as a μ^+ , also right-handed, if we are to conserve angular momentum. The CMS angular distribution is not isotopic, but $(1-\cos\Theta)^2$. Put simply, the initial state has J = 1, but only one of the (2J+1) = 3 components is allowed in the final state. Thus if all partons are particles of spin $^1/2$, we expect $R = \frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{1}{3}$. For <u>any</u> other spin assignment 0, 1, $^3/_2$ --- one can easily see that the ratio $R > \frac{1}{3}$. For spin 0, or for spin $\gg \frac{1}{2}$, R = 1. Furthermore, if the nucleon contains both particle and antiparticle constituents, clearly $R > \frac{1}{3}$, and R = 1 if left and right-handed constituents occur equally.

The data are shown in Fig. 2. The NAL counter experiment gives a value up to E = 75 GeV of R = 0.34 ± 0.08, while the CERN Gargamelle experiment (E = 1-10 GeV) gives R = 0.38 ± 0.02. Thus the observed ratio $R \sim \frac{1}{3}$ or perhaps a little more. This tells us therefore three things:-

(i) partons have spin $\frac{1}{2}$

(ii) there are few antipartons

(iii) the coupling is V-A

To be exact, the CERN result R = 0.38 ± 0.02 suggests that >87% of partons have spin $^1/2$, and < 7% are antipartons. The SLAC-MIT data on electron-nucleon scattering measure the ratio of magnetic to electric scattering (i.e. the gyromagnetic ratio) and indicate ∿94% of partons have spin $^1/2$. (The electron experiments tell us nothing about antipartons, since they measure the $(\text{charge})^2$, which is the same for particle and antiparticle). Again, we note that the ratio $\sim {^1/3}$ holds over a large energy range (2-75 GeV). At the low energy end, one should worry if the parton is really relativistic. If it is not, then the formula becomes

$$R = \frac{1}{3}\,\frac{(1 + 3z + 3z^2)}{(1 + z)^2}$$

where z = m/2E, m being the parton mass. For m = 0.25 GeV, R = 0.37 at E = 2 GeV, so our relativistic approximation is satisfactory.

Our data so far seems to be consistent with the nucleon being built from pointlike objects (quarks) of spin $^1/2$, with few antiparticle constituents. We can get no further without a more detailed analysis; which I shall sketch briefly. From the neutrino data and the electron

electron data taken together we can in principle find out, for example (i) the quark charges (ii) the number of quarks (iii) the fractional nucleon momentum carried by the quarks. Inelastic lepton cross-sections are usually expressed in terms of so-called structure functions (the analogue of form-factors for elastic scattering) and it is necessary at this point to explain how they are defined. According to the Bjorken scaling hypothesis, we get the following formulae:-

Electron Scattering:-

$$\frac{d^2\sigma^e}{dxdy} = \frac{4\pi\alpha^2}{q^4}\left[F_2^{\,e}(x)\ (1-y) + 2xF_1^{\,e}(x)\ \frac{y^2}{2}\right] \qquad (2)$$

Neutrino Scattering:

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G^2ME}{\pi}\left[F_2^{\nu}(x)(1-y) + 2xF_1^{\nu}(x)\frac{y^2}{2} \pm xF_3^{\nu}(x)(y-\frac{y^2}{2})\right]$$

In these formulae, $x = q^2/2M\nu$ and $y = \nu/E$, where E is the energy of the incident lepton, q^2 is the 4-momentum transfer squared, and ν is the energy transfer from lepton to hadron, measured in the rest-frame of the target nucleon. The assumption of <u>single vector particle exchange</u> means that there are, for neutrino and antineutrino scattering, 3 independent polarization states for the exchanged particle ($2J+1 = 3$) and thus 3 structure functions F_1, F_2, F_3. In electron scattering, the F_3 term is absent because of parity conservation. The above formulae represent averages over lepton and nucleon polarizations (if we consider particular polarization states, there are twice as many functions for neutrinos, i.e. 6, and 4 for electrons). For spin $^1/2$ constituents, one expects $2xF_1 = F_2$, which as discussed above, seems to be the case in both the electron and neutrino data.

3. Quark Charge Sumrules

If the constituents are pointlike - and from now on, we think of them as quarks or antiquarks - then the electron experiments simply measure the Rutherford scattering from the quarks. The cross-section, or rather the part in the forward direction, $x \to 0$, determined by F_2 only, therefore measures the product of the number of quarks times the $(\text{charge})^2$ of each. From the neutrino scattering, we get a measure of the number of quarks, and thus between the two results, we should be able to find the charges themselves.

The electron experiments measure cross-sections, as described above, in terms of the structure function $F_2^{eN}(x)$, where the scaling variable $x = q^2/2M\nu$ is the fractional nucleon momentum carried by the quark. If u(x) stands for the probability of finding, in a proton, an isospin "up" quark with momentum x, d(x) that for an isospin "down" quark, s(x) that for a strange quark, and $\bar{u}$, $\bar{d}$ and $\bar{s}$ stand for the corresponding antiquarks, then for a proton target

$$F_2^{ep}(x) = x(\tfrac{2}{3})^2 \, [u(x) + \bar{u}(x)] + x(\tfrac{1}{3})^2 [d(x)+\bar{d}(x)] + x(\tfrac{1}{3})^2 [s(x)+\bar{s}(x)] \quad (3)$$

since in the usual Gell-Mann/Zweig quark model, we have for the quark charges:-

Symbol	Charge	I_3	S	Symbol	Charge	I_3	S
"p quark = u	$+^2/3$	$+^1/2$	0	$\bar{u}$	$-^2/3$	$-^1/2$	0
"n quark" = d	$-^1/3$	$-^1/2$	0	$\bar{d}$	$+^1/3$	$+^1/2$	0
"λ quark" = s	$-^1/3$	0	-1	$\bar{s}$	$+^1/3$	0	+1

For a neutron target, we simply interchange u and d quarks in the formula. So, for a neutron-proton average (i.e. a nucleon), we get

$$F_2^{eN}(x) = \frac{x}{2}\left\{\frac{4}{9}[u(x) + \bar{u}(x) + d(x) + \bar{d}(x)] + \frac{1}{9}[d(x)+\bar{d}(x) + u(x) + \bar{u}(x)] + \frac{2}{9}[s(x) + \bar{s}(x)]\right\} \quad (4)$$

Since we already know from the neutrino data that antiquarks make little contribution, one could at this point consider a nucleon built from 3 quarks only, half 'u' and half 'd'. If they account for all the nucleon momentum, then we should have

$$\int_0^1 x \, [u(x) + d(x)] \, dx = 1$$

Hence

$$\frac{18}{5}\int_0^1 F_2^{eN}(x)\ dx = 1 \qquad (5)$$

Experimentally, the SLAC-MIT data on electron-proton and electron-neutron scattering in the scaling region give

$$\frac{18}{5}\int_0^1 F_2^{eN}(x)\ dx = 0.51\pm0.08 \qquad (6)$$

One way of interpreting this is to say that the active quarks only account for half of the momentum of the nucleon - a point we return to later.

Now consider inelastic neutrino scattering. We deal with the weak analogue of $F_2^{eN}(x)$, called $F_2^{\nu N}(x)$. A neutrino transforms to a μ^-, thus it has to scatter off an isospin "down" quark, denoted d, or off $\bar{u}$ so that the transformations are:-

$$\nu + d \to \mu^- + u \ ; \qquad \nu + \bar{u} \to \mu^- + \bar{d}$$

Charge, Q/e:

$$0 \quad -\tfrac{1}{3} \quad -1 \quad +\tfrac{2}{3} \qquad\qquad 0 \quad -\tfrac{2}{3} \quad -1 \quad +\tfrac{1}{3}$$

Similarly, antineutrinos transform to μ^+ and scatter from u or $\bar{d}$ quarks. Thus one finds, in analogy with (2):-

$$F_2^{\nu p}(x) = 2x\ [d(x) + \bar{u}(x)] \qquad (7)$$

The factor 2 in (7) arises because one naturally assumes, for pointlike quarks, equal contributions from vector and axial-vector coupling. We have neglected strange quarks in (6), because their coupling is suppressed by a factor $\tan^2\Theta_{\text{Cabibbo}} \sim 0.05$. For a neutron-proton average,

$$F_2^{\nu N}(x) = x[d(x) + u(x) + \bar{u}(x) + \bar{d}(x)] \qquad (8)$$

Comparing (4) and (8), we obtain the prediction

$$\int F_2^{\nu N}(x)dx / \int F_2^{eN}(x)dx \leq \frac{18}{5} \qquad (9)$$

where the inequality becomes an equality if we neglect the effects of strange quarks and antiquarks in electron scattering.

Experimentally, $\int F_2^{\nu N}(x)dx = 0.51 \pm 0.03$ from the CERN-Gargamelle experiment, that is, from the slope of Fig. 1, so that the observed ratio is

$$\int F_2^{\nu N}(x)dx/\int F_2^{eN}(x)dx = 3.6 \pm 0.3 \qquad (10)$$

The agreement between (9) and (10) is a confirmation of the "conventional" quark charges. However, there are other, quite different, arguments which arrive at a similar ratio. For example, it is known that the vector part of the strangeness-conserving weak interactions (which involve the isospin raising and lowering operators I^+ and I^-) and the isovector part of the electromagnetic interactions are connected by $\Delta I = 1$ rule - they are different components of an isospin 1 current, carrying electric or weak "charge" as the case may be, just as π^+, π^- and π^o are different components of an isovector pion. Then from the Clebsch-Gordan coefficients we get

$$F_2^{\nu}(\text{Vector}) = 2\ F_2^{e}(\text{Isovector})$$

Also, if we assume that axial vector and vector contributions to the weak scattering are equal, we expect

$$F_2^{\nu}(A,V) = 4\ F_2^{e}(\text{Isovector})$$

From photoproduction data, isoscalar contributions in electromagnetic processes are typically at the 10% level, so one might suppose that $F_2^e(\text{Isovector}) \sim 0.9 F_2^e(\text{Isovector + Isoscalar})$. Hence $F_2^{\nu} \sim 3.6\ F_2^e$, exactly the same as the quark model prediction.

The confrontation with the constituent models becomes more impressive when one considers differential cross-sections, that is $F_2^{eN}(x)$ or $F_2^{\nu N}(x)$ in unintegrated form. Fig. 3 shows the CERN data in the scaling region, compared with the SLAC scaling curve. The evidence is rather compelling that electrons and neutrinos are seeing the same substructure inside the nucleon, with absolute rates standing exactly in the ratio predicted by the quark charge assignments.

