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Peer reviewed

## Search for $B^\pm \rightarrow [K^\mp \pi^\pm]_D K^\pm$ and Upper Limit on the $b \rightarrow u$ Amplitude in $B^\pm \rightarrow DK^\pm$

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We search for  $B^\pm \rightarrow [K^\mp \pi^\pm]_D K^\pm$  decays, where  $[K^\mp \pi^\pm]_D$  indicates that the  $K^\mp \pi^\pm$  pair originates from the decay of a  $D^0$  or  $\bar{D}^0$ . Results are based on  $120 \times 10^6 Y(4S) \rightarrow B\bar{B}$  decays collected with the BABAR detector at SLAC. We set an upper limit on the ratio  $\mathcal{R}_{K\pi} \equiv \frac{[\Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+) + \Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-)]}{[\Gamma(B^+ \rightarrow [K^+ \pi^-]_D K^+) + \Gamma(B^- \rightarrow [K^- \pi^+]_D K^-)]} < 0.026$  (90% C.L.). This constrains the amplitude ratio  $r_B \equiv |A(B^- \rightarrow \bar{D}^0 K^-)/A(B^- \rightarrow D^0 K^-)| < 0.22$  (90% C.L.), consistent with expectations. The small value

of  $r_B$  favored by our analysis suggests that the determination of the Cabibbo-Kobayashi-Maskawa phase  $\gamma$  from  $B \rightarrow DK$  will be difficult.

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Following the discovery of  $CP$  violation in  $B$ -meson decays and the measurement of the angle  $\beta$  of the unitarity triangle [1] associated with the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, focus has turned towards the measurements of the other angles  $\alpha$  and  $\gamma$ . The angle  $\gamma$  is  $\arg(-V_{ub}^* V_{ud}/V_{cb}^* V_{cd})$ , where  $V_{ij}$  are CKM matrix elements; in the Wolfenstein convention [2],  $\gamma = \arg(V_{ub}^*)$ .

Several proposed methods for measuring  $\gamma$  exploit the interference between  $B^- \rightarrow D^0 K^-$  and  $B^- \rightarrow \bar{D}^0 K^-$  (Fig. 1) which occurs when the  $D^0$  and the  $\bar{D}^0$  decay to common final states, as first suggested in Ref. [3].

Following the proposal in Ref. [4], we search for  $B^- \rightarrow \bar{D}^0 K^-$  followed by  $\bar{D}^0 \rightarrow K^+ \pi^- \rho$ , as well as the charge conjugate sequence, where the symbol  $\bar{D}^0$  indicates either a  $D^0$  or a  $\bar{D}^0$ . Here the favored  $B$  decay followed by the doubly CKM-suppressed  $D$  decay interferes with the suppressed  $B$  decay followed by the CKM-favored  $D$  decay. We use the notation  $B^- \rightarrow [h_1^+ h_2^-]_D h_3^-$  (with each  $h_i = \pi$  or  $K$ ) for the decay chain  $B^- \rightarrow \bar{D}^0 h_3^-, \bar{D}^0 \rightarrow h_1^+ h_2^-$ . We also refer to  $h_3$  as the bachelor  $\pi$  or  $K$ . Then, ignoring  $D$  mixing,

$$\begin{aligned} \mathcal{R}_{K\pi}^\pm &\equiv \frac{\Gamma([K^\mp \pi^\pm]_D K^\pm)}{\Gamma([K^\pm \pi^\mp]_D K^\pm)} \\ &= r_B^2 + r_D^2 + 2r_B r_D \cos(\pm\gamma + \delta), \end{aligned}$$

where

$$r_B \equiv \left| \frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} \right|, \quad \delta \equiv \delta_B + \delta_D,$$

$$r_D \equiv \left| \frac{A(D^0 \rightarrow K^+ \pi^-)}{A(D^0 \rightarrow K^- \pi^+)} \right| = 0.060 \pm 0.003$$

[5], and  $\delta_B$  and  $\delta_D$  are strong phase differences between the two  $B$  and  $D$  decay amplitudes, respectively. The expression for  $\mathcal{R}_{K\pi}^\pm$  neglects the tiny contribution to the  $[K^\pm \pi^\mp]_D K^\pm$  mode from the color-suppressed  $B$  decay followed by the doubly CKM-suppressed  $D$  decay.

