PROCEEDINGS OF SCIENCE

Charmless B decays at LHCb

Eduardo Rodrigues[*†]
University of Cincinnati
E-mail: eduardo.rodrigues@uc.edu

A review of the latest analyses from the LHCb experiment on charmless B-meson decays is presented. Emphasis is given on the first observation of the rare two-body baryonic decay $B^0 \to p\overline{p}$ and the observation of several multi-body baryonic decays of the B^0 and B_s^0 mesons. The decay mode $B^0 \to p\overline{p}$ is the rarest decay of the B^0 meson observed to date. Its branching fraction is determined to be

$$\mathscr{B}(B^0 \to p\overline{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}\,,$$

where the first uncertainty is statistical and the second systematic.

The European Physical Society Conference on High Energy Physics
5-12 July
Venice, Italy

*Speaker.
†On behalf of the LHCb collaboration.

https://pos.sissa.it/

PoS(EPS-HEP2017)239

1. Introduction

The LHCb experiment has been pursuing an extensive programme to study the decays of B mesons to final states containing baryons. This type of decays have unique characteristics not found in similar decays involving mesons only. Two-body baryonic decays are suppressed with respect to decays to multibody final states [1, 2] and the characteristic threshold enhancement in the baryon-antibaryon mass spectrum [3, 4] is still not fully understood. The theoretical description of baryonic B decays is a challenge and experimental information is scarce, hence needed to provide input to the various phenomenology models available.

All analyses presented in these proceedings are based on a pp collision data sample collected in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV, respectively, corresponding to a total integrated luminosity of 3 fb^{-1}. The inclusion of charge-conjugate processes is implied, unless otherwise indicated.

2. First observation of the rare $B^0 \to p\overline{p}$ decay

The LHCb collaboration has greatly increased the knowledge of baryonic B decays in recent years [5, 6, 7, 8, 9, 10]. The collaboration had reported the first observation of a two-body charmless baryonic B^+ decay, $B^+ \to p\overline{\Lambda}(1520)$ [6], and the first evidence for a similar B^0 decay, $B^0 \to p\overline{p}$ [5]. The study of these suppressed modes requires large data samples that are presently only available at the LHC. The experimental data is not abundant.

The LHCb collaboration updated the analysis of the $B^0_{(s)} \to p\overline{p}$ decays (the notation $B^0_{(s)} \to p\overline{p}$ stands for either $B^0 \to p\overline{p}$ or $B^0_s \to p\overline{p}$) with the full run-I data set [11]. In the analysis selection chain, the candidates for both the $B^0_{(s)} \to p\overline{p}$ signal decays and for the normalisation channel $B^0 \to K^+\pi^-$ are selected in a similar way. After the hardware and software stages of the trigger, particle identification (PID) criteria and multilayer perceptrons [12] are utilised to effectively separate signals from backgrounds. To avoid potential biases, $p\overline{p}$ candidates with invariant mass in the range $[5230, 5417]\,\mathrm{MeV}/c^2$ (a $\pm 50\,\mathrm{MeV}/c^2$ window approximately three times the invariant mass resolution around the known B^0 and B^0_s masses [13]) were not examined until the analysis procedure was finalised.

Possible sources of non-combinatorial background to the $p\overline{p}$ spectrum are investigated using simulation samples. The sum of such backgrounds does not peak in the B^0 and B^0_s signal regions but rather contributes a smooth $p\overline{p}$ mass spectrum, which is indistinguishable from the dominant combinatorial background. The backgrounds to the $K^\pm\pi^\mp$ spectrum are well known from previous LHCb analyses. In the fit to the signal modes, the partially reconstructed decays $B^+ \to p\overline{p}\ell^+\overline{\nu}_\ell$, where ℓ stands for an electron or a muon and ν_ℓ for the corresponding neutrino, are treated as a source of systematic uncertainty.

