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Search for the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$

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We report a search for the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$. Using a data sample of 471×10^6 $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II2 storage ring at SLAC, we find no events and set an upper limit on the branching fraction $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}) \times \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{0.050} < 2.8 \times 10^{-6}$ at 90% C.L., where we have normalized $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ to the world average value.

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B mesons have approximately 7% [1] baryons among their decay products. This is a substantial fraction justifying further investigations that may allow better understanding of baryon production in B decays and, more generally, quark fragmentation into baryons. The measurement of exclusive branching fractions of baryonic B decays as well as systematic studies of the dynamics of the decay, i.e., the fraction of resonant subchannels, is a direct way for studying the mechanisms of hadronization into baryons.

We report herein a search for the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ [2] using a dataset of about 424 fb^{-1} [3], corresponding to 471×10^6 $B\bar{B}$ pairs. This decay is closely related to $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$ and $B^- \to \Lambda_c^+ \bar{p}\pi^+\pi^-\pi^-$, which have a similar quark content and the (so far) largest measured branching fractions among the baryonic B decays with a Λ_c^+ in the final state. The CLEO Collaboration has measured the branching fraction $\mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^+\pi^-\pi^-) = (23 \pm 7) \times 10^{-4}$ [4]. *BABAR* reported a measurement of $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-) = (12.3 \pm 3.3) \times 10^{-4}$ as well as the branching ratios of resonant subchannels with $\Sigma_c(2455, 2520)^{0,++} \to \Lambda_c^+ \pi^{-,+}$ [5]. The main differences between the decay presented here and the other two decay

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channels are the absence of possible resonant subchannels and the much smaller phase space (PS), e.g.,

$$\frac{\int d\mathrm{PS}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})}{\int d\mathrm{PS}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)} \approx \frac{1}{1500}. \quad (1)$$

Given the fact that the decay products of $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ are limited to a small PS, a significant deviation from the phase space factor of $1/1500$ in the ratio of the branching fractions may occur if hadronization into $\Lambda_c^+ \bar{p}$ and/or $p\bar{p}$ is enhanced due to their generally low invariant masses. This phenomenon is known as threshold enhancement and describes the dynamically enhanced decay rate at the baryon-antibaryon-mass threshold. It has been observed in baryonic B decays with open charm final states [5–8], charmless baryonic B decays [9] and in the decay $J/\psi \to \gamma p \bar{p}$ [10]. An example where the decay with the smaller PS is preferred is the ratio of $\mathcal{B}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)/\mathcal{B}(B^- \to \Lambda_c^+ \bar{p} \pi^-) \approx 3$ [1] with $\int d\mathrm{PS}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)/\int d\mathrm{PS}(B^- \to \Lambda_c^+ \bar{p} \pi^-) \approx 1/70$. The influence of the weak interaction is expected to be similar here since $|V_{cs}| \approx |V_{ud}|$. General phenomenological approaches to describe the threshold enhancement consider, for example, gluonic and fragmentation mechanisms [11] and pole models [12]. In particular, an enhancement at the proton-antiproton mass threshold could be explained by the baryonium candidate $X(1835)$ [1,13,14]. Other theorists propose the possibility of S wave $p\bar{p}$ final state interaction with isospin $I = 1$ [15] and contributions from one-pion-exchange interactions in $N\bar{N}$ states with isospin $I = 1$ and spin $S = 0$ [16].

On the other hand, the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ may be suppressed by the absence of resonant subchannels, which may play an important role for baryonic B decays, e.g., the resonant part of $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ due to Σ_c baryons is $\approx$40% [5]. The size of the branching fraction may allow us to balance the relevance of resonant subchannels against PS in baryonic B decays.

This analysis is based on a data set that was collected with the *BABAR* detector at the PEP-II2 asymmetric-energy e^+e^- storage ring, which was operated at a center-of-mass (CM) energy equal to the $\Upsilon(4S)$ mass. We use EvtGen [17] and JETSET 7.4 74 [18] for simulation of *BABAR* events, and GEANT4 [19] for detector simulation. The sample of simulated decays $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ with $\Lambda_c^+ \to p K^- \pi^+$, both uniformly distributed in PS, is referred to as signal Monte Carlo (MC).

