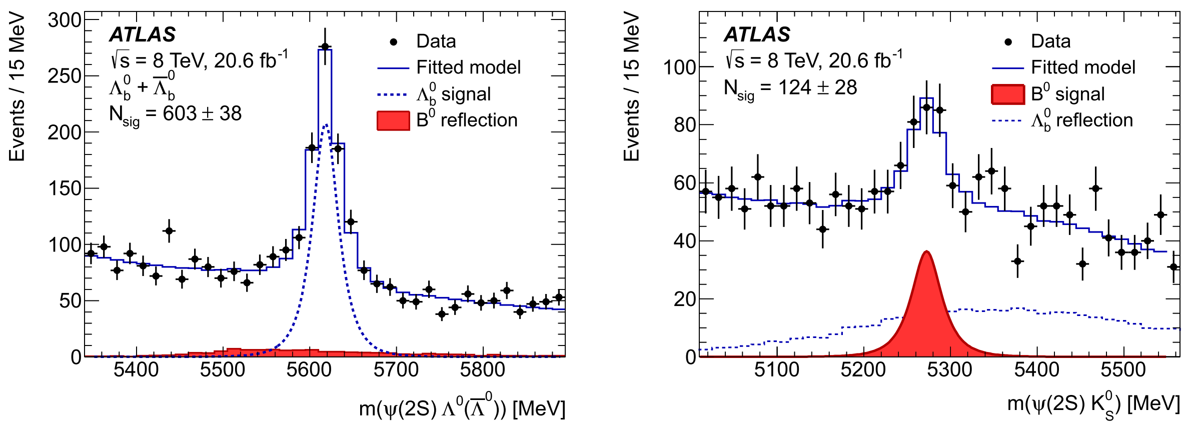

Fig. 3. The invariant mass distributions for the combined sample of the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates obtained after their fits to the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ (left plot) and $B^0 \to \psi(2S)K_S^0$ (right plot) topologies. The solid histograms represent fit results (see text). The Λ_b^0 and B^0 signals and their mutual reflections are also shown.

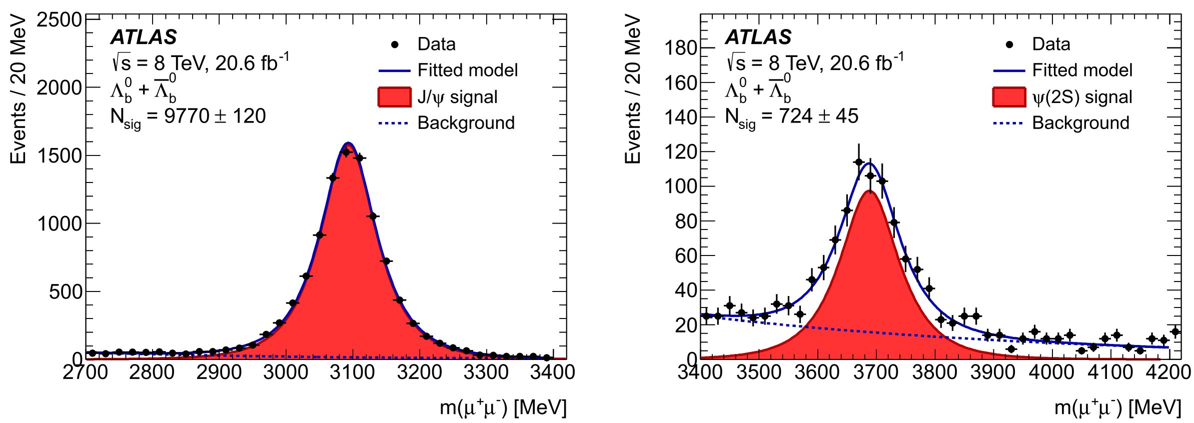

Fig. 4. The $m(\mu^+\mu^-)$ distributions for $\Lambda_b^0 \to J/\psi\Lambda^0$ candidates (left plot) and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ candidates (right plot) after full selection, without a mass constraint on the charmonium mass in the cascade fit. The spectra are fitted with a sum of an exponential function and a modified Gaussian function.

