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Study of the $B^- \to J/\psi K^- \pi^+ \pi^-$ decay and measurement of the $B^- \to X(3872) K^-$ branching fraction

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We study the decay $B^- \to J/\psi K^- \pi^+ \pi^-$ using 117×10^6 $B\bar{B}$ events collected at the $Y(4S)$ resonance with the *BABAR* detector at the PEP-II e^+e^- asymmetric-energy storage ring. We measure the branching fractions $\mathcal{B}(B^- \to J/\psi K^- \pi^+ \pi^-) = (116 \pm 7(\text{stat.}) \pm 9(\text{syst.})) \times 10^{-5}$ and $\mathcal{B}(B^- \to X(3872)\text{K}^-) \times \mathcal{B}(X(3872) \to \text{J}/\psi \pi^+ \pi^-) = (1.28 \pm 0.41) \times 10^{-5}$ and find the mass of the $X(3872)$ to be 3873.4 ± 1.4 MeV/c^2. We search for the h_c narrow state in the decay $B^- \to h_c K^-$, $h_c \to J/\psi \pi^+ \pi^-$ and for the decay $B^- \to J/\psi D^0 \pi^-$, with $D^0 \to K^- \pi^+$. We set the 90% C.L. limits $\mathcal{B}(B^- \to h_c K^-) \times \mathcal{B}(h_c \to J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^- \to J/\psi D^0 \pi^-) < 5.2 \times 10^{-5}$.

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The study of B decays to final states containing charmonium and strange mesons is especially suited to the search for new charmonium states and for intrinsic charm. In particular, the decay $B^- \to J/\psi K^- \pi^+ \pi^-$ [1] can occur via the production of charmonium states decaying into $J/\psi \pi^+ \pi^-$ or possibly via $B^- \to J/\psi D^0 \pi^-$, with $\text{D}^0 \to \text{K}^- \pi^+$. Recently the Belle [2] and CDF [3] collaborations have observed a new state, the $X(3872)$, decaying into $J/\psi \pi^+ \pi^-$. This state is either a charmonium candidate or even possibly a molecule of charmed D and D^* mesons [4]. In this paper, using 117×10^6 $\Upsilon(4S)$ decays into $B\bar{B}$ pairs, we confirm the observation of the $X(3872)$ and search for the unconfirmed charmonium $^1P_1$ state $h_c(3526)$ [5]. In addition, we study the final state involving a D meson to test models developed to explain the excess of low momentum J/ψ mesons in inclusive B decays [6]. The presence of intrinsic charm in B mesons could explain this excess if $\mathcal{B}(B^- \to J/\psi D^0 \pi^-)$ exceeds 10^{-4} [7].

The data were collected at the PEP-II asymmetric-energy e^+e^- B-factory with the *BABAR* detector, which is fully described elsewhere [8]. The detector includes a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field, which detect charged particles and measure their momentum and energy loss. Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter. A ring-imaging Cherenkov detector is used for particle identification. Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel of the flux return. We use a Monte Carlo simulation of the *BABAR* detector based on GEANT4 [9] to validate the analysis procedure and to estimate efficiency corrections.

The event reconstruction and selection follow closely those described in an earlier paper [10]. The present analysis has been optimized to maximize the sensitivity to $B^- \to J/\psi K^- \pi^+ \pi^-$ decays. We reconstruct $J/\psi \to e^+e^-$ candidates from pairs of tracks selected with criteria that are 98% (7%) efficient for electrons (pions). To account for energy losses, we combine the electron pairs with bremsstrahlung-photon candidates and use an asymmetric mass window, $2.95 < m_{ee(\gamma)} < 3.14$ GeV$/c^2$. We reconstruct $J/\psi \to \mu^+\mu^-$ candidates from pairs of tracks selected with criteria that are 77% (8%) efficient for muons (pions), satisfying $3.06 < m_{\mu\mu} < 3.14$ GeV$/c^2$. The nominal J/ψ mass [11] is imposed as a constraint on J/ψ candidates, thereby improving the resolution on the B four-momentum and on any charmonium states in its decay. Kaons are identified using criteria that have an efficiency of 97%, with a 15% pion-misidentification rate. B-meson candidates are formed by combining a J/ψ candidate with a kaon candidate and two additional oppositely charged tracks. To suppress further the background from light-quark production, which is characterized by back-to-back jets, the angle θ_T between the thrust axes of the reconstructed B candidate and the rest of the event in the center-of-mass system is required to satisfy $|\cos\theta_T| < 0.8(0.9)$ for $J/\psi \to e^+e^-$ ($J/\psi \to \mu^+\mu^-$) candidates.

