THE NEUTRINO'S 50^{th} BIRTHDAY

Dieter Haidt
Deutsches Elektronen-Synchrotron DESY
22603 Hamburg, Germany
E-mail: dieter.haidt@desy.de

1. The Beginning of Neutrino Physics

50 years ago, in the year 1956, Cowan and Reines[1)] observed the first neutrino induced interactions and started experimental neutrino physics as a new field. The hypothesized neutrino is finally proven to exist as a real particle. Cowan and Reines wrote on June 14, 1956 a telegram to Wolfgang Pauli, the father of the neutrino :

> *We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse β decay of protons.*

Pauli answered : *Thanks for message. Everything comes to him who knows how to wait.* In fact, he had to wait 26 years to see his *Neutrino Hypothesis* to become reality. The origin of his keen idea[2)] goes back to two puzzles. Chadwick observed 1914, that in β-decays the energy spectrum was continuous contrary to the discrete α- and γ-spectra. The other puzzle concerned the apparently wrong statistics in nitrogen. One has to keep in mind that the only elementary particles known at that time were the *electron, proton and photon.* Electrons were assumed to be present in the nucleus and to take part in nuclear binding. Thus nitrogen with A=14 and electric charge 7 should consist of 14 protons and 7 electrons, hence should obey Fermi statistics contrary to observation.

1.1. The Neutrino Hypothesis

The observation that the β-particles were not emitted with the discrete energy corresponding to the maximum energy given by the mass difference of the nuclei involved, suggested to doubt the conservation of energy in the decay process. Niels Bohr took the view that *we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β ray disintegrations.* According to Pauli he kept this opinion and *only in 1936 did he accept completely the validity of the energy theorem in β decay and the neutrino, when Fermi's theory had already developed successfully.* The calorimetric experiment of Lise Meitner and Wilhelm Orthmann[3)] definitely excluded escaping photons as source of missing energy. In a *desperate way out* Pauli wanted to save energy conservation and postulated the existence of a new penetrating, neutral particle, which sofar escaped detection. In his famous letter dated December 4, 1930 to his radioactive friends at Tübingen he formulated the *Neutrino Hypothesis* :

> *Liebe Radioaktive Damen und Herren!*
> *...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 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...* [a]

Pauli did not dare to publish his idea. He was worried about the experimental detection of such a particle. It is revealing to quote a story Herbert Pietschmann told[4)]. Pauli said to his friend Walter Baade: *Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally!* Walter Baade, an astronomer, apparently had great respect for experimentalists and so he bet Pauli that it will one day be detected. When Reines and Cowan announced the discovery of the neutrino in 1956, Pauli did pay his bet (a case of Champagne)! Herbert Pietschmann inquired later about the truth of this story and asked Fred Reines at the Neutrino Conference at Aachen. Reines furiously confirmed that it is true, but *the Champagne was drank by the theoreticians alone, while I and Cowan did not get any drop of it.*

Also Geiger, a participant of the meeting at Tübingen, did not think impossible the detection of Pauli's *neutron.*

In the year 1932 two new elementary particles were discovered : the *neutron* by Chadwick and the *positron* by Anderson. Heisenberg developed his $n - p$ charge exchange model and laid the fundament to strong interactions. After the discovery of the neutron Fermi introduced the name *neutrino* for Pauli's *neutron.* With the neutron and the proton as constituents of nuclei the *wrong statistics problem* found a satisfactory solution.

The Solvay conference at Brussels 1933 was dominated by nuclear physics. Pauli made a short contribution presenting his idea how to solve the β-decay puzzle. This was the first public presentation of the neutrino[5)]. Fermi picked up Pauli's idea and formulated within only two months a quantum theory of β decay. Fermi's letter submitted to *Nature* was rejected because of *abstract speculations too far from physical reality to be of interest to the readers.* He then published[6)] 1934 his theory in *Zeitschrift für Physik* under the title *Versuch einer Theorie der β-Strahlen*, where the $e\nu$ pair acts like a field coupled to the charge changing pn current. Fermi has conceived his theory in analogy to the theory of photon emission. The $e\nu$-pair may be emitted with spins opposite (Fermi transition) or parallel (Gamow-Teller transition) to each other. Experiment would have to decide which of the possible interaction

[a] Namely, the possibility that there might exist in the nuclei electrically neutral particles, which I want to call neutrons and which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light.The mass should of the order of magnitude as the electron and anyway not larger than 0,01 of a proton mass...

forms (V,A,S,T,P) is realized. Parity was tacitly assumed to be conserved. After two decades emerged eventually the V-A theory[7]. It was first reported by Marshak[8] to the Padua-Venice Conference in September 1957.

1.2. The Neutrino and Parity

The neutrino has been introduced as a light, electrically neutral fermion. It can therefore be described by a Dirac spinor, i.e. a 4-component spinor, or equivalently by two Weyl spinors, i.e. two 2-component spinors. Its properties w.r.to charge conjugation, parity, chirality, helicity have been extensively investigated. One of the fundamental questions was, and still is, whether neutrinos are their own antiparticles[9]. If so, they are called *Majorana* neutrinos, otherwise *Dirac* neutrinos. A distinction is possible, if there exists a charge like quantum number. For instance, neutrinos are always emitted together with an electron. It was natural to introduce a lepton number L as follows :

$$\begin{aligned} L(e^-) &= L(\nu) = +1 \\ L(e^+) &= L(\overline{\nu}) = -1 \end{aligned}$$

Neutrinos and antineutrinos can then be distinguished by their lepton number, if it is conserved. However, no experimental evidence existed.

In a series of experiments more and more stringent upper limits on the neutrino mass were derived from the Kurie plot. The equation of motion of the free neutrino had been considered both for massive and massless neutrinos. In the case of a massless neutrino the Weyl equations are decoupled. Its significance was only appreciated, when parity violation in weak interactions was discovered. The incentive came from the study of strange particle decays[10], which resulted 1956 in the $\theta - \tau$ puzzle and which motivated Lee and Yang to question the validity of mirror symmetry in weak interactions. Parity violation was demonstrated in the Co^{60} experiment of C.S.Wu and collaborators[11] (1957) and immediately confirmed in $\pi_{\mu 2}$ decay[12]. Another fundamental experiment was the one of Goldhaber, Grodzins and Sunyar[13] (1958) proving that the neutrino is a lefthander.

As soon as parity violation was discovered, a concise reformulation of weak interaction theory emerged with the 2-component neutrino and the V-A interaction in a fast sequence of papers:

$$H_{int} = \frac{G_F}{\sqrt{2}} J_\mu J_\mu^+$$

where the weak current consists of a vector and an axialvector contribution and where G_F is the universal weak coupling. This theory described all known low energy weak phenomena and awaited the tests in the forthcoming accelerator ν experiments.

A recent test of V-A came from the *ep* collider HERA using the purely weak process[14] $e^+ + p \rightarrow \overline{\nu}_e + anything$, which was observed for the first time 1993. The

e^+ has two helicity states : $(e^+)_R$ and $(e^+)_L$. In weak processes only $(e^+)_R$ participates, hence $(e^+)_L + p \rightarrow \overline{\nu_e} + anything$ should vanish. This is what the two HERA collaborations[15], H1 and ZEUS, have shown with polarized e^+ beams (see Fig. 1).

