Discovery of Weak Neutral Currents*

Dieter Haidt
Emeritus at DESY, Hamburg

1 Introduction

Following the tradition of previous Neutrino Conferences the opening talk is devoted to a historic event, this year to the epoch-making discovery of *Weak Neutral Currents* four decades ago. The major laboratories joined in a worldwide effort to investigate this new phenomenon. It resulted in new accelerators and colliders pushing the energy frontier from the GeV to the TeV regime and led to the development of new, almost bubble chamber like, general purpose detectors. While the Gargamelle collaboration consisted of seven european laboratories and was with nearly 60 members one of the biggest collaborations at the time, the LHC collaborations by now have grown to 3000 members coming from all parts in the world. Indeed, High Energy Physics is now done on a worldwide level thanks to net working and fast communications. It seems hardly imaginable that 40 years ago there was no handy, no world wide web, no laptop, no email and program codes had to be punched on cards.

Before describing the discovery of weak neutral currents as such and the circumstances how it came about a brief look at the past four decades is anticipated. The history of weak neutral currents has been told in numerous reviews and specialized conferences. Neutral currents have since long a firm place in textbooks. The literature is correspondingly rich - just to point out a few references [1, 2, 3, 4].

2 Four decades

Figure 1 sketches the glorious electroweak way originating in the discovery of weak neutral currents by the Gargamelle Collaboration and followed by the series of eminent discoveries. *The* great achievement is the unification of electromagnetic and weak phenomena within a renormalizable local gauge theory.

*Talk presented at the International XXVI Conference on Neutrino and Astrophysics at Boston USA, June 2, 2014

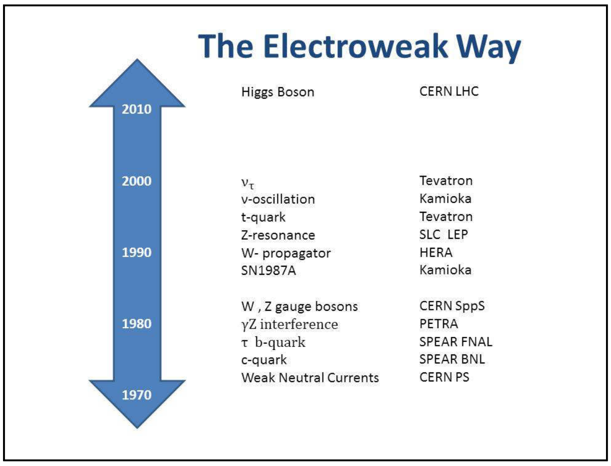

Figure 1: Chronology of major discoveries

What appears in hindsight as a natural evolution was in reality a step by step process with major efforts depending at each time on the actual status. During the years after the discovery the experiments quickly singled out of the host of models the *Glashow-Salam-Weinberg model* characterized at lowest order by a single parameter, the weak mixing angle θ. A first result came about when using the measured $\sin^2\theta$ to predict the mass of the W with the surprise that it must be in the range of 70 GeV, way beyond hope for a measurement with existing detectors and accelerators. This triggered 1976 the idea [5] to propose a $p\overline{p}$ collider, later realized at the SPS at CERN. Both intermediate vector bosons, the W mediating charged current processes and the Z mediating neutral currents processes, were discovered 1983 by the UA Collaborations. With the observation of the W and Z a new way of determining $\sin^2\theta$ arose and with increasingly precise measurements the necessity to account for radiative effects. Unavoidably predictions depended now upon the full particle content of the electroweak theory, in particular upon the yet unknown heavy masses of the *top quark* and the *Higgs boson*. The searches for the top quark and the Higgs boson became new lines of research. The electron-positron colliders PETRA and PEP, followed by TRISTAN, were of high enough energy to demonstrate in the measured angular dependence the (γ, Z) interference. SLD and LEP I provided precision measurements at the Z-resonance, but no sign of the top quark nor the Higgs boson. The ensemble of electroweak data allowed the prediction of the top quark mass. Indeed, a few years later the top quark was observed at the TEVATRON. Nobody anticipated a mass as high as 173 GeV. Together with the ν_τ, observed in the year 2000 by the DONUT collaboration, the third fermion family was completed. The searches for the Higgs boson at LEP II and TEVATRON terminated by leaving a small mass window. ATLAS and CMS running at the LHC finally succeeded in discovering the Higgs boson in the year 2012, thus completing the ingredients of the GSW model.

