

Measurement of the Absolute Branching Fraction of $D^0 \rightarrow K^- \pi^+$

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We measure the absolute branching fraction for $D^0 \rightarrow K^- \pi^+$ using partial reconstruction of $\bar{B}^0 \rightarrow D^{*+} X \ell^- \bar{\nu}_\ell$ decays, in which only the charged lepton and the pion from the decay $D^{*+} \rightarrow D^0 \pi^+$ are used. Based on a data sample of 230 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy *B* Factory at SLAC, we obtain $\mathcal{B}(D^0 \rightarrow K^- \pi^+) = (4.007 \pm 0.037 \pm 0.070)\%$, where the first error is statistical and the second error is systematic.

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The decay $D^0 \rightarrow K^- \pi^+$ [1] is used as a reference mode in many measurements of branching fractions of *D* and *B*-meson decays. A precise measurement of the value of $\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ improves our knowledge of *D* and *B*-meson properties, and of fundamental parameters of the Standard Model, such as the magnitude of the Cabibbo-Kobayashi-Maskawa [2] matrix element V_{cb} . We present here a measurement of this branching fraction as precise as the world average value $\mathcal{B}(D^0 \rightarrow K^- \pi^+) = (3.80 \pm 0.07)\%$ [3]. We identify $D^0 \rightarrow K^- \pi^+$ decays in a sample of D^0 mesons preselected by their production in D^{*+} decays, obtained with partial reconstruction of the decay $\bar{B}^0 \rightarrow D^{*+} X \ell^- \bar{\nu}_\ell$, with $D^{*+} \rightarrow D^0 \pi^+$. This method is inspired by an earlier measurement performed by CLEO [4].

The data sample used in this analysis consists of an integrated luminosity to 210 fb^{-1} , corresponding to 230 million $B\bar{B}$ pairs, collected at the $\Upsilon(4S)$ resonance (on-resonance) and 22 fb^{-1} collected 40 MeV below the resonance (off-resonance) by the *BABAR* detector. The off-resonance events are used to subtract the non- $B\bar{B}$ (continuum) background. A simulated sample of $B\bar{B}$ events with integrated luminosity equivalent to approximately five times the size of the data sample is used for efficiency computation and background studies.

A detailed description of the *BABAR* detector and the algorithms used for charged and neutral particle reconstruction and identification is provided elsewhere [5]. High-momentum particles are reconstructed by matching hits in the silicon vertex tracker (SVT) with track elements in the drift chamber (DCH). Lower momentum tracks, which do not leave signals on many wires in the DCH due to the bending induced by the 1.5 T solenoid field, are reconstructed solely in the SVT. Charged hadron identification is performed by combining the measurements of the energy deposition in the SVT and in the DCH with the information from a Cherenkov detector (DIRC). Electrons are identified by the ratio of the energy deposited in the calorimeter (EMC) to the track momentum, the transverse profile of the shower, the energy loss in the DCH, and the Cherenkov angle in the DIRC. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron. Muon candidates are required to have a path length and hit distribution in the IFR and energy deposition in the EMC consistent with that expected for a minimum-ionizing particle.

We preselect a sample of hadronic events with at least

four charged tracks. To reduce continuum background, we require that the ratio of the 2^{nd} to the 0^{th} order Fox-Wolfram [6] variables be less than 0.6. We then select a sample of partially reconstructed *B* mesons in the channel $\bar{B}^0 \rightarrow D^{*+} X \ell^- \bar{\nu}_\ell$, by retaining events containing a charged lepton ($\ell = e, \mu$) and a low momentum pion (soft pion, π_s^+) which may arise from the decay $D^{*+} \rightarrow D^0 \pi_s^+$. This sample of events is referred to as the “inclusive sample”. The lepton momentum [7] must be in the range $1.4 < p_{\ell^-} < 2.3 \text{ GeV}/c$ and the soft pion candidate must satisfy $60 < p_{\pi_s^+} < 190 \text{ MeV}/c$. The two tracks must be consistent with originating from a common vertex, constrained to the beam-spot in the plane transverse to the beam axis. Finally, we combine p_{ℓ^-} , $p_{\pi_s^+}$ and the probability from the vertex fit into a likelihood ratio variable, optimized to reject $B\bar{B}$ background. Using conservation of momentum and energy, the invariant mass squared of the undetected neutrino is calculated as

