

## Search for a Charged Partner of the $X(3872)$ in the $B$ Meson Decay $B \rightarrow X^- K$ , $X^- \rightarrow J/\psi \pi^- \pi^0$

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We search for a charged partner of the  $X(3872)$  in the decay  $B \rightarrow X^- K$ ,  $X^- \rightarrow J/\psi \pi^- \pi^0$ , using 234 million  $B\bar{B}$  events collected at the  $\Upsilon(4S)$  resonance with the BABAR detector at the PEP-II  $e^+e^-$  asymmetric-energy storage ring. The resulting product branching fraction upper limits are  $\mathcal{B}(B^0 \rightarrow X^- K^+, X^- \rightarrow J/\psi \pi^- \pi^0) < 5.4 \times 10^{-6}$  and  $\mathcal{B}(B^- \rightarrow X^- \bar{K}^0, X^- \rightarrow J/\psi \pi^- \pi^0) < 22 \times 10^{-6}$  at the 90% confidence level.

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The discovery of the  $X(3872)$  by the Belle Collaboration [1], has been confirmed by the CDF [2], D0 [3] and BABAR [4] Collaborations. Numerous theoretical explanations have been proposed for this high-mass, narrow-width state decaying into  $J/\psi \pi^+ \pi^-$ . The possibilities [5] include a bound state of  $D^* \bar{D}$  very close the  $D^{*0} \bar{D}^0$  threshold [6], a hybrid charmonium state [7], a diquark-antidiquark state [8], and a conventional charmonium state [9]. The Cornell potential model [10] predicts a  ${}^3D_2$  ( $J^{PC} = 2^{--}$ ) charmonium state with a 3.830 GeV/ $c^2$  mass. This state is expected to be very narrow since the decay to  $D\bar{D}$  is forbidden by parity and could decay into an isoscalar  $J/\psi \pi^+ \pi^-$  final state.

The charmonium state, however, should also have a significant branching ratio for the radiative decay to  $\gamma \chi_{c1}$  [10], which was not observed for the  $X(3872)$  by Belle [1]. A more detailed examination of the  $X(3872)$  observed by Belle [1] and BABAR [4] indicates that the  $\pi^+ \pi^-$  mass distributions peak near the kinematic upper limit and are consistent with the decay  $\rho^0 \rightarrow \pi^+ \pi^-$ . However, due to limited statistics a spin-parity analysis has not been performed. If the observed decay is  $X(3872) \rightarrow J/\psi \rho^0$  and if these states and their decays respect isospin symmetry, then there must be a  $X(3872)^-$ , which decays to  $J/\psi \rho^-$ , and the rate for  $B \rightarrow X^- K$  should be twice that for  $B \rightarrow X^0 K$ . This would make experimental detection of the  $X^-$  quite favorable. To test this hypothesis, we have performed a search for the  $B$ -meson decays,  $B^0 \rightarrow X^- K^+$  and  $B^- \rightarrow X^- K_s^0$ , where  $X^- \rightarrow J/\psi \pi^- \pi^0$  [11].

Data were collected at the PEP-II asymmetric-energy  $e^+e^-$  storage ring with the BABAR detector, which is described in detail elsewhere [12]. The data used in this analysis correspond to a total integrated luminosity of 212 fb $^{-1}$  taken on the  $\Upsilon(4S)$  resonance, producing a sample of  $234.4 \pm 2.6$  million  $B\bar{B}$  events ( $N_{B\bar{B}}$ ). The BABAR detector uses a silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), both in a 1.5-T solenoidal magnetic field to detect charged particles and measure their momenta and energy loss ( $dE/dx$ ). Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter (EMC). An internally reflecting ring-imaging Cherenkov detector (DIRC)

provides particle identification information that is complementary to that from  $dE/dx$ . Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel flux return (IFR). Track-selection criteria in this analysis follow previous BABAR analyses [13].

This analysis commences with charged and neutral candidate selections. Each charged-track candidate is required to be detected in at least 12 DCH layers and to have a transverse momentum greater than 100 MeV/ $c$ . If it is not associated with a  $K_s^0$  decay, the candidate must extrapolate to a point near the collision axis.

