Evidence for CP Violation in $B^{+} \overline{p} \overline{p} K^{+}$ Decays

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Evidence for CP Violation in $B^+ \rightarrow p\bar{p}K^+$ Decays

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Three-body $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$ decays are studied using a data sample corresponding to an integrated luminosity of 3.0 fb$^{-1}$ collected by the LHCb experiment in proton-proton collisions at center-of-mass energies of 7 and 8 TeV. Evidence of CP violation in the $B^+ \rightarrow p\bar{p}K^+$ decay is found in regions of the phase space, representing the first measurement of this kind for a final state containing baryons. Measurements of the forward-backward asymmetry of the light meson in the $p\bar{p}$ rest frame yield $A_{FB}(p\bar{p}K^+, m_{pp} < 2.85 \text{ GeV}/c^2) = 0.495 \pm 0.012 \text{ (stat)} \pm 0.007 \text{ (syst)}$ and $A_{FB}(p\bar{p}\pi^+, m_{pp} < 2.85 \text{ GeV}/c^2) = -0.409 \pm 0.033 \text{ (stat)} \pm 0.006 \text{ (syst)}$. In addition, the branching fraction of the decay $B^+ \rightarrow \Lambda(1520)p$ is measured to be $B(B^+ \rightarrow \Lambda(1520)p) = (3.15 \pm 0.48 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.26 \text{ (BF)}) \times 10^{-7}$, where BF denotes the uncertainty on secondary branching fractions.

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Direct CP violation can appear as a rate asymmetry in the decay of a particle and its CP conjugate, and it can be observed when at least two amplitudes, carrying different weak and strong phases, contribute to the final state. For $B$ mesons, it was observed for the first time in two-body $B^0 \rightarrow K^+\pi^-$ decays [1,2]. The weak phases are sensitive to physics beyond the Standard Model that may appear at a high energy scale, and their extraction requires a determination of the relative strong phases. Three-body decays are an excellent laboratory for studying strong phases of interfering amplitudes. In particular, charmless decays of $B$ mesons $B^+ \rightarrow K^+\pi^+\pi^-$, $B^+ \rightarrow K^+K^-K^+$, $B^+ \rightarrow \pi^+\pi^-\pi^+$, and $B^+ \rightarrow K^+K^-\pi^+$ have been investigated recently [3–5]. (Throughout the Letter, the inclusion of charge conjugate processes is implied, except in the definition of CP asymmetries.) Similar studies have been conducted for the baryonic final states $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$ [6]. In the $B^+ \rightarrow h^+h^-h^+$ decays ($h = \pi$ or $K$ throughout this Letter), large asymmetries, not necessarily associated to resonances, have been observed in the low $K^+K^-$ and $\pi^+\pi^-$ mass regions. These observations suggest that rescattering between $\pi^+\pi^-$ and $K^+K^-$ pairs may play an important role in the generation of the strong phase difference needed for CP violation to occur [7]. The $B^+ \rightarrow p\bar{p}h^+$ decays, although sharing the same quark-level diagrams, may exhibit different behavior due to the baryonic nature of two out of the three final-state particles.

This Letter reports the first evidence for CP violation in charmless $B^+ \rightarrow p\bar{p}K^+$ decays. These decays are studied in the region with invariant mass $m_{pp} < 2.85 \text{ GeV}/c^2$, below the charmonium resonances threshold. In addition, a more accurate measurement of the branching fraction of the decay $B^+ \rightarrow \Lambda(1520)p$ is performed, using the reconstruction of $\Lambda(1520) \rightarrow K^+\bar{p}$ decays, and improved determinations of the spectra and angular asymmetries are also reported. The mode $B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+$ serves as a control channel. The data used have been collected with the LHCb detector and correspond to 1.0 and 2.0 fb$^{-1}$ of integrated luminosity at 7 and 8 TeV center-of-mass energies in $pp$ collisions, respectively. The data samples are analyzed separately and the results are averaged.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Ref. [8]. The detector allows for the reconstruction of both charged and neutral particles. For this analysis, the ring-imaging Cherenkov detectors [9]—distinguishing pions, kaons, and protons—are particularly important.