For the reconstruction of charged-particle tracks, the *BABAR* detector uses a tracking system that consists of a five-layer double-sided silicon vertex tracker surrounding the beam pipe followed by a 40-layer multiwire drift chamber with stereoangle configuration. A superconducting solenoid generates an approximately uniform magnetic field of 1.5 Tesla inside the tracking system which allows a precise measurement of the momentum of the tracks. The selection of proton, kaon and pion candidates is based on measurements of the energy loss in the silicon vertex tracker and the drift chamber, and measurements of the Cerenkov radiation in the detector of internally reflected Cerenkov light [20]. A detailed description of the *BABAR* detector can be found elsewhere [21,22].

We reconstruct Λ_c^+ in the subchannel $\Lambda_c^+ \to p K^- \pi^+$. For the reconstruction of the B candidate, we fit the entire $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ decay tree simultaneously, including geometric constraints to the $\bar{B}^0$ and Λ_c^+ decay vertices, and require the χ^2 fit probability to exceed 0.1%.

Averaging over the momentum and polar angle of the particles that we use for our reconstruction in the signal MC sample, the track finding efficiency is larger than 97% [23]. The identification efficiency for protons and pions is about 99% and for kaons about 95% while the probability of a pion, kaon or proton to be misidentified is below 2%. In particular, the probability for a pion or kaon to be misidentified as a proton is negligible. Thus, we expect a low combinatoric background level due to the fact that three genuine protons originating from a common B vertex, like for $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$, are rare in *BABAR* events.

To suppress background, we develop selection criteria for the $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ and $\Lambda_c^+ \to p K^- \pi^+$ candidates using correctly reconstructed decays in the signal MC sample.

For $p K^- \pi^+$ combinations from Λ_c^+ decays, we observe a narrow and a broad signal component in the $m_{pK\pi}$ invariant-mass distribution, in which the broad component results from badly reconstructed candidates. Thus, we fit the $m_{pK\pi}$ invariant-mass distribution to a sum of two Gaussian functions with a common mean value (Fig. 1). We extract a standard deviation (σ) of (3.74 ± 0.04) MeV/c^2 for the narrow component and (15.4 ± 0.4) MeV/c^2 for the broad component. The uncertainty is purely statistical. The fraction of the narrow part is approximately 80%. The mean value (μ) of

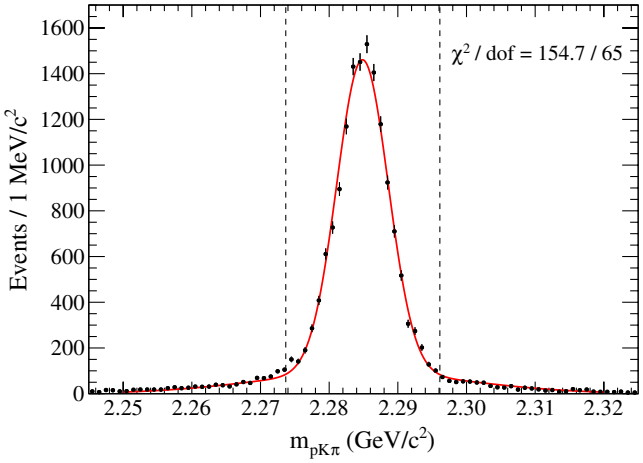

FIG. 1 (color online). Fitted $m_{pK\pi}$ distribution of correctly reconstructed B events in signal MC. The two dashed vertical lines enclose the $m_{pK\pi}$ signal region corresponding to $\pm 3\sigma$.

(2284.85 ± 0.04) MeV/c^2, that corresponds to our reconstructed mass, is in agreement with the generated Λ_c^+ mass used in the simulation. To improve the signal-to-background ratio, we use only the signal region around the Λ_c^+ defined by $\pm 3\sigma$ of the narrow Gaussian function. For this selection, we achieve an efficiency of 89%. We validate our method by reconstructing the Λ_c^+ decay inclusively in the *BABAR* data. For comparison we only select $pK\pi$ combinations whose momentum is inside the momentum range of Λ_c^+ from correctly reconstructed $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ decays in the signal MC sample. We find that the widths and fractions of the fitted distribution to $m_{pK\pi}$ from Λ_c^+ decays in the data sample and the signal MC sample are in agreement but the mean value is shifted by 0.5 MeV/c^2. Thus, the signal region in the $m_{pK\pi}$ distribution in data is shifted correspondingly.

