ATLAS NOTE

ATLAS-CONF-2012-055

June 4, 2012

Measurement of the Λ_b^0 lifetime and mass in the ATLAS experiment

The ATLAS Collaboration

Abstract

A measurement of the Λ_b^0 lifetime and mass in the decay channel $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ is presented here. 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 data collected in 2011 at the LHC centre-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.

1 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 centre-of-mass collision 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 $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ (the charge conjugate mode is implied throughout the paper unless explicitly stated otherwise). The Λ_b^0 lifetime, although measured by many experiments [4, 5, 6], still suffers from a large experimental uncertainty. The decay $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ has a similar topology to 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 Effective Theory (HQET) and perturbative QCD [7, 8] and is of great theoretical interest. The lifetime and mass are determined using a single unbinned maximum likelihood fit to the reconstructed mass and decay time of each selected candidate.

2 Data samples and trigger selection

The ATLAS experiment [3] is a general-purpose detector at the Large Hadron Collider (LHC) at CERN. It covers nearly the entire solid angle around the interaction point with layers of tracking detectors, calorimeters, and muon chambers. This analysis uses two ATLAS sub-systems: 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 micro-strip 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 measurement, resistive plate chambers (RPC) and thin gap chambers (TGC) employed by the muon trigger system. Both the MS and ID have a pseudorapidity coverage of $|\eta| < 2.5$. Only ID tracks with p_{T} above 400 MeV are used in this analysis.

This analysis uses data collected in the year 2011 using single-muon, di-muon, and J/ψ triggers. The ATLAS trigger system [9] has 3 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 searching 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 reduce the output rate. The transverse momentum thresholds for single and di-muon triggers vary from 4 GeV to 22 GeV. The J/ψ triggers are di-muon triggers which in addition require that the muons have an opposite charge and the di-muon mass is 2.5 GeV $< m_{\mu\mu} <$ 4.3 GeV. The majority of the sample was collected by the J/ψ trigger with a p_{T} threshold of 4 GeV applied to both muons, which was the lowest p_{T}-threshold trigger unprescaled in the 2011 data taking. The combined triggers selected muons with p_{T} above 2.5 GeV and the muon p_{T} spectrum peaks at 5 GeV.

A Monte Carlo (MC) sample of 5 million anti-baryon $\bar{\Lambda}_b^0$ 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 MC generator [10] and the events are filtered so that there is a decay $\bar{\Lambda}_b^0 \to J/\psi(\mu^+\mu^-)\bar{\Lambda}^0(p^-\pi^+)$ in each event with the muons having transverse momenta of at least 2.5 GeV. The MC sample is generated with a Λ_b^0 lifetime of $\tau_{\Lambda_b}^{\mathrm{MC}} = 1.391$ ps.

3 Reconstruction and signal selection

3.1 J/ψ and V^0 Pre-selection

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

The di-muon and di-hadron pairs are pre-selected by requiring that their tracks can be successfully fitted to a common vertex [11] 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 di-muon candidates are accepted if the J/ψ vertex-refitted invariant mass lies in the range 2.8 GeV $< m_{\mu\mu} <$ 3.4 GeV. The di-hadron candidates are accepted if the invariant mass is in the range 1.08 GeV $< m_{p\pi} <$ 1.15 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.

3.2 Reconstruction of $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$

The muon and hadronic track pairs pre-selected with the criteria described in the previous section are then refitted with a constraint of a $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ topology. The muons are constrained to intersect in a single vertex while their invariant mass must be equal to the known mass of the J/ψ, $m_{J/\psi}$ = 3096.92 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_{Λ^0} = 1115.68 MeV [1]. The combined momentum of the refitted V^0 track pair is constrained to point to the di-muon vertex in 3-d. Two mass hypotheses are considered: the first assigning a proton mass to the positive track and a pion mass to the negative track and the second hypothesis with the opposite mass assignment. These hypotheses correspond to Λ_b^0 and $\bar{\Lambda}_b^0$ decays, respectively. 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 6. Furthermore, for each track quadruplet, that can be successfully fitted to the Λ_b^0 decay topology, a $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ 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 MeV [1]). This is to label possible B_d^0 decays misidentified as Λ_b^0.

