Study of D^0 and D^+ Decays into Final States with Two or Three Kaons

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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have studied Cabibbo-suppressed D^0 decay modes resulting in the $K^+K^-\pi^+\pi^-$ final state and two-body D^0 decay modes with a ϕ meson in the final state. The $BR(D^0 \to K^0_S K^0_S \pi^+\pi^-)$ was measured for the first time. We also present a measurement of the $D^+ \to K^0_S K^0_S K^+$ branching ratio. The values are compared with other experimental results and model predictions.

1 Introduction

Over the last few years much attention has been given both to experimental and theoretical study of D meson decays. The simple spectator model [1] appears to be inadequate in describing nonleptonic D meson channels, while other approaches (see [2, 3, 4]), need further investigation. Cabibbo-allowed decays have already been studied at a relatively good level, and modern experiments have reached a sensitivity which allows the systematic study of Cabibbo-suppressed channels.

In this paper we report on a study of Cabibbo-suppressed D^0 decays. The decays under consideration include the $D^0 \to K^+K^-\pi^+\pi^-$ and the $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decay modes as well as a number of two-body channels with a ϕ meson in the final state. We also measured the branching ratio for Cabibbo-allowed decay $D^+ \to K^0_S K^0_S K^+$, which is presumed to proceed through the creation of an $s\overline{s}$ pair from the vacuum. This work extends the range of nonleptonic D decays investigated by ARGUS [6, 7, 8, 9, 10].

2 Data analysis

The data used for the analysis were taken on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances and in the nearby continuum using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The integrated luminosity of the sample is equal to 476 pb^{-1}, corresponding to more than $500,000$ D^0 and about $300,000$ D^+ mesons from continuum production. The ARGUS detector is a 4π spectrometer described in detail elsewhere [11].

Charged particles from the main vertex were required to have a polar angle θ with respect to the beam axis satisfying $|\cos\theta| \leq 0.92$. Particle identification was based on specific ionization, time of flight, energy deposition in the shower counters and hits in the muon chambers. This information was combined into likelihood ratios for each of the e, μ, π, K and p particle hypotheses. The likelihood ratio had to exceed 1% for the hypothesis to be accepted. The likelihood ratio for K mesons was required to be more than 5%.

Energy clusters in the calorimeter of more than 80 MeV which were not associated with a charged track were considered as photons. Two-photon pairs having an invariant mass within ± 60 MeV/c^2 of the nominal π^0 mass and a $\chi^2 < 9$ for the π^0 mass hypothesis fit were accepted as π^0 candidates and kinematically constrained to the known mass. We also attributed the π^0 hypothesis to energy clusters of more than 700 MeV. Photon detection and π^0 reconstruction are described in [12].

A K^0_S candidate was defined as a $\pi^+\pi^-$ pair forming a secondary vertex with an invariant mass within ± 30 MeV/c^2 of the K^0_S mass. In addition we required the cosine of the angle

between the momentum of the $\pi^+\pi^-$ system and the vector from the interaction point to the K^0_S decay vertex to exceed 0.9.

D^0 decay modes were analysed either from $D^{*+} \to D^0\pi^+$ [1] decay or without D^{*+} reconstruction. Due to the narrow D^{*+} signal the former method has the advantage of low background level. The latter one provides us with the larger statistics but requires consideration of numerous background sources.

ϕ, η and ω candidates were accepted if they had a measured mass within two standard deviations of the known masses [13]. Narrow intermediate resonances (η,ω) were kinematically fit, constraining their masses to the nominal values. D^0 candidates from reconstructed D^{*+} mesons were also treated in this way.

The invariant mass resolutions, the efficiencies for particle reconstruction and for the kinematical cuts for all channels were obtained from Monte Carlo simulation. The efficiency of the cut on the likelihood ratio for K mesons was determined from the data using K mesons from ϕ decays.

The momentum spectrum of D mesons from continuum production is significantly harder compared to that of the combinatorial background. Therefore all $D^0(D^{*+})$ and D^+ meson candidates were required to satisfy $x_p \geq 0.5$, where the scaled momentum of the D meson candidate is defined by $x_p = p_D/p_D^{max}$.

The mass spectra for the D^0, D^+ and D^{*+} signals were fit with the sum of a gaussian, to parametrize the signal and a polynomial, to parametrize background. In the case of $D^0\pi^+$ mass spectrum a square-root threshold factor was introduced.

