Measurement of the $B^+ \rightarrow ppK^+$ Branching Fraction and Study of the Decay Dynamics

B. Aubert, R. Barate, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zghiche, E. Grauges, A. Palano, M. Pappagallo, A. Pomplii, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu, G. Eigen, I. Ofte, B. Stugu, G. S. Abrams, M. Battaglia, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Grousset, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Y. Gu, G. Kolomensky, G. Kukharskev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Roman, W. A. Wenzel, M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson, M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaues, K. Peters, T. Schroeder, M. Steinke, J. T. Boyd, J. P. Burke, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. Cuhadar-Donszelmann, G. B. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna, A. Khan, P. Kyberd, M. Saleem, L. Teodorescu, A. E. Blinov, V. E. Blinov, A. D. Buiuk, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. P. Onuchin, S. I. Seredynak, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov, D. Best, M. Bondioli, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, J. A. Lankford, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker, C. Buchanan, B. L. Hartfield, A. J. R. Weinstein, S. D. Foulkes, J. W. Gary, 15 O. Long, B. C. Shen, K. Wang, L. Zhang, D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, S. Rahatlou, V. Sharma, J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, M. A. Mazur, J. D. Richman, W. Verkerke, T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesomi, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson, J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel, R. Andreassen, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, F. Blanc, B. Bloom, S. Chen, W. T. Ford, U. Naumenberg, A. Olivas, P. Rankin, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang, A. Chen, E. A. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng, D. Altenburg, E. Feltresi, A. Hauke, B. Spaan, T. Brandt, J. Brose, M. Dickopp, V. Klose, H. M. Lackert, R. Rogowski, S. Otto, A. Petzold, G. Schott, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, D. Bernard, G. Berneaud, P. Grenier, S. Schrenk, Ch. Thiebaux, V. Vasileiadis, M. Verderi, J. D. Bard, P. J. Clark, W. Gradl, F. Muheim, S. Playfer, Y. Xie, M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese, F. Anulli, R. Baldini-Ferroli, A. Calcatarella, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo, A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Mori, E. Won, J. Wu, R. S. Dubitzky, U. Langenegger, J. Marks, S. Schenk, U. Uwer, W. Blumji, D. A. Bowerman, P. D. Nauney, U. Egede, R. L. Flack, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor, W. P. Vazquez, M. J. Charles, W. F. Mader, U. Mallik, A. K. Mohapatra, J. C. Cochran, H. B. Crawley, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi, N. Arnaud, M. Davier, X. Giroux, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, T. C. Petersen, M. Pierini, S. Ptaszczynski, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, G. Wormser, C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright, A. J. Bevan, C. A. Chavez, J. P. Coleman, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, R. J. Parry, D. J. Payne, K. C. Schofield, C. Touramanis, C. M. Cormack, F. Di Lodovico, R. Sacco, C. L. Brown, G. Cowan, H. U. Flaecher, M. G. Green, D. A. Hopkins, S. F. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, D. Brown, C. L. Davis, J. Allison, N. R. Barlow, R. J. Barlow, M. C. Hodgkinson, G. D. Lafferty, M. T. Naisbit, J. C. Williams, C. Chen, A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalsky, C. K. Lae, V. Lillard, D. A. Roberts, G. Simi, G. Blaylock, C. Dallapiccola, R. Hertzbach,
14 University of California at Los Angeles, Los Angeles, California 90024, USA
15 University of California at Riverside, Riverside, California 92521, USA
16 University of California at San Diego, La Jolla, California 92093, USA
17 University of California at Santa Barbara, Santa Barbara, California 93106, USA
18 University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
19 California Institute of Technology, Pasadena, California 91125, USA
