SLAC-PUB-4343
October 1987
(T/E)

# Search for the Decay $D^+ \rightarrow \mu^+\nu_\mu$ and an Upper Limit on the Pseudoscalar Decay Constant†

J. Adler, J.J. Becker, G.T. Blaylock, T. Bolton, J.S. Brown, K.O. Bunnell, T.H. Burnett, R.E. Cassell, D. Coffman, V. Cook, D.H. Coward, D.E. Dorfan, G.P. Dubois, A.L. Duncan, G. Eigen, K.F. Einsweiler, B.I. Eisenstein, T. Freese, G. Gladding, C. Grab, F. Grancagnolo, R.P. Hamilton,‡ J. Hauser, C.A. Heusch, D.G. Hitlin, J. M. Izen, L. Köpke, A. Li, W.S. Lockman, U. Mallik, C.G. Matthews, R. Mir, P.M. Mockett, R.F. Mozley, B. Nemati, A. Odian, L. Parrish, R. Partridge, J. Perrier, D. Pitman, S.A. Plaetzer, J.D. Richman, H.F.W. Sadrozinski, M. Scarlatella, T.L. Schalk, R.H. Schindler, A. Seiden, C. Simopoulos, A.L. Spadafora, I.E. Stockdale, W. Stockhausen, J.J. Thaler, W. Toki, B. Tripsas, F. Villa, S. Wasserbaech, A. Wattenberg, A.J. Weinstein, N. Wermes, H.J. Willutzki, D. Wisinski, W.J. Wisniewski, R. Xu, Y. Zhu

**The MARK III Collaboration**

*California Institute of Technology, Pasadena, CA 91125*
*University of California at Santa Cruz, Santa Cruz, CA 95064*
*University of Illinois at Urbana-Champaign, Urbana, IL 61801*
*Stanford Linear Accelerator Center, Stanford, CA 94305*
*University of Washington, Seattle, WA 98195*

## Abstract

We report the results of a search for the leptonic decay $D^+ \rightarrow \mu^+\nu_\mu$ using the Mark III detector at SPEAR. A data sample of 9.3 $pb^{-1}$ collected at the $\psi(3770)$ resonance yields no signal events, corresponding to a 90% C.L. upper limit of $7.2 \times 10^{-4}$ on the branching ratio $B(D^+ \rightarrow \mu^+\nu_\mu)$. This represents an upper limit on the pseudoscalar decay constant $f_D$ of 290 MeV/$c^2$.

Submitted to *Physical Review Letters*

† This work was supported in part by the U. S. Department of Energy, under contracts DE-AC03-76SF00515, DE-AC02-76ER01195, DE-AC03-81ER40050, DE-AM03-76SF0034, and by the National Science Foundation.

‡ Deceased

The decay constant $f_D$ characterizes the magnitude of the charged weak axial vector current matrix element in $D^+$ decay,[1] and is a direct measure of the overlap of the wavefunctions of the heavy and light quarks in the meson. It thus plays a fundamental role in the understanding of extensions to the light quark spectator model, such as W-exchange and W-annihilation processes,[2][3] and enters in the evaluation of second order weak diagrams leading to $D^0\bar{D}^0$ mixing.[4] In many models[5] a measurement of $f_D$ provides a phenomenological bound on $f_B$ which, when combined with the observed rate for $B_d\bar{B}_d$[6] and $B_s\bar{B}_s$[7] mixing, may yield a lower bound on the mass of the top quark.[8]

A measurement of the leptonic decay of the $D^+$ provides an unambiguous determination of $f_D$ :[9]

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

where $m_D$ is the meson mass, $m_\mu$ the muon mass, $V_{cd}$ the Kobayashi-Maskawa matrix element, $G_F$ the Fermi constant, and $\tau_D$ the lifetime of the $D^+$.

