WEAK NEUTRAL CURRENTS UNVEILED

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À GARGAMELLE, l'heroine des courants neutres.

Abstract

The history of Weak Neutral Currents is briefly reviewed. Neutrino-electron scattering is treated in some detail: the data about three channels are now mutually consistent, and fix the weak neutral electron current to either pure axial vector A, or to vector current V. Parity violation in high energy ed scattering singles out the A-solution of the Salam-Weinberg type. A corresponding analysis of the space-time structure of the quark weak neutral currents reveals almost pure V - A. Assessing the isospin structure wants data from exclusive or semi-inclusive reactions, like elastic neutrino-proton scattering or single-pion production. The result is essentially unique, and leaves the standard Salam-Weinberg $SU_2 \times U_1$ model, with a mixing parameter $\sin^2\theta_W = 0.25 \pm 0.03$ as the sole possibility to describe weak neutral currents.

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1. The Rise of Neutral Currents

The history of Neutral Currents is short. Since 1971 the big heavy liquid bubble chamber GARGAMELLE had been exposed to the neutrino and antineutrino beams from the CERN proton-synchrotron (PS). All during 1972 the GARGAMELLE Collaboration of

Aachen, Bruxelles, CERN, Ecole Polytechnique (Paris),
Milano, Orsay, and University College London

were struggling to see if partons had the properties of quarks [1]. Neutral currents belonged to the unpleasant duties, one was supposed to take care of in one's spare time. The rumors that some theoreticians would like to see them existing, added only an air of bitter scepticism.

But around Christmas 1972 the Aachen Group were lucky enough to find in their batch of antineutrino film an isolated electron of moderate energy, which had been emitted within the accuracy of the measurement, exactly in beam direction (Fig. 1). This is of course precisely what one expects for the recoil from a high-energy neutrino-electron scattering. And if the neutrino has been of the muon-neutrino variety, indeed, the interaction between $\overset{(-)}{\nu}_\mu$ and e had to go through an intermediate neutral current. Therefore, a single unambiguous $\overset{(-)}{\nu}_\mu e$ event suffices to establish the existence of this new force of Nature with certainty*).

*) The situation is not too different from the discovery of the Ω^-, although the single e-signature is simpler. Probably for that reason the notorious Hamburg magazine "Der Spiegel" called the Aachen electron the "event of the century". (Characteristically, the "Spiegel" did not mention the discoverers, confused the relevant theoreticians, and printed, in place of Fig. 1, a completely irrelevant, messy ν_e background photo ...)

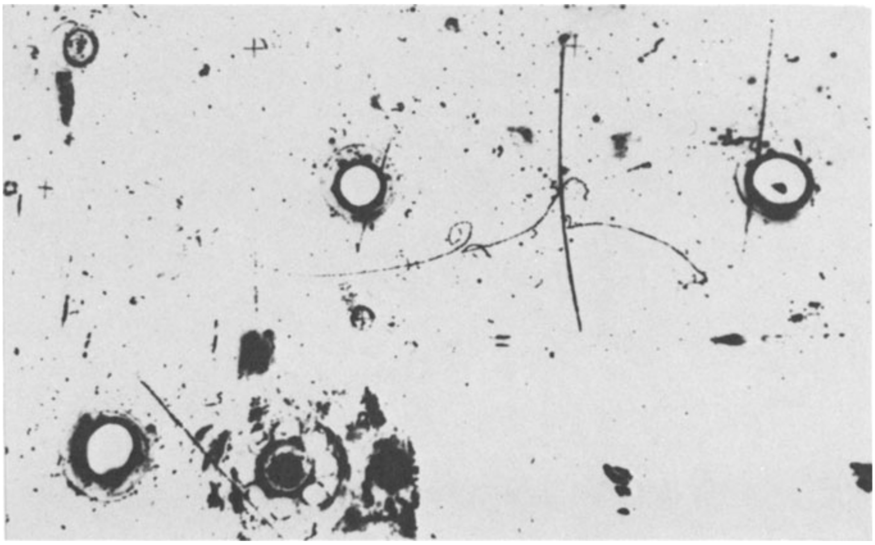

Fig. 1: The Aachen $\bar{\nu}_\mu e$ scattering event - the first evidence for neutral currents. (Neutrinos from the left)

Of course it must be proven that the event in question cannot be explained otherwise, for instance by the < 1% ν_e $(\bar{\nu}_e)$ contamination in the beam, or by asymmetric e^-e^+ pairs from converted photons. A few months of discussions and calibration measurements convinced us that these backgrounds have, at most, a chance of 3% to simulate the event observed. Consequently it was presented to the Bonn Electron-Photon Symposium, in August 1973 [2,3], and shortly afterwards published [4].

In the meantime, the Orsay-Group under the inspiring leadership of the late André Lagarrigue, got evidence that some of the inelastic muon-less hadronic events were in fact neutrino-induced. This was an enormous breakthrough, considering that such messy events, like the one in Fig. 2, had already been noticed in the 1963/64 CERN neutrino bubble chamber [5] and sparkchamber [6]

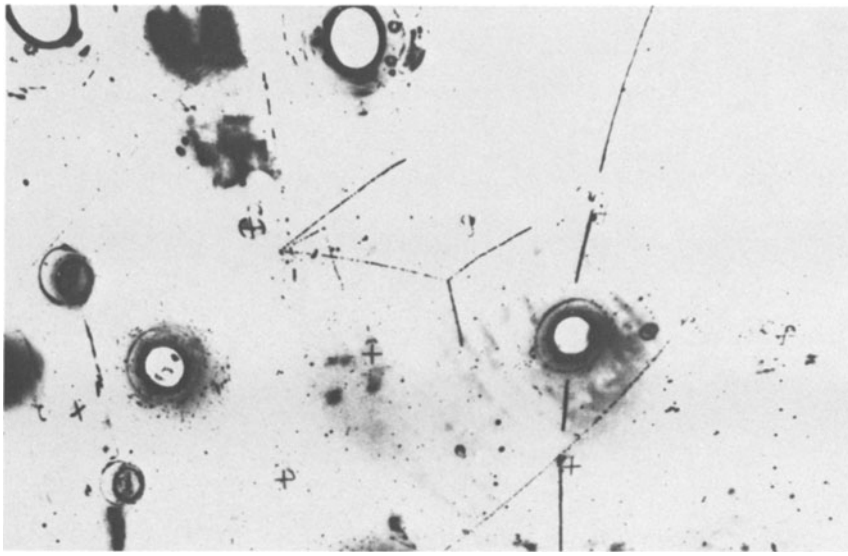

Fig. 2: Muon-less hadron star, as observed in GARGAMELLE.

experiments. (Having seen these photos myself, and too lightly dismissed them as neutron stars, I cannot blame this slip on unfit instrumentation: Our old sparkchambers were well suited for the interaction analysis [7]. That we did not believe what we saw, was an unfortunate conspiration of mental blocking, by theoretical prejudice, and experimental mischief.) The separation of neutron and neutrino induced muonless events took the GARGAMELLE (GGM) Collaboration many months of hard work. It implied the analysis of every track in every event, the meticulous analysis of the spatial and energy distributions [8], experimental studies of neutron-induced events, lengthy Monte Carlo calculations, and hadronic cascade studies initiated in GGM by protons of known energy [9]. Only then the GGM-Group published their evidence for hadronic weak neutral currents [3,8] alongside with their electron.

2. The Theoretical Significance of Neutral Currents

When this happened at the Bonn 1973 Conference [3], the Physics Community was actually eagerly waiting for the weak neutral currents to appear. Almost unnoticed for many years, an old, attractive idea had been gaining ground: that the weak and the electromagnetic interactions are one and the same, and that the weak interaction appears only weak at low energies, because its field quanta are so massive. There are many roots to such a

Unified Gauge Theory:

the idea of unity of forces [10-13], the important question of renormalizability [12-14], and at last the hope of generalizing such a theory eventually to all interactions ...

From all these fascinating aspects we need only consider the analogy between weak and electromagnetic interactions: The latter is known to act between neutral vector currents V_α, by exchange of a mass-less field-quantum, the photon γ. A one-dimensional gauge group insures the universality and conservation of the coupling constant e, the charge. The pre-1973 weak interaction, instead, was short-ranged and acted between charged, left-handed currents $(V - A)_\alpha$, and this called for massive, charged intermediate vector bosons $W^\pm$. Enlarging the e.m. gauge group in the simplest possible way leads to a group

$$G = SU(2) \times U(1) \quad , \qquad (1)$$

where the (mathematical) fields of force are the generators of the group, namely

(W^+, W^o, W^-) for SU(2) - "weak isovector"

and

B^o for U(1) - "weak isoscalar" .

The weak boson triplet $\underline{W}$ plays the same rôle for weak isospin as e.g. the pion does for strong isospin. The appearance of a neutral intermediate vector boson amongst the weak force fields is a mathematical necessity for the group (1). It is not so obvious, though, which neutral particle is going to couple to which current. If G is broken, the physically relevant combinations are, as first realized by Glashow [10] and taken up by Salam [11,12] and Weinberg [13]

$$\begin{aligned} Z^o &= \cos\theta_w\, W^o + \sin\theta_w\, B^o \quad , \\ \gamma &= -\sin\theta_w\, W^o + \cos\theta_w\, B^o \quad . \end{aligned} \tag{2}$$

Z^o is the massive (= weak) neutral current quantum,
γ the familiar, massless photon.

This mixing of fields implies a correspondingly mixed weak neutral current [15]:

$$J_\alpha^{NC} = I_3\,(V - A)_\alpha - 2Q\,\sin^2\theta_w\, V_\alpha^{em} \quad , \tag{3}$$

where I_3 and Q are, respectively, the 3^{rd} component of weak isospin and the charge of the particle in question. θ_w is the weak mixing angle (as before) introduced by Glashow [10], and now generally named after Salam [11,12] and Weinberg [13]. As one sees, the mixing parameter $x_w = \sin^2\theta_w$ measures the admixture of ambidextrous e.m. current to left-handed weak current, and determines thus also the ratio of left-handed (V - A) to right-handed (V + A) current pieces. Note that the result of this mixing does depend on the type of particle (via the quantum numbers I_3 and Q).

According to the spirit of unification the effective Fermi coupling constant G is essentially e^2/M_W^2, in the simplest models:

$$G/\sqrt{2} \;=\; e^2 \;/\; 8\, M_W^{\;2} \sin^2\theta_W \quad . \tag{4}$$

Similarly, the Glashow-Salam-Weinberg $SU_2 \times U_1$ model gives for the coupling strength of the neutral weak current in general:

$$G^{NC}/\sqrt{2} \;=\; \kappa e^2 \;/\; 8\, M_Z^{\;2} \sin^2\theta_W \cos^2\theta_W \quad , \tag{5}$$

whereby in the minimal model of Salam and Weinberg [12,13]:

$$\underline{\text{S-W}}: \quad M_W = \cos\theta_W\, M_Z \quad \text{and} \quad \kappa = 1 \quad \text{i.e.}\; G^{NC} = G. \tag{6}$$

Glashow [10] left the overall normalization κ of neutral and charged coupling constants open. It is clear that one can build a large variety of models, by employing larger groups G, thereby introducing more than one massive intermediate neutral boson Z, several mixing angles θ_ν and so on. A recent count revealed more than 500 proposed models.

Besides, there is the question how one should group the known elementary particles, i.e. quarks and leptons, into multiplets of G. We shall follow the simple prescription of Glashow, Iliopoulos and Maiani [16], and place all left-handers into doublets, all right-handers into singlets.

It is a remarkable achievement of experimental physics, that the structure of weak neutral currents has been widely cleared up within five years. It is just the minimal model of Salam and Weinberg [12,13]. In the following I shall briefly review the experimental data which lead to this conclusion, starting (sec. 3) with neutrino-electron scattering, and adding the beautiful γ-Z^o-interference experiment at SLAC. Then I shall pass over to inclusive (sec. 4) and semi-inclusive (sec. 5) hadronic neutrino interactions, and end with some exclusive ν-reactions (sec. 5 and 6) with nucleons. At the end of each section I shall summarize, what kind of knowledge it has given. There is not much time to dwell with experimental details. But occasionally I shall hint at difficulties which might grow into worries ...

3. Neutrino-Electron Scattering and the Weak Neutral Current of the Electron

As remarked already, a muon-(anti-)neutrino can scatter off an electron only by virtue of a neutral current - to first order, that is, and to the extent that muon-number is conserved. And unlike the many other processes of the neutral current type, neutrino-electron scattering has the advantage of being predictable without any theoretical ambiguity or uncertainty, since the two particles involved are point-like and have no strong interactions. This makes the study of the two reactions

$$\nu_\mu e \rightarrow \nu_\mu e \quad (7) \quad \text{and} \quad \bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e \quad (\bar{7})$$

an experimentum crucis of weak interaction physics.

Its cross section is easily derived: since a neutrino is left-handed, its interaction (A) with a left-handed electron current proceeds through a spin singlet state. Clearly, the distribution of electron center-of-mass (c.m.) recoil angles θ_e^* is isotropic, yielding a flat electron energy distribution in the lab. (B) Similarly, a neutrino encounter with a right-handed electron leads to a spin triplet state, an anisotropic angular distribution in the c.m., and a lab electron energy distribution which peaks at low energies. In terms of energy transfers

$$y = T_e/E_\nu \approx E_e/E_\nu \quad (8)$$

the distributions become:

$$\text{(A)} \quad \text{Singlet}^{+} \quad S = 0 : W(\theta^{*}) \sim 1 \qquad \rightarrow W(y) \sim 1 \qquad (9_1)$$

$$\text{(B)} \quad \text{Triplet}^{+} \quad S = 1 : W(\theta^{*}) \sim (1 - \cos\theta^{*})^2 \rightarrow W(y) \sim (1 - y)^2 \qquad (9_3)$$

In deriving these formulae we have excluded spin-flip, i.e. the "bad" Dirac variants S, P, T.

If we denote by A and B, respectively, the (relative) probability of the weak neutral electron current to be left-handed (V - A) or right-handed (V + A), the differential cross section becomes (for $E_e >> m_e$):

$$\frac{d\sigma}{dy} = \kappa^2 G^2 \frac{2}{\pi} m_e E_\nu \left\{A + B (1 - y)^2\right\} . \qquad (10)$$

The appearance of the (general) weak neutral current coupling constant is clear; the rest is phase-space.

