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The ATLAS Collaboration

Abstract

A measurement of the Λ_b^0 lifetime and mass in the decay channel $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ is presented. The analysis uses a signal sample of about 2200 Λ_b^0 and $\bar{\Lambda}_b^0$ decays that are reconstructed in 4.9 fb^{-1} of ATLAS pp collision data collected in 2011 at the LHC center-of-mass energy of 7 TeV. A simultaneous mass and decay time maximum likelihood fit is used to extract the Λ_b^0 lifetime and mass. They are measured to be $\tau_{\Lambda_b} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})$ ps and $m_{\Lambda_b} = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})$ MeV.

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(Dated: November 4, 2018)

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I. INTRODUCTION

The Λ_b^0 baryon (and its charge conjugate $\bar{\Lambda}_b^0$) is the lightest baryon containing a b (\bar{b}) quark. With a mass of about 5620 MeV [1, 2] it is not produced at B factories, where the collision center-of-mass energy is tuned to produce pairs of B mesons. Currently, hadron colliders are the only facilities where the properties of b baryons can be studied. This paper presents a measurement of the Λ_b^0 mass and lifetime in the ATLAS experiment [3] using the decay channel $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ (the charge conjugate mode is implied throughout the paper unless explicitly stated otherwise). The Λ_b^0 lifetime, although measured by many experiments [1, 4–6], still suffers from a large experimental uncertainty.

The decay $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ has the same topology as the studied Λ_b^0 decay. The B_d^0 mass and lifetime are measured with good precision [1], and therefore this decay provides a useful tool to validate the Λ_b^0 results, as both measurements are subject to similar systematic uncertainties. The lifetime ratio, $\tau_{\Lambda_b}/\tau_{B_d}$, can be predicted by heavy quark expansion calculations [7] and perturbative QCD [8] and is of great theoretical interest. The lifetime and mass are determined using a simultaneous unbinned maximum likelihood fit to the reconstructed mass and decay time of each selected candidate.

II. DATA SAMPLES AND TRIGGER SELECTION

The ATLAS experiment [3] is a general-purpose detector at the Large Hadron Collider (LHC). It covers nearly the entire solid angle around the interaction point with layers of tracking detectors, calorimeters, and muon chambers. The coordinate system has the z axis aligned with the beam direction. The transverse momentum p_T and pseudorapidity, η , of reconstructed particles are defined with respect to that direction. This analysis uses two ATLAS subsystems: the inner detector (ID) and the muon spectrometer (MS). Both are situated in a magnetic field and serve as tracking detectors. The ID consists of three types of detector: the silicon pixel detector (Pixel), the silicon microstrip detector (SCT), and the transition radiation tracker (TRT). The MS consists

of monitored drift tube chambers (MDT) and cathode strip chambers (CSC) for precision muon measurements, resistive plate chambers (RPC) and thin gap chambers (TGC) employed by the muon-trigger system. Tracks are reconstructed in the ID, and the MS is used to identify muons. Only tracks with p_T above 400 MeV and pseudorapidity $|\eta| < 2.5$ are used in this analysis.

The analysis is based on data collected in 2011 using single-muon, dimuon, and J/ψ triggers. The ATLAS trigger system [9] has three levels: the hardware-based Level-1 trigger and the two-stage High Level Trigger (HLT). At Level-1 the muon trigger uses dedicated fast muon-trigger chambers to search for patterns of hits corresponding to muons passing different p_T thresholds. Regions of interest (RoI) around these Level-1 hit patterns then serve as seeds for the HLT muon reconstruction. Since the rate from the low- p_T muon triggers was too high for all accepted events to be saved, prescale factors were applied to a subset of the triggers to reduce the output rate. The muon transverse momentum thresholds for single and dimuon triggers range from 4 to 22 GeV. The J/ψ dimuon triggers require that the muons originate from a common vertex and have opposite charge, and that the dimuon mass is in the range $2.5 \text{ GeV} < m_{\mu\mu} < 4.3 \text{ GeV}$. The majority of the sample was collected by the J/ψ trigger with a p_T threshold of 4 GeV applied to each muon. This was the lowest- p_T un-prescaled trigger in the 2011 data taking; however, other complementary triggers were used, too. The p_T spectrum of the selected muons peaks at 5 GeV; the lowest muon p_T is above 2.5 GeV.