The research during the past four decades was a give and take between experiment and theory. The electroweak theory describes quantitatively all electroweak phenomena and represents a solid basis for the future searches of physics expected beyond the Standard Model. A first hint is given by the observed neutrino oscillations implying a small, but finite mass of the neutrinos contrary to the model assumption.

3 The Way towards Neutral Currents

Beginning of the accelerator era. The absence of the decay $\mu \to e + \gamma$ was puzzling. Feinberg [6] noted 1958 that within the V-A model for weak interactions the (hypothetical) W couples to the fermion pairs (μ, ν) resp. (e, ν) and speculated that a suppression could occur, provided there is not a unique neutrino, but two distinct species of neutrinos, i.e. a ν_μ associated with the μ and a ν_e associated with the e. This inspired Pontecorvo, Markov[1] and Schwartz to the idea to build a neutrino beam to be realized at the new laboratories CERN and BNL. The goal for the first searches concentrated on the intermediate vector boson and the 2-neutrino question. These and other vital questions were formulated 1960 by T.D.Lee [7] for the upcoming neutrino experiments. The first neutrino run at CERN was a failure leaving to the BNL experiment the chance to discover the existence of two neutrino species. More than a year later the 1m heavy liquid bubble chamber and the spark chamber were running in the improved neutrino beam at CERN derived now from an external proton beam and with Van der Meer's horn.

Gargamelle. At the Siena conference 1963 Lagarrigue (Fig. 2) conceived the idea of a second generation bubble chamber. The driving idea was an increase in statistics by an order of magnitude and detailed knowledge about the produced final state. Large statistics implied a detector with large mass. The distinction of the final state muon from a pion of the same charge required long potential paths in order for the hadron to show its nature by a visible interaction. Neutral pions would be detected through their decay into two photons converted into e^+e^--pairs, neutral kaons and lambdas through their decays. These requirements could be met by a 5m long cylindrical bubble chamber of 1m diameter filled with heavy freon. The physics program was discussed in a two-day meeting at Milan 1968. Topics were the search for the intermediate vector boson, the W, elastic, resonance and inelastic interactions with various beam options. A new and exciting issue arose from the just discovered substructure of the proton by

[1] I like to thank Prof. A.Bettini for pointing out the role of Markov.

Figure 2: The father of Gargamelle

SLAC. What are the implications for the neutrino experiment with Gargamelle ? Would the weak current in a neutrino experiment reveal the same parton picture as the electromagnetic current in the *ep* experiment of SLAC ? The topic of a neutral current search, which soon was to become the outstanding topic, was not even mentioned, it merely figured at low prioritity in the proposal [8] submitted in 1970. The collaboration consisted of seven european laboratories : Aachen, Brussels, CERN, Ecole Polytechnique, Milan, Orsay and the UC London. There were also a few guests from the USA. The chamber built at Saclay was moved to CERN in 1970. Fig. 3 shows the chamber at the moment , when it was installed

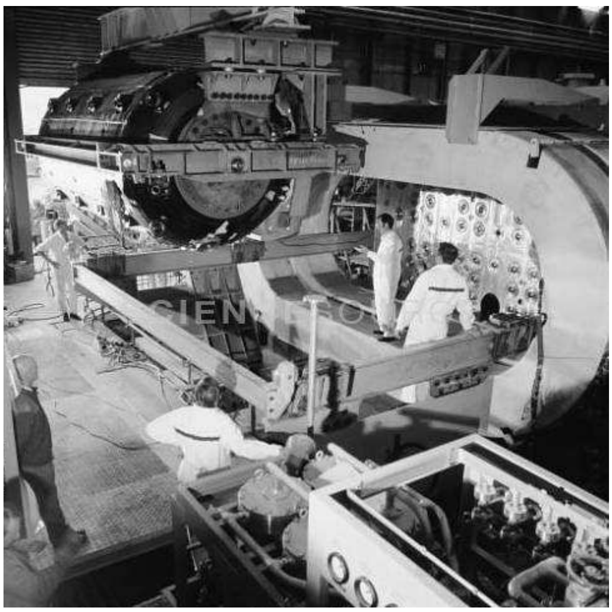

Figure 3: Installing the body of Gargamelle

at CERN. Running started in 1971. The chamber was operated until 1978, when it broke down.