This Letter reports the results of a search for the decay $D^+ \to \mu^+\nu_\mu$[10] using the Mark III detector[11] at the $e^+e^-$ storage ring SPEAR. 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 $\text{pb}^{-1}$ corresponds to $\sim 2 \times 10^4$ produced $D^+D^-$ pairs.[12] Events are selected in which one $D^-$ hadronic decay candidate is found. The recoil system is examined for evidence of $D^+ \to \mu^+\nu_\mu$, thus providing a direct measurement of the absolute branching ratio B($D^+ \to \mu^+\nu_\mu$). The

$D^-$ candidates (tags) are selected as follows: charged particles are identified by time-of-flight (TOF) or by energy loss (dE/dx) in the drift chamber. Seven final states are reconstructed: $K^+\pi^-\pi^-$, $K^0\pi^-$, $K^0\pi^-\pi^-\pi^+$, $K^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, $K^0K^-$, and $K^+K^-\pi^-$. The total energy of the candidate is constrained to the beam energy; if the final state contains a $\pi^0$, the $\pi^0$ mass is imposed as an additional constraint. A $D^-$ tag candidate must have a mass between 1.862 and 1.875 GeV/$c^2$. This procedure[13] results in $2490 \pm 42 \pm 42$ identified $D^-$ tags (Fig. 1).

The isolation of $\mu^+\nu_\mu$ candidates proceeds as follows. The recoil to a tag is required to contain exactly one track with the expected charge. 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 $\theta$ is the polar angle from the beam axis), or is detected only in the central tracking chamber and the calorimeter ($0.65 \leq |\cos\theta| \leq 0.92$).

Recoil tracks within the acceptance of the muon system are subjected to one further requirement to reject hadrons: two (one) layers are required to be hit for track momenta $p_\mu \geq 1$ GeV/$c$ ($p_\mu < 1$ GeV/$c$). As the 95%(90%) rejection of $\pi(K)$ mesons provided by the muon system is sufficient for this analysis, no further event topology cuts are applied to this sample.[14]

For recoil tracks outside the acceptance of the muon system, the barrel and endcap calorimeters (0.4 absorption lengths) provide some hadron rejection. The reduction of $\pi$ and K backgrounds is achieved by requiring the candidate recoil muon to deposit less than 300 MeV in the calorimeter.[15] Those tracks within the acceptance of the TOF or dE/dx systems must have identification consistent with a $\mu$ 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 $D^+ \rightarrow \pi^+\pi^0$, $\bar{K}^0\pi^+$, $\bar{K}^0K^+$, $\bar{K}^0\rho^+$, and the semileptonic decays $D^+ \rightarrow \bar{K}^0\mu^+\nu_\mu$, $\bar{K}^{*0}\mu^+\nu_\mu$, and $\pi^0\mu^+\nu_\mu$. Those background events containing direct $\pi^0$'s or daughter $\pi^0$'s from $K^0_S \rightarrow \pi^0\pi^0$ are rejected by requiring the absence of any isolated photons in an event.[16] This cut also rejects those $K^0_L$ which interact in the shower counter. The fraction of interacting $K^0_L$ is modeled using the decays $J/\psi \rightarrow K^0_S K^0_L$, $K^0_S \rightarrow \pi^+\pi^-$ and $J/\psi \rightarrow \phi\eta, \phi \rightarrow K^0_S K^0_L$, $K^0_S \rightarrow \pi^+\pi^-$ from a separate data set.[17]

Kinematic variables are used to separate remaining $\mu^+\nu_\mu$ candidate events from background. Figure 2 shows a scatter plot of $p_\mu$ versus the square of the missing mass ($M^2_{miss}$) in each event. The $p_\mu$ distribution for two-body $\mu^+\nu_\mu$ events is limited to the region indicated in Fig. 3. Figure 3 also shows the $p_\mu$ projection of the observed events. Requiring $0.775 < p_\mu < 1.125$ GeV/$c$ loses 2% of an expected signal while retaining 18 events in the data. The final separation of a $\mu^+\nu_\mu$ signal from background is obtained from the $M^2_{miss}$ distribution, whose projection after the cut on $p_\mu$ is shown in Fig. 4. A Gaussian peak near $M^2_{miss} = 0$ is expected for $D^+ \rightarrow \mu^+\nu_\mu$, 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 with or without missing neutrinos. No event appears near $M^2_{miss} = 0$.

