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Study of B_c^+ decays to the $K^+K^-\pi^+$ final state and evidence for the decay $B_c^+ \to \chi_{c0}\pi^+$

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A study of $B_c^+ \to K^+K^-\pi^+$ decays is performed for the first time using data corresponding to an integrated luminosity of 3.0 fb^{-1} collected by the LHCb experiment in pp collisions at center-of-mass energies of 7 and 8 TeV. Evidence for the decay $B_c^+ \to \chi_{c0}(\to K^+K^-)\pi^+$ is reported with a significance of 4.0 standard deviations, giving $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to \chi_{c0}\pi^+) = (9.8^{+3.4}_{-3.0}(\mathrm{stat}) \pm 0.8(\mathrm{syst})) \times 10^{-6}$. Here $\mathcal{B}$ denotes a branching fraction while $\sigma(B_c^+)$ and $\sigma(B^+)$ are the production cross sections for B_c^+ and B^+ mesons. An indication of $\bar{b}c$ weak annihilation is found for the region $m(K^-\pi^+) < 1.834\ \mathrm{GeV}/c^2$, with a significance of 2.4 standard deviations.

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Heavy-flavor physics involves studying the decays of hadrons containing at least one b or c valence quark, and offers the possibility of making precision measurements of Standard Model (SM) parameters and detecting effects of new physics. The B_c^+ meson ($\bar{b}c$), the only currently established hadron having two different heavy-flavor quarks, has the particularity of decaying weakly through either of its flavors.[1] In the SM, the B_c^+ decays with no charm and beauty particles in the final or intermediate states can proceed only via $\bar{b}c \to W^+ \to u\bar{q}$ ($q = d,\ s$) annihilation, with an amplitude proportional to the product of Cabibbo-Kobayashi-Maskawa matrix elements $V_{cb}^* V_{uq}$. Calculations predict branching fractions in the range 10^{-8}–10^{-6} [1–3]. Any significant enhancement could indicate the presence of $\bar{b}c$ annihilations involving particles beyond the SM, such as a mediating charged Higgs boson (see, e.g., Ref. [4,5]).

Experimentally, the decays of B_c^+ mesons to three light charged hadrons provide a good way to study such processes. These decay modes have a large available phase space and can include other processes such as $B_c^+ \to D^0(\to K\pi)h^+$ ($h = \pi,\ K$) [6] mediated by $\bar{b} \to \bar{u}$ and $\bar{b} \to \bar{d},\ \bar{s}$ transitions, $B_c^+ \to B_q^0(\to h_1^+h_2^-)h_3^+$ decays [7] mediated by $c \to q$ transitions, or charmonium modes $B_c^+ \to [c\bar{c}](\to h_1^+h_1^-)h_2^+$ [8] mediated by the $b \to c$ transition [9]. In this study, special consideration is given to decays leading to a $K^+K^-\pi^+$ final state in the region well below the D^0 mass, taken to be $m(K^-\pi^+) < 1.834\ \mathrm{GeV}/c^2$, where, after removing possible contributions from $([c\bar{c}], B_s^0) \to K^+K^-$, only the annihilation process remains. The other contributions listed above are also examined. The decay $B^+ \to \bar{D}^0(\to K^+K^-)\pi^+$ is used as a normalization mode to derive

$$R_f \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to f), \tag{1}$$

where $\mathcal{B}$ is the branching fraction, and $\sigma(B_c^+)$ and $\sigma(B^+)$ are the production cross sections of the B_c^+ and B^+ mesons. The quantity R_f is measured in the fiducial region $p_{\mathrm{T}}(B) < 20\ \mathrm{GeV}/c$ and $2.0 < y(B) < 4.5$, where p_{T} is the component of the momentum transverse to the proton beam and y denotes the rapidity. The data sample used corresponds to integrated luminosities of 1.0 and 2.0 fb^{-1} collected by the LHCb experiment at 7 and 8 TeV center-of-mass energies in pp collisions, respectively. Since the kinematics of B meson production is very similar at the two energies, the ratio $\frac{\sigma(B_c^+)}{\sigma(B^+)}$ is assumed to be the same for all the measurements discussed in this paper.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [10,11]. The detector allows the reconstruction of both charged and neutral particles. For this analysis, the ring-imaging Cherenkov detectors [12], distinguishing pions, kaons and protons, are particularly important. Simulated events are produced using the software described in Refs. [13–19].

