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Beauty hadron decays at LHCb

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In these proceedings, I will report the recent results on properties, production and decays of beauty baryons, as well as measurements of B_c^+ meson decays, based on data collected by the LHCb collaboration at the LHC collider in 2011–2012.

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1. Introduction

The start of the LHCb experiment at the LHC collider brings studies of beauty hadrons to a qualitatively new level. While properties and decays of B mesons (B^+, B^0 and, to some extent, B_s^0) have been extensively studied at B factories, other species of beauty hadrons, such as b baryons and B_c^+, are much less explored. The LHCb experiment [1] is specifically designed to study beauty and charm physics in a hadronic environment, and provides the unique opportunity to explore these states with large and pure data samples.

Here, I will cover a few recent studies of b-baryon and B_c^+ properties and their decay modes using the data sample corresponding to $3\,\mathrm{fb}^{-1}$ of integrated luminosity taken in LHC Run 1 (2011–2012).

2. Production and properties of b-baryons

Beauty baryons are hadrons with one heavy b-quark and two light quarks (u, d or s). None of the baryons with two heavy quarks have been found so far. Ground-state b-baryons (*i.e.* those without radial or orbital excitations) can be classified depending on their total spin J and the spin of the system of two light quarks j. The three states where the light quarks form a singlet ($j = 0$) and thus $J = 1/2$ are the lightest b-baryon state Λ_b^0 (with quark content udb) and two strange states Ξ_b^- (dsb) and Ξ_b^0 (usb). The triplet light quark system ($j = 1$) can combine with the b quark to make either $J = 1/2$ which gives six states, $\Sigma_b^{\pm,0}$ (qqb, where $q = u,d$), $\Xi_b'^{(-,0)}$ (qsb) and Ω_b^- (ssb), or $J = 3/2$ with the six states of the same quark content denoted as $\Sigma_b^{*(\pm,0)}$, $\Xi_b{}^{*(-,0)}$ and Ω_b^{*-}, respectively.

Many of these states have been observed at the LEP and Tevatron experiments. Three states have been recently observed at the LHC: Ξ_b^{*0} has been discovered by CMS [2], and $\Xi_b^{'-}$ and Ξ_b^{*-} by LHCb [3]. Four states still remain unobserved; these are $\Sigma_b^{(*)0}$, $\Xi_b'^0$ and Ω_b^{*-} which should decay mostly to the final states with soft neutral particles and thus are very difficult to detect in the hadronic environment.

The measurements of properties of b-baryons, such as masses and lifetimes, are often statistically limited and one needs to choose the modes with the highest experimental yields. The highest branching ratios for weakly decaying baryons (Ξ_b, Ω_b^-) include either the final states with a J/ψ meson and a long-lived hyperon (the latter gives the cascade of long-lived particles, which is difficult to trigger on at LHCb) or a pion and a charmed baryon in the final state (with the favoured decay to hyperons again). At LHCb, the highest experimental yields are obtained with decays of charm baryons to Cabibbo-suppressed multibody decays containing protons, *i.e.* with the decay chains $\Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\pi^-$, $\Xi_b^- \to \Xi_c^0(\to pK^-K^-\pi^+)\pi^-$ and $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\pi^-$. Since no long-lived or neutral particles are involved, the trigger and detection efficiency for these chains is high, which compensates for the lower branching ratios due to Cabibbo suppression.

A number of measurements of b-baryon properties have been performed with this technique. One is the confirmation of the Ξ_b^{*0} state discovered by CMS in the $\Xi_b^-\pi^+$ spectrum [2] and measurement of its mass, width and production cross-section. The LHCb analysis [4] uses the decay chain $\Xi_b^{*0} \to \Xi_b^-\pi^+$, $\Xi_b^- \to \Xi_c^0\pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ for this measurement. The yield of 232 ± 19 signal events is observed (see Fig. 1), which is an order of magnitude larger than used in the CMS observation. This allows one to place constraints on the mass difference $m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068(\text{stat}) \pm 0.023(\text{syst})\,\text{MeV}/c^2$, absolute mass $m(\Xi_b^{*0}) = 5953.02 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}) \pm 0.55(\Xi_b^0)\,\text{MeV}/c^2$ (where the last uncertainty is due to the knowledge of the Ξ_b^0 mass), decay width $\Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16(\text{stat}) \pm 0.08(\text{syst})\,\text{MeV}$ and production cross-section $\frac{\sigma(pp \to \Xi_b^{*0} X)\, \mathscr{B}(\Xi_b^{*0} \to \Xi_b^- \pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.27 \pm 0.03(\text{stat}) \pm 0.01(\text{syst})$. The last of these suggests that a large (if not dominant) fraction of the Ξ_b^- baryons produced in proton-proton collisions comes from the excited Ξ_b^{*0} state.

