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Observation of $D_s^+ \rightarrow \eta\pi^+$, and a New Limit on $D^+ \rightarrow \mu^+\nu_\mu$ and f_D*

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Abstract

We report two new results on charmed D^+ and D_s^+ decays, obtained using the Mark III detector at the e^+e^- storage ring SPEAR. We report the first observation of the decay $D_s^+ \rightarrow \eta\pi^+$. The product branching fraction is measured to be $\sigma(e^+e^- \rightarrow D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \rightarrow \eta\pi^+) = (74 \pm 19 \pm 25)$ *pb*. Second, we describe a search for the leptonic decay $D^+ \rightarrow \mu^+\nu_\mu$. A 90% confidence level upper limit on $B(D^+ \rightarrow \mu^+\nu_\mu)$ of 7.2×10^{-4} is obtained, corresponding to an upper bound of 290 Mev/c^2 on the pseudoscalar decay constant f_D.

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We begin by reporting the first observation of the decay $D_s^+ \rightarrow \eta\pi^+$.[1] The data sample used in this analysis[2] represents an integrated luminosity of $(6.30 \pm 0.46)\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 4.14\,\mathrm{GeV}$, collected with the Mark III detector at the e^+e^- storage ring SPEAR. Tracking information from the drift chamber, TOF measurements, and photon detection from the electromagnetic calorimeter are used in this analysis.

The analysis proceeds as follows. Candidate combinations for the decay chain $D_s^+ \rightarrow \eta\pi^+, \eta \rightarrow \pi^+\pi^-\pi^0$ are required to have at least one $\gamma\gamma$ combination passing a one-constraint (1C) fit to a π^0 hypothesis. The fit γ's must satisfy the relation $\cos(\theta_{\pi^0}^{\gamma}) < 0.9$, where $\theta_{\pi^0}^{\gamma}$ is the angle between the high energy γ and the π^0 in the π^0 rest frame. frame. In addition, there must be three charged tracks whose TOF information[3] is consistent with a pion hypothesis.

In order to reduce combinatorial background before any further kinematic fitting, the following pre-selection requirements are applied to several kinematic variables calculated using the results of the π^0 fit. The $\pi^+\pi^-\pi^0$ mass must be less than 800 MeV/c^2, while the $\pi^+(\pi^+\pi^-\pi^0)$ mass must be greater than 1.6 GeV/c^2. Using the fit π^0 four-momentum, the recoil mass to the $\pi^+(\pi^+\pi^-\pi^0)$ combination must lie within 80 MeV/c^2 of the D_s^* mass (2.109 GeV/c^2).[2] No loss of signal events is expected due to these cuts.

For all combinations passing the above cuts, a 1C fit is performed where the recoil to the $\pi^+(\pi^+\pi^-\gamma\gamma)$ system is required to have the D_s^* mass. Two requirements are imposed on the results of this fit. First, the fit photon energies must be larger than 120 MeV/c^2, rejecting some of the backgrounds resulting from D^* decays and noise photons. Further background rejection is achieved by demanding that the mass of the η candidate $(\pi^+\pi^-\gamma\gamma)$ shift from the $\pi^+\pi^-\pi^0$ mass by less than 40 MeV/c^2. This rejects fake π^0 combinations due to the 1C fit pulling the γ four-momenta away from the values obtained in the direct π^0 fit.

Figure 1 shows the scatter plot of m$(\pi^+(\pi^-\pi^+\gamma\gamma))$ versus m$(\pi^+\pi^-\gamma\gamma)$ for the results of the 1C D_s^* fit after the above cuts have been applied. The $\pi^+\pi^-\gamma\gamma$ mass is shown in Figure 2 (a) where m$(\pi^+(\pi^+\pi^-\gamma\gamma))$ has been required to fall between 1.94 and 2.00 GeV/c^2, the region expected for D_s^+ production. There is no evidence for η production outside the D_s^+ mass region. The results of fits to the η are consistent for Monte Carlo and data, as shown in Fig. 2(b). When the $\pi^+\pi^-\gamma\gamma$ mass of the η candidate is required to be within ± 40 MeV/c^2 around m_η, an accumulation of events is seen near the nominal D_s^+ mass. Figure 3 shows the $\pi^+(\pi^+\pi^-\gamma\gamma)$ mass plot for $\eta\pi^+$ candidates, together with a fit to a Gaussian signal (σ = 25 MeV/c^2, determined from Monte Carlo calculations) and a background shape extracted from a Monte Carlo of D^* production.