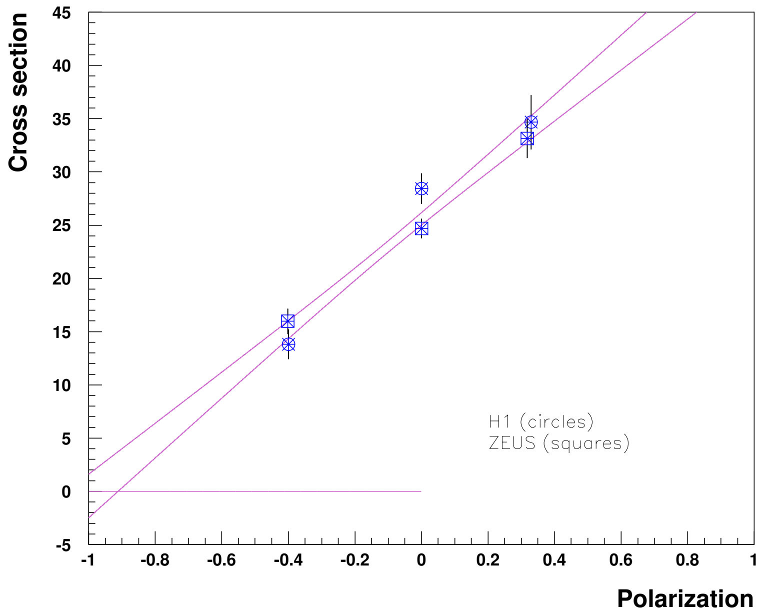


Figure 1: The cross section $e^+ + p \rightarrow \nu_e + anything$ versus positron polarization degree. P=-1 corresponds to the interaction of lefthanded positrons.

2. Accelerator Neutrino Physics

For a long period nuclear β-decays were the only source for studying weak interactions. Then, with the discovery of the mesons and the muon their decays offered new possibilities. The purely leptonic muon decay served as laboratory for detailed studies.

2.1. Feinberg's Argument

The structure of the V-A theory suggested an *Intermediate Vector Boson ($W^\pm$)* as mediator of weak interaction in analogy to the photon in QED. It was known that the decay $\mu^+ \rightarrow e^+\gamma$ is strongly suppressed. Feinberg[17] noticed 1958 that, if the IVB existed, a sizeable decay rate should be expected for the radiative decay and argued that its suppression can only be maintained, if two neutrino species exist (see Fig. 2). How can this argument be tested experimentally? Bruno Pontecorvo (1959) and Melvin Schwartz (1960) proposed the idea for a multi-GeV ν-beam to be realized at the just built CERN and BNL proton synchrotrons as sketched in Fig. 3. In the first step a proton beam hits a nuclear target and generates secondary pions : $p + nucleus \rightarrow \pi^+ + anything$. In the second step the pions decay according

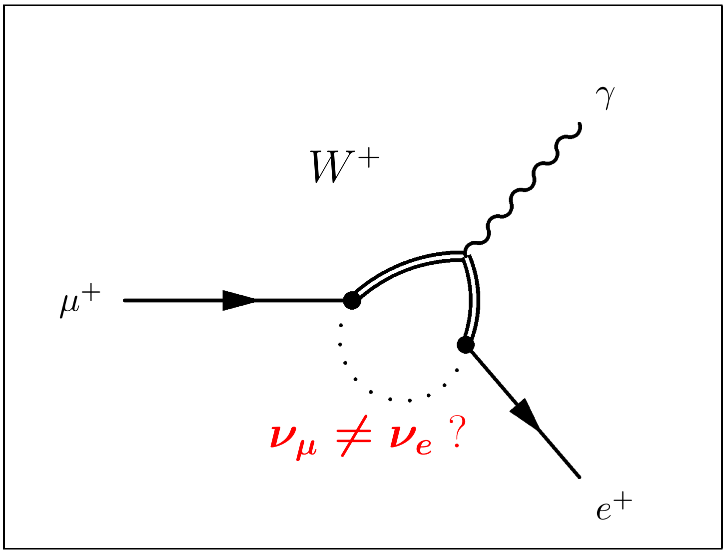


Figure 2: Radiative muon decay.

to $\pi^+ \rightarrow \mu^+ + neutrino$. Finally all particles are absorbed in a thick shielding except for the penetrating neutrinos. Since the decay $\pi^+ \rightarrow e^+ + neutrino$ is experimentally known to be suppressed, the neutrinos which leave the shielding, have been generated together with muons and not with electrons. This enables a unique test: *count the number of muons and electrons in the neutrino-induced events*. If only events with muons are observed, then there must be two neutrino species, otherwise an equal number of muons and electrons is expected.

The two laboratories CERN and BNL started at almost the same time the race for the *two neutrino case*. At CERN Gilberto Bernardini picked up Pontecorvos's

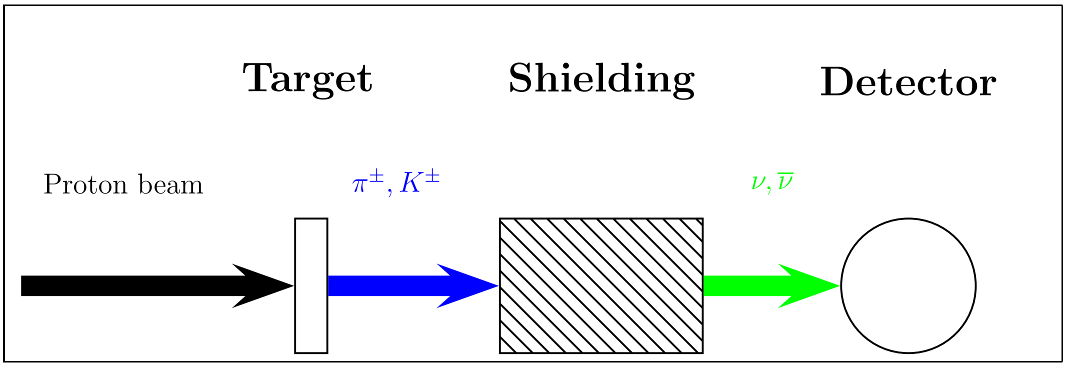


Figure 3: Sketch of an accelerator neutrino beam

idea. Table 1 lists the fast sequence of events [18] :

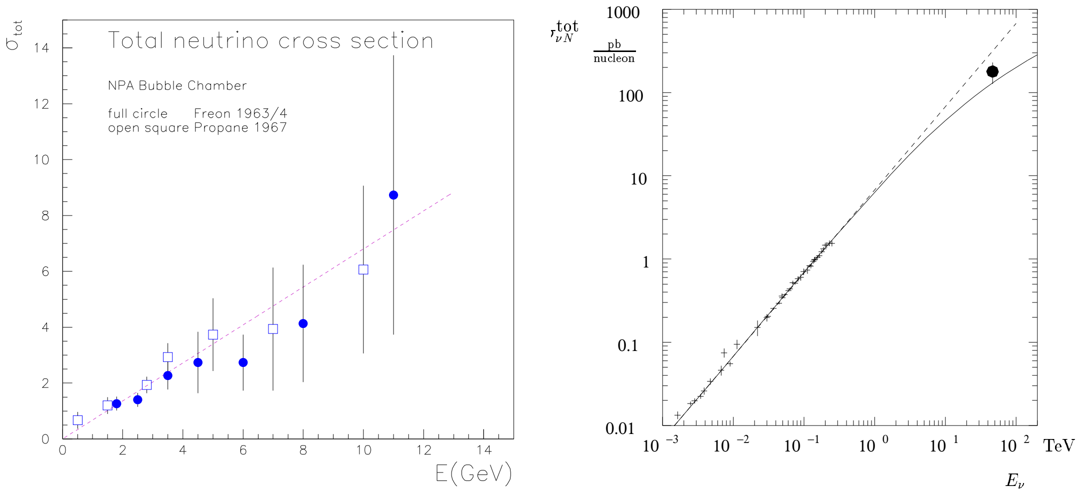
Early 1960	CERN initiates feasibility study : ν flux and shielding (Krienen, Steinberger, Salmeron) bubble chambers (EP and NPA) and counter-cloud chamber (Faissner)
May 1960	SPC: very promising
Summer 1960	AGS at BNL completed : Lederman, Schwartz and Gaillard propose 10 t spark chamber
November 1960	CERN decides to carry out ν experiment in 2 stages: (#1) quick 2-3 weeks run in June 1961 with 2 bubble chambers and counter cloud chamber, (#2) long term program
April 1961	CERN Seminar : T.D.Lee's lecture on neutrino questions
May 1961	Alarm : v.Dardel measures secondary π flux and concludes that ν flux was overestimated by factor 10
June 1962	BNL finds two ν species

Table 1: The two neutrino race.