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

- The global $\chi^2/N_{\mathrm{dof}} < 3$.
- The transverse momentum of the cascade-refitted V^0, $p_{\mathrm{T},V^0} >$ 3.5 GeV.
- The transverse decay length of the cascade-refitted V^0 vertex measured from the Λ_b^0 vertex, $L_{xy,V^0} >$ 10 mm.
- The invariant mass must be in the range 5.38 GeV $< m_{J/\psi\Lambda^0} <$ 5.90 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 Figure 1. In the rest of the paper the Λ_b^0 and $\bar{\Lambda}_b^0$ samples are combined.

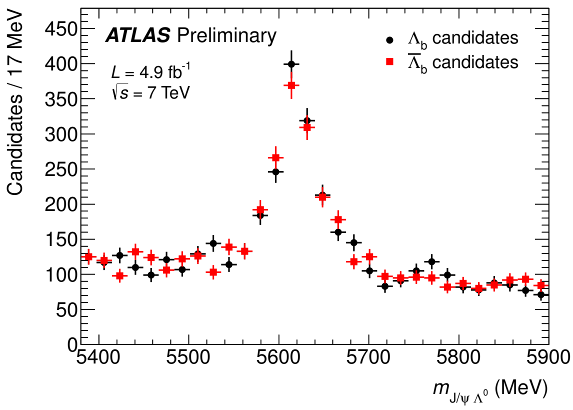

Figure 1: Invariant mass distribution of the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates.

4 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:

$$\tau = \frac{L_{xy} m^{\mathrm{PDG}}}{p_{\mathrm{T}}},$$

where $m^{\mathrm{PDG}} = 5620.2$ 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 3-d 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 background can be divided into two main categories: prompt and non-prompt background. The prompt background consists of J/ψ candidates produced directly in the pp collision that are randomly combined with V^0 candidates, this also includes fake combinatorial Λ^0 or K_S^0 candidates. This background does not have a lifetime and the measured decay length is caused only by the resolution of the vertex reconstruction. The non-prompt background includes events where the J/ψ candidate originates in a decay of a b-hadron. This type of background has a lifetime due to its origin in long-lived b-hadrons (e.g. $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$, with the K_S^0 meson misidentified as Λ^0, forms a non-prompt background for Λ_b^0).

The mass and proper decay time are fitted using a likelihood function defined as follows:

$$L = \prod_{i=1}^{N} \left[f_{\mathrm{sig}} \mathcal{M}_{\mathrm{s}}(m_i|\delta_{m_i}) \mathcal{T}_{\mathrm{s}}(\tau_i|\delta_{\tau_i}) w_{\mathrm{s}}(\delta_{m_i}, \delta_{\tau_i}) + (1 - f_{\mathrm{sig}}) \mathcal{M}_{\mathrm{b}}(m_i|\delta_{m_i}) \mathcal{T}_{\mathrm{b}}(\tau_i|\delta_{\tau_i}) w_{\mathrm{b}}(\delta_{m_i}, \delta_{\tau_i}) \right],$$

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. $\mathcal{M}_{\mathrm{s}}$ and $\mathcal{M}_{\mathrm{b}}$ are probability density functions (PDFs) describing the signal and background mass dependence; $\mathcal{T}_{\mathrm{s}}$ and $\mathcal{T}_{\mathrm{b}}$ describe the dependence on the proper decay time. The invariant mass and proper decay time error distributions, $w_{\mathrm{s(b)}}(\delta_m, \delta_\tau) = w'_{\mathrm{s(b)}}(\delta_m) w''_{\mathrm{s(b)}}(\delta_\tau)$, are extracted from data. It has been verified that using separate PDFs for the signal and background component produces the same results as when a single PDF is used, $w \equiv w_{\mathrm{s}} = w_{\mathrm{b}}$. For this reason the latter case is used.

