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The history of neutrinos, 1930–1985. What have we learned about neutrinos? What have we learned using neutrinos?

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ABSTRACT

An attempt to remember some of the main events which highlight the evolution of our knowledge of the neutrinos and their properties, the "families" of particles, a few of the very interesting persons who contributed to this progress, as well as the contribution of neutrino beam experiments to the validation of the electro-weak and quantum-chromo-dynamic theories, and the structure of the nucleon.

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1. Early history. Continuous spectrum in β-decay, the Pauli letter, the Fermi interaction

In 1914, Chadwick showed that the electron spectrum in the β-decay of Radium B + C is a continuum [1]. The important implications of this were far from clear at the time (see Figs. 1 and 2).

16 years later, in 1930, 2 years before the same Chadwick discovered the neutron, Wolfgang Pauli wrote his famous letter to the Kongress der Radioaktiven. To conserve energy and angular momentum in β-decay, he proposed that together with the electron a new particle is emitted, neutral, with a magnetic dipole and with ionization power no greater than γ-rays. Pauli did not dare to publish this until 3 years later. For me the letter is the most interesting and fun document I know in this field, and I give here the German original, as well as an English translation (see Figs. 3–5).

The next leap forward in our understanding was the brilliant Fermi theory [2] for β-decay in the very early days of field theory. Fermi proposed a Lagrangian, which is the product of two Dirac "currents", one transforming a neutron into a proton, the other an electron into a neutrino, the basis of the weak interaction until this day.

2. "Families" and the "universal fermi interaction"

For me, the history of "families" begins with the 1947 Physical Review Letter of Pontecorvo [3], in the wake of the 1946 cosmic ray experiment of Conversi et al. [4], which had shown that negative cosmic ray mesotrons (now muons), stopped in carbon, had a small probability to be captured by the nucleus, whereas if stopped in iron, the capture probability was most probable. It was immediately understood that the negative muon is captured in the atomic K-orbit in a time very short compared to the muon life time, and consequently recognized that this showed that the interaction strength of the muon and nucleon is much too small to be the "Yukawa particle" proposed by Yukawa to be responsible for nuclear forces, but, in addition, Pontecorvo saw that the interaction strength is comparable to the Fermi interaction strength in β-decay. Pontecorvo's letter was the first suggestion that there is a parallel between electrons and muons, and therefore of what is now known as "families". The proposal was totally rejected at the time by the physics community, including his friend and teacher Fermi, the father of weak interaction theory. The notion of a possible relationship of muon and electron was difficult to imagine at that time (see Fig. 6).

For the next step, I give credit to my thesis experiment of 1948 [5], which showed that the electron spectrum in muon decay is a continuum, and therefore two low mass neutral particles must accompany the electron. It was known that gamma rays are not emitted in muon decay, so the neutral particles were assumed to be neutrinos (see Fig. 7).

Although neither I nor my thesis advisor, Fermi, were clever enough to realize this, it was quickly noted, independently, by Lee et al. [6], who were fellow graduate students at Chicago, Tiomno and Wheeler [7], and Puppi [8], that given the muon lifetime, the three interactions, β-decay, muon capture and muon decay, can be understood by combining three Fermi currents, a neutron–proton current, a muon–neutrino current and an electron–neutrino current, in three different ways, with the same interaction strength, to describe the three different processes. This was the beginning of the "universal Fermi interaction", which was immediately accepted by the community, including Fermi (see Fig. 8).

3. Demonstration of the neutrino

In 1956, three and a half decades after the Pauli letter, Reines and Cowan [9] were able to detect the reactions produced in a cadmium loaded liquid scintillator by the antineutrinos of a nuclear reactor. This was possible for them because of their access to a nuclear reactor of the Atomic Energy Agency, which produced tritium for nuclear weapons, and with considerably higher fluxes than non-military reactors for commercial energy production. In their detector, the antineutrino, reacting with a proton, produces an electron and a neutron, and they observed the coincidence of the electron pulse with the delayed pulse produced by the scattering of the neutron on cadmium (see Fig. 9).

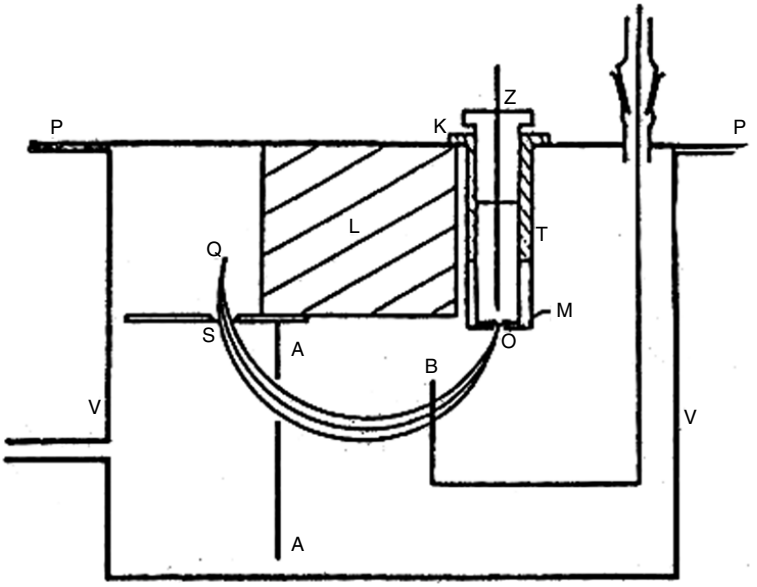


Fig. 1. The spectrometer used by Chadwick in the discovery of the continuous spectrum.

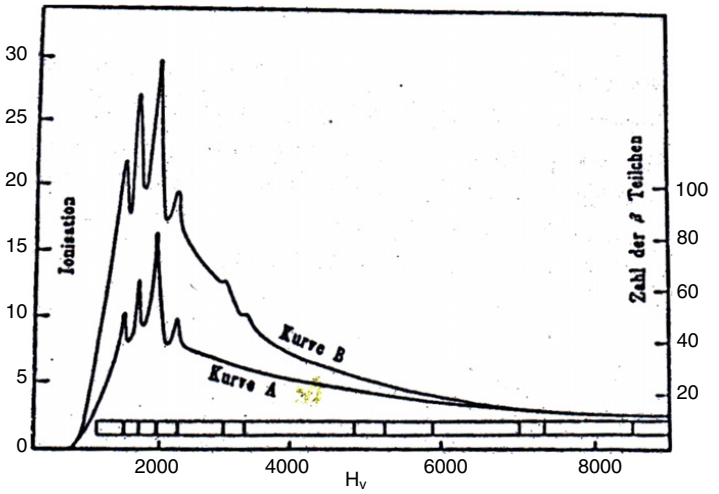


Fig. 2. The continuous electron spectrum observed by Chadwick.

4. The electron neutrino and the muon neutrino are different

This chapter begins in 1958, with a theoretical insight of Feinberg [10], referring to a measurement by Lokanathan and myself, in which we had searched, unsuccessfully, for the decay of the muon into electron and photon [11]. Feinberg calculated that, if the neutrino and antineutrino in muon decay are antiparticles of one another, which was universally assumed at the time, you would expect the decay of the muon into electron and gamma ray, with a branching ratio of 10^{-4}, five times larger than the upper limit we had obtained 3 years earlier. One-half year later Oneda and Pati [12], noted that this could be understood if the neutrinos associated with muons in pion decay are different from those associated with electrons in beta decay, $\nu_\mu \neq \nu_e$, and that one might check to see if electron and muons are associated with different neutrinos. Following this, Pontecorvo [13] proposed that this could be experimentally checked by looking at the leptons emitted in the interaction of neutrinos with nuclei.

Fig. 3. Wolfgang Pauli.

If the neutrinos are different, a neutrino beam generated in pion decay would not produce electrons. Pontecorvo also showed that the future, higher energy accelerators would make this experiment possible, but this possibility did not exist at the time in the Soviet Union, where he was resident (see Fig. 10).

Independently, in 1959, Melvin Schwartz proposed [14], that high energy neutrino beams could be used to study the weak interaction at higher energies. The reflections of Schwartz were motivated by a question asked by Lee at one of the customary Friday lunches, organized at Columbia University by Lee, which brought particle physicists together in good, nearby Chinese restaurants. Lee asked the question: "How could the weak interaction be studied at higher energies than then was possible, using particle decays?" Unfortunately I was not present at this lunch. The Schwartz letter does not mention the possible use of neutrino beams to check the question of $\nu_e - \nu_\mu$ equality, which had been raised by Feinberg.

The design of our experiment, which succeeded in demonstrating that the two neutrinos are different, began in 1960. At the time, two similar proton accelerators of sufficiently high energy and flux to imagine doing neutrino beam experiments, were under construction, one at CERN and one at BNL. These new accelerators, of proton energy ∼25 GeV were made possible by the invention of the "strong focusing" principle by Courant et al. [15]. Fig. 11 shows the layout of the experiment at the BNL AGS.

