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Production and decay of heavy flavour baryons

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With one Λ_b^0 baryon produced for every two B_d^0 mesons, the LHC is a b-baryon factory allowing to explore novel areas for rare decays and CP violation searches. We report on recent results in b-baryon production, spectroscopy and decays from the ATLAS, CMS and LHCb experiments.

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[†] on behalf of the LHCb collaboration and presenting also results of the ATLAS and CMS collaborations.

1. Introduction

Most of the attention in heavy flavour physics was concentrated so far on the B meson sector while b-baryon physics is still a relatively unexplored territory. At the LHC, b-baryons are produced in unprecedented quantities, effectively opening a new field in flavour physics for precision measurements and searches for exotic states. Specific processes involving bottom baryons, such as rare decays involving flavour-changing neutral current (FCNC) transitions, are also potential sources of physics beyond the Standard Model (SM). It is also an interesting quantum chromodynamics (QCD) laboratory providing measurements at a different energy regime with respect to light baryons that can be used as experimental anchor points for QCD models.

As an example, the LHCb collaboration has recently measured the $|V_{ub}|$ Cabibbo-Kobayashi-Maskawa (CKM) matrix element in $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays with a precision competitive with B-factory results [1]. The LHCb collaboration has also measured the differential branching ratio and performed an angular analysis of the FCNC decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ as function of the invariant mass of the dimuon pair to search for possible effects of physics beyond the SM [2]. At the time of the writing of this document, LHCb has observed two exotic structures in the $J/\psi p$ channel, consistent with pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays [3].

Baryons are fermions composed by three quarks plus any number of quark-antiquark pairs. The wave function is antisymmetric under exchange of equal-mass quarks,

$$|qqq\rangle_A = |\text{colour}\rangle_A |\text{space, spin, flavour}\rangle_S \tag{1.1}$$

where the subscripts S and A indicate symmetry or antisymmetry under interchange of any two equal-mass quarks. Bottom baryons made of (u,d,s,b) quarks can be organised in $SU(4)$ multiplets with identical spin and parity values, however the $SU(4)$ symmetry is heavily broken due to the relatively large mass of the b quark. The b-baryon states with quark content (bq_1q_2) can be described by the heavy quark effective theory (HQET) using a simplified dynamics where at first order the b-quark mass becomes very large, generating an effective static colour field, and the other quark masses tend to zero. Higher order corrections are calculated as a perturbative expansion in terms of Λ_{QCD}/m_b where $\Lambda_{QCD} \simeq 0.4$ GeV is the QCD energy scale and $m_b \simeq 4.8$ GeV. The heavy baryon properties are determined by the dynamics of the diquark system (q_1q_2) in the b-quark colour field. Precise measurements of the heavy baryons properties provide a sensitive test of the validity of HQET.

The study of rare b-baryon decays mediated by FCNC transitions, or even semileptonic and radiative b-baryon decays, can be sensitive to physics beyond the SM. However, to reach this goal a strong effort also from the theory side is needed, and in particular are necessary precise QCD calculations of the transition form factors.

2. Bottom baryon production

The measurements from the LHCb collaboration of the b-baryon production cross-section shows a strong dependence as a function of the transverse momentum p_T of the b-hadron [4, 5], as reported in Fig. 1 from Ref. [6]. Different b-quark fragmentation function ratios, $f_{\Lambda_b^0}/f_d$, are measured at LEP and at LHC, where $f_{\Lambda_b^0} = P(b \to \Lambda_b^0)$ and $f_d = P(b \to B_d^0)$ are the probabilities of the quark b to hadronise into Λ_b^0 and B_d^0, respectively. However, this should not be interpreted as variation of $f_{\Lambda_b^0}$ with the energy scale of the process which is expected to be relatively small. Hadrons with identical p_T can come from b jets with very different energies of the original b quark. For a cleaner theoretical interpretation it has been suggested to perform the measurements in terms of b-quark p_T, rather than b-hadron p_T, by reconstructing the b jets [7]. As by product of these studies, the LHCb collaboration has measured the branching ratio of the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decay to be $(4.30 \pm 0.03 \pm^{+0.12}_{-0.11} \pm 0.26 \pm 0.21) \times 10^{-3}$ where the first error is statistical, the second systematic, the third from the previous LHCb measurement of $f_{\Lambda_b^0}/f_d$, and fourth is due to the $\bar{B}^0 \to D^+\pi^-$ branching fraction. This is the most precise measurement of a Λ_b^0 branching fraction to date. A measurement of the differential production cross-section of Λ_b^0 from the CMS collaboration shows that the p_T distribution falls faster than the measured b-meson spectra and than the predicted spectra from Monte Carlo simulations [8].

