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MASTER

Recent Results from Neutrino Interactions in Heavy Neon

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~~We report~~ recent results from an analysis of 100,000 pictures from the Fermilab 15 ft. bubble chamber filled with heavy neon and exposed to the double horn focused, wideband ν_μ beam. ~~We have found~~ 164 dilepton ($\mu^- e^+$) events with 33 vees, in good agreement with the GIM model of charm production. ~~We have~~ also observed the production of the charmed D^o meson, followed by the decay $D^o \rightarrow K^o \pi^+ \pi^-$, at a rate of (0.7 ± 0.2)% of all charged current events. ~~We have carried out~~ searches for charm changing neutral current processes and for heavy lepton production, both with negative results; the upper limits obtained in these searches are given.

I. Introduction

We present recent results from a study of ν_μ interactions in heavy neon. The experiment was carried out at Fermilab using the two-horn focused wideband muon neutrino beam and the 15 ft. chamber filled with a heavy neon-hydrogen mixture (64 atomic % neon). A total of 150,000 pictures was taken with an average of 10^{13} 400 GeV protons per pulse on the neutrino target. The interaction length for hadrons is 125 cm, so that hadrons typically interact, while muons leave the chamber without interaction, and can thus be identified on the scan table. Electrons are easily identifiable through visible bremsstrahlung, since the radiation length is 40 cm. Some previous publications from this experiment are given in Ref. 1.

II. Dilepton Production

We have previously published results on dilepton production from the first 50,000 pictures of our exposure. We have now analyzed 100,000 pictures, corresponding to about 60,000 charged current neutrino interactions. In this sample, we have found 164 events with a μ^-, an e^+ and anything else. The e^+ is required to have two signatures and a momentum over 300 MeV/c. With these cuts, the background from asymmetric Dalitz pairs is a few percent. The μ^- is identified as the fastest negative leaving track. No momentum cut is made. From a comparison of interacting and noninteracting tracks of both signs, the background due to fake μ^- (hadron punchthrough) is determined to be about 10%. After correcting for these backgrounds, scan efficiency ($\sim$90%), and e^+ identification efficiency ($\sim$85%), we obtain a dilepton rate of

$$R = \frac{\nu_\mu + \mathrm{Ne} \to \mu^- + e^+ + \ldots}{\nu_\mu + \mathrm{Ne} \to \mu^- + \ldots} = (0.5 \pm 0.15)\%.$$

This rate is calculated using half of our events for which we have an accurate normalization. Figure 1 shows the momentum distribution of the e^+

and μ^-, and also the total visible energy.

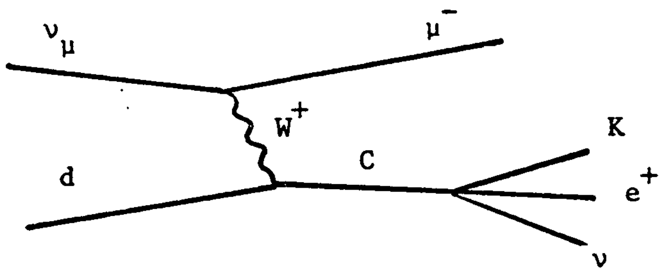
We have examined the 164 μ^-e^+ events for associated $K_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ decays. We find 33 such vees (25 events with a single vee, 4 with a double vee), consisting of 23 K_S^o and 10 Λ decays after resolving the K^o/Λ ambiguities (10 of the 33 vees were ambiguous). This corresponds to a neutral strange particle rate of 0.6 ± 0.2 per dilepton event, in good agreement with the GIM model of charm production by neutrinos. The data on dilepton production by neutrinos from other bubble chamber experiments is summarized in Table I. Both the rate for dilepton production and the number of neutral strange particles per event are consistent with the results of the Columbia-BNL experiment.

From these data we can conclude that dilepton production by neutrinos is dominantly due to the production and semileptonic decays of charmed particles. The strongest evidence is the correlation with strange particles. We observe 6% visible vee production in our sample of 60,000 charged current neutrino interactions. At this rate we expect 10 vees with our sample of 164 μ^-e^+ events, whereas we see 33 vees. This corresponds to a total strange particle production rate of ∿ 1.2 strange particles per μ^-e^+ event, using our result of 0.6 ± 0.2 neutral strange particles per event and the assumption that charged strange particle production equals the amount of neutral strange particle production. We can see that this is consistent with the prediction of the Glashow-Iliopoulos-Maiani model by considering the dominant charm production mechanisms from valence d quarks and from the ocean of $s\bar{s}$ quarks:

Valence:

$d(x)\sin^2\theta_c$

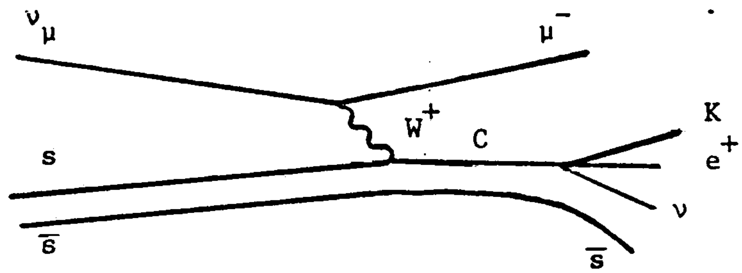
1 S.P. per event



Ocean:

$s(x)\cos^2\theta_c$

2 S.P. per event



In charm production from valence quarks, we expect the total charm production rate to be $\sim \sin^2\theta_c$, where θ_c is the Cabibbo angle, or about 5%, which is quite consistent with our 0.5% rate for μ^-e^+ events and a 10% semileptonic branching ratio. We expect one strange particle per event from the preferential coupling of charm to strangeness. In charm production from $s\bar{s}$ pairs in the ocean, we expect a production rate of $s(x)\cos^2\theta_c$, where $s(x)$ is the probability of finding an s quark with fractional momentum x, and we expect $\sim$ two strange particles per event (one from the decay of c, the other from leftover $\bar{s}$). The two mechanisms can be distinguished by their characteristic x distributions; the production on ocean s quarks is expected to have a distribution peaked at small x, while production on a valence quark has a broader x distribution. We have carried out a fit of our x distribution for the 164 μ^-e^+ events (Fig. 2) to the x distributions measured at SLAC and GARGAMELLE for valence and ocean quarks. The best fit indicates that charm production by neutrinos is about 2/3 from valence and 1/3 from ocean quarks. We thus expect (2/3 x 1 strange particle) + (1/3 x 2 strange particles) = 1.33 strange particles per event, in good agreement with our observed rate of $\sim$1.2 strange particles per event. This ratio between charm production on valence and ocean quarks implies that the ocean s quark content is 3% of the valence d quark content in a neon target.

In Fig. 3 we show various opening angles between selected particles as projected on the plane perpendicular to the beam direction. In general, one expects these angles to be shifted toward 0^o for particles coming from the same production vertex and 180^o for those particles emitted at opposite vertices. These results are consistent with the premise that the e^+ tends to be emitted from the hadronic rather than the leptonic vertex.

Fig. 4 shows the $K^o e^+$ effective mass from 19 $\mu^- e^+$ events with a single K^o. The data are not in good agreement with the distribution expected from the $K^o e^+ \nu_e$ decay of a spin zero D^+ meson at 1868 MeV. The distribution is consistent with a calculation by Barger et al.(2) assuming a $K\pi e\nu$ decay; however, contributions from 3-body decay modes are not excluded.

III. Observation of $D^o \rightarrow K^o \pi^+ \pi^-$

We have measured all events with vees in about 80,000 pictures, corresponding to 46,000 charged current events with a muon momentum over 2 GeV/c. We obtain good 2 or 3 constraint fits for 1815 $K_S \rightarrow \pi^+ \pi^-$ and 1367 $\Lambda \rightarrow p\pi^-$. Correcting for branching ratios and detection efficiencies, this corresponds to a $(K^o + \overline{K}^o)$ rate of (13.6 ± 1.5)% of all charged current events, and a $(\Lambda^o + \Sigma^o)$ rate of (5.0 ± 0.5)%.