A Monte Carlo (MC) sample of 5×10^6 antibaryon $\bar{\Lambda}_b^0$ events is used to study systematic effects and to correct for the efficiency and acceptance of the detector. The sample is generated using the PYTHIA 6 MC generator [10] with the 2011 ATLAS AUET2B L0** tune [11], and the events are filtered so that each accepted event has a decay $\bar{\Lambda}_b^0 \rightarrow J/\psi(\mu^+\mu^-)\bar{\Lambda}^0(\bar{p}\pi^+)$ with the muons having transverse momenta of at least 2.5 GeV. The MC sample is generated with a Λ_b^0 lifetime of $\tau_{\Lambda_b}^{\text{MC}} = 1.391 \text{ ps}$.

III. RECONSTRUCTION AND SIGNAL SELECTION

A. J/ψ and Λ^0 preselection

The decay $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ has a cascade topology. The J/ψ decays instantly at the same point as the Λ_b^0 (secondary vertex), while the Λ^0 lives long enough to form a displaced tertiary vertex. There are four final-state particles: two muons from the J/ψ , and a proton and a pion from the Λ^0 decay.

The dimuon and dihadron (V^0) pairs are preselected by requiring that their tracks be successfully fitted to a common vertex satisfying some basic quality requirements. The J/ψ and V^0 pre-selection is very loose, so that potential candidates are not excluded at this stage. The dimuon candidates are accepted if the J/ψ vertex-refitted invariant mass lies in the range $2.8 \text{ GeV} < m_{\mu\mu} < 3.4 \text{ GeV}$. The dihadron candidates are accepted if the invariant mass is in the range $1.08 \text{ GeV} < m_{p\pi} < 1.15 \text{ GeV}$. The masses of a proton and a pion are assigned to the tracks when the invariant mass is calculated; $p\pi^-$ and $\bar{p}\pi^+$ combinations are tested so that both Λ^0 and $\bar{\Lambda}^0$ candidates are accepted.

B. Reconstruction of $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$

The muon and hadron track pairs preselected with the criteria described in the previous section are then refitted with a constraint of a $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ topology. The muons are constrained to intersect at a single vertex, while their invariant mass is set equal to the known mass of the J/ψ , $m_{J/\psi} = 3096.92 \text{ MeV}$ [1]. The two hadronic tracks are constrained to a second vertex, and their invariant mass is fixed to the mass of the Λ^0 , $m_{\Lambda^0} = 1115.68 \text{ MeV}$ [1]. The combined momentum of the refitted V^0 track pair is constrained to point to the dimuon vertex in three dimensions. The fit is performed on all four tracks simultaneously, taking into account the constraints described above (cascade topology fit) and the full track error matrices. The quality of the fit is characterized by the value of χ^2/N_{dof} , where a global χ^2 involving all four tracks is used. The corresponding number of degrees of freedom, N_{dof} , is six. Furthermore, for each track quadruplet, that can be successfully fitted to the Λ_b^0 decay topology, a $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ topology fit is attempted (i.e. a pion mass is assigned to the hadronic tracks and the V^0 mass is constrained to the mass of K_S^0 , $m_{K_S} = 497.65 \text{ MeV}$ [1]). This is to identify possible B_d^0 decays mistaken for Λ_b^0 .

The Λ_b^0 candidates are then subjected to the following selections:

- The global $\chi^2/N_{\text{dof}} < 3$.
- The transverse momentum of the cascade-refitted V^0 , $p_{T,V^0} > 3.5 \text{ GeV}$.

