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WEAK DECAYS*

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I. Introduction

These lectures will attempt to cover a subject of weak decays from the phenomenological point of view. Clearly, a subject this wide cannot hope to cover all of the possible material in 3 lectures, and thus a choice needs to be made as to what should be included and what excluded. In making this choice I have been guided by the following considerations:

a) the last few years have witnessed a whole spectrum of new theoretical and experimental successes and thus it appears reasonable to emphasize these new results and ideas.

b) In the same last few years there has been a profound change in our ideas as to the number of "elementary"quark and lepton fields. Accordingly, I would like to emphasize the relation of the recent results to this new "standard" theoretical model.

c) Some of the burning questions of five years ago appear to have been settled experimentally in the last few years. Accordingly, as far as the "old" physics is concerned I would like to limit myself to the discussion of those topics that either have received recent experimental attention or else are relevant to the "new" physics being pursued more recently. For more detail on this subject I refer the interested reader to the lectures on this topic at the SLAC Summer Institute of 1972[1)] or to several other more recent reviews in the intervening time.[2)]

These lectures will thus divide themselves naturally into the following topics:

a) Introduction, discussing the general framework within which we view the weak decays, some of the relevant fundamental questions and the standard model against whose predictions the new results on new particles can hopefully be tested in the near future.

b) Discussion of the weak decays of "old" (i.e. noncharmed) hadrons.

c) Discussion of the decays of heavier leptons, i.e. μ and τ decays with the emphasis on new results.

d) Discussion of the decays of charmed particles.

I shall start out the introductory discussion by reviewing very briefly some of the sacred tenets of the weak interaction theory. The general Lagrangian thought to be responsible for the weak interactions in general (and hence weak decays in particular) is

$$\mathcal{L}_{\text{eff}} = \frac{G}{\sqrt{2}} J_\lambda^\dagger J_\lambda$$

where G is the weak interaction coupling constant and J_λ is the current which can be decomposed into the hadronic and leptonic parts, i.e.

$$J_\lambda = J_\lambda^{(h)} + J_\lambda^{(\ell)}$$

The individual components of the current are written in terms of the fundamental fields, i.e. quarks and leptons, based on the belief that the subsequent "dressing" of the quark fields into physically observable hadrons will not obscure the basic features of the fundamental weak interactions.

Thus to understand the full structure of the relevant currents one has to understand the full spectrum of quarks and leptons. It is here, that there has been a very profound revolution in the last few years and I would like to briefly summarize what is our current understanding of this topic. One might start out with some general features that appear to be emerging from both the theoretical and experimental work.

a) SU(2) x U(1)[3] appears to be an important gauge theory group. The spectacular recent successes[4] supporting the Weinberg-Salam model strongly suggest that this group must play an important part in the ultimate theory of weak interactions.

b) Charged weak currents have a lefthanded nature.

c) Leptons and quarks appear in doublets. Some of the empirical evidence for τ lepton not being a singlet will be discussed in Part 3.

d) An "elegant" theory demands an equal number of quark and lepton doublets to cancel the divergences in the triangle graphs (Adler anomalies).

e) Quark mass eigenstate doublets are different from the doublets diagonalizing the weak interactions. The natural question arises here whether the same statement holds true for the leptons.

f) The discovery of the Υ [5,6] and the rapidly growing evidence confirming the leptonic nature of the τ suggest that a six quark, six lepton picture is the most economical one that can accommodate all of the known particles.

I would like to end this introduction by elaborating more fully on these last two points. It has been known for a long time that the up (or p) quark couples both with the down and strange quark, the latter coupling leading to the observable effects of strangeness violation. In the conventional language this has been known as the Cabibbo mixing,[7] where the relative strengths of the $\Delta S=0$ and $\Delta S=1$ transitions were given by $\cos^2\theta_c$ and $\sin^2\theta_c$. The observed strong suppression of the strangeness changing neutral current transitions[8] as evidenced by the absence of the decays $K_L^o \to \mu^+\mu^-$ and $K^+ \to \pi^+\nu\nu$, coupled with the observation at CERN,[9] and later at Fermilab,[10] of the strangeness conserving neutral currents in neutrino interactions, led to the hypothesis of the fourth quark and the so called GIM model.[11] This model provided a natural, up to second order, suppresion of these phenomena, and the spectacular verification of its many predictions, culminating in the discovery of the bare charm[12] led to the acceptance of this 4-quark picture.

The ideas described above can be recast and generalized in an n-quark formalism where the bare quarks can be placed in mass eigenstate doublets $(P_i N_i)$ with the charges of the two members given by $Q_p = 2/3$ and $Q_N = -1/3$. On the other hand the lower members of the doublets that diagonalize the weak interactions are now given by

$$d_i = A_{ik} N_k \qquad i,k = 1, \ldots n$$

and A_{ik} is an n x n unitary matrix. Because of arbitrary phases of the quark fields and the one overall arbitrary phase, one has $(n-1)^2$ free parameters in the A matrix. In the conventional 4 quark picture, we have n=2, and hence 1 free parameter, traditionally called the Cabibbo angle, θ_c. This leads to the A matrix given by

$$A = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix},$$

which relates the traditional bare quark doublets (p n) and (c λ), to the

Q=-1/3 members of the weak interaction doublets i.e.

$$n_w = n\cos\theta_c + \lambda\sin\theta_c$$
$$\lambda_w = -n\sin\theta_c + \lambda\cos\theta_c$$

These ideas have been generalized to the 3 doublet picture by Kobayashi and Maskawa.[13] The 4 free parameters are now 3 "Euler angles" and 1 phase, and the whole matrix can be written as

$$A = \begin{pmatrix} C_1 & -S_1C_3 & -S_1S_3 \\ S_1C_2 & C_1C_2C_3 - S_2S_3e^{i\delta} & C_1C_2S_3 + S_2C_3e^{i\delta} \\ S_1S_2 & C_1S_2C_3 + C_2S_3e^{i\delta} & C_1S_2S_3 - C_2C_3e^{i\delta} \end{pmatrix}$$

where $S_i = \sin\theta_i$ and $C_i = \cos\theta_i$.

Clearly, if S_2 and S_3 are small, as appears to be indicated by the data,[14] (see below) one recovers all of the standard 4 quark phenomenology, with only small couplings for the potential new (t, b) doublet with the other 2 old doublets. The other attractive feature of the K-M model is the natural appearance of a small amount of CP violation without the necessity of introducing a very small, i.e. $\sim 10^{-3}$, parameter characterizing the CP violation.

The obvious question, and one that can only be answered experimentally, is whether this dichotomy between the mass eigenstates and the weak interaction eigenstates is also present in the lepton sector. If so, then we can expect transitions between different lepton doublets, leading to expectations of possible $\mu \to e\gamma$ decay mode. We shall say more about this in the chapter on lepton decays.

Finally one must pose the fundamental question, i.e. can we say anything about maximum potential proliferation of quark and lepton doublets. The theory says very little here and the number of flavors in principle is unlimited. However there have been recently put forth cosmological arguments,[15] based on the big bang theory and the relative abundance of helium in the universe. This argument is summarized in Fig. 1, which shows that with the present measurement of the helium abundance, the number of additional lepton doublets cannot exceed 2 or 3.

Another limit, albeit far less stringent, can be obtained from the limits on the partial widths of the bound heavy quark states, i.e. ψ,Υ,etc. into neutrinos, as pointed out by J. Ellis in a parallel series of lectures.[16] In principle, those states have to decay via

$$\psi \to \nu\bar{\nu} \ , \quad \Upsilon \to \nu\bar{\nu}$$

and existence of more lepton doublets will provide more open channels, leading to a larger width. Experimentally, this decay mode could be observed[17] in a step reaction

$$\psi' \to \psi\ \pi^+\pi^- \ , \ \psi \to \nu\bar{\nu}.$$

Finally, more recently Ma and Okada[18] have suggested measuring the rate for $e^+e^- \to \gamma\nu\bar{\nu}$ as a means of obtaining total number of possible lepton flavors.

II. "Old" Hadronic Decays

In this section we shall discuss several topics dealing with the weak decays of "old" i.e. noncharmed hadrons. Specifically the 5 distinct questions we shall address are:

a) Status of the Cabibbo theory

b) Form factors in the semileptonic decays

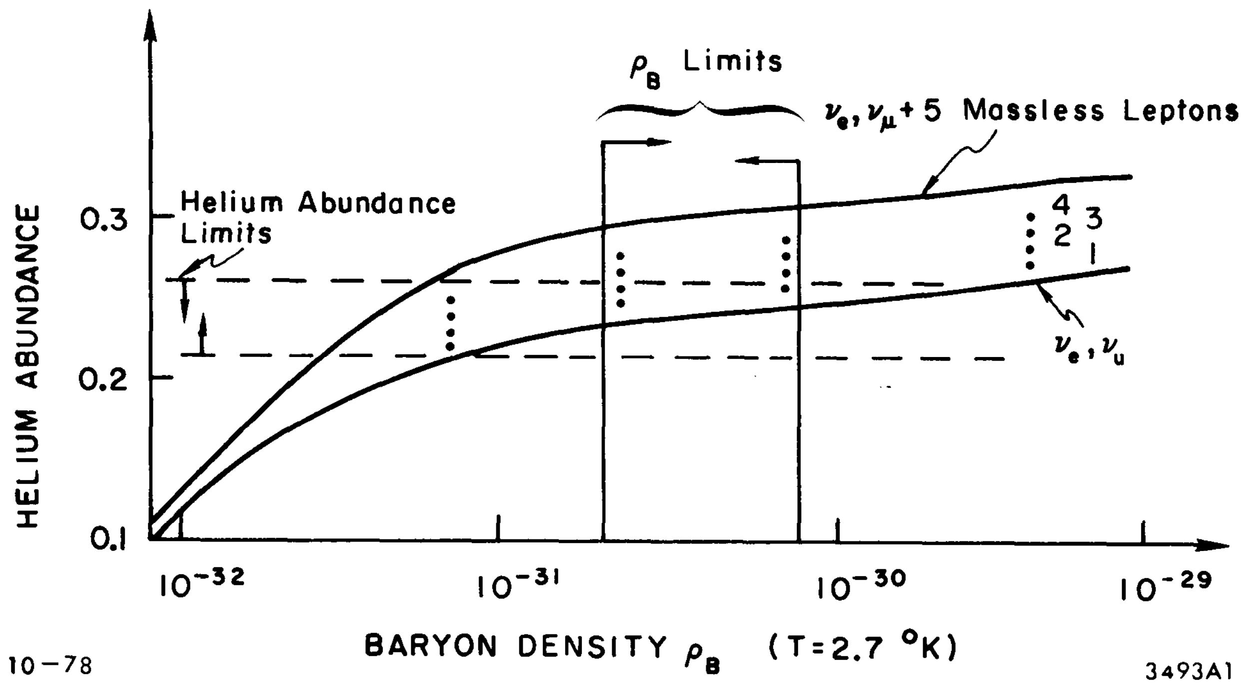

Fig. 1 Helium abundance in the universe versus baryon density as a function of number of neutrino types.

c) $\Delta I=1/2$ rule in hadronic decays

d) Status of the CP violation

e) Status of the $\Delta S=1$ neutral current decays.

In each case we shall emphasize both the most recent results, as well as the relevance of those ideas to our extended "standard" model of six quarks.

a) Cabibbo Theory. The Cabibbo theory was able to extend the basic ideas of Feynman and Gell-Mann's CVC theory to strangeness changing currents by applying the symmetry ideas embodied in SU_3. More specifically the theory firstly provided an elegant framework which incorporated many of the observed regularities in the semileptonic decays of the hadrons, i.e.

1 - Suppression of the hyperon leptonic decays with respect to the nuclear β decays

2 - The $\Delta S=\Delta Q$ rule

3 - $\Delta I=1/2$ rule in semileptonic decays

4 - Absence of $\Delta S=2$ transitions.

Furthermore, however, the theory had a considerable predictive power and its predictions were readily subjected to the experimental tests in the immediate future. We shall start out this section with a brief outline of the basic ideas of the Cabibbo theory, followed by a discussion of the comparison of the experimental results with the predictions of the theory.

The CVC theory incorporated the strangeness conserving charged weak current as a member of an isotopic spin triplet, whose neutral member was the vector part of the electromagnetic current. The Cabibbo theory extended these ideas to strangeness changing currents by postulating that all currents have transformation properties of members of an octet under SU_3. Since we have not only vector weak currents, but also axial weak currents, two distinct SU_3 octets are necessary to incorporate all the possible currents.

To be more specific, the construction of the actual currents can be seen by considering the direct product of two octets, i.e. a baryon and antibaryon one where the baryon octet is given by

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(\Sigma^0 + \frac{1}{\sqrt{3}}\Lambda\right) & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{2}}\left(-\Sigma^0 + \frac{1}{\sqrt{3}}\Lambda\right) & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

and there is a comparable octet for the antibaryons. The direct product of 2 octets can be decomposed as follows:

$$8 \otimes 8 = 27 + 10 + \overline{10} + 8 + 8 + 1$$

Thus we see that there are 2 possible octets in the final sum, i.e. 2 possible ways to couple 2 octets to give us an octet. These are traditionally decomposed into the symmetric coupling (D coupling) and antisymmetric coupling (F coupling). Thus the most general formulation of the weak currents would involve two terms (and thus two arbitrary coupling strengths) for both the axial and vector currents, i.e. we could write symbolically :

for the vector current: $D_V\, 8_S + F_V\, 8_A$

and for the axial current $D_A \, 8_S + F_A \, 8_A$

where the D_V, D_A, F_V, F_A are the coupling constants and the 8_S and 8_A, the symmetric and antisymmetric couplings of the baryon antibaryon octets. The requirement that CVC be incorporated automatically into the Cabibbo scheme imposes some constraints however. These can be seen most readily if we examine the exact nature of the $\Delta S=0$ coupling for both the symmetric and antisymmetric case.

For the symmetric case we have

$$\frac{2\,\bar{\Lambda}\Sigma^+}{\sqrt{6}} + 2\,\frac{\overline{\Sigma^-}\Lambda}{\sqrt{6}} + \bar{n}p + \overline{\Xi^-}\Xi^o$$

and for the antisymmetric case

$$\sqrt{2}\,\overline{\Sigma^-}\Sigma^o + \sqrt{2}\,\Sigma^o\Sigma^+ - \overline{\Xi^-}\Xi^o + \bar{n}p$$

Thus we see that the symmetric coupling generates a transition between members of different isotopic spin multiplets i.e. $\Sigma \rightarrow \Lambda$, a transition that is contrary to the CVC hypothesis. The only way to reconcile the CVC requirement is to demand that this particular coupling vanish, i.e. $D_V=0$ (note that no corresponding requirement exists for the axial currents). Furthermore, by the CVC hypothesis, the strength of the other vector coupling is now completely determined.

The additional Cabibbo hypothesis involves the idea that there is a mixing between the $\Delta S=0$ and $\Delta S=1$ parts of the hadronic current. This mixing is parametrized by one number θ_c, in such a way that the strength of the $\Delta S=0$ transitions is given by $\cos^2\theta_c$ and of the $\Delta S=1$ transitions by $\sin^2\theta_c$. Thus we have 3 free parameters in the theory, D_A, F_A, and θ_c. In principle, the mixing angle could be different for the axial and vector currents giving rise to an additional free parameter. In practice, however, the overall global fit to all of the data is not improved if we allow this extra degree of freedom, so for the purpose of subsequent discussion we shall deal with but one Cabibbo angle.

We have to ask next how do we relate these parameters to the actual observables that we measure in the laboratory. As the bulk of the information comes from the baryonic semi-leptonic decays we shall consider them in some detail. The matrix elements for the vector and axial transitions can be written as

$$\mathcal{M}_V^{\lambda} \propto \begin{pmatrix}\cos\theta_c \\ \sin\theta_c\end{pmatrix} \bar{u}_i \left[f_1(q^2)\gamma^{\lambda} + i\, f_2(q^2)\sigma^{\lambda\rho}\, q_{\rho} + f_3(q^2) q^{\lambda} \right] u_j$$

$$\mathcal{M}_A^{\lambda} \propto \begin{pmatrix}\cos\theta_c \\ \sin\theta_c\end{pmatrix} \bar{u}_i \left[g_i(q^2)\gamma^{\lambda}\gamma^5 + i\, g_2(q^2)\sigma^{\lambda\rho}\gamma^5 q_{\rho} + g_3(q^2)\gamma^5 q^{\lambda} \right] u_j$$

where $\cos\theta_c$ ($\sin\theta_c$) is the multiplicative factor appropriate for the $\Delta S=0$ ($\Delta S=1$) transition, u_i and u_j are the baryon spinors and f_i and g_i the form factors that by Lorentz invariance can depend only on the 4 momentum transfer between the two baryons.

We can now make some assumptions that simplify the whole situation considerably. Firstly, as q^2 is quite low in all the "old" baryon weak decays, we assume that the form factors are constant in the physical region. Secondly, since the contribution of g_3 is multiplied by m_i^2, that term is irrelevant for the electronic decays. Thirdly, f_3 and g_2 are forbidden if second class currents are absent, so we also neglect them. Finally, the contribution of f_2 is small, so it is customary to assume for it the theoretical value.

The form of the symmetric and antisymmetric couplings discussed above yields then the following values for f_1 and g_1 expressed in terms of D and F axial coupling strengths for the baryonic semileptonic decays accessible to the experimental study:

Table I. Cabibbo expressions for form factors.

Decay	f_1	g_1	f_2/f_1	Mixing Multiplier
$n \to pe^-\nu$	1	D+F	$\mu_p - \mu_n$	$\cos\theta_c$
$\Sigma^\pm \to \Lambda\ell^\pm\nu$	0	$\sqrt{2/3}$ D	$-3/2\mu_n/D^*$	$\cos\theta_c$
$\Sigma^- \to n\ell^-\nu$	-1	D-F	$\mu_p + 2\mu_n$	$\sin\theta_c$
$\Lambda \to p\ell^-\nu$	$-3/\sqrt{6}$	$-\frac{1}{\sqrt{6}}$ (D+3F)	μ_p	$\sin\theta_c$
$\Xi^- \to \Lambda\ell^-\nu$	$-3/\sqrt{6}$	$-\frac{1}{\sqrt{6}}$ (D-3F)	$\mu_p + \mu_n$	$\sin\theta_c$

* f_2/g_1 for this decay only

Thus a measurement of g_1 constitutes a measurement of a specific linear combination of D and F coupling constants, and once θ_c is known, this measurement determines a straight line in the D-F space. The prediction of the Cabibbo theory is that there exists an angle θ_c for which all of these lines will intersect at a point (within the approximation of the theory and the experimental errors). The position of this point will determine the D and F coupling constants.

It remains accordingly to discuss the kinds of measurements that allow us to determine f_1 and g_1. These can be divided into five categories and are summarized briefly below:

1 - Decay rate (i.e. branching ratio combined with the lifetime) is proportional to $|f_1|^2 + 3|g_1|^2$.

2 - Measurement of the recoil spectrum of the nucleon (identical to measuring the angle between ℓ and ν, i.e. $\theta_{\ell\nu}$). More specifically we

must have

$$\frac{d\sigma}{d\cos\theta_{\ell\nu}} = \frac{1}{2}\,(1 + \alpha_{\ell\nu}\cos\theta_{\ell\nu}) \text{ with } \alpha_{\ell\nu} = \frac{|f_1|^2 - |g_1|^2}{|f_1|^2 + 3|g_1|^2}$$

3 - Shape of the lepton spectrum.

4 - Decay asymmetry (if the initial baryon is polarized).

5 - Polarization of the final state baryon.

At the present time the available experimental input can be grouped into 9 different kinds of experiments. Some of these reactions must yield the same answer independent of the Cabibbo theory, as a "more fundamental" symmetry principle is also operative. In these cases the two reactions are grouped together, as they contribute only one independent piece of data to the overall Cabibbo fit. The individual experiments are listed below in Table II.

Table II

Different experiments entering into the Cabibbo fit

Reaction	Type of Measurement	Comment
1) $n \to pe^-\nu$	Overall decay	---
2) $\Lambda \to pe^-\bar{\nu}$ $\Lambda \to p\mu^-\nu$	Decay rate	Connected by the μ-e universality
3) $\Sigma^- \to ne^-\nu$	e-ν correlation	---
4) $\Sigma^- \to ne^-\nu$ $\Sigma^- \to n\mu^-\nu$	Decay rate	Connected by the μ-e universality
5) $\Lambda \to pe^-\nu$	Decay asymmetry	---
6) $\Sigma^- \to \Lambda e^-\nu$ $\Sigma^+ \to \Lambda e^+\nu$	Decay rate	Connected by charge symmetry
7) $\Xi^- \to \Lambda e^-\nu$	Decay rate	---
8) $\Sigma^- \to ne^-\nu$	Decay asymmetry	Measures sign of g_1/f_1. Two measurements disagree.
9) $\Sigma^- \to \Lambda e^-\nu$ $\Sigma^+ \to \Lambda e^+\nu$	Decay chain	Tests CVC. Does not effect the parameters resulting from the Cabibbo fit.

The main part of the original work on hyperon semileptonic decays comes primarily from low energy K^-p bubble chamber work and electronic low energy associated production experiments. The last few years have seen the experimental innovation of hyperon beams and the bulk of the recent information on this topic has come from primary beam hyperon decays.

There have been two new high statistics experiments measuring the neutron spectrum in the $\Sigma^- \to ne^-\bar{\nu}$ decays, which disagree however with each other at the level of three standard deviations. The Yale-NAL-BNL experiment at the Brookhaven AGS[19)] obtained for the ratio of form factors $|g_1|f_1| = 0.435 \pm 0.035$ while the Orsay-Ecole Polytechnique group[20)] quotes $|g_1|f_1| = 0.17^{+0.07}_{-0.09}$ based on their work at the CERN PS. The overall situation on the Σ decay is summarized in the accompanying table.

Table III

$\Sigma^- \to ne^- \bar{\nu}_e$ Form Factor Measurements

Group	Method	Events	$\vert g_1\vert f_1\vert$
Maryland	Dalitz plot and (e,ν) Correlation	49	0.23 ± 0.16
Heidelberg		33	$0.37^{+0.26}_{-0.19}$
Columbia - Stony Brook		36	$0.29^{+0.28}_{-0.29}$
Yale - NAL - BNL	Neutron Spectrum	3507	0.435 ± 0.035
Orsay-Ecole Polytechnique		519	$0.17^{+0.07}_{-0.09}$
Heidelberg	Lepton Spectrum		(+) 0.20 ± 0.28
Berkeley	Electron asymmetry with polarized Σ^-	61	(-) $0.19^{+017}_{-0.20}$
BNL, Mass, Yale		63	(+) $0.33^{+0.85}_{-0.30}$
Oxford et al.		43	(+) $0.40^{+1.5}_{-0.52}$

Two new pieces of experimental information on the decay $\Sigma^- \to \Lambda e^- \nu$ from the Σ beam work have been published in the last few years. The Yale-NAL-BNL group has performed an analysis of their 55 reconstructed $\Sigma^- \to \Lambda e^- \nu$ events to obtain $f_1|g_1 = -0.17 \pm 0.35$ based on the assumption that the weak magnetic form factor is given by the theory. The Pittsburgh-BNL group has measured[21)] the branching ratio for that decay mode to be $(0.60 \pm 0.06) \times 10^{-4}$.

Finally, in the same experiment, the Pittsburgh-BNL group has measured the branching ratio for the decay $\Xi^- \to \Lambda e^- \nu$ as $(0.31 \pm 0.11) \times 10^{-3}$ and obtained a preliminary upper limit[22)] for the mode $\Xi^- \to \Sigma^o e \nu$ of 1.3×10^{-4}.

As yet, there are no new results from the work on the neutral hyperon beams, although there is in progress at this time an extensive high statistics study of lambda beta decay by the UMass-BNL group[23)] involving some 150,000 examples of this decay.

Regarding the overall fit of all the baryon data to the Cabibbo theory one can probably say that the fit is quite good but the numerical values of the parameters (especially of the D and F coupling constants) are uncertain due to the confusion regarding the $\Sigma^- \to n e^- \nu$ situation. As an example the fit by Roos[24)] to all the data in 1971 (i.e. before the hyperon beam data were available) gave

$$\theta_c = 0.239 \pm 0.003$$

$$\alpha = \frac{D}{D+F} = 0.638 \pm 0.009$$

That fit utilized the world average value of $|g_1|f_1|$ of that time of 0.23 ± 0.10 and a negative sign i.e. in agreement with the Berkeley result.

On the other hand, a subsequent fit performed by the Yale group[19)] which included their new Σ^- data and a value

$$\left|\frac{g_1}{f_1}\right| = 0.413 \pm 0.033$$

gave for the values of the parameters

$$\theta_c = 0.232 \pm 0.003$$

$$\alpha = 0.651 \pm 0.008$$

Clearly the CERN result is closer to the old average of $|g_1|f_1|$ but an average of the different experiments is probably not meaningful because of the large discrepancy between the two measurements. The other recent results quoted above are consistent with the predictions for the overall fit and their inclusion would not change the value of the fit significantly. In overall summary one might say that the two sets of values quoted above probably represent a reasonable estimate of the systematic uncertainty on these parameters, due to possible systematic uncertainties in some of the measurements.

For completeness, one should summarize here the results obtained for the Cabibbo angle θ_c from other data.

a) from the rates for $K^+ \to \mu^+\nu$ and $\pi^+ \to \mu^+\nu$ one obtains

$$\frac{f_K}{f_\pi} \tan\theta_c = 0.2755 \pm 0.0007$$

In the limit of perfect SU_3 symmetry, i.e. $f_K = f_\pi$, one obtains θ_c=0.269.

b) from the K_{e_3} rate and form factor analysis one obtains

$$f_+(0) \sin\theta_c = 0.220 \pm 0.002$$

Again, if one takes $f_+(0)=1$, since SU_3 symmetry breaking effects should be here of second order, one obtains the results θ_c=0.222±0.002.

c) finally a comparison of μ decay with nuclear β decay transitions yields[25] after inclusion of the radiative corrections

$$\cos^2\theta_c = 0.948 \pm 0.004$$

One might combine this last result with the value of $\sin\theta_c$

from the baryonic decays to obtain (using $\sin\theta_c = 0.235 \pm 0.004$)

$$\sin^2\theta_c + \cos^2\theta_c = 1.003 \pm 0.004.$$

This last comparison is very interesting in the framework of the heavy quark phenomenology. In the Kobayashi-Maskawa picture this sum becomes

$$\cos^2\theta_1 + \cos^2\theta_3 \sin^2\theta_1 = 1.003 \pm 0.004$$

and thus the difference of this sum away from unity is a measure of $\sin^2\theta_1 \; \sin^2\theta_3$. Thus at the 95% confidence limit we obtain the result that

$$\sin^2\theta_1 \sin^2\theta_3 < 0.005$$

or

$$\sin^2\theta_3 < 0.09$$

giving us an upper limit on the strength of the possible coupling of the p quark to the b quark.

b) Form factors in K semileptonic decays. This topic has been a subject of considerable experimental controversy as recently as 5 years ago and also appeared to be one area where the theoretical ideas of current algebra might be in some disagreement with the data. In the last several years, however, considerably improved experiments appear to have converged upon a common answer, one that appears to be in good agreement with the theoretical predictions. In this section I shall attempt briefly to summarize some of the recent work on this subject.

I start out by reviewing briefly the formalism used in the form factor analysis. The general V-A matrix element in $K_{\ell 3}$ decays is

$$\mathcal{M} = \frac{G}{\sqrt{2}} \sin\theta_c \left[f_+(q^2)(p_K+p_\pi)^\lambda + f_-(q^2)(p_K-p_\pi)^\lambda \right] J_\lambda^{\,\ell}$$

where $\sin\theta_c$ is the sine of the Cabibbo angle, and f_+ and f_- the two form factors describing the decay. It is convenient to define two other form factors, i.e.

$$\xi(q^2) \equiv f_-(q^2)/f_+(q^2)$$

and $$f_o(q^2) \equiv f_+(q^2) + \frac{q^2 f_-(q^2)}{m_K^2 - m_\pi^2}$$

and since the range of q^2 in the region of interest (i.e. physically accessible region) is relatively small, we might hope that a linear expansion of the form factors is justified, i.e.

$$f_+(q^2) = f_+(0)\ (1 + \lambda_+\ q^2/m_\pi^2)$$

$$f_o(q^2) = f_o(0)\ (1 + \lambda_o\ q^2/m_\pi^2)$$

It is conventional to use here $f_o(q^2)$ rather than $f_-(q^2)$ since this is the form factor that is more meaningful from the theoretical point of view.

Traditionally, the $K_{\ell 3}$ studies have provided a rich testing ground for some of the theoretical ideas that form the cornerstones of the weak interaction theory. More specifically one can test here:

1) General V-A nature of the decay (i.e. absence of S, P, and T interactions).
2) $\Delta I=1/2$ rule, which predicts that the form factors for the K^o and $K^\pm$ must be the same.
3) μ-e universality, which states that λ_+ as derived from K_{e_3} and $K_{\mu 3}$ must agree with each other (contribution of $f_-(q^2)$ to K_{e3} decay is negligible). In addition, under this hypothesis the K_{μ_3}/K_{e_3} branching ratio must be entirely determined by λ_+ and λ_o.
4) SU_3 breaking effects. In the limit of perfect SU_3, $\xi(q^2)=0$; furthermore up to second order in SU_3 breaking effects, $f_+(0)=1$.
5) Current algebra, i.e. Callan-Treiman prediction.[26] Specifically, it states

$$\frac{f_o(m_K^2)}{f_+(0)} = \frac{f_K}{f_\pi f_+(0)}$$

which gives $f_o(m_k^2) = 1.26\ f_+(0)$. The test of this prediction involves extrapolation to the unphysical region, since the physical region extends only to about $q^2 \approx \frac{m_K^2}{2}$. Assuming linear extrapolation, as motivated partly by the Dashen-Weinstein theorem,[27)] this prediction yields $\lambda_o \approx 0.021$.

6) $K^*(890)$ dominance of the $f_+(q^2)$ form factor. Assuming this pole form, and fitting to a linear variation of the form factor, one obtains $\lambda_+ = 0.029$.

It was mainly on these last three points that there appeared for a long time to be a serious confrontation both between different experiments, and also between the experiment and theory. Before discussing the situation in detail, one must enumerate three kinds of experiments that can provide information on f_+ and f_o form factors.

1) Measurement of the Dalitz plot population yields λ_+ from a study of K_{e_3} decays and λ_+ and λ_o from a study of $K_{\mu 3}$ decays.

2) <u>Direction</u> of polarization of the muon in K_{μ_3} decay gives the value of $\xi(q^2)$, and thus of $f_o(q^2)$ if $f_+(q^2)$ is known.

3) K_{e_3}/K_{μ_3} branching ratio gives a quadratic relationship between λ_+ and λ_o.

There are several general experimental comments that one can make about these experiments, that, at least in my mind, help to understand some of the potential difficulties in obtaining and understanding some of these results available in the literature.

1) The branching ratios for the K^+ decay modes are rather low $(10^{-2}-10^{-1})$.

Thus the sample of $K^+_{\mu_3}$ decays can be easily contaminated by the process $K^+ \rightarrow \pi^+\pi^o$, followed by $\pi^+ \rightarrow \mu^+\nu$ decay in flight.

2) A 2-fold ambiguity in reconstructing the K^o decay provides some confusion on an event by event basis.

3) It is important for the polarization measurements to have the capability both to precess the μ's and to reconstruct the position on the Dalitz plot. This technique allows one to measure directly the direction of the polarization vector rather than its magnitude along some direction. The relative sensitivity to the level of understanding of the Monte Carlo, polarimeter, etc. is considerably reduced in this kind of arrangement.

4) At low q^2, the sensitivity to variations in $f_o(q^2)$ is considerably poorer than at high q^2. This is true both for the Dalitz plot and polarization measurements (see Fig. 2).

5) Partly as a result of the spinoff from CP violation studies, there has been in the last few years a considerable statistical improvement in the K^o Dalitz plot studies.

Having made these rather general comments, I would like now to summarize the experimental status of the $K\ell_3$ form factor situation. Rather than quoting world averages, a job that is done much better by the Particle Data Group, I limit myself to a personal assessment of the present status.

Regarding the λ_+ situation, I feel that a world average is probably meaningful for $K^+_{e_3}$ decay since these experiments are relatively bias free. On the other hand, the $K^+_{\mu_3}$ experiments are much more bias prone, and the existing experiments do not really allow one to disentangle the strong correlation between λ_+ and λ_o. Thus a simple average is probably not very significant

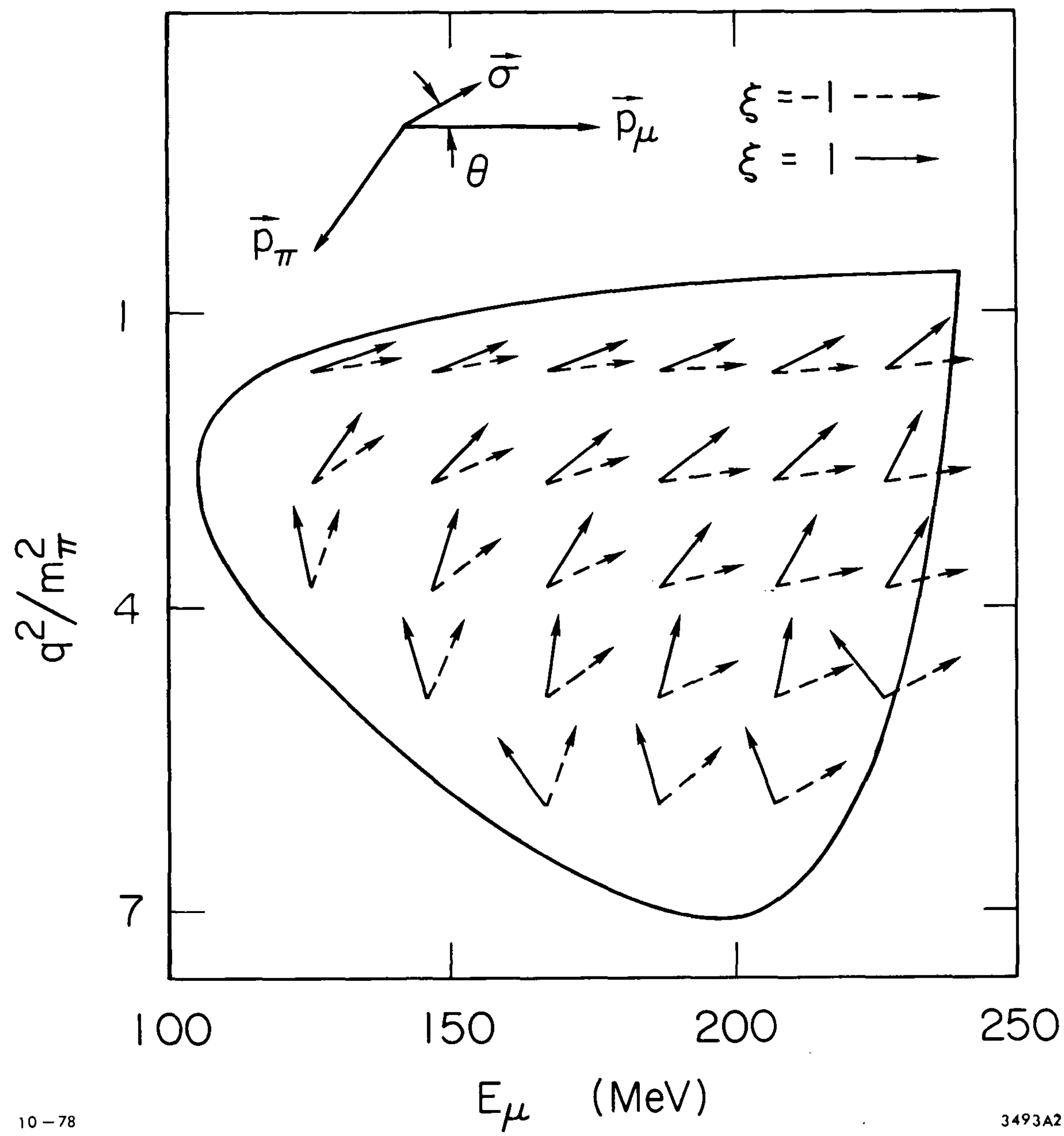

Fig. 2 Muon polarization as a function of Dalitz plot position for Re $\xi = \pm 1$, Im $\xi = 0$. The orientation of the momentum vector is shown at the top of the figure.

in this case. Finally, the situation regarding $K^o_{\mu_3}$ and $K^o_{e_3}$ is entirely dominated by the recent two high statistics experiments,[28,29] and I think it is more meaningful to just quote those two results. In Table IV I display the averages for the two K^+ decays from the Particle Data Group comilation[30] and the values for K^o decays from the two high statistics experiments. As can be seen, the agreement is excellent even for the most suspect average, i.e. $K^+_{\mu_3}$. Furthermore, the values agree with the $K^*(890)$ dominance prediction.

Table IV. λ_+ status in $K\ell_3$ decays

Decay	λ_+	Reference
$K^+ \to e^+ \pi^o \nu$	0.0285±.0043	30
$K^+ \to \mu^+ \pi^o \nu$	0.026 ±.008	30
$K^o \to e^{\pm} \pi^{\mp} \nu$	0.0312±.0025	28
$K^o \to \mu^{\pm} \pi^{\mp} \nu$	0.030 ±.003	29
K^+ dominance prediction	0.029	

As far as the status of the λ_o is concerned, I choose to be even more arbitrary in quoting the relevant results. I quote only the 2 recent high statistics polarization results[31,32] from experiments that both precess the muons and reconstruct the event; the world average[30] for $K^+_{\mu 3}$; Donaldson et al.[27] value for $K^o_{\mu_3}$; the world averages for the λ_o from K^+ and K^o branching ratios, but also separately the one from the most recent experiment[33] measuring the $K^+_{\mu_3}/K^+_{e3}$ relative branching ratio. For reasons mentioned above, the K^+ world average values are probably the most suspect ones. All the values mentioned above are summarized in Table V. Even though the agreement is far from excellent, there appears to be no reason to doubt the validity of the Callan-Treiman prediction, especially if the two suspect averages are partially deemphasized.