4. Quark Counting. The Gross-Llewellyn Smith Sumrule

For spin $^1/2$ constituents, there are two independent structure functions describing neutrino scattering on nucleons, called $F_2(x)$ and $xF_3(x)$, as in (2) above. While F_2 contains both A and V parts in quadrature, xF_3 is the V-A interference term, and changes sign under interchange of neutrino and antineutrino. We adopt the positive sign for neutrinos. The antineutrino/neutrino ratio shows that xF_3 is nearly maximal, and indeed the ratio one finds by integrating (2) over y is:-

$$R = 0.38 = \frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{2-B}{2+B} \quad \text{where } B = \frac{\int xF_3 dx}{\int F_2 dx} = 0.85 \qquad (11)$$

The quantity $xF_3 = \pm F_2$ for collisions of neutrinos on particles (antiparticles) respectively, so that from (8),

$$xF_3^{\nu N}(x) = x[d(x) + u(x) - \bar{u}(x) - \bar{d}(\bar{x})] \qquad (12)$$

Hence

$$\int_0^1 F_3^{\nu N}(x)\, dx = \int_0^1 \frac{xF_3^{\nu N}(x)\, dx}{x}$$

measures the difference in the number of quarks and antiquarks (while $\int F_2^{\nu N}(x)\, dx/x$ measures the sum). For the Gell-Mann/Zweig quark model, we therefore expect

$$\int_0^1 F_3^{\nu N}(x)\, dx = 3 \quad \text{(Gross/Llewellyn-Smith sumrule)} \qquad (13)$$

The sumrule can be investigated experimentally by forming the neutrino-antineutrino cross-section difference (see equation (2)):-

$$F_3(x) = \frac{3\pi}{2G^2ME}\left[\frac{1}{x}\frac{d\sigma(\nu N)}{dx} - \frac{1}{x}\frac{d\sigma(\bar{\nu}N)}{dx}\right] \qquad (14)$$

There are difficulties if one is to remain always in the scaling region of $q^2 > 1$ GeV^2. On the basis of the distribution function u(x), d(x) etc. obtained by empirical fits to the electron-scattering data, it turns out that, near $x \simeq 0$, $F_3(x) \propto x^{-1/2}(1-x^2)^3$ so that contributions to the integral $\int_0^1 F_3(x)\, dx$ near $x = 0$ are very important. In fact, these fits suggest that 20% of the integral arises from values of $x < 0.01$. Since $x = q^2/2M\nu$, this implies that a neutrino energy of several hundred GeV is required to get within 20% of the full integral. Furthermore, the absolute cross-sections must be measured accurately.

No test of (13) has yet been made for events in the scaling region. A test has been made in the CERN experiments, where it is observed (Fig. 4) that if no scaling cuts are made, then even at low energies ($E \sim 2$ GeV), the values of $F_2^{\nu N}(x')$ are in good agreement with

3.6 $F_2^{eN}(x')$ from the SLAC experiments. Here $x' = q^2/(2M\nu + M^2)$ is a modified scaling parameter introduced by Bloom and Gilman. Empirically one finds that, if no kinematic constraints $q^2 > q^2_{min}$, $\nu > \nu_{min}$ are applied to the data, then one observes some average type of "precocious" scaling behaviour in x' when averaged over all values of q^2 and ν allowed by conservation of energy and momentum. The result of the analysis is

$$\int_0^1 F_3(x')dx' = 3.1 \pm 0.4 \qquad (15)$$

There is no observed dependence of the integral on neutrino energy, so the hope is that this value also applies in the true scaling region. At the very least, (15) is an interesting result.

5. Gluon Contributions

So far, the simple quark model looks quite good, barring one mysterious result. From (8), we see that $\int F_2^{\nu N} dx$ measures the total momentum of the (non-strange) quarks and antiquarks, and should be unity if nucleon is composed entirely of such objects. However, for both electron and neutrino scattering, one obtains

$$\left(\frac{\text{Total Quark + Antiquark Momentum}}{\text{Nucleon Momentum}}\right) = {}^1/_2 \begin{matrix}(0.51 \pm 0.08 \text{ for e})\\(0.51 \pm 0.03 \text{ for } \nu)\end{matrix}$$

The extra, unaccounted momentum is ascribed to neutral "gluons" which provide the quark binding forces. What is mysterious is that these contribute exactly half of the nucleon mass. So far, no one has been able to explain this particular magic number.

6. General Comments on the Quark Model of Inelastic Lepton Scattering

I conclude with a few general comments about the quark model. In the context of inelastic lepton scattering, it is an extremely useful form of shorthand, enabling one to compute cross-sections for all types of leptons on nucleons, over a wide range of dynamical variables. This does not imply at all that one has to take the model literally as meaning that a nucleon is actually built from three quarks; indeed there are good reasons for believing that, in a sense, such an idea is not meaningful.

Let us look at some of problems. First, the parton model seeks to describe the deep-inelastic scattering of leptons by nucleons as incoherent elastic scattering of the lepton by one quasi-free constituent. The interaction of the constituents among themselves must be neglected. So the model should only work at high q^2, where the impulse approximation can hold. How large has q^2 to be? Generally one expects that one should have $q^2 \gg M^2$. That means that, by the uncertainty principle, one is isolating a very small region ($\sim$0.1 fermi for $q^2 = M^2$) inside the nucleon, where there is zero probability that one will find 2 constituents together, that is one hits either 0 or 1 parton. However, one is embarrassed to find that scaling, that is the independence of $F_2(x)$ on q^2, holds to a pre ision of order 1% or so, right down to $q^2 \sim 1$ GeV. Even worse, if we modify our x to x', we get some average type of scaling, with the cross-sections determined by the single dimensionless parameter x', down to ridiculously low values of E and average q^2. The asymptotic sum rules work beautifully in this non-asymptotic region of energy. So, precocious scaling is a fact of life which was certainly not expected and is not easy to explain in our parton picture.

Setting these troubles aside, there are deeper problems, or solutions - it is hard to know which! Quarks are not observed as free particles, and in a way this is just as well, for they have properties which are unacceptable for free particles. I am of course referring to the spin-statistics relation, which has been thoroughly tested for free particles; photons, electrons, protons, neutrons, muons. Quarks do not obey this relation, for they have spin $^1/2$ and yet 3 p-quarks with spins parallel, in an S-state, form the Δ^{++}- resonance. This is perfectly admissible if they can never get out, for example if they were held in a simple harmonic oscillator or other potential which increased fast enough with the quark separtion. Their "reality" or otherwise then depends on whether the observer is inside or outside the potential well. In the same way, an observer iside a 'black hole' (as the existing universe may well be) can observe photons; he can define them as free particles. An observer outside the black hole cannot receive those photons, although he might in principle deduce their existence as a contribution to the energy/momentum of the black hole, and hence the gravitational field outside it, which he can detect.

Let me now try to summarize. The quark model of baryons is to say the least, a very useful mnemonic way of describing an enormous mass of inelastic lepton-nucleon scattering data. It has drawbacks in that as far as leptons are concerned, it appears to work only (but rather too well) for states of baryon number 1 (i.e. nucleons) and for spacelike momentum transfers (i.e. scattering). Even then it throws up some unexplained numbers, like the 50% gluon contribution. It fails dismally for timelike processes involving leptons and hadrons of B = 0, that is $e^+e^- \to$ hadrons, where the predicted cross-sections, via $e^+e^- \to q\bar{q}$ are significantly less than what are observed in the recent colliding beam experiments at CEA and SPEAR.

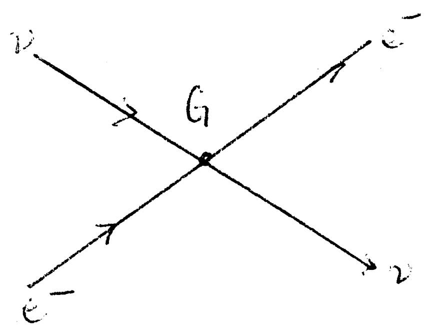
LECTURE II

Neutral Weak Currents

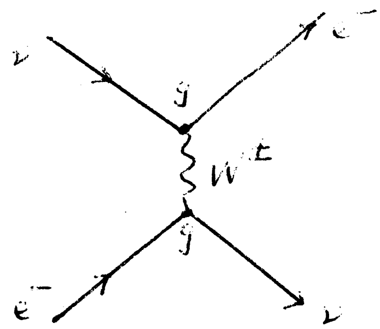
The outstanding development in weak interactions in the last year has been the observations of neutral weak currents, that is, interactions in which a neutrino is scattered, elastically or inelastically, without change of charge. The effects have been observed in four independent experiments at three accelerators, and their existence is firmly established, with couplings comparable with those of the charge-changing weak currents.

It is useful to discuss briefly the theoretical importance of neutral currents. One of the outstanding problems in physics is to understand the inter-relation between the apparently independent fundamental interactions; The strong, weak, electromagnetic and gravitational couplings, not to mention the possible superweak and superstrong interactions. The discovery of neutral currents, at the levels observed, is very strongly suggestive, for the first time, of a basic unification of two of these interactions, the weak and electromagnetic. This is a profound step forward.

It had long been recognised that neutral currents and/or new heavy leptons might be the key to renormalizability of the weak interactions. Let us recall that the old Fermi recipe for β-decay, although successful at low energies, became badly divergent at high energy. For example,



$\sigma \sim G^2 mE$



$\sigma \to G^2 M_W^2$

point, s-wave scattering of neutrinos of energy E by electrons of mass m had a cross-section

$$\sigma(\nu_e + e^- \to e^- + \nu_e) = \frac{4G^2}{\pi} \cdot p^2 = \frac{2G^2 mE}{\pi}$$

where p is the CMS momentum. From ordinary wave theory, the maximum elastic scattering cross-section for CMS wavelength λ is

$$\sigma_{max} = \frac{\pi\lambda^2}{2} \sum (2\ell + 1)$$

$$= \frac{\pi}{2p^2} \quad \text{for s-waves}$$

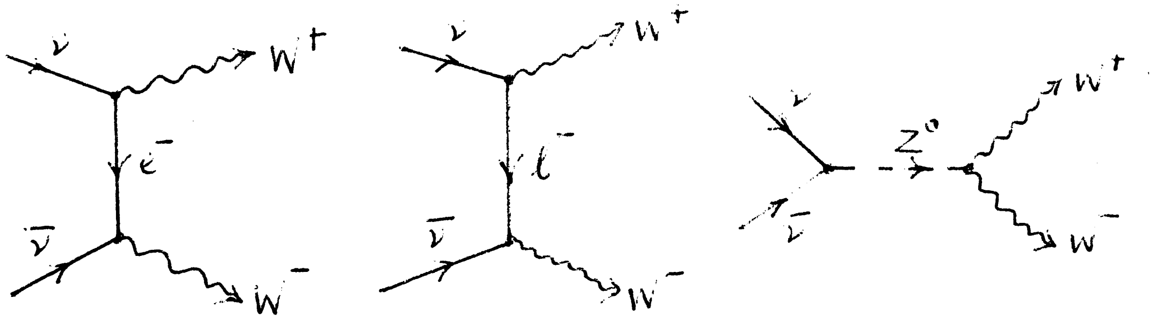
Thus, when

$$pc \gtrsim G^{-1/2} = 300 \text{ GeV}$$

the Fermi cross-section exceeds the wave theory limit, which is impossible. This difficulty could be avoided by introducing the charged intermediate vector boson $W^{\pm}$ to "spread" the weak interaction, thus giving a constant high energy cross-section:-

$$\sigma = \frac{G^2}{\pi} \int_0^{2mE} \frac{dq^2}{\left[1 + \frac{q^2}{M_W^2}\right]^2} \sim \frac{G^2}{\pi} M_W^2 \quad \text{at large E}$$

