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# Measurement of the Branching Fractions and $CP$ Asymmetries of $B^- \to D^0_{(CP)} K^-$ Decays with the *BABAR* Detector

The *BABAR* Collaboration

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## Abstract

We present a study of $B^- \to D^0_{(CP)} K^-$ decays, where $D^0_{(CP)}$ is reconstructed in flavor ($K^-\pi^+$), $CP$-even ($K^-K^+$,$\pi^-\pi^+$) and $CP$-odd ($K^0_S\pi^0$) eigenstates, based on a sample of about 214 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II $e^+e^-$ storage ring. Along with the Cabibbo-suppressed $B^- \to D^0_{(CP)} K^-$ decays we reconstruct also the Cabibbo-favored $B^- \to D^0_{(CP)} \pi^-$ decays. We measure the double ratio of branching fractions

$$R_+ \equiv \frac{\mathcal{B}(B^-\to D^0_{CP+}K^-)/\mathcal{B}(B^-\to D^0_{CP+}\pi^-)}{\mathcal{B}(B^-\to D^0K^-)/\mathcal{B}(B^-\to D^0\pi^-)} = 0.87 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}),$$

$$R_- \equiv \frac{\mathcal{B}(B^-\to D^0_{CP-}K^-)/\mathcal{B}(B^-\to D^0_{CP-}\pi^-)}{\mathcal{B}(B^-\to D^0K^-)/\mathcal{B}(B^-\to D^0\pi^-)} = 0.80 \pm 0.14(\text{stat}) \pm 0.08(\text{syst}),$$

and the $CP$ asymmetries

$$A_{CP+} \equiv \frac{\mathcal{B}(B^-\to D^0_{CP+}K^-) - \mathcal{B}(B^+\to D^0_{CP+}K^+)}{\mathcal{B}(B^-\to D^0_{CP+}K^-) + \mathcal{B}(B^+\to D^0_{CP+}K^+)} = 0.40 \pm 0.15(\text{stat}) \pm 0.08(\text{syst})$$

$$
\begin{aligned}
A_{CP-} &\equiv \frac{\mathcal{B}(B^-\to D^0_{CP-}K^-) - \mathcal{B}(B^+\to D^0_{CP-}K^+)}{\mathcal{B}(B^-\to D^0_{CP-}K^-) + \mathcal{B}(B^+\to D^0_{CP-}K^+)} \\
&= 0.21 \pm 0.17(\text{stat}) \pm 0.07(\text{syst}).
\end{aligned}
$$

All results are preliminary.

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# 1 INTRODUCTION

A theoretically clean measurement of the angle $\gamma = \arg(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$ can be obtained from the study of $B^{-}\!\to\! D^{(*)0}K^{(*)-}$ decays by exploiting the interference between the $b \to c\bar{u}s$ and $b \to u\bar{c}s$ decay amplitudes [1]. The method originally proposed by Gronau, Wyler and London is based on the interference between $B^{-} \to D^{0}K^{-}$ and $B^{-} \to \overline{D}^{0}K^{-}$ when the $D^{0}$ and $\overline{D}^{0}$ decay to *CP* eigenstates.

We define the ratios $R$ and $R_{CP\pm}$ of Cabibbo-suppressed to Cabibbo-favored branching fractions

$$R_{(CP\pm)} \equiv \frac{\mathcal{B}(B^{-}\!\to\! D^{0}_{(CP\pm)}K^{-}) + \mathcal{B}(B^{+}\!\to\! \overline{D}^{0}_{(CP\pm)}K^{+})}{\mathcal{B}(B^{-}\!\to\! D^{0}_{(CP\pm)}\pi^{-}) + \mathcal{B}(B^{+}\!\to\! \overline{D}^{0}_{(CP\pm)}\pi^{+})} \tag{1}$$

with the neutral $D$ meson reconstructed in non-*CP* ($D^{0}$) or *CP*-even/odd eigenstates ($D^{0}_{CP\pm}$) channels, and the direct *CP* asymmetry

$$A_{CP\pm} \equiv \frac{\mathcal{B}(B^{-}\!\to\! D^{0}_{CP\pm}K^{-}) - \mathcal{B}(B^{+}\!\to\! D^{0}_{CP\pm}K^{+})}{\mathcal{B}(B^{-}\!\to\! D^{0}_{CP\pm}K^{-}) + \mathcal{B}(B^{+}\!\to\! D^{0}_{CP\pm}K^{+})}\ . \tag{2}$$