A charged kaon or pion candidate is selected on the basis of  $dE/dx$  information from the SVT and DCH, and the Cherenkov angle measured by the DIRC. An electron candidate is required to have a good match between the expected and measured  $dE/dx$  in the DCH, and the Cherenkov angle in the DIRC. The ratio of the shower energy measured in the EMC to the momentum measured in the DCH, and the number of EMC crystals associated with the track candidate must be appropriate for an electron. A muon is selected on the basis of energy deposited in the EMC, the number and distribution of hits in the IFR, and the match between the IFR hits and the extrapolation of the DCH track into the IFR. A more detailed explanation of particle identification (PID) is given elsewhere [13, 14].

A photon candidate is identified from energy deposited in contiguous EMC crystals, summed to form a cluster that has total energy greater than 30 MeV and a shower shape consistent with that expected for an electromagnetic shower.

The decay modes we use to identify  $B^0 \rightarrow J/\psi \pi^- \pi^0 K^+$  and  $B^- \rightarrow J/\psi \pi^- \pi^0 K_s^0$  are  $J/\psi \rightarrow e^+e^-$ ,  $J/\psi \rightarrow \mu^+ \mu^-$ ,  $\pi^0 \rightarrow \gamma\gamma$ , and  $K_s^0 \rightarrow \pi^+ \pi^-$ . They are selected to be within the mass intervals  $2.95 < m(e^+e^-) < 3.14$  GeV/ $c^2$ ,  $3.06 < m(\mu^+ \mu^-) < 3.14$  GeV/ $c^2$ ,  $0.119 < m(\gamma\gamma) < 0.151$  GeV/ $c^2$ , and  $0.4917 < m(\pi^+ \pi^-) < 0.5037$  GeV/ $c^2$ . We take a larger mass interval for  $e^+e^-$  than for  $\mu^+ \mu^-$  to accept events in which part of the energy is carried away by bremsstrahlung photons. The orientation of the displacement vector between the  $K_s^0$  decay vertex and the  $J/\psi$  vertex in the lab frame is required to be consistent with the  $K_s^0$  momentum direction.

The search for  $B$  signal events utilizes two kinematic variables: the energy difference  $\Delta E$  between the energy of the  $B$  candidate and the beam energy  $E_b^*$  in the  $\Upsilon(4S)$  rest frame, and the beam-energy-substituted mass  $m_{ES} \equiv \sqrt{(E_b^*)^2 - (p_B^*)^2}$ , where  $p_B^*$  is the reconstructed momentum of the  $B$  candidate in the  $\Upsilon(4S)$  frame. Signal events should have  $m_{ES} \approx m_B$ , where  $m_B$  is the mass of the  $B$ -meson [15], and  $|\Delta E| \approx 0$ .

Before the data were analyzed, the selection criteria were optimized and fixed separately for the charged and neutral  $B$  mode using a Monte Carlo (MC) simulation of signal and known backgrounds. The number of reconstructed MC signal events  $n_s^{mc}$  and the number of reconstructed MC background events  $n_b^{mc}$  (scaled to the integrated luminosity) were used to estimate the sensitivity ratio  $n_s^{mc}/(a/2 + \sqrt{n_b^{mc}})$  [16], where  $a$ , the number of standard deviations of significance desired, was set to 3. Note that the maximum of this ratio is independent of the unknown signal branching fraction. This ratio was maximized by varying the selection criteria on  $\Delta E$ ,  $m_{ES}$ , the  $X^-(J/\psi\pi^-\pi^0)$  mass, the  $K_S^0(\pi^+\pi^-)$  mass, the  $K_S^0$  decay-length significance, the  $\gamma\gamma$  invariant mass, and the particle-identification criteria for electrons, muons and charged kaons. When there was more than one candidate per event after applying the optimized cuts (on average there were 1.3 candidates/event), the candidate with the smallest value of  $|\Delta E|$  was chosen. The selections  $|m_{ES} - m_B| < 5$  MeV/ $c^2$  and  $|\Delta E| < 20$  MeV (signal-box region) were found to be optimal for selecting signal events. The plots that follow include only one candidate per event, except for the plots showing  $\Delta E$  itself.

The  $\Delta E$  and  $m_{ES}$  distributions for the neutral and charged  $B$  modes after we apply all the optimized cuts, except the cut for the variable plotted, are shown in Figs. 1 (a-d). A clear peak is observed at zero in the  $\Delta E$  distribution and near 5.279 GeV/ $c^2$  in the  $m_{ES}$  distribution. The other feature in the  $\Delta E$  plots is a wide peak near 0.2 GeV which is due to  $B \rightarrow J/\psi K^*$  decays combined with a random pion.