The CERN Council in June 1962 had to recognize that the race is lost and decided to go for neutrinos *more than ever*. A new and improved ν beam line was built and equipped with Van der Meer's horn and two detectors : the Ramm NPA 1m Heavy Liquid Bubble Chamber filled with Freon (later Propane) and the Spark Chamber. In the runs 1963/4 the questions raised in Lee's catalog and discussed in a seminar by John Bell and Martinus Veltman had been addressed and reported to the Siena Conference 1963. The most burning question concerned the existence of the Intermediate Vector Boson W. The bubble chamber group found one candidate with the characteristic dilepton signature : $\nu_\mu + p \to \mu^- e^+ + X$, indicative of the production of a light W with subsequent leptonic decay $W^+ \to e^+ + \nu$. The Spark Chamber group observed several $\mu^+\mu^-$ events. Eventually these events were attributed to background and an upper limit of a few GeV for the W, *if it existed*, was published. The search for the W was then continued by looking for a propagator effect causing a deviation from linearity in the total neutrino cross section. The existence of the W was a strong prejudice, but nobody would have anticipated its mass to be on the order of 100 GeV.

2.2. The W-Propagator

The search for directly produced W's in the first neutrino experiments ended without success. This was interpreted as being due to its too heavy mass. The existence of the intermediate vector boson would anyway show up as a deviation from the linear rise of the total neutrino cross section. Fig. 4a shows the data from the early CERN neutrino experiments 1963/4 and 1967. Consistency between the data



(a) Data until 1967

(b) Data until 1993

Figure 4: The total neutrino cross section $\sigma(\nu N)$ versus neutrino beam energy E_ν.

and the theoretical cross section including the propagator term (see Eq. 1) yields a lower limit for the W mass.

$$\frac{1}{1 + Q^2/M_W^2} \tag{1}$$

This test was repeated for each new neutrino experiment[19]. 1976 it became clear that this method would never reach the required sensitivity for fixed target neutrino experiments, because the value of the W mass is expected to be around 70 GeV (see Eq. 2). Indeed, only with the advent of the HERA *ep* collider Q^2 values on the order of $\mathcal{O}(M_W^2)$ were accessible. The cross section of the purely weak process[14] $e^+ + p \to \overline{\nu}_e + anything$ is sizeably reduced. If interpreted as inverse neutrino fixed target experiment corresponding to a projectile energy of $\mathcal{O}(50\text{ TeV})$ the measurement could be compared with the neutrino data and manifested the W propagator effect, as seen in Fig. 4b. Since then, the value of the W propagator mass has been improved by H1 and ZEUS to a precision of about 1 GeV in agreement with the precise value measured in the process $e^+e^- \to W^+W^-$ at LEP (see Zerwas in ref. [20]).

2.3. Discovery of Weak Neutral Currents

Gamow and Teller[21] speculated in 1937 on some generalization of the β transformation theory and considered the possibility of emitting an electron pair or a neutrino pair. In today's language this would mean a *neutral current* interaction. It took quite some time until this idea got its real foundation.

Despite the similarity between the V-A theory[7] and QED, there were also fundamental differences: it violates parity maximally and it is not renormalizable. Furthermore, the intermediate vector boson $W^{\pm}$ playing the role of the photon is charged and massive. V-A is fine as an effective low energy theory, but fails badly at high energies. Weinberg described in ref. [20] the various obstacles which had to be overcome to finally arrive at a gauge theory of weak interactions containing as a vital element weak neutral currents.

The theoreticians knew that the W alone would not be sufficient to cure the divergences and postulated the existence of other new types of weak processes, in particular one, where the neutrino is not transformed into a muon, but remains unchanged. They give rise to *neutral current* events as opposed to the known *charged current* events. The current$\times$current form implies the existence of neutral currents. Bell and Veltman carefully distinguished, in today's language, flavor conserving and flavor changing neutral currents. They noted that flavor changing neutral currents, for instance in kaon decays such as $K \to \pi\pi$, were strongly suppressed. This was later explained by introducing the GIM current[22] orthogonal to the Cabibbo current. Searches were performed with the CERN bubble chamber experiment in the elastic and 1-π channels, but failed because of a serious background caused by neutrons entering the chamber along with the neutrino beam. The resulting upper limits were discouragingly low to the extent that the consensus in the community was that neutral currents don't exist. The neutrino groups concentrated on the exploration of the (charged current) neutrino interactions in the elastic channel, the 1π-channels and the high Q^2-regime, called *deep inelastic channel.*

The low neutrino event rate has prompted the proposal of a next generation heavy liquid bubble chamber: Gargamelle. The physics program was discussed 1968 and was influenced by the discovery of the proton substructure at SLAC 1967. The search for the W ranged still at high priority, while Neutral Currents hardly played any role. This was going to change dramatically.

Gargamelle started data taking 1971 and began immediately with the scanning and measuring of the neutrino events. In spring 1972 the emphasis changed, when on the one side 't Hooft's proof of the renormalizability [23] became known to the collaboration and on the other hand the distribution of neutral particle induced events, i.e. events *without* muon candidate, exhibited an apparently flat behaviour as should be expected for neutral current interactions. This was the beginning of a dedicated search for neutral currents. The details of the discovery are described by Haidt in ref. [20]. As in the previous neutrino experiment with the Ramm chamber also Gargamelle had to face the neutron background problem. Once the solution to this problem was found in summer 1973, the claim of the discovery of *neutrino like interactions without charged lepton in the final state*[24] could be made. A typical neutral current candidate is shown in Fig. 5. The Gargamelle collaboration did not get immediate recognition. However, in retrospect, the significance of the discovery stands out, as expressed by Maiani at the occasion of the 30 years anniversary: *The discoveries of neutral current*