Signal and combinatorial background are discriminated using two kinematic variables: the beam-energy-substituted mass, $\text{m}_{\text{ES}} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$, and the difference of the B candidate's measured energy from the beam energy, $\Delta\text{E} \equiv E_B^* - (\sqrt{s}/2)$. Here E_B^* (p_B^*) is the energy (momentum) of the B candidate in the center-of-mass frame and $\sqrt{s}$ is the total center-of-mass energy. The signal region is defined to be $|\Delta\text{E}| < 3\sigma$, where the resolution σ, determined with data, is 12 MeV. A binned likelihood fit to the m_{ES} distribution [Fig. 1(a)] is used to separate the signal, taken as a Gaussian distribution with a fitted width of about 2.5 MeV$/c^2$, plus a small low-mass tail to account for energy losses [12], from the combinatorial background distributed as an ARGUS threshold function [13]. We have checked with Monte Carlo simulation that there is no significant background from B decays that has the same m_{ES} distribution as the signal.

To reduce systematic uncertainties, we measure

$$R = \frac{\mathcal{B}(B^- \to J/\psi \text{K}^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to \psi(2S) K^-)} = \frac{N_{\text{events}}}{N_{\psi(2S)}} \frac{\epsilon_{\psi(2S)}}{\epsilon} \mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-), \quad (1)$$

where $N_{\text{events}} = 2540 \pm 72$ is the number of $B^- \to J/\psi K^- \pi^+ \pi^-$ signal events extracted from the fit to the m_{ES} distribution. The number of $\psi(2S)$ events, $N_{\psi(2S)} = 556 \pm 30$, is obtained by fitting the $m_{J/\psi\pi\pi}$ distribution, after subtracting combinatorial background [14], with two Gaussian distributions representing the $\psi(2S)$ signal and a

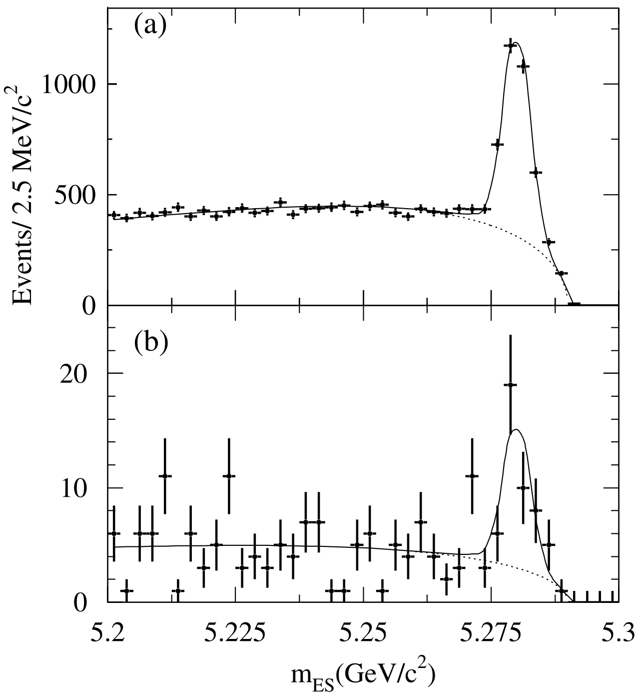

FIG. 1. Distribution of $m_{\rm ES}$ for (a) $B^- \to J/\psi K^- \pi^+ \pi^-$ candidates, and (b) events in the $X(3872)$ region, $3862 < m_{J/\psi\pi\pi} < 3882\ \mathrm{MeV}/c^2$. The solid curves represent the binned likelihood fits described in the text; the combinatorial components are indicated by the dashed curves.