Table V. λ_o status in $K\ell_3$ decay

Experiment		λ_o	Reference
$K^+ \to \mu^+ \pi^o \nu$	Polarization	0.008±0.021	32
$K^o \to \mu^\pm \pi^\mp \nu$	Polarization	0.044±0.009	31
$K^+ \to \mu^+ \pi^o \nu$	Dalitz Plot	-0.003±0.007	30
$K^- \to \mu^\pm \pi^\mp \nu$	Dalitz Plot	0.019±0.004	29
$K^+_{\mu_3}/K^+_{e_3}$	BR	0.014±0.012	30
$K^+_{\mu_3}/K^+_{e_3}$	BR	0.019±0.010	33
$K^o_{\mu_3}/K^o_{e_3}$	BR	0.037±0.011	30

I would like to end the discussion of form factors with a few comments about $K\ell_4$ decays. In the last few years a Geneva-Saclay experiment[34)] studied a sample of 30000 K_{e_4} decays, attaining a considerable statistical improvement over the previously published data. Their overall results can be briefly summarized as follows:

a) the form factors are in fair agreement (∿25% level) with the current algebra predictions.

b) π-π phase shifts obtained from this analysis of $K\ell_4$ decays are consistent with those obtained from the π-π scattering experiments.

c) scattering length is consistent with the PCAC prediction.

d) there is no evidence[35)] for ΔS/ΔQ forbidden decay $K^+ \to \pi^+ \pi^+ e^- \nu$. The obtained 95% C.L. upper limit is

$$\Gamma(K^+_{e_4}(e^-))/\Gamma(K^+ e_4(e^+)) < 3.4 \times 10^{-4}$$

c) $\underline{\Delta I=1/2}$ rule in hadronic decays. We examine here very briefly the general theoretical framework in which this rule has to be viewed, its main experimental implications, and the present experimental status regarding the validity of this rule.

We can start out with two very simple minded ideas. Firstly, if we look at a 4 quark coupling e.g. $(s\bar{p})(n\bar{p})$ that is presumably responsible for the strange particle decay, then we see that a priori the effective Hamiltonian can involve either $\Delta I=1/2$ or $\Delta I=3/2$ in this transition. On the other hand, experimentally the $\Delta I=3/2$ transitions appear to be relatively suppressed. The assumption that $\Delta I=3/2$ transition is identically zero leads to several quantitative predictions; alternatively we can say that the deviation of the experiment from these predictions will allow one to estimate the size of this amplitude. The wide range of the kinds of predictions that are obtained under the assumption of the vanishing of the $\Delta I=3/2$ amplitude are illustrated below:

1) Branching ratios: $\Lambda\to p\pi^- / \Lambda\to n\pi^o = 2$ $\quad K^o_s\to\pi^+\pi^- / K^o_s\to\pi^o\pi^o = 2$

2) Lifetimes: $\tau_{\Xi^o} = 2\,\tau_{\Xi^-}$

3) Decay asymmetries: $\alpha(\Xi^o) = \alpha(\Xi^-)$ $\quad \alpha(\Lambda\to p\pi^-) = \alpha(\Lambda\to n\pi^o)$

4) Suppression of decay modes: $K^+ \not\to \pi^+\pi^o$

5) Dalitz plot population: $G_1 = G_2 = 0$

where $G_1 = g_{+-o} - g_{+oo}$

$$G_2 = g_{++-} + \frac{1}{2}\, g_{+-o}$$

and g is the coefficient in front of the T_{π^o} term (or odd T_π term) in the expression for Dalitz plot density for $K \to 3\pi$.

It should be added that the above predictions must be corrected for the obvious electromagnetic effects, e.g. mass differences.

The second observation (which may or may not be related to the question of $\Delta I=1/2$ rule) has to do with the apparent enhancement of the decays $\Lambda \to p\pi^-$ (i.e. purely hadronic eecays) with respect to the semi-leptonic decays (e.g. $\Lambda \to pe^-\nu$). In a simple quark picture the two types of decay proceed via the processes illustrated in Fig. 3. If the coupling of the W boson to quark antiquark system is of the same strength as to the $\ell\nu$ system, as indicated by universality, then the relative strength of these diagrams (for a single color state in the case of the quark diagram) should be equal except for phase space arguments. This simple minded picture predicts that the electronic decay of the Λ would be of the order of 20% times phase space correction, a prediction that appears too high by at least an order of magnitude. Other more complicated possible diagrams, however, would upset this simple prediction.

Are these two observations related? The answer would be yes if for some reason the $\Delta I=1/2$ part of the purely hadronic weak Hamiltonian were "enhanced" with respect to the naive prediction.

This is basically the origin of the idea of octet enhancement. If the Hamiltonian is of the current-current form, each current being a member of an octet, then their direct product can be written as

$$8 \times 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$

The $\Delta I=3/2$ part (which is contained only in the 27 representation) would be suppressed if the effective Hamiltonian itself also transformed like an octet, i.e. the octet part in the sum were enhanced.

How valid are these simple minded arguments? This is certainly a complex question and we shall limit ourselves here to two statements. Firstly, the theoretical situation[36)] is not very clear and it is not obvious how big a special dynamical enhancement is really necessary here.

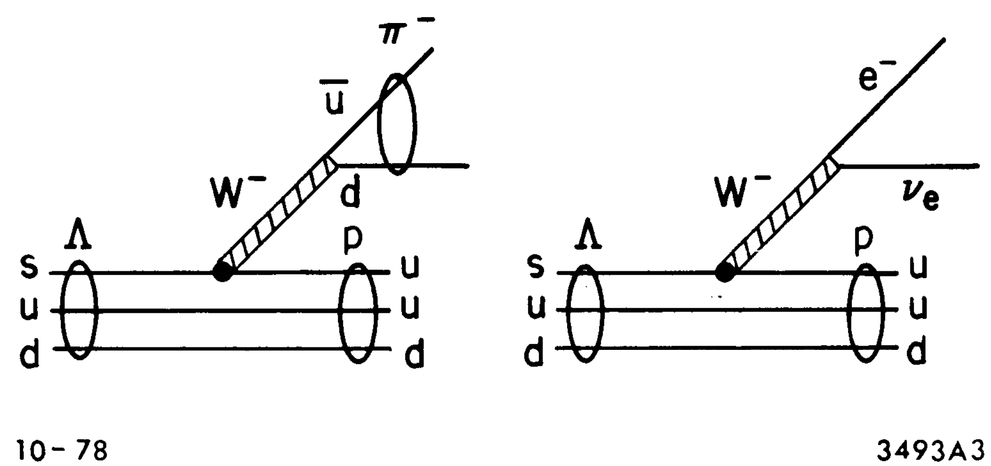

Fig. 3 Simple quark picture for Λ hadronic and beta decays.

Conceivably, a test of $\Delta I=1/2$ rule in a system involving another SU_3 multiplet, e.g. Ω^- decay, might shed some light here. Secondly, these ideas and questions can be extrapolated to the higher group of SU_4 that we have to deal with when we discuss the question of charm non leptonic decays. We shall return to this specific point in the last chapter on charm decays.

We might briefly end this section with a short summary of the experimental situation on the status of the $\Delta I=1/2$ rule. In general, it appears that there does exist a finite $\Delta I=3/2$ amplitude, above and beyond purely electromagnetic corrections, whose magnitude is of the order of few percent of $\Delta I=1/2$ amplitude. Furthermore, in decays where such amplitudes could a priori contribute (e.g. $K\to 3\pi$) there appears to be no need for $\Delta I=5/2$ or $7/2$ at the level of 1% of the dominant amplitude.

As an example we quote several illustrative, and thus by no means exhaustive, examples of the relative magnitudes of the $\Delta I=3/2$ and $\Delta I=1/2$ amplitudes:

1) $A_{3/2}/A_{1/2}$ in $K \to 2\pi$ decay[36] $= 0.0448 \pm 0.0002$

2) $S_{3/2}/S_{1/2}$ in Λ decay[37] $= 0.027 \pm 0.008$

3) $S_{3/2}/S_{1/2}$ in Ξ decay[38] $= 0.041 \pm 0.015$

In addition, the analysis of the decay rates and the slopes of the various charge states for the $K \to 3\pi$ also indicate[39] clear violation of the $\Delta I=1/2$ rule.

d) CP violation. The observation in 1964 by Christenson et al.[40] of the apparent decay process $K_L^o\to\pi^+\pi^-$ has led during the next few years to a burst of experimental and theoretical activity. This activity appears to have culminated after a decade of hard work in the conclusion that no presently experimentally accessible CP violation effects exist outside of the K^o system and that the superweak model of Wolfenstein[41)] appears to adequately explain all the data. The question of CP violation received recently renewed theoretical interest, by virtue of its possible manifestation[42)] in the weak decays of the anticipated heavy quark states. In this section we briefly review the experimental situation that led to the conclusions stated above.

The fact that the process observed by Christenson et al. was indeed due to CP violation and not to some other strange phenomena was established shortly after the initial discovery. Possible effects due to cosmological forces[43)] were soon excluded by lack of any energy dependance in the branching ratio[44)] and the possibility that the observed process is really due to the decay of some new particle was killed by an interference observed between the K^o_L and the regenerated K^o_S component.[45)] The spectacular difference that can be seen in more recent experiments, between the no interference and interference hypothesis is illustrated in Fig. 4, taken from the latest high statistics work at BNL.[46)]

To discuss the experimental work on CP violation in the K^o-$\overline{K^o}$ system one must define a minimum amount of formalism:

Defining $|K^o_1> = \dfrac{K^o> + |\overline{K^o}>}{\sqrt{2}}$ and $|K^o_2> = \dfrac{|K^o> - |\overline{K^o}>}{\sqrt{2}}$

and $|K^o_L> = \dfrac{|K^o_2> + \varepsilon|K^o_1>}{\sqrt{1+|\varepsilon|^2}}$ $|K^o_s> = \dfrac{|K^o_1> + \varepsilon\,|K^o_2>}{\sqrt{1+|\varepsilon|^2}}$

leads to $<K^o_L|K^o_s> = 2\ \mathrm{Re}\ \varepsilon$

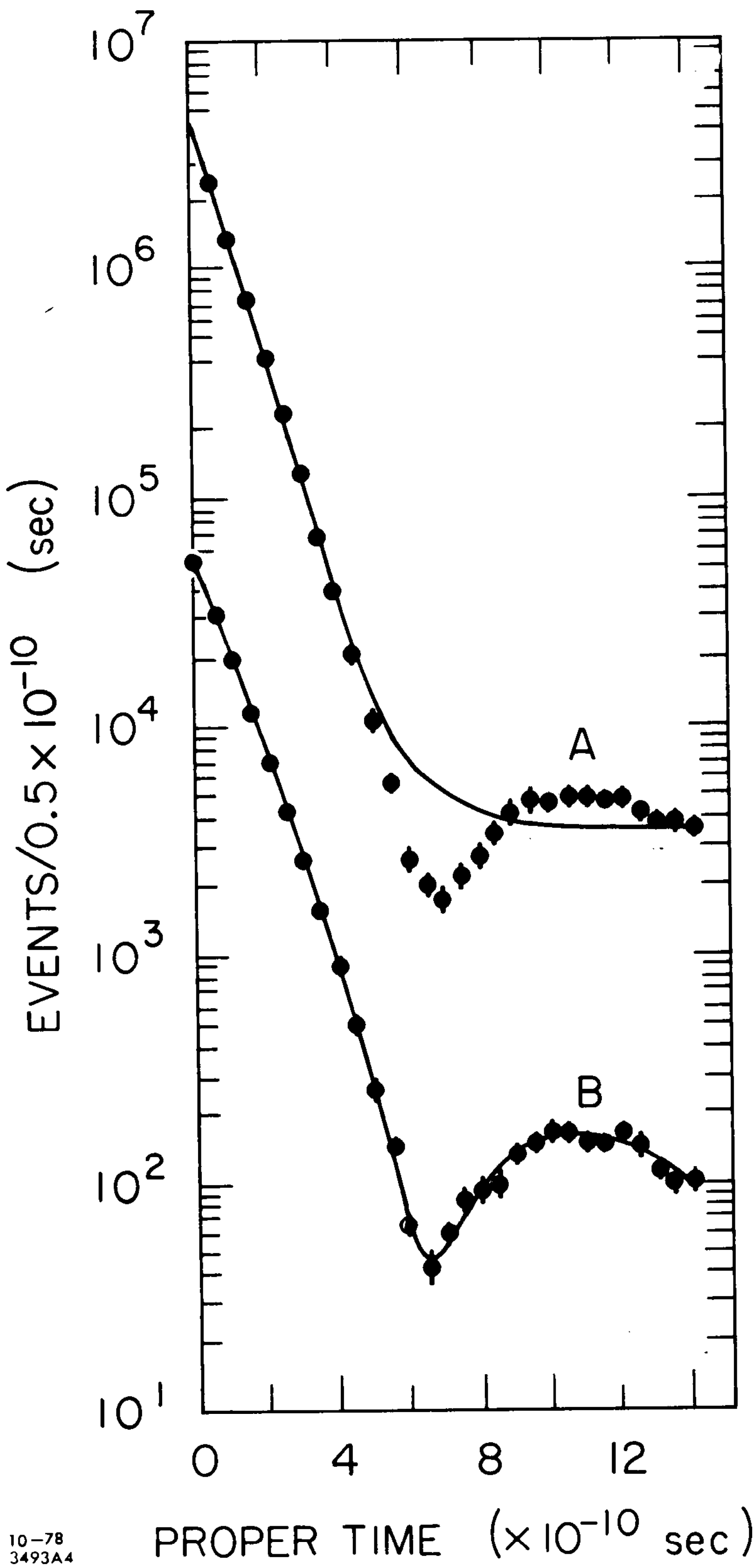

Fig. 4 Time distribution of $K^o \to \pi^+\pi^-$ events behind a regenerator. Curve A is the best fit obtained under the assumption of no interference between K_L^o and K_s^o; curve B is the fit with interference effects.

i.e. ε is just a measure of CP violation in the mass matrix. In addition, CP violation effects can exhibit themselves also through a violation in the $K\to 2\pi$ decay amplitude itself.

We define $A_{0,2}$ as the amplitude for $K\to 2\pi$ decay leading to the 2π system in T=0(2) state. Taking A_0 to be real, we define

$$\varepsilon' = \frac{i}{\sqrt{2}}\, e^{i(\delta_2-\delta_0)}\ \mathrm{Im}\, A_2/A_0$$

where $\delta_{0,2}$ are the π-π scattering phase shifts in the T=0(2) state. Thus CP violation in the decay amplitude simply means a non zero phase between the T=0 and T=2 amplitudes.

We can furthermore define two "experimental" parameters that are related more closely to the actual empirical observations:

$$\eta_{+-} = \frac{A(K^o_L\to\pi^+\pi^-)}{A(K^o_s\to\pi^+\pi^-)} \qquad \eta_{oo} = \frac{A(K^o_L\to\pi^o\pi^o)}{A(K^o_s\to\pi^o\pi^o)}$$

These two sets of complex amplitudes are related by

$$\eta_{+-} = \varepsilon + \varepsilon' \qquad \eta_{oo} = \varepsilon - 2\,\varepsilon'$$

We should next mention the different types of experiments that can provide some of the information about these parameters

1) Measurement of $K^o_L\to\pi^+\pi^-$ determines $|\eta_{+-}|^2$
2) Measurement of $K^o_L\to\pi^o\pi^o$ determines $|\eta_{oo}|^2$
3) Interference between $K^o_L\to\pi^+\pi^-$ and $K^o_s\to\pi^+\pi^-$ gives phase of η_{+-}.
4) Interference between $K^o_L\to\pi^o\pi^o$ and $K^o_s\to\pi^o\pi^o$ gives phase of η_{oo}.
5) Charge asymmetry in $K\ell_3$ decays yields Re ε.

In addition two other pieces of information can be obtained from the data from non-CP experiments.

6) π-π phase shifts measurement (from π-π scattering or $K\ell_4$ decays) yields phase of ε'.

7) From the unitarity condition one obtains the relation

$$-i(m_L-m_s) + \frac{\gamma_L+\gamma_s}{2} \quad \langle K_L^o|K_s^o\rangle = \sum_f \langle f|T|K_L^o\rangle^* \langle f|T|K_s^o\rangle$$

Because of $\Delta I=1/2$ rule and very low decay rate of K_s^o into any other than 2π channel, only important state $|f\rangle$ is $|2\pi$'s in T=0 state$\rangle$. The right hand side can then be simplified to $\gamma_s\varepsilon^*$ and we obtain the relation

$$\tan \arg \varepsilon = \frac{2(m_L-m_s)}{\gamma_s} \qquad \text{since } \gamma_s >> \gamma_L.$$

A graphical way to summarize these data has been suggested by Wu and Yang[47] and is schematically illustrated in Fig. 5.

The statistical and systematic precision of the recent experiments is extremely high and the parameters of the CP violation discussed above can now be determined with very high accuracy.[2] We enumerate here briefly some of those results as compiled by Kleinknecht,[2] and compare them with the predictions of superweak theory (which demands $\varepsilon'=0$).

Experimentally we have

$$\Phi_{+-} = 44.9 \pm 1.3^o$$

$$\Phi_{oo} = 48.0 \pm 13.1^o$$

to be compared with the superweak prediction for both of these of

$$\tan^{-1} \frac{2(m_L-m_s)}{\gamma_s} = 43.8 \pm 0.2^o$$

For the ratio of amplitudes we have experimentally

$$|\eta_{oo}|/|\eta_{+-}| = 1.008 \pm 0.041$$

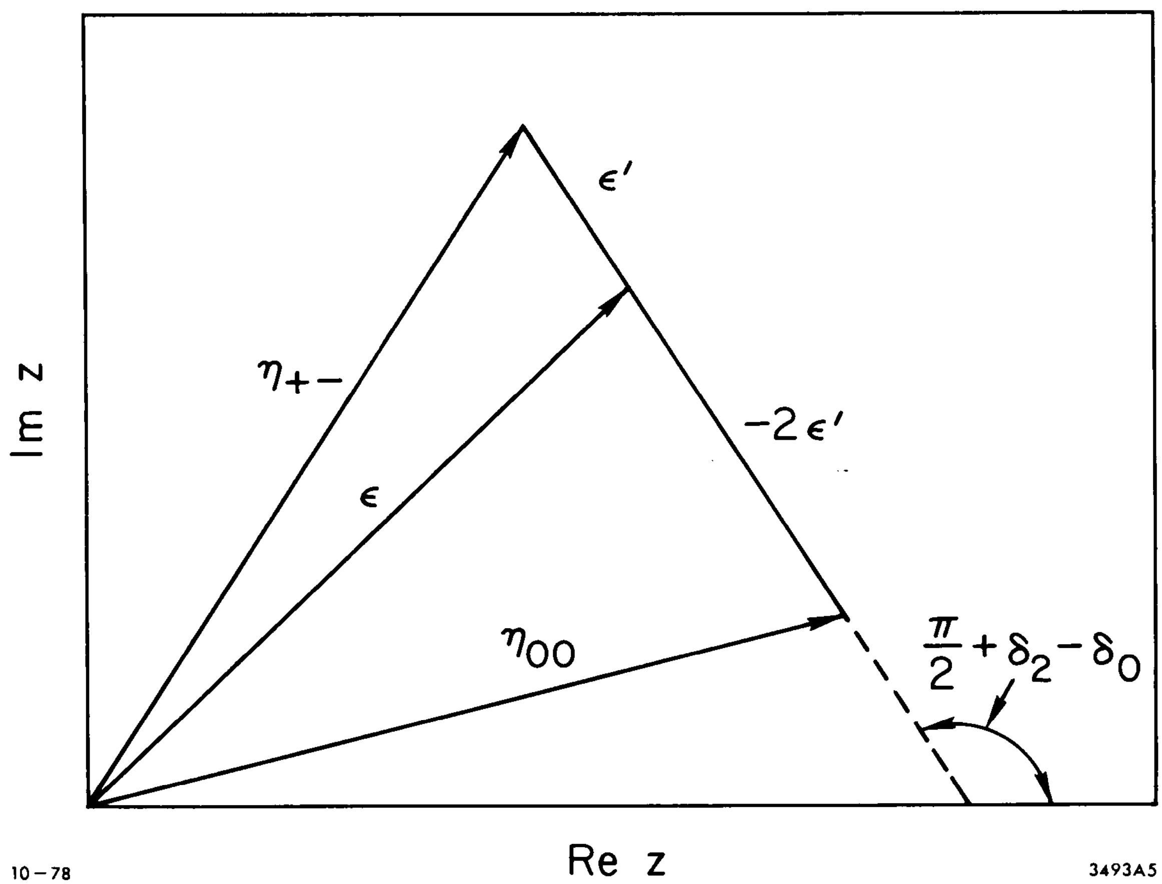

Fig. 5 A schematic representation of the Wu-Yang triangle.

to be compared with unity in superweak theory.

And finally, from charge asymmetry experiments

$$2 \text{ Re } \varepsilon/|\eta_{+-}| = 1.448 \pm 0.055$$

to be compared with the prediction of

$$2 \cos (43.8 \pm .2^{\circ}) = 1.443 \pm 0.005.$$

Clearly the agreement of the data from the $K^{o}-\overline{K^{o}}$ system with the superweak theory is excellent. The results are displayed graphically in Fig. 6 in terms of a Wu-Yang triangle.

For the sake of completeness one should mention that no statistically significant CP (or T) violation has been seen in any other system. The other kinds of experiments looking for those effects included a whole variety of diverse phenomena, such as detailed balancing in nuclear and particle reactions, η and η' charge asymmetry, T violation in $\Delta Q=-\Delta S$ $K\ell_3$ decays, transverse polarization in $K_{\mu 3}$, charge asymmetries in $\bar{p}p$ annihilations, hyperon decays, etc.

By far the most promising place to look for T violating effects appears to be the neutron electric dipole moment which must vanish if either parity or time invariance are good, i.e. absolutely conserved. The present experimental limit[48] i.e. $D_n=(0.4 \pm 1.1) \times 10^{-24}$ e cm, where D_n is the neutron electric dipole moment, appears to exclude all but superweak models from among the "conventional" models of CP violation.

One can ask to what extent the Kobayashi-Maskawa[13] model, with its natural small CP violation, is compatible with all of these experimental results. The answer is that the predicted effects would be far smaller than the existing limits and thus within the present experimental uncertainties, the superweak model and the K-M model are undistinguishable.[42]

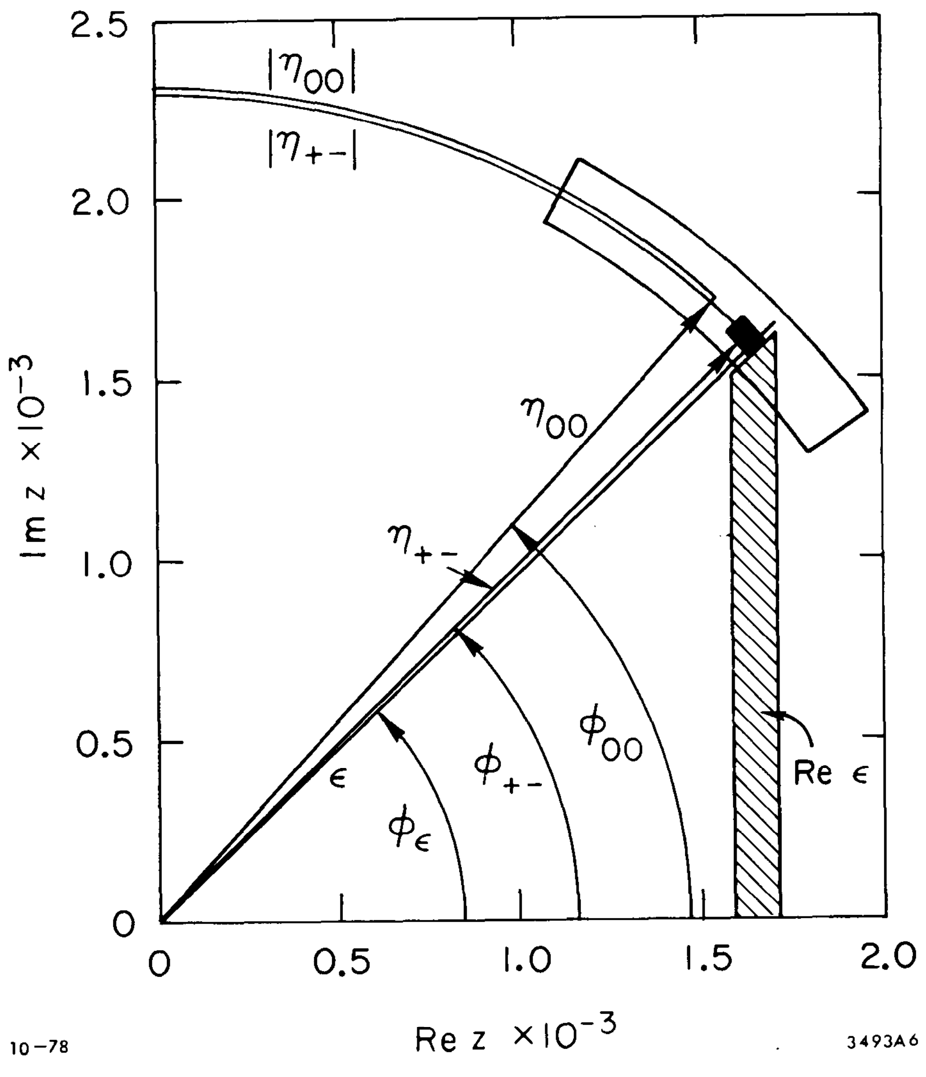

Fig. 6 The K^o CP violation data displayed on the Wu-Yang triangle. The values come from the compilation by Kleinknecht (Ref. 2).

For example, one would expect a finite electric dipole moment for the neutron due to contributions of diagrams illustrated in Fig. 7, but anticipated order of magnitude is only about $10^{-28}-10^{-31}$ e cm. One does however expect in this model potentially observable effects in the decays of new particles composed of heavy (i.e. b and t) quarks.

e) <u>Status of the ΔS=1 neutral current decays</u>. It was the apparent absence of the ΔS=1 neutral current decays, demonstrated most dramatically in the processes

$$K_L^o \to \mu^+\mu^-$$
$$\text{and} \quad K^+ \to \pi^+ \nu\bar{\nu}$$

that led to the formulation of the GIM mechanism. In addition, however, the original search by Clark et al.[8)] for the decay mode $K_L^o \to \mu^+\mu^-$ set an upper limit for this process that was significantly lower than the so called unitarity limit due to the 2γ intermediate state (see Fig. 8). Since that time, however, three different groups[49,50,51)] have studied this process, and all obtained mutually consistent results that were also slightly above the unitarity limit. The original Berkeley result has been recently revised slightly upward,[52)] taking into account a new value of $|\eta_{+-}|$ that was used in the flux determination, and correcting small errors in the original Monte Carlo calculation. It still remains however significantly below the unitarity limit. The overall situation is summarized in Table VI.

For completeness, we should mention that the ΔS=0 counterpart of the $K_L^o \to \mu^+\mu^-$ decay, i.e. $\pi^o \to e^+e^-$ process, has now been observed[53)] with a branching ratio of $(2.23^{+2.4}_{-1.1}) \times 10^{-7}$ (90% C.L.). This number should be

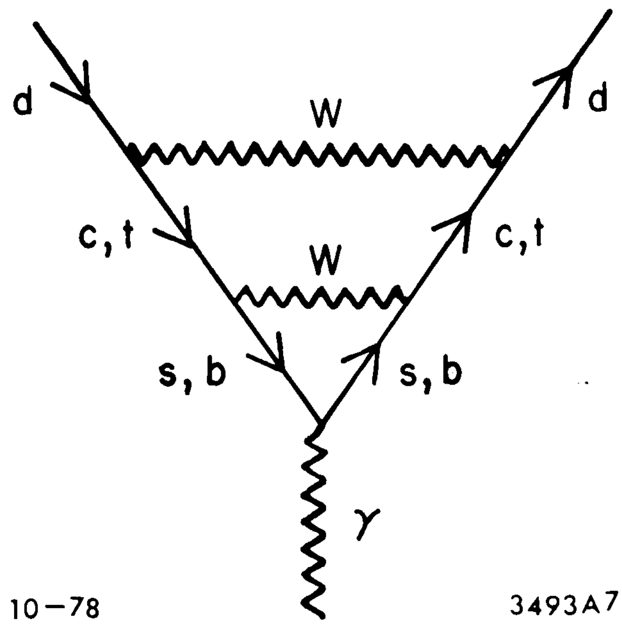

Fig. 7 Typical diagrams involving heavy quarks that give rise to a finite neutron electric dipole moment.

compared with the unitarity limit of 4.75×10^{-8}, and is in fair agreement with the calculations for the second order electromagnetic process by vector mesons.

Table VI

Status of $K_L^o \to \mu^+\mu^-$ branching ratio measurements*

Group	Value($\times 10^{-7}$)	Reference
Berkeley	<3.1(90% C.L.)	52
Columbia - BNL	12^{+8}_{-4}	49
Princeton - U. Mass	$8.8^{+10.7}_{-5.5}$	50
Chicago-Argonne	$8.4^{+2.8}_{-1.8}$	51
Unitarity Limit	6	

* All measurements have been adjusted to the value of 0.21% for $K_L^o \to \pi^+\pi^- / K_L^o \to$ all.

We finally end with some comments about the decay $K^+ \to \pi^+ \nu\bar{\nu}$. The experiment[8)] of J. H. Klems et al. designed to search for this mode set a 90% C.L. limit of 1.4×10^{-6} on its branching ratio by looking for energetic π's unaccompanied by any other particle. Thus this apparatus would have been also sensitive to the possible decay:

$$K^+ \to \pi^+ h$$

where h is any light, non-interacting particle. Because of the two body nature of this decay, the sensitivity of the experiment to this mode is even higher and one can interpret the result as setting a branching ratio limit for this mode[54)] of 2.7×10^{-7} (90% C.L.). The importance of this result stems from the fact that the existence of a low-mass isoscalar pseudoscalar meson (referred to as axion or higglet) is very attractive from the theoretical point of view[55] since it prevents the appearance of strong interaction CP violating effects in QCD and gauge theories of weak interactions. If the axion exists, the theory gives a branching ratio[54,55] for the decay $K^+ \to \pi^+ h$ comparable (within an order of magnitude or so) to the upper limit quoted above.

III. Lepton Decays

We divide this chapter into three sections:

a) discussion of μ decay with special emphasis on the new results on exotic decay modes of the muon

b) few brief comments about neutrinos

c) our present understanding of the τ lepton.

Clearly in the spirit of trying to emphasize the newest results, the large fraction of this chapter shall deal with the τ.

a) μ decay. For a long time the muon decay

$$\mu^\pm \to e^\pm \nu_e \nu_\mu$$

was the unique accessible purely leptonic process. Accordingly, it was a good testing ground for the theory of weak interactions, insofar that this transition is unencumbered by the difficulties associated with the presence of hadrons. This uniqueness aspect of μ decay has disappeared in the last few years as technological improvements and new discoveries have provided us with several new laboratories of pure leptonic interactions. For example, in neutrino interactions we can study the processes

$$\nu e \to \nu e$$

$$\nu e \to \nu \mu \quad \text{(i.e. inverse } \mu \text{ decay)}$$

$$\nu Z \to \ell^+ \ell^- \nu\, Z \text{ (in the field of the nucleus)}$$

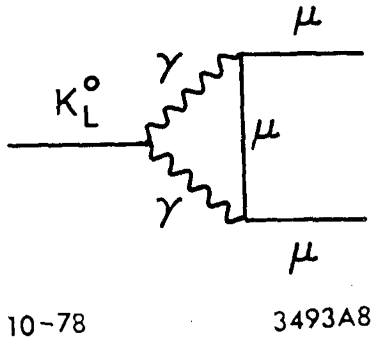

Fig. 8 The diagram for the $K_L^o \to \mu^+\mu^-$ decay via a two photon intermediate state.

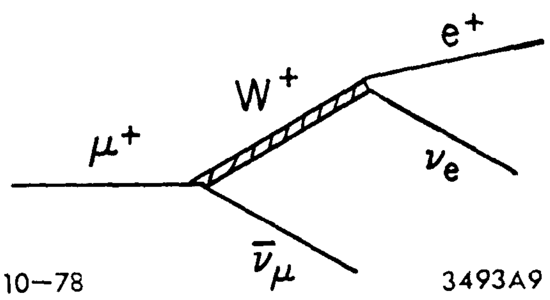

Fig. 9 Conventional diagram for $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay.

and in the colliding beams

$\tau \to e\nu\nu$

$\tau \to \mu\nu\nu$

$e^+e^- \to \mu^+\mu^-$ (or $\tau^+\tau^-$) for weak-electromagnetic interference.

The historical importance of the muon is still there, however. Furthermore, the μ decay provides an opportunity to do very high statistics experiments, albeit in the low q^2 region, and thus test the weak interaction models to a high degree of accuracy.

It is important to remember that to a very high accuracy the muon is a point particle without any anomalous interactions. This conclusion is reached on the basis of the remarkable agreement between the theory and experiment in a variety of experiments involving the muon, i.e. the hyperfine structure of the muonium,[56)] the g-2 of the muon,[57)] and the production cross section of muon pairs in high energy e^+e^- collisions.[58)] Thus we can have great confidence that the μ decay does test solely the weak interaction diagram illustrated in Fig. 9.

We shall commence our discussion by seeing how well do the μ decay data agree with the standard model of weak interaction,[59)] i.e. a model incorporating universality in the framework of the Cabibbo theory and a V-A interaction. Rather than looking at the most general complete theoretical expression for the μ decay, we shall examine it piece by piece in such a way as to be able to compare specific experimental measurements with the predictions of various models. It is conventional in this kind of comparison to look at 6 different experimental parameters.

1) The decay rate i.e. the lifetime of the muon. This is the test of μ-e universality and of the Cabibbo theory, since the integrated muon

decay rate measures weak interaction constant squared G^2, and nuclear β decay $G^2\cos^2\theta_c$. We have already previously discussed Cabibbo theory universality in a slightly different context. Here we merely restate the result as

$$\sin^2\theta_c + \cos^2\theta_c = 1.003 \pm 0.004$$

i.e. an excellent agreement with Cabibbo universality.

2) Overall spectrum of the decay electron. If we define a parameter x

$$x = E_e/E_e^{max}$$

and integrate over all the other variables, then we obtain the expression for the electron energy spectrum

$$N(x)\ dx\ \alpha\ x^2 \left[1 - x + \frac{2}{9}\rho\ (4x-3)\right] dx$$

In general, i.e. for an arbitrary mixture of S, P, T, A, and V interactions, we have the restrictions

$$0 \le \rho \le 1$$

whereas V-A demands $\rho = 0.75$.

The experimental value is 0.752 ± 0.003.

3) Decay asymmetry parameter (averaged over all x). Defining as θ the angle between the direction of the μ spin orientation and the momentum vector of the decay electron, the most general distribution in the variable $\cos\theta$ is

$$N(\cos\theta)\, d\cos\theta\ \alpha (1 + P\,\frac{\xi}{3}\cos\theta)\ d\cos\theta$$

For the most general case, the restrictions on ξ are

$$0 \le |\xi| \le 3 - \frac{8}{3}\rho$$

whereas V-A dictates $\xi = 1$

The experimental value is $\xi = 0.972 \pm 0.013$.

4) The decay asymmetry parameter is in general a function of x, and thus can vary in magnitude (or even change sign) as the energy of the decay electron is varied. This variation is described by a parameter conventionally called δ, and the double distribution is given by

$$N(x,\cos\theta)dxd\cos\theta \;\alpha\; x^2 \left\{\left[1-x+\frac{2\rho}{9}(4x-3)\right] \mp \frac{\xi}{3}\cos\theta \left[1-x+2\delta(4x-3)\right]\right\} dxd\cos\theta$$

The most general restriction is

$$|\xi\delta| \leq \rho$$

and the V-A predicts $\delta = 0.75$

The experiment gives $\delta = 0.755 \pm 0.009$.

5) Helicity of the decay electrons. In general, since parity is violated in μ decay, the decay electrons will be longitudinally polarized along their direction of flight in the muon rest frame, i.e. have a non-zero helicity.

The general requirement on the helicity h is

$$0 \leq |h| \leq 1$$

whereas V-A demands $h_+ = +1$, $h_- = -1$

and the experiment gives:

$$h_+ = 1.03 \pm 0.13$$

$$h_- = -0.89 \pm 0.28$$

6) The low end of the electron energy spectrum. That end of the energy spectrum is influenced by a parameter η, as the general formula for the spectrum contains the term

$$N(x)dx \;\alpha\; x^2 \left[\ldots\ldots + \frac{m_e}{m_\mu}\frac{(1-x)}{x}\eta\right] dx$$

The most general restriction on η is

$$0 \leq |\eta| < 1$$

whereas V-A predicts that $\eta = 0$

The experimental value is $\eta = -0.12 \pm 0.21$.

In conclusion we can say that the μ decay studies are in excellent agreement with the V-A theory. However one can still pose several important questions relevant to this decay. The remainder of this section shall be devoted to the study of those points.

1) How good are the limits on possible admixtures of other possible interactions and how well is the V-A phase determined? In spite of the excellent agreement of the data with a pure V-A theory, there is a surprisingly great deal of room for admixtures of other couplings. We quote here the results of a review by Derenzo[60)]

$$|g_S| \leq 0.33 \ |g_V|$$
$$|g_T| \leq 0.28 \ |g_V|$$
$$|g_P| \leq 0.33 \ |g_V|$$

where g_S, g_T, etc. are the strengths of the S, T, etc. couplings.
The V-A phase ϕ is measured to be

$$\phi = 180 \pm 15^o$$

2) Are the neutrinos really massless? Assuming that the electron neutrino in μ decay is identical to the one in β decay and the muon neutrino identical to that in $\pi \to \mu\nu$ decay we can quote the following upper limits on their masses

$$m_{\nu_e} < 60 \text{ eV}$$ [61)]
$$m_{\nu_\mu} < 550 \text{ KeV}$$ [62)]

However, there is a considerably better limit on these two neutrino's mass difference from the neutrino oscillations. We shall return to this point in our discussion about neutrinos.

3) What is the exact nature of the 2 neutrinos emitted in the μ decay? More specifically, can we have a multiplicative conservation law operative, where we conserve $L_e + L_\mu$ and $(-1)^{L_\mu}$ but not L_e and L_μ separately.[63)] Such a law would allow a process

$$\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$$

in addition to $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

The present data do not exclude completely this situation even though this would be a rather inelegant theory from the point of view of universality. To discuss this question quantitatively we define the ratio r by

$$r \equiv \frac{BR(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)}{\mu^+ \to all}$$

Then r will be 1.0 or 0.5 for additive and multiplicative laws respectively. The results from the recent Gargamelle exposure to the PS ν beam yield:

from the neutrino exposure: $r = 0.9 \pm 0.3$ (from excess of e^+ events)

$r = 1.0 \pm 0.6$ (from lack of e^- events)

and from the antineutrino exposure:

$r = 0.8 \pm 0.2$ (from excess of e^- events)

$r = 1.3 \pm 0.6$ (from lack of e^+ events)

Clearly the data show no evidence for violation of the additive law but are not able to put a very significant limit on the contribution from the multiplicative law. I understand, however, that an experiment currently in progress at the Los Alamos Scientific Laboratory will soon be able to improve on these numbers by almost an order of magnitude.