The chief challenge was the detector, which needed to have sufficient mass, of the order of 10 tons, and to permit the identification of the outgoing particles, muons, electrons and hadrons. Spark chambers were chosen. They had just come on the scene, but the design of such large chambers was a considerable technical challenge at the time, resolved largely by the ingenuity of Schwartz. The detector (Fig. 12) consisted of 10 spark chamber modules, each with 9, 2.5 cm thick, aluminum plates, 112 cm × 112 cm in area and 2.5 cm thick, for a mass of one ton per module (see Figs. 13 and 14).

29 events with single muons were observed. For electrons the triggering efficiency was estimated to be 2/3 of that for muons, so that 20 candidates were expected if muon and electron neutrinos were the same, but only one was observed. It was therefore concluded that muon and electron neutrinos are different [16] (see Figs. 15 and 16).

5. The discovery of "partons", nucleon structure, scaling, in deep inelastic scattering of electrons on protons at SLAC in 1969

In 1969, at SLAC, the 24 GeV electron linear accelerator, constructed under the direction of W.K.H. Panofsky, permitted, for the first time, the study of deep inelastic scattering of leptons by hadrons, and so the discovery by J. Friedman, H. Kendall, R. Taylor and colleagues [17], of scaling.

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Fig. 4. Pauli letter to the Kongress der Radioaktiven.

The experiment showed that in deep inelastic scattering of electrons on nucleons, the cross-section is largely independent of the momentum transfer. This could be understood, following J. Bjorken, as due to the fact that nucleons are complex, composed of particles unknown at the time, then called "partons" by Feynman (see Fig. 17).

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e (10^{-13} cm).

For the moment I would not venture to publish anything on this notion and should like first of all to turn trustingly to you, dear Radioactives, with the question concerning the prospects for experimental verification of the existence of such a neutron if it were to have the same or perhaps a 10 times greater penetrating power as a γ–ray.

I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β–spectrum is illustrated by a statement by my esteemed predecessor in office, Mr. Debye, who recently told me in Brussels: "Oh, it's better to ignore that completely, just like the new taxes". We should therefore be seriously discussing every path to salvation. So, dear Radioactives, consider and judge. Unfortunately I cannot come to Tübingen in person since my presence here is essential as a result of a ball held on the night of 6th to 7th December in Zürich.

With kind regards to all of you and Mr. Back, I remain,
your humble servant,

(signed) W. Pauli

† This states: Fermi statistics and half-numbered spin for nuclei with an odd total number of particles; Bose statistics and integer spin for nuclei with an even total number of particles.

Fig. 5. English translation of the Pauli letter.

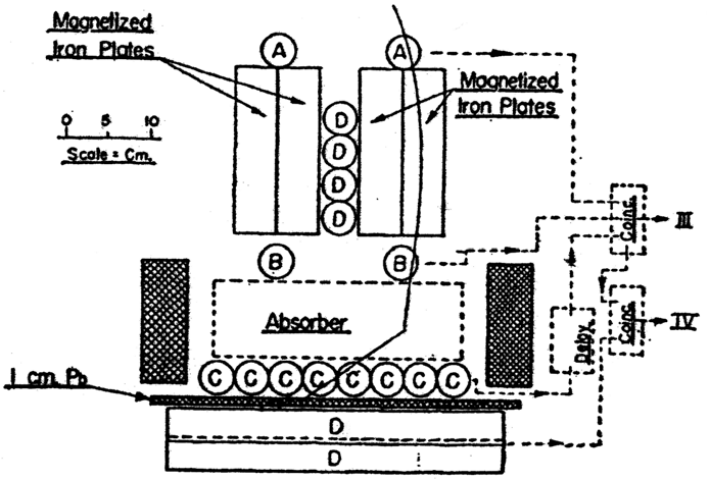


Fig. 6. The cosmic ray detector of Conversi et al.. The iron slabs above the detector were magnetized to focus either positive or negative muons. The decay electrons or positrons below the absorber plates were then detected.

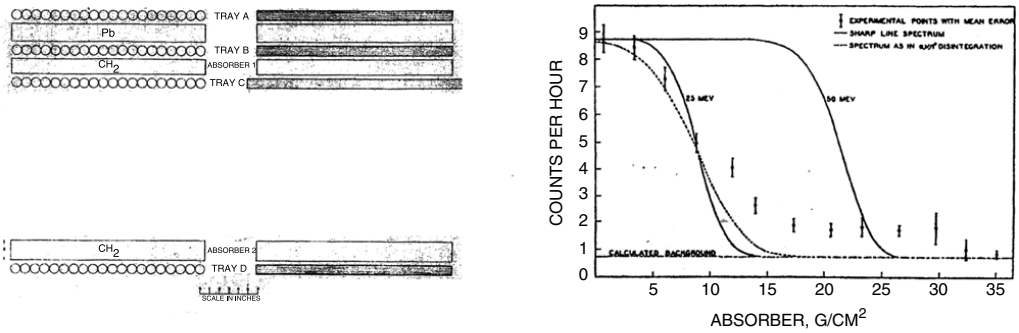


Fig. 7. My cosmic ray thesis experiment, measuring the electron spectrum in muon decay. Left: Detector with 80 Geiger counters. Right: The electron spectrum is continuous.

6. The Gargamelle experiment, the discovery of neutral current, which confirmed the electro-weak theory, and the demonstration that the partons are the quarks proposed by Gell-mann and Zweig, by showing that the SLAC electron and the Gargamelle neutrino structure functions are related by the quark electric charge factor, $(2/3)^2 + (1/3)^2$

In the years following the two neutrino experiments, the technology, and so the power of neutrino beam experiments, rapidly progressed. The first major step was the technology of extracting the proton beam out of the accelerator, to strike an external target. This was quickly followed by the brilliant invention, as well as the development of the challenging technology, by vanderMeer, of the vanderMeer horn, which enabled the focusing of the meson beam in the forward direction, over a wide spectrum, substantially increasing the intensity of neutrino beams (see Figs. 18 and 19).

These years also saw extraordinary progress in particle physics theory. In the late 60's Weinberg, Glashow and Salam, formulated the unified electro-weak gauge theory, which proposed the intermediate vector bosons to propagate the weak interaction as well as a new interaction of neutrinos, the "neutral current". In 1972 Quantum Chromo Dynamics, QCD, the gauge theory of strong interactions of quarks and gluons, was put forward, and in 1973 Gross, Politzer and Wilczek realized that "asymptotic freedom" in QCD made it possible to make quantitative predictions, which could be checked experimentally. These huge theoretical advances posed interesting new challenges to neutrino beam experiments. The Gargamelle experiment was able to show the existence of the neutral

Fig. 8. Fermi, myself and others, in 1954 at a meeting in Varenna on Lake Como, a few months before Fermi's untimely disappearance.

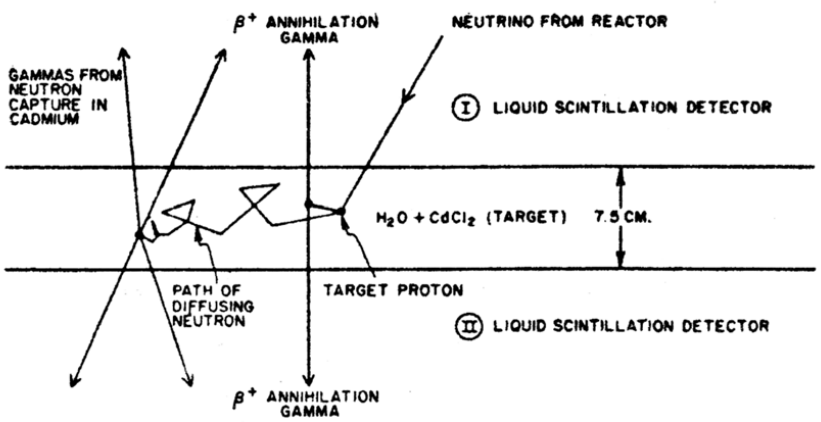


Fig. 9. Schematic diagram of the Reines and Cowan neutrino detector.

currents, and so provided a convincing confirmation of the Electro-Weak theory. This also provided a first measurement of the "Weinberg angle".

The Gargamelle heavy liquid bubble chamber at CERN, designed and built under the direction of André Lagarrigue at Ecole Polytechnique in Paris, was 2.5 m in diameter and 6 m long, by far larger than any pre-existing chamber. It became the outstanding tool for neutrino beam physics in the early 70's (see Fig. 20).

In 1972, motivated by Jacques Prentki, Gargamelle undertook a dedicated search for the neutral weak currents which were predicted by the unified E-W theory. Neutrino interactions producing a hadron shower, but no muon (or electron) were predicted. In 1973 the Gargamelle team [18] published

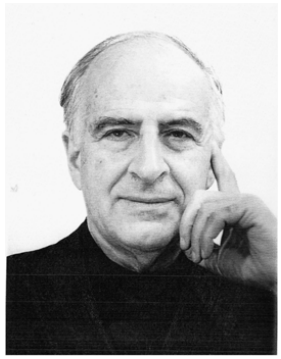


Fig. 10. Bruno Pontecorvo.