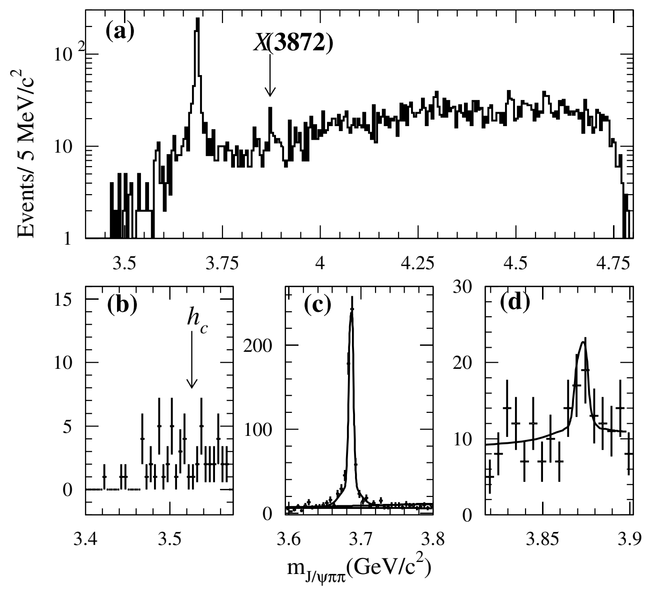

FIG. 2. Distribution of $m_{J/\psi\pi\pi}$ (a) in the entire range, (b) in the h_c region, (c) at the $\psi(2S)$, and (d) in the region of the $X(3872)$ with the projection of the unbinned likelihood fit superimposed. The requirement $m_{\rm ES} > 5.27\ \mathrm{GeV}/c^2$ is applied.

flat distribution representing the remaining background (Fig. 2(c) shows the corresponding unsubtracted distribution). This binned χ^2 fit gives a resolution on $m_{J/\psi\pi\pi}$of $3.1 \pm 0.2\ \mathrm{MeV}/c^2$ for the core Gaussian containing 70% of the events and $12 \pm 3\ \mathrm{MeV}/c^2$ for the broader Gaussian. The total $B^- \to J/\psi K^- \pi^+ \pi^-$ and the $B^- \to \psi(2S) K^-$ selection efficiencies, ϵ and $\epsilon_{\psi(2S)}$, are extracted from Monte Carlo simulation: we obtain $\epsilon_{\psi(2S)}/\epsilon = 1.17 \pm 0.03$. We use $\mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-) = (31.8 \pm 1.0)\%$ [11].

We estimate the systematic error due to the choice of the signal $m_{\rm ES}$ shape function by replacing it with a simple Gaussian. We estimate the uncertainty on the fit to the $m_{J/\psi\pi\pi}$ distribution by using the signal resolution function as measured on Monte Carlo and by varying the background shape. Including all these errors, we measure $R = 1.70 \pm 0.10(\text{stat.}) \pm 0.09(\text{syst.})$ which, combined with $\mathcal{B}(B^- \to \psi(2S) K^-) = (6.8 \pm 0.4) \times 10^{-4}$ [11], yields

$$\mathcal{B}(B^- \to \mathrm{J}/\psi K^- \pi^+ \pi^-) = (116 \pm 7(\text{stat.}) \pm 9(\text{syst.})) \times 10^{-5}. \quad (2)$$

Note that this measurement includes $\mathcal{B}(B^- \to \psi(2\mathrm{S})\mathrm{K}^-)$.