The fact that many laboratories participated made it mandatory to have strict scanning and measuring rules, otherwise the combination of the data would be biased. Four classes were defined:

A. events with a muon candidate

B. multi-prong events without muon

C. proton stars

D. events with isolated electron, positron or gamma

It should be noted that at the moment of defining the event classes a neutrino interaction was supposed to be of the type $\nu N \to \mu + X$ with X consisting of one or more hadrons. There was no need to identify a muon. Any charged particle with the right charge leaving the chamber was a *candidate* for a muon, i.e. μ^- in a neutrino exposure and μ^+ in an antineutrino exposure. This necessitated unavoidably a subtraction due to events with charged hadrons simulating a muon. The purpose of class B was precisely to estimate experimentally (without any Monte Carlo simulation) the fraction of charged hadrons misidentified as muons. The events contributing to class B were supposed to arise from high energy neutron interactions. Neutrons originate in upstream neutrino interactions, enter the chamber volume and, if energetic enough, simulate the topology of neutrino interactions. Such neutron background was the obvious worry.

HPW. At about the same time the Harward-Pennsylvania-Wisconsin group prepared their first neutrino experiment E-A1 at the 400 GeV proton synchrotron of the National Accelerator Laboratory NAL, later named the Fermi Laboratory FNAL. It consisted of a target calorimeter and a muon spectrometer. Compared to the bubble chamber experiment at CERN it had the advantage of running in a beam of 10 times higher energy, thus a 10 times higher neutrino cross section, furthermore interesting events were selected by a suitable trigger, while Gargamelle recorded everything. The original aim was to investigate the process $\nu N \to \mu + X$ at high energies. The obvious worry was the loss of genuine neutrino events, when a muon escaped at wide angles.

Status of theory 1971. The investigation of nuclear and particle decays resulted at the end of the 1950s in the V-A theory. This was a great achievement and gave hope to a theory encompassing both weak and electromagnetic phenomena. The vector character of the weak current suggested an intermediate vector boson in analogy to the photon in QED. However, there were major obstacles for a common gauge theory. During the 1960s theoretical efforts succeeded in establishing a gauge theory unifying weak and electromagnetic interactions: the Glashow-Salam-Weinberg model (GSW) [9]. Its essential ingredients are :

- the gauge group U(1) of QED is enlarged to SU(2)×U(1)
- in addition to the charged intermediate vector boson W also a neutral intermediate vector boson Z is introducted
- spontaneous symmetry breaking
- the GIM mechanism for the quark sector
- 't Hooft-Veltman : the model is renormalizable

The experimental groups largely ignored the tremendous theoretical progress and got alerted by the theoreticians only once the renormalizability [10, 11] of the model had been proven (1971), thus holding the promise of a real theory. Although there was no experimental evidence for the theory neither in the fermion sector nor in the gauge sector nor in the Higgs sector, the GSW model predicted *weak neutral currents* and they would manifest themselves in a neutrino experiment as processes without a final state electron or muon.

Change of priority. Both the Gargamelle and the HPW collaborations took up the challenge being aware that they should come up in due time with a clearcut answer.

