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Observation of $e^+e^- \rightarrow D_s^{\pm} D_s^{*\mp}$ at $\sqrt{s} = 4.14\,\mathrm{GeV}^{\star}$

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Abstract

We present evidence for the exclusive reaction $e^+e^- \rightarrow D_s^{\pm} D_s^{*\mp}$, observed with the Mark III detector at the storage ring SPEAR. The $D_s^{\pm}$ is reconstructed in the $\phi\pi^{\pm}$ decay mode, while the $D_s^{*\mp}$ is detected as a narrow peak in the recoil mass distribution. The mass of the D_s^* is found to be $(2109.3 \pm 2.1 \pm 3.1)\,\mathrm{MeV}/c^2$, yielding a D_s^*-D_s mass difference of $(137.9 \pm 2.1 \pm 4.3)\,\mathrm{MeV}/c^2$. The width of the D_s^* is $< 22\,\mathrm{MeV}/c^2$ at the 90% confidence level. The observed signal corresponds to $\sigma(e^+e^- \rightarrow D_s^+ D_s^{*-} + c.c.) \times B(D_s^+ \rightarrow \phi\pi^+) = (30 \pm 6 \pm 11)\,\mathrm{pb}$ at $\sqrt{s} = 4.14\,\mathrm{GeV}$.

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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^{*+}.[1] In models with hyperfine corrections,[2] the D_s^{*+} mass is predicted 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.[3] [4] 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^*. This Letter reports the first evidence of the exclusive reaction $e^+e^- \rightarrow D_s^+ D_s^{*-}$, where the $D_s^\pm$ is observed in the decay

$$D_s^+ \rightarrow \phi\pi^+ \qquad (1)$$

or in the cascade

$$D_s^{*-} \rightarrow \gamma D_s^-,\ D_s^- \rightarrow \phi\pi^-. \qquad (2)$$

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

The data sample represents an integrated luminosity of $(6.30 \pm 0.46)\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 4.14$ GeV, collected with the Mark III detector at SPEAR. A detailed description of the detector has been given elsewhere.[5] Tracking information from the drift chamber, and time-of-flight (TOF) measurements from scintillation counters are used in this analysis.

The analysis proceeds with the isolation of events containing one or more ϕ's. A charged particle is identified as a kaon using TOF.[6] The π-K separation is better than 5σ for kaons from reactions (1) and (2).[7] Figure 1 shows the mass distribution of oppositely charged kaon pairs. The mass of a ϕ candidate is required to be within 10 MeV/c^2 of the nominal ϕ mass. The $\phi\pi$ candidates 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 2. Evidence for $D_s^+ D_s^{*-}$ production appears as a cluster of events near $M(\phi\pi^+) = 1.97$ GeV/c^2 and $M(\mathrm{recoil}) = 2.10$ GeV/c^2. Another cluster near $M(\phi\pi^+) = 1.87$ GeV/c^2 and $M(\mathrm{recoil}) = 2.01$ GeV/c^2 is evidence for production of D^+D^{*-}, with $D^+ \to \phi\pi^+$.[8] Figure 3(a) shows the recoil mass distribution when the $\phi\pi^+$ mass is restricted to the D_s^+ region, 1.92 to 2.02 GeV/c^2. This distribution contains the recoil from the D_s^+'s produced in reactions (1) and (2). 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. 3(b)]. An unbinned maximum likelihood fit to this distribution with a Gaussian plus background yields 26.7 ± 5.2 *(stat.)* signal events above 5.6 background events. The fitted D_s^+ mass is $(1972.4 \pm 3.7 \pm 3.7)$ 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 mass resolution determined by Monte Carlo simulation ($\sigma = 15.1$ MeV/c^2) is imposed in the fit. The systematic error includes variation of the selection criteria (2.4 MeV/c^2), and uncertainties in the background shape (2.5 MeV/c^2) and in the momentum scale[9] (1.1 MeV/c^2).

