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INCLUSIVE NEUTRAL D^* PRODUCTION AND LIMITS ON F^* PRODUCTION IN $e^+ e^-$ ANNIHILATIONS AT PETRA

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ABSTRACT. D^{*0} mesons, produced in e^+e^- annihilations, are observed in the γD^0 and $\pi^0 D^0$ decay modes, where the D^0 subsequently decays into $K^-\pi^+$. The production cross section and the x_E distribution for D^{*0} mesons are extracted from the data, and compared with corresponding measurements for D^{*+} mesons. The branching ratio for the D^{*0} radiative decay is measured to be 0.53 ± 0.13. An upper limit for the $\sigma \cdot BR$ of the F^{*+} meson, where the associated F^+ decays into $\phi\pi^+$, is also derived.

There has been much recent study of the production of D^{*+} [**1-7**] and F^{*+} [**8**,9] mesons in high energy e^+e^- annihilations. Substantially less is known about the production and decay of D^{*0} mesons. Their production properties at high energies are determined by invoking isospin invariance and using the observed D^{*+} properties, and their decay branching ratios have been measured only by e^+e^- experiments taking data on the $\psi(4030)$. These experiments did not directly observe all of the D^{*0} decay products, but measured $K^-\pi^+$ momentum and recoil spectra [10], or π^0 and γ momentum spectra [11], which include large contributions from sources other than D^{*0} mesons (D^{*+}, D^+, D^0 and continuum production), and D^{*0} branching ratios were then extracted from multireaction fits to the spectra. An attempt to reduce the number of reactions in the fits by invoking isospin constraints on D^* decays resulted in substantially different branching ratios for D^{*0} decays than those derived from the fits without the additional constraints [10].

In this paper we present evidence of the observation of the two allowed decay modes of the D^{*0} meson:

$$D^{*0} \to \gamma D^0, \tag{1}$$

$$D^{*0} \to \pi^0 D^0, \tag{2}$$

with the subsequent decay:

$$D^0 \to K^-\pi^+. \tag{3}$$

When not otherwise noted, the charge conjugate reactions are implicitly included for all reactions described in this paper. The standard Δm technique [**12**] was utilized in isolating the D^* mesons from background. Since we measure both reactions (1) and (2) directly and independently, the branching ratios for reactions (1) and (2) can be calculated in a way which suppresses some systematic errors.

The production and decay of the F^{*+} meson is very similar to the production and radiative decay of the D^{*0}, so we have also searched for evidence of F^{*+} production through the established [8,13-15] decay chain:

$$F^{*+} \to \gamma F^+,\ F^+ \to \phi\pi^+,\ \phi \to K^+K^-. \tag{4}$$

The data used in this analysis are from a sample of 23926 multihadronic e^+e^- annihilations with $29 < \sqrt{s} < 39$ GeV, with an average $\sqrt{s}$ of 34.4 GeV. The data correspond to an integrated luminosity of 75 pb^{-1}. The JADE detector, trigger, and multihadron event selection criteria are described in detail elsewhere [**16**,17]. The critical components of the detector for this analysis are the central jet chamber for the measurement of charged tracks, and the 2604 element barrel lead-glass array for the measurement of electromagnetic showers. The energy resolution of the lead-glass array for isolated photons is $\sigma(E)/E = 0.04/\sqrt{E} + 0.015$ (E in GeV), and the average angular resolution is 20 mrad in θ and ϕ [**18**].

To isolate the decay products of reaction (1), the following procedure was used:

A1. D^0 candidates were selected as all $K^-\pi^+$ combinations with a mass between 1660 and 2060 MeV. No particle identification was required in any of the analysis in this paper; all pairs of oppositely charged particles were tried with $K^-\pi^+$ and π^-K^+ mass assignments.

A2. To reduce combinatorial background, we required that $-0.8 < \cos\theta < 0.8$, where θ is the angle between the π^+ direction in the $K^-\pi^+$ rest frame and the direction of the boost from the lab frame to the $K^-\pi^+$ rest frame. A π^+ from a D^0 decay should have an isotropic distribution in the D^0 rest frame, whereas the background is strongly peaked at $\cos\theta = \pm 1$.