To investigate the possible presence of narrow charmonium states decaying to $J/\psi \pi^- \pi^+$, we have studied the distribution in $m_{J/\psi\pi\pi}$ [Fig. 2(a)]. We observe an excess in the region of the $X(3872)$ [Fig. 2(d)], but do not find any excess in the h_c region [Fig. 2(b)]. The mass of the $X(3872)$ state is extracted from an unbinned maximum likelihood fit to the two-dimensional distribution in $m_{\rm ES}$ and $m_{J/\psi\pi\pi}$. The probability density function (PDF) is taken to be the sum of four terms. The first three describe $B^- \to J/\psi K^- \pi^+ \pi^-$ decays that peak in $m_{\rm ES}$ at the B-meson mass. The PDF of these three terms contains a Gaussian function in $m_{\rm ES}$ times a function of $m_{J/\psi\pi\pi}$ that describes: (i) $\psi(2S)$ candidates, distributed as a double-Gaussian resolution function around a mean value that is allowed to float; and (ii) $X(3872)$ candidates, with the same resolution function as the $\psi(2S)$ but with a mass that floats relative to the $\psi(2S)$ mass; (iii) nonresonant events, distributed as a first order polynomial. This represents an improvement with respect to the Belle branching fraction measurement [2] which omitted the latter component. The fourth term of the PDF describes the combinatorial background, distributed as an ARGUS threshold function in $m_{\rm ES}$ and as a first order polynomial in $m_{J/\psi\pi\pi}$. From the $\psi(2S)$ mass value, $m_{\psi(2S)} = 3685.96 \pm 0.09\ \mathrm{MeV}/c^2$ [11], we find $m_{X(3872)} = 3873.4 \pm 1.4\ \mathrm{MeV}/c^2$, consistent with the previous measurements by Belle [2] and CDF [3]. Since we are actually measuring a mass difference we neglect systematic errors on the absolute mass scale.

The measurement of the branching fraction $\mathcal{B}(B^- \to X(3872) K^-) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)$ is performed with a counting technique. We select events in a $\pm 10\ \mathrm{MeV}/c^2$ window around $m_{J/\psi\pi\pi} = 3872\ \mathrm{MeV}/c^2$, and find the number of events with $m_{\rm ES} > 5.27\ \mathrm{GeV}/c^2$ to be $N_{\rm data} = 63$. We estimate the number of these events due to combinatorial background ($N_{\rm comb} = 22.0 \pm 4.3$) from a fit to the $m_{\rm ES}$ distribution [Fig. 1(b)]. The number of events with the same final state $B^- \to J/\psi K^- \pi^+ \pi^-$, but not belonging to the $X(3872)$ signal, is estimated to be $N_{\rm peak} = 10.5 \pm 3.2$ from a fit to the $m_{\rm ES}$ distribution in the symmetric sideband $15 < |m_{J/\psi\pi\pi} - 3872| < 45\ {\rm MeV}/c^2$. The resulting number of signal events is 30.5 which agrees within the errors with the number of signal events, 25.4 ± 8.7, obtained from the fit to the $X(3872)$ in Fig. 2(d). The branching fractions are determined using a frequentist confidence level [15]. This technique treats properly the small number of events and includes the systematic errors directly in the computation of confidence intervals or limits. The confidence level, α, a function of $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ is computed as the fraction of times that a random number generated according to a Poisson distribution with a mean value of

$$\mu = N_{bkg} + N_{\psi(2S)}\epsilon_w \frac{\mathcal{B}(B^- \to X(3872)K^-)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B^- \to \psi(2S)K^-)\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} \quad (3)$$