Table 1
The numbers of signal events, N_{sig}, signal masses, m_{sig}, and signal widths, σ_{sig}, obtained by the fits (see text). Only statistical uncertainties are shown.

	$\Lambda_b^0 \to J/\psi\Lambda^0$	$B^0 \to J/\psi K_S^0$	$\Lambda_b^0 \to \psi(2S)\Lambda^0$	$B^0 \to \psi(2S)K_S^0$
N_{sig}	6940 ± 130	854 ± 84	603 ± 38	124 ± 28
m_{sig} [MeV]	5620.4 ± 0.4	5274.7 ± 2.3	5618.2 ± 1.2	5272.4 ± 4.9
σ_{sig} [MeV]	19.7 ± 0.5	19.2 ± 2.2	14.3 ± 1.1	16.7 ± 4.1

each other and with the world average Λ_b^0 mass value [12]. The signal widths are different, reflecting the difference in charmonium masses in the two decay channels, in agreement with the MC expectations. The quality, χ^2/N_{dof}, of the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ signal fits are 1.0 and 1.1, respectively.

To verify that the observed Λ_b^0 signals correspond to the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decays the signal reconstruction is repeated with only one mass constraint for either the dimuon or the dihadron track pair in the cascade fit and the Λ_b^0 mass is calculated using the mass-difference method. In the case that the dihadron mass is fixed to the Λ^0 mass, the Λ_b^0 mass is calculated as $m(\mu^+\mu^-\Lambda^0) - m(\mu^+\mu^-) + m_{J/\psi}$ $(m(\mu^+\mu^-\Lambda^0) - m(\mu^+\mu^-) + m_{\psi(2S)})$ for $m(\mu^+\mu^-) < 3.4$ GeV $(m(\mu^+\mu^-) > 3.4$ GeV). When the dimuon mass is fixed to the J/ψ $(\psi(2S))$ mass, the Λ_b^0 mass is calculated as $m(J/\psi p\pi^-) - m(p\pi^-) + m_{\Lambda^0}$ $(m(\psi(2S)p\pi^-) - m(p\pi^-) + m_{\Lambda^0})$. In both cases clean Λ_b^0 signals are reconstructed with numbers of signal events compatible with those in Table 1.

Fig. 4 shows the $m(\mu^+\mu^-)$ distributions for the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ candidates reconstructed with the mass constraint for the dihadron pair and selected within $\pm 3\sigma_{\text{sig}}$ around the world average Λ_b^0 mass. Clear signals from J/ψ and $\psi(2S)$ are seen. The $m(\mu^+\mu^-)$ distributions are fitted to a sum of an exponential function describing the background and a modified Gaussian function describing the signal. The signal yields are found to be $N_{J/\psi} = 9770 \pm 120$ and $N_{\psi(2S)} = 724 \pm 45$. Fig. 5 shows the $m(p\pi^-)$ distributions for the Λ_b^0 candidates reconstructed with the mass constraint for the dimuon pair and selected within $\pm 3\sigma_{\text{sig}}$ around the world average Λ_b^0 mass. Clear signals from Λ^0 are seen. The $m(p\pi^-)$ distributions are fitted to a sum of a threshold function describing the background and a modified Gaussian function describing the signal. The threshold function has the form

$$A \cdot (m - m_p - m_{\pi^-})^B \cdot \exp[C \cdot (m - m_p - m_{\pi^-}) + D \cdot (m - m_p - m_{\pi^-})^2],$$

where m_p and m_{π^-} are the proton and pion masses, respectively, and A, B, C and D are free parameters. The Λ^0 signal yields are found to be 7710 ± 120 and 702 ± 38 for the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ candidates, respectively. The numbers of signal charmonium and Λ^0 events are larger than the numbers of the corresponding Λ_b^0 signal events because the backgrounds are partly due to genuine charmonium and Λ^0 states.