20 University of Cincinnati, Cincinnati, Ohio 45221, USA
21 University of Colorado, Boulder, Colorado 80309, USA
22 Colorado State University, Fort Collins, Colorado 80523, USA
23 Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
24 Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
25 Ecole Polytechnique, LLR, F-91128 Palaiseau, France
26 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
27 Università di Ferrara, Dipartimento di Fisica e INFN, I-44100 Ferrara, Italy
28 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29 Università di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy
30 Harvard University, Cambridge, Massachusetts 02138, USA
31 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
32 Imperial College London, London, SW7 2AZ, United Kingdom
33 University of Iowa, Iowa City, Iowa 52242, USA
34 Iowa State University, Ames, Iowa 50011-3160, USA
35 Laboratoire de l’Accélérateur Linéaire, F-91898 Orsay, France
36 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
37 University of Liverpool, Liverpool L69 72E, United Kingdom
38 Queen Mary, University of London, E1 4NS, United Kingdom
39 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
40 University of Louisville, Louisville, Kentucky 40292, USA
41 University of Manchester, Manchester M13 9PL, United Kingdom
42 University of Maryland, College Park, Maryland 20742, USA
43 University of Massachusetts, Amherst, Massachusetts 01003, USA
44 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
45 McGill University, Montréal, Quebec, Canada H3A 2T8
46 Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
47 University of Mississippi, University, Mississippi 38677, USA
48 Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7
49 Mount Holyoke College, South Hadley, Massachusetts 01075, USA
50 Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
51 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
52 University of Notre Dame, Notre Dame, Indiana 46556, USA
53 Ohio State University, Columbus, Ohio 43210, USA
54 University of Oregon, Eugene, Oregon 97403, USA
55 Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
56 Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France
57 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
58 Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
59 Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
60 Prairie View A&M University, Prairie View, Texas 77446, USA
61 Princeton University, Princeton, New Jersey 08544, USA
62 Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
63 Universität Rostock, D-18051 Rostock, Germany
64 Rutherford Appleton Laboratory, Didcot, Oxford, OX11 0QX, United Kingdom
65 DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
66 University of South Carolina, Columbia, South Carolina 29208, USA
67 Stanford Linear Accelerator Center, Stanford, California 94309, USA
68 Stanford University, Stanford, California 94305-4060, USA
69 State University of New York, Albany, New York 12222, USA
70 University of Tennessee, Knoxville, Tennessee 37996, USA
71 University of Texas at Austin, Austin, Texas 78712, USA
72 University of Texas at Dallas, Richardson, Texas 75083, USA
73 Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
74 Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
75 IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
76 Vanderbilt University, Nashville, Tennessee 37235, USA
77 University of Victoria, British Columbia, Canada V8W 3P6
With a sample of $232 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ events collected with the BABAR detector, we study the decay $B^+ \rightarrow p\bar{p}K^+$ (excluding charmonium decays to $p\bar{p}$) and a study of its resonant substructure. An earlier measurement of the branching fraction $B(B^+ \rightarrow p\bar{p}K^+)=6.7\pm 0.5 \pm 0.5 \times 10^{-6}$. An enhancement at low $p\bar{p}$ mass is observed and the Dalitz plot asymmetry suggests dominance of the penguin amplitude in this $B$ decay. We search for a pentaquark candidate $\Theta^{++}$ decaying into $p\bar{p}K^+$ in the mass range $1.43 \rightarrow 2.00$ GeV/c$^2$ and set limits on $B(B^+ \rightarrow \Theta^{++}\bar{p}) \times B(\Theta^{++} \rightarrow p\bar{p}K^+)$ at the $10^{-7}$ level.

