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Properties of b-hadrons with ATLAS: B_s^0 rare decays and Λ_b^0 decay properties

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Measurements of the properties of b-hadrons are presented based on 5.25 fb^{-1} of pp collision data recorded by the ATLAS experiment during 2011 LHC operation. We present an updated limit on the the $B_s^0 \to \mu^+\mu^-$ branching fraction, a determination of the the Λ_b^0 mass and lifetime and a new measurement of the parity-violating asymmetry parameter α_b and helicity amplitudes of the decay of the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$.

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1. Introduction

Flavour-changing neutral-current processes are strongly suppressed in the standard model (SM). The SM predicts the branching fraction for the decay $B_s^0 \rightarrow \mu^+\mu^-$ to be extremely small: $3.23 \pm 0.27 \times 10^{-9}$ [1]. ATLAS has previously published a measurement [2] based on half of the 2011 ATLAS dataset (2.4 fb^{-1}); here we report an updated measurement [3] using the full 2011 ATLAS dataset.

Currently hadron colliders are the only place where the properties of b baryons can be studied. We present measurements [4] of the mass and lifetime of the Λ_b^0 and the lifetime ratio, $\tau_{\Lambda_b^0}/\tau_{B_d}$, which is of great theoretical interest. The parity-violating asymmetry parameter α_{b} is also of theoretical interest. In the kinematic domain of the Λ_b^0 produced in the LHC, it is expected that the hard scattering function can be accurately calculated in perturbative QCD (pQCD). We have measured α_b and helicity amplitudes in the channel $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ [5].

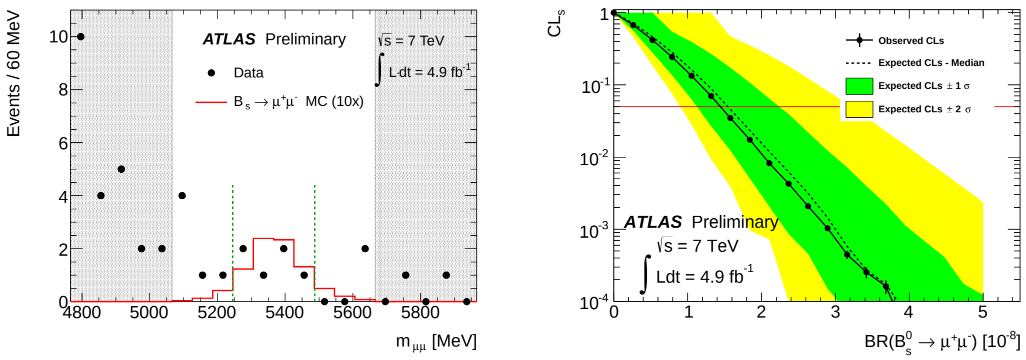
The ATLAS experiment [6] at the LHC [7] is a general purpose particle detector covering almost the full solid angle around the pp collision point with layers of tracking detectors, calorimeters and muon tracking chambers. The measurements presented here are mainly based on the Inner Detector (ID) and the Muon System (MS). The ID consists of a silicon pixel detector surrounded by a silicon strip detector (SCT) and a transition radiation tracker (TRT) that are embedded in a 2 T axial magnetic field. Charged-particle trajectories are measured for $|\eta| < 2.51$. Enclosing the calorimeter, the MS has a toroidal magnetic field and contains a combination of monitored drift tubes and cathode strip chambers, capable of measuring muon trajectories in a range of $|\eta| < 2.7$. Muons are triggered by resistive plate chambers (for $|\eta| < 1.05$) and thin gap chambers (for $1.05 < |\eta| < 2.4$) with coarse resolution, but fast response time. The ATLAS detector has a three-level trigger system, consisting of a hardware-based Level-1 trigger and two software-based levels, Level-2 and Event Filter, which together comprise the High Level Trigger (HLT). The specifics of the trigger selection will be given in the following section.

