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The discovery of neutral currents

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1 Prolog

It is a great honour for me to speak about the discovery of Weak Neutral Currents, the outstanding achievement, which has carried a high yield and assured CERN a place in the front row. The worldwide boost following the discovery is well known. What is perhaps less well known, are the difficulties this new effect had to overcome, before it got accepted by the community. In the 30 minutes allocated to me, I will try to elucidate some of the occurrences.

Shortly after the Siena Conference in 1963, Lagarrigue, Rousset and Musset worked out a proposal for a neutrino detector aiming at an increase in event rate by an order of magnitude. They had in mind a large heavy liquid bubble chamber and a large collaboration. When Leprince-Ringuet got to see the plans, he called the huge chamber *Gargamelle* (Fig. 1) invoking the mother's name of the giant *Gargantua* to pay homage to Rabelais. Lagarrigue formed gradually a strong and large collaboration built on two groups, one consisting of members from Orsay and the Ecole Polytechnique, the other consisting of members from the just finishing neutrino experiments with the NPA 1 m bubble chamber. At the end, the collaboration consisted of 7 European laboratories including guests from Japan, Russia and the United States. Figure 2 gives the list of authors[1] who signed the discovery paper [1][2].

2 The double challenge

At the end of the 50's weak interactions were well described by the $V - A$ theory. A major drawback was the bad high energy behavior and initiated various ideas to cure the problem of infinities. Guided by QED as a gauge theory, attempts were made during the 60's to construct

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a gauge theory of weak interactions [3]. The intermediate vector boson ($W^{\pm}$), although its existence was not yet known, was complemented with a neutral intermedi-

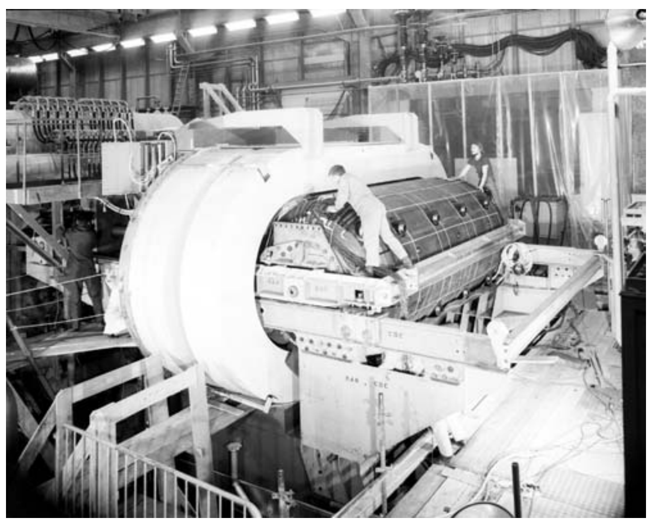

Fig. 1. The Gargamelle bubble chamber at the time of installation into the magnet coils

[1] Further authors who signed only the publication of the *isolated electron* event are: H. Faissner, C. Baltay, M. Jaffré, J. Pinfold.

[2] The authors Lagarrigue, Musset, Rollier, Rousset and Schultze are deceased.

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OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

We have searched for the neutral current (NC) and charged current (CC) reactions:

NC $\nu_\mu/\bar{\nu}_\mu + \mathrm{N} \to \nu_\mu/\bar{\nu}_\mu$ + hadrons, (1)

CC $\nu_\mu/\bar{\nu}_\mu + \mathrm{N} \to \mu^-/\mu^+$ + hadrons (2)

which are distinguished respectively by the absence of any possible muon, or the presence of one, and only one, possible muon. A small contamination of $\nu_e/\bar{\nu}_e$ exists in the $\nu_\mu/\bar{\nu}_\mu$ beams giving some CC events which are easily recognised by the e^-/e^+ signature. The analysis is based on 83 000 ν pictures and 207 000 $\bar{\nu}$ pictures taken at CERN in the Gargamelle bubble chamber filled with freon of density 1.5×10^3 kg/m^3 ‡. The dimensions of this chamber are such that most

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‡ A more detailed account of the analysis of this experiment appears in a paper to be submitted to Nuclear Physics.

