CONSTRAINING THE CKM ANGLE γ AT LHCb

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on behalf of the LHCb collaboration

The LHCb experiment is a general purpose forward spectrometer operating at the Large Hadron Collider, optimised for the study of B and D hadrons. LHCb has collected 3 fb^{-1} of integrated luminosity, which provides an unprecedentedly large sample of B hadron decays to final states involving charmed hadrons. These decays offer many complementary ways to measure the angle γ of the CKM triangle. The latest combination of LHCb measurements to provide a value of γ is presented, along with the first measurements of CP-violating observables in $B^+ \to DK^+$ and $B^+ \to D\pi^+$ decays with $D \to K^0_S K^\pm \pi^\mp$ final states. The first observations of a number of b-baryon decays that have the potential to contribute to measurements of γ are also reported.

1 Introduction

The CKM parameter γ is currently the least well-constrained angle of the CKM triangle. Combinations made in summer 2012 by the CKMFitter [1] and UTFit [2] collaborations, before the inclusion of measurements from LHCb, gave $\gamma = (66 \pm 12)^\circ$ and $\gamma = (76 \pm 10)^\circ$ respectively. Measurements of γ can be made using B decays that are mediated only by tree-level transitions, for example B decays to open charm mesons. Since these transitions are unlikely to be affected by New Physics, they provide a "standard candle" to measure the Standard Model (SM) value of γ. The value of γ measured in this way can then be compared to values measured using B decays mediated by loop-level transitions, for example B decays to light charmless hadrons. A significant difference between these values would indicate a New Physics contribution to the loop processes.

This document presents the latest results from the LHCb experiment [3] measuring CP-violating observables in hadronic B decays to open charm. Results from time-independent analyses of $B^+ \to DK^+$ and $B^+ \to D\pi^+$ decays, with various final states of the D meson, are combined to give a first LHCb value for γ. The first analysis of $B^+ \to DK^+$ and $B^+ \to D\pi^+$ decays with $D \to K^0_S K^\pm \pi^\mp$ final states is also described. Finally, studies of b-baryon decays to $D^0 ph$ and $\Lambda_c h$ final states (where h represents a charged pion or kaon) are reported.

Most of the results reported here are based on data corresponding to 1 fb^{-1} of integrated luminosity, collected in 2011 at a centre-of-mass energy of 7 TeV, while some results also include the 2 fb^{-1} of data collected in 2012 at a centre-of-mass energy of 8 TeV.

2 Gamma combination from time-independent analyses of $B^+ \to DK^+$ and $B^+ \to D\pi^+$

In general, time-independent methods of measuring γ from hadronic B decays to open charm take advantage of the interference between $b \to c$ and $b \to u$ transitions at tree-level, where the D final state is accessible to both D^0 and $\overline{D}^0$. The most commonly used B decays are $B^+ \to DK^+$ and $B^+ \to D\pi^+$. Aside from the weak phase γ, these analyses also measure the hadronic parameters $r_{B(D)}$ and $\delta_{B(D)}$, where the ratio of the favoured to suppressed $B(D)$ decay amplitudes is $r_{B(D)}e^{i(\delta_{B(D)})}$. The method to extract these hadronic parameters and γ depends on the D final state. The three methods discussed in this document are usually referred to by the initials of the authors of the paper(s) that first proposed the method. There is the "GLW" method [4], where the D decays to a CP eigenstate, the "ADS" method [5] where the D decays to a quasi-flavour-specific state, and the "GGSZ" method [6] where the D decays to a self-conjugate three-body final state.

