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E687

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Measurement of the Masses and Widths of L=1 Charm Mesons

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Abstract

We report the measurement of masses and widths of D^{**} and D_s^{**+} mesons ($L = 1$ charm mesons) by the E687 Collaboration at Fermilab. We report on a D^{**0} state of mass (width) 2453±3±2 (25±10±5) MeV/c^2 decaying to $D^+\pi^-$, a D^{**+} state of mass (width) 2453±3±2 (23±9±5) MeV/c^2 decaying to $D^0\pi^+$, a D^{**0} state of mass (width) 2422±2±2 (15±8±4) MeV/c^2 decaying to $D^{*+}\pi^-$, and a D_s^{**+} state of mass 2535.0±0.6±1.0 MeV/c^2 and width less than 3.2 MeV/c^2 at 90% confidence level, decaying to $D^{*+}K_s^0$ and $D^{*0}K^+$.
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In this paper we present results on the spectroscopy of bound states of a charm quark and a lighter quark with orbital angular momentum $L = 1$. For a given pair of quarks, four such states are expected. Their simplest allowed two-body strong decays into a D (or D^*) and a light pseudoscalar meson (π or K) are summarized in Table I. These states probe the interquark potential at larger distances than the charmonium ($c\bar{c}$) states. Mixing between the two 1^+ states is another interesting feature [1]. It has also been suggested recently that the decay properties of these states provide a test of the applicability of heavy-quark symmetry to charm quarks [2]. Because D^{**} states have been observed at a rate of roughly 1/10 of the ground state charm mesons [3], and because they suffer from increased combinatoric background since all daughters do not appear in a single vertex, they are experimentally difficult to study and information about them is sparse.

The data for this analysis were collected by the E687 collaboration during the 1990/91 fixed target run at Fermilab. Charm was generated in a beryllium target with a bremsstrahlung photon beam produced with a 320 GeV electron beam. A multiparticle magnetic spectrometer was used to detect the decay products of charm particles and is described elsewhere [4]. The selection of D and D^* candidates is described elsewhere [5]. Briefly, the tracks used in the D meson must form a vertex whose confidence level exceeds 1%. The requirement on the separation, l, between the primary and secondary vertices (production and decay vertices for the D-meson), divided by the uncertainty in the separation, σ, is listed in Table II for the various decay chains. The values for these cuts are chosen to produce good signal to background ratios for the D^0 and D^+ and are typical of the values used in the experiment to produce clean inclusive charm samples for a variety of studies. The results in this paper have been shown to be insensitive to the detailed choice of values.

I. $D^{**0} \to D^+\pi^-$ and $D^{**+} \to D^0\pi^+$

We begin with a study of the $D^+\pi^-$ and the $D^0\pi^+$ mass spectra. From angular momentum and isospin symmetry these spectra are expected to contain events from decays of $J =$

0 and $J = 2$ D^{**} states. However, according to most calculations using theoretical models, for example that by Godfrey and Kokoski [6], the $J = 0$ and $J = 2$ states are expected to be separated by at least 100 MeV, and the $J = 0$ state is expected to be much wider than the $J = 2$ state.

The D^+ or D^0 candidates were combined with the pion tracks in the primary vertex to form D^{**} candidates. The momentum of the cascade pion was required to be above 20 GeV/c. The cut on the pion momentum was motivated by the observation, from Monte Carlo simulation and experimental data, that the background in the D^{**} invariant mass plot is mainly due to soft pions combining randomly with the $D^+(D^0)$, whereas the pion from the D^{**} decay is expected to be relatively hard.

Fig. 1 shows the distribution in the invariant mass difference $\Delta M = M(D^+\pi^-) - M(D^+)$. The mass difference was used because many sources of error in the measurement of the mass of the D^+) are eliminated when the difference is used. The plot shows a pronounced peak at $\Delta M \approx 600$ MeV, consistent with being due to a D^{**0} of mass $M \approx 2460$ MeV. Due to the narrow width, this state has traditionally been identified as the $J = 2^+$ state [3]. There is an additional enhancement at $\Delta M \approx 420$ MeV which is consistent, as seen from Monte Carlo simulations, with arising from the states ($D^{**0}(2420)$ and $D^{**0}(2460)$), decaying to $D^{*+}\pi^-$, with the D^{*+} subsequently decaying to $D^+\pi^0$.