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Fig. 2. Title page of the discovery paper [1]

ate vector boson to achieve the required cancellations. The invention of the Higgs mechanism solved the problem of having a gauge theory and nevertheless massive mediators of weak interactions. The progress made by Glashow, Salam and Weinberg was completed by the work of Veltman and 't Hooft demonstrating the renormalizability of the theory. So, at the turn from 1971 to 1972 a viable theory of weak interactions claiming weak neutral currents as crucial ingredient was proposed and experiments were prompted to answer by *yes* or *no* whether weak neutral currents existed or not.

In fact, two neutrino experiments were running, the Gargamelle bubble chamber experiment at CERN and the HPWF counter experiment at NAL (now FNAL). Both were confronted with this challenge without preparation. The searches for neutral currents in the previous neutrino experiments resulted in discouraging upper limits and were interpreted in a way that the community believed in their non-existence and the experimentalists turned to the investigation of the copiously existing questions in the just opened field of accelerator neutrino physics. During the two-day meeting in November 1968 at Milan, where the Gargamelle collaboration discussed the future neutrino program, the expression *neutral current* was not even pronounced and, ironically, as seen from today, the search for neutral currents was an also-ran, low in the priority list and subsequently appearing in the neutrino proposal at place 8. The real highlight attracting the interest of all at the time was the exciting observation of the proton's substructure at SLAC provoking the question what structure would be revealed by the W in a neutrino experiment as opposed to the γ in ep-scattering.

At the beginning of 1971 everything was ready: the CERN PS [4], the neutrino beam line with horn and reflector followed by the decay channel and the neutrino shielding and, of course, the chamber itself. Also a well defined procedure for scanning and measuring was established. In order to have a reliable prediction of the neutrino flux a special run with the Allaby spectrometer was carried out. For several nuclear targets the secondary charged pion and kaon spectra were measured [5]. Furthermore, the neutrino shielding was interspersed with muon counters at various depths to monitor the muon flux [6] and so getting a constraint on the neutrino flux.

Even though the question of neutral currents had been ignored, Gargamelle could meet the challenge once it became a burning issue at the beginning of 1972. Benefitting from the experience of the previous neutrino experiment in the NPA bubble chamber a careful classification of event types has been set up for the scanning of the Gargamelle films. As a matter of fact, there was no muon identification, and there was no necessity for it, since neutrino interactions were supposed to always produce a final state muon. Consequently, charged hadrons do simulate a muon, as long as they leave the visible volume of the chamber without visible interaction. Events with a muon candidate were collected in the so called category A, while events consisting of secondaries identified as hadrons were collected in the so called category B. Moreover, there were three other categories, which however are not relevant for the present consideration. The category B events were thought to arise from undetected upstream neutrino interactions emitting a neutron and interacting in the chamber, and for that reason were called neutron stars (n^*'s). It was then easy to use these events to calculate the fraction which would not interact, thus simulating a muon, and to subtract them from the observed number of events in category A.

If indeed weak neutral currents existed, then they would induce events consisting of hadrons only, i.e. would be indistinguishable from those already in category B. This means that such events were just waiting among the already scanned events of category B and their investigation could be undertaken without any loss of time. The notorious problem of distinguishing neutrino-induced from neutron-induced events became then urgent. However, optimism was prevailing, since the much longer visible volume of Gargamelle compared to the NPA chamber increased the detection efficiency of charged particles as hadrons.

3 Euphoria in March 1973

The measurements of the inclusive neutral current candidates were carried out in the seven laboratories mainly between September 1972 and March 1973. In December 1972 an isolated electron was found at Aachen.

