## Search for $\boldsymbol{B}^{ \pm} \rightarrow\left[\boldsymbol{K}^{\mp} \boldsymbol{\pi}^{ \pm}\right]_{D} \boldsymbol{K}^{ \pm}$and Upper Limit on the $\boldsymbol{b} \rightarrow \boldsymbol{u}$ Amplitude in $\boldsymbol{B}^{ \pm} \rightarrow \boldsymbol{D} \boldsymbol{K}^{ \pm}$

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

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Following the discovery of $C P$ 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 $\arg \left(-V_{u b}^{*} V_{u d} / V_{c b}^{*} V_{c d}\right)$, where $V_{i j}$ are CKM matrix elements; in the Wolfenstein convention [2], $\gamma=\arg \left(V_{u b}^{*}\right)$.

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 $B^{-} \rightarrow$ $\tilde{D}^{0} K^{-}$followed by $\tilde{D}^{0} \rightarrow K^{+} \pi^{-} \rho$, as well as the charge conjugate sequence, where the symbol $\tilde{D}^{0}$ 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 $B^{-} \rightarrow\left[h_{1}^{+} h_{2}^{-}\right]_{D} h_{3}^{-}$(with each $h_{i}=\pi$ or $K$ ) for the decay chain $B^{-} \rightarrow \tilde{D}^{0} h_{3}^{-}, \tilde{D}^{0} \rightarrow h_{1}^{+} h_{2}^{-}$. We also refer to $h_{3}$ as the bachelor $\pi$ or $K$. Then, ignoring $D$ mixing,

$$
\begin{aligned}
\mathcal{R}_{\bar{K} \pi}^{ \pm} & \equiv \frac{\Gamma\left(\left[K^{\mp} \pi^{ \pm}\right]_{D} K^{ \pm}\right)}{\Gamma\left(\left[K^{ \pm} \pi^{\mp}\right]_{D} K^{ \pm}\right)} \\
& =r_{B}^{2}+r_{D}^{2}+2 r_{B} r_{D} \cos ( \pm \gamma+\delta),
\end{aligned}
$$

where

$$
\begin{aligned}
r_{B} & \equiv\left|\frac{A\left(B^{-} \rightarrow \bar{D}^{0} K^{-}\right)}{A\left(B^{-} \rightarrow D^{0} K^{-}\right)}\right|, \quad \delta \equiv \delta_{B}+\delta_{D} \\
r_{D} & \equiv\left|\frac{A\left(D^{0} \rightarrow K^{+} \pi^{-}\right)}{A\left(D^{0} \rightarrow K^{-} \pi^{+}\right)}\right|=0.060 \pm 0.003
\end{aligned}
$$

[5], and $\delta_{B}$ and $\delta_{D}$ are strong phase differences between the two $B$ and $D$ decay amplitudes, respectively. The expression for $\mathcal{R}_{\bar{K} \pi}^{ \pm}$neglects the tiny contribution to the $\left[K^{ \pm} \pi^{\mp}\right]_{D} K^{ \pm}$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 $r_{D}, C P$ violation could manifest itself as a large difference between $\mathcal{R}_{K \pi}^{+}$and $\mathcal{R}_{K \pi}^{-}$. Measurements of $\mathcal{R}_{K}^{ \pm}$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 $\tilde{D}^{0}$ 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 $\mathcal{R}_{\bar{K} \pi}^{ \pm}$depend quadratically on $r_{B}$, measurements of $\mathcal{R}_{K}^{ \pm}$can constrain $r_{B}$. In the standard model, $r_{B}=\left|V_{u b} V_{c s}^{*} / V_{c b} V_{u s}^{*}\right| F_{c s} \approx 0.4 F_{c s}$, and $F_{c s}<1$ 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, $F_{c s}=\frac{1}{3}$, 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 $F_{c s} \approx 0.22$ [6], leading to $r_{B} \approx 0.09$; however, recent measurements [7] of color-suppressed $b \rightarrow c$ decays $\left[B \rightarrow D^{(*)} h^{0} ; h^{0}=\pi^{0}, \rho^{0}, \omega, \eta, \eta^{\prime}\right]$ suggest that $F_{c s}$, and therefore $r_{B}$, could be larger, e.g., $r_{B} \approx 0.2$ [8]. A study by the Belle Collaboration of $B^{ \pm} \rightarrow \tilde{D}^{0} K^{ \pm}, \tilde{D}^{0} \rightarrow K_{S} \pi^{+} \pi^{-}$, favors a large value of $r_{B}: r_{B}=0.26_{-0.15}^{+0.11}$ [9].