The analysis uses simulated events generated by PYTHIA 8.1 [10] with a specific LHCb configuration [11]. Decays of hadronic particles are described by EVTGEN [12], in which final-state radiation is generated using PHOTOS [13]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [14], as described in Ref. [15]. Nonresonant $B^+ \rightarrow p\bar{p}h^+$ events are simulated, uniformly distributed in phase space, to study the variation of efficiencies across the Dalitz [16] plane, as well as resonant modes such as $B^+ \rightarrow J/\psi(\rightarrow p\bar{p})K^+$, $B^+ \rightarrow \eta_c(\rightarrow p\bar{p})K^+$, $B^+ \rightarrow \psi(2S)(\rightarrow p\bar{p})K^+$, $B^+ \rightarrow \Lambda(1520)(\rightarrow K^+\bar{p})p$, and $B^+ \rightarrow J/\psi(\rightarrow p\bar{p})\pi^+$.

Three charged particles are combined to form $B^+ \rightarrow p\bar{p}h^+$ decay candidates. The discrimination of signal from background is done through a multivariate analysis using a boosted decision tree (BDT) classifier [17]. Input quantities include kinematic and topological variables related to the $B^+$ candidates and the individual tracks. The momentum,
cross feed between particle identification (PID) requirements are applied to chosen to maximize the signal yield significance. The optimal cut value of the BDT has been derived from calibration data samples of kinematically identified pions, kaons, and protons originating from the resulting in a \( \pi \) from the \( K \) mass. An asymmetric Gaussian function with power-law tails is used to model a possible \( p \pi \) cross-feed component, where the pion is misidentified as a kaon. This contribution is found to be small.

The fit to the \( B^+ \rightarrow p \phi \pi^+ \) decay uses similar parametrizations for the signal, the combinatorial background, the \( p \phi \) cross feed, and the partially reconstructed background from the \( B \rightarrow pp\pi \) decays (with a missing pion from the \( \rho \) decay). The cross feed is found to be negligible.

The \( B^+ \rightarrow p \phi \pi^+ \) invariant mass spectra are shown in Fig. 1. The signal yields obtained from the fits are \( N(p\phi K^+) = 18721 \pm 142 \) and \( N(p\phi \pi^+) = 1988 \pm 74 \), where the uncertainties are statistical only.

The distribution of events in the Dalitz plane—defined by \( (m_{pp}, m_{hp}) \), where \( hp \) denotes the neutral combinations \( h^- p \) and \( h^+ \bar{p} \)—is examined. From the fits to the \( B^+ \) candidate invariant mass, shown in Fig. 1, signal weights are calculated with the Dalitz-plot technique [19]. These weights are corrected for trigger, reconstruction, and selection efficiencies, which are estimated from simulated samples and calibration data. The Dalitz-plot variables are calculated by constraining the \( \phi \) invariant mass to the known \( B^+ \) meson mass [20,21]. Figure 2 shows the Dalitz

![Image](image1.png)

**FIG. 1** (color online). Invariant mass distributions of \( p\phi K^+ \) (left panel) and \( p\phi \pi^+ \) (right panel) candidates. The points with error bars represent data. The solid black line represents the total fit function. The components are represented by blue dashed (signal), purple dotted (cross feed), red long-dashed (combinatorial background), and green dash-dotted (partially reconstructed background) curves.

![Image](image2.png)

**FIG. 2** (color online). Background-subtracted and acceptance-corrected Dalitz-plot distributions for \( B^+ \rightarrow p\phi K^+ \) (left panel) and \( B^+ \rightarrow p\phi \pi^+ \) (right panel).
distributions of the $B^+ \rightarrow \bar p p \phi^+$ events. Similar to the results reported in Refs. [6,22], clear signals of $J/\psi$, $\eta_c$, and $\psi(2S)$ resonances are observed, while $B^+ \rightarrow p \bar p K^+$ and $B^+ \rightarrow p \bar p \pi^+$ noncharm events both accumulate near the $p \bar p$ threshold. However, $B^+ \rightarrow p \bar p K^+$ events preferentially occupy the region with low $K$ invariant mass while $B^+ \rightarrow p \bar p \pi^+$ events populate the region with large $\pi$ invariant mass. This difference in the Dalitz distribution can also be observed as a difference in the distribution of the invariant mass. This difference in the Dalitz distribution can also be observed as a difference in the distribution of the invariant mass.

