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D MESON PRODUCTION AND DECAY IN e^+e^- ANNIHILATION AT 4.03 AND 4.41 GeV C.M. ENERGY*

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ABSTRACT

Decay modes of the charmed mesons, D^o and D^+, are studied in e^+e^- annihilation data at 4.03 and 4.41 GeV c.m. energy. The products of cross section times branching ratio are measured for the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^-$ and $K^-\pi^+\pi^+$ final states. Upper limits are established for the Cabibbo forbidden decays via $\pi^+\pi^-$, K^+K^-, $K^+K^-\pi^+$, $K^+\pi^+\pi^-$ and $\pi^+\pi^-\pi^+$. The $K^-\pi^+\pi^+\pi^-$ final state is shown to be dominated by $K^-\pi^+\rho^o$.

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In previous publications,[1,2] we have established the existence of the charmed mesons D^0 and D^+. The evidence for these new particles was found in a study of multihadron production from e^+e^- annihilation at c.m. energies above 4 GeV.

To investigate the production and properties of these new mesons in some detail, we have collected large samples of data at energies where the multihadron annihilation cross section has maxima, namely 4.03 and 4.41 GeV.[3] Samples of about 27,000 and 25,000 hadronic events, corresponding to luminosities of 1270 nb^{-1} and 1630 nb^{-1} respectively, were recorded at these two energies.

In this paper we present measurements of the products σB of cross section times branching ratio for several D^0 and D^+ decay modes at 4.03 and 4.41 GeV. We also report results of our search for resonance production in the multibody decays of D mesons.

1. Apparatus

The data were collected by the SLAC-LBL magnetic detector at the e^+e^- storage ring SPEAR. The apparatus, trigger requirements, and event selection have been described previously.[4,5] The momentum resolution σ_p/p is 0.013 p (GeV/c) for charged particles produced in the beam interaction region, and is worse by about a factor of 1.5 for tracks such as the decay products of K_S which cannot be constrained to originate from the beam. Time-of-flight (TOF) measurements over a flight path of about 1.5 m are used to provide charged particle identification. The rms TOF resolution is 0.35 ns, and corresponds to a one-standard-deviation separation between kaons and pions at 1.3 GeV/c.

2. Experimental Procedures

a. Particle Identification

To make optimal use of the TOF information up to the highest possible momenta, we have used the weight technique already described in our earlier papers[1,2] to provide a statistical method of separation. Each track is assigned weights $W(\pi)$, $W(K)$, $W(p)$ corresponding to its possible identities. Each weight is proportional to the probability that if the particle has the assumed identity, its flight time would have the measured value, and the normalization is such that the sum of all weights corresponding to a given track is unity. For the purpose of studying invariant mass spectra corresponding to the various particle identities, we weight each combination of tracks entering into the distribution by the product of the weights associated with the tracks. The population of any peak observed in such weighted histograms is translated into a real population of events with specific particle identities by means of a Monte-Carlo simulation as described in the next section.

Neutral kaons are identified in the manner described by Lüth et al.[6] This identification is based on the measurement of dipion mass and the detection of a vertex, defined by the crossing of the two pion tracks, which is displaced from the beam by at least 10 mm. With the cuts used, the K_S signal-to-background ratio in the dipion mass interval 480 - 520 MeV/c^2 is 2.5. In all K_S spectra displayed in this paper, the background has been estimated from the population outside the above K_S signal mass region and subtracted.

b. Detection Efficiency

To go from the weighted-event populations to cross sections and branching ratios, we have performed a Monte-Carlo simulation incorporating all the known experimental effects: geometry, resolution, trigger criteria, cuts introduced in the analysis, etc. In this simulation we have used production models for D^0 and D^+ which reproduce the observed D momentum spectra and the observed multiplicities at both 4.03 and 4.41 GeV. Angular distributions have been taken as isotropic with the exception of those especially simple production channels (DD^*) where angular distributions differing from isotropy have been measured.[7] In general, our calculated efficiencies are relatively insensitive to variations in the production model parameters within limits that are compatible with the experimental observations of momentum and multiplicity spectra. The efficiencies are given in Table I with errors which represent our estimates of systematic uncertainties.