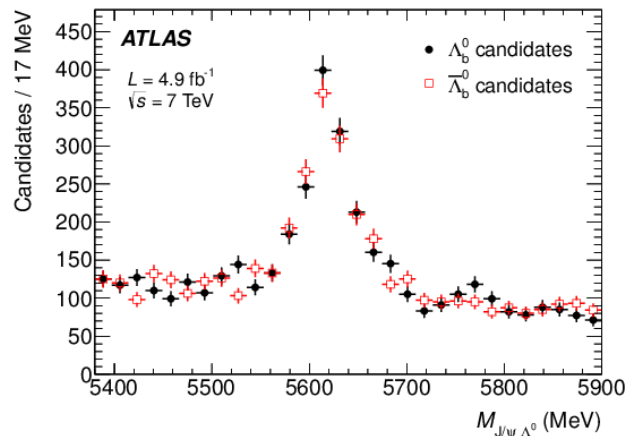


FIG. 1. Invariant mass distribution of the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates.

- The transverse decay length of the cascade-refitted V^0 vertex measured from the Λ_b^0 vertex, $L_{xy,V^0} > 10 \text{ mm}$.
- The invariant mass must be in the range $5.38 \text{ GeV} < m_{J/\psi\Lambda^0} < 5.90 \text{ GeV}$.
- If the four tracks forming a Λ_b^0 candidate also result in an acceptable B_d^0 fit, the candidate must have a difference of cumulative χ^2 probabilities of the two fits, $\mathcal{P}_{\Lambda_b^0} - \mathcal{P}_{B_d} > 0.05$.

With these criteria, 4074 Λ_b^0 and 4081 $\bar{\Lambda}_b^0$ candidates (including background) are selected. No track quadruplet is successfully fitted as both a Λ_b^0 and a $\bar{\Lambda}_b^0$ decay. The mass distributions of the selected candidates are shown in Fig. 1. In the rest of the paper the Λ_b^0 and $\bar{\Lambda}_b^0$ samples are combined.

IV. MASS AND PROPER DECAY TIME FIT

The proper decay time of the Λ_b^0 candidate is calculated from the measured decay distance and the candidate's momentum as follows:

$$\tau = \frac{L_{xy} m^{\text{PDG}}}{p_T},$$

where $m^{\text{PDG}} = 5619.4 \text{ MeV}$ [1], p_T is the reconstructed Λ_b^0 transverse momentum, and L_{xy} is the Λ_b^0 transverse decay distance measured from the primary vertex (PV). On average there are 6.8 collision vertices per event in the selected data resulting from multiple collisions at each LHC bunch crossing (pileup events). The collision vertex that in three-dimensional space lies closest to the trajectory of the reconstructed Λ_b^0 candidate is used as the PV.

An unbinned maximum likelihood fit is used to determine the Λ_b^0 mass and lifetime. The mass and proper decay time are fitted using a likelihood function defined as follows:

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

where f_{sig} denotes the fraction of signal candidates; m_i is the invariant mass of the i -th candidate and τ_i is its proper decay time. The corresponding errors, δ_{m_i} and δ_{τ_i} , are estimated on a candidate-by-candidate basis by the cascade topology fit. \mathcal{M}_s and \mathcal{M}_b are probability density functions (PDFs) describing the signal and background mass dependence; \mathcal{T}_s and \mathcal{T}_b describe the dependence on the proper decay time. The invariant mass and proper decay time error distributions, $w_{s(b)}(\delta_m, \delta_\tau) = w'_{s(b)}(\delta_m) w''_{s(b)}(\delta_\tau)$, are extracted from data. It has been verified that using separate PDFs for the signal and background component produces the same result when a single PDF is used, $w \equiv w_s = w_b$. For this reason the latter case is used.

The background can be divided into two categories: prompt and nonprompt backgrounds. The prompt background consists of J/ψ candidates produced directly in the pp collision that are randomly combined with V^0 candidates, which also include fake combinatorial Λ^0 or K_S^0 candidates. The prompt background decay length is due to the finite resolution of the vertex reconstruction. The nonprompt background includes events where the J/ψ candidate originates in the decay of a b hadron. This type of background has a lifetime due to its origin in long-lived b hadrons [e.g. $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$, with the K_S^0 meson misidentified as Λ^0 , forming a nonprompt background for Λ_b^0].

The signal component of the mass PDF, \mathcal{M}_s , is a Gaussian function with a mean equal to m_{Λ_b} and width $S_m \delta_m$. The mass error scale factor S_m determines how much the errors δ_{m_i} are overestimated or underestimated. The background component is a first order polynomial with a slope b .

