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Search for $D^+ \rightarrow \mu^+\nu_\mu$ Decay, and the Pseudoscalar Decay Constant f_D*

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Abstract

Results of a search for the purely leptonic decay $D^+ \rightarrow \mu^+\nu_\mu$ using the Mark III detector at SPEAR are reported. No signal is observed in a data sample of 9.3 pb^{-1} collected at the $\psi(3770)$ resonance, where $1.2 \pm 0.16(stat.)^{+0.24}_{-0.20}$ background events are expected. The 90 % C.L. upper limit on the branching ratio $B(D^+ \rightarrow \mu^+\nu_\mu)$ is found to be 8.4×10^{-4}, corresponding to an upper limit on f_D of 340 MeV/c^2. This limit has implications for the theoretical understanding of differences in D^0 and D^+ lifetimes, $D^0\bar{D}^0$ and $B^0\bar{B}^0$ mixing, and provides a test of the non-relativistic potential model.

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The D meson decay constant (f_D) is a physical quantity of great experimental and theoretical interest. The constant f_D may be unambiguously measured through the pure leptonic decay of the D^+ :[1]

$$\Gamma_{D^+\rightarrow\mu^+\nu} = \frac{1}{8\pi} {G_F}^2 {f_D}^2 m_D m_\mu^2 |\, V_{cd}\, |^2 (1. - (m_\mu/m_D)^2)^2 \qquad (1)$$

The decay constant is a direct measure of the overlap of the wavefunctions of the heavy and light quarks in the D meson.[2] It thus plays a fundamental role in determining the degree of flavor annihilation and final state interference necessary to account for discrepancies between spectator model predictions[3] and recent experimental results on D decays. These include the inequality of D^+ and D^0 lifetimes,[4] the observation of the decay $D^0 \rightarrow \bar{K}^0\phi$,[5] and the large value of $\Gamma(\bar{K}^0K^+)/\Gamma(\bar{K}^0\pi^+)$.[6] A measurement of f_D also provides a stringent test of potential model[2] and QCD sum rule[7] calculations. In addition, it allows reliable estimates of other heavy meson decay constants (f_F, f_B, etc.). Such estimates are presently difficult to obtain due to the large theoretical uncertainties in extrapolating from the well-measured constants f_π and f_K for mesons containing light quarks, to those for mesons with heavy quarks. The decay constant also is essential in evaluating the magnitude of operators leading to $D^0\bar{D}^0$ and $B^0\bar{B}^0$ mixing.[8]

This letter reports the results of a search for the decay $D^+ \rightarrow \mu^+\nu_\mu$ carried out with the Mark III detector at the e^+e^- storage ring SPEAR. The Mark III detector has been described in detail elsewhere.[9] The data were obtained at an average energy of $\sqrt{s} = 3.768$ GeV (near the peak of the $\psi(3770)$). The integrated luminosity of 9.3 pb^{-1} corresponded to about 16000 produced D^+D^- pairs.[10]

At the $\psi(3770)$, charmed D mesons are produced only in pairs. The search is carried out by selecting a sample of events in which a D^+ candidate is found, and then examining the recoil system for evidence of the $\mu^-\bar{\nu}_\mu$ decay mode. The D^+ candidates are selected as follows. Charged particles are identified by time-of-flight (TOF) or by dE/dx energy loss in the drift chamber. Appropriate particle combinations are formed to construct the seven final states: $K^-\pi^+\pi^+$, $\bar{K}^0\pi^+$, $\bar{K}^0\pi^+\pi^+\pi^-$, $\bar{K}^0\pi^+\pi^0$, $\bar{K}^-\pi^+\pi^+\pi^0$, $\bar{K}^0K^+$, and $K^-K^+\pi^+$. The total energy of the D^+ candidate is constrained to the beam energy; if the final state contains a π^0, the additional constraint of the π^0 mass is also used. This procedure results in $2489.9 \pm 41.9(stat.) \pm 40.0(syst.)$ cleanly identified D^+ tags (cf. Figure 1)

The isolation of the $\mu^-\bar{\nu}_\mu$ candidates proceeds as follows. The D^+ tag is required to have a mass between 1.862 and 1.875 GeV/c^2. The recoil system is required to have only one charged track, with a charge opposite to that of the tag. The data are then separated into two classes depending on whether the recoil track is within the acceptance of the muon detection system ($|\cos\theta| \leq 0.65$, where θ is the polar angle from the beam axis).

Events within the acceptance of the muon system are subject to only one further requirement: two (one) layers are required to be hit for muon momentum $(p_\mu) \geq 1$ GeV/c ($p_\mu < 1$ GeV/c). No further event topology cuts are applied due to the excellent $(90-95\%)$ rejection of π and K decays and punchthrough provided by the muon system.[11]

The lack of muon identification in the end-cap region ($| \cos\theta | \geq 0.65$) necessitates the use of further cuts on those events. The principal sources of background to the $\mu^- \bar{\nu}_\mu$ signal are the decays $D^+ \rightarrow \bar{K}^0\pi^+$, $\pi^+\pi^-$, $\bar{K}^0K^+$, and $\bar{K}^0\mu^+\nu$. Background events with a π^0 (either from the D^- or a K^0_S) are rejected by requiring the absence of any isolated photons in an event (isolated photons are defined as those not used in forming a π^0 in the tag, or which make an angle $| \cos\theta | \leq 0.92$ with respect to any charged track). This cut also rejects K^0_L which interact in the shower counter. The decay $K^0_S \rightarrow \pi^+\pi^-$ has already been rejected by requiring no more than one recoil track against the D^+ . The fraction of K^0_L which interacts is modelled by using the decay $\psi(3100) \rightarrow K^0_S K^0_L$, $K^0_S \rightarrow \pi^+\pi^-$ from a separate data set.[12] Due to the larger cross-section for K^0_L at the energies found in the $\psi(3100)$ data, this procedure is expected to underestimate the background.

For tracks exiting the drift chamber with $0.92 \geq | \cos\theta | \geq 0.65$, the barrel and endcap calorimeters (0.4 interaction lengths) provide some π rejection. The reduction of π and K backgrounds is accomplished by requiring the candidate recoil muon to deposit less than 300 MeV in the shower counter (where the minimum ionizing distribution peaks at about 180 MeV). The region $0.84 \geq | \cos\theta | \geq 0.78$ was removed from further data analysis as it represents the overlap region of the barrel and endcap calorimeter where energy loss can occur. For endcap region tracks falling within the acceptance of the TOF or dE/dx systems, additional background rejection is obtained by requiring the track to be consistent with a π hypothesis.

