Studies of the decays $B^+\to p p^- h^+$ and observation of $B^+\to \Lambda^- (1520) p$

LHCb Collaboration; et al; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A

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DOI: https://doi.org/10.1103/PhysRevD.88.052015

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-91571
Journal Article
 Originally published at:
LHCb Collaboration; et al; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A (2013). Studies of the decays $B^+\to p p^- h^+$ and observation of $B^+\to \Lambda^- (1520) p$. Physical Review D (Particles, Fields, Gravitation and Cosmology), 88:052015.
DOI: https://doi.org/10.1103/PhysRevD.88.052015
Studies of the decays $B^+ \to p\bar{p}h^+$ and observation of $B^+ \to \bar{\Lambda}(1520)p$

R. Aaij et al.*
(LHCb Collaboration)

(Received 23 July 2013; published 19 September 2013)

Dynamics and direct $CP$ violation in three-body charmless decays of charged $B$ mesons to a proton, an antiproton and a light meson (pion or kaon) are studied using data, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, collected by the LHCb experiment in $pp$ collisions at a center-of-mass energy of 7 TeV. Production spectra are determined as a function of Dalitz-plot and helicity variables. The forward-backward asymmetry of the light meson in the $p\bar{p}$ rest frame is measured. No significant $CP$ asymmetry in $B^+ \to p\bar{p}K^+$ decay is found in any region of the Dalitz plane. We present the first observation of the decay $B^+ \to \bar{\Lambda}(1520)(\to K^+\bar{p})p$ near the $K^+\bar{p}$ threshold and measure $B(B^+ \to \bar{\Lambda}(1520)p) = (3.9^{+1.0}_{-0.9}(\text{stat}) \pm 0.1(\text{syst}) \pm 0.3(BF)) \times 10^{-7}$, where BF denotes the uncertainty on secondary branching fractions.

DOI: 10.1103/PhysRevD.88.052015

PACS numbers: 13.25.Hw

I. INTRODUCTION

Evidence of inclusive direct $CP$ violation in three-body charmless decays of $B^+$ mesons\(^1\) has recently been found in the modes $B^+ \to K^+\pi^+\pi^-$, $B^+ \to K^+K^+K^-$, $B^+ \to \pi^+\pi^+\pi^-$, and $B^+ \to K^+K^-\pi^-$ [1,2]. In addition, very large $CP$ asymmetries were observed in the low $K^+K^-$ and $\pi^+\pi^-$ mass regions, without clear connection to a resonance. The localization of the asymmetries and the correlation of the $CP$ violation between the decays suggest that $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering may play an important role in the generation of the strong phase difference needed for such a violation to occur [3,4]. Conservation of $CP$ symmetry imposes a constraint on the sum of the rates of final states with the same flavor quantum numbers, providing the possibility of entangled long-range effects contributing to the $CP$ violating mechanism [5]. In contrast, $h^+h^- \leftrightarrow p\bar{p}$ ($h = \pi$ or $K$ throughout the paper) rescattering is expected to be suppressed compared to $\pi^+\pi^- \leftrightarrow K^+K^-$, and thus is not expected to play an important role.

The leading quark-level diagrams for the modes $B^+ \to p\bar{p}h^+$ are shown in Fig. 1. The $B^+ \to p\bar{p}K^+$ mode is expected to be dominated by the $b \to s$ loop (penguin) transition while the mode $B^+ \to p\bar{p}p\pi^+$ is likely to be dominated by the $b \to u$ tree decay, which is Cabibbo-Kobayashi-Maskawa matrix suppressed compared to the former. Since the short distance dynamics are similar to that of the $B^+ \to h^+h^+h^-$ modes, a $CP$ analysis of $B^+ \to p\bar{p}h^+$ decays could help to clarify the role of long-range scatterings in the $CP$ asymmetries of $B^+ \to h^+h^+h^-$ decays.

First studies were performed at the $B$ factories on the production and dynamics of $B^+ \to p\bar{p}h^+$ decays [6–8]. The results have shown a puzzling opposite behavior of $B^+ \to p\bar{p}K^+$ and $B^+ \to p\bar{p}\pi^+$ decays in the asymmetric occupation of the Dalitz plane. Charmonium contributions to the $B^+ \to p\bar{p}K^+$ decay have been studied by LHCb [9]. This paper reports a detailed study of the dynamics of the $B^+ \to p\bar{p}h^+$ decays and a systematic search for $CP$ violation, both inclusively and in regions of the Dalitz plane. The charmless region, defined for the invariant mass $m_{p\bar{p}} < 2.85$ GeV/$c^2$, is of particular interest. The relevant observables are the differential production spectra of Dalitz-plot variables and the global charge asymmetry $A_{CP}$, defined as

$$A_{CP} = \frac{N(B^- \to f^-) - N(B^+ \to f^+)}{N(B^- \to f^-) + N(B^+ \to f^+)},$$

where $f^\pm = p\bar{p}h^\pm$. The mode $B^+ \to J/\psi(\to p\bar{p})K^+$ serves as a control channel. The first observation of the decay $B^+ \to \bar{\Lambda}(1520)p$ is presented. Its branching fraction is derived through the ratio of its yield to the measured yield of the $B^+ \to J/\psi(\to p\bar{p})K^+$ decay.

II. DETECTOR AND SOFTWARE

The LHCb detector [10] 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 includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/$c$ to 0.6% at 100 GeV/$c$, and

\*Full author list given at the end of the article.

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A multivariate algorithm is used to identify secondary reco-
structed with and without the considered track. A hadronic calorimeter.

corresponding pion, kaon and proton originating

events triggered both on objects independent of the signal, and associated with the signal, are used.