The Dalitz plots in Fig. 2 for the charged- and neutral- $B$  modes use events in the signal-box region and include a mass cut of  $0.67 < m(\pi^-\pi^0) < 0.78$  GeV/ $c^2$  to select the  $\rho^-$  mass region. There are clear bands for  $K_1^0(1270) \rightarrow K^+\rho^-$  and  $K_1^-(1270) \rightarrow K_S^0\rho^-$  corresponding to the decays  $B^- \rightarrow J/\psi K_1^-$  and  $B^0 \rightarrow J/\psi K_1^0$  previously observed by Belle [17].

The  $J/\psi\pi^-\pi^0$  mass spectra from the neutral and charged  $B$  modes are shown in Fig. 3 without a  $\rho$  mass cut. No charged signal,  $X^- \rightarrow J/\psi\pi^-\pi^0$ , is evident at 3.872 GeV/ $c^2$ .

Extracting an upper limit for  $X^- \rightarrow J/\psi\pi^-\pi^0$  requires examining the  $J/\psi\pi^-\pi^0$  mass,  $m_{ES}$ , and  $\Delta E$  distributions. A signal from  $B \rightarrow X^-K$ ,  $X^- \rightarrow J/\psi\pi^-\pi^0$  should produce signal peaks in all three distributions. Background from  $B \rightarrow J/\psi\pi^-\pi^0K$  in which the  $J/\psi\pi^-\pi^0$  is

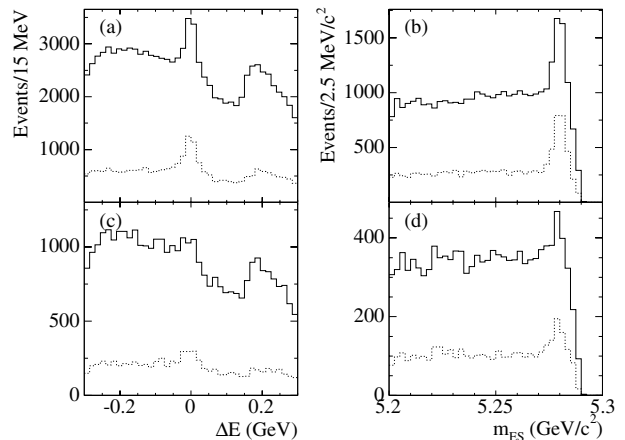


FIG. 1: The  $\Delta E$  (a) and  $m_{ES}$  (b) distributions for the  $B^0 \rightarrow J/\psi\pi^-\pi^0K^+$  mode and the  $\Delta E$  (c) and  $m_{ES}$  (d) distributions for the  $B^- \rightarrow J/\psi\pi^-\pi^0K_S^0$  mode using the optimized cuts. The dotted line shows the same with the additional cut  $0.67 < m(\pi^-\pi^0) < 0.87$  GeV/ $c^2$ .

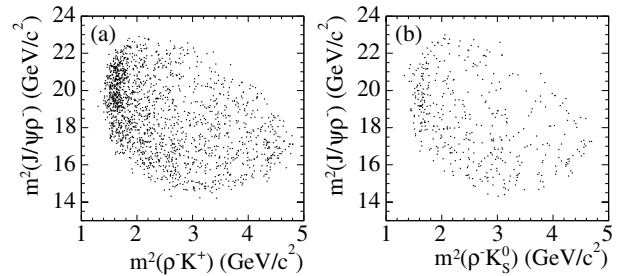


FIG. 2: The  $m^2(J/\psi\rho^-)$  versus the  $m^2(\rho^-K^+)$  distributions (a) for  $B^0 \rightarrow J/\psi\pi^-\pi^0K^+$  and the  $m^2(J/\psi\rho^-)$  versus the  $m^2(\rho^-K_S^0)$  distributions (b) for  $B^- \rightarrow J/\psi\pi^-\pi^0K_S^0$ . A  $B \rightarrow J/\psi K_1$  signal can be seen, however there is no indication for an enhancement in the  $J/\psi\rho^-$  mass spectrum.

nonresonant would produce peaks in the  $m_{ES}$  and  $\Delta E$  distributions but have a flat  $J/\psi\pi^-\pi^0$  mass distribution near 3.872 GeV/ $c^2$ . The combinatoric background will not create peaks in any of the three distributions and should produce an  $m_{ES}$  distribution whose shape can be parametrized by an ARGUS function [18]. To estimate the number of signal events ( $n_s$ ), we count the number of observed events ( $n_{obs}$ ) in the signal region and subtract the estimated number of combinatoric background events ( $n_{comb}$ ) and the estimated number of peaking background events ( $n_{peak}$ ).