Antineutrinos differ from neutrinos <u>only</u> by being right-handed. (This is called a Majorana neutrino theory [17]). Thus the same expression holds also for them, but with A and B interchanged:

$$\frac{d\bar{\sigma}}{dy} = \kappa^2 G^2 \frac{2}{\pi} m_e E_{\bar{\nu}} \left\{B + A (1 - y)^2\right\} . \qquad (\overline{10})$$

The total cross sections are obtained by integration over y:

$$\sigma = \sigma_e E_\nu (A + B/3) , \qquad (11)$$

$$\bar{\sigma} = \sigma_e E_{\bar{\nu}} (A/3 + B) , \qquad (\overline{11})$$

+) Strictly speaking we mean spin projected on momentum direction.

with $\sigma_e = \kappa^2 \times 17.2 \times 10^{-42}$ cm^2/GeV, a rather frightening small number. Soon after 't Hooft [18] had first derived these relations, they attracted the interest of many authors, including Rosen, Sehgal and others [19]. They observed that the two real numbers A and B, which contain all the physics there is, could be extracted in many different ways: from σ and $\overline{\sigma}$, from σ and $\langle y\rangle$, from $d\sigma/dy$ and so on. I have suggested some formulae [20], which use as an input the ratio of measurable quantities, like $\overline{\sigma}/\sigma$ or $\langle\overline{y}\rangle/\langle y\rangle$, which should be less susceptible to experimental backgrounds and biases than the quantities themselves.

Even so, it is not an easy matter to separate neutrino-electron scattering from background, considering that its cross section is tenthousand times smaller than the total neutrino nucleon cross section. Fortunately the majority of these $\overset{(-)}{\nu}_\mu$-reactions has a muon in the final state - a long, non-interacting track, which will never be confused with the short electro-magnetic cascade, into which an electron will develop in the dense ($\rho \approx 1.5$ g/cm^3) media used (see fig. 1). Two potential backgrounds remain:

a) NC induced muon-less hadronic reactions, with only neutral hadrons, and a π^0, of which one decay gamma had been lost.

b) The ν_e contamination in the $\overset{(-)}{\nu}$-beam ($\approx 0.5\%$) can produce genuine electrons, and fairly often the accompanying hadron(s) is (are) not visible.

Both types of background can be rather well rejected, by taking advantage of the peculiar kinematics of genuine neutrino-electron scattering. It is characterized by the smallness of the target mass, which makes it hard to get energy onto the electron - hence the factor m_e in the cross section $\overset{\longleftrightarrow}{(10)}$! By the same token one cannot get much transverse momentum p_T imparted - hence a lab electron angle of order

$$\Theta_e \approx p_T/E_\nu \lessapprox \sqrt{s}/E_\nu \approx \sqrt{2m_e/E_\nu} \approx 30 \text{ mrad} \quad \text{for} \quad E_\nu = 1 \text{ GeV} .$$

The exact formula is [21]:

$$E_e\Theta_e^2 = 2\, m_e\,(1 - y) \quad . \tag{12}$$

The measurable left-hand side of this equation is essentially the mass of the struck particle. This test quantity was first exploited by the Aachen-Padova Group [21,22], and taken over by most other νe scattering groups. Under favourable background conditions it may suffice to require an angle smaller than a few degrees (say 3^o to 5^o). Also, since $\langle y\rangle$ lies between 1/4 and 1/2 for a V,A theory, one expects $\langle E_e\rangle \approx 0.37 \langle E_\nu\rangle$, and can profitably reject electron energies higher than $\langle E_\nu\rangle$. This means an energy cut at $\approx$ 2 GeV for the CERN PS, and reduces the background from inverse β-decay virtually to zero [23-26].

Various groups have succeeded in measuring $\nu_\mu e$ or $\bar\nu_\mu e$ scattering. The cross sections, or upper limits, obtained are given in Table I, along with some information on event numbers and signal-to-noise. Some comments on methods and difficulties may be in order:

a) The GARGAMELLE Collaboration, who had discovered the first $\bar\nu_\mu e$ event [2-4], continued to collect events at a steady pace of 1 per year, (one at Orsay, the last one at Bruxelles). Then the allotted antineutrino beam time was exhausted, and the $\bar\nu_\mu e$ experiment was declared finished [23]. The background was quite small $\approx$ 0.5 events. It consisted mainly of asymmetric $\bar e$ e pairs from NC produced π^o decay gammas.

Table I: Measured cross sections of elastic $\bar{\nu}_\mu e$ and $\nu_\mu e$ scattering

Group	[Ref]	Beam	$<E_\nu>$ GeV	No. of candidates total	good	Cross section 10^{-42} cm^2 GeV^{-1}
GGM	[23]		2.0	3	2.5	$1.0^{+2.1}_{-0.9}$
AC-PD	[28,29]		2.0	8[a)]	6.3	2.2±1.0
BEBC	[35]	$\bar{\nu}$	20	1	0.5	< 3.4
FNAL 15'	[35]		30	0	0	< 2.1
GGM	[36]		20	0	0	< 2.7
World average $\bar{\nu}_\mu e$			2 - 30	11	8.8	1.8±0.9
GGM	[24]		2.2	1	0.7	< 3.0
AC-PD	[28,29]		2.2	11[a)]	7.1	1.1±0.6
BNL-COL	[34]	ν	30	8	7.5	1.8±0.8
GGM	[33]		25	9	8.6	$2.4^{+1.2}_{-0.9}$[b)]
World average $\nu_\mu e$			2.2 - 30	28	23.2	1.6±0.5

a) With tight selection criteria, b) Originally [32]: $7.3^{+4.6}_{-3.8}$.

Hence the existence of $\bar{\nu}_\mu e$ scattering is established with high statistical confidence. Considering the small event numbers, this may sound surprising. But the question is not, whether the signal (here 2.5) could statistically have been zero. Rather one has to ask if the <u>well measured</u> background gives the signal observed by a statistical fluctuation. The confidence of the effect being established hinges, therefore, on the predicted variance of the background. The error of the cross section, instead, comes mainly from the statistics of the observed event numbers, and may be large.

Also $\nu_\mu e$ scattering has been searched for in GGM, and <u>one event</u> has been found (again at Aachen). Background is more severe in neutrinos than in antineutrinos (see below): the observed event should be confronted with 0.5 background events expected [24]. Clearly this does not establish $\nu_\mu e$ scattering, and gives for the cross section only a limit.

b) The Aachen-Padova (AC-PD) Collaboration decided to build a large ($\approx$ 20 ton) multiplate sparkchamber, in which $\bar{\nu}_e e$ and $\nu_\mu e$ scattering could be detected, and also measured to some accuracy [20-22]. The plate thickness was chosen to 1 cm aluminum. This corresponds to a radiation length X_o of 20 cm, and gives an electron around 1 GeV typically a shower pattern like that of Fig. 3. The electron energy can be determined from the total number of sparks, at 1 GeV with an accuracy of 22%. The initial electron direction can be inferred, from the beginning of the track, to about $\pm 1^o$. This suffices for a quantitative analysis, although many of the details, as seen in GARGAMELLE (see Fig. 1), are lost. The real short-coming is the absence of a magnetic field: hence the generated secondary electrons are being spread out by multiple scattering only, and as a result a distinction between e^-, e^+ and an e^-e^+-pair (= "gamma") is not possible.

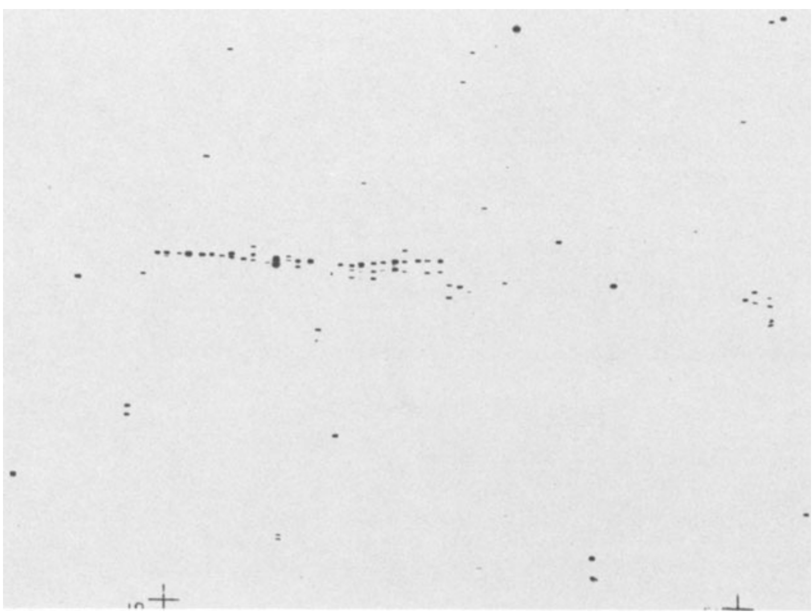

Fig. 3: $\nu_\mu e$ scattering candidate, registered in the Aachen-Padova multi-plate aluminum sparkchamber (ν's from the left).

This makes a sparkchamber more vulnerable by gammas than bubble chambers. Most of this 1γ-background stems from neutral current produced single π^o's, with one decay gamma lost:

$$\overset{(-)}{\nu}_\mu + N \rightarrow \overset{(-)}{\nu}_\mu + N + \pi^o \quad , \qquad (13N)$$
$$\pi^o \hookrightarrow \gamma + (\gamma)$$

$$\overset{(-)}{\nu}_\mu + P \rightarrow \overset{(-)}{\nu}_\mu + P + \pi^o \quad . \qquad (13P)$$
$$\pi^o \hookrightarrow \gamma + (\gamma)$$

An example of a "naked" π^o, with the two decay gammas visible, is given in Fig. 4. Most probably it is an example of NC π^o-production off a neutron (13N), but occasionally also the proton reaction (13P) can appear this way, if the recoil proton is too short, charge-exchanges, or gets absorbed. (We note in passing that these NC reactions had not yet been discovered, when the AC-PD experiment was proposed. 1γ-Background estimates were based on other peoples' upper limits - unfortunately we measured π^o rates a factor of two higher! [25]).

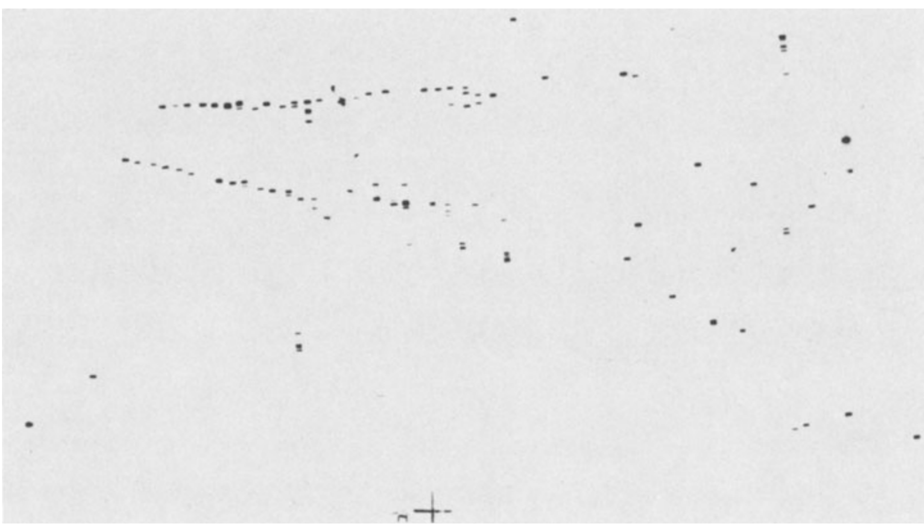

Fig. 4: "Naked" $\pi^o \rightarrow 2\gamma$, initiated by hadronic neutral current in the AC-PD sparkchamber.

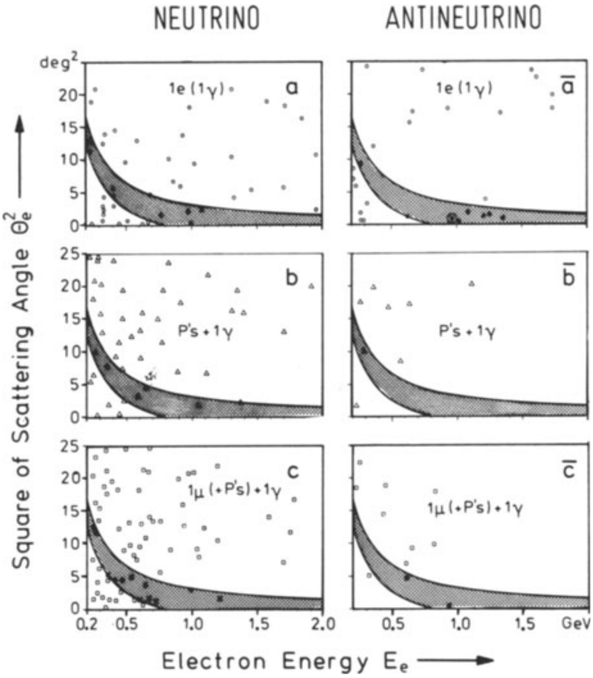

Fig. 5: Θ_e^2 E_e-scatter plot for

$\overset{(-)}{\text{a}})$ $\overset{(-)}{\nu}_\mu e$ candidates,

$\overset{(-)}{\text{b}})$ P associated single γ's (from $P\pi^0$),

$\overset{(-)}{\text{c}})$ μ associated single γ's (from CC $\mu\pi^0$).

How serious the 1γ-background is, may be seen from the main diagnostic tool in νe analysis, the Θ_e^2-E_e scatter plot of Fig. 5: a ($\bar{a}$) shows the single, isolated showers, i.e. the ν_μ ($\bar{\nu}_\mu$) e scattering candidates, which do comprise, however, a certain amount of gammas. The shaded domain is where νe scatterings should lie, with $y > 0$ and $E_{\overset{(-)}{\nu}} > 0.8$ GeV imposed. But there are single showers scattered all over the place. Only for antineutrinos there is a distinct concentration of events inside the allowed band. This different behaviour of neutrino and antineutrino background is easily understood: the 0.8 M pictures, taken in either case, correspond to twice as many ν than $\bar{\nu}$ crossing the chamber, and the single π^0 NC cross section ratio $r = (\bar{\nu}\mathcal{N} \to \bar{\nu}\mathcal{N}\pi^0)/(\nu\mathcal{N} \to \nu\mathcal{N}\pi^0)$ was found to be close to 0.50 [26].