In the latter case, the transverse energy of the hadronic

class is required to be at least 3.5 GeV. The software

tigger requires a two-, three- or four-track secondary

catcher is required to be at least 3.5 GeV. The software

signal are used. In combined subdetector

identification (PID) is applied to the proton, kaon

candidates formed by the combinations are re-

PARTICLES

The trigger [12] consists of a hardware stage, based on

information from the calorimeter and muon systems,

followed by a software stage which applies a full event

reconstruction. Events triggered both on objects indepen-

dent of the signal, and associated with the signal, are used.

The interaction of the generated particles with the

detector is defined as the difference between the χ² of the primary vertex

reconstructed with and without the considered track. A multivariate algorithm is used to identify secondary vertices [13].

The simulated pp collisions are generated using PYTHIA 6.4 [14] with a specific LHCb configuration [15]. Decays of hadronic particles are described by EVTGEN [16] in which final state radiation is generated using PHOTOS [17]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4

toolkit [18] as described in Ref. [19]. Nonresonant B⁺ → p ph⁺ events are simulated, uniformly distributed in phase space, to study the variation of efficiencies across the Dalitz plane, as well as resonant samples such as B⁺ → J/ψ(→ p̅p)K⁺, B⁺ → ηc(→ p̅p)K⁺, B⁺ → ψ(2S)(→ p̅p)K⁺, B⁺ → L(1520)(→ K⁺ p̅)p, and B⁺ → J/ψ(→ p̅p)π⁺.

III. SIGNAL RECONSTRUCTION AND DETERMINATION

Candidate B⁺ → p ph⁺ decays are formed by combining three charged tracks, with appropriate mass assignments. The tracks are required to satisfy track fit quality criteria and a set of loose selection requirements on their momenta, transverse momenta, χ², and distance of closest approach between any pair of tracks. The requirement on the momentum of the proton candidates, p > 3 GeV/c, is larger than for the kaon and pion candidates, p > 1.5 GeV/c. The B⁺ candidates formed by the combinations are required to have p > 1.7 GeV/c and χ² < 10. The distance between the decay vertex and the primary vertex is required to be greater than 3 mm, and the vector formed by the primary and decay vertices must align with the B⁺ candidate momentum. Particle identification (PID) is applied to the proton, kaon and pion candidates, using combined subdetector

identification, the main separation power being provided by the RICH system. The PID efficiencies are derived from data calibration samples of kinematically identified pions, kaons and protons originating from the decays D⁺⁺ → D⁰(→ K⁻ π⁺)π⁺ and Λ → p π⁻.

Signal and background are extracted using unbinned extended maximum likelihood fits to the mass of the p ph⁺ combinations. The B⁺ → p ph⁺ signal is modeled by a double Gaussian function. The combinatorial background is represented by a second-order polynomial function. A Gaussian function accounting for a partially reconstructed component from B → p ph⁺ decays is used. A possible p ph⁺ cross-feed contribution is included in the fit and is found to be small. An asymmetric Gaussian function with power law tails is used to estimate the uncertainties related to the variation of the signal yield.

In the case of the B⁺ → p ph⁺ decay, the signal yield is smaller and the background is larger. The ranges of the signal and cross-feed parameters are constrained to the values obtained in the simulation within their uncertainties. The signal and the p ph⁺ cross-feed contribution are modeled with Gaussian functions. The combinatorial background is represented by a third-order polynomial function.

The B⁺ → p ph⁺ invariant mass spectra are shown in Fig. 2. The signal yields obtained from the fits are N(p ph⁺) = 7029 ± 139 and N(p ph⁺) = 656 ± 70, where the uncertainties are statistical only.

FIG. 1. Leading tree and penguin diagrams for B⁺ → p ph⁺ decays.
IV. DYNAMICS OF $B^+ \to p\bar{p}h^+$ DECAYS

To probe the dynamics of the $B^+ \to p\bar{p}h^+$ decays, differential production spectra are derived as a function of $m_{p\bar{p}}$ and $\cos \theta_p$, where $\theta_p$ is the angle between the charged meson $h$ and the opposite-sign baryon in the rest frame of the $p\bar{p}$ system. The $p\bar{p}h^+$ invariant mass is fitted in bins of the aforementioned variables and the signal yields are corrected for trigger, reconstruction and selection efficiencies. They are estimated with simulated samples and corrected to account for discrepancies between data and simulation. The signal yields are determined with the fit models described in the previous section, but allowing the combinatorial background parameters to vary. The systematic uncertainties are determined for each bin and include uncertainties related to the PID correction, fit model, trigger efficiency, and the size of the simulated samples. The latter is evaluated from the differences between data and simulation as a function of the Dalitz-plot variables. No trigger-induced distortions are found.

A. Invariant mass of the $p\bar{p}$ system

The yields and total efficiency for $B^+ \to p\bar{p}h^+$ in $m_{p\bar{p}}$ bins are shown in Tables I and II. The charmonium contributions originate from the decays $B^+ \to J/\psi(\to p\bar{p})K^+$, $B^+ \to \eta_c(\to p\bar{p})K^+$ and $B^+ \to \psi(2S)(\to p\bar{p})K^+$ for the $B^+ \to p\bar{p}K^+$ mode, and $B^+ \to J/\psi(\to p\bar{p})\pi^+$ for the $B^+ \to p\bar{p}\pi^+$ mode. Before deriving the distributions, the charmonium contributions are unfolded by

| $m_{p\bar{p}}$ [GeV/c$^2$] | $B^+ \to p\bar{p}h^+$ yield | Efficiency (%) | Systematics (%) |
|--------------------------|-----------------------------|---------------|-----------------|
| <2                      | 446 ± 32                    | 1.80 ± 0.08   | 8.1             |
| [2, 2.2]                | 1001 ± 42                   | 1.77 ± 0.05   | 4.4             |
| [2.2, 2.4]              | 732 ± 39                    | 1.77 ± 0.03   | 4.0             |
| [2.4, 2.6]              | 550 ± 35                    | 1.67 ± 0.03   | 3.4             |
| [2.6, 2.85]             | 580 ± 34                    | 1.67 ± 0.02   | 2.9             |