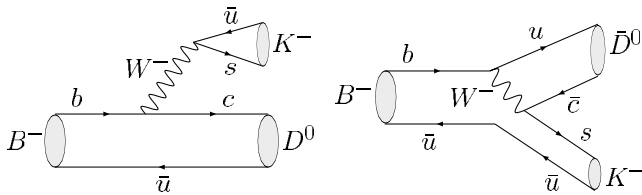


FIG. 1. Feynman diagrams for  $B^- \rightarrow D^0 K^-$  and  $\bar{D}^0 K^-$ . The latter is CKM and color suppressed with respect to the former.

Since  $r_B$  is expected to be of the same order as  $r_D$ ,  $CP$  violation could manifest itself as a large difference between  $\mathcal{R}_{K\pi}^+$  and  $\mathcal{R}_{K\pi}^-$ . Measurements of  $\mathcal{R}_{K\pi}^\pm$  are not sufficient to extract  $\gamma$ , since these two quantities are functions of three unknowns:  $\gamma$ ,  $r_B$ , and  $\delta$ . However, they can be combined with measurements for other  $\bar{D}^0$  modes to extract  $\gamma$  in a theoretically clean way [4].

The value of  $r_B$  determines, in part, the level of interference between the diagrams of Fig. 1. In most techniques for measuring  $\gamma$ , high values of  $r_B$  lead to better sensitivity. Since  $\mathcal{R}_{K\pi}^\pm$  depend quadratically on  $r_B$ , measurements of  $\mathcal{R}_{K\pi}^\pm$  can constrain  $r_B$ . In the standard model,  $r_B = |V_{ub} V_{cs}^*/V_{cb} V_{us}^*| F_{cs} \approx 0.4 F_{cs}$ , and  $F_{cs} < 1$  accounts for the additional suppression, beyond that due to CKM factors, of  $B^- \rightarrow \bar{D}^0 K^-$  relative to  $B^- \rightarrow D^0 K^-$ . Naively,  $F_{cs} = \frac{1}{3}$ , which is the probability for the color of the quarks from the virtual  $W$  in  $B^- \rightarrow \bar{D}^0 K^-$  to match that of the other two quarks; see Fig. 1. Early estimates gave  $F_{cs} \approx 0.22$  [6], leading to  $r_B \approx 0.09$ ; however, recent measurements [7] of color-suppressed  $b \rightarrow c$  decays [ $B \rightarrow D^{(*)} h^0$ ;  $h^0 = \pi^0, \rho^0, \omega, \eta, \eta'$ ] suggest that  $F_{cs}$ , and therefore  $r_B$ , could be larger, e.g.,  $r_B \approx 0.2$  [8]. A study by the Belle Collaboration of  $B^\pm \rightarrow \bar{D}^0 K^\pm, \bar{D}^0 \rightarrow K_S \pi^+ \pi^-$ , favors a large value of  $r_B$ :  $r_B = 0.26_{-0.15}^{+0.11}$  [9].

Our results are based on  $120 \times 10^6 Y(4S) \rightarrow B\bar{B}$  decays, corresponding to an integrated luminosity of  $109 \text{ fb}^{-1}$ , collected between 1999 and 2003 with the BABAR detector [10] at the PEP-II  $B$  Factory at SLAC. A  $12 \text{ fb}^{-1}$  off-resonance data sample, with a c.m. energy 40 MeV below the  $Y(4S)$  resonance, is used to study continuum events,  $e^+ e^- \rightarrow q\bar{q}$  ( $q = u, d, s$ , or  $c$ ).

The event selection was developed from studies of simulated  $B\bar{B}$  and continuum events, and off-resonance data. A large on-resonance data sample of  $B^- \rightarrow D^0 \pi^-$ ,  $D^0 \rightarrow K^- \pi^+$  events was used to validate several aspects of the simulation and analysis procedure. We refer to this mode and its charge conjugate as  $B \rightarrow D\pi$ .

Kaon and pion candidates in  $B^\pm \rightarrow [K\pi]_D K^\pm$  must satisfy  $K$  or  $\pi$  identification criteria that are typically 90% efficient, depending on momentum and polar angle. Misidentification rates are at the few percent level. The invariant mass of the  $K\pi$  pair must be within  $18.8 \text{ MeV}$  ( $2.5\sigma$ ) of the mean reconstructed  $D^0$  mass. The remaining background from other  $B^\pm \rightarrow [h_1 h_2]_D h_3^\pm$  modes is eliminated by removing events where any  $h_i^+ h_j^-$  pair, with any particle-type assignment except for the signal hypothesis for the  $h_1 h_2$  pair, is consistent with  $\bar{D}^0$  decay. We also reject  $B$  candidates where the  $\bar{D}^0$  paired with a  $\pi^0$  or  $\pi^\pm$  in the event is consistent with  $D^* \rightarrow D\pi$  decay.