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This paper describes a measurement of the branching fraction of the baryonic three-body decay $B^+ \rightarrow p\bar{p}K^+$ (excluding charmonium decays to $p\bar{p}$) and a study of its resonant substructure. An earlier measurement of the branching fraction for this channel gave $(5.7^{+0.7}_{-0.6} \pm 0.7) \times 10^{-6}$. This channel is interesting for the dynamical information in the distribution of the three final-state particles and for the possible presence of exotic intermediate states. We also isolate decays $B^+ \rightarrow X_{cc}K^+$, where $X_{cc} = \eta_c$ and $J/\psi$ decaying to $p\bar{p}$, and measure the width of the $\eta_c$.

An important feature of this decay is an enhancement at low $p\bar{p}$ masses reported in Ref. 2, similar to those that have been observed in several other baryonic decays of $B^+$ and $J/\psi$. This could be a feature of a quasi-two-body decay in which the $p\bar{p}$ system is produced through an intermediate gluonic resonance (Fig. 1(c)). It could also be that the decay is a pure three-body process and that the enhancement results from the short-range correlations between $p$ and $\bar{p}$ in the fragmentation chain of the $W$-emission, (c) Okubo-Zweig-Iizuka-suppressed penguin diagram.

The main Feynman diagrams for this decay are presented in Fig. 1. The leading diagrams are penguin diagrams and a doubly Cabibbo-Kobayashi-Maskawa-suppressed tree diagram shown in Fig. 1(a,b). There is also an Okubo-Zweig-Iizuka-suppressed penguin diagram shown in Fig. 1(c), where the $p\bar{p}$ pair is created through a pair of gluons (or a gluonic resonance). There are four additional color-suppressed diagrams: two tree diagrams with an internal $W^+$-emission and an $W^+$-annihilation and two penguin diagrams with an internal gluon-emission that are expected to be small. If the $p\bar{p}$ system is produced independently of the $K^+$ through a tree diagram with an external $W^+$-emission (Fig. 1(b)) or a penguin with an external gluon-emission (Fig. 1(c)), i.e. the $p\bar{p}$ quark lines are not associated with the $u$ or $d$ quarks in the $K^+$, then the distributions $m_{pK^+}$ and $m_{p\bar{p}K^+}$ should be identical. If the $u$ quark in the $K^+$ is associated with a $\bar{u}$ quark in a $p$ (Fig. 1(a)), larger values of $m_{pK^+}$ are favored over those of $m_{p\bar{p}K^+}$. Thus a study of the Dalitz plot provides insight not only into the dominant mechanism of this decay but also into whether the penguin or the tree amplitude is dominant.

This paper is organized as follows: first we describe the event selection and the branching-fraction measurement. Then we describe the $p\bar{p}$ mass spectrum and the measurement of the $\eta_c$ width. We examine the Dalitz plot for an asymmetry between the distributions in $m_{pK^+}$ and $m_{p\bar{p}K^+}$. In the final section we describe searches for $B^+ \rightarrow p\Lambda(1520) \rightarrow (p\bar{p}K^+)$ decay and for the hypothesized $I=1$, $I_3=1$ pentaquark state $\Theta^{++}$ (a member of the baryon 27-plet with quark content $uuuds$) in the decay $B^+ \rightarrow \Theta^{++}\bar{p} \rightarrow (p\bar{p}K^+)\bar{p}$. The $\Theta^{++}$ mass has been predicted to lie in the region $1.43 - 1.70$ GeV/c$^2$.

The analysis uses $232 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II $\epsilon^+\epsilon^-$ storage ring. Charged tracks are measured by a five-layer silicon vertex tracker (SVT) and a 40-layer drift-chamber (DCH) in a 1.5-T solenoidal magnetic field. A Cherenkov radiation detector (DIRC) is used for charged-particle identification. The CsI(Tl) electromagnetic calorimeter detects photon and electron showers. To identify kaons and protons we use $dE/dx$ measurements in the SVT and DCH, and the pattern of Cherenkov photons in the DIRC. The proton efficiency is 93% with 9% kaon misidentification probability. The kaon efficiency is 87% with 2% pion misidentification probability.
We use the kinematic constraints of $B$-meson pair-production at the $\Upsilon(4S)$ to identify the $B^+ \rightarrow p\bar{p}K^+$ signal. Two independent variables are calculated for each $p\bar{p}K^+$ candidate: $m_{ES} = (E_{cm}^2/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^2 - \mathbf{p}_B^2 / 2$, and $\Delta E = E_1^* - E_{cm}/2$, where $E_{cm}$ is the total center-of-mass energy, the subscripts 0 and $B$ refer to the initial $\Upsilon(4S)$ and to the $B$ candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. The resolutions on $\Delta E$ and $m_{ES}$ are about 17 MeV and 2 MeV/$c^2$, respectively.