- Gargamelle was lucky, since their category B events automatically contained neutral current induced events, if such processes really existed, in addition to the notorious neutron interactions. The problem to face was to distinguish the new type of interactions from trivial neutrons. In order to reduce the background from neutrons a severe cut of 1 GeV was applied to the visible energy of the final state hadrons. The analysis started without delay and within a year the results were reported to the collaboration meeting in March 1973 at CERN. For comparison a reference sample of charged current events was collected, where the muon was ignored and the hadron system satisfied the same criteria as the neutral current sample. These events were for sure neutrino introduced.
- HPW was sofar running with a trigger which requested a muon. The initial aim was to investigate the energy dependence of the total neutrino cross section extending up to 100 GeV. However, in order to search for neutral current candidates a new trigger had to be set up in order to select events which deposited enough energy in the target calorimeter and to ensure the absence of a muon. There were two worries : (i) an event with an undetected muon at wide angles simulates a neutral current candidate, (ii)

a fast hadron may punch through and simulate a muon thus causing signal loss. This was indeed the stumbling stone in their attempt to search for neutral currents.

4 The Discovery

During the scanning of all categories a rare event was found in the antineutrino films at Aachen [12], as illustrated and annotated in fig. 4. It consisted of an isolated electron in beam direction and was readily interpreted as a candidate for a leptonic weak neutral current process $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$. The background is small for several reasons : (a) the event occurred in the antineutrino exposure, where the contamination of ν_e is at the percent level, (b) the final state electron must be in forward direction, (c) the hadronic final state must be unobservable. The event found in December 1972 arose great excitement within the collaboration and encouraged the hope for a discovery.

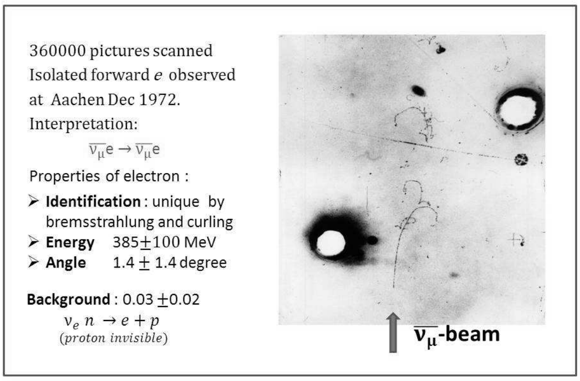

Figure 4: The first leptonic neutral current candidate.

The measurement of the hadronic neutral current candidates took place during fall 1972 and winter 1972/3. By spring 1973 a sizeable sample was ready. Fig. 5 shows a neutral current candidate. Inspecting the tracks of each particle one notices a strong interaction and verifies its nature as hadron.

The Meeting at CERN in March 1973. The Fig. 6 shows the status of the neutral current analysis with hadron final states. The collaboration was in an euphoric state, since a discovery seemed within reach. Infact, three arguments in favour of a new effect sprang to mind.

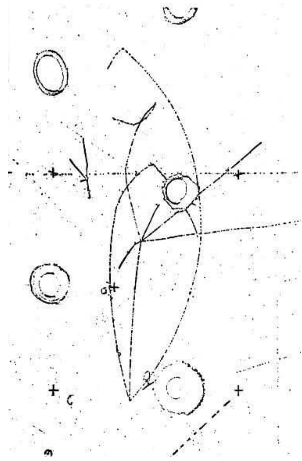

Figure 5: Neutral current candidate.

- *The distributions of the neutral current candidates look neutrino-like*
  Their shapes are compared to the reference sample of neutrino induced events with the same properties as the NC candidates ignoring the muon

- *The ratio of neutral current candidates over charged current events is not small and flat both along the beam direction (X) and radially (R).*

- *The neutral current candidates do not look neutron-like*
  Otherwise the entering neutrons would produce a fall off in the first half of the chamber due to their interaction length being small compared to the chamber dimensions. This was corroborated by a Monte Carlo calculation of the Orsay group assuming simply a source of neutrons at the entrance window of the chamber.

However, two counter arguments were put forward.

- *The neutrino flux has a broad radial distribution*
  The neutrons originating from upstream central neutrino interactions generate indeed a fall-off in the fiducial volume of the chamber, but a substantial fraction of the neutrino flux extends radially way beyond the fiducial volume and produces neutron sources distributed all along the nonvisible part of the chamber and further out to the coils. The net effect is that neutrons enter also laterally and thus generate a flat distribution along the chamber just as genuine neutrino-induced events do. The potential danger is obvious, since the outside material acting as source is a multiple of that contributing at the front.