A little anecdote as passed down by Don Perkins [10] may illustrate the excitement. At the end of December 1972, Faissner together with Von Krogh left for Oxford. Still at the London airport Faissner was waving the event in his hand towards Perkins, who was waiting in the lobby. *"Is it in the neutrino or the antineutrino film?"*, was his only question. With "*antineutrino*" as an answer, they went happily to celebrate the event. In fact, the background level to isolated electrons in the antineutrino film was almost negligible and the interpretation of the event as elastic weak neutral current interaction on an electron [2] was most natural.

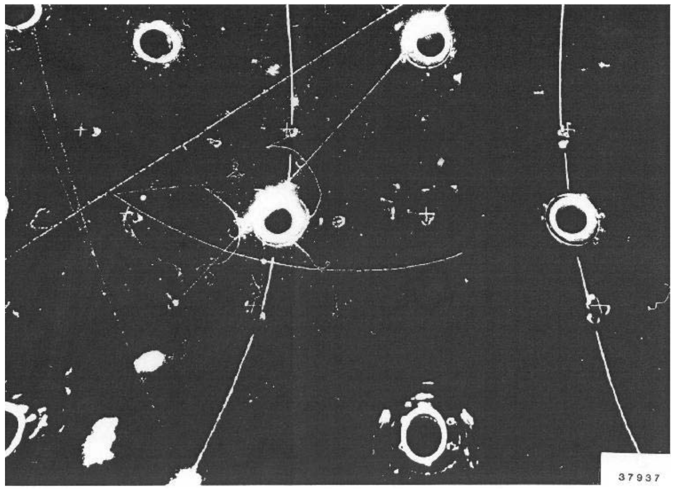

Fig. 3. Neutral Current candidate observed in Gargamelle: the neutrino beam enters from the left. Interpretation of the hadron final state: stopping proton and charged pion with charge exchange

Inspired by this unique event the efforts to check carefully the far more complicated hadronic NC candidates went on vigorously. Figure 3 shows a neutral current candidate. A control sample of events with a muon candidate was prepared in parallel. In order to ensure a meaningful comparison the same criteria were applied to the hadron final state of both the charged current and neutral current candidates, which got dubbed CC and NC. A stringent cut in the total deposited hadron energy, $E_{had} > 1$ GeV, was applied to keep the otherwise abundant number of n^*'s small. The surprising result was the large number of NC candidates in comparison to the number of CC candidates, as seen in Table1. Their spatial distributions are shown in Fig. 4. Both the event numbers and the spatial distributions were extensively discussed in the meeting mid March at CERN. There was no doubt that the only serious background to neutral currents consisted in neutron induced stars. Since their interaction length λ in the chamber liquid CF_3Br is about 70 cm, which is small compared to the longitudinal extension of the chamber, it seemed straightforward to check their presence by looking for an exponential fall-off in the vertex X-distribution. No such behavior was visible (Fig. 4). On the contrary, the X-distribution of NC candidates was rather flat and looked neutrino-like, as the CC candidates did. This was put in evidence by forming the NC/CC ratios of the spatial distributions, which in the years to come played such an important role. Evidently, it was well compatible with being flat both for the data in the neutrino and antineutrino films. Both arguments were corroborated by a Monte Carlo simulation of the ORSAY group based on the simplifying assumption that upstream neutrino-induced neutrons enter directly the chamber along the neutrino direction. The excitement was therefore quite high and a discovery seemed at hand.