A maximum likelihood fit to the $M^2_{miss}$ distribution, incorporating shape information on the background both in and above the signal region, provides an upper limit on the number of $\mu^+\nu_\mu$ events.[18] The acceptance for $D^+ \to \mu^+\nu_\mu$ varies by less than 3% for the seven different tagging modes; the weighted average acceptance is $0.74 \pm 0.01$. An upper limit on the branching fraction $\mathrm{B}(D^+ \to \mu^+\nu_\mu)$ is obtained by performing a likelihood ratio test.[19] This procedure gives $\mathrm{B}(D^+ \to \mu^+\nu_\mu) \leq 6.1 \times 10^{-4}$ at the 90% Confidence Level (C.L.), corresponding to 1.5 produced events. Inclusion of systematic errors[20] increases this to $7.2 \times 10^{-4}$.[21] Using a $D^+$ lifetime of $(10.9 \pm 0.3 \pm 0.25) \times 10^{-13}$s,[22] and $|V_{cd}|^2 = 0.0493$ ,[23] gives $f_D \leq 290$ MeV/c$^2$.[24]

For comparison, a Bayesian application[25] of Poisson statistics, with zero observed events, yields an upper limit of $\mathrm{B}(D^+ \to \mu^+\nu_\mu) < 13.6 \times 10^{-4}$ at the 90% C.L., corresponding to 2.3 signal events. The limit on $f_D$ would be 390 MeV/$c^2$.

The limit on $f_D$ provides a constraint on non-spectator contributions to weak hadronic charmed meson decay. It rules out the large value of $f_D$ required by perturbative calculations[2] to explain the ratio $\tau(D^+)/\tau(D^0) \approx 2.4$. It does not, however, exclude non-perturbative mechanisms[3] proposed to enhance W-exchange contributions to the $D^0$ width.

Most models[5][26] conclude that the pseudoscalar decay constants for mesons containing different species of heavy quarks are ordered in magnitude $f_D \gtrsim f_B \gtrsim f_T$. This limit on $f_D$ may thus be interpreted as a phenomenological bound on $f_B$. Specific calculations[5] lie in the range $0.6 < f_B/f_D < 0.95$. Estimates[8] of lower limits on the top quark mass based on the recent observation of $B^0\bar{B}^0$ mixing[6,7] have employed theoretical values of $f_B$ significantly below this bound. If the limit obtained herein were used, these calculations would result in less stringent bounds[27] on the top quark mass.

This paper is dedicated to the memory of R.P. Hamilton. We gratefully acknowledge the efforts of the SPEAR staff and also wish to thank I. I. Y. Bigi, T. DeGrand, B. F. L. Ward, and P. M. Zerwas for useful discussions. This work was supported in part by the U.S. National Science Foundation and the U.S. Department of Energy under Contracts No.DE-AC03-76SF00515, No.DE-AC02-76ER01195, No.DE-AC03-81ER40050, and No.DE-AM03-76SF00034.

## REFERENCES


1. R. Van Royen and V. F. Weisskopf, Nuovo Cim. **50A**, 617 (1967).
2. M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **44**, 7 (1980).
3. H. Fritzsch and P. Minkowski, Phys. Lett. **90B**, 455 (1980),
   I. I. Y. Bigi, SLAC-PUB-4349 (1987).
4. See for example, I. I. Y. Bigi, G. Köpp, and P. M. Zerwas, Phys. Lett. **166B**, 238 (1986),
   J. F. Donoghue *et al.*, Phys. Rev. D**33**, 197 (1986).
5. S. Godfrey and N. Isgur, Phys. Rev. D**32**, 189 (1985),
   V. A. Novikov *et al.*, Phys. Rev. Lett. **38**, 626 (1977),
   E. Golowich, Phys. Lett. **91B**, 271 (1980),
   H. Krasemann, Phys. Lett. **96B**, 397 (1980),
   V. S. Mathur *et al.*, Phys. Lett. **107B**, 127 (1981),
   L. Reinders, Phys. Rep. **127**, 1 (1985),
   L. Maiani, *Proc. of the XXI International Conference on High Energy Physics*, (Editions de Physique, Les Ulis, France, 1982), pp. 631-657,
   E. Shuryak, Nucl. Phys. **B198**, 83 (1982),
   M. Claudson, Harvard report HUTP-81/A016 (1982),
   P. J. O'Donnell, CERN-TH.4419/86 (1986),
   B. F. L. Ward, Phys. Rev. D**28**, 1215 (1983),
   R. M. Woloshyn *et al.*, Triumf Preprint TRI-PP-87-62 (1987).
6. H. Albrecht *et al.*, Phys. Lett. **192B**, 245 (1987).
7. C. Albajar *et al.*, Phys. Lett. **186B**, 247 (1987).