Figures 5a and 5b show the $K_S^o \pi^+$ and the $K_S^o \pi^+ \pi^-$ mass distributions, respectively. There is a peak in the $K^o \pi^+ \pi^-$ distribution in the mass region of the charmed D^o meson seen at SPEAR.(3) The best fit of a polynomial background plus a Gaussian, shown by the curve on Fig. 6a gives the following parameters.

$$M = 1850 \pm 15 \text{ MeV}, \qquad \sigma = 20 \pm 8 \text{ MeV}$$

corresponding to 64 events above a background of 180, with a statistical significance of four standard deviations. The width is consistent with our experimental mass resolution of 20 MeV. No corresponding peak is apparent near the D mass in the events without a μ^- (Fig. 6b). This is consistent with the prediction of the GIM model that the charm charging neutral current interactions are absent. If the peak were due to K^* production, then one might expect it to be present in events with and without a μ^-.

Correcting for branching ratios and detection efficiencies, we obtain a rate

$$\frac{\nu_\mu + Ne \rightarrow \mu^- + D^o + \ldots,\ D^o \rightarrow K^o\pi^+\pi^-}{\nu_\mu + Ne \rightarrow \mu^- + \ldots} = (0.7 \pm 0.2)\%.$$

Figure 7 shows the distribution in Z, the fraction of the hadronic energy carried by the D^o. We have used the visible hadronic energy for each event, correcting for our estimate of the energy lost due to missing neutrals or charged tracks that interact close to the vertex and, therefore, fail to reconstruct. The solid lines represent all of the events in the D^o region of the $K^o\pi^+\pi^-$ mass distribution, while the dashed lines give the contribution from the background under the D^o, obtained by using control regions above and below the D^o.

There is no significant peak at the D^+ mass in the $K^o\pi^+$ mass distribution. Fitting to a Gaussian with the width of our mass resolution centered on the D^+ mass gives a result of 11 ± 8 $D^+ \rightarrow K^o\pi^+$ events, which is clearly not a significant signal. Using the branching ratios measured at SPEAR of 4 ± 1.3% for $D^o \rightarrow K^o\pi^+\pi^-$ and 1.5 ± 0.6% for $D^+ \rightarrow K^o\pi^+$, we obtain the ratio of D^+ to D^o production by neutrinos of $D^+/D^o = 0.5 \pm 0.4$.

The D^o rate can be compared with our previously measured rate for $\nu_\mu + Ne \rightarrow \mu^- + e^+ + \ldots / \nu_\mu + Ne \rightarrow \mu^- + \ldots$ of $(0.5 \pm 0.15)\%$[1] We cannot obtain an exact value for the ratio of semileptonic to $K^o\pi^+\pi^-$ decays of the D^o since we do not know what fraction of the μ^-e^+ events come from D^o decays. If we assume that all of the μ^-e^+ events are due to semileptonic D^o decays, $D^o \rightarrow e^+ + \ldots$, then we obtain a ratio $R = (D^o \rightarrow e^+ + \ldots)/(D^o \rightarrow K^o\pi^+\pi^-)$ of $R = 0.7 \pm 0.3$. If, on the other hand, only a fraction of the μ^-e^+ events is due to D^o decays, which is more reasonable since there is likely to be some D^+ and charmed baryon decays contributing to the μ^-e^+ events, then the value for R is less than that given above. Recent measurements at SPEAR yielded the branching ratios of (4.0 ± 1.3)% for $D^o \rightarrow K^o\pi^+\pi^-$,[(4)] and (7.2 ± 2.8)% for $D \rightarrow e^+ + \ldots$,[(5)] which correspond to a value of R = 1.8 ± 0.9, assuming equal semileptonic branching ratios for the D^o and the D^+. Our values, with any assumption about the D^o contribution to the μ^-e^+ events, are lower than the SPEAR value for R. However, the errors on all of these numbers are rather large at the present.

IV. Search for Charmed Baryons

We see an indication of charmed baryon production in our dilepton sample. We see 10 events of the type $\nu_\mu + Ne \rightarrow \mu^- + e^+ + \Lambda^o + \ldots$ where we expect about five events from associated production. These Λ^o's can not come from D meson decay nor from the $\bar{s}$ quark left over when the e^+ comes from charm produced on an s quark in the ocean.

We have searched for the hadronic decays of charmed baryons. Figs. 8a and 8b show the $\Lambda^o\pi^+$ and the $\Lambda^o\pi^+\pi^+\pi^-$ mass distribution from events of the type $\nu_\mu + Ne \rightarrow \mu^- + \Lambda^o$ + hadrons. There is no enhancement in the $\Lambda\pi^+\pi^+\pi^-$ mass at 2250 MeV. A small peak with 20 ± 9 events is present in the $\Lambda\pi^+$ mass at 2250 MeV but the signal is not present if a cut in helicity angle (require $\cos\theta^* > -0.6$) is made. This cut was chosen to remove a background of events with a slow Λ and a fast π and should have enhanced the Λ_c^+ signal to background. Thus we consider this to be a statistical fluctuation. From these results we obtain 90% confidence level limits for Λ_c^+ productions into these modes:

$$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^- \qquad \leq 0.2\%$$

$$\Lambda_c^+ \rightarrow \Lambda\pi^+ \qquad \leq 0.1\%$$

V. Limits on Charm Changing Neutral Currents

We have looked for charm changing neutral currents in both production and decay processes. We have found no evidence for charm changing neutral currents in either search, and present the following upper limits:

a) Charm production via neutral currents, $\nu_\mu + Ne \rightarrow \nu_\mu + C + \ldots$, where C is any charmed particle, followed by the semileptonic decay $C \rightarrow e^+ + \nu_e + \ldots$ The signature for this process is an event with an e^+ and any number of additional hadrons but no μ^-. We have 28 such events, most of which are consistent with being $\bar{\nu}_e$ interactions with a fast leading e^+, while the e^+ from charm decay is expected to be slow (see Fig. 1a for the momentum distribution of the e^+ from the μ^-e^+ events). Using the expected e^+ momentum distribution from charm decay (Fig. 1a) and for $\bar{\nu}_e$ interactions, we obtain a 90% confidence level upper limit on charm charging neutral currents by comparing with the number of μ^-e^+ events which are presumably due to charged current charm production of

$$\frac{\text{Charm production by NC}}{\text{Charm production by CC}} \leq 8\%.$$

Note that the semileptonic branching ratio cancels out in this limit.

b) Charm changing neutral currents in the decay process $C \rightarrow$ hadrons $+ e^+ + e^-$, compared to the charged current decay $C \rightarrow$ hadrons $+ e^+ + \nu_e$, where C is any charmed particle produced in the reaction $\nu_\mu + Ne \rightarrow \mu^- + C + \ldots$ The signature for the neutral current decay is an event with three leptons, i.e. $\mu^- + e^+ + e^-$ + hadrons. We observe no such events with $m(e^+e^-) \geq 600$ MeV, to be compared to 164 μ^-e^+ events, which are presumably due to charged current semileptonic charm decays. Using a calculation by Shrock[6] to correct for losses due to the $m(e^+e^-) \geq 600$ MeV cut, we obtain the 90% confidence level upper limit of

$$\frac{\text{Charm changing Neutral Currents}}{\text{Charm changing Charged Currents}} \leq 2\%$$

VI. Limits on Heavy Lepton Production and Check on $\nu_e - \nu_\mu$ Universality

In the first 50,000 pictures we observed

$\nu_e + \text{Ne} \to e^- + \text{hadrons}$	187 ± 14 events
$\bar{\nu}_e + \text{Ne} \to e^+ + \text{hadrons}$	28 ± 6 events

Using a Monte Carlo program we have calculated the ν_e/ν_μ and the $\bar{\nu}_e/\nu_\mu$ flux ratios using measured K/π ratios at the neutrino target (note that overall flux normalizations cancel out in these ratios). Comparing the numbers of ν_e and $\bar{\nu}_e$ interactions with the number of ν_μ interactions in this sample (27,600) and using the calculated flux ratios we obtain the following cross section ratios:

$$\sigma(\nu_e)/\sigma(\nu_\mu) = 0.9 \pm 0.3$$

$$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu) = 1.2 \pm 0.4$$

These ratios are consistent with 1.0, the value expected from $\nu_e - \nu_\mu$ universality. The y distribution for these events, shown in Fig. 9, are consistent with those obtained in ν_μ and $\bar{\nu}_\mu$ interactions.