The $D^0 \to K^0_S\pi^+\pi^-$ channel was used for normalization of the $D^0 \to K^0_SK^0_S\pi^+\pi^-$ mode, while the $D^0 \to K^-\pi^+\pi^-\pi^+$ channel was chosen for other D^0 decays under study. To normalize $D^+ \to K^0_SK^0_SK^+$ we used the $D^+ \to K^-\pi^+\pi^+$ mode. Absolute normalization was obtained using $BR(D^0 \to K^-\pi^+\pi^-\pi^+) = (7.5 \pm 0.5)\%$, $BR(D^0 \to K^0_S\pi^+\pi^-) = (2.7 \pm 0.3)\%$ and $BR(D^+ \to K^-\pi^+\pi^+) = (8.0^{+0.8}_{-0.7})\%$ [13].

Systematic errors were determined by varying the cuts, the background parametrization, the single track reconstruction efficiency and the widths of the signals. When calculating the relative efficiency some portions of these errors cancel. The errors in the PDG values for the branching ratios for $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^0_S\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$ channels were also included in the systematic error.

3 Study of the $D^0 \to K^+K^-\pi^+\pi^-$ resonance structure

D^0 candidates were accepted if their reconstructed masses differed by less than 20 MeV/c^2 from the nominal D^0 mass. $K^+K^-\pi^+\pi^-$ combinations having a $\pi^+\pi^-$ invariant mass consistent with the K^0 mass were not considered as D^0 candidates.

Figure 1 shows a clear signal at the D^{*+} mass in the $D^0\pi^+$ invariant mass distribution for the $D^0 \to K^+K^-\pi^+\pi^-$ channel. A contribution of six events from $D^0 \to K^-\pi^+\pi^-\pi^+$ due to $\pi \to$ "K" misidentification was subtracted, resulting in a signal of 114 ± 20 events.

[1] References to a specific particle state should be interpreted as implying the charge-conjugate state also.

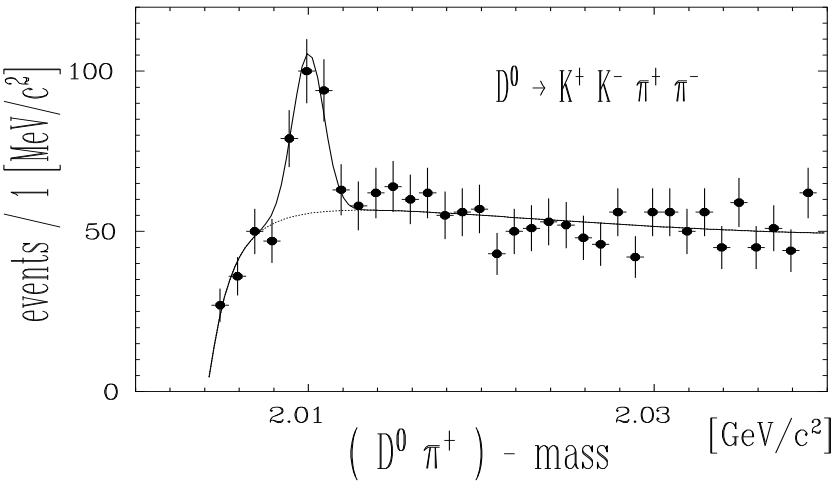

Figure 1: $D^0\pi^+$ invariant mass distribution for $D^0 \to K^+K^-\pi^+\pi^-$ channel

This leads to $BR(D^0 \to K^+K^-\pi^+\pi^-) = (0.31 \pm 0.05 \pm 0.04)\%$ in agreement with CLEO [14], E691 [15] and ACCMOR [16] results (see Table 1).

Table 1. Measurements of BR ($D^0 \to K^+K^-\pi^+\pi^-$)
(the E691 value is rescaled using BR ($D^0 \to K^-\pi^+\pi^-\pi^+$) from [13])

	$\frac{\text{BR }(D^0 \to K^+K^-\pi^+\pi^-)}{\text{BR }(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$BR(D^0 \to K^+K^-\pi^+\pi^-)$
ACCMOR		$(0.28 \pm 0.07)\%$
E691	$0.028^{+0.008}_{-0.007}$	$(0.21^{+0.06}_{-0.05} \pm 0.04)\%$
CLEO	0.0314 ± 0.010	$(0.24 \pm 0.08)\%$
ARGUS	$0.041 \pm 0.007 \pm 0.005$	$(0.31 \pm 0.05 \pm 0.04)\%$

The $K^+K^-\pi^+\pi^-$ final state structure study is discussed below. D^0 candidates consistent with having arisen from D^{*+} decays were used for further analysis. The numbers of events as well as the relative efficiencies for the channels are listed in Table 2.

Among the resonance structures of this final state the greatest focus to date has been on the $D^0 \to \phi\pi^+\pi^-$ and $D^0 \to \phi\rho^0$ modes.