2. Updated $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction limit

The $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction has been measured with respect to the prominent reference decay $B^\pm \rightarrow J/\psi(\mu^+\mu^-)K^\pm$ in order to minimise systematic uncertainties in the evaluation of the efficiencies and acceptances. A blind analysis has been performed with the signal region (5066 MeV $< m_{\mu^+\mu^-} <$ 5666 MeV) only un-blinded in the final analysis step.

The trigger required two muons with $p_{\mathrm{T}} > 4$ GeV at the first level trigger and loose di-muon invariant-mass requirements were applied at the HLT to select J/ψ or B_s^0. The dataset corresponds to 4.9 fb^{-1} after data quality requirements. Following offline reconstruction, only events containing candidates for $B_s^0 \rightarrow \mu^+\mu^-$ and $B^\pm \rightarrow J/\psi K^\pm$ were retained for this analysis. A preselection was made requiring good quality tracks and reconstructed vertices. A J/ψ invariant-mass requirement was applied to reference channel candidates. After preselection, there were approximately 3.9×10^5 $B_s^0 \rightarrow \mu^+\mu^-$ and 2.5×10^5 $B^\pm \rightarrow J/\psi K^\pm$ candidates in the signal regions.

Following the preselection, the combinatorial background was suppressed using a di-muon invariant-mass requirement, Δm, and using a Boosted Decision Tree (BDT) discriminant. Thirteen discriminating variables were used as inputs to the BCT, which was trained using MC datasets.



(a) (b)

Figure 1: (a) Invariant-mass distributions of selected candidates in data (dots). The plot also indicates the signal (continuous line) as predicted by Monte Carlo (MC) assuming $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = 3.5\times10^{-8}$ (scaled by a factor 10), the signal region (two dashed vertical lines) corresponding to the optimised Δm requirement and the sidebands used in the analysis (grey areas). The expected number of $B_s^0 \to \mu^+\mu^-$ in the signal region is 1.7 $\pm$ 0.2 events. The expected background yield per bin in the signal region is 1.7 events. (b) Observed CLs (circles) as a function of $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$. The 95% CL limit is indicated by the horizontal (red) line. The dark (green) and light (yellow) bands correspond to the $\pm1\sigma$ and $\pm2\sigma$ ranges of the background-only pseudo-experiments with the median of the expected CLs given by the dashed line.

In order to ensure good agreement between MC and data, a generator level (GL) re-weighting was applied to correct for GL filter biases and a data-driven re-weighting was applied to correct residual differences. The data-driven re-weighting was performed using half (odd event numbers) of the reference channel data in order to avoid any bias to the extraction of the reference channel yield and background estimate. The selection criteria were chosen by performing a 2D optimization in Δm and the BDT output parameter using the signal MC dataset and half (odd event-numbers) of the sideband data.

The branching fraction for the signal decay, $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$, can be written as follows:

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \mathscr{B}(B^\pm \to J/\psi(\mu^+\mu^-)K^\pm) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu_-}}{N_{J/\psi K^\pm}} \times R_{A\varepsilon}$$

where $\mathscr{B}(B^\pm \to J/\psi(\mu^+\mu^-)K^\pm)$ is the branching fraction from the reference channel, f_u/f_s is the ratio of the relative b-quark hadronisation probabilities of $B^\pm$ and B_s^0, $N_{\mu^+\mu_-}$ is the observed number of $B_s^0 \to \mu^+\mu^-$ events, $N_{J/\psi K^\pm}$ is the reference channel yield and $R_{A\varepsilon}$ is the ratio of acceptance times efficiency of the reference channel to that of the signal channel. The reference channel branching fraction was assigned the PDG [8] value and the ratio f_u/f_s was taken from previous measurements [9]. The value of $R_{A\varepsilon}$ was determined from MC simulation. The reference channel yield of was measured as $N_{J/\psi K^\pm} = 15\,214 \pm 1.1\%$ (stat.) $\pm$ 2.4% (syst.) using an extended maximum likelihood fit to the invariant mass, $m_{\mu^+\mu^-K^\pm}$, of the $\mu^+\mu^-K^\pm$ system in the mass range $4930 - 5630$ MeV and the uncertainty, $\delta m_{\mu^+\mu^-K^\pm}$, of the reconstructed mass propagated from the B-candidate vertex fit uncertainty.

