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Results on Charmed Meson Decays from Mark III*

Steven R. Wasserbaech
Representing the Mark III Collaboration†

Abstract

We report recent results on charmed meson decays, obtained using the Mark III detector at SPEAR. The first topic discussed is the observation of $e^+e^- \rightarrow D_sD_s^*$ at $\sqrt{s} = 4.14\,\text{GeV}$. The D_s^* is detected as a peak in the mass distribution recoiling from $D_s^\pm \rightarrow \phi\pi^\pm$. The mass of the D_s^* is found to be $(2109.3 \pm 2.1 \pm 3.1)\,\text{MeV}/c^2$, yielding a D_s^*-D_s mass difference of $(137.9 \pm 2.1 \pm 4.3)\,\text{MeV}/c^2$. The production cross section times branching ratio is also measured. Next, a search for the decay $D^+ \rightarrow \mu^+\nu_\mu$ is described. A preliminary upper limit (90% CL) on $B(D^+ \rightarrow \mu^+\nu_\mu)$ of 8.4×10^{-4} is obtained, corresponding to an upper limit on the decay constant f_D of $340\,\text{MeV}/c^2$. Finally we present results of a search for the lepton family number violating decay $D^0 \rightarrow \mu e$. We find $B(D^0 \rightarrow \mu e) < 1.5 \times 10^{-4}$ at 90% CL.

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† Members of the Mark III Collaboration are D. Coffman, G.P. Dubois, G. Eigen, J. Hauser, D. Hitlin, C. Matthews, J.D. Richman, J.J. Russell, W.J. Wisniewski, Y. Zhu, *California Institute of Technology;* D.E. Dorfan, F. Grancagnolo, R.P. Hamilton, C.A. Heusch, L. Köpke, W.S. Lockman, R. Partridge, J. Perrier, H.F. Sadrozinski, M. Scarlatella, T.L. Schalk, A. Seiden, A. Weinstein, R. Xu, *University of California at Santa Cruz;* J.J. Becker, G. Blaylock, J.S. Brown, B. Eisenstein, T. Freese, G. Gladding, J. Izen, S.A. Plaetzer, C. Simopoulos, A.L. Spadafora, I.E. Stockdale, J.J. Thaler, B. Tripsas, A. Wattenberg, *University of Illinois, Champaign-Urbana;* T. Bolton, K.O. Bunnell, R. Cassell, D.H. Coward, K.F. Einsweiler, D. Favart, C. Grab, U. Mallik, R.F. Mozley, A. Odian, J. Parker, D. Pitman, R.H. Schindler, W. Stockhausen, W. Toki, F. Villa, S. Wasserbaech, N. Wermes, D.E. Wisinski, G. Wolf, *Stanford Linear Accelerator Center;* T.H. Burnett, V. Cook, A.L. Duncan, A.D. Li, R. Mir, P. Mockett, B. Nemati, L. Parrish, H. Willutzki, *University of Washington, Seattle.*

1. $e^+e^- \to D_s D_s^*$

In the quark model, the lowest-lying $c\bar{s}$ pseudoscalar meson, the D_s, has a higher mass vector meson partner, the D_s^*. The D_s^* mass is predicted[1] to lie 80 to 150 MeV/c^2 above that of the D_s. Evidence has been presented for a narrow state decaying into a D_s meson and a photon.[2] [3] Exclusive production of this state in association with the D_s in e^+e^- annihilation would provide new evidence that it is indeed the D_s^*. We report the first evidence of the exclusive reaction[4] $e^+e^- \to D_s^+ D_s^{*-}$, where the $D_s^\pm$ is observed in the decay

$$D_s^+ \to \phi\pi^+ \tag{1}$$

or in the cascade

$$D_s^{*-} \to \gamma D_s^-, \quad D_s^- \to \phi\pi^-. \tag{2}$$

A precise measurement of the D_s^* mass is also reported.