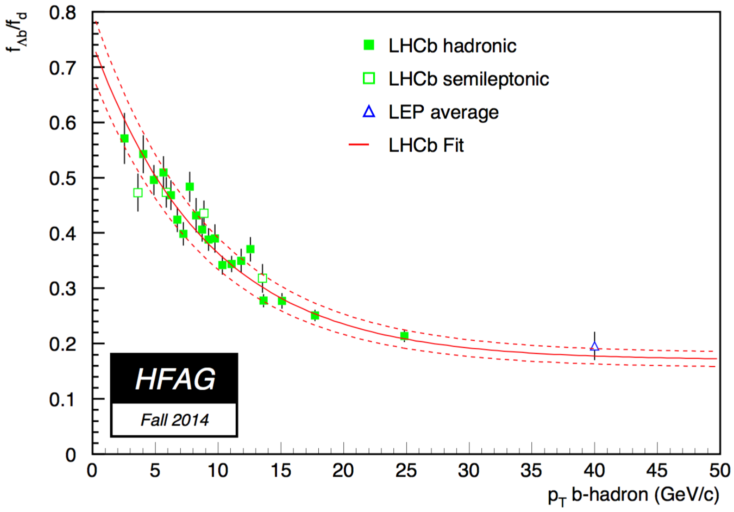

Figure 1: Ratio of production fractions of Λ_b^0 vs B_d^0 as a function of p_T of the b hadron from LHCb measurements using semileptonic and fully hadronic b hadron decays. The fit to LHCb hadronic data is over imposed. The average results from LEP experiments at the Z^0 peak is reported in the plot but is not included in the fit.

3. Measurement of $\Xi_b^{0,-}$ mass and lifetime and new excited $\Xi_b^{0,-}$ states

A new resonant state compatible with the Ξ_b^{*0}, with quark content (usb) and quantum numbers for total angular momentum and parity $J^P = \frac{3}{2}^+$, has been discovered by the CMS collaboration [9] in the decay $\Xi_b^{*0} \to \Xi_b^- \pi^+$ with $\Xi_b^- \to J/\psi \Xi^-$, $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$. The measurement of the mass is $5945.0 \pm 0.7 \pm 0.3 \pm 2.7$ MeV/c^2 where the last uncertainty reflects the present accuracy of the Ξ_b^- mass from the Particle Data Group [10], and the width is measured to be 2.1 ± 0.74 MeV. Two new Ξ_b^- excited baryon states with quark content (dsb) have been discovered by the LHCb collaboration studying the $\Xi_b^0\pi^-$ invariant mass spectrum. One is consistent with the excited state $\Xi_b'^-$ with quantum numbers $J^P = \frac{1}{2}^+$, and the other with Ξ_b^{*-} and $J^P = \frac{3}{2}^+$ [11]. The mass difference $\delta m = m(\Xi_b^0\pi^-) - m(\Xi_b^0) - m(\pi^-)$ with respect to the Ξ_b^0 plus π^- masses has been measured to be $\delta m(\Xi_b'^-) = 3.653 \pm 0.018 \pm 0.006$ MeV/c^2 and $\delta m(\Xi_b^{*-}) = 23.96 \pm 0.12 \pm 0.06$ MeV/c^2 for the $\Xi_b'^-$ and the Ξ_b^{*-} states, respectively. The corresponding widths are measured to be $\Gamma(\Xi_b'^-) < 0.08$ MeV at 95% C.L. and $\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10$ MeV. The distribution of the $\Xi_b^0\pi^-$ mass difference is shown in Fig. 2.

