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Study of Λ_b^0 decay properties with the ATLAS detector

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The measurements of the Λ_b^0 baryon decay properties are presented using $4.6-4.9$ fb^{-1} proton-proton collisions data recorded by the ATLAS detector during 2011 LHC operation. The results of the Λ_b^0 mass, lifetime and the lifetime ratio $\tau(\Lambda_b^0)/\tau(B_d^0)$, as well as the parity-violating decay asymmetry parameter, α_b, and the helicity amplitudes of the decay channel $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ are reported and compared with those of the LHCb, D0 and CDF experiments, as well as with theoretical models based on heavy-quark effective theory and perturbative QCD.

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1. Introduction

The lightest baryon with a constituent b-quark, Λ_b^0, with quark composition udb was firstly observed in 1991 by the UA1 experiment at the $p\bar{p}$ collider at CERN in the decay channel $\Lambda_b^0 \to J/\psi\Lambda^0$ [1]. First lifetime measurements are performed by the DELPHI experiment at LEP in 1992 using the semileptonic Λ_b^0 decays [2], while the first lifetime measurement in the fully reconstructed channel is performed by the CDF experiment at Tevatron [3]. Currently the hadron colliders are the only facilities to study properties of b-baryons.

Measurements of the lifetime of hadrons containing b-quarks provide important tests of the significance of strong interactions between the constituent partons in the weak decay of b-hadrons. These interactions produce measurable differences between b-hadron lifetimes that are predicted with good accuracy through the calculation of lifetime ratios such as $\tau(B^-)/\tau(\bar{B}_d^0)$, $\tau(\bar{B}_s^0)/\tau(\bar{B}_d^0)$, and $\tau(\Lambda_b^0)/\tau(\bar{B}_d^0)$ in the heavy-quark effective theory (HQET) [4].

Within the framework of the Standard Model of weak interactions, it has been known that weak decays violate parity. While parity violation in decays of muon and tau leptons is exhibited in its maximal form, parity violation in the hadronic sector is not maximal and depends on the hadron's constituents. Parity violating asymmetry parameter, α_b, for the decay $\Lambda_b^0 \to J/\psi\Lambda^0$, is of particular interest since it can serve as a test for various quark models such as perturbative QCD (pQCD) and factorization models [5]. A measurement of this parameter is of high interest in order to tune the quark models with realistic predictions.

In this report, we present the measurements of the mass and lifetime of the Λ_b^0, the lifetime ratio $\tau(\Lambda_b^0)/\tau(B_d^0)$ [6], as well as the parity-violating decay asymmetry parameter and the helicity amplitudes [7], with the ATLAS detector [8] at LHC, using the decay channel $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$. The results are compared with those obtained with the LHCb, D0 and CDF experiments, as well as with the theoretical models based on the HQET and pQCD.

The ATLAS detector at the LHC is a general-purpose particle detector designed to be sensitive to a wide range of physics phenomena. It covers almost full solid angle around the pp collision point with layers of tracking detectors, calorimeters and muon chambers. For the measurements presented in this paper, the Inner Detector tracking devices (ID) and the Muon Spectrometer (MS) are of particular importance. The ATLAS ID has acceptance in pseudorapidity $|\eta| < 2.5$, and it is designed to achieve the highest precision in the transverse plane with a relative transverse momentum resolution of $\sigma_{p_\mathrm{T}}/p_\mathrm{T} = 0.05\% \times p_\mathrm{T}(\mathrm{GeV}) \oplus 1\%$ and a transverse impact parameter resolution of 10 μm. The ATLAS MS covers $|\eta| < 2.7$ and has a momentum resolution of $\sim 10\%$ up to 1 TeV. The MS consists of the precision-tracking chambers which are used to determine the coordinate of the muon track in η and the trigger chambers with coarse resolution, but fast response time. Tracks are reconstructed in the ID, and only tracks with p_T above 400 MeV and pseudorapidity $|\eta| < 2.5$ are used in this analysis. Both ID and the MS are used to identify muons.