3. Results

a. Mass Spectra

The weighted mass spectra of $K^{\mp}\pi^{\pm}$, $K_S\pi^+\pi^-$, $K^{\mp}\pi^{\pm}\pi^{\pm}$ and $K^{\mp}\pi^{\pm}\pi^+\pi^-$ at 4.03 and 4.41 GeV are shown in Fig. 1. To improve the D signal/background ratio, we plot only those events for which the recoil mass is larger than 1.8 GeV/c^2. All these channels exhibit significant peaks at 1.87 GeV/c^2. Figure 2 shows the weighted mass spectra of $\pi^+\pi^-$, K^+K^-, $K^{\pm}\pi^+\pi^-$, $\pi^{\pm}\pi^+\pi^-$, $K^+K^-\pi^{\pm}$, $K_S\pi^{\pm}$ at 4.03 GeV. The only significant peaks are in the $\pi^+\pi^-$ spectrum at 1.74 GeV/c^2 and in K^+K^- at 1.98 GeV/c^2. These peaks are produced by $D \to K^{\mp}\pi^{\pm}$ events in which the K or the π have been misidentified. For decay modes with three or more particles this problem does not arise, because misidentifications do not produce sharp peaks.

To evaluate D meson populations, we have fit each of the mass spectra of Fig. 1 with an adjustable Gaussian superimposed on a polynomial background. The χ^2 per degree of freedom is in each case less than one. To obtain upper limits for D decay into the channels of Fig. 2, we have fit each of them with a Gaussian of specified central value and width superimposed on a smooth background. From our fits to Fig. 1, we obtain estimates of the D^0 and D^+ masses of 1868 ± 11 MeV/c^2 and 1874 ± 11 MeV/c^2 respectively; the quoted errors reflect principally our estimated systematic uncertainties in momentum measurement. The width estimates, although subject to considerable statistical uncertainty in those channels with large background, are compatible with the experimental resolution.

Table I gives real event populations, efficiencies, and values of σB, the product of D cross section times branching ratio, for the decay modes studied at 4.03 and 4.41 GeV. For those channels in which no significant signal is observed, a 90% confidence level upper limit is quoted.

Although there is not enough information to separately determine σ and B, one can compare the values of σB for given decay modes at 4.03 and 4.41 GeV to study the energy dependence of the inclusive D^0 and D^+ cross sections. For the $D^{\pm}$, the single identified decay mode $K^{\mp}\pi^{\pm}\pi^{\pm}$ leads to a ratio $\sigma(4.41)/\sigma(4.03)$ of about 0.8. The three identified D^0 decay modes exhibit relative values of σB at 4.03 and 4.41 GeV which do not agree well, although the inconsistencies are not outside the level of a reasonable statistical fluctuation. Consequently we only conclude from our data that the ratio $\sigma(4.41)/\sigma(4.03)$ for D^0 is in the range 0.5 - 1. Because (1) the cross section $\sigma(e^+e^- \rightarrow \text{hadrons})$ is less at 4.41 than at 4.03 GeV, and (2) the cross section for producing new particles other than D's may be larger at 4.41 GeV, one expects that the inclusive D production cross section will exhibit a drop between 4.03 and 4.41 GeV. Our results are compatible with that expectation.

To obtain estimates of relative branching ratios for the various D^0 decay modes, we have combined data at the two energies for each of the three identified modes and refitted to determine the corresponding populations. We obtain 2.2 ± 0.8 for the relative branching ratio $K^{\mp}\pi^{\pm}\pi^+\pi^-/K^{\mp}\pi^{\pm}$, and 2.8 ± 1.0 for the ratio $K^0\pi^+\pi^-/K^{\mp}\pi^{\pm}$. Thus the higher-multiplicity decays are favored.