The K^+K^- mass distribution for the $D^0 \to K^+K^-\pi^+\pi^-$ decay is shown in Figure 2. The corresponding spectrum obtained from the D^{*+} sideband (2.013 - 2.017 GeV/c^2) has been subtracted in this figure. The fit gives 28 ± 8 events for the ϕ signal. This results in $BR(D^0 \to \phi\pi^+\pi^-) = (0.15 \pm 0.04 \pm 0.03)\%$. Our value agrees within errors with the other measurements summarized in Table 3.

Figure 3 shows the D^{*+} sideband subtracted $\pi^+\pi^-$ mass spectrum for D^0 candidates with K^+K^- pairs consistent with being from a ϕ meson. K^+K^- pairs were considered as ϕ mesons if they had an invariant mass within ± 10 MeV/c^2 of the ϕ mass [2]. The distribution

[2] The same cut on the ϕ mass was applied in other modes.

Table 2. Structure of the $D^0 \to K^+K^-\pi^+\pi^-$ mode

Decay mode	Number of events	Relative efficiency
$D^0 \to K^-\pi^+\pi^-\pi^+$	3226 ± 65	1.00
$D^0 \to K^+K^-\pi^+\pi^-$	114 ± 20	0.86
$D^0 \to \phi\pi^+\pi^-$	28 ± 8	0.43
$D^0 \to K^{*0}K^-\pi^+$	55 ± 18	0.40
$D^0 \to \overline{K^{*0}}K^+\pi^-$	30 ± 17	0.40

Table 3. Measurements of $BR\ (\ D^0 \to \phi\pi^+\pi^-\ )$

	$\frac{\text{BR}\ (\ D^0 \to \phi\pi^+\pi^-)}{\text{BR}\ (\ D^0 \to K^-\pi^+\pi^-\pi^+)}$	$BR(D^0 \to \phi\pi^+\pi^-)$
ACCMOR		$(0.24 \pm 0.08)\%$
CLEO	0.024 ± 0.006	$(0.19 \pm 0.05)\%$
ARGUS	$0.020 \pm 0.006 \pm 0.005$	$(0.15 \pm 0.04 \pm 0.03)\%$

was fit to a relativistic p-wave Breit-Wigner with the current average values for the mass and width of the ρ meson [13] taking into account phase-space suppression. The K^0_S mass region was excluded from the fit. The $\pi^+\pi^-$ invariant mass spectrum is consistent with an entirely ρ^0 dominated contribution.

Assuming that $D^0 \to \phi\pi^+\pi^-$ decays proceed exclusively via $D^0 \to \phi\rho^0$, we can compare our result with theoretical predictions for two-body decays. Bauer, Stech and Wirbel predict a $D^0 \to \phi\rho^0$ branching ratio of about 0.10% [2], close to our result. Two different approaches to D meson decays have been considered by Kamal, Verma and Sinha [17]. In the factorization approach the branching ratio ranges from 0.026% to 0.080% and does not contradict what we derive from our measurements. In the nonet symmetry model they calculate $BR(D^0 \to \phi\rho^0) = (0.38 \pm 0.14) * 10^{-2}\%$ [17], which is significantly below our result, as well as the prediction of Bedaque, Das and Mathur [18] of 0.022% for this branching ratio.

Taking into account the π meson charge from the $D^0\pi$ combination in the D^{*+} signal we can distinguish D^0 from $\overline{D^0}$ and thus the decay modes $D^0 \to K^{*0}K^-\pi^+$ and $D^0 \to \overline{K^{*0}}K^+\pi^-$ from each other. After sideband subtraction, the $K^+\pi^-$ and $K^-\pi^+$ mass spectra for $D^0 \to K^+K^-\pi^+\pi^-$ decay appear as shown in Figures 4,5. Kaons (pions) consistent with being from a ϕ (K^0_S) mother were excluded from the analysis. As a consequence we fit the $K\pi$ invariant mass distributions with a relativistic Breit-Wigner function to describe the $K^{*0}(\overline{K^{*0}})$ signal, and a polynomial to parametrize non-K^* contributions. Both threshold factors were included in the fit function.