2. Reconstruction and selection of $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ decays

The decay $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ has a cascade topology with two vertices and four final state particles, two muons from the J/ψ decay, and proton and pion from the Λ^0 decay. The J/ψ decays instantly at the same point as the Λ_b^0, while Λ^0 lives long enough to form a displaced tertiary vertex. The di-muon and di-hadron pairs are pre-selected by requiring that their respective tracks are successfully fitted to a common vertex [9]. The di-muon pairs are accepted if the J/ψ vertex-refitted invariant mass lies in the range $2.8 < m_{\mu\mu} < 3.4$ GeV. The di-hadron candidates are accepted if $1.08 < m_{p\pi} < 1.15$ GeV [6].

The preselected muon and hadron track pairs are refitted with a constraint of a $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ cascade decay topology. The muons (hadrons) are constrained to intersect in a single vertex while their invariant mass must be equal to the known mass of the J/ψ (Λ^0). The combined momentum of the refitted Λ^0 track pair is constrained to point to the di-muon vertex. The fit is performed on all four final state particles tracks simultaneously taking into account the constraints from cascade topology fit and the full track error matrices [9]. The quality of the fit is characterised by the value of χ^2/N_{dof}, where the number of degrees of freedom $N_{dof} = 6$. The Λ_b^0 candidates are selected if: (i) $\chi^2/N_{dof} < 3$, (ii) $p_{\mathrm{T},\Lambda^0} > 3.5$ GeV, (iii) the transverse decay length of the cascade-refitted Λ^0 vertex measured from the Λ_b^0 vertex, $L_{xy,\Lambda^0} > 10$ mm and (iv) $5380 < m_{J/\psi\Lambda^0} < 5900$ MeV. In order to reject background from $B_d^0 \to J/\psi K_S^0$ decays, a difference of cumulative χ^2 probabilities $\mathscr{P}_{\Lambda_b^0} - \mathscr{P}_{B_d^0} > 0.05$ is required, if the four tracks forming the Λ_b^0 candidate also result in an acceptable B_d^0 fit.

3. Λ_b^0 mass and lifetime measurement

The measurements of the Λ_b^0 mass and lifetime is performed using 4.9 fb^{-1} of data collected with the LHC during 2011 in pp collisions at $\sqrt{s} = 7$ TeV. Events are selected using single-muon, di-muon, and J/ψ triggers. To study systematic effects and to correct for the efficiency and acceptance of the detector a Monte Carlo (MC) sample of 5×10^6 antibaryon $\bar{\Lambda}_b^0$ events is used. The sample is generated using the PYTHIA 6 MC generator [10] with the 2011 ATLAS AUET2B L0** tune [11]. After the selection described in Sec. 2, there are about 2200 Λ_b^0 and $\bar{\Lambda}_b^0$ candidates (including background) in the signal region.

The Λ_b^0 lifetime and mass are determined using a simultaneous unbinned maximum likelihood fit to the reconstructed mass and decay time of the selected candidates. For each reconstructed candidate the proper decay time is calculated as $\tau_{\Lambda_b^0} = L_{xy,\Lambda_b^0} \times m^{PDG}/p_{\mathrm{T}}$, where $m^{PDG} = 5619.4$ MeV [12], p_{T} is the reconstructed Λ_b^0 transverse momentum, and L_{xy,Λ_b^0} is the Λ_b^0 transverse decay distance measured from the primary vertex. Measurement procedure consists of selecting signal events, building probability density function (PDF) for mass and proper decay time for signal and background events. The mass and proper decay time are fitted using a likelihood function defined as [6]:

$$L = \prod_{i=1}^{N} [f_{sig}\mathfrak{M}_s(m_i|\delta_{m_i})\mathfrak{T}_s(\tau_i|\delta_{\tau_i})w_s(\delta_{m_i},\delta_{\tau_i}) + (1-f_{sig})\mathfrak{M}_b(m_i|\delta_{m_i})\mathfrak{T}_b(\tau_i|\delta_{\tau_i})w_b(\delta_{m_i},\delta_{\tau_i})]$$