4) Are there μ-e transitions at any level, or are the L_e and L_μ quantum numbers conserved rigorously? Specifically are the processes

$$\mu^+ \to e^+\gamma$$
$$\mu^+ \to e\gamma\gamma$$
$$\mu^+ \to e^+e^+e^-$$
$$\mu^- Z \to e^- Z$$

totally forbidden? This is the question that has received a great deal of experimental and theoretical attention in the last couple of years and we shall conclude the discussion of μ decay by giving a summary of the present status on this point.

The upper limits given on these exotic processes by the recent experiments are summarized in Table VII.

Table VII

Experimental upper limits on various possible μ-e transitions

Process	Upper limit (90% C.L.)	Accelerator and Group	Reference
$\mu^+ \to e^+\gamma$	3.6×10^{-9}	TRIUMF Montreal-UBC-Victoria-TRIUMF-Melbourne	64
	1.1×10^{-9}	SIN ETH-Zurich-SIN	65
	2.0×10^{-10}	LASL LASL-Chicago-Stanford	66
$\mu^+ \to e^+\gamma\gamma$	5×10^{-8}	Theory + $\mu \to e\gamma$ limits	67
μ^- + Sulfur $\to e^-$ + Sulfur	4×10^{-10}	SIN Berne	68
$\mu^+ \to e^+e^+e^-$	1.9×10^{-9}	Dubna	69

These limits, although representing a significant improvement over what was known several years ago, still allow a wide range of theories with a finite rate for μ-e transitions (see discussion below). Accordingly, one might ask how much further one could push the existing limits, and what are the fundamental background and/or flux limitations on improving these numbers. To be specific we shall consider the decay $\mu \to e\gamma$.

The two serious backgrounds appear to be:

a) simultaneous μ decays, one ordinary decay with an electron near the tip of the spectrum, the other a radiative decay with the γ energy being almost half of the muon mass. Alternatively, the electron from the other decay could give an energetic externally radiated γ ray (for example in the stopping target).

b) $\mu \to e\ \nu\nu\gamma$ process with the two neutrinos almost at rest.

We can estimate very roughly the limitation imposed by each of these potential backgrounds. To avoid the accidental problem, we would want to look at individual μ's, 1 at a time, i.e. μ's should stop in a target with a time interval between different μ's that is long compared to μ lifetime, e.g. 10 μsec. That would give us about 10^{10} μ's a day, and assuming a run of 100 days a potential branching ratio limit of 10^{-12} with a 100% detection efficiency. 10% is probably more reasonable, but on the other hand the spatial extent of the stopping target can be made large enough so that there is no ambiguity problem between μ's stopping in different parts of the target. That factor can probably gain us the loss due to detection efficiency, so that 10^{-12} appears to be an achievable limit.

The background due to radiative decays can be reduced only by improving spatial and energy resolution of the detector. The expression for the branching ratio for $\mu\to e\nu\nu\gamma$ with e and γ going off at 180^{o} with respect to each other is

$$B_{rad}\,(180^{o}) = \frac{\alpha}{2\pi}\left[(1-x)^{2} + 4(1-x)(1-y)\right] y\; dy\; dx\; d\cos\theta_{e\nu}$$

where we have defined

$$x \equiv E_{e}/E_{e}^{max} \qquad y \equiv E_{\gamma}/E_{\gamma}^{max}$$

The radiative decay will look like a $\mu\to e\gamma$ decay if within the resolution of our detector all the kinematical variables will be consistent with the 2 body decay. Defining our normalized energy resolution parameters as

$$r_{e} = \Delta E_{e}/E_{e}^{max} \qquad r_{\gamma} = \Delta E_{\gamma}/E_{\gamma}^{max}$$

we obtain[70)] the achievable branching ratio limit as

$$\sqrt{B_{rad}} \approx 2.4 \times 10^{-2}\; r_{e}\; r_{\gamma}\; \delta\theta$$

where $\delta\theta$ is the error on the e-γ angle.

To give an idea of what has been achieved already, one can quote the relevant parameters for the Stanford-Chicago-LASL experiment

$$r_{e} = 3.6\% \qquad r_{\gamma} = 3.3\% \qquad \theta_{\gamma} = 1.9^{o}$$

These set a limit on achievable branching ratio of about 10^{-12}. One can probably improve the resolution on each of these parameters by at least 50%, leading to an order of magnitude improvement on the rate limit. We conclude accordingly that the accidentals probably present the most serious limitation on the quality of the potential upper limit measurement, and that this limit is somewhere in the vicinity of 10^{-12}.

We turn next to some of the theoretical arguments for the importance of searching for μ-e transitions. The basic point is that in general in gauge theories μ-e transitions can occur at levels that conceivably could be as high as 10^{-9} of the total decay rate. The experimental limits on these exotic processes discussed above can thus put stringent limits on determining which of many possible gauge theories are still viable. We shall briefly enumerate some of the possible models predicting finite rate for μ→e transition.

a) standard model with a heavy neutral lepton (Fig. 10a). If the neutral lepton accompanying the τ is massive[71] then in general there will be mixing among the neutral leptons, and weak interaction eigenstates will not be eigenstates of mass matrix in a manner comparable to the quark situation. The limit on the amount of the mixing is given by the available data on hadron-lepton universality, μ-e universality and nonorthoganality between ν_e and ν_μ. For BR $\approx 10^{-9}$ one needs $m_{L^o} \approx$ 12-30 GeV (the branching ratio is preportional to $(m_{L^o}/m_W)^4$ where m_W is the mass of the intermediate vector boson.

b) Presence of right handed doublets, i.e.[72]

$$\begin{pmatrix} N_e \\ e \end{pmatrix}_R, \begin{pmatrix} N_\mu \\ \mu \end{pmatrix}_R, \ldots$$

with massive neutral partners N_e, N_μ, in addition to the conventional left handed doublets (see Fig. 10b). The transition rate here will be proportional to $\left[\cos\phi \sin\phi\,(m_{N_e}{}^2 - m_{N_\mu}{}^2)/m_W^2\right]^2$ where ϕ is the mixing angle and will yield branching ratios $\sim 10^{-10}$ for a mass difference squared

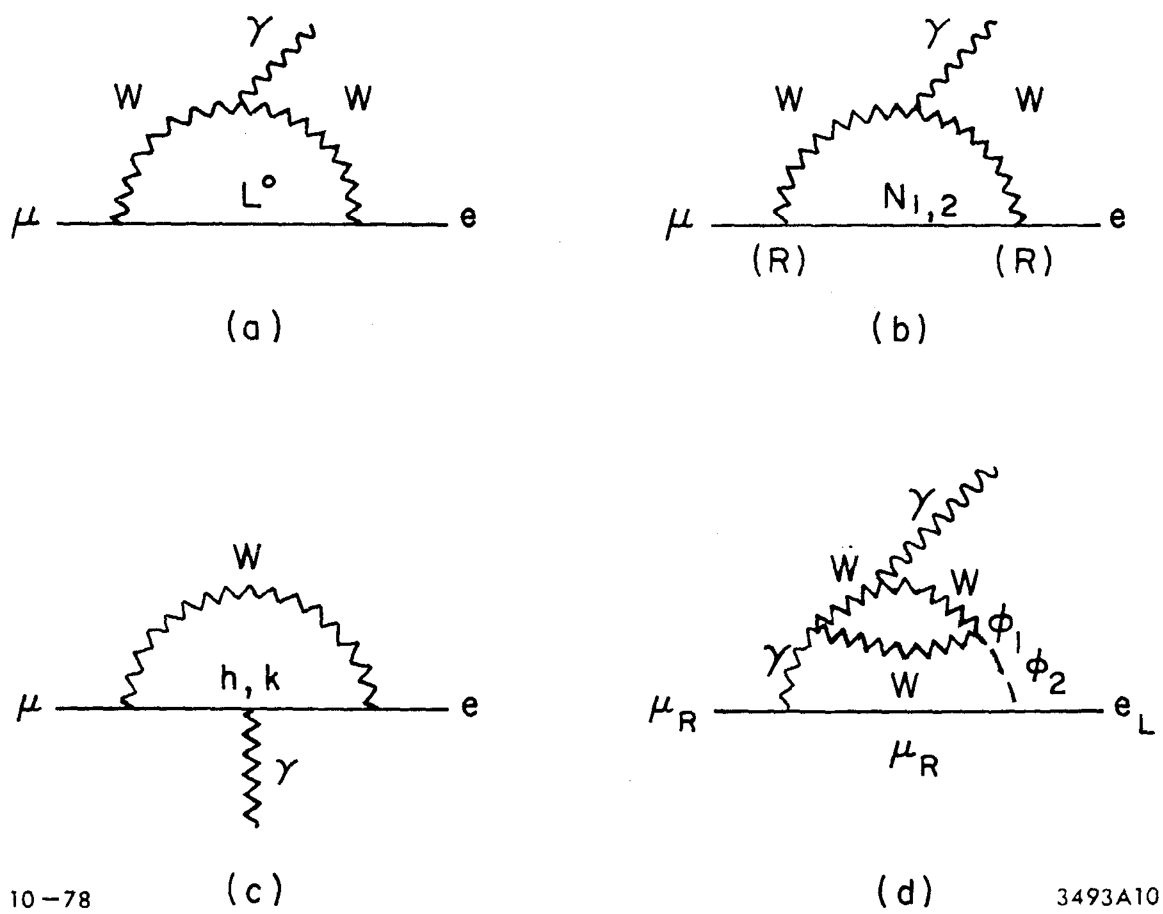

Fig. 10 Examples of possible diagrams generating $\mu \to e\gamma$ transitions. h, k in (c) are postulated doubly charged leptons; Φ in (d) is the Higgs boson.

of 1 GeV^2.

c) Left handed lepton triplets, with the third member of the triplet being doubly charged.[73] The doubly charged leptons (called heptons by the authors) mix with a mixing angle ϕ and thus give rise to μ-e transitions (Fig. 10c). The transition rate has a similar dependance on the parameters of the theory as the theory with the right handed doublets.

d) Existence of several scalar bosons[74] (Higgs particles). The dominant contribution in this case to a μ-e transition is via two-loop diagrams, with the scalar boson coupling once to leptons and the second time to some intermediate heavy particle (e.g. Z^o, $W^{\pm}$, or the Higgs boson itself). An example of one of these diagrams is illustrated in Fig. 10d. The order of magnitude of the branching ratio for $\mu \to e\gamma$ transition is $(\alpha/\pi)^3$.

Clearly, there can be constructed a variety of other models involving larger gauge groups that can also generate $\mu \to e$ transitions. The discussion above is by no means meant to be comprehensive but rather illustrate the order of magnitude of various effects that can be expected within the framework of recently popular models.

Finally, one should say a few words about the relative sensitivity of the various "forbidden" processes involving μ-e transition. Clearly a detailed answer can be only given in the framework of a specific model. In general, however, the decay $\mu \to 3e$ is suppressed with respect to the decay $\mu \to e\gamma$ by a factor comparable to α/π which one might expect a priori. The exception is the triplet model[73] where the $\mu \to 3e$ process can occur by virtue of non-zero transition charge radius and where this rate can actually be larger than the $\mu \to e\gamma$ rate. The nuclear capture process,

$$\mu^- Z \to e^- Z$$

turns out to be generally the most sensitive probe of potential effects generating μe transitions.[74] The reasons are quite general and stem from the fact that this process can occur coherently on all the nucleons in constrast to the "allowed" μ^- capture in nuclei:

$$\mu^- Z \to \nu_\mu (Z-1).$$

There is an additional enhancement factor, as large as an order of magnitude for copper, originating from the Pauli principle suppression of the allowed process. The μ-e capture process, leaving the capture nucleus unchanged, is not subject to the same suppression factor and thus is relatively enhanced. There are,however, models where the $\mu \to e\gamma$ experiment is predicted to be more fruitful. For illustrative purposes we present in Fig. 11 the relative rates calculated by Altarelli et al.[75] for three of the forbidden processes as a function of neutral τ lepton mass assuming standard 6 lepton model and maximum mixing compatible with the data.

b) Neutrino decays and oscillations. In this section we briefly discuss the available limits on neutrino decays and make a few remarks about neutrino oscillations, a topic that has received renewed interest recently in light of the enlarged family of leptons.

If neutrinos have a finite mass, then in principle it is possible for them to decay, the natural mode being

$$\nu \to X + \gamma$$

where X is some lower lying state. As an example, if $m_{\nu_\mu} > m_{\nu_e}$ and lepton number is not rigorously conserved, then we could have

$$\nu_\mu \to \nu_e + \gamma$$

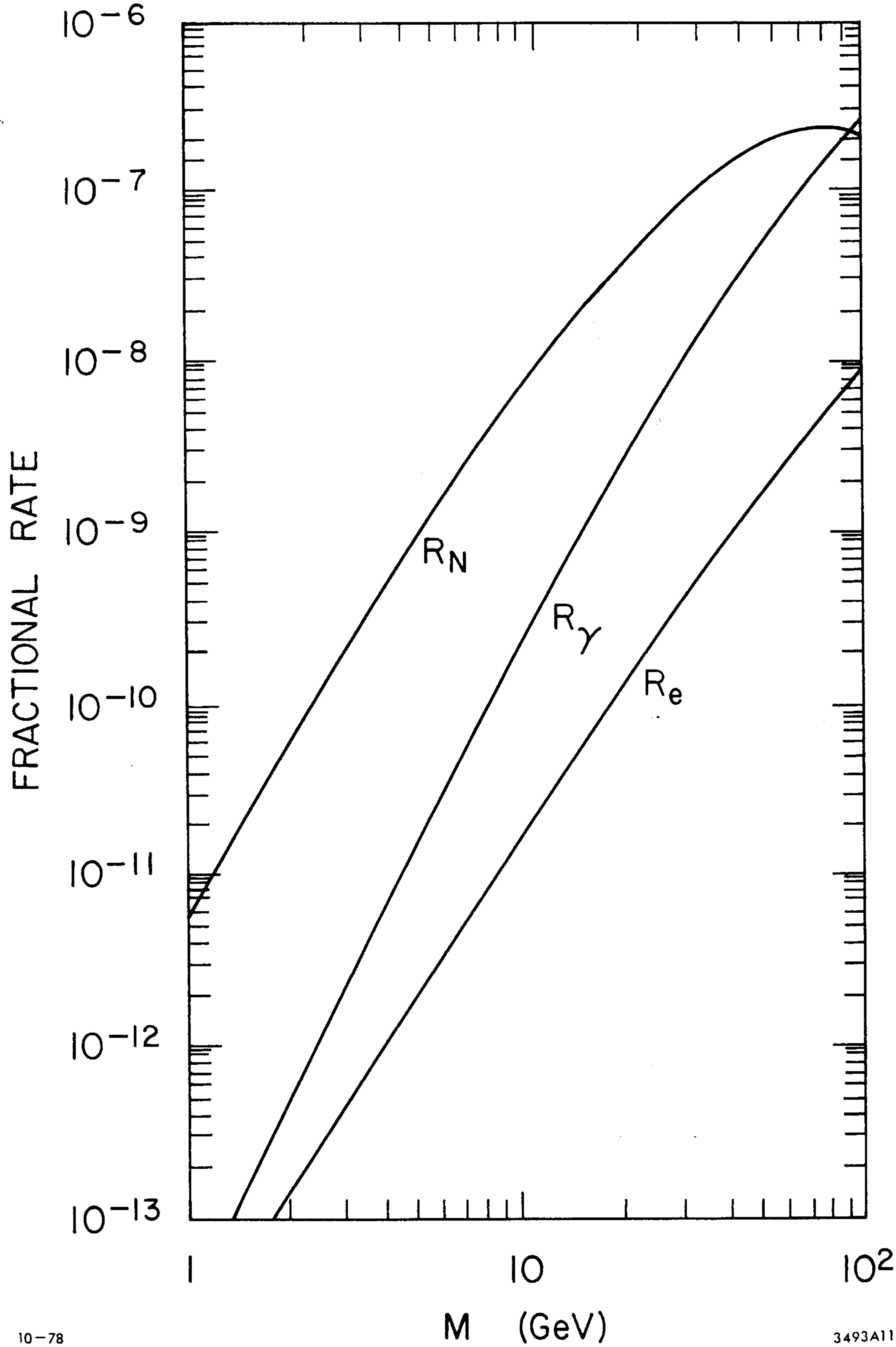

Fig. 11 The fractional rates for μ capture (R_μ), $\mu \rightarrow e\gamma$ decay (R_γ), and $\mu \rightarrow eee$ decay (R_e) as a function of τ neutrino mass according to the calculation in Ref. 75.

In the exposures of large bubble chambers to the accelerator beams of neutrinos a considerable neutrino path length has been accumulated, the appropriate measurement scale being of the order of light years (2.3 light years for the Argonne experiment).[76] If the general decay mode mentioned above exists, then one should see in the bubble chamber e^+e^- pairs pointing along the ν beam direction, and having a typical energy of the order of half of the neutrino energy. Since this technique measures the decay rate in the lab, that is related to the more fundamental quantities by

$$\Gamma_{LAB} = m_\nu \ \Gamma / E_\nu^{LAB},$$

one can set limits only on the product of $m_\nu \Gamma$, Γ being the decay rate in the neutrino rest frame. The upper limits obtained by different experiments are enumerated below in Table VIII.

Table VIII.

Experimental Limits on $m_\nu \Gamma$

Type of Neutrino	Limit (90% C.L.)	Experiment	Reference
ν_μ	4.6×10^{-4} MeV/sec	ANL 12' B.C. Argonne-Purdue	76, 77
ν_μ	1.4×10^{-4} MeV/sec	Gargamelle B.C. Milano	78
$\bar{\nu}_\mu$	2×10^{-5} MeV/sec	Gargamelle B.C. Milano	78
$\bar{\nu}_e$	0.8×10^{-8} MeV/sec	Reactor U.C. Irvine	79

One might ask about the significance of these numbers in the content of general gauge theories, by comparing this limit with the limit on $\mu \to e\gamma$ results discussed previously. The latter corresponds to a partial rate of $\sim 1 \times 10^{-4}$ sec^{-1}. We would expect the decay to be proportional to $(m_{lepton})^5$. Thus if we take the existing experimental upper limit for m_{ν_μ}, we obtain a crude theoretical limit on $m_{\nu_\mu} \Gamma_{\nu_\mu} < 1 \times 10^{-16}$ MeV/sec on the assumption that the same mechanism contributes to the decay $\mu\to e\gamma$ as to $\nu_\mu \to \nu_e\gamma$. Clearly, the existing experimental limits do not approach anywhere near this number.

The neutrino mixing idea has been introduced by Pontecorvo[80] some time ago who observed that if ν_e and ν_μ are not both massless and non degenerate, then the observed states (ν_μ, ν_e) will be different from the mass eigenstates N_1, N_2.[81] Specifically they will appear as linear combinations of N_1 and N_2, characterized by one parameter θ_ν i.e.

$$\nu_\mu = N_1 \cos\theta_\nu + N_2 \sin\theta_\nu$$

$$\nu_e = -N_1 \sin\theta_\nu + N_2 \cos\theta_\nu$$

Thus in analogy with the K^o-$\overline{K^o}$ system, a beam, composed initially only of ν_μ, can give rise to ν_e after traversing a certain distance ℓ. This probability for effective $\nu_\mu \to \nu_e$ transition is a function of the mixing angle and difference of squares of individual masses, i.e.

$$P = \sin^2 (2\theta_\nu) \sin^2 \left(\frac{m_1^2 - m_2^2}{4} \frac{\ell}{pc}\right)$$

The present limit on this effect allows us to set a limit [78] on the difference of squares of masses

$$(m_1^2 - m_2^2) < 1 \text{ ev}^2$$

on the assumption that mixing is maximal (i.e. $\theta_\nu = \pi/4$). This is considerably smaller than the limit on individual neutrino masses obtained from direct measurements.

Just as it is with the quark mixing, the situation here also becomes more complex as the number of different leptons increases. The situation for the 3 neutral lepton case has been discussed recently by Cabibbo[82] who showed that in that case phase factors will occur in the mixing matrix, just as for the 6 quark case, which will give rise to time reversal and CP violation effects.

c) Status of the τ lepton. The initial observation[83] of 2 prong eμ events in e^+e^- annihilations at SPEAR was accompanied by a conjecture that these events are due to the production and subsequent decay of a pair of new particles, denoted initially by U (for unknown) i.e.

$$e^+e^- \to U^\pm \, U^\mp$$
$$U^\mp \to e^\mp + \ldots$$
$$U^\pm \to \mu^\pm + \ldots$$

The absence of any other visible particles besides the eμ pair led to the natural speculation that one or more neutrinos are emitted in the decay together with the charged leptons.

This hypothesis of production of new particles had to overcome two potentially serious objections, namely:

1) Are these events genuine or could they be misidentified hadrons? One must remember here that the probability of misidentifying hadrons as leptons in this initial experiment was close to 20%.

2) If these events are indeed real, could they be somehow associated with charm production? This question was relevant since the apparent threshold for $U\bar{U}$ production appeared to be the same (within the experimental uncertainty of 100 MeV or so) as that for the charm production.

The first of these questions was soon answered[84] by the PLUTO group at DESY who confirmed the SPEAR results with a much better lepton-hadron discrimination. The unambiguous dissociation of U particles from the charm phenomena was achieved by the observation of 2 prong eμ events below charm threshold; at the ψ' by the DASP group[85] and at several other energies by the DELCO group.[86] These data dispelled the last remaining objections against the existence of a new phenomena, and the proposed hypothesis of a new lepton, henceforth referred to as τ, became well accepted.

In the following, I shall try to discuss the evidence leading to the point of view that the τ is most likely another sequential lepton, which together with its own neutrino forms a third doublet of leptons and appears to satisfy e-μ-τ universality. The outline of the discussion will follow the following steps:

1) The τ is apparently a spin 1/2 lepton (i.e. a point particle).

2) The τ needs to have its own neutrino, i.e. the economy model of 5 leptons appears excluded.

3) The τ is unlikely an ortholepton or paralepton.

4) The τ appears to couple to the standard weak interaction current with the standard V-A coupling.

The arguments for the τ being a spin 1/2 lepton have been recently summarized by Tsai.[87)] These are by no means unique arguments and a great deal of additional data support this point of view. They do, however, form a rather brief but cogent argument in support of this thesis and we shall summarize them briefly below.

The τ cannot be a baryon (assuming baryon conservation) since if it were a baryon decay, its decay products would have to include a baryon. On the other hand, the missing neutral(s) in the decay

$$\tau \to e\nu + \text{neutral(s)}$$

has been shown to have a mass well below the mass of a proton.[88)]

The τ also cannot be a boson, since the τ production threshold clearly exhibits s wave behavior.[86)] (see Fig. 12). Since a boson and its antiboson have opposite parity, we cannot have a $\tau^+\tau^-$ production in an s state from an initial J^P state of 1^-. The only possibility is the production process

$$e^+e^- \to \tau\tau^*$$

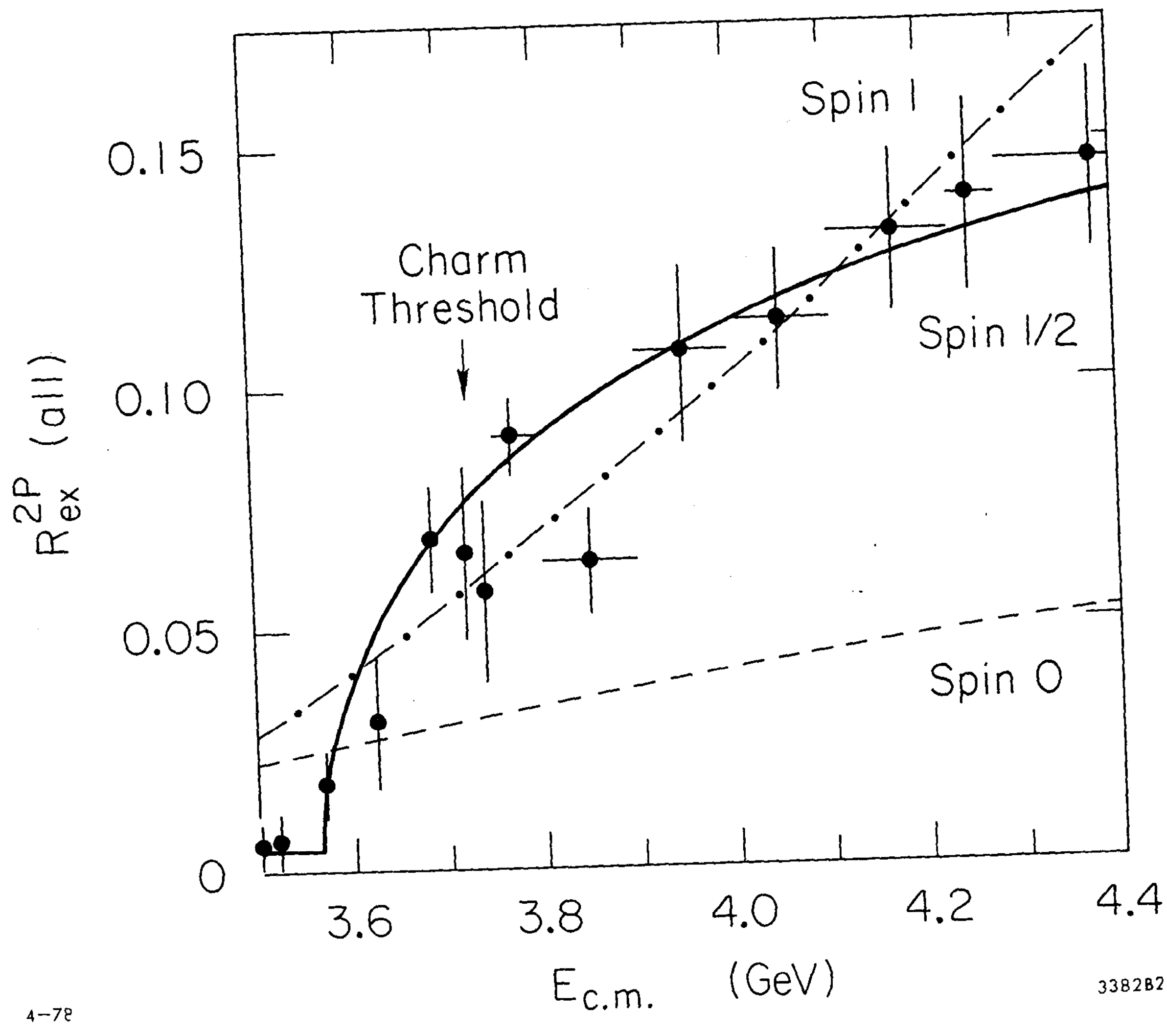

Fig. 12 τ production cross section near threshold as measured in the DELCO experiment. The curves indicate the expected threshold behavior for a pair of spin 0 (dashed), spin 1/2 (solid) and spin 1 particles (dash-dot).

where τ^* is some excited state of the hypothetical τ meson that has <u>opposite</u> parity. In that case the decay mode of τ^* would be expected to be

$$\tau^* \rightarrow \tau + \pi^o \quad \text{or} \quad \tau^* \rightarrow \tau \rightarrow \gamma$$

leading in either case to a large number of γ rays associated with the $e\mu$ events. Experimentally, this is not observed and the only possible out is to require the $\tau^*-\tau$ mass difference to be small enough so that the photons would be below the experimental detection threshold.

Finally, the spin of a point particle τ could not be greater or equal to 3/2, since that threshold behavior is much more divergent. That point is dramatically illustrated in Fig. 13, taken from Ref. 87. One is thus led to the conclusion that the τ is most likely a spin 1/2 lepton. The arguments made further on in this section will only reinforce that conclusion.

We consider next the question whether τ could be a lepton singlet, or do the data require it to have its own neutrino? Clearly, the τ would be stable in the former case (contradicting the data), unless there is μ-e-τ mixing. We need to see, therefore,to what extent other available data set limits on the amount of possible μ-e-τ mixing, and what do those limits in turn tell us about the τ properties. This point has been considered in detail by several authors[89)] with a conclusion that the singlet possibility is excluded. We review briefly the relevant arguments.

The SU(2) x U(1) classification of the leptons in this case would consist of two lefthanded doublets and one left handed singlet, i.e.

$$\begin{pmatrix} \nu_e \\ E \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ M \end{pmatrix}_L, \quad S_L$$

where E, M, and S are linear orthogonal combinations of e,μ, and τ.

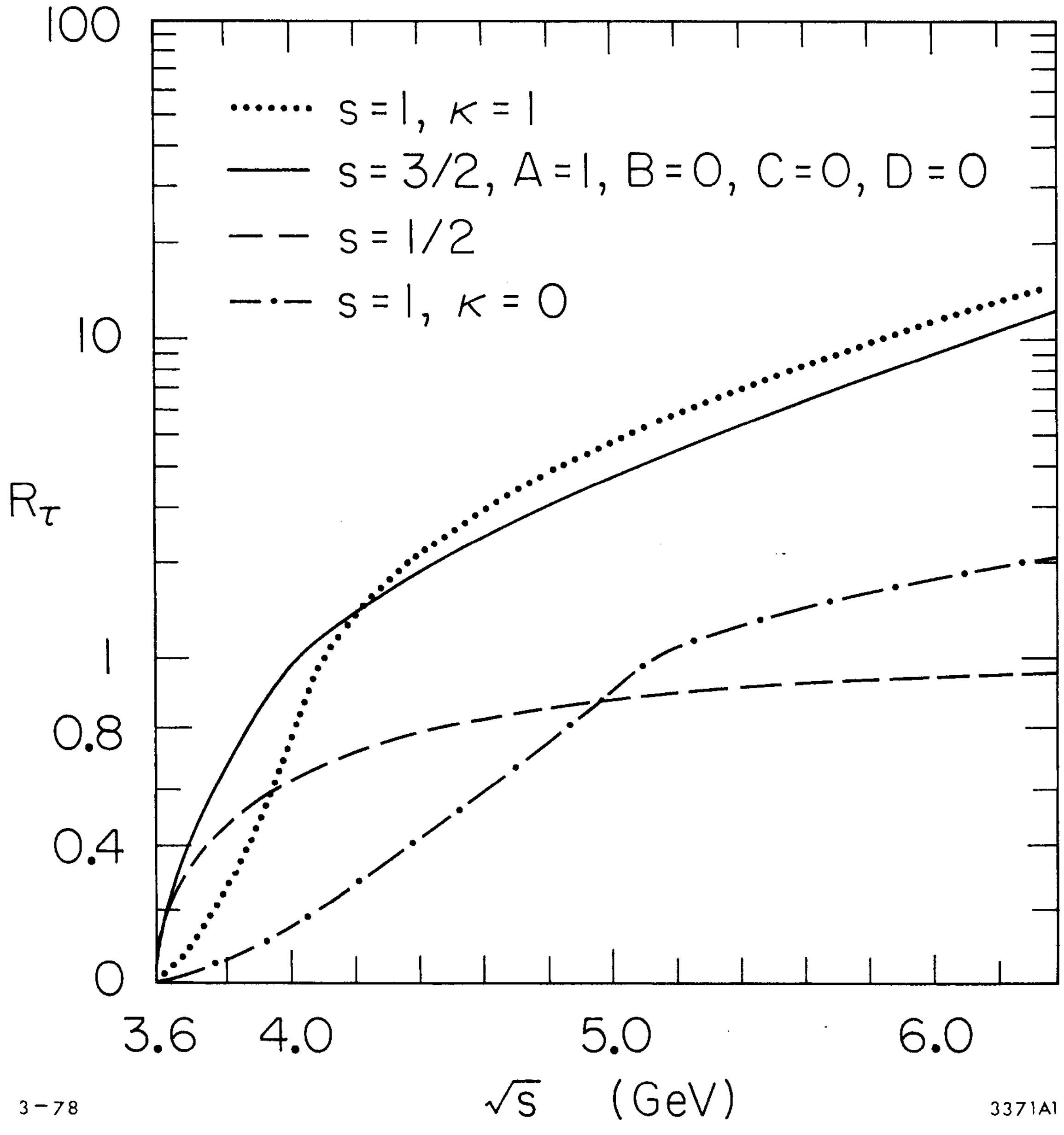

Fig. 13 Expected threshold behavior for a pair of particles with different spins. K, A, B, C, D represent constants related to the gyromagnetic ratio and multipole values of the produced particles (see Ref. 87 for details). Note that the scale of the ordinate is linear up to 1, logarithmic above 1.

The mixing is defined in terms of two real parameters, called γ and β. One can now impose the following limits[90) on γ and β. From the limit on the process

$$\mu^- + Cu \rightarrow e^- + Cu$$

one obtains $\beta^2\gamma^2 \leq 5.3 \times 10^{-9}$

and from the limit on the lifetime of the τ, and hence its total decay rate: $\beta^2 + \gamma^2 > 1.0 \times 10^{-1}$.

The only way to make these two limits compatible with each other is by requiring imbalance between β^2 and γ^2, i.e. $\beta^2 >> \gamma^2$ or $\gamma^2 >> \beta^2$. There are, however, two sets of experimental consequences, violated by the data, which are demanded by this imbalance:

1 - the ratio $R_{\mu e} \equiv \Gamma(\tau \rightarrow \mu\nu\nu)/\Gamma(\tau \rightarrow e\nu\nu)$ must be very close to either 1/2 or 2. The experimental value is very close to unity.[91)]

2 - there would have to be an appreciable decay rate into 3 leptons, i.e. of the order of 2-3%. The experimental limits at the 90% confidence limit are better than 1%.[92)]

Accordingly one concludes that the economy model of a τ singlet is excluded. We turn now to the possibility that τ is a paralepton,[93)] i.e. either a paraelectron meaning that the lepton number assignment for τ^+ is identical to e^-, or a paramuon, which would assign to τ^+ identical lepton numbers as to μ^-. The basic argument which excluded this assignment has to do again with the value of $R_{\mu e}$ defined above. A paraelectron τ^+ could decay either via

$$\tau^+ \rightarrow \mu^+ + \nu_\mu + \nu_e \quad \text{(2 distinct neutrinos)}$$

or

$$\tau^+ \rightarrow e^+ + \nu_e + \nu_e \quad \text{(2 identical neutrinos)} .$$

Because of the Pauli exclusion principle the rate for the second process would be twice as large as for the first one. Thus for a paralepton assignment, $R_{\mu e} = 2$ or $R_{\mu e} = 1/2$. It has been pointed out however recently by Rosen[94)] that this result strictly holds only for a pure V-A assignment for the decay process, which does appear to be favored experimentally (see discussion below). For a more general interaction one could have $R_{\mu e} = 1$ for a paralepton assignment.

An experiment that is relevant to the paralepton question is the search for electrons unaccompanied by muons produced by interactions of predominantly ν_μ beams. Such events could be potential signatures of the process

$$\nu_\mu + Z \rightarrow \tau^- + \ldots$$
$$\hookrightarrow e^- + \ldots$$

and similarly for τ^+. These events were looked for by the Columbia-BNL group in the FNAL 15' bubble chamber filled with neon[95)]. All the events of this nature which were found were consistent with being produced by the ν_e (or $\bar{\nu}_e$) contamination in the beam, allowing one to set a limit on the production cross section times branching ratio for a paramuon of an arbitrary mass. These upper limits could then be compared with the theoretical production rate for such a heavy muon assuming a V-A coupling of standard strength (see Fig. 14). This result can be interpreted in several ways. It excludes a simple paramuon hypothesis for the τ; if the τ does have a muon lepton number then the strength of ν_μ-τ coupling must be only 2.5% of the ν_μ-μ coupling. Finally, for a mixing model, it limits the mixing angle to $\tan^2\theta < 0.025$.

Another kind of a possible lepton is an ortholepton, i.e. a lepton with identical charge and lepton number as the electron or the muon but with a heavier mass. Thus a possible decay mode for a τ orthoelectron

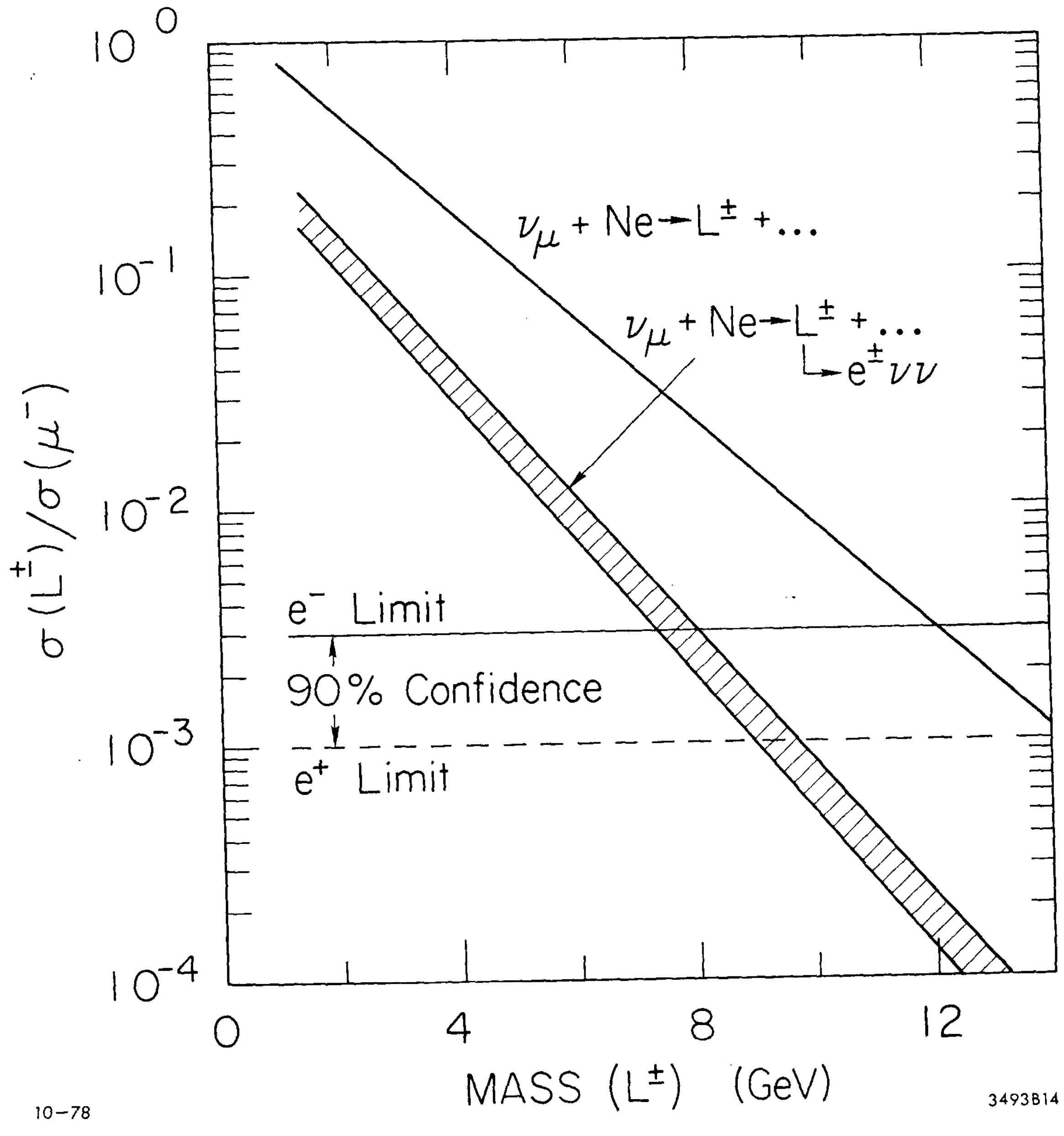

Fig. 14 The expected ratio of heavy lepton to muon production in the Columbia-BNL experiment as a function of the heavy lepton mass together with the experimental 90% confidence limits.

would be

$$\tau^+ \to e^+ + \gamma$$

and similarly for the orthomuon possibility.