The $B_{(c)}^+ \to K^+K^-\pi^+$ decay candidates are reconstructed applying the same selection procedure as in Ref. [20]. A similar multivariate analysis is implemented, using a boosted decision tree (BDT) classifier [21]. Particle identification (PID) requirements are then applied to reduce the combinatorial background and suppress the cross feed from pions misidentified as kaons. The BDT and PID requirements are optimized to maximize the sensitivity to small event yields.

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[1] Charge conjugation is implied throughout the paper.

The B_c^+ signal yield is determined from a simultaneous fit in three bins of the BDT output $\mathcal{O}_{\rm BDT}$, $0.04 < \mathcal{O}_{\rm BDT} < 0.12$, $0.12 < \mathcal{O}_{\rm BDT} < 0.18$ and $\mathcal{O}_{\rm BDT} > 0.18$, each having similar expected yield but different levels of background [20]. The normalization channel $B^+ \to \bar{D}^0(\to K^+K^-)\pi^+$ uses the same BDT classifier, with tighter PID requirements to suppress the abundant background from $B^+ \to K^+\pi^-\pi^+$ decays. Its yield is determined requiring $\mathcal{O}_{\rm BDT} > 0.04$, and demanding $1.834 < m(K^+K^-) < 1.894\ {\rm GeV}/c^2$ to remove charmless $B^+ \to K^+K^-\pi^+$ candidates.

Signal and background yields are obtained from extended unbinned maximum likelihood fits to the distribution of the invariant mass of the $K^+K^-\pi^+$ combinations. The $B_c^+ \to K^+K^-\pi^+$ and $B^+ \to K^+K^-\pi^+$ signals are each modelled by the sum of two Crystal Ball functions [22] with a common mean. For $B_c^+ \to K^+K^-\pi^+$ all the shape parameters and the relative yields in each bin of $\mathcal{O}_{\rm BDT}$ are fixed to the values obtained in the simulation, while for $B^+ \to K^+K^-\pi^+$ the mean and the core width are allowed to vary freely in the fit. A Fermi-Dirac function is used to model a possible partially reconstructed component from decays with $K^+K^-\pi^+\pi^0$ final states where the neutral pion is not reconstructed, resulting in a $K^+K^-\pi^+$ invariant mass below the nominal B_c^+ or B^+ mass. All shape parameters of these background components are fixed to the values obtained from simulation. The combinatorial background is modeled by an exponential function. Figure 1 shows the result of the fit to determine the yield of the $B^+ \to \bar{D}^0(\to K^+K^-)\pi^+$ channel, $N_u = 8577 \pm 109$.

In the B_c^+ region $6.0 < m(K^+K^-\pi^+) < 6.5 {\rm GeV}/c^2$, the signals are fitted separately for regions of the phase space corresponding to the different expected contributions: the annihilation region ($m(K^-\pi^+) < 1.834\ {\rm GeV}/c^2$), the $D^0 \to K^-\pi^+$ region ($1.834 < m(K^-\pi^+) < 1.894 {\rm GeV}/c^2$) and the $B_s^0 \to K^-K^+$ region ($5.3 < m(K^+K^-) < 5.4\ {\rm GeV}/c^2$). For the first two regions, the ranges $3.38 < m(K^+K^-) < 3.46 {\rm GeV}/c^2$ and $5.2 < m(K^+K^-) < 5.5\ {\rm GeV}/c^2$ are vetoed to remove contributions from χ_{c0} (as discussed below) and $B_{(s)}^0 \to h_1^+h_2^-$ decays. A possible signal is seen in the annihilation region, as shown in Fig. 2. The corresponding yield is $N_c = 20.8^{+11.4}_{-9.9}$, with a statistical significance of 2.5 standard deviations (σ), inferred from the difference in the logarithm of the likelihood for fits with and without the signal component.

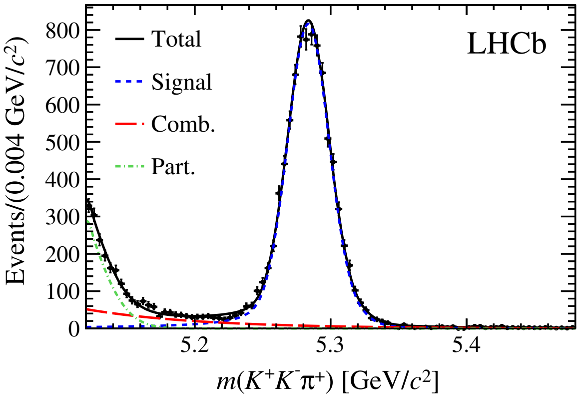

FIG. 1. Fit to the $K^+K^-\pi^+$ invariant mass for the B^+ candidates, with $1.834 < m(K^+K^-) < 1.894\ {\rm GeV}/c^2$. The contributions from the signal $B^+ \to \bar{D}^0(\to K^+K^-)\pi^+$, combinatorial background (Comb.) and partially reconstructed background (Part.) obtained from the fit are shown.