Backgrounds arise primarily from random combinations in continuum events ($e^+e^- \rightarrow q\bar{q}$, where $q = u, d, s, c$). These events are collimated along the original quark directions and can be distinguished from more spherical $BB$ events with a Fisher discriminant ($F$) [12], a linear combination of four event-shape variables. The four variables are $\cos \theta^*_{thr}$, the angle between the thrust axis of the reconstructed $B$ and the beam axis; $\cos \theta^*_{mom}$, the angle between the momentum of the reconstructed $B$ and the beam axis; and the zeroth and second Legendre polynomial momentum moments, $L_0 = \sum_i |\mathbf{p}_i|$ and $L_2 = \sum_i |\mathbf{p}_i^*|[(3 \cos^2 \theta_{thr,B}^* - 1)/2]$, where $\mathbf{p}_i^*$ are the momenta of the tracks and neutral clusters not associated with the $B$ candidate and $\theta_{thr,B}^*$ is the angle between $\mathbf{p}_i^*$ and the thrust axis of the $B$ candidate. The event selection is optimized assuming the previously measured value of the branching fraction [2] to maximize $s/(s+b)$, where $s$ and $b$ are the expected number of signal and background events, respectively. The event selection retains 66% of signal events while removing 93% of continuum background.

The resulting distribution of events in the $m_{ES}-\Delta E$ plane is shown in Fig. 2. A clear signal is observed at the $B$ mass and $\Delta E$=0. Potential backgrounds are studied with Monte Carlo (MC) simulation [14]. The combinatorial background is expected to come predominantly (89%) from continuum events. Background events in the signal region arise mostly from $B^+ \rightarrow X_{cc}(p\bar{p})K^+$, where $X_{cc} = \eta_c, J/\psi, \psi', \chi_{c0,1,2}$ (the charmonium background), while non-charmonium $B$ backgrounds are expected to be negligible. The signal and sideband regions are defined to be “wide” ($5.27 < m_{ES} < 5.29$ GeV/$c^2$ and $5.20 < m_{ES} < 5.26$ GeV/$c^2$, $|\Delta E| < 50$ MeV) for the charmonium background studies and “narrow” ($5.26 < m_{ES} < 5.28$ GeV/$c^2$ and $5.20 < m_{ES} < 5.26$ GeV/$c^2$, $|\Delta E| < 29$ MeV) for the Dalitz plot study.

To extract the $p\bar{p}K^+$ signal yield, we fit the $\Delta E$ distributions for candidates that lie in the $5.27 < m_{ES} < 5.29$ GeV/$c^2$ region separately in nine bins of $m_{pp}$. The size of the bins is shown in Fig. 3. We use a linear function for the background and a double Gaussian distribution for the signal. The widths and means of the Gaussian distributions and their relative areas are fixed to values obtained from MC simulation, which is also used to calculate the detection efficiency ($\varepsilon_{m_{pp}}$) in each $m_{pp}$ bin. Across the allowed kinematic region, $\varepsilon_{m_{pp}}$ declines smoothly from 30% at threshold to 24% at the highest mass. The $\Delta E$ fits for $m_{pp}$ below 2.85 GeV/$c^2$ yield $343_{-26}^{+27}$ signal events. From the known number of charged $B$ mesons in the sample, the branching fraction for $m_{pp}$ below the $\eta_c$ mass is measured to be $B(B^+ \rightarrow p\bar{p}K^+; m_{pp} < 2.85$ GeV/$c^2) = (5.3 \pm 0.4 \pm 0.3) \times 10^{-6}$.