| $m_{p\bar{p}}$ [GeV/c$^2$] | $B^+ \to p\bar{p}K^+$ yield | $B^+ \to p\bar{p}K^+$ cross-feed | Efficiency (%) | Systematics (%) |
|--------------------------|-----------------------------|-----------------------------------|---------------|-----------------|
| <2                      | 140 ± 26                    | 564 ± 61                          | 1.34 ± 0.15   | 11              |
| [2, 2.2]                | 261 ± 31                    | 114 ± 62                          | 1.30 ± 0.10   | 7.9             |
| [2.2, 2.4]              | 95 ± 30                     | 10 ± 29                           | 1.33 ± 0.09   | 7.1             |
| [2.4, 2.6]              | 48 ± 28                     | 14 ± 30                           | 1.35 ± 0.09   | 6.4             |
| [2.6, 2.85]             | 21 ± 20                     | 35 ± 23                           | 1.26 ± 0.07   | 5.9             |

| $m_{p\bar{p}}$ [GeV/c$^2$] | $B^+ \to p\bar{p}\pi^+$ yield | $B^+ \to p\bar{p}\pi^+$ cross-feed | Efficiency (%) | Systematics (%) |
|--------------------------|-----------------------------|-----------------------------------|---------------|-----------------|
| <2                      | 140 ± 26                    | 564 ± 61                          | 1.34 ± 0.15   | 11              |
| [2, 2.2]                | 261 ± 31                    | 114 ± 62                          | 1.30 ± 0.10   | 7.9             |
| [2.2, 2.4]              | 95 ± 30                     | 10 ± 29                           | 1.33 ± 0.09   | 7.1             |
| [2.4, 2.6]              | 48 ± 28                     | 14 ± 30                           | 1.35 ± 0.09   | 6.4             |
| [2.6, 2.85]             | 21 ± 20                     | 35 ± 23                           | 1.26 ± 0.07   | 5.9             |

FIG. 2 (color online). Invariant mass distributions of (left) $p\bar{p}K^+$ and (right) $p\bar{p}\pi^+$ candidates. The points with error bars represent data. The solid black line represents the total fit function. Blue dashed, purple dotted, red long-dashed and green dashed-dotted curves represent the signal, cross-feed, combinatorial background and partially reconstructed background, respectively.
TABLE III. Yields, efficiencies and relative systematic uncertainties of the charmonium modes from the combined ($m_{p\bar{p}h^+}, m_{p\bar{p}}$) fits for the regions $m_{p\bar{p}} \in [2.85, 3.15]$ GeV/c$^2$ (for both $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$) and $[3.60, 3.75]$ GeV/c$^2$ (for $B^+ \rightarrow p\bar{p}K^+$).

| Mode          | Yield (GeV/c^2) | Efficiency (%) | Systematics (%) |
|---------------|----------------|---------------|----------------|
| $B^+ \rightarrow J/\psi (\rightarrow p\bar{p}) K^+$ | 1413 ± 40 | 1.62 ± 0.005 | 2.00 |
| $B^+ \rightarrow \eta_c (\rightarrow p\bar{p}) K^+$ | 722 ± 36 | 1.66 ± 0.005 | 2.00 |
| $B^+ \rightarrow \psi(2S) (\rightarrow p\bar{p}) K^+$ | 132 ± 16 | 1.47 ± 0.011 | 1.50 |
| $B^+ \rightarrow J/\psi (\rightarrow p\bar{p}) \pi^+$ | 59 ± 11 | 1.32 ± 0.011 | 4.20 |

performing two dimensional extended unbinned maximum likelihood fits to the $p\bar{p}h^+$ and $p\bar{p}$ invariant masses. The $J/\psi$ and $\psi(2S)$ resonances are modeled by Gaussian functions and the $\eta_c$ resonance is modeled by a convolution of Breit-Wigner and Gaussian functions. The nonresonant $p\bar{p}$ component and the combinatorial background are modeled by polynomial shapes. Table III shows the yields of contributing charmonium modes. The results are consistent with those reported in Ref. [9].

After unfolding, the efficiency-corrected differential distributions are shown in Fig. 3. An enhancement is observed at low $m_{p\bar{p}}$ mass both for $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$, with a more sharply peaked distribution for $B^+ \rightarrow p\bar{p}\pi^+$. This accumulation of events at low $m_{p\bar{p}}$ is a well known feature that has also been observed in different contexts such as $Y(1S) \rightarrow \gamma p\bar{p}$ [20], $J/\psi \rightarrow \gamma p\bar{p}$ [21] and $B^0 \rightarrow D^{(*)0} p\bar{p}$ [22] decays. It appears to be caused by proton-antiproton rescattering and is modulated by the particular kinematics of the decay from which the $p\bar{p}$ pair originates [23].

B. Invariant mass squared of the $Kp$ system

The $B^+ \rightarrow p\bar{p}K^+$ signal yield as a function of the Dalitz-plot variable $m_{Kp}^2$, is considered, where $Kp$ denotes the neutral combinations $K^- p$ or $K^+ \bar{p}$. Table IV shows the yields and efficiencies, after the charmonium bands have been vetoed in the ranges $m_{p\bar{p}} \in [2.85, 3.15]$ GeV/c$^2$ and $[3.60, 3.75]$ GeV/c$^2$. The differential spectrum derived after efficiency correction is shown in Fig. 4. Contrary to the situation for $m_{p\bar{p}}$, the data distribution is in reasonable agreement with the uniform phase space distribution, with some discrepancies in the region $m_{Kp}^2 \in [4, 12]$ (GeV/c$^2$)$^2$.