Using the estimated decay time error δ_τ , the proper decay time resolution is modeled with a Gaussian function:

$$R(\tau - \tau' | \delta_\tau) = \frac{1}{\sqrt{2\pi} S_\tau \delta_\tau} e^{-\frac{(\tau - \tau')^2}{2(S_\tau \delta_\tau)^2}}, \quad (1)$$

where S_τ denotes the proper decay time error scale factor, and τ and τ' stand for the reconstructed and true proper decay times, respectively.

The signal and nonprompt background proper decay time distributions are modeled as exponential functions, $E(\tau'; \tau_B)$, for $\tau' > 0$, with τ_B being the fitted parameter denoting either the Λ_b^0 lifetime or the pseudolifetime of the long-lived background. The prompt background component is modeled by a sum of two functions: a Dirac δ

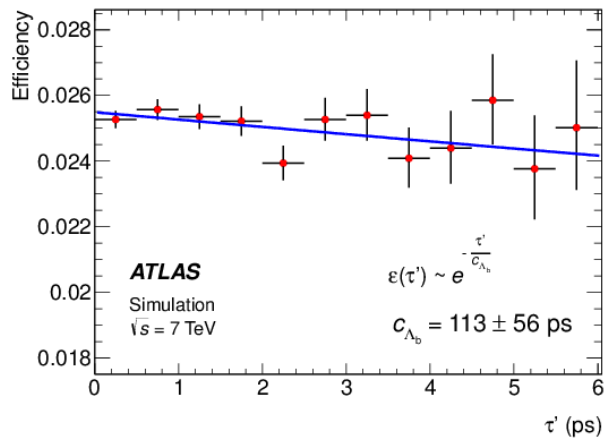


FIG. 2. Extraction of the efficiency correction for Λ_b^0 . The MC efficiency is fitted with an exponential function. The y axis has a suppressed zero. The displayed error is statistical only.

function $\delta_{\text{Dirac}}(\tau')$ and a symmetric exponential (Laplace distribution) $E_{\text{sym}}(\tau')$, to account for the non-Gaussian tails of the prompt background observed in data.

The functions are convolved with the resolution model (1) to obtain the PDFs of the measured proper decay time:

$$\begin{aligned} \mathcal{T}_s(\tau | \delta_\tau) &= \varepsilon(\tau')^{-1} E(\tau'; \tau_{\Lambda_b}) \otimes R(\tau - \tau' | \delta_\tau), \quad (2) \\ \mathcal{T}_b(\tau | \delta_\tau) &= \left[f_1 \mathcal{T}_p(\tau') + (1 - f_1) \mathcal{T}_{\text{np}}(\tau') \right] \otimes \\ &R(\tau - \tau' | \delta_\tau), \end{aligned}$$

with the nonprompt and prompt components defined as

$$\begin{aligned} \mathcal{T}_{\text{np}}(\tau') &= f_2 E(\tau'; \tau_{\text{bkg},1}) + (1 - f_2) E(\tau'; \tau_{\text{bkg},2}), \\ \mathcal{T}_p(\tau') &= f_3 \delta_{\text{Dirac}}(\tau') + (1 - f_3) E_{\text{sym}}(\tau'; \tau_{\text{bkg},3}). \end{aligned}$$

The efficiency correction function $\varepsilon(\tau')$ in Eq. (2) accounts for the decay-time-dependent selection bias.

Two sources are responsible for the selection bias in the Λ_b^0 decay time: the V^0 reconstruction efficiency and the trigger selection. The V^0 reconstruction efficiency depends on the decay distance from the center of the detector, as tracks from decays further away from the center leave fewer hits in the ID. Since the Λ_b^0 decay length and the distance of the Λ^0 vertex from the center of the detector are correlated (the latter includes the former), this biases the measured proper decay time toward smaller values. The other source of the bias is the muon trigger, which affects the distribution of the muon transverse impact parameter, d_0 . Applying the tag-and-probe method to J/ψ decays, the trigger efficiency as a function of d_0 is measured for a single-muon trigger in data. The simulation shows that the dimuon-trigger efficiency can be expressed as a product of single-muon efficiencies.