The fitted D_s^+ mass is $(1974 \pm 7)\,\mathrm{MeV}/c^2$, **where the error is statistical only.** There are 13.7 ± 3.5 events in the Gaussian signal, corresponding to the existence of the $\eta\pi^+$ decay mode of the D_s^+ at the 5σ level.[4] The D_s^+ mass resolution was fixed at $25\,\mathrm{MeV}/c^2$, as determined with the Monte Carlo simulation. A systematic error of 34% is estimated to arise from the following contributions (added in quadrature): Monte Carlo statistical error (10%), efficiency (25%, obtained by varying cuts), choice of background shape (20%), and integrated luminosity (7%). We then obtain a product branching fraction of:

$$\sigma(e^+e^- \to D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \to \eta\pi^+) = (74 \pm 19 \pm 25)\,\mathrm{pb}.$$

Most calculations[5][6][7] indicate that $B(D_s^+ \to \eta\pi^+) \leq B(D_s^+ \to \phi\pi^+)$. The result reported here corresponds to $B(D_s^+ \to \eta\pi^+) = (2.5 \pm .8 \pm .8) \times B(D_s^+ \to \phi\pi^+)$. Although this result is marginally consistent with the predictions, it may indicate an unexpected enhancement of $B(D_s^+ \to \eta\pi^+)$. It is interesting to note that the ratio $B(D_s^+ \to \eta\pi^+)/B(D_s^+ \to \bar{K}^0 K^+) = 2.3 \pm .7 \pm .8$ from the Mark III[8] is in reasonable agreement with expectations.[5][7] The magnitude of $\eta - \eta'$ mixing varies between different calculations. It is not, however, expected to result in the enhancement of $\eta\pi$ production indicated by this measurement. Evidence for large $D_s \to \eta\pi^+$ and $\eta'\pi^+$ production was also presented by the Mark II collaboration at this symposium.[9]

The second result presented is a search for the decay $D^+ \to \mu^+\nu_\mu$. A measurement of this leptonic decay provides an unambiguous determination of f_D:[10]

$$B(D^+ \to \mu^+\nu) = \frac{\Gamma(D^+ \to \mu^+\nu)}{\Gamma(D^+ \to \mathrm{all})} = \frac{G_F^2}{8\pi} f_D^2\, \tau_D\, m_D\, m_\mu^2 \,|\, V_{cd} \,|^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right)^2 \quad (1).$$

Since f_D is a direct measure of the overlap of the wavefunctions of the heavy and light quarks in the D meson,[11] it plays a fundamental role in understanding extensions to the light quark spectator model. The recent observation of large $B_d\bar{B}_d$[12] and $B_s\bar{B}_s$[13] mixing may be due to a large top quark mass, or an unexpectedly large value of f_B. A measurement of f_D may provide information on f_B through a phenomenological extrapolation.

The data,[14] with an integrated luminosity of $9.3\ \mathrm{pb}^{-1}$ corresponding to $\sim 2 \times 10^4$ produced D^+'s,[15] were obtained at the peak of the $\psi(3770)$ resonance. As the $\psi(3770)$ lies below $D\bar{D}^*$ threshold, D^+'s are produced monochromatically in pairs, allowing a clean search for $D^+ \to \mu^+\nu_\mu$ recoiling against an observed D^+ candidate (tag). The $2490 \pm 42 \pm 42$ D^- tags are reconstructed in seven final states: $K^+\pi^-\pi^-$, $K^0\pi^-$, $K^0\pi^-\pi^-\pi^+$, $K^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, K^0K^-, and $K^+K^-\pi^-$.

The $\mu^+\nu_\mu$ candidates are isolated by requiring the recoil system to the tag to contain exactly one track with the expected charge. If the μ^+ candidate is within the acceptance of the muon detection system ($|\cos\theta| \leq 0.65$, where θ is the polar angle from the beam axis), then two (one) layers are required to be hit for track momenta $p_\mu \geq 1$ GeV/c ($p_\mu < 1$ GeV/c). Recoil tracks outside the acceptance of the muon system ($0.65 \leq |\cos\theta| \leq 0.92$), must deposit less than 300 MeV in the barrel and endcap calorimeters. Those tracks within the acceptance of the TOF or dE/dx systems also must have identification consistent with a μ hypothesis.