After these requirements, backgrounds are mostly from continuum, mainly  $e^+e^- \rightarrow c\bar{c}$ , with  $\bar{c} \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$  and  $c \rightarrow D \rightarrow K^-$ . These are reduced with a neural network based on nine quantities that distinguish continuum and  $B\bar{B}$  events: (i) A Fisher discriminant based on the quantities  $L_0 = \sum_i p_i$  and  $L_2 = \sum_i p_i \cos^2 \theta_i$  calculated in the c.m. frame. Here,  $p_i$  is the momentum and  $\theta_i$  is the angle with respect to the thrust axis of the  $B$  candidate of tracks and clusters not used to reconstruct the  $B$ . (ii)  $|\cos \theta_T|$ , where  $\theta_T$  is the angle in the c.m. frame between the thrust axes of the  $B$  and the detected remainder of the event. (iii)  $\cos \theta_B$ , where  $\theta_B$  is the polar angle of the  $B$  in the c.m. frame. (iv)  $\cos \theta_D^K$  where  $\theta_D^K$  is the decay angle in  $\bar{D}^0 \rightarrow K\pi$ , i.e., the angle between the direction of the  $K$  and the line of flight of the  $\bar{D}^0$  in the  $\bar{D}^0$  rest frame. (v)  $\cos \theta_B^D$ , where  $\theta_B^D$  is the decay angle in  $B \rightarrow \bar{D}^0 K$ . (vi) The difference  $\Delta Q$  between the sum of the charges of tracks in the  $\bar{D}^0$  hemisphere and the sum of the charges of the tracks in the opposite hemisphere excluding the tracks used in the reconstructed  $B$ . For signal,  $\langle \Delta Q \rangle = 0$ , while for the  $c\bar{c}$  background  $\langle \Delta Q \rangle \approx \frac{7}{3} \times Q_B$ , where  $Q_B$  is the  $B$  candidate charge. The  $\Delta Q$  rms is 2.4. (vii)  $Q_B \cdot Q_K$ , where  $Q_K$  is the sum of the charges of all kaons not in the reconstructed  $B$ . Many signal events have  $Q_B \cdot Q_K \leq -1$ , while most continuum events have no kaons outside of the reconstructed  $B$ , and hence  $Q_K = 0$ . (viii) The distance of the closest approach between the bachelor track and the trajectory of the  $\bar{D}^0$ . This is consistent with zero for signal events, but can be larger in  $c\bar{c}$  events. (ix) The existence of a lepton ( $e$  or  $\mu$ ) and the invariant mass ( $m_{K\ell}$ ) of the lepton and the bachelor  $K$ . Continuum events have fewer leptons than signal events. Moreover, most leptons in  $c\bar{c}$  events are from  $D \rightarrow K\ell\nu$ , where  $K$  is the bachelor kaon, so that  $m_{K\ell} < m_D$ .

The neural net is trained with simulated continuum and signal events. We find agreement between the distributions of all nine variables in simulation and in control samples of off-resonance data and of  $B \rightarrow D\pi$ . The neural net requirement is 66% efficient for signal, and rejects 96% of the continuum background. An additional requirement,  $\cos \theta_D^K > -0.75$ , rejects 50% of the remaining  $B\bar{B}$  backgrounds and is 93% efficient for signal.

A  $B$  candidate is characterized by the energy-substituted mass  $m_{\text{ES}} \equiv \sqrt{(\frac{s}{2} + \vec{p}_0 \cdot \vec{p}_B)^2 / E_0^2 - p_B^2}$  and the energy difference  $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$ , where  $E$  and  $p$  are energy and momentum, the asterisk denotes the c.m. frame, the subscripts 0 and  $B$  refer to the  $Y(4S)$  and  $B$  candidates, respectively, and  $s$  is the square of the c.m. energy. For signal events  $m_{\text{ES}} = m_B$  within the resolution of about 2.5 MeV, where  $m_B$  is the known  $B$  mass.