The residual combinatorial background in the signal region, after all selection criteria had been applied, was determined by interpolation of the side-bands using even event-number side-band data. In addition to the combinatorial background, there is a small background contribution due to B candidates containing one or two hadrons erroneously identified as muons. The simulation was used to determine the pion and kaon misidentification probabilities and the expected event yield for $B \rightarrow hh'$ was estimated from measured branching fractions [10] taking into account acceptance and efficiency. The estimated number of background events in the signal region was 6.75. After un-blinding, the total number of events observed in the signal region was 6. The upper limit of the $B^0_s \rightarrow \mu^+\mu^-$ branching fraction was extracted using a standard implementation [11, 12] of the CLs method [13]. Figure 1 shows the invariant-mass distribution and the behaviour of the observed CLs for different tested values of the $\mathscr{B}(B^0_s \rightarrow \mu^+\mu^-)$. The observed limit is:

$$\mathscr{B}(B^0_s \rightarrow \mu^+\mu^-) \; < \; 1.5 \times 10^{-8} \; (95\% \text{ CL}).$$

This upper limit is consistent with SM prediction and with recent measurements by LHCb [14] and CMS [15].

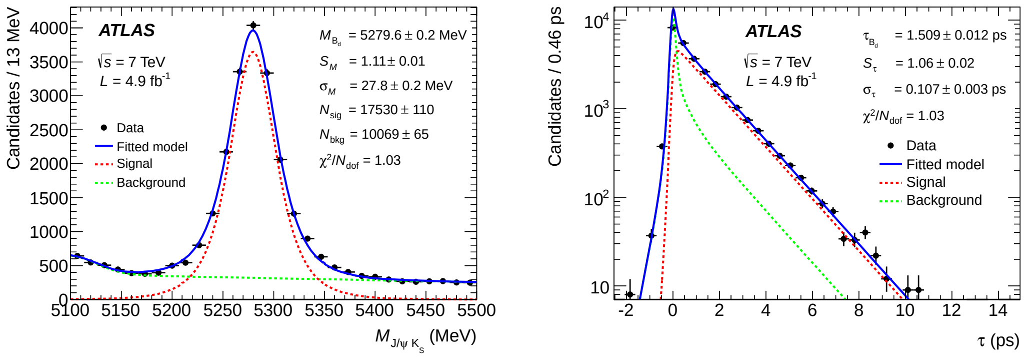
3. Λ^0_b mass and lifetime

The measurement of the Λ^0_b mass and lifetime is based on the 2011 ATLAS dataset (4.9 fb^{-1} after data quality requirements) collected using single-muon, dimuon and J/ψ triggers. Di-muon and di-hadron pairs were pre-selected by requiring that their respective tracks could be successfully fitted to a common vertex. The di-muon (di-hadron) pairs were accepted if they passed a J/ψ (Λ^0) invariant-mass requirement. The muon and hadronic track pairs pre-selected in this way were then refitted with the constraint of a $\Lambda^0_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ cascade decay topology (the J/ψ decays instantly at the same point as the Λ^0_b, while the Λ^0 forms a displaced tertiary vertex). The quality of the fit was characterised by a global χ^2 involving all four tracks and candidates were selected using a requirement on the χ^2 per degree of freedom, $\chi^2/N_{dof} \; < \; 3$. In order to reject background from $B^0_d \rightarrow J/\psi K^0_S$ decays, a difference in the χ^2 probabilities of $\mathscr{P}_{\Lambda^0_b}$ - $\mathscr{P}_{B^0_d} \; > \; 0.05$ was required if the four tracks forming the Λ^0_b candidate also result in an acceptable B^0_d fit. With these criteria, 4074 Λ^0_b and 4081 $\bar{\Lambda}^0_b$ candidates (including background) were selected. An unbinned maximum likelihood fit was used to extract the Λ^0_b mass and lifetime. The results of the fit are shown in Fig. 2 projected onto the mass and proper decay time axes. The measured values are:

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

These results agree with the world average [8] values of $\tau^{PDG}_{\Lambda^0_b} \; = \; 1.425 \pm 0.032$ ps and $m^{PDG}_{\Lambda^0_b} = 5619.4 \pm 0.7$ MeV and recent measurements by LHCb [16, 17] and CMS [18]. In order to determine the ratio of the Λ^0_b and B^0_d lifetimes, the B^0_d lifetime has also been measured using the decay $B^0_d \; \rightarrow \; J/\psi(\mu^+\mu^-)K^0_S(\pi^+\pi^-)$. The selection was designed to be as close as possible to the Λ^0_b selection in order to reduce the overall systematic error on the ratio measurement. The B^0_d lifetime was measured to be $\tau_b \; = \; 1.509 \pm 0.012(\text{stat.}) \pm 0.018(\text{syst.})$ ps and the value of ratio of the Λ^0_b and B^0_d lifetimes was determined to be:

$$R \; = \; \tau_{\Lambda^0_b}/\tau_{B^0_d} \; = \; 0.960 \pm 0.025(\text{stat.}) \pm 0.016(\text{syst.}).$$



(a) (b)

Figure 2: Projection of the fitted PDF onto the mass (a) and the proper decay time (b) axes for Λ_b^0 candidates. Fit results are shown (statistical errors only) for the mass (m_{Λ_b}), lifetime (τ_{Λ_b}), mass and lifetime error scale factors (S_m, S_τ), mass and proper decay time resolutions (σ_m, σ_τ) and the number of signal and background events (N_{sig}, N_{bkg}). Also shown is the χ^2/N_{dof} from the dataset binned in mass and decay time with 61 degrees of freedom.

This value is consistent with measurements by LHCb [17], D0 [19] and CDF [20]. It is in agreement with the prediction of between 0.88 and 0.97 from heavy-quark expansion calculations [21] and is compatible with pQCD predictions [22] of between 0.86 and 0.88 (with an uncertainty of $\pm$ 0.05).

4. Measurement of α_b and helicity amplitudes

Due to parity conservation in the strong interaction, strongly-produced Λ_b^0 can only be polarized in a direction $\hat{n}$ which is perpendicular to the Λ_b^0 momentum [23, 24]. The unit vector $\hat{n}$ is chosen to point in the direction of a cross-product of the beam direction and the Λ_b^0 momentum. The Λ_b^0 decay, as well as the subsequent decays of Λ^0 and J/ψ, are 2-body decays and so each of them can be parametrized by a polar and azimuthal angle in their respective rest frames. A definition of the decay angles is shown in Fig. 3(a). The angle θ is the polar angle of the Λ^0 momentum measured from the normal direction $\hat{n}$ in the Λ_b^0 rest frame. The angles θ_1 and ϕ_1 are 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. Similarly, θ_2 and ϕ_2 are the polar and azimuthal angles of the μ^+ in the J/ψ rest frame with respect to the J/ψ direction in the Λ_b^0 rest frame.