LHCb has published measurements, all based on 1 fb^{-1} of data, using $D \to \pi^+\pi^-$, K^+K^- and $K^\pm\pi^\mp$ in a two-body ADS and GLW analysis [7], $D \to K^\pm\pi^\mp\pi^+\pi^-$ in a four-body ADS analysis [8], and $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+K^-$ in a GGSZ analysis [9]. These measurements have been combined, using a frequentist approach, to obtain a combined LHCb value for γ [10]. In addition to the LHCb measurements, CLEO-c measurements are also used to constrain some of the parameters of the relevant D systems [11]. The experimental likelihoods are combined as

$$\mathcal{L}(\vec{\alpha}) = f_i(\vec{A}_i^{\rm obs}|\vec{A}_i(\vec{\alpha}_i)),$$

where $\vec{A}$ are the experimental observables (such as, R_{CP+}, x_+, etc), and $\vec{\alpha}$ are the physics parameters (such as γ, r_B, etc). Confidence intervals are then obtained from this likelihood in a frequentist way. The confidence intervals are rescaled to account for undercoverage and neglected correlations between systematics. The effects of $D^0 - \overline{D}^0$ mixing, and of possible CP violation in the D decays, are taken into account. The confidence intervals for γ and r_B from a combination of the DK and $D\pi$ measurements are shown in Fig. 1. The 68% confidence interval for γ is $[55.4, 82.3]^\circ$.

Following the publication of Ref. [10], LHCb performed a preliminary update of the GGSZ analysis with $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+K^-$ final states, using 3 fb^{-1} of data [12]. This result has been used to make a preliminary combination [13] with the 1 fb^{-1} LHCb analyses that were used for the published combination described above. The preliminary combination uses measurements from $B^+ \to DK^+$ decays only. The resulting confidence interval for γ is shown in Fig. 2. Also shown is a comparison of the confidence interval for γ from the preliminary combination with that from a combination of $B^+ \to DK^+$ measurements based only on the

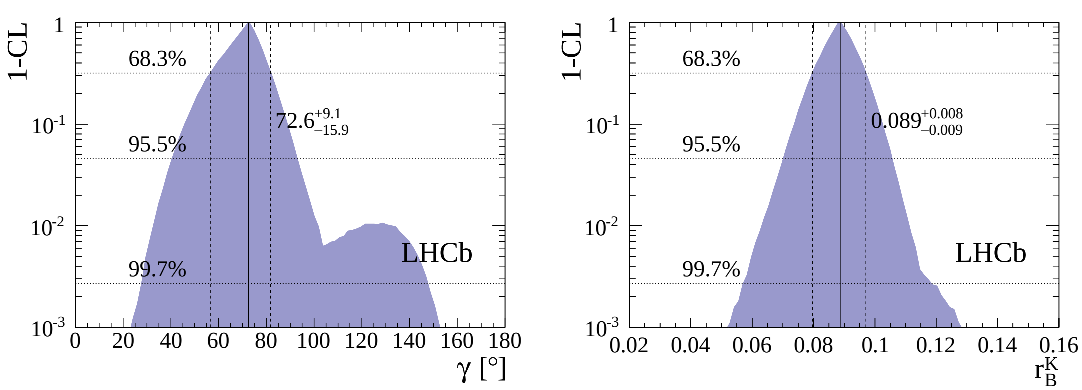

Figure 1: Confidence intervals, resulting from the combination of the DK and $D\pi$ measurements, for γ (left), and r_B (right).

1 fb^{-1} dataset. The preliminary LHCb measurement of γ from this combination is $\gamma = (67 \pm 12)^\circ$. The measurements used for this combination were included in the global CKM fits for the first time in results presented at the summer conferences in 2013. The fitted values for γ were $\gamma = (68.0^{+8.0}_{-8.5})^\circ$ from CKMFitter, and $\gamma = (70.1 \pm 7.1)^\circ$ from UTFit.