Table 1. The NC and CC event samples in the neutrino and antineutrino films

	Neutrino exposure	Antineutrino exposure
Number of NC candidates	102	64
Number of CC candidates	428	148

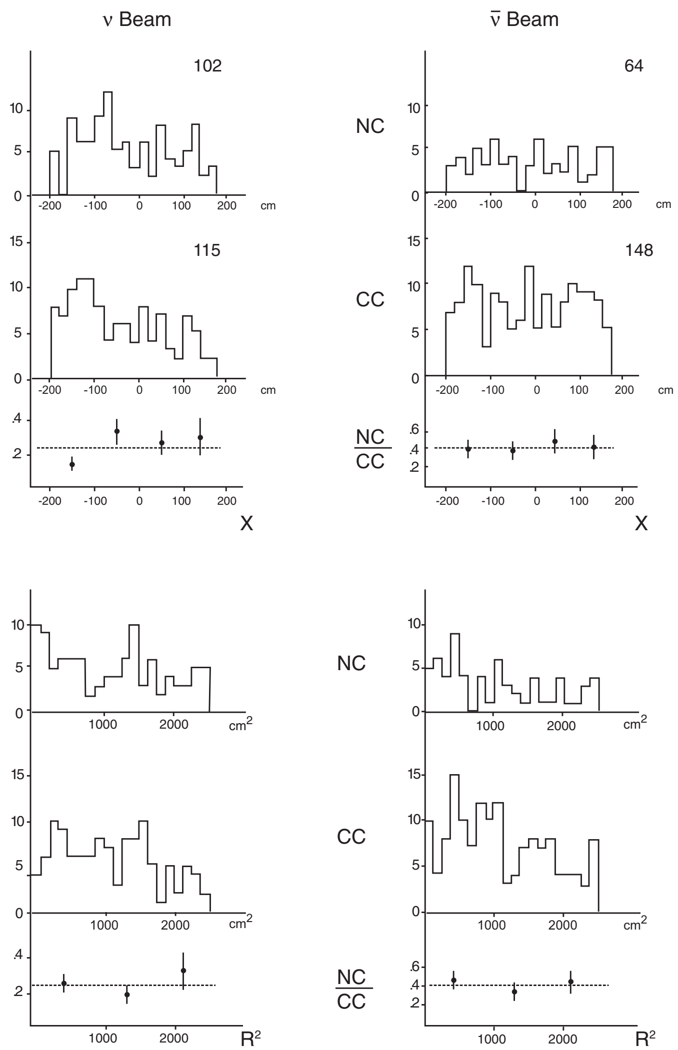

Fig. 4. Spatial distributions of the neutral and charged current candidates. X is the longitudinal vertex position of the events, R the radial position. Note: the numbers of CC candidates refer to the analysis of about a quarter of the available material

Yet, Fry and Haidt argued that the reasoning was not compelling. They brought up two strong arguments, which damped the euphoria.

Their first argument concerned the radial neutrino-flux distribution: it extends well beyond the chamber body and induces in the magnet coils a huge number of neutrino interactions, which in turn emit neutrons, thus generating a uniform flux entering sideways the fiducial volume. The net result is a flat X distribution also of n^*'s indistinguishable from neutrino-induced neutral current events.

The second, more dangerous argument concerned the fact that high-energy neutrons produce a *cascade*. Accordingly, neutrons may have had several cascade steps before entering the chamber. This meant that the relevant measure of the number of background neutrons was therefore not governed by the interaction length λ_i, but rather by the longer and energy dependent cascade length λ_C. The net result is a considerably larger n^* background than anticipated.

In this situation there was only one way out, namely to produce evidence that the number of neutron-induced events is small compared to the observed number of NC candidates despite the two new arguments.

4 The proof

The following months were characterized by feverish activity. An ambitious and detailed program was set up and carried through [9, 11]. The ingredients, which had to be taken into account, were:

– geometry and matter distribution of the whole setup,
– neutrino flux as function of energy and radius,
– dynamics of the hadron final state.