We obtain  $n_{obs}$  by counting the number of events satisfying  $|m_{ES} - m_B| < 5$  MeV/ $c^2$ ,  $|\Delta E| < 20$  MeV, and  $|m(J/\psi\pi^-\pi^0) - 3872| < 12$  MeV/ $c^2$ . We extract  $n_{comb}$  from the  $m_{ES}$  distribution obtained after requiring  $|\Delta E| < 20$  MeV, and  $|m(J/\psi\pi^-\pi^0) - 3872| < 12$  MeV/ $c^2$ . These  $m_{ES}$  distributions for the neutral and charged  $B$  modes are separately fit with the sum of a

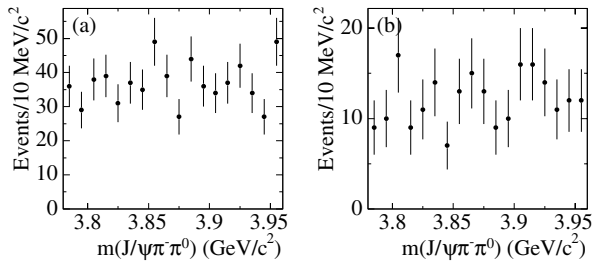


FIG. 3: The  $J/\psi \pi^- \pi^0$  invariant mass in 10  $\text{MeV}/c^2$  bins for (a)  $B^0 \rightarrow J/\psi \pi^- \pi^0 K^+$  and (b) for  $B^- \rightarrow J/\psi \pi^- \pi^0 K_s^0$ . No indication for the decay  $X^- \rightarrow J/\psi \pi^- \pi^0$  can be found.

signal Gaussian function and an ARGUS function. The resulting ARGUS function is integrated over the  $m_{\text{ES}}$  range,  $|m_{\text{ES}} - m_B| < 5 \text{ MeV}/c^2$ , to produce  $n_{\text{comb}}$ . The error  $\sigma_{\text{comb}}$  is obtained from the fit error on the normalization of the ARGUS function. The resulting values for  $n_{\text{comb}}$  and  $\sigma_{\text{comb}}$  are listed in Table 1.

TABLE I: Efficiencies, number of signal-box events, and estimated number of background events  $n_b$  ( $n_{\text{peak}} + n_{\text{comb}}$ ) for the neutral and charged  $B$  decays.

Mode	$\epsilon$	$n_{\text{obs}}$	$n_{\text{peak}} \pm \sigma_{\text{peak}}$	$n_{\text{comb}} \pm \sigma_{\text{comb}}$	$n_b \pm \sigma_b$
$B^0$	10.65%	96	$35.2 \pm 8.4$	$77.6 \pm 6.6$	$112.8 \pm 10.7$
$B^-$	8.50%	36	$2.0 \pm 5.0$	$29.3 \pm 4.1$	$31.3 \pm 6.5$

We extract  $n_{\text{peak}}$  from the  $m_{\text{ES}}$  distribution obtained after requiring  $|\Delta E| < 20 \text{ MeV}$ , and  $48 < |m(J/\psi \pi^- \pi^0) - 3872| < 72 \text{ MeV}/c^2$  which is twice the mass range of the signal band. These  $m_{\text{ES}}$  distributions for the neutral- and charged- $B$  modes are separately fit with the sum of a Gaussian function and an ARGUS function. We calculate  $n_{\text{peak}}$  by counting the number of events in the  $|m_{\text{ES}} - m_B| < 5 \text{ MeV}/c^2$  region, subtracting the number of combinatoric events obtained from integrating the ARGUS function over the same range,  $|m_{\text{ES}} - m_B| < 5 \text{ MeV}/c^2$ , and finally dividing the result by two. Note that the Gaussian distribution used in all fits has a width fixed to the value determined from a fit to the  $m_{\text{ES}}$  distribution obtained using both the  $J/\psi \pi^- \pi^0$  signal band and the  $J/\psi \pi^- \pi^0$  sideband. The error  $\sigma_{\text{peak}}$  is obtained by adding in quadrature the Poisson errors on the number of events in  $|m_{\text{ES}} - m_B| < 5 \text{ MeV}/c^2$  and the fit errors on the normalization of the ARGUS function. The resulting values for  $n_{\text{peak}}$  and  $\sigma_{\text{peak}}$  are listed in Table I.