The distribution of events in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane, for the B_c^+ signal region $6.2 < m(K^+K^-\pi^+) < 6.35\ {\rm GeV}/c^2$, is shown in Fig. 3. A concentration of events is observed around $m^2(K^+K^-) \sim 11\ {\rm GeV}^2/c^4$. A one-dimensional projection of $m(K^+K^-)$ shows clustering near $3.41\ {\rm GeV}/c^2$, close to the mass of the charmonium state χ_{c0}. Among all the charmonia, χ_{c0} has the highest branching fraction into the K^+K^- final state [23]. The accumulation of events near

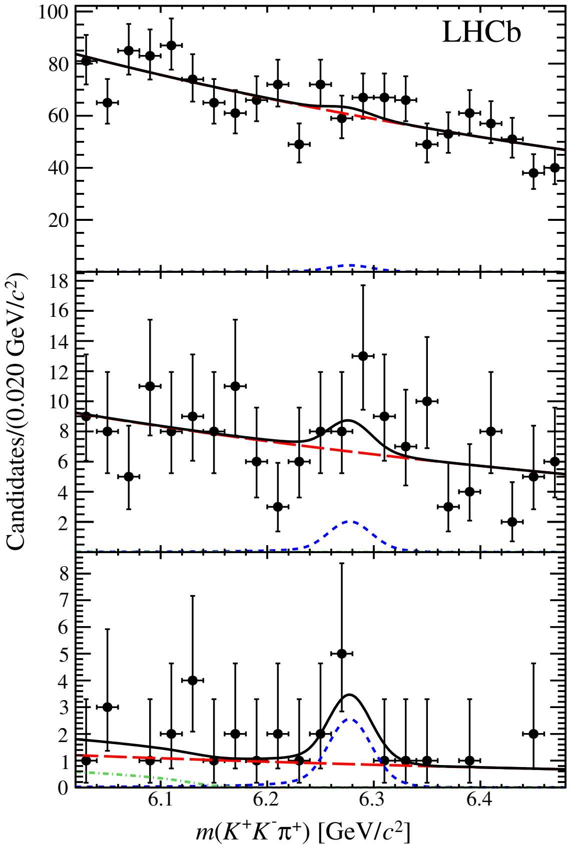

FIG. 2. Projection of the fit to the $K^+K^-\pi^+$ invariant mass in the B_c^+ region, in the bins of BDT output used in the analysis: (top) $0.04 < \mathcal{O}_{\rm BDT} < 0.12$, (middle) $0.12 < \mathcal{O}_{\rm BDT} < 0.18$ and (bottom) $\mathcal{O}_{\rm BDT} > 0.18$, for $m(K^-\pi^+) < 1.834\ {\rm GeV}/c^2$, including the vetoes in $m(K^+K^-)$ (see text). Apart from the signal type, which is given by $B_c^+ \to K^+K^-\pi^+$, the contributions are indicated according to the same scheme as in Fig. 1.

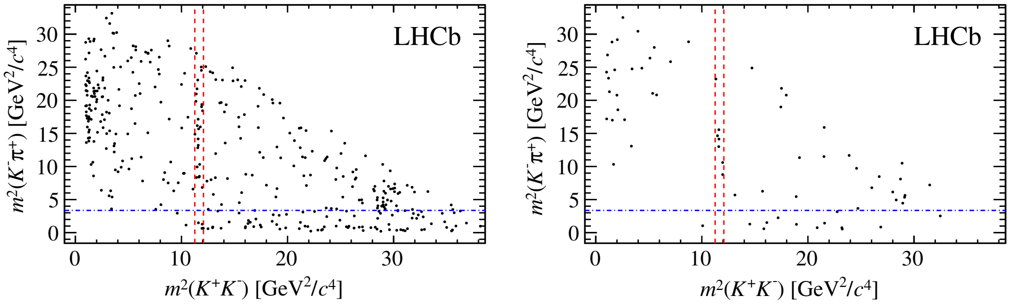

FIG. 3. Distribution of events for the signal region $6.2 < m(K^+K^-\pi^+) < 6.35\ \mathrm{GeV}/c^2$ in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane for (left) $\mathcal{O}_{\mathrm{BDT}} > 0.12$ and (right) $\mathcal{O}_{\mathrm{BDT}} > 0.18$. The vertical red dashed lines represent a band of width $\pm 60\ \mathrm{MeV}/c^2$ around the χ_{c0} mass. The horizontal blue dot-dashed line indicates the upper bound of the annihilation region at $m(K^-\pi^+) = 1.834\ \mathrm{GeV}/c^2$, representing 17% of the available phase space area.

