

## The third family of neutrinos

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This paper retraces the 24 years starting with the appearance of the symbol “ $\nu_\tau$ ” in 1977, until the observation of tau neutrino interactions with matter in 2000. The fact that the neutral particle present in tau decays was a neutrino was demonstrated by 1979; its existence as the third neutrino  $\nu_\tau$ , iso-spin partner of the tau lepton, was definitely established in 1981-1986; it was demonstrated that the number of light active neutrinos is closed with the known ones ( $\nu_e, \nu_\mu, \nu_\tau$ ) in 1989; the  $\nu_\tau$  properties had been precisely determined in  $e^+e^-$  and  $p\bar{p}$  collider experiments.

### 1 Summary

The initial tau lepton observation, in 1975 at SPEAR (Stanford Positron Electron Asymmetric Rings), was based on its decay into neutrinos together with electrons or muons [1] [2] [3]. It took a few more years to identify “ $\nu_\tau$ ”, the neutral, weakly (V-A)-interacting spin 1/2 particle [4] [5], observed also in two-body decays such as  $\tau \rightarrow \pi\nu$  [6] [7] [8], to be the isospin partner of the tau,  $\nu_\tau$ , distinct from  $\nu_e$  and  $\nu_\mu$ . In 1981 [9] the distinct existence of the tau neutrino could be established with moderate statistical significance, from the combination of non-observation of tau leptons in high energy neutrino beams [10] [11] with the first measurements of the tau lifetime [12]; PDG82 [13, 14] thus listed  $\nu_\tau$  as established particle. High significance was gained from i) more precise measurement of the tau lifetime by several experiments; ii) the observation of  $W \rightarrow \tau\nu_\tau$  [15][16] with the same rate as  $W \rightarrow e\nu_e$  and  $W \rightarrow \mu\nu_\mu$  [17]; and iii) the E531 emulsion neutrino experiment at Fermilab [18]. By the start of LEP (Large Electron Positron collider at CERN) in 1989, the tau-neutrino was a well-established particle.

Meanwhile, the impact of the number of light, active neutrinos on cosmology and astrophysics was appreciated, and the question of further families of neutrinos had become a critical input. A

number of measurements, from astrophysics to collider physics, pointed to a number of light active neutrinos,  $N_\nu$ , situated between 2 and 4 [19]. The number of light, active neutrinos was presented by the MARK-II experiment at the SLC [20] and from the first three weeks of data taking by the LEP collaborations L3 [21], ALEPH [22], OPAL [23] and DELPHI [24], in a grand seminar at CERN on 13 October 1989. The combined number  $N_\nu = 3.12 \pm 0.19$  [25] demonstrated that there are no further types of light active neutrinos than the three ( $\nu_e, \nu_\mu, \nu_\tau$ ) that were already known; the latest LEP value is  $N_\nu = 2.984 \pm 0.008$  [26].

A million of tau pairs were produced in Z decays by the LEP collaborations. The tau lifetime and branching ratios were determined with much increased precision, establishing the equality of the  $\tau - \nu_\tau$  coupling with those of the other lepton doublets [27], eventually reaching a precision of a few permil [28]. At LEP2, tens of thousands of W pair events were detected with a clear event-by-event kinematic reconstruction allowing determination of all three W lepton-neutrino couplings at the few percent level [29]. In 2000 the DONUT collaboration, in a dedicated beam containing 5% of the, by then well known, tau neutrino, made the first observation of its charged current interactions with matter [30, 31, 32].

This history leads to a reflexion on the scientific merit of the words *direct*, *indirect* and *discovery* that have sprinkled the history of the third and last light active neutrino. The words *direct* and *indirect* are quite subjective, and used in different ways for different problems; more quantitative gauges, i) the statistical (and systematic) significance, and ii) the possible model-dependence, should be preferred. As for “discovery”, its definition is “the act of finding something that was not known before”. In this definition the moment where the tau-neutrino was discovered (found to exist as a new particle) can be situated between 1981 at the earliest, with the first tau lifetime estimate; and at the latest and definitely in 1986, after it was shown that, while the tau lepton couples with full weak interaction strength to its neutrino, electron and muon neutrinos do not couple to it significantly.

## 2 The first appearance of the symbol “ $\nu_\tau$ ”

The history of the third family neutrino begins with the discovery of the third family lepton in the years 1975 to 1977 by M. Perl and the SLAC-LBL magnetic spectrometer collaboration, now known as MARK-I. A personal recollection of this time was given by G. Feldman in “the tale of three papers” [33] which contains many references of the time, and a step by step review of the physics arguments.

The heavy lepton search was based on the sequential lepton scheme,

$$e^+e^- \rightarrow L^+L^-; L^+ \rightarrow \mu^+\nu\nu \text{ and } L^- \rightarrow e^+\nu\nu \quad (1)$$

and combinations of charge and lepton flavour. The production and decay properties of such particles had been described by P. Tsai [34]. The characteristic signatures are two leptons of different flavours and, importantly, large amounts of missing energy and momentum going into neutrinos, as is clearly visible already on one of the first event displays, Fig. 1, left. We will here concentrate on the neutrinos. While the first MARK-I paper [1] focuses on the appearance of anomalous e- $\mu$  events, the second one [35] is mostly concerned with the demonstration of the fact that the new particle is a lepton. Here the presence of neutrinos in the final state is essential; they were identified by the absence in the anomalous e- $\mu$  events of photons or other electromagnetically decaying particles ( $\pi^0, \eta$  etc.), and of neutral hadrons, neutrons or  $K^0, \Lambda$ .

The new particle being established, it was given the name  $\tau$ , as explained in [33]: *it had to be Greek like the muon, so  $\tau$ , as in  $\tau\rho\iota\tau\omicron\nu$  (third), was chosen* – among other possibilities. This name appears in the third paper [3] (Fig 2) “Properties of the proposed  $\tau$  charged lepton”.

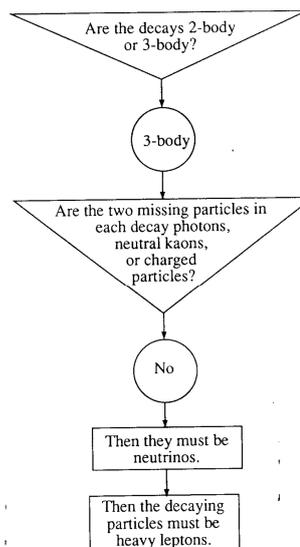
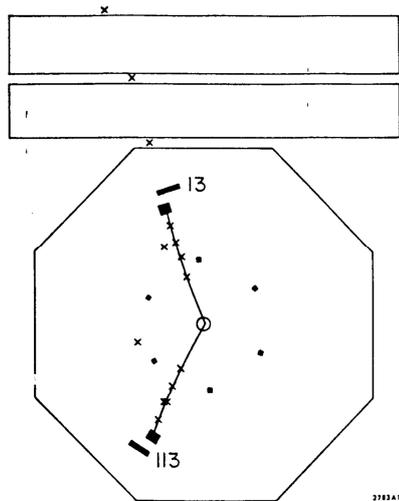


Figure 1: Left: One of the first  $e\text{-}\mu$  events with particle identification in the muon 'tower' and in the shower counters, as shown in the Stanford 1975 Lepton Photon Symposium. Right: the demonstration that the new particle is a lepton is based on the presence of neutrinos in the final state.

### PROPERTIES OF THE PROPOSED $\tau$ CHARGED LEPTON\*

M.L. PERL, G.J. FELDMAN, G.S. ABRAMS, M.S. ALAM, A.M. BOYARSKI, M. BREIDENBACH, J. DORFAN, W. CHINOWSKY, G. GOLDBABER, G. HANSON, J.A. JAROS, J.A. KADYK, D. LÜKE<sup>1</sup>, V. LÜTH, R.J. MADARAS, H.K. NGUYEN<sup>2</sup>, J.M. PATERSON, I. PERUZZI<sup>3</sup>, M. PICCOLO<sup>3</sup>, T.P. PUN P.A. RAPIDIS, B. RICHTER, W. TANENBAUM, J.E. WISS

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The anomalous  $e\mu$  and 2-prong  $\mu x$  events produced in  $e^+e^-$  annihilation are used to determine the properties of the proposed  $\tau$  charged lepton. We find the  $\tau$  mass is  $1.90 \pm 0.10 \text{ GeV}/c^2$ ; the mass of the associated neutrino,  $\nu_\tau$ , is less than  $0.6 \text{ GeV}/c^2$  with 95% confidence;  $V - A$  coupling is favored over  $V + A$  coupling for the  $\tau - \nu_\tau$  current; and the leptonic branching ratios are  $0.186 \pm 0.010 \pm 0.028$  from the  $e\mu$  events and  $0.175 \pm 0.027 \pm 0.030$  from the  $\mu x$  events where the first error is statistical and the second is systematic.

Figure 2: The first appearance of the symbol  $\nu_\tau$  [3].

Together with it, without much further ado, appears the symbol " $\nu_\tau$ " as in "We find the  $\tau$  mass is  $1.90 \pm 0.10 \text{ GeV}/c^2$ ; the mass of the associated neutrino  $\nu_\tau$  is less than  $0.6 \text{ GeV}/c^2$  with 95% confidence;  $V-A$  coupling is favored over  $V+A$  coupling for the  $\tau - \nu_\tau$  current;" etc.

The fact that the  $\tau$  lepton behaved as expected from a sequential heavy lepton could certainly justify the presumption that the additional neutral particle, that had to be there in the three body leptonic decays  $\tau \rightarrow e/\mu \nu e^-/\mu^- \nu$  in addition to the anti-neutrino of the same flavour as the tagging lepton ( $e/\mu$ ) would be the  $\tau$ 's weak isospin partner,  $\nu_\tau$ . However this was not a fool-proof demonstration, and there could be other hypotheses. This caused a general and long lasting impression

that the existence of the tau neutrino had been 'inferred' rather than properly demonstrated. We will see that a solid demonstration would take place from then to 1986.

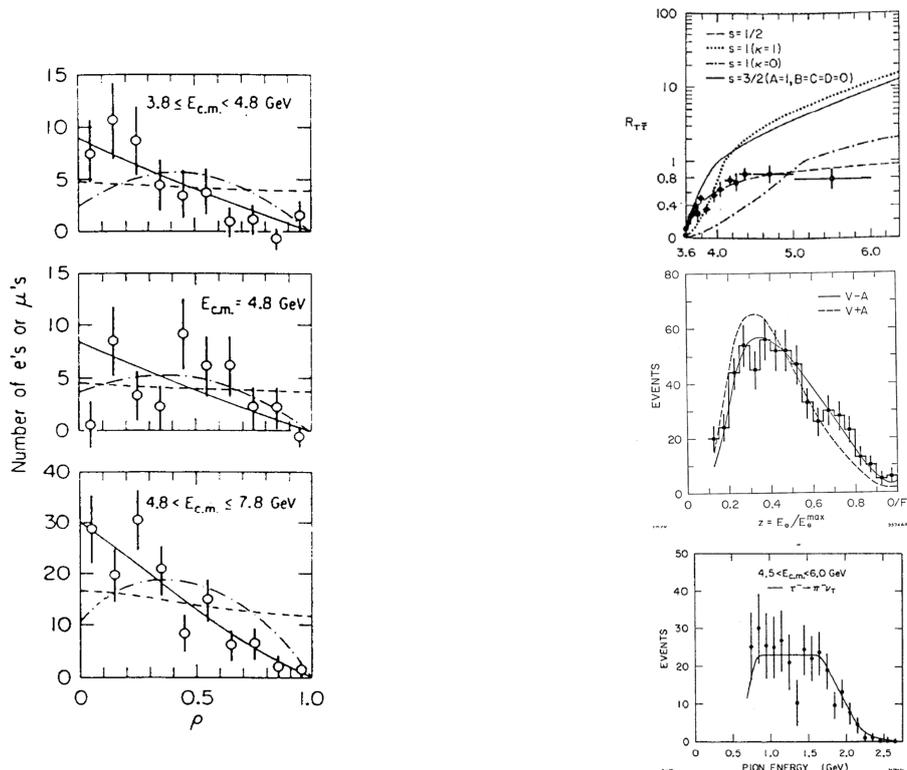


Figure 3: Left: normalized spectra ( $\rho = p/p_{\text{beam}}$ ) of the leptons in the anomalous  $e\text{-}\mu$  events, showing that the V-A coupling is favored over V+A coupling for the  $\tau\text{-}\nu_\tau$  current. Right, top: the tau cross-section from 3.5 to 6.5 GeV  $e^+e^-$  center-of-mass energy (ECM), demonstrating that the new particle is a spin 1/2 lepton [5]; middle: The full lepton spectrum consistent with V-A in DELCO [5]; bottom: the momentum spectrum of pions in the decay  $\tau \rightarrow \pi\nu$ , showing consistency with the neutrino has a mass  $< 250 \text{ MeV}/c^2$ .