The yields of the signals and background candidates in both the signal and normalisation samples are determined using unbinned maximum likelihood fits to the invariant mass distributions. The $p\overline{p}$ invariant mass distribution is presented in Fig. 1 together with the result of the fit. The yields of the $B^0_{(s)} \to p\overline{p}$ signals are $N(B^0 \to p\overline{p}) = 39 \pm 8$ and $N(B^0_s \to p\overline{p}) = 2 \pm 4$, where the uncertainties are statistical only. The significance of each of the signals is determined from the change in the logarithm of the likelihood between fits with and without the signal component [14].

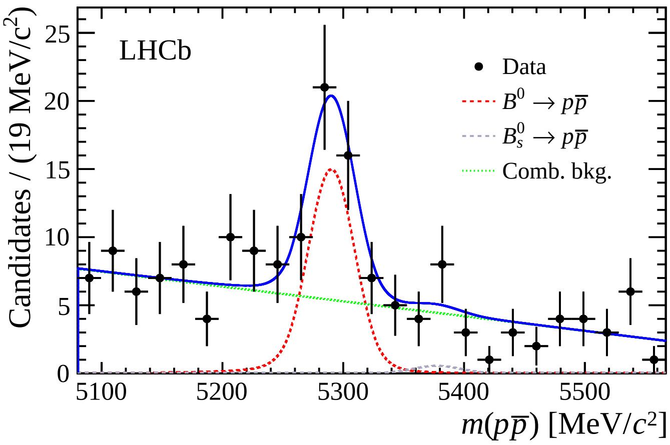

Figure 1: Invariant mass distribution of $p\overline{p}$ candidates. The fit result (blue, solid line) is shown together with each fit model component: the $B^0 \to p\overline{p}$ signal (red, dashed line), the $B_s^0 \to p\overline{p}$ signal (grey, dashed line) and the combinatorial background (green, dotted line).

The $B^0 \to p\overline{p}$ decay mode is found to have a significance of 5.3 standard deviations, including systematic uncertainties, and the $B_s^0 \to p\overline{p}$ mode is found to have a significance of 0.4 standard deviations, where, given its size, the significance has been evaluated ignoring systematic effects. The high significance of the $B^0 \to p\overline{p}$ signal implies the first observation of a two-body charmless baryonic B^0 decay.

The $B^0 \to p\overline{p}$ branching fraction is determined to be

$$\mathscr{B}(B^0 \to p\overline{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8},$$

where the first uncertainty is statistical and the second systematic. The systematic uncertainty includes the contribution from external inputs, namely the uncertainty on the branching fraction of the normalisation decay, $\mathscr{B}(B^0 \to K^+\pi^-) = (1.96 \pm 0.05) \times 10^{-5}$ [13], and, in the case of the determination of the upper limit on $\mathscr{B}(B_s^0 \to p\overline{p})$, the uncertainty on the measurement of the ratio of b-quark hadronisation probabilities $f_s/f_d = 0.259 \pm 0.015$ [15]. The main sources of systematic uncertainty arise from the description of the fit model and from uncertainties on the selection efficiencies, which do not completely cancel given the nature of the final states of the signals and the normalisation channel. Since no $B_s^0 \to p\overline{p}$ signal is seen, the world's best upper limit $\mathscr{B}(B_s^0 \to p\overline{p}) < 1.5 \times 10^{-8}$ at 90% confidence level (C.L.) is set on the decay branching fraction using the Feldman-Cousins frequentist method [16].

The first observation of the decay $B^0 \to p\overline{p}$, the rarest B^0 decay ever observed, provides valuable input towards the understanding of the dynamics of hadronic B decays, helping to discriminate among several QCD-based models. The measured $B^0 \to p\overline{p}$ branching fraction is compatible with recent theoretical calculations, as is the upper limit on the $B_s^0 \to p\overline{p}$ branching fraction [1, 2, 17].

3. First observation of a baryonic B_s^0 decay

Up till last year, baryonic B decays had been observed for all species except the B_s^0 meson. Since two-body baryonic B decays typically have small branching fractions, the LHCb experiment carried out searches for baryonic B_s^0 decays in multi-body final states. It searched for the three-body decay $B_s^0 \to p\overline{\Lambda}K^-$ and analysed the family of $B_{(s)}^0 \to p\overline{p}hh'$ decays, see the following section.