It was straightforward to describe accurately the experimental setup with the chamber, its corpus and the interior consisting of fiducial, visible, non-visible volumes, the surrounding coils and the shielding in front of the chamber. The neutrino flux $\Phi(E,R)$ was well understood, since it relied on the direct measurement of the parent distributions and the measured muon flux [6] at various depths and radial positions in the shielding [5]. On the contrary, the description of the complex final state of a neutrino interaction appeared as an insurmountable task given the short time available. It would have implied to predict for each neutrino-induced topology the tracking of all final state particles including in addition all the possible branchings. The breakthrough to a solution came from the consideration that π- or K-induced interactions never give rise to secondary neutrons, which would still be energetic enough to fake a NC candidate. The problem was then reduced to controlling the behavior of final state nucleons, i.e. protons or neutrons. Since the neutrino energy spectrum extended up to about 10 GeV, the generated nucleons can be fast and indeed propagate over several steps. However, the kinematics of nucleon–nucleon [NN] interactions is such that at each step there is at best *one* secondary nucleon able to continue the cascade and still have enough energy that at the end it is a neutron, which enters the chamber and deposits more than 1 GeV. With

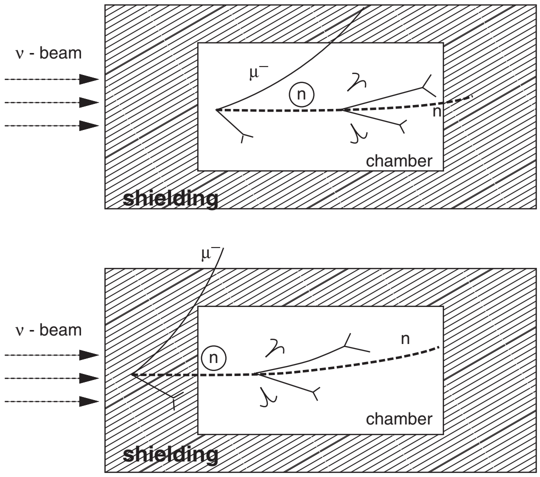

Fig. 5. Two topologies of a neutron cascade. *Above*: associated event (AS), *below*: background event (B)

this considerable simplification the problem boiled down to establishing the nucleon elasticity distribution at each cascade step. There were plenty of NN data to derive the required distribution.

A neutrino event emitting a neutron can appear in two topologies, called AS and B events. Figure 5 shows on top an *associated* event (AS), where both the neutrino interaction and the downstream neutron star are visible in the chamber. On the other hand, *background* events (B) sketched below, are produced when the neutrino interaction occurs in the invisible upstream shielding and the emitted fast nucleon cascade eventually ends up in a neutron entering the chamber and depositing enough energy to fake a NC candidate. It is important to note, that the two topologies probe different parts of the nucleon cascade: in AS events the *beginning* of the neutron cascade is directly observed, while in B events the observed n^* represents the *end* of the nucleon cascade and therefore depends on the kinematics of the whole upstream cascade, which cannot be inspected.

The strategy consisted then in combining the relation between the two topologies and the observed number of AS events (n_{AS}):

$$n_{\mathrm{B}} = \frac{B}{AS} \times n_{\mathrm{AS}} \; .$$

The number of background events (n_{B}) is obtained from the observed number of AS events and the ratio B/AS calculated with the cascade program. Since B/AS is a ratio, several systematic effects cancel out or are at least reduced. The really critical aspect in calculating B/AS concerned the treatment of the cascade. Also this aspect was under control, since it was based on data from pp and pA experiments carried out in the few-GeV region.

At the beginning of July 1973 the neutron background program was complete. It had no free parameters, was flexible and very fast. All sensitive parameters could be easily accessed and varied. All imaginable questions and worries raised from within the collaboration could be investigated and answered quantitatively and unambiguosly.