The D^{**0} signal was fit with a non-relativistic D-wave Breit-Wigner function, convoluted with a Gaussian resolution function ($\sigma = 7$ MeV) determined by Monte Carlo simulation for the decay mode (the same technique was used for all of the modes discussed in this paper). The variation of the acceptance across the signal was shown to shift the mass values and widths by amounts small compared to the statistical error for all the states reported in this paper and was neglected in the fits. The background was fit with the function

$$F = A(\Delta M - m_\pi)^B \exp[-C(\Delta M - m_\pi)], \tag{1}$$

where m_π is the pion mass, and A, B, and C are free parameters in the fit. The region around the enhancement at $\Delta M \approx 420$ MeV was excluded from the fit. The $\Delta M =$

$M(D^0\pi^+) - M(D^0)$ mass difference spectrum (Fig. 2) shows structures similar to those in the $\Delta M = M(D^+\pi^-) - M(D^+)$ spectrum. The peak at $\Delta M \approx 600$ MeV in this spectrum is interpreted as being due to the decay of a D^{**+} of mass M $\approx$ 2460 MeV decaying to $D^0\pi^+$, while the enhancement at $\Delta M \approx 420$ MeV is consistent with being due to D^{**+} states decaying to $D^{*0}\pi^+$, with the D^{*0} subsequently decaying to $D^0\pi^0$. The spectrum was fit with a function similar to that used for the $\Delta M = M(D^0\pi^+) - M(D^0)$ distribution.

For the $D^+\pi^-$ spectrum, we obtain 583.3 ± 3.1 MeV, 24.8 ± 8.5 MeV, 128 ± 28 and 35.5/35 for the position and width of the peak, the number of events (in a 100 MeV region around the peak) and the χ^2/df. The corresponding quantities for the $D^0\pi^+$ spectrum are 588.4 ± 2.9 MeV, 23.1 ± 9.6 MeV, 185 ± 42 and 34.8/35. For the isospin splitting between the D^{**0} and the D^{**+} we obtain $M(D^{**+}) - M(D^{**0}) = 0 \pm 4$ MeV/c^2. The only other measurement of this splitting is from ARGUS [3], which obtained a value of $+14 \pm 5 \pm 8$ MeV/c^2.

II. $D^{**0} \rightarrow D^{*+}\pi^-$

We turn next to the $D^{*+}\pi^-$ spectrum. The momentum of the cascade pion from the D^{**0} was required to be greater than 5 GeV/c. The $\Delta M = M(D^{*+}\pi^-) - M(D^{*+})$ mass difference spectrum is shown in Fig. 3a. The superimposed curve shows the best fit to the function in Eq. 1. The interval 350 - 500 MeV, the region in which ARGUS, E691 and CLEO have observed D^{**} states, was excluded from the fit. Just like the others we see a wide peak at ΔM $\approx$ 420 MeV above the fitted background. In light of previous observations by others [3] and our observation of the $J = 2$ state in the $D^+\pi^-$ decay mode, the peak is expected to have contributions from the $J = 2$ state decaying to $D^{*+}\pi^-$ and one or both of the $J = 1$ states decaying to $D^{*+}\pi^-$. The 2^+ state decays through a D-wave resulting in a distribution in $\cos\theta$, proportional to $\sin^2\theta$, where θ is the angle between the pions from the decays of the D^{**} and the D^*, measured in the D^* rest frame. The 1^+ states can decay through an S-wave or a D-wave, resulting in distributions in $\cos\theta$ which are flat and proportional to $(1 + 3\cos^2\theta)$ respectively. The 2^+ state was virtually eliminated by requiring that $|\cos\theta| > 0.8$. The resulting mass spectrum, shown in Fig 3b, exhibits a peak at $\Delta M \approx 410$ MeV. The spectrum in Fig. 3b was fitted with the background function of eq. 1 added to two D-wave Breit-Wigner peaks, broadened using a resolution of 4 MeV. One of the peaks represented the remaining contribution from the 2^+ state, and its mass and width were fixed at the values obtained for the $D^{**}(2460)$ from the $D^+\pi^-$ mass-spectrum. We obtain 412.1 ± 2.4 MeV and 14.8 ± 7.5 MeV for the position and width of the second peak, which represents the contributions from 1^+ states. We obtain 51 ± 18 for the number of events in a 60 MeV region around the peak. The solid curve superimposed on the histogram represents the best fit.