The separation of signal from background in the B candidate sample is obtained using the invariant mass $m_{\rm B}$ and the energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_{\rm i} \cdot \mathbf{p}_{\rm B} \cdot c^2)^2/E_{\rm i}^2 - (|\mathbf{p}_{\rm B}| \cdot c)^2}/c^2$, where $\sqrt{s}$ is the CM energy of the e^+e^- pair. $(E_{\rm i}, \mathbf{p}_{\rm i})$ is the four-momentum vector of the e^+e^- CM system and $\mathbf{p}_B$ the B-candidate momentum vector, both measured in the laboratory frame. For correctly reconstructed B decays, $m_{\rm B}$ and $m_{\rm ES}$ are centered at the B meson mass. Figure 2(a) shows the $m_{\rm ES}$ vs $m_{\rm B}$ distribution for all reconstructed B candidates, including the selection criteria for $m_{pK\pi}$. Both $m_{\rm ES}$ and $m_{\rm B}$ peak at the nominal $\bar{B}^0$ meson mass and have a correlation coefficient of 2.6%.

We define a signal region for $\bar{B}^0$ decay candidates in the $m_{\rm ES}$-$m_{\rm B}$ plane that lies within a 3σ covariance ellipse around the nominal $\bar{B}^0$ mass [Fig. 2(a)]. Beside the correlation coefficient, the ellipse is defined by the mean value (μ) and the standard deviation (σ) of both variables, whose determination is described in the following section. The prefix "3σ" refers to the fact that the length of the two half-axes of the ellipse is three times the σ value of $m_{\rm ES}$ and $m_{\rm B}$, respectively.

We fit a single Gaussian function to the $m_{\rm ES}$ invariant-mass distribution yielding a mean of $\mu(m_{\rm ES}) = (5279.44 \pm 0.03)$ MeV/c^2 and a standard deviation of $\sigma(m_{\rm ES}) = (2.62 \pm 0.02)$ MeV/c^2. As in the $m_{pK\pi}$ case, the $m_{\rm B}$ invariant-mass distribution has both a narrow and broad component and we fit it to a sum of two Gaussian functions with a common mean. We obtain a mean of $\mu(m_{\rm B}) = (5279.34 \pm 0.05)$ MeV/c^2 consistent with the nominal $\bar{B}^0$ mass. The narrow component contains 80% of the signal and has a standard deviation of $\sigma(m_{\rm B}) = (5.26 \pm 0.07)$ MeV/c^2 while that of the broad component is $\sigma(m_{\rm B}) = (14.5 \pm 0.5)$ MeV/c^2. The uncertainties again are purely statistical. The selection in $m_{\rm ES}$ and $m_{\rm B}$, using the described signal region, has an efficiency of 82%.

To validate the viability of our selection in the $m_{\rm ES}$-$m_{\rm B}$ plane, we perform studies in the control channels $B \to \bar{D}^{(*)} D^{(*)} K$ [24] and $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ [5]. For both decay channels, we find that the distributions of $m_{\rm ES}$ vs $m_{\rm B}$ in the signal MC and in the data are in agreement, confirming that our MC is able to describe the data correctly.

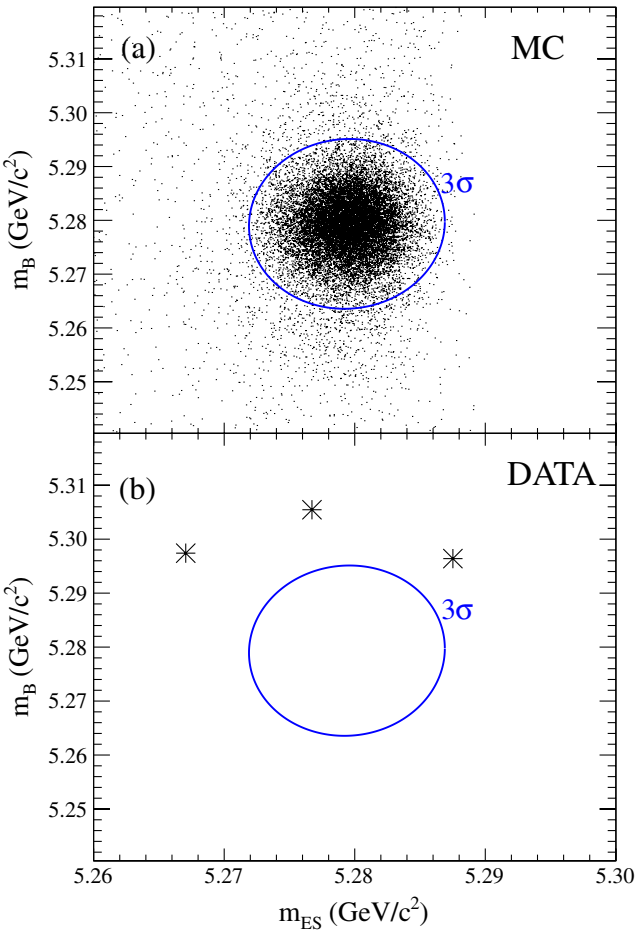

FIG. 2 (color online). The $m_{\rm ES}$ vs $m_{\rm B}$ distribution of selected events in (a) signal MC and (b) data. No signal candidates are observed within the signal region of the data sample.