The most elegant argument consisted in testing the hypothesis that *all NC candidates are background events*. According to this worst-case hypothesis one has: $n_{\mathrm{B}} = n_{NC}$. Consequently, the ratio B/AS would be equal to the ratio of the observed numbers of NC and AS events, i.e. 102/15 in the neutrino film and 63/12 in the antineutrino film (see Table 1). The angular and energy distributions are readily derived from the NC samples, which are neutron stars by hypothesis, and have the form

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-n}; \quad \frac{\mathrm{d}N}{\mathrm{d}\cos\theta} \sim \mathrm{e}^{-\frac{\theta^2}{2\theta_0^2}}$$

For $n = 1.1 \pm 0.1$ and $\theta_0 = 0.35 \pm 0.05$ agreement with the event sample was obtained. With this as input to the cascade program the calculated ratio B/AS resulted in 1.0 ± 0.3 in blatant contradiction to the hypothesis 102/15 and 63/12. Thus the hypothesis must be rejected and the neutron background does not dominate the NC candidates. This argument found immediate approval.

Putting in the experimental best values the prediction for the ratio B/AS was 0.7 ± 0.3. With this value the predicted neutron background was indeed small compared to the observed number of NC candidates, thus a new effect could be safely claimed and published in *Physics Letters* at the end of July. Thus ended the hot months, but a dramatic after-play was to come.

There was also another approach. Pullia [12] applied the Bartlett method to the spatial distributions. For each event, it was assumed that the interaction was induced along the direction of the total 3-momentum of the observed hadron system. Then for each event two quantities can be measured: the actual flight path l and the potential flight path L providing the probability

$$\frac{1 - \mathrm{e}^{-\frac{l}{\lambda}}}{1 - \mathrm{e}^{-\frac{L}{\lambda}}} \; .$$

A maximum likelihood analysis yielded the apparent interaction length λ. Figure 6 [7] shows, at 90% confidence level, that the result for the NC sample was $\lambda^{NC} = 2.2\,\mathrm{m}$ to be compared with the slightly larger value $\lambda^{CC} = 2.7\,\mathrm{m}$ in the CC sample. This was also evidence for the NC sample not to be dominated by neutron stars.

Furthermore, handy formulae for estimating the neutron background were obtained by Perkins [10] based on the attenuation length of neutrons and by Rousset [13] based on an equilibrium argument. They were useful, though qualitative, since the experimental conditions were considerably simplified.

5 Attack and final victory

The new results were reported at the Electron–Photon Conference one month later at Bonn together with the results of the HPWF experiment. C.N. Yang announced at the end of the conference the existence of weak neutral currents as the highlight of the conference.

There was no time for celebrating the great achievement. On the contrary, a painful time of defense against

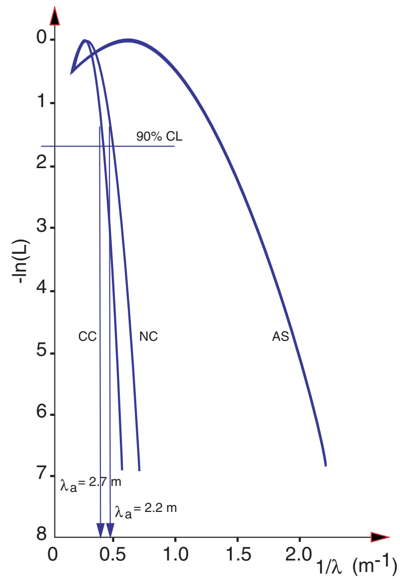

Fig. 6. Bartlett analysis of NC and CC events

unjustified attacks started. Shortly after the Bonn Conference, the HPWF Collaboration modified their apparatus with the net result that the previously observed signal of neutral currents disappeared. These news quickly reached CERN. They caused dismay and were reason for distrust in the Gargamelle result. The opponents focused their criticism on the neutron background calculation and in particular on the treatment of the neutron cascade λ_C. Although the members of the Gargamelle Collaboration withstood all critical questions, the willingness to accept the validity of the Gargamelle observation had to wait until the end of the year. In a special run Gargamelle (filled with the same liquid CF_3Br) was exposed to shots of protons with fixed momentum of 4, 7, 12 and 19 GeV. In order to exclude any escape, the background program was applied to predict in advance the proton induced neutron cascade length versus initial momentum. Figure 7 shows a prominent example of a multi-step cascade. The four exposures were quickly evaluated by Rousset, Pomello, Pattison and Haidt. The final results were reported at the APS Conference in April 1974 [14] in Washington. The overlay of the predicted and measured cascade length (Fig. 8) resolved all doubts.