If one assigns the total excess population of the 4.03 and 4.41 GeV total cross-section bumps to pair production of charmed mesons, the D meson decays observed amount to roughly 10% of all charmed mesons produced. This low fraction is not surprising because semi-leptonic decay modes and hadronic modes involving neutral mesons other than K^0 cannot be identified in the present detector, and decays to higher multiplicity states are difficult to detect because of limited solid angle and increasing background.

Decays of the D^0 to final states of zero strangeness are suppressed relative to states involving a single K meson. We find $B(\pi^+\pi^-)/B(K\pi) < 0.07$, and $B(K^+K^-)/B(K\pi) < 0.07$ at the 90% confidence level. From weak interaction theory we expect these rates to be suppressed by $\tan^2\theta \sim 0.05$, where θ is the Cabibbo angle. The same mechanism doubly suppresses (~ 0.0025) the decay of the charged D to nonexotic strange final states. Our 90% C.L. limit for $B(K^\pm\pi^+\pi^-)/B(K^\mp\pi^\pm\pi^\pm)$ is 5%. No significant signal for the decay $\bar{K}^0\pi^+$ has been observed, but the sensitivity is rather low.[8]

b. <u>Resonance Production in D Decays</u>[9]

We have previously shown[10] that the $D^\pm \rightarrow K^\mp\pi^\pm\pi^\pm$ Dalitz plot appears uniformly populated and hence does not contain a significant $K^*(890)\pi$ component. Similarly we find that within the limited statistics the $D^0 \rightarrow K_S\pi^+\pi^-$ does not exhibit either K^* or ρ production at a substantial level. However we find that the $D^0 \rightarrow K^\mp\pi^\pm\pi^+\pi^-$ decay is dominated by the intermediate state $K^\mp\pi^\pm\rho^0$.

To maximize the statistics this analysis uses all data collected at center-of-mass energies between 3.8 and 4.6 GeV, a total of about 90,000 multihadronic events. Figure 3a shows the invariant mass for $K3\pi$ combinations having at least one of the two neutral dipions within a ρ^0 cut defined from 650 to 850 MeV/c^2. Figure 3b shows the invariant mass for $K3\pi$ combinations which have <u>no</u> neutral dipions within the ρ^0 cut. We estimate that $(85 \pm 15)\%$ of the total $K3\pi$ signal resides in Fig. 3a. This ρ^0 fraction is substantially larger than the 47% predicted by $K\pi\pi\pi$ phase space, but consistent with the 81% predicted by a pure $K\pi\rho^0$ final state.

To search for the presence of $K^{*0}(890)$ we define a K^{*0} mass region from 820 to 960 MeV/c^2. We evaluate the fraction of events in the $K3\pi$ signal which have at least one of the two $K^{\mp}\pi^{\pm}$ combinations in this K^{*0} region, and also the fraction of events which have both a $K\pi$ in the K^{*0} band and the remaining $\pi\pi$ in the ρ^0 region.

Assuming that the $K3\pi$ signal is the sum of the four decays, direct $K3\pi$, $K^{*0}\pi^+\pi^-$, $K^{\mp}\pi^{\pm}\rho^0$, $K^{*0}\rho^0$, we unfold the signal fractions by comparison with the Monte-Carlo calculation for each mode. The results of the fit are summarized below:

Phase Space	$K^{\mp}\pi^{\pm}\rho^0$	$K^*\pi^+\pi^-$	$K^*\rho^0$
$0.05^{+0.11}_{-0.05}$	$0.85^{+0.11}_{-0.22}$	$0.00^{+0.2}_{-0.0}$	$0.10^{+0.11}_{-0.10}$

Remarkably enough, there is no significant K^* production whereas $K^{\mp}\pi^{\pm}\rho^0$ seems to be the dominant mode. We find no evidence of A_2, and set a 90% confidence level upper limit of 0.06 for the ratio of $K^{\mp}A_2^{\pm}$ to total $K3\pi$.