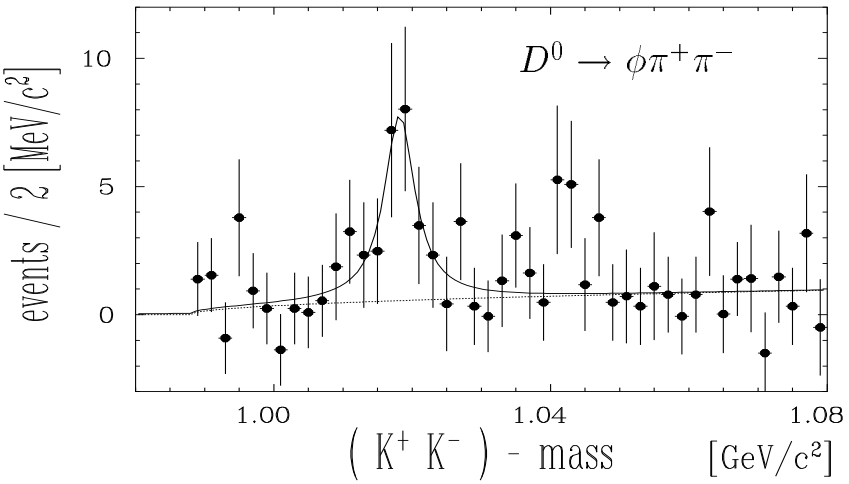

Figure 2: K^+K^- invariant mass distribution for $D^0 \to K^+K^-\pi^+\pi^-$ channel

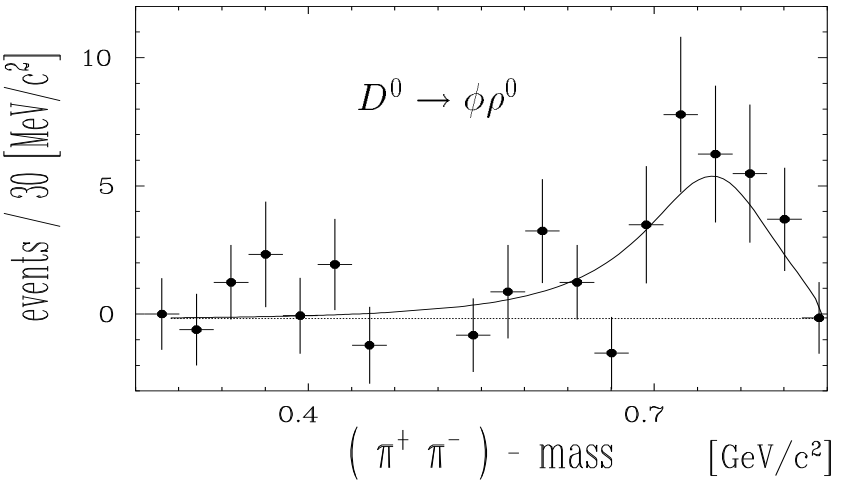

Figure 3: $\pi^+\pi^-$ invariant mass spectrum for $D^0 \to \phi\pi^+\pi^-$ channel

Finally we obtain :

$$\frac{BR(D^0 \to K^{*0}K^-\pi^+)}{BR(D^0 \to K^-\pi^+\pi^-\pi^+)} = 0.043 \pm 0.014 \pm 0.009,$$

$$\frac{BR(D^0 \to \overline{K^{*0}}K^+\pi^-)}{BR(D^0 \to K^-\pi^+\pi^-\pi^+)} = 0.023 \pm 0.013 \pm 0.009,$$

and hence

$$BR(D^0 \to K^{*0}K^-\pi^+) = (0.32 \pm 0.10 \pm 0.07)\%,$$
$$BR(D^0 \to \overline{K^{*0}}K^+\pi^-) = (0.17 \pm 0.10 \pm 0.07)\%.$$

This is the first measurement of BR ($D^0 \to \overline{K^{*0}}K^+\pi^-$). Earlier, E691 [15] set a 90% confidence level upper limit on the sum of both branching ratios of 0.28%.

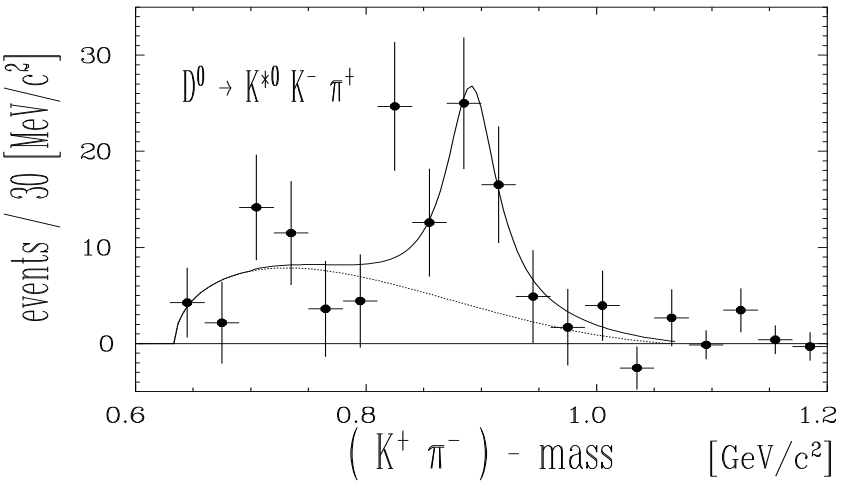

Figure 4: $K^+\pi^-$ invariant mass distribution for $D^0 \to K^{*0}K^-\pi^+$ channel