### 3 “ $\nu_\tau$ ” is a neutrino

During the following four years (1977-1981), measurements of cross-section and decays by MARK-I, MARK-II, DELCO, at SPEAR, PLUTO and DASP at DORIS (Hamburg), (individual references can be found in the PDG, 1982 edition [13]) were performed. They readily showed the following, also summarized in Fig. 3.

- The tau decays into leptons and two neutrinos and the decay is V-A [3, 5].
- The tau pair cross section raises sharply from the threshold around 3.5 GeV and reaches quickly the same level as that of muon pairs, demonstrating that the tau lepton itself is a spin 1/2 particle [5].
- It was reported already in 1977 [6] [7] [8], that the tau decays into hadron and one neutrino, in particular  $\tau \rightarrow \pi\nu$ , with a two body decay – this is a very direct proof of the existence of a single spin 1/2 neutral particle, the spin 1/2 tau cannot decay into a spin 0 pion and a spin 3/2 (or more) particle [5].
- The tau was also observed to decay in  $\rho\nu, K^*\nu, A_1\nu$  etc... in a way that is consistent with the weak hadronic current. In particular the  $K^*/\rho$  ratio is consistent with the Cabbibo angle, a trademark of the weak hadronic current.

- Further studies of the  $\tau \rightarrow \pi\nu$  decay [8] showed excellent agreement with the two body hypothesis with an upper limit on the mass of the “ $\nu_\tau$ ” of  $250 \text{ MeV}/c^2$ .

All this established the “ $\nu_\tau$ ” particle as a spin 1/2 neutral lepton interacting by V-A interactions, and with a mass consistent with zero within the experimental resolution. This is what we call a neutrino.

The situation at that point was comparable to that preceding the 1962 Brookhaven neutrino experiment [36], for which Lederman, Schwartz and Steinberger were awarded the Nobel Prize in 1988. There was no question in the late fifties that there was a neutrino produced in the two body decay  $\pi^\pm \rightarrow \mu^\pm(\nu/\bar{\nu})$ , see Fig. 4. The question was whether this neutrino was the same as in beta-decay ( $\nu_e$ ) or whether it was a neutrino of a new kind. Similarly for the “ $\nu_\tau$ ” in the late seventies, the question was not whether there was a neutrino in e.g.  $\tau \rightarrow \pi\nu$  decays, but whether it was one of a new kind.

There was however a very significant difference: producing a 99% pure beam of “ $\nu_\tau$ ” would be extremely difficult and it was out of reach at the time – and still is difficult. So that another method had to be found, to demonstrate that the “ $\nu_\tau$ ” is a new particle and not  $\nu_e, \nu_\mu$  or some mix or superposition thereof.

**OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE  
OF TWO KINDS OF NEUTRINOS\***

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(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^\pm \rightarrow \mu^\pm + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used pro-

duce  $\mu$  mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in  $\beta$  decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

Figure 4: The first page of the Brookhaven neutrino experiment of 1962 [36].

## 4 A new neutrino?

Is it possible that the “ $\nu_\tau$ ” would not be the weak isospin partner of the tau? Yes.

At the same epoch, (1977-1981) the b-quark had been discovered, decaying into charm and not into a new third generation quark, because the top quark is heavier than the b quark. As a consequence the b decay is suppressed by the CKM element (“mixing angle”)  $V_{cb}$ , and the b-meson lifetime was indeed found to be much longer than would be expected given its mass [37, 38].

The same thing could happen with the tau lepton, for instance if  $\nu_\tau$  were heavier than the tau lepton. Then what had been initially called “ $\nu_\tau$ ” would be indeed a  $\nu_e$  or  $\nu_\mu$  or some mix or superposition thereof. Parenthetically, it had been also proposed that the “ $\nu_\tau$ ” would be either  $\bar{\nu}_e$  or  $\bar{\nu}_\mu$ ; however this would have affected either the corresponding leptonic partial widths, challenging their already observed equality and/or their relation to the  $\pi\nu$  decay mode [39]; this would have eventually been also ruled out later, once the tau neutrino helicity had been measured. In the following we concentrate on the hypothesis that the “ $\nu_\tau$ ” would be indeed a  $\nu_e$  or  $\nu_\mu$  or some mix or superposition thereof.

This hypothesis would imply that: i) the tau lifetime would be longer than predicted if a 100%  $\tau - \nu_\tau$  is assumed; ii) because the tau would couple to  $\nu_e$  and/or  $\nu_\mu$ , taus could be produced in neutrino beams of sufficient energy; the kinematic threshold being 3.5 GeV neutrino energy, beams at the CERN SPS or Fermilab Tevatron, with typical energies of 20 GeV or more, would do it.

To demonstrate that the tau neutrino was a the weak isospin partner of the tau one should therefore demonstrate both of the following.

1. Show that the coupling of the tau to its neutrino has the full weak interaction strength – this could be done by measuring the tau lifetime, and from this and from the branching ratio into  $e\nu\nu$  extract the  $\tau \rightarrow e\nu\nu$  partial width and, *mutandis mutandi*, show that the coupling strength is the same as that of the muon; alternatively show that the W boson decays into  $W \rightarrow \tau\nu$  with the same rate as  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$ .
2. Show that neither  $\nu_e$  nor  $\nu_\mu$  couple to the tau.

The tau lifetime measurements can be made in  $e^+e^-$  experiments with sufficient beam energy and if the tracking device can measure a significantly positive impact parameter for the tau lepton decay products. Experiments at the time did not have the precise silicon vertex detectors that are now customary in collider experiments. In addition, in the energy range of SPEAR and DORIS (from threshold to 7 GeV) the tau lepton velocity was too small to observe a significant life-time. The first measurements were made at the higher energy  $e^+e^-$  colliders PETRA at DESY and PEP at SLAC, with TASSO [40] from 12 to 31.6 GeV ECM, and MARK-II [12] at 29 GeV ECM respectively. The detectors were drift chambers of 200-300 micron r- $\phi$  point resolution situated 10-15 cm from the beam axis. In 1981 the existing measurements averaged to  $(4.6 \pm 1.9) \times 10^{-13} s$ , for the lifetime and  $16.2 \pm 1.0\%$  for the  $e\nu\nu$  branching ratio [13].

The search for production of tau leptons (and more generally heavy leptons) in neutrino interactions was already started in 1977, in the 15-foot cryogenic bubble chamber at Fermilab, filled with liquid neon [10]. The liquid neon having a radiation length of 40 cm and interaction length of 1 m, all in a magnetic field of 3 T, it was readily possible to identify prompt electrons and prompt muons from hadrons. The tau production signal would be production of an excess of prompt electrons at high energies (over the intrinsic contamination from the beam). In a sample of 27600 charged current  $\nu_\mu$  interactions, 187  $e^-$  and 28  $e^+$  were observed against an expectation of  $215 \pm 60 \nu_e$  and  $23 \pm 8 \bar{\nu}_e$  interactions from the beam calculations. Hence an upper limit on coupling strength of  $\nu_\mu$  to the tau must be less than 0.025 of the coupling strength of  $\nu_\mu$  to the muon.

The limit for the direct coupling of electron neutrinos to the tau was more difficult to achieve, and would require either a good positive identification of the tau, which would come later, or a higher fraction of electron neutrinos in the beam. The latter was achieved using a beam dump neutrino beam, in which the component of neutrinos from pion and kaon decays is reduced by a factor 1000 to 3000 by using a large copper dump where the interaction length is much shorter than their decay length. Remain neutrinos from charm or b decays. For the CERN beam of 400 GeV protons, b production is still very small and so is the prompt tau neutrino production. Charm itself produces essentially equal rates of muon and electron neutrinos. CERN ran beam dump experiments in 1977-1979, with dumps of various density to make it possible to interpolate to infinite density. The Big European Bubble Chamber, BEBC, filled with a neon-hydrogen mixture of density 0.71 for a radiation length of 44 cm, observed a signal of 15-20 prompt electron and muon neutrinos, confirming charm production in hadronic interactions. A tau signal would manifest itself by an increase of events classified as neutral current interactions, because of hadronic tau decays. No such excess was observed and a limit of 0.35 at 90% C.L for the  $\nu_e - \nu_\tau$  mixing was set. The authors also concluded that “the hypothesis that the  $\nu_e - \nu_\tau$  are identical would lead to

DOES THE  $\nu_\tau$  EXIST?

We are finally ready to show that the  $\nu_\tau$  exists independently of a specific theoretical framework. Let us assume that it does not exist. We know from the momentum spectrum of  $\tau$  decay products that there is an unseen light spin 1/2 particle in the final state. If the  $\nu_\tau$  does not exist, this must be either the  $\nu_e$  or the  $\nu_\mu$ . Then the  $\tau$  must couple via the weak current to the linear combination  $(\epsilon_e \nu_e + \epsilon_\mu \nu_\mu)$ , where the  $\epsilon$ 's are normalized so that either  $\epsilon = 1$  gives the normal full strength weak coupling. From the absence of excess electrons in the final states of  $\nu_\mu N$  interactions,<sup>40</sup>

$$\epsilon_\mu^2 < 0.025 \quad \text{at 90\% C.L.} \quad , \quad (15)$$

and from the absence of apparent excess neutral currents in the BEBC beam dump experiment,<sup>41</sup>

$$\epsilon_e^2 < 0.35 \quad \text{at 90\% C.L.} \quad . \quad (16)$$

Combining (15) and (16),

$$\epsilon_\mu^2 + \epsilon_e^2 < 0.375 \quad \text{at 90\% C.L.} \quad , \quad (17)$$

but from either the Mark II or TASSO  $\tau$  lifetime measurement,

$$\epsilon_\mu^2 + \epsilon_e^2 > 0.398 \quad \text{at 90\% C.L.} \quad . \quad (18)$$

Figure 5: Reproduction of the section of G. Feldman's conference paper explaining that the existence of the tau neutrino can be demonstrated by confronting the upper limit on the tau life time (i.e. lower limit on the coupling) with the upper limit on the rate of electron and muon neutrino coupling to the tau in neutrino beam experiments.

an anomalously high neutral current / charged current (NC/CC) ratio for  $\nu_e$  and  $\bar{\nu}_e$ . Using the value reported above this hypothesis can be excluded at the 90% confidence level".

This conclusion did not cover, of course, the more realistic hypothesis described in the early part of this section, of mixing with a heavier state. This would require a measurement of the tau lifetime.