The yields of the decays $B^+ \rightarrow \bar p p \phi^+$ in the region $m_{\bar p p} < 2.85$ GeV/c$^2$ are obtained with the same model used for the integrated signals. Those of the resonant modes are extracted through two-dimensional extended unbinned maximum likelihood fits to invariant mass distributions of $p \bar p \phi^+$ and $p \bar p$ or $K^+ \bar p$, using the same signal and background models for $m_{\bar p p}$ or $m_{K^+ \bar p}$ as in Ref. [6]. The results are shown in Table I. The branching fractions of the decays $B^+ \rightarrow \Lambda(1520)(\rightarrow K^+ \bar p)p$ and $B^+ \rightarrow p \bar p \pi^+$, $m_{\bar p p} < 2.85$ GeV/c$^2$ are measured relative to the $J/\psi$ modes as

$$
\frac{\mathcal{B}(B^+ \rightarrow \Lambda(1520)(\rightarrow K^+ \bar p)p)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow p \bar p)K^+)} = 0.033 \pm 0.005 \text{ (stat)} \pm 0.007 \text{ (syst)},
$$

$$
\frac{\mathcal{B}(B^+ \rightarrow p \bar p \pi^+, m_{\bar p p} < 2.85 \text{ GeV/c}^2)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow p \bar p)\pi^+)} = 12.0 \pm 1.2 \text{ (stat)} \pm 0.3 \text{ (syst)}.
$$

The systematic uncertainties also include contributions from the background model. Using $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.016 \pm 0.033) \times 10^{-3}$, $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+) = (4.1 \pm 0.4) \times 10^{-5}$, $\mathcal{B}(J/\psi \rightarrow p \bar p) = (2.17 \pm 0.07) \times 10^{-3}$ [21], and $\mathcal{B}(\Lambda(1520) \rightarrow K^- p) = 0.234 \pm 0.016$ [25], the branching fractions are measured to be $\mathcal{B}(B^+ \rightarrow \Lambda(1520)p) = \cdots$.

TABLE I. Event yields and selection efficiency for $B^+ \rightarrow p \bar p K^+$ and $B^+ \rightarrow p \bar p \pi^+$ final states.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi(\rightarrow p \bar p)K^+$</td>
<td>4260 ± 67</td>
<td>1.55 ± 0.02</td>
</tr>
<tr>
<td>$B^+ \rightarrow \eta_c(\rightarrow p \bar p)K^+$</td>
<td>2182 ± 64</td>
<td>1.47 ± 0.02</td>
</tr>
<tr>
<td>$B^+ \rightarrow \psi(2S)(\rightarrow p \bar p)K^+$</td>
<td>368 ± 20</td>
<td>1.59 ± 0.02</td>
</tr>
<tr>
<td>$B^+ \rightarrow \Lambda(1520)(\rightarrow K^+ \bar p)p$</td>
<td>128 ± 20</td>
<td>1.39 ± 0.01</td>
</tr>
<tr>
<td>$B^+ \rightarrow p \bar p K^+$, $m_{\bar p p} &lt; 2.85$ GeV/c$^2$</td>
<td>8510 ± 104</td>
<td>1.58 ± 0.02</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi(\rightarrow p \bar p)\pi^+$</td>
<td>122 ± 12</td>
<td>1.07 ± 0.01</td>
</tr>
<tr>
<td>$B^+ \rightarrow p \bar p \pi^+$, $m_{\bar p p} &lt; 2.85$ GeV/c$^2$</td>
<td>1632 ± 64</td>
<td>1.15 ± 0.01</td>
</tr>
</tbody>
</table>
Asymmetries of the number of signal events in bins of the Dalitz-plot variables for $B^+ \rightarrow p\bar{p}K^\pm$. The number of events in each bin is approximately 300.