A3. Isolated photons [18] in the barrel lead-glass array with $E(\gamma) > 400$ MeV were combined with the $K^-\pi^+$ combinations to form D^{*0} candidates.

A4. All charged tracks and photons forming a D^{*0} candidate were required to be in the same sphericity hemisphere (sphericity hemispheres will hereafter be referred to as "jets").

A5. The scaled energy of a D^{*0} candidate, $x_E = E(\gamma K^+\pi^-)/E_{BEAM}$, was required to be between 0.5 and 1.0.

A6. The γ in a D^{*0} candidate was required not to form a π^0 with any other γ in the same jet. This meant that $100 < m(\gamma\gamma) < 170$ MeV was vetoed, corresponding to 2σ of the JADE π^0 signal [18].

The $\Delta m = m(\gamma K^-\pi^+) - m(K^-\pi^+)$ distribution for the combinations which passed the above cuts is shown in Figure 1. A clear enhancement is seen between 120 and 160 MeV, corresponding to the D^{*0} radiative decay. The curve shown in Fig. 1 is a fit to a four parameter background function of the form $C_1(\Delta m - C_2)^{C_3}e^{C_4\Delta m}$, plus one Gaussian for the $D^{*0} \to \gamma D^0$ signal and another for the remaining amount of $D^{*0} \to \pi^0 D^0$ reflection not removed by cut A6. The central masses and widths of the Gaussians were fixed using the results of Monte Carlo studies. The Gaussian for the remaining reflection from reaction (2) is not really needed. If it is omitted, the background function plus signal Gaussian fit the data well, without changing the number of entries under the signal Gaussian. Monte Carlo studies show that photons from reaction (2) produce Δm values lower than 100 MeV, so this reflection contributes to the low Δm background but not to the $D^{*0} \to \gamma D^0$ signal.

The procedure used to isolate candidates for reaction (2) was similar to that used for reaction (1), and the steps are denoted B1-B5. Steps B1, B2, B4, and B5 are identical to A1, A2, A4, and A5, except that the term D^{*0} candidate now refers to a $\pi^0 K^-\pi^+$ combination. Step B3 defines the π^0 in reaction (2):

B3. We looked for combinations of two photons, each with $E(\gamma) > 100$ MeV, which formed a π^0 ($100 < m(\gamma\gamma) < 170$ MeV) with $E(\pi^0) > 400$ MeV. The two photons were constrained to the π^0 mass using a kinematic fit. The π^0 mesons were then combined with $K^-\pi^+$ combinations from D^0 candidates to form D^{*0} candidates.

The quantity $\Delta m = m(\pi^0 K^-\pi^+) - m(K^-\pi^+)$ was then histogrammed for all combinations which passed this procedure (solid line in Fig. 2). An enhancement is observed at $\Delta m < 160$ MeV, corresponding to a signal for reaction (2). The dashed line in Fig. 2 is the Δm distribution for D^0 "candidates" from the D^0 high mass sideband $2070 < m(K^-\pi^+) < 2470$ MeV, after application of steps B2-B6.

The signal regions for reactions (1) and (2) were then defined as $120 < \Delta m < 160$ MeV in their respective Δm distributions. Cross sections were calculated on the basis of the number of jets containing D^{*0} mesons, using the assumption that there should be at most one D^{*0} per jet. A fraction of the signal entries in Figures 1 and 2 are from jets with more than one D^{*0} in them, mostly due to the $K^-\pi^+$ and π^-K^+ mass assignments of the same pair being within the D^0 mass cut. The two data samples were separately binned in five x_E bins. Then, on a bin-by-bin basis, backgrounds were subtracted and corrections were made for acceptance, initial state radiation, and reflections from other D^0 decays (satellite resonances), using the results of Monte Carlo studies.