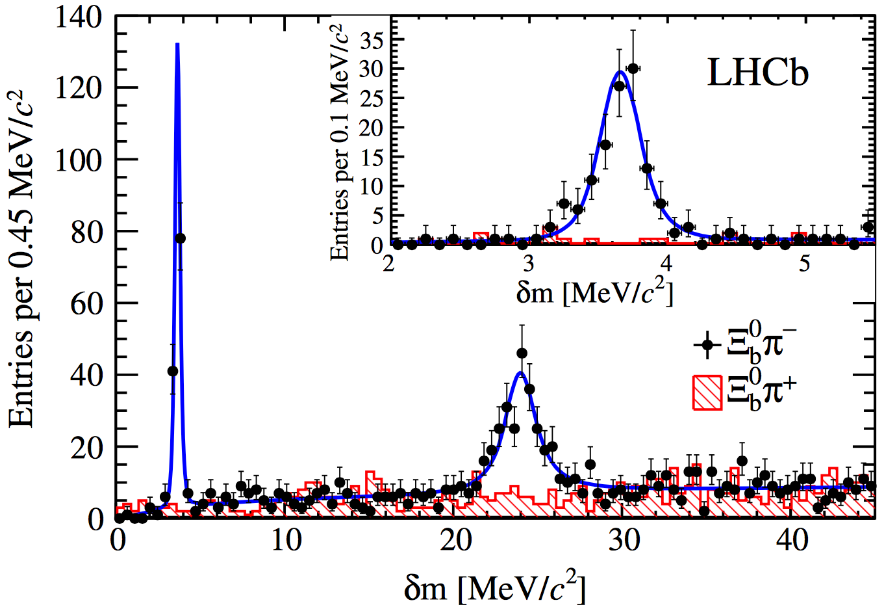

Figure 2: Distribution of the mass difference δm for candidates in data. The signal peaks corresponding to the new states are evident; the hatched histogram shows the distribution of wrong-sign candidates. Inset: detail of the region 2.0-5.0 MeV/c^2.

The helicity angle distributions of the Ξ_c^+ in the rest frame of the Ξ_b^0, from the decays $\Xi_b^{(',*)-} \to \Xi_b^0\pi^-$ with $\Xi_b^0 \to \Xi_c^+\pi^-$, has been studied and data are consistent with quark model predictions of $J = \frac{1}{2}$ and $J = \frac{3}{2}$. However, it is not possible to determine directly the value of J of the excited states since other values of J are not excluded.

Precise measurements of Ξ_b^0 mass and lifetime have been performed by the LHCb collaboration using a data sample corresponding to 3 fb^{-1} collected at the center-of-mass (CM) energies of 7 and 8 TeV [12]. The Ξ_b^0 mass difference and the lifetime ratio relative to the Λ_b^0 was measured using decays with identical final state particles, in particular using 3,800 $\Xi_b^0 \to \Xi_c^+(pK^-\pi^+)\pi^-$ and 180,000 $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$ signal events. This measurement is affected by relatively low systematic uncertainties which cancel in the difference of masses and in the ratio of lifetimes. The ratio of efficiency corrected yields,

$$\frac{N_{\Xi_b^0}(t)}{\Lambda_b^0(t)} = \exp\left(\frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^0}}\right) t \tag{3.1}$$

is fit with an exponential function and it is measured for the first time the lifetime of the Ξ_b^0 baryon relatively to the Λ_b^0 to be $\tau_{\Xi_b^0}/\tau_{\Lambda_b^0} = 1.006 \pm 0.018 \pm 0.010$.

Experiment	Mass (MeV/c^2)	Lifetime (ps)
ATLAS	$5619.7 \pm 0.7 \pm 1.1$	$1.449 \pm 0.036 \pm 0.017$
CMS	-	$1.503 \pm 0.052 \pm 0.031$
LHCb	5619.36 ± 0.26	$1.479 \pm 0.009 \pm 0.010$

Table 1: Measurements of Λ_b^0 mass and lifetime from ATLAS, CMS and LHCb experiments.

The mass difference $m(\Xi_b^0) - m(\Lambda_b^0) = 172.44 \pm 0.39 \pm 0.17$ MeV/c^2 is determined with a precision more than 4 times better than the current world averages. The precision measurements of the Λ_b^0 mass and lifetime from ATLAS [13], CMS [14] and LHCb [15, 16] experiments are reported in Table 1 and can be used to determined the value of the mass and lifetime of the Ξ_b^0 baryon.