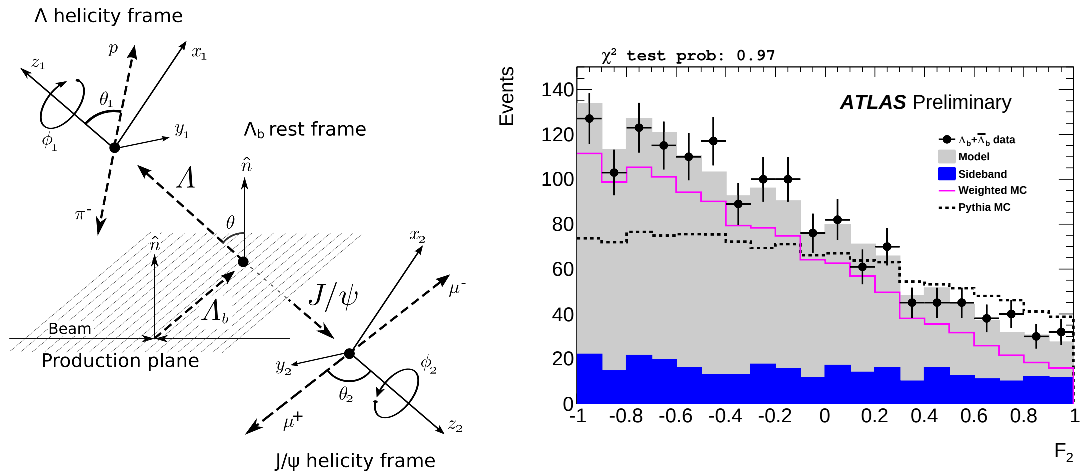
The decay $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ can be described by the following four helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$ where λ_Λ and $\lambda_{J/\psi}$ represent the helicity of the Λ^0 and J/ψ: $a_+ \equiv A(1/2,0)$; $a_- \equiv A(-1/2,0)$; $b_+ \equiv A(-1/2,-1)$; $b_- \equiv A(1/2,1)$. The sum of the squares of the amplitudes are normalised to unity. The full angular probability function (PDF) of the decay angles collection $\Omega = (\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$ is [5]:

$$w(\vec{\Omega}, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega) \qquad (4.1)$$

where $f_{1i}(\vec{A})$ are bilinear combination of the helicity amplitudes, $\vec{A} \equiv (a_+, a_-, b_+, b_-)$ and f_{2i} takes a value of $P\alpha_V$, P, α_V or 1 where α_Λ is the decay asymmetry parameter for the decay $\Lambda^0 \to p\pi^-$

Table 1: The coefficients f_{1i} and F_i of the PDF (Equation 4.1) for the six terms remaining after setting polarization $P = 0$. The parameter f_{2i} has a value of 1 for $i = 0,4$ and α_Λ for $i = 2,6,18,19$.

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



(a) (b)

Figure 3: The $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ decay angles (a), defined in the text, and distributions of the F_2 variable (b) for the model prediction (grey histogram) compared to data (black points). The model prediction is obtained by summing the weighted MC (magenta line) and the background (blue).

and P is the the Λ_b^0 polarization. There are nine unknown parameters with a real value in the PDF: four complex helicity amplitudes: $a_+ = |a_+|e^{i\rho_+}$, $a_- = |a_-|e^{i\rho_-}$, $b_+ = |b_+|e^{i\omega_+}$, $b_- = |a_-|e^{i\omega_-}$ each with a magnitude and a phase, and polarization, P. As the LHC is a proton-proton collider, the initial state is symmetric in the beam direction (z-axis in the ATLAS coordinate system). This together with the symmetry of the ATLAS detector in rapidity means that the overall polarization of the collected data-sample will be zero. As a result, the PDF is reduced (from 19 terms) to the six terms listed in Table 1 where the f_{1i} have been written in terms of the following five parameters chosen to define the model:

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$

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

$$\Delta_+ = \rho_+ - \omega_+ \qquad \Delta_- = \rho_- - \omega_-$$

The dataset for this analysis (4.6 fb^{-1}) was collected using single-muon and J/ψ triggers. The event selection was the same as for the mass and lifetime analysis, apart from a tighter B_d^0 veto requirement, $\mathscr{P}_{\Lambda_b^0} > \mathscr{P}_{B_d^0}$, the addition of a Λ_b^0 proper decay time requirement, $\tau > 0.35$ ps, and a tighter invariant-mass constraint around the mass of the Λ_b^0: $5560 < m_{J/\psi\Lambda^0} < 5680$ MeV. After the selection, there are a total of 1548 Λ_b^0 and $\bar{\Lambda}_b^0$ candidates (including background) in the signal region. If *CP* symmetry is conserved, the PDFs of the Λ_b^0 and $\bar{\Lambda}_b^0$ decays will have exactly the same form. Therefore, assuming *CP* conservation, the Λ_b^0 and $\bar{\Lambda}_b^0$ samples were combined.