The branching ratio for reaction (1) is given by:

$$BR(D^{*0} \to \gamma D^0) = \frac{N_1^c}{N_1^c + N_2^c}, \quad (5)$$

where N_1^c and N_2^c are the corrected numbers of D^{*0} mesons observed in reactions (1) and (2), respectively. The D^{*0} mesons we observed for reactions (1) and (2) both had the same subsequent D^0 decay (3), so the uncertainty in the branching ratio of reaction (3) does not directly contribute to the uncertainty in our value for the branching ratio for reaction (1). Likewise, since the same $x_E = E(D^{*0})/E_{BEAM}$ cuts were applied to the data samples for reactions (1) and (2), the uncertainty in the shape of the D^{*0} x_E spectrum does not contribute to the uncertainty in the calculated branching ratio. The branching ratio for reaction (1), from the corrected numbers of observed D^{*0} mesons in the two data samples, is:

$$BR(D^{*0} \to \gamma D^0) = 0.53 \pm 0.09(stat.) \pm 0.10(sys.).$$

This number is in agreement with the Particle Data Group average of 0.45 ± 0.15 [19].

The corrected dN/dx_E distributions for the two data samples were then combined. The total number of entries in this distribution corresponds to a cross section times branching ratio of:

$$\sigma(D^{*0} + \overline{D}^{*0}, x_E > 0.5) \cdot BR(D^0 \to K^-\pi^+) = 5.8pb \pm 1.6pb.$$

With a value of $BR(D^0 \to K^-\pi^+) = 0.030 \pm 0.006$ [20], the $s \cdot d\sigma(D^{*0} + \overline{D}^{*0})/dx_E$ distribution is shown in Fig. 3 (closed circles), along with the JADE $s \cdot d\sigma(D^{*+} + D^{*-})/dx_E$ distribution [5] (open circles; the curve is a fit of a Peterson-type fragmentation function of x_E [21,22] to the D^{*+} data). We see that, within errors, the x_E distribution for D^{*0} production is consistent with that measured for D^{*+} production.

With the D^0 branching ratio from Ref. [20], we find $\sigma(D^{*0} + \overline{D}^{*0}, x_E > 0.5) = 0.19nb \pm 0.06nb$. JADE has previously measured $\sigma(D^{*+} + D^{*-}, x_E > 0.4) = 0.14nb \pm 0.04nb$ [5], which corresponds to $0.11nb \pm 0.03nb$ for $x_E > 0.5$. We expect $\sigma(c + \bar{c}) = 0.22nb$ at $\sqrt{s} = 34$ GeV, or $R_{c,\bar{c}} = 2.9$, and we see $R(D^{*0} + \overline{D}^{*0}, x_E > 0.5) = 2.6 \pm 0.8$. Using the Lund 5.2 Monte Carlo program [23] with a standard set of assumptions,[1] we expect $\sigma(D^{*0} + \overline{D}^{*0}, x_E > 0.5) \approx 50pb$ (including $1.5pb$ from $b\bar{b}$ production), and our measurement is 2.2σ above this Monte Carlo value. One contribution to our calculation which could make our measured cross section too large is that the value used for $BR(D^0 \to K^-\pi^+)$ might be too low. The MARK III

[1] The critical assumptions are $s\bar{s}/u\bar{u} = 0.3$, PS/V=0.33 for heavy quarks, and $\epsilon_c = 0.05$ and $\epsilon_b = 0.018$ for Peterson-type fragmentation functions of z, where $z = (E + p_{||})_{MESON}/(E + p_{||})_{QUARK}$ [22].

experiment has recently measured this branching ratio in both single and double tagged D^0 production [24], and both measurements give a value larger than the 0.030 ± 0.006 which we used in our calculation. Using the MARK III double tagged D^0 branching ratio of $0.049 \pm 0.009 \pm 0.005$, our measured cross section would be $\sigma(D^{*0} + \overline{D}^{*0}, x_E > 0.5) = 0.12nb \pm 0.04nb$, closer to the expectation of the Lund Monte Carlo program.

In order to search for F^{*+} candidates via reaction (4), we used the following procedure:

C1. ϕ candidates were selected as all oppositely charged tracks which satisfied the requirement $970 < m(K^+K^-) < 1070$ MeV. We then combined all ϕ candidates with other charged tracks in the event to form $K^+K^-\pi^+$ combinations, and required that $1770 < m(K^+K^-\pi^+) < 2170$ MeV to define F^+ meson candidates.