Finally, kinematic cuts are applied to separate the surviving $\mu^- \bar{\nu}_\mu$ events from the background. The muon momentum is expected to be mono-energetic in the D^+ center-of-mass frame, while it is shifted for the "punch-through" from $D^+ \rightarrow \bar{K}^0\pi^+$, $\pi^0\pi^+$, and $\bar{K}^0K^+$ decays (the muon from $D^+ \rightarrow \bar{K}^0\ \mu^-\bar{\nu}_\mu$ is not mono-energetic). Due to the Lorentz boost, the muon momentum distribution for $\mu^-\bar{\nu}_\mu$ events in the lab system (p_μ^{lab}) results in a box-shaped distribution (cf. Fig. 2(a)). Furthermore, the expected missing mass squared (M^2_{miss}) is zero for $D^+ \rightarrow \mu^-\bar{\nu}_\mu$, while it is expected to peak near $\mathrm{m}^2_{\pi^0}$ or $\mathrm{m}^2_{K^0_S}$ for the two body backgrounds. In the case of $\bar{K}^0\ \mu^-\bar{\nu}_\mu$, the missing ν_μ makes M^2_{miss}peak above $\mathrm{m}^2_{K^0_S}$. Figure 2 a,b,c,d,e shows plots of p_μ^{lab} and $\mathrm{M}^2_{miss}$for the expected signal and for the four major background sources. Based on these Monte Carlo calculations, we require $\mathrm{M}^2_{miss} < 0.175\ (\mathrm{GeV/c^2})^2$ and $0.775 < p_\mu^{lab} < 1.125$ GeV/c, losing about 5 % of the signal. When these cuts are applied to the data, no event is found to survive. The closest event to the M^2_{miss}cut appears at $0.196\ (\mathrm{GeV/c^2})^2$ (cf. Fig. 2f).

The expected background with these cuts is $1.16 \pm 0.16(stat.) \pm 0.20(syst.)$[13] The error from the underestimate of the background component containing a K^0_L is excluded from the systematic error because of the uncertainty in the size of the effect. The background calculation is tested by loosening the muon selection criteria, and comparing the number of events observed to that predicted by the Monte Carlo. When the barrel muon system identification is removed, 8 events are accepted within the kinematic cuts as compared to a prediction of 4.1. When the isolated photon and calorimeter energy cuts (which are applied for end-cap region muon candidates) are also removed, 4 additional events are accepted, while the Monte Carlo predicts an additional 1.7 events. A further check is made using the observed M^2_{miss}distribution. Events from $D^+ \rightarrow \bar{K}^0\mu^+\nu_\mu$ and $D^+ \rightarrow \bar{K}^0\pi^+$ are expected to have M^2_{miss}larger than $m^2_{\bar{K}^0}$ (cf. Fig. 2). Ten events are observed in the data from 0.2 to 0.5 $(GeV/c^2)^2$. This is consistent with 7.6 events predicted by the Monte Carlo, thus providing additional experimental verification for the background estimate.

The observation of no events of the type $D^+ \rightarrow \mu^+\nu_\mu$ together with the background prediction yields a 90 % Confidence Level (C.L.) upper limit of 1.35 signal events.[14] The probability of observing no events when 1.0 background events are expected is 0.37. The acceptance for this decay mode varies by less than 3 % for the seven different tagging modes; a weighted average of $0.721 \pm .008(stat.) \pm .051(syst.)$ is used. Dividing by the acceptance and the total number of D^+ tags[15] gives a 90 % C.L. upper limit on the branching ratio of 8.4×10^{-4}. Using a D^+ lifetime of $(10.1 \ {}^{+0.7}_{-0.6}) \times 10^{-13}s$,[16] and $| V_{cd} |^2 = 0.0506 \pm .0065$,[17] then the 90 % C.L. branching ratio limit corresponds to $f_D = 310$ MeV/c². (see Figure 3). When the errors on τ_{D^+} and $| V_{cd} |^2$ are included, we obtain a 90 % C.L. upper limit on f_D of 340 MeV/c².

Calculations of the pseudoscalar decay constants obtain values which either increase (QCD sum rule method[7]) or decrease (non-relativistic potential[2] and bag model methods[18]) with the meson mass. While our result does not probe the small values of f_D suggested by the bag model or QCD sum rule calculations ($f_D \sim 150 \rightarrow 280$ MeV/c), it restricts the range of values predicted by recent potential model calculations ($f_D \sim 208 \rightarrow 450$ MeV/c). It also excludes the very high values of f_D which have been suggested[19] as an explanation for the large observed ratio of $\tau(D^+)/\tau(D^0)$. This in turn may imply that final state interference in D^+ decay is a more important factor (as suggested by measurements of Cabibbo suppressed D meson branching ratios[20]) than the W-exchange mechanism. This limit on f_D also places a bound on the box diagram contribution to possible $D^0\bar{D}^0$ mixing and through extrapolation to f_B, to $B^0\bar{B}^0$ mixing.

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13. The number of expected background events was obtained by generating samples of each of the four major sources against a $K\pi^+\pi^-$ tag. The number of observed events passing all analysis cuts in the barrel and endcap regions (with and without muon system identification, respectively) were scaled to the total sample size using measured branching ratios (cf. refs. 4, 6, and 10, see also D. Coffman, Proceedings of XXI Recontre de Moriond, 9-16 March 1986), and the measured number of tags. The $\pi^+\pi^0$ decay mode was the only background for which no branching ratio was available; the Kobayashi-Maskawa matrix elements were used to scale BR($D^+ \rightarrow \bar{K}^0\pi^+$) as an estimate. All systematic errors were propagated linearly.