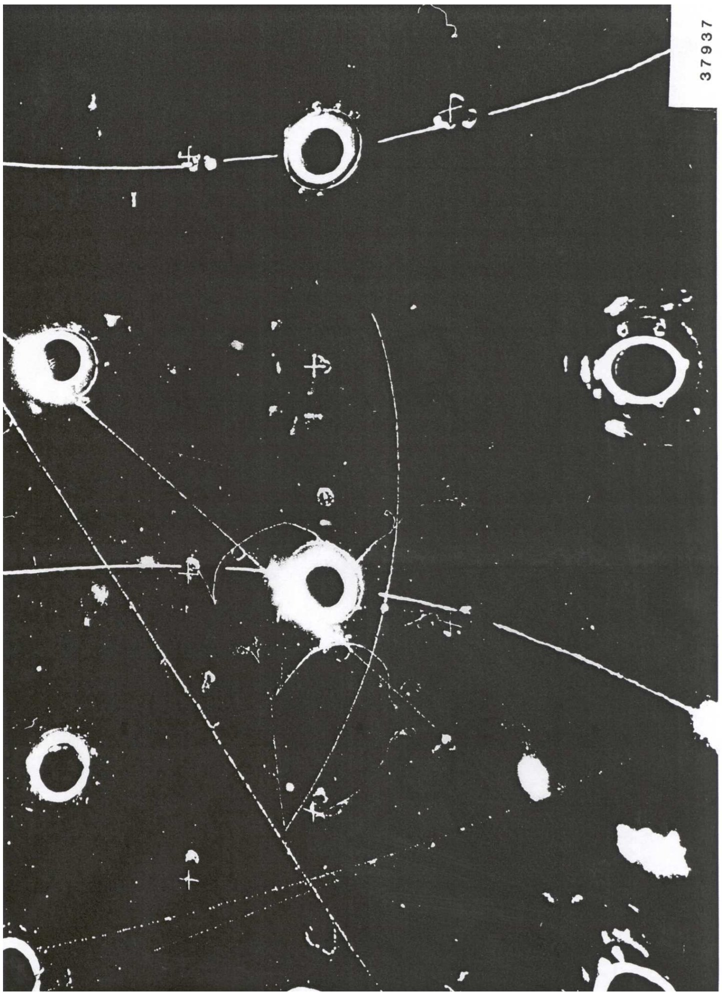


Figure 5: Candidate of a neutral current event in Gargamelle. The neutrino beam enters the chamber from below. The charged final state particles manifest themselves as hadrons. Note the charge exchange to a π^0 decaying into two close-by γ's.

and of the W and Z bosons marked a watershed in the fortunes of CERN (see ref. [20]).

3. The Neutrino and the Standard Model

With the discovery of weak neutral currents in Gargamelle 1973 started a new chapter in neutrino physics and in particle physics in general. All big laboratories have reassessed their scientific program with an immense impact on accelerators with higher energies and intensity, colliders, omni-purpose detectors, sociology of collaborations, but also on astroparticle physics and cosmology. The dream of a theory embracing both weak and electromagnetic phenomena became reality. Among the host of models the Glashow-Salam-Weinberg model[25] (GSW) attracted particularly the attention of the experimentalists, since with the *weak mixing angle* θ_W only one new parameter had to be considered. The investigation of the properties of the weak neutral current is described in ref. [19].

3.1. The Beginning of the Standard Model

In the rather short period from 1973 until 1978 the basic properties of weak neutral currents have been established. The measurement of all 4 single pion channels, also $\nu + n \to \nu + \pi^0 + n$ with only neutral particles in the final state, revealed the importance of the Δ resonance production and served some 20 years later as useful input in interpreting the Superkamiokande events. The *ed* experiment at SLAC with polarized electrons demonstrated (γ, Z)-interference and proved parity violation in weak neutral currents. Only for a short while the early atomic parity violation experiments caused some confusion. The variety of measurements have singled out the GSW model, which then became the *Standard Model*.

3.2. Key to the W Mass

By the time of the Aachen ν conference 1976 the neutrino experiments yielded $\sin^2\theta_W \approx 0.3 \pm 0.05$. Since GSW relates G_F and α, the measurement of the weak mixing angle offered the key to the W-mass :

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{\sin^2\theta_W} = \frac{(37.3\,\mathrm{GeV})^2}{\sin^2\theta_W} \tag{2}$$

resulting in $m_W \approx 70\,\mathrm{GeV}$. The immediate consequence was that current fixed target neutrino experiments had no chance to detect the W. Cline, Rubbia and McIntyre[26] proposed the $p\overline{p}$ project, which was later on realized at CERN. The two experiments UA1 and UA2 observed 1983 the weak bosons W and Z (see Darriulat in ref. [20]).

3.3. Testing Quantum Corrections

After the successful tests of the Standard Model at lowest order, the next crucial step consisted in testing it at its quantum level. This question was addressed in a workshop at CERN 1981[27] and the following proposal came out : *Measure M_W at the $Sp\overline{p}S$ and predict M_W through* $\sin^2\theta_W$. This comparison would be conclusive, if in a new round of neutrino experiments an accuracy in $\sin^2\theta_W$ of $\pm$ 0.005 can be achieved. Neutrino physics entered its high statistics phase. CDHS and CHARM indeed achieved the required precision in $\sin^2\theta_W$. Together with the measurements of UA1 and UA2 the test of the electroweak quantum correction worked out successfully. Throughout the high intensity phase the bubble chambers, particularly BEBC, filled with hydrogen and deuterium contributed unique information, which could not be obtained in the experiments with isoscalar targets.

A summary of low energy neutral current data is shown in Fig. 6 [28] in the charge form factor plane $(\overline{s}^2(0), \overline{g}_z^2(0))$ shifted to $Q^2 = M_Z^2$ for ease of comparison with data from Z-decays. Note that $\sin^2\theta_{eff} \approx \overline{s}^2(M_Z^2)+0.0010$ and $\overline{g}_z^2(0)$ is related to the ρ parameter.

The ellipse marked νq is a combination of 41 individual neutrino experiments reanalyzed using the same nuclear structure functions for all data[29]. Also shown are