$m^2(K^+K^-) \sim 29\ \mathrm{GeV}^2/c^4$ for the loose $\mathcal{O}_{\mathrm{BDT}}$ cut appears to be mainly caused by $B_s^0 \to K^+K^-$ decays combined with random pions since no peak is seen in $m(K^+K^-\pi^+)$ at the B_c^+ mass [9].

To determine the $B_c^+ \to \chi_{c0}(\to K^+K^-)\pi^+$ signal yield, the two-dimensional $m(K^+K^-\pi^+)$ vs $m(K^+K^-)$ distributions are fitted simultaneously for each of the three BDT bins. The $m(K^+K^-\pi^+)$ distribution is modeled in the same way as described above. The $m(K^+K^-)$ distribution is fitted in the range $3.20 < m(K^+K^-) < 3.55\ \mathrm{GeV}/c^2$. The $\chi_{c0} \to K^+K^-$ shape is modeled by a Breit-Wigner function, with mean and width fixed to their known values [23], convolved with a Gaussian resolution function, while a first-order polynomial is used to represent the K^+K^- background. Figure 4 shows the projections of the fit result. The yield obtained is $N_{\chi_{c0}} = 20.8^{+7.2}_{-6.4}$, with a

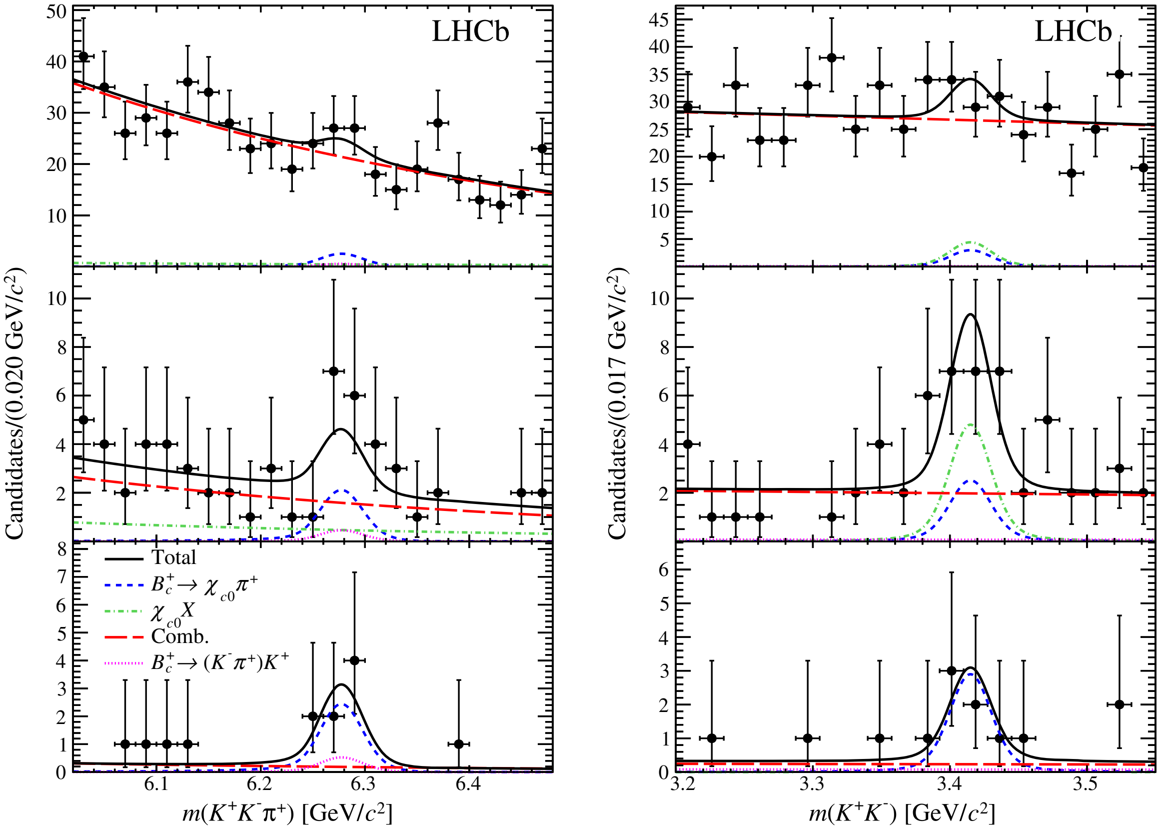

FIG. 4. Fit projections to the (left) $K^+K^-\pi^+$ and (right) K^+K^- invariant masses, in the bins of BDT output (top) $0.04 < \mathcal{O}_{\mathrm{BDT}} < 0.12$, (middle) $0.12 < \mathcal{O}_{\mathrm{BDT}} < 0.18$ and (bottom) $\mathcal{O}_{\mathrm{BDT}} > 0.18$, for the extraction of the $B_c^+ \to \chi_{c0}(\to K^+K^-)\pi^+$ signal. The contributions from the $B_c^+ \to \chi_{c0}(\to K^+K^-)\pi^+$ signal, combinatorial background (Comb.), possible pollution from the annihilation region $B_c^+ \to (K^-\pi^+)K^+$, and combinations of $\chi_{c0} \to K^+K^-$ with a random track X are shown.

statistical significance of 4.1σ. The fits for the D^0 and B_s^0 regions, where no signal is observed, can be found at Ref. [9].

For each region of phase space considered, the efficiencies for the signals, ϵ_c, and normalization channel, ϵ_u, are inferred from simulated samples and are corrected using data-driven methods as described in Ref. [20]. They include the effects of reconstruction, selection and detector acceptance. An efficiency map defined in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane is computed. Because of limited statistics, the distribution of the signal events in the annihilation region is not well known. Therefore, the efficiency for the annihilation region is estimated in two ways: first, by taking the simple average efficiency