14. The C.L. is defined as the probability that a given hypothesis (here, the sum of the signal (n_s) and background (n_b)) will give an observed number of events that is greater than the number actually seen by the experiment. The probability of an experimental result is the joint probability of two Poisson distributions (for n_s and n_b). See M. Aguilar-Benitez *et al.*, Rev. Mod. Phys. 56, S46 (1984), A. G. Frodesen *et al.*, , **Probability and Statistics in Particle Physics** (Universitettsforlaget, Bergen, 1979), pp. 167-168, 378-379. Thus, the limit on n_s at the 90 % C.L. is derived from the limit on $(n_s + n_b)$ by subtraction of n_b from 2.3 events. The statistical error on n_b is incorporated by fluctuating n_b in the Poisson with a Gaussian distribution, while the systematic error is directly subtracted from the central value of n_b, to provide a more conservative limit. This gives 1.35 events as the 90 % C.L. limit. Alternately, if an a priori uniform distribution of signal events

is assumed, then the 90 % C.L. upper limit on n_s would be 2.3 events.

15. The errors on the number of tags and the acceptance are subtracted in order to give a more conservative limit. We thus use .662 for the acceptance, and 2408 as the number of tags.

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FIGURE CAPTIONS

1. Shown are the mass plots for the seven D^+ tags used in this analysis: (a) $K^-\pi^+\pi^+$, (b) $\bar{K}^0\pi^+$, (c) $\bar{K}^0\pi^+\pi^+\pi^-$, (d) $\bar{K}^0\pi^+\pi^0$, (e) $\bar{K}^-\pi^+\pi^+\pi^0$, (f) $\bar{K}^0K+$, and (g) $K^-K^-\pi^+$.

2. The variables $M^2_{miss}$and p_μ^{lab} are plotted for Monte Carlo generated events of the types: (a) $D^+ \to \mu^+\nu_\mu$; and for the four major backgrounds: (b) $D^+ \to \bar{K}^0\pi^+$, (c) $\pi^+\pi^-$, (d) $\bar{K}^0K^+$, and (e) $\bar{K}^0\mu^+\nu$. The data is shown in (f). The plots of M^2_{miss}show the effect of the cut on p_μ^{lab}, and vice versa.

3. Shown is the Confidence Level (C.L.) for our result as a function of (a) $D^+ \to \mu^+\nu_\mu$, and (b) f_D. The limit calculation is described in reference 14. The dashed curve in (b) includes the effects of lowering the values of τ_{D^+} and $| V_{cd} |^2$ by their stated errors.

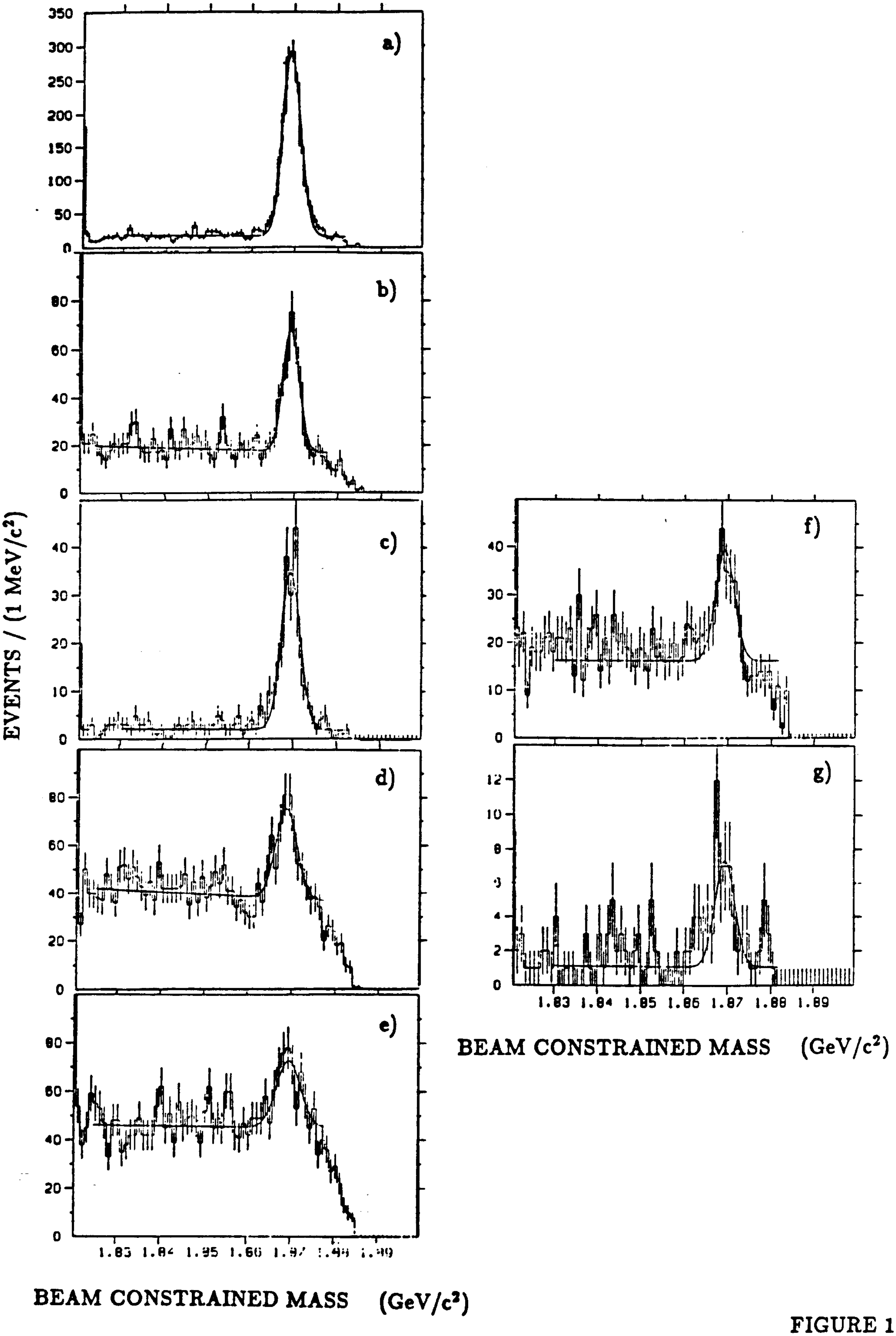

a)
b)
c)
d)
e)
f)
g)
350
300
250
200
150
100
50
0
80
60
40
20
0
40
30
20
10
0
12
10
8
4
2
EVENTS / (1 MeV/c^2)
1.83
1.84
1.85
1.86
1.87
1.88
1.89
BEAM CONSTRAINED MASS (GeV/c^2)
BEAM CONSTRAINED MASS (GeV/c^2)