$$\mathcal{M}_\nu^2 \equiv (E_{\text{beam}} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2, \quad (1)$$

where E_{beam} is half the total center-of-mass energy and E_ℓ (E_{D^*}) and \vec{p}_ℓ (\vec{p}_{D^*}) are the energy and momentum of the lepton (the D^* meson). Since the magnitude of the *B* meson momentum, p_B , is sufficiently small compared to p_ℓ and p_{D^*} , we set $p_B = 0$ in obtaining Eq. 1. As a consequence of the limited phase space available in the D^{*+} decay, the soft pion is emitted nearly at rest in the D^{*+} rest frame. The D^{*+} four-momentum can therefore be computed by approximating its direction as that of the soft pion, and parameterizing its momentum as a linear function of the soft-pion momentum. We select pairs of tracks with opposite electric charge for our signal ($\ell^\mp \pi_s^\pm$) and we use same-charge pairs ($\ell^\pm \pi_s^\pm$) for background studies.

All events where D^{*+} and ℓ^- originate from the same *B*-meson, producing a peak near zero in the \mathcal{M}_ν^2 distribution, are considered as signal candidates. Several processes contribute: (a) $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$ decays (primary); (b) $\bar{B} \rightarrow D^{*+}(n\pi) \ell^- \bar{\nu}_\ell$ where the $D^{*+}(n\pi)$ may or may not originate from an excited charm state (D^{**}) and $n \geq 1$; (c) $\bar{B}^0 \rightarrow D^{*+} \bar{D}$, $\bar{D} \rightarrow \ell^- X$ and $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$, $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$ (cascade); (d) $\bar{B}^0 \rightarrow D^{*+} h^-$ (fake-lepton), where the hadron ($h = \pi, K$) is erroneously identified as a lepton (in most of the cases, a muon). We also include radiative events, where photons with energy above 1 MeV are emitted by any charged particle, as described by PHOTOS [8] in our simulation. We define the signal region $\mathcal{M}_\nu^2 > -2 \text{ GeV}^2/c^4$, and the sideband

$$-10 < \mathcal{M}_\nu^2 < -4 \text{ GeV}^2/c^4.$$

The background in the inclusive sample consists of continuum and combinatorial $B\bar{B}$ events, which also include events where true D^{*+} and ℓ^- from the two different B mesons are combined. We determine the number of signal events in our sample with a minimum χ^2 fit to the \mathcal{M}_ν^2 distribution in the interval $-10 < \mathcal{M}_\nu^2 < 2.5 \text{ GeV}^2/c^4$. We perform the fit in ten bins of the lepton momentum in order to reduce the sensitivity of the result to the details of the simulation. In each bin we fix the continuum contribution to the off-resonance events, rescaled to account for the luminosity ratio between the on- and the off-resonance samples, while we scale independently the number of signal events from primary, from D^{**} , and from combinatorial $B\bar{B}$, as predicted by the simulation. We fix the contributions from cascade and fake-lepton decays, which account for about 3% of the signal sample, to the Monte Carlo (MC) prediction. Figure 1 shows the result of the fit in the \mathcal{M}_ν^2 projection. We find the number of signal events with $\mathcal{M}_\nu^2 > -2 \text{ GeV}^2/c^4$ is $N^{\text{incl}} = (2170.64 \pm 3.04(\text{stat}) \pm 18.1(\text{syst})) \times 10^3$. The statistical error includes the statistical uncertainties of the off-resonance and of the simulated events. The systematic error is discussed below.