Unfortunately, there are other amplitudes such as that in (a) below, which are found to be divergent even in first order. A possible cure is to introduce extra amplitudes which are

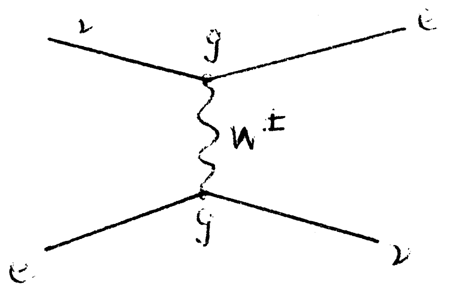


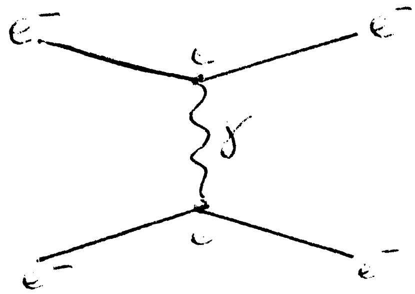
(a) (b) (c)

arranged to exactly cancel the divergent terms. These could be in the t-channel in the form of a new heavy lepton $\ell^{\pm}$, as in (b), or in the s-channel via a neutral boson Z°, that is a neutral current, in the context of the Salam-Ward-Weinberg theory.

The possible renormalizability of weak interactions, that is the finiteness of amplitudes to all orders in the coupling constant and at all energies, is sought in analogy with the prototype renormalizable interaction, namely quantum electrodynamics. Here, renormalizability is connected with gauge invariance and the zero photon mass, and the new theory enlarges the gauge symmetry to include weak processes, by introducing further charged and neutral vector bosons, in addition to the photon. In the infinite energy limit, all particle masses, both of leptons and bosons, can be neglected, and the coupling of the members of the boson family to the leptons is essentially specified by a single coupling constant, α (the fine structure constant). In the Salam-Ward-Weinberg model, the bosons consist of an "isospin" triplet W^+, W^-, W° and an "isosinglet" B_o.

In the real world, such zero-mass, charged fields cannot exist since all charged particles have mass. The mass is supposed to be acquired as a result of some symmetry-breaking mechanism, which however leaves the couplings unaltered. Thus the intrinsic couplings of weak and electromagnetic interactions are supposed to be identical (and the actual ones would be, at sufficiently high energy). At normal energies however, the effective couplings are very different, since the weak interaction is mediated by massive bosons and is consequently of short range, while the electromagnetic interaction is of infinite range (zero photon mass). It is easy to compute the approximate boson mass required to produce the observed effective coupling ratios:-





(a) (b)

From (a) we see that the Fermi coupling G is given by

$$G = \mathop{Lt}_{q^2 \to 0} \frac{g^2}{(q^2+M_W^2)}$$, so that $M_W = g/\sqrt{G}$. If (a) weak and (b)

electromagnetic, interactions have the same coupling g = e, then $M_W = e/\sqrt{G} \sim 30$ GeV. So the charged boson mass in this model is huge, simply expressing the fact that weak interactions are extremely short range, of order 10^{-2} fermi. In detail, the neutral bosons w° and B_0 mix to form

$$Z° = w°\cos\Theta_W + B°\sin\Theta_W$$

$$\gamma = B°\cos\Theta_W - w°\sin\Theta_W$$

where Θ_W, the Weinberg mixing angle, is the only free parameter of the theory. As a result of the gauge symmetry-breaking mechanism, which we do not discuss here, three of the four bosons acquire mass. $W^{\pm}$ mediate the charged weak currents; Z° and the massless γ mediate the neutral weak and electromagnetic interactions respectively. The masses are given by

$$M^2_{W^\pm} = \sqrt{2}\, e^2/(8G\sin^2\Theta_W); \quad M_{W^\pm} = 37/\sin\Theta_W \text{ GeV}$$

$$M^2_{Z°} = \sqrt{2}\, e^2/(8G\cos^2\Theta_W\sin^2\Theta_W); \quad M_{Z°} = 37/(\sin\Theta_W\cos\Theta_W) \text{ GeV} \quad (16)$$

and $M_\gamma = 0$ ≥ 74 GeV

Finally, it should be mentioned that two isodoublets of scalar bosons have to be introduced in the model (to provide the symmetry-breaking mechanism). There is no prediction on their masses. A necessary consequence of the model is that neutral and charged weak bosons have comparable couplings (in the limit $\theta_W = 0$, the amplitude ratio (neutral/charged) = $^1/2$, which is simply a Clebsch-Gordan coefficient). It is most important to understand that this model is one of leptons and mediating bosons; hadrons do not enter specifically, and one has to make further hypotheses to include them.

We now discuss the experimental situation. We expect the experiments of course to tell us much more than simply whether or not neutral currents exist. For example they should determine the Weinberg angle, or, equivalently, the relative amount of V and A coupling (and any other) associated with neutral currents. In addition to the space transformation properties, one should get indications, when dealing with hadrons, on the isospin properties, whether the inclusive neutral current interactions obey scaling, and so on.

(i) Leptonic Neutral Currents - the CERN Gargamelle Experiment

The CERN experiment uses a so-called focussed wideband beam, obtained by directing 26 GeV protons into a beryllium target, thus producing charged pions and kaons which decay to neutrinos in a 60 m long decay tunnel. Hadrons and muons are filtered out by a 22m steel shield. The beam of about 10^9-10^{10} neutrinos/sec traverses a large bubble chamber (Gargamelle, 1.8 m diameter x 5 m long) filled with heavy liquid (CF_3Br, density 1.5). The useful mass of liquid is about 10 tons. The pions and kaons of one sign of charge from the target can be partly focussed by specially-shaped, pulsed conductors, and one can select a beam of ν_μ (positives focussed) or $\bar{\nu}_\mu$ (negatives focussed). The neutrino spectrum is continuous, with a peak at 2 GeV and falling off rapidly at higher energy - see Figs. 5 and 6. In addition to ν_μ, a small component ($\sim ^1/2\%$) of ν_e, from μ and Ke3 decay, is present.

The lepton couplings in the Weinberg theory are given in the accompanying table. The differential cross-section for projecting an electron with energy E is

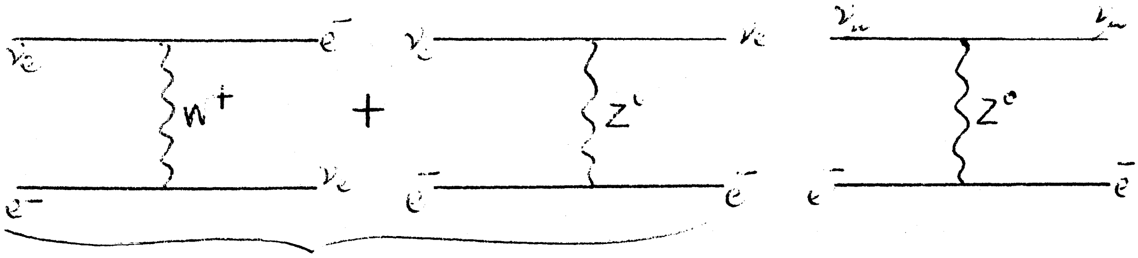
$$\frac{d\sigma}{dE} = \frac{G^2 m}{2\pi} [(g_V + g_A)^2 + (g_V - g_A)^2 (1-E/E_o)^2] \qquad (17)$$

Elastic Scattering of	Weinberg Theory g_V	Weinberg Theory g_A	V-A Theory g_V	V-A Theory g_A
$\nu_e + e^-$	$\frac{1}{2} + 2\sin^2\Theta$	$\frac{1}{2}$	1	1
$\bar{\nu}_e + e^-$	$\frac{1}{2} + 2\sin^2\Theta$	$-\frac{1}{2}$	1	-1
$\nu_\mu + e^-$	$-\frac{1}{2} + 2\sin^2\Theta$	$-\frac{1}{2}$	0	0
$\bar{\nu}_\mu + e^-$	$-\frac{1}{2} + 2\sin^2\Theta$	$\frac{1}{2}$	0	0

Θ = Weinberg Angle

for a neutrino energy $E_o >> m$, the electron mass. The total cross-sections obtained by integrating this expression are shown in Fig. 7.

While electron neutrinos can scatter via both charge-changing and neutral currents, muon neutrino-electron scattering can take place only via a neutral current:-



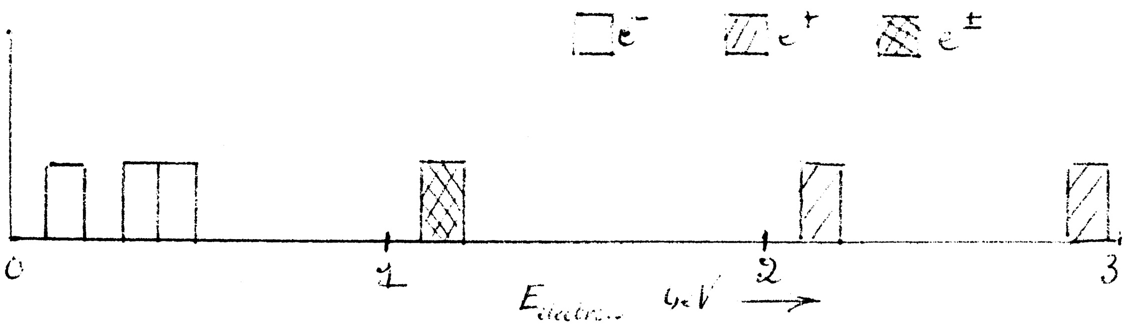
ν_e - e scattering $\qquad$ ν_μ - e scattering

Note that not only the total cross-section but also the recoil energy spectrum depends quite critically on Θ_W. We shall be concerned mostly with $\bar{\nu}_\mu$ interactions, for which the spectrum is fairly flat for $\sin^2\Theta_W \gtrsim {}^1/2$, but is sharply peaked to low values, and of the form $(1-E/E_o)^2$, for small Θ_W. The minimum cross-section for $\bar{\nu}_\mu$ on electrons occurs for $\sin^2\Theta_W = 0.125$, and has the value $G^2mE_o/8\pi = 1.06.10^{-42}E$ cm^2/electron/GeV. For a 10-ton detector, $10^9\bar{\nu}_\mu/m^2$/pulse, this corresponds to one interaction in every million pulses. This dismally low rate is compensated by the fact that the interactions have very clear signatures, since the maximum angle of emission of the electron is small:

$$\Theta_e = \sqrt{2m(\frac{1}{E} - \frac{1}{E_o})} < \sqrt{\frac{2m}{E}}$$

For E > 200 MeV, $\Theta_e < 4°$.