The branching fraction of the $B_s^0 \to p\overline{\Lambda}K^-$ decay has been predicted to be of the order of 10^{-6} [18], the same as for its similar mode $B^0 \to p\overline{\Lambda}\pi^-$. The current experimental situation on the family of $B_{(s)}^0 \to p\overline{\Lambda}h^-$ decays ($h = \pi, K$) and related modes such as $B_{(s)}^0 \to p\overline{\Sigma}^0 h^-$, with $\Sigma^0 \to \Lambda\gamma$, is rather poor: the $B^0 \to p\overline{\Lambda}\pi^-$ decay has been studied by the BaBar [19] and Belle [20] collaborations; the Belle collaboration also reported the 90% C.L. upper limits $\mathscr{B}(B^0 \to p\overline{\Lambda}K^-) < 8.2 \times 10^{-7}$ and $\mathscr{B}(B^0 \to p\overline{\Sigma}^0\pi^-) < 3.8 \times 10^{-6}$ [21].

The LHCb analysis measures the branching fraction of the signal decay $B_s^0 \to p\overline{\Lambda}K^-$ relative to that of the normalisation mode $B^0 \to p\overline{\Lambda}\pi^-$ [9]. Due to the long lifetime of the Λ baryon, the $\Lambda \to p\pi^-$ decays are reconstructed in two different categories: the *long* category consists of Λ hadrons that decay early enough for the daughter particles to be reconstructed in the vertex detector, and the *downstream* category refers to the case when the Λ daughter particles decay later such that track segments cannot be reconstructed in the vertex detector. The $B_s^0 \to p\overline{\Lambda}K^-$ and $B^0 \to p\overline{\Lambda}\pi^-$ candidates are selected in a similar way throughout the selection chain. Multilayer perceptrons are utilised to effectively separate signals from combinatorial background. Particle identification requirements separate the candidates in either the $p\overline{\Lambda}\pi^-$ or the $p\overline{\Lambda}K^-$ spectra.

Background can arise from misidentified decays to the other signal final state; from b-hadron decays where one or more decay products are misidentified, such as decays with K_S^0 mesons misidentified as Λ baryons; and partially reconstructed backgrounds in which one or more particles from the decay of the b hadron are not associated with the signal candidate, such as decays with a Σ^0 baryon. Extensive background studies are performed with simulation samples.

The yields of the signal and background candidates are determined using a simultaneous unbinned extended maximum likelihood fit, with the eight subsamples corresponding to the 2011 and 2012 data-taking periods, the two Λ reconstruction categories, and the two $p\overline{\Lambda}\pi^-$ and $p\overline{\Lambda}K^-$ final states. Figure 2 presents the fit to the $p\overline{\Lambda}h^-$ invariant mass distributions for all subsamples combined. Both $B^0 \to p\overline{\Lambda}\pi^-$ and $B_s^0 \to p\overline{\Lambda}K^-$ signals are prominent. Their total yields (summed over all subsamples) are $N(B^0 \to p\overline{\Lambda}\pi^-) = 519 \pm 28$ and $N(B_s^0 \to p\overline{\Lambda}K^-) = 234 \pm 29$, where the uncertainties are statistical only. The statistical significance of the $B_s^0 \to p\overline{\Lambda}K^-$ decay, above 15 standard deviations, is estimated from the change in log-likelihood between fits with and without the $B_s^0 \to p\overline{\Lambda}K^-$ signal component [14]. This is the first observation of a baryonic B_s^0 decay.

The $B_s^0 \to p\overline{\Lambda}K^-$ branching fraction is determined to be [9]

$$\mathscr{B}(B_s^0 \to p\overline{\Lambda}K^-) + \mathscr{B}(B_s^0 \to \overline{p}\Lambda K^+) = \left[5.46 \pm 0.61 \pm 0.57 \pm 0.50(\mathscr{B}) \pm 0.32(f_s/f_d)\right] \times 10^{-6}\,,$$

where the first uncertainty is statistical and the second systematic, the third uncertainty accounts for the experimental uncertainty on the branching fraction of the $B^0 \to p\overline{\Lambda}\pi^-$ decay used for normalisation, and the fourth uncertainty relates to the knowledge of f_s/f_d. The dominant source of systematic uncertainty comes from the poor knowledge of other baryonic B decays representing backgrounds to the signals, which implies a challenging description of the spectra and non-negligible uncertainties on the fit model components.