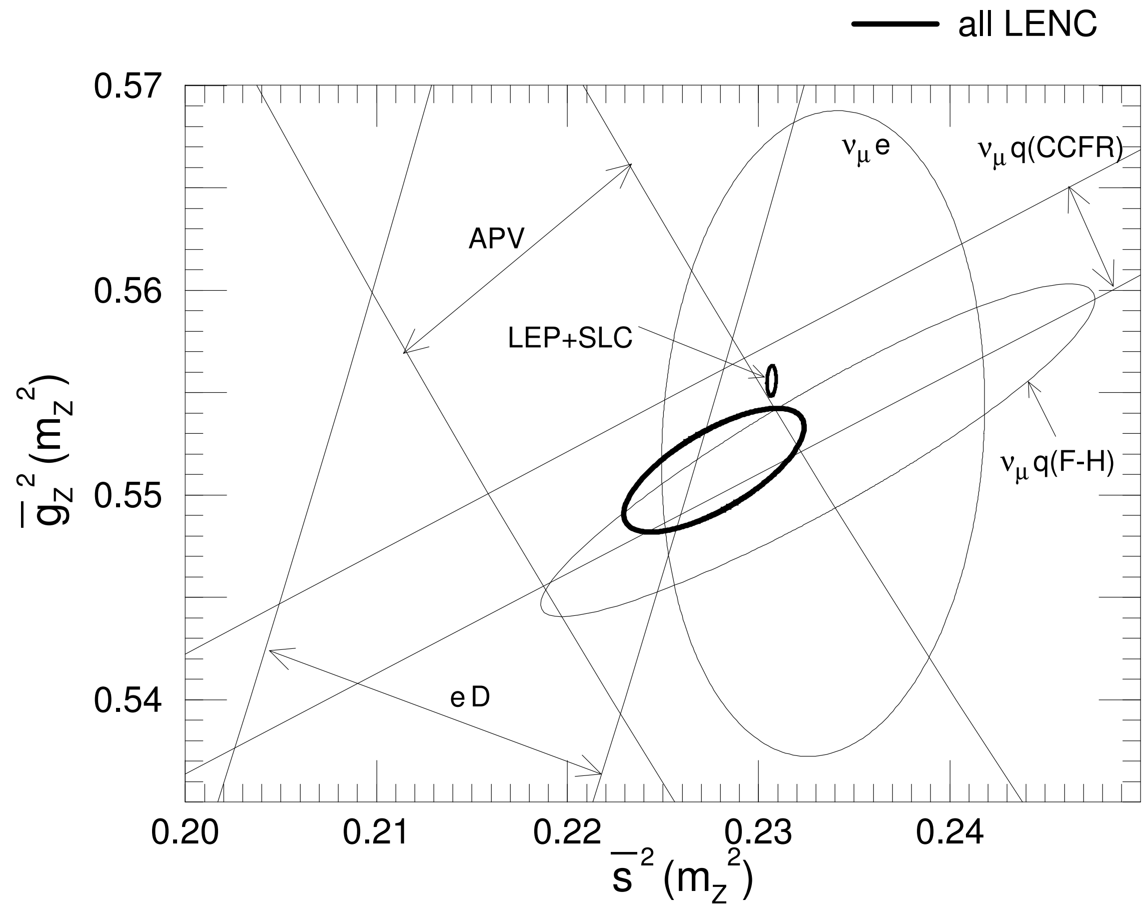


Figure 6: Comparison of low energy neutral current experiments.

all data on elastic $\nu_\mu e$ and $\overline{\nu}_\mu e$ scattering dominated by the CHARM experiment. The CCFR data define a band. The other two bands come from the (γ, Z)-interference experiments. All data agree well and the common fit is represented by the thick ellipse. The account of the radiative effects is essential for obtaining a good fit.

After the fixed target era the e^+e^- collider experiments took over and improved the precision by more than an order of magnitude as indicated by the tiny ellipse marked LEP,SLC. The impact of W and Z physics at LEP is outlined by Zerwas in ref. [20].

3.4. More Neutrinos

With the observation 1962 that two species of neutrinos exist, an asymmetry between the lepton and hadron world became apparent. The nucleon structure is scrutinized by the photon in ep scattering at SLAC and similarly by the $W^{\pm}$ in $\nu, \overline{\nu}N$ scattering with Gargamelle at CERN. This led 1973 to the identification of the partons with the quarks (u,d,s) and the gluon. The discovery of charm 1974 has restored the symmetric ordering between quarks and leptons. Gargamelle had found events with lepton and strange particle as clear hint to the production and decay of open charmed particles and similarly in a ν experiment at FNAL. The definite proof came from e^+e^- experiments.

Now the ordering scheme of the spin 1/2 fermions emerged clearly. They are represented in two families : (ν_e, e, u, d) and (ν_μ, μ, c, s). Neutrino experiments at the SPS and the Tevatron performed a detailed study of the charm changing current.

1975 the heavy lepton τ was observed at SLAC and interpreted as the first element of a third family. Data on $e^+e^- \to \tau\overline{\tau}$ made clear that the τ belongs to an iso-doublet, thus implying the existence of its neutral partner, the ν_τ. The measurement of the Z-decay width by the LEP experiments[33)] demonstrated unambiguously that there are exactly three light neutrinos.

Finally the DONUT[34)] Collaboration reported the first observation to the Sudbury Neutrino Conference in Canada (2000). An example is shown in Fig. 7. It is a

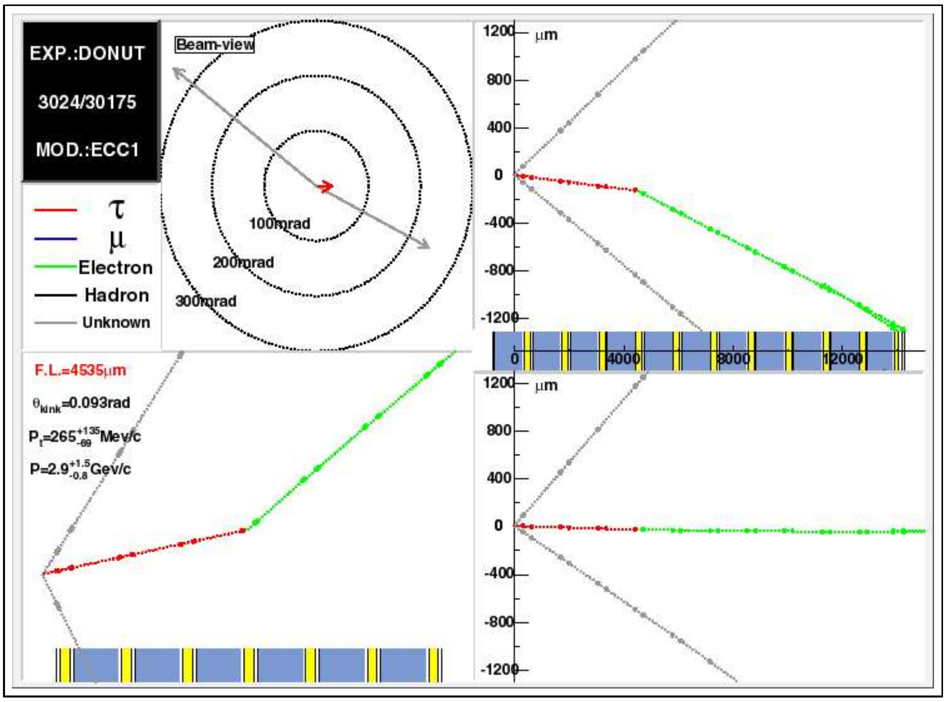


Figure 7: ν_τ event observed in the DONUT detector.

beam dump experiment generating a ν_τ beam according to $p + N \to D_s + anything$ followed by the decay $c\overline{s} \to \nu_\tau + x$. ν_τ-induced interactions $\nu_\tau + N \to \tau + anything$

in emulsions were scanned for 1-prong τ-decays (86 %).

4. Neutrino Astrophysics

4.1. The Solar Neutrino Puzzle

Ray Davis pioneered and first observed solar neutrinos. The attitude towards astrophysicists in the early period was not very encouraging. An expression attributed to Maurice Goldhaber says : *No astrophysicist can calculate anything with sufficient precision to be of any interest to any particle physicist.* This attitude gradually changed to the extent that today astroparticle physicists may claim to contribute precise measurements.

Davis could rely on important theoretical work by v.Weizsäcker(1937) and Bethe (1938) on energy production of stars, by Pontecorvo (1946) on the radiochemical process (ν capture) $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ and by Bahcall (1964) on the calculation of the solar ν-flux.

After first experimenting at the Savannah River Davis performed the chlorine experiment in the Homestake mine[30] and published 1968:

$$\Phi(meas)/\Phi(calc) \approx 0.3 \neq 1.$$

This is the solar neutrino problem. Its origin may be a

- problem in the measurement itself
- problem in solar nuclear fusion processes
- problem in particle physics

The first two possibilities were considered most likely. Further runs excluded the first possibility. Helioseismography supported the solar model. The chlorine experiments is only sensitive to a very small fraction of the solar neutrino flux, mainly the neutrinos from B decays. It was therefore desirable to perform experiments sensitive to the pp cycle of the sun. These experiments, namely GALLEX/GNO and SAGE, were performed much later and confirmed the deficit.

4.2. The Long Way to Neutrino Oscillations

$K^0 - \overline{K}^0$ mixing (1956) inspired Pontecorvo [31] to the idea of $\nu - \overline{\nu}$ oscillations. At that moment there was only one neutrino species. Many studies of the Kurie plot in β-decays have resulted in low upper limits for the ν-mass. For all practical purposes it was sufficient to set m_ν=0. However, there is no principle requiring the mass to be exactly zero.