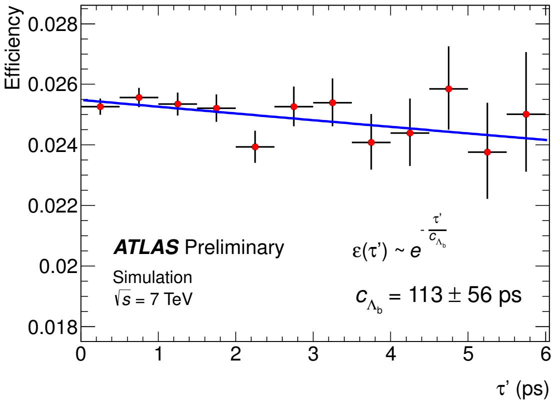

Figure 2: Extraction of the efficiency correction for Λ_b^0. The MC data are fitted with an exponential function. The y-axis has a suppressed zero.

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 over or under-estimated. The background component is a first order polynomial with a slope b.

Since the proper decay time of each candidate is reconstructed with a certain error, the proper decay time resolution is modeled with a Gaussian function:

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

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

The signal and non-prompt 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 pseudo-lifetime of the long-lived background. The prompt background component is modeled by a sum of two functions: a Dirac δ-function, $\delta_{\rm Dirac}(\tau')$, and a symmetric exponential (Laplace distribution), $E_{\rm sym}(\tau')$, 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:

$$\begin{aligned} \mathcal{T}_{\rm s}(\tau|\delta_\tau) &= \varepsilon(\tau')^{-1} E(\tau'; \tau_{\Lambda_b}) \otimes R(\tau - \tau'|\delta_\tau), \\ \mathcal{T}_{\rm b}(\tau|\delta_\tau) &= \left[f_1 \mathcal{T}_{\rm p}(\tau') + (1 - f_1) \mathcal{T}_{\rm np}(\tau') \right] \otimes R(\tau - \tau'|\delta_\tau), \end{aligned} \tag{2}$$

with the non-prompt and prompt components defined as

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

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

Two sources are responsible for the selection bias of 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 centre of the detector as tracks from decays further away from the centre leave fewer hits in the ID. Since the Λ_b^0 decay length and the distance of the Λ^0 vertex from the centre 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. Using the tag-and-probe method for J/ψ, the trigger efficiency as a function of d_0 is measured for a single-muon trigger in data. The simulation shows that the di-muon trigger efficiency can be expressed as a product of single muon efficiencies. The MC data are re-weighted to make sure that the observed trigger bias is well modelled in the MC. The efficiency correction, $\varepsilon(\tau')$, is determined using this weighted MC sample. It is modelled as a simple exponential, $\varepsilon(\tau') \propto e^{-\tau'/c_{\Lambda_b}}$, where c denotes the slope of the efficiency correction. The exponential form is chosen for $\varepsilon(\tau')$ because it describes the MC data well and is particularly easy to convolve with the resolution model. The slope of the exponential, c_{Λ_b}, is extracted by a fit to the MC decay time efficiency plot shown in Figure 2. The extracted value is $c_{\Lambda_b} = 113 \pm 56$ ps, i.e. for the decay time of 6 ps the efficiency decreases by 5%.

4.1 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, $\tau_{\mathrm{bkg},1}$ and $\tau_{\mathrm{bkg},2}$; the slope of the non-Gaussian prompt background, $\tau_{\mathrm{bkg},3}$; and
- the relative fractions of the various background contributions, f_1, f_2, and f_3.

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

5 Extraction of the Λ_b^0 mass and lifetime

5.1 Results of the maximum likelihood fit

The results of the maximum likelihood fit are listed in Table 1. The table shows only the most important fitted 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 size of the bins corresponds to the measured mass and decay time resolutions and only bins with more than 11 entries are used for the χ^2 calculation. This is to ensure 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 Section 4); 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 decay time axes are shown in Figure 3.

Table 1: 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 χ^2 calculation is $N_{\text{dof}} = 61$.

