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Observation of $B_c^+ \rightarrow D^0K^+$ Decays

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Using proton-proton collision data corresponding to an integrated luminosity of 3.0 fb$^{-1}$, recorded by the LHCb detector at center-of-mass energies of 7 and 8 TeV, the $B_c^+ \rightarrow D^0K^+$ decay is observed with a statistical significance of 5.1 standard deviations. By normalizing to $B^+ \rightarrow D^0\pi^+$ decays, a measurement of the branching fraction multiplied by the production rates for $B_c^+$ relative to $B^+$ mesons within the LHCb acceptance is obtained, $R_{D^0K} = (f_{c\to u}/f_u) \times B(B_c^+ \rightarrow D^0K^+) = (9.3_{-2.5}^{+2.8} \pm 0.6) \times 10^{-7}$, where the first uncertainty is statistical and the second is systematic. This decay is expected to proceed predominantly through weak annihilation and penguin amplitudes, and is the first $B_c^+$ decay of this nature to be observed.

The $B_c^+$ meson is the only ground-state meson consisting of two heavy quarks of different flavor, namely a $b$ and a $c$ quark. As such, its formation in $pp$ collisions is suppressed relative to the lighter $B$ mesons. Unlike $B^0$, $B_c^+$ and $B_c^0$ mesons, the $b$-quark decay accounts for only $\sim 20\%$ of the $B_c^+$ width [1]. Around 70% of its width is due to $c$-quark decays, where the $c$-quark transition has been observed with $B_c^+ \rightarrow D_c^0\pi^+$ decays [2]. This leaves $\sim 10\%$ for $\bar{b}c \rightarrow W^+ \rightarrow q\bar{q}$ annihilation amplitudes, which can be unambiguously probed in charmless final states. No charmless $B_c^+$ decays have been reported to date, although searches show an indication at the level of 2.4 standard deviations ($\sigma$) [3].

To test QCD factorization and explore the new physics potential of $B_c^+$ decays, rarer decays such as suppressed tree-level $b \rightarrow u$ transitions and $b \rightarrow s$ loop-mediated (penguin) decays can be studied, where the charm quantum number remains unchanged. The simplest decay is the color-allowed $B_c^+ \rightarrow D^{(*)0}\pi^+$ decay, illustrated in Fig. 1(a). The expected branching fraction for this decay is a factor $|V_{ub}/V_{cb}|^2 \approx 0.007$ lower than the favored $b \rightarrow c$ and color-allowed $B_c^+ \rightarrow J/\psi\pi^+$ decay [4,5], placing this mode at the limit of sensitivity with current LHCb data. However, this expectation may be enhanced by penguin and weak annihilation amplitudes, which will be more pronounced in the $B_c^+ \rightarrow D^{(*)0}K^+$ mode [see Fig. 1(b) and 1(c)]. This motivates a search for the $B_c^+ \rightarrow D^{(*)0}\pi^+$ and $B_c^+ \rightarrow D^{(*)0}K^+$ decays, particularly as the branching fraction estimates in the literature vary considerably [6–8].

The decay $B^+ \rightarrow D^0\pi^+$ is used for normalization. Since the ratio of production rates for $B_c^+$ and $B^+$ mesons within the LHCb acceptance, $f_{c\to u}/f_u$, is unknown, the measured observables are

$$R_{D^{(*)0}h} = \frac{f_c}{f_u} \times B(B_c^+ \rightarrow D^{(*)0}h^+) , \quad (1)$$

where $h$ is $\pi$ or $K$ and $B(B_c^+ \rightarrow D^{(*)0}h^+)$ represents the corresponding branching fraction. The four observables are measured with a simultaneous fit to the $D^0\pi^+$ and $D^0K^+$ invariant mass distributions. Theoretical estimates for $B(B_c^+ \rightarrow J/\psi\pi^+)$ range from $6.0 \times 10^{-4}$ [9] to $1.8 \times 10^{-3}$ [10], which implies $f_{c\to u}/f_u$ values in the range 0.004–0.012 using the production ratio measured in Ref. [5] and the branching fraction $B(B^+ \rightarrow J/\psi K^+)$ [11]. Estimates for $B(B_c^+ \rightarrow D^0K^+)$ vary from $1.3 \times 10^{-7}$ [6] to $6.6 \times 10^{-5}$ [8], while estimates for $B(B_c^+ \rightarrow D^{(*)0}h^+)$ vary from $2.3 \times 10^{-7}$ [6] to $2.3 \times 10^{-6}$ [7]. Using Eq. (1), the expectation for $R_{D^{(*)0}}$ is seen to cover the range $9 \times 10^{-10} – 3 \times 10^{-8}$, while $R_{D^{(*)0}K}$ covers the range $5 \times 10^{-10} – 8 \times 10^{-7}$.