4. Summary

In summary, we have identified a heretofore unreported D^0 decay mode, namely $K_S\pi^+\pi^-$ and have measured values of σB for it as well as for other D^0 and D^+ decay modes at both 4.03 and 4.41 GeV. Inclusive D cross sections at these two energies are comparable. D^0 relative branching ratios favor the higher multiplicity final states. Nonstrange final states of D mesons are substantially suppressed as expected from the standard weak interaction theory. Finally the $D^0 \to K3\pi$ decay is dominated by the intermediate state $K^{\mp}\pi^{\pm}\rho^0$.

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FIGURE CAPTIONS

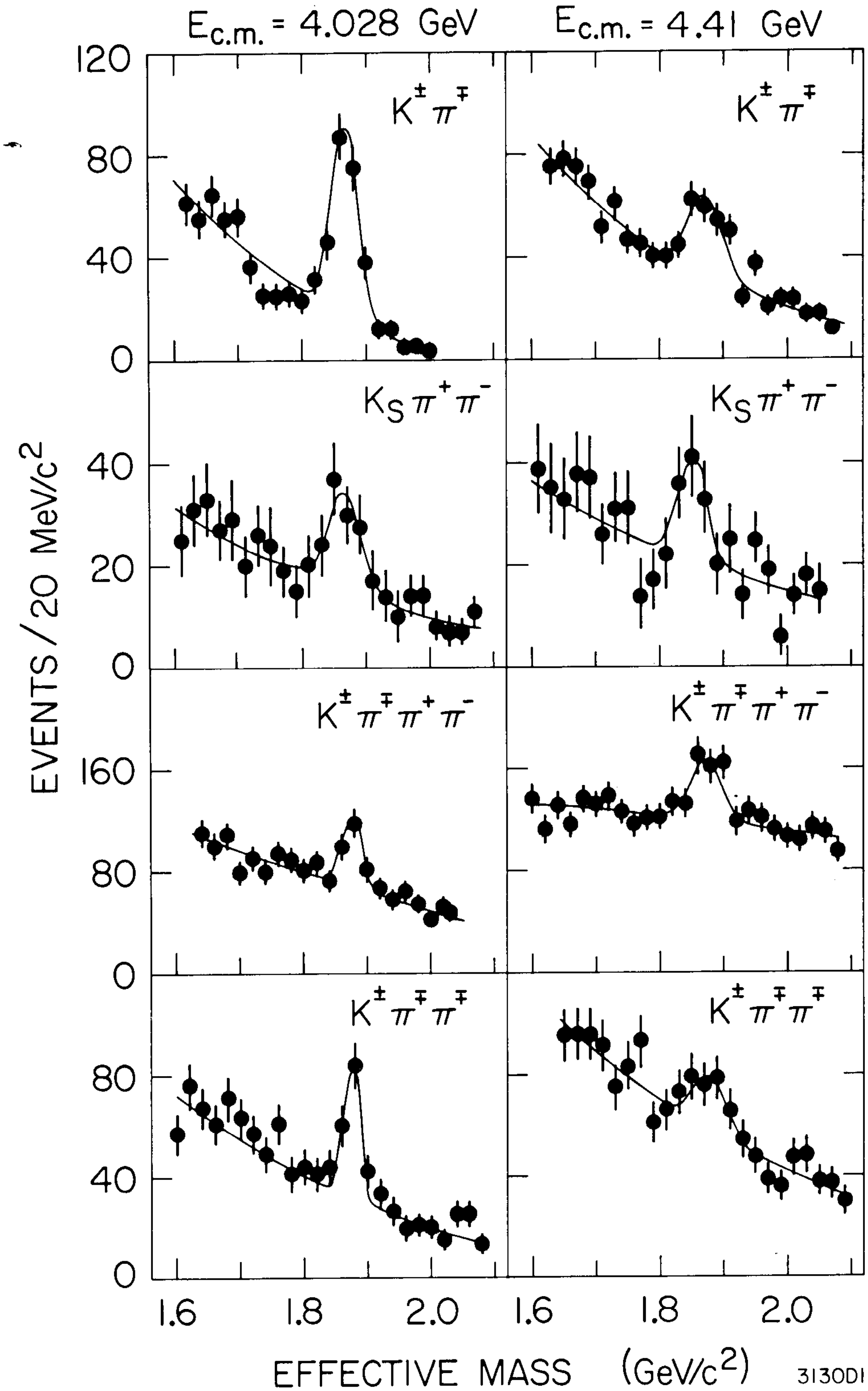
Fig. 1. Weighted invariant mass distributions for various particle combinations at 4.03 GeV and 4.41 GeV c.m. energy. A cut on the recoil mass at 1.8 GeV has been applied. The curves represent fits to the data.