from the map for $m(K^-\pi^+) < 1.834\ \text{GeV}/c^2$ and, alternatively, by taking the efficiency weighted according to the sparse distribution of candidates in data in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane. The average of the two values is taken as the efficiency and the difference is treated as a systematic uncertainty (labeled as "event distribution" in Table I). A correction accounting for the vetoed $m(K^+K^-)$ regions described above is included. In the calculation of the observable R_f the efficiency ratio ϵ_u/ϵ_c is required. The values obtained are 1.698 ± 0.015 for the annihilation region and 1.241 ± 0.012 for the $B_c^+ \to \chi_{c0}(K^+K^-)\pi^+$ mode. The uncertainties are due to the limited sizes of the simulated samples. The differences between the B^+ and B_c^+ efficiencies are caused by the different lifetimes and masses of the two mesons.

The measured quantities are determined as

$$R_{\text{an},KK\pi} = \frac{N_c}{N_u} \times \frac{\epsilon_u}{\epsilon_c(\text{an}, KK\pi)} \times \mathcal{B}(B^\pm \to D^0\pi^\pm) \times \mathcal{B}(D^0 \to K^+K^-)$$

for the annihilation region and

$$R_{\chi_{c0}\pi} = \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to \chi_{c0}\pi^+) = \frac{N_{\chi_{c0}}}{N_u} \times \frac{\epsilon_u}{\epsilon_c(\chi_{c0})} \times \frac{\mathcal{B}(B^\pm \to D^0\pi^\pm) \times \mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(\chi_{c0} \to K^+K^-)}$$

for the $B_c^+ \to \chi_{c0}\pi^+$ decay, where ϵ_x are the efficiencies and N_x are the yields obtained from the fits.

Systematic uncertainties are associated with the yield ratios, the efficiency ratios and the branching fractions $\mathcal{B}(B^+ \to \bar{D}^0\pi^+) = (4.81 \pm 0.15) \times 10^{-3}$, $\mathcal{B}(D^0 \to K^-K^+) = (4.01 \pm 0.07) \times 10^{-3}$ and $\mathcal{B}(\chi_{c0} \to K^-K^+) = (5.91 \pm 0.32) \times 10^{-3}$ [23]. Table I summarizes the uncertainties. The yields are affected by the uncertainties on the fit functions and parameters, and by the variation of the yield fractions in the BDT output bins, due to the uncertainty on the BDT output distribution. The uncertainties on the efficiency ratios reflect the PID calibration, the limited sizes of the simulated samples, the effect of the detector acceptance, the B_c^+ lifetime 0.507 ± 0.009 ps [24], and the trigger and fiducial cut corrections.