The data sample used in this analysis represents an integrated luminosity of $(6.30 \pm 0.46)\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 4.14\,\mathrm{GeV}$. The analysis proceeds with the isolation of events containing one or more ϕ's. Charged kaons are identified using time-of-flight (TOF), and K^+K^- combinations with mass within 10 MeV/c^2 of the ϕ mass are selected. Candidate $\phi\pi^+$ decays are selected by combining a ϕ with each of the remaining charged tracks, assumed to be pions. A scatter plot of the $\phi\pi^+$ mass versus the recoil mass is shown in Fig. 1. Evidence for $D_s D_s^*$ production appears as a cluster of events near $M(\phi\pi^+) = 1.97\,\mathrm{GeV}/c^2$ and $M(\mathrm{recoil}) = 2.10\,\mathrm{GeV}/c^2$. Another cluster near $M(\phi\pi^+) = 1.87\,\mathrm{GeV}/c^2$ and $M(\mathrm{recoil}) = 2.01\,\mathrm{GeV}/c^2$ is evidence for production of D^+D^{*-}, with $D^+ \to \phi\pi^+$.[5] No significant evidence for $e^+e^- \to D_s^+ D_s^-$, $D_s^+ \to \phi\pi^+$ is observed.

The decay $D_s \to \phi\pi^+$ is isolated by requiring the recoil mass to lie between 2.04 and 2.18 GeV/c^2 (Fig. 2). A fit to this distribution yields 26.7 ± 5.2 (*stat.*) signal events above 5.6 background events. The fitted D_s mass is $(1972.4 \pm 3.7 \pm 3.7)\,\mathrm{MeV}/c^2$. The background shape is determined from the $\phi\pi^+$ mass distribution obtained by combining ϕ candidates with pions from different events.

The D_s^* signal in the recoil mass distribution is measured after restricting the $\phi\pi^+$ mass to the D_s region, 1.92 to 2.02 GeV/c^2. To improve the D_s^* mass resolution, a D_s mass[6] of 1971.4 MeV/c^2 is imposed as a constraint in the calculation of the recoil mass.[7] The resulting recoil mass distribution [Fig. 3] shows a narrow peak at 2.11 GeV/c^2 from reaction (1), on a broad structure between 2.07 and 2.15 GeV/c^2 from reaction (2). A fit to this distribution yields

$$M(D_s^*) = (2109.3 \pm 2.1 \pm 3.1)\,\mathrm{MeV}/c^2.$$

The shape of the signal distribution and the resolution (5.0 MeV/c^2) are determined from a Monte Carlo simulation which includes radiative corrections.[8] The result implies[9]

$$M(D_s^*) - M(D_s) = (137.9 \pm 2.1 \pm 4.3)\,\text{MeV}/c^2.$$

A maximum likelihood calculation using the constrained recoil mass yields $\Gamma(D_s^*) < 22\,\text{MeV}/c^2$ at 90% CL.

The production cross section times branching fraction is determined assuming $B(D_s^* \to \gamma D_s) = 100\%$. Using the number of observed $D_s^+ \to \phi\pi^+$ decays, and a $D_s^+ \to \phi\pi^+$ detection efficiency of 0.071, the result is

$$\sigma(e^+e^- \to D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \to \phi\pi^+) = (30 \pm 6 \pm 11)\,\text{pb}.$$

We have also presented the following preliminary results:

$$\sigma(e^+e^- \to D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \to \bar{K}^{*0}K^+) = (31 \pm 6 \pm 11)\,\text{pb},$$
$$\sigma(e^+e^- \to D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \to \bar{K}^{0}K^+) = (32 \pm 6 \pm 10)\,\text{pb}.$$

In the analysis of these channels, candidate events are fit to the hypothesis $e^+e^- \to D_s^* D_s$, where the D_s^* is not reconstructed, and $D_s \to$ *mode*. These final states could be produced via the internal W emission and the annihilation diagrams.

The measured D_s^*-D_s mass difference can be compared with other vector-pseudoscalar splittings. For mesons containing at least one light quark, the mass-squared difference $\Delta_{M^2} = M^2(1^-) - M^2(0^-)$ is approximately constant.[10] This effect has motivated calculations of the mass-squared difference within models which assume a simple confining potential.[11] An approximately constant mass-squared difference is predicted for specific choices of α_s and the form of the potential. Our measurement of the D_s^*-D_s mass difference results in $\Delta_{M^2} = (0.563 \pm 0.020)(\text{GeV}/c^2)^2$, which is consistent with this empirical rule.