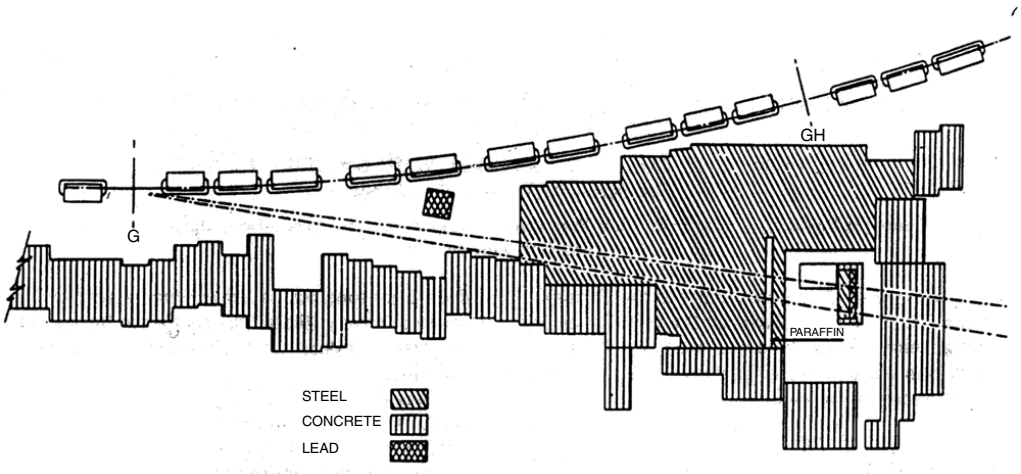


Fig. 11. Plan view of the 2nd neutrino experiment.

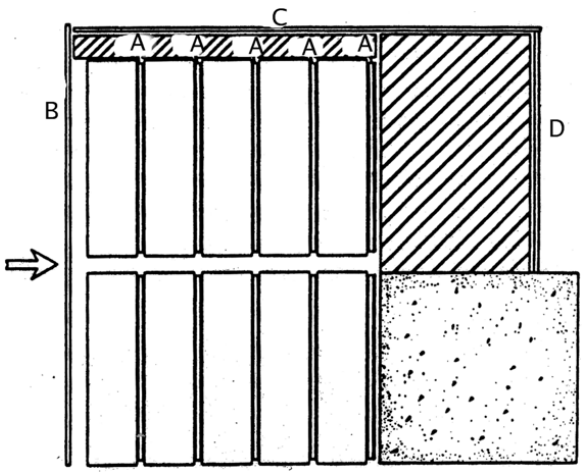


Fig. 12. Spark chamber and counter arrangement. A are triggering counters; B, C, and D are anticoincidence counters.

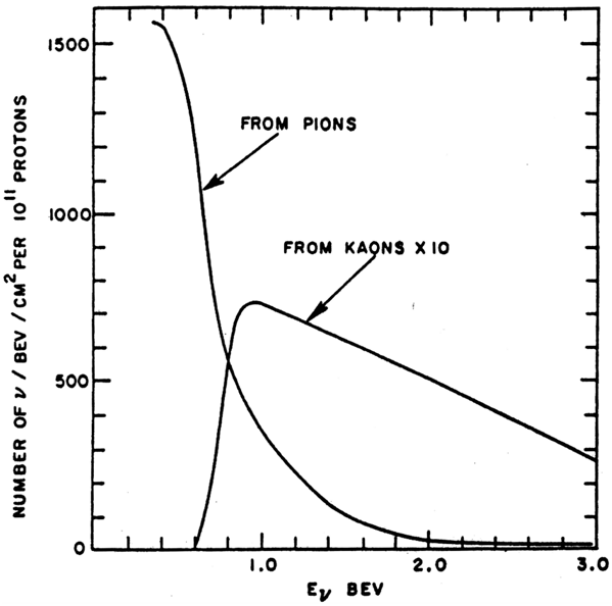


Fig. 13. Calculated energy spectrum of neutrino beam, pion and kaon contributions.

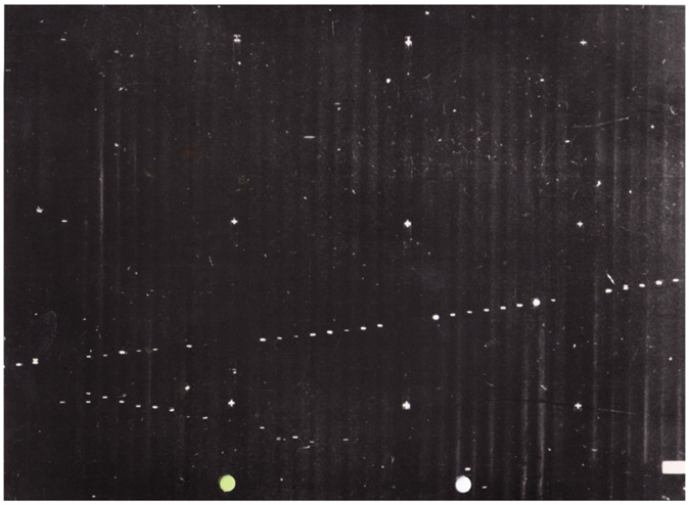


Fig. 14. Event with penetrating muon and hadron shower.

results which demonstrated the existence of muon-less events and so confirmed the E-W theory. For me, although I was slow to accept it, this is the most important discovery at CERN, ever. It established the electro weak unified theory. The ratio of neutral current to charged current events, approximately 0.3, provided the first measure of the Weinberg angle, $\sin^2\theta_W = 0.3$–0.4 (see Fig. 21).

Another very important contribution of Gargamelle was the first quantitative verification of the quark hypothesis of Gell-man and Zweig. A comparison of the $F_2(x, y)$ structure function obtained in neutrino scattering by Gargamelle with that obtained in electron scattering at SLAC verified the ratio predicted in the quark theory of partons, $F_2^{(l)}/F_2^{(\nu)} = \frac{1}{2}((2/3)^2 + (1/3)^2) = 5/18$ (see Figs. 22 and 23).

Fig. 15. The group of the $\nu_\mu \neq \nu_e$ experiment at BNL in 1962, left to right: J.S., Goulianos, Gaillard, Mistry, Danby, technician (name forgotten), Lederman, Schwartz.

Fig. 16. Same group, 26 years later, at Nobel prize ceremony in Stockholm.

7. Deep inelastic experiments at higher energy, at the Fermilab Tevatron and the CERN SPS, in the later 70's and 80's

The Tevatron and SPS permitted neutrino and antineutrino beams of ten times higher energies, up to 250 GeV, as well as considerably higher intensities.

Electronic detectors, with neutrino targets of up to 1000 tons dominated over the bubble chambers. Typical exposures now yielded hundreds of thousands of events, instead of a handful.

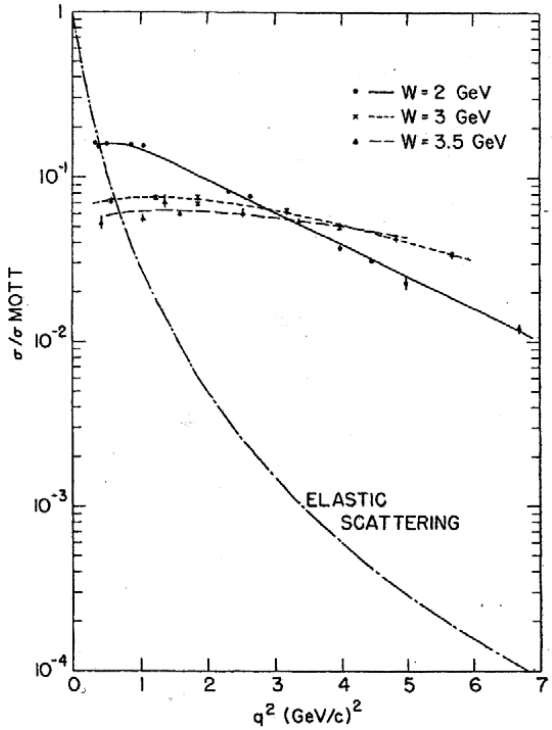


Fig. 17. Discovery of nucleon structure at SLAC in 1969. The cross-section for different masses W of the final state hadronic system, in first approximation, is independent of q^2, the square of the electron momentum transfer.

Fig. 18. Simon vanderMeer.

The physics centered on:

- Precise checks of the Quark Parton Model (QPM).
- Checks on E-W model, determination of $\sin^2\theta_W$.
- Determination of nuclear structure functions.
- Checks on QCD. First quantitative confirmation of QCD predictions and determination of the QCD interaction strength Λ, in measuring the scaling violations predicted by "asymptotic freedom" in QCD.