Figure 2(b) shows the distribution of $m_{\rm ES}$ vs $m_{\rm B}$ for $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ candidates in the data sample. Only three events remain after the selection in the vicinity of the signal region, and we do not observe any events inside the signal region.

We determine the selection efficiency from the number of reconstructed events in the signal MC sample inside the signal region normalized to the total number of generated events; this yields an efficiency of $\varepsilon = (3.52 \pm 0.05)\%$. We estimate the systematic uncertainty on the efficiency by repeating the analysis in the $m_{\rm ES}$ vs ΔE plane, where $\Delta E = E_{\rm B}^* - \sqrt{s}/2$ is the deviation from the nominal energy of the B candidate in the e^+e^- CM system. As before, we define a 3σ signal region, where we find no B candidates in the data sample, and determine the selection efficiency in the signal MC sample. The absolute difference in efficiencies is 0.02%. In addition, we account for the statistical uncertainty in the efficiency of 0.03% resulting from the limited

size of the signal MC sample. Furthermore, we estimate the uncertainty in the efficiency from tracking to be 0.03%. Summing these values in quadrature, we determine a total uncertainty of 0.05%. Other systematic uncertainties that influence the measurement of the branching fraction are due to uncertainties on the number of B events and particle identification efficiency. We find these values to be negligible compared to the uncertainty of the reconstruction efficiency in the signal MC sample.

In Eq. (2), we define a modified branching fraction ($\mathcal{B}_{\rm mod}$),

$$\mathcal{B}_{\rm mod} = \mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}) \times \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{0.050}, \\ = \frac{N_{\rm observed}}{\varepsilon \cdot N_B \cdot 0.050}, \quad (2)$$

which is the usual product branching fraction normalized to the world average value of $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = (0.050 \pm 0.013)$ [1]. $N_{\rm observed}$ is the number of signal events and $N_B = 471 \times 10^6$ is the number of $\bar{B}^0$ mesons in the *BABAR* data set, assuming equal production of $B^0\bar{B}^0$ and B^+B^- by $\Upsilon(4S)$ decays. The definition is equivalent to $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})$ but independent of the large external uncertainty on the branching fraction for $\Lambda_c^+ \to p K^- \pi^+$.

In a Bayesian approach, we evaluate the probability density function (pdf) of $\mathcal{B}_{\rm mod}$ given by $N_{\rm observed}$ and ε by performing pseudoexperiments and determine an upper limit at 90% C.L. We vary the value of $N_{\rm observed}$ and ε according to the following distributions:

$$P(x = N_{\rm observed}) = \left[\frac{x^n}{n!} \cdot e^{-x}\right]_{n=0} = e^{-x}, \quad (3)$$

$$P(\varepsilon) = \frac{1}{\sqrt{2\pi}\sigma(\varepsilon)} \cdot \exp\left[-\frac{1}{2}\left(\frac{\varepsilon - \mu(\varepsilon)}{\sigma(\varepsilon)}\right)^2\right]. \quad (4)$$

Equation (3) is a Poisson distribution that describes the pdf for finding no signal events ($n = 0$) given by the true number of $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ decays (x). Equation (4) represents a Gaussian distribution that models the pdf of the reconstruction efficiency. We use the determined efficiency as the mean value (μ) and the uncertainty on the efficiency as the standard deviation (σ). Figure 3 shows the distribution of $\mathcal{B}_{\rm mod}$ for the given uncertainty of $\sigma(\varepsilon) = 0.05\%$ and for a 20 times higher uncertainty of $\sigma(\varepsilon) = 1.0\%$ to assess the impact of systematic uncertainties on this quantity. We determine branching fraction upper limits at the 90% confidence level of BF $< 2.8 \times 10^{-6}$ for $\sigma(\varepsilon) = 0.05\%$ and BF $< 3.1 \times 10^{-6}$ for $\sigma(\varepsilon) = 1.0\%$, respectively. The upper limit rises to 2.9×10^{-6} only at $\sigma(\varepsilon) = 0.55\%$. This demonstrates that our result is robust against systematic uncertainties.