3 Time-independent analyses of $B^+ \to DK^+$ and $B^+ \to D\pi^+$ with $D \to K^0_S K^\pm \pi^\mp$ final states

LHCb has made the first study of CP violation in $B^+ \to DK^+$ and $B^+ \to D\pi^+$ decays with $D \to K^0_S K^\pm \pi^\mp$ final states, using 3 fb^{-1} of data [14]. This is the first time an "ADS-like" analysis has been performed with a Singly-Cabibbo-Suppressed (SCS) final state [15]. The final states are labelled Opposite-Sign (OS) or Same-Sign (SS) by comparing the charge of the kaon from the D decay with the charge of the initial B meson. The analysis of the three-body D final state requires knowledge of how the average interference amplitude ($\kappa_{K_S K\pi}$) and strong phase difference ($\delta_{K_S K\pi}$) vary across the D Dalitz plot. This information is taken from measurements by the CLEO-c collaboration [16]. The LHCb analysis measures the yield ratios ($\mathcal{R}$) and charge asymmetries ($\mathcal{A}$) between OS and SS final states, and between DK and $D\pi$ final states. Combining this information with the CLEO-c measurements allows γ, r_B, r_D and δ_B to be extracted. The analysis is performed across the whole D Dalitz plane, and also in a restricted region around the $K^{*\pm}$ resonance, to take advantage of the higher coherence factor ($\kappa_{K_S K\pi}$) in that region.

Examples of the fits to the invariant mass of the B candidates are shown in Fig. 3. The measured values of the observables are shown in Table 1. The scans of the χ^2 probability over

Table 1: Results for $B^+ \to DK^+$ and $B^+ \to D\pi^+$ observables measured in the whole Dalitz region, and in the region around the $K^{*\pm}$ resonance. The first uncertainty is statistical and the second is systematic.

Observable	Whole Dalitz plot	$K^{*\pm}$ window
$\mathcal{R}_{SS/OS,D\pi}$	$1.528 \pm 0.058 \pm 0.025$	$2.57 \pm 0.13 \pm 0.06$
$\mathcal{R}_{DK/D\pi,SS}$	$0.092 \pm 0.009 \pm 0.004$	$0.084 \pm 0.011 \pm 0.003$
$\mathcal{R}_{DK/D\pi,OS}$	$0.066 \pm 0.009 \pm 0.002$	$0.056 \pm 0.013 \pm 0.002$
$\mathcal{A}_{SS,DK}$	$0.040 \pm 0.091 \pm 0.018$	$0.026 \pm 0.109 \pm 0.029$
$\mathcal{A}_{OS,DK}$	$0.233 \pm 0.129 \pm 0.024$	$0.336 \pm 0.208 \pm 0.026$
$\mathcal{A}_{SS,D\pi}$	$-0.025 \pm 0.024 \pm 0.010$	$-0.012 \pm 0.028 \pm 0.010$
$\mathcal{A}_{OS,D\pi}$	$-0.052 \pm 0.029 \pm 0.017$	$-0.054 \pm 0.043 \pm 0.017$

the $\gamma - r_B$ parameter space are shown in Fig. 4, for the fit to the whole D Dalitz region and the

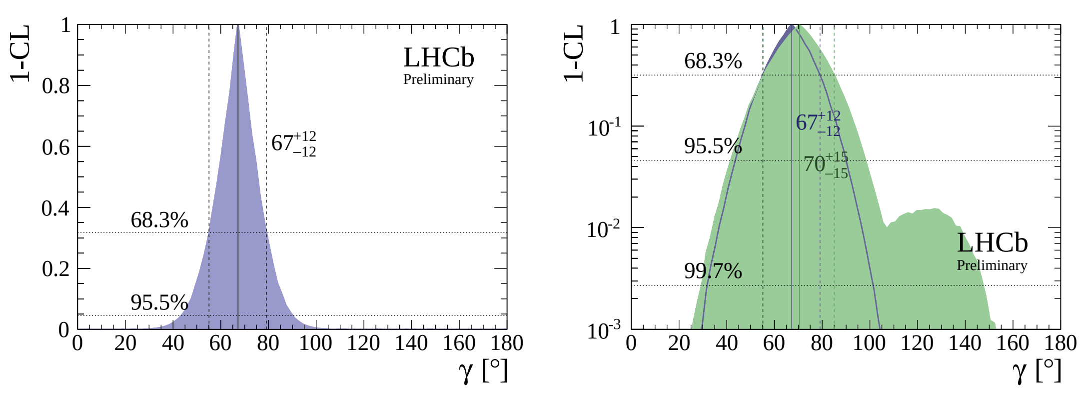

Figure 2: Left: confidence interval for γ from the preliminary combination of DK measurements including the 3 fb^{-1} GGSZ analysis. Right: comparison with the combination of DK measurements based only on the 1 fb^{-1} dataset. The purple (green) interval corresponds to the updated (1 fb^{-1} only) combination.

fit to the region around the $K^{*\pm}$ resonance. It can be seen that the constraints from this analysis are consistent with those obtained by LHCb from other final states. With a larger dataset, this analysis will provide valuable constraints on γ.