Par.	Value	Par.	Value
m_{Λ_b}	5619.7 ± 0.7 MeV	σ_m	31.1 ± 0.8 MeV
τ_{Λ_b}	1.449 ± 0.036 ps	σ_τ	0.117 ± 0.003 ps
f_{sig}	0.268 ± 0.007	N_{sig}	2184 ± 57
S_m	1.18 ± 0.03	N_{bkg}	5970 ± 160
S_τ	1.05 ± 0.02	χ^2/N_{dof}	1.09

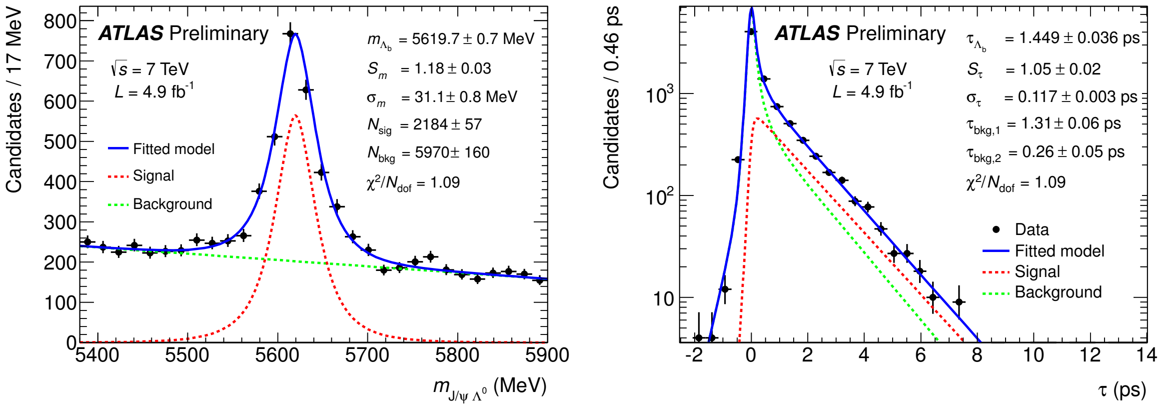

Figure 3: Projections of the fitted PDF onto the mass (left) and the proper decay time (right) axes for Λ_b^0 candidates. The displayed errors are statistical only. The χ^2/N_{dof} value is calculated from the dataset binned in mass and decay time with the number of degrees of freedom $N_{\text{dof}} = 61$.

5.2 Systematic errors

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 error. The non-negligible systematic errors are summarized in Table 2. The individual errors are added in quadrature, obtaining a total systematic error of the lifetime and mass measurements, $\sigma_\tau^{\text{syst}} = 17$ fs and $\sigma_m^{\text{syst}} = 1.1$ MeV, respectively. Details on the systematic error determination follow:

Event selection and reconstruction bias Two effects that lead to a selection bias of the Λ_b^0 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 by determining the efficiency as a function of the decay time as described in Section 4. The slope of the efficiency correction function, c_{Λ_b}, is determined with a statistical error of 56 ps. Using standard error propagation, the contribution of this uncertainty to the overall error is evaluated to be 9 fs.

Since the bias correction relies on MC simulation, an additional systematic uncertainty due to the correction is estimated. This error is determined separately for the V^0 reconstruction bias and for the trigger bias. In the MC the bias correction accounts for a Λ_b^0 lifetime shift of 26 fs, of which 10 fs is due to the V^0 reconstruction and 16 fs is 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 to probe the p_T dependence of the correction. The magnitude of the variation is about three times the difference between the mean p_T in data and MC. The corresponding error is estimated to be 4 fs. To ensure a good description of the trigger bias, the MC sample is re-weighted using the single-muon trigger efficiencies expressed as a function of muon d_0, that are extracted from data. The weighting functions are parametrized as linear functions, $w(d_0) \propto 1 + ad_0$, and their slope, a, is determined in bins of muon p_T and η with a certain precision. 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 of the event selection on the mass measurement, the MC distribution of $\Delta m = m^{MC} - m$, where m^{MC} stands for 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 better probability of being selected than low-p_T muons, which creates a small asymmetry of the mass peak.