The main problem was, to determine the 1γ-background in either case, utilizing suitable control reactions. This was done in several ways. The most direct and convincing of them was to take several hundred naked π^0's, as shown in Fig. 4, and to compute from their observed angular and energy distributions the probability for one gamma to fulfill the νe criteria. The calculation [27], though lengthy, invested only kinematics, γ-conversion, and geometry - all subtle hadronic questions, like proton visibilities and cross section ratios, were by-passed. Purely experimental background determinations are given in Fig. 5: b($\bar{b}$) show scatter plots of $\nu(\bar{\nu})$ induced single gammas, associated with protons, and thus presumably stemming from NC π^0 production off protons (13P). This reaction must have a cross section quite similar to that with neutrons (13N), and thus, apart from known factors of order one, the 1γ-background to graphs a and $\bar{a}$ can be read off the bands in b and $\bar{b}$: perhaps 4 events for ν and only 1 for $\bar{\nu}$! A similar answer comes from CC single π^0 production, given in Figs. 5c and $\bar{c}$. Statistically more relevant numbers come from the events outside the allowed bands, in case of single showers extended to angles as large as 30°, and extrapolated into the νe region with the help of the Monte Carlo simulation [27]. Within errors, the different methods agreed.

The final results were presented to the Hamburg Lepton Conference 1977 by Hans Reithler [28]. The two measured cross sections in the σ-$\bar{\sigma}$ plane evince the space-time structure immediately (Fig. 6): the AC-PD error ellipse, (and also the GGM rectangle), appear to favour a right-handed electron (V + A), but are compatible with an ambidextrous one (A or V). A pure left-hander

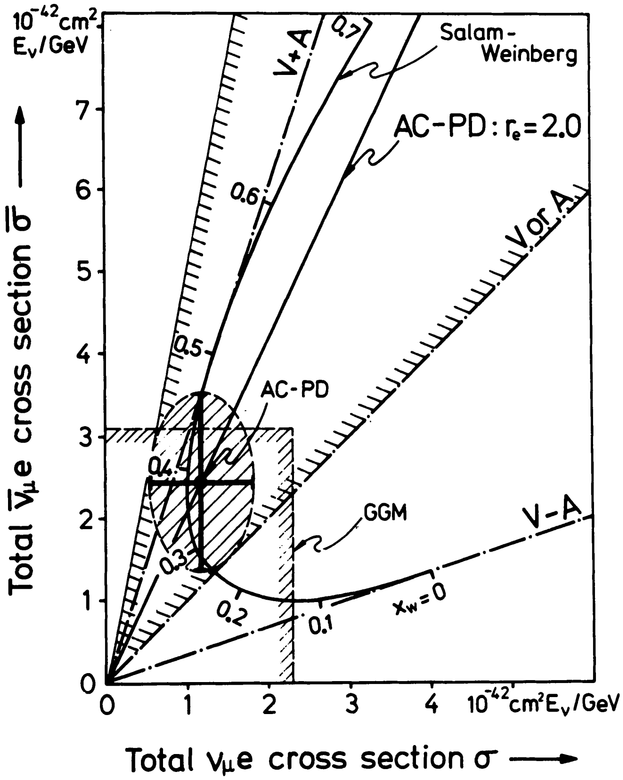

Fig. 6: Total $\overset{(-)}{\nu}_\mu e$ cross sections, measured around 2 GeV by Aachen-Padova and GARGAMELLE. Straight lines delineate simple V,A interactions; the curve is the Salam-Weinberg prediction.

(V - A) is excluded. Agreement with Salam-Weinberg is amazing, $\sin^2\Theta_W = 0.35 \pm 0.08$. Reithler also gave an answer to the non-trivial question, how one can compare the two energy-distributions, although both of them are based on only 7 good events. The answer is: one can - V + A being favoured over A or V, albeit only on a 1.5 to 2 standard deviation (st.d.) level [27,28]. The subsequent publication [29], and later Conference Reports [30] contain, in addition, the results of a maximum likelihood method by Milla Baldo-Ceolin and associates of Padova.

c) The Gargamelle SPS Neutrino Group was first to try measuring $\nu_\mu e$ scattering at the energies available at the Super-Proton-Synchrotron at CERN, and the corresponding accelerator at Fermilab (FL). These energies are more than ten times as high as those at the CERN PS, and every reasonable guess would have been that the νe experiment would be easier, since the νe cross section increases linearly with energy, whereas all the hadronic background would eventually flatten off. But - "it ain't necessarily so ..." [31].

The group found 10 events in the very first runs, and this would have corresponded to a $\nu_\mu e$ cross section about 7 times the Aachen-Padova value [32]. A look at Fig. 5 shows that this is impossible: even if one assumed no background at all - quite improbable in view of the parallel reaction in Fig. 5b! - the AC-PD cross section could at most double! Besides, the new GGM group had abandoned the stringent acceptance criteria, consistently applied at PS energies [20-24,27-30]. Then they collected a large fraction of high energy electrons. Not all of them could come from νe scattering, lest $\langle y \rangle$ should approach unity! - This internal inconsistency convinced me more than anything else that the majority of these electrons had nothing to do with $\nu_\mu e$ scattering. In principle they could have come from a new process - unlikely, as it is, at a c.m. energy of typically 300 MeV.

As it turned out, the high new GGM result seems to have been a combination of too liberal cuts and of a statistical fluke. The cross section went monotonously down in time, and the last value reported [33] is perfectly compatible with the Aachen-Padova measurement, and with the old GARGAMELLE limit [s. Table I]!

d) Even before the rise and fall of the high energy $\nu_\mu e$ cross section came to a good end, a Columbia-FL-Group, under Baltay, looked into $\nu_\mu e$ scattering at Fermilab. They used the 15' bubble chamber, filled with 64 atomic % Ne-H_2, applied the kinematical procedures described, and wound up with perfectly normal distributions in energy and 'target mass' ($\approx \Theta_e^2 E_e$). From 10 events found - at a very low background level - they deduced a cross section of 1.8 ± 0.8 in our unit of 10^{-42} cm^2 GeV^{-1} [34]. (This is, incidentally, the minimal νe cross section in the Salam-Weinberg model.) This cross section is in flat contradiction with the original high GGM SPS value, but it agrees nicely with the AC-PD result, the difference being a 0.7 standard deviation.

e) $\bar{\nu}_\mu e$ has been tried by a Gargamelle Group at the CERN SPS - without success thus far. Not a single candidate showed up. This sets a rather low limit on the $\bar{\nu}_\mu e$ cross section [36]. Similar results were obtained with BEBC and at FNAL [35].

f) Low energy $\bar{\nu}_e e$ scattering has been measured by Reines <u>et al.</u> at a nuclear reactor [37]. In contrast to muon-neutrinos, the scattering of electron-neutrinos can proceed through both, neutral and charged currents. Reines found a cross section equal [38] to that of the classical V - A theory [39]. Thus, taken by itself the $\bar{\nu}_e e$ measurement does not reveal any neutral currents. But in conjunction with the $\overset{(-)}{\nu}_\mu e$ data it will be most significant.

<u>Summary of νe:</u>

Table I summarizes what we know about νe cross sections. The world averages over the three ν_μ, and the two $\bar{\nu}_\mu$ measurements, respectively, fall pretty close together: the $\bar{\nu}_\mu/\nu_\mu$ asymmetry, suggested by the early data, has vanished. This may well be due to slight statistical fluctuations: all PS values are within half a st.d. of the present averages! But it ought to be checked by energy measurements and y-distributions.

Taken at their face values the ν_μ and $\bar{\nu}_\mu$ cross sections imply an almost pure A or V neutral current for the electron. In the framework of the minimal model [12,13], it must be A, and it would correspond to a mixing angle

$$\nu_\mu e \text{ and } \bar{\nu}_\mu e: \quad \sin^2\Theta_W = 0.24 \pm 0.06 \quad . \tag{14}$$

This value suits also the $\bar{\nu}_e e$ data quite well [36].

A model-free analysis was attempted by Reithler |28| and myself [20], and carried further by Milla Baldo-Ceolin [30]. The idea was to free oneself from the limitations and pre-set tracks of a particular model, and to use the data in their own right [19]. Apart from the SU(2)-U(1) mixing, described by $\sin^2\Theta_W$, we want to gain insight into the Higgs sector [12,13] characterized by the isospin of the Higgs particle I_ϕ, and finally into the multiplet structure, mentioned before, which concentrates on the isospin of the right-handed electron I_R.

Ross and Veltman have suggested a practical way how to do that [40]: They observe that $x_W = \sin^2\Theta_W$ can be extracted from the ratio r_e of $\bar{\nu}_\mu e$ and $\nu_\mu e$ cross sections $\bar{\sigma}$ and σ. Taking the only measured r_e (by AC-PD), this gives $x_W = 0.35 \pm 0.10$, in reasonable agreement with the values extracted from the cross sections themselves. We used this mixing parameter, (and assumed $I_R = 0$), to predict the sum of the ν_μ and $\bar{\nu}_\mu$ cross sections, and compared it to our experimental result. This gives directly the NC normalization constant κ of eqs. (5) and (6):

$$\kappa = 1.04 \pm 0.15 \quad , \tag{15}$$

and with the Ross-Veltman identification

$$\kappa = 1/2\ I_\phi \tag{16}$$

the Higgs isospin to 1/2. To the best of my knowledge this is the first experimental statement about the elusive Higgs particle at all.

Taken this simplest Higgs structure for granted, the final analysis is best performed in the plane of the relative NC axial-vector and vector coupling constants, C_A and C_V, (Fig. 7), which are related to our chiral coefficients by:

$$A = \frac{1}{4}(C_V + C_A)^2 \quad , \quad B = \frac{1}{4}(C_V - C_A)^2 \quad .$$

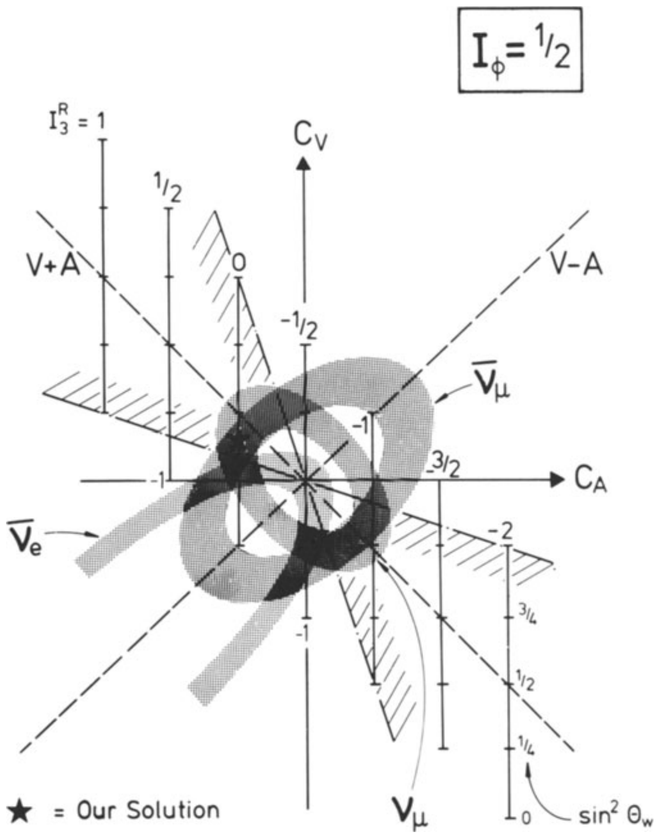

Fig. 7: Constraints imposed by the measured $\nu_\mu e$, $\overline{\nu}_\mu e$ and $\overline{\nu}_e e$ total cross sections on the vector and axialvector coupling constants C_V and C_A [20]. Vertical lines allowed by different gauge models.

Hence, and from eqs. (11) and $(\overline{11})$ one sees at once that a fixed total cross section gives in the C_V-C_A diagram an ellipse; the errors make it an elliptical ring. It is clear that the ellipses have their main axes respectively parallel and orthogonal to the V - A and V + A directions. Thus, any attempt to determine C_A and C_V from σ and $\bar{\sigma}$ faces, in general, a fourfold ambiguity. From the AC-PD data alone the $\sigma - \bar{\sigma}$ overlap (dark-dashed) is fairly large. But, as Reithler was first to show [28], when combined with the $\bar{\nu}_e$e data [37], they reduce the allowed regions for C_A and C_V to the tiny black triangels in Fig. 7. They exclude all gauge models, which are characterized by the different vertical lines - except two: a Salam-Weinberg [12,13] solution close to pure A, and a vectorlike ("hybrid") solution close to pure V. Milla Baldo-Ceolin [30] arrived at this conclusion also by a simultaneous fit on I_ϕ and I_R^3. Numerically from Fig. 7:

$$\begin{aligned} &\text{A-like: } C_A = -0.57 \pm 0.08, \quad C_V = +0.09 \pm 0.08\,; \\ &\text{V-like: } C_A = +0.09 \pm 0.08, \quad C_V = -0.57 \pm 0.08\,, \end{aligned} \tag{17}$$

with the A-like S-W-solution corresponding to $\sin^2\Theta_W = 0.29 \pm 0.04$.

It was argued [20] that the vector solution is improbable, since it is outside the limit placed by the measured $\langle\bar{y}\rangle/\langle y\rangle$ (dashed straight lines). In view of the increasing similarity of ν_μ and $\bar{\nu}_\mu$ cross sections (Tab. I) this argument has lost in strength.

But there is the eD scattering asymmetry measurement at SLAC [41] now, which excludes the vector solution altogether (Fig. 8). Note, by the way, what a broad band the many scattered electrons still admit, and how incisive the 60 νe scatterings are. By contrast, not much light was shed on the problem by the optical experiments [42].

Nevertheless, after 7 years of experimentation, the structure of the weak neutral electron current gradually looms up: it is Salam-Weinberg with $\sin^2\Theta_W$ close to 1/4.

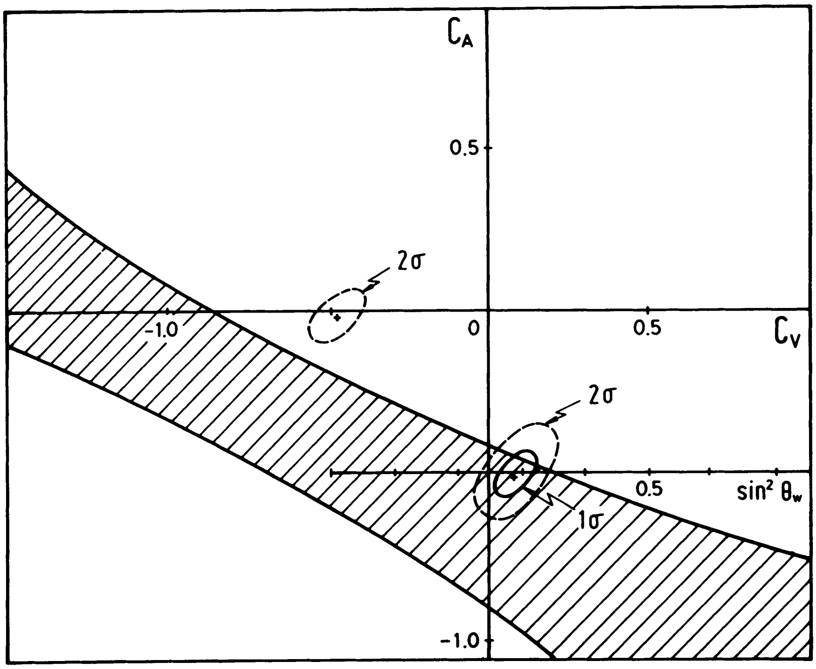

Fig. 8: Values of C_V and C_A allowed by the SLAC polarized eD scattering experiment (dashed band). Contour lines follow from the νe scattering data of Fig. 7.