Fig. 3c shows the distribution in $|\cos\theta|$ for events in a 25 MeV region around $\Delta M = 412$ MeV in the spectrum of Fig. 3a. The dashed curve represents the best fit to $A(1 + 3\cos^2\theta)$ with A as the free parameter. The χ^2/df obtained was 0.6. The distribution from 25 MeV wide sidebands on either side of the peak-region, was found to be flat. We conclude that the decay of the D^{**} state at $M \approx 2420$ MeV to $D^{*+}\pi^-$ is is consistent with a decay through a D-wave. The dotted and solid curves represent the best fits to $A\sin^2\theta$ and A respectively. The χ^2/df obtained are 3.7 and 2.2 respectively.

The uncertainty in the values of the mass and width of each D^{**} state, due to the possibility of a wrong representation of the background in the region of the mass plot around the signal, was investigated using various functions to describe the background and varying the regions of the mass spectrum included in the fit and the cuts used in the analysis. The uncertainty in the mass and width due to the uncertainty in the estimated resolution for the mass differences was determined by varying the input parameters in the Monte Carlo used to find the resolution. The effect of the variation of acceptance with invariant mass was studied using Monte Carlo simulations and found to be negligible in comparison with uncertainties from other sources. The final systematic uncertainties in the mass and the width were dominated by uncertainty in the background. The uncertainty in the mass had a comparable contribution from the uncertainty in the masses of the D^0 and D^+.

III. $D_S^{**+} \rightarrow D^{*+}K^0$ and $D^{*0}K^+$

D_s^{**+} candidates were obtained by combining a D^{*+} with the K_s^0 in the event or combining a D^0 with a K^+. The $\Delta M = M(D^{*+}K^0) - M(D^{*+})$ mass difference spectrum is shown in Fig. 4. It has a narrow peak at $\Delta M \approx 525$ MeV. This has been interpreted as arising from a D_s^{**+} of mass ≈ 2535 MeV decaying to $D^{*+}K^0$.

The Gaussian width of the peak is found to be 4.0 ± 1.4 MeV. This is consistent with being entirely due to the resolution of the spectrometer, which is estimated to be 3.4 ± 0.2 MeV. Fitting with the background function of Eq. 1, added to a broadened Breit-Wigner function, we get 524.1 ± 1.3 and 9 ± 3 for the position of the peak and the number of events respectively. The Breit-Wigner width of the peak, Γ is less than 6.2 MeV at 90% confidence level. The probability that a statistical fluctuation in the background could cause 9 or more events to appear in the signal region was estimated to be 2.5 X 10^{-8}.