C. Helicity angle of the $p\bar{p}$ system

The $B^+ \rightarrow p\bar{p}h^+$ signal yields are considered as a function of $\cos \theta_p$. Tables V and VI show the corresponding yields and efficiencies. The differential distributions are shown in Fig. 5.

The forward-backward asymmetries are derived by comparing the yields for $\cos \theta_p > 0$ and $\cos \theta_p < 0$, accounting for the weighted-average efficiencies in each region

$$A_{FB} = \frac{N_{pos} - N_{neg}}{N_{pos} + N_{neg}} = \frac{N_{pos} - fN_{neg}}{N_{pos} + fN_{neg}},$$

where $\epsilon_{pos} = \epsilon(\cos \theta_p > 0)$ and $\epsilon_{neg} = \epsilon(\cos \theta_p < 0)$ are the averaged efficiencies, $f = \epsilon_{pos}/\epsilon_{neg}$ and

![FIG. 3 (color online). Efficiency-corrected differential yield as a function of $m_{p\bar{p}}$ for (left) $B^+ \rightarrow p\bar{p}K^+$ and (right) $B^+ \rightarrow p\bar{p}\pi^+$. The data points are shown with their statistical and total uncertainties. For comparison, the solid lines represent the expectations for a uniform phase space production, normalized to the efficiency-corrected area.](052015-4)
FIG. 4 (color online). Efficiency-corrected differential yield as a function of $m_K^2$, for $B^+ \rightarrow p \bar{p} K^+$. The data points are shown with their statistical and total uncertainties. The solid line represents the expectation for a uniform phase space production, normalized to the efficiency-corrected area, for comparison.

\[ N_{\text{pos}} = N(\cos \theta_p > 0), \quad N_{\text{neg}} = N(\cos \theta_p < 0). \]

The values obtained are $A_{FB}(p \bar{p} K^+) = 0.370 \pm 0.018(\text{stat}) \pm 0.016(\text{syst})$ and $A_{FB}(p \bar{p} \pi^+) = -0.392 \pm 0.117(\text{stat}) \pm 0.015(\text{syst})$, where the systematic uncertainties are evaluated from the uncertainties on the efficiencies listed in Tables V and VI, taking into account the relative weights of the bins.

A clear opposite angular correlation between $B^+ \rightarrow p \bar{p} K^+$ and $B^+ \rightarrow p \bar{p} \pi^+$ decays is observed; the light meson $h$ tends to align with the opposite-sign baryon for $B^+ \rightarrow p \bar{p} K^+$ while it aligns with the same-sign baryon for the $B^+ \rightarrow p \bar{p} \pi^+$ mode. A quark level analysis suggests that the meson should align with the same-sign baryon, since the opposite-sign baryon has larger momentum, being formed by products from the decaying quark [24]. This is in agreement with the angular spectrum of $B^+ \rightarrow p \bar{p} \pi^+$ but not for $B^+ \rightarrow p \bar{p} K^+$ decays.

D. Dalitz plot

From the fits to the $B$-candidate invariant mass, shown in Fig. 2, signal weights are calculated with the sPlot technique [25] and are used to produce the signal Dalitz-plot distributions shown in Fig. 6. To ease the comparison, the cos $\theta_p$ curves corresponding to the boundaries of the eight bins used to make the angular distributions in Fig. 5 are superimposed.

With the exception of the charmonium bands [ $\eta_c$, $J/\psi$, $\psi(2S)$ for $B^+ \rightarrow p \bar{p} K^+$, and $J/\psi$ for $B^+ \rightarrow p \bar{p} \pi^+$], the structure of the low $p \bar{p}$ mass enhancement is very different between $B^+ \rightarrow p \bar{p} K^+$ and $B^+ \rightarrow p \bar{p} \pi^+$. The $B^+ \rightarrow p \bar{p} K^+$ events are distributed in the middle and lower $m_K^2$ half, exhibiting a possible $p \bar{p}$ band structure near $4 \text{ GeV}^2/c^4$. An enhancement at low $m_{Kp}$ is also observed and is caused to a large extent by a $\Lambda(1520)$ signal, as will be shown in the next section. The $B^+ \rightarrow p \bar{p} \pi^+$ events are mainly clustered in the upper $m_{Kp}^2$ half, with also a few events

### Table V. Fitted $B^+ \rightarrow p \bar{p} K^+$ yields, efficiencies and relative systematic uncertainties in bins of $\cos \theta_p$.

| $\cos \theta_p$ range | $B^+ \rightarrow p \bar{p} K^+$ yield | Efficiency (%) | Systematics (%) |
|-----------------------|--------------------------------------|----------------|----------------|
| [-1, -0.75]           | 508 ± 34                             | 1.54 ± 0.01    | 2.7            |
| [-0.75, -0.5]         | 497 ± 31                             | 1.51 ± 0.02    | 3.0            |
| [-0.5, -0.25]         | 309 ± 27                             | 1.48 ± 0.01    | 2.9            |
| [-0.25, 0]            | 381 ± 28                             | 1.49 ± 0.01    | 2.6            |
| [0, 0.25]             | 640 ± 46                             | 1.51 ± 0.01    | 2.9            |
| [0.25, 0.5]           | 799 ± 42                             | 1.52 ± 0.01    | 2.2            |
| [0.5, 0.75]           | 976 ± 41                             | 1.56 ± 0.01    | 2.8            |
| [0.75, 1]             | 1346 ± 51                            | 1.55 ± 0.01    | 2.7            |

### Table VI. Fitted $B^+ \rightarrow p \bar{p} \pi^+$ signal yields, efficiencies and relative systematic uncertainties in bins of $\cos \theta_p$.