Neglecting the $D^{0} - \overline{D}^{0}$ mixing and the ratio $r_{\pi} = A(B^{-} \to \overline{D}^{0}\pi^{-})/A(B^{-} \to D^{0}\pi^{-})$ of the amplitudes of the $B^{-} \to \overline{D}^{0}\pi^{-}$ and $B^{-} \to D^{0}\pi^{-}$ processes ($|r_{\pi}| < 0.02$), we can write $R_{\pm} \equiv R_{CP\pm}/R = 1 + r^{2} \pm 2r\cos\delta\cos\gamma$ and $A_{CP\pm} = \pm 2r\sin\delta\sin\gamma/(1 + r^{2} \pm 2r\cos\delta\cos\gamma)$. Here $r = |A(B^{-} \to \overline{D}^{0}K^{-})/A(B^{-} \to D^{0}K^{-})|$ is the magnitude of the ratio of the amplitudes for the processes $B^{-} \to \overline{D}^{0}K^{-}$ and $B^{-} \to D^{0}K^{-}$, expected from theory to be about $0.1 - 0.2$, and $\delta$ is the relative strong phase between these two amplitudes [1]. The measurement of $R_{\pm}$ and $A_{CP\pm}$ allows one to constrain the three unknowns $r$, $\delta$ and the CKM angle $\gamma$. In this paper we present the measurement of $R_{\pm}$ and $A_{CP\pm}$.

# 2 THE *BABAR* DETECTOR AND DATASET

The measurements reported in this paper have been obtained from a sample of about 214 million $\Upsilon(4S)$ decays to $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy $B$ factory. The *BABAR* detector is described in detail elsewhere [2]. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification, ionization energy loss in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device (DIRC) are used. Photons are identified by the electromagnetic calorimeter (EMC), which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5-T solenoidal superconducting magnet. The segmented flux return, including endcaps, is instrumented with resistive plate chambers (IFR) for muon and $K^{0}_{L}$ identification. We use the GEANT [3] software to simulate interactions of particles traversing the detector, taking into account the varying accelerator and detector conditions.

# 3 ANALYSIS METHOD

We reconstruct $B^{-}\!\to\! D^{0}h^{-}$ decays, where the prompt track $h^{-}$ is a kaon or a pion. Reference to the charge-conjugate state is implied here and throughout the text unless otherwise stated. Candidates for $D^{0}$ are reconstructed in the *CP*-even eigenstates $\pi^{-}\pi^{+}$ and $K^{-}K^{+}$, in the *CP*-odd eigenstate $K^{0}_{S}\pi^{0}$, and in the non-*CP* flavor eigenstate $K^{-}\pi^{+}$. $K^{0}_{S}$ candidates are selected in the $\pi^{-}\pi^{+}$ channel.

The prompt particle $h^-$ is required to have momentum greater than 1.4 GeV/$c$. Particle ID information from the drift chamber and, when available, from the DIRC must be consistent with the kaon hypothesis for the $K$ meson candidate in all $D^0$ modes and with the pion hypothesis for the $\pi^\pm$ meson candidates in the $D^0 \to \pi^-\pi^+$ mode. For the prompt track to be identified as a pion or a kaon, we require that at least five Cherenkov photons are detected to insure a good measurement of the Cherenkov angle. We reject a candidate track if its Cherenkov angle is not within $3\sigma$ of the expected value for either the kaon or pion mass hypothesis. We also reject candidate tracks that are identified as electrons by the DCH and the EMC or as muons by the DCH and the IFR.

Photon candidates are clusters in the EMC that are not matched to any charged track, have a raw energy greater than 30 MeV and lateral shower shape consistent with the expected pattern of energy deposit from an electromagnetic shower. Photon pairs with invariant mass within the range 115–150 MeV/$c^2$ ($\sim 3\sigma$) and total energy greater than 200 MeV are considered $\pi^0$ candidates. To improve the momentum resolution, the $\pi^0$ candidates are kinematically fit with their mass constrained to the nominal $\pi^0$ mass [4].