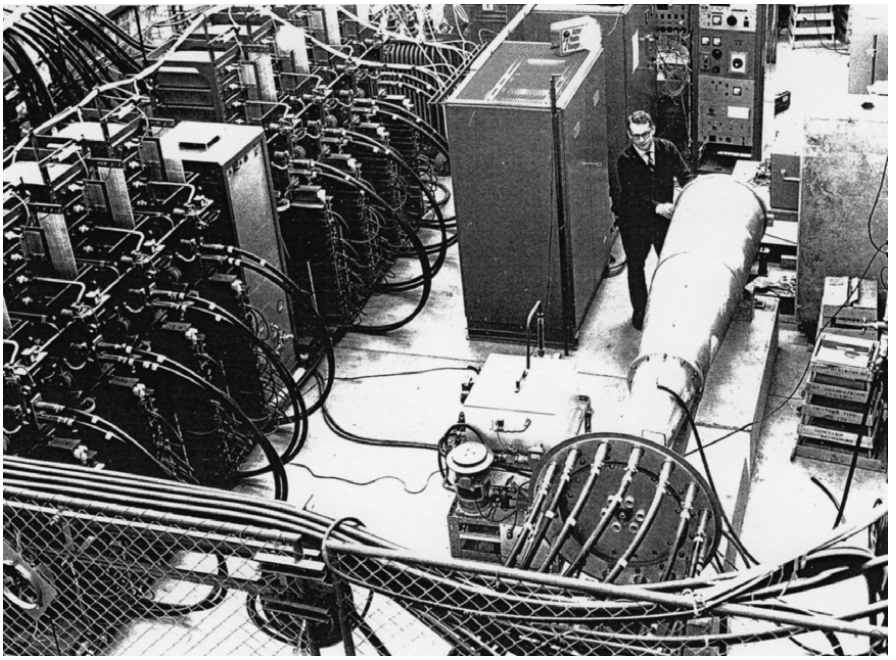


Fig. 19. A vanderMeer horn.

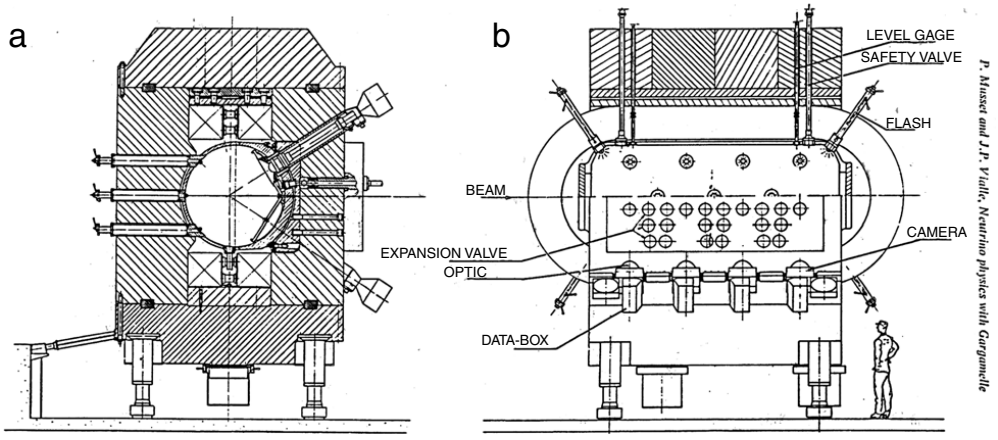


Fig. 20. The Gargamelle bubble chamber.

There were two electronic detectors at the Tevatron: *HPWF* (Harvard, Pennsylvania, Wisconsin and Fermilab), and *CCFR* (Caltech, Columbia, Fermilab and Rochester), and two detectors at the SPS: *CDHS* (CERN, Dortmund, Heidelberg and Saclay) and *CHARM* (Cern, Hamburg, Amsterdam, Rome, and Moscow). In addition, both at CERN and Fermilab, the existing large hydrogen bubble chambers were used to measure the neutrino interactions in hydrogen and deuterium. In the following I will concentrate on results from CDHS, the more powerful of the detectors as well as the one with which I was associated.

There were two types of neutrino beams at the SPS, narrow band beams (NBB), using momentum selected charged hadrons (pions and kaons), positive for neutrinos, negative for antineutrinos, which permitted the determination of the energies also of neutral current events, using the radial position of the event in the detector, and much more intense wide-band beams (WBB), using vanderMeer horns.

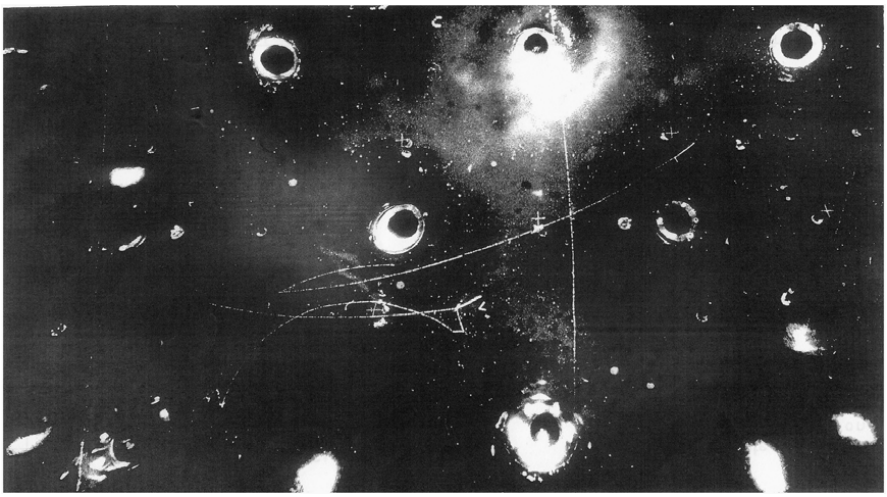


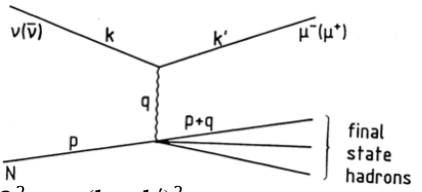
Fig. 21. Muon-less event in Gargamelle. The neutrino comes in from the left. It produces a Λ^0 and K^+, but no muon. The Λ^0, the V on top, is seen to decay into a proton and pion, the K^+, after scattering on a proton, stops and decays, producing a muon (not seen), which stops and decays, producing an electron.

The beam focusing was followed by the 300 m long decay tunnel and the 400 m long iron shield. After the shield followed three detectors, the Big European Bubble Chamber, BEBC, which could be filled with hydrogen or deuterium, and the two electronic detectors, CDHS, and CHARM (see Figs. 24–26).

The CDHS detector consisted of 19 modules of toroidally magnetized iron plates, 1.5 T, the coil running through the center. They were 3.75 m in diameter, with total iron thickness 75 cm. The first 9 modules consisted of 15 plates, each 5 cm thick, the remaining 10 of 5 plates, each 15 cm thick. Between plates were scintillators which served to measure the hadron shower energy as well as to trigger. Between modules were drift proportional wire chambers, in three projections, at 60° to one another, to measure the muon momenta as well as the hadron shower positions. In front of the modules was a vacuum insulated tank which could be filled with hydrogen (see Figs. 27–29).

Phenomenology.

Event diagram, (four momenta):



Momentum transfer:	$Q^2 = -(\mathbf{k} - \mathbf{k}')^2$;	
Energy transfer to hadrons:	$\nu = (\mathbf{k}-\mathbf{k}')\cdot\mathbf{p}/m_p = E_{had} - m_p$;	$\nu \sim E_{had}$;
Parton mass fraction:	$x = Q^2/2m_p\nu$; $0 \le x \le 1$;	$x \sim Q^2/(2m_pE_{had})$;
Fraction of neutrino energy transferred to hadrons:	$y = m_p\nu/\mathbf{k}\cdot\mathbf{p}$; $0 \le y \le 1$;	$y \sim E_{had}/E_\nu$

where ν is the energy transferred to the hadronic system, x is the momentum transfer squared relative to the neutrino energy and nucleon mass, equal to the effective target mass struck by the neutrino, m_p is the nucleon mass, y is the fraction of the neutrino energy transferred to hadrons. In the following, we neglect terms of the oder m_p/E_ν.