FIGURE 1

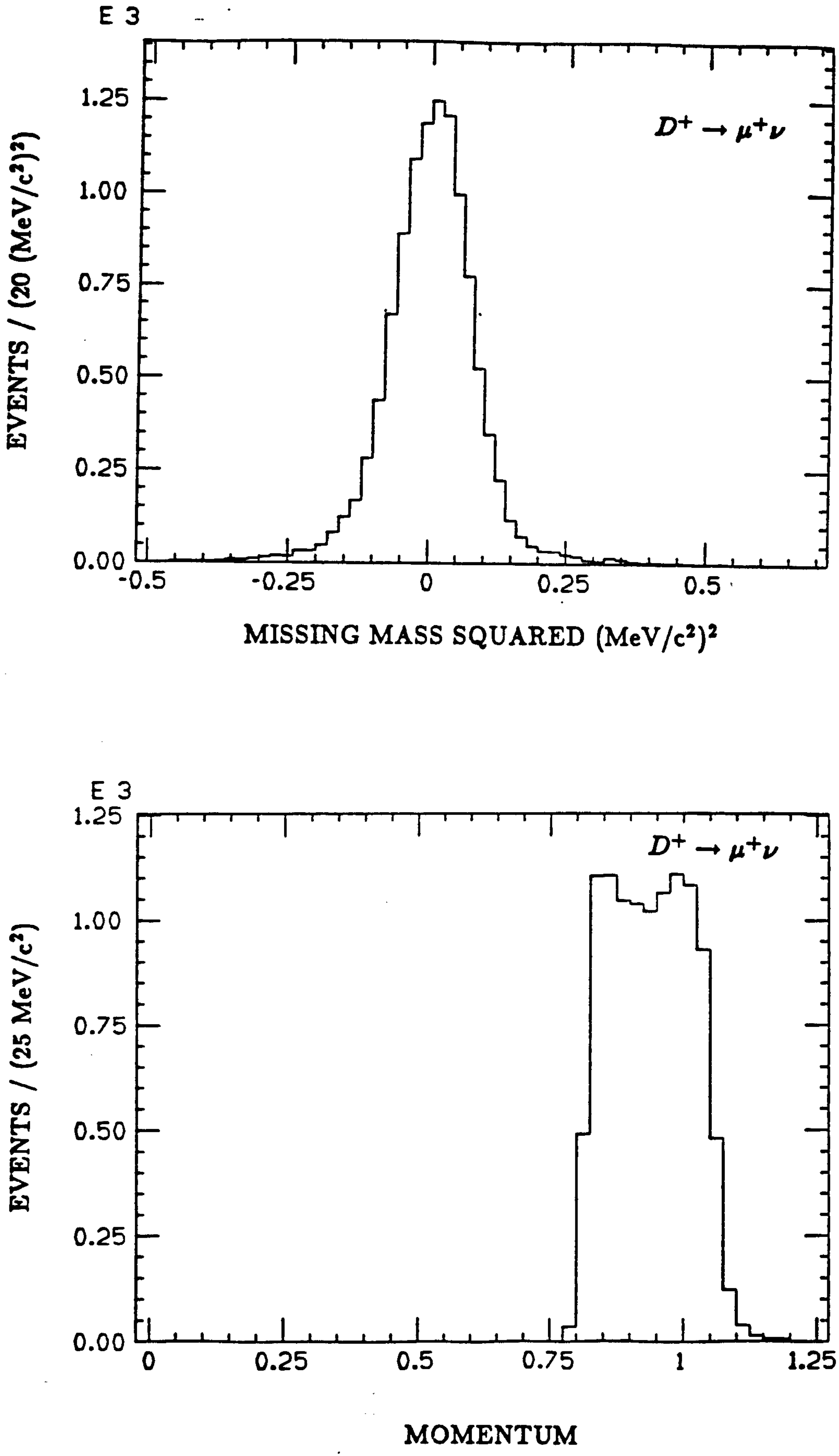

E 3
1.25
1.00
0.75
0.50
0.25
0.00
EVENTS / (20 (MeV/c²)²)
$D^+ \to \mu^+\nu$
-0.5
-0.25
0
0.25
0.5
MISSING MASS SQUARED (MeV/c²)²
E 3
1.25
1.00
0.75
0.50
0.25
0.00
EVENTS / (25 MeV/c²)
$D^+ \to \mu^+\nu$
0
0.25
0.5
0.75
1
1.25
MOMENTUM