Neutral kaons are reconstructed from pairs of oppositely charged tracks with the invariant mass within 10 MeV ($\sim 3\sigma$) from the nominal $K^0$ mass. We also require that the ratio between the flight length distance in the plane transverse to the beams direction and its uncertainty is greater than 3.

The invariant mass of a $D^0$ candidate, $m(D^0)$, must be within $3\sigma$ of the $D^0$ mass. The $D^0$ mass resolution $\sigma$ is about 7.5 MeV in the $K^-\pi^+$, $K^-K^+$ and $\pi^-\pi^+$ modes, and about 21 MeV in the $K^0_S\pi^0$ mode. Selected $D^0$ candidates are fitted with a constraint to the nominal $D^0$ mass.

We reconstruct $B$ meson candidates by combining a $D^0$ candidate with a track $h^-$. For the $K^-\pi^+$ mode, the charge of the track $h^-$ must match that of the kaon from the $D^0$ meson decay. We select $B$ meson candidates by using the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(E_i^{*2}/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - p_B^2}$ and the energy difference $\Delta E = E_B^* - E_i^*/2$, where the subscripts $i$ and $B$ refer to the initial $e^+e^-$ system and the $B$ candidate respectively, and the asterisk denotes the center-of-mass (CM) ($\Upsilon(4S)$) frame. The $m_{\rm ES}$ distributions for $B^- \to D^0 h^-$ signal events are Gaussian distributions centered at the $B$ mass with a resolution of $2.6\,\mathrm{MeV}/c^2$, which does not depend on the decay mode or on the nature of the prompt track. In contrast, the $\Delta E$ distributions depend on the mass assigned to the prompt track. We evaluate $\Delta E$ with the kaon mass hypothesis so that the distributions are centered near zero for $B^- \to D^0 K^-$ events and shifted, on average, by approximately 50 MeV for $B^- \to D^0\pi^-$ events. The $\Delta E$ resolution depends on the momentum resolution for the $D^0$ meson and the prompt track $h^-$, and is typically 17 MeV for all the $D^0$ decay modes. All $B$ candidates are selected with $m_{\rm ES}$ within $2.5\sigma$ of the mean value and with $\Delta E$ in the range $-0.15 < \Delta E < 0.18\,\mathrm{GeV}$.

To reduce background from continuum production of light quarks, we construct a Fisher discriminant based on the following quantities: (i) the scalar sum of the momenta of all charged and neutral particles (exluding the $B$ decay products) flowing into nine concentric cones centered on the $B$ candidate thrust axis in the CM frame; (ii) the normalized second Fox-Wolfram moment [5], $R_2 \equiv H_2/H_0$, where $H_l$ is the $l$–order Fox-Wolfram moment of all the charged tracks and neutral clusters in the event; (iii) $|\cos\theta_T|$, where $\theta_T$ is the angle between the thrust axes of the $B$ candidate and of the remaining charged tracks and neutral clusters, evaluated in the CM frame; (iv) $|\cos\theta_B|$, where $\theta_B$ is the polar angle of the $B$ candidate in the CM frame; (v) $|\cos\theta_{hel}(D^0)|$, where $\theta_{hel}(D^0)$ is the angle between the direction of one of the decay products of the $D^0$ and the direction of flight of the $B$, in the $D^0$ rest frame. Each cone in (i) subtends an angle of $10^\circ$ in the CM and is folded to combine the forward and the backward intervals. A cut on the value of the Fisher discriminant rejects more than 90% of the continuum background while retaining 77% of the signal in the $K^-\pi^+$, $K^-K^+$ and $K^0_S\pi^0$ modes and 65% in the $\pi^-\pi^+$ channel.

Multiple $B^-\to D^0h^-$candidates are found in about 4% of the events for the $K^0_S\pi^0$ and in less than 1% of the events for the other $D^0$ decays. In these events a $\chi^2$ is constructed from $m(\pi^0)$ (for $K^0_S\pi^0$ only), $m(D^0)$, and $m_{\rm ES}$ and only the candidate with the smallest $\chi^2$ is retained. The total reconstruction efficiencies, based on simulated signal events, are about 33%($K^-\pi^+$), 28%($K^-K^+$), 26%($\pi^-\pi^+$) and 17%($K^0_S\pi^0$).