An estimate of the number of charmonium events in the $m_{pp} > 2.85$ GeV/$c^2$ region is required to determine the total non-charmonium branching fraction. To minimize the systematic error on that quantity, we fit the $m_{pp}$ spectrum for the number of the non-charmonium events in the primary “charmonium” region ($2.85 < m_{pp} < 3.15$ GeV/$c^2$). To improve the $p\bar{p}$ mass resolution in the $m_{pp}$ fit, we perform a kinematic fit fixing the mass and energy of each $B$ candidate in the wide signal and sideband regions to their known values. The $m_{pp}$ distribution is shown in Fig. 3 where prominent signals for the $\eta_c$ and $J/\psi$ decaying into $p\bar{p}$ are visible. The region used in the $m_{pp}$ fit, $2.4 < m_{pp} < 3.4$ GeV/$c^2$, is chosen wider than the “charmonium” region of inter-
est (2.85 < m_{pp} < 3.15 GeV/c^2), shown in Fig. 3 inset), to improve the statistical uncertainties on the ppK^+ signal and combinatorial background yield. The ηc peak is described by a convolution of a Breit-Wigner distribution and a Gaussian distribution, and the J/ψ peak by a sum of two Gaussian distributions with a common mean. The shapes are obtained from MC simulation. The width of the broader J/ψ Gaussian distribution and ratio of areas of the two J/ψ Gaussian distributions are constrained in the fit to their MC values. A common width is used for the narrow Gaussian distributions for J/ψ and ηc, and is a free parameter in the fit. The ppK^+ signal and combinatorial background distributions are modeled by a linear function of m_{pp}. The inset of Fig. 4 shows this fit, which results in 114^{+15}_{-12} ηc events and 137^{+13}_{-12} J/ψ events. Correcting for the detection efficiency of (26.9 ± 0.2)%, we find B(B^+ → ηcK^+)B(ηc → pp) = (1.8^{+0.3}_{-0.2}±0.2) × 10^{-6} and B(B^+ → J/ψK^+)B(J/ψ → pp) = (2.2±0.2±0.1) × 10^{-6} in agreement with the accepted values 13. The fit yields a total ηc width of Γ(ηc) = 25^{+6}_{-5}±3 MeV/c^2 consistent with the current values 13 and a mass resolution of 5.7 ± 0.4 MeV/c^2 in agreement with MC expectations.

The m_{pp} fit yields 88±6 ppK^+ signal and combinatorial background events in the charmonium region (see Fig. 3). In this region, the latter contribution is estimated from the ΔE fit to be 53±5 events, resulting in a non-charmonium ppK^+ signal of 35±8 events. The contribution from higher-mass charmonium modes is estimated to be 24±5 events from the accepted values for their branching fractions. Adding the ppK^+ signal yield obtained from the ΔE fits outside the “charmonium” region with non-charmonium ppK^+ signal in the “charmonium” region, and subtracting the contribution of the higher mass charmonium modes results in a total non-charmonium signal yield of 433±33 events. Correcting the signal yield for efficiency in each of the m_{pp} bins and normalizing to the number of B^+ mesons in the data sample results in a total branching fraction of B(B^+ → ppK^+) = (6.7 ± 0.5 ± 0.4) × 10^{-6} with charmonium decays to pp excluded. Figure 4 shows the background-subtracted and efficiency-corrected pp mass spectrum and the expectation for a three-body phase-space decay. The existence of a low-mass enhancement in the pp mass as previously observed by Belle 2 is confirmed.

The charge asymmetry is defined as A_{ch} = (N_{B^-} - N_{B^+})/(N_{B^-} + N_{B^+}), where N_{B^±} is the number of B^± → ppK^± events. We use the same fitting procedure as for the branching fraction measurement, and find A_{ch} = -0.16^{+0.07}_{-0.08} ± 0.04 for m_{pp} < 2.85 GeV/c^2.

For the remainder of this paper to increase the signal purity, only events in the narrow signal and m_{ES}-sideband regions are considered. After selecting the B candidates, we perform a kinematic fit for each B candidate, fixing its mass and energy to their known values.

We study the dynamics of the three-body decay by constructing signal and sideband Dalitz plots (Fig. 5). There are 780 (1661) events in the signal (sideband) region. The sideband contains about eight times more combinatorial events than are expected in the signal region. To study the m_{pK^+} and m_{pK^+} asymmetry, we divide the Dalitz plot along the m_{pK^+} = m_{pK^+} line (dashed line in Fig. 5) and each of the two halves is projected...
onto the nearer axis. The corresponding distributions
for the events in signal and rescaled sideband regions
are shown in Fig. 6(a,b). No asymmetry is expected from
variations in \( \varepsilon_{m_{\eta p}} \) which is charge-symmetric and slowly
varying with \( m_{\eta p} \), nor from the small combinatorial back-
ground shown in Fig. 6(a,b). The asymmetry appears as
a broad enhancement peaking at about 4 GeV in the \( pK^+ \)
combinations (Fig. 6(c)). This could be an indication of
a correlation between quarks in \( \bar{p} \) and \( K^+ \) if the \( B \)
decay proceeds through a penguin diagram (Fig. 6(a)).