| $\cos \theta_p$ range | $B^+ \rightarrow p \bar{p} \pi^+$ yield | Efficiency (%) | Systematics (%) |
|-----------------------|--------------------------------------|----------------|----------------|
| [-1, -0.75]           | 150 ± 31                             | 1.23 ± 0.02    | 5.5            |
| [-0.75, -0.5]         | 85 ± 27                              | 1.15 ± 0.02    | 5.5            |
| [-0.5, -0.25]         | 104 ± 24                             | 1.19 ± 0.02    | 5.5            |
| [-0.25, 0]            | 77 ± 23                              | 1.19 ± 0.02    | 5.5            |
| [0, 0.25]             | 43 ± 21                              | 1.14 ± 0.02    | 5.5            |
| [0.25, 0.5]           | 24 ± 20                              | 1.16 ± 0.02    | 5.5            |
| [0.5, 0.75]           | 10 ± 12                              | 1.19 ± 0.02    | 5.5            |
| [0.75, 1]             | 93 ± 26                              | 1.19 ± 0.02    | 5.2            |
for the data with the decay by \(N/C18p\) function of the total yield iso-
the data sample reported earlier.

Another correction has been applied to account for the proton-antiproton asymmetry, which exactly cancels for \(J/\psi(\rightarrow p \bar{p})K^\pm\) but not necessarily in the full phase space of \(p\bar{p}K^\pm\) events. This effect has been estimated in simulation studying the difference in the interactions of protons and antiprotons with the detector material between \(J/\psi(\rightarrow p \bar{p})K^\pm\) and \(p\bar{p}K^\pm\) events generated uniformly over phase space. We obtained a \(m_{p\bar{p}}^2\)-dependent bias, up to 3% for the highest bin, for \(A_{raw}\).

To measure \(A_{raw}\) for charmonium modes, and in particular \(J/\psi(\rightarrow p \bar{p})K^\pm\), a two-dimensional \((m_B, m_{p\bar{p}})\) simultaneous fit to the \(B^+\) and \(B^-\) samples is performed. The systematic uncertainties are estimated by varying the fit functions and splitting the data sample according to trigger requirements or magnet polarities, and recombining the results from the sub-samples. The procedure is applied to obtain a global value of \(A_{CP}\) as well as the variation of the asymmetry as a function of the Dalitz-plot variables. The results are \(A_{CP} = -0.022 \pm 0.031(\text{stat}) \pm 0.007(\text{syst})\) for the full \(p\bar{p}K^\pm\) spectrum, and \(A_{CP} = -0.047 \pm 0.036(\text{stat}) \pm 0.007(\text{syst})\) for the region \(m_{p\bar{p}} < 2.85\) GeV/c\(^2\). Figure 7 shows the variation of \(A_{CP}\) as a function of the Dalitz-plot variables.

For the charmonium resonances, the values are \(A_{CP}(\eta, K^\pm) = 0.046 \pm 0.057(\text{stat}) \pm 0.007(\text{syst})\) and
A_{CP}(\psi(2S)K^\pm) = -0.002 \pm 0.123\text{(stat)} \pm 0.012\text{(syst)}. All results indicate no significant CP asymmetries.

VI. OBSERVATION OF THE $B^+ \rightarrow \Lambda(1520)p$ DECAY

In the $p\bar{p}K^+$ spectrum, near the threshold of the neutral $Kp$ combination, a peak in invariant mass at 1.52 GeV/c^2 is observed, as shown in Fig. 8, corresponding to the $\bar{u}\bar{d}\bar{s}$ resonance $\Lambda(1520)$. The possible presence of higher $\Lambda$ and $\Sigma$ resonances may explain the enhancement in the range of $[1.6, 1.7]$ GeV/c^2.

To identify the $\Lambda(1520)$ signal, the $B^+$ signal is analyzed in the region $m_{KP} \in [1.44, 1.585]$ GeV/c^2. Figure 9 shows the $B$ signal weighted $KP$ invariant mass, and the expected $\Lambda(1520)$ shape obtained from a model based on an asymmetric Breit-Wigner function derived from an EVTGEN [16] simulation of the decay $B^+ \rightarrow \Lambda(1520)p$, convolved with a Gaussian resolution function, and a second-order polynomial function representing the tail of the non-$\Lambda(1520)$ $B^+ \rightarrow p\bar{p}K^+$ decays.

These shapes are then used in a two-dimensional $(m_{p\bar{p}K^+}, m_{KP})$ extended unbinned maximum likelihood fit to obtain the $B^+ \rightarrow \Lambda(1520)p$ yield. The fit results in $N(B^+ \rightarrow \Lambda(1520)p) = 47^{+17}_{-12}$ with a statistical significance of 5.3 standard deviations, obtained by comparing the likelihood at its maximum for the nominal fit and for the background-only hypothesis. Figure 10 shows the projections of the fit for the $Kp$ and $p\bar{p}K^+$ invariant masses.

To test the robustness of the observation, different representations of the $Kp$ background have been used, combining first- or second-order polynomials and a contribution modeled by a Breit-Wigner function, for which the mean ($\mu$) and width ($\Gamma$) are allowed to vary within the known values of the $\Lambda(1600)$ baryon ($\mu \in [1.56, 1.7]$ GeV/c^2, $\Gamma \in [0.05, 0.25]$ GeV/c^2). Fits in a wider $m_{KP}$ range were also considered. In all cases the yield was stable with a statistical significance similar to the nominal fit case.