Events with a recoil track lying outside the muon system are subjected to further cuts to suppress backgrounds. The principal sources of background to the $\mu^+\nu_\mu$ signal are the hadronic decays $D^+ \to \pi^+\pi^0$, $\bar{K}^0\pi^+$, $\bar{K}^0K^+$, $\bar{K}^0\rho^+$, and the semileptonic decays $D^+ \to \bar{K}^0\mu^+\nu_\mu$, $\bar{K}^{*0}\mu^+\nu_\mu$, and $\pi^0\mu^+\nu_\mu$. Those background events containing π^0's or K_L^0 which interact in the shower counter are rejected by requiring the absence of any isolated photons in an event.[16] The fraction of interacting K_L^0 is modeled using the J/ψ decays.

Background is further rejected by requiring $0.775 < p_\mu < 1.125$ GeV/c. This cut loses 2% of an expected signal, while retaining 18 events in the data (Fig. 4). The final separation of a $\mu^+\nu_\mu$ signal from background is obtained by performing a maximum likelihood fit[17] to the distribution of the missing mass (Fig. 5) in the event (M^2_{miss}). A Gaussian peak near $M^2_{miss} = 0$ is expected for $D^+ \to \mu^+\nu_\mu$, while a peak near $m^2_{\pi^0}$ or $m^2_{K^0}$ is expected for the two-body backgrounds. The distribution peaks at higher M^2_{miss} in the case of three-body backgrounds.

The best fit to the M^2_{miss} distribution yields zero events. An upper limit on $B(D^+ \to \mu^+\nu_\mu)$ is obtained by performing a likelihood ratio test.[14][18] Using a weighted average acceptance for $D^+ \to \mu^+\nu_\mu$ of 0.74 ± 0.01, this procedure gives $B(D^+ \to \mu^+\nu_\mu) \leq 6.1 \times 10^{-4}$ at the 90% Confidence Level (C.L.). Inclusion of systematic errors[19] increases this to 7.2×10^{-4}. Using a D^+ lifetime of $(10.9 \pm 0.3 \pm 0.25) \times 10^{-13}$s,[20] and $|V_{cd}|^2 = 0.0493$,[21] gives $f_D \leq 290$ MeV/c^2.[22][23]

This limit excludes the large values of f_D (~ 400 MeV/c^2) suggested by perturbative calculations to explain the ratio $\tau(D^+)/\tau(D^0)$. It does not, however, exclude non-perturbative mechanisms[24] proposed to enhance W-exchange contributions to the D^0 width.[25] Most calculations[26] conclude that the pseudoscalar decay constants for the three heavy quarks are ordered in magnitude $f_D \gtrsim f_B \gtrsim f_T$. Under this assumption, our result may be interpreted as a phenomenological bound $f_B \leq 290$ MeV/c^2. Recent papers[27] which extract lower limits on m_t from $B\bar{B}$ mixing have employed theoretical values for f_B significantly below this phenomenological upper limit. If the limit obtained above is used, these calculations result in less stringent bounds on m_t.

In summary, the decay $D_s^+ \to \eta\pi^+$ is observed at $\sqrt{s} = 4.14$ GeV, with a production cross section times branching fraction of $(74 \pm 19 \pm 25)pb$. A search has been performed for the leptonic decay $D^+ \to \mu^+\nu_\mu$. The branching fraction $B(D^+ \to \mu^+\nu_\mu)$ is found to be $< 7.2 \times 10^{-4}$ at the 90% C.L., corresponding to $f_D < 290\,\mathrm{MeV}/c^2$.

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References

1. Throughout this paper reference to a particle state also implies reference to its charge conjugate.
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3. The charged π tracks are required to have $|(t_\pi - t_m)/\sigma_\pi| < 3$ where $t_\pi(\sigma_\pi)$ is the predicted TOF (TOF error) for a π mass hypothesis, and t_m is the measured TOF.
4. This corresponds to a log(likelihood) difference of 14.7 between fits with and without a Gaussian D_s^+ signal.
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11. See for example, R. Van Royen and V. F. Weisskopf, Nuovo Cim. **50A**, 617 (1967).
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15. J. Adler *et al.*, , SLAC-PUB 4291 (1987), submitted to Phys. Rev. Lett.
16. Isolated photons are defined as those showers with energy greater than 100 MeV which are not used in forming a π^0 in the tag, or which make an angle $\cos\alpha \leq 0.92$ with respect to any charged track.
17. The likelihood function contains contributions from all D backgrounds. A contribution of 1.9 ± 0.8 events from erroneously tagged D mesons is propagated in the analysis.
18. The C.L. is defined as the probability that a given hypothesis, here B($D^+ \to \mu^+\nu_\mu$) and a set of background branching fractions, will give an observed likelihood ratio $\lambda = L_{\mathrm{true}}/L_{\mathrm{max}}$ that is greater than that measured by this experiment (cf. A. G. Frodesen *et al.*, **Probability and Statistics in Particle Physics** (Universitettsforlaget, Bergen, 1979), pp. 388-395).