The relative rate of Ξ_b^0 to Λ_b^0 baryon production is measured to be

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \frac{B(\Xi_b^0 \to \Xi_c^+ \pi^-)}{B(\Xi_b^0 \to \Xi_c^+ \pi^-)} \frac{B(\Xi_c^+ \to pK^-\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^-)} = (1.88 \pm 0.04 \pm 0.03) \times 10^{-2}, \tag{3.2}$$

and assuming naive Cabibbo factors $B(\Xi_b^0 \to \Xi_c^+\pi^-)/B(\Xi_b^0 \to \Xi_c^+\pi^-) \simeq 1$ and $B(\Xi_c^+ \to pK^-\pi^-)/B(\Lambda_c^+ \to pK^-\pi^-) \simeq 0.1$, one obtains the estimate for the ratio of the fragmentation functions to be $f_{\Xi_b^0}/f_{\Lambda_b^0} \simeq 0.2$.

A similar analysis has been performed, on a data sample corresponding to an integrated luminosity of 3 fb^{-1}, by the LHCb collaboration to measure the Ξ_b^- baryon mass and lifetime using about 1,800 signal events in $\Xi_b^- \to \Xi_c^0\pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ decays [17]. The $\Lambda_b^0 \to \Lambda_c^+\pi^-$ is used as reference mode. The mass difference was measured to be $m(\Xi_b^-) - m(\Lambda_b^0) = 178.36 \pm 0.46 \pm 0.16$ MeV/c^2 and the lifetime time ratio $\tau_{\Xi_b^-}/\tau_{\Lambda_b^0} = 1.089 \pm 0.026 \pm 0.011$, in agreement with predictions from Heavy Quark Expansion (HQE) theory.

4. Observation of $\Lambda_b^0 \to J/\psi p\pi^-$ and search for $\Lambda_b^0 \to \Lambda\eta^{(\prime)}$ decays

The decay $\Lambda_b^0 \to J/\psi p\pi^-$ is mediated by tree and penguin diagrams. The tree decay amplitude is proportional to the product of the CKM matrix elements $|V_{cb}^* V_{cd}| \sim \lambda^3$ while the penguin amplitude, assuming it is dominated by the top quark contribution in the loop, is proportional to $|V_{tb}^* V_{td}| \sim \lambda^3$, where $\lambda = |V_{us}| \simeq 0.23$. Interference between amplitudes with different strong and weak phases could generate non negligible *CP* violation. On the other hand, the decay $\Lambda_b^0 \to J/\psi pK^-$ is largely dominated by tree amplitudes and very small *CP* violation effects are expected. The measurement of the difference of the *CP*-violating asymmetries, A_{CP}, defined as

$$\begin{aligned}\Delta A_{CP} = \;& A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) = \\ & A_{\rm raw}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{\rm raw}(\Lambda_b^0 \to J/\psi pK^-) + A_{\rm reco}(\pi^+) - A_{\rm reco}(K^+)\end{aligned} \tag{4.1}$$

can be expressed in terms of difference of raw asymmetries, $A_{\rm raw}$. It is not sensitive to $\Lambda_b^0/\bar{\Lambda}_b^0$ production asymmetry and the proton reconstruction asymmetry cancels in the difference of the raw asymmetries, defined as

$$A_{\rm raw}(\Lambda_b^0 \to J/\psi p h^-) = \frac{N(\Lambda_b^0 \to J/\psi p h^-) - N(\bar{\Lambda}_b^0 \to J/\psi \bar{p} h^+)}{N(\Lambda_b^0 \to J/\psi p h^-) + N(\bar{\Lambda}_b^0 \to J/\psi \bar{p} h^+)} \quad (4.2)$$

where ($h = K, \pi$). In order to obtain the difference of the CP-violating asymmetries, ΔA_{CP}, the remaining pion and kaon reconstruction asymmetries $A_{\rm reco}(\pi^+)$ and $A_{\rm reco}(K^+)$, respectively, are determined from the raw asymmetry of the $B^0 \to J/\psi K^*(892)^0$ control sample assuming no CP violation and negligible production asymmetries. Using a data sample corresponding to 3 fb^{-1} the LHCb collaboration has reconstructed 2,100 $\Lambda_b^0 \to J/\psi p\pi^-$ and 11,200 $\Lambda_b^0 \to J/\psi pK^-$ signal events and measured $\Delta A_{CP} = (5.7 \pm 2.4 \pm 1.2)\%$, which is compatible with the CP conserving hypothesis at 2.2σ level. The measurement of the relative branching ratio $B(\Lambda_b^0 \to J/\psi p\pi^-)/B(\Lambda_b^0 \to J/\psi pK^-) = 0.0824 \pm 0.0025 \pm 0.0042$ is found to be compatible with the expected value.