We can use these events to set upper limits on heavy lepton production via the process $\nu_\mu + \text{Ne} \to L^\pm + \text{hadrons}$ followed by the decay of $L^\pm$, the heavy lepton, $L^\pm \to \nu + e^\pm + \overset{(-)}{\nu}$. The signature for this process is an event with $e^\pm$ with any number of hadrons but no muon, like the 187 e^- and the 28 e^+ events. We now assume $\nu_e - \nu_\mu$ universality and subtract the expected number of ν_e and $\bar{\nu}_e$ interactions from the observed number of events to obtain the 90% confidence level upper limits.

$$\frac{\nu_\mu + Ne \to L^- + \ldots,\ L^- \to e^- + \ldots}{\nu_\mu + Ne \to \mu^- + \ldots} \leq 3 \times 10^{-3}$$

$$\frac{\nu_\mu + Ne \to L^+ + \ldots,\ L^+ \to e^+ + \ldots}{\nu_\mu + Ne \to \mu^- + \ldots} \leq 1 \times 10^{-3}$$

The rate of heavy lepton production as a function of the heavy lepton mass $m(L^{\pm})$, as well as the heavy lepton decay rate into $e^{\pm}\nu\nu$ have been calculated by Carl Albright et al.[7] Comparing our upper limits with these calculations we conclude that:

a) Muon type heavy leptons that couple with the usual V-A interactions to the usual quarks must be heavier than

$$m(L^-) \geq 7.5 \text{ GeV}$$
$$m(L^+) \geq 9.0 \text{ GeV}$$

b) The recently discovered 1.9 GeV heavy lepton, the τ, does not have the quantum numbers of the muon; i.e. the coupling strength of the ν_μ to the τ is less than 0.025 of the ν_μ to μ^- coupling strength. Alternately, if the τ is not a member of the same multiplet as the μ but there is a mixing between the μ and the τ, then our results imply a limit on the mixing angle of $\tan^2\phi \leq 0.025$.

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C. Baltay et al., Phys. Rev. Lett. 41, 73 (1978).

2. V. Barger et al., Phys. Rev. D16, 746 (1977).

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4. I. Peruzzi et al., Phys. Rev. Lett. 39, 1301 (1977).

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There have been other results on the semileptonic branching ratio (W. Bacius et al., Phys. Rev. Lett. 40, 671 and R. Brandelik et al., Phys. Lett. 70B, 387). We use the results of J.M. Feller et al. since they were obtained in the same experiment as the $K\pi\pi$ branching ratio of Ref. 4.

6. R. Shrock, private communication.

7. C.H. Albright, J. Smith and J.A.M. Vermaseren, State University of New York at Stonybrook Report No. ITP-SB-77-43, and C.H. Albright and C. Jarlskog, Nucl. Phys. B84, 467 (1975).

Figure Captions

Fig. 1: Momentum of a) the e^+, and b) the μ^-, the dilepton sample. The shaded events are the background from hadron punchthrough. c) The total visible energy.

Fig. 2: X and Y variables for dilepton events. The curves represent fitted contributions from valence and sea quarks.

Fig. 3: Opening angles as projected onto the plane normal to the ν_μ beam direction.

Fig. 4: $K^o e^+$ mass from dilepton sample.

Fig. 5: a) $K^o\pi^+\pi^-$ and b) $K^o\pi^+$ invariant mass distributions from charged current events.

Fig. 6: $K^o\pi^+\pi^-$ invariant mass distributions for a) events with μ^- candidates and b) events without μ^- candidates.

Figure Captions (Cont'd.)

Fig. 7: Distribution of z of the D^o, where $z = E_{D^o}/E_{hadronic}$. The solid lines are all of the events in the D^o region; the dashed lines are the estimate of the background under the D^o.

Fig. 8: a) $\Lambda\pi^+$ and b) $\Lambda\pi^+\pi^+\pi^-$ invariant mass distributions from charged current events.

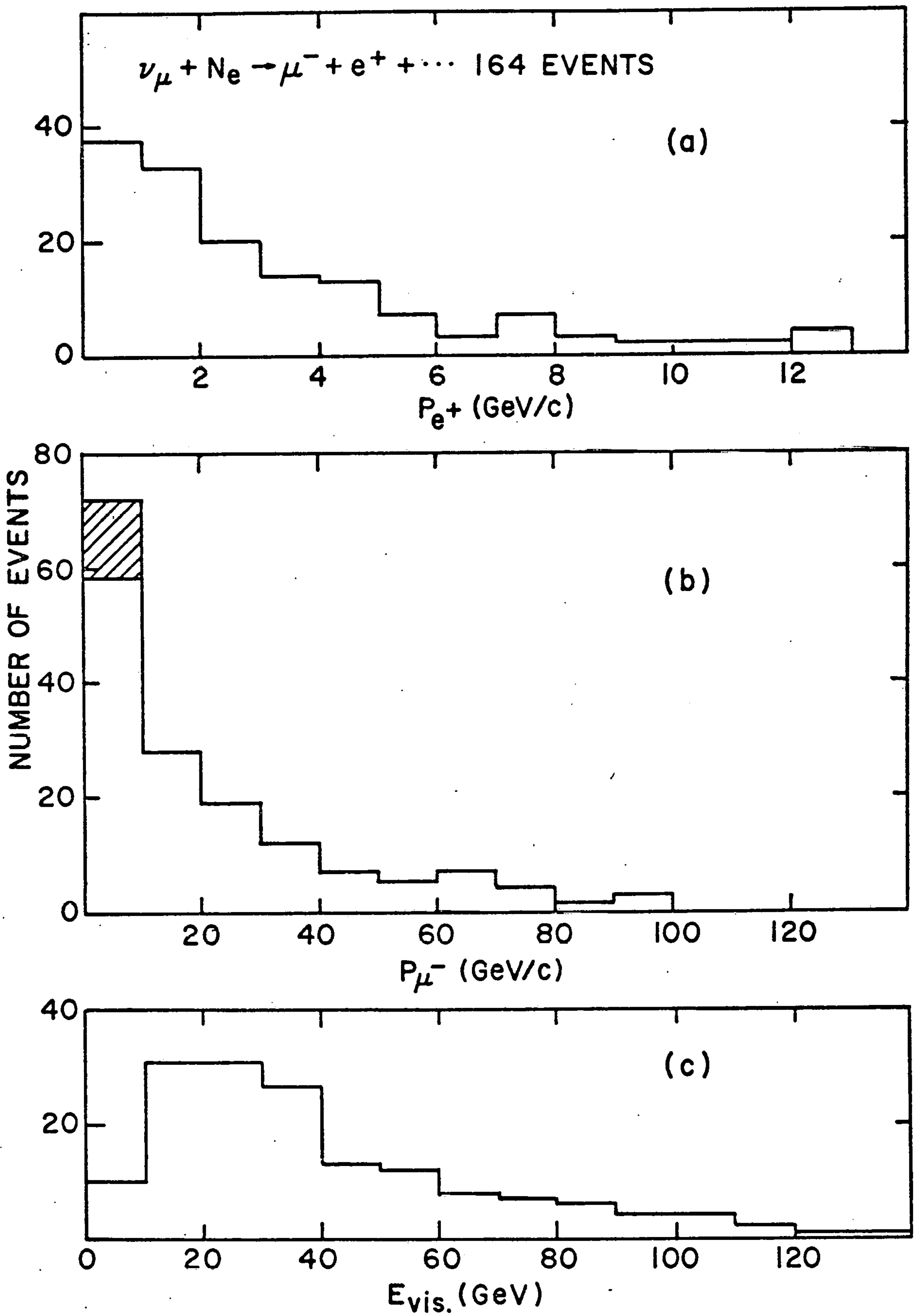
Fig. 9: Y distributions for a) ν_e and b) $\bar{\nu}_e$ events. The continuous lines indicate that expected if the e's were coming from the decay of a τ meson.