8. See for example, J. Ellis, J. S. Hagelin, and S. Rudaz, Phys. Lett. **192B**, 201 (1987),

I. I. Y. Bigi and A. I. Sanda, Phys. Lett. **194B**, 307 (1987),

H. Harari and Y. Nir, SLAC-PUB-4341 (1987),

V. A. Khoze, N. G. Uraltsev, Leningrad Preprint 1290 (1987),

G. Altarelli and P. Franzini, CERN-TH-4745/87 (1987),

J. R. Cudell *et al.*, Wisconsin Preprint MAD/PH/353 (1987).

9. E. D. Commins and P. H. Bucksbaum, *Weak Interactions of Leptons and Quarks*, (Cambridge University Press, Cambridge, UK, 1983), pp. 155-156.

10. Throughout this paper we adopt the convention that reference to a particle state also implies reference to its charge conjugate.

11. D. Bernstein *et al.*, Nucl. Inst. Meth. **226**, 301 (1984).

12. J. Adler *et al.*, SLAC-PUB-4291 (1987), submitted to Phys. Rev. Lett.

13. R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).

14. R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 1842 (1985).

15. The distribution of energy deposited by minimum ionizing particles peaks at about 180 MeV. The overlap region $0.78 \leq |\, cos\theta \,| \leq 0.84$ between the barrel and endcap calorimeters was removed from the analysis, as no $\mu$-$\pi$ separation is possible there.

16. Isolated photons are defined as those showers with energy greater than 100 MeV which are not used in forming a $\pi^0$ in the tag, and which make an angle $\alpha \geq 23^o$ with respect to each charged track.

17. R. M. Baltrusaitis *et al.*, Phys. Rev. **D32**, 566 (1985).

18. The likelihood function contains contributions from all noted $D$ backgrounds. The branching ratios are constrained within errors by existing measurements, or by theoretical expectations for unmeasured Cabibbo-suppressed modes. The leptonic decay $D^+ \to \tau^+\nu_\tau$ is coupled in the fit to the $\mu^+\nu_\mu$ fraction by eqn. (1). A contribution of $1.9 \pm 0.8$ events from erroneously tagged $D$ mesons is also propagated.

19. 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 $\lambda = L_{\text{true}}/L_{\max}$ 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). Here, $L_{\text{true}}$ denotes the likelihood of the true hypothesis, while the maximum likelihood is $L_{\max}$. The 90% C.L. is found by generating and analyzing Monte Carlo experiments with different values of $B(D^+ \to \mu^+\nu_\mu)$, and then determining that value of $\lambda$ which rejects 10% of the Monte Carlo experiments for each branching ratio.

20. Systematic errors are propagated linearly. The uncertainties in the modeling 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 of the isolated photon cuts.

21. J. J. Aubert *et al.*, Nucl. Phys. **B213**, 31 (1983) obtained

B($D^+ \rightarrow \mu^+\nu_\mu$)$<$ 0.02 at 90% C.L.

22. J.C. Anjos *et al.*, FNAL-PUB-87-144 (1987), submitted to Phys. Rev. D.

23. M. Aguilar-Benitez *et al.*, Phys. Lett. **170B**, 1 (1986).

24. Dividing B($D^+ \rightarrow \mu^+\nu_\mu$) by the central value of $\tau_D$, we obtain $f_D < 280$ MeV/$c^2$. The final result (290 MeV/$c^2$) includes the error on $\tau_D$, and is obtained by dividing B($D^+ \rightarrow \mu^+\nu_\mu$) by ($\tau_D - \delta\tau_D^{\mathrm{stat}} - \delta\tau_D^{\mathrm{syst}}$).

25. J.J. Becker *et al.*, Phys. Lett. **193B**, 147 (1987), footnote 8.

26. S. N. Sinha, Phys. Lett. **178B**, 110 (1986). Exceptions are
V. S. Mathur and M. T. Yamawaki, Phys. Rev. D**29**, 2057 (1984),
B. Margolis *et al.*, Phys. Rev. D**33**, 2666 (1986).

27. The bag constant remains a parameter in these calculations; the presence of either a fourth generation of fermions or exotic extensions of the standard model is not considered.