where f_{sig} is the fraction of reconstructed signal candidates, m_i is the invariant mass of the i^{th} candidate and τ_i is its proper decay time. The corresponding errors, δm_i and $\delta\tau_i$, are estimated on a candidate-by-candidate basis by the cascade topology fit. The $\mathfrak{M}_s$ and $\mathfrak{M}_b$ are PDFs describing the signal and background dependence on mass; $\mathfrak{T}_s$ and $\mathfrak{T}_b$ describe the dependence on the proper decay time. The invariant mass and proper decay time error distributions, $w_{s(b)}(\delta_{m_i},\delta_{\tau_i})$, are extracted from data. The free parameters of the fit are: the Λ_b^0 mass and lifetime, $m_{\Lambda_b^0}$ and $\tau_{\Lambda_b^0}$, the fraction of signal events, f_{sig}, the error scale factors, S_m and S_τ, and seven parameters describing the background shapes. The other quantities are calculated from the fit parameters. The results from the maximum likelihood fit are listed in Table 1. Projections of the PDF onto the mass and proper decay time axes are shown in Fig. 1.

Table 1: Results from the simultaneous mass and decay time maximum likelihood fit for Λ_b^0 [6].

Parameter	*Value*	*Parameter*	*Value*
$m(\Lambda_b^0)$	5619.7 ± 0.7 MeV	χ^2/N_{dof}	1.09
$\tau(\Lambda_b^0)$	1.449 ± 0.036 ps	N_{sig}	2184 ± 57
f_{sig}	0.268 ± 0.007	N_{bkg}	5970 ± 160
S_m	1.18 ± 0.03	σ_m	31.1 ± 0.8 MeV
S_τ	1.05 ± 0.02	σ_τ	0.117 ± 0.003 ps

The measured values for the Λ_b^0 lifetime and mass are:

$$\tau_{\Lambda_b^0} = 1.449 \pm 0.036(stat) \pm 0.017(syst) \text{ ps};$$
$$m_{\Lambda_b^0} = 5619.7 \pm 0.7(stat) \pm 1.1(syst) \text{ MeV}.$$

In order to cross-check the Λ_b^0 results and to determine the ratio $\tau(\Lambda_b^0)/\tau(B_d^0)$, the B_d^0 lifetime and mass has also been measured using the decay $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$. The selection is chosen to be as close as possible to the Λ_b^0 selection in order to reduce the overall systematic error on the lifetime ratio measurement. Using an unbinned maximum likelihood fit, the B_d^0 lifetime and mass are measured to be $\tau_{B_d^0} = 1.509 \pm 0.012(stat) \pm 0.018(syst)$ ps and $m_{B_d^0} = 5279.6 \pm 0.2(stat) \pm 1.0(syst)$ MeV. These values are consistent with the world averages [12]. The value of Λ_b^0 and B_d^0 lifetime ratio is:

$$R = \tau_{\Lambda_b^0}/\tau_{B_d^0} = 0.960 \pm 0.025(stat) \pm 0.016(syst).$$

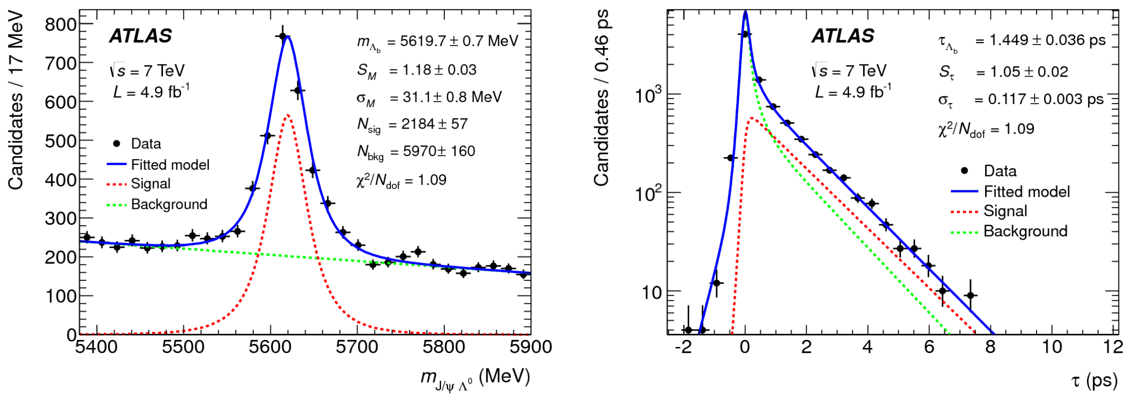

Figure 1: Projections of the fitted PDF onto the mass (left) and the proper decay time (right) axes for Λ_b^0 candidates. The errors are statistical only. The χ^2/N_{dof} value is calculated from the data set binned in mass and decay time with the number of degrees of freedom, $N_{dof} = 61$ [6].