The analysis procedure and the absolute mass scale are checked by investigating D decays in the data sample. The decay $D^+ \to \phi\pi^+$ is observed by restricting the recoil mass to the D^* mass region, 1.97 to 2.05 GeV/c^2. The result is shown in Fig. 3(c); a fit with a Gaussian and a flat background yields a D^+ mass of $(1860 \pm 7 \pm 4)$ MeV/c^2. The reactions $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$ are analyzed with similar particle identification and recoil requirements, giving fitted masses of (1865.3 ± 1.2) MeV/c^2, (1865.3 ± 1.3) MeV/c^2, and (1870.6 ± 2.6) MeV/c^2 respectively (statistical errors only).

To improve the D_s^* mass resolution, a D_s mass[10] of 1971.4 MeV/c^2 is imposed as a constraint in the calculation of the recoil mass.[11] The resulting recoil mass distribution [Fig. 4] 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 ($5.0\,\mathrm{MeV}/c^2$) are determined from a Monte Carlo simulation which includes radiative corrections.[12] The background shape is determined from K^+K^- sidebands around the ϕ. The systematic error includes contributions from the uncertainties in the D_s^+ mass ($1.7\,\mathrm{MeV}/c^2$), the center-of-mass energy at SPEAR ($1.7\,\mathrm{MeV}$), the radiative corrections ($1.2\,\mathrm{MeV}/c^2$), the selection criteria ($1.5\,\mathrm{MeV}/c^2$), the background shape ($0.5\,\mathrm{MeV}/c^2$), and the momentum scale ($0.1\,\mathrm{MeV}/c^2$). The result implies[13]

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

A maximum likelihood calculation using the constrained recoil mass yields $\Gamma(D_s^*) < 22\,\mathrm{MeV}/c^2$ at 90% C.L. The width and mass of the D_s^* are allowed to vary, while the resolution is fixed.

The decay angle distributions for the ϕ in the D_s^+ helicity frame, and the K^+ in the ϕ helicity frame are shown in Fig. 5. Since the D_s^+ helicity frame cannot be determined for the D_s^+ decays produced in reaction (2), all events are assumed to arise from reaction (1). For the hypothesis $J^P(D_s) = 0^-$ and $J^P(D_s^*) = 1^-$, the confidence levels of the $\cos\theta_\phi$ and $\cos\theta_{K^+}$ distributions using the Kolmogorov-Smirnov test[14] are 0.62 and 0.39, respectively.

The production cross section times branching fraction is determined assuming $B(D_s^{*+} \rightarrow \gamma D_s^+) = 100\%$. Using the number of observed $D_s^+ \rightarrow \phi\pi^+$ decays (26.7 ± 5.2), and a $D_s^+ \rightarrow \phi\pi^+$ detection efficiency of 0.071, the result is

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

The systematic error includes contributions from the uncertainties in the detection efficiency (31%), the integrated luminosity (7%), and the background shape (15%). The contamination of the $\phi\pi^+$ sample by non-resonant $D_s^+ \rightarrow K^+K^-\pi^+$ decays is negligible (< 0.5 events) for $B(D_s^+ \rightarrow K^+K^-\pi^+) \simeq B(D_s^+ \rightarrow \phi\pi^+)$.

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.[15] This effect has motivated calculations of the mass-squared difference within models which assume a simple confining potential.[16] These models predict $\Delta_{M^2} \simeq 64\pi\alpha_s|\psi(0)|^2/9\mu$, where $\psi(0)$ is the wave function at the origin and μ is the reduced mass of the quarks. An approximately constant mass-squared difference follows for specific choices of α_s and the form of the potential.[16] Our measurement of the D_s^*-D_s mass difference results in $\Delta_{M^2} = (0.563 \pm 0.020)\ (\mathrm{GeV}/c^2)^2$, which is consistent with this empirical rule.