Fig. 2. Weighted invariant mass distributions at 4.03 GeV, with a 1.8 GeV recoil mass cut.

Fig. 3. $K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$ weighted effective mass for (a) combinations with at least one $\pi^+\pi^-$ pair with mass in the ρ^0 cut (650 - 850 MeV/c^2). (b) Combinations with neither of the two $\pi^+\pi^-$ pairs with mass inside the ρ^0 cut (650 - 850 MeV/c^2).

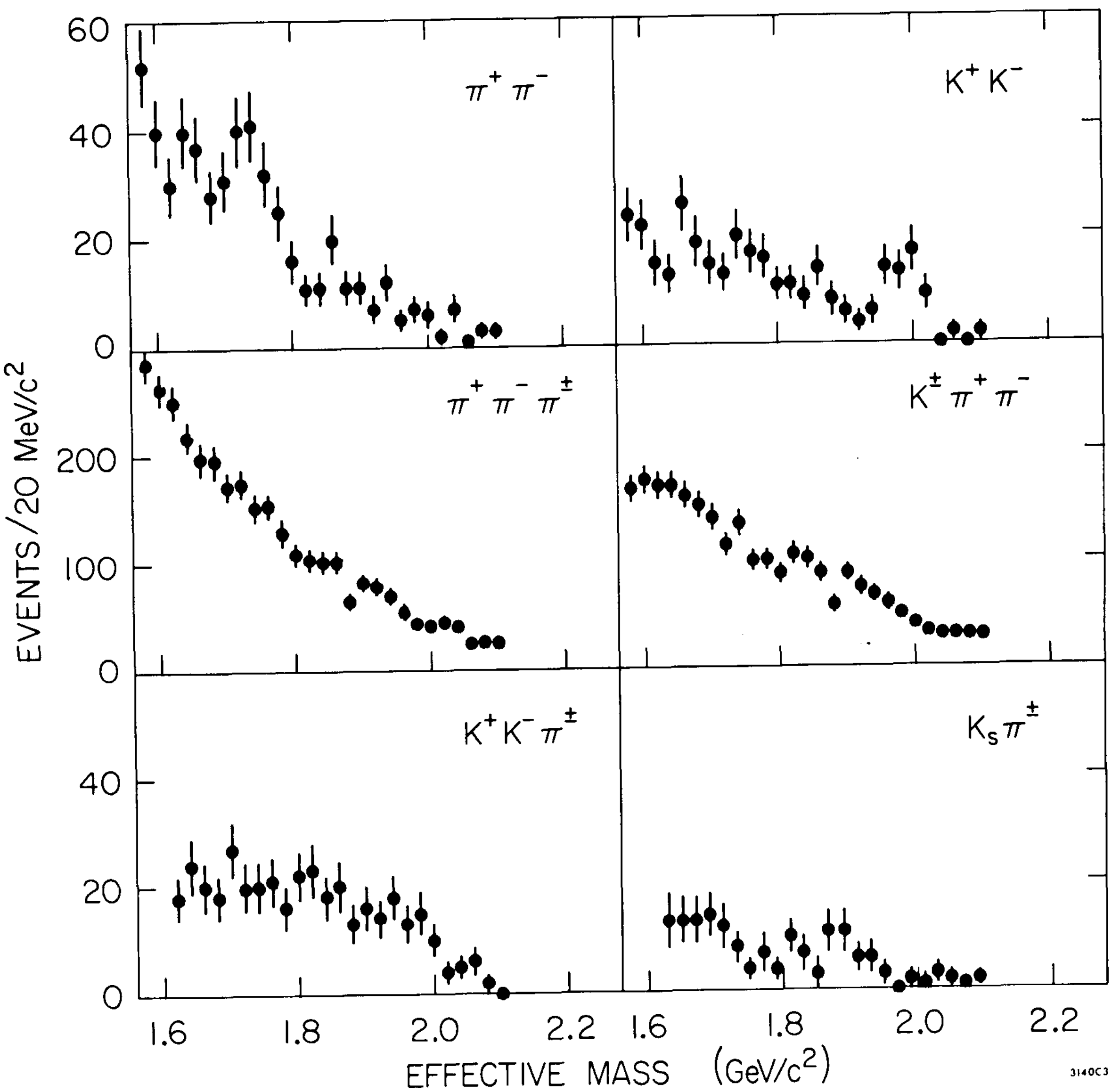
Table I. Event populations, efficiencies and values of σB for several D^o, $\bar{D}^o$ and D^+, D^- decay modes.