- *Energetic neutrons in the iron shielding propagate in cascades*
  Neutrons entering the chamber and depositing there more than 1 GeV may

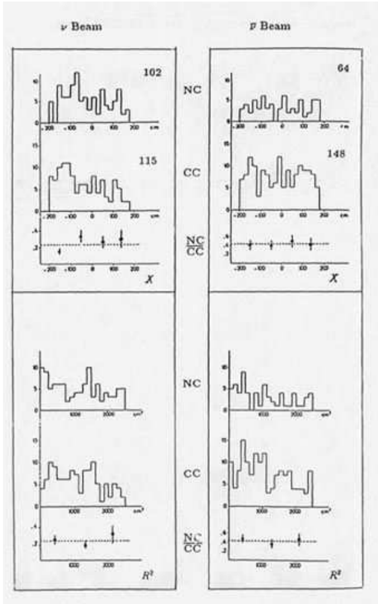

Figure 6: NC distributions [14]

be the result of a hadron cascade induced by the original neutrino interaction in the shielding. This means that the neutron background is in reality proportional to the bigger cascade length rather than to the interaction length.

At the end of the hot meeting it was clear that a quantitative estimate of the neutron background was indispensable. A new effect may only be claimed, if it can be demonstrated unambiguously that the contributing neutron background is small compared to the number of observed neutral current candidates.

The neutron background estimate. The ingredients of the calculation are :

- Matter distribution
- Neutrino flux
- Dynamics of the hadron final state
- Propagation of hadrons in matter

The Fig. 3 illustrates the extent of heavy material around the chamber. The geometrical and matter distribution of the experimental setup has been determined in detail consisting of the chamber itself with its liquid and body, the upstream iron shielding and the magnet coils. It is evident that the amount of heavy material is far bigger than the target material of the fiducial volume. The neutrino flux was also well known. It has been measured carefully both in energy and radially by combining the muon flux in the shielding and the production of secondary pions and kaons in proton nuclei interactions. The knowledge about the final state properties in neutrino interactions could be derived from the data themselves.

These three ingredients were obtained in a short time. The difficult aspect concerned the question of what happened inside the shielding, where no information from direct observation existed. There was no apriori ready procedure at hand, on how to handle the propagation of a many-hadron final state. The problem looked unsurmountable in a short time, until it was recognized that the meson component is unable to generate a neutron entering the chamber and depositing more than 1 GeV. The task reduced to the handling of a linear nucleon cascade. The essential information required for describing its propagation was the evaluation of the effective interaction length, the charge exchange rate and the amount of energy deposited at each interaction. The cascade length in the shielding could then be determined from the requirement that the last nucleon must be a neutron energetic enough to simulate a neutral current candidate. The relevant experimental knowledge could be extracted from published data of proton-nucleon and proton-nucleus experiments such that the prediction of the neutron background was free of arbitrary parameters.

All ingredients were built in a Monte Carlo program. The program [13] was ready to predict the neutron background at the beginning of July 1973. The modular structure of the program ensured an easy access to and checking of all critical aspects. This turned out to be crucial when, in the following weeks, the members of the collaboration challenged the validity of the background calculation. Even unrealistic adhoc assumptions could be quickly checked and rejected. Such questions scrutinized the treatment of the hadron cascade in the shielding. So, for instance, the consequences of modifying at will the properties of the cascade could be studied instantly. In this way the collaboration got convinced and at the same time was well prepared for all kind of critical questions to be expected from the community afterwards.

Fast neutrons originate from neutrino interactions. The properties of the neutron cascade can be checked experimentally in two configurations, namely the beginning and the end of the cascade in the chamber. A genuine neutrino interaction in the chamber generates sometimes a fast neutron which interacts in the chamber and thus represents the first step of its propagation. Such events called *associated events* (AS) were recorded along with the neutral current candidates. On the other hand the neutrons entering the chamber, i.e. the *background events* (B), represent the end of the otherwise unobservable cascade in the shielding. The worst possible case consisted in the hypothesis that *all* neutral current candidates be the result of neutron interactions. Under this extreme assumption the observed number of background events (#B) equals the number of neutral current candidates, i.e. #B = #NC, which was for the neutrino film 102. In the same portion of film the observed number of associated events was 15, i.e. #AS