TABLE I

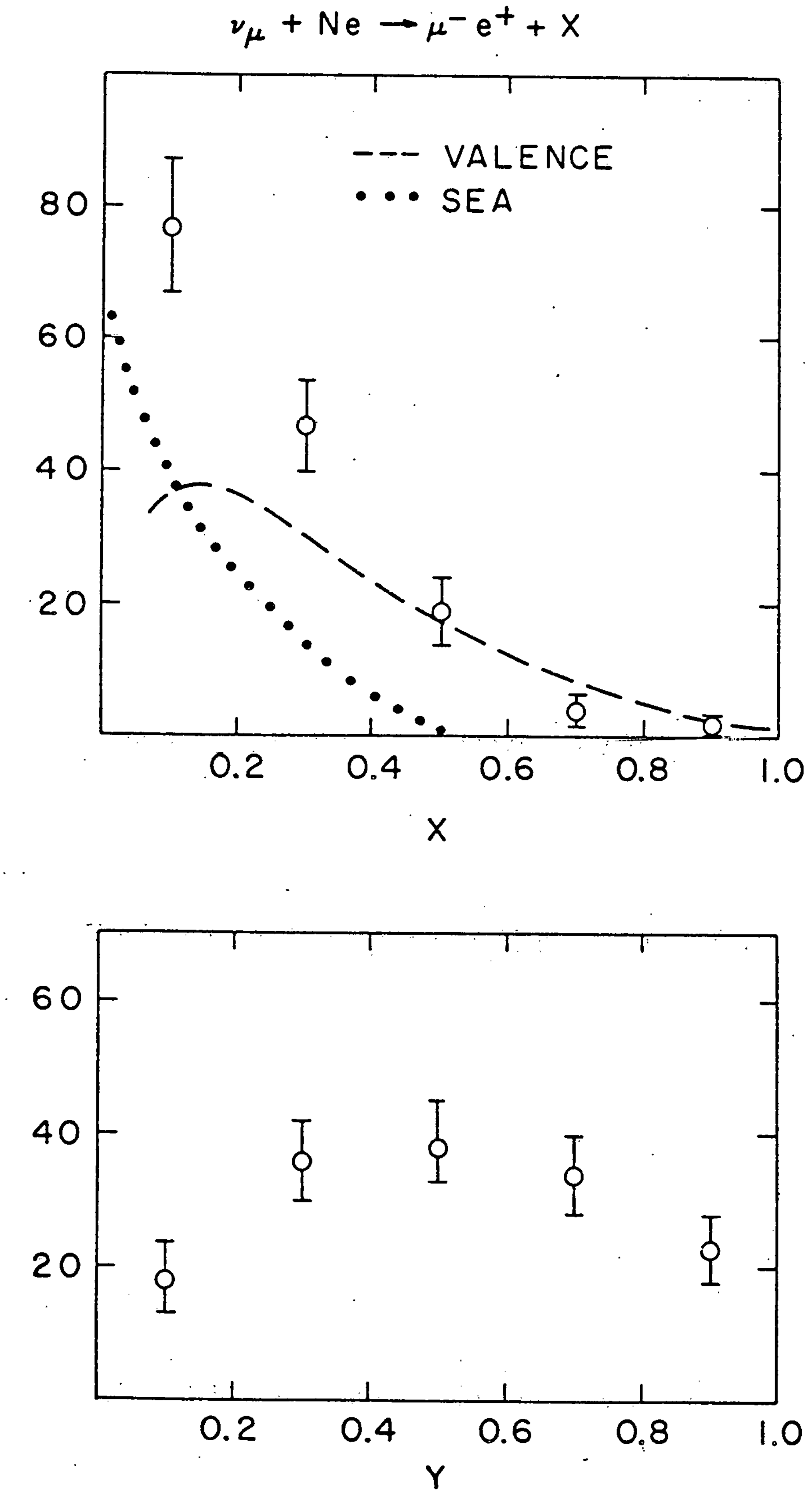
Dilepton Production by Neutrinos in Bubble Chambers

Experiment	$\langle E_\nu \rangle$ BeV	Liquid	Events Observed	Vees* Observed	$\mu^- e^+/\mu^-$ Rate (%)
Gargamelle CERN PS	1-8	Freon	14 $\mu^- e^+$	3	
Wisconsin-CERN-Hawaii-Berkeley Fermilab 15 foot B.C., E28	∿30	21% Ne	17 $\mu^- e^+$	11	0.8 ± 0.3
Columbia-Brookhaven Fermilab 15 foot B.C., E53	∿30	64% Ne	164 $\mu^- e^+$	33	0.5 ± 0.15
Berkeley-Seattle-LBL-Hawaii Fermilab 15 foot B.C., E172	∿30	64% Ne	6 $\mu^- e^+$	1	$0.34 {+0.23 \atop -0.13}$
Fermilab-LBL-Hawaii Fermilab 15 foot B.C., E460	∿30	50% Ne	9 $\mu^- \mu^+$	1	
BEBC Narrow band CERN SPS	∿75	60% Ne	11 $\mu^- \mu^+$ 5 $\mu^- e^+$	6 2	0.7 ± 0.3
BEBC Wide band CERN SPS	∿30	60% Ne	21 $\mu^- e^+$	6	0.5 ± 0.17
Fermilab-Michigan-IHEP-ITEP Fermilab 15 foot B.C., E180	∿30	64% Ne	6 $\mu^- e^+$	1	1 ± 1/2

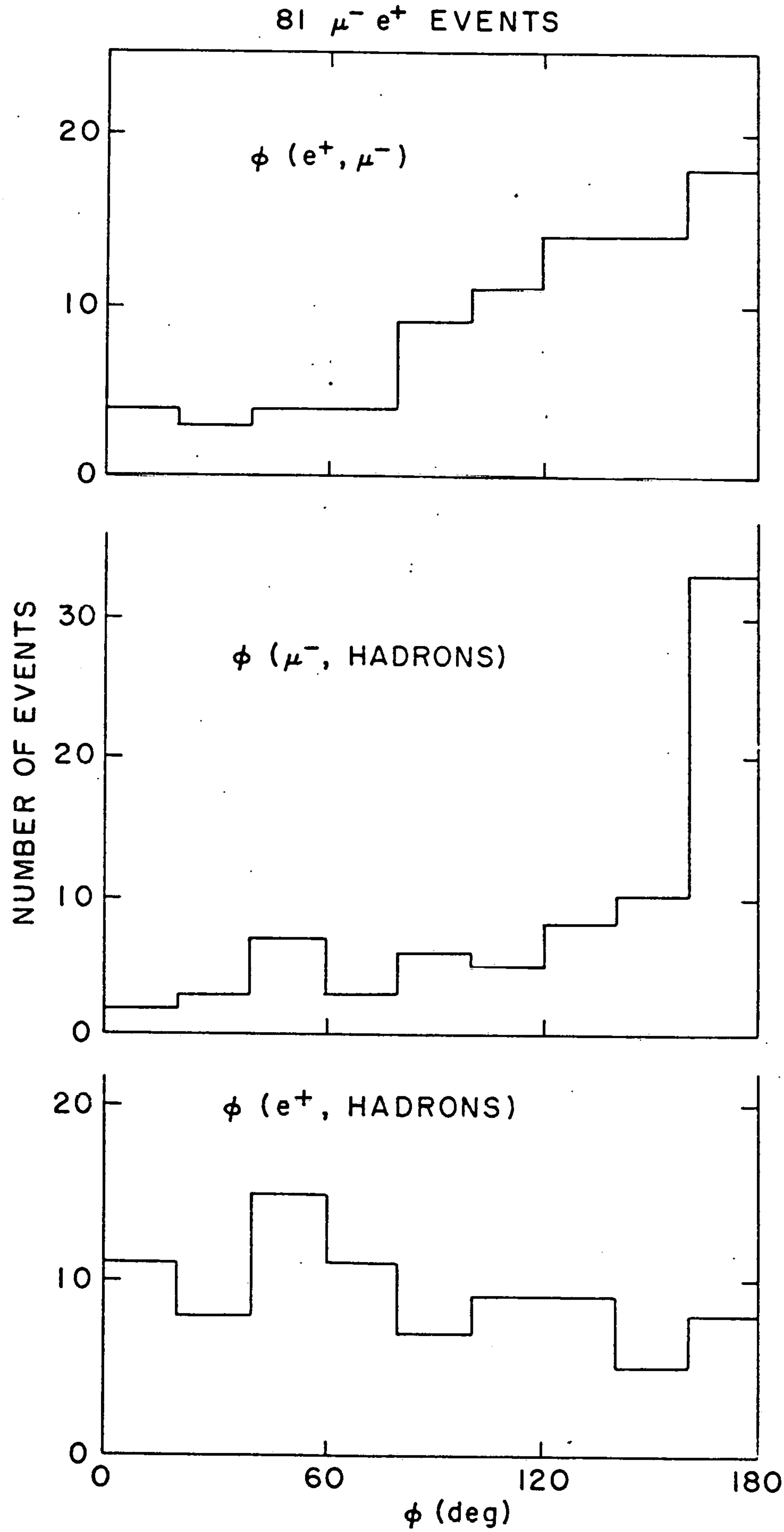
*Vees stand for $K_s^o \to \pi^+ + \pi^-$ or $\Lambda^o \to p + \pi^-$ decays