The observation of a D_s^{**+} decaying to $D^{*+}K^0$ leads one to expect a decay of the same state to $D^{*0}K^+$. With the branching fraction for $D^{*0} \rightarrow D^0\pi^0 \approx 1/2$ and small Q-value for the π^0 resulting from the decay of the D^{*0}, the state should be observable in the $M(D^0K^+) - M(D^0)$ spectrum. From a Monte Carlo simulation of the decay of a D_s^{**+} with mass 2535.0 MeV and infinitesimally narrow width, the peak is expected to appear at $\Delta M = 527.1$ MeV and have a Gaussian width 2.8 MeV. The $\Delta M = M(D^0K^+) - M(D^0)$ spectrum of Fig. 5 does indeed exhibit a narrow peak at approximately 525 MeV. The Gaussian width of the peak is consistent with being entirely due to the resolution of the spectrometer. With the hypothesis that this peak is due to the D_s^{**+} the spectrum was fit with a background function added to a broadened Breit-Wigner peak. The best fit is shown in Fig. 5. We obtain N=66 $\pm$ 14 and 527.0 ± 0.7 MeV for the number of events and position of the peak and $\Gamma<3.2$ MeV at 90% confidence level for the width of the peak. Combining the results from the D^*K^0 and D^0K^+ spectra we obtain M=2535.0 $\pm$ 0.6 and $\Gamma<3.2$ MeV at 90% confidence level for the mass and width of the D_s^{**+} state. The systematic uncertainty is dominated by the uncertainty in the D^0 mass.

IV. DISCUSSION

Table III lists the results for the masses and widths obtained for the various $L = 1$ states, along with the statistical and systematic uncertainties, in that order.

While the decay $D^{**0} \to D^+\pi^-$ has been observed by E691, ARGUS and CLEO [3], the corresponding decays of the isospin partner D^{**+}, $D^{**+} \to D^0\pi^+$, has been observed only by ARGUS. The decay of the D^{**+} is more difficult to observe because the background in the $D^0\pi^+$ spectrum due to random combinations of D^0 and π^+ is higher than the corresponding background in the $D^+\pi^-$ spectrum. The reason for the higher background is that all the D^{*0} decay to D^0 and a neutral particle, while only half of the D^{*+} decay to a D^+ and a neutral particle. Using a requirement on the momentum of the pion to be combined with the D^0, E687 was able to reduce background in the $D^0\pi^+$ mass spectrum and make a good measurement of the mass and width of the D^{**+}.

The variation in the masses measured for the D^{**} states in different experiments compared to the quoted statistical errors, indicates that statistical fluctuations in the signal and background constitute only a small part of the uncertainty in the measurements. A look at the $D\pi$ mass plots from E691, ARGUS, and CLEO reveals that accurate background determination on the low mass side of the peak is hampered by the presence of the reflection from the decay $D^{**0} \to D^{*+}\pi^-$, $D^{*+} \to D^+\pi^0$ in case of the D^{**0}, and from the decay $D^{**+} \to D^{*0}\pi^+$, $D^{*0} \to D^0\pi^0$ in the case of the D^{**+}. A small region on the lower mass side beyond this reflection has been used in the determination of the background shape. The use of a very limited region even beyond the reflection is probably due to the presence of other structures at lower masses, which we see in our mass spectra. These are perhaps due to decays of excited D states with the state only partially reconstructed. Our Monte Carlo simulations show that D^{**} decays to $D\eta$ or $D\rho$, would cause such structures. However a momentum requirement (momentum >20 GeV) on the pion combined with a D-candidate to obtain a D^{**+} candidate, virtually eliminates these structures and enables one to make a reliable background determination using a wider range. When we make such a momentum cut, we do indeed find that we have a smooth background over a wide range.

To conclude, we observe a D^{**0} state which we identify as the 2^+ state $D^{**0}(2460)$ observed previously by E691, ARGUS and CLEO [3], and a D^{**+} state which is identified as the isospin partner of the $D^{**0}(2460)$ observed previously by ARGUS [3]. We obtain a value of $0 \pm 4 \pm 3$ MeV/c^2 for the isospin mass splitting between the D^{**+} and the D^{**0} which is lower than but compatible with that obtained by ARGUS [3]. We also observe a D^{**0} state which is identified as the 1^+ state $D^{**0}(2420)$ observed by ARGUS and CLEO [3]. Finally, we observe a D_s^{**+}, which we identify as the $D_s^{**+}(2536)$ observed by ARGUS and CLEO [3].