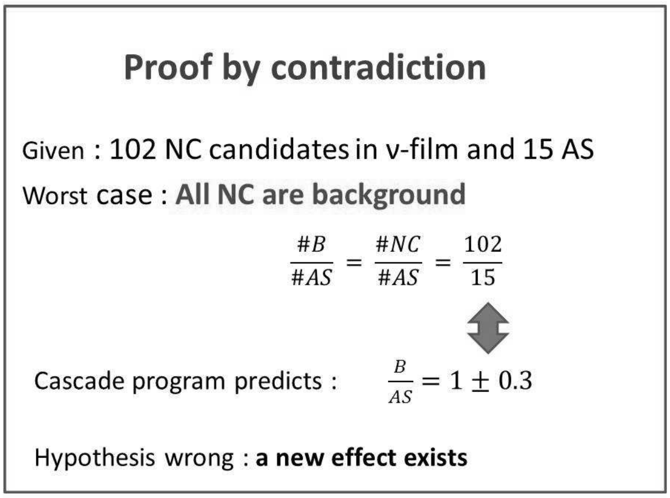

Figure 7: Test the extreme hypothesis

= 15. Therefore, the observed rate of #B / #AS = 102 / 15 can be confronted with the ratio predicted by the cascade program, as illustrated in the figure 7. The eclatant contradiction allowed to reject the hypothesis and thus to conclude that the majority of the observed neutral current candidates must be attributed to a genuinely new effect. Similar arguments held for the antineutrino data.

The neutron background calculated under the actual conditions of the experiment accounted for 10 % of the signal, thus a new effect could be claimed. The paper was submitted at the end of July 1973 [14], while the leptonic event [12] already at the beginning of the month.

The Electron-Photon Conference The discovery was reported to the Electron-Photon Conference, which took place at the end of August 1973 at Bonn. It was for the first time that in this conference series also results from neutrino experiments were included. By the way, from that moment on the name of the conference changed to *Lepton-Photon Conference*. The presentation of the Gargamelle discovery with a last minute addition from the Harvard-Pennsylvania-Wisconsin experiment was intensively discussed in a special session. In his concluding talk C.N.Yang announced the existence of weak neutral currents as the highlight of the conference.

5 The hot fall

The HPW collaboration had proposed and set up their experiment at the new National Accelerator Laboratory at about the same time as the Gargamelle experiment. The original scope was the investigation of the process $\nu_\mu N \to \mu + anything$

in an energy regime 10 times higher that at CERN. Their detector consisted of a target calorimeter followed by a muon spectrometer [15]. The emphasis turned 1972 to the search for events without final state muon. This necessitated a new trigger in order to distinguish events with and without muon. After the Bonn conference the collaboration decided, before publishing the present results, to wait and improve their apparatus with the intention to come up with increased statistics and better control of topologies, where a muon is lost at wide angles. To their surprise it turned out that the original signal of about 30 % with respect to charged currents shrank to such a small rate that doubts about the existence of neutral currents became stronger and stronger.

These unexpected news soon reached CERN. The opponents of the Gargamelle experiment felt reinforced in their criticism, which was focussed on the argument that the existence of a new effect stands and falls with the reliability of the neutron background estimation. More pertinently the treatment of the neutron cascade was questioned. The Gargamelle collaboration was well prepared to reject the arguments put forward. Some people could be convinced, others remained with *yes, but...* and quite a few were unwilling to admit that their arguments were not stringent.

The prolonged and unpleasant disbelief in the Gargamelle result caused the CERN management finally to bring about a rapid and binding decision. To this end a special experiment was carried out with the aim to measure the crucial aspects of the neutron background calculation and to confront them with the ingredients to the neutron background program.

6 The Proton Experiment

In two short runs at the end of November and in the middle of December 1973 Gargamelle was exposed to single proton pulses in a fast extraction from the CERN Proton Synchrotron. Their energy was chosen to be 4, 7 12 and 19 GeV. The entering protons would generate an observable cascade just as neutrons do. This should ensure a detailed insight in the properties of the induced cascade as a function of the proton energy.