The standard orthomuon picture is again excluded by the bubble chamber experiment discussed above, since that would require again a full strength coupling between ν_μ and τ. The orthoelectron possibility is rather unlikely in light of the low reported branching ratio[96] for $\tau \to e\gamma$, i.e. $\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all}) \leq 2.6\%$ (90% C.L.).

We conclude accordingly that the possibilities other than that of sequential lepton appear to be highly unlikely for the τ, and the most reasonable possibility is that τ forms a new lepton doublet $(\tau\ \nu_\tau)$. The typical decays of the τ might thus be expected to proceed via diagrams illustrated in Fig. 15. The subsequent discussion then naturally will break up into 2 parts; firstly, is the current to which τ couples the standard weak interaction current, i.e. we examine the right hand side of the diagrams of Fig. 15; and, secondly, how do the τ and ν_τ couple to this current, i.e. the nature of the left hand side of the vertex.

The first question is answered by studying the different decay modes of the τ and comparing them with the predictions based on the assumption that we are dealing here with the standard current.[97]

1 - <u>equality of electronic and muonic branching ratios</u>. The various measurements relevant here and available as of April, 1978, have been summarized by Feldman.[91] His overall fit to all the data gives $R_{\mu e} = 1.07 \pm 0.17$ to be compared with the theoretical prediction of 0.97. Clearly the agreement is excellent.

2 - <u>absolute value of e,μ branching ratios</u>. The theoretical numbers are here less certain because of the uncertainly associated with the rate into

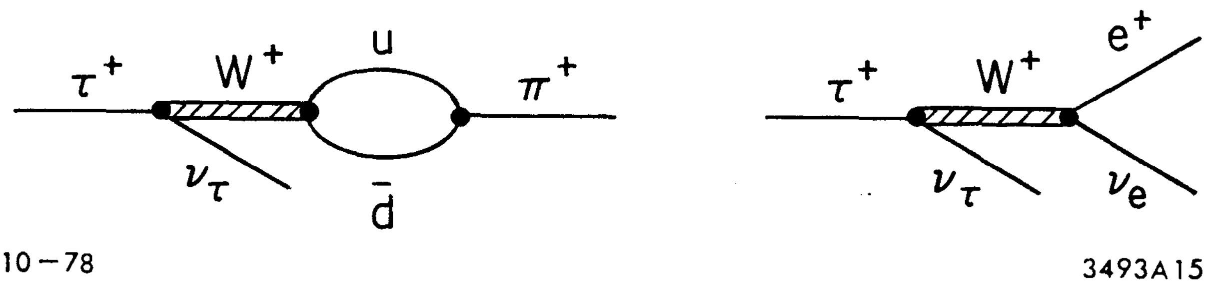

Fig. 15 The standard diagrams for the decay $\tau \to \pi\nu$ and $\tau \to e\nu\nu$.

multipion final states. The best theoretical estimates are 16.4% for the $e\nu\nu$ mode and 16.0 for the $\mu\nu\nu$ mode. These numbers should be compared with Feldman's fit yielding 17.4 ± 2.1% and 18.7 ± 2.0% for the electronic and muonic decay modes respectively, and a recent number for the $\mu\nu\nu$ decay mode from the DELCO experiment[98] of 21±5%.

3 - $\pi\nu$ decay mode. The theoretical estimate for this decay rate is on very firm ground, insofar as the calculation relies solely on the $\pi\to\mu\nu$ decay rate and the assumption that we are dealing in τ decay with a standard weak current. Accordingly, the early low value for the branching ratio for this mode reported by the DASP group,[99] 2.4 ± 3.0% to be compared with the theoretical 9.8%, gave rise to serious doubts as to whether the τ does indeed fit into the standard weak decay picture. Subsequently, however, 3 different experiments have yielded results in very good agreement with the theory, so the issue of the $\pi\nu$ decay also appears to be settled in favor of the standard model.

The most direct observation of this mode has been made by the DELCO group[100] who used a hadron filter to identify π's and the Cerenkov counter to identify electrons and thus were able to isolate a sample of the events of the type

$$e^+e^- \to \tau^\pm \tau^\mp, \quad \tau^\mp \to \pi^\mp \nu_\tau, \quad \tau^\pm \to e^\pm \nu_e \nu_\tau$$

and quote a branching ratio of 8.0 ± 3.2 ± 1.3%, where the first error is statistical and second systematic. The spectrum of π's and μ's (from $\mu\nu\nu$ decay) shown in Fig. 16 agrees very well with the Monte Carlo calculation, supporting the hypothesis of correct identification of the events.

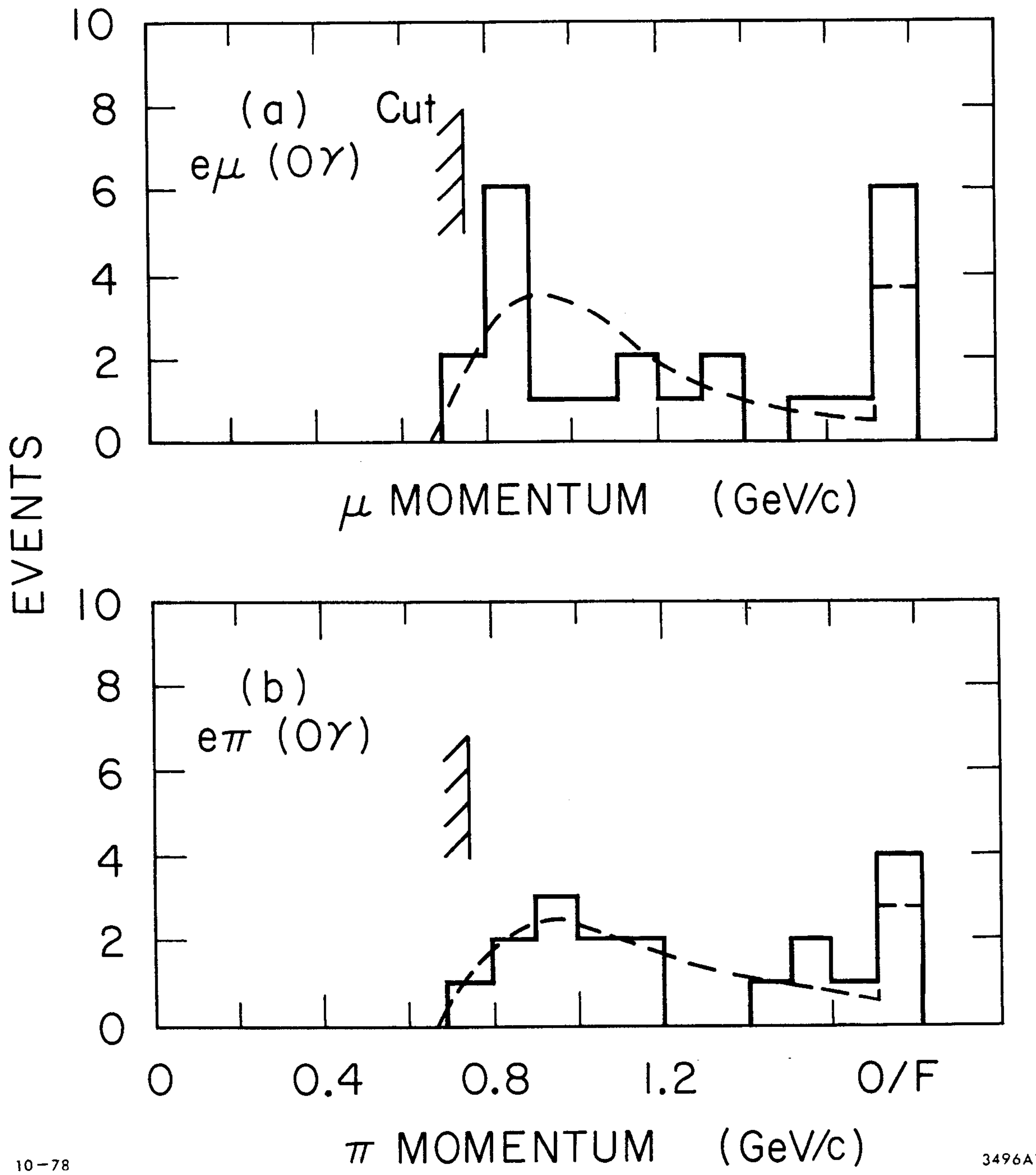

Fig. 16 Momentum spectrum of the μ in eμ events (a) and of the π in eπ, 0γ events (b). The dashed lines indicate the predicted shapes expected from the τ decays. The data is from DELCO.

The SLAC-LBL group used a more indirect method[101)] by looking for 2 prong events with an energetic pion and no detected γ rays. A clear excess (Fig. 17) is observed over what one would expect if no $\tau\to\pi\nu$ mode were present. Estimating the hadronic background on the basis of a jet model, they calculate the $\pi\nu$ branching fraction to be $9.3 \pm 3.9\%$.

More recently, the PLUTO group[102)] has looked for 2 prong events with an identified hadron and no photons to obtain a branching rate for this mode of $9.0 \pm 2.9\%$.

4 - <u>$K\nu$ decay mode</u>. This should be the Cabibbo suppressed mode and the theoretical expectation is 0.62%. The only experimental input here is by the DASP group who find[99)] BR ($K\nu$) $< 1.6\%$ (90% C.L.).

5 - <u>$\rho\nu$ decay mode</u>. This should be one of the major decay modes, with the standard model predicting 23%. To my knowledge the only information available on this subject is the preliminary data presented by the DASP group at the Hamburg meeting[99)] who quote $24 \pm 9\%$. Their evidence rests on the observation of the channel

$$e^+e^- \to \pi^\pm \pi^o + 1 \text{ charged track}$$

where the $\pi^\pm\pi^o$ mass spectrum, and the momentum of the $\pi^+\pi^o$ system (Fig. 18) is consistent with those events coming from the process

$$e^+e^- \to \tau^\pm \tau^\mp$$
$$\tau^\mp \to \rho^\mp \bar{\nu}, \quad \rho^\mp \to \pi^\mp \pi^o$$
$$\tau^\pm \to 1 \text{ charged track} + \ldots$$

6 - <u>Multiprong decay modes and their composition</u>. The rates for these decay modes, as well as their composition can be calculated from the e^+e^- annihilations in the appropriate energy range since the isovector electromagnetic current is believed to be directly related to the weak hadronic

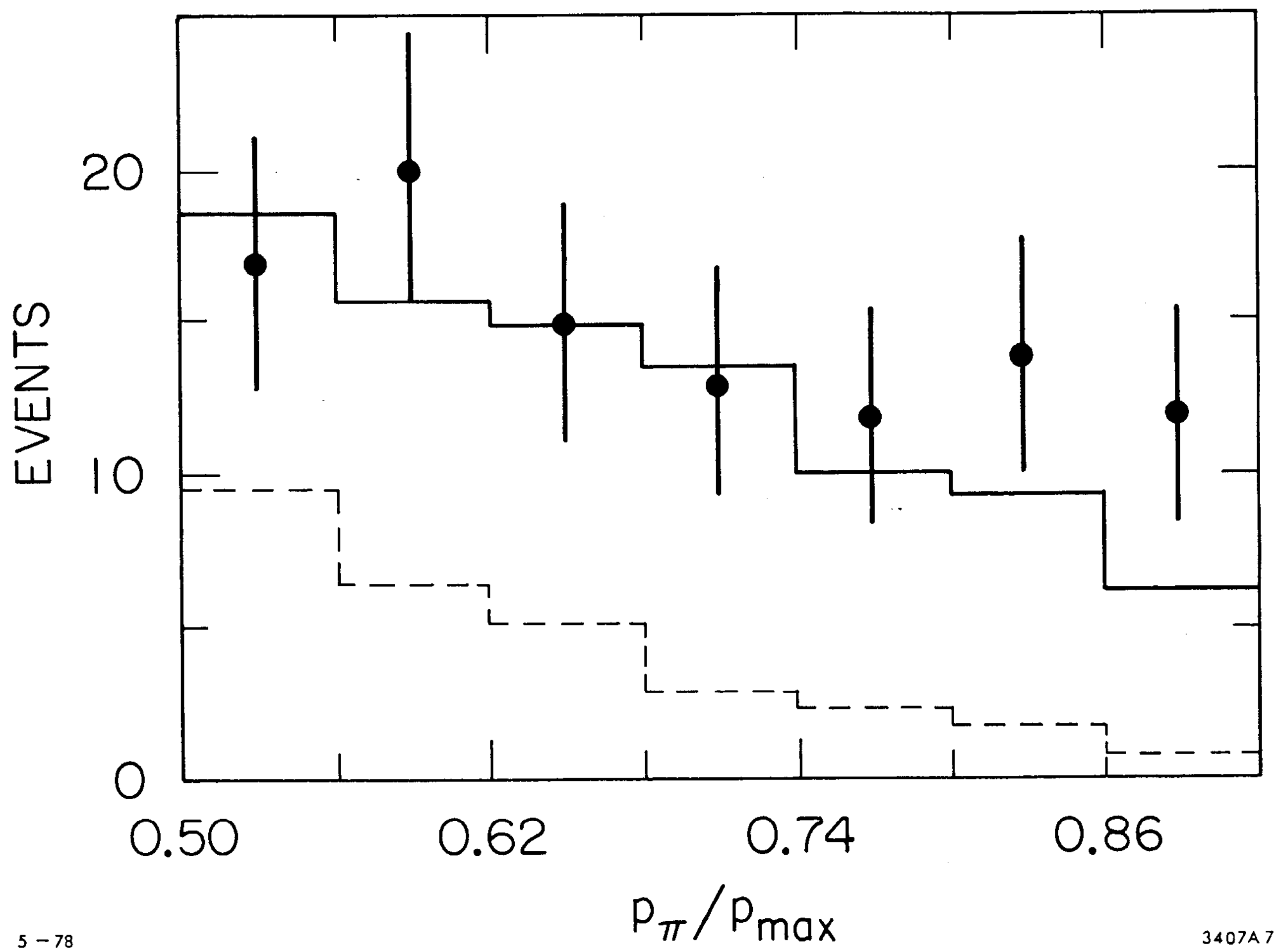

Fig. 17 The ratio of the pion momentum to its maximum value for τ decay for the SLAC-LBL events with a pion, another charged particle, and no detected photons. The solid curve is the expected distribution if the τ decays normally; the dashed curve if $\pi\nu$ decay is absent.

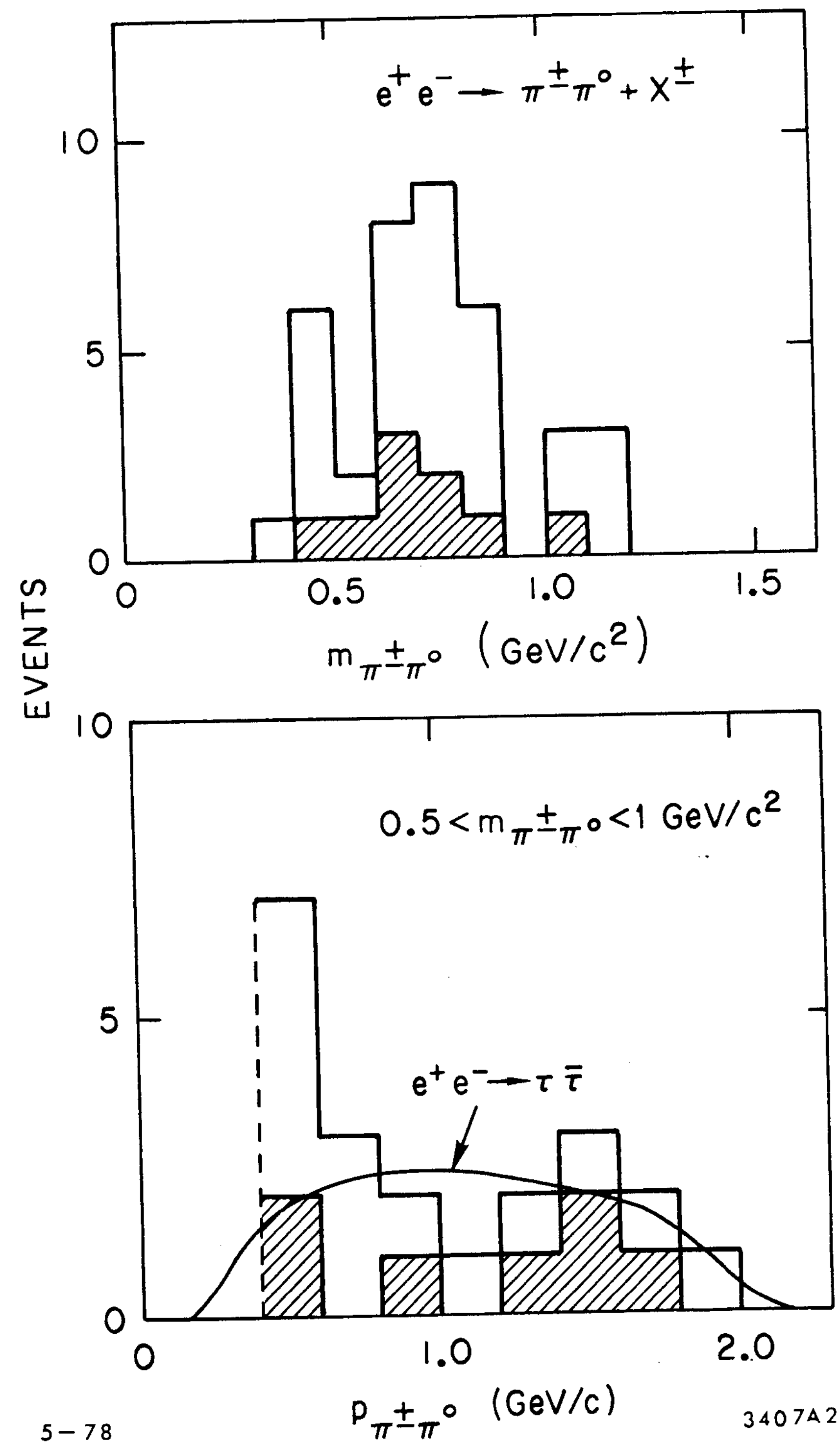

Fig. 18 The DASP invariant mass distribution of the $\pi^\pm\pi^o$ system (a) and the momentum distribution of the $\pi^+\pi^o$ system for the events in the ρ mass band (b). The shaded events have the second charged particle identified as electron.

current.[103] The results of the standard model are listed in Table IX.

Table IX

τ branching ratios into various multibody channels

Mode	Predicted branching ratio
$A_1 \nu_\tau$	9.3%*
$Q\ \nu_\tau$	0.4%
$\nu_\tau + \bar{u}d$ ($M_{\bar{\mu}d}$>1.1 GeV)	21.3%
$\nu_\tau + \bar{u}s$ ($M_{\bar{\mu}s}$>1.1 GeV)	1.5%

*half of this mode will go into single prong topology.

The experimental situation is in good agreement with the theory, although there is room for considerably more work here on the experimental side. We attempt to summarize the experimental situation very briefly. The PLUTO collaboration[104] has reported a branching fraction of 5 $\pm$ 1.5% for the decay mode $\tau^+ \to \nu\ \rho^o \pi^+$. They argue that the mass spectrum of the 3π system is consistent with coming from an A_1 (see Fig. 19). A similar measurement has been performed[105] by the SLAC-LBL collaboration, who however do not claim to be able to separate out the events with extra π^o's. Accordingly, they choose to quote a total rate for $\tau^\pm \to \nu\pi^+\pi^-\pi^\pm (n\pi^o$'s) as 18 $\pm$ 6.5%. Again, there is some enhancement in the data in the 3π mass spectrum around the A_1 mass, as demonstrated in Fig. 20.

The total branching ratio into multiprongs has been measured by several groups. The DELCO group has obtained a branching fraction of 32$\pm$5% in 2 different ways, i.e. by measuring[86] the rate for eX events which yields $2b_e(1 - b_e - b_{mp})$ and by plotting[106] the ratio of the observed multiprong events with an electron to the eX events as a function of minimum electron momentum cutoff. The asymptotic value of this ratio will be free of charm

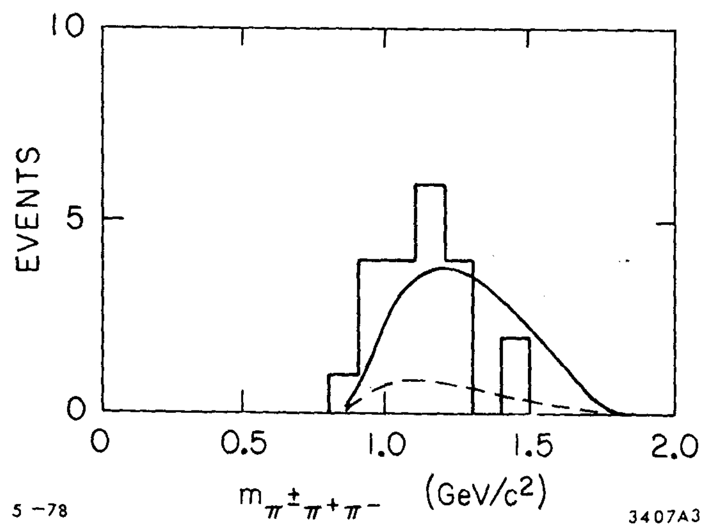

Fig. 19 The PLUTO invariant mass distribution of $\rho^o\pi^\pm$ combinations in events with electron and 3 π's, compatible with $\tau^+\tau^-$ hypothesis. The solid curve represents a nonresonant $\rho^o\pi^\pm$ spectrum from τ decay; the dashed line is an estimate of the background.

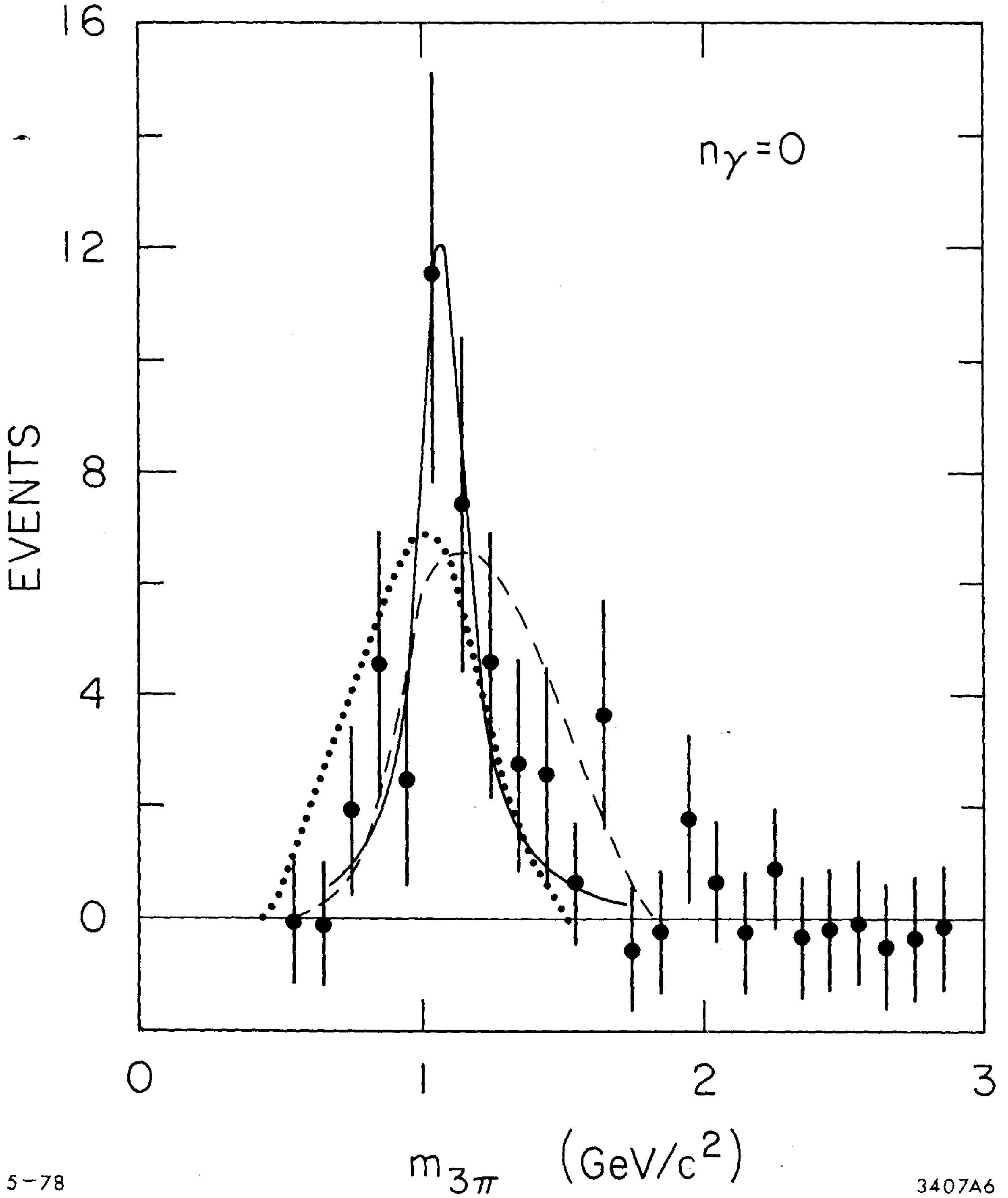

Fig. 20 SLAC-LBL mass spectrum of 3 π's from events with a μ, 3 charged π's, and no detected γ's. The dotted line represents $\tau \to \pi^{\pm}\pi^{+}\pi^{-}\pi^{0}\nu$ hypothesis, the dashed line non resonant $\tau \to \pi^{\pm}\pi^{+}\pi^{-}\nu$, and the solid line $\tau \to A_1\nu$, with mass and width of A_1 being 1.1 GeV/c^2 and 200 MeV/c^2 respectively.

contamination and thus measures the ratio of multiprongs to 1 prong non-electron decays (corrected for slightly different detection efficiencies) in τ decays. These data are displayed in Fig. 21.

The DASP group has measured[85)] the same quantity utilizing the relationship $b_{mp} = 1 - b_e - b_{ns}$ where b_{ns} is the branching ratio into a non-showering single charged prong. They obtain 35 ± 11% for the multiprong mode. Finally the PLUTO group[107)] has obtained 30 ± 12% for this rate by looking at multiprong events associated with a muon.

7 - Rare decay modes. The standard current model predicts that there should not be any exotic decay modes, besides those discussed above. This is indeed the case experimentally, as can be seen from Table X reproduced from the Hamburg Conference proceedings.

Table X

Upper Limits on τ Rare Decay Modes

Experimental Group or Detector	Mode	Upper Limit on Branching Ratio	C.L.	Ref.
PLUTO Group	$\tau^- \to (3\text{ charged particles})^-$	0.01	95%	108
PLUTO Group	$\tau^- \to (3\text{ charged particles})^-$	0.01	95%	108
SLAC-LBL Magnetic Detector	$\tau^- \to (3\text{ charged particles})^-$	0.006	90%	92
SLAC-LBL Magmetic Detector	$\tau^- \to \rho^- + \pi^0$	0.024	90%	109
PLUTO Group	$\tau^- \to e^- + \gamma$ $\tau^- \to \mu^- + \gamma$	0.12	90%	108
LBL-SLAC Lead Glass Wall	$\tau^- \to e^- + \gamma$	0.026	90%	96
LBL-SLAC Lead Glass Wall	$\tau^- \to \mu^- + \gamma$	0.013	90%	96

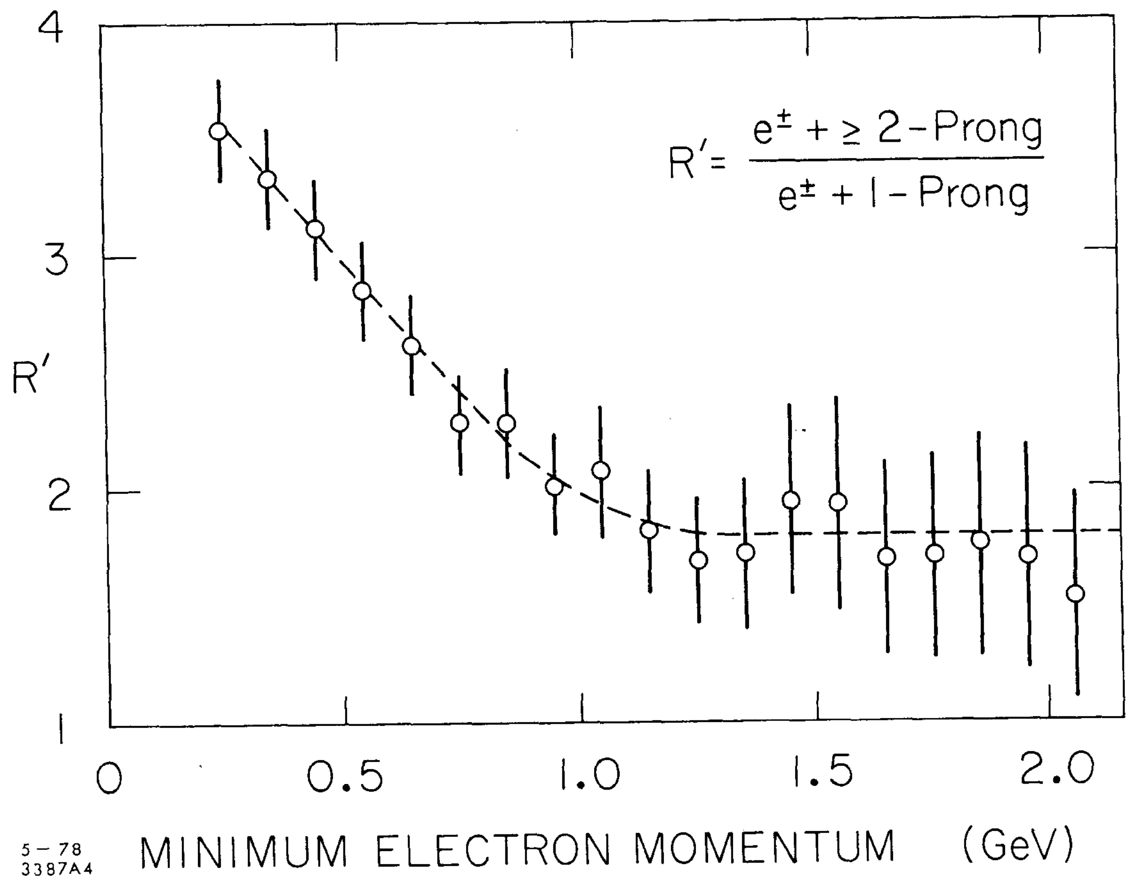

Fig. 21 The ratio of observed multiprong electron events to the observed two prong electron events at electron momenta above the value indicated on the horizontal axis. The dashed curve is drawn to guide the eye. Note the suppressed zero on the vertical scale. The data is from DELCO.

In summary, we conclude that the branching ratios of the τ lepton are in excellent agreement with the standard model predictions and thus the evidence is very strong that the τ couples to the same weak interaction current that appears to be responsible for all the other hitherto observed weak processes.

We can now turn to the other vertex and discuss what we know about the τ-ν_τ-W vertex. We first consider the electron spectrum which can distinguish between the V-A and V+A couplings. One can characterize the spectrum by the Michel parameter, ρ, which takes on the value of 0 for V+A hypothesis and results in a spectrum peaked near the center of possible electron energies, or the value of 0.75 for V-A which gives an electron energy distribution peaked at the maximum possible value. These two distributions, illustrated roughly in Fig. 22, become less distinguishable as we go from the τ rest frame to the laboratory system because of Lorentz smearing. The radiative corrections[110)] effect significantly the lower part of the spectrum and have the phenomenological effect of reducing the expected ρ value for each hypothesis by about 0.1.

The experimental data is in good agreement with the V-A and appears to exclude the V+A hypothesis. The most powerful data statistically comes from the DELCO experiment[111)] and is displayed in Fig. 23, both for all the energies and the energies near threshold, where the statistics are poorer but the sensitivity considerably higher. The preliminary result quoted by the DELCO group is $\rho=0.66 \pm 0.13$.

The overall τ decay rate, i.e. its lifetime, measures the strength of the τ-ν_τ-W coupling. In the standard model, i.e. assuming universality and no lepton mixing, the expected decay rate is 3.3×10^{12} sec^{-1} yielding

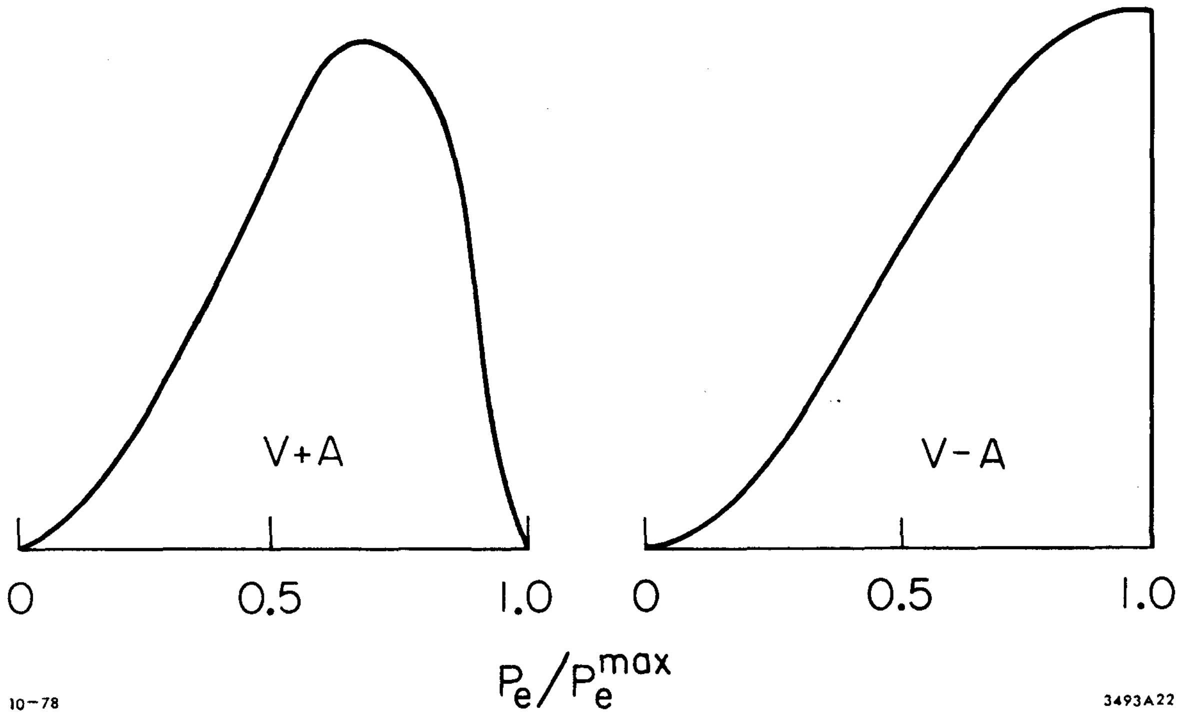

Fig. 22 Rough sketch of the expected electron momentum from τ decay for V+A and V-A hypotheses.

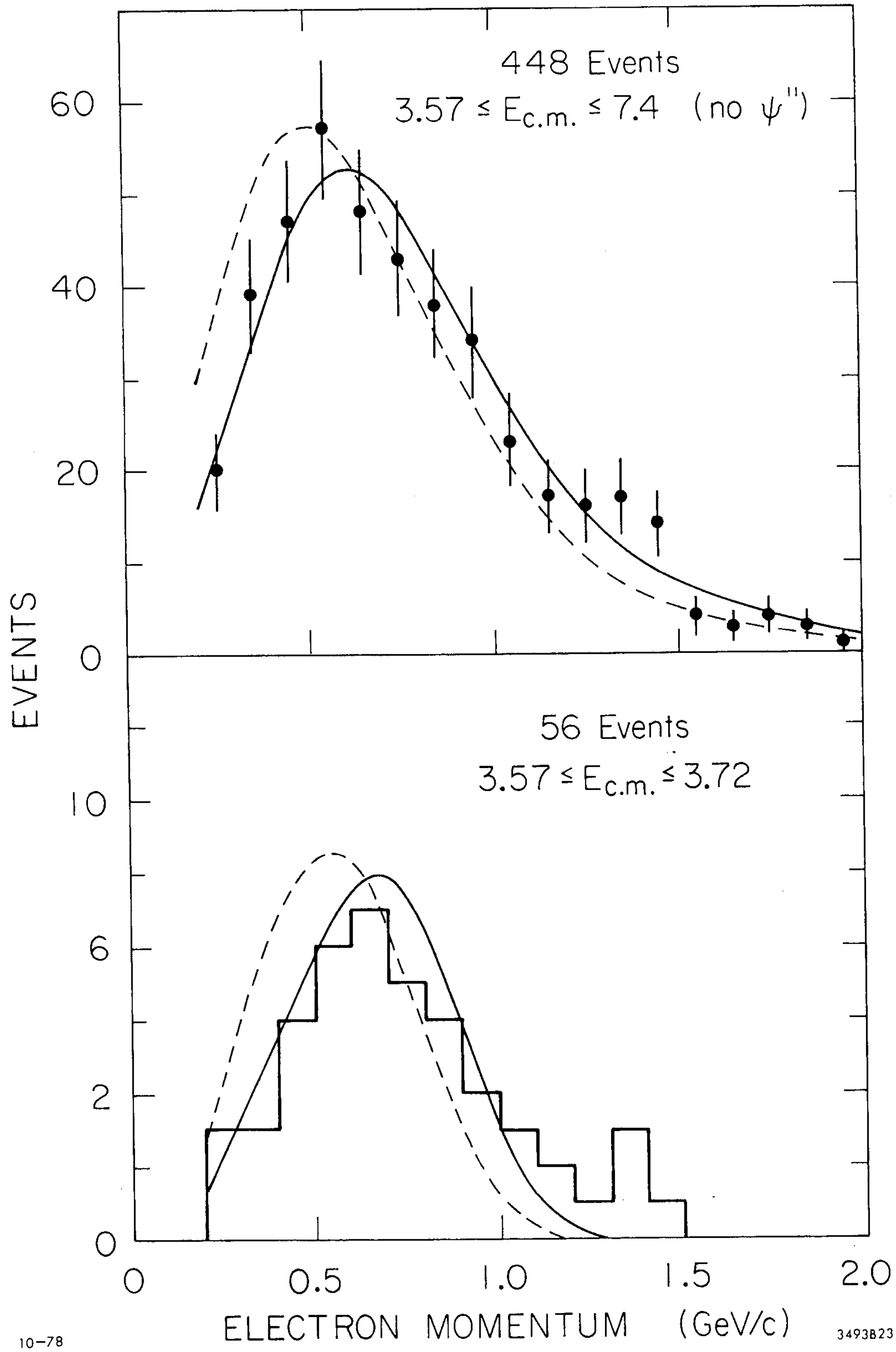

Fig. 23 The preliminary electron momentum spectrum for eX events from DELCO. The solid line is the V-A prediction, the dashed line V+A prediction. (a) all events; (b) events below charm threshold.

a lifetime of 3.0×10^{-13} sec. Such a value appears to be below the capability of the present measurements, but an upper limit would nevertheless be useful in putting a severe constraint on the various models incorporating lepton mixing. The best limits came from the DELCO[111] and PLUTO[112] groups who quote $\tau_\tau < 3 \times 10^{-12}$ sec and $\tau_\tau < 3.5 \times 10^{-12}$ sec respectively, obtained by looking for a finite distance between the annihilation point of e^+e^- and τ decay point.