To summarize, we have searched for the decay $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ using a sample corresponding to an integrated luminosity of 424 fb^{-1} in e^+e^- collisions at the $\Upsilon(4S)$ resonance, collected with the *BABAR* detector. We find no events and derive the upper limit on the branching fraction,

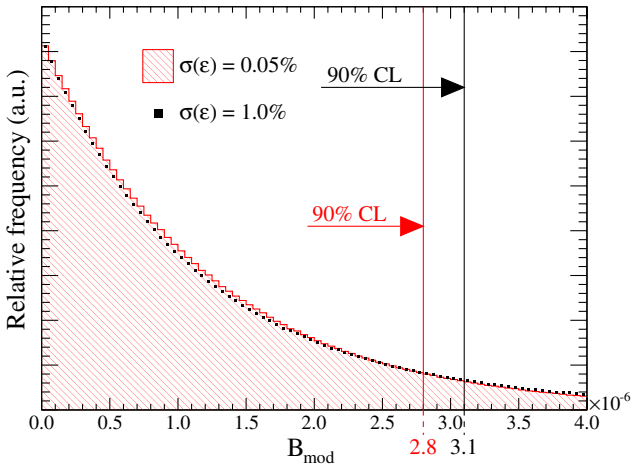

FIG. 3 (color online). The distribution of the modified branching fraction $\mathcal{B}_{\rm mod}$ from pseudoexperiments using the calculated uncertainty of the reconstruction efficiency $\sigma(\varepsilon) = 0.05\%$ (hatched) and a 20 times higher uncertainty $\sigma(\varepsilon) = 1.0\%$ (squares). The two vertical lines indicate the upper limit of the 90% C.L., respectively.

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}) \times \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{0.050} \\ < 2.8 \times 10^{-6} \text{ at } 90\% \text{ C.L.}, \quad (5)$$

where we normalize the product branching fraction to the world average value of $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = 0.050$. We interpret the upper limit on $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})$ in comparison to the nonresonant branching fraction of $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)$. We use the result $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)_{\text{non-}\Sigma_c} = (7.9 \pm 2.1) \times 10^{-4} = (0.64 \pm 0.17) \cdot \mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)$ published in [5]. In addition, we take into account contributions from additional intermediate states including $\bar{\Delta}^{--}$ and ρ resonances that are not accounted for in the analysis, but that are visible in the invariant mass spectra of $\bar{p}\pi^-$ and $\pi^+\pi^-$. In summary, we estimate that $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)_{\text{non-res}} \approx 0.5 \cdot \mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)$. Therefore, we calculate

$$\frac{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})}{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)_{\text{non-res}}} \lesssim \frac{1}{220}. \quad (6)$$

If we separate the dynamic and kinematic factors that contribute to the branching fraction according to $\mathcal{B} \sim \int |M|^2 \cdot d\text{PS} = \langle |M|^2 \rangle \times \int d\text{PS}$, where $\langle |M|^2 \rangle = \frac{\int |M|^2 d\text{PS}}{\int d\text{PS}}$ is the average quadratic matrix element of the decay, we can write

$$\frac{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})}{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-)_{\text{non-res}}} = r \times \frac{1}{1500}. \quad (7)$$

In Eq. (7) we applied $\frac{\int d\text{PS}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})}{\int d\text{PS}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-)} = \frac{1}{1500}$ and introduced an effective scaling factor r that quantifies the enhanced production rate of baryons due to dynamic effects. Using the result from Eq. (6), we obtain

$$r = \frac{\langle |M(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})|^2 \rangle}{\langle |M(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-)|^2 \rangle} \lesssim 6.8.$$

This is in tension with the quantities $\mathcal{B}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)/\mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^-) \approx 3$ and $\int d\text{PS}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)/\int d\text{PS}(B^- \to \Lambda_c^+ \bar{p}\pi^-) \approx \frac{1}{70}$, which leads to a factor of $r = 210$ without subtracting contributions from intermediate states in $B^- \to \Lambda_c^+ \bar{p}\pi^-$. Under the used assumptions, we conclude that a significantly enhanced decay rate of $\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$ w.r.t. $(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-)_{\text{non-res}}$ due to dynamic effects that are related to the threshold enhancement does not exist.

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