Background fit models Alternative background models are tried to assess the sensitivity of the result to the choice of background parametrization. A second-order polynomial and an exponential dependence of the $\mathcal{M}_b$ PDF are tested. The decay time dependence is modified by adding a third exponential into the non-prompt 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 mass range limits, m_{min} and m_{max}, are varied independently by 60 MeV, which 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 modelling.

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 GeV $< m_{J/\psi\Lambda^0} <$ 5.72 GeV, under the hypothesis that they are $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ decays. A fit to a Gaussian on a linear background yields 82 ± 46 B_d^0 candidates. Since these candidates are treated as Λ_b^0, their pseudo-lifetime is scaled-up by the ratio between the Λ_b^0 and B_d^0 masses, $\tau^*_{B_d} = \tau_{B_d} m_{\Lambda_b}/m_{B_d} =$ 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 contributed 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.

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 on MC 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.

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

Table 2: Summary of the systematic errors of the lifetime measurement, $\sigma_\tau^{\rm syst}$, and the mass measurement, $\sigma_m^{\rm syst}$, for Λ_b^0.

Systematic error	$\sigma_\tau^{\rm syst}$ **(fs)**	$\sigma_m^{\rm syst}$ **(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 $p_{\rm T}$ scale	-	0.5
Total systematic error	17	1.1

a material map. To explore this uncertainty, the MC simulation is made assuming 20% of extra material in the ID silicon detectors (Pixel and SCT) and their supporting services, which is large compared to the estimated uncertainty of 6% in Pixel and 9% in the 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.

Uncertainty of the tracking momentum scale The K_S^0 mass value is used to estimate the uncertainty of the track momentum determination. The K_S^0 mass extracted from a fit to the invariant mass agrees with the PDG 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 ±0.05%. In the MC the momenta of all tracks are shifted by this amount, which yields a Λ_b^0 mass shift of 0.5 MeV. No significant lifetime shift is observed.

Other systematics Other sources of systematic errors are investigated, such as an alternative choice of the PV (e.g. using the collision vertex with the largest sum of tracks' $p_{\rm T}^2$) and a different modeling of the decay time error distributions. These changes do not result in a significant mass or lifetime shift.

5.3 Cross-check with $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$

The $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ channel has a similar decay topology as $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ 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 studies, described in the previous sections, are repeated for 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 preselection is 440 MeV $< m_{\pi^+\pi^-} <$ 570 MeV, the B_d^0 invariant mass must lie in the range 5.1 GeV $< m_{J/\psi K_S^0} <$ 5.5 GeV. Using the Λ_b^0 kinematic cuts results in a B_d^0 signal yield, which is much smaller than can be achieved with a B_d^0-optimized selection. Using the maximum likelihood fit, the B_d^0 lifetime and mass are measured to be $\tau_{B_d} = 1.509 \pm 0.012$(stat) $\pm$ 0.018(syst) ps and $m_{B_d} = 5279.6 \pm 0.2$(stat) $\pm$ 1.0(syst) MeV. These values are consistent with the world averages, $\tau_{B_d}^{\rm PDG} = 1.519 \pm 0.007$ ps and $m_{B_d}^{\rm PDG} = 5279.50 \pm 0.30$ MeV [1].

6 Results and conclusions

The Λ_b^0 lifetime and mass are measured to be

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

The presented results agree with the world average values of the Λ_b^0 lifetime, $\tau_{\Lambda_b}^{\text{PDG}} = 1.425 \pm 0.032$ ps and mass, $m_{\Lambda_b}^{\text{PDG}} = 5620.2 \pm 1.6$ MeV [1]. The estimated precision of the mass measurement is better than that of the world average and the result is consistent with a recent determination, $m_{\Lambda_b}^{\text{LHCb}} = 5619.19 \pm 0.70(\text{stat}) \pm 0.30(\text{syst})$ MeV [2], which is not included in the quoted world average value. The ratio of the Λ_b^0 and B_d^0 lifetimes measured by ATLAS 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 close to 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 is compatible with the theoretical predictions in Ref. [7], $R_1^{\text{NLO}} = 0.88 \pm 0.05$, and Ref. [8], $R_2^{\text{NLO}} = 0.86 \pm 0.05$.