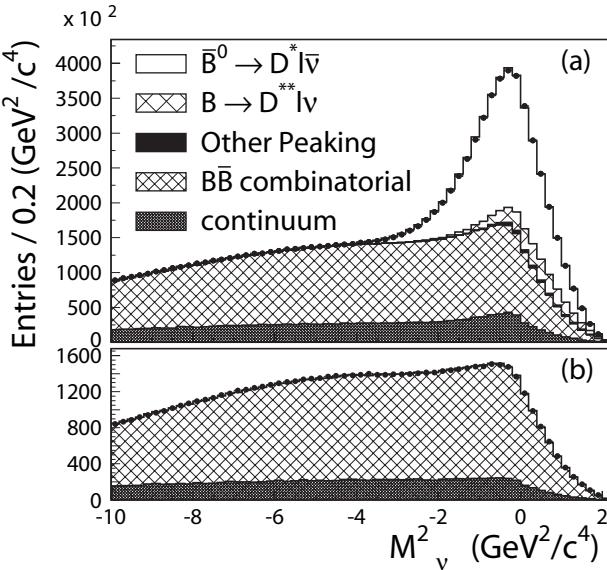


FIG. 1: The \mathcal{M}_ν^2 distribution of the inclusive sample, for right-charge (a) and wrong-charge (b) samples. The data are represented by solid points with error. The MC fit results are overlaid to the data, as explained in the figure.

We next look for $D^0 \rightarrow K^-\pi^+$ decays in the inclusive sample. We consider all tracks in the event, aside from the ℓ^- and π_s^+ , with momenta in the direction transverse to the beam axis exceeding $0.2 \text{ GeV}/c$. We combine pairs of tracks with opposite charge, and compute the invariant mass $M_{K\pi}$ assigning the kaon mass to the track with charge opposite the π_s charge. The kaon candidate must

satisfy a loose kaon identification criterion that retains more than 80% of true kaons, while rejecting more than 95% of pions. We select events in the mass range $1.82 < M_{K\pi} < 1.91 \text{ GeV}/c^2$. We combine each D^0 candidate with the π_s^+ and compute the mass difference $\Delta M = M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$. We look for signal in the range of $142.4 < \Delta M < 149.9 \text{ MeV}/c^2$.

This exclusive sample consists of signal events and of the following background sources: continuum, combinatorial $B\bar{B}$, uncorrelated peaking D^{*+} and Cabibbo-suppressed decays. We subtract the continuum using rescaled off-resonance events selected with the same criteria as the on-resonance data. Figure 2 shows the continuum-subtracted distribution for the data with the simulated $B\bar{B}$ backgrounds overlaid. Combinatorial events are due to any combination of three tracks, in which at least one does not come from the D^{*+} . We determine their number from the $B\bar{B}$ MC. We normalize the simulated events to the data in the ΔM sideband, $153.5 < \Delta M < 162.5 \text{ MeV}/c^2$, properly accounting for the small fraction of signal events (less than 1%) contained in the sideband. We verify that the background shape is properly described in the simulation using a sample of D^{*+} -depleted events, obtained as follows. We use wrong flavor events where the kaon has the same charge as the π_s , selected in the \mathcal{M}_ν^2 sideband. More than 95% of the events so selected in the ΔM signal region are combinatorial background, with a residual peaking component from Cabibbo suppressed decays (K^+K^- and $\pi^+\pi^-$, see below). After normalizing the level of the simulated events in the sideband, the number of events in the signal region is consistent with the data within the statistical precision of $\pm 1.3\%$.

The background from uncorrelated peaking D^{*+} decays occurs when the D^{*+} and the ℓ^- originate from the two different B mesons. These events exhibit a peak in ΔM but behave as combinatorial background in \mathcal{M}_ν^2 . We compute their number in the \mathcal{M}_ν^2 sideband data and rescale it to the \mathcal{M}_ν^2 signal region using the \mathcal{M}_ν^2 distribution of the combinatorial simulated events.

Cabibbo-suppressed decays $D^0 \rightarrow K^-K^+$ ($\pi^-\pi^+$) contribute to the peaking background, where one of the kaons (pions) is wrongly identified as a pion (kaon). Simulation shows that these events peak in ΔM , while they exhibit a broad $M_{K\pi}$ distribution. We subtract this background source using the simulation prediction. It should be noted that the contribution from doubly Cabibbo suppressed decays is negligible.

The exclusive selection yields $N^{\text{excl}} = 33810 \pm 290$ signal events, where the error is statistical only. The detailed composition of the inclusive and exclusive data sets is listed in Table I.

