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Abstract. The properties and decays of baryonic b hadrons have been studied using $3\,\mathrm{fb}^{-1}$ of LHCb data. A determination of $|V_{\mathrm{ub}}|$ is made using the ratio of $\frac{\mathcal{B}(\Lambda_b^0 \to \mathrm{p}\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)}$, the mass and lifetime of the Ω_b^- and Ξ_b^* are measured, the mass of the Λ_b^0 is precisely determined using $\Lambda_b^0 \to (\mathrm{c}\overline{\mathrm{c}})\mathrm{p}\mathrm{K}^-$ and the angular distributions and the forward-backward asymmetries in the dimuon and hadron systems are measured in the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$.

1. Introduction

The study of baryons containing a b quark provides a window into the structure of hadrons and allows sensitive tests of the Standard Model. Bound states of three quarks allow complementary measurement of parameters also accessible from B meson decays. They also allow tests of QCD models, where heavy quark effective theory (HQET) [1] can predict the quark structure in baryons. Branching fractions, masses and lifetimes measurements for b baryons were performed with LHCb data, as well as the CKM parameter $|V_{\mathrm{ub}}|$ and distrubutions and asymmetries of the decays of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$. Charge conjugate processes are implied throughout.

2. LHCb Detector and data sample

The LHCb detector [2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector elements that are particularly relevant to this analysis are: a silicon-strip vertex detector surrounding the pp interaction region that allows c- and b-hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of momentum, p, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. The analyses mentioned in this proceeding use pp collision data, corresponding to an integrated luminosity of $3.0\,\mathrm{fb}^{-1}$, collected during 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV, respectively.

3. $|V_{\mathrm{ub}}|$ measured with decays of the Λ_b^0

The most precise measurements of the CKM parameter $|V_{\mathrm{ub}}|$ come from measurements of the semileptonic quark-level transition $\mathrm{b} \to \mathrm{u}\ell^-\overline{\nu}_\ell$. The world average from Ref. [3] for this method, using the decays $\mathrm{B}^0 \to \pi^+\ell^-\overline{\nu}_\ell$ and $\mathrm{B}^- \to \pi^0\ell^-\overline{\nu}_\ell$, is $|V_{\mathrm{ub}}| = (3.28 \pm 0.29) \times 10^{-3}$, where the most precise experimental inputs come from the BaBar [4, 5] and Belle [6, 7] experiments. The results are also senstive to lattice QCD (LQCD) calculations [8, 9]. These have a tension with the measurements of $|V_{\mathrm{ub}}|$ from the differential decay rate in an inclusive way over all

possible B meson decays containing the $b \to u\ell^-\overline{\nu}_\ell$ quark level transition. This result is $|V_{\mathrm{ub}}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$ [10], which is approximately three standard deviations from the other measurement.

$|V_{\mathrm{ub}}|$ can also be measured using the ratio of branching fractions of the Λ_b^0 to $\mathrm{p}\mu^-\overline{\nu}_\mu$ and $\Lambda_c^+\mu^-\overline{\nu}_\mu$ final states, using the ratio

$$\frac{|V_{\mathrm{ub}}|^2}{|V_{\mathrm{cb}}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to \mathrm{p}\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\mathrm{FF}}, \tag{1}$$

where $\mathcal{B}$ denotes the branching fraction and R_{FF} is a ratio of the relevant form factors, calculated using LQCD. Many of the systematic uncertainties cancel in the ratio and the relatively large yields of these decays reconstructed in the LHCb detector allow a precise measurement to resolve the discrepancy.

The LHCb event selection [11] is deliberately biased toward high values of q^2, the square of the invariant mass of the leptons, as the systematic uncertainties on R_{FF} are smaller there.

The measurement is

$$\frac{\mathcal{B}(\Lambda_b^0 \to \mathrm{p}\mu^-\overline{\nu}_\mu)_{q^2 > 15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2 > 7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

which can be combined with equation 1 and $R_{\mathrm{FF}} = 0.68 \pm 0.07$ from [12] for the restricted q^2 regions, the measurement

$$\frac{|V_{\mathrm{ub}}|^2}{|V_{\mathrm{cb}}|^2} = 0.083 \pm 0.004 \pm 0.004$$

is obtained, where the uncertainties are experimental and from the LQCD prediction. Finally, using the world average $|V_{\mathrm{cb}}| = (39.5 \pm 0.8) \times 10^{-3}$ measured using exclusive decays [10], giving $|V_{\mathrm{ub}}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$, where the uncertainties are experimental, from LQCD and the normalisation to $|V_{\mathrm{cb}}|$. This disfavours models with a right-handed component to the weak coupling, which were proposed to explain the tension in the meson measurements [13].