\[ (3.15 \pm 0.48 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.26 \text{ (BF)} ) \times 10^{-7}. \]

$B^+ \rightarrow p\bar{p}K^\pm, m_{\bar{p}p} < 2.85 \text{ GeV}/c^2 = (1.07 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.11 \text{ (BF)}) \times 10^{-6}$, where BF denotes the uncertainty on the aforementioned secondary branching fractions. The former measurement supersedes what is reported in Ref. [6].

The raw charge asymmetry is measured from the yields $N$ as

\[ A_{\text{raw}} = \frac{N(B^- \rightarrow p\bar{p}h^-) - N(B^- \rightarrow p\bar{p}h^+)}{N(B^- \rightarrow p\bar{p}h^-) + N(B^- \rightarrow p\bar{p}h^+)} , \]

and it is investigated in the Dalitz plane using signal weights inferred from the fits shown in Fig. 1, for $B^-$ and $B^+$ samples. This asymmetry includes production and detection asymmetries. For the $B^- \rightarrow p\bar{p}K^\pm$ case, the statistics allows us to perform a full two-dimensional analysis: an adaptive binning algorithm is used so that the sum of $B^-$ and $B^+$ events in each bin is approximately constant. Figure 5 shows the distribution of $A_{\text{raw}}$ in the Dalitz plane. A clear pattern is observed near the $p\bar{p}$ threshold where $A_{\text{raw}}$ is negative for $m_{\bar{p}p} < 10 \text{ GeV}^2/c^4$ and positive for $m_{\bar{p}p} > 10 \text{ GeV}^2/c^4$. Figure 6 shows the $m_{\bar{p}p}$ projections of $N(B^-) - N(B^+)$ in bins of $m_{\bar{p}p}^2$ for $m_{\bar{p}p} < 10 \text{ GeV}^2/c^4$ (black filled circles) and $m_{\bar{p}p} > 10 \text{ GeV}^2/c^4$ (open triangles).

$A_{\Delta} = A_{\text{raw}}(B^\pm \rightarrow J/\psi(p\bar{p})K^\pm) - A_{\text{raw}}(B^\pm \rightarrow J/\psi K^\pm)$.

The value $A_{\Delta}(B^\pm \rightarrow J/\psi K^\pm) = 0.6 \pm 0.4\%$ is taken from Ref. [27]. When using $A_{\text{raw}}(B^\pm \rightarrow J/\psi(p\bar{p})K^\pm)$, differences in the momentum asymmetry of the $p\bar{p}$ pair between $B^\pm \rightarrow J/\psi(p\bar{p})K^\pm$ and nonresonant $B^\pm \rightarrow p\bar{p}K^\pm$ decays are accounted for. A similar procedure

### Table II. $CP$ asymmetries for $B^\pm \rightarrow p\bar{p}K^\pm$ and $B^\pm \rightarrow p\bar{p}\pi^\pm$ decays. The systematic uncertainties are dominated by the precision on the measurement $A_{\text{CP}}(B^\pm \rightarrow J/\psi K^\pm)$.