Decay Mode	c.m. Energy (GeV)	No. of Events	Detection Efficiency	Cross Section × Branching Ratio σB (nb)
$K^{\mp}\pi^{\pm}$	4.03	182 ± 18	0.25 ± 0.04	0.57 ± 0.11
$\bar{K}^o\pi^+\pi^- + K^o\pi^+\pi^-$		61 ± 14	0.044 ± 0.007	1.09 ± 0.30
$K^{\mp}\pi^{\pm}\pi^+\pi^-$		95 ± 23	0.09 ± 0.02	0.83 ± 0.27
$K^{\mp}\pi^{\pm}\pi^{\pm}$		82 ± 14	0.16 ± 0.03	0.40 ± 0.10
$\bar{K}^o\pi^{\pm} + K^o\pi^{\pm}$		9.5 ± 6.5	0.07 ± 0.01	< 0.18
$\pi^-\pi^+$		$5.4 {+8.8 \atop -4.5}$	0.27 ± 0.04	< 0.04
K^-K^+		$5.2 {+7.5 \atop -5.2}$	0.24 ± 0.04	< 0.04
$\pi^{\mp}\pi^+\pi^-$		$0.0 {+8.0 \atop -0.0}$	0.22 ± 0.03	< 0.03
$\pi^{\mp}K^+K^-$		$2.7 {+7.1 \atop -2.7}$	0.13 ± 0.03	< 0.06
$K^{\mp}\pi^+\pi^-$		$0.0 {+4.7 \atop -0.0}$	0.16 ± 0.03	< 0.02
$K^{\mp}\pi^{\pm}$	4.41	92 ± 18	0.19 ± 0.04	0.30 ± 0.09
$\bar{K}^o\pi^+\pi^- + K^o\pi^+\pi^-$		55 ± 14	0.037 ± 0.010	0.91 ± 0.34
$K^{\mp}\pi^{\pm}\pi^+\pi^-$		119 ± 41	0.08 ± 0.02	0.91 ± 0.39
$K^{\mp}\pi^{\pm}\pi^{\pm}$		67 ± 19	0.125 ± 0.03	0.33 ± 0.12



E c.m. = 4.028 GeV
E c.m. = 4.41 GeV
K±π∓
KSπ+π-
K±π∓π+π-
K±π∓π∓
EVENTS / 20 MeV/c2
EFFECTIVE MASS (GeV/c2)
3130D1

Fig. 1



60
40
20
0
200
100
0
40
20
0
EVENTS/20 MeV/c²
π⁺ π⁻
K⁺ K⁻
π⁺ π⁻ π^±
K^± π⁺ π⁻
K⁺ K⁻ π^±
K_s π^±
1.6
1.8
2.0
2.2
1.6
1.8
2.0
2.2
EFFECTIVE MASS (GeV/c²)
3140C3