The Gargamelle experiment is still in progress. The runs started in 1971, and are being continued (through 1973/4) with the CERN booster ($\sim 5.10^{12}$ppp). From 0.3 million antineutrino pictures without, and 0.5 million with, the booster, the very preliminary results, for single e^- or e^+ events, or events of undetermined sign, with $\Theta_e < 5°$, looks roughly as follows:



The radiation length in the liquid freon employed is 0.11 m; this means that an e^+ or e^- may undergo bremstrahlung with pair conversion after only a few cms., and it is then not possible to measure the sign of charge from curvature. In events of the type $\nu_e + n \to e^- +$ hadrons, it is known that such confusion arises in 30% of the events.

The main source of e^+ events is the elastic reaction produced by $\bar{\nu}_e$:-

$$\bar{\nu}_e + p \to n + e^+ \qquad (18)$$

where the e^+ has $\Theta < 5°$, and there is correspondingly small q^2 of order 0.01 or less. Analysis of numerous events of the type $\nu_\mu + n \to p + \mu^-$ allows one to evaluate the probability of such low q^2 processes which are of course suppressed by the Pauli principle in complex nuclei. Since the e^+carries off essentially the full energy of the incident $\bar{\nu}_e$, and the cross-section at low q^2 is independent of energy, we expect the positron spectrum to follow that of the antineutrinos, with a pronounced peak at 2 GeV.

Background single electron events can arise from the reaction

$$\nu_e + n \rightarrow e^- + (p) \qquad (19)$$

where, on account of the low q^2, the proton is not observed. As compared with (18), the event rate should be suppressed by a factor 5-10 (depending on energy), since in the antineutrino runs, the neutrino parents (π^+ and K^+) are defocussed. The energy spectrum of e^- and e^+ from the elastic interactions on nucleons will be similar.

The important features of the signal and background processes is that electrons from neutral current interactions will be of predominantly low energy (less than 1 GeV usually), while e^+ and e^- from the background will be of high energy (>2 GeV usually). This feature is illustrated in Fig. 8, and seems to be borne out by the data. The table below gives an approximate calculation of expected numbers of signal and background events.

Film	Flux/m^2	Weinberg max	Weinberg min	BGND $\nu_e n \rightarrow e^-(p)$ $+\gamma$	Observed ($\theta < 5°$)	
ν	2.10^{15}	6.0	0.6	0.3 ± 0.2	0	e^-
$\bar{\nu}$	$3\text{-}4.10^{15}$	20	1	0.12 ± .04 (>1 GeV)	3→4	e^- (<1 GeV)
		—	—	$\bar{\nu}_e p \rightarrow (n) e^+, +\gamma$ ∿1.8 (>1 GeV)	2→3	e^+ (>1 GeV)

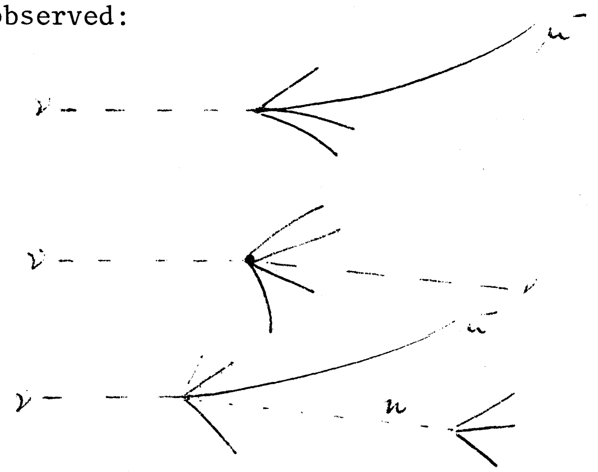
The 90% confidence levels from the experiment to date are

$$0.6 > \sin^2\theta_W > 0.1$$

(ii) Inclusive Neutral Current Interactions on Nucleons. The CERN and NAL experiments.

These experiments have observed examples of the process ν_μ, $\bar{\nu}_\mu$ + nucleon $\rightarrow$ ν_μ, $\bar{\nu}_\mu$ + hadrons. The CERN experiment was carried out in the heavy liquid chamber Gargamelle (Hasert et al 1973) with a wideband beam produced by 26 GeV protons. The NAL experiment employed a large liquid scintillator calorimeter, followed by a muon spectrometer, and used both wideband and narrowband neutrino beams, produced by 200-400 GeV protons (Benvenuti et al 1974).

There is not space to go into these experiments in detail, but the principals of the experiments were as follows. In the CERN experiment, events were recorded which contained identified hadrons only (so-called "NC" events), with no other event in the same picture. The main problem was to establish that these were not due to neutrons produced by neutrino interactions in the shielding or other material surrounding the bubble chamber liquid. This was done by recording associated star ("AS") events, in which a neutrino interaction (with muon secondary), together with the interaction of a secondary neutron, was observed:



Charged current (CC) event

Neutral current (NC) event

Associated star (AS) event.

From a detailed analysis of the event distributions, and Monte Carlo calculations of neutron production and propagation through the shielding, it was concluded that only 10% of the NC events could be ascribed to neutrons, and the remainder must be ascribed to some new process; neutral currents are the obvious candidates. For hadron energies >1 GeV, the observed ration R_ν = (NC events)/(CC events) = 0.26 ± 0.03 for neutrinos and $R_{\bar{\nu}}$ = 0.46 ± 0.09 for antineutrinos.

The NAL counter experiment observed "muonless" events as those which gave a certain minimum hadron energy release in the calorimeter, but no signal in the spark chambers of the downstream spectrometer. From these events must be subtracted those with muons which missed the spectrometer. The muon detection efficiency was measured and the conclusion, after some 6 months of hesitation on the part of the groups involved, was that a genuine neutral current signal remained. In order to improve the muon detection efficiency, the experiment was modified to require that muons should only penetrate a 30 cms thick iron plate at the rear of the calorimeter; one then has to correct genuine NC events for the hadron punch-through probability, that is, the probability that a hadron would give a track in a counter behind the iron plate. This can be measured using events with an identified muon in the spectrometer. The experiments used a wideband, unseparated or partly separated beam, and the early results gave for the ratio R = (NC events)/(CC events) = 0.27 ± .09; the later runs gave R = 0.20 ± .05. In a still later version, using a narrow-band, dichromatic beam, separate values for neutrino and antineutrino runs have been given: $R_\nu = 0.13 \pm 0.06$, $R_{\bar{\nu}} = 0.34 \pm 0.12$.

The results from both CERN and NAL experiments are given in the following table:-

Laboratory	Min Hadron energy	Mean neutrino energy	R_ν	$R_{\bar{\nu}}$	Beam
CERN	> 1 GeV	∿3 GeV	0.26±0.03	0.46±0.09	Wideband separated
NAL	> 6 GeV	∿50 GeV	0.13±0.06	0.34±0.12	Narrow Band separated

We note that the two sets of experimental results are not very consistent; this may be attributable to different values of the ratio (hadron energy)/(mean neutrino energy), to the different energy range, or, more likely, systematic errors or biasses arising from the experimental criteria.

The results may be interpreted in the Weinberg theory, if we are prepared to make additional assumptions regarding the coupling of hadrons to neutral currents. These interpretations are very model-dependent.

As an example, Fig. 9 shows R_ν plotted against $R_{\bar{\nu}}$. The curve shown indicates the variation expected for equal V and A coupling with maximum V-A interference (as is the case for charged currents). This curve represents a lower limit to the ratios R_ν and $R_{\bar{\nu}}$, for pure isovector coupling and zero isoscalar contribution. While the CERN result sits on the limiting curve, the NAL result is not consistent with it. Because of these discrepancies, it is hard to draw conclusions. There is however some other circumstantial evidence to suggest that isoscalar contributions to the neutral coupling are unimportant. For example, the ratio of neutral to charged pion secondaries observed in the Gargamelle experiment is 0.9 ± 0.1 in both charged and neutral current events, as expected if they are the $I_\pm$ and I_3 components of an isospin 1 current.

If the neutral current inclusive cross-sections for neutrino and antineutrino are denoted σ_o and $\bar{\sigma}_o$, then the result $\sigma_o = \bar{\sigma}_o$ could indicate that the coupling is pure V or pure A, with no V/A interference term. The results observed are

$$\frac{\bar{\sigma}_o}{\sigma_o}\ (\mathrm{CERN}) = 0.46 \pm 0.12; \qquad \frac{\bar{\sigma}_o}{\sigma_o}\ (\mathrm{NAL}) = 0.9 \pm 0.5$$

Thus, pure A or pure V coupling does not appear very likely, but it must be borne in mind that the selection of events introduces possible biasses and one has to exercise caution.

In summary, the study of inclusive hadron processes has demonstrated the existence of semi-leptonic neutral currents. It is too early to draw definite conclusions regarding their transformation properties, but it seems likely that they are predominantly isovector with both V and A spatial components. A value of the Weinberg angle $\sin^2\Theta_W = 0.3\text{-}0.5$ is consistent with the rates observed.

(iii) Exclusive Hadronic Neutral Currents - Single Pion Production

It has long been recognized that more precise information regarding the nature of semi-leptonic neutral currents could be obtained, with fewer theoretical assumptions, by studying exclusive final states with well-defined properties, such as isospin.

