PROCEEDINGS OF SCIENCE

Studies of Λ_b^0 in ATLAS: decays to charmonium states and parity violating asymmetry

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The measurements of Λ_b^0 lifetime and decay asymmetry parameter in $\Lambda_b^0 \to J/\psi\Lambda^0$ using 2011 7 TeV pp collision data taken by ATLAS at LHC are presented. The measured value of Λ_b^0 lifetime is $\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})$ ps, and the parity violating decay asymmetry parameter is measured to be $\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$.

The 15th International Conference on B-Physics at Frontier Machines at the University of Edinburgh, 14 -18 July, 2014
University of Edinburgh, UK

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PoS(Beauty2014)046

1. Introduction

Although the Λ_b^0 baryon has been discovered for more than two decades, many of its basic properties are not measured as precisely as other lighter hadrons. For example, its lifetime had been a puzzle in the Tevatron days. The measurements from CDF [1] and D0 [2] have more than two standard deviation discrepancy. The CDF measurement of Λ_b^0 and B_d^0 lifetime ratio $R = \tau_{\Lambda_b^0}/\tau_{B_d^0}$ is also more than two standard deviation higher than the theoretical predictions. Another basic but unknown parameter before LHC is the decay asymmetry parameter of $\Lambda_b^0 \to J/\psi\Lambda^0$. The theoretical predictions of this parameter varies in a large range, from -0.2 to 0.78 (see references in Ref. [3]). The $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ events in 2011 collision data collected by ATLAS detector [4] at LHC are used to measure the lifetime and the decay asymmetry parameter.

2. Λ_b^0 reconstruction

Data taken by ATLAS detector in 2011 using single muon, dimuon and J/ψ muon trigger corresponding to an integrated luminosity of about 5 fb^{-1} are used to reconstruct Λ_b^0. In the preselection, J/ψ candidates are reconstructed from muon pairs, and Λ^0 candidates are reconstructed by fitting two inner detector tracks. Both J/ψ and Λ^0 candidates are required to be within a mass window around their mass values [5]. The four tracks are then fitted simultaneously using the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ hypothesis, in which the masses of J/ψ and Λ^0 are fixed to their values. Good fit quality $\chi^2/N_{\mathrm{dof}} < 3$ is required. Furthermore, the refitted Λ^0 is required to have $p_{\mathrm{T}} > 3.5$ GeV and transverse decay length $L_{xy} > 10$ mm with respect to the dimuon vertex to suppress combinatorial backgrounds. To reject B_d^0 background, a $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ hypothesis fit is also performed to the track-quadruplet and the event will be kept only if the cumulative probability for Λ_b^0 is higher than the B_d^0 hypothesis by 0.05. The reconstructed mass of Λ_b^0 and $\bar{\Lambda}_b^0$ candidates are shown in Fig. 1. The Λ_b^0 and $\bar{\Lambda}_b^0$ events have similar distributions, and they are combined for these measurements.

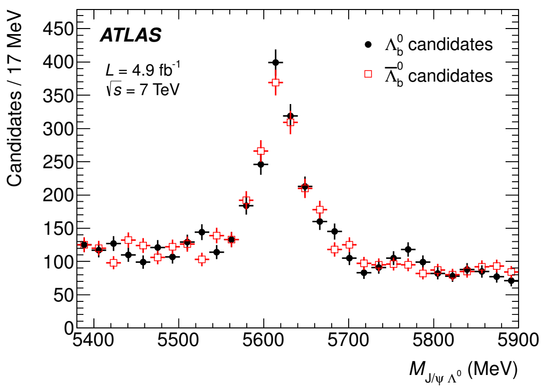

Figure 1: The mass distribution of the reconstructed Λ_b^0 and $\bar{\Lambda}_b^0$ candidates [6].

3. Λ_b^0 lifetime measurement

The lifetime of Λ_b^0 are measured by a two dimensional simultaneous fit of the reconstructed mass and proper decay time of each selected candidate [6]. The mass of Λ_b^0 is also measured from this fit.

