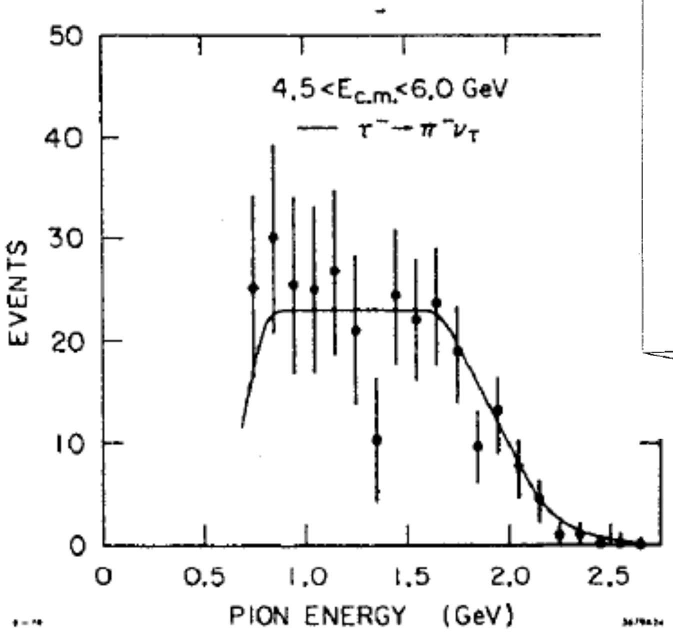
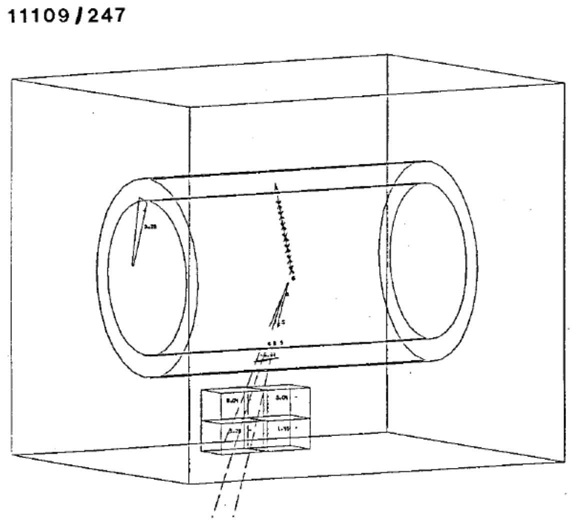
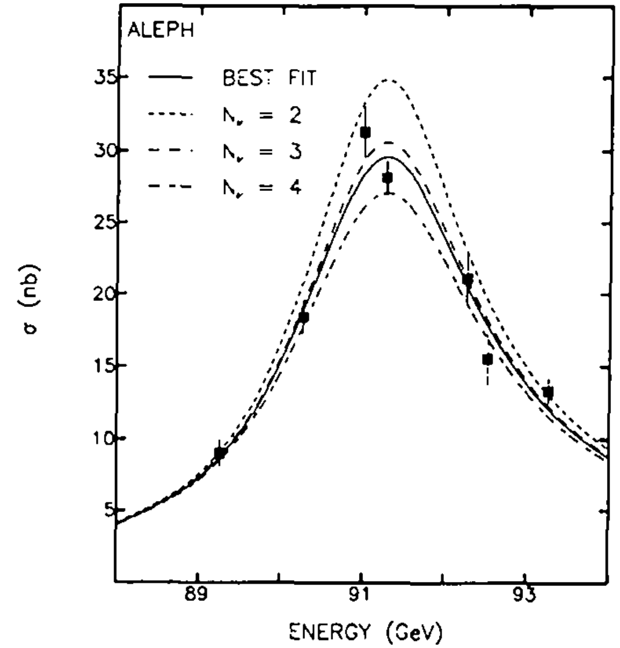
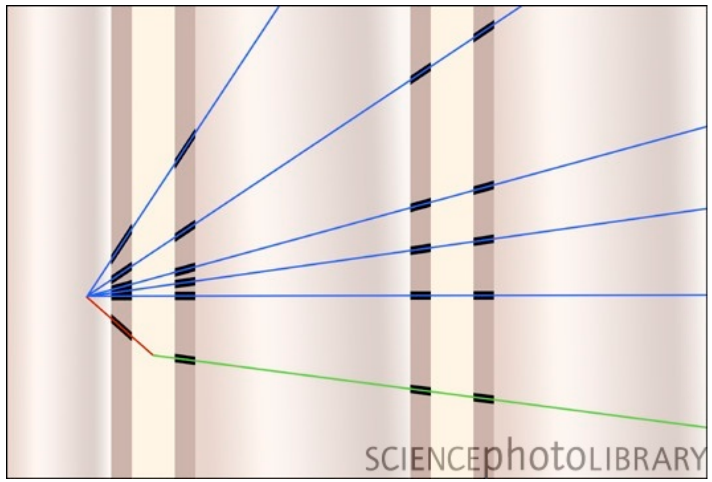
The Third Family of Neutrinos