19. Systematic errors are propagated linearly. The uncertainty in the knowledge of K_L^0 interactions contributes 6%. The remaining 8.6% arises from uncertainty in the counting of D tags, the Monte Carlo simulation of the muon system, drift chamber track reconstruction, and in the effect of the isolated photon cuts.

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21. M. Aguilar-Benitez *et al.,* Phys. Lett. **170B**, 74 (1986).

22. This is obtained by dividing $\mathrm{B}(D^+ \to \mu^+\nu_\mu)$ by $(\tau_D - \delta\tau_D^{\mathrm{stat}} - \delta\tau_D^{\mathrm{syst}})$.

23. For comparison, a Bayesian application of Poisson statistics, with zero observed events, yields an upper limit of $\mathrm{B}(D^+ \to \mu^+\nu_\mu) < 9.2 \times 10^{-4}$ at the 90% C.L., corresponding to 2.3 signal events. The limit on f_D would be 390 MeV/c^2. See footnote 8 of J. J. Becker *et al.,* Phys. Lett. **193B**, 147 (1987).

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I. I. Y. Bigi, SLAC-PUB-4349 (1987).

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An exception is V. S. Mathur and M. T. Yamawaki, Phys. Rev. **D29**, 2057 (1984). See footnote 5 of Ref. 14 for a detailed list of f_D calculations.

27. See footnote 8 of Ref. 14 for a selection of theoretical analyses.

FIGURE CAPTIONS

1. Scatter plot of m($\pi^+(\pi^+\pi^-\gamma\gamma)$) versus m($\pi^+\pi^-\gamma\gamma$) for the results of the 1C D_s^* fit. The lines indicate the D_s^+ and η cuts described in the text.
2. The $\pi^+\pi^-\gamma\gamma$ mass after cut on $\pi^+(\pi^+\pi^-\gamma\gamma)$ mass for (a) data, and (b) Monte Carlo. The results of η fits are: $m(\eta) = 554 \pm 2$ MeV/c^2 and $\sigma(\eta) = 14 \pm 2$ MeV/c^2 for the Monte Carlo, and $m(\eta) = 557 \pm 4$ MeV/c^2 and $\sigma(\eta) = 11 \pm 3$ MeV/c^2 for the data.
3. The $\pi^+(\pi^+\pi^-\gamma\gamma)$ mass after cut on $\pi^+\pi^-\gamma\gamma$ mass for the data.
4. Momentum of recoil muons, p_μ, for tagged D^- candidates (solid line) and for Monte Carlo generated events (dashed line).
5. The M^2_{miss} distribution after cutting on p_μ. The best fit (containing no $\mu^+\nu_\mu$ events) is shown as a solid line; the dashed line corresponds to the 90% C.L. limit of 1.5 observed events (see text).