After 1962, when two species of neutrinos were known, the possibility of neutrino mixing was systematically considered [32)]. The Homestake experiments gave the first hint to neutrino oscillations and the incentive to many subsequent experiments.

The mass eigenstates and the weak eigenstates are related by a unitary mixing matrix U analogously to quark mixing

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \quad (\alpha = \nu_e, \nu_\mu, \nu_\tau)$$

Propagation leads to oscillations

$$P_{\nu_\alpha \to \nu_\beta} = |\delta_{\alpha\beta} - \sum_{j=2}^{3} U_{\alpha j} U^*_{\beta j} (1 - e^{-2\pi i \ L/\lambda_{j1}})|^2$$

The oscillation length λ is defined as follows :

$$\lambda = 4\pi \frac{E}{\Delta m^2_{j1}} = 2.5 \text{ km } \frac{E}{\text{GeV}} \frac{\text{eV}^2}{\Delta m^2_{j1}}$$

The sensitivity to Δm_{j1} is related to L/E.

A priori there was no hint as to which part of the multi-parameter phase space should be investigated. The general prejudice, however, was to expect small values for the mixing angles.

In order to observe oscillations the ratio between the baseline L and the oscillation length λ

$$\frac{L}{\lambda} = 0.4 \frac{\Delta m^2}{eV^2} \frac{L/km}{E/GeV}$$

should be of $\mathcal{O}(1)$.

Short baseline experiments were carried out systematically at reactors and accelerators in the 70's and 80's. They explored Δm^2 down to 10^{-2}. The null results allowed to restrict the (Δm^2,$\sin^2 2\,\theta$)-plot. Some excitement came from the claim of a 30 eV ν_e-mass in the Moscow tritium β decay experiment and from the LSND experiment.

In the beginning 80's GUT theories motivated searches for proton decay. Various underground experiments were built : Nusex, IMB, Kamioka, Fréjus, Soudan. The japanese group at Kamioka pioneered a new technique and built a water Cerenkov detector. While pushing the upper limit for the proton lifetime a serious background from atmospheric neutrinos attracted more and more the experimental groups. The experiments turned into long baseline atmospheric neutrino experiments. The measurement $R(\mu/e)$ of the flux ratio μ/e relative to the theoretical expectation yielded inconclusive values between 0.5 and 1. The Kamioka result, for instance, measured $R \approx 0.5$, which implied, if interpreted in terms of neutrino oscillations, values for Δm^2 around 10^{-3} eV^2 and an unexpected large value for $\sin^2\theta$. Some hesitation came from the uncertainties in the simulation of the neutrino fluxes and the systematics in the detection of e and μ like events. The japanese groups increased their efforts and built a much larger detector, called Superkamiokande, and finally achieved the breakthrough.

4.3. Observation of ν Oscillations

At the Takayama neutrino conference 1998 the Kamioka/Superkamioka group gathered enough information to claim evidence of neutrino oscillations. The observation of the zenith angle distribution of the atmospheric $\nu, \overline{\nu}$ fluxes yielded compelling evidence. As seen in Fig. 8 for GeV neutrino energies there is a clear deficit of ν_μ in the up/down ratio, while there is no effect for ν_e [35]. The L/E ratio varies from about 15 km/GeV up to about 15000 km/GeV. The up/down ratio is robust against

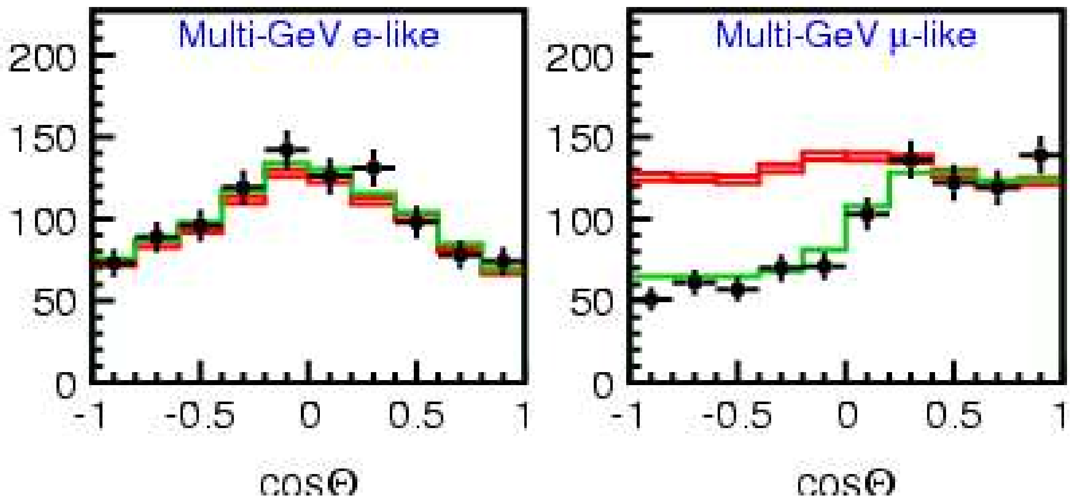


Figure 8: Zenith angle distribution.

systematics. The interpretation is $\nu_\mu \leftrightarrow \nu_\tau$ with large mixing angle. A confirmation came from the K2K experiment[36], which used the accelerator ν_μ beam of KEK directed to the 250 km distant detector at Kamioka.

4.4. Solar Neutrino Flux

The most precise measurement of the solar neutrino flux was performed by Superkamiokande [37] in the years 1996-2001 (see Fig. 9). The detector has a small energy threshold and with its directional information is capable of measuring neutrinos from the sun, mainly those from boron decay. The result is : $\Phi^B = 2.35 \pm 0.02 \pm 0.08\ 10^6$ cm^{-2}sec^{-1}. The observed electron is the result of elastic neutrino electron scattering and is induced by all neutrino species :

- $\nu_e + e \rightarrow \nu_e + e$ (via CC+NC)

- $\nu_{\mu,\tau} + e \to \nu_{\mu,\tau} + e$ (only NC)

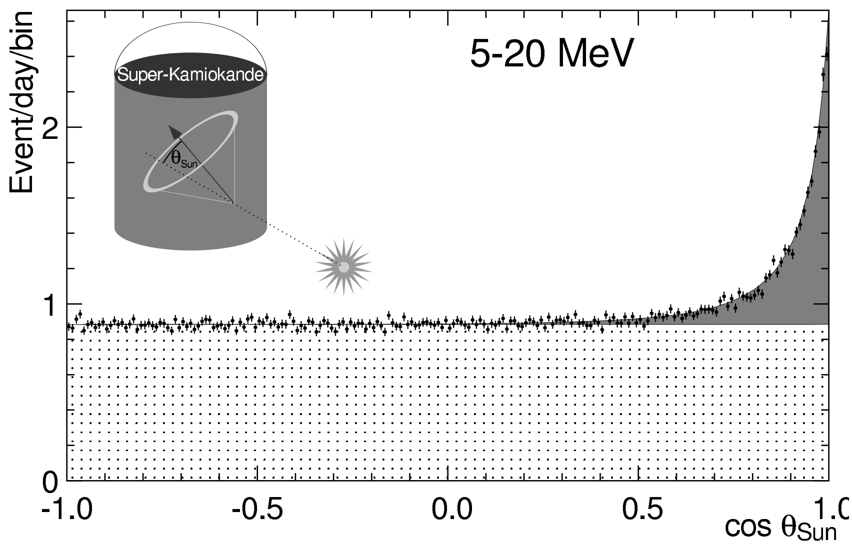


Figure 9: Observation of the solar neutrino flux.