4. Measurement of α_b and helicity amplitudes

The measurement of the parity-violating asymmetry parameter, α_b, and the decay amplitudes is performed by using an angular analysis of $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ weak decay. For strongly-produced Λ_b^0 baryons, a large fraction of the transverse b-quark polarisation is predicted by HQET to be retained after hadronisation [13], while the longitudinal polarisation should vanish due to parity conservation in strong interactions. The analysis uses 4.6 fb^{-1} of data collected with the LHC during 2011 in pp collisions at $\sqrt{s} = 7$ TeV. Events are selected using single-muon and J/ψ triggers. To study the efficiency and acceptance of the detector, MC sample of inclusive inelastic events is generated using the PYTHIA 6.4.

The reconstruction and selection of the Λ_b^0 decays is done as described in Sec. 2 with additional requirements: (i) $\mathscr{P}_{\Lambda_b^0} > \mathscr{P}_{B_d^0}$, (ii) $\tau > 0.35$ ps and (iii) 5560 MeV $< m_{J/\psi\Lambda^0} <$ 5680 MeV. After the selection, in total there are 1548 Λ_b^0 and $\bar{\Lambda}_b^0$ candidates (including background) in the signal region.

In the helicity formalism, the process $\Lambda_b^0 \to \Lambda V(1^-)$ can be described by four helicity amplitudes $A(\lambda_1,\lambda_2): a_+ \equiv A(1/2,0), a_- \equiv A(-1/2,0), b_+ \equiv A(-1/2,-1), b_- \equiv A(1/2,1)$, where $\lambda_{1(2)}$ is the helicity of the $\Lambda(V)$ particle and $|a_+|^2+|a_-|^2+|b_+|^2+|b_-|^2 = 1$. The angular distribution of the decay ($\frac{d\Gamma}{d\Omega_5}$) is reported in [14]. It depends on the five angles shown in Fig. 2: (i) θ, the polar angle of the Λ^0 momentum in the Λ_b^0 rest frame with respect to $\hat{n}$, a unit vector perpendicular to the production plane, (ii) θ_1 and ϕ_1, the polar and azimuthal angles of the proton in the Λ^0 rest frame with respect to the Λ^0 direction in the Λ_b^0 rest frame, (iii) θ_2 and ϕ_2, the polar and azimuthal angles of μ^+ in the J/ψ rest frame with respect to the J/ψ direction in the Λ_b^0 rest frame.