Mark III Preliminary

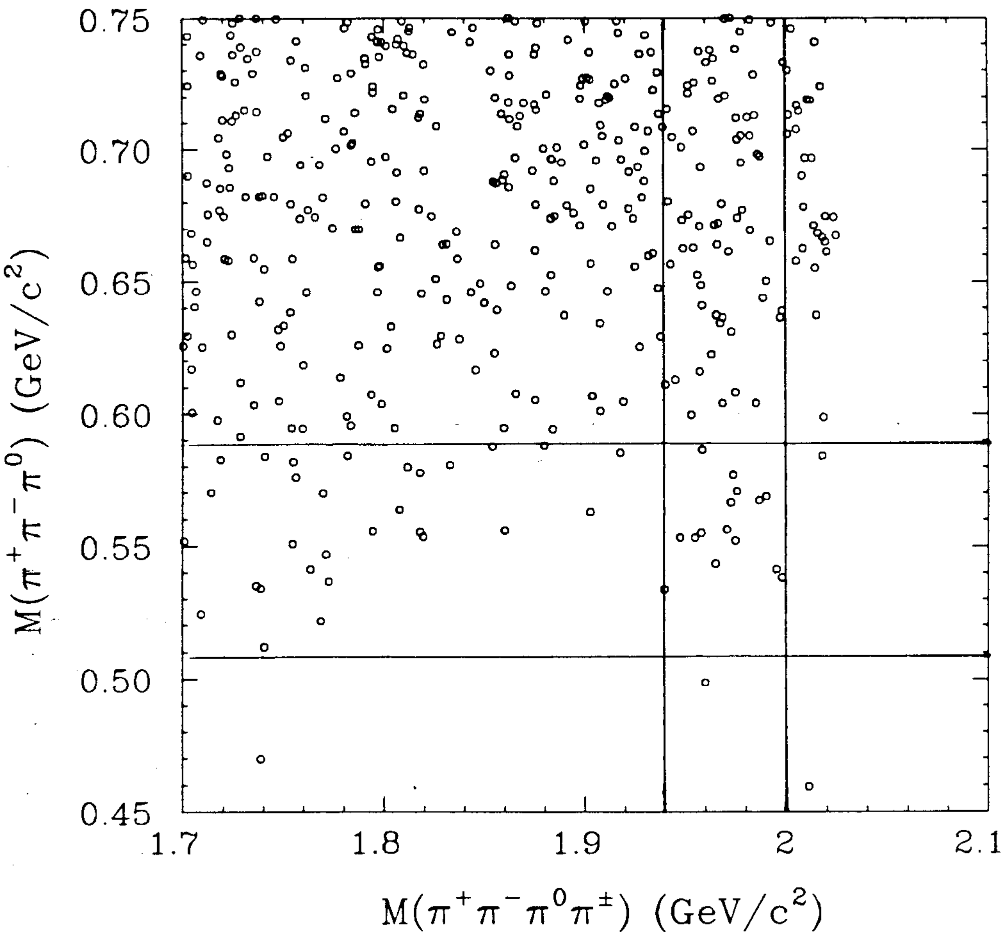
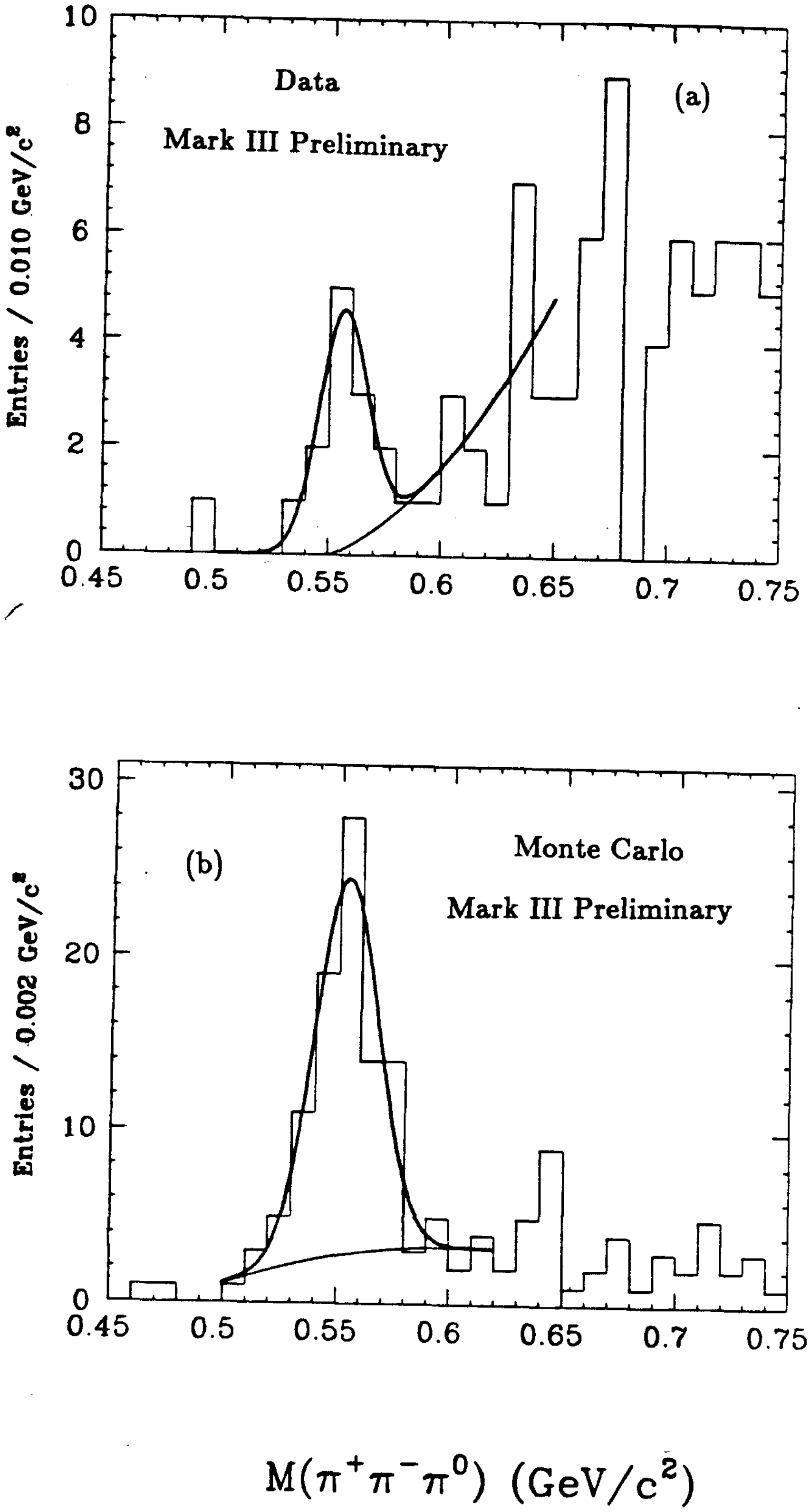