Figure 3 shows the $m(p\overline{\Lambda}\ )$ invariant mass distributions for the $B^0 \to p\overline{\Lambda}\pi^-$ and $B_s^0 \to p\overline{\Lambda}K^-$ candidates after correcting for the distribution selection efficiencies. These phase space distributions of signal candidates are obtained with the *sPlot* technique [22]. Both distributions show a

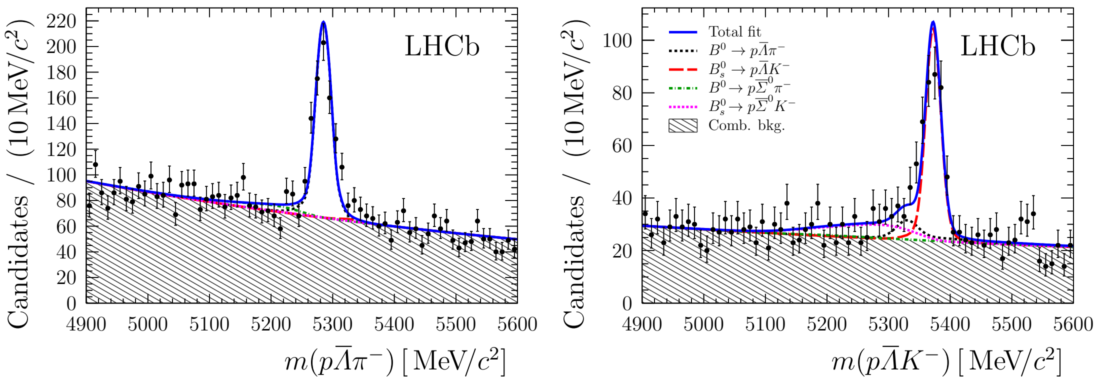

Figure 2: Mass distributions for b-hadron candidates for (left) the $p\overline{\Lambda}\pi^-$ and (right) the $p\overline{\Lambda}K^-$ sample for the combined long and downstream categories. The black points represent the data, the solid blue curve the result of the fit, the red dashed curve the $B_s^0 \to p\overline{\Lambda}K^-$ contribution, the black (magenta) dotted curve the $B^0 \to p\overline{\Lambda}\pi^-$ ($B_s^0 \to p\overline{\Sigma}^0 K^-$) and the green dash-dotted curve the contribution from $B^0 \to p\overline{\Sigma}^0\pi^-$ decays. The combinatorial background distribution is indicated by the shaded histogram.