FIGURE 2a

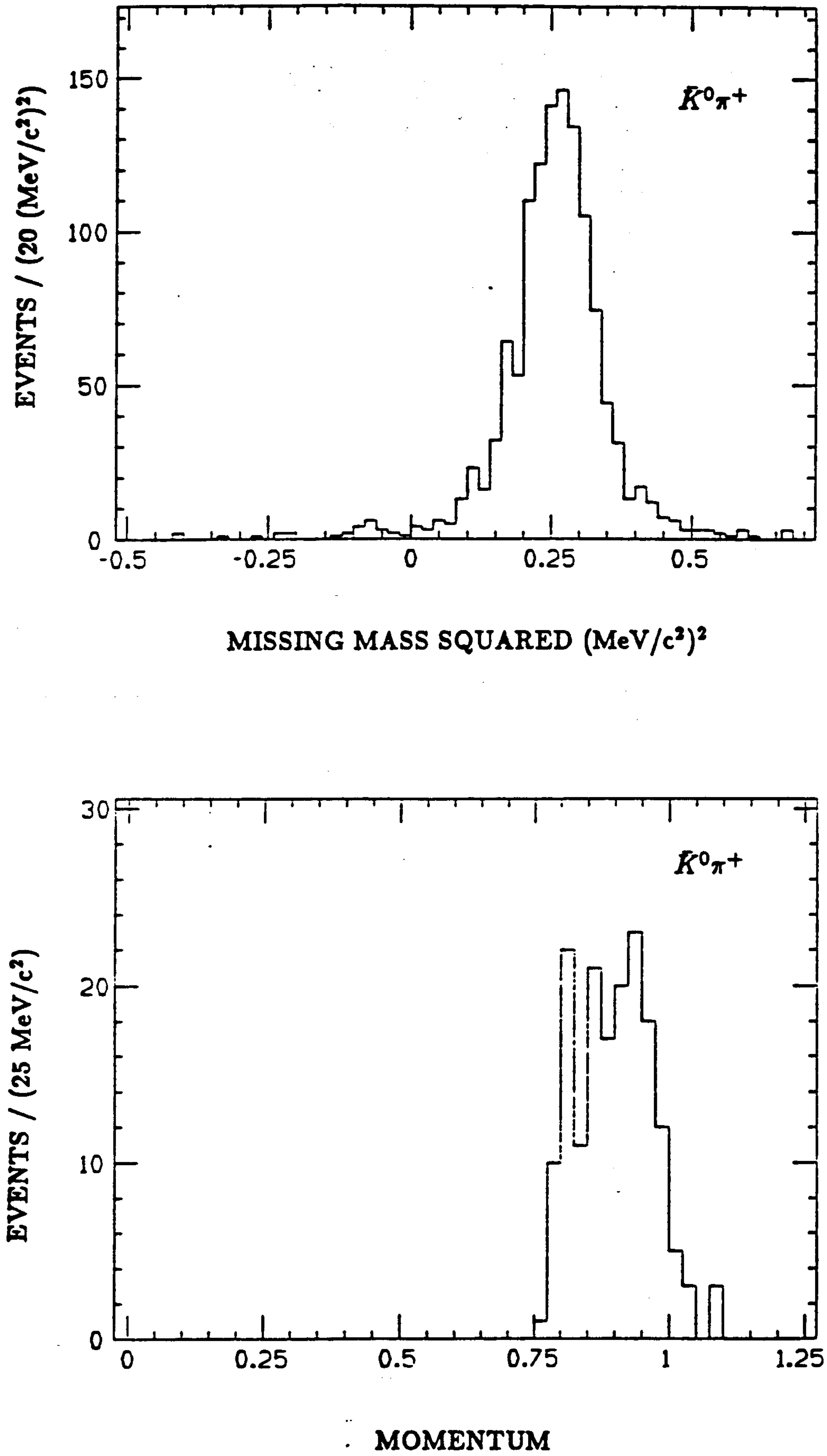
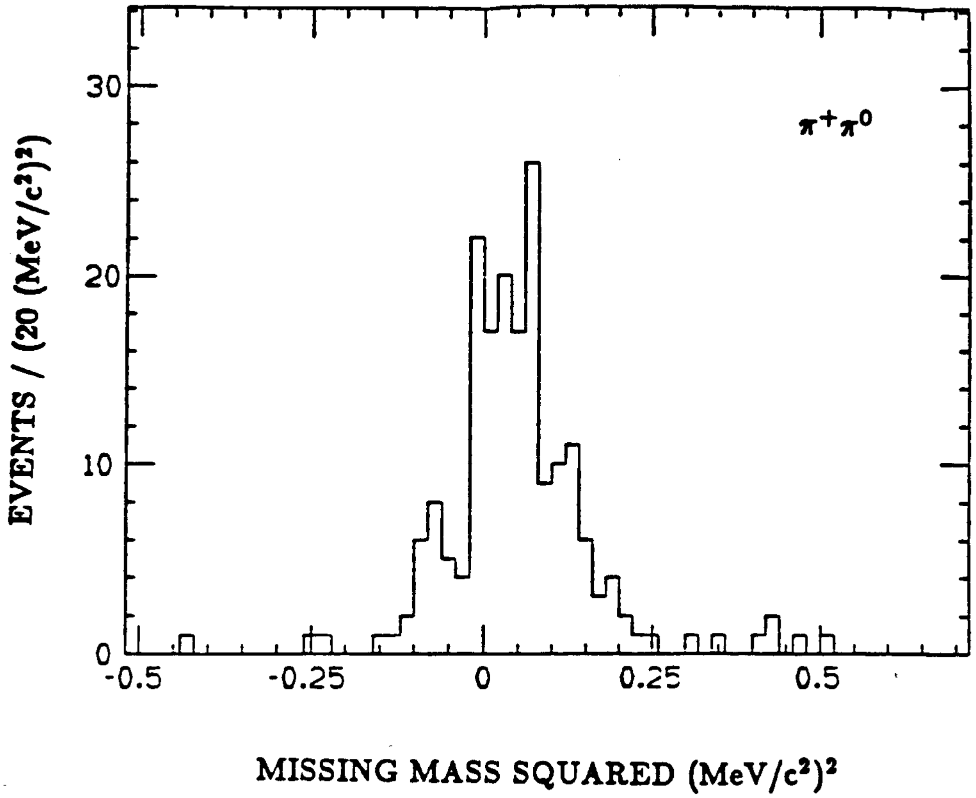
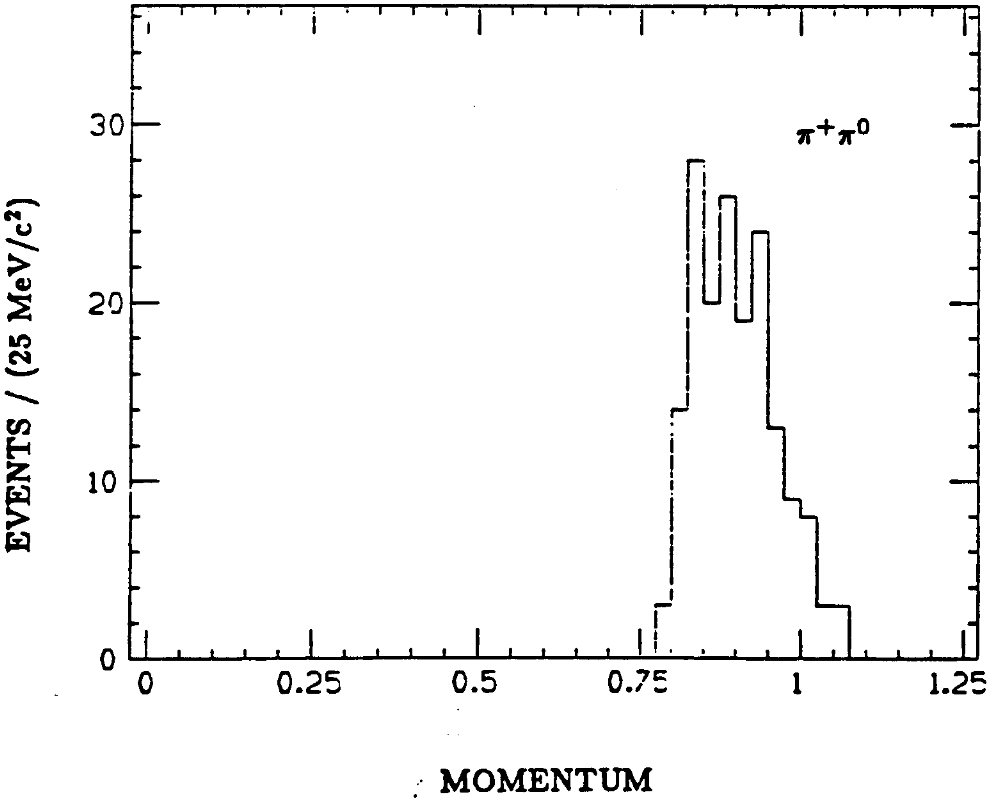

