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$D^+ \to K^-K^+\pi^+$ Meson Decays: A Search for *CP* Violation and a Measurement of the Branching Ratio

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of the *CP* asymmetry in singly Cabibbo-suppressed $D^+ \to K^-K^+\pi^+$ decays and in the resonant decays $D^+ \to \phi\pi^+$ and $D^+ \to \overline{K}^{*0}K^+$. We use a data sample of 79.9 fb^{-1} recorded by the *BABAR* detector. The Cabibbo-favored $D_s^+ \to K^-K^+\pi^+$ branching fraction is used as normalization in the measurements to reduce systematic uncertainties. Preliminary results of the *CP* asymmetries obtained are $A_{CP}(K^+K^-\pi^\pm) = (1.4 \pm 1.0(\text{stat.}) \pm 1.1(\text{syst.})) \times 10^{-2}$, $A_{CP}(\phi\pi^\pm) = (0.2 \pm 1.5(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-2}$, and $A_{CP}(K^\pm\overline{K}^{*0}) = (0.9 \pm 1.7(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-2}$. A preliminary determination of the branching ratio is $\frac{\Gamma(D^+ \to K^-K^+\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = (10.7 \pm 0.1(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-2}$.

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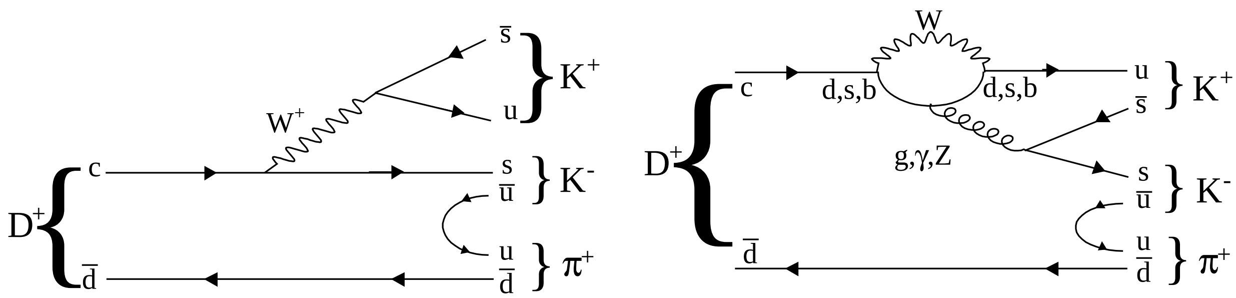

(a) (b)

Figure 1: Examples of $D^+ \to K^- K^+ \pi^+$ decays: (a) a tree diagram, and (b) a penguin process.

1 INTRODUCTION

Singly Cabibbo-suppressed (SCS) charged D-meson decays are predicted in the standard model (SM) to exhibit CP-violating charge asymmetries of the order of 10^{-3} [1]. Direct CP violation in SCS decays is possible in the interference between tree-level, Fig. 1(a), and penguin, Fig. 1(b), decay processes. Doubly Cabibbo-suppressed (DCS) and Cabibbo-favored (CF) decays are expected to be CP invariant in the SM because they are dominated by a single weak amplitude. Measurements of CP asymmetries in SCS processes greater than $\mathcal{O}(10^{-3})$ would be strong evidence of physics beyond the standard model [2].

We define the CP asymmetry by

$$A_{CP} = \frac{|\mathcal{A}|^2 - \left|\overline{\mathcal{A}}\right|^2}{|\mathcal{A}|^2 + \left|\overline{\mathcal{A}}\right|^2}, \tag{1}$$

where $\mathcal{A}$ is the total decay amplitude for D^+ decays and $\overline{\mathcal{A}}$ is the amplitude for the charge-conjugate decays. A_{CP} is different from zero only if there are at least two different decay amplitudes where there has to be a relative weak phase and an induced phase shift between the amplitudes due to final-state interaction. Eq. (1) can be expressed as a function of the branching fractions with the CPT invariance, $\Gamma(D^+) = \Gamma(D^-)$. Assuming that CF decays are invariant under the CP transformation, we use them as normalization factors in the asymmetry,

$$A_{CP} = \frac{\frac{\mathcal{B}(D^+ \to K^+K^-\pi^+)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} - \frac{\mathcal{B}(D^- \to K^+K^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}}{\frac{\mathcal{B}(D^+ \to K^+K^-\pi^+)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} + \frac{\mathcal{B}(D^- \to K^+K^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}}. \tag{2}$$

This procedure reduces systematic errors since most of the particle identification (PID) and tracking errors cancel out. We also measure the CP asymmetry in the resonant decays $D^+ \to \phi\pi^+$ and $D^+ \to \overline{K}^{*0}K^+$.