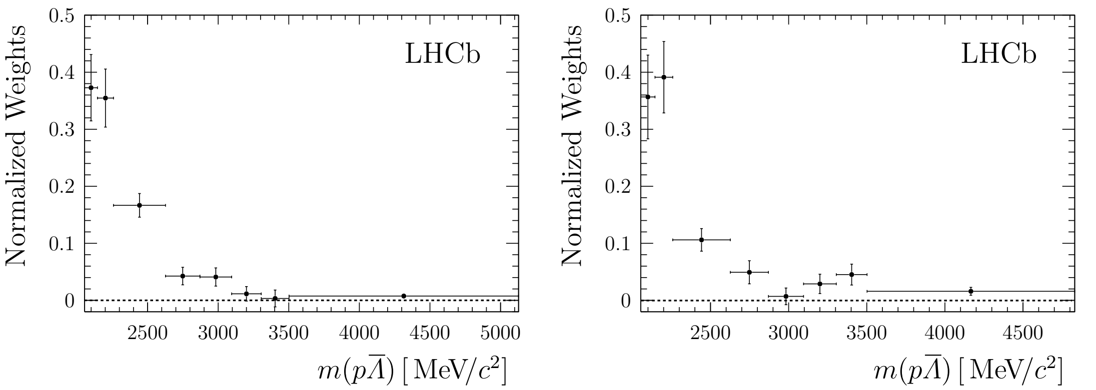

Figure 3: Efficiency-corrected and background-subtracted $m(p\overline{\Lambda}\ )$ invariant mass distributions for (left) $B^0 \to p\overline{\Lambda}\pi^-$ and (right) $B_s^0 \to p\overline{\Lambda}K^-$ candidates. The distributions are normalised to unity.

pronounced enhancement at threshold in the baryon-antibaryon invariant mass, first suggested in Ref. [3]. A threshold enhancement in baryonic B_s^0 decays is observed for the first time.

4. Observation of charmless $B^0_{(s)} \to p\overline{p}hh'$ decays

The LHCb experiment studied the decays of B^0 and B_s^0 mesons to the charmless baryonic final states $p\overline{p}h^+h'^-$, where h and h' each denote a kaon or a pion [10]; for simplicity, the charges of the $h^+h'^-$ combinations will be omitted unless necessary. Multi-body final states are an ideal place to investigate *CP* violation with triple-product correlations whose definitions, compared to those for three-body decays (see Refs. [23, 24] and references therein), do not involve the spin of final-state particles. So far, only evidence of *CP* violation in baryonic B decays has been reported, from an analysis of $B^+ \to p\overline{p}K^+$decays [6]. Of the family of $B^0_{(s)} \to p\overline{p}hh'$ decays, only the resonant