<table>
<thead>
<tr>
<th>Mode/region</th>
<th>$A_{\text{CP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(p\bar{p})K^\pm$</td>
<td>$0.040 \pm 0.034 \text{ (stat)} \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>$\psi(2S)(p\bar{p})K^\pm$</td>
<td>$0.092 \pm 0.058 \text{ (stat)} \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>$p\bar{p}K^\pm, m_{\bar{p}p} &lt; 2.85 \text{ GeV}/c^2$</td>
<td>$0.021 \pm 0.020 \text{ (stat)} \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>$p\bar{p}K^\pm, m_{\bar{p}p} &lt; 2.85 \text{ GeV}/c^2, m_{\bar{p}p} &lt; 10 \text{ GeV}^2/c^4$</td>
<td>$-0.036 \pm 0.023 \text{ (stat)} \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>$p\bar{p}K^\pm, m_{\bar{p}p} &lt; 2.85 \text{ GeV}/c^2, m_{\bar{p}p} &gt; 10 \text{ GeV}^2/c^4$</td>
<td>$0.096 \pm 0.024 \text{ (stat)} \pm 0.004 \text{ (syst)}$</td>
</tr>
<tr>
<td>$p\bar{p}\pi^\pm, m_{\bar{p}p} &lt; 2.85 \text{ GeV}/c^2$</td>
<td>$-0.041 \pm 0.039 \text{ (stat)} \pm 0.005 \text{ (syst)}$</td>
</tr>
</tbody>
</table>
is applied to obtain \( A_{CP}(B^\pm \to \eta_c(p\bar{p})K^\pm) \) and \( A_{CP}(B^\pm \to \psi(2S)(p\bar{p})K^\pm) \). The \( B^\pm \to p\bar{p}\pi^\pm \) decays are also considered in the region \( m_{p\bar{p}} < 2.85 \text{ GeV}/c^2 \). In this case, the correction also involves the pion detection asymmetry \( A_{\Delta} = A_{\text{raw}}(B^\pm \to J/\psi(p\bar{p})K^\pm) - A_{CP}(B^\pm \to J/\psi K^\pm) - A_{\text{det}}(K^\pm) + A_{\text{det}}(\pi^\pm) \). The value \( A_{\text{det}}(K^\pm) - A_{\text{det}}(\pi^\pm) = (-1.2 \pm 0.1)\% \) is taken from studies of prompt \( D^\pm \) decays [28]. Table II shows the results, including asymmetries of resonant modes.

The systematic uncertainties are estimated by using alternative fit functions and splitting the data sample according to trigger requirements and magnet polarity. The overall systematic uncertainties are dominated by the uncertainty on the \( A_{CP}(B^\pm \to J/\psi K^\pm) \) measurement.

In summary, an interesting sign-inversion pattern of the \( B^\pm \to \eta_c(p\bar{p})K^\pm \) asymmetry is observed at low \( p\bar{p} \) invariant masses in \( B^\pm \to p\bar{p}K^\pm \) decays. Although this resembles what is observed at low \( h^+h^- \) masses in the \( B^\pm \to h^+h^-h^- \) decays, the strong phase difference could involve a specific mechanism such as interfering long-range \( p\bar{p} \)-waves with different angular momenta [24]. In the region \( m_{p\bar{p}} < 2.85 \text{ GeV}/c^2 \), the measured asymmetry is positive with a significance of nearly 4\( \sigma \), which represents the first evidence of \( CP \) violation in \( b \)-hadron decays with baryons in the final state. The \( h^- \) hadron forward-backward asymmetry in noncharm \( B^\pm \to p\bar{p}h^+ \) decays is measured as \( A_{FB}(p\bar{p}K^+, m_{p\bar{p}} < 2.85 \text{ GeV}/c^2) = 0.495 \pm 0.012 \) (stat) \( \pm 0.007 \) (syst) and \( A_{FB}(p\bar{p}K^+, m_{p\bar{p}} < 2.85 \text{ GeV}/c^2) = -0.409 \pm 0.033 \) (stat) \( \pm 0.006 \) (syst). These asymmetries could be interpreted as being due to the dominance of nonresonant \( p\bar{p} \) scattering [24]. Finally, an improved measurement of \( B(B^\pm \to \Lambda(1520)p) = (3.15 \pm 0.48 \) (stat) \( \pm 0.07 \) (syst)\( \pm 0.26 \) (BF)) \times 10^{-7} \) is obtained.

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See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.113.141801 for the fits in the range $m_{p\bar{p}} < 2.85 \text{ GeV}^2/c^4$, regions $m_{Kp} < 10 \text{ GeV}^2/c^4$ and $m_{\bar{K}p} > 10 \text{ GeV}^2/c^4$.

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