4. Inclusive Muon-less ν_μ $(\bar{\nu}_\mu)$-Reactions (Truly Elastic ν_μ $(\bar{\nu}_\mu)$-Quark Scattering)

It sounds like a historical accident that the neutral weak current (NC) of hadrons was discovered in inclusive neutrino interactions, where the final hadron state (X) could be anything, from a single pion (π) to a rather complicated meson-nucleon cascade:

$$\overset{(-)}{\nu}_\mu + \mathcal{N} \to \overset{(-)}{\nu}_\mu + X \quad . \tag{18}$$

Indeed, it is relatively easy to prove that there was no muon produced (see Fig. 2) - and no electron, for that matter - but it is not trivial at all to show that these reactions were induced by neutrinos, and not by high-energy neutrons. As mentioned in the introduction, this analysis took the GARGAMELLE (GGM) Group many months of hard work. Let me just mention one of the many arguments proposed, which I always found particularly simple and convincing: the calibration of the neutron background by means of "associate events" (AS). These events are normal, charged current (CC) induced $\overset{(-)}{\nu}_\mu$-reactions - except that they show a hadron star nearby, which could be ascribed to a high-energy neutron from the CC-reaction. Clearly, such neutrons can be copiously produced <u>outside</u> the visible volume of the bubble chamber, may enter it, and produce a neutron star (N^*). But as one convinces oneself easily, the frequency ratio of neutron stars to associated events is a simple function of the neutron interaction length and of the chamber geometry; in fact for the actual GARGAMELLE disposition [43] $N^*/AS \approx 1$. Thus, having observed $AS/NC \approx 10\%$, the GARGAMELLE group could safely trust their effect [3,8], and check the elaborate N^* subtraction [8] by a direct physical measurement.

None such detailed background study was possible in the next generation of experiments, which used large counter-sparkchamber arrangements, [44,45] exposed to (anti)neutrino beams from the 400 GeV proton-synchrotron at Fermilab (FNAL). The decision, whether or not a particular track was due to a muon, was made on the basis of range only, and it took the Harvard-Pennsylvania-Wisconsin (HPW) team some time until all systematic effects were under control: Penetrating pions faked muons, and large angle (or short) muon tracks tended to get lost in the hadron splash. Besides, the wide-band neutrino beams employed by HPW were quite often rather ill defined, which made the interpretation of the data fairly difficult. Yet in 1974 the HPW Group managed, after some fluctuation, to confirm GARGAMELLE'S discovery [3,8] of inclusive muon-less neutrino events, and obtained - despite the higher energies - practically the same NC/CC cross section ratios [44].

A Caltec Group at Fermilab (CITF), using a similar apparatus but a better defined narrow-band beam, obtained almost the same results some time later [45]. By then weak neutral hadronic currents had been seen by three different groups, working at different labs, with different techniques, in different beams, and at very different energies. No doubt this new force of Nature was established.

The next step would be to clarify, which structure these neutral currents have - or, to put the question in a more fundamental way: are the observed muon-less events really of the V,A-current type, inherent of unified gauge theories? - There are many aspects to that: a very basic one is, if the neutral particle in the final state is really identical to the primary neutrino. This is very badly known, but according to Sehgal it can be tested by NC-CC interference in ν_e e-scattering [46]. And even taking this for granted - do ν_μ and ν_e behave the same also in neutral current interactions? This is not known at all, but Sehgal and Sakakibara [47] expect only small differences. Lacking anything more definite, we accept these prejudices.

Even so, the new interaction could have any amount of S,P,T mixed into our preferred V,A-current structure. Under favourable conditions this might be seen from the $\bar{\nu}/\nu$ cross section ratio r, which could exceed then the V,A limits [48]:

$$\text{V,A:} \quad \frac{1}{3} \leqq r \leqq 3 \quad ; \quad \text{but S,P,T:} \quad \frac{1}{7} \lessapprox r \lessapprox 7 \; . \tag{19}$$

Nothing can be concluded instead, if the V,A-bounds happen to be respected: According to a well known "Confusion Theorem" [49] any V,A cross section can be reproduced by a suitable combination of S,P,T. In principle one can distinguish them, say by polarization experiments - but this is presently out of reach. Thus, all the groups worrying about the Lorentz structure of the neutral weak current <u>assumed</u> V,A, and checked how well this would fit the data. With some inner reluctance I shall follow this path.

The theoretical treatment of deep inelastic neutral current neutrino nucleon encounters is then quite easy, provided one accepts the quark-parton picture of the nucleon [50]. This was conceived on the basis of deep inelastic electron nucleon scattering experiments, at SLAC [51], which showed essentially constant q^2-distributions, i.e. a behaviour as if the hit objects were points! That these point-partons had all the properties of quarks, was shown subsequently by the GARGAMELLE collaboration. While we were still striving to get the first results [52], it occured to me that they could possibly be explained by the action of the 3 valence quarks of the nucleon alone [53]*. This valence quark dominance (VQD) was found to hold good to ≈ 90% at energies of a few GeV [52], and still to be valid to ≈ 80% at some 100 GeV [54]. The remaining percent are supplied by antiquarks, from the meson cloud (or "sea"). An overall normalization factor of 1/2 is ascribed to "gluons", and will not bully us here.

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* Although this little paper contained, for the first time, the "naive" quark-parton $\nu\mathcal{N}$ and $\bar{\nu}\mathcal{N}$ cross sections, as used by all groups ever since (and a first estimate of the effective quark-parton mass too), it was rejected by "Physics Letters". When Rein re-submitted its substance, embellishing it with lots of formulae and integrals, it was (of course) accepted.

A point-like quark q will have essentially the same cross section for elastic ν $(\bar{\nu})$ scattering as an electron, namely eqs. (10) and $(\overline{10})$, respectively. But quarks are no real particles, and thus the target rest mass m has to be replaced by x M, where M is the proton mass. The new scaling variable x is defined between 0 and 1, and can, in a way, be connected with an effective quark-parton mass [55]. More commonly, however, x is identified with the fraction of the nucleon's momentum, P this particular quark carries [50]. Then it is easy to show that x is given essentially by the ratio of four-momentum transfer squared, q^2, to energy transferred ν:

$$x = - q^2/2M\nu \quad . \tag{20}$$

The distribution of x is some quark density $\rho_q(x)$ in momentum space, normalized to 1. It has repeatedly been measured [51,52,54].

In analogy to νe scattering (10) the νq cross section is:

$$\frac{d^2\sigma_q}{dxdy} = \kappa^2 G^2 \frac{2}{\pi} M E_\nu \; x \, \rho_q(x) \quad \left\{ A_q + B_q \, (1 - y)^2 \right\} , \tag{21}$$

$$\equiv \sigma_q \quad x \, \rho_q(x) \quad \left\{ A_q + B_q \, (1 - y)^2 \right\} , \tag{21'}$$

where q can be either:

a (proton-like) up-quark (u), or

a (neutron-like) down-quark (d).

The cross section $\bar{\sigma}_q$ for (right-handed) antineutrinos $\bar{\nu}$ is obtained by interchanging A and B. Since all what matters is the relative spin orientation between projectile and target, this is also the cross section of (left-handed) neutrinos ν against (right-handed) antiquarks $\bar{q}$:

$$\sigma_{\bar{q}} = \bar{\sigma}_q \, , \quad \text{and (of course)} \quad \sigma_q = \bar{\sigma}_{\bar{q}} \quad . \tag{22}$$

With these relations the $\overset{(-)}{\nu}P$ and $\overset{(-)}{\nu}N$ cross sections can easily be written down, in full generality. We just note the practically important case of an isoscalar target, i.e. of a nucleus with A = 2Z, and take for example the deuteron. With complete valence quark dominance:

$$\frac{d^2\sigma_D}{dxdy} = \frac{1}{2}\,\sigma_q\; x \left\{2\rho_u(x) + \rho_d(x)\right\} \left\{(A_u+A_d) + (B_u+B_d)\;(1-y)^2\right\} \qquad (23)$$

Again it would make no trouble to include antiquarks as well.

Lalit Sehgal, at Aachen, who introduced this sort of analysis [56], is a strong believer in VQD, and therefore neglected antiquarks for a start. He also used chiral coupling constants in place of their squares:

$$\begin{aligned} A_u &= u_L^2 \;, \quad B_u = u_R^2 \;; \\ A_d &= d_L^2 \;, \quad B_d = d_R^2 \;; \end{aligned} \qquad (24)$$

and connected them with the axialvector and vector coupling constants, as usual:

$$\begin{aligned} u_L &= \tfrac{1}{2}\,(C_V^u + C_A^u) \;, \quad u_R = \tfrac{1}{2}\,(C_V^u - C_A^u) \;; \\ d_L &= \tfrac{1}{2}\,(C_V^d + C_A^d) \;, \quad d_R = \tfrac{1}{2}\,(C_V^d - C_A^d) \;. \end{aligned} \qquad (25)$$

In the standard model for the neutral current [12,13]:

$$C_A^i = I_3^i \;, \qquad C_V^i = I_3^i - 2Q^i \sin^2\Theta_W \;, \qquad i = u,d \;, \qquad (26)$$

where I_3 is the 3^{rd} component of (weak) isospin I, Q the quark's charge. Now one computes easily the single ν $(\bar{\nu})$ q total cross sections [in units of $\frac{\sigma_q}{4}$, defined by eq. (21')] :

$$\sigma_{\nu u} = 1 - \frac{8}{3} \sin^2\Theta_w + \frac{64}{27} \sin^4\Theta_w \ , \qquad (27u)$$

$$\sigma_{\nu d} = 1 - \frac{4}{3} \sin^2\Theta_w + \frac{16}{27} \sin^4\Theta_w \ , \qquad (27d)$$

$$\sigma_{\bar{\nu} u} = \frac{1}{3} - \frac{8}{9} \sin^2\Theta_w + \frac{64}{27} \sin^4\Theta_w \ , \qquad (\overline{27u})$$

$$\sigma_{\bar{\nu} d} = \frac{1}{3} - \frac{4}{9} \sin^2\Theta_w + \frac{16}{27} \sin^4\Theta_w \ . \qquad (\overline{27d})$$

Hence any NC cross section can be calculated, provided one knows the quark (and antiquark) densities ρ (and $\bar{\rho}$). In the NC/CC ratios R_i they may cancel in part, and we give some popular R's for $\rho_u = \rho_d$, and complete valence quark dominance:

$$R_P = \frac{3}{4} - \frac{5}{3} \sin^2\Theta_w + \frac{4}{3} \sin^4\Theta_w \ , \qquad (28P)$$

$$R_N = \frac{3}{8} - \frac{2}{3} \sin^2\Theta_w + \frac{4}{9} \sin^4\Theta_w \ , \qquad (28N)$$

$$\bar{R}_P = \frac{3}{8} - \frac{5}{6} \sin^2\Theta_w + 2 \sin^4\Theta_w \ , \qquad (\overline{28P})$$

$$\bar{R}_N = \frac{3}{4} - \frac{4}{3} \sin^2\Theta_w + \frac{8}{3} \sin^4\Theta_w \ . \qquad (\overline{28N})$$

By averaging one obtains R ($\bar{R}$), valid for an isoscalar target. It is clear that $\sin^2\Theta_w$ can be obtained from either of them. From the early GGM data [43] Sehgal obtained the first value for this mixing angle, namely

$$x_w \equiv \sin^2\Theta_w = 0.39 \pm 0.09 \ . \qquad (29)$$

Considerable progress has been made since then. Not only did the GGM, HPW, and CITF groups continue their efforts: we had also BEBC [54], and the CERN-Dortmund-Heidelberg-Saclay-Collaboration [57] entering the sçene. The CDHS-collaboration had an unusually large apparatus constructed, consisting of 5 cm thick magnetized iron plates, interleaved with wire chambers for the measurement of muon angles and momentum, and with scintillation counters to register the deposited hadron energy. The set-up was operated in the CERN SPS narrow-band neutrino beam, with tunable energies between 50 and 200 GeV. The arrangement is ideally suited for studying charged

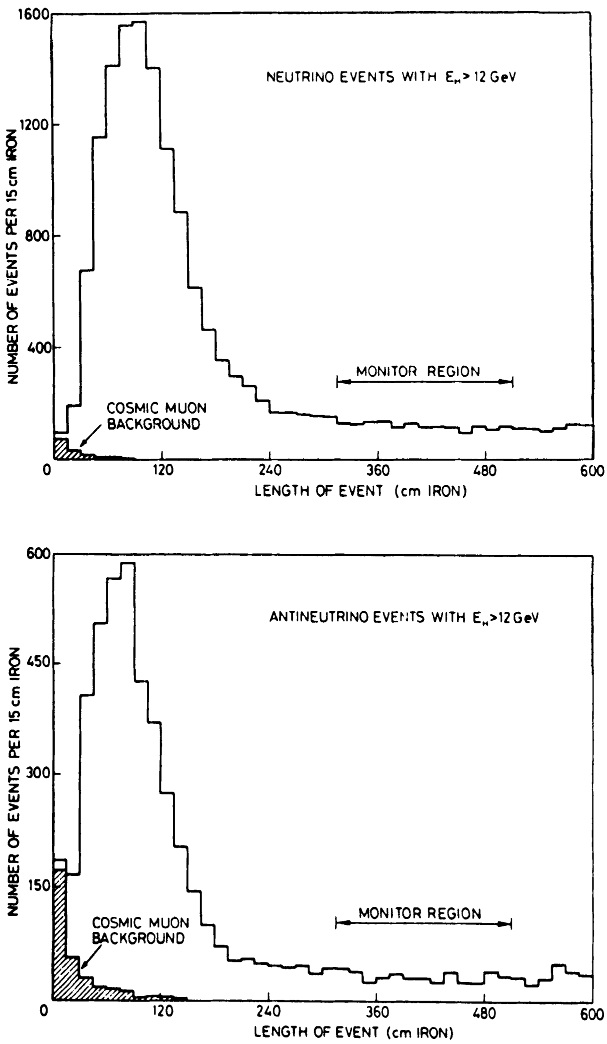

Fig. 9: Distributions of projected range ("event length") of inclusive events: top for neutrinos, bottom for antineutrinos.