The total background  $n_b$  is the sum of the peaking and combinatoric backgrounds and its error  $\sigma_b$  combines in quadrature the errors from the peaking and combinatoric backgrounds. The backgrounds and their errors are summarized in Table I.

The efficiencies  $\epsilon$  for the processes,  $B^0 \rightarrow X^- K^+$ ,

$X^- \rightarrow J/\psi \pi^- \pi^0$  and  $B^- \rightarrow X^- K_s^0$ ,  $X^- \rightarrow J/\psi \pi^- \pi^0$  are determined by MC simulation with an  $X^-$  signal of zero width, mass  $3.872 \text{ GeV}/c^2$ , and a model consisting of the sequential isotropic two-body decays  $B \rightarrow X^- K$ ,  $X^- \rightarrow J/\psi \rho^-$  and  $\rho^- \rightarrow \pi^- \pi^0$ .

These efficiencies are corrected to account for the small differences observed in PID, neutral-particle detection, and tracking efficiency that are found by comparing well-understood control samples taken from data and MC. The final efficiencies for each mode are listed in Table I.

The systematic errors include uncertainties in the number of  $B\bar{B}$  events in the data sample, secondary branching fractions, efficiency calculation due to limited MC statistics, decay model for the generated events, background parametrization, PID, charged particle tracking, and  $\pi^0$  reconstruction. The individual uncertainties are given as percentages in Table II. The secondary branching fractions [15] include  $\mathcal{B}(J/\psi \rightarrow e^+ e^-, \mu^+ \mu^-) = 0.1181 \pm 0.0014$  and  $\mathcal{B}(K_s^0 \rightarrow \pi^+ \pi^-) = 0.686 \pm 0.0027$ . The decay-model uncertainty is estimated by comparing the efficiencies for phase space and different decay models [19] with  $J^{PC} = 1^{++}$  and  $J^{PC} = 2^{--}$ . The back-

TABLE II: Percentage systematic errors on the branching ratios from the neutral and charged  $B$  decay modes.

Systematic Errors(%)	$B^0$	$B^-$
$N_{B\bar{B}}$	1.1	1.1
Branching fractions	5.3	5.3
MC statistics	2.1	2.3
MC decay model	1.1	3.0
Bkgd sideband width	0.3	1.7
Particle ID	5.0	5.0
Tracking $\pi^-$	1.4	1.4
Tracking $K^+$	1.4	-
Tracking $K_s^0 \rightarrow \pi^+ \pi^-$	-	2.6
Tracking $J/\psi \rightarrow e^+ e^-, \mu^+ \mu^-$	1.8	1.8
$\pi^0$ reconstruction efficiency	3.2	3.2
TOTAL ( $\sigma_{\text{sys}}$ )	8.8	9.7

ground parametrization uncertainty is estimated by varying the background sideband width, refitting the  $m_{\text{ES}}$  distributions, and recalculating the number of events. The uncertainties in PID, charged-tracking efficiency, and  $\pi^0$ -reconstruction efficiency are determined by studying control samples [13]. The total fractional errors  $\sigma_{\text{sys}}$ , listed at the bottom of Table II, are determined by adding the individual contributions in quadrature.

The probability distribution of the signal events is modeled as a Gaussian with a mean  $n_s$  and standard deviation  $\sigma_s$ . For each  $B$ -decay mode the mean is  $n_s = n_{\text{obs}} - n_b$  and the sigma is  $\sigma_s = \sqrt{n_{\text{obs}} + \sigma_b^2 + n_s^2 \sigma_{\text{sys}}^2}$ . The systematic error is added in quadrature and scales the errors on  $n_{\text{obs}}$  and  $n_b$  by the same fraction. We note the mean values  $n_s$ , for the charged and neutral modes are consistent with zero, within errors.

The number of events  $N_{90}$  corresponding to the 90%

confidence level (C.L.) upper limit is calculated using the Gaussian probability distribution with the assumption that the number of signal events is always greater than zero. The integral of the distribution from zero to  $N_{90}$  will be 90% of the total area above zero. Combining  $N_{90}$ ,  $\epsilon$ ,  $N_{B\bar{B}}$ , and the secondary branching fractions, we obtain 90% C.L. upper limits for the neutral and charged  $B$  modes of  $< 5.4 \times 10^{-6}$  and  $< 11 \times 10^{-6}$ , respectively. For completeness we include the central value (68% confidence interval) for the branching fraction using the  $n_s \pm \sigma_s$  values. The neutral and charged  $B$  mode branching fractions are  $(-5.7 \pm 4.9) \times 10^{-6}$  and  $(2.0 \pm 3.8) \times 10^{-6}$ , respectively. The results are summarized in Table III.