The cleanest experiment of this type has been carried out in the ANL 12' H_2/D_2 chamber, over the past 2-3 years. Because of the kinematic constraints and high precision of the hydrogen bubble chamber technique, it is possible to evaluate backgrounds in a rather direct way; for example, the neutron background flux can be measured by observing events of the type $np \to pp\pi^-$ (1C fit). There is not space here to do justice to a very clever analysis, which is unfortunately and rather naturally limited by poor statistics. After making all background corrections, the single pion production channels (either a π^+ or a π° giving, on occasion, a single $\gamma \to e^+e^-$) lead to the results

Weinberg/Adler Model

$$R_+ = \frac{\nu p \to \nu n\pi^+}{\nu p \to \mu^- p\pi^+} = 0.17 \pm 0.08 \,; \quad 0.06 \lesssim R_+ \lesssim 0.17$$

$$R_o = \frac{\nu p \to \nu p\pi^\circ}{\nu p \to \mu^- p\pi^+} = 0.48 \pm 0.24 \,; \quad 0.06 \lesssim R_o \lesssim 0.22$$

There is therefore a clear neutral current signal (13 events against a background of $\sim$2.4), the rates being consistent with various models, but favouring $\sin^2\theta_W < 0.5$.

The interesting result $R_o/R_+ = 2.9 \pm 2.0$ can be compared with the expectation of 2 for a final state of $I = {}^3/2$ (therefore $\Delta I = 1$), and ${}^1/2$ for a final state of $I = {}^1/2$ (isoscalar current). Again, isovector neutral currents are favoured.

(iv) Conclusions

Four different experiments find significant evidence for neutral weak currents, in both leptonic and semi-leptonic processes. We can regard the effect as well established.

This result must be set against the very stringent limits on the complete absence of hadronic neutral currents in $\Delta S = 1$ decay processes, for example $K^+ \to \pi^+\nu\bar{\nu}$ has a branching ratio $<10^{-6}$. How these results can be reconciled on the basis of a hadron model is not clear. One suggestion has been to cancel the $\Delta S = 1$ amplitude by introducing extra quantum numbers. The Glashow, Iliopoulos, Maiani SU4 scheme has a quarter of quarks; the usual p, n, λ plus a "charmed" quark p', with the correct Cabibbo coupling to cancel the $\Delta S = 1$ neutral current amplitude. The p' has charge $+^2/3$, $S = -1$, $I = 0$ and the extra "charm" quantum number ($C = 1$). If the new quark is heavier than p, n, λ, one can ascribe the success of SU3 to the fact that observed baryon resonances are below the "charm" threshold. The mass difference cannot be more than a few GeV however, otherwise the forbidden $\Delta S = 1$ neutral current transitions would proceed in second order at an unacceptably high rate.

The fact that the charged-current processes show no evidence for charmed particle production may be due to the fact that charmed particles contribute only a small part of the cross-section. Thus, in the GIM model, either transitions are of the $\Delta S = 1$ type $n \rightarrow p'$, and therefore suppressed by the Cabibbo factor $\sin^2\Theta_C \sim 0.05$; or they are $\Delta S = 0$, such as $\lambda \rightarrow p'$, where the target quark λ can arise only from the quark-antiquark sea, again making $\sim$5% contribution to the cross-section. Thus, more refined tests are required. The question of charmed particles is at present an open one.

Finally, one might speculate (perhaps idly) about the space properties of neutral lepton currents. Maximum economy of hypothesis could have been obtained by having pure V electromagnetic interactions, pure A neutral weak currents, and charged weak currents with equal V and A contributions, with maximum interference (i.e. maximum parity violation). The first and last options were taken up by nature, but the second, apparently, was not. It would require $\sin^2\Theta_W = 0.25$ ǂ which is on the verge of exclusion by the experimental data.

ǂ See the table on leptonic couplings in the first part of this lecture.

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Total Cross-Sections

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NAL: Benvenuti et al, PRL. 30, 1084 (1973)

Barish B. et al; 32, 125 (1974) (Philadelphia Conf., May 1974)

Neutral Currents

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Inclusive; CERN, Hasert et al, PL. 46B, 138 (1973)

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Exclusive (1π); Barish S. et al, Private Communication (1974)

Other References

Glashow S.L., Iliopoulos J. and Maiani L., PR. D2, 1285 (1970)

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Salam A and Ward J.C., PL 13 168 (1964)

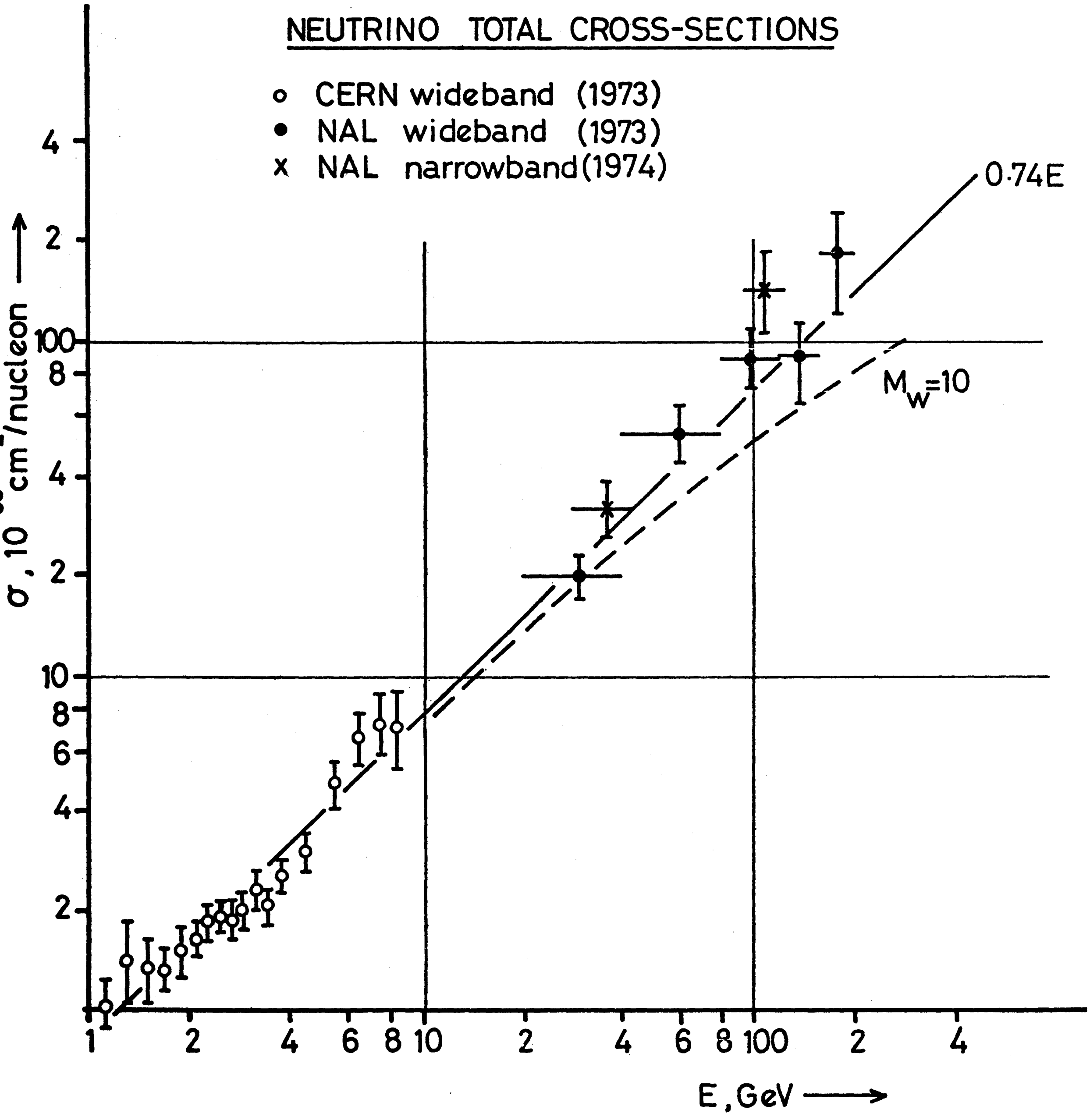

NEUTRINO TOTAL CROSS-SECTIONS
o CERN wideband (1973)
• NAL wideband (1973)
x NAL narrowband (1974)
0·74E
M_W=10
σ, 10^-38 cm^2/nucleon
E, GeV
1
2
4
6
8
10
100