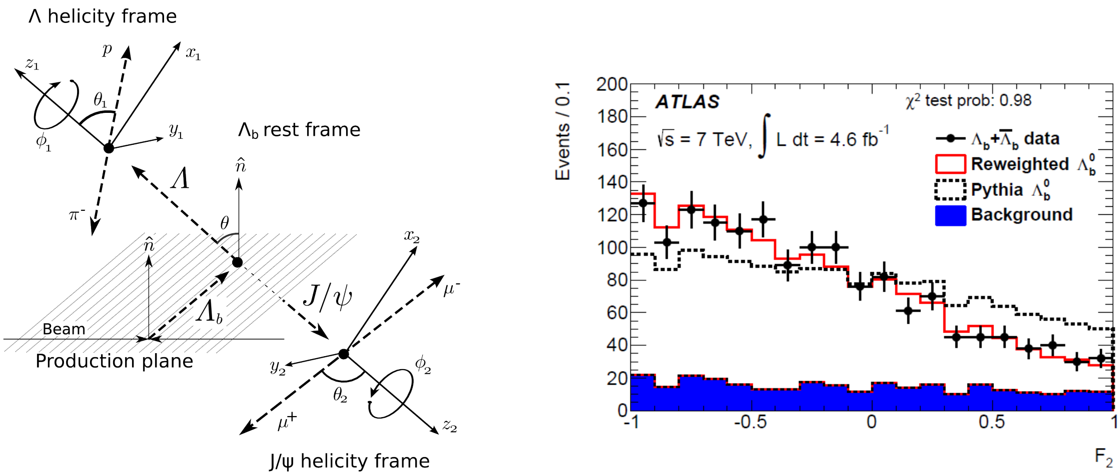

Figure 2: The $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0$ $(p\pi^-)$ decay angles (left), and distributions of the F_2 variable (right) for the model prediction compared to data (black points). The model prediction is obtained by plotting the weighted MC (red solid histogram) on the top of the background (blue area). The prediction obtained using the un-weighted MC (black dashed histogram) is also shown [7].

The full angular PDF of the decay angles collection $\Omega = (\theta,\phi,\theta_1,\phi_1,\theta_2,\phi_2)$ is [7]:

$$\omega(\Omega,\vec{A},P) = \frac{1}{(4\pi)^3}\sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P,\alpha_\Lambda) F_i(\Omega)$$

Table 2: The coefficients f_{1i}, f_{2i} and F_i of the remaining six terms of the PDF for $P=0$. The f_{1i} functions are expressed using the five free parameters defined in the text [7].

i	f_{1i}	f_{2i}	F_i
0	1	1	1
2	$(k_0^2+k_1^2-1)+\alpha_b(k_0^2-k_1^2)$	α_Λ	$\cos\theta_1$
4	$\frac{1}{4}[(3k_1^2-3k_0^2-1)+3\alpha_b(1-k_1^2-k_0^2)]$	1	$\frac{1}{2}(3\cos^2\theta_2-1)$
6	$-\frac{1}{4}[(k_0^2+k_1^2-1)+\alpha_b(3+k_0^2-k_1^2)]$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2-1)\cos\theta_1$
18	$\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_1^2(1-k_1^2)}\cos(-\Delta_-)-\frac{1+\alpha_b}{2}\sqrt{k_0^2(1-k_0^2)}\cos(\Delta_+)]$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
19	$-\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_1^2(1-k_1^2)}\sin(-\Delta_-)-\frac{1+\alpha_b}{2}\sqrt{k_0^2(1-k_0^2)}\sin(\Delta_+)]$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$

where $f_{1i}(\vec{A})$ are bilinear combinations of the helicity amplitudes, $\vec{A}\equiv(a_+,a_-,b_+,b_-)$, f_{2i} is equal to: $P\alpha_\Lambda$, P, α_Λ or 1, where α_Λ is the decay asymmetry parameter for the decay $\Lambda^0\to p\pi^-$ and P is the Λ_b^0 polarisation. $F_i(\Omega)$ are orthogonal functions of the decay angles.

There are nine unknown parameters in the given PDF: four complex helicity amplitudes, $a_+ = |a_+|e^{i\rho_+}$, $a_+ = |a_-|e^{i\rho_-}$, $b_+ = |b_+|e^{i\rho_+}$, $b_- = |b_-|e^{i\rho_-}$, and P. Due to a symmetry of the initial state in the beam direction at pp collider (z-axis in the ATLAS coordinate system) and the symmetry of the ATLAS detector in rapidity, the overall polarisation of the collected data-sample will be zero. As a result, the PDF is reduced from twenty to six terms listed in Table 2 and five free parameters: three magnitudes of the helicity amplitudes and two relative phases (from seven parameters). The coefficients f_{1i} are written in terms of the following five parameters chosen to define the model:

$$\alpha_b = |a_+|^2-|a_-|^2+|b_+|^2-|b_-|^2$$
$$k_0 = |a_+|/\sqrt{|a_+|^2+|b_+|^2} \qquad k_1 = |b_-|/\sqrt{|a_-|^2+|b_-|^2}$$
$$\Delta_+ = \rho_+ - \omega_+ \qquad \Delta_- = \rho_- - \omega_-$$

Assuming CP conservation, the PDF of Λ_b^0 and $\bar{\Lambda}_b^0$ decay have the same form, and the samples are combined to measure the asymmetry parameter α_b and the helicity amplitudes with better precision.