The neutrino and antineutrino cross-sections are described by three structure functions, $F_2(x, Q^2)$, $2xF_1(x, Q^2)$, and $xF_3(x, Q^2)$:

$$d^2\sigma^{\nu(\bar\nu)}/dxdy = G^2E_\nu m_p/\pi\left\{(1-y)\cdot F_2(x,Q^2) + y^2/2\cdot 2xF_1(x,Q^2) \pm (y - y^2/2)\cdot xF_3(x,Q^2)\right\}.$$

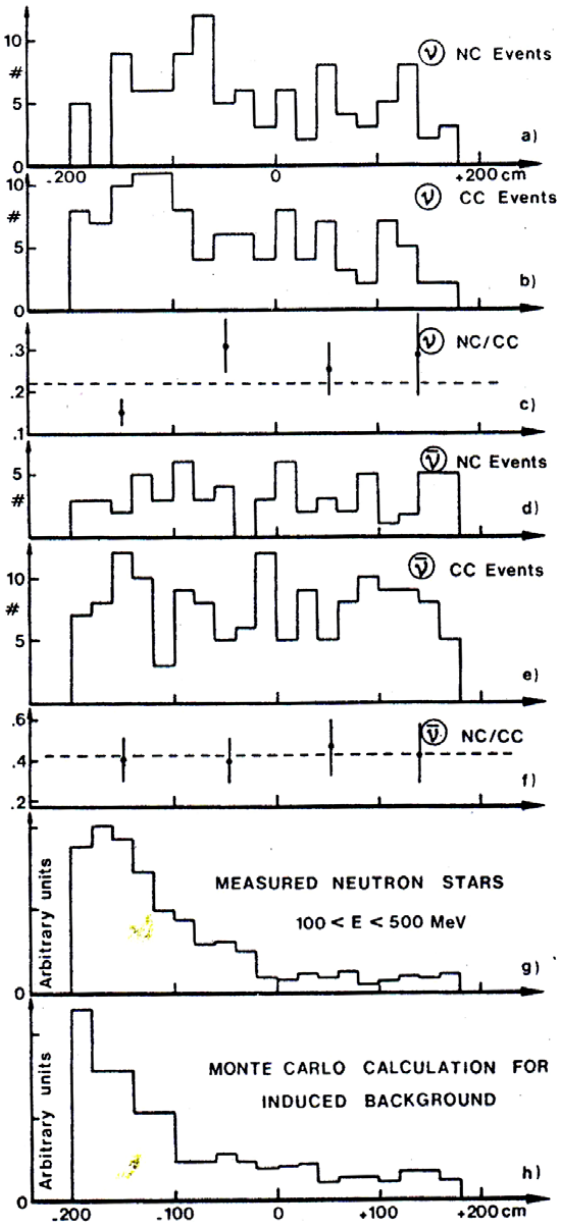


Fig. 22. Distribution of events in Gargamelle along the beam direction. Events identified as due to neutrons are attenuated along the beam, neutrino produced muon-less events are not. This shows that the muon-less events are not due to neutron background.

The charged lepton cross-sections depend only on two structure functions:

$$d^2\sigma^{l^\pm}/dxdy = 4\alpha\pi^2/Q^4 \cdot E_l m_p/\pi \cdot \{(2-2y+y^2)F_2^l(x,Q^2) - 2xF_1^l(x,Q^2)y^2\}.$$

In the *Parton model*:
Callan–Gross relation: $2xF_1(x,Q^2) = F_2(x,Q^2)$,
Gross–Llewellyn Smith sum rule: $\int \frac{1}{x}\, xF_3(x)\, dx = 3$.
With $q(x)$ and $\bar{q}(x)$ the sum of all quark and antiquark structure functions respectively,

$$q(x) = u(x) + d(x) + s(x) + c(x) + \cdots \quad \text{and} \quad \bar{q}(x) = \bar{u}(x) + \bar{d}(x) + \bar{s}(x) + \bar{c}(x) + \cdots,$$

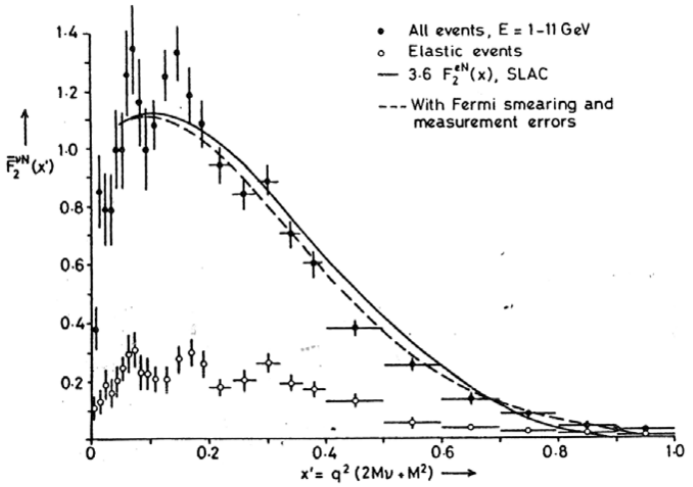


Fig. 23. First confirmation of the validity of the Quark Parton Model. Comparison of the F_2 structure function obtained in neutrino scattering, with the F_2 structure function previously obtained in electron deep inelastic scattering at SLAC, multiplied by 18/5.
Source: From Ref. [19], Gargamelle collaboration.

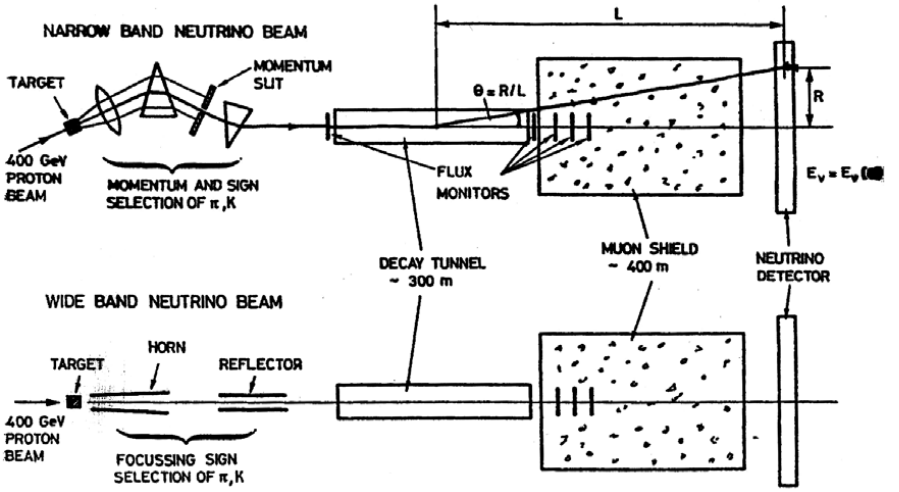


Fig. 24. Beam layouts at SPS.

$$F_2(x, Q^2) = q(x) + \bar{q}(x), \qquad q(x) = (F_2(x, Q^2) + xF_3(x, Q^2))/2,$$
$$xF_3(x, Q^2) = q(x) - \bar{q}(x) = q(x)_{\text{valence}}, \qquad \bar{q}(x) = (F_2(x, Q^2) - xF_3(x, Q^2))/2,$$
$$F_L(x, Q^2) = F_2(x, Q^2) - 2xF_1(x, Q^2) = 0,$$

and in the *quark–parton model*,

$$F_2^l(x, Q^2) = 5/18F_2^\nu(x, Q^2).$$

Results on Weinberg angle, using neutral-charged current ratio:
In the electro-weak theory:

$$\sigma^{NC,\nu}/\sigma^{CC,\nu} = \frac{1}{2} - \sin^2\theta_W + 5/9(1 + r)\sin^4\theta_W; \quad r = \sigma^{CC,\bar{\nu}}/\sigma^{CC,\nu};$$
$$\sigma^{NC,\bar{\nu}}/\sigma^{CC,\bar{\nu}} = \frac{1}{2} - \sin^2\theta_W + 5/9(1 + 1/r)\sin^4\theta_W.$$

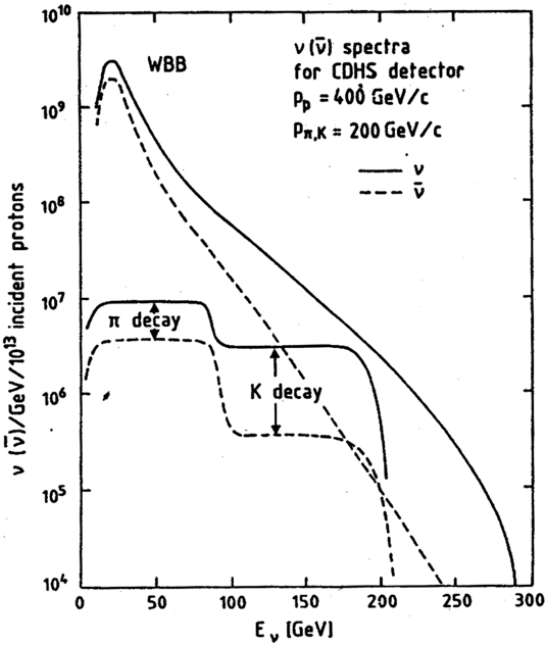


Fig. 25. Neutrino and antineutrino beam energy spectra. The lower flat spectra are the narrow band beams.

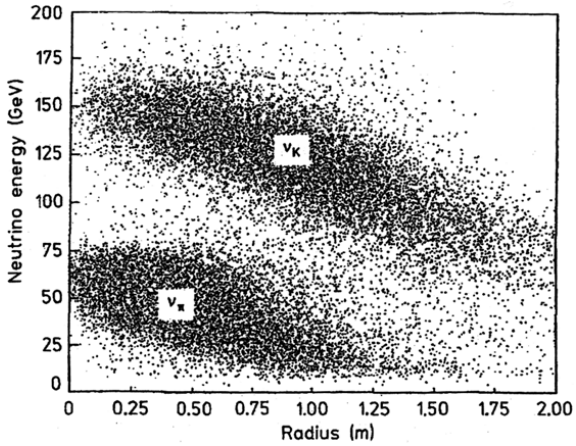


Fig. 26. Narrow band beam energy vs. radius of events in the CDHS detector, top group from kaon decay, bottom from pion decay, measured using charged current events.