The unbinned likelihood function is given by

$$L = \prod_{i=1}^{N} [f_{\rm sig} \mathscr{M}_{\rm s}(m_i|\delta_{mi}) \mathscr{T}_{\rm s}(\tau_i|\delta_{\tau i}) w_{\rm s}(\delta_{mi}, \delta_{\tau i}) + (1 - f_{\rm sig}) \mathscr{M}_{\rm b}(m_i|\delta_{mi}) \mathscr{T}_{\rm b}(\tau_i|\delta_{\tau i}) w_{\rm b}(\delta_{mi}, \delta_{\tau i})], \quad (3.1)$$

where $f_{\rm sig}$ is the fraction of signal events; m_i and τ_i are the reconstructed mass and proper decay time of the ith event. The reconstructed mass distribution and proper decay time distribution are found uncorrelated, so they can be modeled separately. For the reconstructed mass, the probability density function (PDF) for signal ($\mathscr{M}_{\rm s}(m_i|\delta_{mi})$) is modeled using Gaussian distribution, and for background ($\mathscr{M}_{\rm b}(m_i|\delta_{mi})$), a linear distribution is used. The proper decay time PDF of signal events, $\mathscr{T}_{\rm s}(\tau_i|\delta_{\tau i})$, is given by a exponential function. For the proper decay time PDF of background, $\mathscr{T}_{\rm b}(\tau_i|\delta_{\tau i})$, the prompt background is modeled using a delta function and a symmetric exponential function, and non-prompt contribution are modeled by two exponential functions. All these proper decay time PDFs are convolved by a Gaussian resolution function. The distribution of reconstructed mass uncertainty and proper decay time uncertainties for signal and background, $w_{\rm s}(\delta_{mi}, \delta_{\tau i})$ and $w_{\rm b}(\delta_{mi}, \delta_{\tau i})$, are extracted from data and have the same form. The values of mass and lifetime measurement from the fit is shown in Fig. 2. The PDF is projected to the reconstructed mass and proper decay time distributions and is compared with data. The major systematic un-

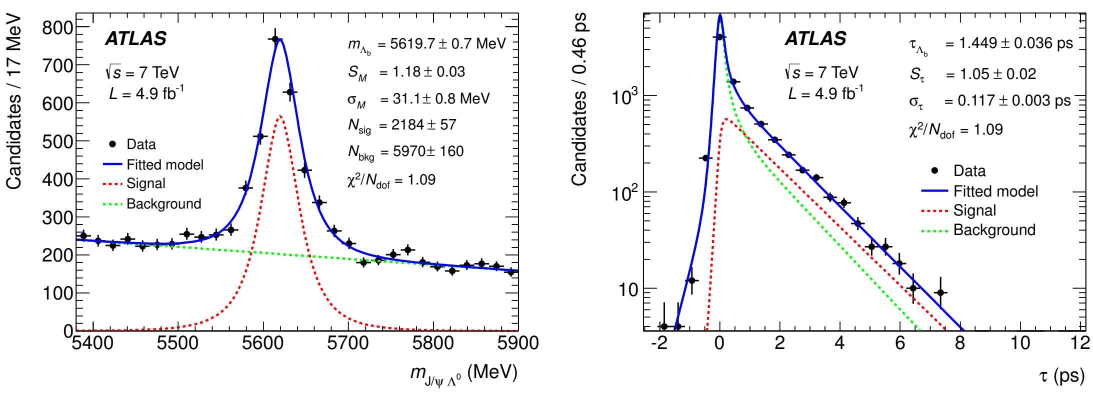

Figure 2: Mass-proper decay time fit results projected to mass (left) and proper decay time (right) and compared with data [6].

certainties are related to the Λ^0 reconstruction and selection performed at trigger level. The final measured values of the mass and lifetime

$$m_{\Lambda_b^0} = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst}) \text{ MeV},$$
$$\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst}) \text{ ps}, \quad (3.2)$$

and the ratio,

$$R = \tau_{\Lambda_b^0} / \tau_{B_d^0}^{\rm PDG} = 0.960 \pm 0.025(\text{stat}) \pm 0.016(\text{syst}), \quad (3.3)$$

are consistent with the later results from CMS [7] and LHCb [8]. But the recent lifetime measurement from CDF [9] is still more than two standard deviation higher than this value.