C2. We required that $-0.8 < \cos\theta < 0.8$, where θ is the angle between the π^+ direction in the $K^+K^-\pi^+$ rest frame and the direction of the boost from the lab frame to the $K^+K^-\pi^+$ rest frame, for the same reason as in A2.

C3. Isolated photons in the barrel lead-glass array with $E(\gamma) > 400$ MeV were combined with the $K^+K^-\pi^+$ combinations to form F^{*+} candidates.

C4. All charged tracks and photons forming an F^{*+} candidate were required to be in the same jet.

C5. The x_E of an F^{*+} candidate was required to be between 0.5 and 1.0.

The $\Delta m = m(\gamma K^+K^-\pi^+) - m(K^+K^-\pi^+)$ distribution is shown in Fig. 4 for all combinations which pass the above procedure. Monte Carlo results indicate that an F^{*+} signal should appear in the $120 < \Delta m < 160$ MeV region for $m(F^{*+}) - m(F^+) = 144$ MeV, and we observe no signal above background in this region. Using the results of the Monte Carlo studies and assuming a value for $m(F^{*+}) - m(F^+)$ similar to that measured in Refs. [8] and [9], we set an upper limit on the production of F^{*+} mesons:

$$\sigma(F^{*+} + F^{*-},\ x_E > 0.5) \cdot BR(F^+ \to \phi\pi^+) < 5.4\ pb\ (95\%\ C.L.).$$

From the Lund 5.2 Monte Carlo program with the same parameters as those used to estimate the D^{*0} production cross section, we expect $\approx$ 14.4 pb of F^{*+} and F^{*-} production for $x_E > 0.5$. This expectation and the $\sigma \cdot BR$ upper limit can be converted to an upper limit on the F^+ branching ratio:

$$BR(F^+ \to \phi\pi^+) < 0.37\ (95\%\ C.L.).$$

Since measurements and expectations for this branching ratio are in the range of 5-15% [13-15], our upper limit for the F^{*+} production cross section times the F^+ branching ratio is consistent with the expected level of F^{*+} production in e^+e^- annihilations at these energies.

In conclusion, we have observed evidence of D^{*0} meson production and its subsequent decay into its allowed decay modes, γD^0 and $\pi^0 D^0$. The branching ratio for the D^{*0} radiative decay is measured to be 0.53 ± 0.13. The D^{*0} x_E distribution is consistent with that previously measured for D^{*+} production over the x_E range studied, and the D^{*0} production cross section times the D^0 branching ratio into $K^-\pi^+$ is measured to be $5.8pb \pm 1.6pb$ in the range $x_E > 0.5$. We searched for F^{*+} meson production using the subsequent $F^+ \to \phi\pi^+$ decay mode. No evidence was observed for F^{*+} production, and we calculate an upper limit on the F^{*+} and F^{*-} production cross section times the F^+ branching ratio of $5.4pb$ ($95\% C.L.$) for $x_E > 0.5$.