In 1981, Feldman concluded that the first measurements of the tau lepton lifetime combined with the absence of tau production in e.g. these neutrino experiments, excluded that the " $\nu_\tau$ " could be entirely made of a mix or superposition of  $\nu_e$  and/or  $\nu_\mu$  [9]. The argument is reproduced in Fig. 5. It followed from this that the " $\nu_\tau$ " could not be entirely composed of the known  $\nu_e$  and/or  $\nu_\mu$  and was likely to comprise a new neutrino. To modern eyes and eighties alike, the statistical significance provided by two 90% C.L. exclusions almost touching each-other was not very strong.

PDG1982 [13] faithfully reported the milestone achieved by the tau neutrino, by elevating it to the status of "established stable particle", although qualifying the achievement of 'indirect'. Feldman's paper was quoted – to this day (5 September 2018) it has been cited a total of 5 times. Apparently, the question whether the tau neutrino existed was considered too evident to capture the passion of the masses, and the answer was a bit involved. Be as it may, this same wording would remain in the full listing until 2002, although much more significant evidence would be gathered in the following few years.

# TABLES OF PARTICLE PROPERTIES

April 1982

M. Aguilar-Benitez, R.L. Crawford, R. Frosch, G.P. Gopal, R.E. Hendrick, R.L. Kelly, M.J. Losty,  
L. Montanet, F.C. Porter, A. Rittenberg, M. Roos, L.D. Roper, T. Shimada, R.E. Shrock, T.G. Trippe, Ch. Walck, C.G. Wohl, G.P. Yost

(Closing date for data: Jan. 1, 1982)

## Stable Particle Table

For additional parameters, see Addendum to this table.

Quantities in italics have changed by more than one (old) standard deviation since April 1980.

Particle	$I^G(J^P)C_q^a$	Mass <sup>b</sup> (MeV) Mass <sup>2</sup> (GeV <sup>2</sup> )	Mean life <sup>b</sup> (sec) or (cm)	Partial decay mode		
				Mode	Fraction <sup>b</sup>	$p$ or $p_{max}^c$ (MeV/c)
PHOTON						
$\gamma$	$0,1(1^-)$	$<6 \times 10^{-22}$	-----	stable		
LEPTONS						
$\nu_e$	$J=\frac{1}{2}$	$<0.000046^d$	stable ( $>3 \times 10^8 m_{\nu_e}$ (MeV))	stable		
$e$	$J=\frac{1}{2}$	$0.5110034$ $\pm 0.0000014$	stable ( $>2 \times 10^{22}y$ )	stable		
$\nu_\mu$	$J=\frac{1}{2}$	$0 (<0.52)$	stable ( $>1.1 \times 10^5 m_{\nu_\mu}$ (MeV))	stable		
$\mu$	$J=\frac{1}{2}$	$105.65943$ $\pm 0.00018$ $m^2=0.01116392$	$2.19714 \times 10^{-6}$ $\pm 0.00007$ $cr=6.5868 \times 10^4$	$\mu^- \rightarrow \mu^- \nu \bar{\nu}$ (or $\mu^+ \rightarrow \mu^+ \nu \bar{\nu}$ )	(98.6 ± 0.4)%	53
				$e^- \bar{\nu} \nu$	(1.4 ± 0.4)%	53
				$e^- \nu \bar{\nu}$	( $<9$ )%	53
				$e^- \nu \mu$	( $<1.9$ ) $\times 10^{-10}$	53
				$e^- e^+ e^-$	( $<1.9$ ) $\times 10^{-9}$	53
$\nu_\tau$	$J=\frac{1}{2}$	$<250$				
$\tau$	$J=\frac{1}{2}$	$1784.2$ $\pm 3.2$ $m^2=3.18$	$(4.6 \pm 1.9) \times 10^{-13}$ $cr=0.014$	$\tau^- \rightarrow \tau^- \nu \bar{\nu}$ (or $\tau^+ \rightarrow \tau^+ \nu \bar{\nu}$ )	(18.5 ± 1.2)%	889
				$e^- \bar{\nu} \nu$	(16.2 ± 1.0)%	892
				hadron <sup>-</sup> neutrals	(37.0 ± 3.2)%	
				3(hadron <sup>2</sup> ) neutrals	(28.4 ± 3.0)%	
				5(hadron <sup>2</sup> ) neutrals	( $<6$ )%	
				†[3(hadron <sup>2</sup> ) $\nu$ ]	(13 ± 8)%	
				3(hadron <sup>2</sup> ) $\nu$ ( $\geq 1\gamma$ )	(15 ± 7)%	
				† $\pi^- \nu$	(10.7 ± 1.6)%	887
				$\rho^- \nu$	(21.6 ± 3.6)%	726
				$K^-$ neutrals	(small)	
				$\pi^- \pi^+ \nu$	(7 ± 5)%	864
				$\pi^- \pi^+ (\geq 0\pi^0) \nu$	(18 ± 7)%	864
†[ $K^* (892) \nu$ ]	(1.7 ± 0.7)%	669				
$K^* (1430) \nu$	( $<0.9$ )%	316				
$\pi^- \rho^+ \nu$	(5.4 ± 1.7)%	718				

(continued next page)



### 36 NU-TAU(J=1/2)

EXISTENCE INDIRECTLY ESTABLISHED FROM TAU DECAY DATA  
COMBINED WITH NU REACTION DATA. SEE FOR EXAMPLE  
FELDMAN 81. KIRKBY 79 RULES OUT J=3/2 USING  
TAU --> PI NUTAU BRANCHING RATIO.

NOT IN GENERAL A MASS EIGENSTATE. SEE NOTE ON NEUTRINOS  
IN THE ELECTRON NEUTRINO SECTION ABOVE.

Figure 6: PDG1982: the title and the Stable Particle Table, showing for the first time the tau neutrino as an established, stable particle, with spin 1/2,  $m < 250$  MeV (from  $\tau \rightarrow \pi \nu$  decay). The life time measurement is still poor. A large number of hadronic decays is reported; the  $K^* \nu / \rho \nu$  decay ratio is consistent with the Cabibbo angle, a trademark of the hadronic weak decay. At the bottom is reproduced the full listing entry, indicating that the tau neutrino existence is *indirectly* established, referring to Feldman's paper.

## 5 The tau neutrino is established

In the following years the ingredients to the demonstration of existence of the tau neutrino as a particle distinct from the  $\nu_e$  and/or  $\nu_\mu$  and isospin partner of the tau would be gathered. More precise measurements of the tau lifetime, and a more dedicated search for neutrino charged current events with a tau in the final state were made.

## 5.1 Improvements in $\tau$ lifetime measurements

The lifetime measurements of charm, b and tau were of great interest and dedicated vertex chambers were built. This effort was pioneered by the MARK-II collaboration with a high resolution drift chamber [41], soon followed by the TASSO and MAC experiments for an average of  $3.3 \pm 0.4 \cdot 10^{-13} \text{s}$  in the 1986 PDG average [42], a factor 7 better than that of 1981. Together with the tau to electron branching ratio of  $17.4 \pm 0.5 \%$ , this established that the tau coupling to the “ $\nu_\tau$ ” was consistent with that of the muon to its neutrino at a level of precision of  $\pm 10 \%$ .

## 5.2 W decays

After the 1983 discovery in the UA1 and UA2 experiments of the W in the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  channels, search continued in particular in the hope of finding the top quark or signals of supersymmetry by means of the missing energy and transverse momentum signatures. Those of us who were listening to that channel at that time will remember that such missing events were indeed reported, and caused some excitement [43], until it was realized that what had been observed was the ‘Altarelli Cocktail’ [44] composed mainly of  $W \rightarrow \tau\nu$  and Z decays into neutrinos accompanied with jets. See Di Lella for a recent recollection [45] and this delightful quote: *Experimenters and theorists alike should stop wishful thinking about new physics and [...] start a serious, quantitative background evaluation.* I let the reader project this moral to his favorite, more recent, situations.

In 1985 the UA1 collaboration reported a handful of  $W \rightarrow \tau\nu$  candidates [15, 16], with a hadronic Jet on one side and missing transverse momentum in the other, as in the example given in Fig. 7. The ratio of decay fractions to taus and electrons was measured to be  $\Gamma_{W \rightarrow \tau\nu} / \Gamma_{W \rightarrow e\nu} = 1.01 \pm 0.2 \pm 0.13$ , a “direct” measurement of the universality of couplings as predicted in the sequential lepton hypothesis and the Standard Model.

What appeared at the time like a revenge of the Standard Model, was actually an important moment in the history of the tau neutrino, for its production in (real or virtual) W decay is what is used today as a definition of the neutrino flavour, (Fig. 7, right).

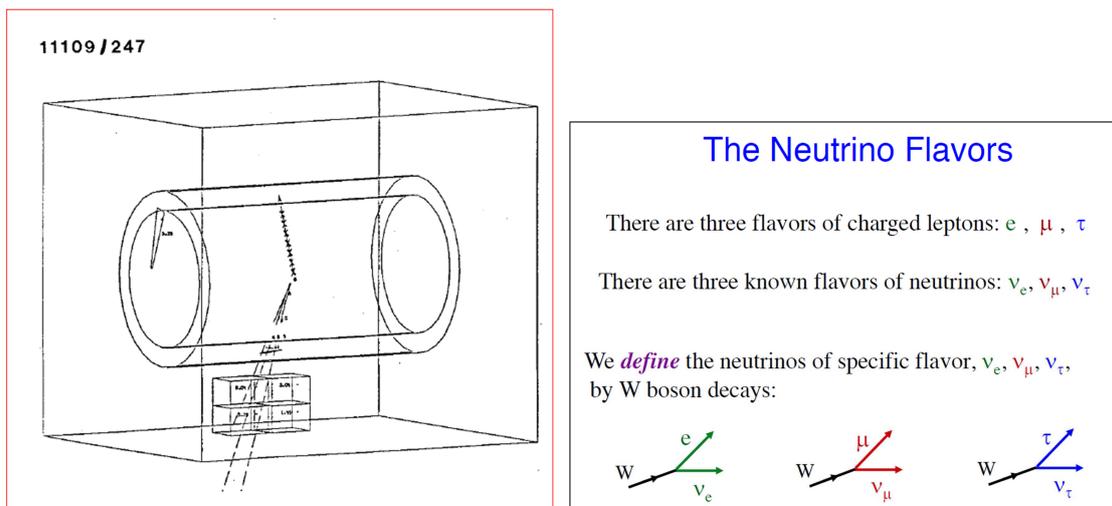


Figure 7: Left: Observation in UA1 of the W decay  $W \rightarrow \tau\nu$  with the tau decaying into 3 pions and a missing transverse momentum of 40 GeV. Right: the definition of neutrino flavour from the W decay (B. Kayser, VII<sup>th</sup> Pontecorvo School, August 2017).

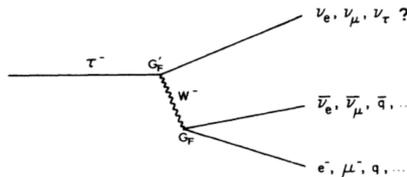
A major improvement came from the Fermilab E531 neutrino experiment [18]. E531 was designed to measure the lifetimes of charmed particles produced by the Fermilab neutrino beam and produced lifetimes for the  $D^0$ ,  $D^\pm$ ,  $F^\pm$ , and  $\Lambda_c^+$ . This time the tau signature could be “direct”, namely a secondary vertex and no other prompt lepton. In this way both the electron neutrino and muon neutrinos contained in the beam could be used as normalisation to set a limit. Having seen no tau neutrino candidate event out of 1870  $CC_{\nu_\mu}$  events with an identified muon and an estimated 53  $CC_{\nu_e}$  events, the collaboration could proceed put strong limits of 0.002 (0.073) for the direct coupling of the  $\nu_\mu$  ( $\nu_e$ ) to the  $\tau$ , see Fig. 8. With the same argument as Feldman’s in comparison with the tau lifetime, this paper was able to establish at the  $\approx 8\sigma$  level that most tau decays must contain a neutral lepton other than  $\nu_e$  and  $\nu_\mu$ .