The MC events are reweighted to reproduce the observed trigger bias. The efficiency correction, $\varepsilon(\tau')$, is

TABLE I. Results of the simultaneous mass and decay time maximum likelihood fit for Λ_b^0 . The uncertainties shown are statistical only. The number of degrees of freedom used for the χ^2 calculation is $N_{\text{dof}} = 61$.

Parameter	Value	Par.	Value
m_{Λ_b}	5619.7 ± 0.7 MeV	χ^2/N_{dof}	1.09
τ_{Λ_b}	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

determined using this weighted MC sample. It is modeled as a simple exponential, $\varepsilon(\tau') \propto e^{-\tau'/c_{\Lambda_b}}$, where c_{Λ_b} denotes the slope of the efficiency correction. The exponential form is chosen for $\varepsilon(\tau')$ because it describes the MC well and is particularly easy to convolve with the resolution model. The slope of the exponential, c_{Λ_b} , is extracted from a fit to the MC decay time efficiency plot shown in Fig. 2. The extracted value is $c_{\Lambda_b} = 113 \pm 56$ ps; i.e. for a decay time of 6 ps the efficiency decreases by 5%.

A. Parameters determined from the fit

The full PDF has 12 free parameters: the Λ_b^0 mass and lifetime, m_{Λ_b} and τ_{Λ_b} ; the fraction of signal events, f_{sig} ; the error scale factors, S_m and S_τ ; the slope of the mass dependence of the background, b ; the pseudo-lifetimes of the long-lived background, $\tau_{\text{bkg},1}$ and $\tau_{\text{bkg},2}$; the exponential slope of the non-Gaussian prompt background, $\tau_{\text{bkg},3}$; and the relative fractions of the various background contributions, f_1 , f_2 , and f_3 .

Other quantities are calculated from the fit parameters. The number of signal and background candidates, N_{sig} and N_{bkg} , are calculated as $N_{\text{sig}} = f_{\text{sig}}N$ and $N_{\text{bkg}} = (1 - f_{\text{sig}})N$, where N is the total number of candidates. The mass and proper decay time resolutions are calculated from the fit parameters, too. By analogy with a Gaussian distribution, the mass resolution σ_m is defined as half of that mass range for which the integral of \mathcal{M}_s retains 68.3% of the number of signal events symmetrically around the fitted Λ_b^0 mass. The proper decay time resolution, σ_τ , is determined in the same fashion by integrating the prompt background PDF.

V. EXTRACTION OF THE LIFETIME AND MASS

A. Results of the maximum likelihood fit

The results of the maximum likelihood fit are listed in Table I. The table shows only the most important fitted