The final question has to do with the nature of the neutrino associated with the τ. On the assumption that it is indeed the τ neutrino that is emitted in τ decay we have the following most recent experimental limits on its mass:

from the DASP group[85] $m_{\nu_\tau} < 0.74$ GeV (90% C.L.) for V-A

$m_{\nu_\tau} < 0.54$ GeV (90% C.L.) for V+A

from the PLUTO group[113] $m_{\nu_\tau} < 0.36$ GeV (90% C.L.) } for V-A

and from the DELCO group[88] $m_{\nu_\tau} < 0.25$ GeV (90% C.L.) } for V-A

On the other hand there exists the possibility that $m_{\nu_\tau} > m_\tau$,[114] and τ decays via a non zero mixing angle between ν_τ and ν_μ and ν_e. In that case we observe either the electron or muon neutrino in the decay and those experimental limits are meaningless. One should point out, however, that this possibility is probably already ruled out experimentally.[81]

The mixing in the six lepton picture involves two parameters, a and b, which are bounded from below by the limit on the τ lifetime, i.e.

$$a^2 + b^2 > 1.0 \times 10^{-1}$$

for $\tau_\tau \leq 3 \times 10^{-12}$ sec. On the other hand, the relative rates for $\pi \to e\nu$ and $\pi \to \mu\nu$ put limits on $b^2 - a^2$. Specifically there is a 1.5σ difference[115] in the ratio of these 2 rates from what one expects from theory giving

$$b^2 - a^2 = (3 \pm 2) \times 10^{-2}.$$

Thus this inequality may be interpreted as setting a bound on the value of $|b^2 - a^2|$, i.e.

$$|b^2 - a^2| < 7 \times 10^{-2}$$

within 95% confidence limits.

Finally, in the framework of this model there will be a finite probability for the muon neutrinos to turn themselves into electron neutrinos. Experimentally, this would allow a neutrino beam, that is initially a pure ν_μ beam to produce electrons unaccompanied by muons. This rate is given by

$$\frac{\nu_\mu + N \rightarrow e^- + \ldots.}{\nu_\mu + N \rightarrow \mu^- + \ldots} = a^2 b^2$$

and the experimental 95% confidence limit bound obtained from the Gargamelle experiment of J. Blietschau et al.,[63] is

$$a^2 b^2 < 1.2 \times 10^{-3}$$

Interpreting these last two numbers literally, we obtain an upper bound on the higher of a^2, b^2, i.e.

$$\text{Max }(a^2, b^2) < 8.3 \times 10^{-2}$$

The value of the smaller parameter corresponding to this limit would then be 1.3×10^{-2}, thus barely disagreeing with the limit on $b^2 + a^2$ and ruling out the hypothesis of a heavy neutral τ lepton.

A similar conclusion can be reached in a slightly more direct way by considering the Cabibbo uniersality, i.e. comparison of muon decay with the nuclear β decay. In Chapter I we have shown that

$$\sin^2\theta_c + \cos^2\theta_c = 1.003 \pm 0.004$$

i.e. at a 95% confidence limit the violation of universality is less than 1.1%. In terms of a^2 and b^2, this limit can be written as

$$b^2 < 1.1 \times 10^{-2}$$

in the approximation that terms $O(\sin^2\theta_c)$ can be ignored. Combining this with the data from the $\pi \rightarrow e\nu/\pi \rightarrow \mu\nu$ ratio, we obtain a clear contradiction with the lower limit on $a^2 + b^2$ from the lifetime limit, thus ruling out the heavy τ neutrino hypothesis.

One can conclude this section with a summary of what we know today about the τ.

1 - It appears to be a sequential spin 1/2 lepton with its own neutrino.

2 - Mass of the τ neutrino is probably low, and a mixing scheme with $m_{\nu_\tau} > m_\tau$ appears to be ruled out by the data.

3 - The three precise measurements of the τ mass are in good agreement and are listed in Table XI.

Table XI

τ Mass Determinations

Group	Value (GeV)	Reference
DASP	1.807 ± 0.020	85
DELCO	$1.782 \begin{smallmatrix} +0.002 \\ -0.007 \end{smallmatrix}$	86
Heidelberg	$1.787 \begin{smallmatrix} +0.010 \\ -0.018 \end{smallmatrix}$	116

4 - Branching ratios are in good agreement with the standard model

5 - Coupling appears to be of the V-A form.

6 - Decay rate consistent with universality but within rather large limits, however.

On the other hand, one would still like to obtain better information on the following points:

1 - how exact is the e-μ-τ universality.

2 - what is the nature of ν_τ? Is it massless? If no, what is the mixing with the ν_μ and ν_e.

3 - better branching ratio measurements in the multibody sector.

Unless these last three questions will be answered in a surprising and unexpected way, we can assume that most likely τ is a standard sequential lepton. If so, and the mass of its neutrino is zero, then unfortunately we shall not see any of the exciting experimental possibilities like neutrino oscillations, CP violation in the lepton sector, and μ-e transitions due to mixing phenomena. One has to regretfully conclude that the standard model is a dull model.

IV. Charm Decays

In this chapter we shall discuss the available experimental information on charm decays and compare it with the standard charm model. As shall be hopefully apparent from this discussion, there is still a lot to be learned on this topic and many questions remain unanswered. This can be contrasted with the question of τ decays, where we appear to be much closer to the ultimate understanding.

We shall discuss in this chapter the following topics:

a) expected charm spectroscopy

b) evidence for weak decays

c) comparison with GIM predictions

d) semileptonic decays

e) pure hadronic decays

f) D^o-$\overline{D^o}$ mixing

g) F meson and charmed baryons

h) the status on the lifetime of D meson.

a) expected charm spectroscopy. We shall review here very briefly some of the fundamental ideas put forth for the first time in great detail by

Gaillard, Lee, and Rosner.[117)] Their classic paper is remarkable in its great predictive power and in the good accuracy of their quantitative predictions.

In the quark picture the mesons are bound states of a $q\bar{q}$ system. Before the introduction of charm, different mesons could be obtained by allowing the general $q\bar{q}$ system to be a different combination of the u, d, and s quarks and the $\bar{u}$, $\bar{d}$, and $\bar{s}$ antiquarks. The introduction of the new quark, the c quark, will allow one to create new meson states by forming systems composed of a c quark plus an antiquark. Thus the expected mesonic states with c=1 quantum numbers are:

$$\left.\begin{array}{l} \left.\begin{array}{l} c\bar{d} \Rightarrow D^+ \\ c\bar{u} \Rightarrow D^o \end{array}\right\} \quad T = 1/2 \\ c\bar{s} \Rightarrow F^+ \qquad\quad T = 0 \end{array}\right\} \text{ and their antiparticles}$$

We also indicate above the isotopic spin multiplets and the conventionally assigned names to the new quark states. Fig. 24 exhibits the expected mesonic states (old and new) displayed in the 3-dimensional space defined by the C, Y, and I_3 (Y is the hypercharge).

Clearly, if the charm quantum number is to be conserved by the strong and electromagnetic interactions in analogy with strangeness, then at least one of the 3 new meson states should be stable against those interactions and thus have to decay weakly. In the conventional picture, all three: D^+, D^o, and F, were predicted to decay weakly, since the electromagnetic splitting is expected to be less than a pion mass and the predicted masses of the quarks were such that the transition $F \to D + K$ would be energetically forbidden.

The baryons are qqq states and thus we can form charmed baryonic states with charm quantum number equal to 1 by replacing one of the old

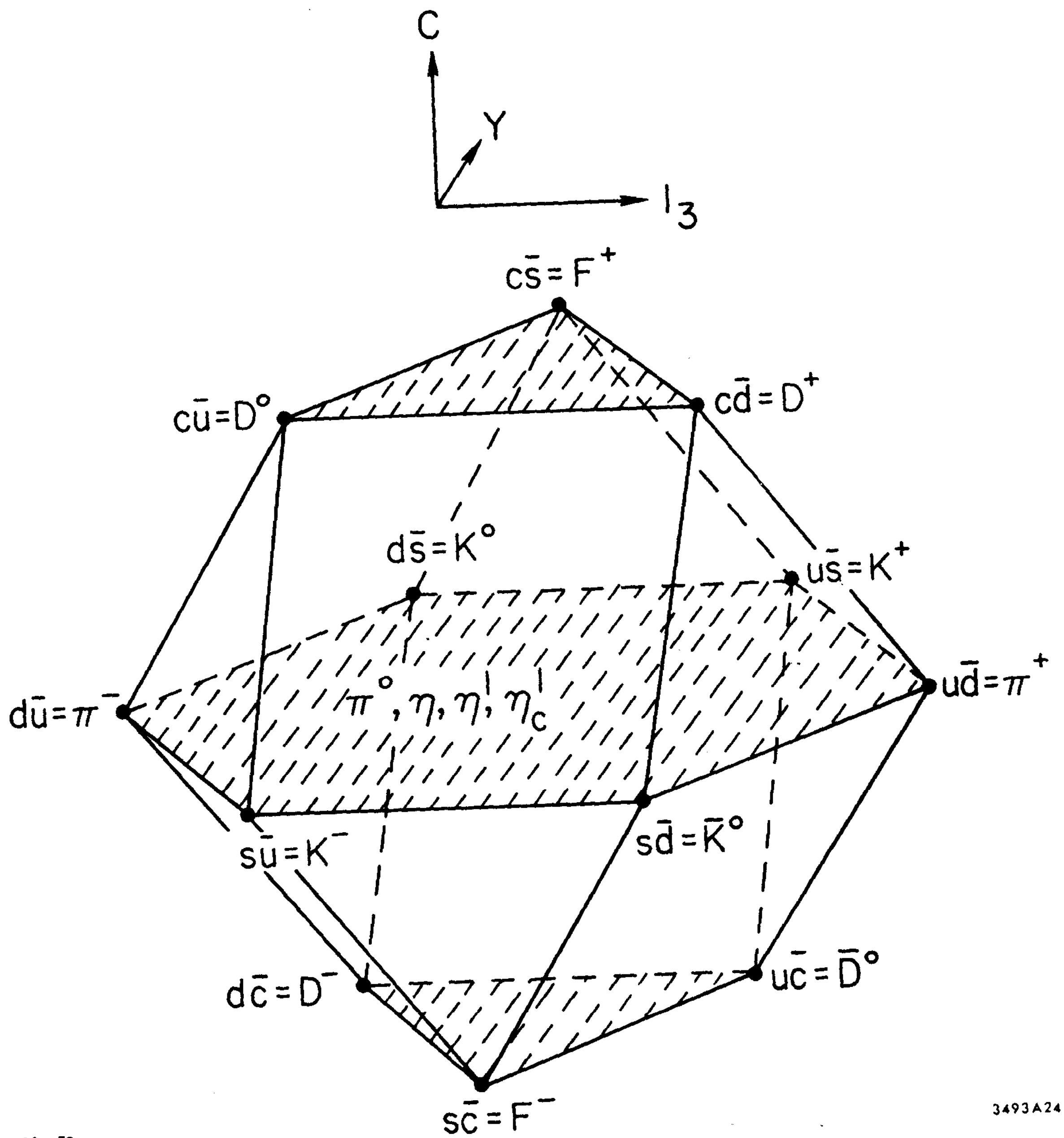

Fig. 24 The predicted meson spectrum in the charm scheme.

quarks with a c quark, or equal to 2 by using 2 charmed quarks. The three c quark state would be expected to be a 3/2+ state in analogy with Ω^-. Accordingly, we can expect to have:

9 C = 1 states i.e.	S = 0	triplet and singlet
	S = -1	two doublets
	S = -2	singlet

and 3 C = 2 states i.e.	ccu, ccd	T = 1/2, S = 0
	ccs	T = 0, S = -1

Together with the 1/2+ ground state octet of the old baryons, they will form a 20 representation of SU_4 which is displayed in Fig. 25 in the 3 dimensional C, Y, I_3 space. The figure is a truncated tetrahedran and each of the 4 large sides represents an SU_3 octet composed with a different set of 3 out of the 4 quarks.

Considering the charmed baryonic decays in general, we have 2 distinct possibilities, i.e.

1 - $B^{charmed} \to B^{old} + M^{charmed}$, i.e. strong decay

2 - $B^{charmed} \to B^{old} + M^{old}$, i.e. weak decay.

Whether the first process goes is strictly a kinematical question, i.e. is it energetically allowed. If the answer is yes, then we would see no weak charmed baryon decays. That is the possibility that appeared more plausible to Gaillard, Lee, and Rosner. The nature, however, appears to have chosen the second possibility as we shall discuss towards the end of this chapter.

b) <u>evidence for weak decays</u>. We would like to consider next two points that appear to confirm the theoretical prejudice that the D decays proceed via weak interactions, i.e. their narrow width and the existence of parity violation in the decay process.

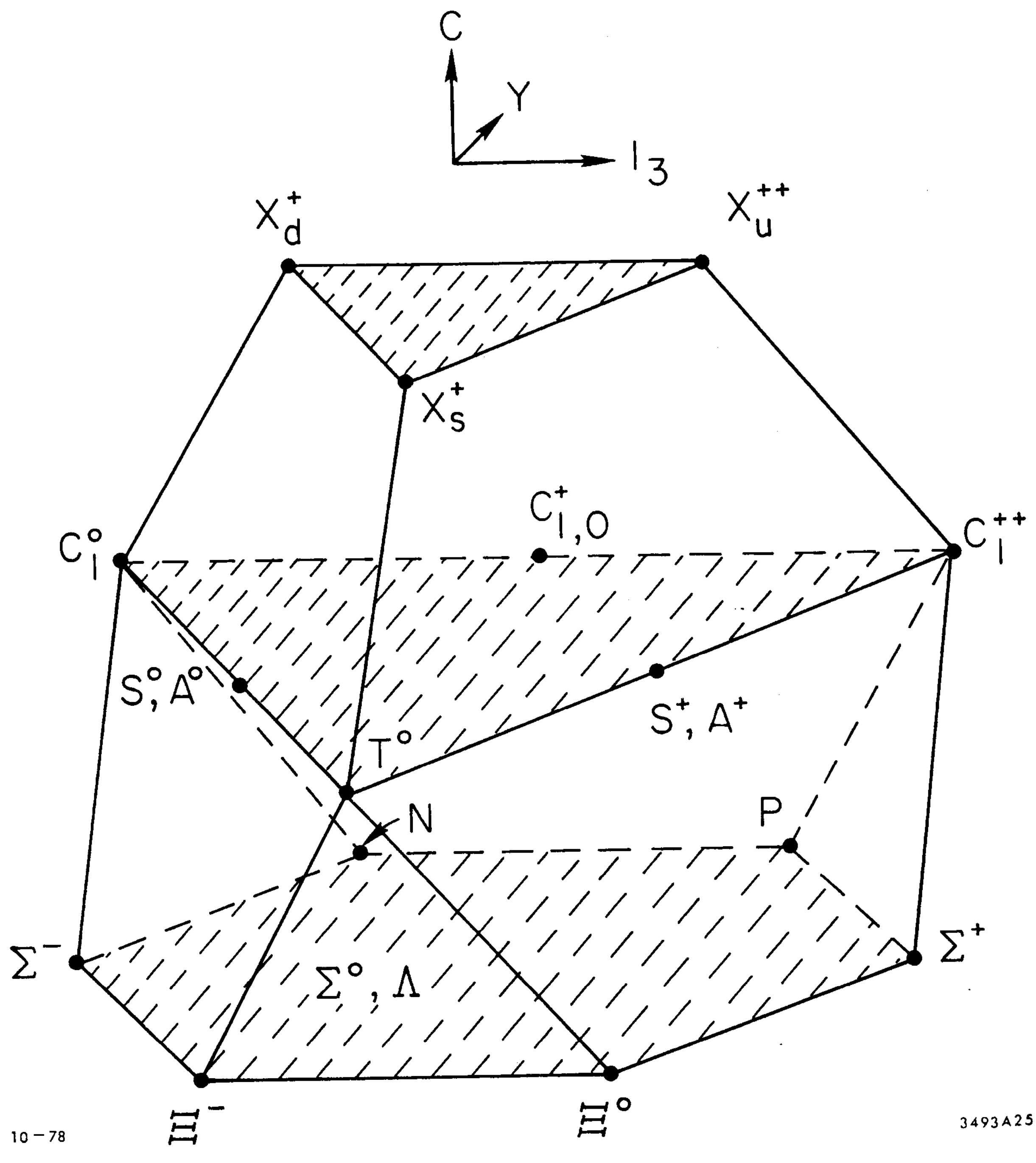

Fig. 25 The predicted baryon spectrum in the charm scheme.

In spite of the relatively large Q value released in most charm decays, their mass can be measured experimentally in e^+e^- collisions quite accurately, leading to a stringent upper limit on the natural $D^o(D^\pm)$ width. To see this we can consider the process

$$e^+e^- \to D\bar{D}$$

near threshold. In general, we have for the mass of the D squared

$$M^2 = \Sigma E_i{}^2 - \Sigma \vec{p}_i{}^2$$

where the summation is over all the D decay products.

$$\delta M^2 = \Sigma 2E_i \delta E_i - \Sigma 2\, \vec{p}_i\, \delta\vec{p}_i$$

$$= 2\, E_{tot}\, \delta E_{tot} + 2|\vec{P}_{tot}|\, \delta P_{tot}$$

where the last sum implies that the proper correlations between δE_{tot} and δP_{tot} are taken into account. Now usually near threshold $\vec{P}_{tot} \approx 0$ i.e. $E_{tot} >> P_{tot}$, and thus the first term tends to dominate the error. But in e^+e^- collisions $E_{tot} = E_{beam}$ which is known very well, and thus δE_{tot} and hence δM^2 is indeed very small.

This technique is especially useful in the case of the $D\bar{D}$ system because of the presence of ψ'' just past the $D\bar{D}$ threshold[118], resulting in an appreciable rate (about 1 R unit) for the $D\bar{D}$ production. The narrow peaks seen at the D mass[119] are exhibited in Fig. 26, with a typical $\Gamma^{FWHM}_{exp} \lesssim 10$ MeV. Parenthetically, one might add that the circumstances discussed above allow one to measure the D mass with a very high accuracy, yielding[120]

$$m_{D^o} = 1863.3 \pm 0.9 \;\; \text{MeV}/c^2$$

$$m_{D^+} = 1868.4 \pm 0.9 \;\; \text{MeV}/c^2$$

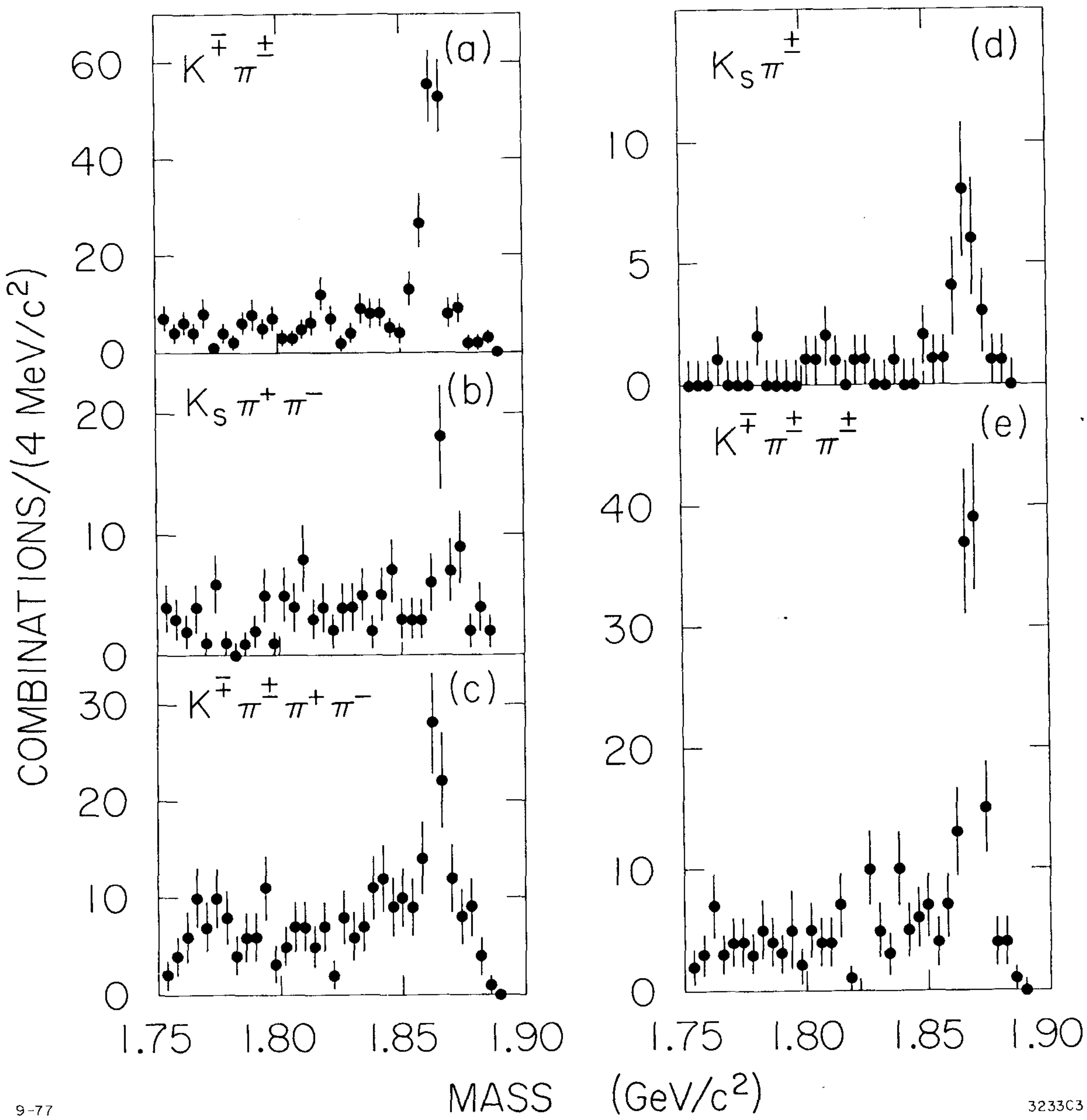

Fig. 26 The mass spectra for different neutral and exotic $K n\pi$ combinations. The data is from the SLAC-LBL collaboration.

The evidence for parity violation parallels very closely the arguments relevant to the old τ-θ puzzle. We recall that in the days before the discovery of the parity violation, the two distinct decay modes of the K meson

$$\theta^+ \rightarrow \pi^+\pi^o \quad \text{and} \quad \tau^+ \rightarrow \pi^+\pi^-\pi^+$$

were believed to have to have been two distinct mesons since the parity of the two final states had to be different for the same value of angular momentum.

The experimental situation in the case of the D is very similar. A sharp enhancement around 1870 MeV is observed both in[120] the $K^o_S\ \pi^\pm$ and in the $K^\mp\ \pi^\pm\ \pi^\pm$ spectrum[119] (see Fig.26d and e). The identical value of the mass for both of these cases leads one to believe that these are two decay modes of the same particle.

Considering now spin-parity assignments for the 2 decay modes, we note that $K^o\pi^\pm$ is a system of 2 0^- mesons. Accordingly, its J^P assignment has to have natural spin parity, namely $P = (-1)^J$ i.e. 0^+, 1^-, 2^+, 3^-.... On the other hand, the $K\pi\pi$ system is composed of 3 0^- mesons and as such has to have a vanishing population at the boundaries[121] for natural spin-parity assignments. This is not the case, as illustrated by the data[122] shown in Fig. 27. The symmetrized Dalitz plot shows no depopulation around the boundaries for the resonant $K^\mp\pi^\pm\pi^\pm$ events (Fig. 27a). For comparison we also show the non-resonant $K^\pm\pi^\mp\pi^\mp$ events in the same mass region.

For low values of the spin, the argument can be made even more quantitative. We consider the J^P assignments of 0^+, 1^-, 2^+. The first state is absolutely forbidden for 3 0^- mesons. The 1^- assignment would

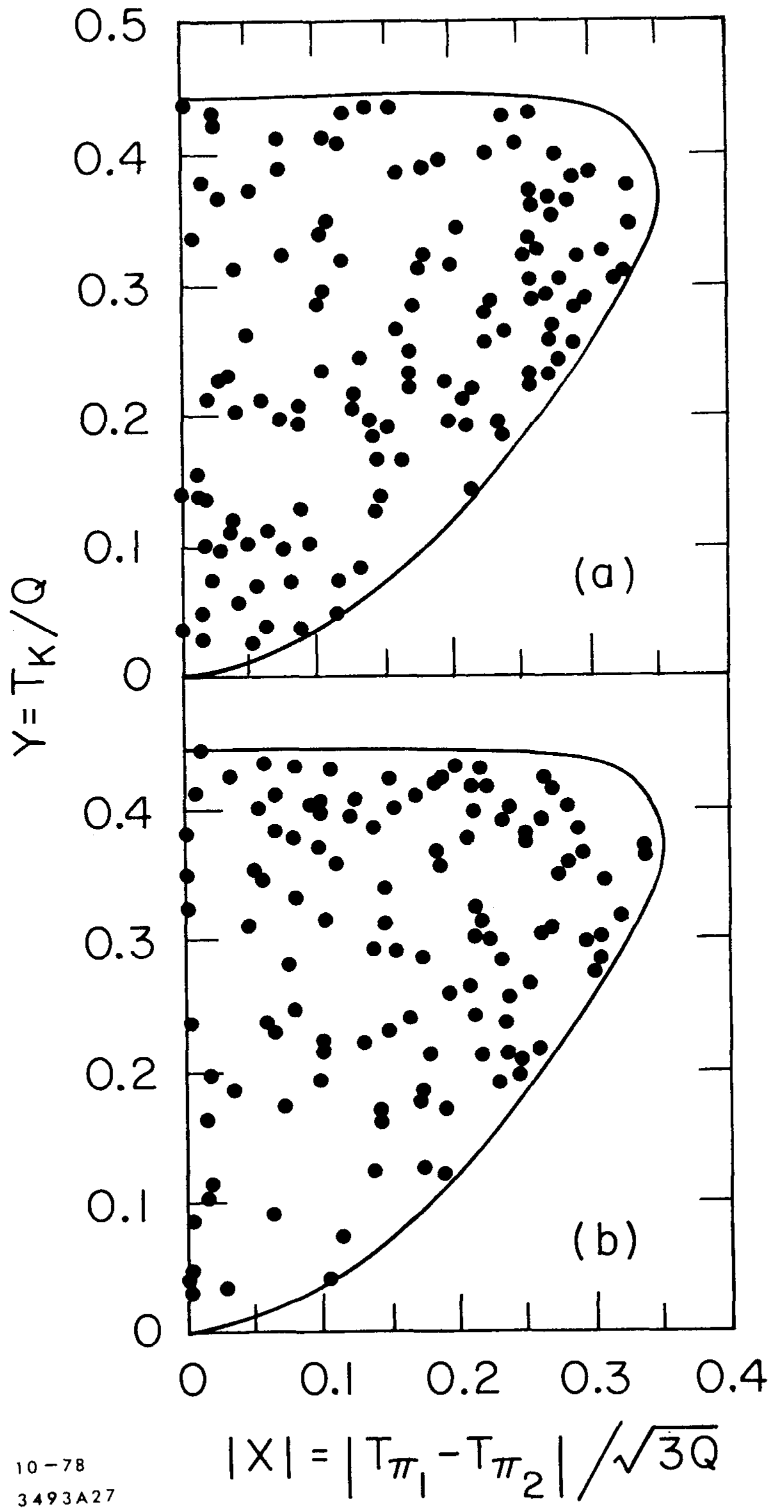

Fig. 27 Synmetrized Dalitz plots for the $K\pi\pi$ system in the mass region of 1.86-1.92 GeV/c^2. (a) Exotic combinations $K^{\mp}\pi^{\pm}\pi^{\pm}$; (b) Non-exotic combinations $K^{\pm}\pi^{+}\pi^{-}$. Q is the sum of the kinetic energies of the 3 final state mesons. The data is from the SLAC-LBL collaboration.

predict an additional zero at the symmetry axis and the 2^+ on additional zero at the top of the Dalitz plot.[121] Accordingly we can now consider the size of the enhancement in the $K^{\mp}\pi^{\pm}\pi^{\pm}$ mass spectrum for both the allowed and forbidden regions of the Dalitz plot under the hypothesis that the J^P assignment is either 1^- or 2^+. The dividing line on the Dalitz plots was chosen in such a way that for a 0^- assignment (i.e. a flat Dalitz plot population) the two peaks would be equal. As is clear from Fig.28, the two enhancements are equal within statistics (the ratio of the enhancement in the allowed to the forbidden regions would be 8.2 and 5.6 for the 1^- and 2^+assignments respectively)excluding the natural spin parity assignments. Accordingly,we must conclude that the parity is not conserved in this process.

c) Comparison with the GIM predictions. We have already seen how the central prediction of the GIM model, i.e. existence of narrow states characterized by the new quantum number charm has been verified experimentally. In this section we shall consider how well does the data agree with the other predictions of the GIM model.

The GIM model requires that the final state of the decay products of $D^{\pm}$ have exotic quantum numbers, i.e. quantum numbers that can not be possessed by any $q\bar{q}$ combination. This is because in terms of quark transitions, the D decay corresponds to

$$c \rightarrow s + W^+$$

and thus the final physical state can have quantum numbers S=-1, Q=1 (for D^+ the quark composition of the initial state is $c\bar{d}$) which are inaccessible to any $q\bar{q}$ pair.

Thus, more specifically,we have the prediction that

$$D^+ \rightarrow K^-\pi^+\pi^+$$

should be an allowed decay whereas

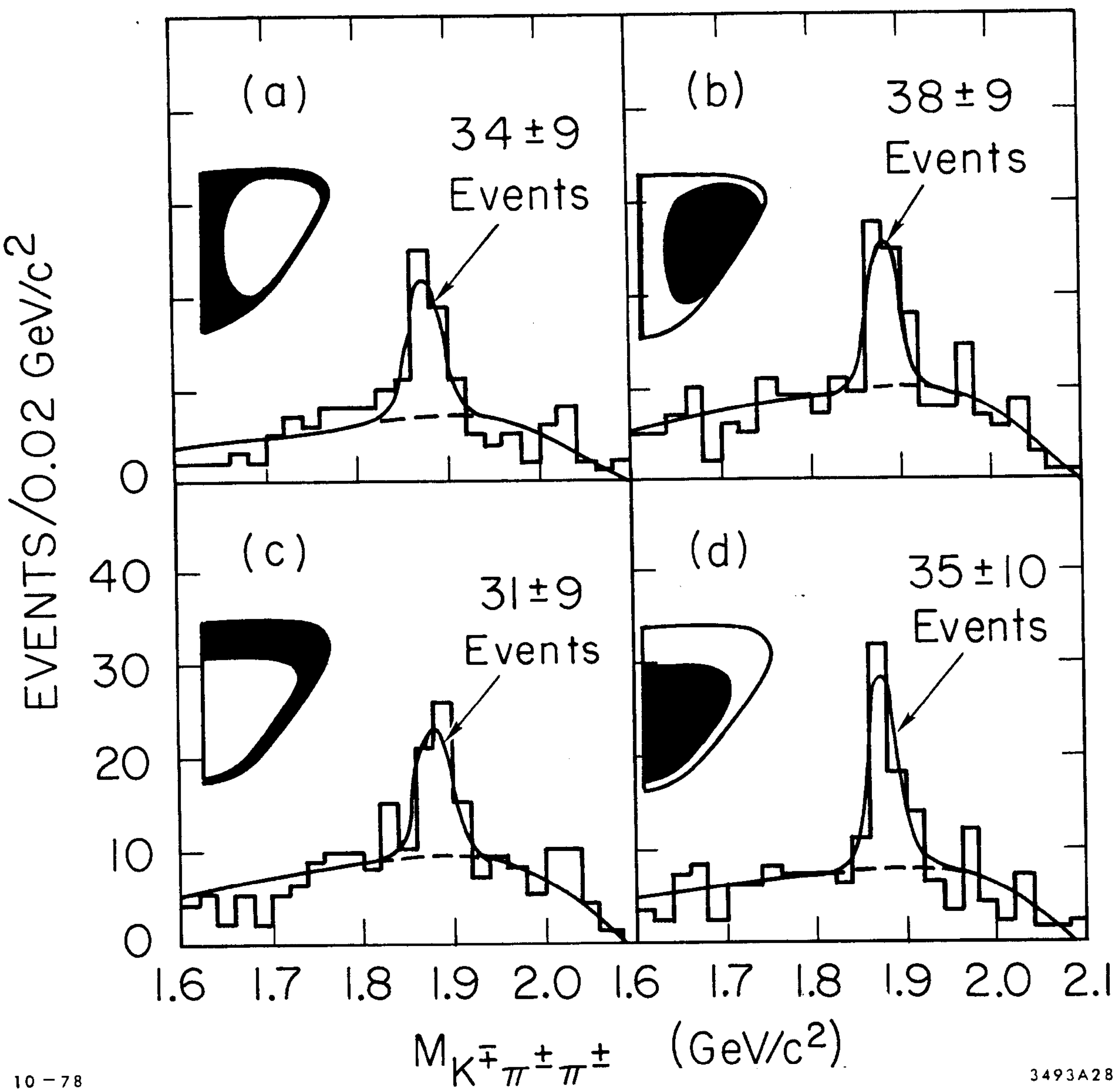

Fig. 28 Mass plot for the exotic Kππ system. Forbidden (a) and allowed (b) regions for 1^- matrix element and forbidden (c) and allowed (d) regions for 2^+ matrix element. The data is from SLAC-LBL callaboration.

$$D^+ \to K^+\pi^+\pi^-$$

should be forbidden. This prediction was confirmed in the first observation[123) of a bump in the $K\pi\pi$ state by Peruzzi et al. whose data is displayed in Fig. 29. The sharp enhancement present at 1.876 GeV/c^2 in the exotic combination is totally absent in the nonexotic channel.

The second quantitative prediction of the GIM model has to do with the Cabibbo favored nature of the $c \to s$ transition, and hence the Cabibbo suppressed nature of the $c \to d$ transition. Thus the former decays should be enhanced by a factor of $\tan^2\theta$ as compared to the decays into non strange final states. This prediction will be somewhat modified by the phase space factor that will enhance the non-strange decays by ≈ 2 and by possible dynamical effects. The experimental data at 4.028 GeV for both 2 and 3 body decays[124) is summarized in Table XII.

Table XII

Comparison of Cabibbo suppressed and forbidden decays

	σB for $K^\mp\pi^\pm(K^\mp\pi^\pm\pi^\pm)$	σB for $\pi^+\pi^-(\pi^+\pi^-\pi^\pm)$	σB for K^+K^-
2 body	0.57 ± 0.11 mb	< 0.04 mb	< 0.04 mb
3 body	0.40 ± 0.10 mb	< 0.03 mb	

Even though the Cabibbo suppressed decays have not yet been observed, the data does indicate strongsuppression of $\Delta S=0$ transitions á la GIM model.