2. $D^+ \to \mu^+\nu_\mu$ AND THE DECAY CONSTANT f_D

The D meson decay constant f_D is a direct measure of the overlap of the wavefunctions of the heavy and light quarks in the D meson,[12] and sets the scale for processes such as weak flavor annihilation and Pauli interference invoked to account for the differences in D^+ and D^0 lifetimes.[13] 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.[14] The constant f_D may be unambiguously determined from the pure leptonic decay of the D^+:

$$\Gamma(D^+ \to \mu^+\nu_\mu) = \frac{G_F^2}{8\pi} f_D^2\, M_D\, M_\mu^2\, |V_{cd}|^2 \left(1 - \frac{M_\mu^2}{M_D^2}\right)^2 .$$

The data employed (9.3 pb^{-1}) were obtained at $\sqrt{s} = 3.768$ GeV, where charmed D mesons are produced only in pairs. The search is carried out by isolating 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. Seven hadronic D^+ tag modes are used, resulting in $2490 \pm 42 \pm 40$ D^+ candidates.

Candidate events are isolated by requiring the recoil system from a tag to have one track with charge opposite to that of the tag whose momentum lies between 0.775 and 1.125 GeV/c. The event is also required to have missing mass squared M_{miss}^2 between -0.265 and $0.175\,(\mathrm{GeV}/c^2)^2$, rejecting about 5% of the expected signal. Muon candidates are selected using the muon system, or (for tracks outside of the muon system acceptance) a combination of TOF, dE/dx, and calorimeter. In the latter case the event is required to contain no extra isolated photons.

Important sources of background to this process are $D^+ \to K_L^0\pi^+$, $D^+ \to K_L^0K^+$, $D^+ \to K_L^0\mu^+\nu$, $D^+ \to \pi^0\pi^+$, and $D^+ \to K_S^0\pi^+$. Decays with K_L^0's are rejected by the M_{miss}^2 cut. The selection process reduces the total expected background to $1.16 \pm 0.16 \pm 0.20$ events.

When these cuts are applied to the data, no events are found to survive. The nearest event to the M_{miss}^2 cut lies at $0.196\,(\mathrm{GeV}/c^2)^2$. The observation of no events of the type $D^+ \to \mu^+\nu_\mu$ together with the background prediction yields a 90% CL upper limit of 1.35 signal events.[15] The acceptance for this decay mode is $0.72 \pm 0.01 \pm 0.05$. Dividing by the acceptance and the total number of D^+ tags[16] gives the preliminary limit $B(D^+ \to \mu^+\nu_\mu) < 8.4 \times 10^{-4}$ at 90% CL. Using a D^+ lifetime[17] of $(10.1^{+0.7}_{-0.6}) \times 10^{-13}\,\mathrm{s}$, and[18] $|V_{cd}|^2 = 0.0506 \pm 0.0065$, the branching ratio limit implies $f_D < 310\,\mathrm{MeV}/c^2$. When the errors on τ_{D^+} and $|V_{cd}|^2$ are included, we obtain $f_D < 340\,\mathrm{MeV}/c^2$ (90% CL).

This result does not probe the small values of f_D suggested by bag model[19] or QCD sum rule[20] calculations (150 to $280\,\mathrm{MeV}/c^2$), but it restricts the range of values predicted by recent potential model[12] calculations (208 to $450\,\mathrm{MeV}/c^2$). It also excludes the very high values of f_D which have been suggested[21] as an explanation for the large observed value of $\tau(D^+)/\tau(D^0)$.

3. SEARCH FOR $D^0 \to \mu e$

There has recently been great interest in searching for lepton family number violating processes such as $\mu \to e\gamma$, $\mu \to eee$, $K_L^0 \to \mu e$, $D^0 \to \mu e$, and ν oscillations.[22] The decay $D^0 \to \mu e$ could be induced by massive leptoquarks whose existence is predicted in various extensions[23] [24] of the Standard Model. Within certain models,[23] scalar leptoquarks are expected to couple the "up-type" quarks (u, c, t) to charged leptons, and the "down-type" quarks (d, s, b) to neutral leptons. Thus, the decay $D^0 \to \mu e$ can be enhanced with respect to the experimentally more accessible $K_L^0 \to \mu e$ decay.[25]

The data sample at $\sqrt{s} = 3.768\,\text{GeV}$ corresponds to $41400\,^{+3100}_{-2700} \pm 2700$ produced D^0's.[26] The data are first searched for events containing at least two lepton candidates: one muon and one electron. The kinematics of the two-body D^0 decay require that both leptons have momentum p $> 0.75\,\text{GeV}/c$ in the laboratory frame. Leptons are selected on the basis of the momentum, energy deposited in the calorimeter, TOF, and range in the muon system.