exceeds the observed data. For a given value of $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ the variables N_{bkg}, $N_{\psi(2S)}$, $\mathcal{B}(B^- \to \psi(2S)K^-)$, and $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$ are randomly generated to determine a value of μ, which is then used in a Poisson distribution to generate a new value of the number of detected events. The generation is repeated many times and the fraction of times the random number exceeds $N_{\rm data} = 63$ yields the value of α. The variables N_{bkg}, $N_{\psi(2S)}$, $\mathcal{B}(B^- \to \psi(2S)K^-)$, and $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$, are generated according to Gaussian distributions. The mean of $N_{\psi(2S)}$ is 556 and $\sigma = 30$. The mean of N_{bkg} is $N_{\rm comb} + N_{\rm peak} = 32.5$ and $\sigma = 5.9$, which includes a systematic error on $N_{\rm peak}$ calculated by varying the boundaries of the sideband. We use published values [11] for the remaining branching fractions and their errors, assumed to be Gaussian. Finally, $\epsilon_w = (92 \pm 1)\%$ is the fraction of events that fall in the $m_{J/\psi\pi\pi}$ window, from applying the same mass window cut to the $\psi(2S)$ and assuming the same efficiency. From the values of $\mathcal{B}(B^- \to X(3872)K^-)$ at which $\alpha = 16\%$ and 84% we measure

$$\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.28 \pm 0.41) \times 10^{-5}. \quad (4)$$

The probability that the observed events are a background fluctuation in the considered mass window is 5.4×10^{-4}, corresponding to 3.5 Gaussian standard deviations. As a check, we performed the same measurement on the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ samples separately, obtaining $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.94 \pm 0.62) \times 10^{-5}$ and $(0.52 \pm 0.46) \times 10^{-5}$ respectively, consistent within 1.8 standard deviations.

The decay of a charmonium state into $\rho J/\psi$ is a strongly suppressed isospin-violating process. In order to investigate the nature of the $X(3872)$ state, we plot the invariant mass of the $\pi^+\pi^-$ system in both the $X(3872)$ and the $\psi(2S)$ region (Fig. 3). In the $\psi(2S)$ case, the events are concentrated near the kinematic limit. Such behavior is not excluded for the $X(3872)$, but the statistics are too small to allow a clear conclusion. Measuring both the $m\pi^+\pi^-$ and angular distributions with significantly greater statistics would provide important information on the nature of the $X(3872)$.

The search for the h_c is performed with the same frequentist technique in a $\pm 10\ {\rm MeV}/c^2$ mass window centered on $m_{J/\psi\pi\pi} = 3526\ {\rm MeV}/c^2$ [5]. With $N_{\rm data} = 9$, $N_{\rm comb} = 6.9 \pm 3.5$, $N_{\rm peak} = 0.6 \pm 1.5$, and assuming the same efficiency $\epsilon_w = (92 \pm 1)\%$, we set a 90% C.L. limit $\mathcal{B}(B^- \to {\rm h_c}K^-) \times \mathcal{B}({\rm h_c} \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$. The probability that we would see a signal as large as the one observed from background fluctuations alone is 39%.

Finally, we search for $B^- \to J/\psi D^0 \pi^-$ decays with $D^0 \to K^-\pi^+$. The decay $D^0 \to K^-\pi^+$ would have an r.m.s. width of $5.4\ {\rm MeV}/c^2$ in $m_{K^-\pi^+}$ as determined from Monte Carlo. We study this distribution in the same way we studied $m_{J/\psi\pi\pi}$. The $m_{K^-\pi^+}$ combinatorial-subtracted distribution (Fig. 4) shows no significant structure, and it is therefore used to set a limit. We fit the