Finally, we present a preliminary measurement of the branching ratio $\frac{\Gamma(D^+ \to K^-K^+\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$.

2 THE *BABAR* DETECTOR AND DATASET

This analysis is performed with a data sample recorded on and below the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring. The *BABAR* detector is described in detail in Ref. [3]. The silicon vertex tracker (SVT) and the 40-layer cylindrical drift chamber (DCH) within a 1.5-T solenoid measure the momenta and energy deposition of charged particles. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. Photons are detected and electrons identified with a CsI(Tl) electromagnetic calorimeter (EMC). Muons are identified in the instrumented flux return (IFR), composed of resistive-plate chambers and layers of iron, which return the magnetic flux of the solenoid.

We split our 89.7 fb^{-1} sample into a 9.8 fb^{-1} randomly selected subsample used to optimize the selection criteria and the remainder, 79.9 fb^{-1} sample used for the analysis. The subsample is used to finalize the analysis procedure including the study of systematic errors. This procedure limits selection bias. Furthermore, the same selection criteria are applied to the CF and SCS modes whenever possible to reduce systematic errors. We use 145 fb^{-1} equivalent of (generic) $c\overline{c}$ Monte Carlo (MC) [4] events to determine efficiencies.

3 ANALYSIS METHOD

We reconstruct D^+ and D_s^+ [5] mesons by selecting events containing at least three charged tracks. Tracks are required to have at least 12 measured DCH coordinates, a minimum transverse momentum of 0.1 GeV/c, and to originate within 1.5 cm in xy (transverse to the beam) and ±10 cm along the z-axis (along the e^- beam) of the nominal interaction point. Kaons are identified with a likelihood ratio constructed with $\mathrm{d}E/\mathrm{d}x$ likelihood functions from the SVT and DCH, and a DIRC likelihood function constructed with the Cherenkov angle and number of photons. Pions are identified as tracks that fail a loose kaon identification criteria. Three charged tracks are fitted constraining their paths to a common vertex, and accepted if the fit probability $P(\chi^2) > 1\%$. We reject D^+ and D_s^+ mesons from B decays by requiring that the D momentum in the center-of-mass (CM) frame be above 2.4 GeV/c.

In order to reduce the remaining combinatorial background we construct a likelihood ratio (r) from the probability density functions (PDFs) of the following discriminating variables for the D^+ and D_s^+ mesons: CM momentum (p_{CM}) and vertex probability (χ^2-based) with beam spot constraint ($P_{\text{BS}}(\chi^2)$). The signal PDFs are obtained with a background-subtraction technique from the data subsample. For D^+ decays, the signal band is defined as $m_{D^+} \in [1.854, 1.882]$ GeV/c^2 and the sideband mass regions as $m_{D^+} \in \{[1.819, 1.833] \cup [1.903, 1.917]\}$ GeV/c^2 [see Fig. 2 (g)]. A joint likelihood function is constructed for the signal, $\mathcal{L}_{\text{sig}} = \prod_i \mathcal{L}^i_{\text{sig}}(x_i)$, and the background, $\mathcal{L}_{\text{bkg}} = \prod_i \mathcal{L}^i_{\text{bkg}}(x_i)$, where i runs over the variables used. The ratio of the joint likelihoods $r = \mathcal{L}_{\text{sig}}/\mathcal{L}_{\text{bkg}}$ is a powerful variable to separate signal and background. About 16% of the events have more than one D^+ meson. For such events the likelihood ratio is calculated for each candidate and the candidate with the highest likelihood ratio is selected.

The sensitivity $S/\Delta S$, where S is the signal and ΔS is its error, is optimized as a function of the likelihood ratio. Using the subsample, the optimal selection is found to be $r \geq 4.3$. This criterion is applied to both CF and SCS decays.