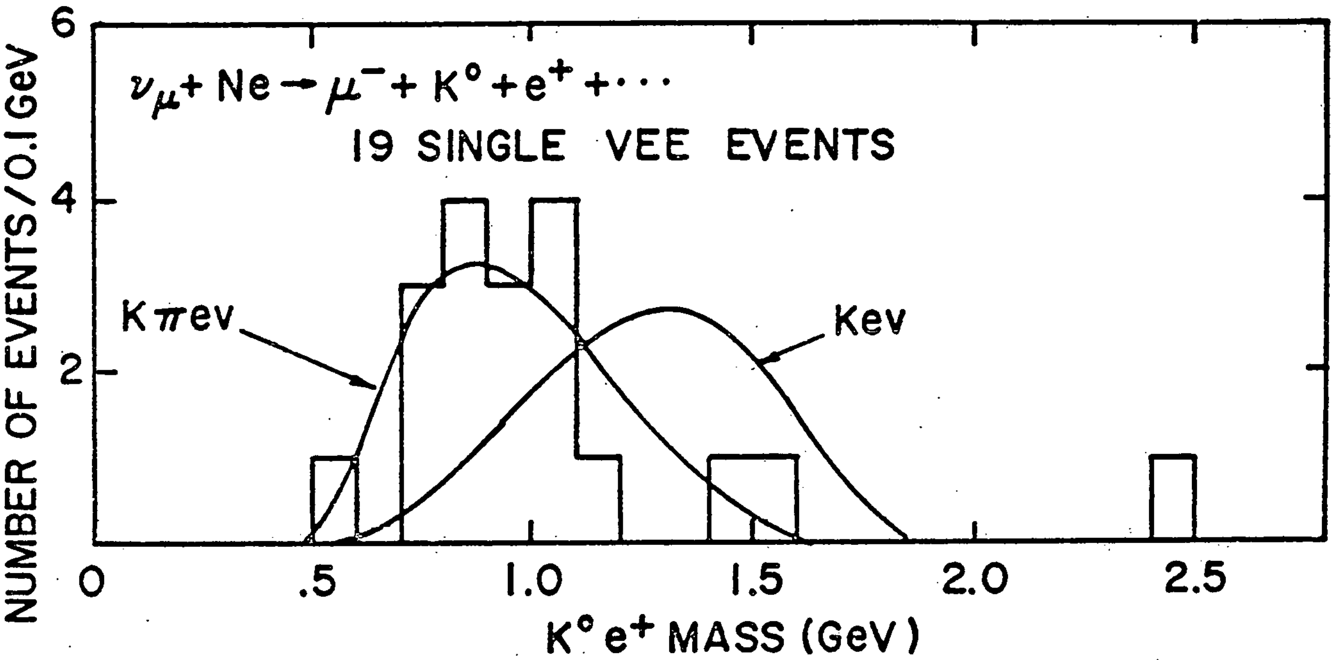
ν_μ + N_e → μ⁻ + e⁺ + ··· 164 EVENTS
(a)
40
20
0
2
4
6
8
10
12
P_e+ (GeV/c)
80
60
40
20
0
NUMBER OF EVENTS
(b)
20
40
60
80
100
120
P_μ⁻ (GeV/c)
40
20
(c)
0
20
40
60
80
100
120
E_vis. (GeV)



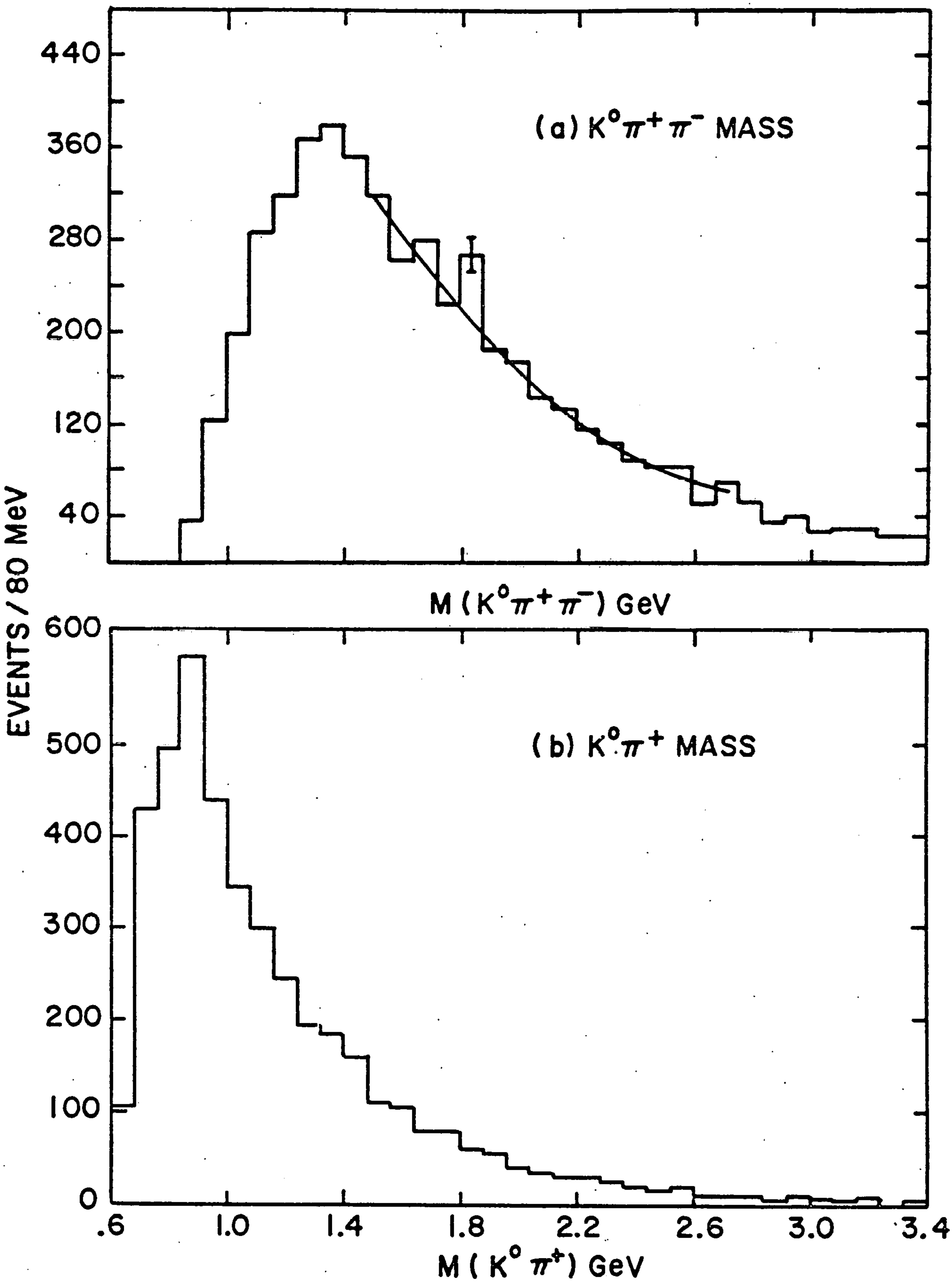
ν_μ + Ne → μ^- e^+ + X
VALENCE
SEA
80
60
40
20
0.2
0.4
0.6
0.8
1.0
X
60
40
20
0.2
0.4
0.6
0.8
1.0
Y