Finally we can ask what is the measured number of K's associated with the D production, since the GIM model predicts this number to be very close to 2. Experimentally, one looks at multihadron events with an electron, on the hypothesis that those events represent associated production of $D\bar{D}$ pair, followed by a semileptonic D decay, and measures the $K^\pm$ content in those

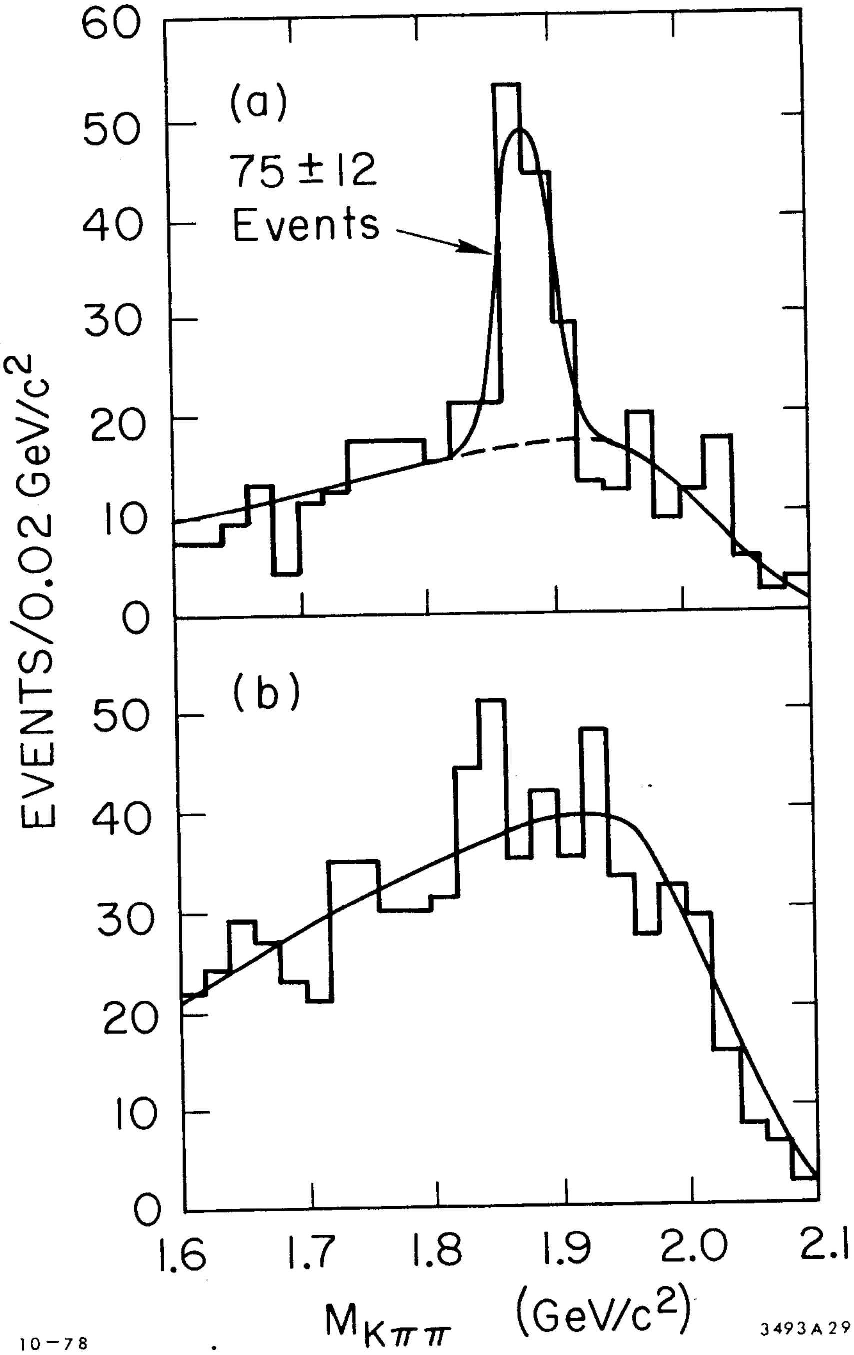

Fig. 29 The $K\pi\pi$ mass distribution with the cuts designed to enhance the signal to background ratio: E_{CM}= 3.90-4.25 GeV and M_{rec}=1.96-2.04 GeV/c^2. (a) Exotic combinations; (b) non-exotic combinations. The data is from the SLAC-LBL collaboration.

events. The result is 0.90 ± 0.18 $K^{\pm}$/electron event, in excellent agreement with GIM if one doubles this number for possible K^{o}'s.

d) <u>(Semi) leptonic decays</u>. We shall start by making some comments about purely leptonic decays of the charmed mesons. In general for the decay

$$M \to \ell \nu$$

where M is a 0^- meson, we have

$$\Gamma = \frac{G^2}{8\pi} f_M{}^2 \begin{pmatrix}\cos^2\theta \\ \sin^2\theta\end{pmatrix} m_\ell{}^2 \left(1 - \frac{m_\ell^2}{m_M^2}\right) m_M$$

where f_M is the coupling constant that in the limit of perfect SU_4 would be equal to f_π, and $\cos^2\theta$ ($\sin^2\theta$) is used for the Cabibbo favored (suppressed) decays. We now make some general observations:

1 - electronic decays are totally negligible

2 - F leptonic decays will be enhanced over D leptonic decays by roughly a factor of $\tan^2\theta$. Specifically, we expect

$$\Gamma\ (D \to \mu^+\nu) \approx 2 \times 10^8\ \text{sec}^{-1}$$

$$\Gamma\ (F \to \mu^+\nu) \approx 3.6 \times 10^9\ \text{sec}^{-1}$$

Compared to a total <u>estimated</u>[126)] semileptonic rate of the F of $\approx 10^{12}\ \text{sec}^{-1}$.

3 - expected decay rate for

$$F^+ \to \tau^+\nu$$

should be about 16 times larger than the $F \to \mu\nu$ rate.

Not surprisingly, none of these decays have been observed as yet.

We turn next to the question of semileptonic decay modes of charmed mesons. The first interesting problem here is the total semileptonic branching ratio. That number tells us right away whether there exists in the charm decays an enhancement of the purely hadronic decays analogous to the situation in strangeness violating decays (see our previous discussion of $\Delta I=1/2$ rule).

Very crudely we can estimate the total D semileptonic decay rate by assuming that it proceeds via the fundamental process

$$c \to s + \ell + \nu$$

and then the rate can be related easily to the total muon decay rate via

$$\Gamma^{tot}_{D\to e\nu x} = \Gamma^{tot}_{D\to\mu\nu x} = \left(\frac{m_D}{m_\mu}\right)^5 \Gamma^{tot}_{\mu}$$

This kind of calculation gives $\sim 3 \times 10^{12}$ $\sec^{-1}$ for the total semileptonic rate into $e\nu$ + hadrons (or $\mu\nu$ + hadrons). In this simple picture, the total hadronic decay rate would then be given by

$$c \to s + \mu + \bar{d}$$

resulting in a comparable rate times the appropriate hadronic enhancement factor.

There appears to be some theoretical disagreement whether the mechanisms believed responsible[127)] for the octet enhancement in "old" particle decays will be relevant when carried over to the case of charm decays. More specifically the quantitative estimates for semileptonic branching ratios range from a low[128)] of about 1%, corresponding to an enhancement equivalent to one found in strange particle decays to about 25%, corresponding to essentially no enhancement at all.[126)] We shall say more about the details of hadronic enhancement when we discuss the nonleptonic decays, but in the meanwhile we turn to see what do the semileptonic decay data have to say about this question.

There are now several independent measurements of the total semileptonic rate, obtained by means of slightly different primary measurements.

One can measure the total semileptonic rate by comparing $R_e(R_\mu)$ i.e. cross section for production of hadrons associated with an electron (muon) expressed in terms of point cross section, with R_{charm} i.e. total charm contribution to R. We have then

$$BR(e) = 2\ R_e/R_{charm}.$$

We should note that this procedure gives the branching ratio for all charmed ground states (i.e. states decaying weakly) weighed by their production rate, i.e.

$$2\ R_e/R_{charm} = \sum_i \sigma_i\ BR_i/\Sigma\sigma_i$$

Alternatively one can compare the rise in R_e vs. the rise in R at ψ''. This has the fundamental simplicity of measuring effectively an average branching ratio for D^o and D^+ since their production rates there are almost equal (except for phase space factors).

Finally, the branching ratio can be extracted by a comparison of R_{2e} with R_e (R_{2e} is the total rate of hadronic events accompanied by 2 electrons). The last 2 measurements together can in principle disentangle any possible difference between the D^o and D^+ branching ratios.

We shall discuss first the experimental measurements at low energies:

1 - The lead glass wall (LGW) collaboration[129)] has measured the D^o-$D^\pm$ B.R. into $e\nu X$ at the ψ'' (3.77) to be 7.2 ± 2.6% by looking at the total number of eX events. The result is mildly dependent through the detection efficiency on the assumption that the two dominant decay modes $Ke\nu$ and $K^*(890)e\nu$ are equal.

2 - The DELCO group[130)] has measured the same branching ratio at the ψ'' by comparing the relative sizes of the Breit-Wigner peaks in both R_e and R (see Fig. 30). They obtained 11 ± 2%.

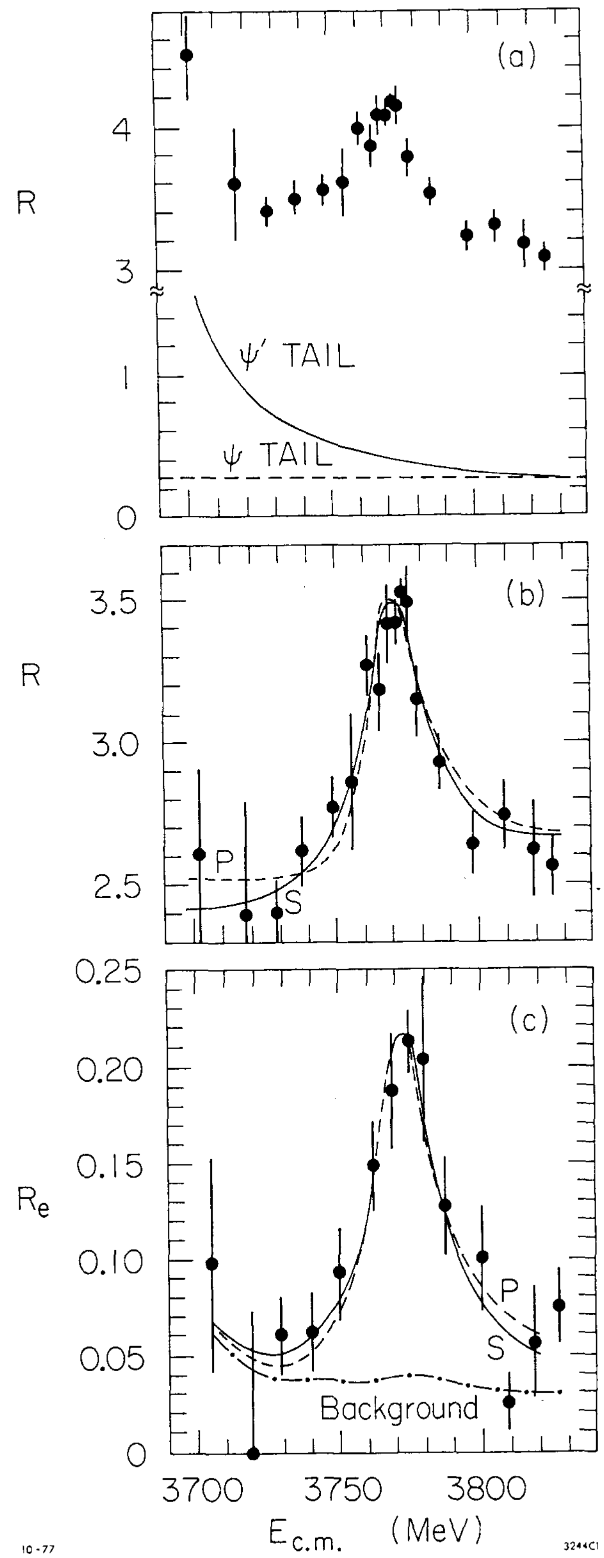

Fig. 30 DELCO data used in extracting the D semileptonic branching ratio at the ψ". (a) raw R plot, (b) R plot after subtracting the ψ and ψ′ tails and (c) R_e plot. The curves are P wave and S wave fits to the resonance.

3 - The DASP group[131)] has obtained 11 ± 3% for the eX branching ratio overaged over a wide energy range. The majority of their data however comes from 4.03 GeV total energy point, and thus should reflect mainly D^o and $D^\pm$ contributions.

As we can see, all the experiments are consistent with a number $BR_e \approx 10\%$, indicating that the hadronic enhancement discussed above is probably not very important in the charm decays.

The lead glass wall collaboration[132)] has also published their determination of BR_e as a function of energy. Their average value, 8.2 ± 1.9% is consistent with the DASP value quoted above and with the low energy (3.77 GeV) measurements. Taken at face value, that implies either that there is very little F and charmed baryon production or that the F and the charmed baryons have a semileptonic rate comparable to that of the D mesons. As seen from Fig. 31, however, the experimental errors are large enough so as yet no strong statement on this point can be made from the published data.

We should finally mention two values for the electronic branching ratio obtained from the comparison of R_{2e} and R_e, i.e. 16 ± 6% from the DASP collaboration[131)] and a preliminary value from DELCO of 16 ± 4%.[133)] The experimental uncertainties are too high to be able to conclude anything meaningful at this time about the possible difference of $D^\pm$ and D^osemileptonic branching ratios.

We turn next to the question of specific exclusive channels responsible for the D semileptonic decay rate. The most likely candidates are the Keν and K^*(890)eν final states, the K^*(1400)eν final state being suppressed by phase space, and the Keν(nπ) channels expected to be negligible by virtue of the soft pion theorems.[117,134)] One rough theoretical estimate[126)]

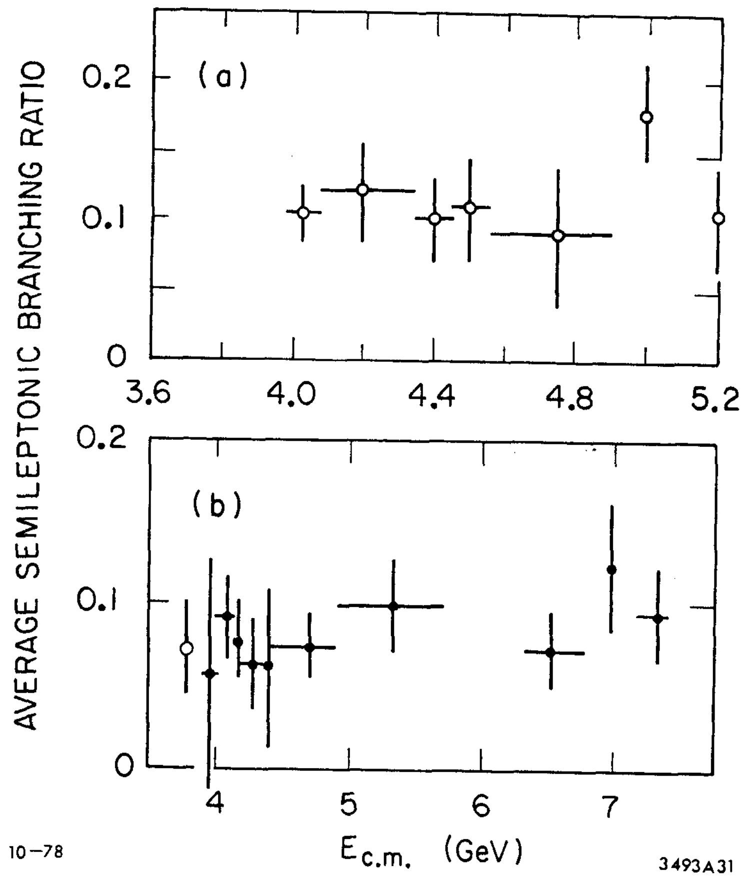

Fig. 31 The average branching ratio for charmed particle decay into an electron plus additional particles vs. the center of mass energy (a) DASP data; (b) LGW data.

indicates that the $Ke\nu$ rate should form about 30% of the total semileptonic rate.

Experimentally, the electron momentum spectrum appears to be the most sensitive way to extract this information from the e^+e^- annihilation data. The two expected spectra, however, i.e. for $Ke\nu$ and $K^*e\nu$ decay modes, do not differ very much[134,135] and one has to exercise considerable care in understanding the experimental backgrounds and detection efficiencies to be able to draw correct conclusions. Some of the relevant backgrounds are:

1 - hadrons misidentified as electrons

2 - τ multibody decays

3 - Cabibbo suppressed decays.

The first source would tend to enhance the lower end of the spectrum, the latter two the higher end. The experimental situation at the present time is inconclusive, appearing to favor sizable contributions from both the $Ke\nu$ and $K^*(890)e\nu$ modes. Figs 32 and 33 display the published DASP[131] and LGW[132] data together with some curves giving an estimate of the expected spectral shapes for the two hypotheses as well as the shape of the backgrounds. The DASP collaboration quotes 35 ± 30% as the fraction of $Ke\nu$ in the total semileptonic rate. The preliminary data from DELCO[136] is shown in Fig. 34. A 50-50 mixture of $Ke\nu$ and $K^*e\nu$ gives an adequate fit to the data. This problem can probably be best settled by looking at $D\bar{D}$ events at 3.77 GeV where one D is tagged by its hadronic mode and then doing kinematical reconstruction on the remaining particles.

A slightly more indirect information on this question can be obtained from the study of $D^{\pm} \to K^{\mp} + X$ inclusive rate. The hadronic rates contributing to this process would be $K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^o$, and other final states involving 4 or more pions. Furthermore, the $Ke\nu$ state cannot contribute

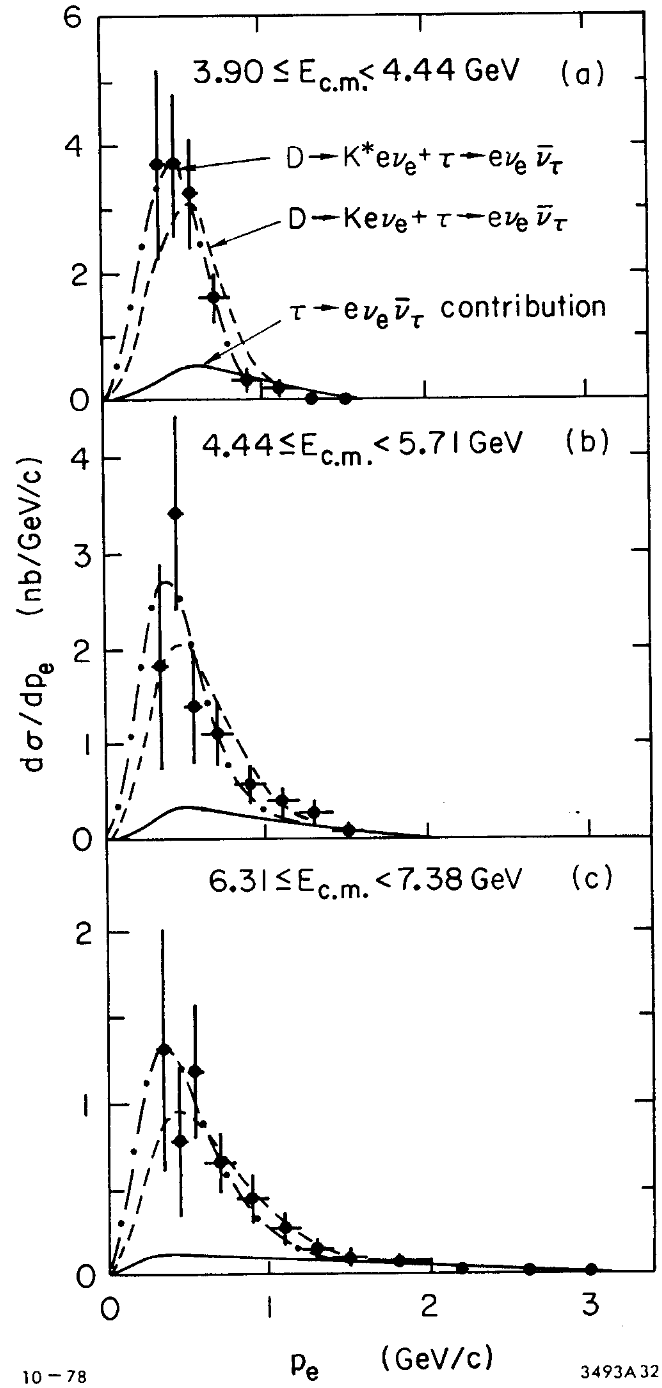

Fig. 32 The electron momentum spectrum from the electron multi-prong events from the LGW experiment for the 3 different center of mass energies.

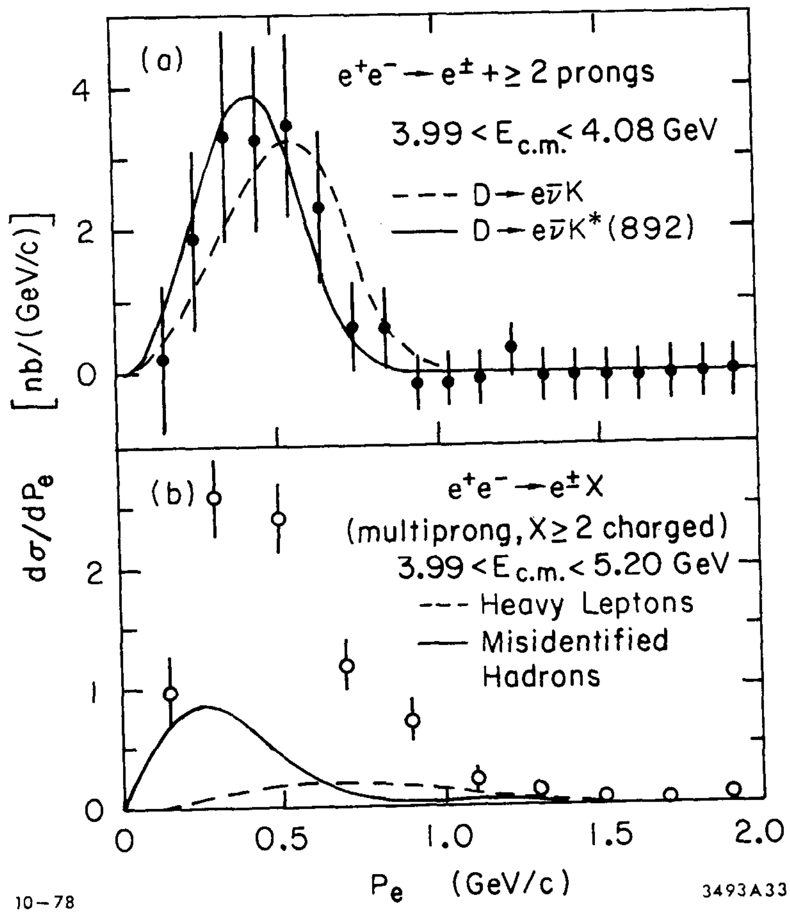

Fig. 33 The electron momentum spectrum from electron-multi prong events from the DASP experiment for the 4 GeV E_{CM} region (a) and all the data (b).

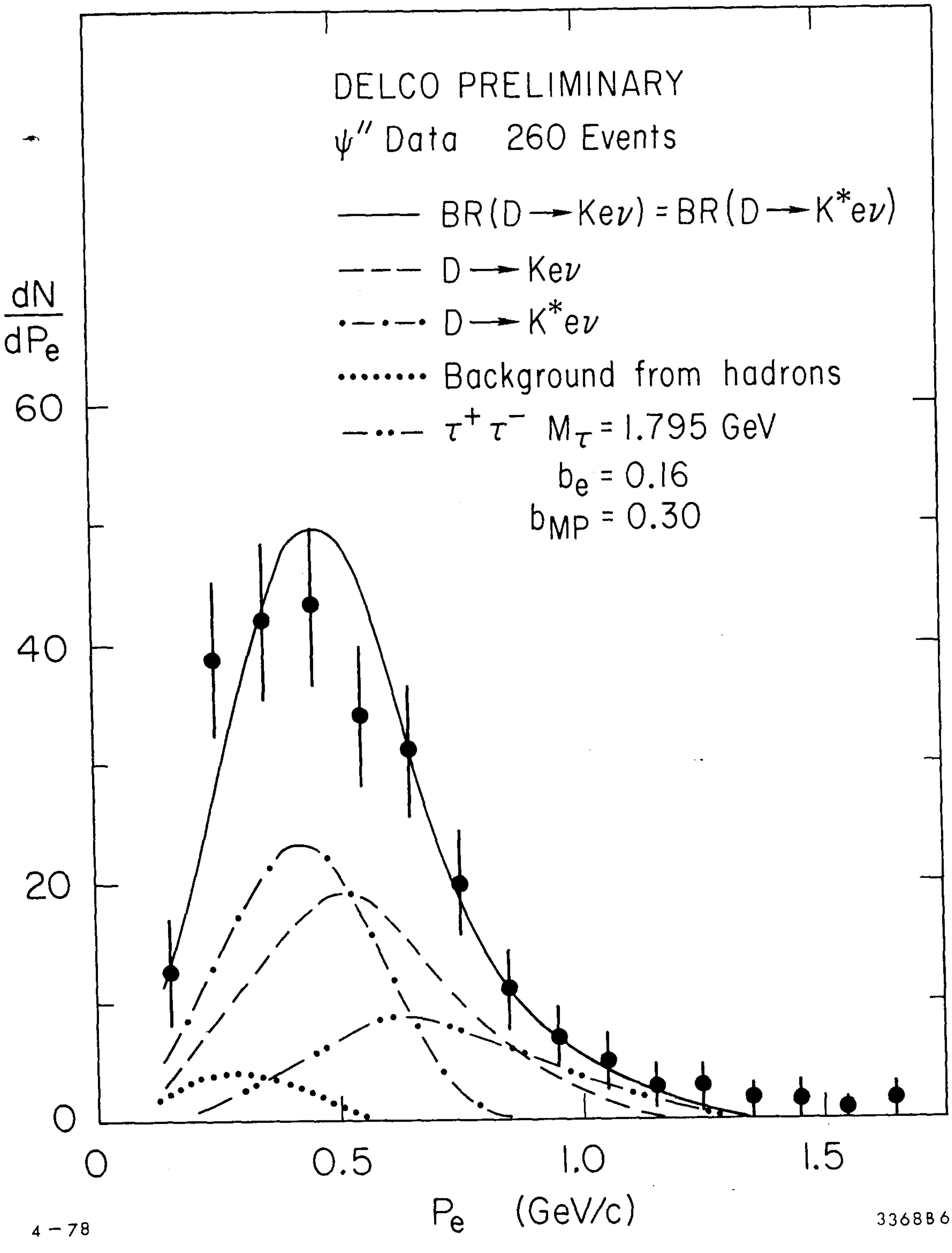

Fig. 34 The preliminary electron momentum spectrum from the electron multi-prong events from the DELCO experiment.

here (final state is $K^o e^+ \nu$) but 2/3 of the $K^{*o} e^+ \nu$ state will decay via $K^- \pi^+ e^+ \nu$. Thus we can see whether the purely hadronic states already saturate the experimental inclusive rate, or is there still room for some $K^* e\nu$ and $K^* \mu\nu$ decay.

The published experimental number from the SLAC-LBL collaboration[137)] for the inclusive rate is 10 ± 7% to be compared with the $K^- \pi^+ \pi^+$ rate of 3.5 ± 0.9% and the expected contribution of the 4 and 5 body hadronic states with a charged K of about 20-25% according to the statistical model of Quigg and Rosner.[138)] A 100% $K^* e\nu$ contribution to the semileptonic rate would add another 13% to this rate (assuming 10% BR each for e and μ semileptonic rate of $D^\pm$). Thus the room for an appreciable amount of $K^* e\nu$ appears limited.

Some information on the $Ke\nu/K^* e\nu$ ratio question is also available from the high energy ν-Ne interactions at FERMILAB. The Columbia-BNL group has observed both the $\mu^- e^+$ events[139)] and the process[140)]

$$\nu_\mu + Ne \rightarrow \mu^- + D^o + \ldots . \qquad D^o \longrightarrow K^o \pi^+ \pi^-$$

(see Fig. 35). Thus, at least some fraction of the $\mu^- e^+$ events must be due to

$$\nu_\mu + Ne \rightarrow \mu^- + D^o + \ldots \qquad D^o \longrightarrow e^+ + \ldots .$$

and therefore study of μe events with a K^o, and specifically of the $K^o e^+$ and $K^o \pi^-$ mass spectra should provide some information about the relative strenths of the $D^o \rightarrow Ke\nu$ and $D^o \rightarrow K^* e\nu$ decay modes.

The experimental situation[141)] on these points is far from clear for the following reasons:

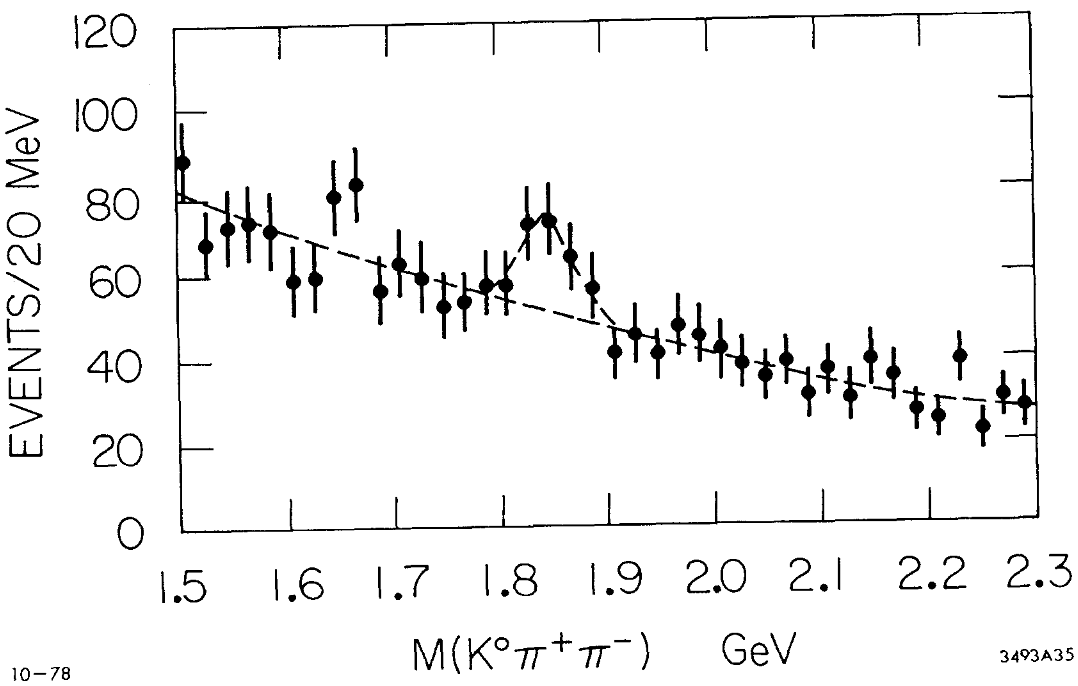

Fig. 35 $K^o\pi^+\pi^-$ mass spectrum for events with a μ^- from the Columbia-BNL ν-Ne experiment.

1 - Presumably some of the $\mu^- e^+$ events come from semileptonic decays of charmed particles other than D^o, i.e. D^+, F, charmed baryons, etc. Thus, we should have the inequality

$$\frac{\mu^- e^+}{\mu^- (K^o \pi^+ \pi^-)_{D^o}} \geq \frac{BR(D^o \to e^+ + \ldots)}{BR(D^o \to K^o \pi^+ \pi^-)}$$

where the left hand side represents the number of events of each type from the Columbia-BNL experiment and the right hand side can be obtained from e^+e^- annihilation measurements on <u>the assumption</u> that the D^o and D^+ semileptonic decay rates are equal. Using the data of ref. 140 and the LGW data on branching ratios, the inequality reduces to

$$(0.7 \pm 0.3) \geq (1.8 \pm 0.9)$$

Use of the DELCO or DASP numbers would raise 1.8 on the right hand side to 2.7. Maybe even more importantly, if one also uses the DELCO and DASP data, the error on the right hand side becomes essentially the fractional error on $K^o \pi^+ \pi^-$ branching ratio, i.e. $\approx$ 30%. Thus there appears to be a discrepancy here, possible explanations of which are:

a) statistical fluctuation
b) BR $(D^+ \to e^+) >> $ BR $(D^o \to e^+)$
c) an error in one of the data inputs.

2 - The mass spectrum of the $K^o_s\, e^+$ system (Fig. 36) appears to favor the $K^* e\nu$ decay hypothesis rather than the $Ke\nu$ hypothesis. It must be remembered, however, that if it is the D^o's that are dominantly produced here, then the 3 body semileptonic decay mode would not give a K^o (since $D^o \to K^- e^+ \nu$). The majority of the K^o's that are observed would then be produced directly rather than come from the D decay (i.e. we have charm production from the sea s quarks).

3 - There appears to be no significant enhancement in the $K^o \pi^-$ spectrum at 890 MeV for those events where $m(K^o \pi^- e^+) < 1900$ MeV, i.e. $K^o \pi^-$ combinations compatible with having originated from a D^o decay (see Fig. 36a).

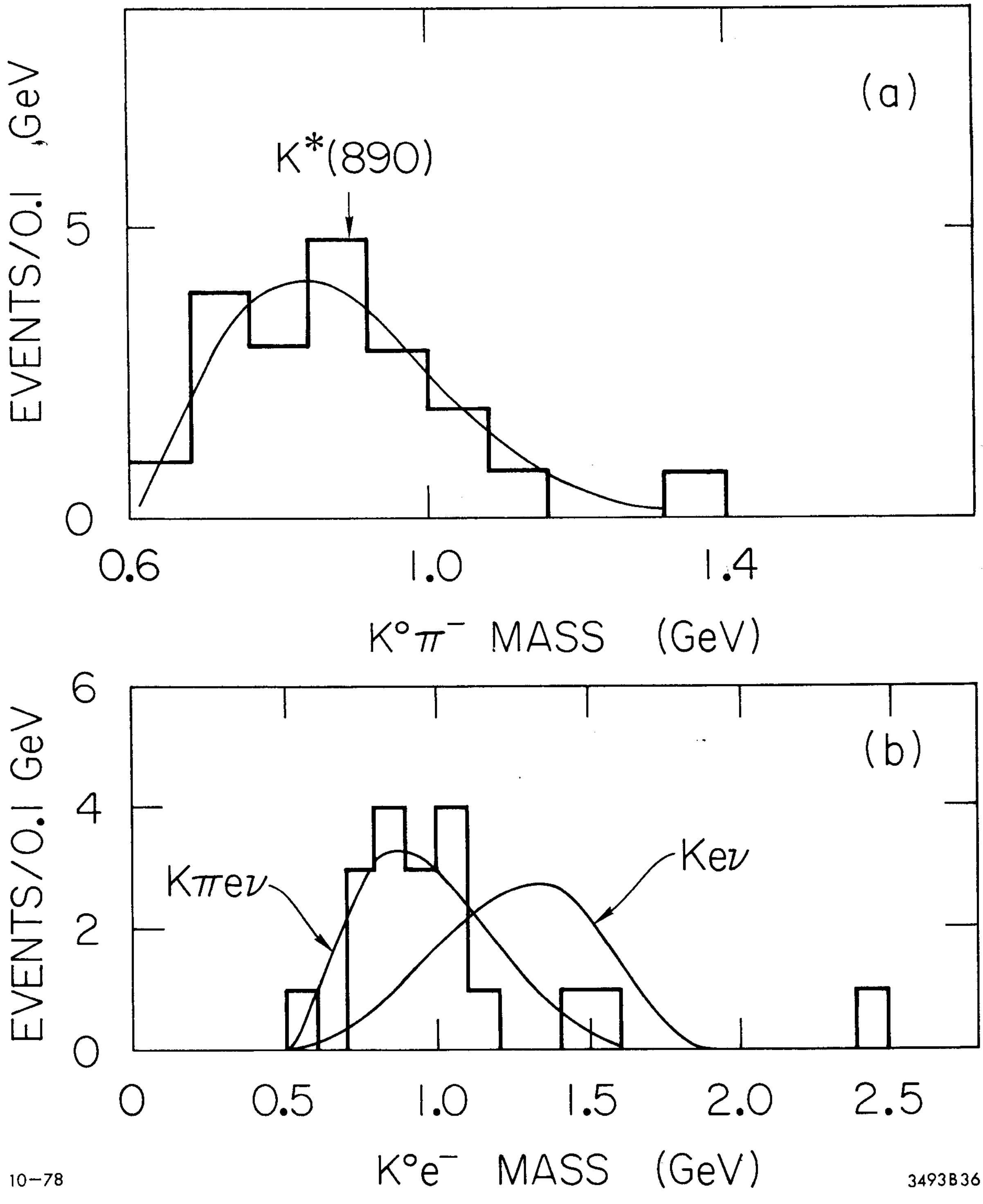

Fig. 36 (a) $K^o\pi^-$ mass spectrum for Columbia-BNL events of the type ν_μ+Ne → $\mu^-K^oe^+\pi^-$+ ... with $M(K^oe^+\pi^-) < M_D$.

(b) K^oe^+ mass spectrum for events of the type ν_μ+Ne → μ^-+K^oe^++ .... Only single V events have been included.

Clearly, no conclusion can be drawn here and the resolution of some of these experimental discrepancies must await further data.

e) Hadronic decays of the D mesons. We start by reviewing briefly the theoretical ideas leading to the possible extension to the SU_4 of the octet enhancement concept in SU_3. Consider a product of 2 hadronic currents i.e. $(\bar{u}d)(\bar{s}\mu)$; its transformation properties will be those of a $\pi^- K^+$ system and thus the isotopic spin decomposition will give

$$\sqrt{\frac{2}{3}}\, |\ 1/2,\ -1/2 > - \frac{1}{\sqrt{3}}\, |\ 3/2,\ -1/2 >$$

i.e., both T=1/2 and T=3/2 pieces. Experimentally, we have the $\Delta I=1/2$ rule which appears to work to a few percent; theoretically[127,128] it is attractive to explain it through the idea of octet enhancement. The Hamiltonian in general can have transformation properties of an octet or a 27 representation; it is only the latter that contains a T=3/2 pieces and thus enhancing the 8 will automatically generate the approximate $\Delta I=1/2$ rule.

In SU_4, the 8 is replaced by the 15, so again if our Hamiltonian is to be of the current form, i.e.

$$H_w = JJ^+ + \text{h.c.}$$

then we must decompose 15 x 15. If we limit ourselves to the symmetric terms since H_w is symmetric, then we are left with $1 \oplus 15 \oplus 20 \oplus 84$. The presence of charm and strangeness changing transistions excludes the singlet, and the 15 does not occur for the GIM current.[142] We can now consider the SU_3 decomposition of the two remaining representations, i.e. 20 and 84. The charm conserving SU_3 multiplet in the 20 is the 8; in the 84 we have 1, 8, and 27. Thus it is clear that to eliminate the 27 in SU_3 one should eliminate the 84 in SU_4, and the SU_4 equivalent of octet enhancement in the 20-plet enhancement.

To consider the experimental ramifications of this ansatz we decompose the 20 into SU_3 multiplets i.e.

$$20 = 6 \oplus 8 \oplus 6^*$$

where the 8 gives us the charm conserving transitions, and 6 and 6^* $\Delta C=+1$ and $\Delta C=-1$ transitions respectively. The sextet dominance reduces the number of parameters needed to describe the $\Delta C=\pm 1$ transitions and thus leads to some rather stringent relations between different possible decay modes. Specifically, all 26 charm changing decays of a pseudoscalar meson into two pseudoscalar mesons can be represented in terms of one common parameter.[143) As mentioned before, there have been arguments put forth[126) to the effect that the 20 enhancement in SU_4 will be minimal, a point of view at least partially supported by the semileptonic total branching ratios. What we want to emphasize here, however, is that the enhancement hypothesis is subject to a rather direct experimental test.

Experimentally, the most significant pieces of information have to do with the measured branching ratio for $D^+ \to \overline{K^o}\,\pi^+$, $D^o \to K^-\pi^+$, and $D^o \to K^-\pi^+\pi^o$. The interest in the two body decays stems from the fact that in the sextet dominance model we have the prediction,

$$\Gamma\,(D^+ \to \overline{K^o}\pi^+) = 0 \qquad \Gamma\,(D^o \to K^-\pi^+) \neq 0$$

On the other hand, the experimental <u>branching ratios</u> for these two decay modes are comparable, i.e.[120)

$$BR\,(D^+ \to \overline{K^o}\pi^+) = 1.5 \pm .6\%$$

$$BR\,(D^o \to K^-\pi^+) = 2.2 \pm .6\% \quad .$$

To reconcile the data with the prediction of the sextet dominance we have to require that the D^+ lifetime be significantly larger than the D^o lifetime. We can define ratio R by

$$R \equiv \Gamma_{TOT}\,(D^+)/\Gamma_{TOT}\,(D^o) \quad .$$

The model would be in good shape if R were small. Accordingly, we shall consider next the general theoretical considerations regarding the value of R.

If the Hamiltonian for the charm charging decays is of the current current form then it must be mainly of the $\Delta T=1$ type. This can be seen easily if we consider the relevant transition in the quark picture, i.e. $c \to s\, u\, \bar{d}$. This has the implication that in D^+ decays the final state can be only $T = 3/2$; in the D^o decays however, it can be a mixture of both $T = 3/2$ and $T = 1/2$ (to see that consider for example $D^+ \to K^-\pi^+\pi^+$ and $D^o \to \overline{K^o}\pi^+\pi^-$). This difference leads to bounds on R, i.e.

$$0 \le R \le 3$$

as first pointed out by Peshkin and Rosner[144] and independently by Pais and Treiman[143];

We consider next the experimental information on the $D \to K\pi\pi$ channels that has a bearing on this question.