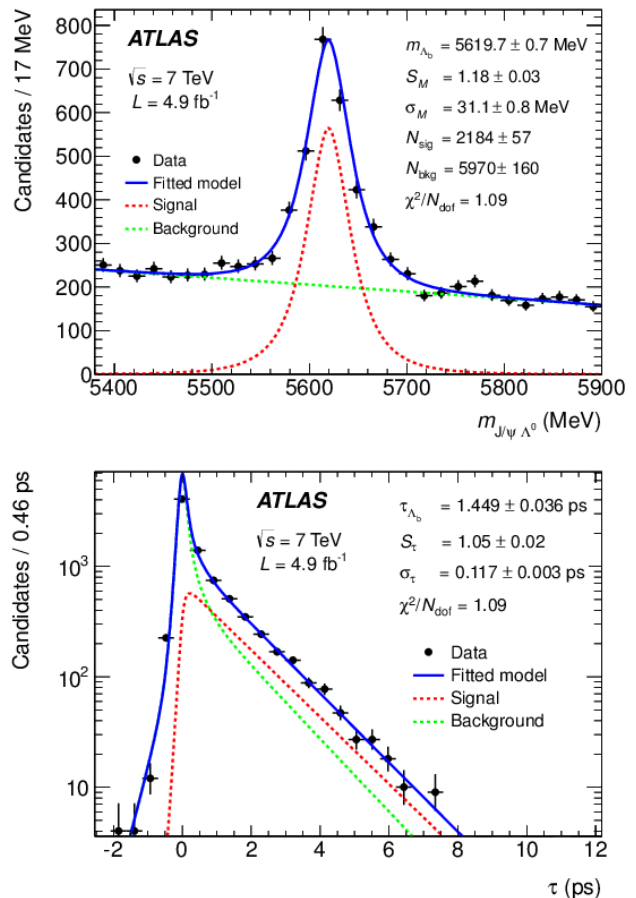


FIG. 3. Projections of the fitted PDF onto the mass (top panel) and the proper decay time (bottom panel) axes for Λ_b^0 candidates. The errors of the listed fit result values are statistical only. The χ^2/N_{dof} value is calculated from the data set binned in mass and decay time with the number of degrees of freedom, $N_{\text{dof}} = 61$.

parameters, calculated parameters, and a χ^2/N_{dof} value which quantifies the fit quality. The χ^2/N_{dof} value is calculated from the dataset binned in mass and decay time with 61 degrees of freedom. The sizes of the bins are commensurate with the measured mass and decay time resolutions, and only bins with more than 11 entries are used for the χ^2 calculation. This requirement is imposed so that the error on the number of entries in each bin can be taken as Gaussian. The lifetime result is corrected for the selection bias (see Sec. IV); the size of the correction is +19 fs. The estimated correlation between the mass and lifetime is small, 0.002. Projections of the PDF onto the mass and proper decay time axes are shown in Fig. 3.

B. Systematic uncertainties

Systematic errors are estimated by changing various parameters of the analysis and observing the shift in the

extracted mass and lifetime. The shift with respect to the baseline result is then quoted as a systematic uncertainty. The non-negligible systematic uncertainties are summarized in Table II. The individual errors are added in quadrature, yielding total systematic errors of the lifetime and mass measurements, $\sigma_{\tau}^{\text{synt}} = 17$ fs and $\sigma_m^{\text{synt}} = 1.1$ MeV, respectively. Details of the determination of the systematic uncertainties follow.

1. Event selection and reconstruction bias

Two effects that lead to a selection bias for Λ_b^0 candidates as a function of decay time have been identified: the dominant contribution comes from the muon trigger, which slightly biases the transverse impact parameter of muons, d_0 , toward smaller values. The second bias comes from the V^0 reconstruction. The event selection bias is corrected using the MC simulation to determine the efficiency as a function of the decay time as described in Sec. IV. The slope of the efficiency correction function, c_{Λ_b} , is determined with a statistical accuracy of 50% (56 ps). Using standard error propagation, the contribution of this uncertainty to the overall error is evaluated to be 9 fs.

Since the two bias corrections rely on MC simulation, systematic uncertainties due to the corrections are estimated. These are determined separately for the V^0 reconstruction bias and for the trigger bias. In the MC simulation the bias correction shifts the Λ_b^0 lifetime by 26 fs, of which 10 fs are due to the V^0 reconstruction and 16 fs are due to the trigger requirement. The systematic error due to the V^0 bias correction is estimated by varying the Λ_b^0 transverse momentum in the MC simulation (using kinematic reweighting) to probe the p_T dependence of the correction. The magnitude of the variation is about 3 times the difference between the mean p_T in data and the MC simulation. The corresponding error is estimated to be 4 fs. To ensure a good description of the trigger bias, the MC sample is reweighted using single-muon-trigger efficiencies expressed as a function of muon d_0 values that are extracted from data. The weighting functions are parameterized as linear functions, $w(d_0) \propto 1 + ad_0$, and their slope a is determined by a linear fit in bins of the measured muon p_T and η . To assess the systematic error on the trigger bias correction, the weighting parameters a are varied by their errors. This produces a lifetime shift of 7 fs, which is used as a systematic error. The total systematic error calculated as a quadratic sum of the individual contributions is 12 fs.

To assess the systematic error in the mass measurement due to the event selection, the MC distribution of $\Delta m = m^{\text{MC}} - m$, where m^{MC} is the generated mass, is fitted with a double Gaussian. The systematic error, given by the shift of the mean of the double Gaussian, is estimated to be 0.9 MeV. The mass shift is caused by the muon-trigger p_T thresholds: muons with larger p_T have higher probability of being selected than low- p_T muons.