This Letter reports a search for $B_c^+ \rightarrow D^0\pi^+$ and $B_c^+ \rightarrow D^0K^+$ decays in $pp$ collision data corresponding to

FIG. 1. Tree (a), penguin (b), and weak annihilation (c) diagrams for the decays studied. In each case, the meson appearing before the comma denotes the favored decay.
integrated luminosities of 1.0 and 2.0 fb\(^{-1}\) taken by the LHCb experiment at center-of-mass energies of 7 and 8 TeV, respectively, where the \(D^0\) meson is reconstructed in the Cabibbo-favored final states \(D^0 \rightarrow K^{-}\pi^+\) or \(D^0 \rightarrow K^{-}\pi^+\pi^-\pi^+\) (inclusion of charge-conjugate processes is implied throughout). Partially reconstructed \(B^+_c \rightarrow (D^{(*)0} \rightarrow D^0(x^2, \gamma))h^+\) decays, where the neutral particle indicated in braces is not considered in the invariant mass calculation, are treated as additional signal channels. The number of \(B^+_c\) decays is normalized by comparison to the number of \(B^+ \rightarrow \bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-\) decays. A fit to the invariant mass distribution of \(D^{(*)0}h^+\) candidates in the range 5800–6900 MeV/c\(^2\) enables a measurement of

\[
R_{D^{(*)0}h^+} = \frac{N(B^+_c \rightarrow D^{(*)0}h^+)}{N(B^+ \rightarrow \bar{D}^0\pi^+)} \times B(B^+ \rightarrow D^0\pi^+) \times \xi,
\]

where \(N(B^+_c \rightarrow D^{(*)0}h^+)\) represents the \(B^+_c \rightarrow D^{(*)0}h^+\) yield, \(N(B^+ \rightarrow \bar{D}^0\pi^+)\) represents the yield of \(B^+ \rightarrow \bar{D}^0\pi^+\) normalization decays, \(B(B^+ \rightarrow \bar{D}^0\pi^+)\) is the normalization mode branching fraction [11], and \(\xi\) is the ratio of efficiencies for reconstructing and selecting \(B^+\) and \(B^+_c\) mesons decaying to these final states.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range \(2 < \eta < 5\), described in detail in Refs. [12,13]. The detector allows the reconstruction of both charged and neutral particles. For this analysis, the ring-imaging Cherenkov (RICH) detectors [14], distinguishing pions, kaons, and protons, are particularly important. Simulated events are produced using the software described in Refs. [15–22].

After reconstruction of the \(D^0\) meson candidate, the same selection is applied to the \(B^+_c\) and \(B^+\) candidates. The invariant mass of the \(D^0\) candidate must be within \(\pm 25\) MeV/c\(^2\) of its known value [11]. The other hadron originating from the \(B\) decay must have transverse momentum \((p_T)\) in the range 0.5–10.0 GeV/c and momentum \((p)\) in the range 5–100 GeV/c, ensuring that the track is within the kinematic coverage of the RICH detectors that provide particle identification (PID) information. A kinematic fit is performed to each decay chain [23], with vertex constraints applied to both the \(B\) and \(D\) vertices, and the \(D^0\) candidate mass constrained to its known value. The \(B^+\) (\(B^+_c\)) meson candidates with an invariant mass in the interval 5080–5900 MeV/c\(^2\) (5800–6900 MeV/c\(^2\)) and with a proper decay time above 0.2 ps are retained. Each \(B\) candidate is associated with the primary vertex (PV) to which it has the smallest impact parameter (IP), defined as the distance of closest approach of the candidate’s trajectory to a given PV.

Two boosted decision tree (BDT) discriminators [24] are used for further background suppression. They are trained using simulated \(B^+_c \rightarrow \bar{D}^0 \rightarrow K^-\pi^+\pi^-\pi^+\pi^-\) signal decays and a sample of wrong-sign \(K^+\pi^-\pi^+\pi^-\) signal decays for the two-body (four-body) \(D^0\) decay. The uncertainties are systematic, arising from the use of...
finite simulated samples and possible mismodeling of the
simulated $B^+_c$ lifetime and production kinematics.