The experimental facts are the following:

1 - The two relevant branching ratios are

$$BR(D^+ \to K^-\pi^+\pi^+) = 3.9 \pm 1\%$$ [120]

$$BR(D^o \to K^-\pi^+\pi^o) = 12 \pm 6\%$$ [146]

2 - The Dalitz plot population for the $K^-\pi^+\pi^+$ decay mode is consistent with being flat[122] i.e. there is no evidence for any $K\rho$ or $K^*\pi$ contribution.

In addition, from the consideration of the $\Delta T=1$ rule in this decay, we have a theoretical prediction

$$\Gamma(D^+ \to K^-\pi^+\pi^+) = 4\ \Gamma(K^-\pi^+\pi^o)$$

which is valid for the case of no important intermediate state (i.e. flat Dalitz plot).

Combining the experimental information with the theoretical prediction one obtains $R=12 \pm 6$. The errors on this number are still large, but should this result hold up with better statistics, it would be a serious problem as emphasized by Rosen.[148)] The least painful way to get out of it would be to accept important contributions due to $K^*\pi$ and/or $K\rho$ which, in light of limited statistics at the present time, might still be compatible with the data.

We see thus the fundamental contradicting demands made on R; the 2 body data requires R to be significantly less than 1, the 3 body data wants R as large as possible. One should emphasize here that the $K\pi\pi$ problem is independant of the idea of sextet dominance; even if we abandon the sextet enhancement, on much more general grounds we have the requirement that $R \leq 3$. Parenthetically, we should remind the reader that a small R would also solve the apparent discrepancy discussed previously between the νNe data and the D branching ratios.

In principle, at least, the question discussed above can be resolved by extracting the separate semileptonic branching ratios for D^o and D^+, since the absolute rates for these decays have to be equal.[149)] That question should be answered soon, either by comparing the R_{2e}/R_e rates or by comparing the D branching ratio numbers extracted at 3.77 and at 4.03 where the relative production rates for D^o and $D^\pm$ are significantly different.

We finally say a few words about some more general treatments of hadronic decays of charmed particles. Quigg and Rosner[138)] have used a statistical model to estimate the relative branching ratios. That kind of model would be expected to be very good in the limit of very high mass of the parent particle and large multiplicity. On the other hand, for decays involving only 2 or 3 particles special dynamical effects might become important. The general predictions of this model are illustrated in Fig. 37, for both the D^o and $D^\pm$ decays. The predicted branching ratios

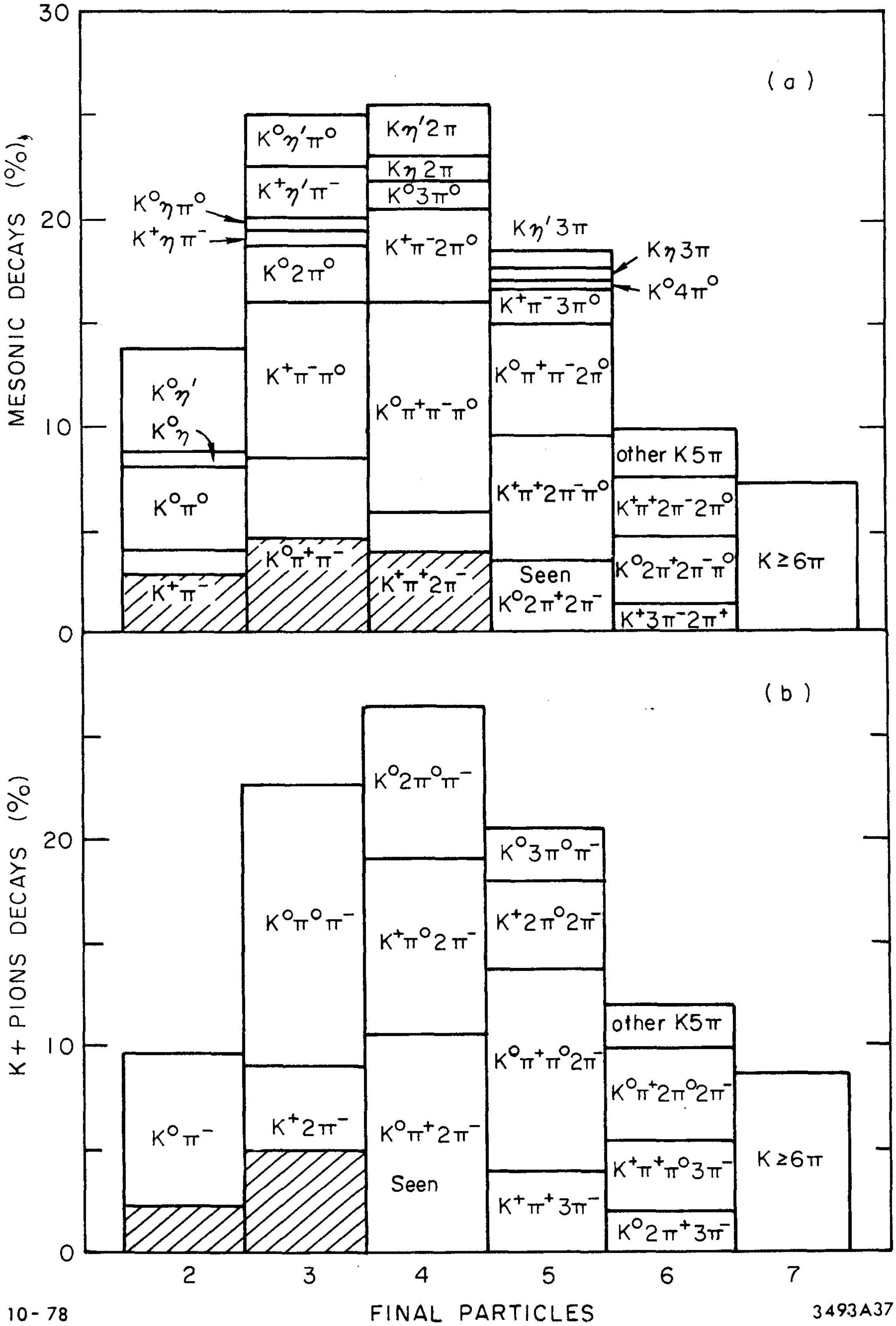

Fig. 37 Predictions of the statistical model for (a) D^0 hadronic decays and (b) $D^{\pm}$ hadronic decays. The shaded areas are the experimental results from the LGW collaboration.

have been renormalized to take account of the fact that the model does not calculate the semileptonic decays (or decays involving η's for $D^{\pm}$). The shaded regions represent the experimental measurements.

In general, as can be seen from Table XIII the model predicts a higher charged multiplicity than is observed experimentally.

Table XIII

Comparison of statistical model predictions with experiment

	$\langle n_{c_{D^o}} \rangle$	$\langle n_{c_{D^+}} \rangle$
Model predictions	3.0	3.1
Experiment (Ref. 137)	2.3±0.3	2.3±0.3

S. Kaptanoglu has adopted a different approach,[151)] namely one utilizing PCAC with an extrapolation to physical region that takes final state interactions into account. He also explicitly requires the validity of ΔT=1. He finds that final state interactions without requiring a specific resonant state contributions, can give significant enhancements for some of the decay modes. We should also mention that L. Maiani[152)] has calculated the two body decay rates of charmed particles using the parton model. He gets a good agreement with the experiment for the ratio of the branching fractions for $D^o \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^o \pi^+$.

In summary, we can say that the situation of the hadronic decays of D mesons is far from understood. As can be seen from Fig. 37, the experimental data is very scanty, and some of these questions probably will not be answered until more information is forthcoming.

f) <u>D^o - $\overline{D^o}$ mixing</u>. We expect here an analogous situation with the K^o-$\overline{K^o}$ system, i.e. physical states will be

$$\psi = \frac{1}{\sqrt{2}} (D^o \pm \overline{D^o})$$

where ψ is a state characterized by a definite mass and lifetime. In other words just as we have second order transitions, i.e.

$$K^o \leftrightarrow i \leftrightarrow \overline{K^o}$$

where i is some intermediate state that can communicate both with the K^o and $\overline{K^o}$ system via 1st order weak interaction so we expect also to have

$$D^o \leftrightarrow i \leftrightarrow \overline{D^o}$$

There is, however, an important difference here: whereas in the K^o, $\overline{K^o}$ system one of the intermediate states could have been $|\pi^+\pi^-\rangle$, i.e. the dominant decay mode, here the allowed intermediate states are the Cabibbo suppressed states i.e. $|n\pi's\rangle$ since the states with non zero strangeness cannot communicate with both D^o and $\overline{D^o}$. Thus, whereas for K^o-$\overline{K^o}$ system we have $\Gamma_s \approx \Delta m$, in the charmed system the ratio of the off-diagonal to diagonal terms is expected to be $\approx \tan^4\theta_c$ i.e. $\approx 10^{-3}$. The experimental ramification is that D^o(or $\overline{D^o}$) will not live long enough to transform itself into the state of opposite charm and mixing effects will be negligible. In addition, as pointed out by Kingsley et al.[143] in the limit of exact SU_3, the mixing would vanish altogether, and thus the effects could be considerably smaller than 10^{-3}.

On the other hand, one could have[153] first order $|\Delta C|=2$ neutral currents which would create D^o-$\overline{D^o}$ mixings effects on a time scale of the order of D^o lifetime. This interaction then would manifest itself as a 50% mixing effect. The experimental data exclude the latter hypothesis but is far too poor in sensitivity to approach the standard model prediction.

In the $3.9 < E_{CM} < 4.6$ GeV region in e^+e^- annihilations a search has been performed[154] for charm events exhibiting apparent strangeness violation. The absence of such events allows one to put a limit of 18% (90% C.L.) on this kind of a process.

A search[155] in the $5 < E_{CM} < 7.8$ GeV region for the process

$$D^{*+} \rightarrow \pi^+ D^o$$
$$\hookrightarrow K^+\pi^-$$

has yielded a 90% C.L. of 16% for this process. This decay chain, representing a $\Delta C=-\Delta S$ transition, would also have to result from some sort of D^o-$\overline{D^o}$ mixing mechanism. A better limit on this mixing parameter should be soon forthcoming from the DELCO experiment, from the search for 2 electron hadronic events, where the 2 electrons have the same charge.

The D^o-$\overline{D^o}$ mixing phenomena can also give rise to observable CP violating effects in analogy to the K^o-$\overline{K^o}$ system. Since these effects are expected to be small, however, and as yet no experimental data is available on this subject, we refer the interested reader to the extensive literature on this topic.[156]

g) Status of the F and charmed baryons. The experimental situation on these two topics is very scanty. Let us first summarize the totality of relevant experimental data on the subject of charmed baryons.

1 - One famous event[157] of the type

$$\nu_\mu p \rightarrow \mu^- \Lambda \pi^+\pi^+\pi^+\pi^-$$

has been observed in a BNL 7' bubble chamber exposure. None of the other possible interpretations are stated to have a probability in excess of 3×10^{-5} and thus the event is most likely an example of

$\Delta Q = -\Delta S$ which could be understood as a production and decay of a charmed baryon. The effective mass of the $\Lambda 4\pi$ system is 2426 ± 12 Mev.

2 - A narrow peak has been observed[158] in a photoproduction experiment at Fermilab in the $\bar{\Lambda}\pi^+\pi^-\pi^-$ system with a mass of 2.26 ± 0.01 GeV/c^2. (see Fig. 38) The quantum numbers are consistent with the state being a charmed baryon. In addition the experimental width of the state is consistent with the resolution and thus compatible with a weak decay. One should note that one of the 3 possible $\Lambda\pi^+\pi^+\pi^-$ combinations in the BNL event has a mass of 2.26 GeV/c^2.

3 - The inclusive $p(\bar{p})$ cross section (expressed in terms of the point cross section) is reported to have a step[159] around 5 GeV center of mass energy. (see Fig. 39) To a lesser extent a similar behavior is seen in the $\Lambda(\bar{\Lambda})$ cross section, but the statistics there are much less significant.

4 - There appears no significant step in the inclusive antiproton cross section in the preliminary DASP data[160] as evidenced by Fig. 40. Note, however, that this plot is in terms of absolute cross section.

5 - There is some weak evidence[161] from the UCLA-SLAC collaboration for a rise in the $\overline{\Sigma^\pm}$ production in e^+e^- annihilations at 7 GeV as compared to 4 GeV. The evidence comes from a presence of a significant peak in the $\bar{n}\pi^\pm$ mass spectrum at the mass of $\Sigma^\pm$ at 7 GeV, whereas no such peak is seen at 4 GeV (Fig. 41).

Clearly the data are very scanty and some of the results quoted above may not hold up with better statistics. One can however draw some tentative conclusions accepting on face value the main features of the results quoted above.

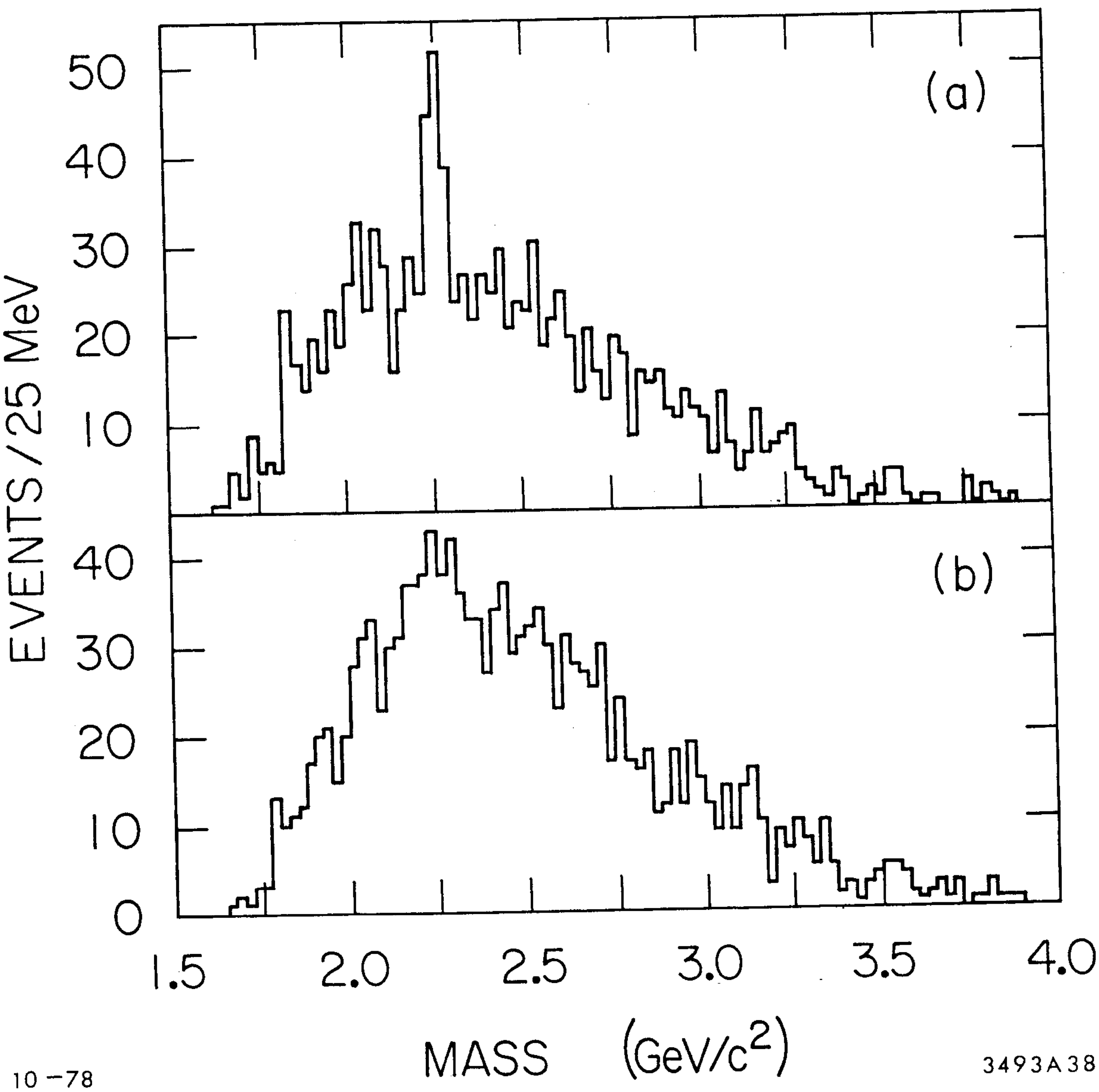

Fig. 38 Mass distribution for (a) $\bar{\Lambda}\pi^+\pi^-\pi^-$ events and (b) $\bar{\Lambda}\pi^+\pi^+\pi^-$ events from the photoproduction experiment at Fermilab.

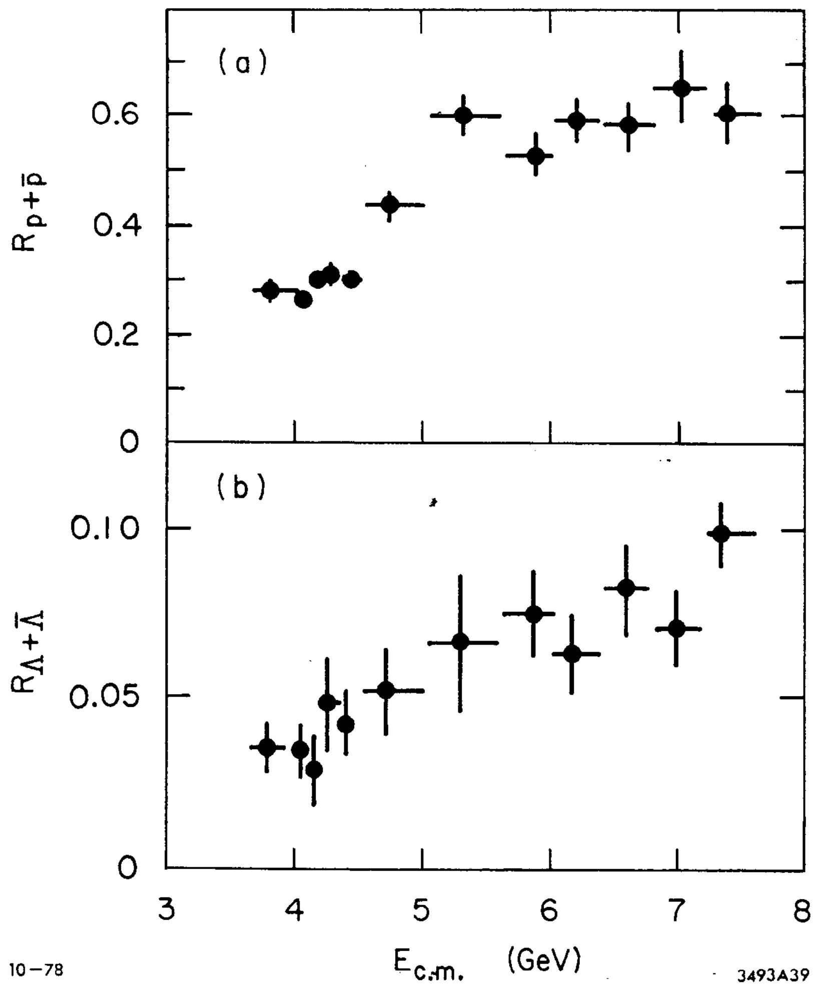

Fig. 39 Plot of the R value for (a) $\bar{p}p$ production and (b) $\bar{\Lambda}\Lambda$ production as a function of the center of mass energy. The data is from the SLAC-LBL collaboration.

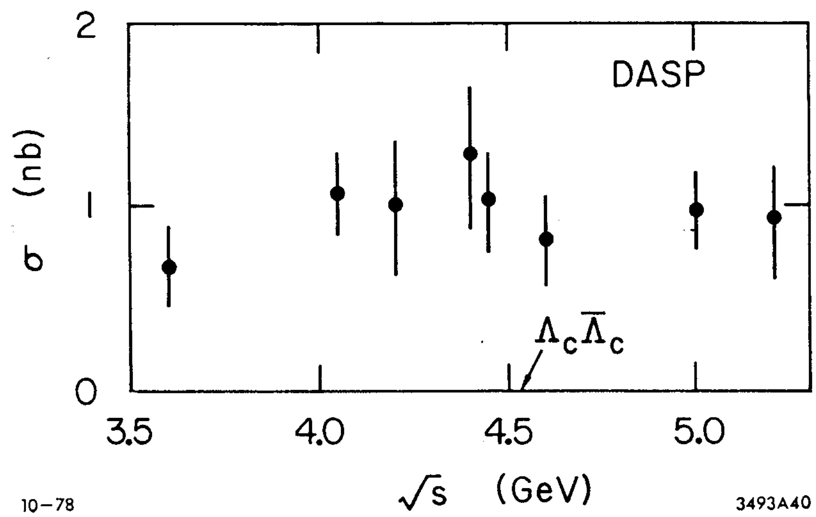

Fig. 40 The cross section for $\bar{p}p$ production as a function of center of mass energy from the DASP experiment. The data shown is preliminary and includes only events with momenta above 500 MeV/c.

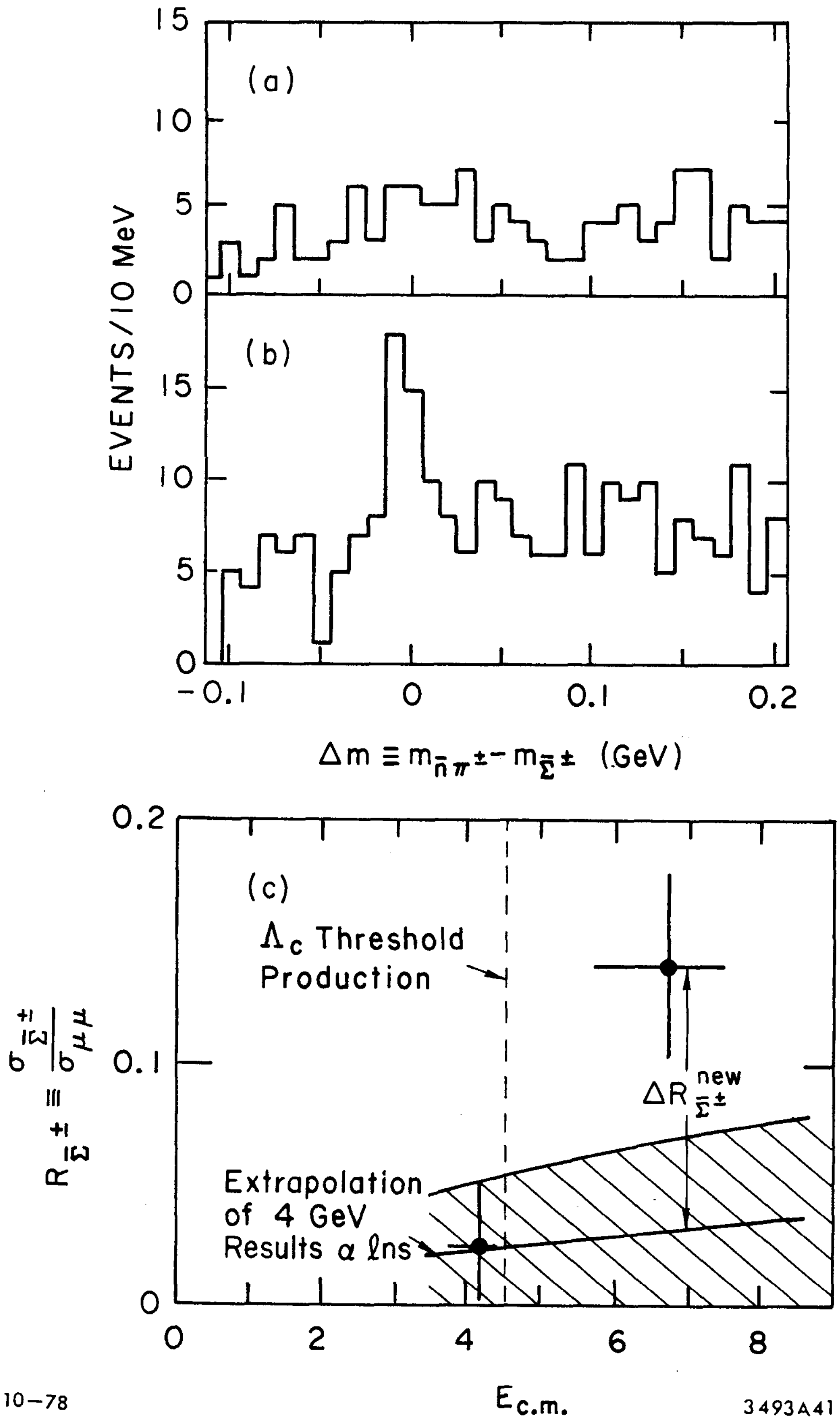

Fig. 41 The $\overline{\Sigma^{+}}$ data from the UCLA-Mark I collaboration. In (a) is displayed the difference between the mass of the $\bar{n}\pi^{\pm}$ system and the $\overline{\Sigma^{\mp}}$ mass at 4 GeV, and in (b) the same quantity at 7 GeV. The corresponding R_{Σ} value at these two energies is shown in (c).

1 - The mass of the ground state of charmed baryon spectrum is low enough (2.26 GeV/c^2) so that it decays weakly.

2 - The production of charmed baryons in e^+e^- annihilations bears the same ratio to non-charmed baryons as charmed mesons to non charmed mesons (assuming that the rise in $R_{p,\bar{p}}$ is due entirely to charmed baryon production).

3 - The observed larger rise in the $p\bar{p}$ system than in the $\Lambda\bar{\Lambda}$ system would argue that a $\bar{K}N$ ($n\pi$'s) decay modes are relatively more important than the hyperon modes.

The experimental situation with respect to the F's is almost as scanty. The F being a $c\bar{s}$ combination, the searches have concentrated on particle systems containing either an η or a $K\bar{K}$ combination (η has some $s\bar{s}$ content). Again we summarize the overall situation:

1 - The DASP collaboration[162)] finds evidence for an enhanced production of η's associated with a soft photon at 4.4 GeV. One possible mechanism explaining such an observation would be

$$e^+e^- \to F^* + \ldots$$
$$\hookrightarrow F + \gamma$$
$$\hookrightarrow \eta + \ldots$$

The relevant data are displayed in Fig. 42.

2 - The same group[163)] also found evidence for enhanced η production at 4.16 GeV when no soft photon requirement was made (Fig. 43). The detailed $m_{\gamma\gamma}$ spectra in the region of these two enhancements (4.16 and 4.4 GeV) are shown in Fig. 44.

3 - The same group has also looked at specific events[162,163)] to see whether any 2γ + soft $\gamma + \pi$ events at this energy gave an acceptable fit either to the hypothesis

$$e^+e^- \to F + (F + \gamma_{soft})$$
$$\hookrightarrow \pi + \eta$$
$$\hookrightarrow \gamma + \gamma$$

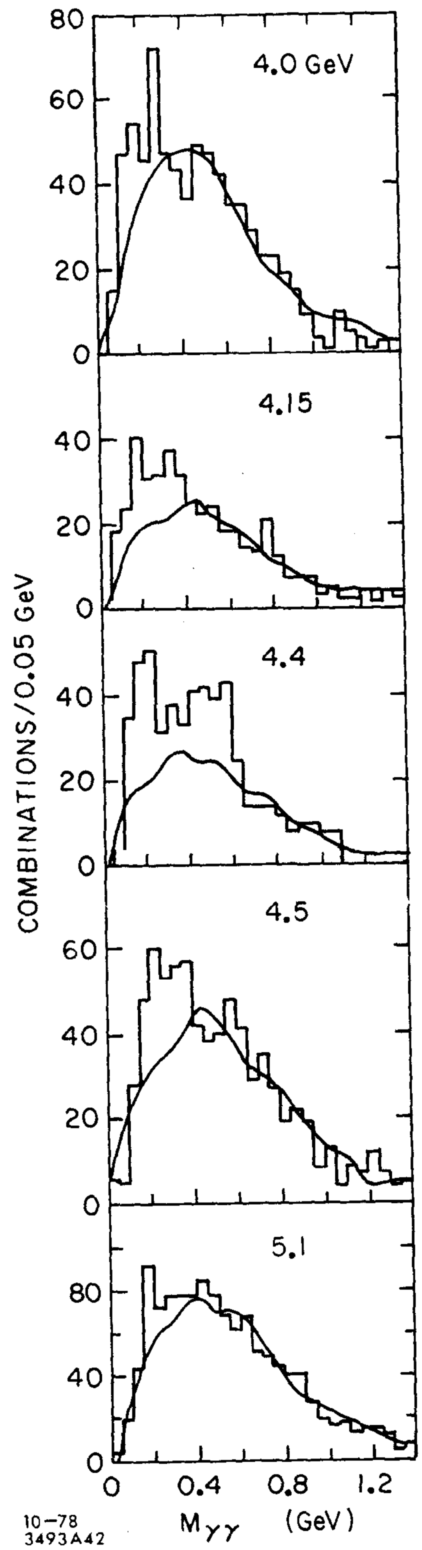

Fig. 42 Distribution of $m_{\gamma\gamma}$ for events having an additional low energy photon (E_{γ} < 140 MeV). The solid lines are estimates of uncorrelated photon background. The data is from DASP.

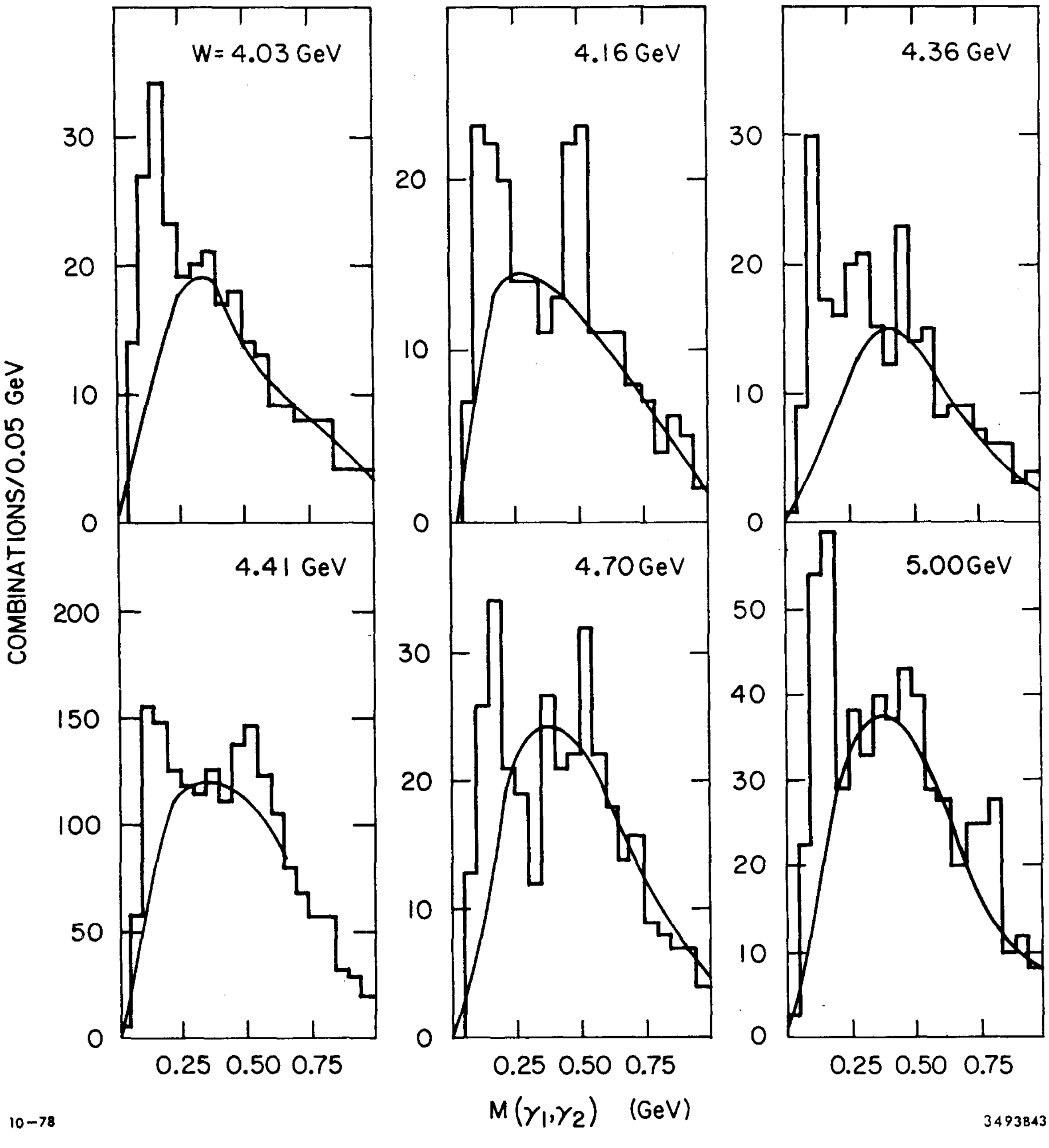

Fig. 43 Distribution of $m_{\gamma\gamma}$ without requiring the low energy photon. The data is from the DASP experiment.

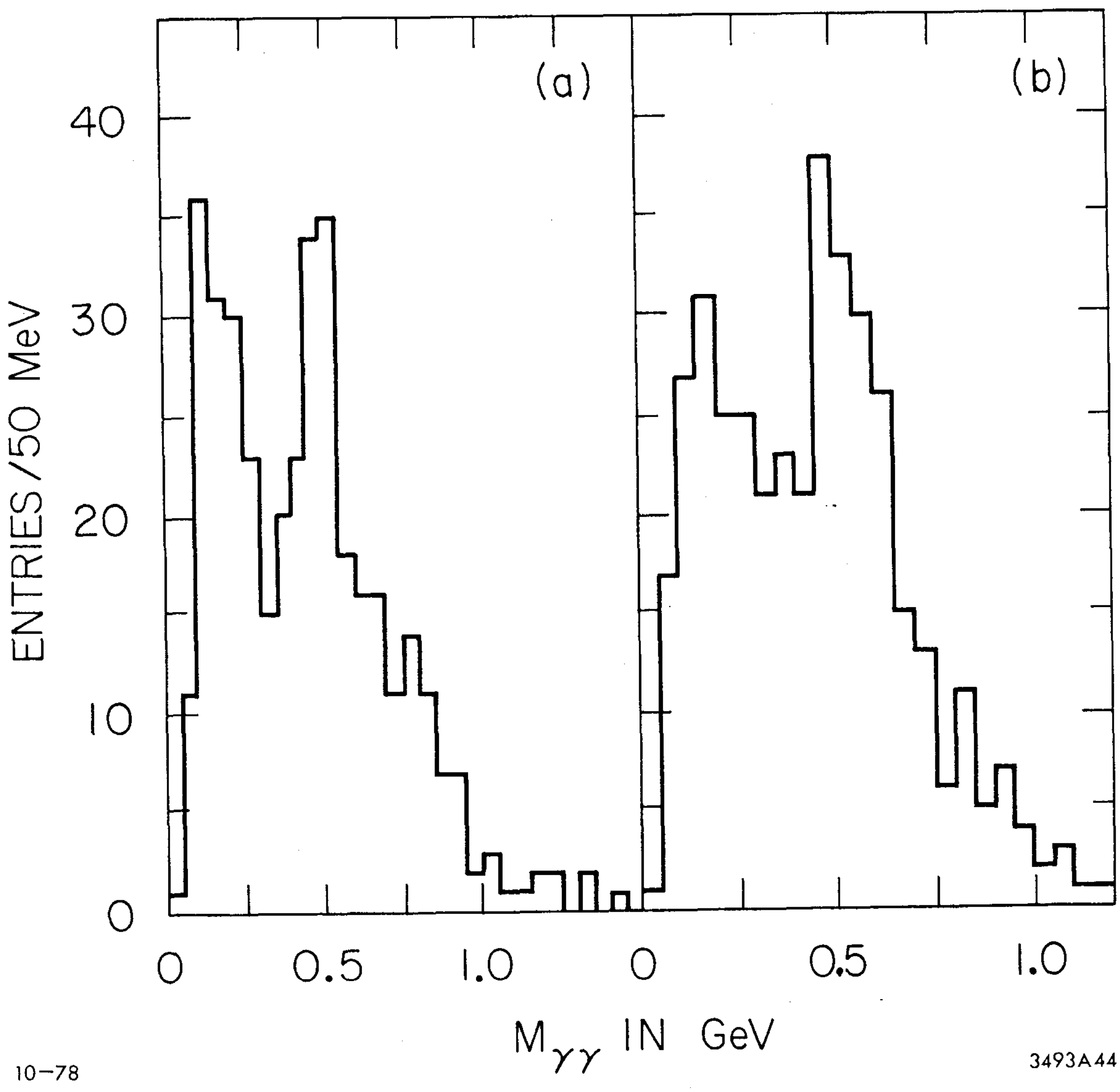

Fig. 44 Distribution of $m_{\gamma\gamma}$ for (a) E_{CM} between 4.10 and 4.22 GeV without soft photon requirement, and (b) at 4.4 GeV with the soft photon requirement. The data is from the DASP experiment.

or

$$e^+e^- \rightarrow F^* + F^*$$
$$\hookrightarrow F + \gamma_{soft}$$
$$\hookrightarrow \pi + \eta$$
$$\hookrightarrow \gamma + \gamma$$

For each event the mass of the F (or F^*) were allowed to be a free parameter but the mass was forced to be the same for the 2F's (or F^*'s) in any given event. The events fitting one hypothesis generally also gave a satisfactory χ^2 for the second one with slightly different mass values. The events satisfying the first hypothesis are displayed in Fig. 45. The cluster in the upper right hand corner is interpreted as coming from the FF^* production giving $m_F = 2030 \pm 60$ MeV and $m_{F^*} = 2140 \pm 60$ MeV.

4 - The SLAC-LBL collaboration[164)] has studied the $K\bar{K}$ ($n\pi$) combinations at the E_{CM} energy of 4.161 GeV. Their preliminary data analyzed on the hypothesis of $e^+e^- \rightarrow F\bar{F}$ is shown in Fig. 46 indicating a possible F with a mass of 2039.5 $\pm$ 1.0 MeV. The channels into which the F is forbidden to decay according to the GIM scheme, show no such enhancement.