In summary, the exclusive reaction $e^+e^- \rightarrow D_s^+ D_s^{*-}$ at $\sqrt{s} = 4.14$ GeV is observed. The production cross section times branching fraction and the D_s^* mass are measured. The decay angular distributions are consistent with those expected for a pseudoscalar D_s and a vector D_s^*. These results are in good agreement with previous measurements of the D_s[17] and the D_s^*.[4]

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References

1. The D_s^+ and D_s^{*+} were formerly denoted the F^+ and F^{*+}, respectively. Throughout this paper we adopt the convention that reference to a state also implies reference to its charge conjugate.

2. For a recent discussion see S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985), and references therein.

3. 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).

4. H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2465 (1984);
H. Albrecht *et al.*, Phys. Lett. **146B**, 111 (1984).

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

6. The charged kaon tracks are required to have $|(t_K^p - t^m)/\sigma_K| < |(t_\pi^p - t^m)/\sigma_\pi|$ where t_K^p (t_π^p) is the predicted TOF for a kaon (π) mass hypothesis, t^m is the measured TOF, and σ_K (σ_π) is the TOF error for the kaon (π) mass hypothesis.

7. In the Monte Carlo simulation, the D_s and D_s^* are assumed to be pseudoscalar and vector, respectively, with $B(D_s^* \to \gamma D_s) = 100\%$.

8. The Cabbibo-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).

9. The uncertainty in the absolute momentum scale, $\sigma(p) = 0.1\% \times p$, has been estimated using the reactions: $e^+e^- \to \mu^+\mu^-$; $K_S^0 \to \pi^+\pi^-$; $J/\psi \to p\bar{p}$; $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$; and $D^+ \to K^-\pi^+\pi^+$.

10. 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.).

11. $M(\mathrm{recoil}) = \{ [\sqrt{s} - \sqrt{M^2(D_s) + p^2(D_s)}\,]^2 - p^2(D_s)\}^{\frac{1}{2}}$, where $M(D_s)$ is fixed.

12. Only initial state radiation is considered using a method from F. Behrends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981).

13. For $e^+e^- \to D_s^* D_s$ at $\sqrt{s} = 4.14$ GeV, $\delta M(D_s^*) \cong -\delta M(D_s)$.
The systematic errors are $\sigma[M(D_s^*)] = \{(2.6\,\mathrm{MeV}/c^2)^2 + \sigma^2[M(D_s)]\}^{\frac{1}{2}}$ and $\sigma[M(D_s^*) - M(D_s)] = \{(2.6\,\mathrm{MeV}/c^2)^2 + 4\sigma^2[M(D_s)]\}^{\frac{1}{2}}$.

14. D.B. Owen, *Handbook of Statistical Tables* (Reading, MA: Addison-Wesley, 1962).

15. $\Delta_{M^2} = 0.575\,(\mathrm{GeV}/c^2)^2$ 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).

16. K. Igi and S. Ono, Phys. Rev. **D32**, 232 (1985), and M. Frank and P. O'Donnell, CERN-TH-4367/86 (1986) (preprint).

17. M. Aguilar-Benitez *et al., op. cit.*

Figure Captions

1. The K^+K^- invariant mass distribution. A fit to this distribution, using a Breit-Wigner line shape and a polynomial background, with $\Gamma(\phi) = 4.2\,\mathrm{MeV}/c^2$, yields $M(\phi) = (1019.3 \pm 0.4)\,\mathrm{MeV}/c^2$ and $\sigma = (2.1 \pm 0.8)$ MeV/c^2.

2. Scatter plot of $M(\phi\pi^+)$ versus $M(\text{recoil})$.

3. (a) The projection of $M(\text{recoil})$ for $1.92 < M(\phi\pi^+) < 2.02\,\mathrm{GeV}/c^2$. (b) The projection of $M(\phi\pi^+)$ for $2.04 < M(\text{recoil}) < 2.18\,\mathrm{GeV}/c^2$. The fit is described in the text. (c) The projection of $M(\phi\pi^+)$ for $1.97 < M(\text{recoil}) < 2.05\,\mathrm{GeV}/c^2$.