For comparison : 1973 the first event $\overline{\nu}_\mu + e \to \overline{\nu}_\mu + e$ was observed in Gargamelle and the rate was 1 event per year.

4.5. The solution of the Solar Neutrino Puzzle

The first Neutrino Oscillation Conference at Venice (NO-VE) in 2001 was dedicated to the discussion of the brandnew results from the Sudbury Neutrino Observatory experiment SNO and their combination with SuperKamiokande. SNO was designed to measure three processes :

CC: $\nu_e + d \to e^- + p + p$

ES: $\nu + e^- \to \nu + e^-$

NC: $\nu + d \to \nu + p + n$

Arthur McDonald presented the results for the first two processes [38]. The measured fluxes in units of 10^6 cm^{-2}sec^{-1} were :

- $\Phi(\nu_e + d \to e^- + p + p) = 1.75 \pm 0.07 \pm 0.13$
- $\Phi(\nu + e^- \to \nu + e^-) = 2.39 \pm 0.34 \pm 0.16$
  in agreement with SuperKamiokande $2.35 \pm 0.02 \pm 0.08$

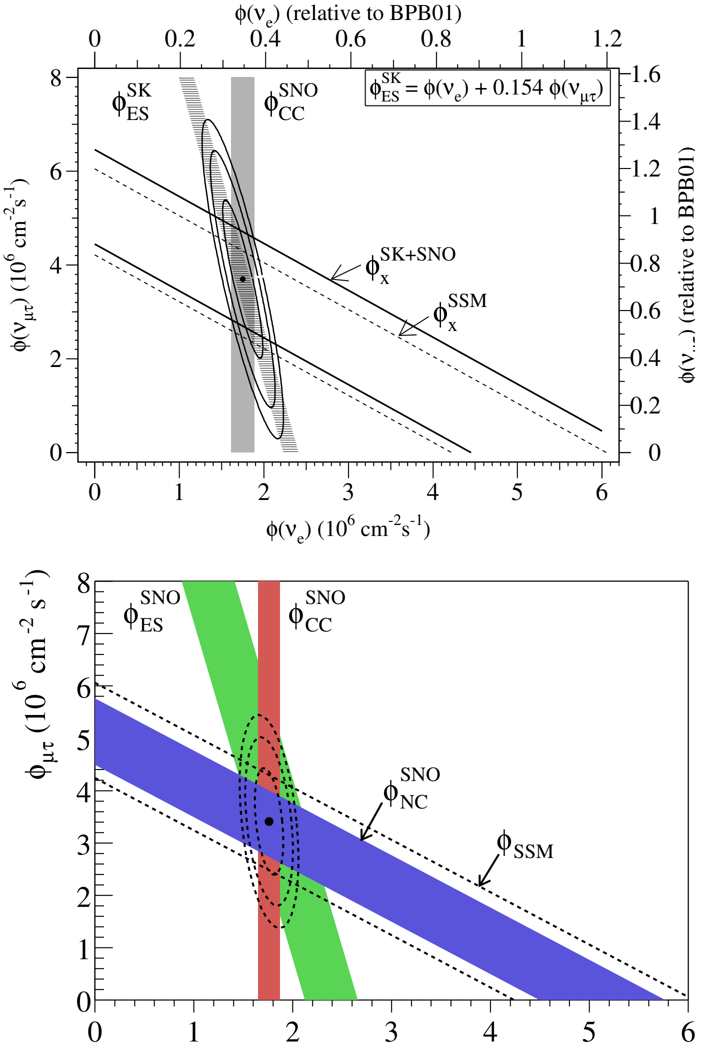


Figure 10: Above:First SNO measurements combined with Superkamiokande, below: Updated SNO results

Fig. 10 above illustrates the results. Note: $\Phi(\nu e) = \Phi(\nu_e e)+0.154\ \Phi(\nu_{\mu,\tau})$. This shows the crucial role of the neutral current contribution which enables to disentangle the ν_e component from the other contributions. An active oscillation component is established in agreement with Standard Solar Model. The solar neutrino problem is solved. In the following year the SNO collaboration also published the NC-reaction [39] : $\nu + d \rightarrow \nu + p + n$ and improved the statistics in the elastic channel (see Fig. 10 below). Thus, the solution to the solar neutrino puzzle can be summarized as follows :

- $\Phi^{CC}(\nu_e) \approx \frac{1}{3}\ \Phi_{theory}$
- $\Phi^{NC}(\nu)\ \approx\ 3\ \Phi^{CC}(\nu_e)$

It is interesting to note that the ^8B solar neutrinos exit the sun as nearly a pure ν_2 state because of matter effects[40].

4.6. Impact of Kamland

Kamland[41] is a multi-reactor long baseline experiment. They observed oscillatory behaviour (see Fig. 11). Kamland complemented with solar data isolates the *large*

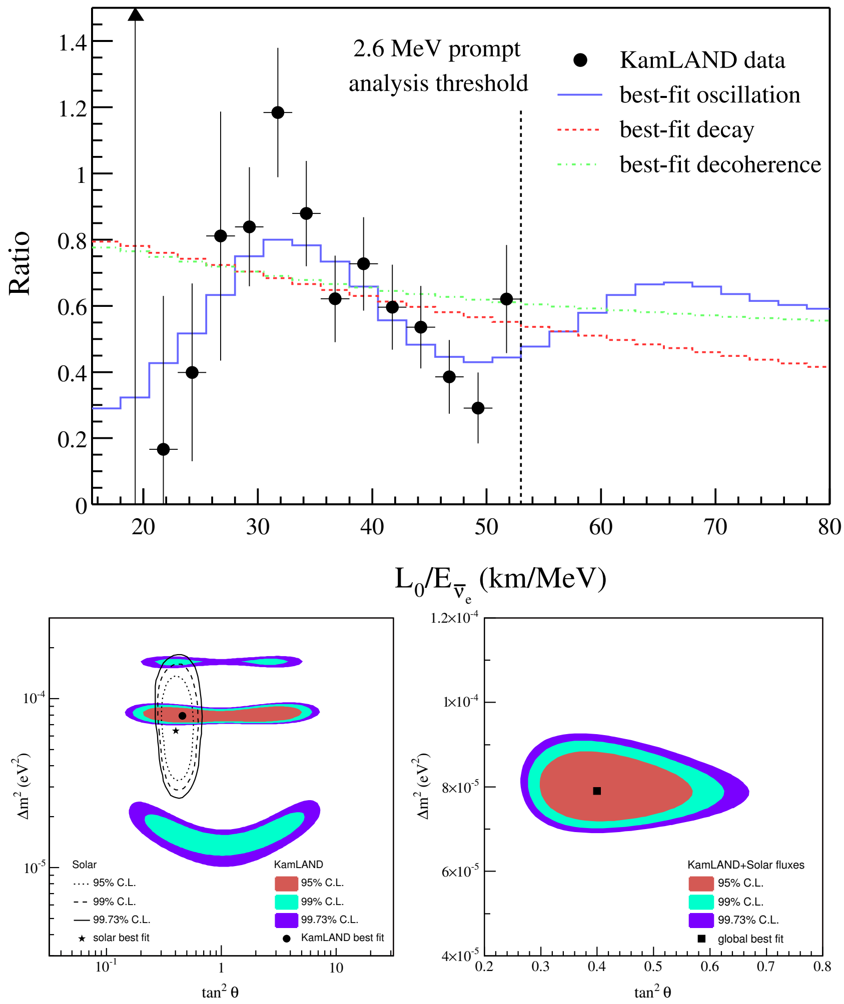


Figure 11: KamLAND results on L/E and the large mixing angle solution.

mixing angle solution.