4. Measurements of $\Omega_b^- \to \Omega_c^0 (\to \mathrm{p}K^+K^-\pi^+)\pi^-$

The HQET predictions for the lifetimes of heavy b baryons suggest a hierarchy of lifetimes [14–16] of $\tau(\Omega_b^-) \simeq \tau(\Xi_b^-) > \tau(\Xi_b^0) \approx \tau(\Lambda_b^0)$. The signal of $\Omega_b^- \to \Omega_c^0 (\to \mathrm{p}K^-K^-\pi^+)\pi^-$ were searched for in the LHCb data with the signal $\Xi_b^- \to \Xi_c^0 (\to \mathrm{p}K^-K^-\pi^+)\pi^-$ as the control channel [17]. In total 62.9 ± 9.0 Ω_b^- decays and 1384 ± 39 Ξ_b^- decays were reconstructed, which were then split into four decay lifetime bins, fit to get the baryon lifetimes and corrected for the relative efficiencies for the two decay chains. The lifetime ratio and absolute lifetime of the Ω_b^- baryon are measured to be

$$\frac{\tau(\Omega_b^-)}{\tau(\Xi_b^-)} = 1.11 \pm 0.16 \pm 0.03 \text{ and}$$

$$\tau(\Omega_b^-) = 1.78 \pm 0.26 \pm 0.05 \pm 0.06\,\mathrm{ps},$$

where the uncertainties are statistical, systematic and from the calibration mode for the absolute measurement. A measurement is also made of the mass differences which yields

$$m(\Omega_b^-) - m(\Xi_b^-) = 247.4 \pm 3.2 \pm 0.5\,\mathrm{MeV}/c^2 \text{ and}$$

$$m(\Omega_b^-) = 6045.1 \pm 3.2 \pm 0.5 \pm 0.6\,\mathrm{MeV}/c^2.$$

These results are consistent with previous measurements and HQET predictions for the lifetime ratios.

5. Properties of the Ξ_b^*

The Ξ_b^* resonance was first reported by the CMS collaboration [18], close to the threshold for $\Xi_b^* \to \Xi_b^0 \pi^+$ decays and is reconstructed with that decay followed by $\Xi_b^0 \to \Xi_c^0 (\to pK^+K^-\pi^+)\pi^-$. The measurement at LHCb shows only one significant resonance in the $X \to \Xi_b^0 \pi^+$ distribution [19], which is compatible with the $J^P = \frac{3}{2}^+$ state expected in the quark model [20]. The measured properties of the Ξ_b^* resonance are

$$m(\Xi_b^*) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023 \text{ MeV}/c^2,$$
$$m(\Xi_b^*) = 5953.02 \pm 0.07 \pm 0.02 \pm 0.55 \text{ MeV}/c^2 \text{ and}$$
$$\Gamma(\Xi_b^*) = 0.90 \pm 0.16 \pm 0.08 \text{ MeV}$$

where the uncertainties are first experimental then systematic, with the third error on the mass being the uncertainty on $m(\Xi_b^-)$ [21]. The inclusive ratio of production cross-sections is $\frac{\sigma(pp \to \Xi_b^* X)\mathcal{B}(\Xi_b^* \to \Xi_b^- \pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.27 \pm 0.03 \pm 0.01$ showing that a large fraction of Ξ_b^- are produced in feed-down decays from higher mass states.

6. Evidence for strangeness-changing weak decays in $\Xi_b^- \to \Lambda_b^0 \pi^-$

HQET predicts that the decay of the b quark dominates the decay width of b baryons, with the s quark contributing about 1% of the total decay width. There are models [22] where the light quarks in the b baryon are in a $J^P = 0^+$ state, which could enhance the contribution from the weak decay of the s in the Ξ_b^- baryon to a level that ranges from 2% to 8%. This is tested with LHCb data by evaluating

$$r_s \equiv \frac{f(\Xi_b^-)}{f(\Lambda_b^0)} \mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-) = \frac{N(\Xi_b^- \to \Lambda_b^0 \pi^-)}{N(\Lambda_b^0)} \epsilon_{\text{rel}}, \tag{2}$$

where $f(X)$ are the fragmentation functions, $N(X)$ is the signal yield and ϵ_{rel} is the relative efficiency. The results [23] is that

$$\frac{f(\Xi_b^-)}{f(\Lambda_b^0)} \mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-) = \left(5.7 \pm 1.8^{+0.8}_{-0.9}\right) \times 10^{-4}.$$