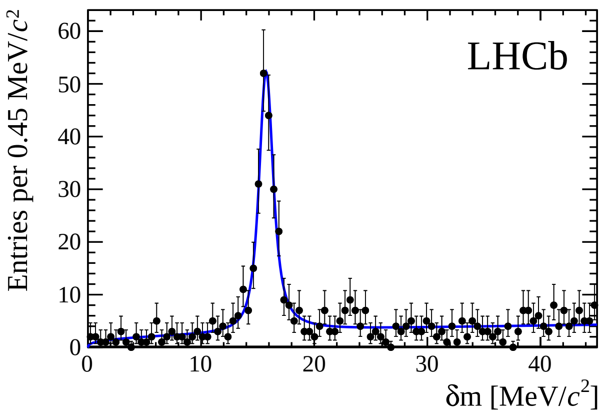

Figure 1: Spectrum of the mass difference $\delta m = m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+)$ for $\Xi_b^{*0} \to \Xi_b^- \pi^+$, $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ candidates and its fit result including the observed Ξ_b^{*0} state.

Another example of using the Cabibbo-suppressed charm baryon final states is the measurement of the properties of the doubly-strange b-baryon Ω_b^-. The Ω_b^- state has been discovered at the Tevatron, and there was a long-standing discrepancy between its mass values measured by the CDF [5] and D0 [6] collaborations which was resolved in favour of CDF in the measurement performed by LHCb [7] with the $\Omega_b^- \to J/\psi\,\Omega^-$ decay mode. The measurement of the Ω_b^- lifetime serves as a good test of HQE, which expects $\tau(\Xi_b^0) \simeq \tau(\Lambda_b^0) \simeq 0.95[\tau(\Omega_b^-) \simeq \tau(\Xi_b^-)]$ (see, *e.g.* [8]). The recent LHCb analysis [9] uses the decay chain $\Omega_b^- \to \Omega_c^0 \pi^-$, $\Omega_c^0 \to pK^-K^-\pi^+$ (Fig. 2(left)) to measure the mass and lifetime of the Ω_b^- with respect to those of the Ξ_b^0, reconstructed via the $\Xi_b^0 \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$ chain. The following results are obtained: the mass difference $m(\Omega_b^-) - m(\Xi_b^-) = 247.4 \pm 3.2(\text{stat}) \pm 0.5(\text{syst})\,\text{MeV}/c^2$, the lifetime ratio $\tau(\Omega_b^-)/\tau(\Xi_b^-) = 1.11 \pm 0.16(\text{stat}) \pm 0.03(\text{syst})$, which give the absolute values for the Ω_b^- mass $m(\Omega_b^-) = 6045.1 \pm 3.2(\text{stat}) \pm 0.5(\text{syst}) \pm 0.6(\Xi_b^-)\,\text{MeV}/c^2$ and its lifetime $\tau(\Omega_b^-) = 1.78 \pm 0.26(\text{stat}) \pm 0.05(\text{syst}) \pm 0.06(\Xi_b^-)\,\text{ps}$ (where the last uncertainties are due to the uncertainties in the Ξ_b^- calibration modes).

3. Decays of b-baryons

Measurements of decays to excited charmonium are important to evaluate QCD factorisation-breaking effects. LHCb has recently measured the decays of Λ_b^0 into the $\psi(2S)pK^-$ final state (with both $\psi(2S) \to \mu^+\mu^-$ and $J/\psi\,\pi^+\pi^-$ decays) using the $\Lambda_b^0 \to J/\psi\,pK^-$ decay as normalisation [10].