The two principal sources of background to the decay $D^0 \to \mu e$ are hadronic charged two-body D^0 decays, and $\tau^+\tau^-$ pairs. Contamination from $D^0 \to K^-\pi^+$ decays is reduced by requiring candidate pairs to have invariant mass within $50\,\text{MeV}/c^2$ of the D^0 mass. This cut does not reject the Cabibbo-suppressed decay $D^0 \to \pi^+\pi^-$. Since the τ background consists mainly of two-prong events accompanied by undetected neutrinos, requiring the missing energy[27] E_{miss} to be less than 1 GeV *in two-prong events only* eliminates this contamination. The expected background in the data sample is estimated to be $0.18 \pm 0.06 \pm 0.05$ $\pi^+\pi^-$ events.[26]

After all particle identification and kinematic cuts have been applied, the beam-constrained mass M_{bc} is calculated for each surviving candidate pair by constraining its energy to the beam energy. Two events with $M_{\text{bc}} > 1.82\,\text{GeV}/c^2$ are found. A study of the M_{bc} distribution of $D^0 \to K^-\pi^+$ in the same data sample shows that 90% of those two-body decays lie within $\pm 0.0055\,\text{GeV}/c^2$ of the D^0 mass (Fig. 4). No μe candidate falls within this range. The efficiency for $D^0 \to \mu e$ is found to be $0.433 \pm 0.004 \pm 0.029$, while that for the background channel $D^0 \to \pi^+\pi^-$ is $0.0024 \pm 0.0004 \pm 0.0002$. After all analysis cuts, neither $D^0 \to K^-\pi^+$ decays nor $\tau^+\tau^-$ pair production contribute significantly.

The observation of no events of the type $D^0 \to \mu e$ yields a 90% CL upper limit ($N_{0.9}^{sb}$) of 2.30 on the total number of signal and background events. The upper limit on the branching fraction $\text{B}(D^0 \to \mu e)$ is obtained by dividing by the efficiency and the total number of produced D^0's. When all systematic errors are included, we obtain $B(D^0 \to \mu e) < 1.5 \times 10^{-4}$ at 90% CL. This bound, which is model-independent, is approximately an order of magnitude lower than previous model-dependent measurements.[28]

Further details concerning these three topics are given elsewhere.[29] We gratefully acknowledge the efforts of the SPEAR staff. This work was supported by the Department of Energy, under contracts DE-AC03-76SF00515, DE-AC02-76ER01195, DE-AC03-81ER40050, DE-AM03-76SF00034 and by the National Science Foundation.

References

1. For a recent discussion see S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985), and references therein.
2. The first evidence for the D_s^{*+} was reported by R. Brandelik *et al.*, Phys. Lett. **70B**, 132 (1977), and R. Brandelik *et al.*, Phys. Lett. **80B**, 412 (1979). These measurements were not confirmed by R. Partridge *et al.*, Phys. Rev. Lett. **47**, 760 (1981), and R.P. Horisberger, Ph.D. Thesis, SLAC Report No. 266 (1984) (unpublished).
3. H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2465 (1984); H. Albrecht *et al.*, Phys. Lett. **146B**, 111 (1984).
4. Throughout this paper we adopt the convention that reference to a state also implies reference to its charge conjugate.
5. The Cabibbo-suppressed decay $D^+ \to \phi\pi^+$ has been observed by R. Bailey *et al.*, Phys. Lett. **139B**, 320 (1984) and R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985).
6. A weighted average of $M(D_s) = (1971.4 \pm 1.7)\,\mathrm{MeV}/c^2$ is obtained using the measurements tabulated in M. Aguilar-Benitez *et al.* (Particle Data Group), Phys. Lett. **170B**, 1 (1986), replacing the previous ACCMOR value with their later measurement, $M(D_s) = (1972.7 \pm 1.5 \pm 1.0)\,\mathrm{MeV}/c^2$, H. Becker *et al.*, CERN-EP/86-172 (1986) (preprint, to be published in Phys. Lett.).
7. $M(\mathrm{recoil}) = \{ [\sqrt{s} - \sqrt{M^2(D_s) + p^2(D_s)}\,]^2 - p^2(D_s)\}^{\frac{1}{2}}$, where $M(D_s)$ is fixed.
8. In the Monte Carlo simulation, the D_s and D_s^* are assumed to be pseudoscalar and vector, respectively, with $B(D_s^* \to \gamma D_s) = 100\%$. Only initial state radiation is considered using a method from F. Behrends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981).
9. For $e^+e^- \to D_s^* D_s$ at $\sqrt{s} = 4.14$ GeV, $\delta M(D_s^*) \cong -\delta M(D_s)$.
10. $\Delta_{M^2} = 0.575\,(\mathrm{GeV}/c^2)^2$ for ρ^0-π^0, $0.556\,(\mathrm{GeV}/c^2)^2$ for K^{*0}-K^0, and $0.551\,(\mathrm{GeV}/c^2)^2$ for D^{*0}-D^0. For a discussion of this empirical relation see A. Martin, Comm. Nucl. Part. Phys. **16**, 249 (1986).
11. K. Igi and S. Ono, Phys. Rev. **D32**, 232 (1985), and M. Frank and P. O'Donnell, CERN-TH-4367/86 (1986) (preprint).
12. S. N. Sinha, Alberta THY-3-86 (1986); P. J. O'Donnell, CERN-TH-4419/86 (1986); L. Maiani, *Proceedings of XXI International Conference on High Energy Physics* (Editions de Physique, Le Ulis, France, 1982) pp. 631-657; H. Krasemann, Phys. Lett. **96B**, 397 (1980).