All relevant properties had been predicted beforehand by the neutron background program, such as the apparent interaction lenght, the cascade length, the charge exchange rate. The data were evaluated with high priority. Fig. 8 illustrates a cascade with four visible steps inside Gargamelle induced by a proton of 7 GeV.

The two most salient results are shown in fig. 9. Indeed, the cascade length λ_C increases with the energy of the initial proton and is much longer than the apparent interaction λ_a. The *apparent* interaction length itself is a nontrivial quantity and cannot be simply taken from the tables in the Particle Data booklet, since a neutron travelling in the chamber had to deposite a minimum visible

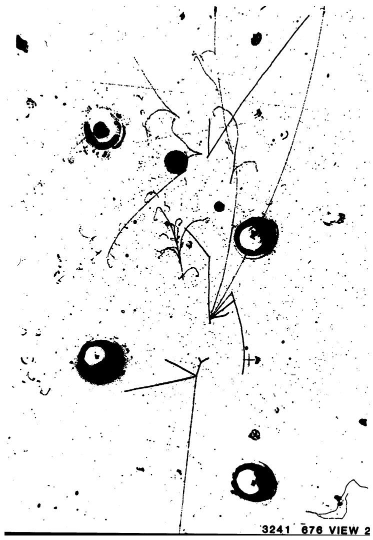

Figure 8: Proton-induced cascade observed in the Gargamelle chamber.

amount of its energy otherwise it is not recognized as such.

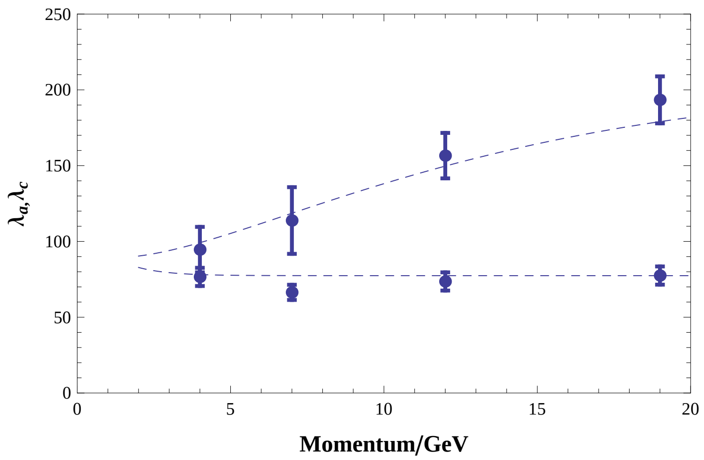

Figure 9: Comparison of the measured and predicted interaction lengths

All features of the background program have been verified. The agreement between observation and prediction dissipated any doubt in the validity of the background estimate in the discovery paper. The final results of the proton experiment were reported to the Meeting of the Americal Physical Society at Washington in April 1974 [16].

7 Final Acceptance

In Spring 1974, nearly a year after the publication of the discovery, the evidence for the correctness of Gargamelle's result was overwhelming.

Gargamelle has increased the statistics [17] and found agreement with the published data. The background calculation has been confirmed by the proton experiment and finally a new method, called the *internal* method, to estimate the background has been proposed and worked out [18]. The idea of this method exploited the fact that the interaction lengths of neutron and genuine neutrino induced interactions in the chamber are widely different. The flight direction was assumed to be given by the vector sum of the final state particle momenta. Measuring the flight path l and the potential path L the quantity $\frac{1-e^{-l/\lambda}}{1-e^{-L/\lambda}}$ relying only on information internal to the chamber discriminates between background and signal. This is illustrated by a maximum likelihood analysis as shown in fig. 10. The comparison of the curve for charged current events, which are for sure in-

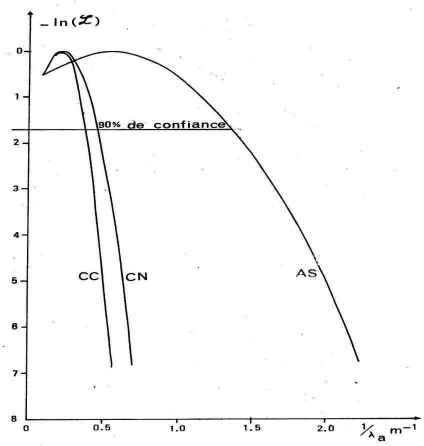

Figure 10: Results from the internal method.

duced by neutrinos, with the curve for the neutral current candidates shows that the observed increase of the inverse of the interaction lengths due to the neutron contribution is indeed small corroborating the claim in the discovery paper.