## FIGURE CAPTIONS

1. Combined mass plot for the seven $D^-$ tags used in this analysis: $K^+\pi^-\pi^-$, $K^0\pi^-$, $K^0\pi^-\pi^-\pi^+$, $K^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, $K^0K^-$, and $K^+K^-\pi^-$.
2. Scatter plot of $p_\mu$ *vs* $M^2_{miss}$ for the data. Dashed lines indicate the momentum cut and the region in $M^2_{miss}$ that is fit.
3. Momentum of recoil muons, $p_\mu$, for tagged $D^-$ candidates (solid line) and for Monte Carlo generated events (dashed line).
4. The $M^2_{miss}$ distribution. 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 produced events.

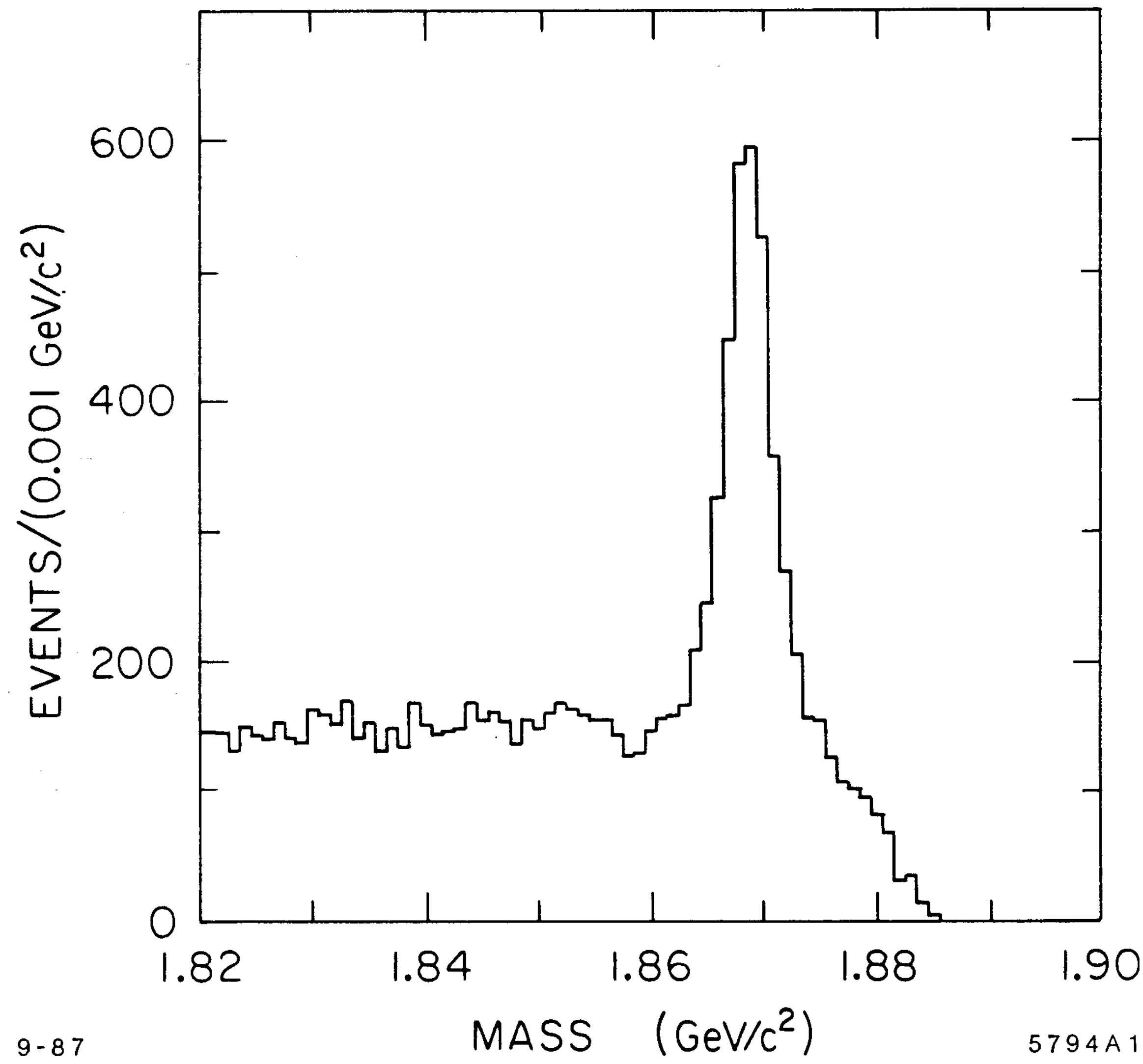
600
400
200
0
EVENTS/(0.001 GeV/c²)
1.82
1.84
1.86
1.88
1.90
MASS (GeV/c²)
9-87
5794A1