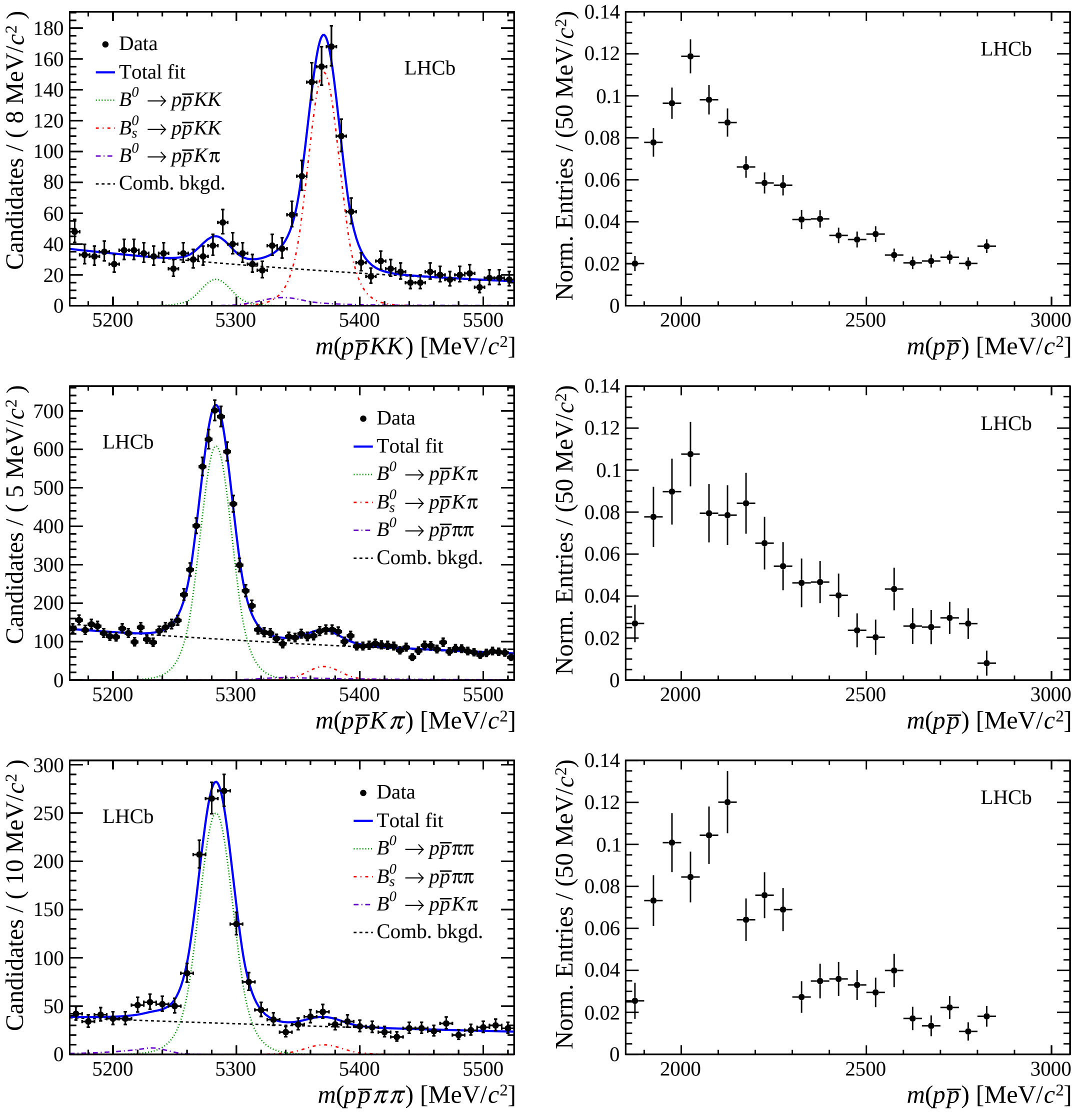

Figure 4: (Left) Invariant mass distributions for $B^0_{(s)}$ candidates and (right) efficiency-corrected and background-subtracted $m(p\overline{p})$ distributions for (top) $B^0 \to p\overline{p}K\pi$, (middle) $B^0_s \to p\overline{p}KK$, and (bottom) $B^0 \to p\overline{p}\pi\pi$ candidates. The results of the fits (left) are shown with blue solid lines. In these figures signals for B^0 and B^0_s decays are shown, respectively, with green dotted and red dot-dashed lines, combinatorial backgrounds are shown with black dashed lines and cross-feed backgrounds are shown with violet dot-dashed lines. All $m(p\overline{p})$ distributions are normalised to unity. The events with entries in the charmonium or D^0 mass regions have been removed from the samples.

Table 1: Fitted yields, signal yield significances and branching fractions. The uncertainties on the yields are statistical only. The first uncertainty on each branching fraction is statistical, the second systematic, the third comes from the uncertainty on the branching fraction of the normalisation mode and the fourth, where present, is due to the uncertainty on f_s/f_d.

Decay channel	Yield	Significance [σ]	Branching fraction / 10^{-6}
$B^0 \to p\bar{p}KK$	68 ± 17	4.1	$0.113 \pm 0.028 \pm 0.011 \pm 0.008$
$B^0 \to p\bar{p}K\pi$	4155 ± 83	> 25	$5.9 \pm 0.3 \pm 0.3 \pm 0.4$
$B^0 \to p\bar{p}\pi\pi$	902 ± 35	> 25	$2.7 \pm 0.1 \pm 0.1 \pm 0.2$
$B^0_s \to p\bar{p}KK$	635 ± 32	> 25	$4.2 \pm 0.3 \pm 0.2 \pm 0.3 \pm 0.2$
$B^0_s \to p\bar{p}K\pi$	246 ± 39	6.5	$1.30 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08$
$B^0_s \to p\bar{p}\pi\pi$	39 ± 16	2.6	< 0.66 at 90% C.L.

mode $B^0 \to p\bar{p}K^*(892)^0$ has been seen by the BaBar [25] and Belle [26] collaborations, which measured its branching fraction to be $\mathscr{B}(B^0 \to p\bar{p}K^*(892)^0) = (1.24^{+0.28}_{-0.25}) \times 10^{-6}$ [13]. An upper limit $\mathscr{B}(B^0 \to p\bar{p}\,\pi^+\pi^-) < 2.5 \times 10^{-4}$ at 90% C.L. has been set by the CLEO collaboration [27].