The analysis used the method of moments to extract α_b and the helicity amplitudes from measured average values of each of the moments, F_i. The measured parameters were extracted by minimizing the χ^2 function:

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

where $\mathbf{V}$ is the covariance matrix of the measured $< F_i >$ values and $< F_i >^{expected}$ can be written as: $< F_i >^{expected} = \sum f_j(\vec{A}) C_{ij}$ where f_i represents the product $f_{1i} f_{2i}$, determined by the model parameters and α_Λ. Detector effects are encoded in the correction matrix $\mathbf{C}$. The elements of the correction matrix do not depend on the helicity parameters and were determined from MC simulated data samples generated with flat angular distributions. The $< F_i >$ values were calculated after subtraction of the estimated contribution from the combinatorial background and B_d^0 events. Since the combinatorial background changes linearly with the Λ_b^0 mass, its contribution to the measured $< F_i >$ values was estimated using events from the invariant-mass sidebands. The estimated number of B_d^0 events in the signal region was determined from a three component fit (signal, combinatorial background and B_d^0 background) to the Λ_b^0 invariant-mass distribution in order to obtain the estimated contributions from signal, combinatorial background and B_d^0 background. The number of Λ_b^0 was 1243 $\pm$ 44 and the number of B_d^0 events was estimated to be 73 $\pm$ 30. A B_d^0 MC sample, together with the estimated number of B_d^0 events was used to calculate the contribution of the B_d^0 events to the measured $< F_i >$. 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 were added and compared with data. Figure 3(b) shows this comparison for the parameter F_2 (comparisons are shown for the full set of parameters in Ref. [5]).

The values of the asymmetry parameter and helicity amplitudes obtained from the results of the χ^2 fit are:

$$\alpha_b = 0.28 \pm 0.16(\text{stat.}) \pm 0.06(\text{syst.})$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat.}) \pm 0.06(\text{syst.}); \quad |a_-| = 0.59^{+0.06}_{-0.07}(\text{stat.}) \pm 0.04(\text{syst.})$$

$$|b_+| = 0.78^{+0.04}_{-0.05}(\text{stat.}) \pm 0.02(\text{syst.}); \quad |b_-| = 0.08^{+0.13}_{-0.08}(\text{stat.}) \pm 0.05(\text{syst.})$$

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 polarized. The measured value of the asymmetry parameter, α_b, is consistent with a recent LHCb measurement [25].

5. Conclusions

We have presented three measurements of b-hadron properties that provide tests of theoretical models. The measured upper limit $B_s^0 \to \mu^+\mu^-$ branching fraction is consistent with SM prediction. The measured ratio of the Λ_b^0 and B_d^0 lifetimes is in agreement with the prediction of heavy-quark expansion calculations and is compatible with pQCD predictions. The value of the asymmetry parameter, α_b, measured by ATLAS is consistent with the recent measurement of LHCb at the level of one standard deviation. Comparing to theoretical models, the ATLAS measurement differs by about 2.5 standard deviations from the range of $\alpha_b \sim -(0.14 \sim 0.18)$ expected from pQCD [26] and by about 2.9 standard deviations from the HQET expectation [23, 27] of $\alpha_b = 0.78$. Measurements will be updated with greater precision using the 2012 ATLAS dataset (21.7 fb^{-1} recorded) and with data collected in the future LHC Run 2.

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