The decays of b-baryons to final states with η and η' have not yet been observed. The measurement of the branching ratios of $\Lambda_b^0 \to \Lambda\eta$ and $\Lambda_b^0 \to \Lambda\eta'$ decays would provide useful information for the study of $\eta - \eta'$ mixing and $SU(3)$ flavour symmetry breaking. Isoscalar states with the same J^{PC} are allowed to mix. The η and η' can be described as an admixture of light $|\eta_q\rangle = \frac{1}{2}|u\bar{u} + d\bar{d}\rangle$, strange $|\eta_s\rangle = s\bar{s}\rangle$ quark flavour eigenstates. In principle also the flavour singlet gluonic wavefunction $|gg\rangle$ could contribute and with good approximation this would only occur in the heavier η' meson [18],

$$\begin{aligned} \eta &= \cos\phi_p|\eta_q\rangle - \sin\phi_p|\eta_s\rangle \\ \eta' &= \cos\phi_G \sin\phi_p|\eta_q\rangle + \cos\phi_p \cos\phi_p|\eta_s\rangle + \sin\phi_G|\eta_G\rangle. \end{aligned} \quad (4.3)$$

Most recently, the mixing angles have been measured by the LHCb collaboration using $B_s^0 \to J/\psi\eta^{(\prime)}$ decays, and are found to be $\phi_p = (43.5 \pm 1.5)^\circ$ and $\phi_G = (0 \pm 25)^\circ$ [19]. The LHCb collaboration using a data sample corresponding to 3 fb^{-1} has measured the relative branching ratio of the $\Lambda_b^0 \to \Lambda\eta'$ and $\Lambda_b^0 \to \Lambda\eta$ using the $B_d^0 \to K_S^0\eta'$ decay as normalisation mode [20]. Long-lived K_S^0 and $\Lambda \to p\pi^-$ candidates are divided between Long and Downstream categories according to the fact that the charged tracks produce hits in the vertex detector or not. The two categories are characterised by different track resolutions and have been reconstructed using distinct selection optimisations. The entire decay chain was refitted evaluating the primary vertex using tracks not originated from b-hadron decays and fixing the Λ, K_S^0, η and η' masses to their nominal values [10]. Evidence of signal was found in the $\Lambda_b^0 \to \Lambda\eta$ decay mode with 3.0σ significance while for the $\Lambda_b^0 \to \Lambda\eta'$ decay mode the upper limit on the branching ratio was calculated using the Feldman-Cousins unified method approach for C.L. [21],

$$\begin{aligned} &\frac{B(\Lambda_b^0 \to \Lambda\eta)}{B(B_d^0 \to K^0\eta')} = 0.142^{+0.11}_{-0.08} \Rightarrow B(\Lambda_b^0 \to \Lambda\eta') = 9.3^{+7.3}_{-5.3} \times 10^{-6} \quad \text{at 68\% C.L.} \\ &\frac{B(\Lambda_b^0 \to \Lambda\eta')}{B(B_d^0 \to K^0\eta')} < 0.047 \Rightarrow B(\Lambda_b^0 \to \Lambda\eta') < 3.1 \times 10^{-6} \quad \text{at 90\% C.L.} \end{aligned} \quad (4.4)$$

where the known value for $B(B_d^0 \to K^0\eta')$ is used [10].