4. The recoil mass distribution with the D_s^+ mass constrained at 1971.4 MeV/c^2. The fit is described in the text.

5. (a) The $\cos\theta_\phi$ distribution in the D_s^+ helicity frame. (b) The $\cos\theta_{K^+}$ distribution in the ϕ helicity frame. The data are not acceptance corrected. The curves show the distributions from a Monte Carlo simulation which includes equal amounts of reactions (1) and (2), plus 18% background as determined from the fit to Fig. 3(b).

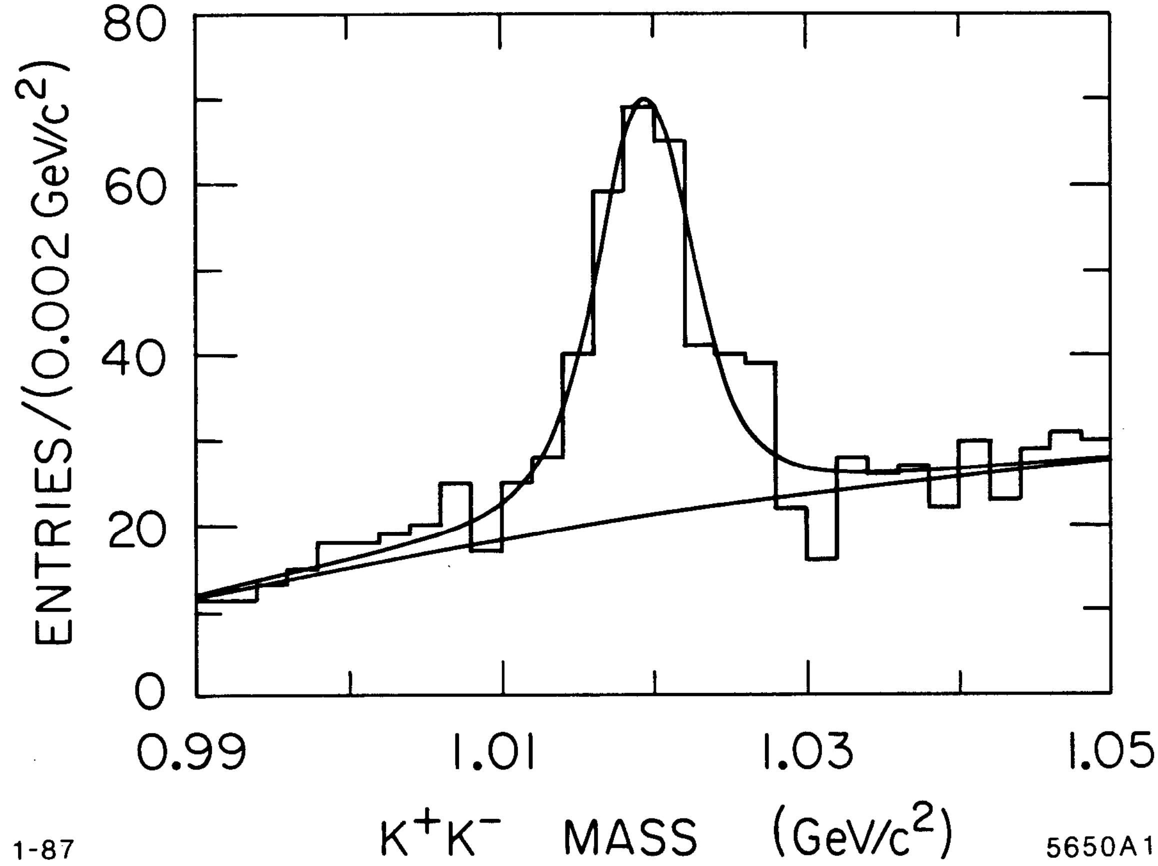
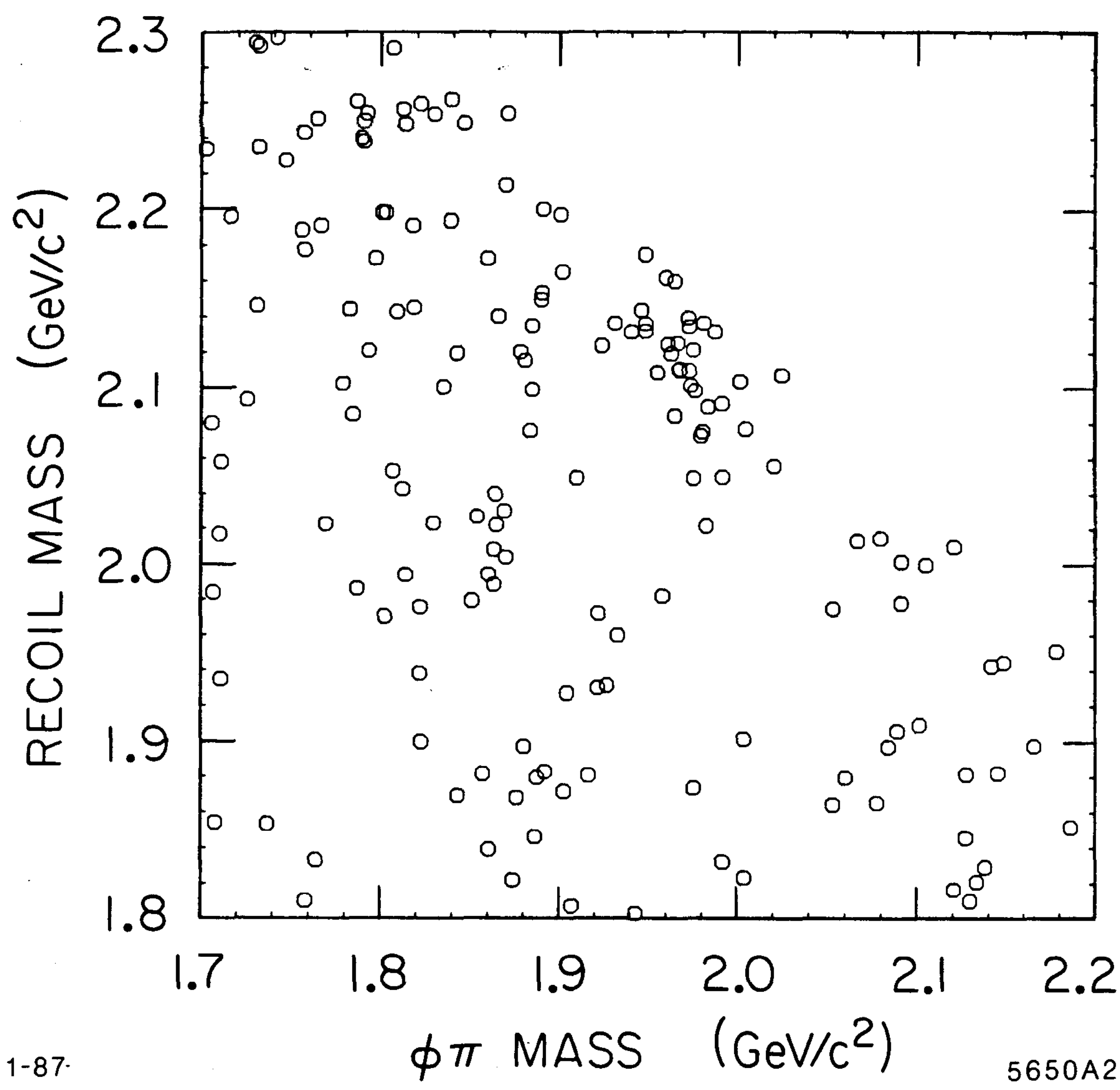