To measure $\mathcal{N}(B^+ \to \bar{D}^0 \pi^+)$, binned maximum like-
ilhood fits to the invariant mass distributions of selected $B^+$
candidates are performed, where separate fits are employed
for the two-body and four-body $\bar{D}^0$ modes. The total
probability density function (PDF) is built from four
contributions. The $B^+ \to \bar{D}^0 \pi^+$ decays are modeled by
the sum of two modified Gaussian functions with asym-
metric power-law tails and an additional Gaussian function
as used in Ref. [26], all of which share a common peak
position. Misidentified $B^+ \to D^0 K^+$ candidates have an
incorrect mass assignment and form a distribution dis-
placed downward in mass, with a tail extending to lower
invariant masses. They are modeled by the sum of two
modified Gaussian PDFs with low-mass power-law tails.
All PDF parameters are allowed to vary, with the exception
of the tail parameters which are fixed to the values found in
simulation.

Partially reconstructed decays form a background at
invariant masses lower than that of the signal peak. This
background is described by a combination of parametric
PDFs, with yield and shape parameters that are allowed to vary.
A linear function describes the combinatorial back-
ground. The yield of $B^+ \to \bar{D}^0 K^+$ decays, where the kaon
misidentified as a pion, is fixed using a simultaneous fit
to correctly identify $B^+ \to \bar{D}^0 K^+$ events. Using a data-
driven analysis of approximately 20 million $D^+$ decays
reconstructed as $D^+ \to D^0 \pi^+, D^0 \to K^- \pi^+$, the proba-
bility of kaon misidentification is determined to be 32%.
The invariant mass fits to $B^+ \to (\bar{D}^0 \to K^+ \pi^-) \pi^+$ and
$B^+ \to (\bar{D}^0 \to K^+ \pi^- \pi^+ \pi^-) \pi^+$ decays determine a total
observed yield $\mathcal{N}(B^+ \to \bar{D}^0 \pi^+) = 309462 \pm 550$.

To measure $\mathcal{N}(B^+_c \to D^{(*)0} h^+)$, a simultaneous invariant
mass fit to the $B^+_c \to D^0 \pi^+$ and $B^+_c \to D^0 K^+$ samples is
performed in the region 5800–6900 MeV/c^2. Two-body
and four-body $D$-decay candidates are included, where a
Gaussian PDF describes the fully reconstructed $B^+_c$ signals.
The mean of this Gaussian is fixed to the known $B^+_c$ mass
[11]. The width of the $B^+_c \to D^0 \pi^+$ PDF is taken from a fit
to suppressed $B^+ \to (\bar{D}^0 \to \pi^+ K^-) \pi^+$ decays, scaled up
by a factor 1.3 to account for the difference in momenta
of the decay products in $B^+_c \to D^0 \pi^+$ and $B^+ \to \bar{D}^0 \pi^+$
decays. The width of the $B^+_c \to D^0 K^+$ peak is related to
that of $B^+_c \to D^0 \pi^+$ decays by the ratio of the widths of the
$B^+ \to \bar{D}^0 K^+$ and $B^+ \to \bar{D}^0 \pi^+$ peaks found in the normal-
ization mode fits. Partially reconstructed $B^+_c \to D^0 h^+$
signal decays are modeled using a combination of para-
metric PDFs, with yield and shape parameters that are
allowed to vary. These decays contribute at lower invariant
masses than the fully reconstructed signal decays, as a
result of not considering the natural particle in the invariant
mass calculation. An additional background component at
low invariant mass is included to describe $B^+_c$ decays where
two particles are missed, with shape parameters taken from
simulated $B^+ \to D^{(*)0} \pi^0$ decays and scaled to account
for the different momenta of the decay products in $B^+_c$ and
$B^+$ decays.

Misidentified $B^+_c \to D^0 (K^+) \pi^+$ decays in the
$B^+_c \to D^0 (K^+) \pi^+$ sample are modeled using the same
PDFs as the normalization fits, with widths and peak
positions scaled for the decay momentum difference.
These shapes are fixed in the fit. Signal decays are split
into separate samples with correct and incorrect kaon
identification, with a kaon misidentification rate of 7% and
a corresponding pion identification efficiency of 91% fixed
using the data-driven $D^+$ analysis described above.
An exponential function describes the combinatorial back-
ground, which is fitted independently in the $B^+_c \to D^0 \pi^+$
and $B^+_c \to D^0 K^+$ samples. The combinatorial yields, signal
yields, and partially reconstructed $B^+_c \to D^0 h^+ \{\pi^0\}$
and $B^+_c \to D^0 h^+ \{\pi^0\}$ background yields are all free to vary.
The fit to data is shown in Fig. 2, where a $B^+_c \to D^0 K^+$
yield of $20 \pm 5$ events is found. All other signal yields are
consistent with zero.