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TABLES

TABLE I. Allowed 2-body strong decays into D or D^* mesons and pions or kaons

State	J^P	Decay mode(D^{**})	Decay Mode (D_s^{**})
$^3P_2$	2^+	$D^*\pi$, $D\pi$	D^*K, DK
$^3P_1$	1^+	$D^*\pi$,	D^*K
$^1P_1$	1^+	$D^*\pi$	D^*K
$^3P_0$	0^+	$D\pi$	DK

TABLE II. Vertex Separation cuts used for the various decay chains

Decay Chain	l/σ
$D^{**0} \rightarrow D^+\pi^-$, $D^+ \rightarrow K^-\pi^+\pi^+$	20
$D^{**+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$	8
$D^{**+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$	8
$D^{**0} \rightarrow D^{*+}\pi^-, D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$	2
$D^{**0} \rightarrow D^{*+}\pi^-, D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	4
$D_s^{**+} \rightarrow D^{*+}K^0, D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$	2
$D_s^{**+} \rightarrow D^{*+}K^0, D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	4
$D_s^{**+} \rightarrow D^{*0}K^+, D^{*0} \rightarrow D^0\pi^0, D^0 \rightarrow K^-\pi^+$	8
$D_s^{**+} \rightarrow D^{*0}K^+, D^{*0} \rightarrow D^0\pi^0, D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	8

TABLE III. Results : Masses and Widths in MeV/c^2

State	Decay Mode	Mass	Width
D^{**0}	$D^+\pi^-$	$2453 \pm 3 \pm 2$	$25 \pm 10 \pm 5$
D^{**+}	$D^0\pi^+$	$2453 \pm 3 \pm 2$	$23 \pm 9 \pm 5$
D^{**0}	$D^{*+}\pi^-$	$2422 \pm 2 \pm 2$	$15 \pm 8 \pm 4$
D_s^{**+}	$D^{*+}K^0$,$D^{*0}K^+$	$2535.0 \pm 0.6 \pm 1.0$	<3.2(90%CL)

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FIGURES

FIG. 1. The $M(D^+\pi^-) - M(D^+)$ mass-difference spectrum.

FIG. 2. The $M(D^0\pi^+) - M(D^0)$ mass-difference spectrum.

FIG. 3. a) $M(D^{*+}\pi^-) - M(D^{*+})$ mass-difference spectrum. b) $M(D^{*+}\pi^-) - M(D^{*+})$ mass-difference spectrum with $|cos\theta| > 0.8$. c) Distribution in $|cos\theta|$ for 400 MeV/c^2 $< M(D^{*+}\pi^-) - M(D^{*+}) <$ 425 MeV/c^2.

FIG. 4. The $M(D^{*+}K_s^0) - M(D^{*+})$ mass-difference spectrum.

FIG. 5. The $M(D^0K^+) - M(D^0)$ mass-difference spectrum.

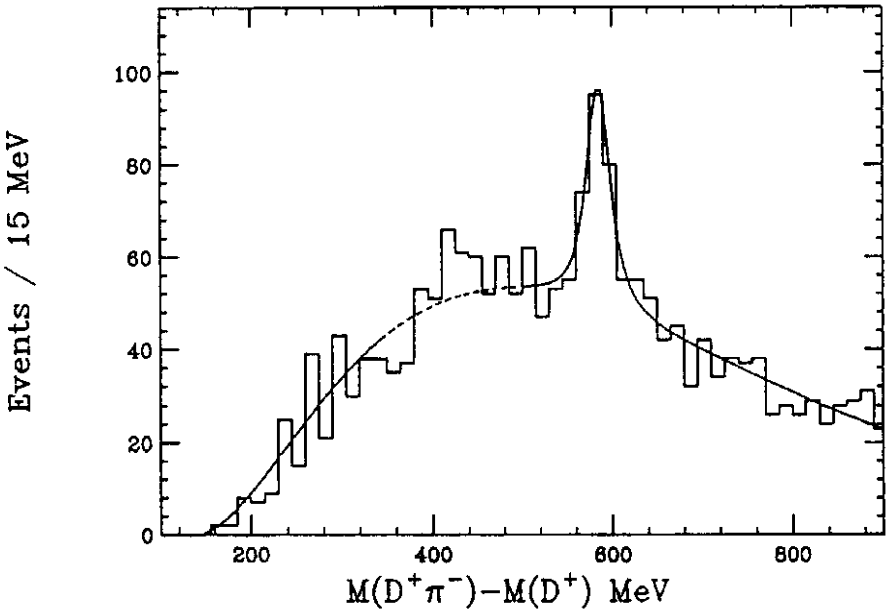

FIG. 1. The $M(D^+\pi^-) - M(D^+)$ mass-difference spectrum.