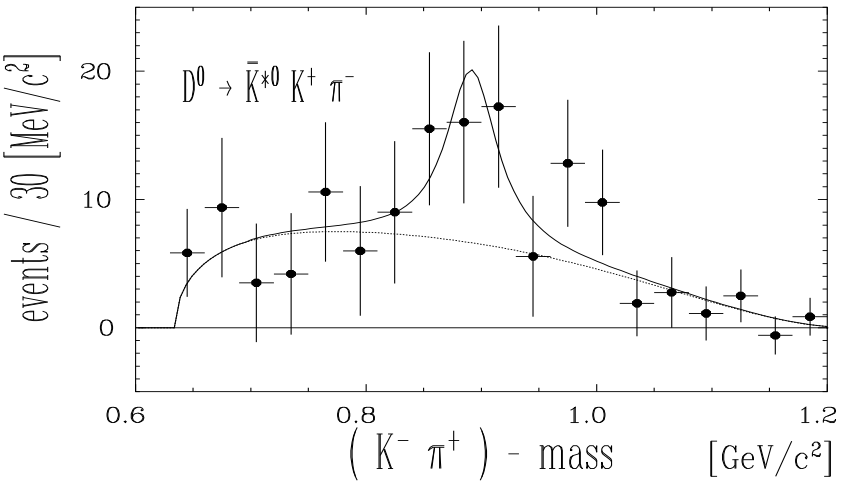

Figure 5: $K^-\pi^+$ invariant mass distribution for $D^0 \to \overline{K^{*0}}K^+\pi^-$ channel

4 Search for $D^0 \to \phi\pi^0, D^0 \to \phi\omega, D^0 \to \phi\eta$ decays

We have searched for other two-body decays of the D^0 with a ϕ meson in the final state. $D^0 \to \phi\pi^0$, $D^0 \to \phi\eta$ and $D^0 \to \phi\omega$ can all occur via internal emission of a W^+ boson. To reduce the combinatorial background associated with the soft photons used for the analysis only one combination per event was allowed by selecting the candidate with the maximum kinematical fit probability. The theoretical predictions as well as the numbers of events, the relative efficiencies and the upper limits obtained for the modes under consideration are included in Table 4.

To search for the $D^0 \to \phi\pi^0$ decay mode D^0 candidates were required to have a measured mass within ± 35 MeV/c^2 of the nominal D^0 mass. Since the ϕ must have helicity zero in the D^0 rest frame, the helicity angle θ_h, the angle between the π^0 meson and the direction

Table 4. Search for $D^0 \to \phi\pi^0, D^0 \to \phi\omega, D^0 \to \phi\eta$ decays

Decay mode	Number of events (Upper Limit @90% CL)	Relative efficiency	BR (Upper Limit @90% CL) (%)	Theoretical predictions (%)
$D^0 \to K^-\pi^+\pi^-\pi^+$	2734 ± 60	1.00	7.5 ± 0.5	
$D^0 \to \phi\pi^0$	< 5.3	0.10	< 0.14	0.06 [2] 0.05 [19] 0.21 [4]
$D^0 \to \phi\omega$	< 4.4	0.06	< 0.21	0.094 [2] 0.0035 ± 0.0013, 0.023...0.072 [17]
$D^0 \to \phi\eta$	< 5.7	0.06	< 0.28	0.014 [2]

of either K in the ϕ rest frame, was required to satisfy the condition $|\cos\theta_h| > 0.5$. A cut of $\cos\theta^* > -0.7$, where θ^* is the angle of the π^0 flight direction in the D^0 rest frame with respect to the D^0 boost direction, was also applied [3]. This takes advantage of the fact that the π^0 momentum in the D^0 rest frame is isotropic for signal events, while for combinatorial background it is peaked in the backward direction. The spectrum obtained shows no signal at the D^{*+} mass (see Figure 6).

From the theoretical point of view, the $D^0 \to \phi\omega$ decay bears strong resemblance to $D^0 \to \phi\rho^0$, although the more restricted phase space leads to a slight decrease in the branching ratio (see Table 4). For the decay $D^0 \to \phi\omega$ the mode $\omega \to \pi^+\pi^-\pi^0$ was used. We required the reconstructed ω (D^0) masses to lie within ± 40 MeV/c^2 (± 45 MeV/c^2) of the nominal masses. The resulting $D^0\pi^+$ mass distribution is shown in Figure 7. The fit leads us to an upper limit of 4.4 events @90%CL.