We require  $\Delta E$  to be within 47.8 MeV ( $2.5\sigma$ ) of the mean value of  $-4.1$  MeV found in the  $B \rightarrow D\pi$  control sample. The yield of signal events is extracted from a fit to the  $m_{\text{ES}}$  distribution of events satisfying all of the requirements discussed above.

Our selection includes contributions from backgrounds with  $m_{\text{ES}}$  distributions peaked near  $m_B$  (peaking backgrounds). We distinguish those with a real  $\bar{D}^0 \rightarrow K^+\pi^\pm$  and those without, e.g.,  $B^- \rightarrow h^+h^-h^-$ . The latter are estimated from events with  $K^+\pi^\pm$  mass in a sideband of the  $\bar{D}^0$ . The former are from  $B^- \rightarrow D^0\pi^-$ , followed by the CKM-suppressed decay  $D^0 \rightarrow K^+\pi^-$ , with the bachelor  $\pi$  misidentified as a  $K$ . These are estimated as  $N_{\text{peak}}^D = r_D^2 N_{D\pi}$ , where  $N_{D\pi}$  is the number of observed  $B \rightarrow D\pi$  events with the  $\pi$  misidentified as a  $K$ . The technique used to measure  $N_{D\pi}$  is described below. Studies of simulated  $B\bar{B}$  events indicate that other peaking background contributions are negligible.

Because of the small number of events, we combine the  $B^+$  and  $B^-$  samples. We define the quantity

$$\mathcal{R}_{K\pi} \equiv \frac{\Gamma(B^- \rightarrow [K^+\pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^-\pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^-\pi^+]_D K^-) + \Gamma(B^+ \rightarrow [K^+\pi^-]_D K^+)}$$

$$\mathcal{R}_{K\pi} = \frac{\mathcal{R}_{K\pi}^+ + \mathcal{R}_{K\pi}^-}{2} = r_B^2 + r_D^2 + 2r_B r_D \cos \gamma \cos \delta,$$

assuming no  $CP$  violation in  $[K^\mp \pi^\pm]_D K^\mp$ .

We determine  $\mathcal{R}_{K\pi} = c N_{\text{sig}} / N_{DK}$ , where  $N_{\text{sig}}$  is the number of  $B^\pm \rightarrow [K^\mp \pi^\pm]_D K^\pm$  signal events and  $N_{DK}$  is the number of  $B^\pm \rightarrow [K^\pm \pi^\mp]_D K^\pm$  events, a mode that we denote by  $B \rightarrow DK$ . Most systematic uncertainties cancel in the ratio. The factor  $c = 0.93 \pm 0.04$ , determined from simulation, accounts for a difference in the event selection efficiency between the signal mode and  $B \rightarrow DK$ . This difference is mostly due to a correlation between the efficiencies of the  $\cos \theta_D^K$  requirement and the  $\bar{D}^0$  veto constructed using the bachelor track and the oppositely charged track in the  $[K\pi]$  pair. This correlation depends on the relative sign of the kaon and the bachelor track, and is different in the two modes.

The value of  $\mathcal{R}_{K\pi}$  is obtained from a simultaneous unbinned maximum likelihood fit to four  $m_{\text{ES}}$  and three  $\Delta E$  distributions. These distributions are used to extract the parameters needed to calculate  $\mathcal{R}_{K\pi}$  (e.g.,  $N_{\text{sig}}$ ) or to constrain the shapes of other distributions. The likelihood is expressed directly in terms of  $\mathcal{R}_{K\pi}$ .

The  $m_{\text{ES}}$  distribution for signal candidates is fit to the sum of a threshold background function and a Gaussian centered at  $m_B$ . The number of events in the Gaussian is  $N_{\text{sig}} + N_{\text{peak}}^D + N_{\text{peak}}^{hhh}$ , where  $N_{\text{peak}}^D$  and  $N_{\text{peak}}^{hhh}$  are the number of peaking background events with and without a real  $\bar{D}^0$ , respectively. The Gaussian parameters are constrained by the fit to the  $m_{\text{ES}}$  distribution of  $B \rightarrow DK$  events. The shape of the threshold function is constrained by fitting the  $m_{\text{ES}}$  distribution of candidates in a sideband of  $\Delta E$  ( $-125 < \Delta E < 200$  MeV, excluding the signal region). The  $m_{\text{ES}}$  distribution for events passing all signal requirements, but with  $K^\mp \pi^\pm$  mass in the sideband of the  $\bar{D}^0$  is fit in the same manner. We estimate  $N_{\text{peak}}^{hhh}$  from the Gaussian yield of this last fit, accounting for the different sizes of the signal and sideband  $\bar{D}^0$  mass ranges. The  $m_{\text{ES}}$