The resonant final states $D^+ \to \phi\pi^+$ and $D^+ \to \overline{K}^{*0}K^+$ are selected by requiring that the invariant mass of the resonant decays be within 0.01 GeV/c^2 and 0.05 GeV/c^2 of the nominal ϕ and $\overline{K}^{*0}$ masses, respectively. In addition, the signal is optimized by a selection on the cosine of the helicity angle ($\cos\theta_H$). In the $D^+ \to \phi\pi^+$ decay mode, the helicity angle is defined as the angle between the K^- and the π^+ in the ϕ rest frame. In the $D^+ \to \overline{K}^{*0}K^+$ decay mode, the helicity angle is defined as the angle between the K^- from the $\overline{K}^{*0}$ and the K^+ in the $\overline{K}^{*0}$ rest frame. Maximum sensitivity is obtained when $|\cos\theta_H| \geq 0.2$ and $|\cos\theta_H| \geq 0.3$ for $D^+ \to \phi\pi^+$ and $D^+ \to \overline{K}^{*0}K^+$, respectively.

The CF $D_s^+ \to K^-K^+\pi^+$ decays are selected similarly. The signal and sideband mass regions are chosen to be $m_{KK\pi} \in [1.944, 1.992]$ GeV/c^2, and $m_{KK\pi} \in \{[1.914, 1.938] \cup [1.938, 1.998]\}$ GeV/c^2, respectively [see Fig. 2 (a)]. The only difference from the SCS case is that contamination from $D^+ \to K^-\pi^+\pi^+$ decays is removed. In the $KK\pi$ candidates, the kaon with the same charge as the pion is labeled as a pion and then the $K\pi\pi$ invariant mass is calculated. We observe a D^+ peak indicating that part of the D_s^+ signal is composed of misidentified D^+ candidates. Events in the region $1.855 \leq m_{K\pi\pi} \leq 1.883$ GeV/c^2 are removed from the D_s^+ sample.

Contamination from $D^{*+} \to D^0(\to K^-\pi^+, K^-K^+)\pi^+$ decays is removed with a kinematic requirement on the D^0 invariant mass, $m_{K^-h^+} \geq 1.84$ GeV/c^2. In the case of the $D^+ \to K^-\pi^+\pi^+$ decays, both $K\pi$ combinations must satisfy the requirement. Partially reconstructed $D^0 \to K^-\pi^+\pi^0$ events are also misidentified as D^+ events when the π^0 is missed and the charged pion is misidentified as a kaon. Most of these events are removed by labeling a kaon track as a pion and applying a restriction on the mass difference $0.139 \leq (m_{K^-\pi^+\pi^+} - m_{K^-\pi^+}) \leq 0.150$ GeV/c^2.

The optimized selection criteria are applied to the final sample to obtain the signal yields. Figure 2 shows the mass distributions. The yields, listed in Table 1, are computed by subtracting a scaled background estimate obtained from the sideband mass regions from the number of events in the signal region. This technique minimizes sensitivity to background shape assumptions.

Table 1: Summary of yields in signal and normalization modes.

Parent Charge	$+$	$-$
$D^+ \to K^-K^+\pi^+$	21632 ± 228	20940 ± 226
$D^+ \to \phi\pi^+$	5452 ± 87	5327 ± 86
$D^+ \to \overline{K}^{*0}K^+$	5247 ± 96	5113 ± 96
$D_s^+ \to K^-K^+\pi^+$	23066 ± 217	22928 ± 214
$D^+ \to K^-\pi^+\pi^+$	236254 ± 570	237616 ± 571

The efficiencies needed for the A_{CP} calculation are obtained from a sample of MC (generic) $c\bar{c}$ events. The selection criteria optimized for the subsample are applied to the MC sample. Efficiencies are then calculated as ratios of the numbers of selected signal MC events to numbers of generated events. The decay efficiencies are shown in Table 2.

We use Eq. (2) (recognizing that branching fractions are proportional to yields divided by efficiencies) to obtain A_{CP}. As cross-checks, we calculate the *CP* asymmetries with two other methods (which would have larger systematic errors than the primary method): (i) using the CF $D^+ \to K^-\pi^+\pi^+$ branching fraction as normalization, $A_{CP}^{(1)}$, and (ii) without any normalization factor, $A_{CP}^{(2)}$, and the results are shown in Table 3. A study of the *CP* asymmetry in bins of the $D^+ \to K^-K^+\pi^+$ Dalitz plot indicates that the asymmetry is consistent with being constant and zero.