To complete the study of two-body decays with a ϕ meson, the $D^0 \to \phi\eta$ mode was searched for. The η mesons were reconstructed in the decay mode $\eta \to \gamma\gamma$. The D^0 candidates masses were allowed to differ by less than 50 MeV/c^2 from the known mass (the same cut for the η mass was set at ± 100 MeV/c^2). The same angular cuts used for the $D^0 \to \phi\pi^0$ channel were applied. The fit to the $D^0\pi^+$ invariant mass spectrum (Figure 8) provides us with an upper limit of 5.7 events for this decay.

In general our sensitivity is at the boundary of the values proposed by the various theoretical models. The upper limit on $D^0 \to \phi\pi^0$ mode is in contradiction to the Chau and Cheng value of 0.21% [4].

[3] The efficiencies of the angular cuts applied amount to 88% and 85% correspondingly.

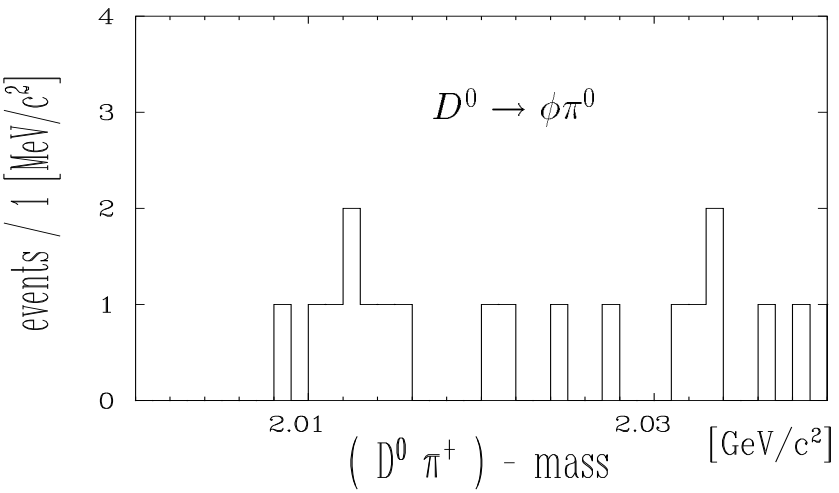

Figure 6: Search for $D^0 \to \phi\pi^0$ decay mode. $D^0\pi^+$ invariant mass distribution

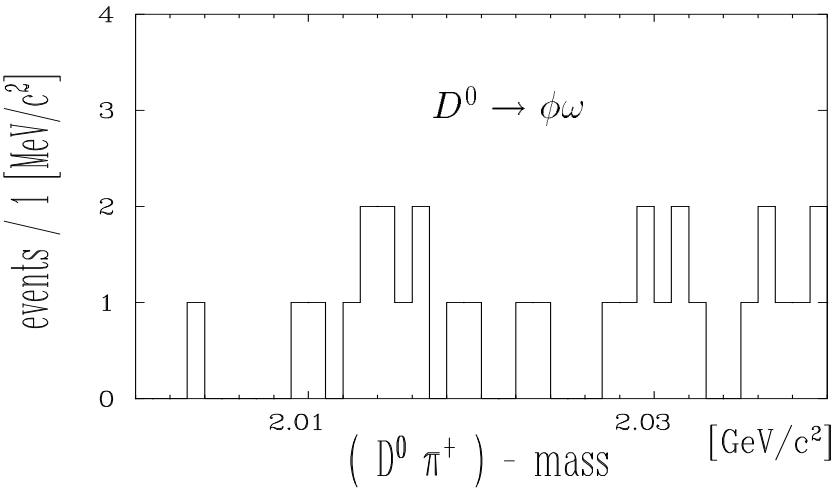

Figure 7: Search for $D^0 \to \phi\omega$ decay mode. $D^0\pi^+$ invariant mass distribution

5 $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decay mode

Good K^0_S mass resolution and secondary vertex requirement provide us with a clean event sample of D decays with K^0_S mesons in the final state. The Cabibbo-suppressed $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decay will be discussed here.

In order to avoid feeddown from the $D^0 \to K^0_S K^0_S K^0_S$ mode, $K^0_S K^0_S \pi^+\pi^-$ combinations with the $\pi^+\pi^-$ pair having a mass within ± 30 MeV/c^2 of the K^0_S mass were not used for the analysis. The D^0 resolution for this mode was found to be 9.2 MeV/c^2 from Monte Carlo. The $D^0\pi^+$ invariant mass spectrum is shown in Figure 9. The fit yields a signal of 8.6 ± 3.1 events at the D^{*+} mass. Assuming that whole mass range does not contain any signal, a background level has been fit and the Poisson probability for the background to fluctuate to the enhancement at D^{*+} mass has been obtained to be $7 \cdot 10^{-4}$. This conservative estimate