The branching fraction for the decay $B^+ \rightarrow \Lambda(1520)p$ is derived from the ratio

$$\frac{\mathcal{B}(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+\bar{p})p)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+)} = \frac{N_{\Lambda(1520)}^{\text{gen}} - N_{J/\psi\rightarrow p\bar{p}}^{\text{gen}}}{N_{J/\psi\rightarrow p\bar{p}}^{\text{gen}}} \times \frac{\epsilon_{\Lambda(1520)\rightarrow KP}^{\text{sel}}}{\epsilon_{J/\psi\rightarrow p\bar{p}}^{\text{sel}}},$$

where $N_{J/\psi\rightarrow p\bar{p}}^{\text{gen}}$ and $N_{\Lambda(1520)}^{\text{gen}}$ are the yields for the decay $J/\psi(\rightarrow p\bar{p})K^+$ and $\Lambda(1520)\rightarrow KP$, respectively, and $\epsilon_{J/\psi\rightarrow p\bar{p}}^{\text{sel}}$ and $\epsilon_{\Lambda(1520)\rightarrow KP}^{\text{sel}}$ are the selection efficiencies for the $J/\psi(\rightarrow p\bar{p})K^+$ and $\Lambda(1520)\rightarrow KP$ channels, respectively.
where \( N_i \) is the yield of the decay chain \( i \), and \( \varepsilon^{\text{gen}} \) denotes the efficiency after geometrical acceptance and simulation requirements. The global selection efficiency \( \varepsilon^{\text{sel}} \) includes the reconstruction, the trigger, the offline selection, and the particle identification requirements. The ratio of branching fractions obtained is

\[
\frac{\mathcal{B}(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+ \bar{p})p)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+)} = 0.041^{+0.011}_{-0.010}(\text{stat}) \pm 0.001(\text{syst}).
\]

The systematic uncertainties include effects of the \( Kp \) background model, the particle identification, the limited simulation sample size, and the uncertainties on the relative trigger efficiencies, and they are summarized in Table VII. Convolving the systematic uncertainty with the statistical likelihood profile, the global significance is 5.1 standard deviations.

Using \( \mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.016 \pm 0.033) \times 10^{-3} \), \( \mathcal{B}(J/\psi \rightarrow p\bar{p}) = (2.17 \pm 0.07) \times 10^{-3} \) \[26\], and \( \mathcal{B}(\Lambda(1520) \rightarrow K^- p) = 0.234 \pm 0.016 \) \[27\], the branching fraction is

\[
\mathcal{B}(B^+ \rightarrow \Lambda(1520)p) = (3.9^{+1.0}_{-0.9})(\text{stat}) \pm 0.1(\text{syst}) \pm 0.3(\text{BF}) \times 10^{-7}.
\]

The last error corresponds to the uncertainty on the secondary branching fractions. This result is in agreement with the upper limit set in Ref. [6], \( \mathcal{B}(B^+ \rightarrow \Lambda(1520)p) < 1.5 \times 10^{-6} \). Considering the separate \( B^\pm \) signals in the range \( m_{Kp} \in [1.44, 1.585] \text{ GeV/}c^2 \), the yields are \( N(B^-) = 50 \pm 12 \) and \( N(B^+) = 27 \pm 11 \).

VII. SUMMARY

Based on a data sample, corresponding to an integrated luminosity of 1.0 \( \text{fb}^{-1} \), collected in 2011 by the LHCb experiment, an analysis of the three-body \( B^+ \rightarrow p\bar{p}h^+ \) decays \( (h = K \text{ or } \pi) \) has been performed. The dynamics of the decays has been probed using differential spectra of Dalitz-plot variables and signal-weighted Dalitz plots. The charmless \( B^+ \rightarrow p\bar{p}K^+ \) decay populates mainly the low \( m_{p\bar{p}}^2 \) and lower \( m_{p\bar{p}}^2 \)-half regions whereas the \( B^+ \rightarrow p\bar{p}\pi^+ \) decay has a similar enhancement at low \( m_{p\bar{p}}^2 \) but with an upper \( m_{p\bar{p}}^2 \)-half occupancy. From the occupation pattern of the Dalitz plots, it is likely that the \( B^+ \rightarrow p\bar{p}K^+ \) decay is primarily driven by \( p\bar{p} \) rescattering with a secondary contribution from neutral \( Kp \) rescattering while the \( B^+ \rightarrow p\bar{p}\pi^+ \) decay is also dominated by \( p\bar{p} \) rescattering but with a secondary contribution from doubly charged \((p\pi)^{++}\) rescattering, along the lines of the rescattering amplitude analysis performed in Ref. [28]. This difference of behavior is reflected in the values of the forward-backward asymmetry of the light meson in the \( p\bar{p} \) rest frame

\[
A_{FB}(p\bar{p}K^+) = 0.370 \pm 0.018(\text{stat}) \pm 0.016(\text{syst}),
\]

\[
A_{FB}(p\bar{p}\pi^+) = -0.392 \pm 0.117(\text{stat}) \pm 0.015(\text{syst}).
\]

\( CP \) asymmetries for the \( B^+ \rightarrow p\bar{p}K^+ \) decay have been measured and no significant deviation from zero observed: \( A_{CP} = -0.047 \pm 0.036(\text{stat}) \pm 0.007(\text{syst}) \) for the charmless region \( m_{p\bar{p}} < 2.85 \text{ GeV/}c^2 \), \( A_{CP}(\eta_c K^+) = 0.046 \pm 0.057(\text{stat}) \pm 0.007(\text{syst}) \) and \( A_{CP}(\psi(2S)K^+) = -0.002 \pm 0.123(\text{stat}) \pm 0.012(\text{syst}) \). These measurements are consistent with the current known values, \( A_{CP}(B^\pm \rightarrow p\bar{p}K^\pm, m_{p\bar{p}} < 2.85 \text{ GeV/}c^2) = -0.16 \pm 0.07 \) \[26\], \( A_{CP}(\eta_c K^\pm) = -0.16 \pm 0.08(\text{stat}) \pm 0.02(\text{syst}) \) \[8\].