The two-body decay \( B^+ \rightarrow p \Lambda(1520) \) could also be
present in the \( ppK^+ \) signal sample. The efficiency for
detection of this channel is determined in dedicated MC
simulations to be \( (4.7 \pm 0.1)\% \), including \( B(\Lambda(1520) \rightarrow
p\bar{K}^-) \). The \( m_{\bar{p}K^+} \) spectrum, shown in Fig. 6(a), is
fit with an ARGUS function \( \mathcal{L} \) for the background
and a Breit-Wigner convolved with a double Gaussian (with
a common mean) for the \( \Lambda(1520) \) signal shape. The mass
resolutions and the ratio of areas of the Gaussians are
fixed to the values obtained from MC simulation, while
we fix the mean and the natural width to established
values \( \mathcal{L} \); the endpoint of the ARGUS function is fixed
to the sum of the proton and kaon masses. An unbinned
maximum likelihood fit (Fig. 6(a)) results in an upper
limit (U.L.) on \( B(\Lambda(1520) \rightarrow p\bar{K}^-) \) of \( 1.5 \times 10^{-9} \)
at 90\% C.L. (including a systematic error of 16\%).

The search for a light \( \Theta^{+++} \) pentaquark candidate
\( (m_{\Theta^{+++}} < 2 \text{ GeV}/c^2) \) proceeds as follows. From
\( B^+ \rightarrow ppK^+ \) three-body phase-space MC as well

### Table I: Systematic uncertainties in percent on the branching
fraction measurements and in the values of uncertainties
for the symmetry measurements. Values for \( m_{p\bar{p}} \) below
2.85 GeV/\( c^2 \) are given in brackets.

| Type                     | \( p\bar{K}^+ \) | \( \eta_K \) | \( p\Lambda(1520) \) | \( p\Theta^{+++} \) | \( \Lambda_{ch} \) |
|--------------------------|-----------------|-------------|----------------------|-------------------|------------------|
| B-counting               | 1.1(1.1)        | 1.1         | 1.1                  | 1.1               | –                |
| Tracking/PID             | 3.8(3.8)        | 3.4         | 4.2                  | 4.2               | 0.02             |
| MC Statistics            | 2.1(2.4)        | 0.7         | 1.0                  | 0.5               | 0.03             |
| B.F. Errors              | 0.9(−)          | –           | 2.2                  | –                 | –                |
| Selection                | 0.2(−)          | 0.4         | 3.9                  | 3.9               | –                |
| \( \Delta E/\text{Mass Fits} \) | 3.6(2.4) | 8.9     | 14.3                 | –                 | 0.01             |
| Total                    | 5.8(5.2)        | 13.5        | 15.6                 | 6.1               | 0.03             |

![Figure 6](image1)

**FIG. 6:** Efficiency-corrected distributions in the narrow sig-
(al (points) and rescaled sideband (shade) regions: (a) \( m_{p\bar{K}^+} \)
(\( m_{p\bar{K}^+} > m_{pK^+} \)), (b) \( m_{p\bar{K}^+} \) (\( m_{p\bar{K}^+} < m_{pK^+} \)), and (c) differ-
cence between (a) and (b). Errors shown are statistical
only.

![Figure 7](image2)

**FIG. 7:** (a) The \( m_{p\bar{K}^+} \) distribution for data events in \( \Lambda(1520) \)
mass region; (b) The \( m_{p\bar{K}^+} \) distributions for data events
in the signal region outside (dashed) or inside (solid) the
2.85 < \( m_{p\bar{p}} < 3.15 \text{ GeV}/c^2 \) region. Distributions are not
efficiency corrected.