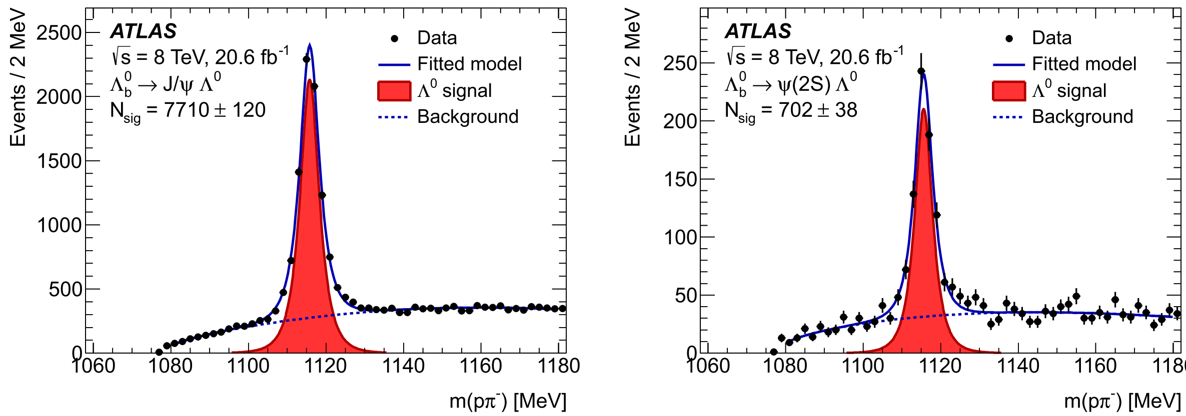

Fig. 5. The $m(p\pi^-)$ distributions for $\Lambda_b^0 \to J/\psi\Lambda^0$ candidates (left plot) and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ candidates (right plot) after full selection, without a mass constraint on the Λ^0 mass in the cascade fit. The spectra are fitted with a sum of a threshold function and a modified Gaussian function.

4. Measurement of the Λ_b^0 branching ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$

The numbers of Λ_b^0 signal events in the two decay modes, reported in Table 1, are corrected for detector effects and selection efficiencies as $N_{\rm cor} = N_{\rm sig}/\mathcal{A}$, where $N_{\rm cor}$ is the corrected number and $\mathcal{A}$ is the MC acceptance. The MC events with the $\psi(2S)/J/\psi$ muons having transverse momenta above 3.5 GeV and pseudorapidities within ±2.5, and Λ^0 transverse momentum above 1 GeV, passed through the detector simulation and event reconstruction, are used to correct the numbers of signal events in the fiducial range, defined as follows:

$$p_{\rm T}(\Lambda_b^0) > 10\ \text{GeV},\ |\eta(\Lambda_b^0)| < 2.1,$$
$$p_{\rm T}(\mu^\pm) > 4\ \text{GeV},\ |\eta(\mu^\pm)| < 2.3,$$
$$p_{\rm T}(\Lambda^0) > 2.5\ \text{GeV}.$$

The acceptances are calculated as the ratio of the number of reconstructed Λ_b^0 signal events passing all selection requirements in the above fiducial range to the number of Λ_b^0 baryons in the same decay mode and fiducial range at the MC generator level. These acceptances are $4.16 \pm 0.02(\text{stat})\%$ and $4.30 \pm 0.03(\text{stat})\%$ for the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decays, respectively. In the fiducial range, the ratio of the corrected numbers of Λ_b^0 signal events in the two decay modes is $0.0841 \pm 0.0055(\text{stat})$.

Then the numbers are corrected, using generator-level MC samples with no requirements on the $\mu^\pm$ and Λ^0 selection, from the above fiducial range to the kinematic range of the Λ_b^0 measurement

$$p_{\rm T}(\Lambda_b^0) > 10\ \text{GeV},\ |\eta(\Lambda_b^0)| < 2.1.$$

The acceptances of the latter corrections are $7.57 \pm 0.06(\text{stat})\%$ and $9.61 \pm 0.07(\text{stat})\%$ for the $\Lambda_b^0 \to J/\psi\Lambda^0$ and $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decays, respectively. Finally, the branching ratio of the two Λ_b^0 decays is calculated as

$$\frac{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)} = \frac{N_{\rm cor}(\Lambda_b^0 \to \psi(\mu^+\mu^-)\Lambda^0)}{N_{\rm cor}(\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0)} \cdot \frac{\mathcal{B}(J/\psi \to \ell^+\ell^-)}{\mathcal{B}(\psi(2S) \to \ell^+\ell^-)},$$