Fig. 2

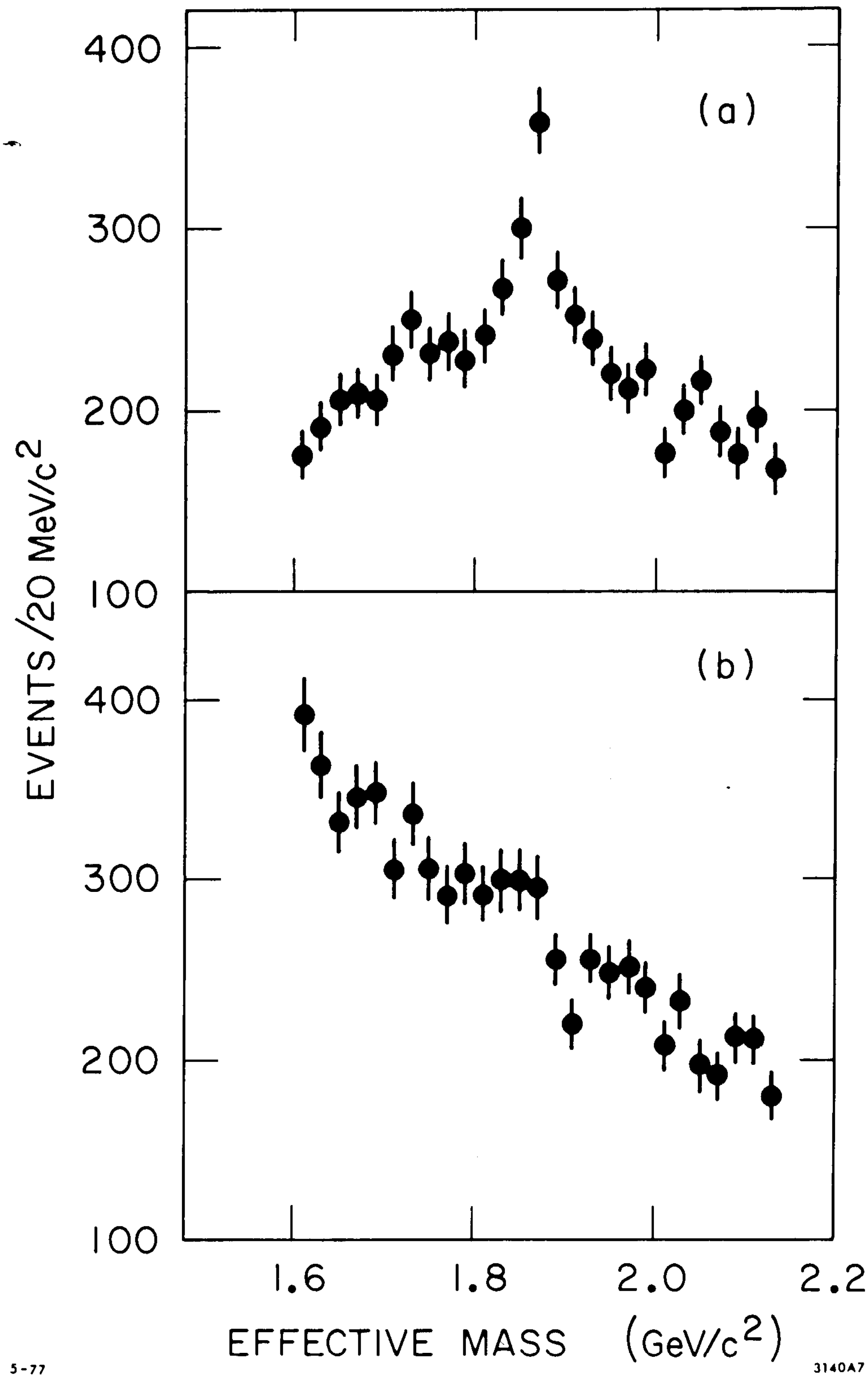

EVENTS /20 MeV/c^2
400
300
200
100
(a)
(b)
1.6
1.8
2.0
2.2
EFFECTIVE MASS (GeV/c^2)
5-77
3140A7

Fig. 3