The relative branching ratio $\frac{\Gamma(D^+\to K^-K^+\pi^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$ has been calculated as follows. The CF and SCS Dalitz plots are first binned to have equally populated bins. Then, the signal and normalization yields and efficiencies are calculated bin by bin. The efficiency-corrected yields are then summed and divided to obtain the ratio. We obtain a branching ratio of $(10.7 \pm 0.1(\text{stat.})) \times 10^{-2}$ with the final sample.

Table 2: Summary of the efficiencies for positively (ε^+) and negatively (ε^-) charged $D_{(s)}$-meson decays. Efficiencies are in percent [%].

Decay	ε^+	ε^-
$D^+ \to K^-K^+\pi^+$	8.20±0.04	8.26±0.04
$D^+ \to \phi\pi^+$	7.67±0.07	7.63±0.07
$D^+ \to \overline{K}^{*0}K^+$	5.88±0.07	5.90±0.07
$D^+ \to K^-\pi^+\pi^+$	9.90±0.02	10.17±0.02
$D_s^+ \to K^-K^+\pi^+$	3.77±0.02	3.79±0.02

Table 3: Summary of *CP* asymmetries measured in three different ways.

	A_{CP} $[10^{-2}]$	$A_{CP}^{(1)}$ $[10^{-2}]$	$A_{CP}^{(2)}$ $[10^{-2}]$
$(K^-K^+\pi^\pm)$	$+1.36 \pm 1.01$	$+0.58 \pm 0.86$	$+2.07 \pm 0.84$
$(\phi\pi^\pm)$	$+0.24 \pm 1.45$	-0.54 ± 1.35	$+0.94 \pm 1.33$
$(\overline{K}^{*0}K^\pm)$	$+0.88 \pm 1.67$	$+0.10 \pm 1.58$	$+1.58 \pm 1.57$

4 SYSTEMATIC ERRORS AND CROSS-CHECKS

We estimate the systematic error on the *CP* asymmetries in three different ways. The first approach combines estimates of the contributions from various identified sources listed in Table 4. The second and third estimates come from partly redundant direct studies of asymmetries in the normalization and control samples.

The first row of Table 4 gives the error (0.06%) assigned to A_{CP} due to small differences in momentum spectra of π, K from D^+ and D_s^+ decays. This error is estimated as three times the maximum difference in π, K MC-efficiency asymmetries in D^+ and D_s^+ decays. We evaluate an error for the background subtraction by changing the widths of the sideband mass regions. The error is taken to be the difference in the central values of A_{CP}. The errors in the likelihood-ratio technique are estimated with two variants: (i) tightening the likelihood ratio to produce a 10% change in the decay yields, and (ii) using another likelihood ratio (r_1) which incorporates a third variable, the distance in the xy-plane from the interaction point to the D^+ vertex (d_{xy}). Case (i) is obtained at $r \geq 6.0$ and the maximum sensitivity in case (ii) is at $r_1 \geq 8.8$. Table 4 summarizes these systematic errors for the *CP* asymmetries. The total errors are 0.8%, 0.7%, and 0.7% on the $D^+ \to K^-K^+\pi^+$, $D^+ \to \phi\pi^+$, and $D^+ \to \overline{K}^{*0}K^+$ asymmetries, respectively.

Our second estimate is the larger of the differences between A_{CP} and the other two measurements $A_{CP}^{(1)}$ and $A_{CP}^{(2)}$. The error is 0.8% on both the inclusive $D^+ \to K^-K^+\pi^+$ and for the resonant asymmetries.