As a consequence, muons whose p_T is mismeasured as larger than the true value have a higher probability of being reconstructed than muons whose p_T is mismeasured as smaller, which creates a small asymmetry of the mass peak.

2. Background fit models

Alternative background models are used to assess the sensitivity of the results to the choice of background parametrization. A second-order polynomial and an exponential mass dependence of the \mathcal{M}_b PDF are tested. In addition the decay time dependence is modified by adding a third exponential into the nonprompt background component, \mathcal{T}_{np} . The alternative background PDFs fit the data well. These changes result in a lifetime shift of 2 fs and a mass shift of 0.2 MeV. In the fit model the decay time and mass are assumed to be uncorrelated. To test this assumption the fit's mass range limits, m_{min} and m_{max} , are varied independently by 60 MeV. This changes the relative contribution of the background from the left and right sidebands, and the mass and lifetime are extracted again for these new mass ranges. While the change of m_{max} has a minimal impact on the extracted mass and lifetime, the change of m_{min} produces a lifetime shift of 9 fs. This value is added to the total systematic error due to background modeling.

3. B_d^0 contamination

The number of B_d^0 candidates misidentified as Λ_b^0 is estimated by a fit to the mass distribution of the candidates which fall in the Λ_b^0 signal region, $5.52 \text{ GeV} < m_{J/\psi\Lambda^0} < 5.72 \text{ GeV}$, under the hypothesis that they are $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ decays. A fit to a Gaussian peak on a linear background yields 82 ± 46 B_d^0 candidates. Since these candidates are treated as Λ_b^0 , their pseudolifetime is scaled up by the ratio of the Λ_b^0 and B_d^0 masses, $\tau_{B_d}^* = \tau_{B_d} m_{\Lambda_b}^{\text{PDG}} / m_{B_d}^{\text{PDG}} = 1617$ fs (the decay time change due to the difference in p_T reconstructed under the two hypotheses is negligible). If all such background candidates contribute to the fitted Λ_b^0 lifetime, it would cause a shift of 7 fs. This is quoted as a conservative estimate of the systematic error. The error on the mass measurement is estimated by relaxing the $\mathcal{P}_{\Lambda_b^0} - \mathcal{P}_{B_d}$ cut to double the estimated B_d^0 background. This results in a Λ_b^0 mass shift of 0.2 MeV.

4. Residual misalignment of the ID

The distribution of the transverse impact parameter, d_0 , of tracks originating from the PV is used to estimate the geometrical distortions due to residual misalignment. The geometry in the MC simulation is distorted by adjusting the positions of the ID modules so that the d_0 of

tracks coming from the PV is biased by the same amount as observed in data. The mass-lifetime fit is performed with simulated data using the default (ideal) geometry and the sample with geometry distortions. A shift of 1 fs is observed between the two measurements and is assigned as a systematic error due to residual misalignment. No significant mass shift is observed.

5. Uncertainty in the amount of ID material

Inaccurate modeling of the amount of material in the ID could affect the measurement since the tracking algorithm estimates the particle energy loss using a material map. To explore this uncertainty, the MC simulation is repeated with 20% more material in the ID silicon detectors (Pixel and SCT) and their supporting services, which is large compared to the estimated uncertainty of 6%(9%) in the Pixel (SCT) detectors (see Ref. [12]). The resulting shifts of 3 fs in lifetime and 0.2 MeV in mass are conservative estimates of the systematic uncertainties from this source.

6. Uncertainty in the tracking momentum scale

The K_S^0 mass value is used to estimate the uncertainty in the track momentum determination. The K_S^0 mass extracted from a fit to the invariant mass agrees with the PDG's world average within 0.03%. Such a shift corresponds to a track momentum scale shift of 0.05%. The momentum scale can be further tested using the reconstructed J/ψ mass. The observed mass shift corresponds to a momentum scale error of -0.03% , in agreement with the assumption of $\pm 0.05\%$. Shifting the momenta of all tracks in the MC simulation by this amount yields a Λ_b^0 mass shift of 0.5 MeV. No significant lifetime shift is observed.