TABLE III: The estimated number of signal events, 90% C.L. upper limit of signal events, the branching fraction upper limits, and the branching fraction  $\mathcal{B}$  for the decay modes  $B^0 \rightarrow X^- K^+$  and  $B^- \rightarrow X^- K_s^0$ .

Mode	$n_s \pm \sigma_s$	$N_{90}$	90% C.L. ( $\times 10^{-6}$ )	$\mathcal{B}(\times 10^{-6})$
$B^0$	$-16.8 \pm 14.7$	15.9	$< 5.4$	$-5.7 \pm 4.9$
$B^-$	$4.7 \pm 8.8$	17.8	$< 11$	$2.0 \pm 3.8$

We test the isovector- $X$  hypothesis at a mass of 3872 MeV/ $c^2$  using a likelihood ratio test [15]. Here we determine the ratio of the two probabilities from the null ( $H_0$ ) and signal ( $H_1$ ) hypotheses using our experimental observation of 96 events in the signal-box.

The null hypothesis assumes the background produced all the observed signal-box events. Assuming the background probability distribution is a Gaussian function with mean  $n_b$  and width  $\sigma_b$ , we calculate a probability of  $P(H_0)=5.82 \times 10^{-2}$  to measure 96 or fewer events.

The isovector signal hypothesis predicts the product branching fractions to be related by  $\mathcal{B}(B \rightarrow X^- K, X^- \rightarrow J/\psi \rho^-) = 2 \times \mathcal{B}(B \rightarrow X(3872)K, X(3872) \rightarrow J/\psi \rho^0)$ . Using the BABAR branching fraction [4]  $\mathcal{B}(B^- \rightarrow X(3872)K^-, X(3872) \rightarrow J/\psi \pi^+ \pi^-) = (1.28 \pm 0.41) \times 10^{-5}$  and assuming all  $\pi^+ \pi^-$  decays originate from  $\rho^0$ , we expect  $\mathcal{B}(B^0 \rightarrow X^- K^+, X^- \rightarrow J/\psi \rho^-) = (2.56 \pm 0.82) \times 10^{-5}$ . This would produce  $75 \pm 25$  observed signal events in a data sample of 234 million  $B\bar{B}$  events. The error combines the uncertainty on the branching fraction and the systematic error  $\sigma_{sys}$  on our efficiency. The probability distributions for the signal events and the estimated background events are modeled as two uncorrelated Gaussian functions. The probability of observing 96 or fewer events (including background) with this probability distribution is  $P(H_1)=8.41 \times 10^{-5}$ .

The likelihood ratio ( $\lambda$ ) test of the null hypothesis relative to the signal hypothesis yields  $\lambda = P(H_0)/P(H_1) = 692$ . This corresponds to a probability of less than 1 part in 600 that the isovector- $X$  hypothesis is compatible with the outcome of our search for  $B^0 \rightarrow X^- K^+$ ,  $X^- \rightarrow J/\psi \pi^- \pi^0$ . Performing the same study in our

search for  $B^- \rightarrow X^- K_s^0$ ,  $X^- \rightarrow J/\psi \pi^- \pi^0$  we obtain  $\lambda = 17$ . The combined likelihood ratio is  $1.1 \times 10^4$ . Our result does not support the hypothesis that the  $X(3872)$  is an isovector particle decaying to  $J/\psi \rho$ .

In conclusion, we have performed a search for a charged partner of the  $X(3872)$  decaying to  $J/\psi \pi^- \pi^0$ . Our results set upper limits on the product branching fractions of  $\mathcal{B}(B^0 \rightarrow X^- K^+, X^- \rightarrow J/\psi \pi^- \pi^0) < 5.4 \times 10^{-6}$  and  $\mathcal{B}(B^- \rightarrow X^- \bar{K}^0, X^- \rightarrow J/\psi \pi^- \pi^0) = 2 \times \mathcal{B}(B^- \rightarrow X^- K_s^0, X^- \rightarrow J/\psi \pi^- \pi^0) < 22 \times 10^{-6}$  at the 90% confidence level.

We exclude the isovector- $X$  hypothesis with a likelihood ratio test which favors the null hypothesis by a factor  $1.1 \times 10^4$  over the isovector signal hypothesis.

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