Our third and final estimate, which is applicable only to the inclusive three-body final states, is based on *CP* asymmetries for the CF decays $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$ (since these are expected to be zero within the SM). The high-statistics $D^+ \to K^-\pi^+\pi^+$ control mode is used to search for the scale of systematic effects intrinsic to the detector. The $D_s^+ \to K^-K^+\pi^+$ mode, which is also our primary normalization mode, is largely insensitive to these effects since it has the same final state as our signal decay. In $D_s^+ \to K^-K^+\pi^+$ decays, both the D_s^+ and the D_s^- decay to two oppositely charged kaons; only pion charge differs in particle and antiparticle decays. In $D^+ \to K^-\pi^+\pi^+$ decays however, all three particles have opposite charges in particle and antiparticle decays. For these control samples, we obtain asymmetries of $(+1.1 \pm 0.2) \times 10^{-2}$ and $(+0.6 \pm 0.8) \times 10^{-2}$ (statistical errors only) for $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$, respectively.

We find that these observed control-sample asymmetries are almost entirely in the efficiencies derived from our simulation of the detector, rather than the signal yields (see Tables 1 and 2). With corrections based on estimates of low-energy nuclear interaction effects which are not accounted for in the simulation we find the smaller asymmetries $+0.8 \times 10^{-2}$ and $+0.4 \times 10^{-2}$ for $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$, respectively. These results we interpret to mean that our present simulation of particle interactions in the material of the detector is incomplete.

Even though our definition of A_{CP} [see Eq. (2)] invokes a normalization chosen to eliminate effects that may be important here, we choose here the conservative estimate that the systematic error is measured by the magnitude of the departure of these CF asymmetries from the expected null values.

We chose as our systematic error in the *CP* asymmetry the largest of all applicable estimates, 1.1% on $D^+ \to K^-K^+\pi^+$ and 0.8% on the resonant decays.

The *CP* asymmetry has been cross-checked as a function of the D^+ lab momentum as well as by the year of data production. The χ^2-based probability of the asymmetry to be constant is 32% and 63% for momentum and time-period dependences, respectively.

A summary of the systematic errors for the branching ratio $\frac{\Gamma(D^+ \to K^-K^+\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$ is given in Table 5. The fractional error due to PID and tracking has been estimated as 2.1% of the branching ratio, computed as the sum in quadrature of 1.1% for PID and 1.8% for tracking [6].

Table 4: Summary of systematic errors for the *CP* asymmetries.

Source	$(K^-K^+\pi^\pm)$ A_{CP} $[10^{-2}]$	$(\phi\pi^\pm)$ A_{CP} $[10^{-2}]$	$(\overline{K}^{*0}K^\pm)$ A_{CP} $[10^{-2}]$
MC simulation	0.06	0.06	0.06
Background estimate	0.63	0.32	0.49
Using $r \geq 6.0$	0.22	0.15	0.01
Using $r_1 \geq 8.8$	0.46	0.54	0.54
Total	0.81	0.65	0.73

5 RESULTS and SUMMARY

In summary, we have searched for a *CP* asymmetry in $D^+ \to K^-K^+\pi^+$, $D^+ \to \phi\pi^+$, and $D^+ \to \overline{K}^{*0}K^+$ decays and measured the branching ratio of $D^+ \to K^-K^+\pi^+$ decays all with a data sample