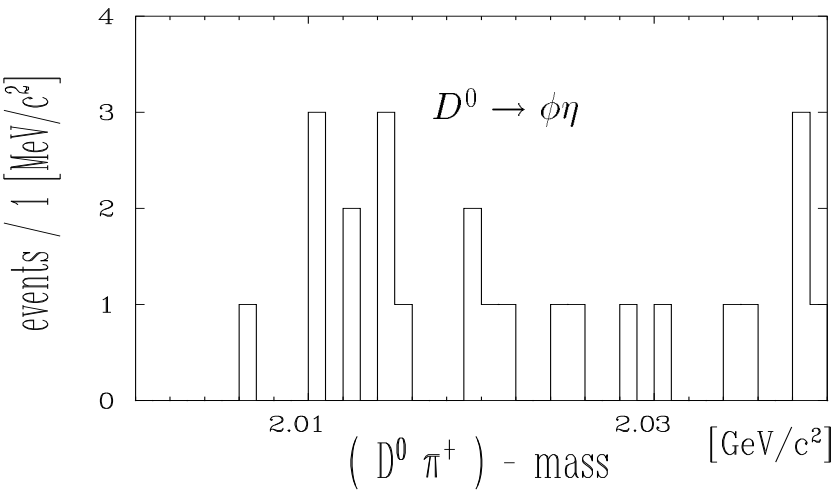

Figure 8: Search for $D^0 \to \phi\eta$ decay mode. $D^0\pi^+$ invariant mass distribution

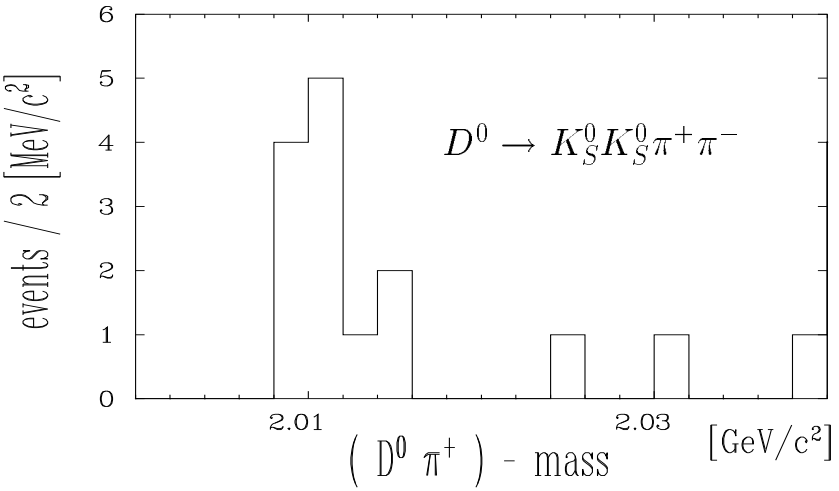

Figure 9: $D^0\pi^+$ invariant mass distribution for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ channel

corresponds to a significance of about 3.5 standard deviation. A signal is also observed in the $K^0_S K^0_S \pi^+\pi^-$ invariant mass spectrum without D^{*+} reconstruction at the level of 24.6 ± 9.7 events (Figure 10). The contribution from $D^0 \to K^0_S \pi^+\pi^-\pi^+\pi^-$ is less than 1 event.

For the $D^0 \to K^0_S \pi^+\pi^-$ mode used for normalization we obtained 521 ± 26 events at the D^{*+} mass and 2110±86 events without D^{*+} reconstruction. After averaging the independent parts of the signals in D^0 and D^{*+} we obtain $BR(D^0 \to K^0_S K^0_S \pi^+\pi^-) = (0.17 \pm 0.05 \pm 0.04)\%$.

6 $D^+ \to K^0_S K^0_S K^+$ decay mode

The $D^+ \to K^0_S K^0_S K^+$ decay is so far the only observed decay mode of the D^+ into three kaons, which involves the popping of an $s\bar{s}$ pair. Unlike most charm meson decays it seems to proceed as a three-body decay. The $K^0_S K^0_S K^+$ invariant mass spectrum is shown in Figure