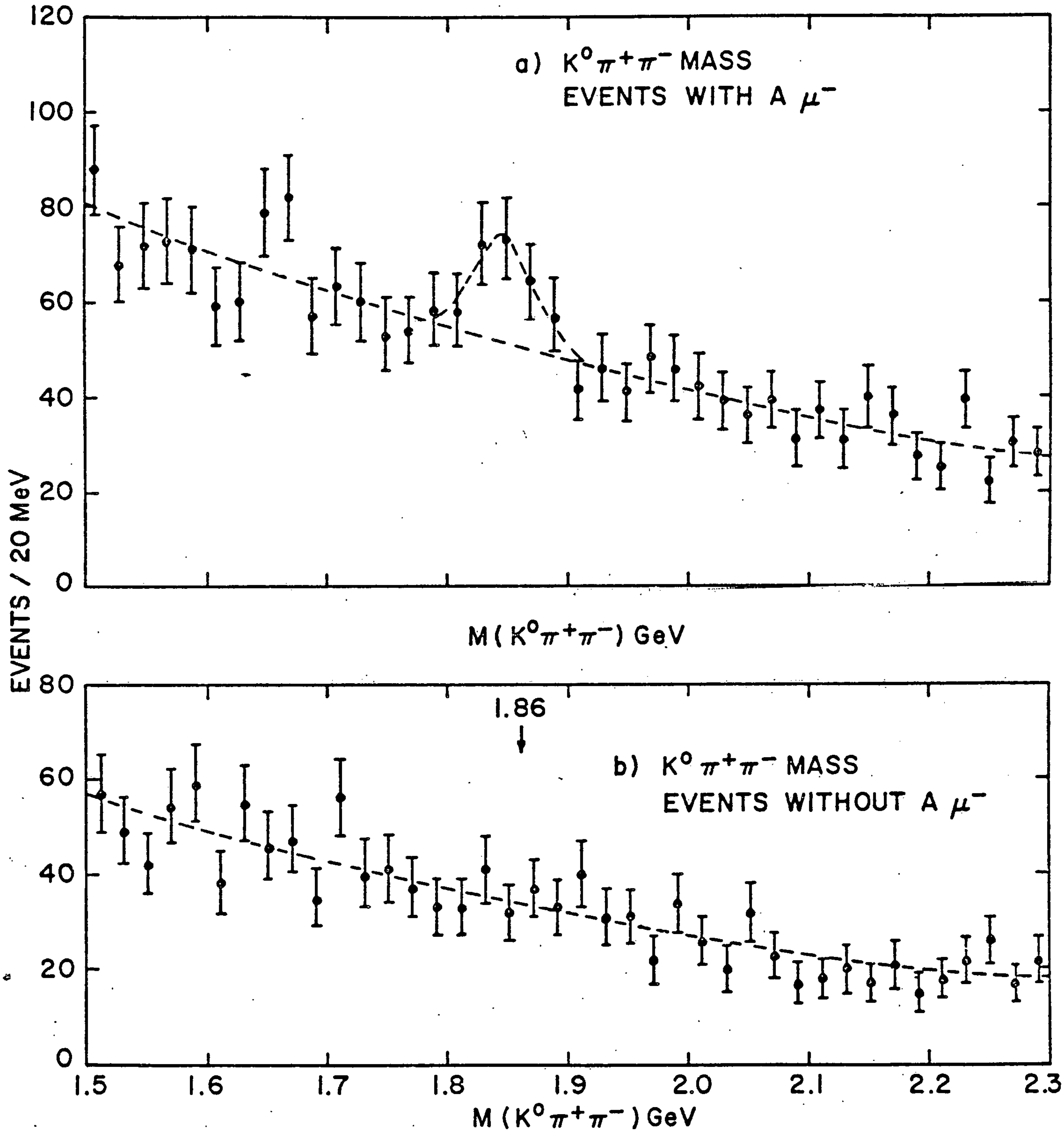
81 $\mu^- e^+$ EVENTS
$\phi\ (e^+, \mu^-)$
$\phi\ (\mu^-$, HADRONS)
$\phi\ (e^+$, HADRONS)
NUMBER OF EVENTS
0
10
20
30
0
60
120
180
ϕ (deg)



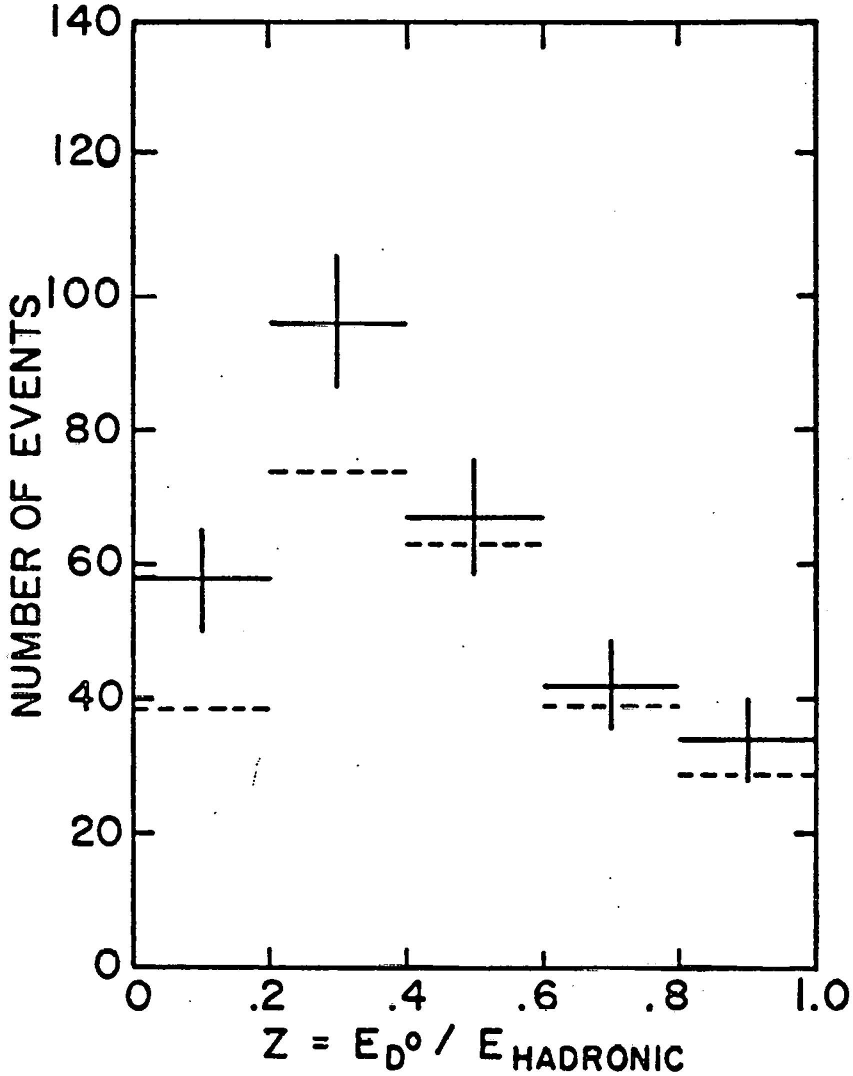
$\nu_\mu + Ne \rightarrow \mu^- + K^\circ + e^+ + \cdots$
19 SINGLE VEE EVENTS
$K\pi e\nu$
$Ke\nu$
NUMBER OF EVENTS/0.1 GeV
6
4
2
0
.5
1.0
1.5
2.0
2.5
$K^\circ e^+$ MASS (GeV)