The main contributions to the $B\overline{B}$ background come from the processes $B\to D^*h$ $(h=\pi,K)$, $B^-\to D^0\rho^-$ and mis-reconstructed $B^-\to D^0h^-$. For $D^0\to K^-K^+$, $D^0\to\pi^-\pi^+$ and $D^0\to K^0_S\pi^0$ decays, the peaking backgrounds $B^-\to K^-K^+K^-$, $B^-\to K^-\pi^+\pi^-$ and $B^-\to K^0_S\pi^0K^-$ must also be considered, since they have the same $\Delta E$ and $m_{\rm ES}$ distribution as the $D^0K^-$ signal. Their yields are estimated from the existing measurements[4, 6] and subtracted from the $B^-\to D^0K^-$ signal yields.

For each $D^0$ decay mode an extended unbinned maximum-likelihood fit to the selected data events determines the signal and background yields $n_i$ ($i=1$ to $M$, where $M$ is the total number of signal and background channels). Two kinds of signal events, $B^-\to D^0\pi^-$ and $B^-\to D^0K^-$, are considered, and four kinds of backgrounds: candidates selected either from continuum or from $B\overline{B}$ events, in which the prompt track is either a pion or a kaon.

The input variables to the fit are $\Delta E$ and a particle identification probability for the prompt track based on the Cherenkov angle $\theta_C$, the momentum $p$ and the polar angle $\theta$ of the track. The extended likelihood function $\mathcal{L}$ is defined as

$$\mathcal{L}=\exp\left(-\sum_{i=1}^{M}n_i\right)\prod_{j=1}^{N}\left[\sum_{i=1}^{M}n_i\mathcal{P}_i\left(\Delta E,\theta_C;\vec{\alpha}_i\right)\right], \tag{3}$$

where $N$ is the total number of observed events. The $M$ functions $\mathcal{P}_i(\Delta E,\theta_C;\vec{\alpha}_i)$ are the probability density functions (PDFs) for the variables $\Delta E,\theta_C$, given the set of parameters $\vec{\alpha}_i$. Since these two quantities are sufficiently uncorrelated, their probability density functions are evaluated as a product $\mathcal{P}_i=\mathcal{P}_i(\Delta E;\vec{\alpha}_i)\times\mathcal{P}_i(\theta_C;\vec{\alpha}_i)$.

The $\Delta E$ distribution for $B^-\to D^0K^-$ signal events is parametrized with a Gaussian function. The $\Delta E$ distribution for $B^-\to D^0\pi^-$ is parametrized with the same Gaussian used for $B^-\to D^0K^-$ with a relative shift of the mean, computed event by event as a function of the prompt track momentum, arising from the wrong mass assignment to the prompt track. The offset and width of the Gaussian are kept floating in the fit and are determined from data together with the yields.

The $\Delta E$ distribution for the continuum background is parametrized with a linear function whose slope is determined from off-resonance data. The $\Delta E$ distribution for the $B\overline{B}$ background is empirically parametrized with the sum of a Gaussian and an exponential function when the prompt track is a pion, and with an exponential function when the prompt track is a kaon. The parameters are determined from simulated events.

The particle identification PDF is obtained from a pure control sample of kaons and pions produced in the decay chain $D^{*+}\to D^0\pi^+$ ($D^0\to K^-\pi^+$), selected using kinematical information only, without any inputs from the *BABAR* particle identification system. The parametrization of the particle identification PDF is performed by fitting with a Gaussian distribution the background-subtracted distribution of the difference between the reconstructed and expected Cherenkov angles of the selected kaons and pions.

## 4 PHYSICS RESULTS AND SYSTEMATIC STUDIES

The results of the fit are summarized in Table 1. Figure 1 shows the distributions of $\Delta E$ for the $K^-\pi^+$, $CP+$ and $CP-$ modes after enhancing the $B \to D^0K$ purity by requiring that the prompt track be consistent with the kaon hypothesis. This requirement is about 95% efficient for the $B^-\to D^0K^-$signal while retaining only 4% of the $B^-\to D^0\pi^-$candidates. The projection of a likelihood fit, modified to take into account the tighter selection criteria, is overlaid in the figure.