Assuming $\frac{f(\Xi_b^-)}{f(\Lambda_b^0)}$ is bounded between 0.1 and 0.3, the branching fraction $\mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-)$ would be in the range from $0.19\% - 0.76\%$ as predicted in Ref. [24] assuming the diquark transitions have roughly the same weak amplitude as in B, D and K meson decays. This disfavours a large enhancement to the decay rate of Ξ_b^- baryons from the $s \to u\bar{u}d$ transition, which could occur if the short-distance correlations within the $J^P = 0^+$ diquark system are enhanced.

7. Observation of the decays $\Lambda_b^0 \to \psi(2S)pK^-$, $\Lambda_b^0 \to J/\psi \pi^+\pi^- pK^-$ and a measurement of $m(\Lambda_b^0)$

The decays of Λ_b^0 to $\psi(2S)pK^-$ and $J/\psi \pi^+\pi^- pK^-$ have been observed, where the final state $J/\psi \pi^+\pi^- pK^-$ implicitly includes all intermediate resonances, such as $\psi(2S)pK^-$. The branching fraction measurements are made in the ratio to the control channel $\Lambda_b^0 \to J/\psi pK^-$.

The measurements [25] are

$$\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = (20.70 \pm 0.76 \pm 0.56 \pm 0.37) \times 10^{-2} \text{ and}$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \pi^+\pi^- pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = (20.86 \pm 0.96 \pm 1.34) \times 10^{-2},$$

Table 1. Measured Λ_b^0 mass in different decay channels and for the combination of all channels. The first uncertainty is statistical and the second is systematic.

Channel	$m(\Lambda_b^0)[\,\mathrm{MeV}/c^2]$
$\Lambda_b^0 \to J/\psi\,pK^-$	$5619.62 \pm 0.04 \pm 0.34$
$\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-)pK^-$	$5619.84 \pm 0.18 \pm 0.19$
$\Lambda_b^0 \to \psi(2S)(\to J/\psi\,\pi^+\pi^-)pK^-$	$5619.38 \pm 0.33 \pm 0.18$
$\Lambda_b^0 \to J/\psi\,\pi^+\pi^- pK^-$ excluding $\psi(2S)$	$5619.08 \pm 0.30 \pm 0.27$
Combined	$5619.65 \pm 0.17 \pm 0.17$

where the first uncertainties are statistical, the second are systematic and the third is related to knowledge of J/ψ and $\psi(2S)$ branching fractions.

The mass of the Λ_b^0 can be determined from each of these modes plus the control channel, while $\mathcal{B}(\Lambda_b^0 \to J/\psi\,pK^-)$ is the largest of the branching fractions, it also has the largest momentum scale uncertainty. This is a consequence of the detector calibration in which the momentum scale is set to optimise the reconstructed $m(J/\psi)$. The other channels have fewer events and a larger statistical uncertainty, in combination the most precise measurement of the mass of the Λ_b^0 can be made, shown in table 1.

8. Differential branching fraction and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays

The decay channel $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ is evaluated using $\Lambda_b^0 \to J/\psi\,(\to \mu^+\mu^-)\Lambda$ as a control channel. The results are observed as a function of q^2, the square of the invariant mass of the $\mu^+\mu^-$ system. The reconstruction of the $\Lambda \to p\pi^-$ is done for decays inside the VELO using *long* tracks and after the VELO using *downstream* tracks which have less precise directional information.

The signal yield is evaluated as

$$N_S(\Lambda\mu^+\mu^-)_k = \left[\frac{d\mathcal{B}(\Lambda\mu^+\mu^-)/dq^2}{\mathcal{B}(J/\psi\,\Lambda)}\right] \cdot N_s(J/\psi\,\Lambda)_k \cdot \epsilon_k^{\mathrm{rel}} \cdot \frac{\Delta q^2}{\mathcal{B}(J/\psi \to \mu^+\mu^-)}$$

where k is the candidate category (long or downstream), Δq^2 is the width of the q^2 interval considered and $\epsilon_k^{\mathrm{rel}}$ is the relative efficiency.

The distribution of $d\mathcal{B}(\Lambda\mu^+\mu^-)/dq^2$ is shown in figure 1 [26], compared to predictions from the Standard Model. Figure 1 also shows the first measurements of the forward-backward asymmetries, in the dimuon and pμ systems, A_{FB}^l and A_{FB}^h respectively. The measurements of the A_{FB}^h are in good agreement with the predictions of the Standard Model, while for the A_{FB}^l measurements are consistently above the prediction.