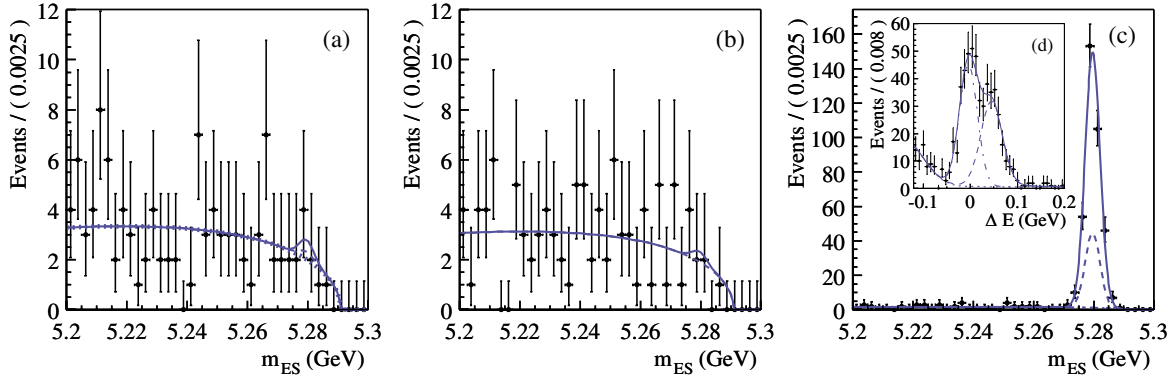


FIG. 2 (color online).  $m_{ES}$  distributions for (a) signal ( $[K^{\pm}\pi^{\pm}]_D K^{\pm}$ ) candidates, (b) candidates from the  $\bar{D}^0$  sideband, and (c)  $B \rightarrow DK$  candidates. The  $\bar{D}^0$  sideband selection uses a  $K^{\pm}\pi^{\pm}$  invariant mass range 2.72 times larger than the signal selection. (d)  $\Delta E$  distribution for  $B \rightarrow DK$  candidates; the peak centered at  $\approx 0.05$  GeV is from  $B \rightarrow D\pi$ . The superimposed curves are described in the text. In (c), the dashed Gaussian centered at  $m_B$  represents the  $B \rightarrow D\pi$  contribution estimated from (d).

distributions for signal and  $\bar{D}^0$  sideband candidates are shown in Figs. 2(a) and 2(b).

The  $m_{ES}$  distribution for  $B \rightarrow DK$  candidates with  $|\Delta E + 4.1 \text{ MeV}| < 47.8 \text{ MeV}$  [see Fig. 2(c)] is also fit to a Gaussian and a threshold function. The number of events in the Gaussian is  $N_{DK} + N_{D\pi}$ , where, as previously defined,  $N_{DK}$  is the number of  $B \rightarrow DK$  events and  $N_{D\pi}$  is the number of  $B \rightarrow D\pi$  events with the bachelor  $\pi$  misidentified as a  $K$ . The ratio  $N_{DK}/N_{D\pi}$  is obtained by fitting the  $\Delta E$  distribution for  $B \rightarrow DK$  candidate events with  $m_{ES} > 5.27$  GeV [see Fig. 2(d)]. This is modeled as the sum of a combinatoric background function, a double Gaussian for the  $B \rightarrow D\pi$  background, and a Gaussian for the  $B \rightarrow DK$  signal. The parameters of the Gaussians in the  $\Delta E$  fit are constrained from fits to the  $\Delta E$  distributions of well-identified  $B \rightarrow D\pi$  events with the bachelor  $\pi$  assumed to be a  $\pi$  or a  $K$ .

We find  $\mathcal{R}_{K\pi} = (4 \pm 12) \times 10^{-3}$ , consistent with zero. The number of signal, normalization, and peaking background events are  $N_{\text{sig}} = 1.1 \pm 3.0$ ,  $N_{DK} = 261 \pm 22$ ,  $N_{\text{peak}}^D = r_D^2 N_{D\pi} = 0.38 \pm 0.07$ , and  $N_{\text{peak}}^{hh} = 0.4 \pm 1.1$ . The uncertainties are mostly statistical. From this likelihood, we set a Bayesian limit  $\mathcal{R}_{K\pi} < 0.026$  at the 90% confidence level (C.L.), assuming a constant prior probability for  $\mathcal{R}_{K\pi} > 0$  (see Fig. 3).