(The Fermilab E531 Collaboration)

(Received 19 August 1986)

We have located 3886 neutrino interactions in the fiducial volume of a hybrid emulsion spectrometer installed in the Fermilab wide-band neutrino beam. A search for  $\tau^-$  decays yielded no candidate, resulting in an upper limit of 0.002 (0.073) for direct coupling of  $\nu_\mu$  ( $\nu_e$ ) to  $\tau^-$ . The  $\nu_\mu$  ( $\nu_e$ ) to  $\nu_\tau$  limits to mass differences and mixing angles ( $\alpha$ ) between the neutrinos are at maximum mixing  $\Delta M^2 < 0.9$  (9.0)  $eV^2$ , and at maximum sensitivity  $\sin^2(2\alpha) < 0.004$  (0.12). The direct-coupling limits are also used to show that most  $\tau^-$  decays must contain a neutral lepton other than  $\nu_\mu$  or  $\nu_e$ .

PACS numbers: 14.60.Gh

FIG. 3.  $\tau$ -decay diagram.

The direct-coupling limits can also be used to indicate that  $\tau^-$  decays produce  $\nu_\tau$ . If we use the description of  $\tau^-$  decay implied by Fig. 3, in which it is assumed that the  $\tau^-$  couples directly to a neutrino, the semileptonic decay width<sup>16</sup> of the  $\tau^-$  is given (on the assumption of universal Fermi coupling) by

$$\Gamma(\tau^- \rightarrow l^- \bar{\nu}_l \nu_x) = G_F^2 m_\tau^5 / 192 \pi^3 \\ = 4.132 \times 10^{-10} \text{ MeV.}$$

Combining the measured<sup>8</sup>  $\tau$  semileptonic branching ratios and lifetime gives an average semileptonic decay width of  $(3.5 \pm 0.5) \times 10^{-10}$  MeV, which is consistent with the above calculation.

$$\Gamma(\tau^- \rightarrow l^- \bar{\nu}_l \nu_e / \nu_\mu) = G_F^2 m_\tau^5 / 192 \pi^3,$$

where  $G_F^2 = G_F R(e^-/\mu^-)$ . This yields the following upper limits (90% C.L.) for the semileptonic decay width, on the assumption of this direct coupling:

$$\Gamma(\tau^- \rightarrow l^- \bar{\nu}_l \nu_\mu) < 8.3 \times 10^{-13} \text{ MeV,} \\ \Gamma(\tau^- \rightarrow l^- \bar{\nu}_l \nu_e) < 3.0 \times 10^{-11} \text{ MeV,}$$

as compared with the experimental average of  $(3.5 \pm 0.5) \times 10^{-10}$  MeV mentioned above.<sup>18</sup> Thus, direct coupling to  $\nu_e$  and  $\nu_\mu$  cannot dominate the  $\tau$ -decay diagram shown in Fig. 3, indicating that the  $\tau$  decays into something else, most likely the  $\nu_\tau$ .<sup>19</sup>

Figure 8: Abstract of the E531 paper and cuttings from the section where the comparison of the tau leptonic partial width – extracted by combining the tau lifetime (expressed here in MeV) and the tau leptonic branching fraction, with upper limits on the couplings obtained from the non observation of tau production in the  $(\nu_e, \nu_\mu)$  neutrino beam, leads to the conclusion that most of decays of the tau, whose lifetime agrees with full weak interaction coupling to its neutrino, must produce a new neutral lepton, most probably the  $\nu_\tau$ .

Thus the neutral spin 1/2 particle observed in tau decays, which has all the properties of a neutrino, interacts with the tau with a strength that is within 10% of that of the full V-A weak interaction, which is distinct from  $\nu_e$  and  $\nu_\mu$  and nearly orthogonal in the quantum sense of it, had been established as the isospin partner of the tau lepton.

**In 1986, the existence of the tau neutrino was solidly established.**

## 5.4 Discussion

I had not been personally involved in any of the papers that are quoted earlier although I did sign a few of the MARK-II papers. I got interested in the question, and had several discussions with Jack Steinberger, Friedrich Dydak and Tony Pich, while preparing actively in 1988-1989, as ALEPH physics workshop convener, to execute the measurement of the number of neutrino families – would we discover the tau neutrino? Having recently moved offices (Aug. 2018) I retrieved a few papers that I had been reading at that time; below are a few quotes – all calling for a 'direct' experiment to observe tau neutrino interactions.

- B. Barish and R. Stroynowski [46]: *Measurements of the lifetime of the  $\tau$  plus these (reference to E531) limits provide indirect evidence that the  $\nu_\tau$  is distinct from  $\nu_e$  and  $\nu_\mu$ . On the other hand, there have been no direct observations of  $\nu_\tau$ , that is, interactions resulting from neutrinos produced in tau lepton decay.*
- Friedrich Dydak [47]: *However the  $\nu_\tau$  remains today's best established yet unobserved particle...*
- Antonio Pich [48] (After a couple paragraphs summarizing the knowledge of the existence of the tau neutrino as distinct from  $\nu_e$  and  $\nu_\mu$ , including quote to E531): *However, no direct observation of  $\nu_\tau$ , that is, interactions resulting from neutrinos produced in tau decay, has been done so far.*
- Denegri, Sadoulet and Spiro [19]: *Until now the direct detection of neutrinos has been achieved only for  $\nu_e$  and  $\nu_\mu$ . The third generation  $\nu_\tau$  has not yet been directly observed through its characteristic interactions with matter. The evidence for  $\nu_\tau$  as an independent species, with (universal) Fermi coupling (...), is indirect. It is obtained from the tau lifetime (references) or (...) from the W partial production cross-section ratios (...) (reference to UA1).*
- K. Winter [49]: *Does the tau-neutrino exist as a particle? Surprisingly, this question cannot be answered by yes or no. Its existence can be proved by direct observation of the charged current reaction  $\nu_\tau + N \rightarrow \tau^- + X$ . (N.B.: this paper was originally presented at a conference in Russia in March 1989 and published in Acta Physica Hungarica 68 (1-2) pp. 135-143.)*

So there seems to have been a collective feeling of dissatisfaction at the way the tau neutrino had been discovered, and the desire for a 'direct' observation of tau neutrino interactions with matter was widely expressed. It is difficult to trace the origin of this desire, except for the impression that the tau neutrino should be properly discovered like the other neutrinos by their interaction with matter.

One thing is certain: none of these calls was backed up by a reference that would explain what, from this observation, would be learned that was not already known. Also, most of these papers refer to the E531 paper, although not necessarily in the quote above.

In all the arguments above two primary facts are missing:

1. The tau had actually been *observed* to decay into a neutrino, for which the question was not of its existence but of its nature; nature which had taken until 1986 to firmly establish, by a combination of several experimental facts.
2. The tau having been shown factually to be decaying into some neutrino state " $\nu_\tau$ ", it is clear that if one could make a beam of " $\nu_\tau$ ", they would NECESSARILY interact giving taus with a rate related to the tau lifetime, irrespective of the nature of " $\nu_\tau$ ", for instance whether it is a coherent superposition or mixing of  $\nu_e$  and  $\nu_\mu$  or pure  $\nu_\tau$ .

So why was the existence of the tau neutrino declared 'established indirectly'? My first reaction was to assimilate 'direct' with a mountain itinerary. Direct would be that which was simplest, indirect would be a more complicated route – though maybe easier. In scientific term, maybe direct would mean 'can be understood using zero or one equation'. Then 'indirect' proof would require two or more equations. In that case there would be no scientific hierarchy between direct and indirect and an indirect proof would be just as good.

There seemed to be more to it. After giving it a bit of thought I concluded that 'indirectly' could in this case only be *defined* by contrast with the 'direct' "observation of  $\nu_\tau$ , **that is**, (i.e. *by definition*), interactions resulting from neutrinos produced in tau lepton decay". In this case like in many others the word 'direct' has a context-sensitive definition, and 'indirect' being its opposite, is even worse.

We had several discussions on this topic with Jack Steinberger before and after he received his Nobel Prize in fall 1988. He consistently considered that the existence of the tau neutrino having already been established, (for which he referred to "that Fermilab experiment") we couldn't discover it a second time. More later.

## 6 What is the number of families of neutrinos?

At the time SLC at Stanford and LEP at CERN started, the basic properties of the weak interaction were already well known. One pressing question, however, could not be answered either by theoretical arguments or by direct experiments: what is the number of families of fermions? LEP answered this fundamental question, at least for the light active neutrinos, in a few weeks by measuring the Z resonance. With six years of data and meticulous measurements of luminosity and energy the LEP experimentalists determined the Z boson mass and width, as well as the Z decay rates, with a precision which is unlikely to be surpassed soon.

All elementary quarks and leptons that have been observed are organised in *exactly* three families: (or generations).

$$\begin{array}{ll}
 \begin{pmatrix} u \\ d' \end{pmatrix} & \begin{pmatrix} c \\ s' \end{pmatrix} & \begin{pmatrix} t \\ b' \end{pmatrix} & \text{doublets of left – handed quarks} \\
 \\
 \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} & \text{singlets of right – handed quarks} \\
 \\
 \begin{pmatrix} \nu_e \\ e \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} & \text{doublets of left – handed leptons} \\
 \\
 \begin{pmatrix} ?\nu_e \\ e \end{pmatrix} & \begin{pmatrix} ?\nu_\mu \\ \mu \end{pmatrix} & \begin{pmatrix} ?\nu_\tau \\ \tau \end{pmatrix} & \text{singlets of right – handed leptons}
 \end{array}$$

As far as we can tell the Electroweak theory could not easily accommodate further isolated fermions, but it could accommodate any number of families of the same type. One could easily envisage a situation where many families including heavy charged quarks and leptons could exist, without these heavy leptons being ever produced in accessible experiments, by lack of available energy. Nevertheless, since the known neutrinos are very light, it is natural to expect that these additional families would include light neutrinos as well, leading to the possibility that many families of light neutrinos would exist.

The existence of many light neutrinos would have considerable cosmological consequences. In particular, the evolution of the universe within the first second after the Big Bang would be profoundly affected. The argument, developed in [50], is the following. At the time where energies are large enough, reactions such as  $e^+e^- \rightarrow \nu\bar{\nu}$  transform a fraction of available energy

into neutrinos in a democratic way. The creation of neutrons and protons however is controlled by reactions involving the electron neutrino, such as  $\nu_e + n \rightarrow p + e^-$ , and is consequently very sensitive to the number of light neutrino families,  $N_\nu$ , which compete with electron neutrinos. The relative abundance of Hydrogen, Deuterium and Helium, and therefore the entire chemical constitution of our universe is a sensitive function of this number.

Before SLC and LEP started, limits on the number of light neutrinos were given from the above cosmological considerations, since there are data on the relative abundance of various nuclei in the universe, in particular the ratio of helium to hydrogen, or, with similar arguments, from the time development of the supernova 1987A. There were also indications from the direct search for the process  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  (single-photon experiments), or from the early measurements of the Z and W boson properties in the CERN and Fermilab  $p\bar{p}$  experiments. A review of these constraints published in 1989 [19] evaluated the best estimate of  $N_\nu$  to be  $N_\nu = 2.1^{+0.6}_{-0.4}$ , and stated that “ $N_\nu = 3$  is perfectly compatible with all data, but four families still provide a reasonable fit”.