Table 1: Results of the $B^-\to D^0K^-$ and $B^-\to D^0\pi^-$ yields from the maximum-likelihood fit on data.

| $D^0$ mode | $N(B\to D^0\pi)$ | $N(B\to D^0K)$ | $N(B^-\to D^0K^-)$ | $N(B^+\to \overline{D}^0K^+)$ |
|---|---|---|---|---|
| $K^-\pi^+$ | $11930\pm 120$ | $897\pm 34$ | $441\pm 24$ | $456\pm 25$ |
| $K^-K^+$ | $1093\pm 37$ | $75^{+13}_{-12}$ | $54^{+10}_{-9}$ | $22^{+8}_{-7}$ |
| $\pi^-\pi^+$ | $345\pm 22$ | $18\pm 7$ | $12\pm 5$ | $7^{+5}_{-4}$ |
| $K^0_S\pi^0$ | $1248\pm 40$ | $76^{+13}_{-12}$ | $46^{+10}_{-9}$ | $30^{+9}_{-8}$ |

The double ratios $R_\pm$ are computed by scaling the ratios of the numbers of $B^-\to D^0K^-$ and $B^-\to D^0\pi^-$ mesons by correction factors (ranging from 0.997 to 1.020 depending on the $D^0$ mode) that account for small differences in the efficiency between the $B^-\to D^0K^-$ and $B^-\to D^0\pi^-$ selections, estimated with simulated signal samples. The results are listed in Table 2.

The direct $CP$ asymmetries $A_{CP\pm}$ for the $B^\pm \to D^0_{CP\pm}K^\pm$ decays are calculated from the measured yields of positive and negative charged meson decays and the results are reported in Table 2.

Table 2: Measured double branching fraction ratios $R_\pm$ and $CP$ asymmetries $A_{CP\pm}$ for different $D^0$ decay modes. The first error is statistical, the second is systematic.

| $D^0$ decay mode | $R_{CP}/R$ | $A_{CP}$ |
|---|---|---|
| $K^-K^+$ | $0.92\pm 0.16\pm 0.07$ | $0.43\pm 0.16\pm 0.09$ |
| $\pi^-\pi^+$ | $0.70\pm 0.29\pm 0.09$ | $0.27\pm 0.40\pm 0.09$ |
| $CP$-even combined | $0.87\pm 0.14\pm 0.06$ | $0.40\pm 0.15\pm 0.08$ |
| $K^0_S\pi^0$ | $0.80\pm 0.14\pm 0.08$ | $0.21\pm 0.17\pm 0.07$ |

Systematic uncertainties in the double ratios $R_\pm$ and in the $CP$ asymmetries $A_{CP\pm}$ arise primarily from uncertainties in signal yields due to the estimate of the peaking backgrounds and from the imperfect knowledge of the PDF shapes. The systematic uncertainty associated to peaking backgrounds is evaluated by taking into account the uncertainties on their branching fractions and by allowing for Poisson fluctuations of their yields in the selected data sample. The estimated yields are $29\pm 7$ ($B^-\to K^-K^+K^-$), $4\pm 4$ ($B^-\to K^-\pi^+\pi^-$) and $0.0^{+5.6}_{-0.0}$ ($B^-\to K^0_S\pi^0K^-$). Possible $CP$ asymmetries up to 30% in their yields are also taken into account. The parameters of the PDFs that are fixed in the nominal fit are varied by $\pm 1\sigma$ and the difference in the signal yields is taken as a systematic uncertainty.

The uncertainties in the branching fractions of the channels contributing to the $B\overline{B}$ background have been taken into account. The correlations between the different sources of systematic errors, when non-negligible, are considered. An upper limit on intrinsic detector charge bias due to acceptance, tracking, and particle identification efficiency has been obtained from the measured asymmetries in the processes $B^-\to D^0[\to K^-\pi^+]h^-$ and $B^-\to D^0_{CP\pm}\pi^-$, where *CP* violation is expected to be negligible. This limit ($\pm 0.04$) has been added in quadrature to the total systematic uncertainty on the *CP* asymmetry.