ENTRIES/(0.002 GeV/c^2)
80
60
40
20
0
0.99
1.01
1.03
1.05
K$^+$K$^-$ MASS (GeV/c^2)
1-87
5650A1

Fig. 1



2.3
2.2
2.1
2.0
1.9
1.8
RECOIL MASS (GeV/c²)
1.7
1.8
1.9
2.0
2.1
2.2
φπ MASS (GeV/c²)
1-87
5650A2

Fig. 2

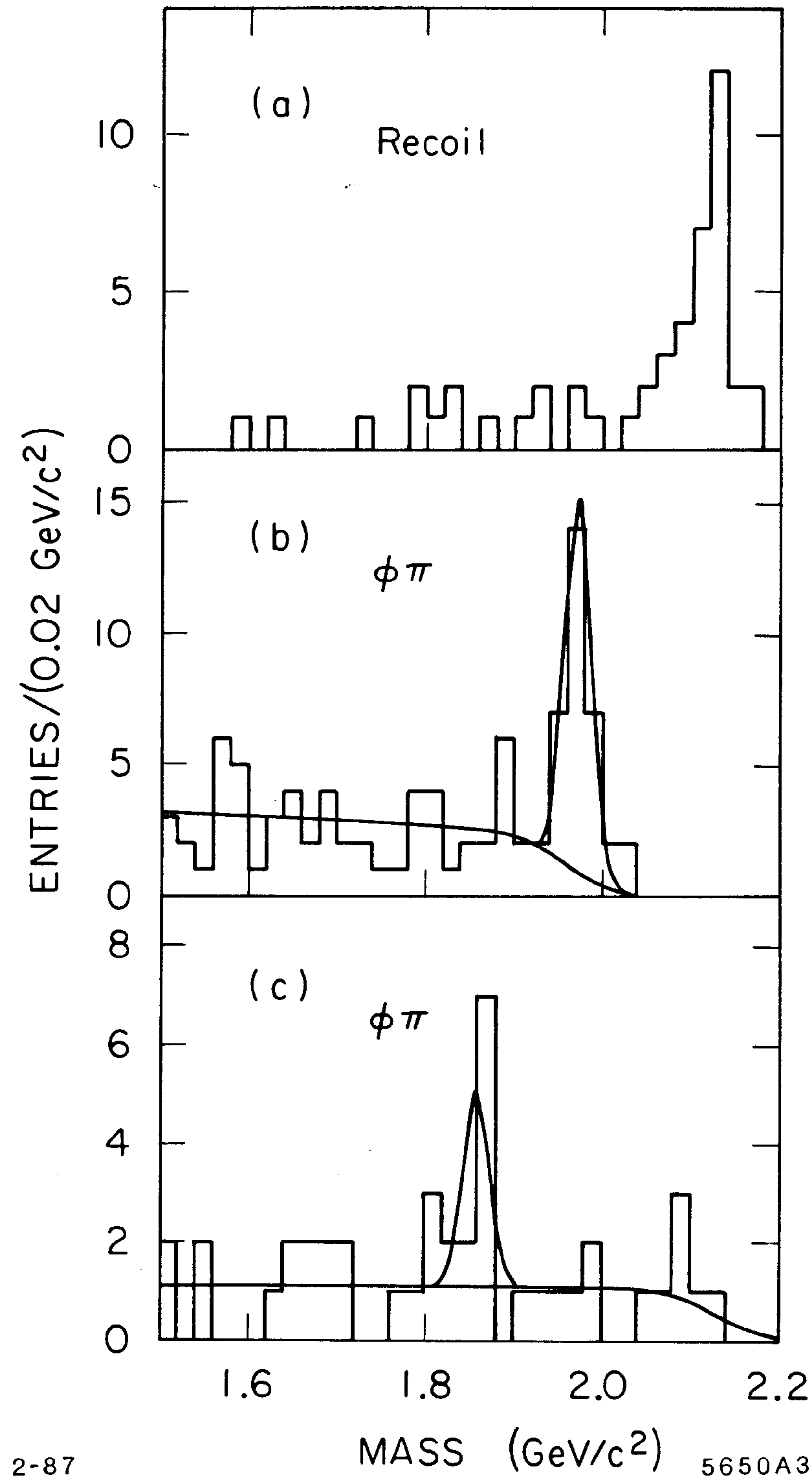