In searching for further families of neutrinos, it will be assumed that their couplings are the same as those of  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ . Universality is deeply embedded in the Standard Model, identical multiplets having the same coupling constant. It is very well verified for charged current interactions of  $e$ - $\mu$ - $\tau$  leptons, including the neutrinos, and for neutral current interactions of charged leptons.

## 7 Determination of the number of light neutrino species at LEP and SLC

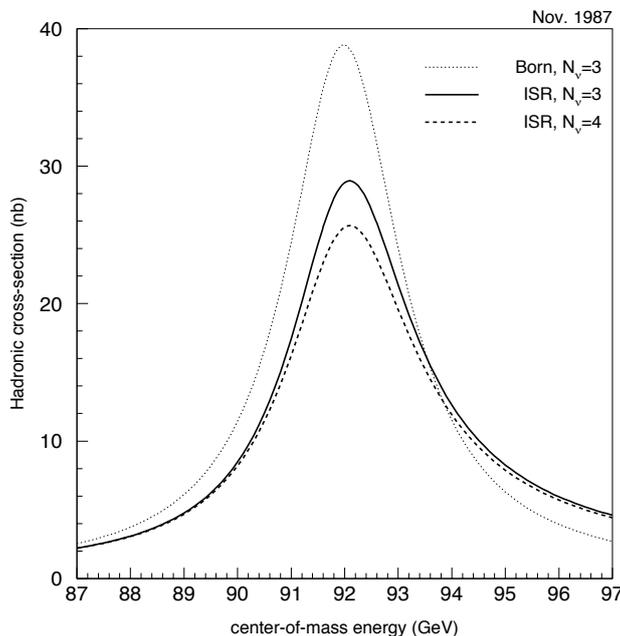


Figure 9: The  $e^+e^- \rightarrow$  hadrons cross section as a function of center-of-mass energy. This curve was drawn in 1987, before LEP start-up. At that time the Z mass was measured to be around 92 GeV with an error of 1.5 GeV. The dotted line represents the Born approximation prediction for three species of light neutrinos. The full line includes the effect of initial state radiation. The dashed line represents the effect of adding one more type of light neutrino with the same couplings as the first three. It is clear from this picture that the cross-section at the peak of the resonance contains most of the information on the number of light neutrino species.

The most precise determination of the number of light neutrino species is obtained from measurements of the visible cross-sections of  $e^+e^-$  annihilation at and around the Z resonance, as is made explicit in figure 9. If the Z is allowed to decay into more types of light neutrinos which will lead to an invisible final state, it will decay less often into the visible ones.

The realization that the visible cross-sections might be sensitive to the number of light neutrinos is rather ancient, one finds the question asked in John Ellis “Zedology” [51]: *The Z peak is large and dramatic, as long as there are not too many generations of fermions. Is it conceivable that there might be so many generations as to wash out the Z peak?* Since at that time the bound on the number of light neutrinos was very weak (about 6000), this certainly was a frightening possibility for those planning to build LEP! Dramatic also were the few first weeks of SLC and LEP operation where it was quickly realized that the Z peak was there indeed, large and dramatic, and that, alas, the number of light neutrinos was three.

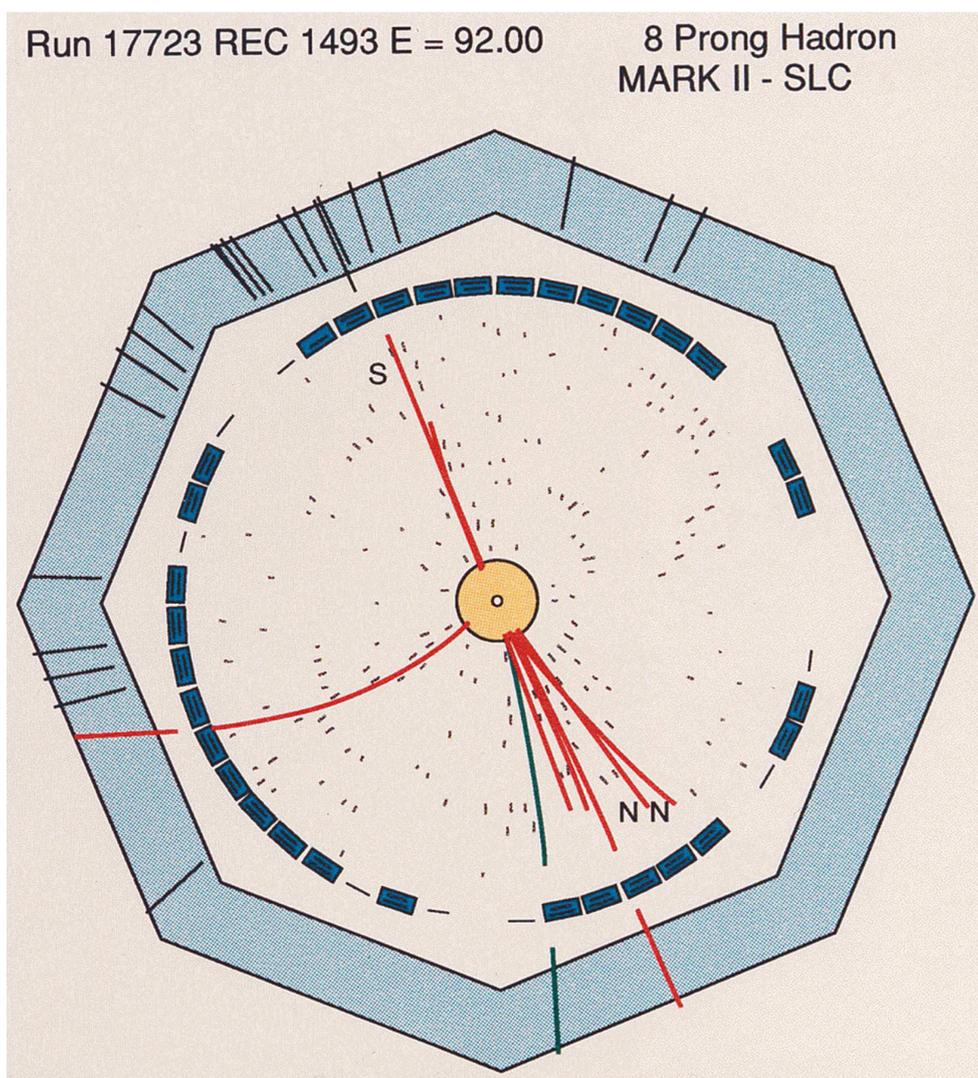


Figure 10: *The First hadronic Z decay recorded in the MARK-II detector at the SLC on 12 April 1989.*

There was intense competition between the SLC at SLAC (California, USA) and LEP at CERN (Switzerland). The two projects were rather different in concept. LEP was built as the largest possible conventional  $e^+e^-$  storage ring, with a circumference of 27 km. This standard technique would ensure few surprises and a reliable high luminosity. SLC on the other hand, was the prototype of a new concept of accelerator, the linear collider; it was re-using the old Stanford linac, with improvements in the acceleration technique (SLED) and addition of arcs to

bring  $e^+$  and  $e^-$  in collisions, as well as of challenging positron source and damping rings.

The commissioning of SLC started in early 1987, and led to a number of technical difficulties, not surprising in retrospect for such a new project. The first Z hadronic decay was produced on April 11 1989, and recorded in the MARK-II detector (see fig. 10). Luminosity was very low, a few  $10^{27}/\text{cm}^2/\text{s}$ , leading to a few Z hadronic decays per day. With the LEP start-up advertised for the 14 of July, the time where SLC would hold the lead was going to be short, and intense. Nevertheless the SLC collaboration was able to collect a total of 106 Z decays by 24 July and submit a publication [52], where the Z mass was determined to be  $M_Z = 91.11 \pm 0.23$  GeV, and the number of light neutrinos species  $N_\nu = 3.8 \pm 1.4$ .

Table 1: First results from LEP and SLC on the Z mass and the number of light neutrino species, as published around 12 October 1989 (in order of submission to the journal).

Experiment	hadronic Zs	Z mass (GeV)	$N_\nu$
MARK-II	450	$91.14 \pm 0.12$	$2.8 \pm 0.60$
L3	2538	$91.13 \pm 0.06$	$3.42 \pm 0.48$
ALEPH	3112	$91.17 \pm 0.05$	$3.27 \pm 0.30$
OPAL	4350	$91.01 \pm 0.05$	$3.10 \pm 0.40$
DELPHI	1066	$91.06 \pm 0.05$	$2.4 \pm 0.64$
Average		$91.10 \pm 0.05$	$3.12 \pm 0.19$

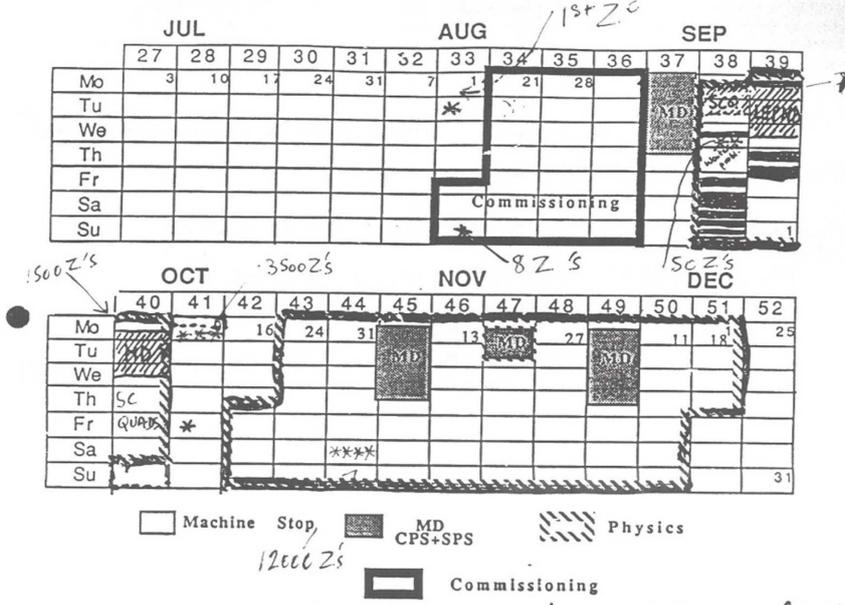
LEP had first beams on 14 of July and collisions on 8 August for one week. The LEP 1989 schedule is shown on Fig. 11. The high luminosity optics were however not yet commissioned and events came at a rate of 1 a day for the four experiments; this was not enough to make a measurement. Running resumed on 20 September with superconducting quadrupoles and in just three weeks, until 9 October, around 3000 Zs were collected in each of the experiments. By 13 October, a seminar was organized at CERN where the four collaborations presented their first results: L3 [21], ALEPH [22], OPAL [23] and DELPHI [24]; the results are compiled in Table 1. The day before, SLC had organized a public conference where updated MARK-II [20] competitive results had been presented. The “online average” of these results is also shown in Table 1,  $N_\nu = 3.12 \pm 0.18$ . The number of light neutrinos was three.

Following this important contribution, SLC was shaken by an earthquake on 24 October 1989, from which it took more than a year to recover, and then concentrated on polarized beam physics. LEP went on, to the end of 1989 and for 6 more years (1989 to 1995), each experiment collecting 4 million hadronic Z decays. With the final results now available, the number of light neutrinos determined to be  $N_\nu = 2.9841 \pm 0.0082$  [26].

The early results were unexpectedly precise, and the precision of final ones exceeded by a factor 100 the expectations that could be found in the studies preceding the start of LEP. Once the method is explained in more detail, it will become clear that the unexpected capacity of the experiments to perform precise measurement of hadronic cross-sections is the reason for this success.