4 Studies of b-baryon decays to D^0ph and $\Lambda_c h$ final states

Compared to the b-meson sector, the b-baryon sector remains largely unexplored. Decays such as $\Lambda_b^0 \to D^0\Lambda$ and $\Lambda_b^0 \to D^0pK^-$ can be used to measure γ [17]. The first step towards this goal is to observe such decays. Using 1 fb^{-1} of data, LHCb has made the first observation of the $\Lambda_b^0 \to D^0pK^-$ decay [18], where the D^0 meson is reconstructed using the Cabibbo-favoured $D^0 \to K^-\pi^+$ decay mode. Decay modes having a similar final state to $\Lambda_b^0 \to D^0pK^-$ are also studied, namely $\Lambda_b^0 \to D^0p\pi^-$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+K^-$, where the Λ_c^+ baryon is reconstructed using the Cabibbo-favoured $\Lambda_c^+ \to pK^-\pi^+$ decay mode.

A loose selection, based on rectangular cuts, is applied to measure the ratio of branching fractions of the favoured decays $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to D^0p\pi^-$. The invariant mass distributions of candidates passing this loose selection are shown in Fig. 5 for the $\Lambda_c^+\pi^-$ (left) and $D^0p\pi^-$ (right) final states. The ratio of branching fractions is measured to be

$$R_{\Lambda_b^0\to D^0p\pi^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to D^0p\pi^-) \times \mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.0806 \pm 0.0023 \pm 0.0035,$$

where the first error is statistical and the second systematic. The largest systematic uncertainty

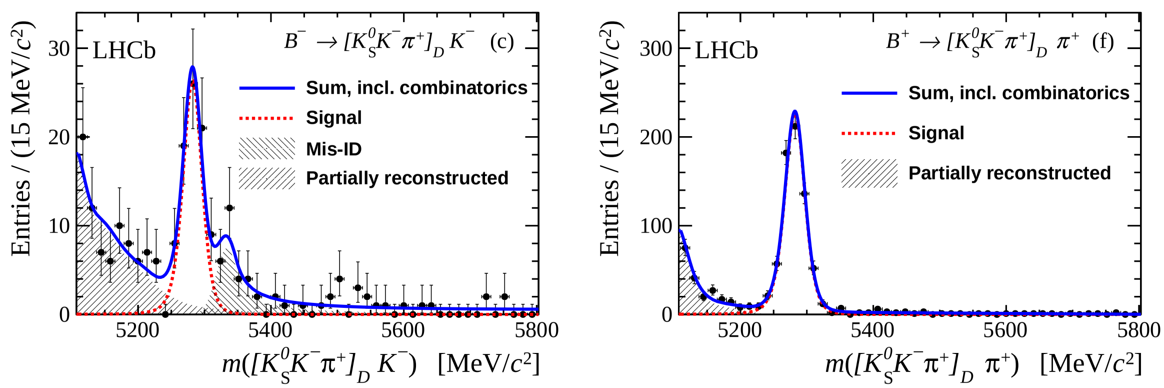

Figure 3: Distributions of the invariant mass of the B candidates for two subsamples of the data — the SS $B^- \to DK^-$ (left), and the OS $B^+ \to D\pi^+$ (right). The fit PDFs are superimposed.