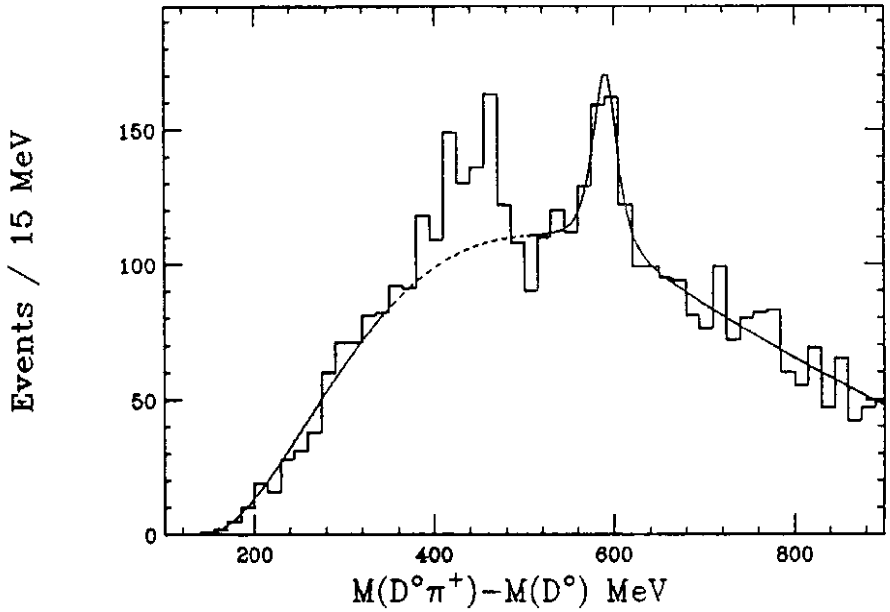

FIG. 2. The $M(D^0\pi^+) - M(D^0)$ mass-difference spectrum.

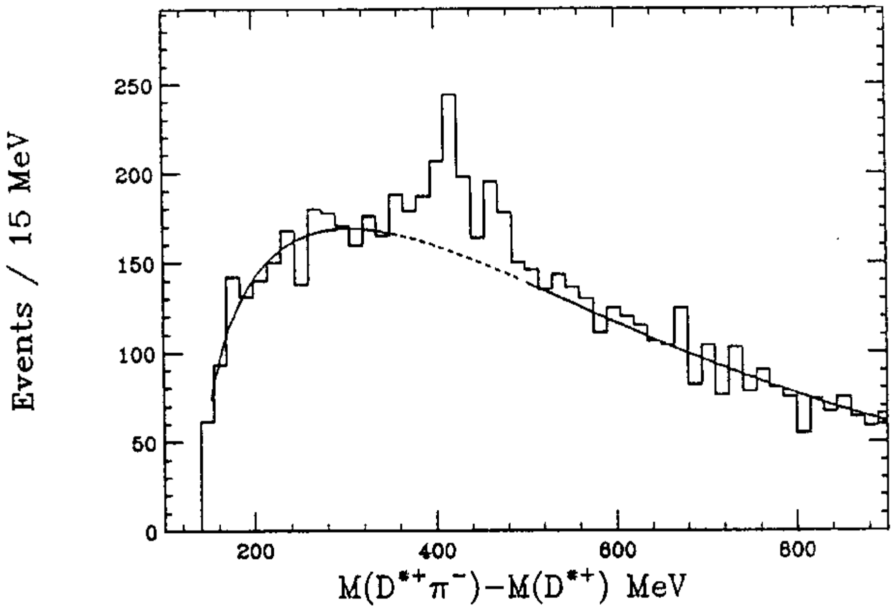

FIG. 3.a.) $M(D^{*+}\pi^-)$ - $M(D^{*+})$ mass-difference spectrum.