Fig. 1

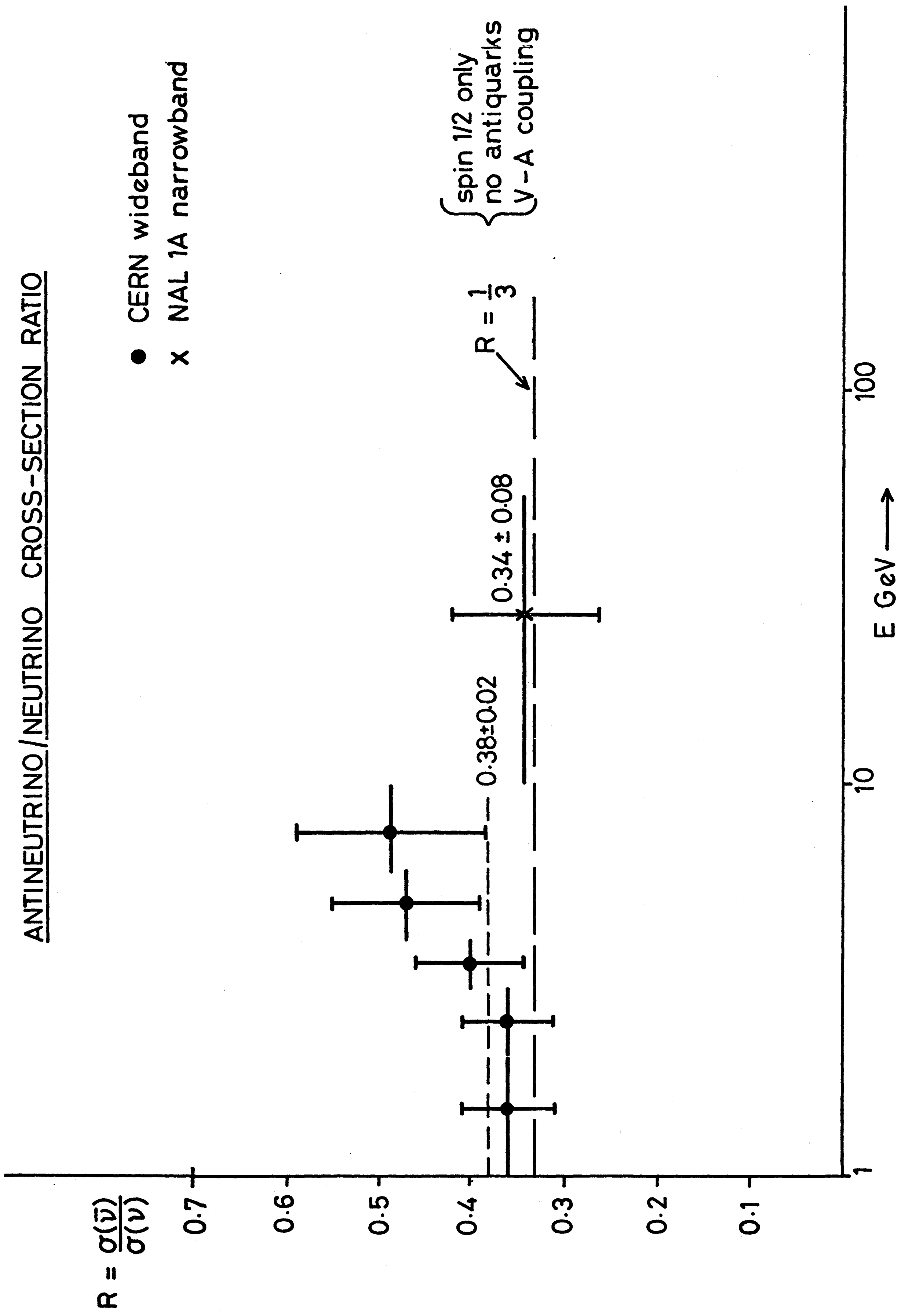

ANTINEUTRINO/NEUTRINO CROSS-SECTION RATIO
● CERN wideband
× NAL 1A narrowband
R = $\frac{\sigma(\bar{\nu})}{\sigma(\nu)}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
10
100
E GeV ⟶
0.38±0.02
0.34 ± 0.08
R = $\frac{1}{3}$
spin 1/2 only
no antiquarks
V–A coupling

Fig. 2

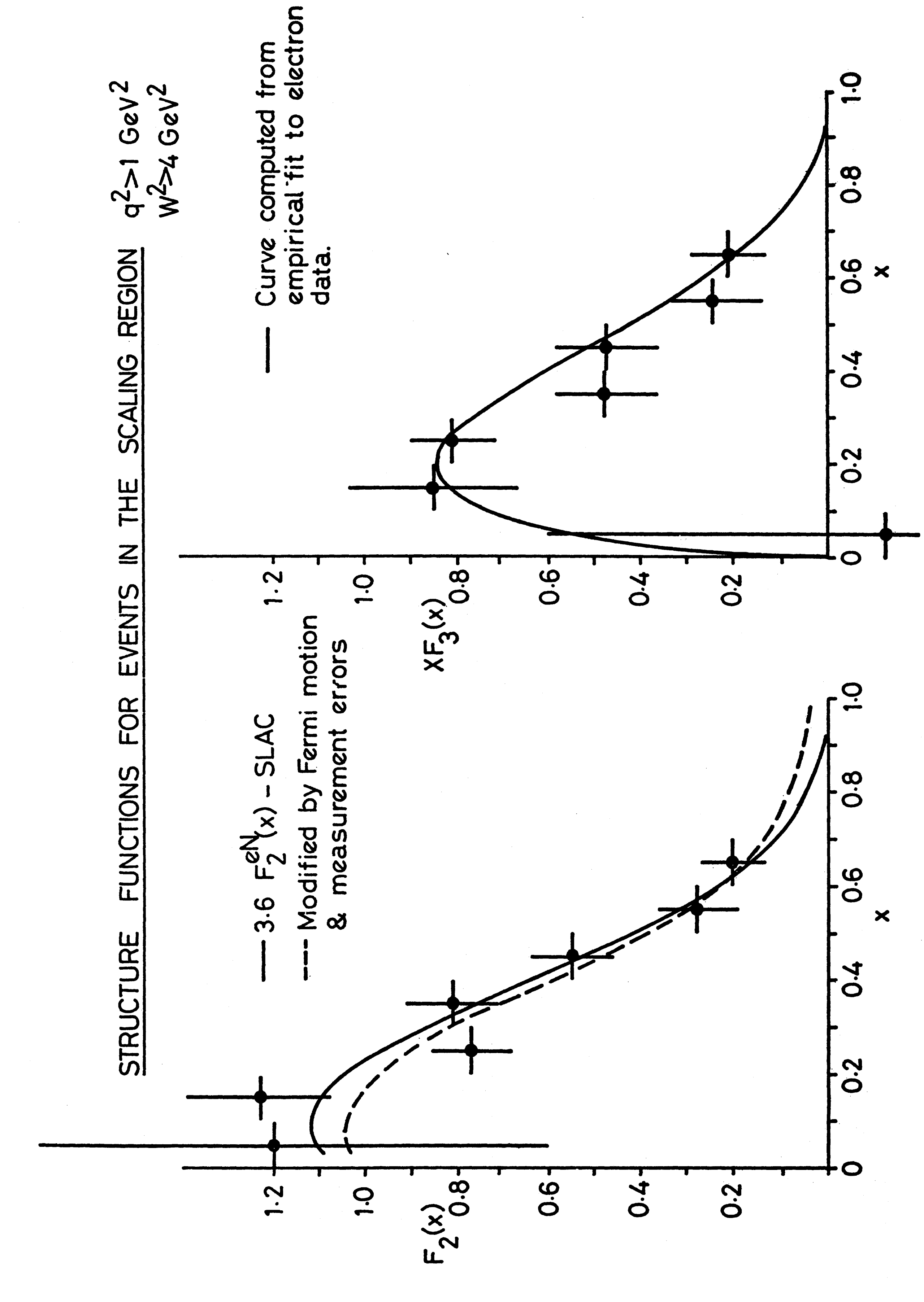
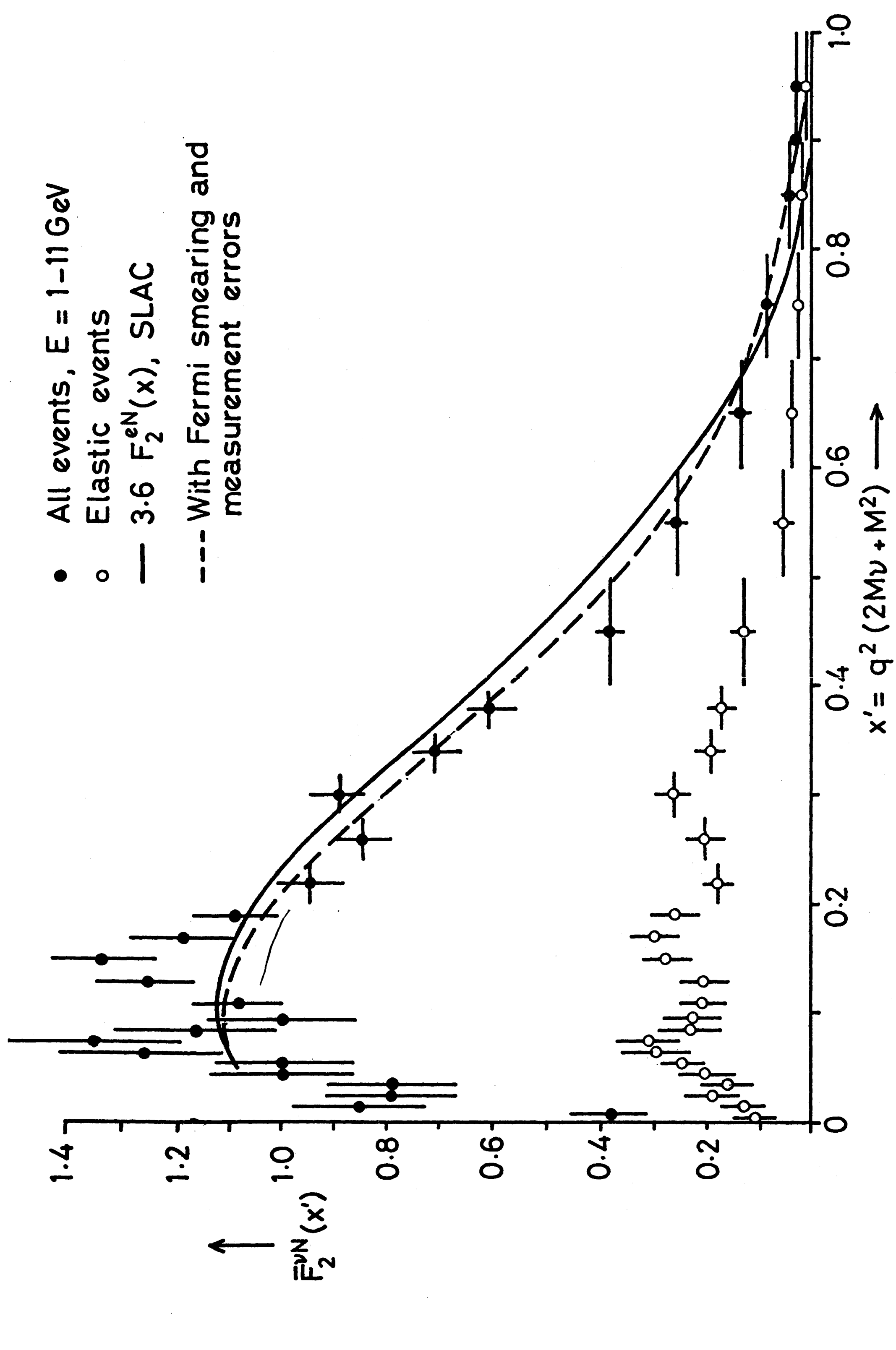

STRUCTURE FUNCTIONS FOR EVENTS IN THE SCALING REGION
$q^2 > 1\ GeV^2$
$W^2 > 4\ GeV^2$
— 3.6 $F_2^{eN}(x)$ - SLAC
--- Modified by Fermi motion & measurement errors
$F_2(x)$
x
— Curve computed from empirical fit to electron data.
$xF_3(x)$
x

Fig. 3



● All events, E = 1–11 GeV
○ Elastic events
— 3.6 $F_2^{eN}(x)$, SLAC
--- With Fermi smearing and measurement errors
$\overline{F}_2^{\nu N}(x')$
$x' = q^2 (2M\nu + M^2)$
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Fig. 4