Fig. 1

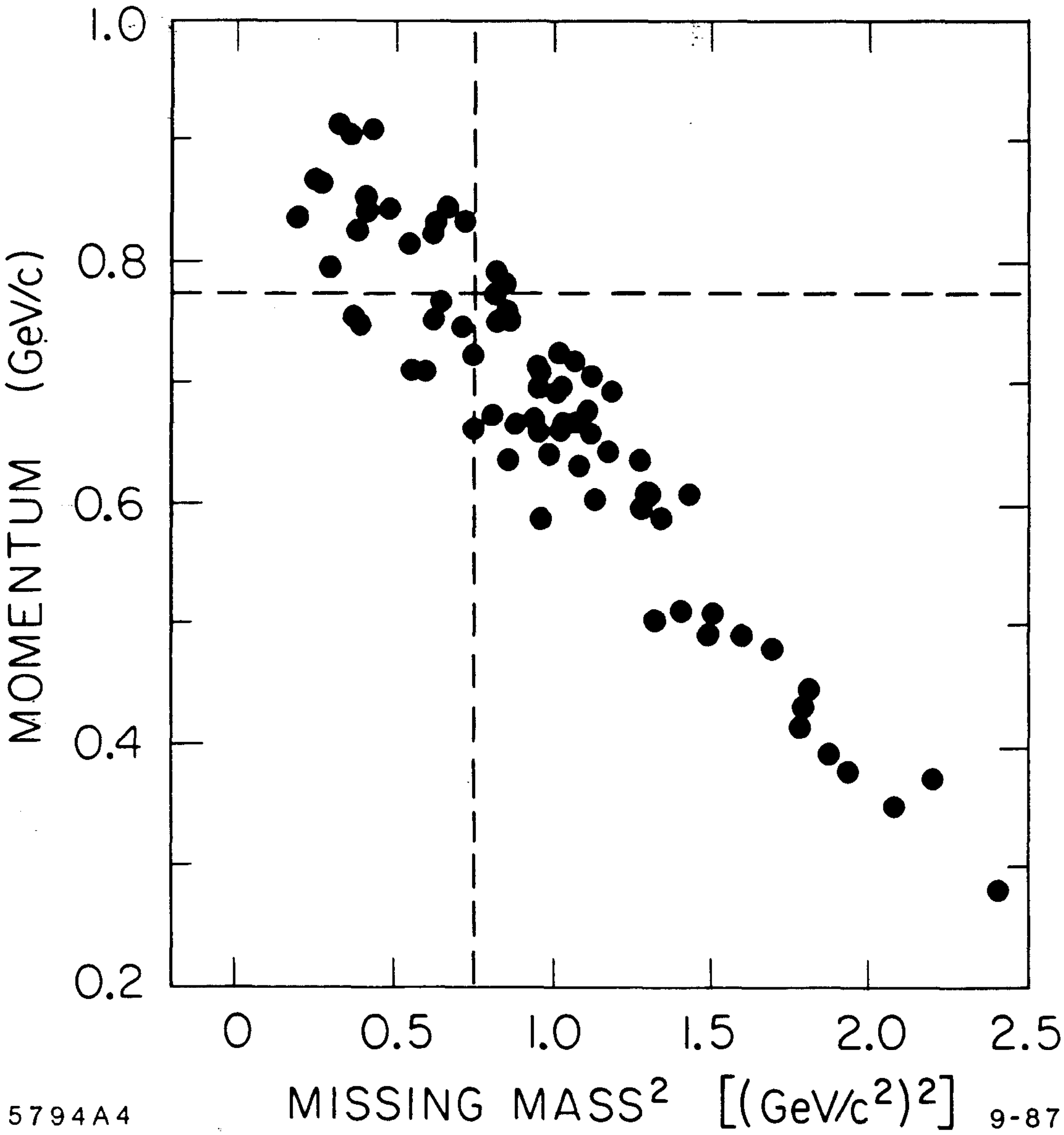
1.0
0.8
0.6
0.4
0.2
MOMENTUM (GeV/c)
0
0.5
1.0
1.5
2.0
2.5
MISSING MASS² [(GeV/c²)²]
5794A4
9-87