References

[1] Particle Data Group Collaboration, K. Nakamura et al. J. Phys. G **37** (2010) 075021 and 2011 partial update for the 2012 edition: http://pdglive.lbl.gov.

[2] LHCb Collaboration, R. Aaij et al., *Measurement of b-hadron masses*, Phys. Lett. B **708** (2012) 241 – 248.

[3] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[4] CDF Collaboration, T. Aaltonen et al., *Measurement of the Λ_b^0 Lifetime in $\Lambda_b^0 \to \Lambda_c^+\pi^-$ Decays in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. Lett. **104** (2010) 102002.

[5] CDF Collaboration, T. Aaltonen et al., *Measurement of b hadron lifetimes in exclusive decays containing a J/psi in p-pbar collisions at sqrt(s)=1.96TeV*, Phys.Rev.Lett. **106** (2011) 121804.

[6] D0 Collaboration, V. M. Abazov et al., *Measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \to J/\psi\Lambda^0$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, arXiv:1204.2340 [hep-ex].

[7] C. Tarantino, *Beauty hadron lifetimes and B meson CP violation parameters from lattice QCD*, Eur. Phys. J. **C33** (2004) S895–S899.

[8] F. Gabbiani, A. I. Onishchenko, and A. A. Petrov, *Spectator effects and lifetimes of heavy hadrons*, Phys.Rev. **D70** (2004) 094031.

[9] ATLAS Collaboration, *Performance of the ATLAS Trigger System in 2010*, Eur. Phys. J. **C72** (2012) 1849.

[10] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **05** (2006) 026.

[11] ATLAS Collaboration, V. Kostyukhin, *VKalVrt - package for vertex reconstruction in ATLAS*, ATL-PHYS-2003-031, http://cdsweb.cern.ch/record/685551, 2003.

[12] ATLAS Collaboration, *A study of the material in the ATLAS inner detector using secondary hadronic interactions*, JINST **7** (2012) P01013.

A Additional plots

The invariant masses of the pre-selected J/ψ and Λ^0 candidates are shown in Figure 4. Figure 5 (right) shows the efficiency correction extraction for B_d^0. The B_d^0 invariant mass spectrum is shown in Figure 5 (left) and projections of the PDF fitted to the B_d^0 data are shown in Figure 6.

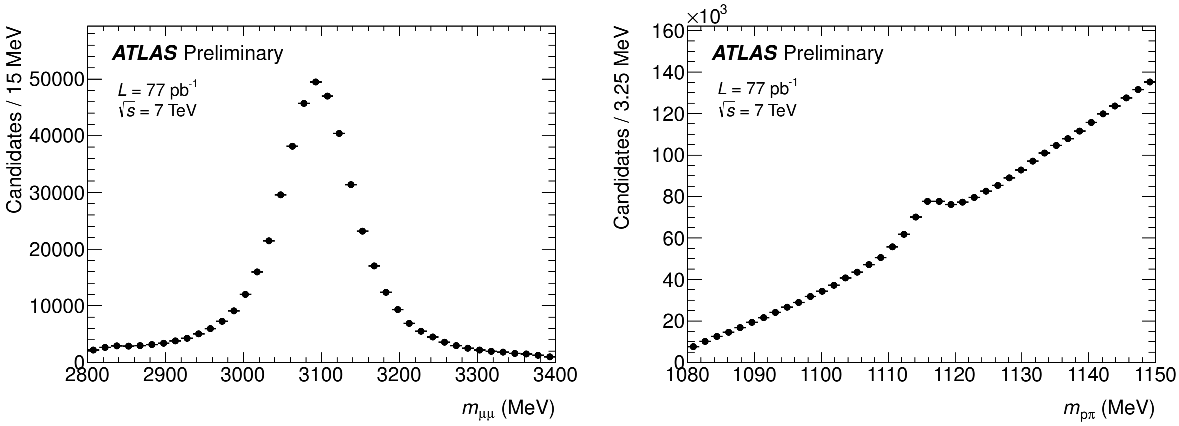

Figure 4: Invariant mass distribution of pre-selected J/ψ (left), Λ^0 and $\bar{\Lambda}^0$ (right) candidates. A single run of 77 pb^{-1} is used to make the plots.