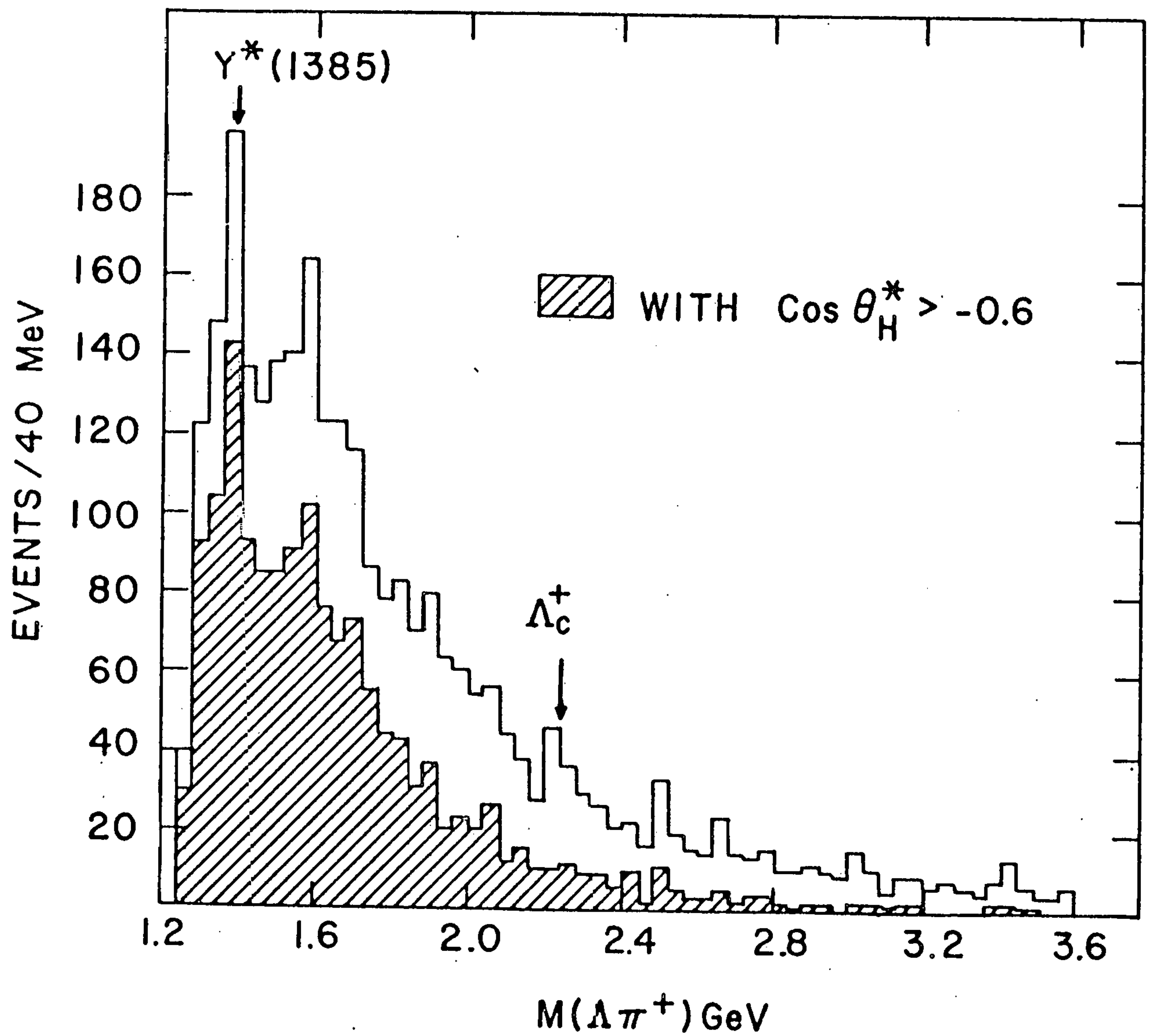


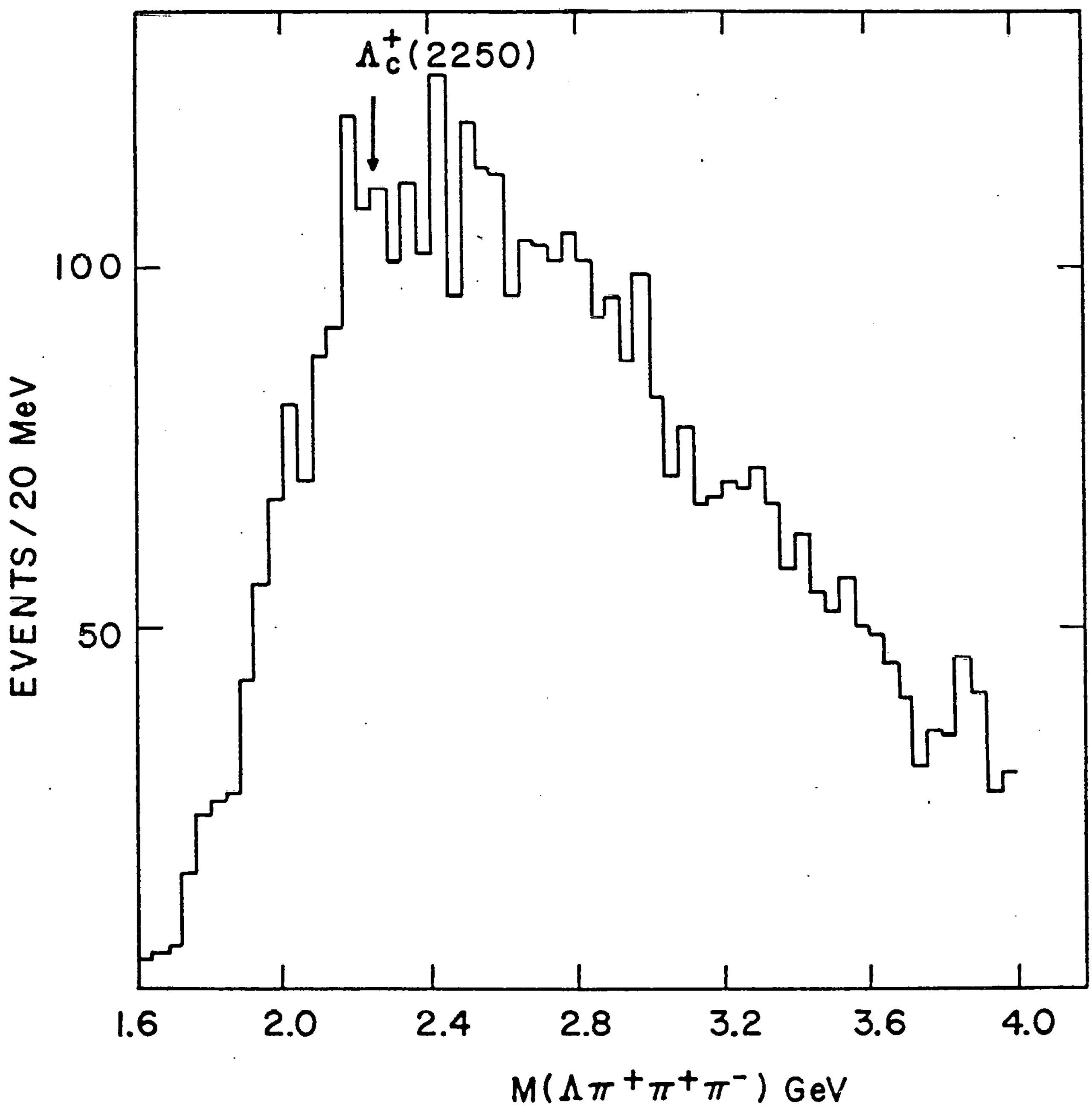
(a) $K^0\pi^+\pi^-$ MASS
440
360
280
200
120
40
$M(K^0\pi^+\pi^-)$ GeV
EVENTS / 80 MeV
(b) $K^0\pi^+$ MASS
600
500
400
300
200
100
0
.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
$M(K^0\pi^+)$ GeV