where $\mathcal{B}$ is the branching fraction of the corresponding charmonium decay to a lepton pair. In the case of J/ψ, the branching fraction $\mathcal{B}(J/\psi \to \mu^+\mu^-) = 0.05961 \pm 0.00033$ [12] is used. For $\mathcal{B}(\psi(2S) \to \ell^+\ell^-)$, the branching fraction $\mathcal{B}(\psi(2S) \to e^+e^-) = 0.00789 \pm 0.00017$ is used, assuming lepton universality, because it is measured with better precision than in the muon channel, $\mathcal{B}(\psi(2S) \to \mu^+\mu^-) = 0.0079 \pm 0.0009$ [12].

Five groups of systematic uncertainty sources are considered. The effect of each group on the measured ratio, obtained by adding in quadrature the effects of independent sources, is shown in parentheses:

- Dependence on the Λ_b^0 production model (±0.1%). The uncertainty is obtained by
  - varying the MC $p_{\rm T}(\Lambda_b^0)$ and $|\eta(\Lambda_b^0)|$ distributions while preserving agreement with the data distributions,
  - varying the MC ratio of Λ_b^0 and $\bar{\Lambda}_b^0$ baryons in the range allowed by the separate data fits (Section 3),
  - varying the lifetimes of the Λ^0 and Λ_b^0 baryons in the ranges of their uncertainties [12].
- Dependence on the Λ_b^0 polarisation model (±1.1%). The uncertainty is obtained by varying the MC $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ helicity amplitudes in the range of their uncertainties [2], and by changing the MC $\Lambda_b^0 \to \psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ helicity amplitudes to those measured by ATLAS for the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ decay [2].
- The uncertainty of the signal extraction procedures (±2.8%). The uncertainty is determined by changing the background parameterisations to second order polynomials and by reducing the ranges used for the signal fits by 20 MeV from either left or right side, independently for the two Λ_b^0 signals. In addition, the corrections of the reflection normalisations, obtained from MC simulation, are varied by half of their values. This uncertainty is affected by statistical fluctuations.
- The uncertainty originating from the MC statistical uncertainty (±1.3%).
- The uncertainty of the charmonium branching fractions $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ and $\mathcal{B}(\psi(2S) \to e^+e^-)$ (±2.2%).

The measured branching ratio of the two Λ_b^0 decays is

$$\frac{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \to J/\psi\,\Lambda^0)} = 0.501 \pm 0.033(\text{stat}) \pm 0.016(\text{syst}) \pm 0.011(\mathcal{B}),$$

where the contributions from the first four groups of systematic uncertainty are added in quadrature. The uncertainty due to the uncertainties of the charmonium branching fractions $\mathcal{B}$ is quoted separately. The luminosity uncertainty, uncertainties of the muon and hadron track reconstruction and the vertexing uncertainties cancel out in the ratio. The bias in the measured ratio due to contributions from the rare decay $\Lambda_b^0 \to \mu^+\mu^-\Lambda^0$ is estimated using the LHCb measurement [9] of the rare decay's differential branching fraction to be below 0.5% and thus neglected. Consistent ratio values are found when calculated in bins of $p_T(\Lambda_b^0)$ or separately for Λ_b^0 and $\bar{\Lambda}_b^0$ baryons.

The measured ratio lies in the range 0.5–0.8 found for the branching ratios of analogous B meson decays [12]. The only available calculation for the branching ratio of the two Λ_b^0 decays (0.8 ± 0.1 [11]) exceeds the measured value.

5. Summary

The $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay has been observed with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV at the LHC using an integrated luminosity of 20.6 fb^{-1}. The branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays has been measured to be $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0) = 0.501 \pm 0.033(\text{stat}) \pm 0.016(\text{syst}) \pm 0.011(\mathcal{B})$. The ratio falls into the range 0.5–0.8, as found for the branching ratios of analogous B meson decays [12]. The only available theoretical expectation for the branching ratio of the two Λ_b^0 decays (0.8 ± 0.1 [11]) exceeds the measured value.

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