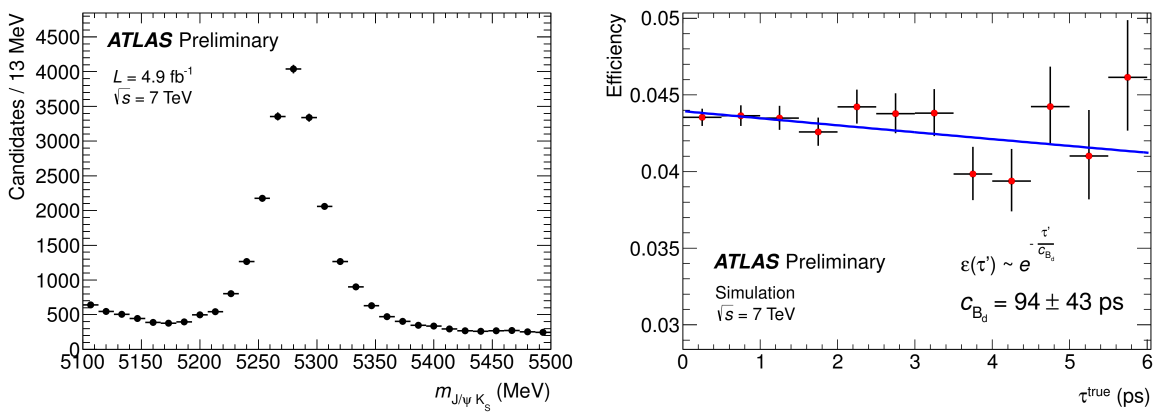

Figure 5: Invariant mass distribution of the selected B_d^0 candidates (left). Extraction of the efficiency correction for B_d^0 (right). The y-axis has a suppressed zero.

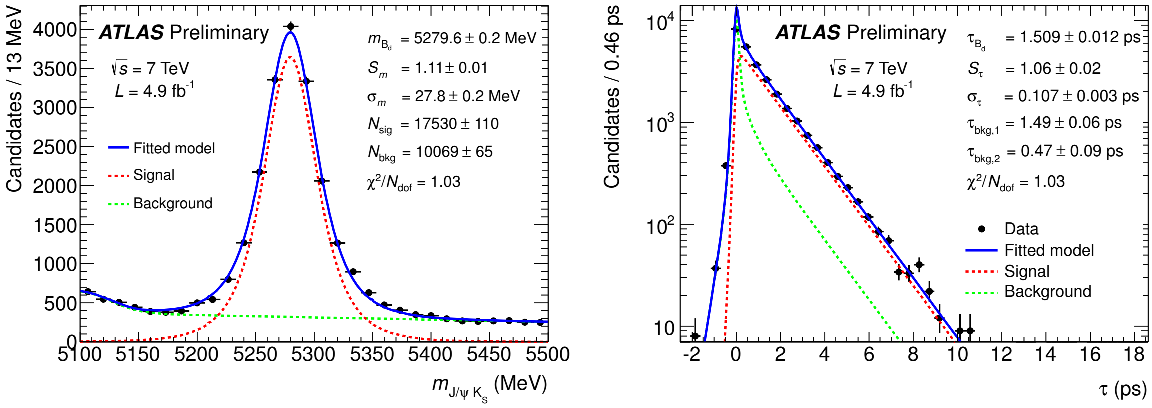

Figure 6: Projections of the fitted PDF onto the mass (left) and the proper decay time axes (right) for B_d^0 candidates. The displayed errors are statistical only. The $\chi^2/N_{\rm dof}$ value is calculated from the dataset binned in mass and decay time using bins with more than 11 entries. The number of degrees of freedom is $N_{\rm dof} = 92$.