To finish this section let me quote the conclusion of the ALEPH paper [22]: “The demonstration that there is a third neutrino confirms that the  $\tau$  neutrino is distinct from the  $e$  and  $\mu$  neutrinos. The absence of a fourth light neutrino indicates that the quark-lepton families are closed with the three which are already known except for the possibility that higher order families have neutrinos with mass in excess of 30 GeV.” The first sentence had been written by Jack Steinberger; I wrote the second one. This latter statement is now also demonstrated for quarks, the fact that the Higgs boson at the LHC is produced by gluon-gluon fusion at the expected cross-section ruling out that further families of quarks heavier than the top contribute to this loop diagram.

# 1989 LEP SCHEDULE



- NOTES
- a) The LEP stop due to the PS and SPS MD of 11-14 Sept. will be extended to the 18th Sept. at noon to allow the repair of the L3 TEC.
  - b) The October stop will take place from the 8th to the 19th October. It is however possible for the injectors to supply leptons to LEP during the 8th October. There is therefore a possibility to delay the start of the LEP October stop by one day if need be.
  - c) In addition to the October shutdown there will be possibilities of access to LEP during parts of the CPS+SPS MD periods.
  - d) All CERN accelerators have to be turned off at 6 am on 22nd December at the latest.

Figure 11: The 1989 LEP schedule as shown to ALEPH collaboration by Jorg Wotschack. The Z event numbers recorded in ALEPH are shown, starting on 13 August 1989.

## 8 Determination of the Z line shape parameters

Around the Z pole, the  $e^+e^- \rightarrow Z \rightarrow f\bar{f}$  annihilation cross-section is given by:

$$\sigma_f = \frac{12\pi(\hbar c)^2}{M_Z^2} \frac{s\Gamma_e\Gamma_f}{(s - M_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{M_Z^2}} \quad (2)$$

which is a general formula for a spin one particle produced in  $e^+e^-$  annihilation into a visible channel  $f$ . This typical resonance shape peaks around the Z mass,  $\sqrt{s} = M_Z$ , and has a width  $\Gamma_Z$ . If the Z decays a fraction  $B_f$  of the time into a final state  $f$  the corresponding partial width is defined as  $\Gamma_f = B_f\Gamma_Z$ .

The Standard Model predicts the numerical values for the Z partial widths, as displayed in table 2. The main decay mode of the Z is into hadrons (70%), each of the leptons representing only 3% and three neutrinos would contribute 20%. There are no other substantial decay modes unless there are new particles; the Higgs branching ratio, in particular, is very small. In this

L3  
hadrons

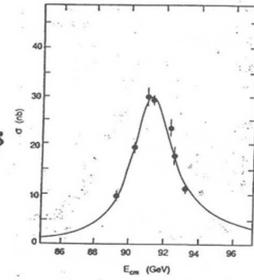


Fig. 7. Measured cross section for  $e^+e^- \rightarrow \text{hadrons}$  as a function of  $\sqrt{s}$ . Data are shown with statistical errors only. The curve shows a fit to the Cahn formula [13] in which  $M_{Z^0}$  and  $\Gamma_{\text{hadrons}}$  were left free. The normalization was floated within the quoted 6% systematic error. The widths  $\Gamma_{\text{hadrons}}$ ,  $\Gamma_{\text{lep}}$ ,  $\Gamma_{\text{tot}}$  and  $\Gamma_{\text{hadrons}}$  were taken from the standard model.

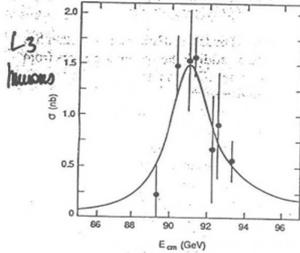


Fig. 8. Measured cross section for  $e^+e^- \rightarrow \mu^+\mu^-$  as a function of  $\sqrt{s}$ . The solid line is the standard model fit. Data are shown with statistical errors only.

ALEPH  
hadrons

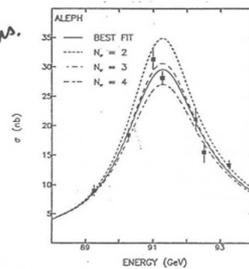
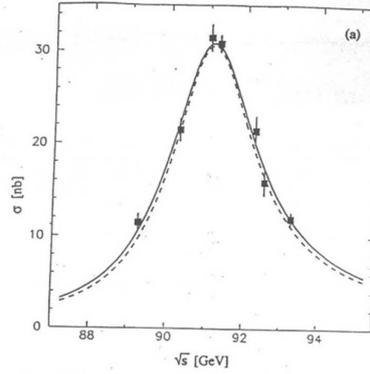


Fig. 5. The cross-section for  $e^+e^- \rightarrow \text{hadrons}$  as a function of centre-of-mass energy and result of the three parameter fit.

OPAL



"My line-shape  
is the prettiest of all"

Tatiana Faberé  
Theory christmas Party 1989

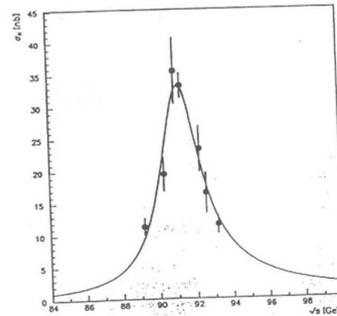


Fig. 4. The measured  $Z^0$  peak. The data points and the fit are described in the text.

DELPHI hadrons

Figure 12: The 1989 LEP line shapes as presented in the seminar on 13 October 1989. A comment extracted from the 1989 CERN Theory Christmas party is also reported (from lectures given in Cargèse 1990).

expression the number of neutrinos intervenes through the total Z width  $\Gamma_Z$ :

$$\Gamma_Z = 3\Gamma_\ell + \Gamma_{\text{had}} + N_\nu\Gamma_\nu \quad (3)$$

If  $N_\nu$  increases, the total width which is in the denominator of equation 2 increases, and the cross-section is decreased.

The equation 2 receives a number of modifications to account for the contribution of the photon exchange process (this is less than one percent), and more importantly what is called 'initial state radiation' (ISR), in which one or both of the initial state electrons lose energy into photons. This phenomenon reduces the initial state energy and smears out the resonance significantly as can be seen in figure 9. Due to the availability of calculations up to second order in perturbation theory, this large (30% at the peak) effect can be corrected for with a relative precision of  $5 \times 10^{-4}$ .

The principle of the analysis is then as follows: all visible channels are detected by large acceptance detectors and classified according to four categories: i) hadrons, ii) electron pairs,

Table 2:

Numerical values of quantum numbers, neutral current couplings, and Z decay partial widths, for the four types of fermions, for hadrons and total width. The value of  $\sin^2 \theta_w^{\text{eff}}$  is 0.2315.

$f$	$I_{3f}$	$Q_f$	$g_{Af}$	$g_{Vf}$	$\Gamma_f$ (MeV)
$\nu$	1/2	0	1/2	1/2	167
$e$	-1/2	-1	-1/2	-0.04	84
$u$	1/2	2/3	1/2	0.19	300
$d$	-1/2	-1/3	-1/2	-0.35	383
$b$	-1/2	-1/3	-1/2	-0.35	376
hadrons = $u + d + c + s + b$	–	–	–	–	1740
total for three neutrinos	–	–	–	–	2500
total for four neutrinos	–	–	–	–	2670

iii) muon pairs, iv) tau pairs. Examples of such events are shown in figure 13. These events are easy to detect, with high and well known efficiencies (as high as  $99 \pm 0.05\%$  for hadronic decays), and to separate from each other.

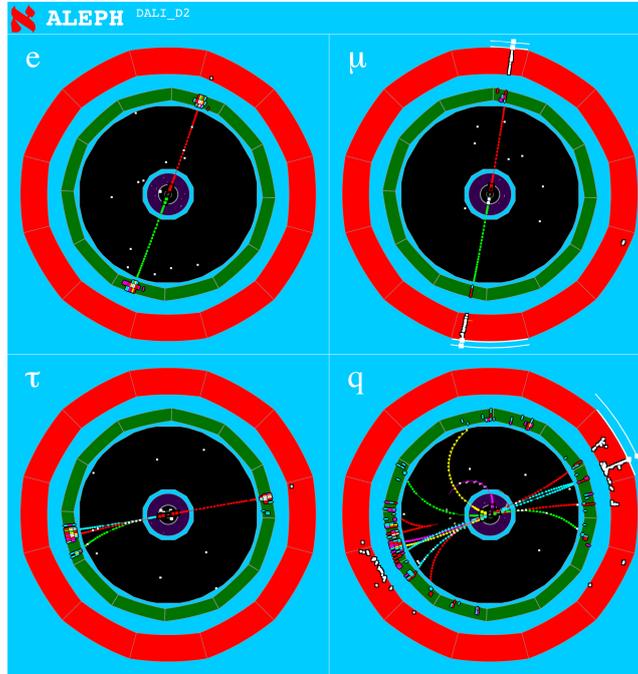


Figure 13: *The four types of Z boson decays. Up left a decay into a pair of electrons, up right into a pair of muons, bottom left a pair of tau leptons, one decaying into an electron and the other into three particles, bottom right a pair of quarks that fragments into a number of hadrons.*

In order to extract a cross-section from the number of events, the luminosity of the accelerator needs to be determined ( $N = \mathcal{L} \cdot \sigma$ ). This is done by measuring at the same time another process with known cross-section, the elastic scattering  $e^+e^- \rightarrow e^+e^-$ , known as Bhabha scattering, which results in two low angle electron and positron. To this effect, the LEP experiments were equipped ab initio with low angle detectors, to detect these scattered electrons. The precision with which these detectors can measure this process is determined by the knowledge of the solid angle they cover and by the accuracy with which they measure the angle of the scattered electrons. The initial detectors were able to reach a precision of about one percent, but were progressively replaced with extremely precisely machined silicon tungsten calorimeters or silicon trackers (as in figure 14 which allowed a determination of the luminosity with an accuracy of  $5 \times 10^{-4}$  or better. It took many

years of detailed higher order calculations to achieve a similar precision on the theoretical estimate of the cross-section within this well defined acceptance.

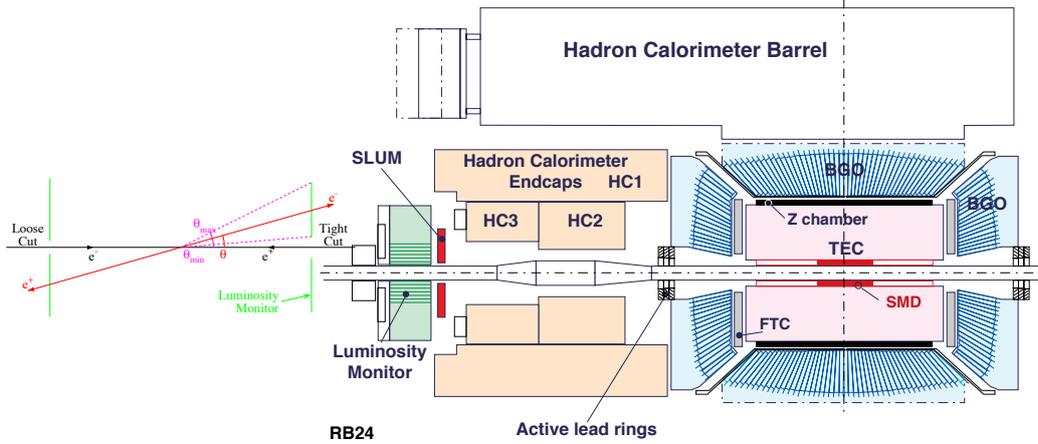


Figure 14: Example of a LEP luminosity monitor (the L3 experiment). The process to be detected is elastic  $e^+e^- \rightarrow e^+e^-$  scattering, shown on the left, which is seen by a coincidence of an electron in each of the detectors placed in the forward regions of the detector as shown on the right. In order to determine the solid angle seen by this coincidence in a way which is independent of the exact location of the collision point (which is difficult to determine) a set of two different acceptances is defined for the two arms. The precise definition of the acceptance is obtained by a precisely machined silicon telescope (SLUM) positioned in front of the electron calorimeters (luminosity monitor); there is a symmetric device on the other side of the detector.