To test the significance of each signal yield, CL_s
hypothesis tests [27] are performed. Upper limits at
95% confidence level (C.L.) are determined by the point

![FIG. 2. Results of the simultaneous fit to the $D^0 K^+$ (top plot)
and $D^0 \pi^+$ (bottom plot) invariant mass distributions in the $B^+_c$
mass region, including the $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^- \pi^+$
final states. Inclusion of the charge conjugate decays is implied.
The red solid curve illustrates $B^+_c \to D^0 K^+$ decays, the red
dashed curve illustrates $B^+_c \to D^0 \pi^+$ decays, the green dashed
curve represents $B^+_c \to D^0 \pi^+$ decays, the gray shaded region
represents partially reconstructed background decays, the cyan
dashed line represents the combinatorial background, and the
total PDF is displayed as a blue solid line. The small drop
visible in the total $B^+_c \to D^0 K^+$ PDF around the $B^+_c$ mass arises
from the fact that the fit finds a small negative value for the
$B^+_c \to D^0 \pi^+$ yield.](image-url)
at which the \( p \)-value falls below 5%. All free variables in the fit are considered as nuisance parameters in this procedure. The \( p \)-value distributions for each \( R_{D^0 K} \) measurement are shown in Fig. 3. The \( B^+_c \to D^0 h^+ \) modes demonstrate no excess, and the \( R_{D^0 h^+} \) confidence intervals are determined similarly to that of \( R_{D^0 \pi} \). The upper limits at 95% confidence level found for \( R_{D^0 \pi} \), \( R_{D^0 K} \), and \( R_{D^0 K} \) are

\[
R_{D^0 \pi} < 3.9 \times 10^{-7},
R_{D^0 K} < 1.1 \times 10^{-6},
R_{D^0 K} < 1.1 \times 10^{-6}.
\]

The systematic uncertainties affecting the measurements are found to be much smaller than the statistical uncertainty, and do not alter the above upper limits.

In the case of \( R_{D^0 K} \), the observed signal is of much higher significance. To determine the full uncertainty for \( R_{D^0 K} \), the systematic uncertainties affecting the measurement are accounted for. A systematic uncertainty of \( 1.1 \times 10^{-8} \) is incurred from the use of fixed terms in the invariant mass fit. According to Eq. (2), several terms with associated relative uncertainties scale the measured signal yield: \( \xi \) with 5.3% uncertainty, \( B(B^+ \to D^0 \pi^+) \) with 3.1% uncertainty [11], and \( \mathcal{N}(B^+ \to D^0 \pi^+) \) with 0.14% uncertainty. The total systematic uncertainty, given by the sum in quadrature, is 6.2%.

To determine the significance of the \( B^+_c \to D^0 K^+ \) peak, a likelihood scan is performed. The resulting \(-\Delta \log(L)\) value for the \( R_{D^0 K} = 0 \) hypothesis corresponds to a statistical significance of \( \sqrt{-2\Delta \log(L)} = 5.1\sigma \) for the signal. The final result is

\[
R_{D^0 K} = (9.3^{+2.8}_{-2.5} \pm 0.6) \times 10^{-7},
\]

where the first uncertainty is statistical and the second is systematic. This is the first observation of the \( B^+_c \to D^0 K^+ \) decay. The value of \( R_{D^0 K} \) is at the high end of theoretical predictions [6–8] and an expectation based on the observed \( B^+_c \to J/\psi \pi^+ \) yield at LHCb [28]. From Refs. [5] and [11], \( R_{J/\psi \pi} = (7.0 \pm 0.3) \times 10^{-6} \) is obtained. As \( f_c/f_u \) is common to both \( R_{J/\psi \pi} \) and \( R_{D^0 K} \), the ratio of branching fractions is measured to be \( \mathcal{B}(B^+_c \to D^0 K^+) / \mathcal{B}(B^+_c \to J/\psi \pi^+) = 0.13 \pm 0.04 \pm 0.01 \pm 0.01 \), where the first uncertainty is statistical, the second is systematic, and the third comes from \( R_{J/\psi \pi} \).

The absence of the \( B^+_c \to D^0 \pi^+ \) mode shows that the \( B^+_c \to D^0 K^+ \) amplitude is not dominated by the tree-level \( b \to u \) transition shown in Fig. 1(a), but rather by the penguin 1(b) and/or weak annihilation 1(c) diagrams. This result constitutes the first observation of such amplitudes in the decay of a \( B^+_c \) meson.

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