$K^0\pi^+$
EVENTS / (20 (MeV/c²)²)
150
100
50
0
-0.5
-0.25
0
0.25
0.5
MISSING MASS SQUARED (MeV/c²)²
$K^0\pi^+$
EVENTS / (25 MeV/c²)
30
20
10
0
0
0.25
0.5
0.75
1
1.25
MOMENTUM

FIGURE 2b

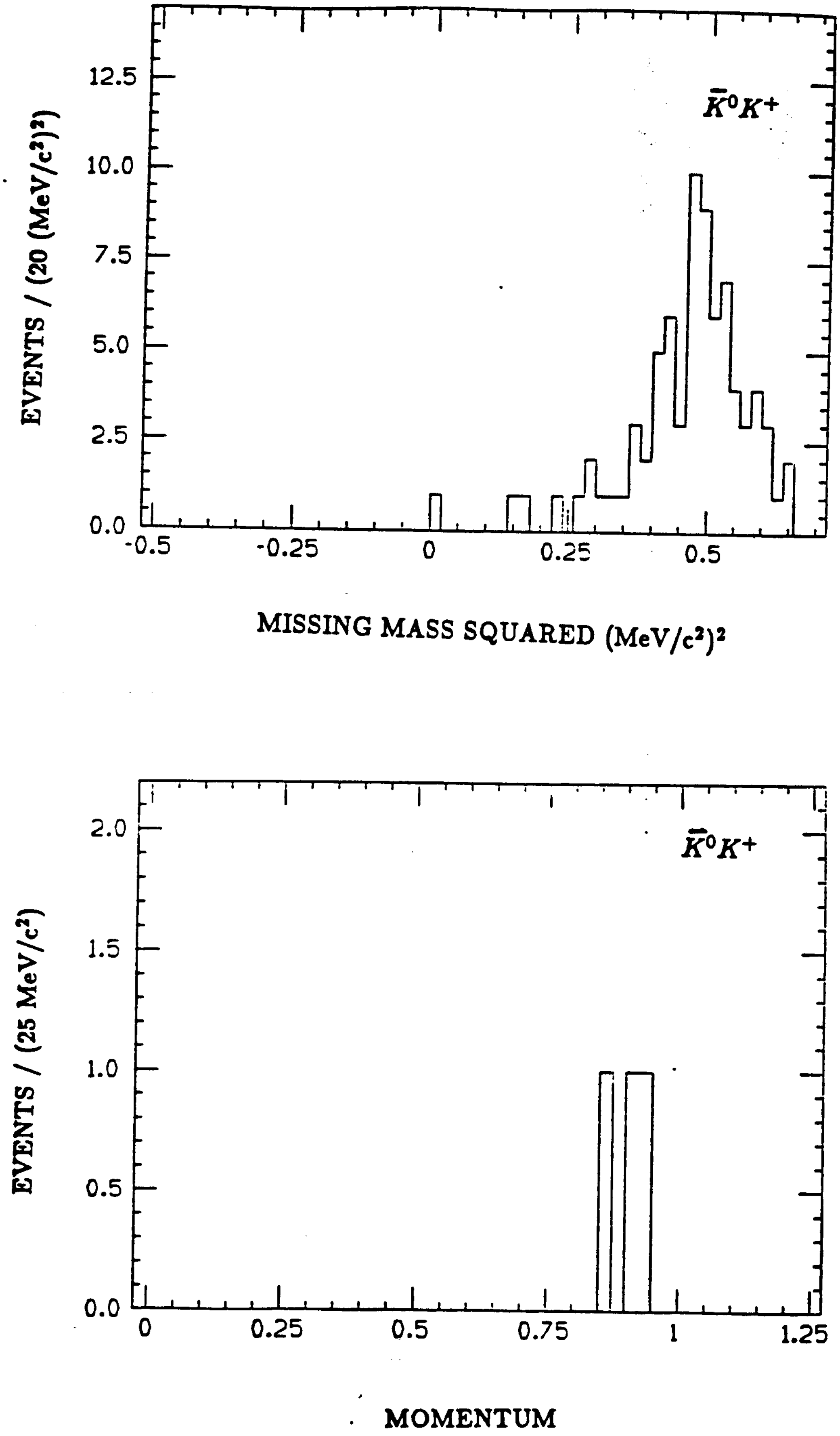


EVENTS / (20 (MeV/c²)²)
30
20
10
0
-0.5
-0.25
0
0.25
0.5
π⁺π⁰
MISSING MASS SQUARED (MeV/c²)²



EVENTS / (25 MeV/c²)
30
20
10
0
0
0.25
0.5
0.75
1
1.25
π⁺π⁰
MOMENTUM

FIGURE 2c


$\bar{K}^0K^+$
EVENTS / (20 (MeV/c²)²)
12.5
10.0
7.5
5.0
2.5
0.0
-0.5
-0.25
0
0.25
0.5
MISSING MASS SQUARED (MeV/c²)²
$\bar{K}^0K^+$
EVENTS / (25 MeV/c²)
2.0
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1.0
0.5
0.0
0
0.25
0.5
0.75
1
1.25
MOMENTUM