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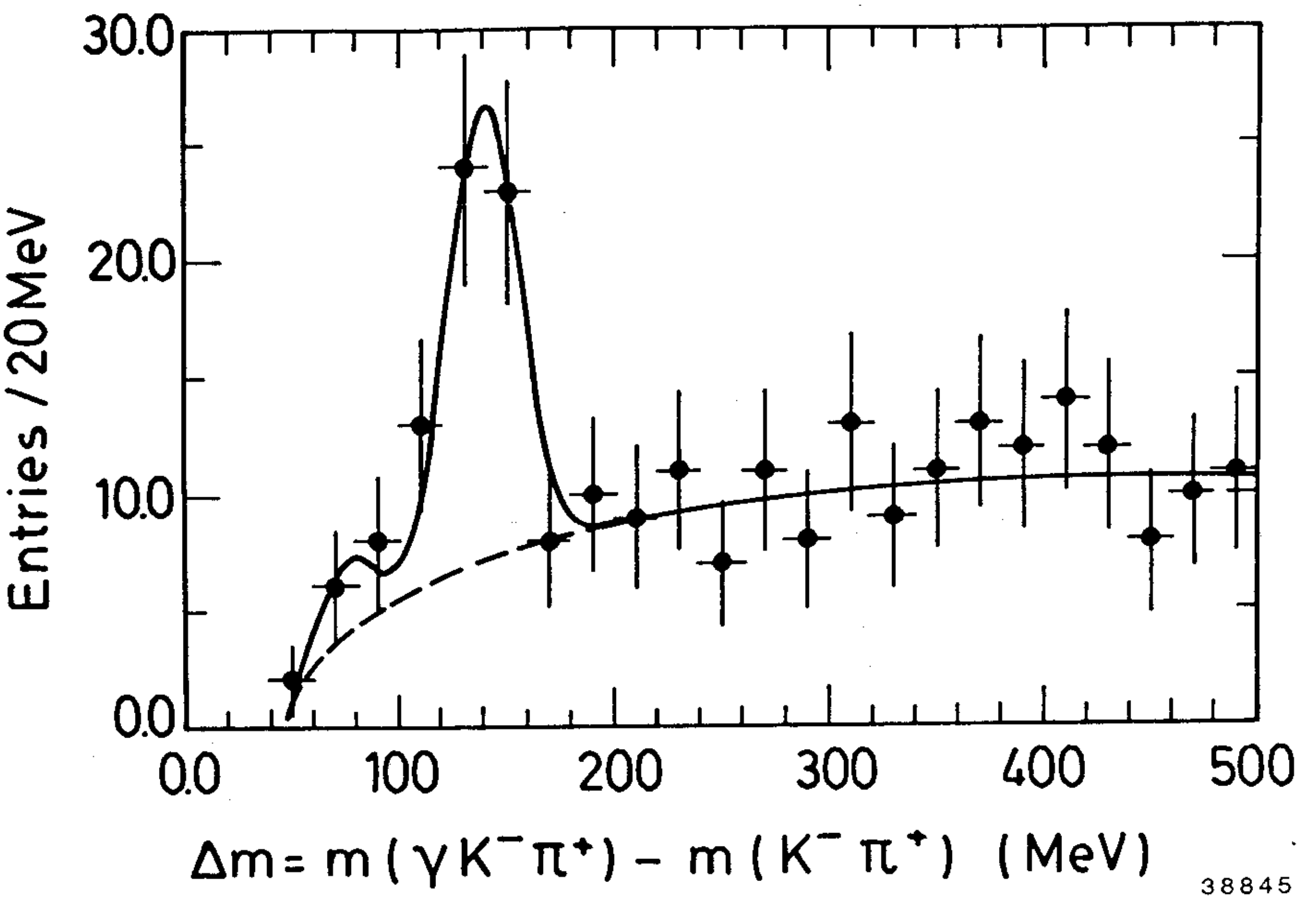
Figure Captions

Figure 1. The $\Delta m = m(\gamma K^-\pi^+) - m(K^-\pi^+)$ distribution for those combinations which pass the cuts A1-A6, designed to enhance D^{*0} radiative decays (reaction (1)). The curve is a fit to the data described in the text. The errors are statistical only.

Figure 2. The $\Delta m = m(\pi^0 K^-\pi^+) - m(K^-\pi^+)$ distribution for those combinations which pass the cuts B1-B5, designed to enhance reaction (2). The errors are statistical only. The curve represents the expected distribution as calculated by Monte Carlo methods. The dashed histogram shows all combinations which pass the B series of cuts with B1 modified to select the $D^0 \to K^-\pi^+$ high mass sideband, $2060 < m(K^-\pi^+) < 2400$ MeV.