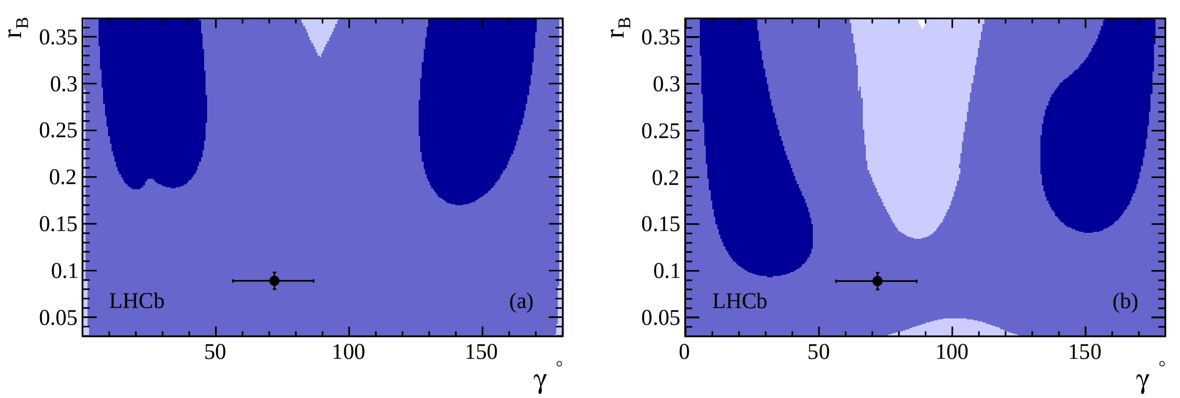

Figure 4: Scans of the χ^2 probability over the $\gamma - r_B$ parameter space for (a) the whole Dalitz fit and (b) the fit inside the $K^{*\pm}$ region. The confidence regions for 1, 2 and 3 standard deviations are shown in dark, medium and light blue respectively. The current LHCb measurement of γ and r_B is indicated by the black data point.

is due to knowledge of the efficiency of the PID cuts used to separate protons from kaons and pions. The charm hadron branching fractions are included in the quoted ratio to avoid dependence on the poorly-known $\Lambda_c^+ \to pK^-\pi^+$ branching fraction.

A tighter selection, based on a Boosted Decision Tree, is used to search for the previously unobserved modes where the "bachelor" particle from the b-baryon decay is a kaon rather than a pion. The invariant mass distributions of candidates passing this tighter selection are shown in Fig. 6 for the D^0pK^- (left) and $\Lambda_c^+K^-$ (right) final states. In the D^0pK^- final state, peaks are observed at both the Λ_b^0 and Ξ_b^0 masses. The significances of these peaks are 9.0σ for the $\Lambda_b^0 \to D^0pK^-$ signal, and 5.9σ for the $\Xi_b^0 \to D^0pK^-$ signal. Both decays are therefore observed for the first time, with ratios of branching fractions measured to be

$$R_{\Lambda_b^0\to D^0pK^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to D^0pK^-)}{\mathcal{B}(\Lambda_b^0 \to D^0p\pi^-)} = 0.073 \pm 0.008^{+0.005}_{-0.006},$$