We compute the branching fraction as

$$\mathcal{B}(D^0 \rightarrow K^-\pi^+) = \frac{N^{\text{excl}}}{N^{\text{incl}}} \frac{1}{\varepsilon_{(K^-\pi^+)} \zeta}, \quad (2)$$

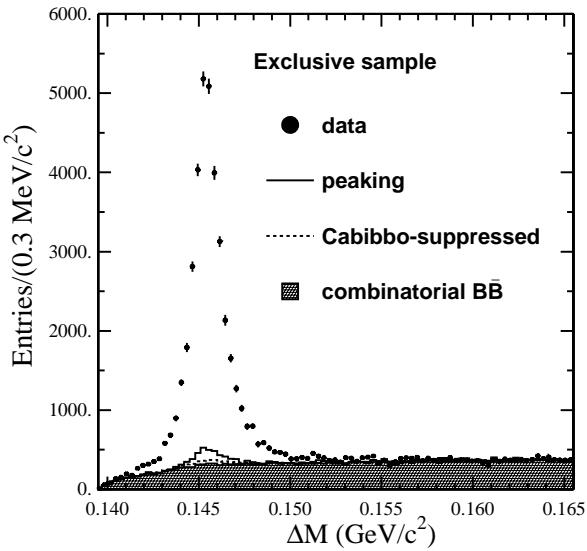


FIG. 2: The ΔM distribution of the exclusive sample after continuum subtraction. The data are represented by solid points with error. The backgrounds are overlaid to the data, as shown in the figure.

TABLE I: Composition on the inclusive and exclusive samples.

Source	Inclusive	Exclusive
Data	4412390 ± 2100	47270 ± 220
Continuum	460030 ± 2090	3090 ± 170
Combinatorial $B\bar{B}$	1781720 ± 680	8190 ± 50
Peaking	–	1630 ± 80
Cabibbo-suppressed	–	550 ± 10
Signal	2170640 ± 3040	33810 ± 290

where $\varepsilon_{(K-\pi^+)} = (36.96 \pm 0.09)\%$ is the D^0 reconstruction efficiency as computed in the simulation, and $\zeta = 1.033 \pm 0.002$ is the selection bias introduced by the partial reconstruction. Only the statistical errors are reported here. The bias factor ζ is introduced to account for the larger efficiency of the inclusive event reconstruction for final states with two or fewer tracks from D^0 decays due to the smaller density of hits near the π_s^+ track. We study these effects by comparing in the data and in MC the distributions of the charged track multiplicity (n_{trk}) and of other quantities sensitive to the soft pion isolation (angle to nearest track and track density within 10° cone around the π_s^+ direction). We weight simulated events in order to reproduce the data and compute the bias again. We observe an efficiency variation of 0.33% due to n_{trk} and 0.08% due to the other variables. The bias does not depend on some other variables ($p_{\pi_s^+}$, number of π_s^+ hits in the SVT) we have considered. We assign

a $\pm 0.35\%$ systematic error due to this selection bias.

The main systematic uncertainty on N^{incl} is due to the non-peaking combinatorial $B\bar{B}$ background. We perform the same fit to the $\ell^\pm\pi_s^\pm$ background control sample and the signal-dominated sample. We take the systematic error in the combinatorial background to be the RMS scatter in the ratio, calculated for each \mathcal{M}_ν^2 bin as shown in Figure 1(b), of continuum-subtracted data to the value of the combinatorial background determined from the fit, resulting in an error of 0.89%. As first noticed in [4], the decays $\bar{B}^0 \rightarrow \ell^-\bar{\nu}_\ell D^+$, with $D^+ \rightarrow K^*\rho(\omega)\pi^+$, constitute a right-charge peaking background, because the charged pion is produced almost at rest in the D^+ rest frame. In order to estimate the systematic error due to this peaking combinatorial background, we vary its total fraction by $\pm 100\%$ in the $B\bar{B}$ events in the Monte Carlo. The corresponding systematic uncertainty is $\pm 0.34\%$.