Fig. 2

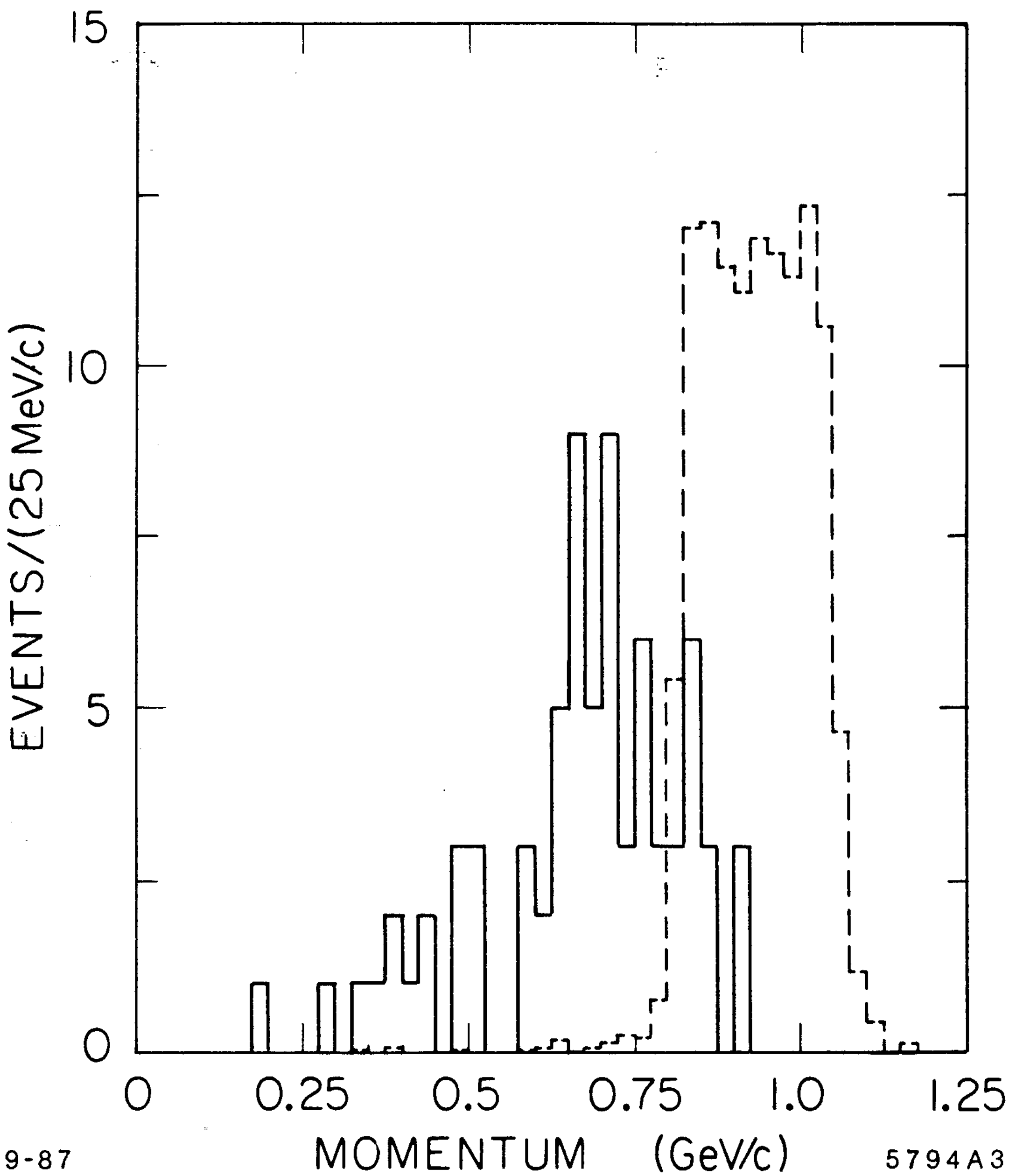
15
10
5
0
EVENTS/(25 MeV/c)
0
0.25
0.5
0.75
1.0
1.25
9-87
MOMENTUM (GeV/c)
5794A3