9. Conclusion

Many measurements of hadrons with a b quark have been made with LHCb data. The results improve our knowledge on the CKM parameters, as well as the properties and decays of heavy baryons. These constrain models extending the Standard Model and allow the study of the internal structure of hadrons. LHCb is continuing to take data and more results on properties of b baryons will follow and extend our understanding of both QCD and new physics models.
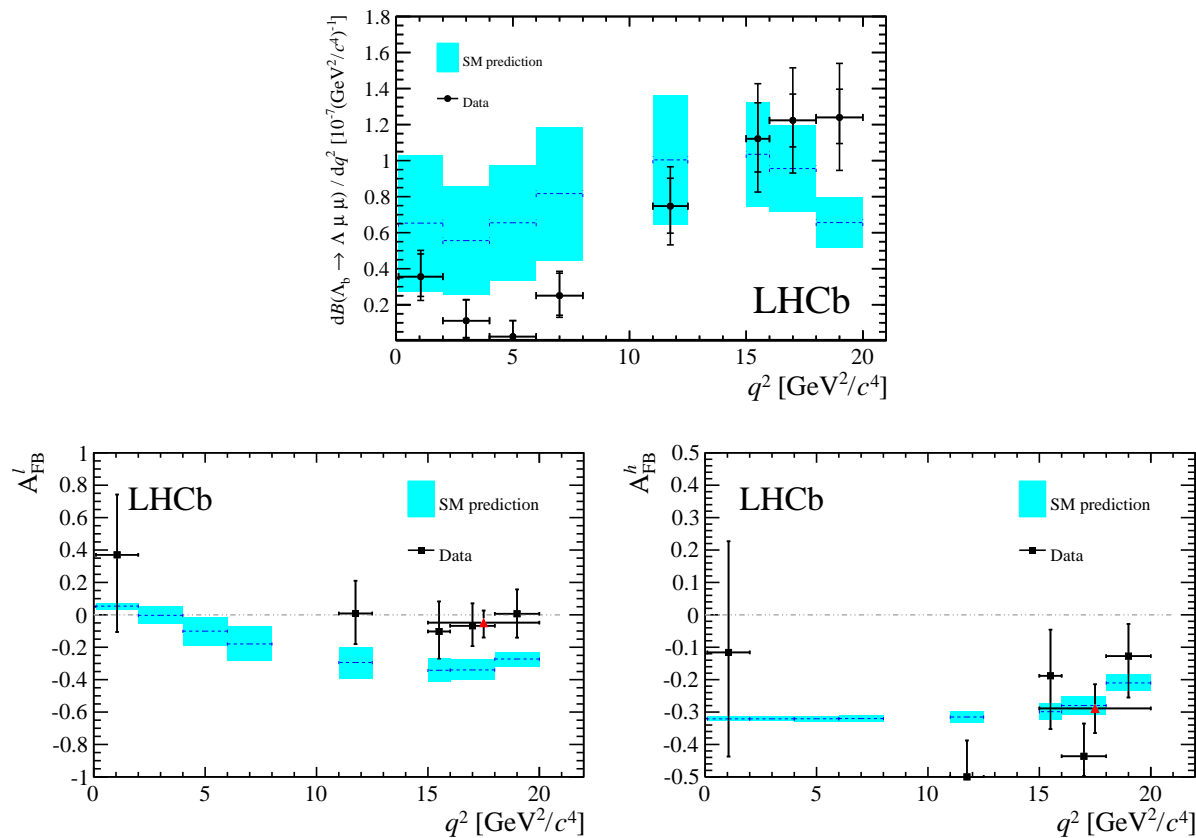
Figure 1. Top row: $d\mathcal{B}(\Lambda\mu^+\mu^-)/dq^2$ with the predictions of the SM [27] superimposed. The inner error bars on data points represent the total uncertainty on the relative branching fraction (statistical and systematic); the outer error bar also includes the uncertainties from the branching fraction of the normalisation mode.

Bottom row: Measured values of (left) the leptonic and (right) the hadronic forward-backward asymmetries in bins of q^2. Data points are only shown for q^2 intervals where a statistically significant signal yield is found. The (red) triangle represents the values for the $15 < q^2 < 20$ GeV^2/c^4 interval. Standard Model predictions are obtained from [28].

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