We consider all the sources of systematic uncertainty that affect the signal \mathcal{M}_ν^2 distribution. We vary by $\pm 30\%$ in turn the number of events where at least one photon with energy above 1 MeV is radiated by either the ℓ or the π_s^+ , or where the π_s^+ decays to a muon. We vary also by $\pm 30\%$ the fractions of cascade and fake-lepton decays, which are not determined by the fit. Finally, we vary in turn by $\pm 100\%$ the amount of events from each of the five sources constituting the D^{**} samples (two narrow and two broad resonant states, and non-resonant D^{*+} - π combinations). In each of the above studies we repeat the measurement and take the variation as the systematic uncertainty.

The dominant contribution to the systematic uncertainty on N^{excl} is due to the charged-track reconstruction efficiency. The single charged-track reconstruction efficiency is determined with 0.50% precision, which corresponds to $\pm 1.00\%$ overall uncertainty. The efficiency for K^- identification is measured with $\pm 0.70\%$ systematic uncertainty from a large sample of $D^{*+} \rightarrow D^0\pi_s^+, D^0 \rightarrow K^-\pi^+$ decays, produced in $e^+e^- \rightarrow c\bar{c}$ events. To estimate the systematic uncertainty due to the combinatoric background subtraction on N^{excl} , we first vary the number of events from combinatorial background below the signal peak by $\pm 1.3\%$ (see above), which translates in $\pm 0.3\%$ systematic uncertainty on the result. We vary the number of signal events contained in the sideband by $\pm 30\%$ for background normalization. This induces a systematic uncertainty of $\pm 0.16\%$. We vary the fraction of events from Cabibbo suppressed decays by $\pm 10\%$. The systematic uncertainty due to the uncorrelated peaking events, which we compute from data, is negligible.

Final state photon radiation in D^0 decays alters the distribution of $M_{K-\pi^+}$ and thus affects the efficiency computation. We estimate a systematic uncertainty of $\pm 0.07\%$ by varying by $\pm 30\%$ [8] the fraction of events in the simulation where at least one photon with energy above 1 MeV is emitted in the $D^0 \rightarrow K^-\pi^+$ decay.

When comparing the simulated $M_{K\pi}$ distribution to

the data in a high purity signal sample, we observe a slight discrepancy, causing $\pm 0.56\%$ systematic uncertainty in the reconstruction efficiency. We compute the total relative systematic error of $\pm 1.74\%$ from the quadratic sum of all uncertainties described above and listed in Table II. We cross check our results using dif-

TABLE II: The relative systematic errors of $\mathcal{B}(D^0 \rightarrow K^- \pi^+)$.

Sample Source	$\delta(\mathcal{B})/\mathcal{B}$ (%)
Selection bias	± 0.35
N^{incl}	
Non-peaking combinatorial background	± 0.89
Peaking combinatorial background	± 0.34
Soft pion decays in flight	± 0.10
Fake leptons	± 0.08
Cascade decays	± 0.08
Monte Carlo events shape	± 0.08
Continuum background	± 0.05
D^{**} production	± 0.02
Photon radiation	± 0.02
N^{excl}	
Tracking efficiency	± 1.00
K^- identification	± 0.70
D^0 invariant mass	± 0.56
Combinatorial background shape	± 0.30
Combinatorial background normalization	± 0.16
Soft pion decay	± 0.12
Cabibbo-suppressed decays	± 0.10
Photon radiation in D^0 decay	± 0.07
Total	± 1.74

ferent definitions of the ΔM and $M_{K^-\pi^+}$ signal regions and particle identification. We split our data into different sub-samples, depending on the run conditions. All the results are consistent.

In summary, we have measured the absolute branching fraction of $D^0 \rightarrow K^- \pi^+$ decay with partial reconstruction of $\bar{B}^0 \rightarrow D^{*+} X \ell^- \bar{\nu}_\ell$, and obtain the result

$$\mathcal{B}(D^0 \rightarrow K^- \pi^+) = (4.007 \pm 0.037 \pm 0.070)\%, \quad (3)$$

where the first error is statistical and the second error is systematic. This result is comparable in precision with the present world average, and it is consistent with it within two standard deviations.

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