current inclusive processes. In order to single out neutral current induced inclusive reactions as well, the CDHS group resorted to a technique, originally devised by CITF [45]: It is based on the projected range, or "length" ℓ, of each event, and assumes all very long events to contain muons. Then one extrapolates the number of charged current events, found in this "monitor region", back to short events, which are mainly due to neutral currents (Fig. 9). Compared with the meticulous track-by-track analysis of GARGAMELLE [8], the CDHS method is simple, fast and elegant. Neutron stars could be a problem, but the enormous iron thicknesses adequate to these high energies make them much less important than at PS energies. Of course, the whole CC-subtraction hinges on the

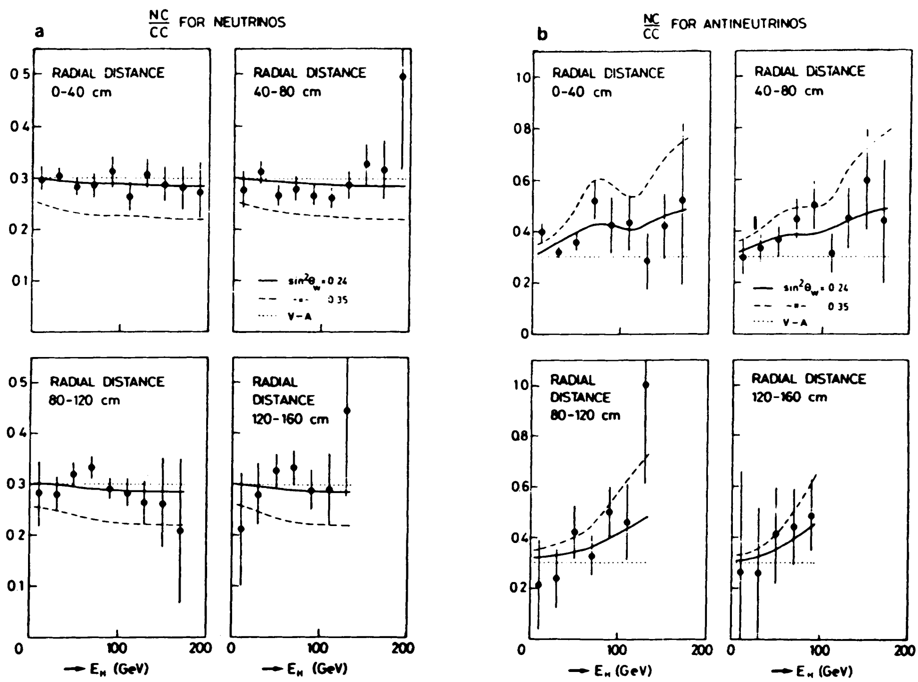

Fig. 10: Ratio of neutral to charged current event numbers, as a function of hadron energy for different radial bins, for ν and $\bar{\nu}$. - Curves are minimal model fits with x_W = 0.24 (——), 0,35 (- - -), and 0,0 = V-A (.....).

quark-parton model assumed, but the authors are confident that they do it right.

This systematic reliability, combined with enormous statistics, enabled CDHS to solve a number of problems, which had not been completely settled before. The most salient of them is the proof that the hadronic neutral current is definitely <u>not</u> pure V - A, i.e. not completely left-handed as the charged current is. This is equivalent to saying that the mixing constant $\sin^2\Theta_W$ does not vanish. This had certainly been surmised right from the start [3,8], but now it is proved with > 3 standard deviation (st.d.). In addition, the CDHS data suggest that the previous

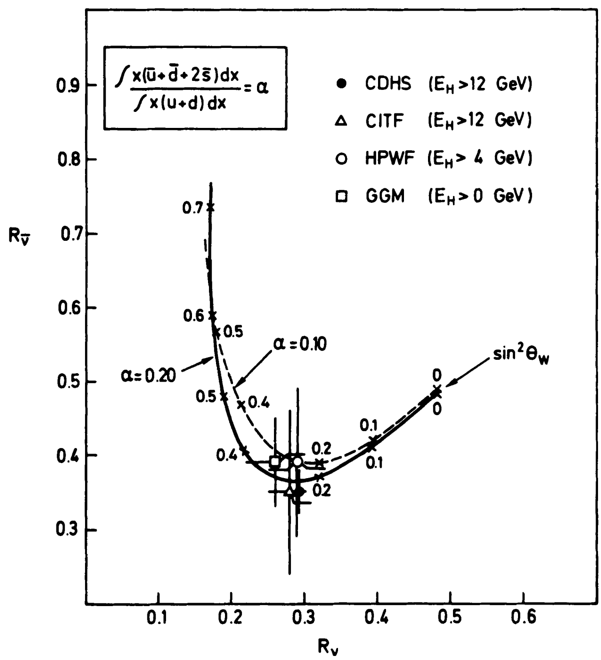

Fig. 11: Comparison of experimental results on the inclusive NC/CC ratios, R and $\bar{R}$, with the minimal model prediction after Sehgal [56] with $\bar{q}/q$ = 10% (dashed line) and 20% (full line).

values of $\sin^2\Theta_w$ were too high (by ≈ 1 st.d.). All that is demonstrated in Fig. 10, where the experimental NC/CC ratios R ($\bar{R}$), for the nucleon $\mathcal{N}$, are plotted against hadron energy, and in bins of radial distance in the apparatus (which determines the ν ($\bar{\nu}$) energy).

A summary of the R and $\bar{R}$ values obtained so far by the different groups [43-45, 57] is given in Fig. 11. They are plotted in the R-$\bar{R}$-plane, together with the prediction of the minimal model [56] ("Weinberg's nose"). The mutual agreement of the experiments is quite good. Their consent with Salam-Weinberg could not be better. The mixing constant $\sin^2\Theta_w$, which was around 1/3 before CDHS, is now brought down close to 1/4:

$$\text{Inclusive world average:} \quad \sin^2\Theta_w = 0.26 \pm 0.02 \ . \qquad (29)$$

Within the frame-work of a more general phenomenological analysis, of course, the inclusive measurements of R and $\bar{R}$ impose just two constraints on the squares of the coupling constants: $u_L^2 + d_L^2$, and $u_R^2 + d_R^2$, must each be a constant. In the $u_L - d_L - (u_R - d_R)$ -planes this defines a circle, i.e. a ring, if errors are included. This is depicted in Fig. 12, with the cross-hatched areas fore-shadowing already future developments. In order to resolve this circular ambiguity we have to resort to less inclusive reactions.

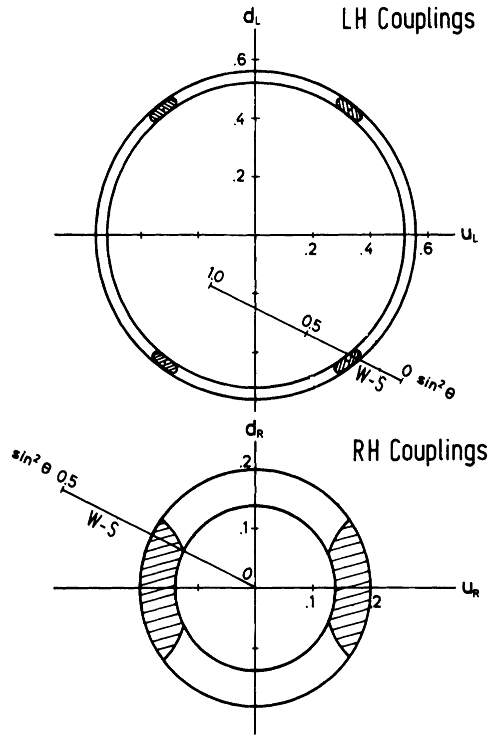

Fig. 12: Left- and right-handed u- and d-quark neutral current coupling constants. The rings are allowed by the inclusive measurements of CDHS et al., the dashed regions are singled out by pion production data (see Sec. 5)

5. Muon-less Pion Production and the Isospin Structure of the Weak Neutral Current

Indeed, the isospin structure of the weak neutral current could be extracted from inclusive measurements, if one compared the cross section off a proton with that of the neutron, (or an isoscalar nucleon for that matter). Because of the different number of u- and d-quarks involved, and because of the incoherent action of the single quarks [50-54], two such measurements on different targets would give the u- and d-quark cross sections separately. If they came out different, the neutral current could not be an isoscalar. Measurements with liquid hydrogen have been started [58], but are not yet finished.

At this stage Sehgal decided, to derive the isospin-properties from comparing the frequency of the different charge (i.e. I_3) states of semi-inclusive pions [59]. These pions are assumed to stem from the quarks hit in the first place [50,54]. A detailed analysis of these reactions implies thus some knowledge about the quark's transformation (or "fragmentation") into ordinary hadrons. This can be gathered from several weak and electromagnetic reactions.

The experimental study of muon-less semi-inclusive pion production by neutrinos and antineutrinos:

$$\overset{(-)}{\nu}_\mu + \mathcal{N} \rightarrow \overset{(-)}{\nu}_\mu + \pi^{\pm,o} + X \qquad \overset{(\text{——})}{(30)}$$

was done, at Aachen and Bruxelles, by a small sub-group of GARGAMELLE [60], using film from the exposure with freon (CF_3 Br). The type of target is important in these more detailed studies, since re-interactions of the produced pions in the parent nucleus may change their observable numbers (and charges) in a charge-dependent way! The treatment of these nuclear effects is intricate. It requires extended Monte Carlo calculations, and numerous experimental checks. But it has been done by two groups [61,62]. The results indicate effects of typically 20% for pion absorption (and/or charge-exchange), such that the corrected experimental charge <u>ratios</u> should be systematically good to better than 10%.

These <u>charge ratios</u> were deduced by Kluttig, Morfin and Van Doninck [60] from a raw sample of about 500 pions $\pi^{\pm,o}$, in each of the six channels. They are given in Table II, both, uncorrected and corrected after Pohl [62]. Also listed are a few trivial theoretical predictions: If the weak neutral current was an isoscalar ($I_{NC} = 0$), then all the three charge states of the pion must occur with the same weight. In the case of a pure isovector ($I_{NC} = 1$) this equality still holds for the two charged pions. Of course, all these equalities should be true for ν and $\bar{\nu}$.

A glimpse at Tab. II reveals that the $\pi^{\pm}/\pi^{o}$ ratios are completely off from unity: a pure isoscalar neutral current is thus absolutely excluded. The case against pure isovector is not quite as strong, but if one takes the totality of data, still suggestive enough. Thus we may conclude that the weak neutral current is a mixture of isovector and isoscalar.

In order to proceed further, Sehgal restricted the analysis to the "current-fragmentation region", where disintegrating quark and ensuing hadrons are most directly connected. In the data this

Table II: Ratios of numbers of pion charge states: a) observed, b) corrected, c) predicted by isoscalar, and d) isovector neutral current.

Frequency ratio:		π^{+}/π^{o}	π^{-}/π^{o}	π^{+}/π^{-}	$(\pi^{+}+\pi^{-})/\pi^{o}$
a) Observed for	ν	0.74±0.13	0.72±0.13	1.03±0.23	1.46±0.20
	$\bar{\nu}$	0.74±0.13	0.58±0.13	1.28±0.34	1.32±0.20
b) Corrected for	ν	0.77±0.16	0.60±0.15	1.29±0.38	1.37±0.24
	$\bar{\nu}$	0.76±0.16	0.43±0.15	1.77±0.67	1.18±0.23
c) Theory IS		1.0	1.0	1.0	2.0
d) Theory IV		-	-	1.0	-

selection could not be made exactly, since muon-less events are not sufficiently constrained. Instead, the experimenters [60] asked simply for an energy transfer $\nu > 1$ GeV, and for a value of the fragmentation variable $z_\pi = E_\pi/\nu$ between 0.3 and 0.7. By comparing with charged current data the authors concluded that the NC sample, collected this way, contains 80% current-fragmentation events, indeed.

The charge-ratios derived from this restricted sample (Table III) do differ from those of the unselected events: Again, the sheer fact that these numbers differ from each other (and from unity) demonstrates, without any model assumption at all, that the hadronic neutral current is a mixture of isovector and isoscalar. Besides, the $(\pi^+ + \pi^-)/\pi^0$ ratio of ≈ 2 confirms the idea that the pions observed stem from the "decay" of quarks with isospin $I_q = 1/2$. And as Sehgal remarked [59], "the direction of

Table III: Frequency ratios (%) of semi-inclusive pion charge states, with $\nu > 1$ GeV, and $0.3 \leq z_\pi \leq 0.7$, experimental and minimal model (with $x_W = 0.40$)

Frequency ratios in %	ν exp.	ν theory	$\bar{\nu}$ exp.	$\bar{\nu}$ theory
a) π^+/π^-	77 ± 14	71 ± 5	164 ± 36	143 ± 11
b) π^+/π^0	82 ± 17	83 ± 4	126 ± 21	118 ± 3
c) π^-/π^0	107 ± 22	116 ± 4	77 ± 21	82 ± 3
d) $(\pi^+ + \pi^-)/\pi^0$	190 ± 35	200 !	203 ± 45	200 !

the π^+/π^- asymmetry, in the ν and $\bar{\nu}$ data, holds an important message concerning the structure of the current", (namely the sign of the isoscalar-isovector interference term).

The analysis proper is quite straight-forward: Sehgal wrote the charge ratios in terms of the NC coupling constants, and of the quark fragmentation functions D_q^π for ν and $\bar{\nu}$ [59]:

$$\left(\frac{\pi^+}{\pi^-}\right)_\nu = \frac{(u_L^2 + \frac{1}{3} u_R^2) D_u^{\pi^+} + (d_L^2 + \frac{1}{3} d_R^2) D_d^{\pi^+}}{(u_L^2 + \frac{1}{3} u_R^2) D_u^{\pi^-} + (d_L^2 + \frac{1}{3} d_R^2) D_d^{\pi^-}} , \quad (31)$$

$$\left(\frac{\pi^+}{\pi^-}\right)_{\bar{\nu}} = \frac{(u_R^2 + \frac{1}{3} u_L^2) D_u^{\pi^+} + (d_R^2 + \frac{1}{3} d_L^2) D_d^{\pi^+}}{(u_R^2 + \frac{1}{3} u_L^2) D_u^{\pi^-} + (d_R^2 + \frac{1}{3} d_L^2) D_d^{\pi^-}} . \quad (\overline{31})$$

From charge symmetry:

$$D_u^{\pi^+} = D_d^{\pi^-} , \quad \text{and} \quad D_u^{\pi^-} = D_d^{\pi^+} . \quad (32)$$

Thus the π^+/π^- ratios can be written just in terms of the two $D_u^{\pi^\pm}$ - fragmentation functions - in fact, they depend on their ratio only. This ratio is known from charged current and electroproduction data; the experimental cuts have been taken into account.