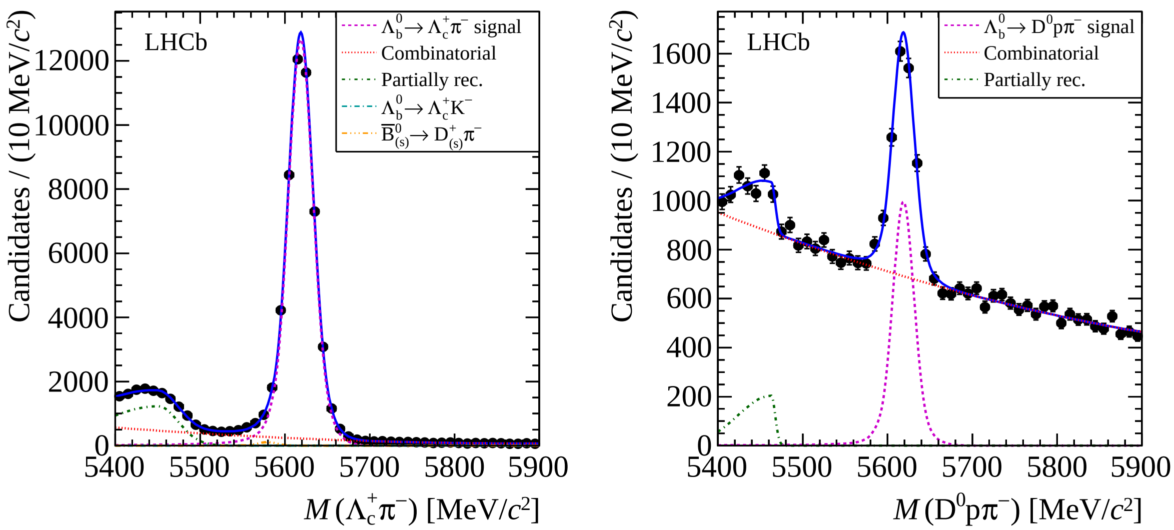

Figure 5: Invariant mass distributions for $\Lambda_b^0 \to \Lambda_c^+\pi^-$ (left) and $\Lambda_b^0 \to D^0p\pi^-$ (right) candidates passing the loose selection.

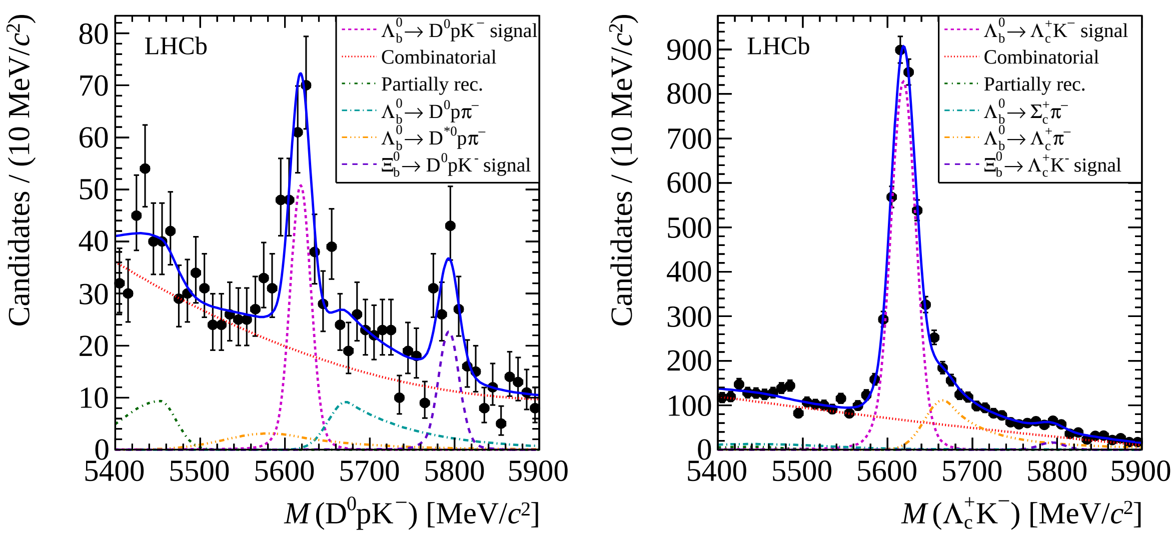

Figure 6: Invariant mass distributions for D^0pK^- (left) and $\Lambda_c^+K^-$ (right) candidates passing the tighter selection.

$$R_{\Xi_b^0 \to D^0 pK^-} \equiv \frac{f_{\Xi_b^0} \times \mathcal{B}(\Xi_b^0 \to D^0 pK^-)}{f_{\Lambda_b^0} \times \mathcal{B}(\Lambda_b^0 \to D^0 pK^-)} = 0.44 \pm 0.09 \pm 0.06,$$

where the first error is statistical and the second systematic. The ratio of fragmentation functions $f_{\Xi_b^0}/f_{\Lambda_b^0}$ is included in the quoted ratio, as its value is currently unmeasured. The $D^0 pK^-$ mass spectrum is also used to precisely measure the difference between the masses of the Ξ_b^0 and Λ_b^0 baryons:

$$m_{\Xi_b^0} - m_{\Lambda_b^0} = 174.8 \pm 2.4 \pm 0.5 \quad \mathrm{MeV}/c^2,$$

where the first error is statistical and the second systematic. For both the ratios of branching fractions and the mass difference, the largest systematic uncertainty is due to the modelling of the background contributions to the $D^0 pK^-$ mass fit. The measurement of the mass difference can be combined with the LHCb measurement of $m_{\Lambda_b^0}$ in the $\Lambda_b^0 \to J/\psi \Lambda$ decay mode [19] to give

$$m_{\Xi_b^0} = 5794.3 \pm 2.4 \pm 0.7 \quad \mathrm{MeV}/c^2,$$

where the first error is statistical and the second is systematic and includes the error on $m_{\Lambda_b^0}$. This is the most precise measurement of $m_{\Xi_b^0}$ to date.