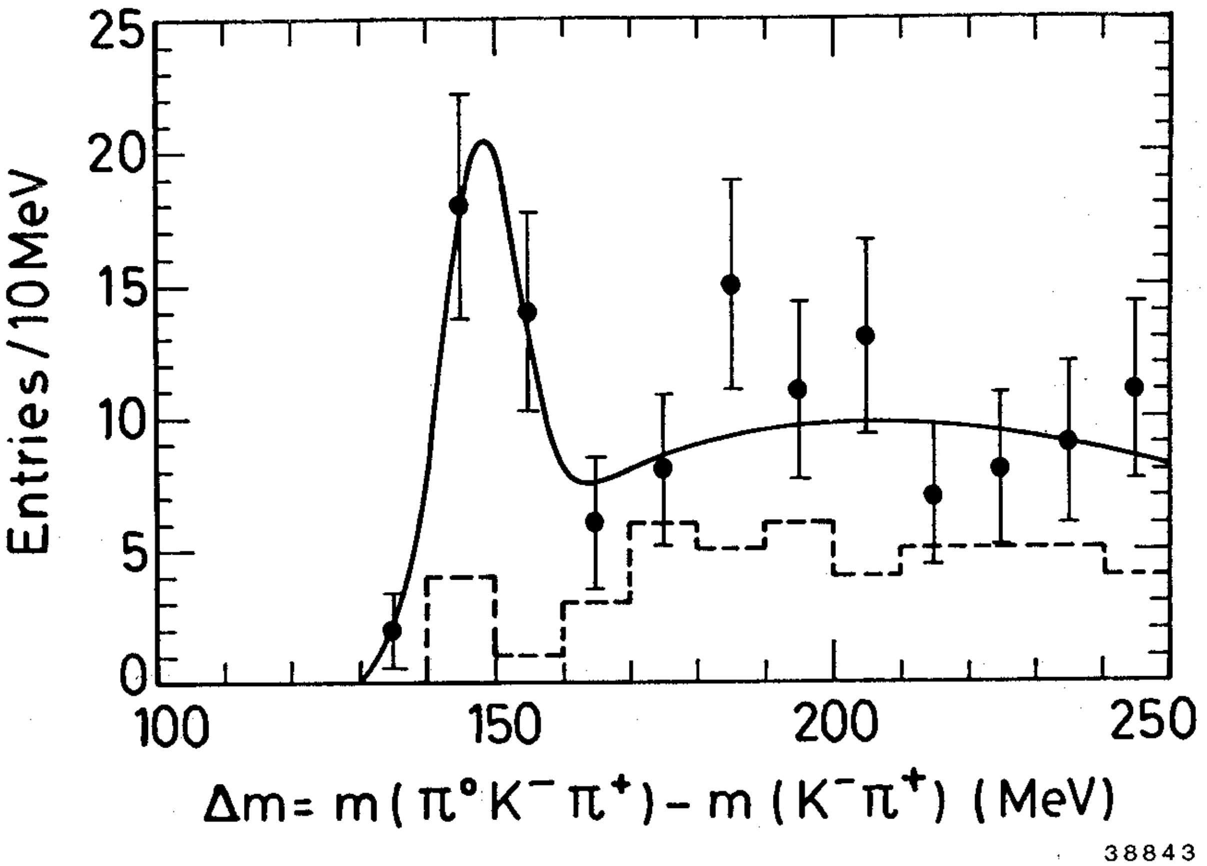
Figure 3. The scaled differential cross section for D^{*0} mesons (closed circles). The errors are a combination of statistical errors, errors in the efficiency calculation, and the quoted error on the $D^0 \to K^-\pi^+$ branching ratio. The scaled differential cross section for D^{*+} mesons (open circles) and the curve, which is a fit to the D^{*+} cross section, are from Ref. [5].

Figure 4. The $\Delta m = m(\gamma K^+K^-\pi^+) - m(K^+K^-\pi^+)$ distribution for those combinations which pass the cuts C1-C5, designed to enhance F^{*+} radiative decays (reaction (4)). The curve is a fit to the data of a function of the type used to parametrize the background in reaction (1) (see text). The errors are statistical only.