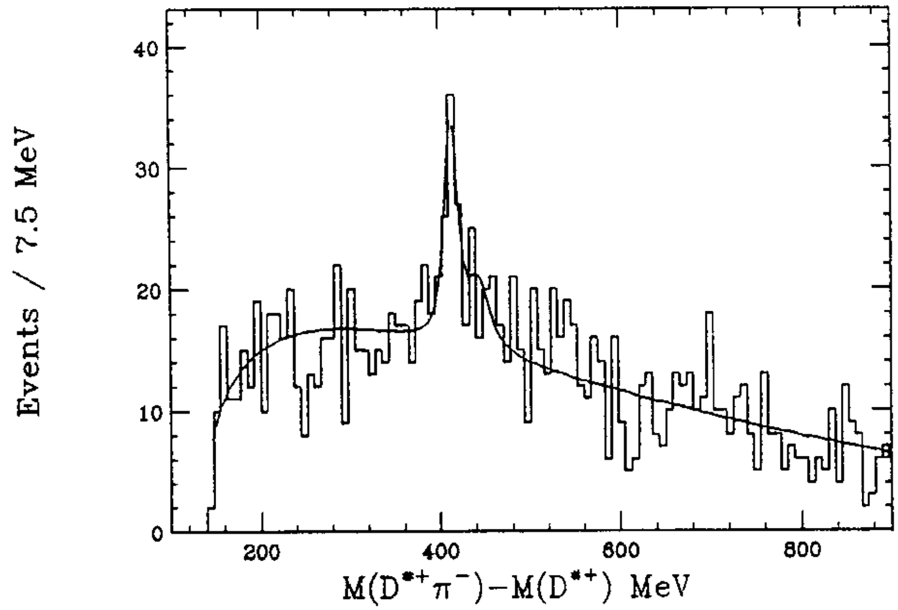

FIG. 3.b.) $M(D^{*+}\pi^-)$ - $M(D^{*+})$ spectrum with $|cos\theta| > 0.8$

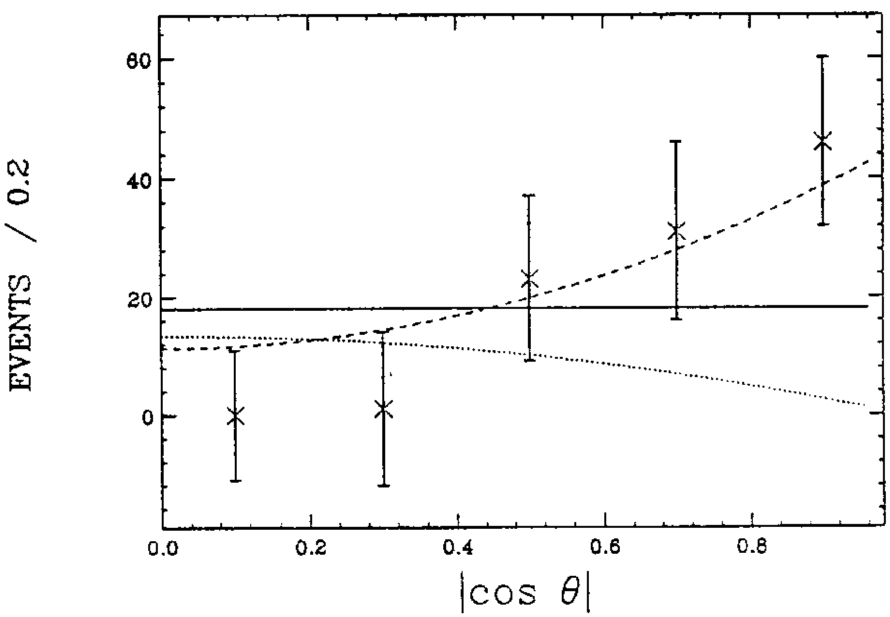

FIG. 3.c.) Distribution in $|cos\theta|$ for
$400\ MeV/c^2 < M(D^{*+}\pi^-) - M(D^{*+}) < 425\ MeV/c^2$.