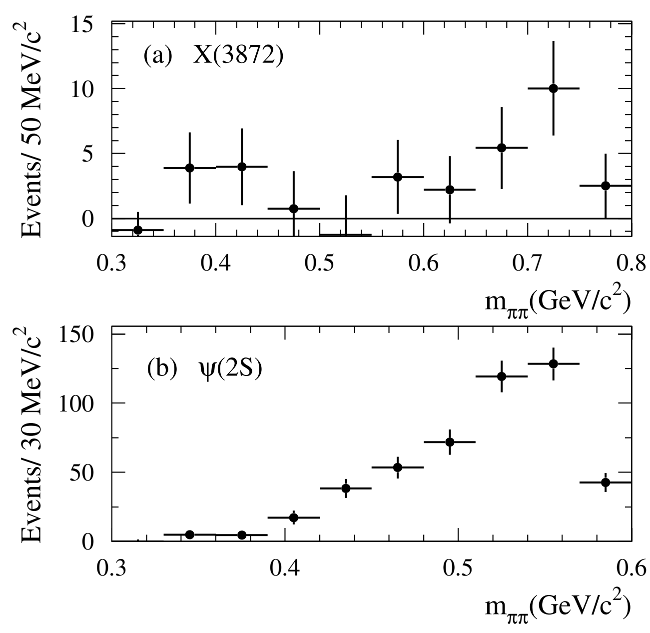

FIG. 3. Distribution of $m_{\pi^+\pi^-}$ (a) at the $X(3872)$ and (b) at the $\psi(2S)$, after subtraction of combinatorial and peaking background.

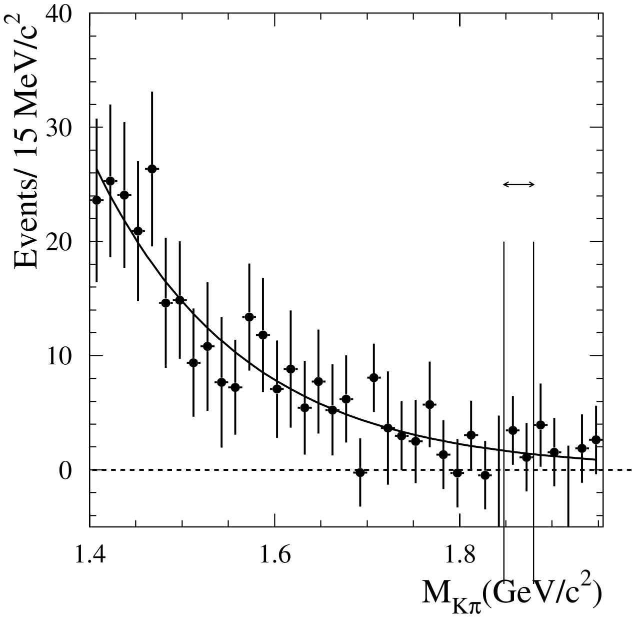

FIG. 4. Distribution of $mK^-\pi^+$ in events $B^- \to J/\psi K^- \pi^+ \pi^-$, with combinatorial background removed. Overlaid is an exponential fit. The arrow indicates the 3σ region expected for $D^0 \to K^- \pi^+$.

background from other $B^- \to J/\psi K^- \pi^+ \pi^-$ decays with an exponential function of $m_{K^-\pi^+}$ and obtain $N_{\rm peak} = 2.9 \pm 1.4$. The frequentist approach described above, with $N_{\rm data} = 10$, $N_{\rm comb} = 7.8 \pm 2.8$ and $\epsilon/\epsilon_{\psi(2S)} = 1.00 \pm 0.07$ yields the 90% C.L. limit $\mathcal{B}(B^- \to J/\psi D^0 \pi^-) < 5.2 \times 10^{-5}$.

In summary, we measured $\mathcal{B}(B^- \to J/\psi K^- \pi^+ \pi^-) = (116 \pm 7(\text{stat.}) \pm 9(\text{syst.})) \times 10^{-5}$ with an error almost a factor two smaller than the present average [11] and we confirmed the observation of $B^- \to X(3872)K^-$ [2,3]. We performed an accurate measurement of the branching fraction $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) = (1.28 \pm 0.41) \times 10^{-5}$ and of the mass $m_{X(3872)} = 3873.4 \pm 1.4$ MeV/c^2. We also studied the $m_{J/\psi\pi\pi}$ distributions searching for $B^- \to h_c K^-$ decays and set limits on their branching fractions, $\mathcal{B}(B^- \to h_c K^-) \times \mathcal{B}(h_c \to J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$ at 90% C.L. Finally, from the $m_{K^-\pi^+}$ distribution we find $\mathcal{B}(B^- \to J/\psi D^0 \pi^-) < 5.2 \times 10^{-5}$ at 90% C.L., thus ruling out the explanation of the inclusive J/ψ momentum spectrum with intrinsic charm proposed in [7].

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