as five dedicated signal MC samples with \( m_{\Theta^{+++}} =
1.5, 1.6, 1.7, 1.8, 1.9 \text{ GeV}/c^2 \), we find the mass resolu-
tion \( (\sigma_{pK^+}) \) to vary from 1.0 to 3.0 MeV/\( c^2 \) for
\( 1.43 < m_{p\bar{K}^+} < 2.00 \text{ GeV}/c^2 \), and the average reconstruc-
tion efficiency to be \( (20.5 \pm 0.1)\% \) in this mass region.
The events with \( m_{p\bar{p}} \) in the charmonium region are
 vetoed. The \( pK^+ \) mass distribution of the remaining
events is shown in Fig. 7(b). A Bayesian approach is
used to calculate the U.L. at 90\% C.L. as a function
of \( m_{pK^+} \), assuming Poisson-distributed events in the
absence of background. Each limit is increased by the
total systematic error of 6\%. The U.L. for \( B(\Theta^{+++} \rightarrow
p\bar{p}) \times B(\Theta^{+++} \rightarrow pK^+) \) is measured to be \( 0.5 \times 10^{-7} \)
for \( 1.43 < m(\Theta^{+++}) < 1.50 \text{ GeV}/c^2 \), \( 0.9 \times 10^{-7} \)
for \( 1.50 < m(\Theta^{+++}) < 1.72 \text{ GeV}/c^2 \), and \( < 1.2 \times 10^{-7} \)
for \( 1.72 < m(\Theta^{+++}) < 2.00 \text{ GeV}/c^2 \).

The systematic uncertainties for each analysis are sum-
marized in Table I. The \( \mathcal{T}(4S) \) is assumed to decay
equally to \( B^0B^0 \) and \( B^+B^- \) mesons. Incomplete knowl-
edge of the luminosity and cross-section leads to a 11\% uncertainty.
Charged-tracking and particle-identification (PID) studies in the data
lead to small corrections applied to each track in these simulations.
Limitation of statistics and purity in these data-MC comparisons lead
to residual tracking/PID uncertainties. A large control sample of $B^+\rightarrow J/\psi (e^+e^-)K^+$ is separately studied in data and MC simulations to understand the residual errors from the event-shape, $\Delta E$, and $m_{ES}$ cuts. Limitation of MC statistics employed in each analysis contributes to a small uncertainty. Branching fraction uncertainties (B.F. Errors) $^{14}$ on $\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow pp\bar{p})$, where $X = \chi_{c[0,1,2]}$, $\psi'$ and $\mathcal{B}(A(1520) \rightarrow pK^-)$ affect the total $ppK^+$ and the $p\bar{A}$ branching fraction measurements, respectively. Where the MC values are used to fix signal shape parameters in a fit, the parameters are varied within their uncertainties and the data are refit to propagate this uncertainty. In a similar fashion, different ranges and background functions are employed to establish the uncertainty on the mass spectra fits (resulting, for example, in the $\Gamma(\eta_c)$ uncertainty of 3 MeV).

In summary, with $210 fb^{-1}$ of data, we isolate the $B^+ \rightarrow pp\bar{p}K^+$ final state, and measure its non-charmonium branching fraction to be $(5.3 \pm 0.4 \pm 0.3) \times 10^{-6}$ for $m_{pp\bar{p}}$ below 2.85 GeV/$c^2$ and $(6.7 \pm 0.5 \pm 0.4) \times 10^{-6}$ for the whole $m_{pp\bar{p}}$ range. We measure $A_{c\bar{c}} = -0.16^{+0.07}_{-0.06} \pm 0.04$ for $m_{pp\bar{p}}$ below 2.85 GeV/$c^2$. The existence of a low-mass enhancement of the $pp\bar{p}$ pair is confirmed. The asymmetry between $pK^+$ and $\bar{p}K^+$ final states in the Dalitz plot is demonstrated, providing evidence supporting the dominance of the penguin amplitude in this $B$ decay. We measure the total width of $\eta_c$ to be $25^{+8}_{-6} \pm 3$ MeV/$c^2$. An upper limit of the decay rate to $p\bar{A}(1520)$ is set at $1.5 \times 10^{-6}$. No evidence is found for the pentaquark candidate $\Theta^{++}$ in the mass range 1.43 to 2.0 GeV/$c^2$, decaying into $pK^+$, and branching fraction limits are established at the $10^{-7}$ level.

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* Also with Universit`a di Perugia, Dipartimento di Fisica, Perugia, Italy
† Also with Universit`a della Basilicata, Potenza, Italy
‡ Deceased
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