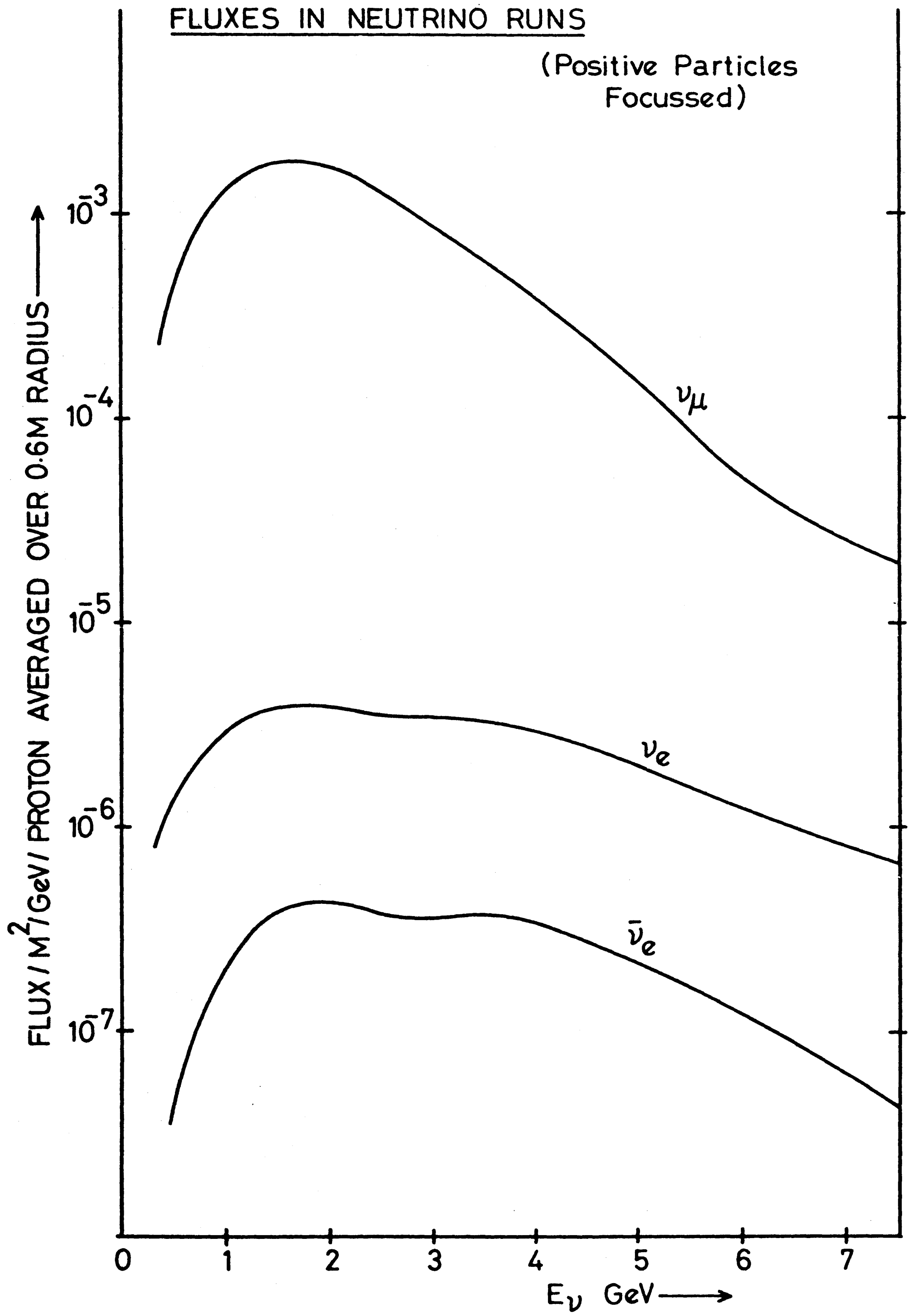

FLUXES IN NEUTRINO RUNS
(Positive Particles Focussed)
FLUX / M²/GeV/ PROTON AVERAGED OVER 0·6M RADIUS
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
νμ
νe
ν̄e
0
1
2
3
4
5
6
7
Eν GeV

Fig. 5

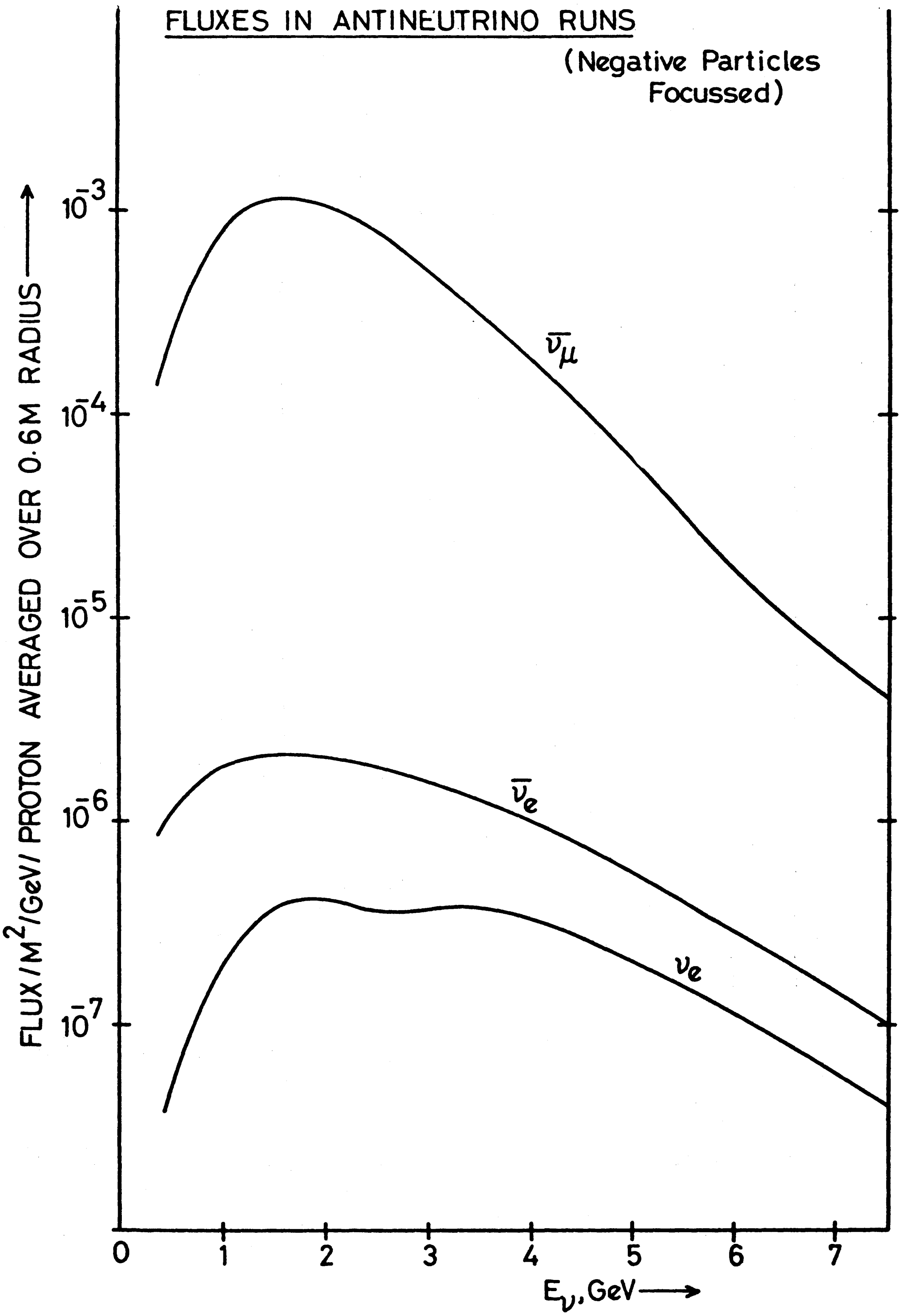

FLUXES IN ANTINEUTRINO RUNS
(Negative Particles Focussed)
FLUX/M²/GeV/ PROTON AVERAGED OVER 0.6M RADIUS
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\bar{\nu}_\mu$
$\bar{\nu}_e$
ν_e
0
1
2
3
4
5
6
7
E_ν, GeV