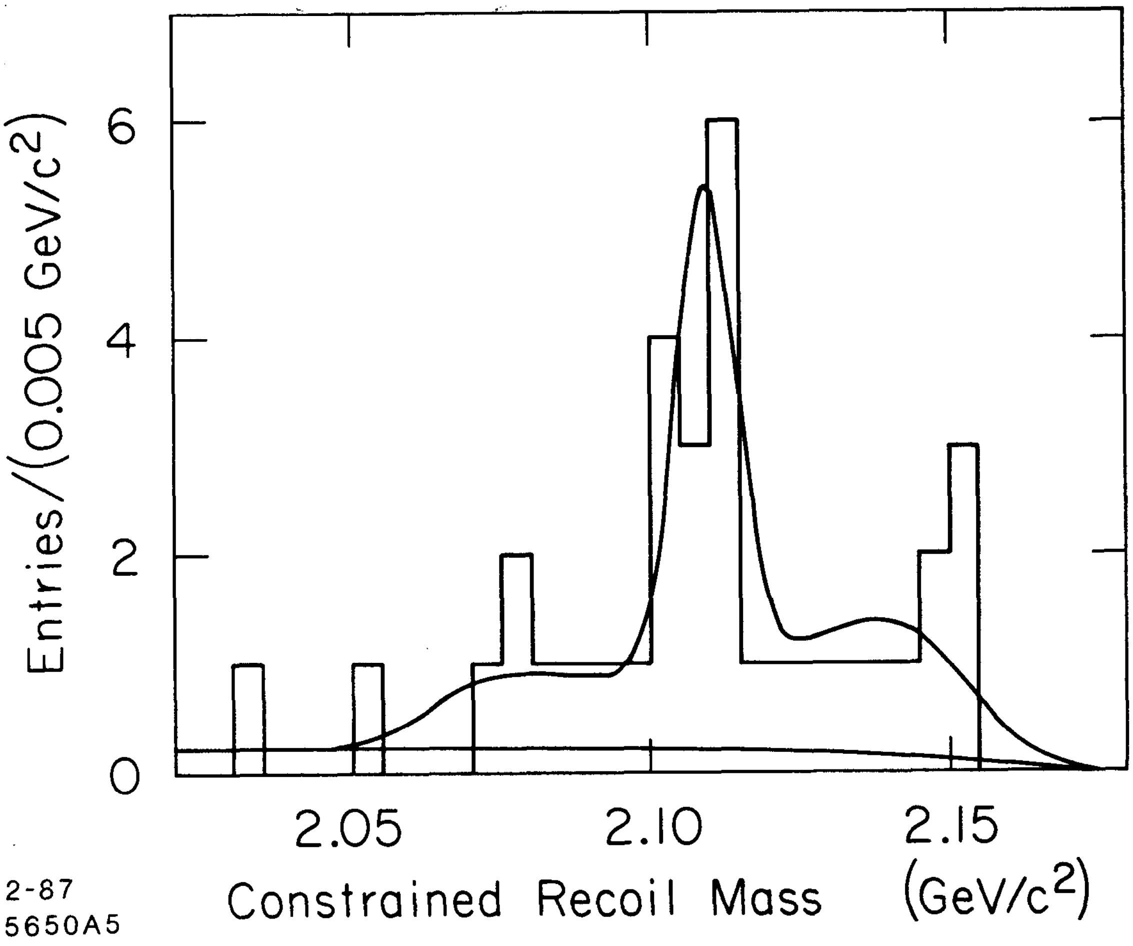
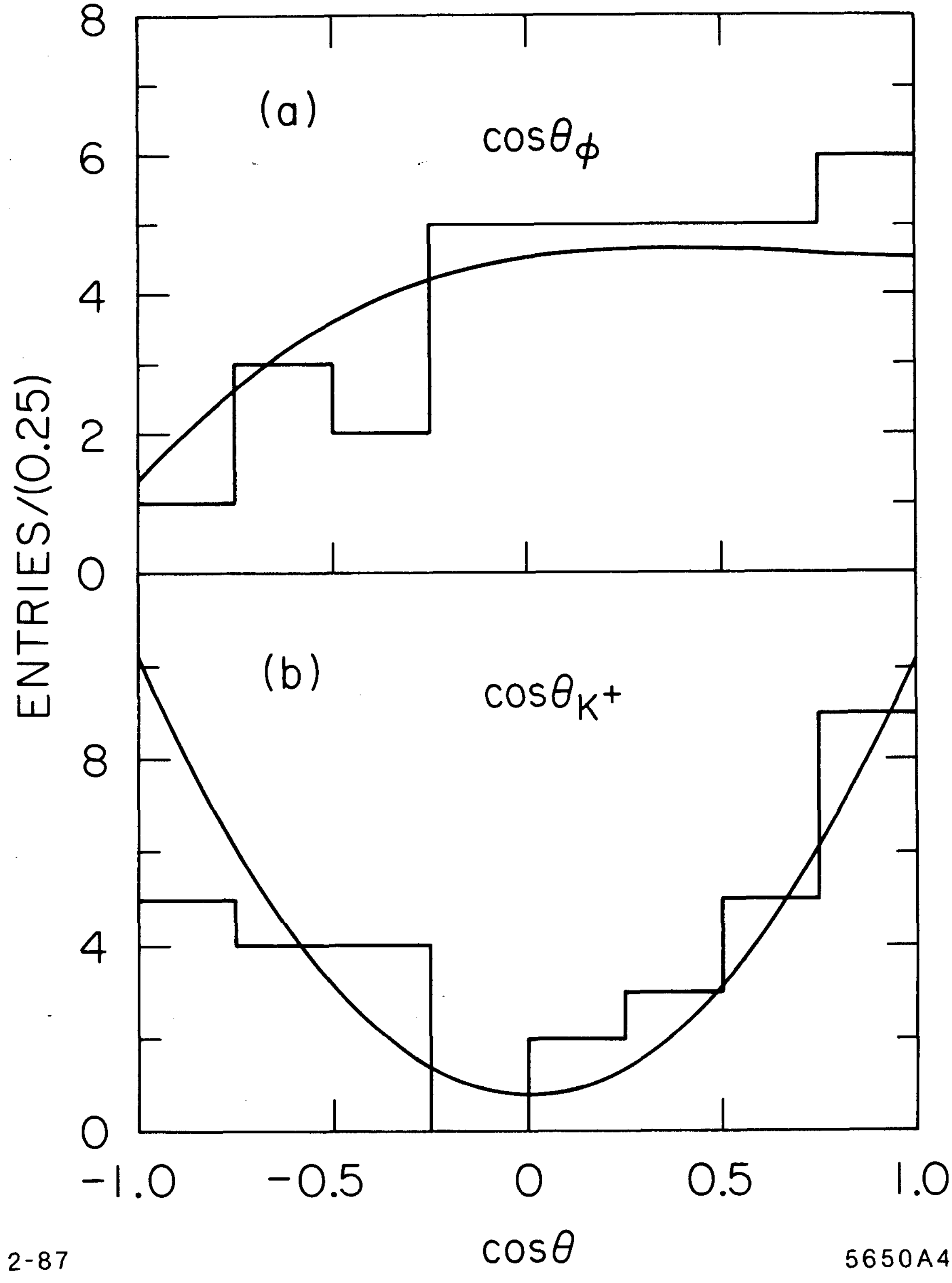

(a)
Recoil
(b)
$\phi\pi$
(c)
$\phi\pi$
ENTRIES/(0.02 GeV/c^2)
10
5
0
15
10
5
0
8
6
4
2
0
1.6
1.8
2.0
2.2
MASS (GeV/c^2)
2-87
5650A3

Fig. 3



Entries/(0.005 GeV/c²)
0
2
4
6
2.05
2.10
2.15
Constrained Recoil Mass (GeV/c²)
2-87
5650A5

Fig. 4



8
6
4
2
0
(a)
$\cos\theta_\phi$
ENTRIES/(0.25)
8
4
0
(b)
$\cos\theta_{K^+}$
−1.0
−0.5
0
0.5
1.0
$\cos\theta$
2-87
5650A4

Fig. 5