The analysis procedure largely uses the same techniques utilised in the analyses presented above. The branching fractions of the $B^0_{(s)} \to p\bar{p}hh'$ decays are determined relative to the branching fraction of the $B^0 \to J/\psi(\to p\bar{p})K^*(892)^0(K^+\pi^-)$ normalisation decay. The charm and charmonium resonances in the signal modes are explicitly removed with the requirement $m(p\bar{p}) < 2850\,\mathrm{MeV}/c^2$.

The signal yields are obtained from a simultaneous unbinned extended maximum likelihood fit to the $B^0_{(s)}$ candidate invariant mass distributions in the three $p\bar{p}hh'$ final states. For each final state the dominant $B^0_{(s)} \to p\bar{p}hh'$ cross-feed background is included. The yield of the normalisation decay is determined from a separate simultaneous fit to the $p\bar{p}K\pi$, $p\bar{p}$ and $K\pi$ invariant mass distributions.

The $p\bar{p}hh'$ invariant mass distributions with the results of the fit overlaid are shown in Fig. 4. The signal yields and significances are collected in Table 1 together with the branching fractions determined in the kinematic region $m(p\bar{p}) < 2850\,\mathrm{MeV}/c^2$. The $B^0 \to p\bar{p}\pi\pi$, nonresonant $B^0 \to p\bar{p}K\pi$, $B^0_s \to p\bar{p}KK$ and $B^0_s \to p\bar{p}K\pi$ decays are observed for the first time. In particular, four-body charmless baryonic B^0_s decays are observed for the first time. Evidence at 4.1 standard deviations (σ) is found for the $B^0 \to p\bar{p}KK$ decay. The significance for the $B^0_s \to p\bar{p}\pi\pi$ mode is less than $3\,\sigma$; an upper limit on its branching fraction is set integrating the likelihood after multiplying by a uniform prior in the region of positive branching fraction.

The $m(p\bar{p})$ invariant mass distributions are investigated to further study the effect of threshold enhancement in multi-body final states. The normalised, background-subtracted and efficiency-corrected distributions are presented on the righthand side of Fig. 4. An enhancement near threshold is clearly visible in each case.

References

[1] Y. K. Hsiao and C. Q. Geng, *Violation of partial conservation of the axial-vector current and two-body baryonic B and D_s decays*, Phys. Rev. **D91** (2015) 077501, arXiv:1407.7639.

PoS(EPS-HEP2017)239

[2] H.-Y. Cheng and C.-K. Chua, *On the smallness of tree-dominated charmless two-body baryonic B decay rates*, Phys. Rev. **D91** (2015) 036003, arXiv:1412.8272.

[3] W.-S. Hou and A. Soni, *Pathways to rare baryonic B decays*, Phys. Rev. Lett. **86** (2001) 4247, arXiv:hep-ph/0008079.

[4] BaBar and Belle collaborations, A. J. Bevan *et al.*, *The physics of the B factories*, Eur. Phys. J. **C74** (2014) 3026, arXiv:1406.6311.

[5] LHCb collaboration, R. Aaij *et al.*, *First evidence for the two-body charmless baryonic decay $B^0 \to p\overline{p}$*, JHEP **10** (2013) 005, arXiv:1308.0961.

[6] LHCb collaboration, R. Aaij *et al.*, *Evidence for CP violation in $B^+ \to p\overline{p}K^+$ decays*, Phys. Rev. Lett. **113** (2014) 141801, arXiv:1407.5907.

[7] LHCb collaboration, R. Aaij *et al.*, *First observation of a baryonic B_c^+ decay*, Phys. Rev. Lett. **113** (2014) 152003, arXiv:1408.0971.

[8] LHCb collaboration, R. Aaij *et al.*, *Evidence for the two-body charmless baryonic decay $B^+ \to p\overline{\Lambda}$*, JHEP **04** (2017) 162, arXiv:1611.07805.

[9] LHCb collaboration, R. Aaij *et al.*, *First observation of a baryonic B_s^0 decay*, Phys. Rev. Lett. **119** (2017) 041802, arXiv:1704.07908.