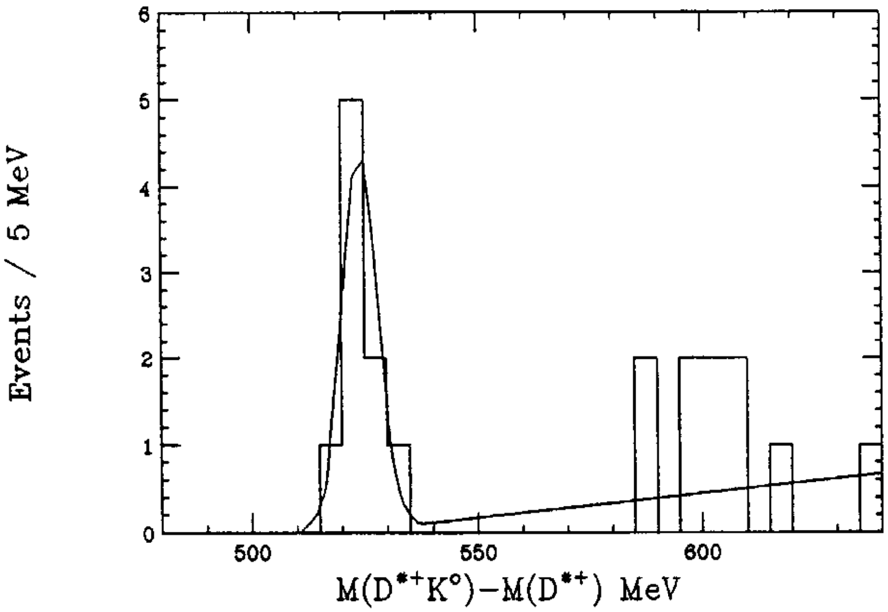

FIG. 4. The $M(D^{*+}K_s^0) - M(D^{*+})$ mass-difference spectrum.

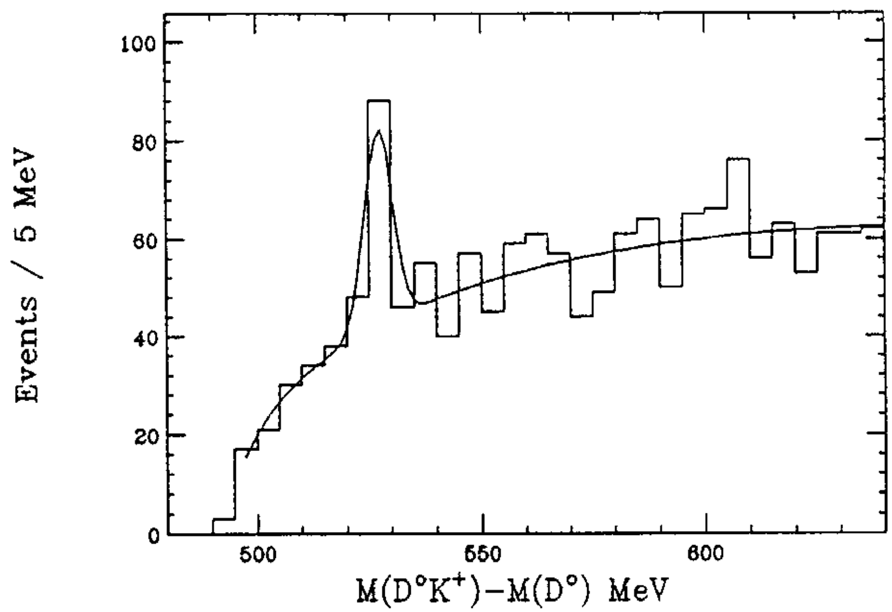

FIG. 5. The $M(D^0K^+) - M(D^0)$ mass-difference spectrum.