TABLE VII. Systematic uncertainties for the \( \mathcal{B}(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+ \bar{p})p)/\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+) \) branching fraction ratio. The total uncertainty is the sum in quadrature of the individual sources.

| Source                  | Uncertainty (%) |
|-------------------------|-----------------|
| \( Kp \) background     | 2.1             |
| PID                     | 1.7             |
| Simulation sample size  | 0.5             |
| Trigger                 | 1.0             |
| Total                   | 2.9             |
and $A_{CP}(\psi(2S)K^-) = -0.025 \pm 0.024$ [26]. The absence of any significant charge asymmetry, contrary to the situation for $B^+ \rightarrow h^+ h^+ h^-$ decays [1,2], may be due to different long-range behavior. Final state interactions in the $B^+ \rightarrow p\bar{p}h^+$ case do not change the nature of the particles, such as $p\bar{p} \rightarrow p\bar{p}$ or $ph \rightarrow ph$, while $B^+ \rightarrow h^+ h^+ h^-$ modes can be affected by $\pi^+ \pi^- \rightarrow K^+ K^-$ scattering.

Finally, the observation of the decay $B^+ \rightarrow \bar{\Lambda}(1520)p$ is reported, with the branching fraction

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda}(1520)p) = (3.9^{+1.0}_{-0.9}\text{(stat)} \pm 0.1\text{(syst)} \pm 0.3\text{(BF)}) \times 10^{-7}$$

in agreement with the current existing upper limit [6].

**ACKNOWLEDGMENTS**

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centers are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

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V. Niess,5 R. Niet,9 N. Nikitin,11 T. Nikodem,11 A. Nomerotski,54 A. Novoselov,34 A. Oblakowska-Mucha,26 V. Obraztsov,54 S. Oggero,40 S. Ogilvy,50 O. Okhrimenko,43 R. Oldeman,15,d M. Orlandea,28 J. M. Otalora Goicochea,2 P. Owen,52 A. Oyanguren,35 B. K. Pal,58 A. Palano,13,b M. Palutan,18 J. Panman,37 A. Papanestis,48 M. Pappagallo,50 C. Parkes,53 C. J. Parkinson,52 G. Passaleva,17 G. D. Patel,51 M. Patel,52 G. N. Patrick,48 C. Patrignani,19,i C. Pavel-Nicorescu,28 A. Perez Trigo,36 A. Perez-Calero Yzquierdo,35 P. Perret,5 M. Perrin-Terrin,6 L. Pescatore,44 E. Perez Trigo,36 A. Pe´ rez-Calero Yzquierdo,35 P. Perret,5 M. Perrin-Terrin,6 L. Pescatore,44 E. Pesen,61 K. Petridis,52 A. Petrolini,19,i A. Phan,58 E. Picatoste Olloqui,35 B. Pietrzyk,4 T. Pilarˇ,47 D. Pinci,24 S. Playfer,49 M. Plo Casasus,36 F. Polci,8 G. Polok,25 A. Poluektov,47,33 E. Polycarpo,2 A. Popov,34 D. Popov,10 B. Popovici,28 C. Poterat,35 A. Powell,54 J. Prisciandaro,38 A. Pugazzelli,43 A. Puig Navarro,38 G. Punzi,22,r W. Qian,4 J. H. Rademacker,45 B. Rakotomiaramanana,38 M. S. Rangel,2 I. Raniuk,42 G. Raven,41 S. Redford,54 M. M. Reid,57 A. C. dos Reis,1 S. Ricciardi,48 A. Richards,52 K. Rinnert,51 V. Rives Molina,35 D. A. Roa Romero,5 P. Robbe,7 D. A. Roberts,57 E. Roditi,33 E. Rodrigues,53 P. Rodriguez Perez,36 S. Roiser,37 V. Romanovsky,34 A. Romero Vidal,36 J. Rouvinet,38 T. Ruf,37 F. Ruffini,22 H. Ruiz,35 P. Ruiz Valls,35 G. Sabatino,24,k J. J. Saborido Silva,36 N. Sagidova,29 P. Sail,50 B. Saitta,15,d V. Salustino Guimaraes,2 B. Sanmartin Sedes,36 M. Sannino,19,i A. Santillan,18,l C. Santovetti,23,k M. Sapunov,6 A. Sarti,18,l C. Satriano,24.m A. Satta,23 M. Savrie,16,e D. Savrina,30,31 P. Schaack,52 M. Schiller,41 H. Schindler,37 M. Schlupp,9 M. Schmelling,10 B. Schmidt,37 O. Schneider,38 A. Schopper,5 M.-H. Schune,7 R. Schwemmer,37 B. Sciascia,18 A. Sciubba,24 M. Seco,46 A. Semennikov,30 K. Senderowska,26 I. Sepp,52 N. Serra,39 J. Serrano,6 P. Seyfert,11 M. Shapkin,34 I. Shapoval,16,42 P. Shatalov,30 Y. Shcheglov,29 T. Shears,51,37 L. Shekhtman,33 O. Shevchenko,42 V. Shevchenko,40 A. Shires,9 R. Silva Coutinho,47 M. Sirendi,46 N. Skidmore,45 T. Skwarnicki,58 N. A. Smith,51 E. Smith,54,48 J. Smith,46 M. Smith,53 M. D. Sokoloff,56 F. J. P. Soler,50 F. Soomro,18 D. Souza,45 B. Souza De Paula,2 B. Spaan,9 A. Sparkes,49 P. Spradlin,50 F. Stagni,26 S. Stahl,11 O. Steinkamp,39 S. Stevenson,54 S. Stoica,28 S. Stone,58 B. Storaci,39 M. Straticiuc,28 U. Straumann,39 V. K. Subbiah,37 L. Sun,56 S. Swientek,9 V. Syropoulos,41 M. Szczepik,38 T. Szumlak,26 S. T'Jampens,4 M. Teklishyn,7 E. Teodorescu,28 F. Teubert,37 C. Thomas,54 E. Thomas,37 J. van Tilburg,11 V. Tisserand,4 M. Tobin,38 S. Tolk,41 D. Tonelli,37 S. Topp-Joergensen,54 N. Torr,54 E. Towner,4,52 S. Tourneur,38 M. T. Tran,38 M. Tresch,39 A. Tsaregorodtsev,6 P. Tsopelas,40 N. Tuning,40 M. Ubeda Garcia,37 A. Ukleja,27 D. Urner,53 A. Ustyuzhanin,52,F U. Uwer,11 V. Vagnoni,14 G. Valenti,14 A. Vallier,7 M. Van Dijk,45 R. Vazquez Gomez,18 P. Vazquez Regueiro,36 C. Vázquez Sierra,36 S. Vecchi,16 J. J. Velthuys,45 M. Veltri,17,g G. Veneziano,38 M. Vesterinen,37 B. Viaud,7 D. Vieira,2 X. Vilasis-Cardona,35 A. Vollhardt,39 D. Voliansky,10 D. Voong,45 A. Vorobyev,29 V. Vorobyev,33 C. Voß,60 H. Voss,10 R. Wald,60 C. Wallace,47 R. Wallace,12 S. Wandernoth,11 J. Wang,58 D. R. Ward,36 N. K. Watson,44 A. D. Webber,55 D. Websdale,52 M. Whitehead,47 J. Wicht,37 J. Wiechczynski,25 D. Wiedner,11 L. Wiggers,40 G. Wilkinson,54 M. P. Williams,47,48 M. Williams,55 F. F. Wilson,48 J. Wimberley,57 J. Wishahi,9 M. Witok,25 A. C. S. Wotton,36 S. Wright,46 S. Wu,3 K. Wyllie,37 Y. Xie,49,37 L. Xing,48 Z. Yang,3 R. Young,49 X. Yuan,3 O. Yushchenko,34 M. Zangoli,14 M. Zavertyaev,10,l F. Zhang,3 L. Zhang,38 W. C. Zhang,12 Y. Zhang,3 A. Zhelezov,11 A. Zhokhov,30 L. Zhong,7 and A. Zvyagin37 (LHCb Collaboration)