Figure 1



10
8
6
4
2
0
0.45
0.5
0.55
0.6
0.65
0.7
0.75
Entries / 0.010 GeV/c²
Data
Mark III Preliminary
(a)
30
20
10
0
0.45
0.5
0.55
0.6
0.65
0.7
0.75
Entries / 0.002 GeV/c²
(b)
Monte Carlo
Mark III Preliminary
M(π⁺π⁻π⁰) (GeV/c²)

Figure 2

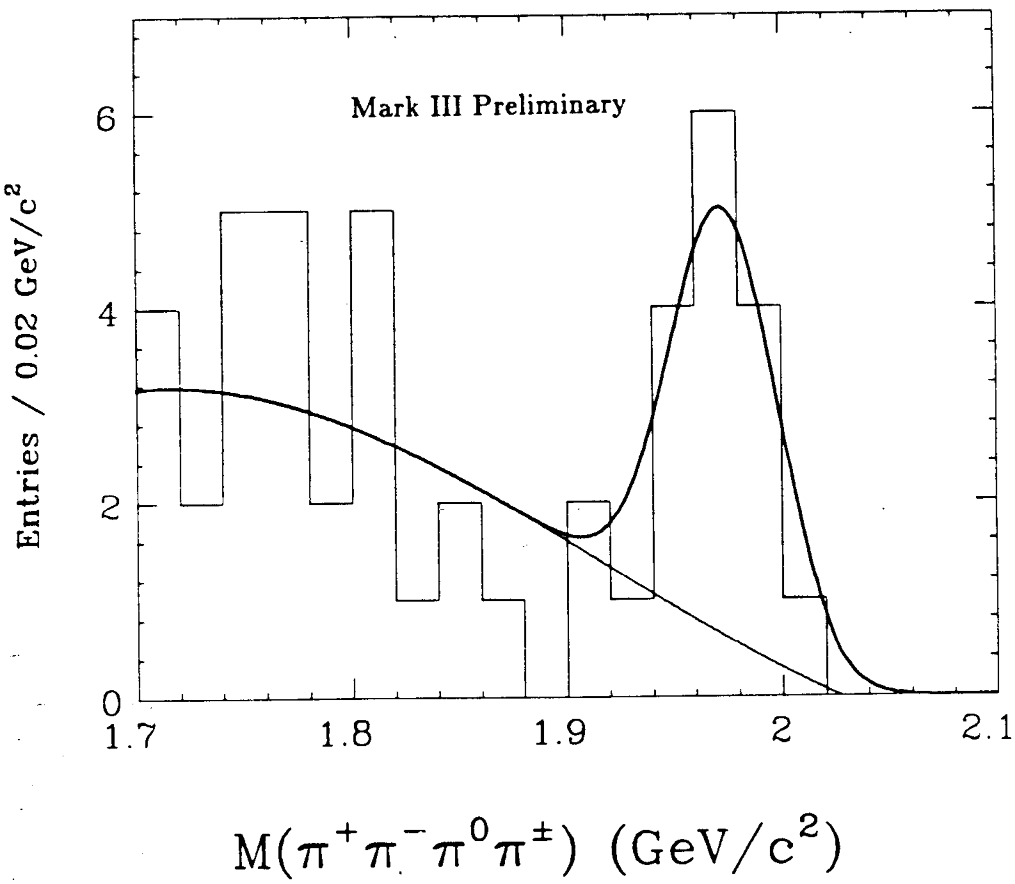

Mark III Preliminary
Entries / 0.02 GeV/c²
0
2
4
6
1.7
1.8
1.9
2
2.1
M(π⁺π⁻π⁰π^±) (GeV/c²)