In Fig. 4 we show the dependence of  $\mathcal{R}_{K\pi}$  on  $r_B$ , together with our limit. This is shown allowing a  $\pm 1\sigma$

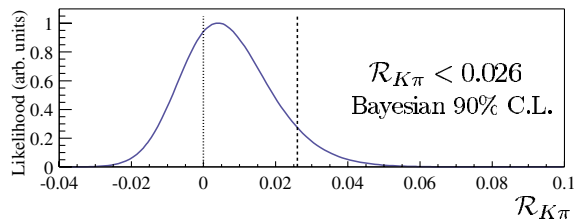


FIG. 3 (color online). Likelihood as a function of  $\mathcal{R}_{K\pi}$ . The integral for  $0 < \mathcal{R}_{K\pi} < 0.026$  is 90% of the integral for  $\mathcal{R}_{K\pi} > 0$ .

variation on  $r_D$ , for the full range  $0^\circ - 180^\circ$  for  $\gamma$  and  $\delta$ , as well as with the restriction  $48^\circ < \gamma < 73^\circ$  suggested by global CKM fits [11]. The least restrictive limit on  $r_B$  is computed assuming maximal destructive interference:  $\gamma = 0^\circ$ ,  $\delta = 180^\circ$  or  $\gamma = 180^\circ$ ,  $\delta = 0^\circ$ . This limit is  $r_B < 0.22$  at 90% C.L.

In summary, we find no evidence for  $B^{\pm} \rightarrow [K^{\pm}\pi^{\pm}]_D K^{\pm}$ . We set a 90% C.L. limit on the ratio  $\mathcal{R}_{K\pi}$  of rates for this mode and the favored mode  $B^{\pm} \rightarrow [K^{\pm}\pi^{\pm}]_D K^{\pm}$ . Our limit is  $\mathcal{R}_{K\pi} < 0.026$  at 90% C.L. With the most conservative assumption on the values of  $\gamma$  and of the strong phases in the  $B$  and  $D$  decays, this results in a limit on the ratio of the magnitudes of the  $B^- \rightarrow \bar{D}^0 K^-$  and  $B^- \rightarrow D^0 K^-$  amplitudes  $r_B < 0.22$  at 90% C.L. Our analysis suggests that  $r_B$  is smaller than the value reported by the Belle Collaboration,  $r_B = 0.26^{+0.11}_{-0.15}$  [9], but given the uncertainties the two results are not in disagreement. A small value of  $r_B$  will make it diffi-

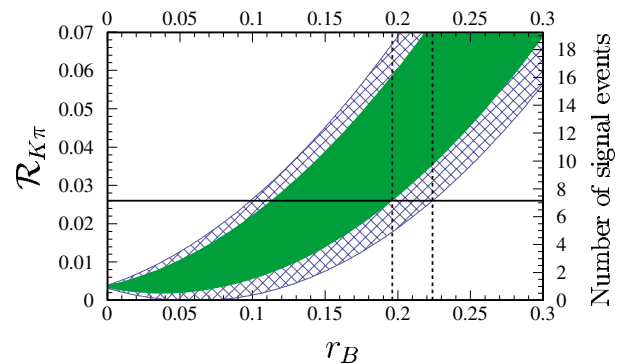


FIG. 4 (color online). Expectations for  $\mathcal{R}_{K\pi}$  and  $N_{\text{sig}}$  vs  $r_B$ . Shaded area: allowed region for any value of  $\delta$ , with a  $\pm 1\sigma$  variation on  $r_D$ , and  $48^\circ < \gamma < 73^\circ$ . Hatched area: additional allowed region with no constraint on  $\gamma$ . The horizontal line represents the 90% C.L. limit  $\mathcal{R}_{K\pi} < 0.026$ . The dashed lines are drawn at  $r_B = 0.196$  and  $r_B = 0.224$ . They represent the 90% C.L. upper limits on  $r_B$  with and without the constraint on  $\gamma$ .

cult to measure  $\gamma$  with other methods [3,12] based on  $B \rightarrow \bar{D}K$ .

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