FIGURE 2d

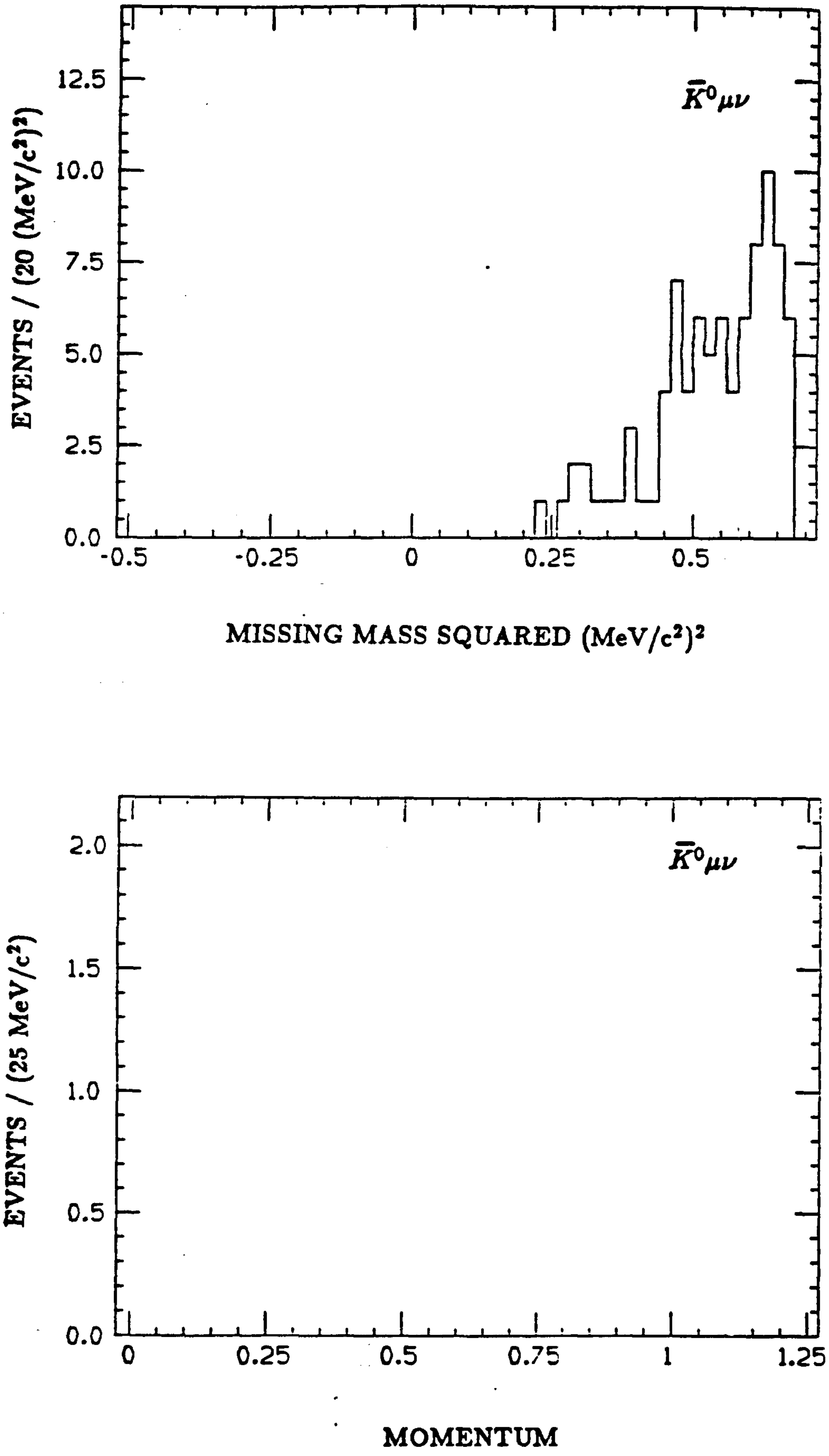
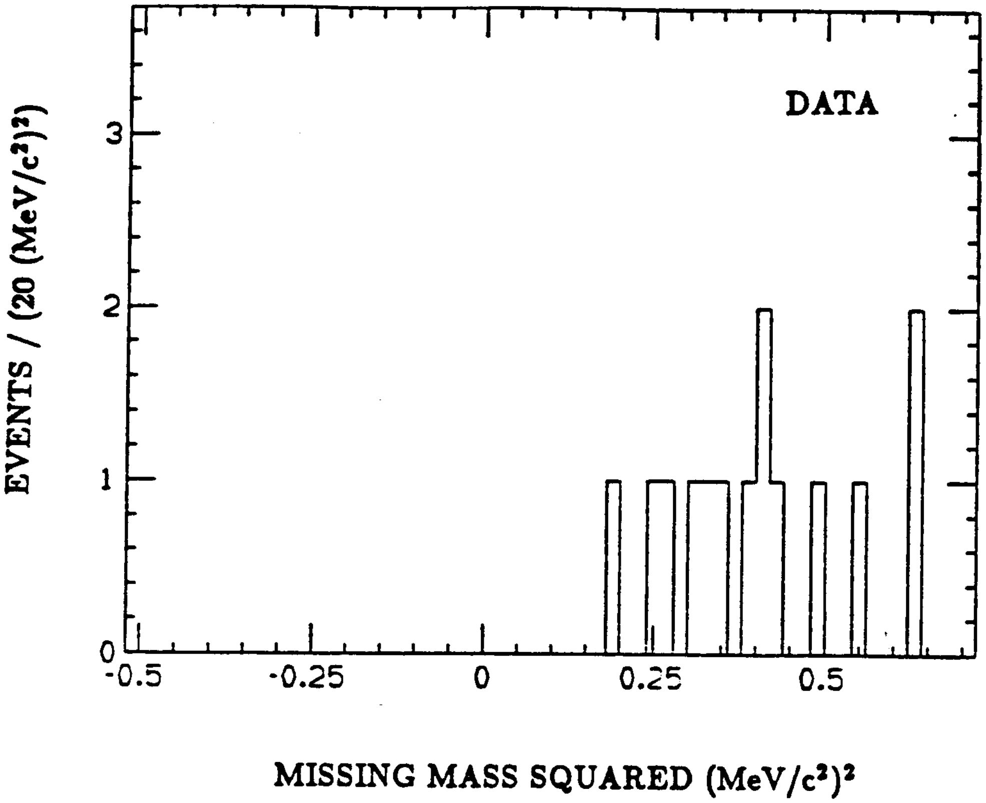

$\bar{K}^0\mu\nu$
EVENTS / (20 (MeV/c²)²)
12.5
10.0
7.5
5.0
2.5
0.0
-0.5
-0.25
0
0.25
0.5
MISSING MASS SQUARED (MeV/c²)²
$\bar{K}^0\mu\nu$
EVENTS / (25 MeV/c²)
2.0
1.5
1.0
0.5
0.0
0
0.25
0.5
0.75
1
1.25
MOMENTUM