[10] LHCb collaboration, R. Aaij *et al.*, *Observation of charmless baryonic decays $B^0_{(s)} \to p\overline{p}h^+h'^-$*, Phys. Rev. **D96** (2017) 051103, arXiv:1704.08497.

[11] LHCb collaboration, R. Aaij *et al.*, *First observation of the rare purely baryonic decay $B^0 \to p\overline{p}$*, arXiv:1709.01156, submitted to Phys. Rev. Lett.

[12] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, *Parallel distributed processing: explorations in the microstructure of cognition*, vol. 1, MIT, Cambridge, USA, 1986.

[13] Particle Data Group, C. Patrignani *et al.*, *Review of particle physics*, Chin. Phys. **C40** (2016) 100001.

[14] S. S. Wilks, *The large-sample distribution of the likelihood ratio for testing composite hypotheses*, Ann. Math. Stat. **9** (1938) 60.

[15] LHCb collaboration, R. Aaij *et al.*, *Measurement of the fragmentation fraction ratio f_s/f_d and its dependence on B meson kinematics*, JHEP **04** (2013) 001, arXiv:1301.5286, f_s/f_d value updated in LHCb-CONF-2013-011.

[16] G. J. Feldman and R. D. Cousins, *Unified approach to the classical statistical analysis of small signals*, Phys. Rev. **D57** (1998) 3873.

[17] C.-K. Chua, *Rates and CP asymmetries of charmless two-body baryonic $B_{u,d,s}$ decays*, Phys. Rev. **D95** (2017) 096004, arXiv:1612.04249.

[18] C. Q. Geng, Y. K. Hsiao, and E. Rodrigues, *Three-body charmless baryonic $\bar{B}_s^0$ decays*, Phys. Lett. **B 767** (2017) 205, arXiv:1612.08133.

[19] BaBar collaboration, B. Aubert *et al.*, *Measurement of the branching fraction and $\overline{\Lambda}$ polarization in $B^0 \to \overline{\Lambda}p\pi^-$*, Phys. Rev. **D79** (2009) 112009, arXiv:0904.4724.

[20] Belle collaboration, M.-Z. Wang *et al.*, *Study of $B^+ \to p\overline{\Lambda}\gamma, p\overline{\Lambda}\pi^0$ and $B^0 \to p\overline{\Lambda}\pi^-$*, Phys. Rev. **D76** (2007) 052004, arXiv:0704.2672.

[21] Belle collaboration, M. Z. Wang *et al.*, *Observation of $B^0 \to p\bar{\Lambda}\pi^-$*, Phys. Rev. Lett. **90** (2003) 201802, arXiv:hep-ex/0302024.

[22] M. Pivk and F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, arXiv:physics/0402083.

[23] M. Gronau and J. L. Rosner, *Triple product asymmetries in K, $D_{(s)}$ and $B_{(s)}$ decays*, Phys. Rev. **D84** (2011) 096013, arXiv:1107.1232.

[24] C. Q. Geng and Y. K. Hsiao, *Direct CP and T violation in baryonic B decays*, Int. J. Mod. Phys. **A23** (2008) 3290, arXiv:0801.0022.

[25] BaBar collaboration, B. Aubert *et al.*, *Evidence for the $B^0 \to p\bar{p}K^{*0}$ and $B^+ \to \eta_c K^{*+}$ decays and study of the decay dynamics of B meson decays into $p\bar{p}h$ final states*, Phys. Rev. **D76** (2007) 092004, arXiv:0707.1648.

[26] Belle collaboration, J. H. Chen *et al.*, *Observation of $B^0 \to p\bar{p}K^{*0}$ with a large K^{*0} polarization*, Phys. Rev. Lett. **100** (2008) 251801, arXiv:0802.0336.

[27] CLEO collaboration, C. Bebek *et al.*, *Search for the charmless decays $B \to p\bar{p}\pi$ and $p\bar{p}\pi\pi$*, Phys. Rev. Lett. **62** (1989) 8.