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

14. I.I. Bigi, G. Köpp, and P.M. Zerwas, Phys. Lett. **166B**, 238 (1986); J.F. Donoghue *et al.*, Phys. Rev. **D33**, 197 (1986).

15. The CL 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. 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. The limit on n_s at the 90% CL is derived from the limit on $(n_s + n_b)$ by subtraction of n_b from 2.30 events. Including the errors on n_b gives a 90% CL upper limit on n_s of 1.35 events.

16. The errors on the number of tags and the acceptance are subtracted in order to give a more conservative limit. We thus use 0.662 for the acceptance, and 2408 as the number of tags.

17. V. Lüth, *Proceedings of International Symposium on Production and Decay of Heavy Flavors*, Heidelberg, 20-23 May 1986 (to be published), SLAC-PUB-4052 (1986).

18. M. Aguilar-Benitez *et al.*, Rev. Mod. Phys. **56**, S43 (1984).

19. E. Golowich, Phys. Lett. **91B**, 271 (1980); M. Claudson, HUTP-81/A016 (1982).

20. V.S. Mathur and M.T. Yamawaki, Phys. Rev. **D29**, 2057 (1984); V.A. Novikov *et al.*, Phys. Rev. Lett. **38**, 626 (1977).

21. M. Bander, D. Silverman, A. Soni, Phys. Rev. Lett. **44**, 7 (1980).

22. H.K. Walter, *Fifth Workshop on Grand Unification*, K. Kang, H. Fried, P. Frampton, eds., (World Scientific Press, Singapore,1984), p. 134; F. Boehm, *ibid.*, p. 315.

23. W. Buchmüller and D. Wyler, Phys. Lett. **B177**, 377 (1986); W. Buchmüller, CERN-TH-4499/86 (July 1986).

24. B.A. Campbell, J. Ellis, K. Enqvist, M.L. Gaillard, and D.V. Nanopoulos, in preparation.

25. M. Aguilar-Benitez, *et al.*, Phys. Lett. **B170**, 1 (1986).

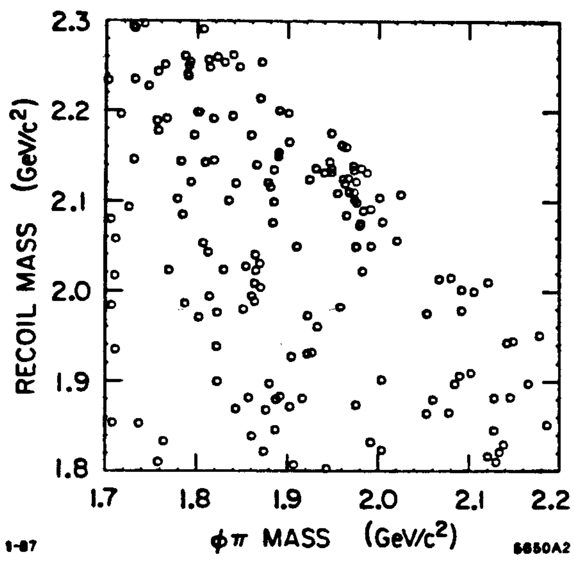
26. R.M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2140 (1986). The number of D^0's has been scaled to reflect the different integrated luminosity used in this analysis. The branching fractions employed: $B(D^0 \to K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$; $B(D^0 \to \pi^+\pi^-) = 0.0018 \pm 0.0006 \pm 0.0004$.