Inserting the experimental π^+/π^--ratios of Table III into eqs. (31) and $(\overline{31})$ gives two equations for the unknown coupling constants (squared). Two additional equations are known from the inclusive data already, namely (from GGM):

$$u_L^2 + d_L^2 = 0.24 \pm 0.04 ; \quad u_R^2 + d_R^2 = 0.055 \pm 0.030 . \quad (33)$$

Solution of this system of four equations is easy, and gives:

$$u_L^2 = 0.082 \pm 0.035 \quad , \quad d_L^2 = 0.158 \pm 0.035 \quad ; \qquad (34L)$$

$$u_R^2 = 0.055 \pm 0.025 \quad , \quad d_R^2 = 0.001 \pm 0.025 \quad , \qquad (34R)$$

where the (strongly correlated) errors come mainly from $D_u^{\pi^+}/D_u^{\pi^-}$. Despite these limitations something remarkable has been achieved: for the first time the strength of the four fundamental N.C. quark couplings has been disentangled! From the inclusive data we know already left-quarks to dominate. Now we see that it is mainly the d_L-quark which couples. Right-handed couplings, instead, are very much smaller, and, if any, it is the u-quark which does the job ...

This considerable increase of knowledge is illustrated in Fig. 13: the bands in the $u_L^2 - d_L^2 - (u_R^2 - d_R^2)$ - planes come from the inclusive measurements (33), the ellipses from the semi-inclusive results (34). The unavoidable comparison with the minimal model [12,13] reveals again stupefying agreement, and suggests, for ν $(\bar{\nu})$ a most probable mixing constant $x_W = \sin^2\Theta_W$ of 0.31 ± 0.06 (0.34 ± 0.05). Accordingly, the Salam-Weinberg predictions for the charge-ratios in Table III were computed with $x_W = 0.30$. The spectacular agreement with experiment means, amongst other things, that the sign for the isovector-isoscalar interference term is right.

Sehgal's analysis has been resumed, modified, and extended by Sakurai [63], Ecker [64], Abott & Barnett [65] and others [66]. There is no time to describe all the tricks invented, nor all the data used, in order to make the analysis of neutral currents complete. Let us just register the main conclusions: all these authors agree essentially on the set of coupling constants

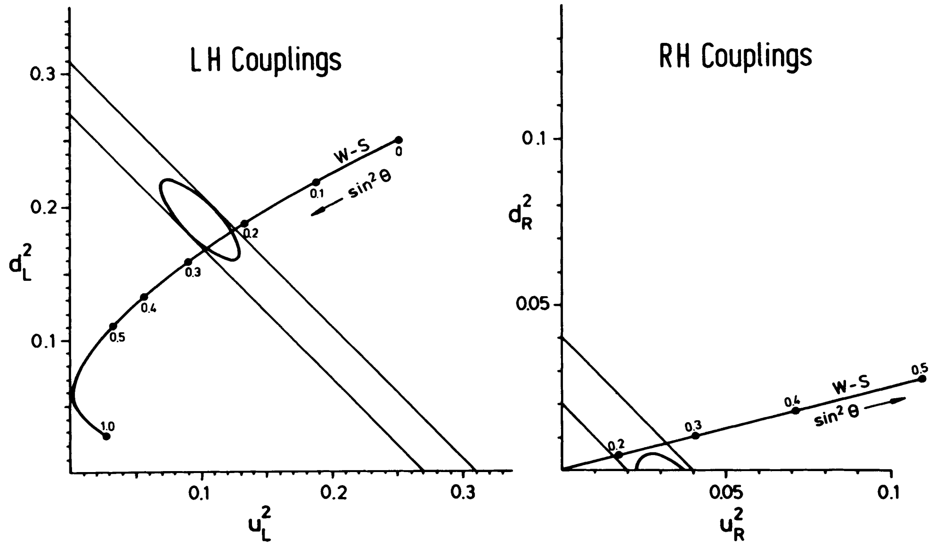

Fig. 13: Restrictions imposed by semi-inclusive NC pion production (ellipses) on left-handed and right-handed u and d couplings from inclusive data (bands). Curve minimal model.

(squared), as given in eq. (34). As we have seen, they follow from the minimal model with $x_W \approx 0.25$ to 0.3.

We close this chapter with a remark on NC induced exclusive pion production:

$$\overset{(-)}{\nu} + \mathcal{N} \rightarrow \overset{(-)}{\nu} + \mathcal{N} + \pi \quad , \qquad (35)$$

where $\mathcal{N}$ can be either a proton P or a neutron N, and π a pion of any charge permitted by charge conservation. We have mentioned the π^0-channels already in eqs. (13), and we stressed their importance as νe background. As demonstrated by the sparkchamber event of Fig. 4, exclusive single π^0 production, giving one or two visible decay gammas (and perhaps a proton at the origin) is a very characteristic process. It was amongst the first NC reactions to be discovered: by GARGAMELLE at first [67] and then in quick succession by Aachen-Padova [25] and Columbia Illinois-Rockefeller [68]. Charged pion production was studied by an ANL group [69], under grave difficulties with statistics and neutron background, and again by GARGAMELLE [70]. Finally, a breakthrough was achieved, when the GARGAMELLE chamber was filled with propane offering free protons as targets, and when the reactions off a proton were seperated from those off a neutron, so that all NC 1π channels could be studied simultaneously [71].

It was quite natural that Abott and Barnett [65] used exclusive one-pion data, and in particular the π^0 results, in their analysis. This has been criticized, in particular by Evelyn Monsay [72], because the data show systematic discrepancies, the worst one being in the measured π^0 NC/CC ratio for neutrinos R_0', which was found to be 0.40 ± 0.06 by AC-PD [25], and barely half as high in the early GGM freon data [67], and by CIR [68]. The reason for that lies probably in the very different experimental biases and cuts, which in turn imply substantial differences in the nuclear corrections. For example: AC-PD asked for two visible π^0 decay-gammas, whereas all other groups were content with one of them. In this way AC-PD put a very high energy threshold (≈ 300 MeV) into their acceptance. This experimental hardening of the π^0 spectrum, decreases the nuclear effects, so that the measured NC/CC ratio R_0' should be not far off the true value R_0.

But this remains to be proven by detailed Monte Carlo calculations. Until that is accomplished we shall not use the old ratios. Instead, we illustrate the power of exclusive data by some high-lights from the recent GARGAMELLE propane experiment [71]: Fig. 14 shows $P\pi$-invariant mass distributions, from top to bottem: in the NC $P\pi^0$ and $P\pi^-$ channels, and below in the CC $P\pi^0$ channel for comparison. In all three channels the Δ resonance

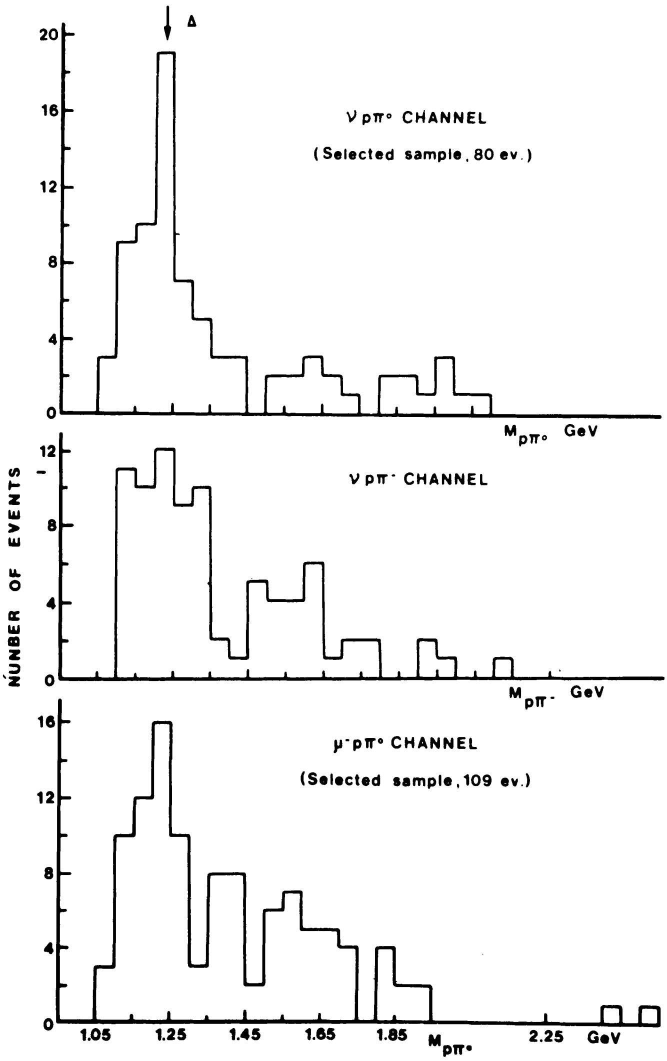

Fig. 14: Invariant mass distributions of the $\pi\mathcal{N}$ system in the final states: $\nu_\mu P\pi^0$, $\nu_\mu P\pi^-$; and (for comparison) $\mu^- P\pi^0$.

is clearly visible, (actually in the π^0 channels more cleanly than with π^-). This is the direct, and long awaited proof [73] that the neutral current does contain an isovector piece. And, comparing NC with CC, one has the impression that this isovector component dominates in both!

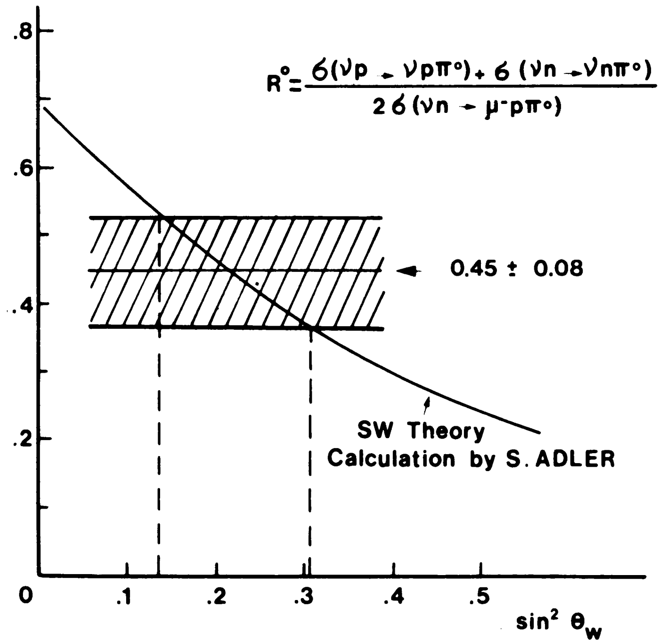

Fig. 15: Exclusive single π^0 ν-induced NC/CC ratio R^0 vs. $\sin^2\Theta_W$. Calculation by Adler, experimental band (dashed) from the GARGAMELLE propan experiment.

Finally, let us have a glimpse at the NC/CC ratio from the GARGAMELLE propane experiment [71], and its comparison to the Salam-Weinberg model [12,13], as worked out by Adler [61] (Fig. 15). The value of R_0 = 0.45 ± 0.08 may signal hope to AC-PD. Besides, the mixing angle comes out comfortingly low.

6. Elastic Neutrino-Nucleon Scattering and the Signs of the Neutral Current Coupling Constants

The pion data yielded the magnitude of the NC coupling constants u_i and d_j, but they did not fix their sign. These ambiguities imply considerable disparities in the physical meaning of the different sign combinations ("solutions"). In order to remove them, one has to perform some sort of interference experiment.

We had this sort of ambiguity already in the νe data of Fig. 7: the $\nu_\mu e$ and $\bar{\nu}_\mu e$ total cross sections, even if measured with infinite precision, intersect in <u>four</u> points, which are completely equivalent and differ just by the 2×2 sign combinations of C_A and C_V. Reithler [28] removed half of them by combining the $\overset{(-)}{\nu}_\mu e$ data with the $\bar{\nu}_e e$ result. He was left with the A vs. V dilemma, expressed by eq. (17), which could be resolved by the eD asymmetry (i.e. interference!) experiment at SLAC [41].

In principle, the hadron situation is more complicated, since hadrons carry (strong) isospin. But there is unanimous agreement [59,63-66] that the inclusive and semi-inclusive data admit just four physically different sets of coupling constants, labeled "Solution A to D". Their leading couplings are, respectively:

$$A = (A,\ iV),\quad B = (V,\ iV)\quad ;\quad C = (A,\ iS),\quad D = (V,\ iS) \qquad (36)$$

Solution A is practically identical with the Salam-Weinberg model, solution B is its vector-like alternative, and the two remaining, isoscalar dominated, solutions are rendered already quite improbable by the semi-inclusive and exclusive pion production results.

There are many ways to decide amongst these four possibilities. Quite a few of them have been tried in the analyses mentioned. It is comforting that the conclusions are nearly the same ... We shall limit ourselves to a very simple and obvious reaction, namely to elastic ν_μ ($\bar{\nu}_\mu$) scattering off protons (and neutrons!):

$$\nu_\mu + P \to \nu_\mu + P \qquad (37P)\ , \qquad \bar{\nu}_\mu + P \to \bar{\nu}_\mu + P\ ; \qquad (\overline{37P})$$

$$\nu_\mu + N \to \nu_\mu + N \qquad (37N)\ , \qquad \bar{\nu}_\mu + N \to \bar{\nu}_\mu + N\ . \qquad (\overline{37N})$$

It is intuitively clear that these truly elastic $\nu\mathcal{N}$ scattering processes entail interference between different amplitudes, as the quarks act coherently. And the detailed analysis [14] of these processes reveals that their discrimination power between different models and solutions is remarkable.

Experimentally, $\nu_\mu P$ scattering has been looked for long before the structure of neutral currents was under dispute - actually long before neutral currents were discovered [75]. In the very first CERN neutrino beam I had a scintillation counter sandwich running [76], which was rather sensitive to low energy proton recoils from (37P) - unfortunately also to a very heavy background from neutrons:

$$N + P \to P + N\ . \qquad (38)$$

Consequently only a very liberal limit could be placed on the NC/CC cross section ratio R_P between (37P) and the quasi-elastic ν_μ-reaction:

$$\nu_\mu + N \to \mu^- + P \qquad (39)\ , \qquad \bar{\nu}_\mu + P \to \mu^+ + N\ . \qquad (\overline{39})$$

(To the $\bar{\nu}_\mu$ reaction we shall be getting later). A terribly stringent limit on R_P of $\leq$ 3% was reported by the CERN heavy liquid bubble chamber [77]. It discouraged many people (including myself), but turned out to be wrong! A more solid limit from the same data was derived much later by Cundy <u>et al.</u> [78]: $R_P \leq 10\%$, a number which coincides actually with today's value.