Measurements of cross-section for a given final state  $f\bar{f}$  around the Z pole allows to extract three parameters: the position of the peak, the width of the resonance and an overall normalisation, that is best obtained from the peak cross-section,

$$\sigma_f^0 = \frac{12\pi(\hbar c)^2}{M_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} = \frac{12\pi(\hbar c)^2}{M_Z^2} B_e \cdot B_f . \quad (4)$$

By measuring cross-sections for hadrons, electron pairs, muon pairs and tau pairs, one can obtain six numbers: the mass, the total width, and four other parameters which could be four branching ratios, or four partial widths. A better choice is to use the peak cross-section for hadrons  $\sigma_{\text{had}}^{\text{peak},0}$ , and the ratios of hadrons to the various leptonic partial widths,  $R_\ell \equiv \Gamma_{\text{had}}/\Gamma_\ell$ . The Standard Model implies lepton universality, and if this is assumed, the number of parameters can be reduced to four,  $m_Z, \Gamma_Z, \sigma_{\text{had}}^{\text{peak},0}, R_\ell$ . The choice of these observables to fit the line-shape measurements is dictated by the fact that they are experimentally uncorrelated, both from the point of view of statistical and systematic errors.

By reporting the expression for  $\Gamma_Z$  of eq. 3 into the peak cross-section for hadrons, eq. 4, the number of neutrinos can be extracted from quantities that are measured at the peak only:

$$N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu} \cdot \left( \sqrt{\frac{12\pi R_\ell}{M_Z^2 \sigma_{\text{had}}^{\text{peak},0}}} - R_\ell - 3 \right) . \quad (5)$$

The sensitivity of  $N_\nu$  to  $R_\ell$  is small, as there is a cancellation between the two terms containing this quantity. As a result the experimental measurement that enters most in the determination of  $N_\nu$  is the peak cross-section, as already guessed intuitively from figure 9. This observation was made for the first time by G. Feldman [53]. This explains how quickly the number of neutrinos was obtained, a few weeks after the start-up of LEP and SLC.

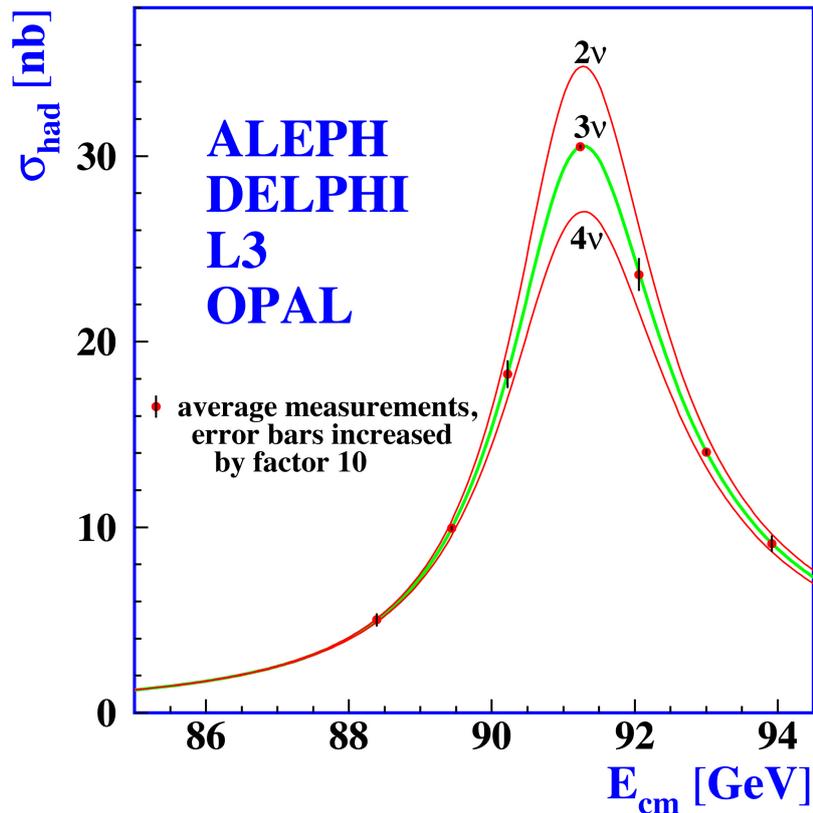


Figure 15: The  $e^+e^- \rightarrow \text{hadrons}$  cross section as a function of center-of-mass energy, as measured by the LEP experiments. The curves represent the Standard Model predictions for two, three and four species of light neutrinos. It is clear from this picture that there is no further light neutrino species with couplings identical to the first three.

### 8.1 The radiative method

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy  $e^+e^-$  colliders by measuring the cross section of the process  $e^+e^- \rightarrow \nu\nu\gamma$ . The ASP, CELLO, MAC, MARK-J, and VENUS experiments observed a total of 3.9 events above background [54], leading to a 95 % C.L. limit of  $N_\nu < 4.8$ .

This process has a much larger cross section at center-of-mass energies above the  $Z$  mass. The event signal is a photon of an energy consistent with being the recoil against a  $Z$  boson. This has been measured at LEP by the ALEPH, DELPHI, L3, and OPAL experiments [55]. These experiments have observed several thousand such events, and the combined result is  $N_\nu = 3.00 \pm 0.08$ . The same process has also been measured by the LEP experiments at much higher center-of-mass energies, between 130 and 208 GeV, in searches for new physics [56]. Combined with the lower energy data, the result is  $N_\nu = 2.92 \pm 0.05$ .

The methods are discussed in [57]. The radiative method has sometimes been dubbed 'direct' because the observation of a photon with the proper energy signals the production of an invisible  $Z$  boson. By opposition, the  $Z$  peak method (which is so far much more precise) was dubbed indirect because the "invisible"  $Z$  decays are not counted. This qualification is, again, misleading. In the radiative method, the number of events  $e^+e^- \rightarrow \nu\nu\gamma$  consistent with a  $Z$  recoil is proportional to  $N_{\nu\nu\gamma} \propto \frac{\Gamma_\nu \Gamma_\nu}{\Gamma_Z}$ . Thus a model-independent determination requires an independent measurement of the  $Z$  width and its electron partial width. Furthermore the sensitivity to the number of neutrinos is reduced by the fact that  $\Gamma_Z$  itself contains the neutrino partial width. This is another example

of a 'direct' method which ends up being more model-dependent than the indirect one.

The radiative method has been proposed in the forthcoming Electroweak factories such as the FCC-ee/TLEP [58] for a high precision measurement of the neutrino partial width, a quantity sensitive to the mixing of possible heavy right-handed neutrinos with the light active ones. Many systematic limitations can be eliminated by measuring directly the ratio  $R = \frac{e^+e^- \rightarrow \gamma \nu \nu}{e^+e^- \rightarrow \gamma \mu \mu}$  for which, thanks to the high luminosity available at the FCC-ee, a precision of  $\Delta N_\nu = \pm 0.0008$  i.e. a gain of at least a factor 10, could be achieved.

## 9 Further developments

### 9.1 Measurements of the tau-neutrino couplings in tau decays

Among the 20 million of visible Z recorded by the LEP collaborations in the seven years 1989-1995, figured in good place one million  $Z \rightarrow \tau^+ \tau^-$ . From these large samples a quantum leap in precision was obtained on tau physics, which also benefited from the excellent condition of separation of the tau pair signal from hadronic Z decays at these energies. Of great interest are the tau life time measurements, the branching ratios into leptons (e,  $\mu$ ) and hadrons, and the  $\tau$  mass itself. From these the individual charged current couplings to  $e - \nu_e$ ,  $\mu - \nu_\mu$ ,  $\tau - \nu_\tau$  can be extracted. A good summary is published in [59].

In 1991 three of the LEP detector were equipped with silicon vertex detectors and the life time measurements, and in 1992 the Beijing Electron Positron Collider (BEPC) provided an improved measurement of the tau mass, and the combination of these results led to greatly improved tests of the universality of charged current couplings, as given for instance for the  $\mu - \nu_\mu$ , vs.  $\tau - \nu_\tau$  couplings at the Moriond conference in 1993 [27]:

$$\frac{g_\tau}{g_\mu} = 0.996 \pm 0.008 \quad (6)$$

A few years later with the full LEP statistics the precision was down to a few parts permil. Recently these tau measurements have been the object of a yearly update [28], the latest value being:

$$\frac{g_\tau}{g_\mu} = 1.0010 \pm 0.0015 ; \frac{g_\tau}{g_e} = 1.0029 \pm 0.0015 \quad (7)$$

### 9.2 Measurements of the tau-neutrino couplings in W decays

At LEP2, tens of thousands of W pair events were detected with a clear event-by-event kinematic reconstruction. An event reconstructed as:

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}\tau^-\bar{\nu}_\tau \quad (8)$$

is shown in Fig.16.

These events allowing determination of all three W lepton-neutrino couplings at percent level [29].

From the W decays at LEP [29], one can extract the ratios of couplings as follows:

$$\frac{g_\tau}{g_\mu} = 1.070 \pm 0.026 \quad (9)$$

and from PDG2018, combining the LEP and the Tevatron experiments [60]:

$$\frac{g_\tau}{g_e} = 1.043 \pm 0.024 \quad (10)$$

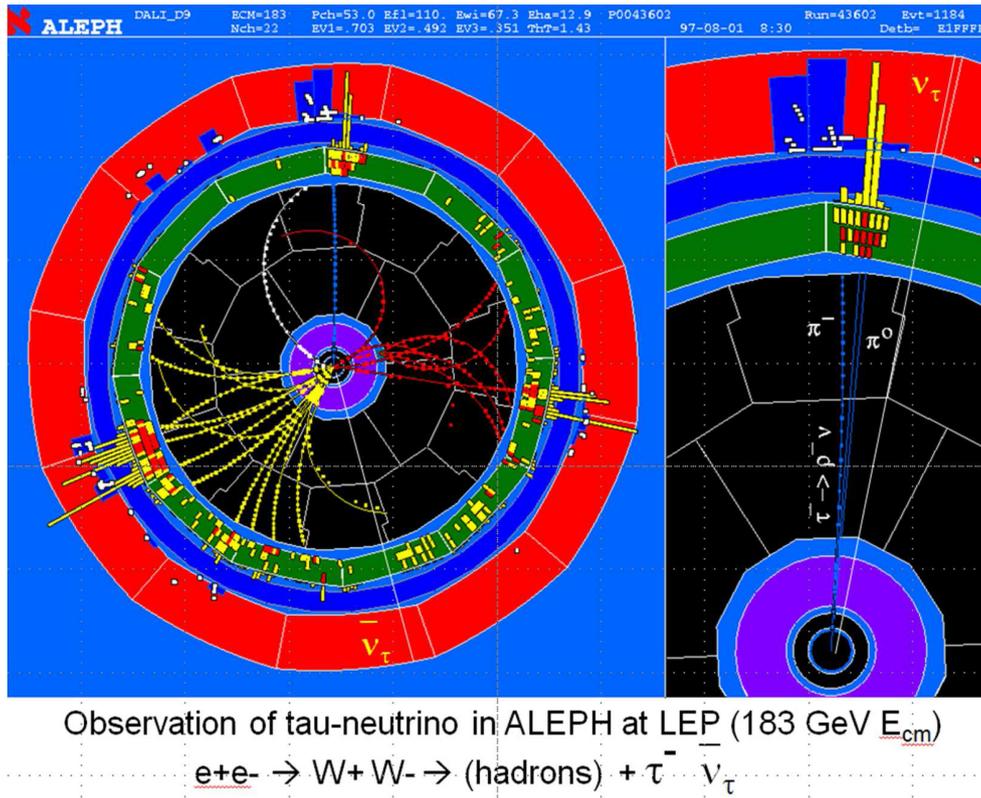


Figure 16: A  $W$  pair event recorded in the ALEPH experiment at a center-of-mass energy of 183 GeV (in 1998). One of the  $W$  decays in a pair of quark, giving a final state with two jets of hadrons. The other one decays into a  $\tau^- \rightarrow \rho^- \bar{\nu}_\tau$  and a tau neutrino which can be reconstructed by constrained kinematics.

which are both less precise than from tau decays and somewhat higher for the tau than for the electron or muon – a measurement to follow.