Again, to summarize the situation, we can say that there appears now to be a reasonably good and self consistent evidence for the existence of an F meson with a mass in the appropriate range. Its apparent weak decays support the conventional charm picture.

h) Charmed particle lifetime. We shall finally discuss the theoretical and experimental situation on the D lifetime. As we saw above, only crude hand waving arguments can be made about the total decay rate; on the other hand, one can estimate the $D \rightarrow K\ell\nu$ rather reliably, since presumably one knows the matrix elements reasonably well, and the only uncertainty comes

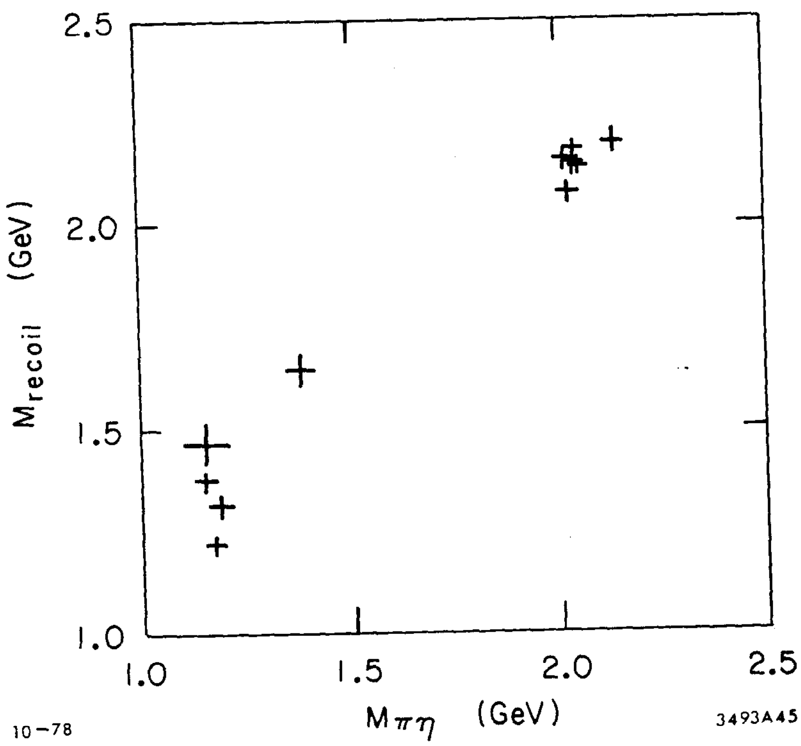

Fig. 45 Scatter plot of events that fit the reaction $e^+e^- \to FF^*$, $F \to \eta\pi$, $F^* \to \gamma_{soft}$ F. The data is from the DASP experiment.

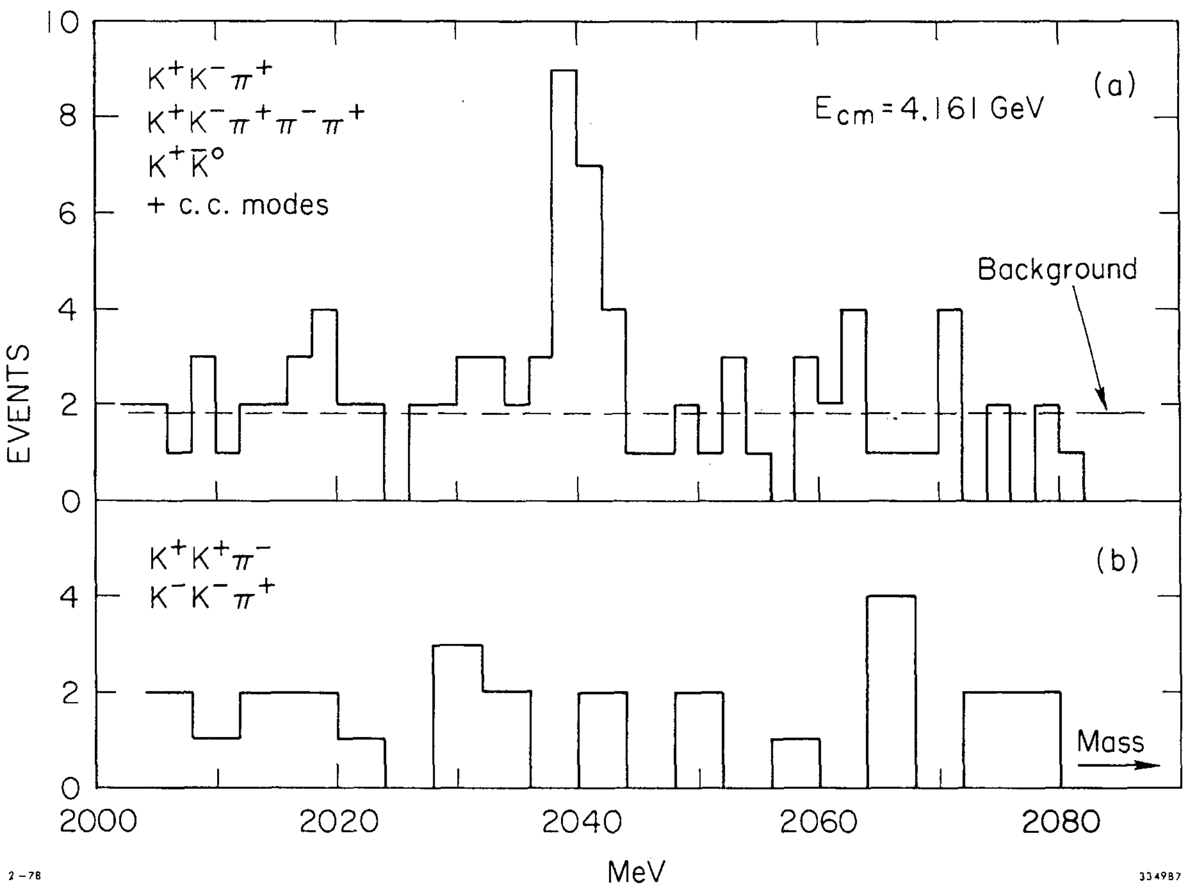

Fig. 46 Preliminary invariant mass spectra at 4.161 for (a) $K^+K^-\pi^+$, $K^+K^-\pi^+\pi^-\pi^+$, $K^+\bar{K}^o$ combinations and their charge conjugate states and (b) $K^+K^+\pi^-$ and $K^-K^-\pi^+$ combinations. The results are from the SLAC-LBL collaboration.

from the value of the form factor f_+ (the other form factor, f_-, will not contribute to the Keν decay). If $K\ell_3$ data can be our guide, then one can probably assume that $f_+(0)=1$ and pole dominance (F^* in this case) are reasonable assumptions.

The calculations for <u>constant</u> form factors give[165)] $\Gamma(D \to K\ell\nu)$ $\approx 1.1 \times 10^{11}$ sec^{-1}; inclusion of form factor dependance raises this to 1.4×10^{11} sec^{-1}. The less reliable calculations[165),147)] for $\Gamma(D \to K^*\ell\nu)$ and $\Gamma(D \to K\pi\ell\nu)$ give 0.8 and 0.5×10^{11} sec^{-1} respectively. This is in good agreement with qualitative indications from DELCO that Keν is responsible for 50% of total electronic decay rate of the D. These arguments give us $\approx 3 \times 10^{-13}$ sec for the D lifetime, and a pretty rigorous limit of $\tau_D \geq 9 \times 10^{-13}$ sec, on the assumption of constant form factors and no $K^*e\nu$ or $K\pi e\nu$ contribution.

There is indirect experimental evidence on the question of D lifetime through measurements of lifetime dependent limits on charm production on one hand, and positive results which can be interpreted as observation of charm production in hadronic interactions on the other hand. We shall end these lectures with the discussion of these experiments and comparison with the numbers discussed above obtained through theoretical arguments.

In principle, the most stringent limits on charm production in hadronic interactions come from the emulsion exposures at Fermilab. These experiments look for short tracks emenating from a proton interaction, and to avoid backgrounds require two such tracks (i.e. associated production of charm) to classify an event as a charm producing one. The two most sensitive experiments by G. Goremans-Bertrend et al.[166)] and by W. Bozzoli et al.[167)] have comparable sensitivity, insofar as the latter experiment looks at a smaller sample of events but accepts a larger field of view. Neither experiment sees any double decay events, but the limit that corresponds to it is very highly lifetime dependent since the efficiency for detecting two decays varies strongly as a function of lifetime (see Fig. 47).

Three CERN experiments have recently reported evidence for excess of electron neutrino events coming from the beam dump. Both the Gargamelle[168] and BEBC[169] collaborations have been able to identify the individual electron neutrino events; the CDHSB collaboration[170] has seen an excess of <u>apparent</u> neutral current events whose characteristics were such that they are most readily interpretable as the ν_e events. The details of the three experiments have been summarized by Wachsmuth[171] and his comparison of expected and observed event rates is reproduced below in Table XIV.

If one interprets these data as due to the process

$$p + \text{nucleon} \to D\bar{D} + \text{anything}$$

followed by semileptonic decay of the D then one obtains the following pp cross sections, on the assumption of $A^{2/3}$ dependance

BEBC, Gargamelle	100-200 μb
CDHSB	40 μb

A linear A dependance, which might be a more reasonable assumption on the basis of the ψ production data[172] would give cross sections a factor of 4 smaller. We can make several comments about these data:

1 - For the purpose of subsequent comparison with the emulsion data the A dependance question is irrelevant since the value of A in emulsion and the beam dump experiment (which used copper) is very comparable.

2 - The CERN experiments do not contradict the most stringent lifetime <u>independent</u> experimental limit on charm production in this energy range[173]

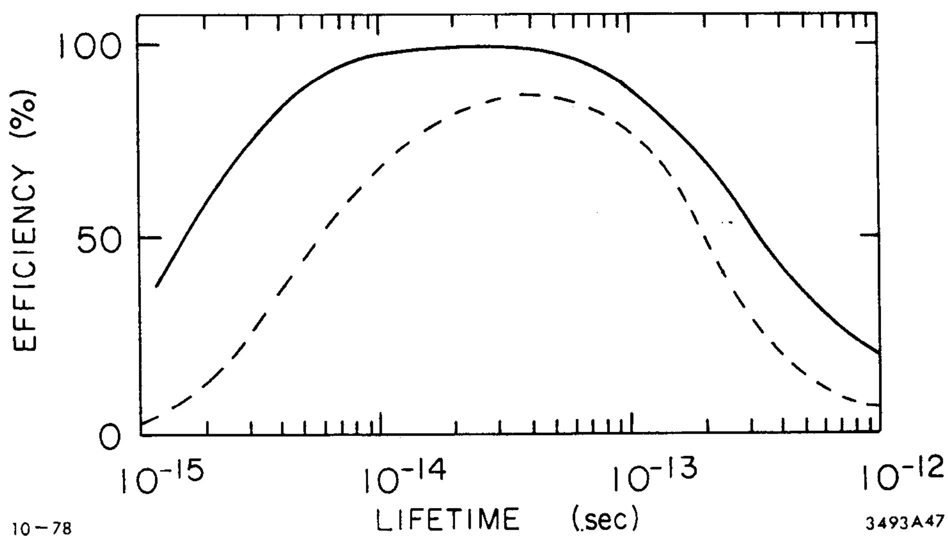

Fig. 47 Detection efficiency for the observation at 300 GeV of the decay of one (solid line) or two (dashed line) charmed particles plotted as function of charmed particle lifetime. The curves are relevant for experiment of Ref. 167.

Table XIV

Observed and expected relative event rates

	BEBC		CDHSB			GARGAMELLE
	e^-/μ^-	e^+/μ^+	$NC/CC^\pm$	μ^+/μ^-		$(e^-+e^+)/(\mu^-+\mu^+)$ (*)
	$E_{vis}>10$ GeV		$E_H>20$ GeV	$E_{vis}>20$	$E_{vis}>50$ GeV	$E_{vis}>10$ GeV
Expected ratio ± 10% 0 mr	0.07(1.4/21)	0.09(0.3/3.4)	0.3	0.16	0.12	0.07
15 mr	0.16(1.3/8)					
Observed 0 mr	0.37(11/30)	0.80(4/5)	0.86±0.08	0.22±0.02	0.19±0.02	0.56 (9/16)
15 mr	0.67(8/12)	not analysed				absent

(*) Due to the short radiation length in Gargamelle (11 cm) e^+ and e^- could not be distinguished.

obtained by looking for $D^o \rightarrow K^{\mp} + \pi^{\pm}$ decay. With some assumptions about y dependance, their limit is about 25μb for D^o and $\overline{D^o}$ production. It thus should be multiplied by at least a factor of 2 (to allow for $D^{\mp}$, F's, charmed baryons) for comparison with the CERN beam dump experiments. Clearly the A dependance assumption is important here.

3 - There is clearly an internal inconsistency between the bubble chamber experiments and the CDHSB experiment. The data relevant to the 3 detectors has been summarized by Wachsmuth[171)] and is reproduced in Table XV. The origin of the discrepancy is not understood at the present time.

Table XV

Comparison of the signal in the three detectors

	BEBC		CDHSB	GARGAMELLE
	0 mr	15 mr*	0 mr	0 mr
mass (t)	13	12	580	10.5
solid angle (μsr)	10	9	10.8	1.8
length (m)	∿3		9.3	4.6
interacting protons (10^{17})	3.5	3.7	4	3.5
distance from target (m)	820		890	950
neutrino flux dilution	1.0		0.85	0.75
μ^- events (E_{vis} > 20 GeV) predicted	17	4.5	790	10
observed	26	7	850	∿11
excess e^+ and e^- events (E_{vis}>20 GeV)	11.3	1.7	236	7.3
normalized to BEBC (0 mr)	1	.16	.48	1.1
<E> of excess events (E_{vis}>20 GeV)	71	30	85	73
ν_e flux per proton and μsr, derived from excess e^+, e^- events (E_{vis}>20 GeV)	5×10^{-8}	2.1×10^{-8}	1.8×10^{-8}	5×10^{-8}

* 15 mr data were obtained with a Be (rather than Cu) target

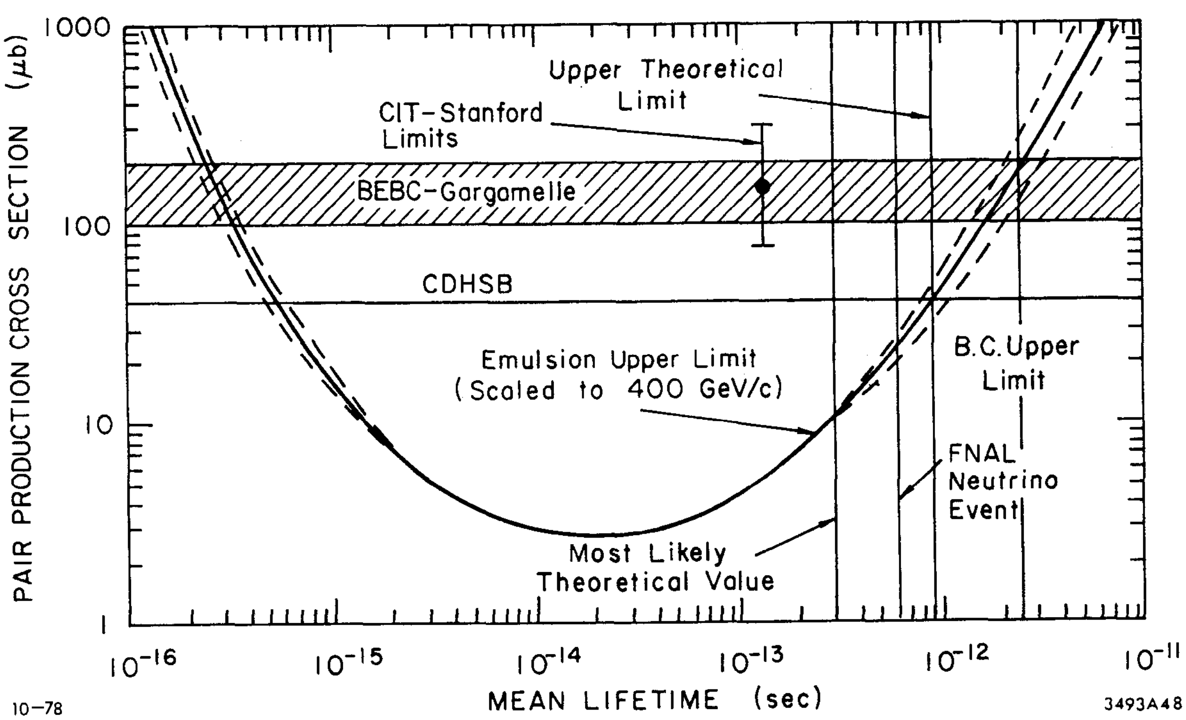

Fig. 48 The relevant data that has a bearing on the production cross section and lifetime of charmed particles. For ease of comparison all the experiments on nuclear targets have been converted to the nucleon cross sections by assuming $A^{2/3}$ dependence.

Recently the Cal Tech-Stanford collaboration has presented results[174) indicating the production of single prompt μ's in p-Fe collisions. Their preliminary analysis indicates that the observed rate, if interpreted as due to production and semileptonic decay rate of D mesons, would correspond to a cross section of about 40 μb (uncertain to a factor of 2) if one assumes <u>linear</u> A dependance.

There are a couple of final experimental comments to be made about the D lifetime. The Fermilab neutrino emulsion event,[175) interpreted as a possible charm condidate, had an observed lifetime of 6×10^{-13} sec. Furthermore, the analysis of 2μ events in the ν bubble chamber exposures appear to exclude lifetimes longer than $2\text{-}3 \times 10^{-12}$ sec.[176)

The experimental data and theoretical considerations discussed above are displayed in Fig. 48. The translation of the emulsion limits to a curve in the $\sigma_{D\bar{D}} - \tau_D$ space has been taken from the analysis of Crennell et al.[177) There is probably a narrow window i.e.

$$5 \times 10^{-13} < \tau_D < 10^{-12}$$

with which all the pieces of information can be made compatible. Whether this is indeed the case, or whether this topic contains some deeper mysteries, will be hopefully answered in the future with more experimental results.

The lifetime range quoted above, coupled with a $\gamma \approx 10$ gives a typical mean decay path of the order of one millimeter. These distances unfortunately fall into the awkward region of being too short for a bubble chamber or electronic detectors, but unconveniently long for the emulsion experiments. The newly developed high resolution steamer chamber[178) should however be able to cover well this lifetime range.

References

1) Experimental Phenomenology, M. Schwartz and S. Wojcicki, Proceedings of Stanford Summer Institute on Particle Physics, July 9-28, 1973, p. 23, vol. II.

2) Konrad Kleinknecht, CP violation and K^o decays, Ann. Rev. of Nucl. Sc. p.1, vol. 26, 1976; Lee G. Pondrom, Weak Decay Processes, Proceedings of the Annual Meeting of the American Physical Scoiety, Division of Particles and Fields, BNL, October 6-8, 1976, p. C1.

3) A. Salam, in "Elementary Particle Physics", ed. by N. Svartholm (Almquist and Wiskells, Stockholm, 1968); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967).

4) see for example the results presented at the XIX International Conference on High Energy Physics in Tokyo, Japan, August 23-30, 1978.

5) S. W. Herb et al., Phys. Rev. Lett. 29, 252 (1977).

6) C. H. Berger et al., Phys. Lett. 76B, 243 (1978); C. W. Darden et al., Phys. Lett. 76B, 246 (1978).

7) N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).

8) A. R. Clark et al., Phys. Rev. Lett. 26, 1667 (1971); J. H. Klems, R. H. Hildebrand, and R. Stiening, Phys. Rev. D4, 66 (1971).

9) F. J. Hasert et al., Phys. Lett. 46B, 138 (1973).

10) A. Benvenuti et al., Phys. Rev. Lett. 32, 1025 (1974).

11) S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970); B. J. Bjorken and S. L. Glashow, Phys. Lett. 11, 255 (1964).

12) G. Goldhaber et al., Phys. Rev. Lett. 37, 255 (1976).

13) M. Kobayashi and K. Maskawa, Progr. Theor. Phys. 49, 652 (1973).

14) J. Ellis, M. K. Gaillard, D. V. Nanopoulos, and S. Rudez, Nucl. Phys. B131, 285 (1978).

15) For a recent review of these ideas see David N. Schramm, Cosmology and New Particles, Proceedings of the 1977 Annual Meeting of the Division of Particles and Fields, Argonne, Ill., October 6-8, 1977, p.87.

16) J. Ellis, Lectures at this Institute.

17) For a detailed discussion of a possible experimental arrangement see J. Rich and D. R. Winn, Phys. Rev. D14, 1283 (1976).

18) E. Ma and J. Okada, Phys. Rev. Lett. 41, 287 (1978).

19) W. Tanenbaum et al., Phys. Rev. D12, 1871 (1975).

20) D. Décamp et al., The ratio $|g_A|g_V|$ in the decay $\Sigma^- \to ne^-\nu$, Orsay preprint.

21) M. L. Herbert et al., Phys. Rev. Lett. 40, 1230 (1978).

22) W. E. Cleland et al., Bull. Am. Ph. Soc., 23 (1978), paper DL6.

23) J. Wise et al., Bull. Am. Ph. Soc., 23 (1978), paper DL10.

24) M. Roos, Phys. Lett. 36B, 130 (1971).

25) M. M. Nagels et al., Nucl. Phys. B109, 1 (1976).

26) C. Callan and S. Treiman, Phys. Rev. Lett. 16, 153 (1966).

27) R. Dashen and M. Weinstein, Phys. Rev. Lett. 22, 1337 (1969).

28) S. Gjesdal et al., Nucl. Phys. B109, 118 (1976).

29) G. Donaldson et al., Phys. Rev. D9, 2960 (1974).

30) C. Bricman et al., Phys. Lett. 75B, 1 (1978).

31) A. R. Clark et al., Phys. Rev. D15, 553 (1977).

32) G. D. Law, Determination of the $K_{\mu_3}^+$ Form Factor, $\xi(q^2)$ From the Muon Polarization, U. of Michigan Ph. D. thesis; W. G. Wilke, U . of Wisconsin Ph.D. Thesis.

33) J. Heintze et al., Phys. Lett. 70B, 482 (1977).

34) L. Rosselet et al., Phys. Rev. D15, 574 (1977).

35) P. Bloch et al., Phys. Lett. 60B, 393 (1976).

36) T. J. Devlin and J. O. Dickey, Weak Hadronic Decays: $K \to 2\pi$ and $K \to 3\pi$, U. of Rutgers preprint, RU 78-79.

37) O. E. Overseth, Appendix II in Ref. 30.

38) G. Bunce et al., A New Measurement of the Λ Helicity in the Decay $\Xi^o \to \Lambda\pi^o$, submitted to Phys. Rev. D, BNL preprint 24047.

39) see Appendix I in Ref. 30 for the most recent summary; also ref. 36.

40) J. H. Christenson et al., Phys. Rev. Lett. 13, 138 (1964).

41) L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).

42) J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B109, 213 (1976); see also H. Harari, SLAC Summer Institute 1977, SLAC-204.

43) J. S. Bell and J. K. Perring, Phys. Rev. Lett. 13, 348 (1964); J. Bernstein, N. Cabibbo and T. D. Lee, Phys. Lett. 12, 146 (1964).

44) X. De Bouard et al., Phys. Lett. 15, 58 (1965); W. Galbraith et al., Phys. Rev. Lett. 14, 383 (1965).

45) V. L. Fitch et al., Phys. Rev. Lett. 15, 73 (1965), C. Alff-Steinberger et al., Phys. Lett. 20, 207 (1966).

46) W. C. Carithers et al., Phys. Rev. Lett. 34, 1244 (1975).

47) T. T. Wu and C. N. Yang, Phys. Rev. Lett. 13, 380 (1964).

48) N. F. Ramsey, Bull-Am. Phys. Soc. 21, 61 (1976).

49) W. C. Carithers et al., Phys. Rev. Lett. 30, 1336 (1973) and 31, 1025 (1973).

50) Y. Fukushima et al., Phys. Rev. Lett. 36, 348 (1976).

51) M. J. Shochet et al., Phys. Rev. Lett. 39, 59 (1977).

52) R. C. Field, Revision of Bevatron Branching Ratio Results on $K_L^o \to \mu^+\mu^-$ and $K_L^o \to \pi^+\pi^-$, SLAC-PUB-1498, October 1974.

53) J. Fischer et al., Phys. Lett. 73B, 364 (1978).

54) T. Goldman and C. M. Hoffman, Phys. Rev. Lett. 40, 220 (1978).

55) S. Weinberg, Phys. Rev. Lett. 40, 223 (1978); F. Wilchek, to be published; see also R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).

56) R. DeVoe et al., Phys. Rev. Lett. 25, 1779 (1970).

57) J. Bailey et al., Phys. Lett. 68B, 191 (1977).

58) B. L. Beron et al., Phys. Rev. D11, 2839 (1978).

59) For a detailed discussion of μ decay see for example A. M. Sachs and A. Sirlin, in Muon Physics, Vol. II, p.49, ed. by V. W. Hughes and C. S. Wu or E. D. Commins, Weak Interactions, McGraw Hill, 1973.

60) S. Derenzo, Phys. Rev. 181, 1854 (1969).

61) E. T. Tretyakov et al., paper presented at the XVIIIth International Conference on High Energy Physics, Tbilisi, 1976.

62) M. Daum et al., Phys. Lett. 74B, 126 (1978).

63) G. Feinberg and S. Weinberg, Phys. Rev. Lett. 6, 38 (1966); for experimental results quoted see J. Blietschau et al., Nucl. Phys. B133, 205 (1978).

64) P. Depommier et al., Phys. Rev. Lett. 39, 1113 (1977).

65) H. P. Povel et al., Phys. Lett. 72B, 183 (1977).

66) C. M. Hoffman et al., LASL report LA-UR 78-1686; also paper presented at this institute.

67) J. D. Bowman et al., Phys. Rev. Lett. 41, 442 (1978).

68) A. Bodertscher et al., Phys. Rev. Lett. 39, 1385 (1977).

69) S. M. Korenchenko et al., Sov. Phys. JETP 43, 1 (1976).

70) S. Frankel, in Muon Physics, Vol. II p.86, ed. by V. W. Hughes and C. S. Wu.

71) B. W. Lee et al., Phys. Rev. Lett. 38, 937 (1977).

72) T. P. Cheng and Ling-Fong Li, Phys. Rev. Lett. 38, 381 (1977).

73) F. Wilczek and A. Zee, Phys. Rev. Lett. 38, 531 (1977).

74) J. D. Bjorken and S. Weinberg, Phys. Rev. Lett. 38, 622 (1977).

75) For a detailed discussion of predictions by different models see W. J. Marciano and A. I. Sanda, Phys. Rev. Lett. 38, 1512, (1977) and G. Altarelli et al., Nucl. Phys. B125, 285 (1977).

76) V. E. Barnes et al., Phys. Rev. Lett. 38, 1049 (1977).

77) V. E. Barnes, Phys. Lett. 65B, 174 (1976).

78) E, Bellotti et al., Lett. Nuovo Cim. 17, 553 (1976); J. Blietschau et al., Nucl. Phys. B133, 205 (1978).

79) F. Reines et al., Phys. Rev. Lett. 32, 180 (1974).

80) B. Pontecorvo, Soviet Physics JETP 53, 1717 (1967).

81) For a more detailed review of neutrino mixing phenomenology and its present status see N. Cabibbo, Quark and Lepton Mixing, Lectures given at the XV Ettore Majorana School for subnuclear physics,Erice 1977, and B. Pontecorvo, Lepton Charges and Lepton Mixing, rapporteur talk given at the European Conference on Particle Physics,Budapest,Hungary 4-9 July,1977.

82) N. Cabibbo, Phys. Lett. 72B, 333 (1978).

83) M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975).

84) J. Burmester et al., Phys. Lett. 68B, 297 and 301 (1977).

85) R. Brandelik et al., Phys. Lett. 73B, 109, (1978).

86) W. Bacino et al., Phys. Rev. Lett. 41, 13 (1978).

87) Y. S. Tsai, Evidence for τ being a spin 1/2 lepton, SLAC-PUB-2105.

88) The present best limits on the mass of the missing neutral X in the decay $\tau \to e\nu X$ come from the DELCO and PLUTO groups who quote limits of 0.25 GeV (Ref.100) and 0.36 GeV (Ref.113) respectively.

89) D. Horn and G. G. Ross, Phys. Lett. 67B, 460 (1977); G. Altarelli, N. Cabibbo, L. Maiani, and R. Petronzio, Phys. Lett. 67B, 463 (1977).

90) We quote the numbers here from G. Altarelli et al., ref. 89, who have actually used some older and less stringent experimental limits for μ^- capture than presently available. Clearly, the argument becomes stronger if one used the more recent data.

91) R. Brandelik et al.(ref. 85) quote 0.92±0.32 for this number. See also G. Feldman, invited talk at the Neutrino 78 Conference in Purdue SLAC-PUB-2138, for a summary of other measurements; see also Ref. 86 and W. Bacino et al., ref. 98.

92) G. Feldman, private communication, quoted by M. Perl, review talk given at the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, West Germany.

93) J. D. Bjorken and C. H. Llewellyn-Smith, Phys. Rev. D7, 887 (1973).

94) S. P. Rosen, Phys. Rev. Lett. 40, 1057 (1978).

95) A. M. Cnops et al., Phys. Rev. Lett. 40, 144 (1978).

96) J. Jaros, private communication, quoted by M. Perl at the 1977 Hamburg conference.

97) Y. S. Tsai, Phys. Rev. D4, 2821 (1971). The more up to date numbers for these branching ratios can be found in ref. 87.

98) W. Bacino et al., Measurement of the Branching Ratios for $\tau\to\pi\nu_\tau$ and $\tau\to\mu\nu_\mu\nu_\tau$, submitted to Phys. Rev. Lett., SLAC-PUB-2223.

99) S. Yamada, invited talk at the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, West Germany.

100) See W. Bacino et al., ref. 98. The preliminary results of this work were presented by J. Kirkby in an invited talk at the International Conference on Neutrino Physics and Neutrino Astrophysics, Purdue University, SLAC-PUB-2127.

101) G. Hanson, unpublished analysis, quoted by G. Feldman, Ref. 91.

102) G. Alexander et al., Phys. Lett. 78B, 162 (1978).

103) see Y. S. Tsai, ref. 87 and 97; F. J. Gilman and D. H. Miller, Phys. Rev. D17, 1846 (1978); N. Kawamoto and A. I. Sanda, DESY preprint 78/14 (1978).

104) G. Alexander et al., Phys. Lett. 73B, 99 (1978).

105) J. A. Jaros et al., Phys. Rev. Lett. 40, 1120 (1978).

106) J. Kirkby, ref. 100.

107) J. Burmester et al., Phys. Lett. 68B, 297 (1977).

108) G. Flugge in Proceedings of the 1977 Experimental Meson Spectroscopy Conference at Northeastern University, Boston, 1977.

109) H. K. Nguyen, private communication, quoted by M. Perl at the 1977 Hamburg conference.

110) A. Ali and Z. Z. Aydin, Nuov. Cim. 43A, 270 (1978).

111) J. Kirkby, talk presented at this summer institute; see also J. Kirkby, Ref.100 and A.M.Diamant-Berger, Ref.136, for discussion of ρ parameter.

112) J. Burger, invited talk at the XIII Rencontre de Moriand, Les Ares (1978).

113) G. Knies, Sixth Trieste Conference on Particle Physics, Trieste, June, 1978.

114) D. A. Bryman and C. Picciotto, Phys. Rev. D11, 1337 (1975).

115) H. Fritzsch, Phys. Lett. 67B, 451 (1977).

116) W. Bartel et al., A Precise Determination of the τ-Mass, Heidelberg University preprint.

117) M. K. Gaillard, B. W. Lee and J. L. Rosner, Rev. Mod. Ph. 47, 277 (1975).

118) P. Rapidis et al., Phys. Rev. Lett. 39, 526 (1977).

119) G. Goldhaber et al., Phys. Rev. Lett. 37, 255 (1976).

120) Lead-glass Wall Collaboration, reported by A Litke in Proceedings of the 1977 European Conference on Particle Physics, Budapest, Hungary, 4-9 July, 1977, p. 687; I. Peruzzi et al., Phys. Rev. Lett.39, 1301(1977).

121) C. Zemach, Phys. Rev. B133, 1201 (1964).

122) J. E. Wiss et al., Phys. Rev. Lett. 37, 1531 (1976).

123) I. Peruzzi et al., Phys. Rev. Lett. 37, 569 (1976).

124) G. J. Feldman, Properties of the D mesons, Proceedings of the SLAC Summer Institute 1977, p. 241.

125) R. Brandelik et al., Phys. Lett. 70B, 125 (1977); see also V. Luth et al., Phys. Lett. 70B, 120 (1977).

126) J. Ellis, M. K. Gaillard, D. V. Nanopoulos, Nucl. Phys. B100, 313(1975).

127) M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. 33, 108 (1974); G. Altarelli and L. Maiani, Phys. Lett. 52B, 351 (1974).

128) G. Altarelli, N. Cabibbo, L. Maiani, Nucl. Phys. B88, 285 (1975).

129) J. M. Feller et al., Phys. Rev. Lett. 40, 274 (1978).

130) W. Bacino et al., Phys. Rev. Lett. 40, 671 (1978).

131) R. Brandelik et al., Phys. Lett. 70B, 387(1977).

132) J. M. Feller et al., Phys. Rev. Lett. 40, 1677 (1978).

133) J. Kirkby, invited talk at the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, West Germany.

134) I. Hinchliffe and C. Llewellyn Smith, Nucl. Phys. B114, 45 (1976).

135) F. Bletzacker, H. T. Nieh and A. Soni, Phys. Rev. D16, 732 (1977); A. Ali and T. C. Yang, Phys. Lett. 65B, 275 (1976).

136) A-M. Diamant-Berger, in Proceedings of the XIII Rencontre de Moriand at Les Arcs, 1978.

137) V. Vuillemin et al., Inclusive Studies of D Meson Decays at the $\psi(3772)$, Phys. Rev. Lett. 41, 1149 (1978).

138) C. Quigg and J. L. Rosner, Hadronic Decays of Charmed Mesons, FERMILAB-Pub-77/60 THY (1977).

139) C. Baltay et al., Phys. Rev. Lett. 39, 62 (1977).

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

141) C. Baltay, et al., Recent Results from Neutrino Interactions in Heavy Neon, paper presented to Neutrinos-78 Conference, Purdue U., BNL-24663; A. M. Cnops et al., Lepton and Charm Production in the 15 foot FNAL Bubble Chamber, paper presented at the XIIIth Rencontre de Moriond Conference by Robert B. Palmer, BNL-24536.

142) M. B. Einhorn and C. Quigg, Phys. Rev. D12, 2015 (1975).

143) R. L. Kingsley et al., Phys. Rev. D11, 1919 (1975).

144) M. Peshkin and J. L. Rosner, Nucl. Phys. B122, 144 (1977).

145) A. Pais and S. B. Treiman, Phys. Rev. D15, 2529 (1977).

146) D.L. Scharre et al., Phys. Rev. Lett. 40, 74 (1978).

147) M. Matsuda et al., Prog. Theor. Phys. 58, 1502 (1977).

148) S. P. Rosen, Phys. Rev. Lett. 41, 3 (1978).

149) see for example M. Katuya and Y. Koide, Is the total D^+ Width Much Smaller than the Total D^o Width?, SH-78-05, preprint, July 1978.

150) A. Barbaro-Galtieri, Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energy in Hamburg, West Germany, p.21.

151) Sinan Kaptanoglu, Non-leptonic Charm Decays, SLAC-PUB-2072, January 1978.

152) L. Maiani, Two Body Decays of Charmed Particles, Ecole Normale preprint.

153) S. L. Glashow and S. Weinberg, Phys. Rev. D15, 1958 (1977); E. A. Paschos, Phys. Rev. D15, 1966 (1977).

154) G. Goldhaber, Bull. Am. Phys. Soc. 22, 20(T) (1977); also G. Goldhaber, invited talk given at the European Conference on Particle Physics, Budapest, Hungary, July 1977, p. 509.

155) G. J. Feldman et al., Phys. Rev. Lett. 23, 1313 (1977).

156) R. L. Kingsley, Phys. Lett. 63B, 329 (1976); A. Pais and S. B. Treiman, Phys. Rev. D12, 2744 (1975); M. Goldhaber and J. L. Rosner, Phys. Rev. D15, 1254 (1977); L. B. Okun, V. I. Zakharov, and B. M. Pontecorvo, Lett. Nuov. Cim. 13, 218 (1975).

157) E. G. Cazzoli et al., Phys. Rev. Lett. 34, 1125 (1975).

158) B. Knapp et al., Phys. Rev. Lett 37, 882 (1976).

159) M. Piccolo et al., Phys. Rev. Lett. 39, 1503 (1977).

160) W. de Boer, Recent Results from Doris, invited talk given at the SLAC Summer Institute on Particle Physics, p. 270.

161) H. F. W. Sadrozinski, Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energy in Hamburg, West Germany, p. 59.

162) R. Brandelik et al., Phys. Lett. 70B, 132 (1977); see also G. Weber, Recent e^+e^- Results from Doris, DESY 78/35, July 1978.

163) H. Meyer, Results on e^+e^- Annihilation Studies at Doris, Particles and Fields - 1977 (APS-DPF, Argonne) p. 413.

164) D. Lüke, e^+e^- Production of Charmed Particles at the Spear Magnetic Detector, Particles and Fields - 1977 (APS-DPF, Argonne) p. 441.

165) D. Fakirov and B. Stech, Nucl. Phys. B133, 315 (1978); see also ref.147.

166) G. Goremans-Bertrand et al., Phys. Lett. 65B, 480 (1976).

167) W. Bozzoli et al., Lett. Nuov. Cim. 19, 32 (1977).

168) P. Alibran et al., Phys. Lett. 74B, 134 (1978).

169) P. C. Bosetti et al., Phys. Lett. 74B, 143 (1978).

170) T. Hansl et al., Phys. Lett. 74B, 139 (1978).

171) H. Wachsmuth, 400 GeV proton induced prompt neutrinos at 0 and 15 milliradians, invited talk given at the Topical Conference on Neutrino Physics, Oxford, July 1978, CERN/EP/PHYS 78-29.

172) A. Bamberger et al., Nucl. Phys. B134, 1, (1978).

173) W. R. Ditzler et al., Phys. Lett. 71B, 451 (1977).

174) K. W. Brown et al., talk presented by M. H. Shaevitz at the 3rd International Conference at Vanderbilt on New Results in High Energy Physics, Nashville, Tenn., March 6-8, 1978.

175) A. L. Read et al., Fermilab PUB-78-56 Exp. (1978).

176) Aachen-Bonn-CERN-London-Munich-Oxford-Saclay Collaboration, talk presented by L. Pape at the Topical Conference on Neutrino Physics, Oxford, July 2-7, 1978, CERN/EP/PHYS 78-25.

177) D. J. Crennell, C. M. Fisher and R. L. Sekulin, Understanding Hadronic Charm Production Data and Particle Lifetime, Rutherford Laboratory preprint, RL-78-051/A; also Phys. Lett. 78B, 171 (1978).

178) T. Cardello et al., Search for Short-Lived Particles Using a High Resolution Streamer Chamber, May 1977, Fermilab Proposal #490.