Our results are based on $120 \times 10^{6} \mathrm{Y}(4 S) \rightarrow B \bar{B}$ decays, corresponding to an integrated luminosity of $109 \mathrm{fb}^{-1}$, collected between 1999 and 2003 with the $B A B A R$ detector [10] at the PEP-II $B$ Factory at SLAC. A $12 \mathrm{fb}^{-1}$ off-resonance data sample, with a c.m. energy 40 MeV below the $\mathrm{Y}(4 S)$ 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 MeV $(2.5 \sigma)$ of the mean reconstructed $D^{0}$ mass. The remaining background from other $B^{ \pm} \rightarrow\left[h_{1} h_{2}\right]_{D} h_{3}^{ \pm}$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 $\tilde{D}^{0}$ decay. We also reject $B$ candidates where the $\tilde{D}^{0}$ 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) $\left|\cos \theta_{T}\right|$, 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 $\tilde{D}^{0} \rightarrow K \pi$, i.e., the angle between the direction of the $K$ and the line of flight of the $\tilde{D}^{0}$ in the $\tilde{D}^{0}$ rest frame. (v) $\cos \theta_{B}^{D}$, where $\theta_{B}^{D}$ is the decay angle in $B \rightarrow$ $\tilde{D}^{0} K$. (vi) The difference $\Delta Q$ between the sum of the charges of tracks in the $\tilde{D}^{0}$ 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 $\tilde{D}^{0}$. 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 $\left(m_{K \ell}\right)$ 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 energysubstituted mass $m_{\mathrm{ES}} \equiv \sqrt{\left(\frac{s}{2}+\vec{p}_{0} \cdot \vec{p}_{B}\right)^{2} / E_{0}^{2}-p_{B}^{2}}$ 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 $\mathrm{Y}(4 S)$ and $B$ candidates, respectively, and $s$ is the square of the c.m. energy. For signal events $m_{\mathrm{ES}}=m_{B}$ within the resolution of about 2.5 MeV , where $m_{B}$ is the known $B$ mass.

We require $\Delta E$ to be within $47.8 \mathrm{MeV}(2.5 \sigma)$ 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 $m_{\mathrm{ES}}$ distribution of events satisfying all of the requirements discussed above.

Our selection includes contributions from backgrounds with $m_{\mathrm{ES}}$ distributions peaked near $m_{B}$ (peaking backgrounds). We distinguish those with a real $\tilde{D}^{0} \rightarrow K^{\mp} \pi^{ \pm}$ and those without, e.g., $B^{-} \rightarrow h^{+} h^{-} h^{-}$. The latter are estimated from events with $K^{\mp} \pi^{ \pm}$mass in a sideband of the $\tilde{D}^{0}$. 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

$$
\begin{gathered}
\mathcal{R}_{K \pi} \equiv \frac{\Gamma\left(B^{-} \rightarrow\left[K^{+} \pi^{-}\right]_{D} K^{-}\right)+\Gamma\left(B^{+} \rightarrow\left[K^{-} \pi^{+}\right]_{D} K^{+}\right)}{\Gamma\left(B^{-} \rightarrow\left[K^{-} \pi^{+}\right]_{D} K^{-}\right)+\Gamma\left(B^{+} \rightarrow\left[K^{+} \pi^{-}\right]_{D} K^{+}\right)}, \\
\mathcal{R}_{K \pi}=\frac{\mathcal{R}_{K \pi}^{+}+\mathcal{R}_{K \pi}^{-}}{2}=r_{B}^{2}+r_{D}^{2}+2 r_{B} r_{D} \cos \gamma \cos \delta,
\end{gathered}
$$