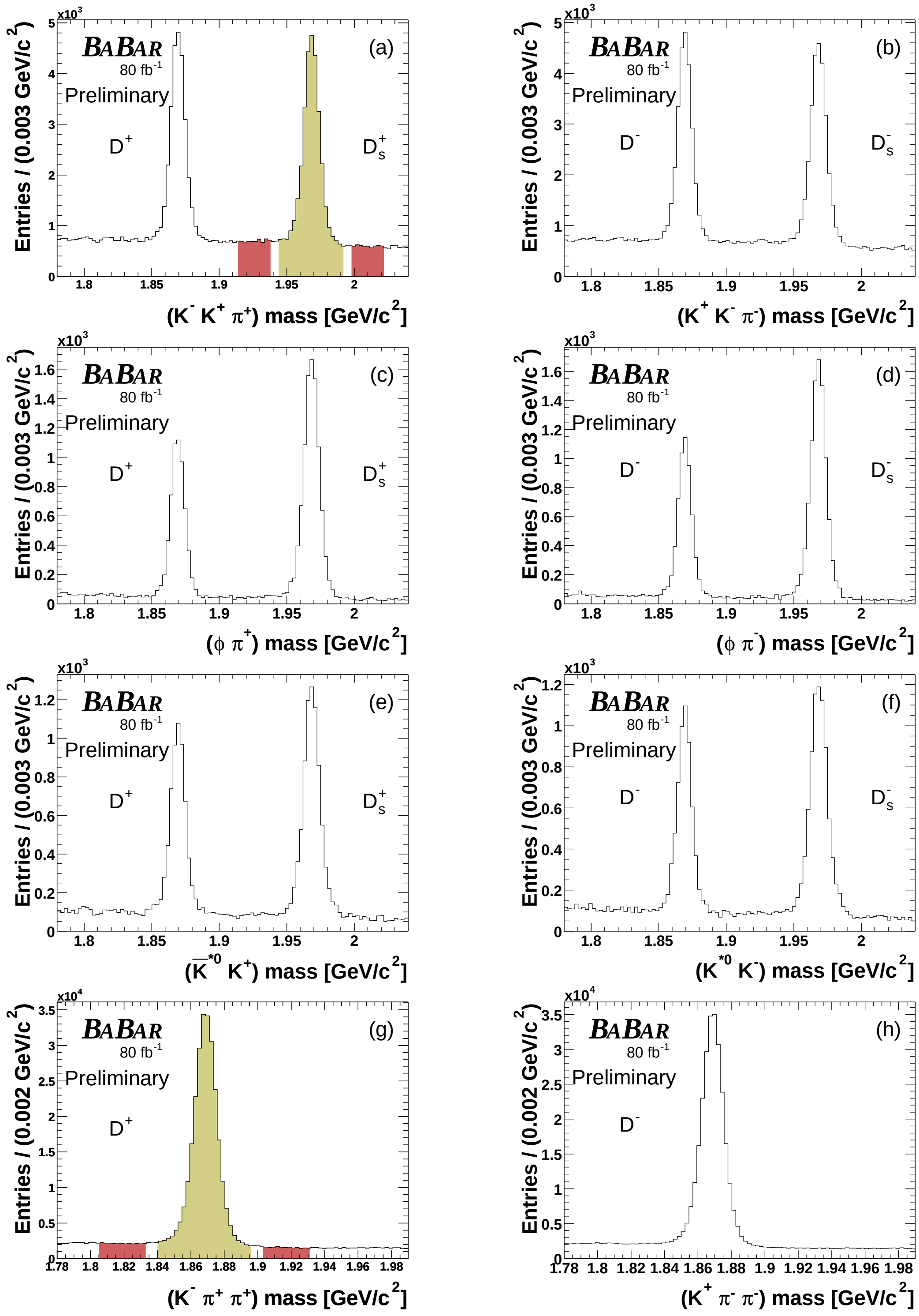

Figure 2: Mass distributions for positively charged (left) and negatively charge (right) $D_{(s)}$ mesons for events satisfying the requirement on $r \geq 4.3$. Figures (a) and (b) are for all $KK\pi$ candidates, while (c) and (d) are for $\phi\pi$ candidates, and (e) and (f) for $\overline{K}^{*0}K$ candidates. Figures (g) and (h) are for $K\pi\pi$ candidates. Signal (yellow or light shaded) and sidebands (red or darker shaded) regions are shown for D_s^+ and D^+ decays in (a) and (g), respectively.

of 79.9 fb^{-1} collected by the *BABAR* experiment.

Preliminary measurements of the *CP* asymmetries are $A_{CP}(K^+K^-\pi^\pm) = (1.4 \pm 1.0(\text{stat.}) \pm 1.1(\text{syst.})) \times 10^{-2}$, $A_{CP}(\phi\pi^\pm) = (0.2 \pm 1.5(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-2}$, and $A_{CP}(K^\pm\overline{K}^{*0}) = (0.9 \pm 1.7(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-2}$. These results are in agreement with previous published results [7], with our results in the resonant modes having significantly smaller errors.

Further, we obtain a preliminary branching ratio for $D^+ \to K^-K^+\pi^+$ decays relative to $D^+ \to K^-\pi^+\pi^+$ decays of $(10.7 \pm 0.1(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-2}$. This result is a significant improvement over previous measurements [8].

Table 5: Systematic errors for the branching ratio.

Source	Error $[10^{-2}]$
PID + tracking	0.22
Background estimate	0.05
Using $r \geq 6.0$	0.00
Using $r_1 \geq 8.8$	0.02
Total	0.23

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