7. Other systematic errors

Other sources of systematic errors are investigated, such as an alternative choice of the PV (e.g. using the collision vertex whose tracks have the highest sum of p_T^2) and the use of a PDF with the error distributions modeled separately for signal and background. These changes do not result in a significant mass or lifetime shift.

C. Cross-check with $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$

The $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ channel has the same decay topology as $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ and can be used to cross-check the Λ_b^0 results and to determine the ratio of the Λ_b^0 and B_d^0 lifetimes. The analysis and systematic error studies, described in the previous

TABLE II. Summary of the systematic uncertainties of the lifetime measurement, $\sigma_\tau^{\text{syst}}$, and the mass measurement, σ_m^{syst} , for Λ_b^0 .

Systematic uncertainty	$\sigma_\tau^{\text{syst}}$ (fs)	σ_m^{syst} (MeV)
Selection/reco. bias	12	0.9
Background fit models	9	0.2
B_d^0 contamination	7	0.2
Residual misalignment	1	...
Extra material	3	0.2
Tracking p_T scale	...	0.5
Total systematic error	17	1.1

sections, are repeated for the B_d^0 . The B_d^0 channel is subjected to exactly the same kinematic cuts as for the Λ_b^0 channel and therefore has similar systematic effects. The mass range used for the K_S^0 pre-selection is $440 \text{ MeV} < m_{\pi^+\pi^-} < 570 \text{ MeV}$, and the B_d^0 invariant mass must lie in the range $5.1 \text{ GeV} < m_{J/\psi K_S^0} < 5.5 \text{ GeV}$. This selection is chosen to be as close as possible to the Λ_b^0 selection rather than to maximize the B_d^0 signal yield. Using the maximum likelihood fit, the B_d^0 lifetime and mass are measured to be $\tau_{B_d} = 1.509 \pm 0.012(\text{stat}) \pm 0.018(\text{syst}) \text{ ps}$ and $m_{B_d} = 5279.6 \pm 0.2(\text{stat}) \pm 1.0(\text{syst}) \text{ MeV}$. These values are consistent with the world averages, $\tau_{B_d}^{\text{PDG}} = 1.519 \pm 0.007 \text{ ps}$ and $m_{B_d}^{\text{PDG}} = 5279.50 \pm 0.30 \text{ MeV}$ [1].

VI. RESULTS AND CONCLUSIONS

The Λ_b^0 lifetime and mass are measured to be

$$\begin{aligned} \tau_{\Lambda_b} &= 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst}) \text{ ps}, \\ m_{\Lambda_b} &= 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst}) \text{ MeV}. \end{aligned}$$

These results agree with the world average values of the Λ_b^0 lifetime, $\tau_{\Lambda_b}^{\text{PDG}} = 1.425 \pm 0.032 \text{ ps}$ and mass, $m_{\Lambda_b}^{\text{PDG}} = 5619.4 \pm 0.7 \text{ MeV}$ [1], and with a recent determination of the Λ_b^0 mass by the LHCb experiment, $m_{\Lambda_b}^{\text{LHCb}} = 5619.19 \pm 0.70(\text{stat}) \pm 0.30(\text{syst}) \text{ MeV}$ [2]. The ratio of the Λ_b^0 and B_d^0 lifetimes is

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

The statistical and systematic errors are propagated from the errors of the lifetime measurements. The systematic errors are conservatively assumed to be uncorrelated. This value is between the recent determination by DØ, $R^{\text{DØ}} = 0.864 \pm 0.052(\text{stat}) \pm 0.033(\text{syst})$ [6], and the measurement by CDF, $R^{\text{CDF}} = 1.020 \pm 0.030(\text{stat}) \pm 0.008(\text{syst})$ [5]. It agrees with the heavy quark expansion calculations which predict the value of the ratio between 0.88 and 0.97 [7] and is compatible with the next-to-leading-order QCD predictions with central values ranging between 0.86 and 0.88 (uncertainty of ± 0.05) [8].

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