Truly elastic $\nu_\mu P$ scattering was discovered by the Columbia-Illinois-Rockefeller (CIR) Collaboration [79], and independently by the Harvard-Pennsylvania-Wisconsin (HPW) Group [80], both working at the Brookhaven National Lab (N.Y.). CIR used an aluminum spark-chamber, similar to that of Aachen-Padova. HPW employed a scintillator counter sandwich interleaved with drift-chambers, which was specially taylored to detect and to measure ν_μ- and $\bar{\nu}_\mu$-P scattering, and made ample use of counter pulse-height and time-of-flight information. They have recently obtained very impressive data on $\nu_\mu P$, and were the only ones to report on $\bar{\nu}_\mu P$ [81]. Comparison with the GARGAMELLE measurement in propane [82] shows that here (for a change) counter techniques are superior.

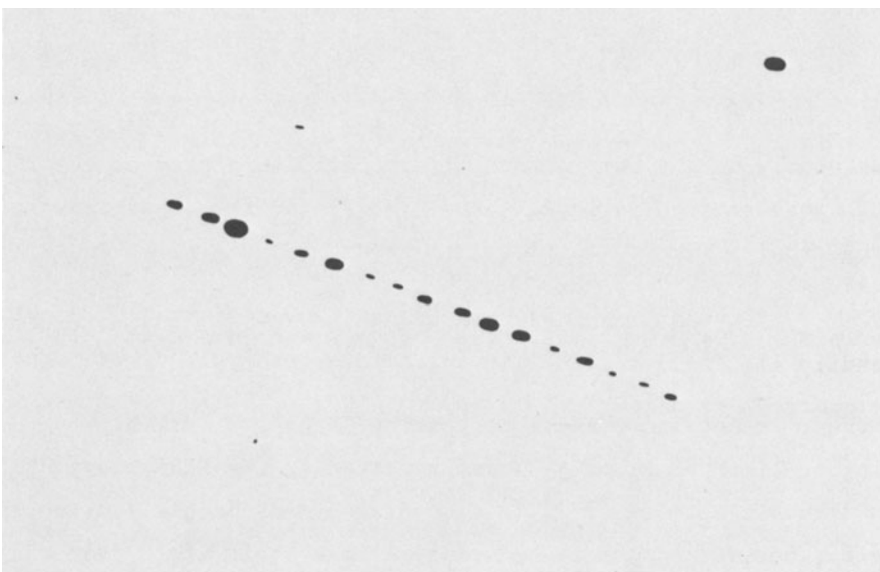

Fig. 16: Recoil proton in the Aachen-Padova sparkchamber.

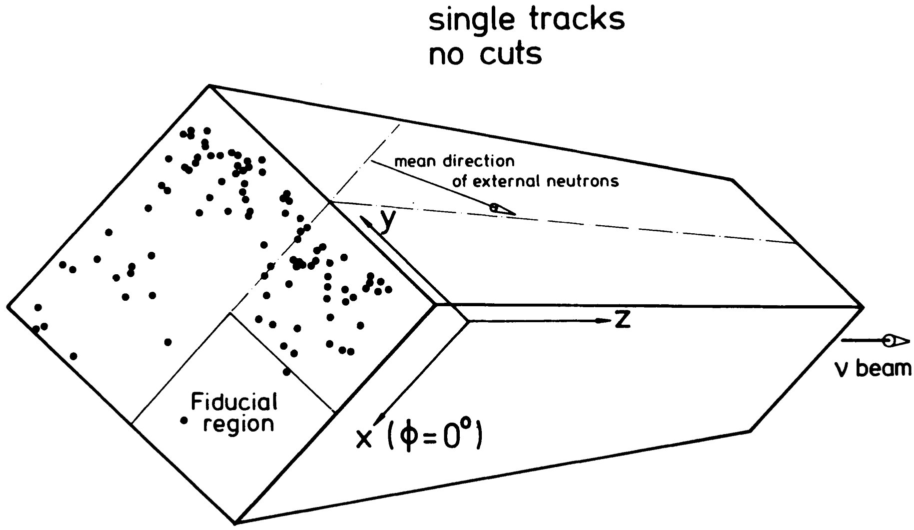

Fig. 17: Spatial distribution of proton starting points (projected on the front face) in the AC-PD sparkchamber.

Soon after the discovery of $\nu_\mu P$, the Aachen-Padova Group saw a recoil proton signal appearing in their spark chamber [83]. I shall spend the rest of my review describing this experiment, partly, because it is not yet as well published as the others are, but mainly because it gave me great pleasure, to watch our students, Uli Samm and Elisabeth Frenzel, overcoming slowly but steadily all difficulties. Indeed, to observe a single straight proton track is easy (Fig. 16). But the distribution of their starting points, projected onto the front side of the chamber (Fig. 17), is highly non-uniform. Together with a very strong azimuthal angular asymmetry it proves that most of these protons stem from neutrons entering the chamber from above, and with an average angle as indicated in Fig. 17.

A detailed study of these neutrons was the first task, notably of their spectrum and angular distributions, and of their interaction properties. Spectrum and interaction length were found in good agreement with the study of Fry and Haidt [9]. It became also clear, how the majority of these neutrons could be removed: by choosing a small fiducial volume (see Fig. 17), and by accepting only protons in an azimuthal angle interval opposite to that of the impinging neutrons. The energy spectrum of this selected sample shows a definite excess, at high energies, over what one would expect from neutrons.

In order to separate these neutrino events from the remaining neutron background, two-body kinematics is employed, specifically the correlation between proton recoil angle Θ_P and kinetic energy T_P. For a proton initially at rest:

$$E_P \ (1 - v_o \ v_P \ \cos\Theta_P) \ = \ M \ (1 - y) \quad , \qquad (40)$$

where the initial projectile's velocity $v_o = 1$ for ν, and $= P_N/E_N$ for N. Fermi motion and/or nuclear interactions disturb this relation, but on average it will still hold [84]. A scatter plot of range ($\sim T_P$) against $\cos\Theta_P$ is thus a reasonable diagnostic means to tell the rams from the sheep, as it were. Fig. 18a shows the ν_μP candidates selected as described, Fig. 18b the protons from the quasi-elastic CC reaction (39) where there is no neutron background at all, and Fig. 18c gives the full single proton sample, consisting almost entirely of neutron recoils. Hence one sees confirmed, what one could have anticipated from the start: neutron recoils cluster at small angles and small energies! No such cluster is seen in the genuine neutrino events (Fig. 18b), but the ν_μP candidate sample (Fig. 18a) shows both, large angle-high energy neutrino-like events, and the bad neutron blob near the origin. I cut it out by demanding a (reconstructed) neutrino

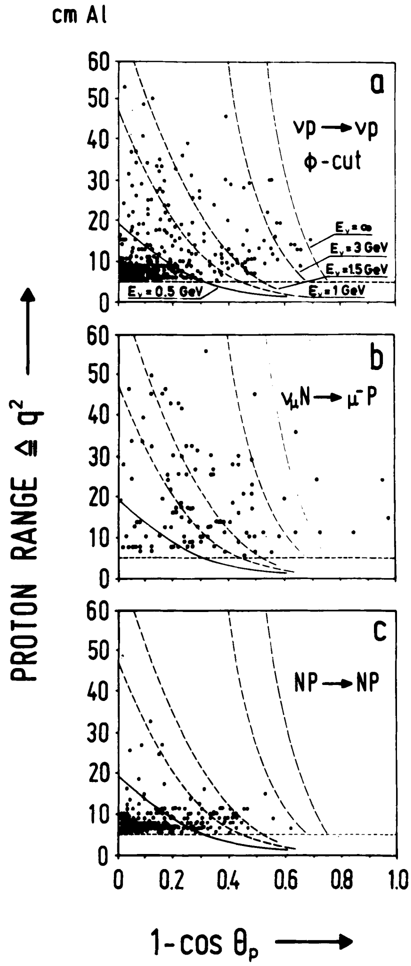

Fig. 18: Proton range and emission angle Θ_P scatter plots for a) $\nu_\mu P$ candidates, b) elastic CC ν-induced P's, c) protons from neutron background (AD-PD).

energy > 0.5 GeV. The remaining neutron background can safely be subtracted, since the spectrum is known.

In order to derive a meaningful NC/CC ratio R_P, the protons from the quasi-elastic sample (Fig. 18b) have been treated in exactly the same way as the $\nu_\mu P$ scattering candidates. Thus, nuclear corrections tend to cancel. Even so, it took several months of hard work, and all the machinery provided by Adler [61], Pohl [62] and others, to convince ourselves that all the pion contaminations in either sample, and all the proton and neutron absorption and charge exchange reactions were under control. The result is a raw ratio

$$R_P' = (15 \pm 4)\% \quad .$$

This result is in good agreement with the older values published [79,80,82]. However, as Samm was first to notice, it is really due to a mixture of $\nu_\mu P$- and $\nu_\mu N$-scatters! Depending on the ratio of νN to νP scattering cross sections, and on the experimental conditions, the contribution from neutrons may be quite large. Conventionally one subtracts the νN admixture by assuming a certain $\nu N/\nu P$ cross section ratio r_N, and tries to reach some conclusion by iteration.

Instead, we decided to accept our imperfections, and to take advantage of them.* Thus, we admit measuring a mixture of $\nu_\mu P$ and $\nu_\mu N$, and hence an experimental NC/CC ratio

$$R_P' = R_P + f_{PN} R_N \quad , \tag{41}$$

where f_{PN} is the (relative) probability that a neutrino produced neutron makes an acceptable proton. This transformation may happen:

a) in the parent nucleus,
b) somewhere in the chamber.

Case a) can be treated by looking at protons in the quasi-elastic $\bar{\nu}_\mu$ reaction ($\overline{37}$), case b) by investing the interaction

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* This attitude was called "Faissner's Principle" by Mitter.

properties of neutrons, and the geometry of the set-up, in lengthy Monte-Carlos. Samm got the combined result [84]:

$$f_{PN} = (33 \pm 4)\% \; .$$

With this number plugged into (41), our experimental NC/CC ratio defines a band in the R_P-R_N plane (Fig. 19). The four solutions are also shown, and there is no doubt that we favour A, and exclude C. Since D is out, for the pions' sake, we are again left with the A-V ambiguity first encountered in νe. Fortunately, the new Harvard et al. data on $\nu_\mu P$, and even more incisively those on $\bar{\nu}_\mu P$, eliminate the vector-like solution B at a three st.dev. level [81]. Hence we can take solution A - or right away Salam-Weinberg - and determine the relevant parameters from the upper intersection point of our experimental line with "Weinberg's nose", (the second solution is unphysical):

$$R_P = 0.10 \pm 0.03, \quad \sin^2\Theta_W = 0.32 \begin{smallmatrix} +0.18 \\ -0.09 \end{smallmatrix} \; ; \quad R_N = 0.15 \pm 0.04 \qquad [85]$$

The first two numbers are in perfect agreement with those of HPW [81]. The neutron ratio R_N is new, and I emphasize that it was as directly (or indirectly) derived as R_P was.

Little remains to be said: from its origin with the fairy GARGAMELLE the weak neutral current has grown into a veritable stream, fecundating such different regions as electron scattering and annihilation, atomic and nuclear physics, astronomy and cosmology. Its structure has been unveiled, and it is improbable that the still controversial experiments, like those in optics, will force us to resort to more complicated, parity conserving gauge models, like that of Fritzsch and Minkowski [86].

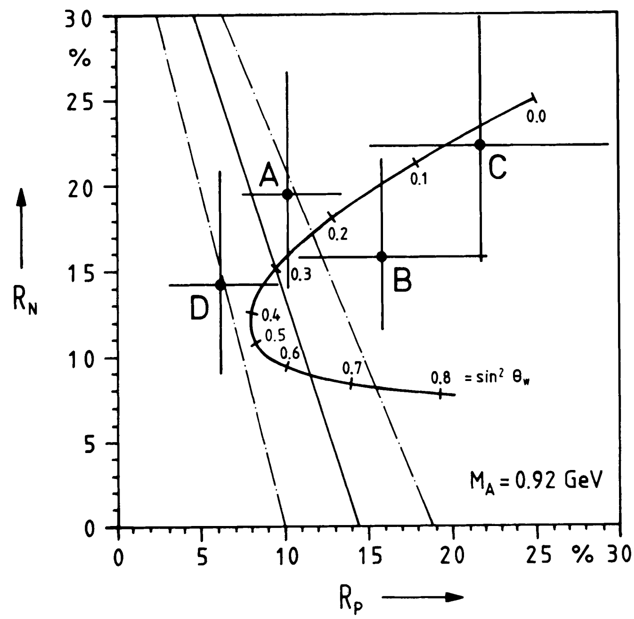

Fig. 19: Model-free comparison of the AC-PD $\nu_\mu P + \nu_\mu N$ scattering result (band) with the four coupling constant solutions A-D, and Weinberg-Salam.

This is not to say that we should be idle. Many experiments have to be improved, some must be undertaken anew. Let me close with my personal list of "things to be done":

- all exclusive reactions have to be measured an order of magnitude better than now (i.e. with a factor of 1/3 in error!)
- e.m.-weak interference ought to be done at varying q^2,
- the atomic and nuclear mess has to be cleaned up,
- I want to see if ν_e's have the same neutral current as ν_μ,

- to study ν_e e (with interference term!) would be particularly nice,
- nuclear spectroscopy by neutrino induced N.C. looks extremely attractive [87]
- the neutral current of the muon must be explored by $\bar{e}e \to \bar{\mu}\mu$ (say at PETRA).

Last not least:

- coupling constants, like $\sin^2\Theta_w$, could be a function of q^2, and, therefore, of energy. This should be explored by all means, and might explain some of the discrepancies which occured in comparing experiments done at different energies [88].

This ends my list of urgent experiments, I do not feel competent to adjoin an analogous list for theoreticians, I add just one wish: that they continue to look for symmetries beyond our minimal $SU_2 \times U_1$ group, striving for the ultimate unification of all forces of Nature.