The early CDHS result [20,21], with $r = 0.48 \pm 0.02$, $\sigma^{NC,\nu}/\sigma^{CC,\nu} = 0.295 \pm 0.010$ and $\sigma^{NC,\bar{\nu}}/\sigma^{CC,\bar{\nu}} = 0.35 \pm 0.03$ gave $\sin^2\theta_W = 0.24 \pm 0.02$. The original Gargamelle result was: $\sin^2\theta_W =$ 0.3–0.4. The later CDHS result [22] with $r = 0.39 \pm 0.01$ and $\sigma^{NC,\nu}/\sigma^{CC,\nu} = 0.3059 \pm 0.0035$ gave $\sin^2\theta_W = 0.227 \pm 0.007$.

CDHS results on structure functions:

Results are illustrated in Figs. 30–34.

CDHS results relative to QCD. Measurement of the scaling violations constituted the first quantitative validation of QCD.

The most important contribution of the neutrino high energy deep inelastic scattering experiments was probably, in 1979, the first quantitative evidence for the validity of QCD. Following the proposal of

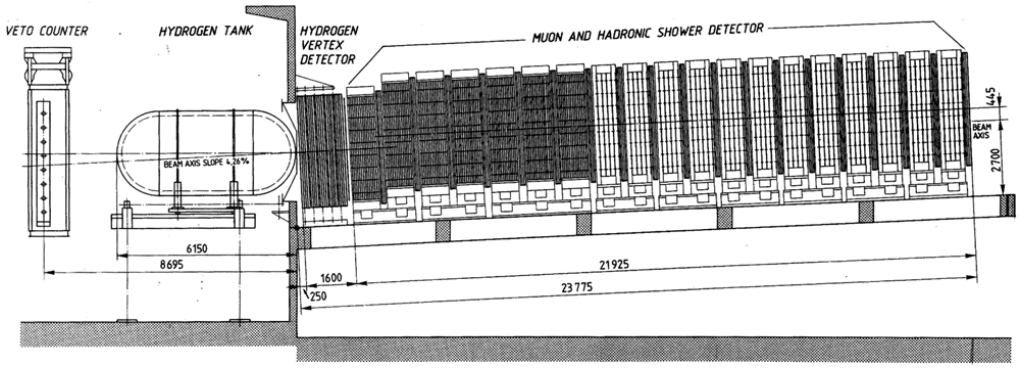


Fig. 27. CDHS detector.

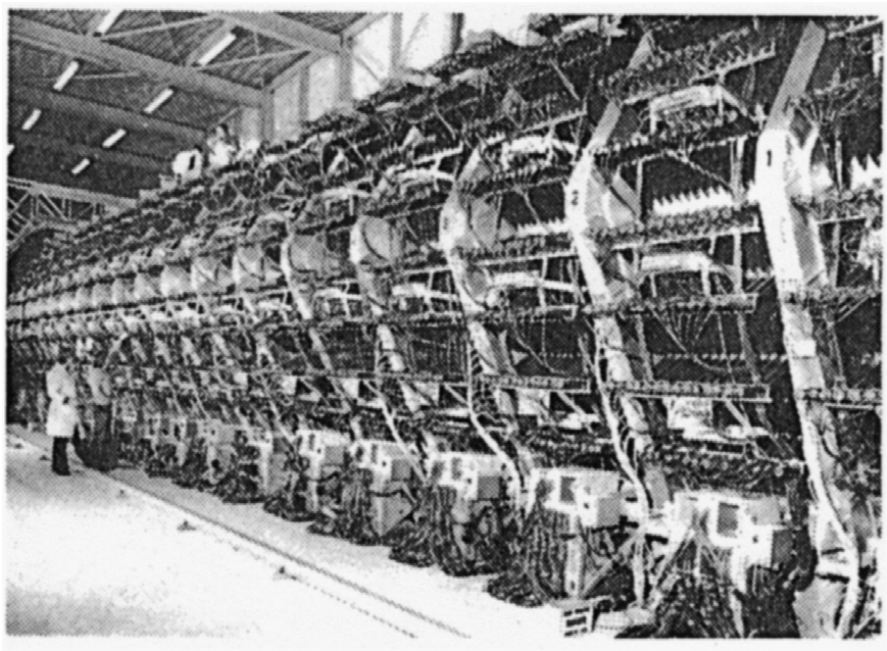


Fig. 28. CDHS detector.

the E-W theory by Weinberg, Glashow and Salam in 1969, and its verification in 1973, in the discovery of neutral currents by Gargamelle, the similarly beautiful strong interaction gauge theory of quarks and gluons, QCD, was put forward in 1972 by Fritzsch, Gell-Mann and Leutwyler, but no possibility existed to check its predictions. The discovery in 1973 by Gross and Wilczek, and by Politzer, of "Asymptotic Freedom" opened the possibility of quantitative experimental checks of QCD, in the form of Q^2 scaling violations of the structure functions. The first of these was provided by neutrino deep inelastic scattering. The first CDHS results [27], shown in Fig. 35-left, clearly agreed with the prediction of the theory, and also permitted a first, rather rough, determination of the QCD interaction strength, $\Lambda = 0.5 \pm 0.2$. The later result [23], shown in Fig. 35-right, yielded the QCD interaction strength $\Lambda = 0.25 \pm 0.12$.

Structure functions in hydrogen.

In the parton model, the structure functions are expected to be approximately equal for protons, neutrons and nuclei. Proton and deuterium structure functions were measured in the bubble chamber

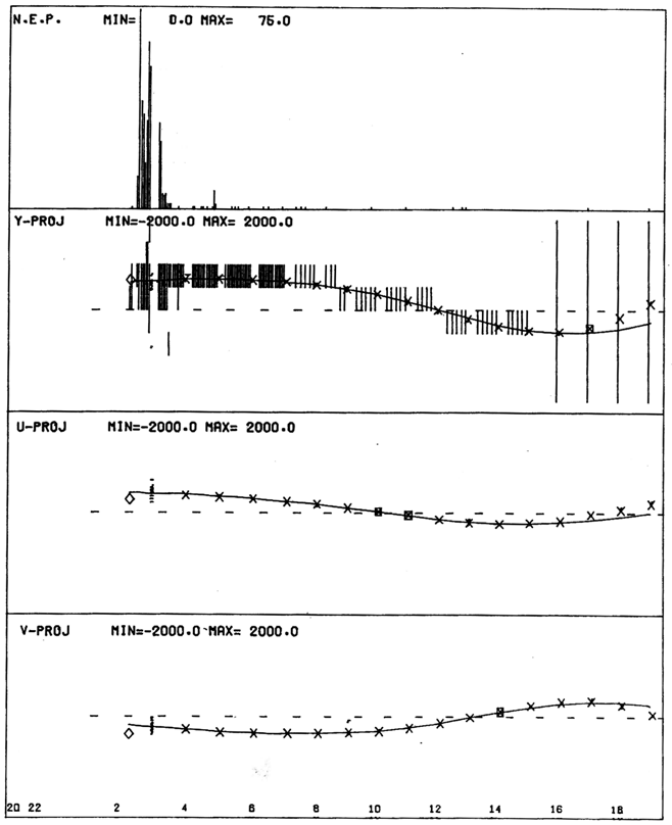


Fig. 29. CDHS charged current event.

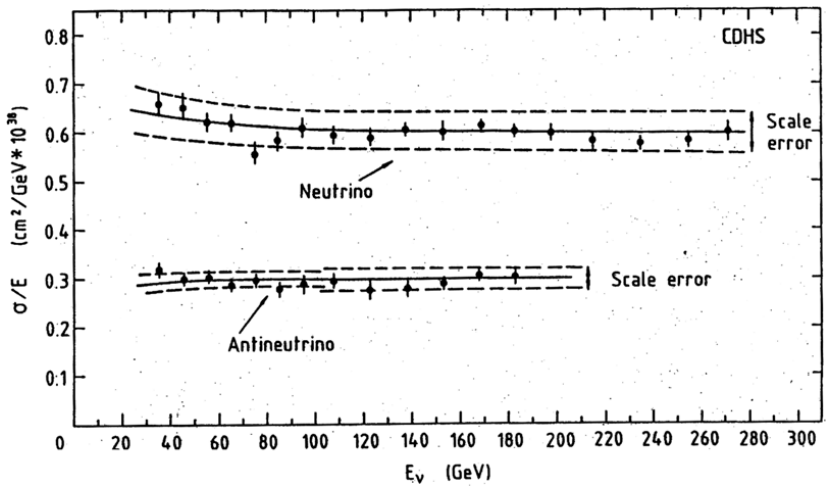


Fig. 30. Scaling. Total cross-sections, divided by the neutrino energy, for neutrinos and antineutrinos, in the energy interval 30–270 GeV illustrate the scaling feature of deep inelastic scattering in the parton model [23].

experiments at Fermilab and CERN, and the proton structure functions were measured by CDHS. The main results are given here [28] (see Figs. 36 and 37).