Fig. 3

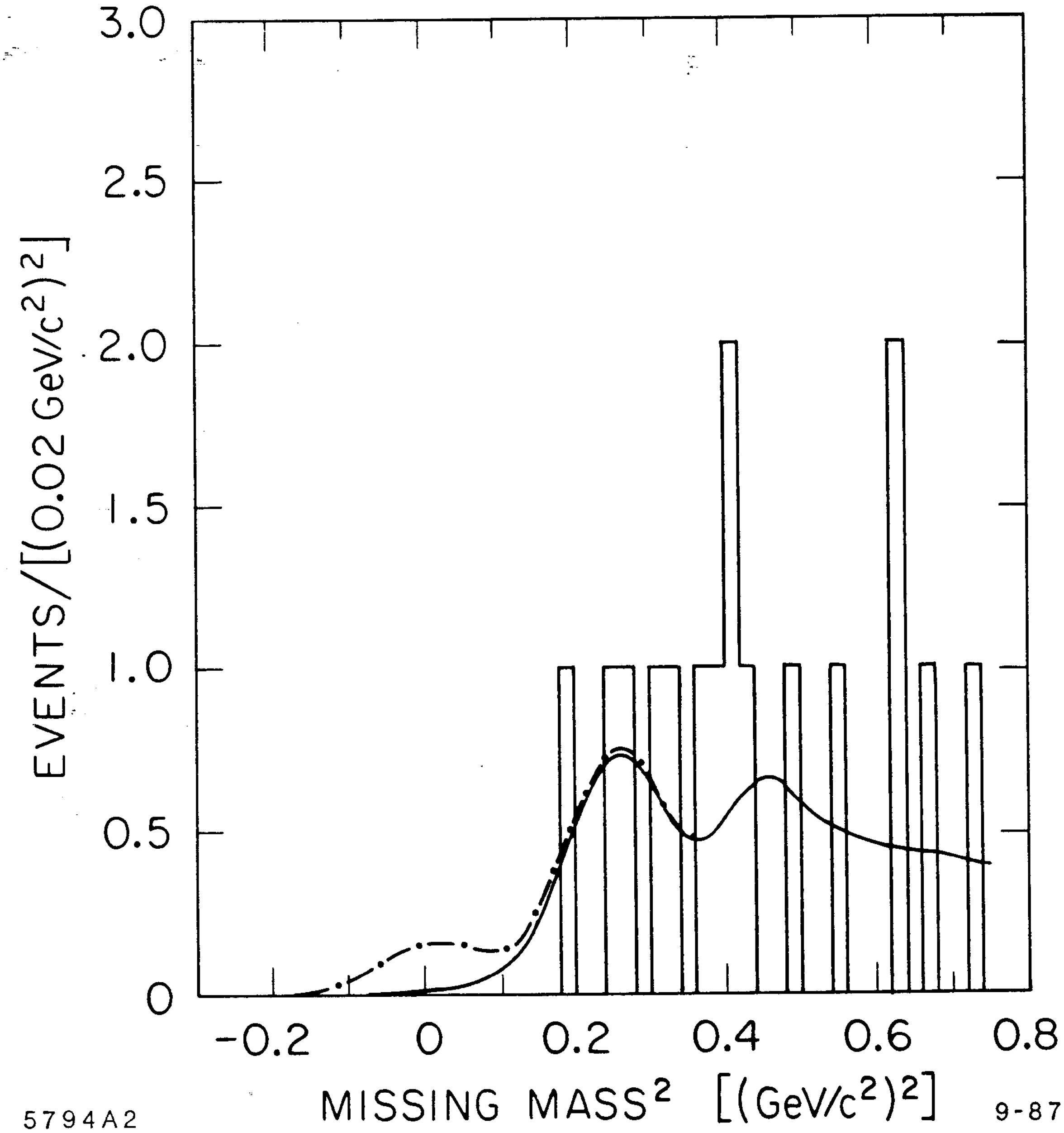
3.0
2.5
2.0
1.5
1.0
0.5
0
EVENTS/[(0.02 GeV/c²)²]
-0.2
0
0.2
0.4
0.6
0.8
MISSING MASS² [(GeV/c²)²]
5794A2
9-87

Fig. 4