The results obtained are $R_{\text{an},KK\pi} = (8.0^{+4.4}_{-3.8}(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-8}$ and $R_{\chi_{c0}\pi} = (9.8^{+3.4}_{-3.0}(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-6}$. Accounting for the systematic uncertainties related to the signal extraction, the significances of these measurements are 2.4σ and 4.0σ, respectively. For the annihilation region, a 90(95)% confidence level (C.L.) upper limit, $R_{\text{an},KK\pi} < 15(17) \times 10^{-8}$, is estimated by making a scan of $R_{\text{an},KK\pi}$, comparing profile likelihood ratios for the "signal + background" and "background-only" hypotheses [9,25].

For the modes $B_c^+ \to B_s^0(\to K^+K^-)\pi^+$ and $B_c^+ \to D^0(\to K^-\pi^+)K^+$, no significant deviation from the background-only hypothesis is observed. Using $\mathcal{B}(B_s^0 \to K^+K^-) = (2.50 \pm 0.17) \times 10^{-5}$ and $\mathcal{B}(D^0 \to K^-\pi^+) = (3.93 \pm 0.04)\%$ [23], the following 90(95)% C.L. upper limits are obtained: $R_{B_s^0\pi} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to B_s^0\pi^+) < 4.5(5.4) \times 10^{-3}$ and $R_{D^0K} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to D^0K^+) < 1.3(1.6) \times 10^{-6}$. The first limit is consistent with the result of Ref. [26], which gives $R_{B_s^0\pi} = (6.2 \pm 1.0) \times 10^{-4}$, using $\sigma(B_s^0)/\sigma(B^+) = 0.258 \pm 0.016$ [27,28].

In summary, a study of B_c^+ meson decays to the $K^+K^-\pi^+$ final state has been performed in the fiducial region $p_T(B) < 20\ \text{GeV}/c$ and $2.0 < y(B) < 4.5$. Evidence for the decay $B_c^+ \to \chi_{c0}\pi^+$ is found at 4.0σ significance. This result can be compared to the measurement involving another charmonium mode, $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to J/\psi\pi^+) = (7.0 \pm 0.3) \times 10^{-6}$, obtained from Refs. [23,29].

A indication of $\bar{b}c$ weak annihilation with a significance of 2.4σ is reported in the region $m(K^-\pi^+) < 1.834\ \text{GeV}/c^2$. The branching fraction of $B_c^+ \to \bar{K}^{*0}(892)K^+$ has been recently predicted to be $(10.0^{+1.8}_{-3.4}) \times 10^{-7}$ [3]. The contribution of the mode

TABLE I. Relative systematic uncertainties (in %) of the measurements of $R_{\text{an},KK\pi}$ and $R_{\chi_{c0}\pi}$.

Source	$R_{\text{an},KK\pi}$	$R_{\chi_{c0}\pi}$
Normalization yield	1.3	1.3
Event distribution	1.6	...
Fit model	2.4	2.3
BDT shape	5.0	2.9
PID	1.0	1.0
Simulation	0.8	0.8
Detector acceptance	0.4	0.3
B_c^+ lifetime	2.0	2.0
Hardware trigger	1.5	1.4
Fiducial cut	0.1	0.1
Branching fractions	3.6	6.2
Total	7.5	7.8

$B_c^+ \to \bar{K}^{*0}(892)(\to K^-\pi^+)K^+$ to $R_{\mathrm{an},KK\pi}$ could be prominent, for which an estimate is made as follows. Using the predictions listed in Ref. [30] for $\mathcal{B}(B_c^+ \to J/\psi\pi^+)$, which span the range $[0.34, 2.9] \times 10^{-3}$, and the value of $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)$ based on Ref. [29] quoted above, $\frac{\sigma(B_c^+)}{\sigma(B^+)} \sim [0.23, 2.1]\%$ is obtained. Combined with the prediction of Ref. [3], a value of $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to \bar{K}^{*0}(892)(\to K^-\pi^+)K^+) \sim [0.1, 1.7] \times 10^{-8}$ is obtained, including the theoretical uncertainties and the $\bar{K}^{*0}(892) \to K^-\pi^+$ branching fraction. This estimate is lower than the $R_{\mathrm{an},KK\pi}$ measurement. The statistical uncertainty, however, is at present too large to make a definite statement. The data being accumulated in the current run of the LHC will allow LHCb to clarify whether the weak annihilation process of B_c^+ meson decays involves significant contributions from heavier $K^-\pi^+$ states, or is enhanced by other sources.

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