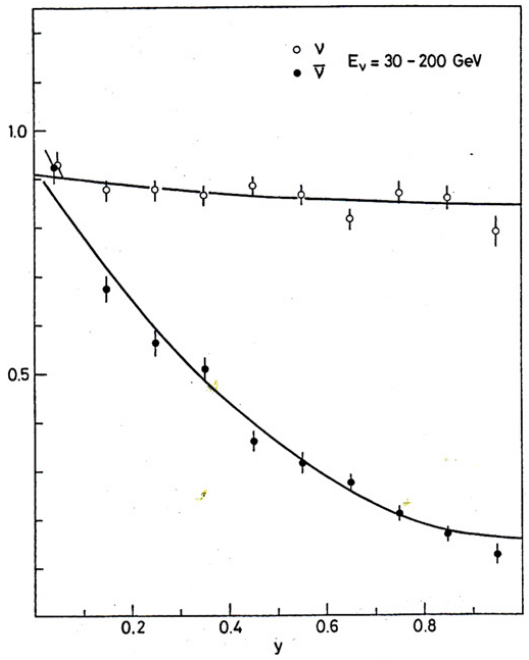


Fig. 31. CDHS results for the y distributions for neutrino and antineutrino cross-sections [24], in agreement with prediction of the parton model.

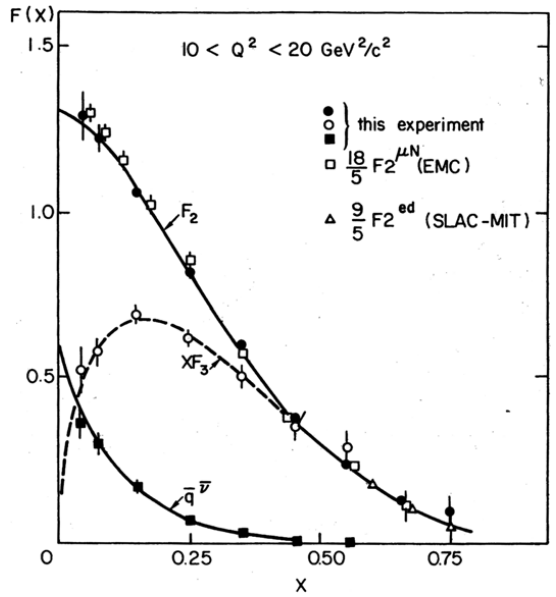


Fig. 32. CDHS results [23] for the $F_2(x)$ and $xF_3(x)$ structure functions, and $\bar{q}(x)$, one-half of their difference, the quark sea structure function. $xF_3(x)$ is the structure function of the valence quarks.

8. LEP, and the demonstration, in 1989, that there are three neutrino families

One of the most important things we learned from neutrinos is that there are just three families. This we learned from the production cross-section and decay width of the Z^0 gauge boson at the

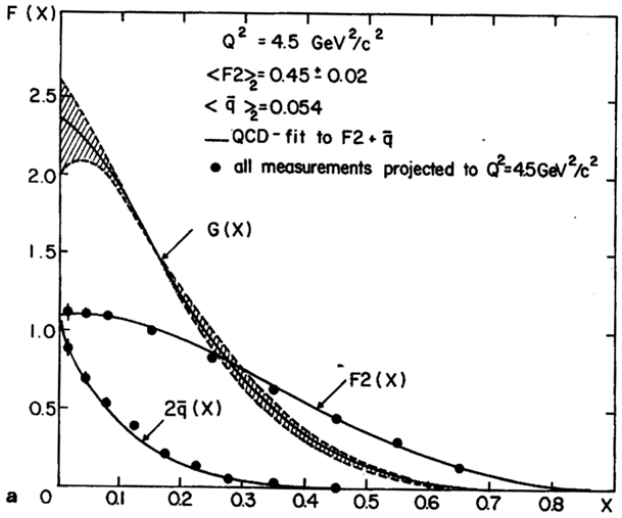


Fig. 33. CDHS results for the gluon structure function $G(x)$ [25]. The gluons do not interact with neutrinos. $G(x)$ is determined on the basis of the QCD interactions of the quarks with the gluons, causing scaling violations in $F_2(x)$.

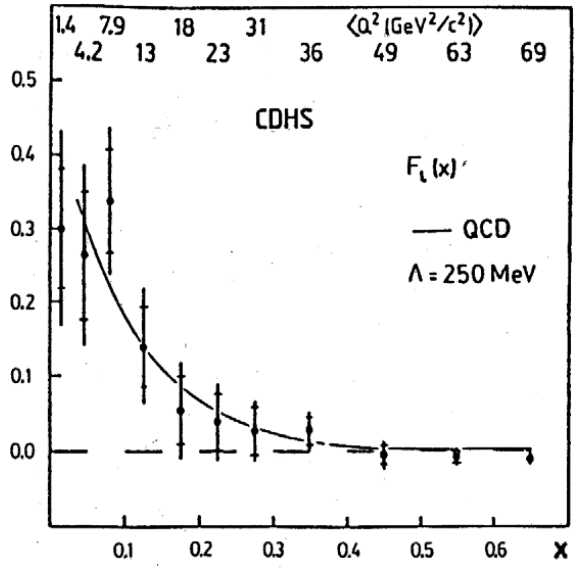


Fig. 34. CDHS results for the longitudinal structure function [26] $F_L(x) = F_2(x) - 2xF_1(x)$.

electron–positron collider LEP, at CERN, in its first weeks of operation, in the fall of 1989. The Z^0 production rate and decay width are predicted by the E-W theory, and could be well measured at LEP. The width is the sum of the partial widths of the different decay channels. Contributing to the charged Z^0 decays are the three charged leptons, and 5 of the 6 quarks (the top quark is too heavy). The interesting question was, might there be additional families, whose charged members are too heavy to be produced in Z^0 decay but which would contribute to the decay into neutrinos? Each neutrino family increases the width by 6% and decreases the height by 12%, so both the height and the width permit a measurement of the number of neutrino families. Using the height is statistically more powerful, but this needs a knowledge of the luminosity, and in the beginning, only ALEPH had prepared this. First results [31], obtained within a few weeks of the start of LEP, gave $N_\nu = 3.27 \pm 0.30$. The final

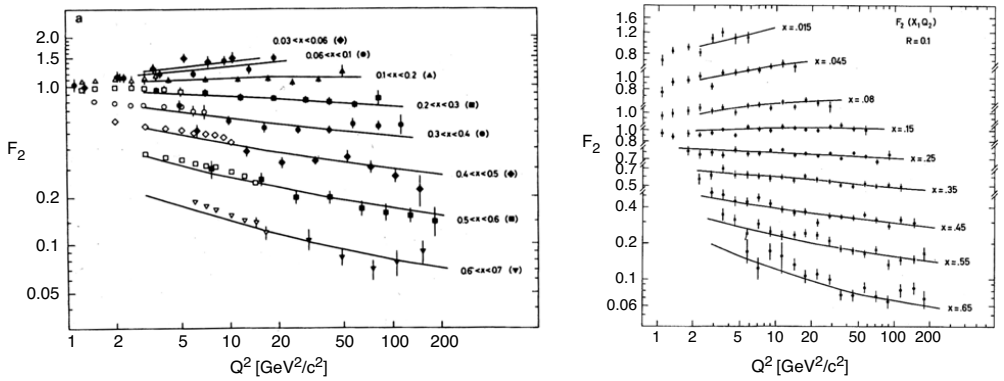


Fig. 35. Left: First CDHS results [27] on a QCD fit to the Q^2 dependence of the structure function $F_2(x, Q^2)$ in 1979 showed agreement with QCD prediction. SLAC results for electron deuteron scattering are shown as open symbols. Right: Later CDHS results [23] on QCD fit to $F_2(x, Q^2)$.

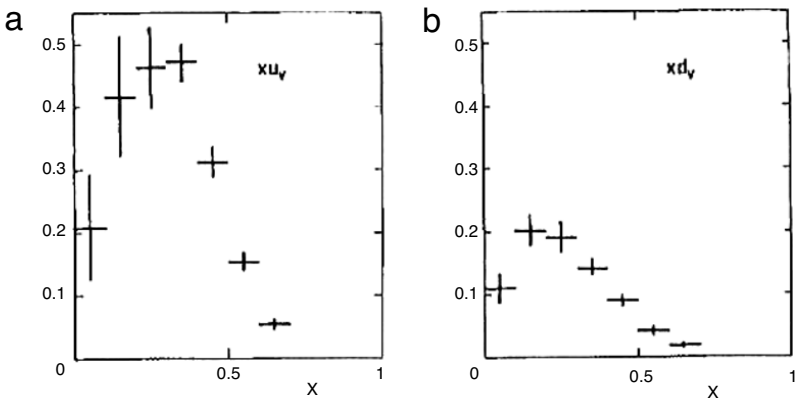


Fig. 36. CDHS measurements of the valence up quark (left) and valence down quark (right) structure functions of the proton.