30.0
20.0
10.0
0.0
Entries /20MeV
0.0
100
200
300
400
500
Δm = m (γK⁻π⁺) − m (K⁻π⁺) (MeV)
38845

Fig. 1



25
20
15
10
5
0
Entries /10MeV
100
150
200
250
Δm = m (π⁰K⁻π⁺) − m (K⁻π⁺) (MeV)
38843

Fig. 2

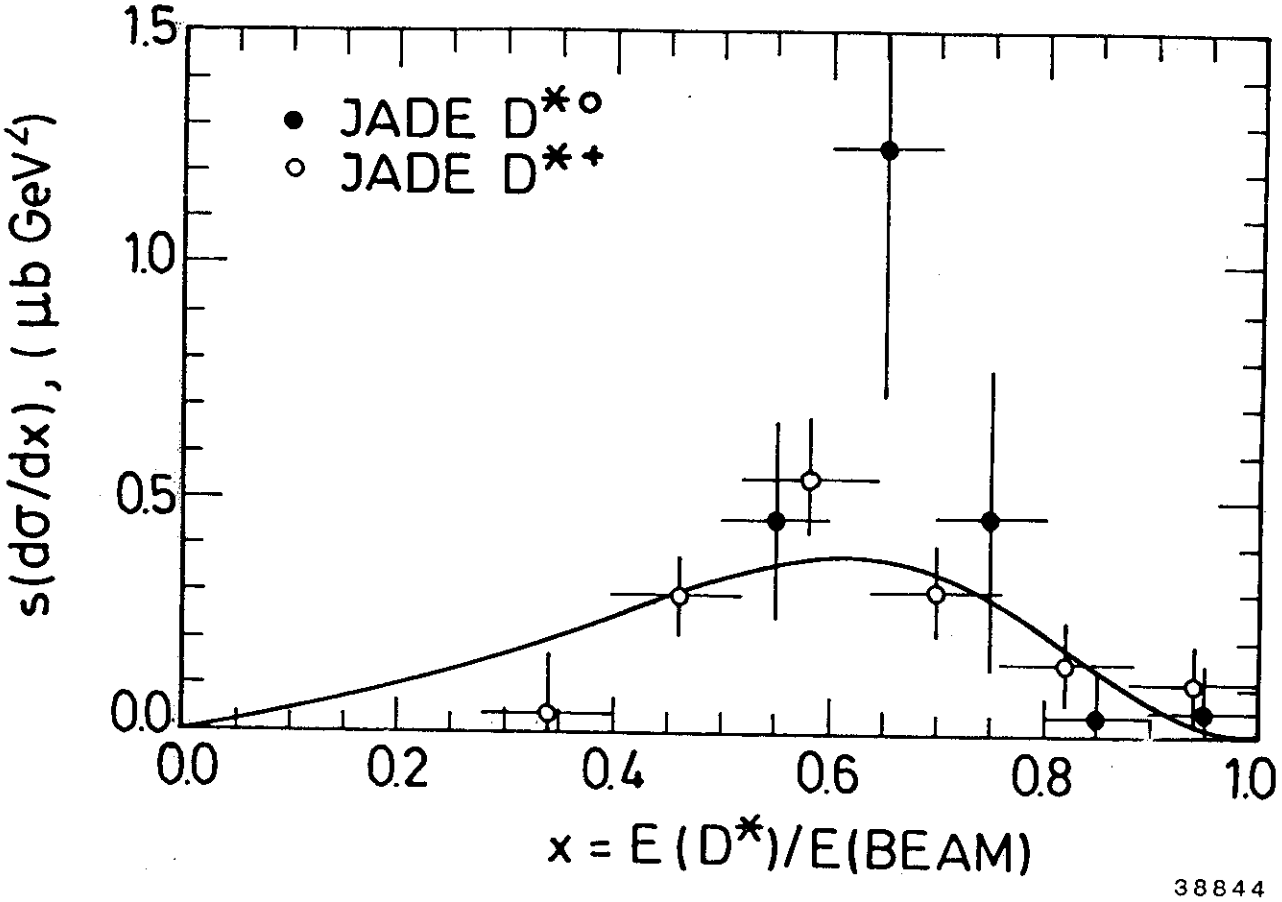

JADE D*0
JADE D*+
s(dσ/dx), (μb GeV²)
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
x = E(D*)/E(BEAM)
38844