The analysis uses the method of moments, by measuring the average values of each of the moments, $\langle F_i\rangle$, to extract the helicity amplitudes and α_b from them. The χ^2 fit is performed to determine the five main parameters of the measurement:

$$\chi^2 = \sum_{i=1}^{5}\sum_{j=1}^{5}(\langle F_i\rangle^{expected}-\langle F_i\rangle)V_{ij}^{-1}(\langle F_j\rangle^{expected}-\langle F_j\rangle)$$

where $\mathbf{V}$ is the covariance matrix of the measured $\langle F_i\rangle$ values and $\langle F_i\rangle^{expected}$ can be calculated from the PDF as: $\langle F_i\rangle^{expected} = \sum f_{1j}(\vec{A})f_{2j}(\alpha_\Lambda)C_{ij}$. Detector effects are given in the correction matrix $\mathbf{C}$, which is independent of the measured helicity amplitude parameters and is therefore determined from MC simulation with flat angular distributions. The $\langle F_i\rangle$ are measured directly from data after subtraction of the estimated contribution from the combinatorial background and B_d^0 events. Since the combinatorial background[1] depends linearly on the Λ_b mass, its contribution to the measured

[1] *Combinatorial background* consists of real or fake J/ψ and Λ^0 candidates randomly combined to create a Λ_b^0-like topology. It is the main component of the background.

$\langle F_i \rangle$ values is estimated using events from the invariant-mass sidebands. The estimated number of B_d^0 events in the signal region (peaking background) is used to calculate the contribution of the B_d^0 events to the averaged $\langle F_i \rangle$ and the estimated contribution is subtracted. To determine the number of signal, combinatorial and B_d^0 background events, a binned maximum likelihood fit to the Λ_b^0 invariant mass distribution is performed. The observed number of Λ_b^0 is 1243 ± 44, and the number of B_d^0 events is estimated to be 73 ± 30. To check the fit results, the MC events were weighted using the signal PDF with the parameters obtained from the fit. This weighted MC and sideband background distributions of F_i are added and compared with data. Figure 2 (right) shows this comparison for the parameter F_2. The values of the asymmetry parameter and helicity amplitudes obtained from the results of the χ^2 fit are:

$$\alpha_b = 0.30 \pm 0.16(stat) \pm 0.06(syst.)$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(stat.) \pm 0.09(syst.) \qquad |a_-| = 0.59^{+0.06}_{-0.07}(stat.) \pm 0.03(syst.)$$

$$|b_+| = 0.79^{+0.04}_{-0.05}(stat.) \pm 0.02(syst.) \qquad |b_-| = 0.08^{+0.13}_{-0.08}(stat.) \pm 0.06(syst.)$$

The large measured values for the helicity amplitudes $|a_-|$ and $|b_+|$ mean that the negative-helicity states for Λ_0 are preferred. The Λ_0 and J/ψ from Λ_b^0 decay are highly polarised. The measured value of the asymmetry parameter is consistent with a recent LHCb measurement [15].

5. Conclusions

The measurements of the Λ_b^0 mass, lifetime and the ratio of the Λ_b^0 and B_d^0 lifetimes, as well as the parity-violating asymmetry parameter and helicity amplitudes are presented. Measured values for the Λ_b^0 mass and lifetime by the ATLAS experiment agree with the world average values [12] and recent measurements by the LHCb [16, 17] and the CMS [18] experiments. The ratio of the Λ_b^0 and B_d^0 lifetimes is consistent with the measurements by the LHCb [17], the D0 [19] and the CDF [20] experiments. The value of the ratio obtained by this measurement is in agreement with the prediction from heavy-quark expansion calculations which predict the value between 0.88 and 0.97 [21] and is compatible with pQCD prediction [22] which is between 0.86 and 0.88 (with an uncertainty of ± 0.05). The value of the asymmetry parameter, α_b, measured by the ATLAS experiment is consistent with the recent measurement of the LHCb experiment at the level of one standard deviation. Comparing to theoretical models, the ATLAS measurement of α_b differs by about 2.5 standard deviations from the range of $\alpha_b \sim -(0.14 \sim 0.18)$ expected from pQCD [5] and by about 2.9 standard deviations from the HQET expectation [23, 24] of α_b = 0.78.

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