assuming no $C P$ violation in $\left[K^{\mp} \pi^{ \pm}\right]_{D} K^{\mp}$.
We determine $\mathcal{R}_{K \pi}=c N_{\text {sig }} / N_{D K}$, where $N_{\text {sig }}$ is the number of $B^{ \pm} \rightarrow\left[K^{\mp} \pi^{ \pm}\right]_{D} K^{ \pm}$signal events and $N_{D K}$ is the number of $B^{ \pm} \rightarrow\left[K^{ \pm} \pi^{\mp}\right]_{D} K^{ \pm}$events, a mode that we denote by $B \rightarrow D K$. 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 $B \rightarrow D K$. This difference is mostly due to a correlation between the efficiencies of the $\cos \theta_{D}^{K}$ requirement and the $\tilde{D}^{0}$ 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 $m_{\mathrm{ES}}$ 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 $m_{\mathrm{ES}}$ 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 $N_{\text {sig }}+N_{\text {peak }}^{D}+N_{\text {peak }}^{h h h}$, where $N_{\text {peak }}^{D}$ and $N_{\text {peak }}^{h h h}$ are the number of peaking background events with and without a real $\tilde{D}^{0}$, respectively. The Gaussian parameters are constrained by the fit to the $m_{\mathrm{ES}}$ distribution of $B \rightarrow D K$ events. The shape of the threshold function is constrained by fitting the $m_{\text {ES }}$ distribution of candidates in a sideband of $\Delta E(-125<\Delta E<200 \mathrm{MeV}$, 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 $\tilde{D}^{0}$ is fit in the same manner. We estimate $N_{\text {peak }}^{\text {hh }}$ from the Gaussian yield of this last fit, accounting for the different sizes of the signal and sideband $\tilde{D}^{0}$ mass ranges. The $m_{\text {ES }}$


FIG. 2 (color online). $m_{\text {ES }}$ distributions for (a) signal ( $\left[K^{\mp} \pi^{ \pm}\right]_{D} K^{ \pm}$) candidates, (b) candidates from the $\tilde{D}^{0}$ sideband, and (c) $B \rightarrow D K$ candidates. The $\tilde{D}^{0}$ sideband selection uses a $K^{\mp} \pi^{ \pm}$invariant mass range 2.72 times larger than the signal selection. (d) $\Delta E$ distribution for $B \rightarrow D K$ candidates; the peak centered at $\approx 0.05 \mathrm{GeV}$ 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 $\tilde{D}^{0}$ sideband candidates are shown in Figs. 2(a) and 2(b).

The $m_{\text {ES }}$ distribution for $B \rightarrow D K$ candidates with $|\Delta E+4.1 \mathrm{MeV}|<47.8 \mathrm{MeV}$ [see Fig. 2(c)] is also fit to a Gaussian and a threshold function. The number of events in the Gaussian is $N_{D K}+N_{D \pi}$, where, as previously defined, $N_{D K}$ is the number of $B \rightarrow D K$ events and $N_{D \pi}$ is the number of $B \rightarrow D \pi$ events with the bachelor $\pi$ misidentified as a $K$. The ratio $N_{D K} / N_{D \pi}$ is obtained by fitting the $\Delta E$ distribution for $B \rightarrow D K$ candidate events with $m_{\mathrm{ES}}>5.27 \mathrm{GeV}$ [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 $B \rightarrow D K$ 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 $N_{\text {sig }}=1.1 \pm 3.0, N_{D K}=261 \pm 22$, $N_{\text {peak }}^{D}=r_{D}^{2} N_{D \pi}=0.38 \pm 0.07$, and $N_{\text {peak }}^{h h h}=0.4 \pm 1.1$. 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 $B^{ \pm} \rightarrow$ $\left[K^{\mp} \pi^{ \pm}\right]_{D} K^{ \pm}$. We set a $90 \%$ C.L. limit on the ratio $\mathcal{R}_{K \pi}$ of rates for this mode and the favored mode $B^{ \pm} \rightarrow$ $\left[K^{ \pm} \pi^{\mp}\right]_{D} K^{ \pm}$. 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, $r_{B}=0.26_{-0.15}^{+0.11}$ [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 $B \rightarrow \tilde{D} K$.

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