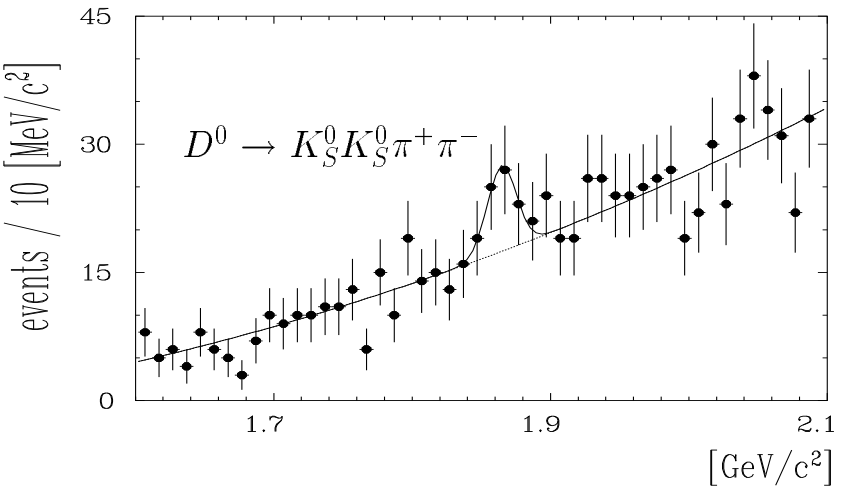

Figure 10: $K^0_S K^0_S \pi^+\pi^-$ invariant mass distribution for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ channel

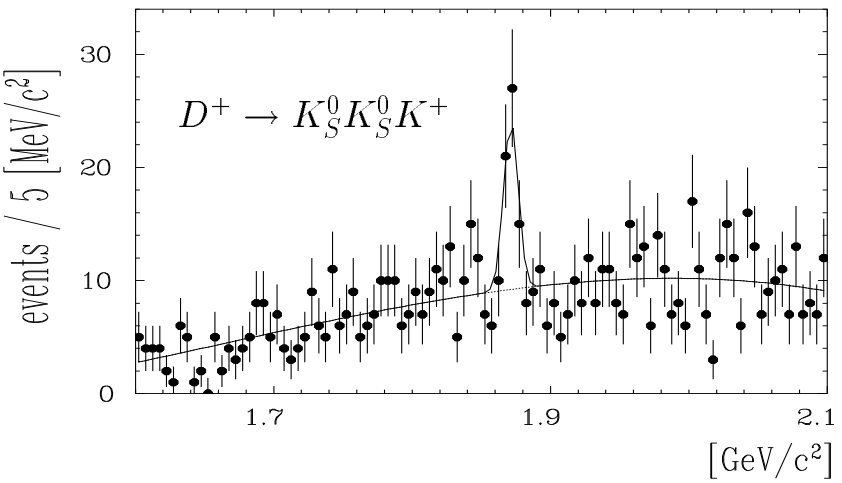

Figure 11: $K^0_S K^0_S K^+$ invariant mass distribution for $D^+ \to K^0_S K^0_S K^+$ channel

11. The distribution was fit with a gaussian (a width of 5.2 MeV/c^2 was determined from Monte Carlo) and a third-order polynomial to describe the background, yielding 39.2 ± 8.8 events in the signal region. The efficiency was found to equal 2.0% for D^+ candidates with $x_p \geq 0.5$.

To normalize the $D^+ \to K^0_S K^0_S K^+$ channel we use $D^+ \to K^-\pi^+\pi^+$ mode analyzed in detail in [20] and obtain $BR(D^+ \to K^0_S K^0_S K^+) = (0.28 \pm 0.08 \pm 0.05)\%$, which corresponds to $BR(D^+ \to \overline{K^0}\,\overline{K^0}\,K^+) = (1.1 \pm 0.3 \pm 0.2)\%$. Our branching ratio is somewhat smaller than the CLEO result, $BR(D^+ \to \overline{K^0}\,\overline{K^0}\,K^+) = (2.7 \pm 0.6)\%$ [14].

7 Summary

In conclusion, we have studied the D^0 decay modes resulting in the final state $K^+K^-\pi^+\pi^-$ and found $BR(D^0 \to K^+K^-\pi^+\pi^-) = (0.31 \pm 0.05 \pm 0.04)\%$. The branching ratios for $D^0 \to K^+K^-\pi^+\pi^-$ and $D^0 \to \phi\pi^+\pi^-$ agree with other measurements [14, 15, 16]. Our value for the $D^0 \to \phi\rho^0$ branching ratio agrees with the theoretical value from [2], while the prediction of [18] is smaller than our result. The BR$(D^0 \to K^{*0}K^-\pi^+) = (0.32 \pm 0.10 \pm 0.07)\%$ was measured for the first time.

We also looked for other two-body decay modes with a ϕ meson. The upper limits obtained are at the boundary of model predictions. Our upper limit for the $D^0 \to \phi\pi^0$ mode is in contradiction with the prediction of [4].

The $D^0 \to K^0_S K^0_S \pi^+\pi^-$ branching ratio was measured for the first time and found to be $(0.17 \pm 0.05 \pm 0.04)\%$.

The branching ratio of $(1.1 \pm 0.3 \pm 0.2)\%$ we obtained for $D^+ \to \overline{K^0}\ \overline{K^0}\ K^+$ is somewhat smaller than the previous CLEO result [14].

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