Fig. 6

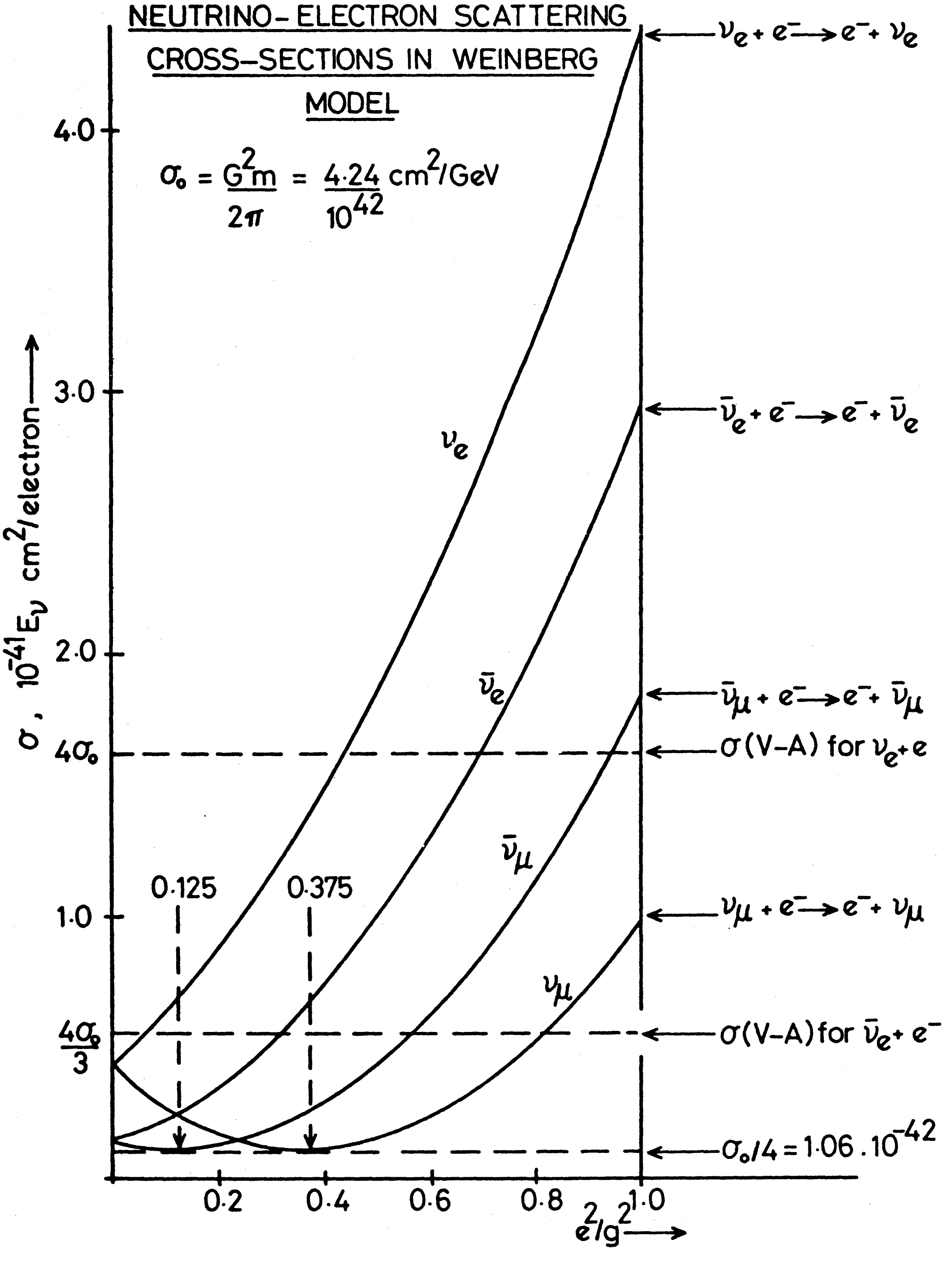

NEUTRINO-ELECTRON SCATTERING
CROSS-SECTIONS IN WEINBERG
MODEL
σ₀ = G²m/2π = 4·24/10⁴² cm²/GeV
σ , 10⁻⁴¹ E_ν cm²/electron
4·0
3·0
2·0
4σ₀
1·0
4σ₀/3
0·125
0·375
ν_e
ν̄_e
ν̄_μ
ν_μ
ν_e + e⁻ → e⁻ + ν_e
ν̄_e + e⁻ → e⁻ + ν̄_e
ν̄_μ + e⁻ → e⁻ + ν̄_μ
σ(V-A) for ν_e + e
ν_μ + e⁻ → e⁻ + ν_μ
σ(V-A) for ν̄_e + e⁻
σ₀/4 = 1·06 . 10⁻⁴²
0·2
0·4
0·6
0·8
1·0
e²/g²

Fig. 7

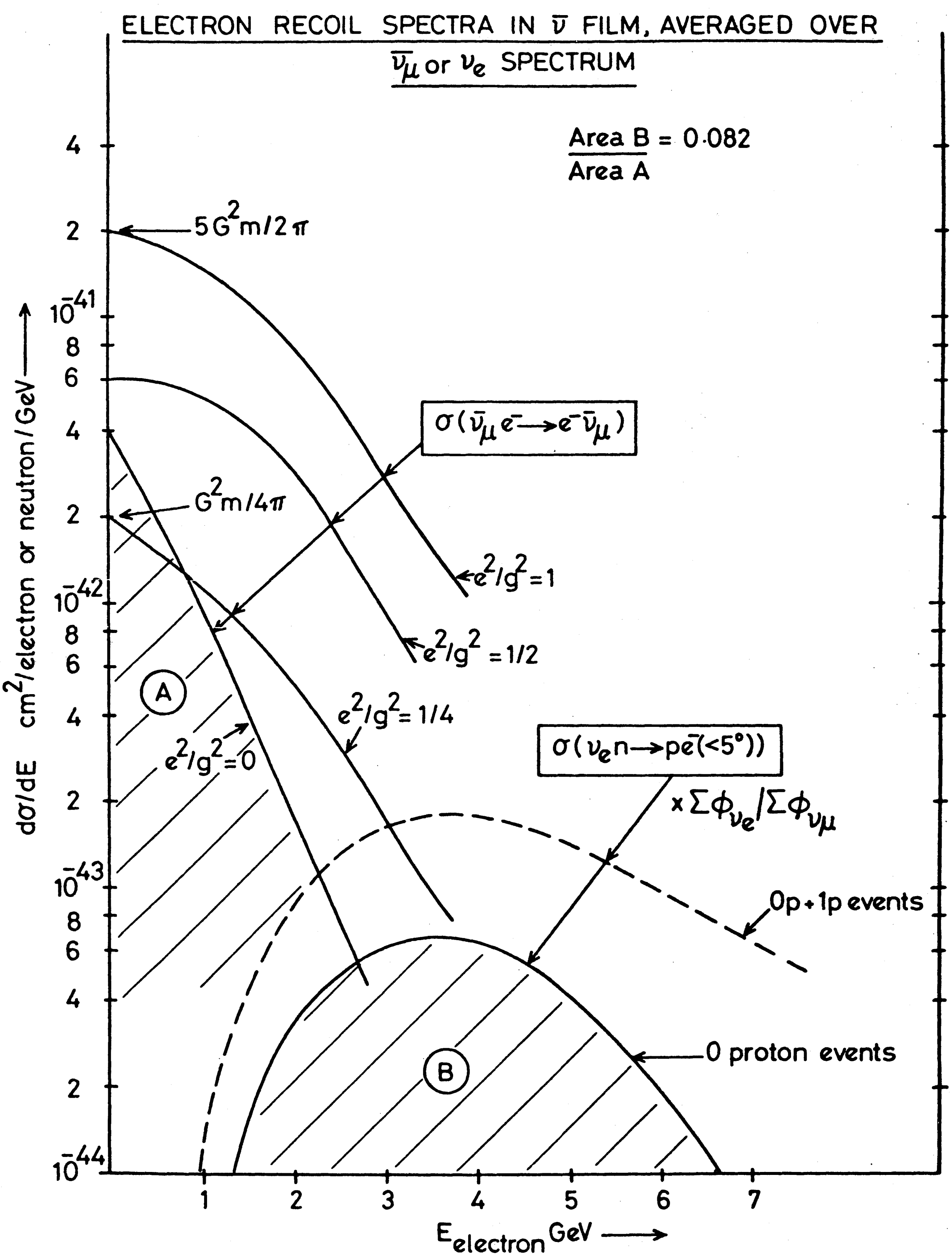

ELECTRON RECOIL SPECTRA IN $\bar{\nu}$ FILM, AVERAGED OVER
$\bar{\nu}_\mu$ or ν_e SPECTRUM
Area B / Area A = 0.082
$5G^2m/2\pi$
$G^2m/4\pi$
$\sigma(\bar{\nu}_\mu e^- \to e^- \bar{\nu}_\mu)$
$e^2/g^2 = 1$
$e^2/g^2 = 1/2$
$e^2/g^2 = 1/4$
$e^2/g^2 = 0$
A
B
$\sigma(\nu_e n \to p e^-(<5°))$
$\times \Sigma\phi_{\nu_e}/\Sigma\phi_{\nu_\mu}$
0p + 1p events
0 proton events
$d\sigma/dE$ cm^2/electron or neutron / GeV
$E_{electron}$ GeV
4
2
10^{-41}
8
6
4
2
10^{-42}
8
6
4
2
10^{-43}
8
6
4
2
10^{-44}
1
2
3
4
5
6
7

Fig. 8

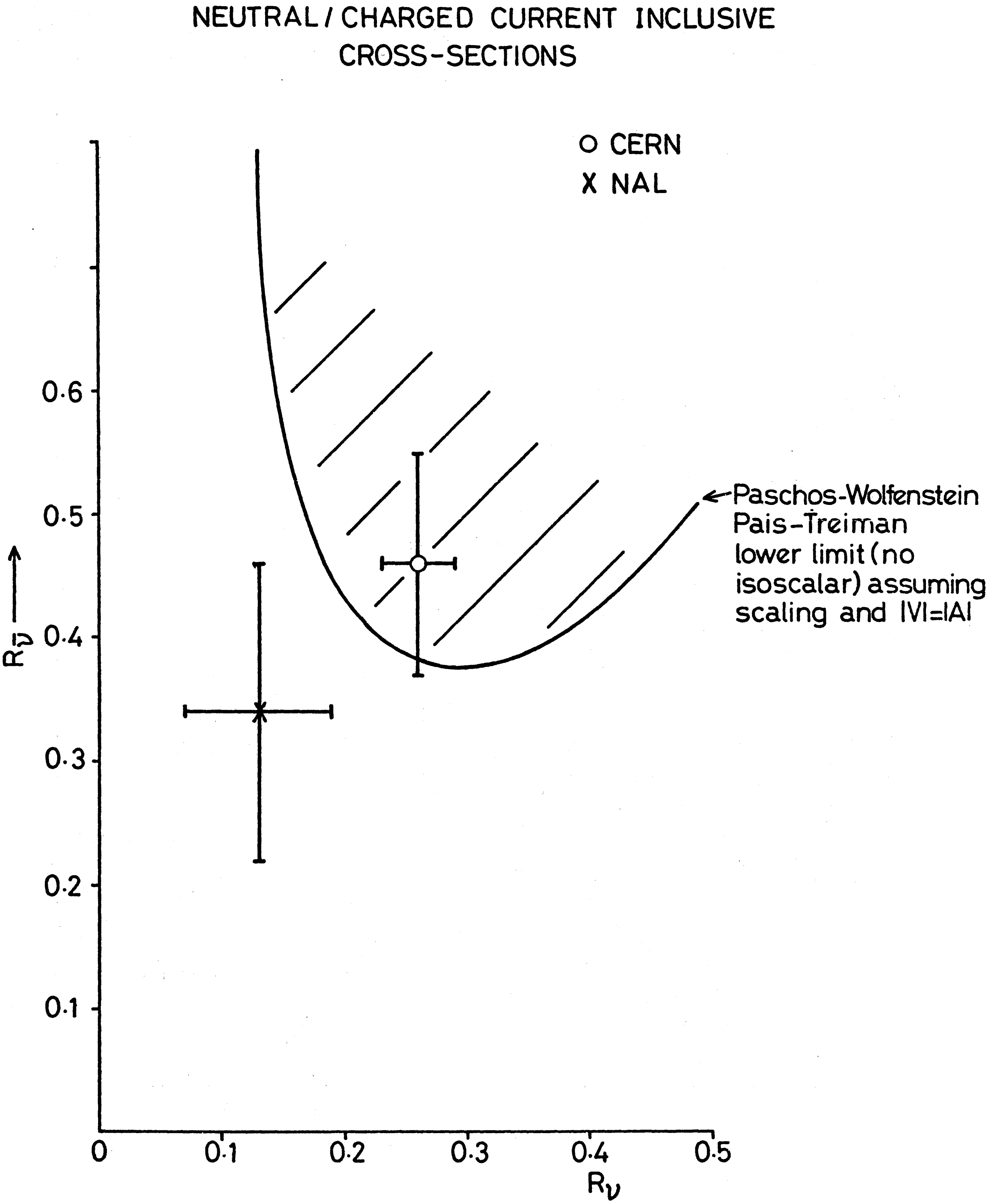

NEUTRAL / CHARGED CURRENT INCLUSIVE CROSS-SECTIONS
O CERN
X NAL
Paschos-Wolfenstein
Pais-Treiman
lower limit (no
isoscalar) assuming
scaling and |V|=|A|
$R_{\bar{\nu}}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
R_{ν}

Fig. 9

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