1Centro Brasileiro de Pesquisas Fisicas (CBPF), Rio de Janeiro, Brazil
2Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3Center for High Energy Physics, Tsinghua University, Beijing, China
4LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France
5Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
7LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
8LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
10Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
11Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
12School of Physics, University College Dublin, Dublin, Ireland
13Sezione INFN di Bari, Bari, Italy
14Sezione INFN di Bologna, Bologna, Italy
15 Sezione INFN di Cagliari, Cagliari, Italy
16 Sezione INFN di Ferrara, Ferrara, Italy
17 Sezione INFN di Firenze, Firenze, Italy
18 Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
19 Sezione INFN di Genova, Genova, Italy
20 Sezione INFN di Milano Bicocca, Milano, Italy
21 Sezione INFN di Padova, Padova, Italy
22 Sezione INFN di Pisa, Pisa, Italy
23 Sezione INFN di Roma Tor Vergata, Roma, Italy
24 Sezione INFN di Roma La Sapienza, Roma, Italy
25 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
26 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Kraków, Poland
27 National Center for Nuclear Research (NCBJ), Warsaw, Poland
28 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
29 Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
30 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
31 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
32 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
33 Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
34 Institute for High Energy Physics (IHEP), Protvino, Russia
35 Universitat de Barcelona, Barcelona, Spain
36 Universidad de Santiago de Compostela, Santiago de Compostela, Spain
37 European Organization for Nuclear Research (CERN), Geneva, Switzerland
38 Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
39 Physik-Institut, Universität Zürich, Zürich, Switzerland
40 Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
41 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
42 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
43 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
44 University of Birmingham, Birmingham, United Kingdom
45 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
46 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
47 Department of Physics, University of Warwick, Coventry, United Kingdom
48 STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
49 School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
50 School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
51 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
52 Imperial College London, London, United Kingdom
53 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
54 Department of Physics, University of Oxford, Oxford, United Kingdom
55 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
56 University of Cincinnati, Cincinnati, Ohio, USA
57 University of Maryland, College Park, Maryland, USA
58 Syracuse University, Syracuse, New York, USA
59 Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil associated to Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
60 Institut für Physik, Universität Rostock, Rostock, Germany associated to Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
61 Celal Bayar University, Manisa, Turkey associated to European Organization for Nuclear Research (CERN), Geneva, Switzerland

a Also at Università di Firenze, Firenze, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Università di Padova, Padova, Italy.
Also at Università di Milano Bicocca, Milano, Italy.
Also at LIFAFELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Roma Tor Vergata, Roma, Italy.
Also at Università di Genova, Genova, Italy.
STUDIES OF THE DECAYS $B^+ \to p\bar{p}h^+ \ldots$

$^j$Also at Università di Ferrara, Ferrara, Italy.

$^k$Also at Università di Cagliari, Cagliari, Italy.

$^l$Also at Scuola Normale Superiore, Pisa, Italy.

$^m$Also at Hanoi University of Science, Hanoi, Viet Nam.

$^n$Also at Università di Bari, Bari, Italy.

$^o$Also at Università di Roma La Sapienza, Roma, Italy.

$^p$Also at Università di Pisa, Pisa, Italy.

$^q$Also at Institute of Physics and Technology, Moscow, Russia.

$^r$Also at Università di Urbino, Urbino, Italy.

$^s$Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.