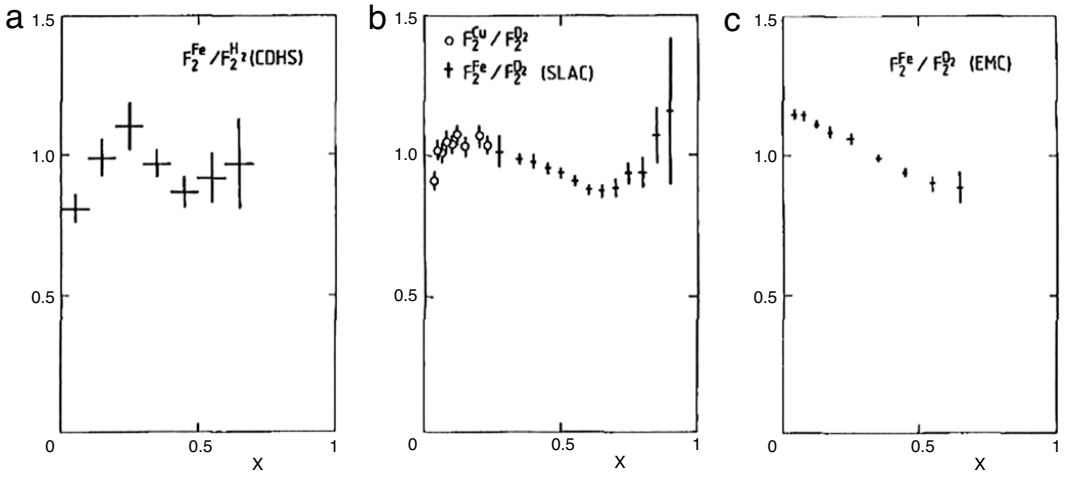


Fig. 37. Ratios of the F_2 structure function in iron and hydrogen (deuterium). Left: neutrinos, CDHS at CERN; center: electrons at SLAC [29]; right: muons, EMC at CERN [30].

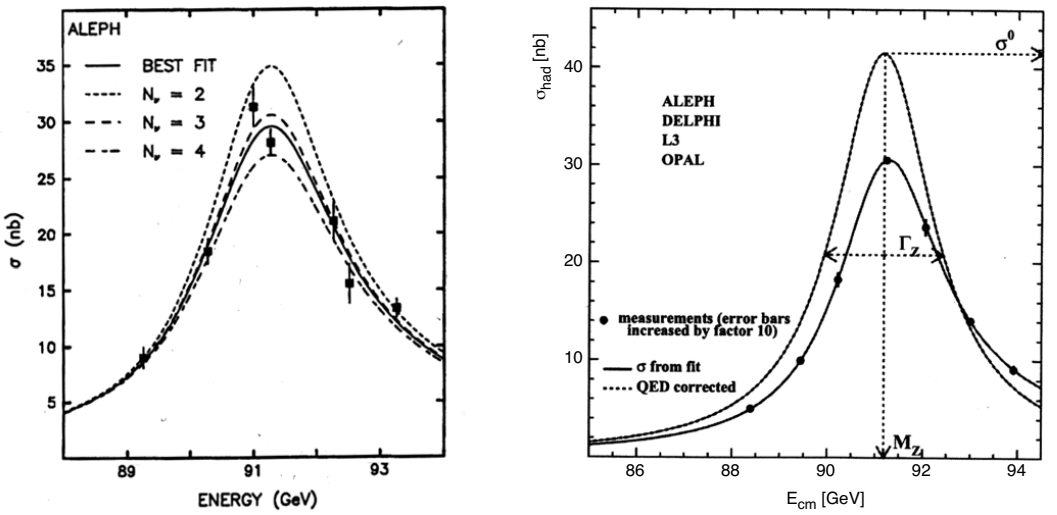


Fig. 38. Left: First ALEPH measurements of the Z^0 resonance at LEP, the cross-section for $e^+e^- \rightarrow$ hadrons, as function of center of mass energy, which permitted the determination of the number of neutrino families. $N_\nu = 3.27 \pm 0.30$. Right: Final LEP result on the Z^0 resonance, by the four experiments. $N_\nu = 2.987 \pm 0.008$.

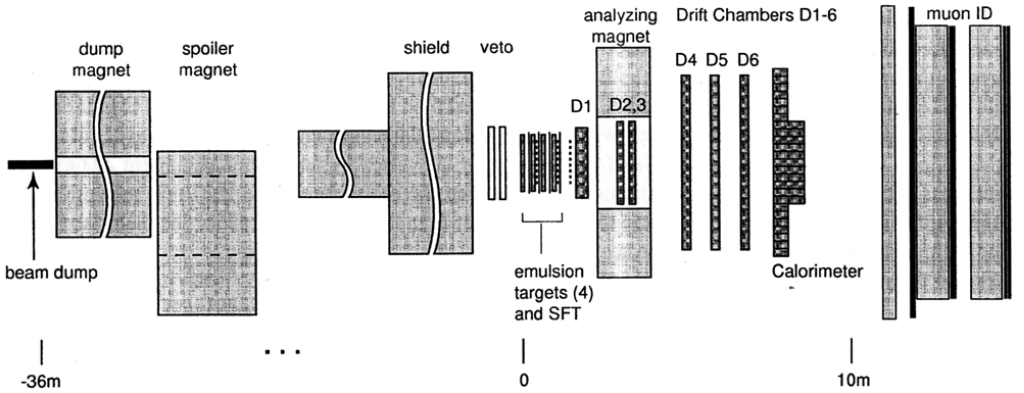


Fig. 39. Layout of DONUT experiment to detect tau neutrinos. SFT = Silicon Fiber Trackers.

result [32] of the four LEP experiments, ALEPH, DELPHI, L3 and OPAL, two and a half decades later, is $N_\nu = 2.9874 \pm 0.0082$ and is shown in Fig. 38.

9. Detection of the third neutrino

The first detection [33] of the tau neutrino was by the DONUT experiment at the Fermilab Tevatron in 2001. Tau mesons produced in a neutrino interaction were identified by their decay in an emulsion stack, which also served as the target material for the neutrino interaction. The neutrinos were produced by 800 GeV protons in a 1 m long tungsten beam dump, mostly in the decay of D_s mesons to tau's and the subsequent decay of the tau. As shown in Fig. 39, the tungsten target was followed by magnets and shields, then followed by the emulsion targets. Between the emulsion layers and following them were scintillation fiber trackers to locate and time the tau decay particle, and this was followed by a spectrometer and muon identifier. Of 204 neutrino events, 4 could be identified as tau neutrinos. Two of these are shown in Fig. 40.

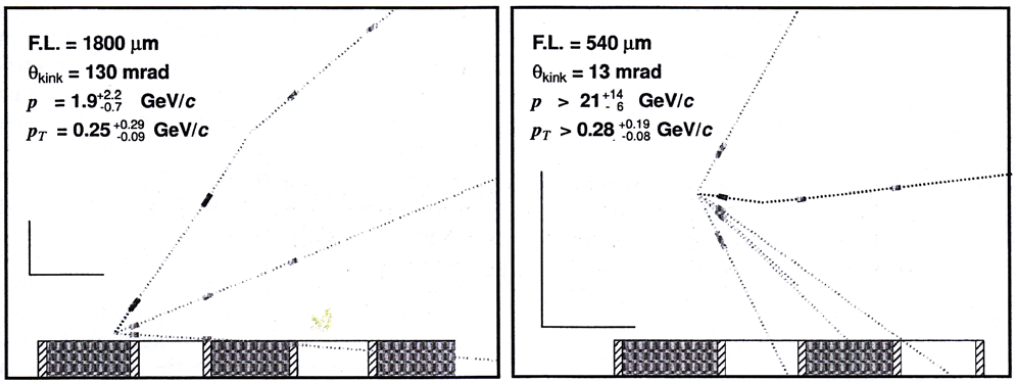


Fig. 40. Two events in which a neutrino produces a tau meson, and can therefore be identified as a tau neutrino. The neutrinos enter from the left. Scales: vertical bar = 0.1 mm, horizontal bar = 1.0 mm. Target material shown by horizontal bar on bottom: steel is shaded, emulsion is cross-hatched.

10. Conclusions

We have learned a lot about neutrinos, and about particle physics, with the help of neutrinos. It has been my privilege to participate in a good part of this, and I look forward to learning about progress in neutrino mixing and oscillation at this conference. Thank you for inviting me, and so giving an old man a chance to try to be of some use. My warmest thanks to Dr. Brigitte Bloch-Devaux for the preparation of this presentation.

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