# 5 SUMMARY

In conclusion, we have reconstructed $B^-\to D^0K^-$ decays with $D^0$ mesons decaying to non-*CP* ($K^-\pi^+$), *CP*-even ($K^-K^+$,$\pi^-\pi^+$) and *CP*-odd ($K^0_S\pi^0$) eigenstates. We have measured the *CP* asymmetries $A_{CP+} = 0.40 \pm 0.15(\text{stat}) \pm 0.08(\text{syst})$, $A_{CP-} = 0.21 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$, and the double ratio of branching fractions $R_+ = 0.87 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$, $R_- = 0.80 \pm 0.14(\text{stat}) \pm 0.08(\text{syst})$. These results improve the previous existing measurements from *BABAR* [7]. All results presented in this document are preliminary.

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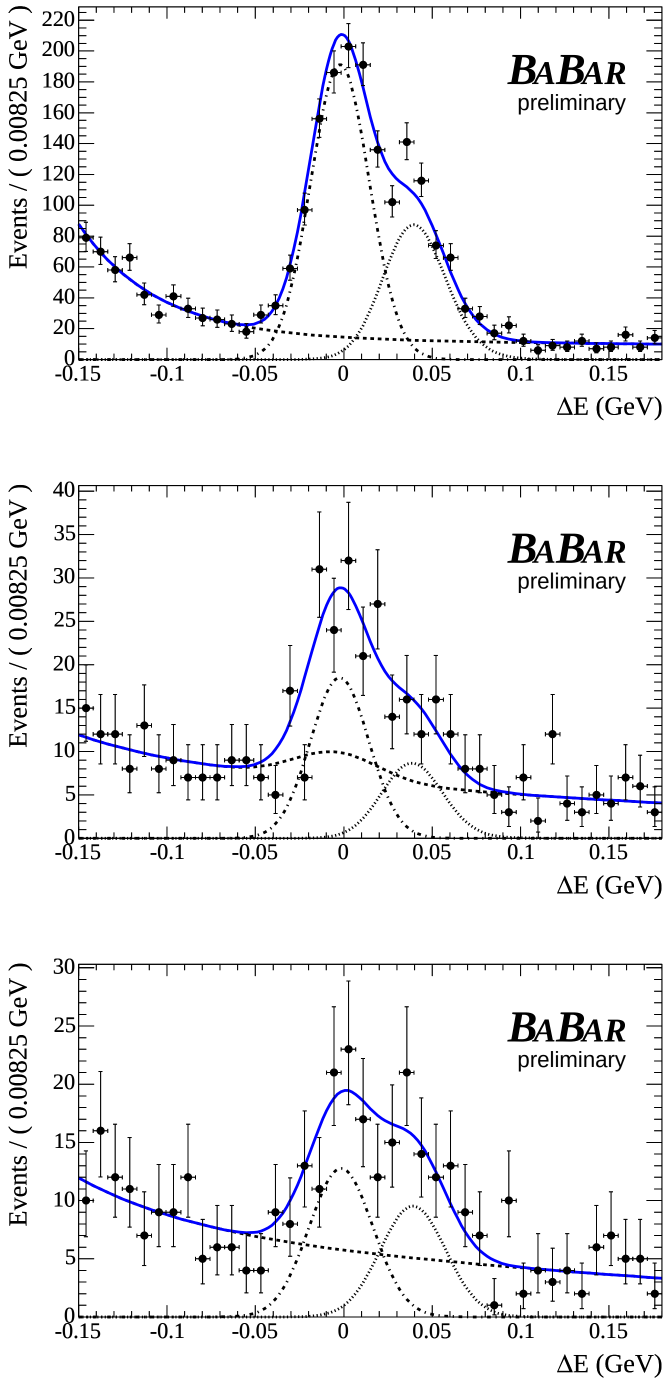


Figure 1: $\Delta E$ distributions of $B^-\!\to\!D^0h^-$ candidates, where a charged kaon mass hypothesis is assumed for $h$. Events are enhanced in $B^- \to D^0K^-$ purity by requiring the Cherenkov angle of the track $h$ to be within $2\sigma$ of the kaon hypothesis. Top: $B^- \to D^0[K^-\pi^+]K^-$; middle: $B^- \to D^0_{CP+}[K^-K^+, \pi^-\pi^+]K^-$; bottom: $B^- \to D^0_{CP-}[K^0_S\pi^0]K^-$. Solid curves represent projections of the maximum likelihood fit; dashed-dotted, dotted and dashed curves represent the $B \to D^0K$, $B \to D^0\pi$ and background contributions.