ANL. In the 12 ft bubble chamber of Argonne filled with hydrogen and deuterium the exclusive processes $\nu p \to \nu p \pi^0$ and $\nu p \to \nu n \pi^+$ have been reported to the APS meeting at Washington in April 1974 and published later [19]. This is the first observation of an exclusive neutral current process.

CITF. In the CalTech-Fermilab detector [20] in a narrow band beam centred at 45 and 125 GeV an inclusive neutral current search was performed. A new method based on the *event length* was applied to distinguish events with and without final state muon. A clear effect was seen in both neutrino and antineutrino running.

HPW. The loss of the signal in their modified detector was finally understood. The introduction of an additional steel plate with the aim to reduce the loss of muons at wide angles created an unexpected new problem. Fast hadrons could now punch through and infact cause the observed signal loss. With this insight the collaboration also found a definite signal of muonless events [21]. Some people have called jokingly the appearance-disappearance-appearance of the effect the discovery of the *alternating* neutral current.

The High Energy Community has now happily accepted the discovery and was ready to put all efforts in elucidating the central and detailed features of the new effect.

References

[1] D. Haidt and A. Pullia: *The weak neutral current - discovery and impact*, Rivista del Nuovo Cimento, Vol. 36, N. 8, 2013

[2] D. H. Perkins: *Gargamelle and the Discovery of Neutral Currents*, Proc. of the Third International Symposium on the History of Particle Physics, SLAC 24-27 June, 1992

[3] D. Haidt and H. Pietschmann: *Electroweak Interactions*, Landolt-Börnstein New Series I/10, 1988

[4] Proceedings of the International Conference at Paris 1993: *Neutral currents twenty years later*;

[5] D. Cline, C. Rubbia and McIntyre: Proceedings of the International Neutrino Conference Aachen 1976, p.683

[6] G. Feinberg: Phys.Rev. 110 (1958) 1482

[7] T. D. Lee: Phys.Rev.Lett.4 (1960) 307

[8] Gargamelle Collaboration: *ν-proposal*, CERN TCC/70-12 (1970)

[9] S. L. Glashow, Nucl.Phys. 22 (1961) 579; A. Salam, in: Elementary Particle Theory, Stockholm 1969; S. Weinberg, Phys.Rev.Lett. 19 (1967) 1264

[10] G. 't Hooft: Nucl.Phys.B33 (1971) 173; Nucl.Phys.B35 (1971) 167

[11] G. 't Hooft and M. Veltman: Nucl.Phys.B44 (1972) 189

[12] F.J.Hasert et al.: Phys.Lett.46B (1973) 121;

[13] W. F. Fry and D. Haidt: CERN Yellow Report 75-1 19751; see also [4]

[14] F.J.Hasert et al.: Phys.Lett.46B (1973) 138;

[15] L. Sulak, see [4], p.95

[16] D.Haidt: Contribution to the *APS* Meeting at Washington, April 1974

[17] F. J. Hasert F.J. et al.: Nucl.Phys. B73 (1974)1

[18] A. Pullia: Invited Talk at the Conference of the Società Italiana di Fisica (SIF), Florence, September 1973; Proceedings of the XVII International Conference on High Energy Physics London, July 1974; see also [4] p.55-66

[19] S. .J. Barish et al.: Contribution to the APS Meeting at Washington, April 1974 ; Phys.Rev.Lett 33 (1974) 1454

[20] B. Barish: Contribution to the London Conference, June 1974; Phys.Rev.Lett. 33 (1975) 538

[21] A. Benvenuti et al.: Phys.Rev.Lett.32 (1974) 800