The non-resonant decay mode, $\Lambda_b^0 \to J/\psi\, p\pi^+\pi^- K^-$, has been measured as well. The ratios of branching fractions are found to be $\frac{\mathscr{B}(\Lambda_b^0 \to \psi(2S)pK^-)}{\mathscr{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = (20.70 \pm 0.76(\text{stat}) \pm 0.46(\text{syst}) \pm 0.37(\text{BF})) \times 10^{-2}$ (here the last uncertainty is due to the knowledge of the $\psi(2S)$ and J/ψ branching fractions) and $\frac{\mathscr{B}(\Lambda_b^0 \to J/\psi\,\pi^+\pi^- pK^-)}{\mathscr{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = (20.86 \pm 0.96(\text{stat}) \pm 1.34(\text{syst})) \times 10^{-2}$. In addition, the low energy release on this decay mode allows for precise measurement of the Λ_b^0 mass. The result, $M(\Lambda_b^0) = 5619.65 \pm 0.17(\text{stat}) \pm 0.17(\text{syst})\,\text{MeV}/c^2$, is the most precise for any b-hadron so far.

By comparing this result with the other measurements of $\mathscr{B}(b \to \psi(2S)X)/\mathscr{B}(b \to J/\psi X)$ ratios (such as the ratio of B_c^+ decay rates, $\frac{\mathscr{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathscr{B}(B_c^+ \to J/\psi\,\pi)} = 0.268 \pm 0.032(\text{stat}) \pm 0.007(\text{syst}) \pm 0.006(\text{BF})$ [11]) one can see a significant difference in decay rate ratios, which indicates large factorisation-breaking effects.

Studies of Λ_b^0 decays can shed light on the properties of light hadrons. One recent example is the search for the charmless decays $\Lambda_b^0 \to \Lambda\eta$ and $\Lambda_b^0 \to \Lambda\eta'$ [12]. Studies of this decay mode probe $\eta - \eta'$ mixing and place constraints on the mixing angles ϕ_p (which characterises the $s\bar{s}$ admixture in η') and ϕ_g (gluonic admixture). The search has been performed with the decay modes $\eta \to \gamma\gamma$ and $\eta' \to \pi^+\pi^-\eta, \pi^+\pi^-\gamma$. The decays $B^0 \to K_S^0\eta^{(\prime)}$ served as the control channels. Evidence of the $\Lambda_b^0 \to \Lambda\eta$ decay has been found with 3σ significance, with the corresponding branching ratio measured to be $\mathscr{B}(\Lambda_b^0 \to \Lambda\eta) = (9.3^{+7.3}_{-5.3}) \times 10^{-6}$. No $\Lambda_b^0 \to \Lambda\eta'$ events have been found, and an upper limit on the branching fraction has been placed: $\mathscr{B}(\Lambda_b^0 \to \Lambda\eta') < 3.1 \times 10^{-6}$ at 90% confidence level.

The last example of recent progress in studies of b-baryon decays is the evidence of the strangeness-changing decay $\Xi_b^- \to \Lambda_b^0\pi^-$. Typically, the lifetime of b-hadrons is determined by the decay of the b quark, while the light quark serves as spectator in the decay. However, in the decays of hadrons containing a strange quark, if the weak decay of the s quark is kinematically allowed, the decay of the latter can contribute to the lifetime at the level of 1%. Some models suggest that this contribution can be enhanced up to 8% [13]. No decays of this kind have been observed before. LHCb has searched for the strangeness-changing transition in the decay chain $\Xi_b^- \to \Lambda_b^0\pi^-$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$, $\Lambda_c^+ \to pK^-\pi^+$ [14]. Using a large sample of $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decays (around 265×10^3), 103 ± 33 candidates for the $\Xi_b^- \to \Lambda_b^0\pi^-$ decay are found (Fig. 2(right)) with a signal significance of 3.2 standard deviations. The combination of the branching ratio and the ratio of fragmentation fractions is measured to be $\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\mathscr{B}(\Xi_b^- \to \Lambda_b^0\pi^-) = (5.7 \pm 1.8(\text{stat})^{+0.8}_{-0.9}(\text{syst})) \times 10^{-4}$. Assuming the ratio $0.1 < \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} < 0.3$, this gives the branching ratio $\mathscr{B}(\Xi_b^- \to \Lambda_b^0\pi^-)$ in the range $(0.19 - 0.76)\%$.