4. α_b measurement

Taking λ_Λ and $\lambda_{J/\psi}$ to represent the helicity of the Λ^0 and the J/ψ, the decay $\Lambda_b^0 \to J/\psi\Lambda^0$ can be described by four helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$: $a_+ \equiv A(1/2,0)$, $a_- \equiv A(-1/2,0)$, $b_+ \equiv A(-1/2,-1)$ and $b_- \equiv A(1/2,1)$. The distribution of the five decay angles shown in Fig. 3, $\Omega = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$, depends on these helicity parameters, and can be written as [10]:

$$w(\Omega) = \frac{1}{(4\pi)^3} \sum_i f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega). \tag{4.1}$$

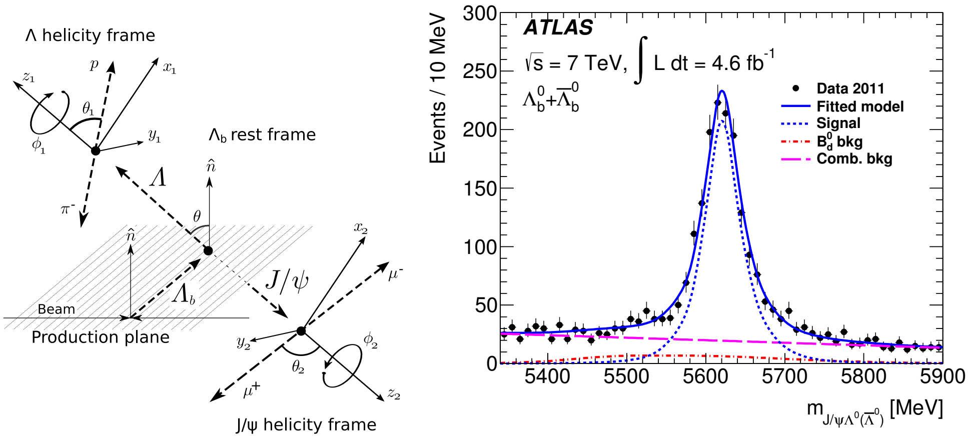

Figure 3: Definition of the decay angles (left) and the reconstructed mass of the selected Λ_b^0 and $\bar{\Lambda}_b^0$ candidates (right) [3].

As the overall polarization is 0 due to the symmetry of the detector, the PDF is simplified and only six out of twenty terms remain, for $i = 0, 2, 4, 6, 18$, and 19. Five unconstrained parameters can be determined from data, and they are chosen as: the decay asymmetry parameter $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$, two helicity amplitude ratio parameters ($k_+ = \frac{|a_+|}{\sqrt{|a_+|^2+|b_+|^2}}$, $k_- = \frac{|b_-|}{\sqrt{|a_-|^2+|b_-|^2}}$) and two relative phase parameters (Δ_+, Δ_-). Table 1 shows the form of f_{1i} and F_i of these six terms. The parameter f_{2i} equals the value of the decay asymmetry parameter of $\Lambda^0 \to p\pi^-$, $\alpha_\Lambda = 0.642 \pm 0.013$ [5], for $i = 2, 6, 18, 19$, and is unit for $i = 0$ or 4.

Table 1: The coefficients f_{1i}, and F_i of the remaining six terms of the simplified PDF [3].

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

To determine the value of the helicity parameters, the following function of the helicity parameters,

$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\text{expected}} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\text{expected}} - \langle F_j \rangle), \tag{4.2}$$

is minimized, where $\langle F_i \rangle^{\text{expected}}$ is the expected value of F_i predicted by the given helicity parameters; $\langle F_i \rangle$ and V_{ij} are the measured average values and their covariance matrix elements [3].

The expected values are calculated from the PDF (Eqn. 4.2) and corrected for the detector effects, which is estimated from Monte Carlo (MC) simulation. Fig. 4 shows the expected distributions of $\cos\theta_1$ and $\cos\theta_2$ for various α_b values.