### 9.3 Observation of tau neutrino interactions

#### 9.3.1 Intent

In a Fermilab letter of intent from March 1993 [61], Byron Lundberg and a handful of collaborators (Rameika, Niwa, Reay, Stanton and Paolone) proposed to undertake a 'Measurement of  $\tau$  lepton production from the process  $\nu_\tau + N \rightarrow \tau$ ', which would provide 'the first direct evidence for the existence of the  $\tau$  neutrino'.

Interestingly the cover letter "makes it clear that this experiment [...] is a necessary precursor to a sensitive and complete program to measure neutrino mass/mixing here at Fermilab". The experiment was indeed seen as a demonstration that  $\tau$  neutrinos could be detected and isolated from backgrounds in the forthcoming NUMI oscillation experiments, which at the time envisaged to place an emulsion neutrino detector in front of MINOS. This motivation was, of course, completely justified, although as it turns out, the experimental demonstration that neutrino oscillations take place mainly among the active flavours would end up being done by MINOS in a completely different way, from charged and neutral current events survival [62].

The 'first direct evidence of existence' motivation is contained in the Letter of Intent (LOI) as follows: "Though the top quark has yet to be found, few doubt of its existence. [...] Yet compulsion to produce it and measure it is essential [...]. The existence of a tau neutrino partner for the tau was assumed and indirectly confirmed by the tau decay spectrum. (...) Like with the

top quark, few doubt that the tau lepton does have its own neutrino, however direct observation of the  $\nu_\tau \rightarrow \tau$  charged current interaction would confirm its existence”.

### 9.3.2 Discussion

It is evident that the writers of these lines were not aware of the details reported in the earlier sections of this article, by which the existence of the tau neutrino had been duly and rigorously established in the 1980's – 1986 at the latest. Ignored is  $\tau \rightarrow \pi\nu$  decay, the measurement of the tau lifetime, of the observation of  $W \rightarrow \tau\nu_\tau$  or the findings of Fermilab experiment E531, and indeed there is in the LOI no reference at all to the earlier existing information concerning the tau neutrino.

The analogy with the top quark is particularly telling (of course it could simply be done to catch the ears of a committee more occupied in 1993 with the top quark search than with tau neutrinos): the postulated existence of the top quark was purely theoretical, being a consequence of the isospin symmetry of the Standard Model, the b quark (resp  $\tau$  lepton) having been found with isospin  $-1/2$ , a particle with isospin  $+1/2$  had to exist. Nevertheless many “topless models” existed in the late 80's to early 90's [63][64][65][66][67][68][69], showing that the existence of the top quark was not only 'indirect' but more importantly and meaningfully, 'uncertain'. Even in 1994, after the top quark effect had been seen in the self-energy radiative corrections e.g. to the Z width, allowing an 'indirect' prediction of its mass, this was still a model-dependent prediction, specifically assuming that the minimal Standard Model with three families, a single Higgs boson and *nothing else* is at play.

Of course there is no such parallel between the top and the tau neutrino: nobody had ever seen the production of the top quark in 1993, while hundreds of thousands of tau neutrinos had been seen to be produced in tau decays, as well as in on-shell and off-shell W decays, its existence as distinct from  $\nu_e$  and  $\nu_\mu$  established, and its properties duly measured. While the existence of the top quark was not only 'indirect' but arguably 'uncertain', the status of the tau neutrino was 'established' and even 'measured' – two very, very different levels of status, confused by the thin and ill-defined link of using the word 'indirect'.

Why was there such a gap in appreciation between the neutrino beam community and the collider community? As I personally know both of them, I can say that at collider a neutrino is a missing 4-momentum (less  $p_z$  for a hadron collider) of invariant mass consistent with 0, and which has, by definition, the same lepton flavour (if one cares) as the lepton it appears with. When a neutrino beam physicist talks of a 'muon neutrino', he has in mind a neutrino interaction producing a muon, ( $CC_{\nu_\mu}$ ), same with an 'electron neutrino' producing an electron, and of course a 'tau neutrino' will be a neutrino interaction producing a tau. The two definitions are of course completely equivalent scientifically, but not visually; both encompass a large amount of underlying demonstration of the fact that the neutrino states are essentially orthogonal (oscillations happen at much longer time scale). Thus the neutrino part of the particle physics world had been longing for nearly twenty years to **see** a 'tau neutrino' – that is, its interaction. Indeed, to see it would be a feast... especially since it is very difficult to achieve!

### 9.3.3 The DONUT experiment

The DONUT experiment principle [31] is to produce a beam enriched in tau neutrinos by using a beam dump. The highest energy (800 GeV) protons ever available for fixed target experiments are delivered from the Tevatron on a tungsten beam dump, where  $D_s$  mesons are produced and decay into  $D_s \rightarrow \tau + \bar{\nu}_\tau$ , followed by the tau decay into a tau neutrino. The tau neutrino from the tau decay is more energetic, thus better focused and of higher cross-section than the tau antineutrino, so its interactions are expected to dominate. The beam dump ensures that most

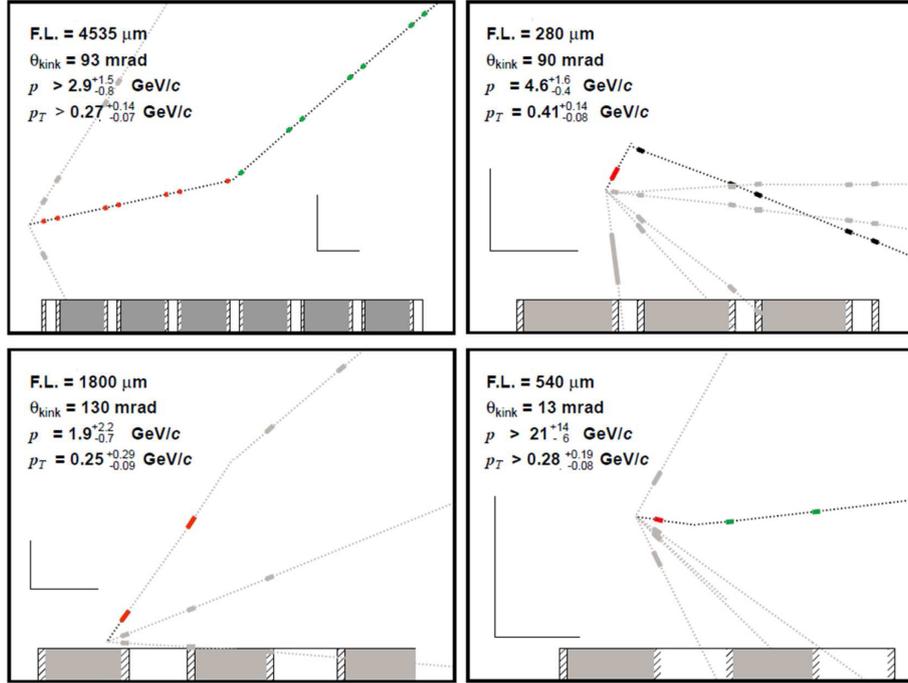
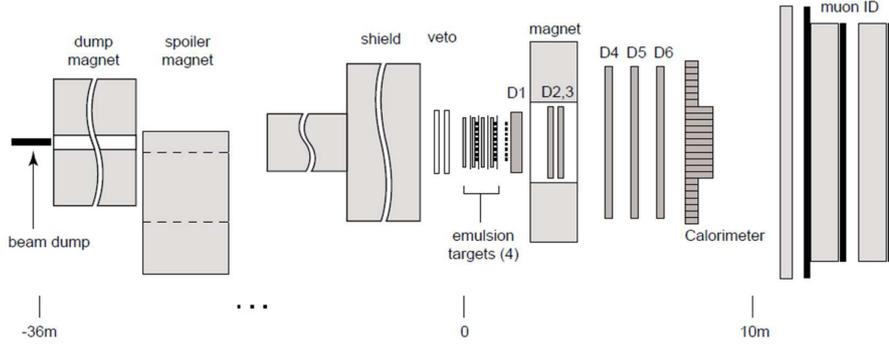


Figure 17: *The DONUT experiment. Top: overall set-up, with the beam coming from the left. In succession, the beam dump; spoiler magnet to remove sweep muons aside; shield and veto counter; the emulsion targets followed by the magnetic spectrometer, a calorimeter and muon filter. Bottom: four tau neutrino events of the first publication.*

pions and kaons are absorbed. Thanks to a magnetized iron muon sweeping magnet and to a shield, the detector is situated remarkably close (38m) from the beam dump. Altogether the neutrino interactions are expected to consist of 95% electron and muon (anti)neutrinos and 5% tau neutrinos. This is a striking difference with the E531 experiment mentioned above, which was situated in a regular neutrino beam in which the tau neutrino component is proportionally more than 3000 times smaller.

The overall set-up is illustrated in Fig.17. It is notable that the experiment made first use of the Emulsion Cloud Chamber (ECC) where metal plates were interleaved with two planes of emulsions separated by 0.8mm of plastic, allowing both a higher target mass and precision determination of the direction of tracks.

The first publication [31] 'observation of tau neutrino interactions' reported four such events, also pictured in Fig. 17, out of 203 neutrino interactions located in the emulsion.

The paper was careful to stress that "It should be noted that since the neutrino flux had only an estimated 5% component, the possibility that the  $\nu_\tau$  is a superposition of  $\nu_\mu$  and  $\nu_e$  cannot

be eliminated using the results of this experiment. Results from other experiments (quoting the E531 results and more recent ones from Chorus and NOMAD) which were sensitive to  $\tau$  leptons, show that the direct coupling of  $\nu_\mu$  to  $\tau$  is very small ( $2 \times 10^{-4}$ ). The upper limit (90 % C.L.) for  $\nu_e$  to  $\tau$  is much larger,  $1.1 \times 10^{-2}$  (90 % C.L.). Assuming this upper limit, the estimated number of  $\tau$  events from this hypothetical source is  $0.27 \pm 0.09$  (90 % C.L.)”.

The probability that four events came from the background was  $4 \times 10^{-4}$  – equivalent to a 3.5 sigma significance, perfectly sufficient to convince everyone that DONUT had indeed seen the first tau neutrino interactions with matter ever recorded and identified; and the events were beautiful. “Direct observation of  $\nu_\tau$ , that is, interactions resulting from neutrinos produced in tau lepton decay”, had been made. “That is”, by definition.

With great enthusiasm the Fermilab News announced that “DONUT Finds Missing Puzzle Piece” [70]. This was of course over-enthusiastic, this piece of the Standard Model puzzle having been found many years before. Just to be clear: DONUT did not discover the tau neutrino, and the collaboration never made this claim in a scientific paper. However DONUT had satisfied a long-standing longing of the neutrino community, and fulfilled its mission by demonstrating the feasibility of observing tau neutrino interactions, in view of possible neutrino oscillation experiments.

## Acknowledgements

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