4. Decays of the $\mathbf{B_c}$ meson

The only doubly-heavy state known so far, B_c^+, is another system where LHCb can significantly improve experimental knowledge. The B_c^+ is a unique laboratory to study QCD effects. For instance, its decays into charmonia are colour-favoured (while for light b-mesons they are colour-

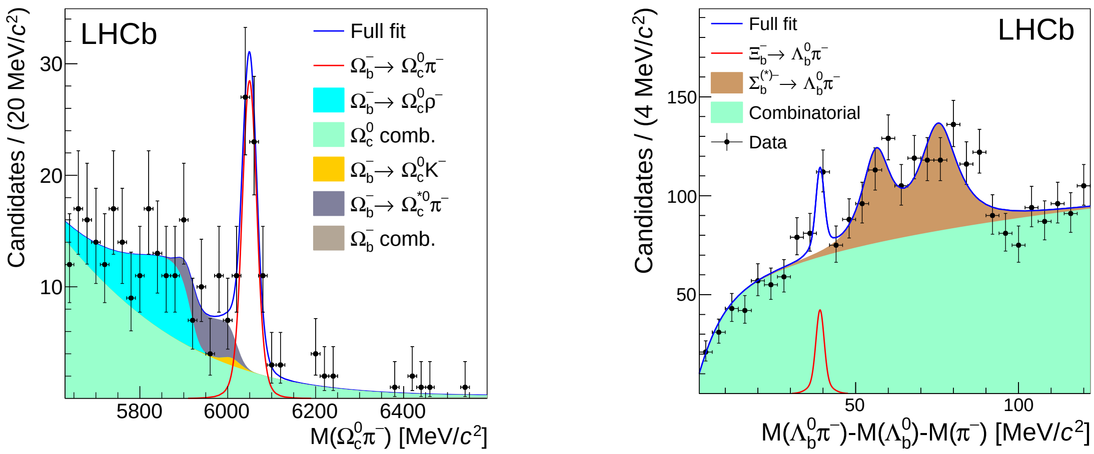

Figure 2: (left) Invariant mass distribution for $\Omega_b^- \to \Omega_c^0\pi^-$, $\Omega_c^0 \to pK^-K^-\pi^+$ candidates. (right) Spectrum of the mass difference $M(\Lambda_b^0\pi^-) - M(\Lambda_b^0) - M(\pi^-)$ showing the evidence of the $\Xi_b^- \to \Lambda_b^0\pi^-$ decay (red peak).

suppressed), which allows one to test QCD factorisation. One related LHCb measurement, the measurement of the branching ratio for the decay $B_c^+ \to \psi(2S)\pi^+$ [11], has been mentioned above. Further, the decays of B_c^+ meson into charmless final states are another interesting example, since they have a purely annihilation topology (contrary to light b-mesons where they are always an interference of annihilation or exchange and penguin diagrams).

The search for such a purely annihilation-type decay has been performed at LHCb in the decays $B_c^+ \to p\overline{p}\pi^+$ [15]. The presence of the proton-antiproton pair in the final state allows to drastically reduce the combinatorial background. The decay $B^+ \to p\overline{p}\pi^+$ was used as the control mode. The phase space of the three-body decay has been divided into two parts: low-$m(p\overline{p})$ (with $m(p\overline{p}) < 2.85\,\text{MeV}/c^2$), where only the charmless contribution is expected; and charmonium region ($2.85 < m(p\overline{p}) < 3.15\,\text{MeV}/c^2$), which could receive contribution from $B_c^+ \to J/\psi(\to p\overline{p})\pi^+$ decay chain. No signal has been found in either of those regions, and the upper limits on the branching fractions have been set: $\frac{f_c}{f_u}\mathscr{B}(B_c^+ \to p\overline{p}\pi^+) < 3.6\times10^{-8}$ for the low-$m(p\overline{p})$ region and $\frac{f_c}{f_u}\mathscr{B}(B_c^+ \to J/\psi(\to p\overline{p})\pi^+) < 8.4\times10^{-8}$ for the charmonium region at 95% confidence level.

5. Conclusion

The studies of properties of heavy beauty hadrons, such as beauty baryons and B_c^+ meson, are extremely interesting from the theoretical point of view. Examples are the searches for New Physics effects in their rare decays, precision measurements of the Unitarity Triangle and *CP* violation, and probing QCD in a regime different to that of the light B mesons. Before the start of the LHC, however, the decays of beauty baryons and B_c^+ meson have been a mostly unexplored territory. LHCb has great potential to improve our knowledge of these states. LHCb is producing many new results on b-baryon production, spectroscopy and decay properties, including the fully hadronic, semileptonic decays and decays with neutral particles in the final state, which were not accessible before. Many new decay modes of B_c^+ meson have been studied. These mostly include the decays with charmonium in the final state that is easier to trigger for LHCb, but investigations with fully hadronic final states are starting as well.

Acknowledgments

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