In the $\Lambda_c^+ K^-$ final state, a prominent peak is observed at the Λ_b^0 mass. There is also evidence for a peak at the Ξ_b^0 mass, with a significance of 3.3σ. The ratios of branching fractions are measured to be

$$R_{\Lambda_b^0 \to \Lambda_c^+ K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0731 \pm 0.0016 \pm 0.0016,$$

$$R_{\Xi_b^0 \to \Lambda_c^+ K^-} \equiv \frac{\mathcal{B}(\Xi_b^0 \to \Lambda_c^+ K^-) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_b^0 \to D^0 pK^-) \times \mathcal{B}(D^0 \to K^-\pi^+)} = 0.57 \pm 0.22 \pm 0.21,$$

where the first error is statistical and the second systematic. For both ratios of branching fractions, the largest systematic uncertainty is due to the modelling of the background contributions to the $\Lambda_c^+ K^-$ mass fit. The ratios of branching fractions measured in this analysis are consistent with expectations based on consideration of the CKM matrix elements involved in the dominant decay processes.

References

1. J. Charles *et al.*, *Eur. Phys. J.* C **41**, 1 (2005)
2. M. Bona *et al.*, *JHEP* **10**, 081 (2006
3. A. A. Alves Jr. *et al.*, *JINST* **3**, S08005 (2008)
4. M. Gronau and D. London, *Phys. Lett.* B **253**, 483 (1991)
   M. Gronau and D. Wyler, *Phys. Lett.* B **265**, 172 (1991)
5. D. Atwood, I. Dunietz and A. Soni, *Phys. Rev. Lett.* **78**, 3257 (1997)
   D. Atwood, I. Dunietz and A. Soni, *Phys. Rev.* D **63**, 036005 (2001)
6. A. Giri, Y. Grossman, A. Soffer and J. Zupan, *Phys. Rev.* D **68**, 054018 (2003)
   A. Poluektov *et al.*, *Phys. Rev.* D **70**, 072003 (2004)
   A. Bondar, Proceedings of BINP special analysis meeting on Dalitz analysis, unpublished (2002)
7. A. A. Alves Jr. *et al.*, *Phys. Lett.* B **712**, 203 (2012)
8. A. A. Alves Jr. *et al.*, *Phys. Lett.* B **723**, 44 (2012)
9. A. A. Alves Jr. *et al.*, *Phys. Lett.* B **718**, 43 (2012)
10. A. A. Alves Jr. *et al.*, *Phys. Lett.* B **726**, 151 (2013)
11. N. Lowrey *et al.*, *Phys. Rev.* D **80**, 031105 (2009)

12. A. A. Alves Jr. *et al.*, LHCb-CONF-2013-004 (2013)
13. A. A. Alves Jr. *et al.*, LHCb-CONF-2013-006 (2013)
14. A. A. Alves Jr. *et al.*, LHCb-PAPER-2013-068, submitted to *Phys. Lett.* B
15. Y. Grossman, Z. Ligeti and A. Soffer, *Phys. Rev.* D **67**, 071301R (2003)
16. J. Insler *et al.*, *Phys. Rev.* D **85**, 092016 (2012)
17. I. Dunietz, *Z. Phys.* C **56**, 129 (1992)
    Fayyazuddin, *Mod. Phys. Lett.* A **14**, 63 (1999)
    A. Giri, R. Mohanta and M. Khanna, *Phys. Rev.* D **65**, 073029 (2002)
18. A. A. Alves Jr. *et al.*, *Phys. Rev.* D **89**, 032001 (2014)
19. A. A. Alves Jr. *et al.*, *Phys. Rev. Lett.* **110**, 182001 (2013)