4.7. Supernova SN1987A

An epochal event occurred 1987 : the neutrinos generated in the Supernova burst have been observed by the Superkamioka and IMB detectors. Wolfenstein's comment in last year's conference at Venice[42] was :

> *These neutrinos have been travelling for 150000 years from the Magellanic Cloud and arrived only shortly after the Kamioka and IMB detectors came into operation.*

5. Summary and Outlook

In the past half century the neutrino has shaped particle and astroparticle physics. It is the ideal messenger over cosmological distances. The early theory of weak interactions by Fermi evolved through a fast series of major discoveries into the electroweak gauge field theory. This is an outstanding accomplishment by theory and experiment. Many Nobel prizes go along with it.

There are still basic properties of the neutrino which remain to be settled. Is it a Majorana or a Dirac neutrino ? The answer is expected come from $\beta\beta$-experiments. The oscillation experiments have provided the mass differences between the neutrino species, but the absolute values are still unknown. Great efforts are made to further refine the tritium decay measurements with the hope to obtain eventually a finite mass value for ν_e or at least a stringent upper limit. A precise determination of the neutrino mixing matrix is a challenge, in particular the size of θ_{13} and the existence of phases, which would manifest CP violation. The question of sterile neutrinos which was brought up by the LSND experiment is about to be checked by MiniBoone.

A discrepancy at the level of 3 standard deviations between $\sin^2\theta_W$ from NuTev and the other measurements is still open.

Neutrino physics is an active field. There are many experiments in progress : Antares, Cuore, Genius, Icarus, Icecube, Minos, Nemo, Nestor, Opera, T2K, and others. On the long run a neutrino factory and Superbeams are envisaged.

In conclusion, neutrino physics has a bright future.

6. Acknowledgement

It is a pleasure to thank Prof. Milla Baldo-Ceolin for the invitation to this conferences celebrating the 50^{th} anniversary of the neutrino. This conference series at Venice constitutes a marvelous forum to meet experts and to discuss the latest results and ideas.

I like to thank Prof. P.M.Zerwas for valuable comments.

7. References

1) C.Cowan and F.Reines: *Science* **124** (1956) 103

2) H.Pietschmann: *Wolfgang Pauli - eine biographische Notiz*, Uni Wien Preprint 2000, UW ThPh-2000-18
3) L.Meitner and W.Orthmann: *Z.Phys.* **60** (1930) 143
4) H.Pietschmann: *George Marx Memorial lecture*, 2005, UWThPh-2005-8
5) L.M.Brown and H.Rechenberg, Nuclear structure and beta decay, *Am.J.Phys.* **56** (1988) 982
6) E.Fermi: *Z.Phys.* **88** (1934) 161
7) R.E.Marshak, E.C.G.Sudarshan, *Phys.Rev.* **109** (1958) 1860; R.P.Feynman and M.Gell-Mann, *Phys.Rev.* **109** (1958) 193
8) R.E.Marshak, E.C.G.Sudarshan, *Proc. Padua-Venice Conference on Mesons and Recently Discovered Particles*, pp V-14, 1957;
9) B.Kayser, hep-ph/0504052 (2005)
10) M.Baldo-Ceolin, *The discreet charm of the nuclear emulsion era*, Annual Review of Nuclear and Particle Science **52** (2002) 1-21
11) C.S.Wu, E.Ambler, R.W.Heyward, D.D.Hoppes, R.P.Hudson, *Phys.Rev.* **105** (1957) 1413
12) R.L.Garwin, L.M.Lederman, M.Weinrich, *Phys.Rev* **105** (1957) 1415; J.L.Friedman, V.L.Telegdi, *Phys.Rev* **105** (1957) 1681
13) M.Goldhaber, L.Grodzins, A.W.Sunyar, *Phys.Rev* **109** (1958) 1015
14) T.Ahmed et al., *Phys.Lett.* **B324** (1994) 241
15) A.Aktas et al., *Phys.Lett.* **B634** (2006) 173; ZEUS Collaboration: Contribution to *ICHEP Beijing*, EW 4-0256, 2004
16) A.Aktas et al., *Phys.Lett.* **B634** (2006) 173
17) G.Feinberg, *Phys.Rev.* **110** (1958) 1482
18) U.Mersits, CERN Preprint CHS-25 (1987)
19) D.Haidt and H.Pietschmann, *Electroweak Interactions - Experimental Facts and Theoretical Foundations*, Landolt-Börnstein **I10** (1988) 1
20) Prestigious discoveries at CERN, eds. R.Cashmore, L.Maiani and J-P.Revol, *Eur.Phys.J.* **34** (2003) 1
21) G.Gamow and E.Teller, *Phys.Rev.* **51** (1937) 289
22) S.L.Glashow, J.Iliopoulos, L.Maiani, *Phys.Rev.* **D2** 1285
23) G.'t Hooft, *Nucl.Phys.* **B35** (1971) 167; G.'t Hooft and M.Veltman, *Nucl.Phys.* **B44** (1972) 189;
24) F.J.Hasert et al., *Phys.Lett.* **B46** (1973) 138
25) S.L.Glashow, *Nucl.Phys.* **22** (1961) 579; A.Salam, in: Elementary Particle Theory, Stockholm 1969; S.Weinberg, *Phys.Rev.Lett.* **19** (1967) 1264
26) C.Rubbia, P.McIntyre, D.Cline, *Proceedings of the International Neutrino Conference*, Aachen 1976, eds.H Faissner; H Reithler; P Zerwas, p.683
27) D.Haidt, in *SPS Fixed Target Worksop* CERN-Yellow Report 83-02
28) K.Hagiwara, S.Matsumoto, D.Haidt, *Eur.Phys.J* **C2** (1998) 95
29) G.L.Fogli, D.Haidt, *Z.Phys.* **C40** (1988) 379
30) R.Davis Jr. et.al., *Phys.Rev.Letters* **20** (1968) 1205.
31) B.Pontecorvo, *Zh.Eksp.Teor.Fiz.* **33** (1957) 549

32) B.Pontecorvo: *Zh.Eksp.Teor.Fiz.* **53** (1967) 1717;
Gribov and B.Pontecorvo: *Phys.Lett.* **28B** (1969) 493

33) LEP Electroweak Working Group, hep-ex/0212036

34) DONUT Collaboration, http://www-donut.fnal.gov

35) Y.Ashie et al., A Measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I,hep-ex/0501064 (2005)

36) K2k Collaboration, http://neutrino.kek.jp

37) J.Hosaka et al., Solar Neutrino measurements by Super-Kamiokande I, hep-ex/0508053 (2005)

38) A.McDonald, in *Proceedings of the NO-VE International Workshop on Neutrino Oscillations at Venice*, ed. by M.Baldo-Ceolin, 2001, p.1

39) Q.R.Ahmad et al., *Phys.Rev.Lett.* **89** (2002) 011301

40) S.J.Parke, *Phys.Rev.Lett.* **57** (1986) 1275

41) T.Araki et al., Measurement of Neutrino Oscillations with KamLAND - Evidence of spectral distortion, hep-ex/0406035 (2004)

42) L.Wolfenstein, in *Proceedings of the 11-th International Workshop on Neutrino Telescopes at Venice*, ed. by M.Baldo-Ceolin, 2005, p.1