One year after the discovery, at the time of the June 1974 London Conference, overwhelming confirmation for the existence of weak neutral currents came from Gargamelle itself [7] with twice the original statistics. In the meantime the HPWF Collaboration had elucidated the reason why they lost the signal and now also affirmed weak neutral currents. Further confirmation came from the new counter experiment of the CITF Collaboration and from the observation neutrino-induced single pion events without muon in the 12 ft ANL bubble chamber.

6 Epilog

In retrospect the significance of the observation of weak neutral currents is highly visible. It is the key element in giving substance to the similarity in structure of weak and electromagnetic interactions. Rightly the new term *electroweak* came into circulation.

The discovery of weak neutral currents crowned the long range neutrino program initiated by CERN at the beginning of the 60's and brought CERN a leading role in the field. The new effect marked the experimental beginning of *the Standard Model of electroweak interactions* and triggered a huge activity at CERN and all over the world, both experimentally and theoretically.

The most immediate success was the prediction of the mass value of the elusive intermediate vector boson W on the basis of the Glashow–Salam–Weinberg model combined with the first measurements of the weak mixing angle θ_W, namely

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W} = \frac{37\ \text{GeV}}{\sin\theta_W} \approx 70\ \text{GeV}\ .$$

The large value made it evident that neutrino experiments had no chance to observe the W propagator effect. This led to the idea to produce W's in high-energy $\bar{p}p$ collisions. The transformation of the CERN SPS into the S$\bar{p}p$S col-

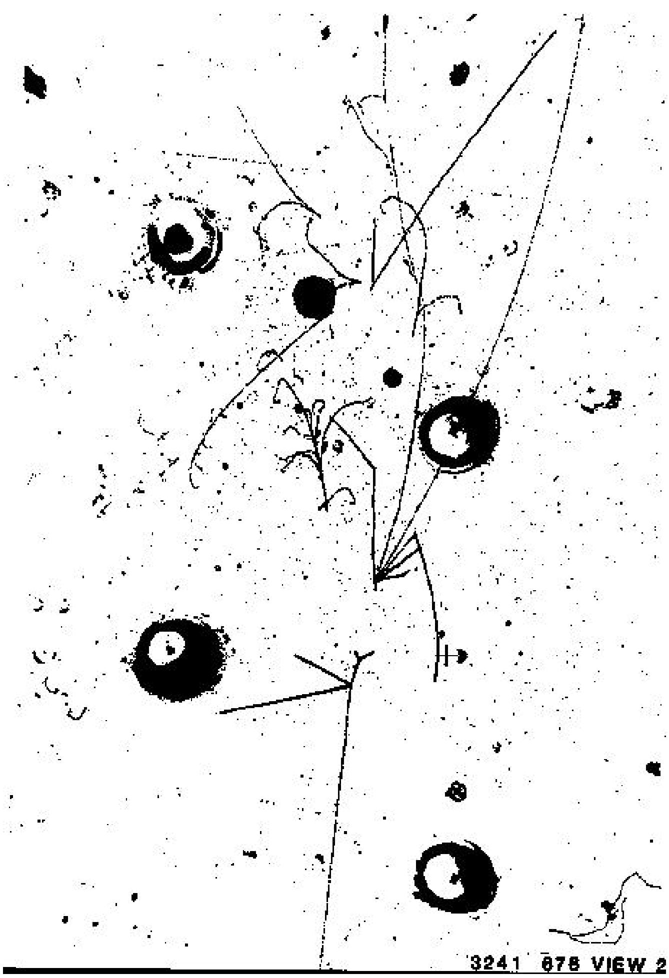

Fig. 7. A proton of 7 GeV enters Gargamelle from below and induces a three-step neutron cascade