27. We define $E_{\text{miss}} = \sqrt{s} - (E_e + E_\mu + \sum_i E^i_{\text{neutral}})$. All neutral tracks are used in this calculation, which benefits from the full solid angle coverage of the calorimeter. No photon selection cuts are applied.

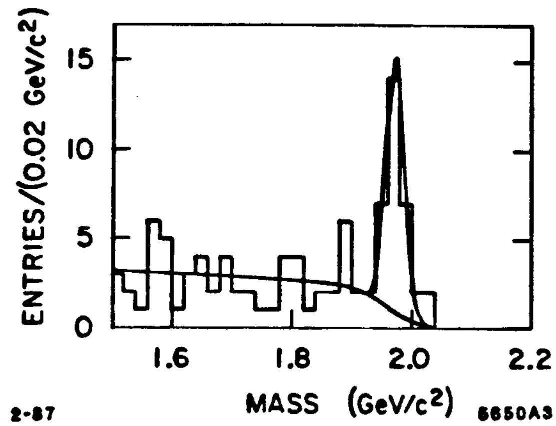
28. H. Palka *et al.*, CERN-EP/87-10 (1987); a 90% CL upper limit of 1.0×10^{-3} is reported; K. Riles *et al.*, SLAC-PUB-4156 (1986) give 2.1×10^{-3}. These limits depend on the production mechanisms, fragmentation functions, and D^0 branching ratios.

29. G.T. Blaylock *et al.*, SLAC-PUB-4158 (1987) (submitted to Phys. Rev. Lett.); W. Toki, *Proceedings of 14th SLAC Summer Institute on Particle Physics*, Stanford, 28 July-8 August 1986 (to be published), SLAC-PUB-4153 (1986); R.H. Schindler, *Proceedings of XXIII International Conference on High Energy Physics*, Berkeley, 16-23 July 1986 (to be published), SLAC-PUB-4055 (1986); J.J. Becker *et al.*, SLAC-PUB-4194 (1987) (submitted to Phys. Rev. Lett.).

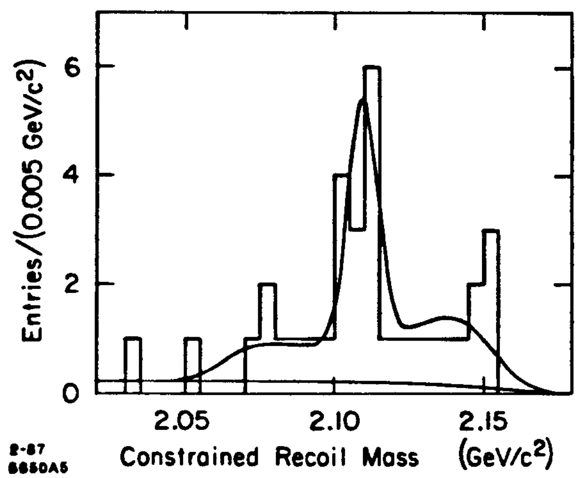
Figures



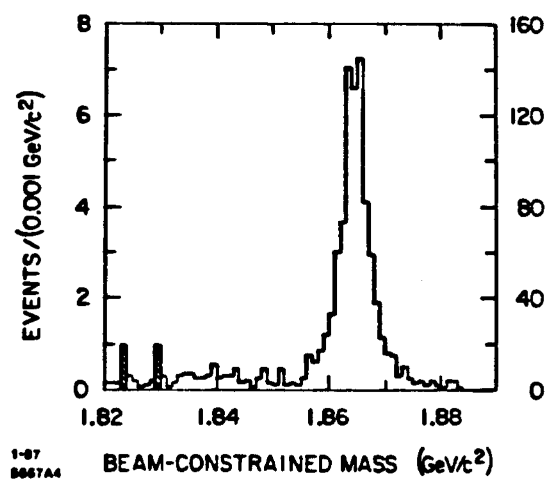
1. Scatter plot of $M(\phi\pi^+)$ versus M(recoil).



2. The projection of $M(\phi\pi^+)$ for $2.04 < M(\text{recoil}) < 2.18\,\text{GeV}/c^2$.



3. The recoil mass distribution with the D_s mass constrained at $1971.4\,\text{MeV}/c^2$.



4. M_{bc} distribution for $K^-\pi^+$ events in the data (used to determine the $\pm 5.5\,\text{MeV}/c^2$ cut on M_{bc}). Superimposed are the two closest $D^0 \to \mu e$ candidates which pass all other cuts.