Fig. 5

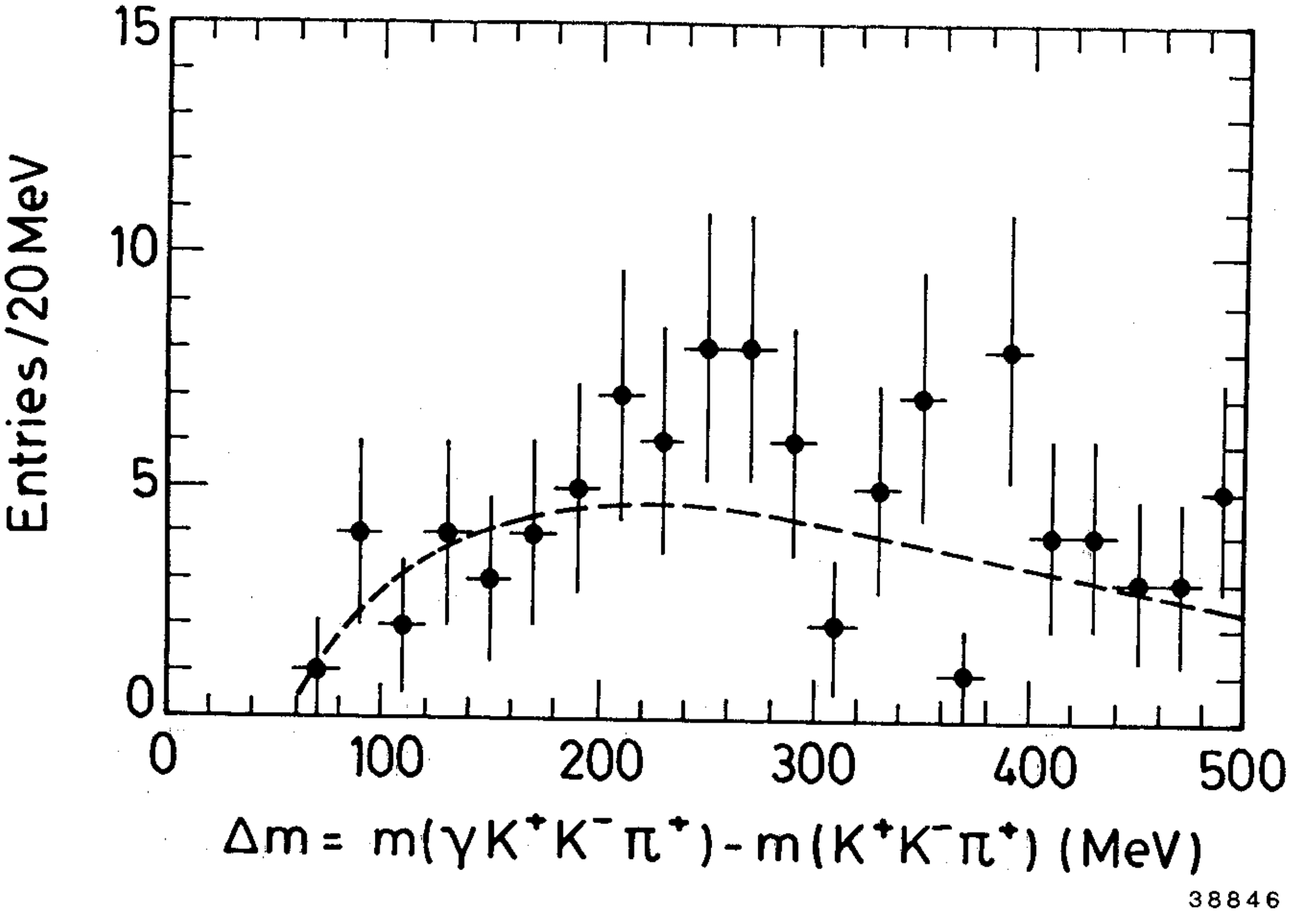

Entries/20 MeV
15
10
5
0
0
100
200
300
400
500
Δm = m(γK⁺K⁻π⁺) - m(K⁺K⁻π⁺) (MeV)
38846

Fig. 4