Acknowledgements

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References

[1] P. Musset and J.-P. Vialle, Neutrino Physics with Gargamelle, Physics Reports 39C, No. 1 (1978) p. 1

[2] H. Faissner et al., Contribution No. 273 to: Proc. 6th Internat. Symposium on Electron and Photon Interactions at High Energies, Bonn 1973, Ed. H. Rollnik and W. Pfeil (North-Holland 1974) p. 550

[3] G. Myatt, ibid. p. 389

[4] H.J. Hasert et al., Phys. Letters 46B, 121 (1973)

[5] E.C. Young, Oxford Thesis (1966), and Yellow Report CERN 67-12
M. Paty, Paris Thesis (1965), and CERN 65-12

[6] M. Holder, Aachen Thesis (1967) and Aachen Report PITHA-19 (1967)

[7] H. Faissner et al., Nucl. Instrum. and Meth. 20, 213 (1963)
H. Faissner, Acta Physica Austriaca, Suppl. I (1964) p. 189

[8] H.J. Hasert et al., Phys. Letters 46B, 138 (1973)

[9] W.F. Fry and D. Haidt, CERN-Report 75-1 (1975)
D. Haidt, Phys. Blätter 31, 654 (1975)

[10] S. Glashow, Nucl. Phys. 22, 579 (1961)

[11] A. Salam and J.C. Ward, Phys. Letters 13, 168 (1964)

[12] A. Salam, Elementary Particle Theory, ed. N. Svartholm (Almquist and Wiksells, Stockholm 1968) p. 367

[13] S. Weinberg, Phys. Rev. Letters 19, 1264 (1967); 27, 1688 (1971)
see also Phys. Rev. D5, 1412 (1972)

[14] G. 't Hooft, Nucl. Phys. B33, 173 (1971) and B35, 167 (1971)
G. 't Hooft and M. Veltman, Nucl. Phys. B44, 189 (1972)

[15] see E.S. Abers and B.W. Lee, Phys. Reports 9C, No. 1 (1973)
S. Weinberg, Aix-en-Provence Conf. (1973), J. Physique, Suppl. 10, 34, C1 (1973)
L.M. Sehgal, Aachen Report PITHA-68 (1973)

[16] S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D12, 1285 (1970)

[17] K.M. Case, Phys. Rev. 107, 307 (1957)

[18] G. 't Hooft, Phys. Letters 37B, 195 (1971)

[19] P. Rosen, Proc. Neutrino Conf. Downington 1974 (AIP, New York 1974) p. 5
L.M. Sehgal, Nucl. Phys. B70, 61
M. Gourdin, Proc. Neutrino Conf. Aachen 1976, ed. H. Faissner, H. Reithler, and P. Zerwas (Vieweg, Braunschweig 1977) p. 234

[20] H. Faissner, Proc. B.W. Lee Memorial Conf. 1977, ed. D. Cline (FNAL, Batavia, 1978) p. 85

[21] see H. Faissner, Proc. Varenna 1977 School, Nuovo Cim. Suppl., in press

[22] H. Faissner et al. pres. by F. Bobisut, Proc. Neutrino Aachen 1976, loc.cit., p. 223
H. Faissner et al., Proc. Neutrino Conf. Baksan 1977, ed. M.A. Markov et al. (Nauka, Moscow, 1978) Vol. 2, p. 142

[23] J. Blietschau et al., Nucl. Phys. B114, 189 (1976)
see also F.J. Hasert, La physique du neutrino à haute energie (Paris, 1975) p. 257

[24] J. Blietschau et al., Phys. Letters 73B, 232 (1978)

[25] H. Faissner et al. pres. by T. Hansl, Proc. Neutrino 1976, loc.cit., p. 278

[26] H. Faissner et al., Phys. Letters 68B, 377 (1977)

[27] H. de Witt, Diplomarbeit T.H. Aachen (1978)

[28] H. Reithler, Proc. Int. Conf. Lepton Physics High Energies, Hamburg 1977, Ed. F. Gutbrod (DESY 1977) p. 343

[29] H. Faissner et al., Phys. Rev. Letters 41, 213 (1978)

[30] H. Faissner et al., presented by M. Baldo-Ceolin, Proc. Neutrino Conf. Purdue, 1978, ed. E.C. Fowler (Purdue, West Lafayette, Ind. 1978) p. 387
E. Radermacher, Proc. Tokyo High Energy Conf. 1978, ed. S. Homma, M. Kawaguchi, and H. Miyazawa (Phys. Soc. Japan 1979) p. 321
M. Baldo-Ceolin et al., Proc. Tokyo, loc.cit., contr. paper No. 1087
G. Puglierin, Proc. Conf. Neutrino Phys. Acc. Oxford 1978, ed. A.G. Michette and P.B. Renton (Rutherford, 1978) p. 279

[31] G. Gershwin, Porgy and Bess, Aria of "Sportin' Life"

[32] P. Alibran et al., Phys. Letters 74B, 422 (1978)

[33] N. Armenise et al., Phys. Letters 81B, 385 (1979)

[34] A.M. Cnops et al., Phys. Rev. Letters 41, 357 (1978)
C. Baltay et al., Proc. Neutrino Conf. Purdue, loc.cit. p. 413
C. Baltay, Proc. Tokyo Conf. loc.cit. (1979) p. 882

[35] N. Armenise et al., Phys. Letters 81B, 385 (1979) - BEBC
J.B. Berge et al., Phys. Rev. Letters 41, 357 (1978) - 15'

[36] D. Bertrand et al., Phys. Letters (1979) in press, Aachen Report PITHA-79/09

[37] F. Reines et al., Phys. Rev. Letters 37, 315 (1976) and Proc. Aachen Conf. 1976, loc.cit., p. 217

[38] Fred Reines, in his publications [37], gave the cross section only as a function of energy. Upon my insistence he also averaged it, and telephoned the result plotted in Fig. 7 from California.

[39] R.P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958)
E.C.G. Sudarshan and R.E. Marshak, Phys. Rev. 109, 1860 (1958)

[40] D.A. Ross and M. Veltman, Nucl. Phys. 95B, 135 (1975)

[41] C.Y. Prescott et al., Phys. Letters 77B, 347 (1978)

[42] see N. Fortson, Proc. Neutrino Conf. Purdue, 1978, loc.cit. p. 417
L.M. Barkov and M.S. Zolotorev, ibid., p. 423
L. Wilets, ibid., p. 437

[43] F.J. Hasert et al., Nucl. Phys. B73, 1 (1974) - Final discovery
J. Blietschau et al., Nucl. Phys. B118, 218 (1977) - Last data

[44] A. Benvenuti et al., Phys. Rev. Letters 32, 800 (1974)
B. Aubert et al., ibid. 32, 1454 (1974)
T.Y. Ling, Proc. Neutrino Conf. Aachen 1976, loc.cit., p. 296
P. Wanderer et al., Phys. Rev. D17, 1679 (1978) - data

[45] B.C. Barish et al., Phys. Rev. Letters 34, 538 (1975)
L. Stutte, Weak Interaction Workshop, Ohio State Univ. (1975), unpublished
F.S. Merritt et al., CALT 68-601 (1977) - data
B.C. Barish et al., CALT 68-605 (1977) - data

[46] L.M. Sehgal, Phys. Letters 55B, 205 (1975)

[47] S. Sakakibara and L.M. Sehgal, Phys. Letters 83B, 77 (1979)

[48] S.P. Rosen, Proc. Neutrino Conf. Downingtown 1974, ed. C. Baltay (AIP, New York, 1974) p. 5
S.P. Rosen et al., Proc. Neutrino Conf. Balaton 1975, ed. A. Frenkel and G. Marx (Budapest 1975), Vol. I, p. 186
M. Gronau, Haifa Tech preprint (1975)
S. Pakvasa and G. Rajasekaran, Phys. Rev. D12, 113 (1975)
J.J. Sakurai, Neutrinos-1974, loc.cit. p. 57

[49] B. Kayser et al., Phys. Letters 52B, 385 (1974)
see also R.L. Kingsley, Phys. Rev. D10, 2216 (1974)
T.C. Yang, Phys. Rev. D10, 3744 (1974)
C. Jarlskog, Nuovo Cim. Letters 4, 377 (1970)

[50] R.P. Feynman, Photon-Hadron Interactions (Reading, Mass., 1972); Proc. Neutrino Conf. Balaton 1972, ed. A. Frenkel and G. Marx (Budapest 1972) Vol. 2, p. 75
J.D. Bjorken and E.A. Paschos, Phys. Rev. 185, 1975 (1969)

[51] E.D. Bloom et al., Phys. Rev. Letters 23, 930 (1969)
M. Breidenbach et al., Phys. Rev. Letters 23, 935 (1969)
see also W.K.H. Panofsky, Proc. Int. Conf. High-Energy Phys. Vienna 1968, ed. J. Prentki and J. Steinberger (Vienna 1969) p. 23

[52] T. Eichten, H. Faissner et al., Phys. Lett. 46B, 274 (1973)
H. Deden et al., Nucl. Phys. B85, 269 (1975)
see also W. Krenz, Neutrino-1976 Aachen, loc.cit., p. 385 and Habilitationsschrift Aachen (1978)

[53] H. Faissner, Aachen Report PITHA-60 (1972)
D. Rein, Phys. Letters 43B, 209 (1973)
The concept of valence quarks was introduced by J. Kuti and V.F. Weisskopf, Phys. Rev. D4, 3418 (1971); see also S.D. Drell and K. Johnson, Phys. Rev. D6, 3248 (1972)

[54] P.C. Bosetti et al., Phys. Letters 70B, 273 (1977) - CC
P.C. Bosetti et al., Phys. Letters 76B, 505 (1978) - NC
H. Deden et al., Nucl. Phys. B149, 1 (1979) - NC, and Proc. Oxford Conf. (1978), loc.cit. p. 292

[55] H. Faissner et al., Proc. Neutrino-1976, Aachen, loc.cit., p. 393
H. Faissner and B. Kim, to be published

[56] L.M. Sehgal, Nucl. Phys. B65, 141 (1973);
see also R.B. Palmer, Phys. Letters 46B, 240 (1973)
A. de Rûjula et al., Rev. Mod. Phys. 46, 391 (1974)

[57] M. Holder et al., Phys. Letters 71B, 222 and 72B, 254 (1977)
Also F. Dydak, Facts and Prospects of Gauge Theories, Schladming Lectures (1978), ed. P. Urban (Wien & New York 1978) p. 436 and Habilitationsschrift Heidelberg (1978)
J. Steinberger, Hadron Structure and Lepton-Hadron Interactions, Cargèse 1977, ed. M. Lévy et al. (New York & London 1979) p. 201

[58] Traudl Hansl (CDHS), private communication

[59] L.M. Sehgal, Phys. Letters 71B, 99 (1977); and Proc. Neutrino Purdue (1978) loc.cit. p. 253

[60] H. Kluttig, J.G. Morfin, and W. Van Doninck, Phys. Letters 71B, 446 (1977)

[61] S.L. Adler, S. Nussinov, and E.A. Paschos, Phys. Rev. D9, 2125 (1974)

[62] M. Pohl, Aachen Thesis (1979)
C. Longemare, Orsay Thesis (1978)

[63] P.Q. Hung and J.J. Sakurai, Phys. Letters 63B, 295 (1976); 69B, 323 (1977); and 72B, 208 (1977)
see also J.J. Sakurai, Proc. Neutrino Conf. Aachen 1976, loc.cit. p. 515; Proc. Neutrino Conf. Baksan 1977, loc.cit. Vol. 2, p. 242; Proc. Conf. Neutrino Acc. Oxford 1978, loc.cit. p. 338; Current Trends in the Theory of Fields, (Dirac-Symp.) ed. J.E. Lannutti and P.K. Williams (AIP, New York 1978) p. 38

[64] G. Ecker, Phys. Lett. 72B, 450 (1977)
G. Ecker and H. Pietschmann, Acta Phys. Austr. 45, 313 (1976)

[65] L.F. Abbott and R.M. Barnett, Phys. Rev. D18, 3214 (1978)

[66] P. Langacker and D.P. Sidhu, Phys. Letters 74B, 233 (1978)

[67] F.J. Hasert et al., Phys. Letters 59B, 485 (1975)

[68] W. Lee et al., Proc. Neutrino Conf. Aachen 1976, loc.cit., p. 319

[69] S.J. Barish et al., Phys. Rev. Letters 33, 448 (1974) and 36, 179 (1976)
see also P. Schreiner, Proc. Neutrino Conf. Aachen 1976, loc.cit., p. 333

[70] G.H. Bertrand-Coremans, P. Musset et al., Phys. Letters 61B, 207 (1976)

[71] W. Krenz et al., Nucl. Phys. B135, 45 (1978), and M. Pohl, Ref. [62]

[72] E.H. Monsay, Phys. Rev. Letters 41, 728 (1978)

[73] see B.W. Lee, Proc. Neutrino Conf. Aachen 1976, loc.cit., p. 704

[74] C.H. Albright et al., Phys. Rev. D14, 1780 (1976)
E. Fischbach et al., Phys. Rev. D15, 97 (1977)

[75] see H. Faissner, Proc. Neutrino Conf. Balaton 1975, loc.cit., Vol. I, p. 85

[76] H. Faissner et al., Nuovo Cim. 32, 782 (1964)

[77] M.M. Block et al., Phys. Letters 12, 281 (1964) - On p. 285 the statement is even: G^{NC}/G^{CC} ($\Delta S = 0$) < 3%!
see also H.H. Bingham et al., Proc. Siena Conf. 1963, ed. G. Bernardini and G.P. Puppi (Bologna 1963), Vol. I, p. 555

[78] D.C. Cundy et al., Phys. Letters 31B, 478 (1970)

[79] W. Lee et al., Phys. Rev. Letters 37, 186 (1976), and Ref. [68]

[80] D. Cline et al., Phys. Rev. Letters 37, 252 (1976) and 37, 648 (1976);
brilliant: L.R. Sulak et al., Proc. Neutrino Conf. Aachen 1976, loc.cit., p. 302

[81] L.R. Sulak et al., Proc. Neutrino Conf. Purdue 1978, loc.cit., p. 355
H.H. Williams, Proc. Conf. Neutrino Acc. Oxford 1978, loc.cit., p. 315
A. Entenberg et al., Phys. Rev. Letters 42, 1198 (1979)

[82] M. Pohl et al., Phys. Letters 72B, 489 (1978)

[83] H. Faissner et al., Proc. Neutrino Conf. Baksan 1977, loc.cit., Vol. 2, p. 164

[84] U. Samm, Diplomarbeit Aachen (1979)

[85] H. Faissner et al., Proc. Neutrino Conf. Purdue 1978, loc.cit., p. C89 and Phys. Rev., to be published

[86] H. Fritzsch and P. Minkowski, Nucl. Phys. B103, 61 (1976)

[87] T.W. Donnolly and R.D. Peccei, Phys. Reports 50, 1 (1979)

[88] Traudl Hansl, in the discussion following her Aachen talk [25], had envisaged such an energy dependence. (She was well ahead of her time ...)