5. Measurement of $|V_{ub}|$ with the semileptonic $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decay

In the SM the decay of a quark to another one by emission of a virtual W boson is described by the CKM matrix. The matrix element V_{ub}, which describes the transition of a b quark to a

u quark, can be measured via the semileptonic quark-level transition $b \to u\ell\bar{\nu}_\ell$ to minimise the uncertainties due to the strong interaction of quarks in the final state. The absolute value of the CKM matrix element $|V_{ub}|$ has been measured by the LHCb collaboration using for the first time a baryonic decay, *i.e.* $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decay, with a data sample corresponding to 2 fb^{-1} collected at CM energy of 8 TeV [1]. The $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ decay, mediated by $|V_{cb}|$, is used as normalisation mode. The selection of the signal sample is mainly based on stringent selection criteria for the reconstruction of the Λ_b^0 decay vertex position and for the identification of proton and muon tracks. In order to suppress background from b-hadron decays with additional charged tracks in the decay production, a dedicated multivariate machine learning algorithm, namely the isolation algorithm, has been used and allows to reject 90% of the background. The Λ_b^0 mass is reconstructed using the corrected mass, defined in Eq. 5.1, which is fit to extract the signal yield,

$$M_{corr} = \sqrt{p_\perp^2 + m_{h\mu}^2} + p_\perp, \tag{5.1}$$

where $m_{h\mu}^2$ is the reconstructed mass $h = (p, \Lambda_c^+)$, and $p_\perp$ is the momentum of the $h\mu$ pair transverse to the Λ_b^0 flight direction. The distribution of the corrected mass is shown in Fig. 3

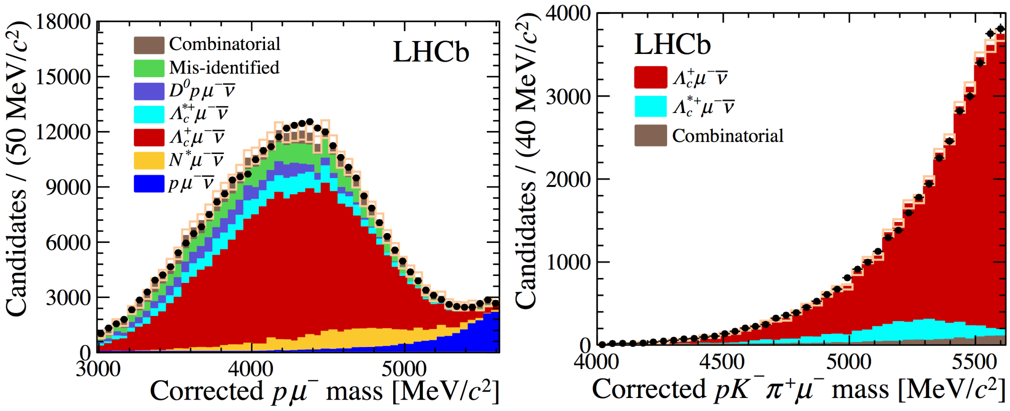

Figure 3: The fit to the corrected mass distribution is used to extract the $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ (left) and $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ (right) signal yields.

Background contributions are estimated using “ad hoc” control sample directly from data. The measurement of the ratio of branching ratios together with lattice QCD (LQCD) calculations allows for the extraction of $|V_{ub}|/|V_{cb}|^2$ according to

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{B(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{B(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF} \tag{5.2}$$

where R_{FF} is a ratio of the relevant form factors, calculated using LQCD [22]. Using the world average $|V_{cb}|$ measurement [10], we obtain

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}, \tag{5.3}$$

where the first uncertainty is due to the experimental measurement, the second arises from the uncertainty in the LQCD prediction and the third from the normalisation to $|V_{cb}|$. The $|V_{ub}|$ mea-

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surement is in agreement with the world average of measurements in exclusive decays, but disagrees with the measurement from inclusive decays at a significance level of 3.5 standard deviations. However, this measurement does not support explanation of this discrepancy based on right handed current added to SM.

6. Conclusions

At the LHC, b-baryons represent a new field in flavour physics for precision measurements. It is a relatively new territory for experiments and theory. Precision measurements of mass, lifetimes and branching ratios of Λ_b^0, $\Xi_b^{(0,-)}$ provide already experimental anchor points for LQCD calculations and QCD models. Rare decays mediated by FCNC are sensitive to physics beyond SM and a program of measurements has just started with, for example, the study of the $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decay. CP violation is expected to be non negligible in b-baryon decays. However, no evidence of CP violation is found so far. The measurement of $|V_{ub}|$ using the semileptonic $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays is an outstanding example of advancement of both experimental techniques and LQCD calculations, providing a stringent test of SM. Finally, more recently, the study of $\Lambda_b^0 \to J/\psi pK^-$ decays reserved an intriguing surprise represented by the discovery of two $J/\psi p$ exotic states, compatible with pentaquarks.

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