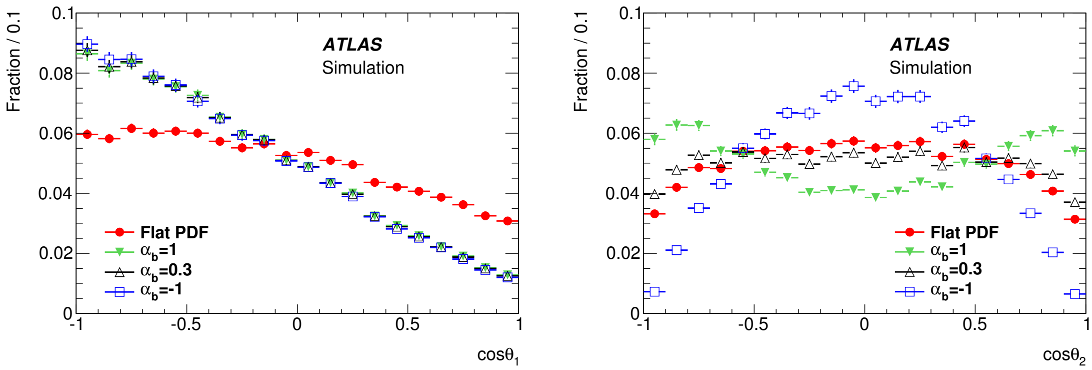

Figure 4: $\cos\theta_1$ and $\cos\theta_2$ distribution of MC events for various α_b value settings. In the flat PDF, $\alpha_b = 0$ and other parameters are set so that the distributions are flat at generator level. For $\alpha_b = -1, 0.3$ and 1, other parameters are set to $k_+ = 0.21$ and $k_- = 0.13$ (measured values), and $\Delta_+ = \Delta_- = 0$ [3].

To further reduce the combinatorial background, proper decay time $\tau > 3.5$ ps is required, and the events are selected requiring cumulative probability for Λ_b^0 larger than the one for B_d^0 hypothesis. The reconstructed mass distribution of the selected events is shown in Fig. 3. The combinatorial background is estimated from sidebands. Both data and MC are used to estimate the B_d^0 background.

The final result of the helicity amplitude measurement is

$$\begin{aligned} \alpha_b &= 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst}), \\ k_+ &= 0.21^{+0.14}_{-0.21}(\text{stat}) \pm 0.13(\text{syst}), \\ k_- &= 0.13^{+0.20}_{-0.13}(\text{stat}) \pm 0.15(\text{syst}), \end{aligned} \tag{4.3}$$

corresponding to the magnitude of helicity amplitudes

$$\begin{aligned} |a_+| &= 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}), & |a_-| &= 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}), \\ |b_+| &= 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}), & |b_-| &= 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}). \end{aligned} \tag{4.4}$$

The phase parameters (Δ_+ and Δ_-) are consistent with the entire allowed range. The systematic uncertainty mainly come from combinatorial background shape estimation and MC statistics.

The Λ_b^0 decay has large amplitudes $|a_-|$ and $|b_+|$, which means the negative-helicity states for Λ^0 are preferred and the Λ^0 and J/ψ from Λ_b^0 decay are highly polarized. Adding in quadrature the statistical and systematic uncertainties, the observed value of α_b is consistent with the recent measurement $\alpha_b = 0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$ by LHCb [11] at the level of one standard deviation. However, it is not consistent with the expectation from pQCD [12] (α_b in the range from -0.17 to -0.14), and HQET [13] ($\alpha_b = 0.78$) at a level of about 2.6 and 2.8 standard deviations, respectively.

5. Summary

The $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ events in ATLAS 7 TeV collision data taken in 2011 are used to measure the Λ_b^0 lifetime and decay helicity amplitudes. Λ_b^0 lifetime is measured to be $\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})$ ps, consistent with the world average and the later measurements by other experiments, and the parity violating decay asymmetry parameter α_b is measured to be $\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$, compatible with the LHCb results [11] but lying in the middle of two theory predictions, both separated by more than two standard deviations. The Λ^0 from Λ_b^0 decay is found highly polarized.

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