Figure 3

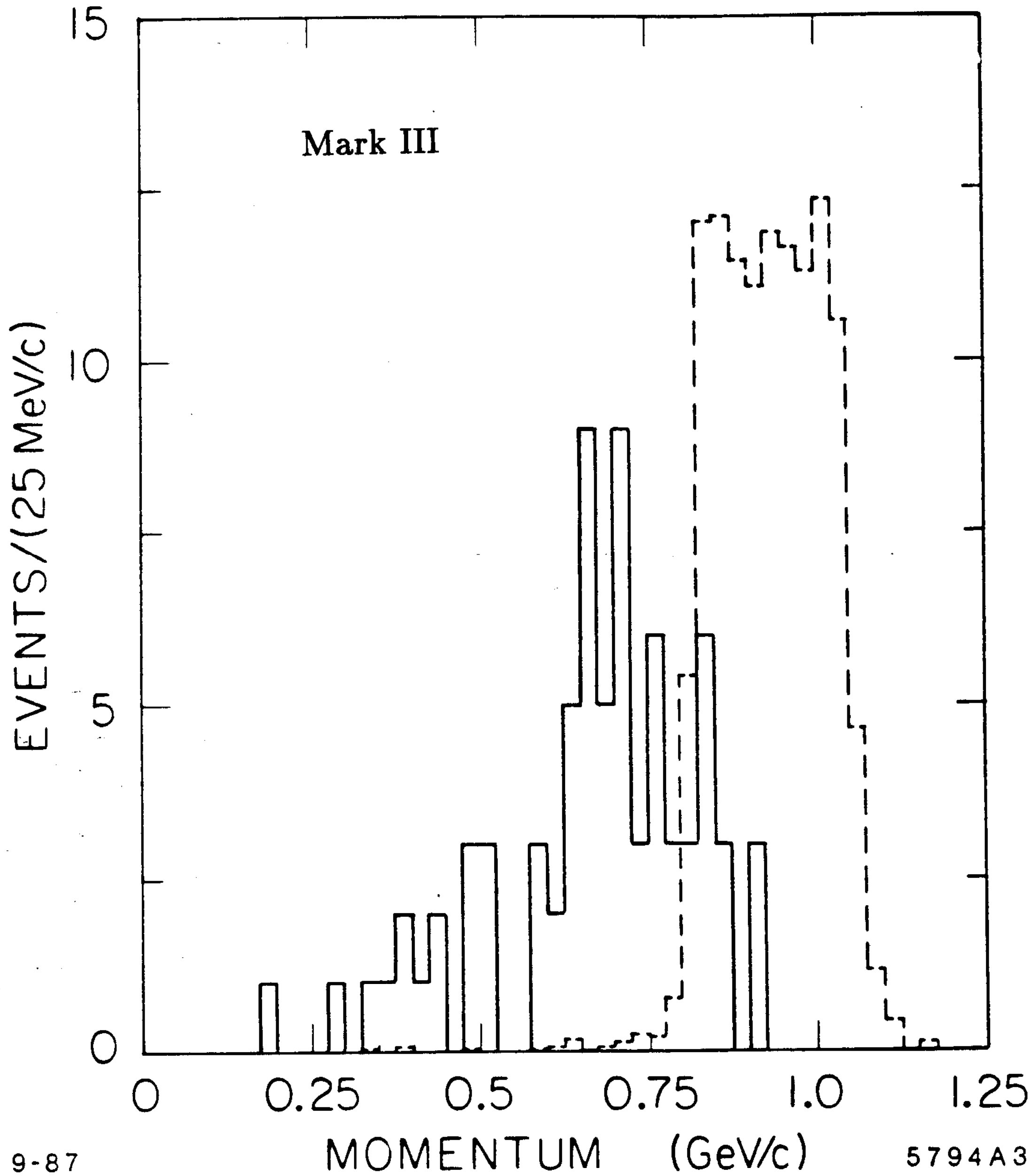
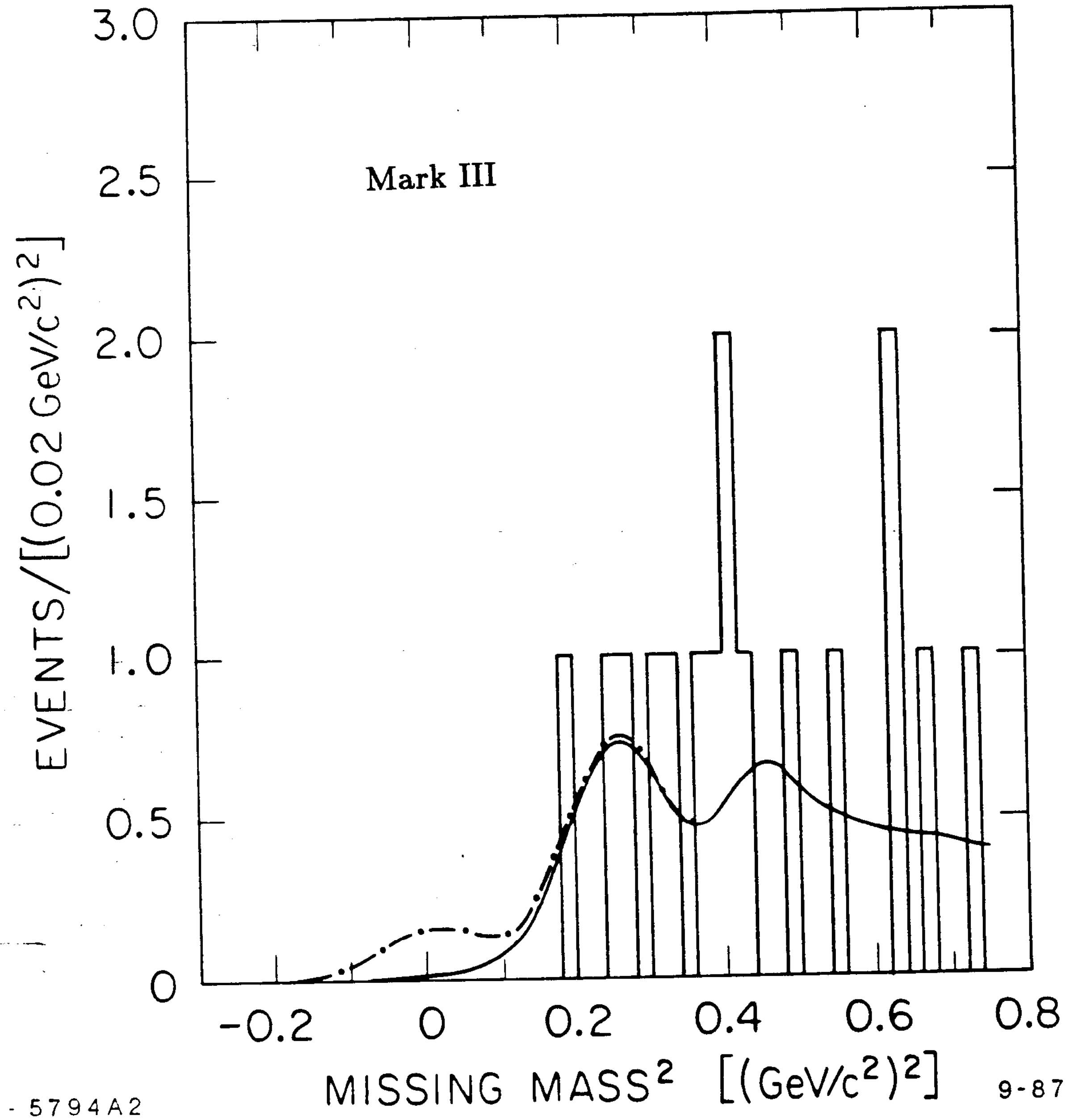

Mark III
EVENTS/(25 MeV/c)
15
10
5
0
0
0.25
0.5
0.75
1.0
1.25
MOMENTUM (GeV/c)
9-87
5794A3

Figure 4



Mark III
EVENTS/[(0.02 GeV/c^2)^2]
3.0
2.5
2.0
1.5
1.0
0.5
0
−0.2
0
0.2
0.4
0.6
0.8
MISSING MASS^2 [(GeV/c^2)^2]
9-87
5794A2

Figure 5