FIGURE 2e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EVENTS / (20 (MeV/c²)²)
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2
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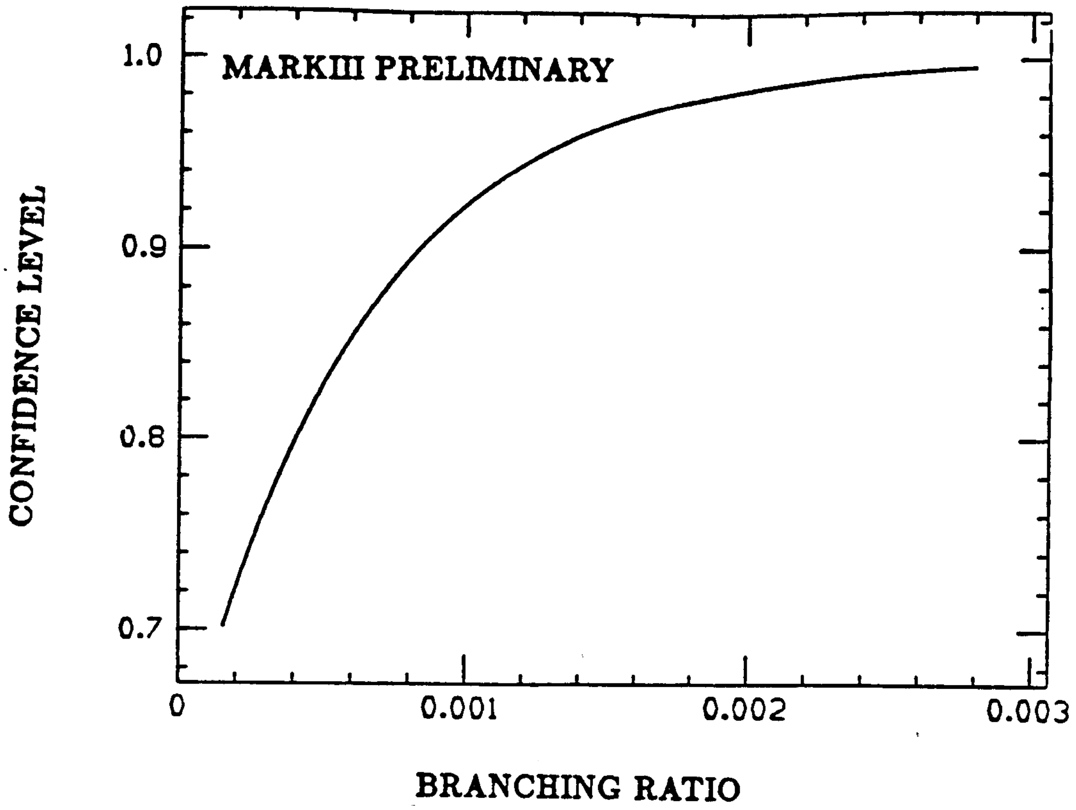
0
0.25
0.5
MISSING MASS SQUARED (MeV/c²)²

FIGURE 2f


MARKIII PRELIMINARY
CONFIDENCE LEVEL
1.0
0.9
0.8
0.7
0
0.001
0.002
0.003
BRANCHING RATIO

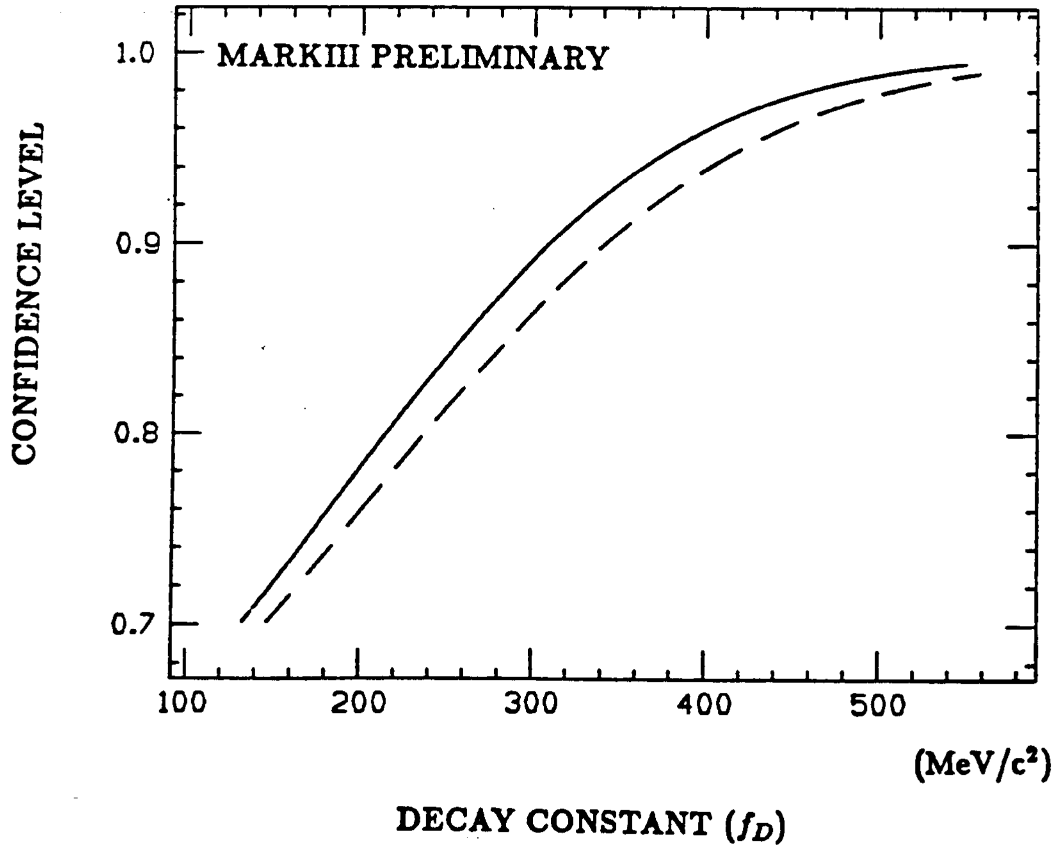

MARKIII PRELIMINARY
CONFIDENCE LEVEL
1.0
0.9
0.8
0.7
100
200
300
400
500
(MeV/c²)
DECAY CONSTANT (f_D)

FIGURE 3