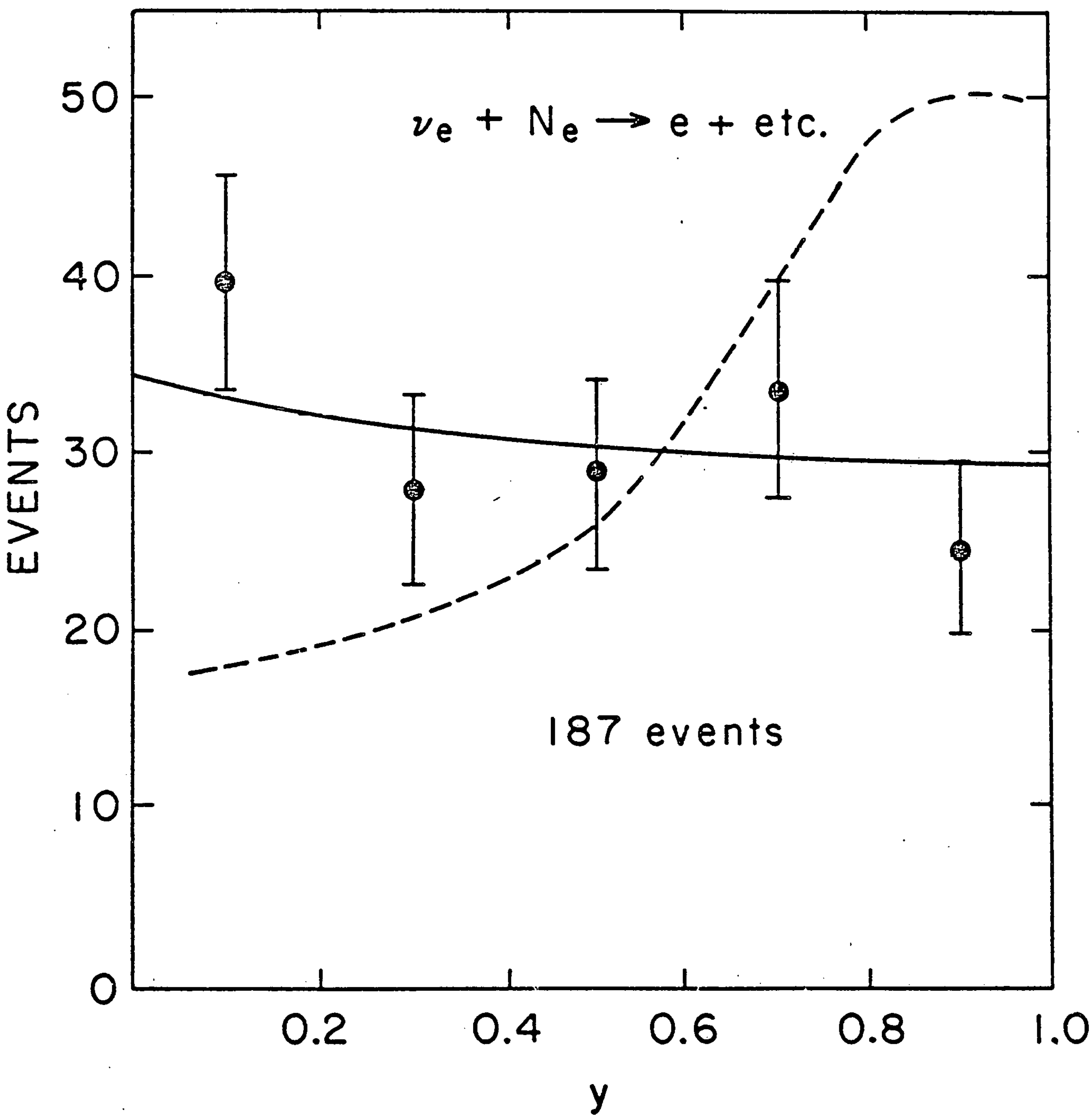
a) $K^0\pi^+\pi^-$ MASS
EVENTS WITH A μ^-
EVENTS / 20 MeV
$M(K^0\pi^+\pi^-)$ GeV
1.86
b) $K^0\pi^+\pi^-$ MASS
EVENTS WITHOUT A μ^-
$M(K^0\pi^+\pi^-)$ GeV


140
120
100
80
60
40
20
0
NUMBER OF EVENTS
0
.2
.4
.6
.8
1.0
Z = E_{D^0} / $E_{HADRONIC}$

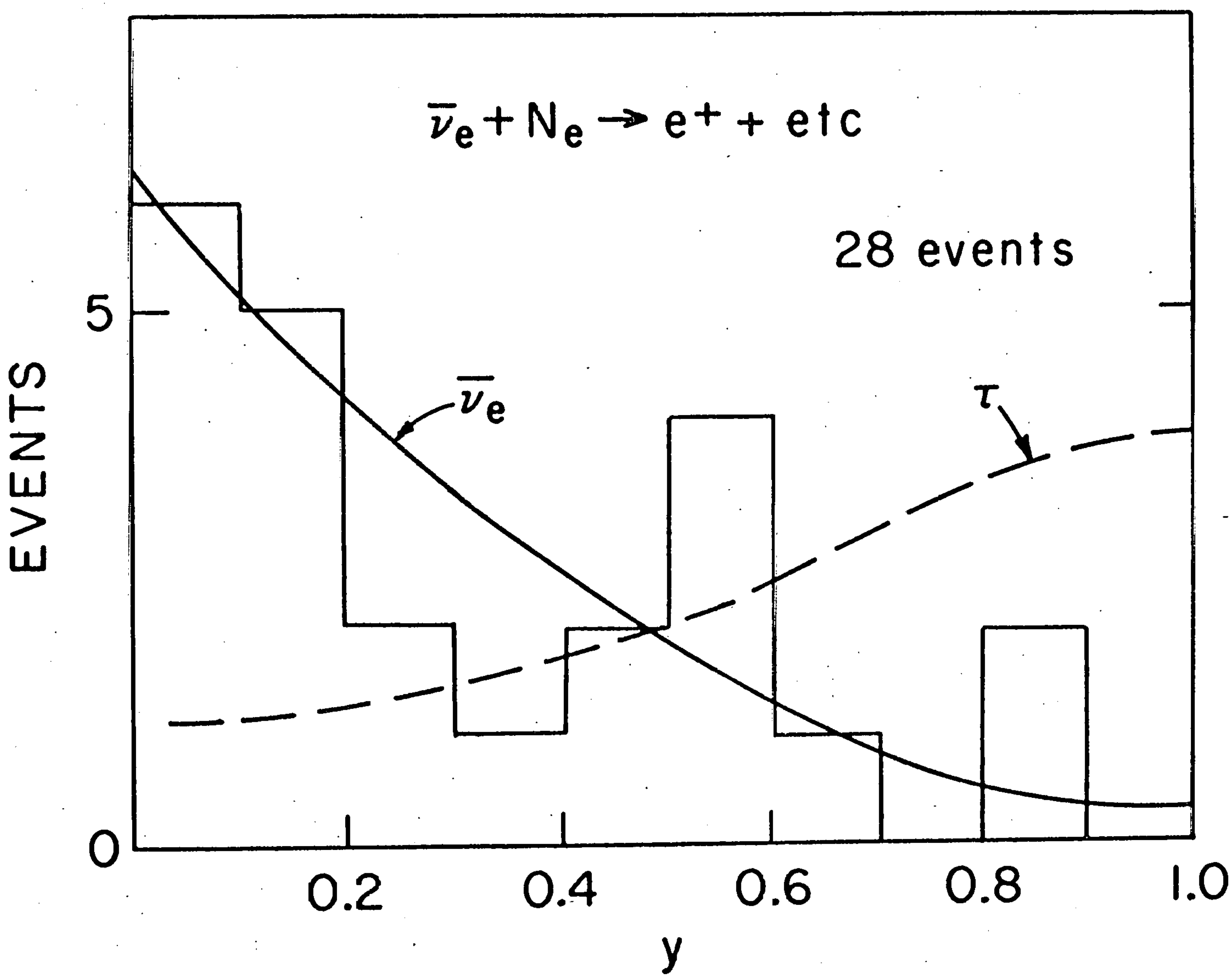

Y*(1385)
WITH Cos θ_H^* > -0.6
Λ_c^+
EVENTS/40 MeV
180
160
140
120
100
80
60
40
20
1.2
1.6
2.0
2.4
2.8
3.2
3.6
M($\Lambda\pi^+$) GeV



$\Lambda_c^+(2250)$
100
50
EVENTS / 20 MeV
1.6
2.0
2.4
2.8
3.2
3.6
4.0
$M(\Lambda\pi^+\pi^+\pi^-)$ GeV



$\nu_e + N_e \rightarrow e + etc.$
187 events
EVENTS
y
0
10
20
30
40
50
0.2
0.4
0.6
0.8
1.0



$\bar{\nu}_e + N_e \rightarrow e^+ + etc$
28 events
5
0
EVENTS
$\bar{\nu}_e$
τ
0.2
0.4
0.6
0.8
1.0
y