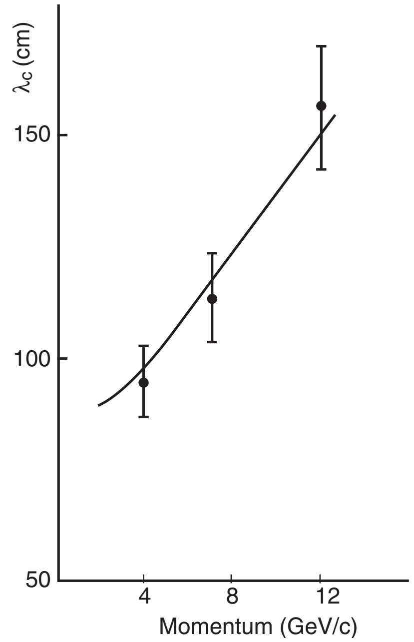

Fig. 8. The measured and predicted cascade lengths

lider succeeded in the observation of the mediators of the weak force, the W and Z [8].

The neutrino experiments at the CERN SPS increased in accuracy to the extent that the first test of electroweak radiative corrections was made possible by comparing the directly observed W mass with the one obtained by GSW putting in the precisely measured weak angle θ_{W}. In the limited time available in this talk only a summary [15] of low energy experiments is presented in Fig. 9. All low energy neutral current experiments can be displayed in a plane spanned by two effective charge couplings [15] $\bar{s}^2$

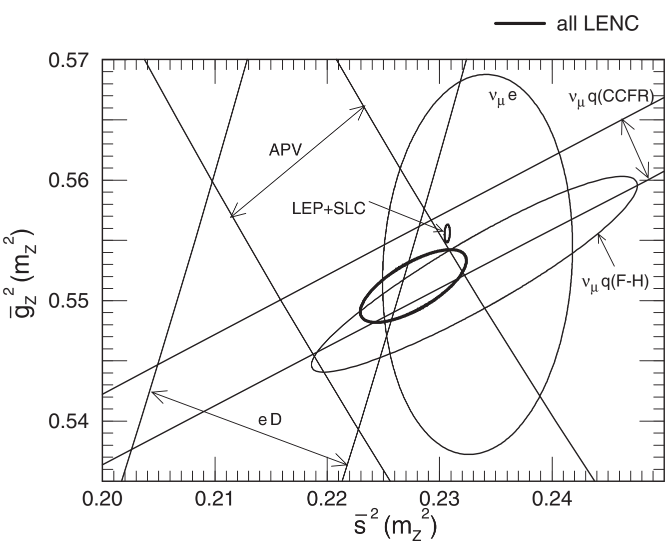

Fig. 9. Summary of four classes of low energy neutral current experiments. The effective charge parameters are determined from the data for $Q^2 \sim 0$ and then propagated to the Z-mass scale for comparison with the LEP and SLC data

and $\bar{g}_Z^2$, which are related to $\sin^2\theta_{\mathrm{W}}$ and the overall neutral current strength. The ellipse marked νq combines the results from 41 neutrino experiments. Also included in the figure are the results from the elegant ed experiment at SLAC, the clean νe data and results from atomic parity violating experiments. All low energy data agree well, as is evident from the thick ellipse representing the result of the combined fit.

The continuously improved knowledge on weak interactions justified building the e^+e^- collider LEP for an in-depth study of the Z decay parameters and later WW production allowing stringent tests of the electroweak theory at the quantum level [16]. All results combined make the search for the Higgs, the last element of the electroweak Standard Model, a central issue for the Large Hadron Collider, which is presently under construction.

I would like to end this talk on a personal note. I had the privilege to be a member of the excellent Gargamelle Collaboration, to contribute to the discovery and to feel the responsibility – it was an experience for life.

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