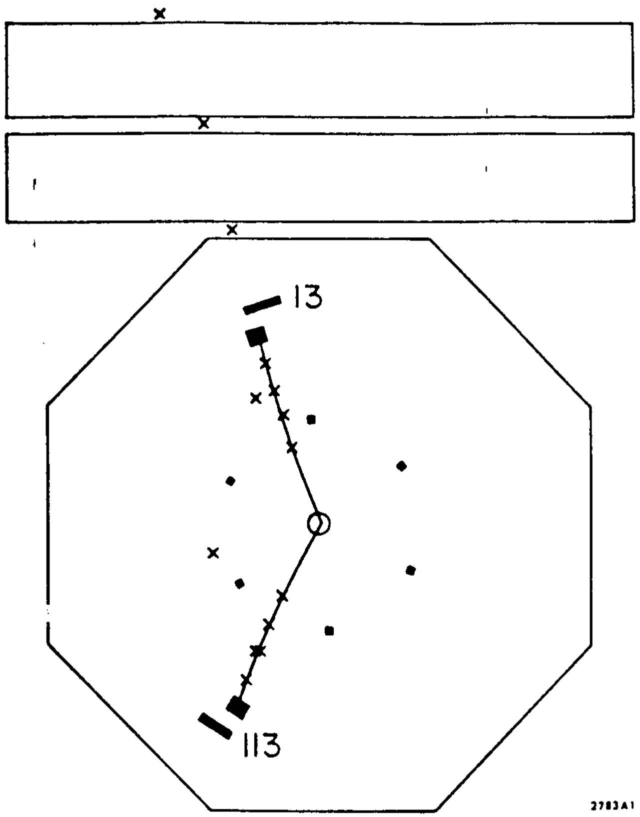






The discovery of the third family of neutrinos begins with

The discovery of a new lepton



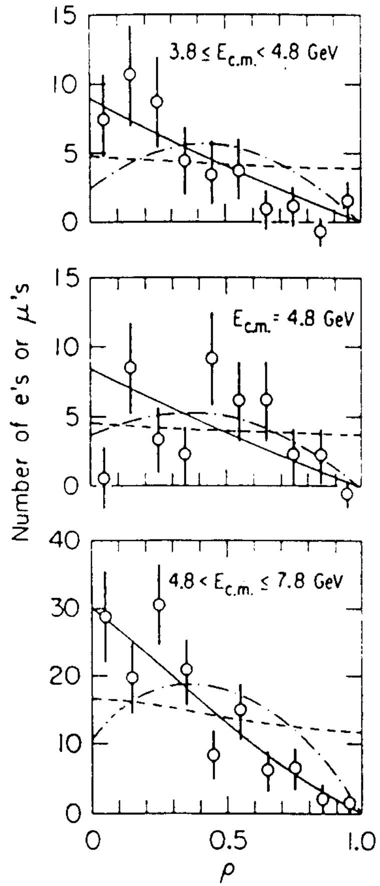


Figure 13. The scaled momentum spectrum of leptons from $e\mu$ events in three energy regions. The solid curve represents the expectation of a 1.8 GeV/c^2 lepton with V-A interactions. The dashed and dot-dashed curves represent the expectations from a 1.8 GeV/c^2 boson with spin 0 and spin 1, helicity 0, respectively. (From the second paper, Ref. 13.)

Figure 12. An $e\mu$ event in which the muon penetrates both layers of the muon tower. Shown at the Stanford conference, August 1975 (Ref. 37).

at that time the 'new lepton' was called *U*

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

The presence of neutrinos was used as a proof that the new particle was a lepton

Volume 63B, number 4 PHYSICS LETTERS 16 August 1976

PROPERTIES OF ANOMALOUS $e\mu$ EVENTS PRODUCED IN e^+e^- ANNIHILATION☆

M.L. PERL, G.J. FELDMAN, G.S. ABRAMS, M.S. ALAM, A.M. BOYARSKI, M. BREIDENBACH, F. BULOS, W. CHINOWSKY, J. DORFAN, C.E. FRIEDBERG, G. GOLDHABER[1], G. HANSON, F.B. HEILE, J.A. JAROS, J.A. KADYK, R.R. LARSEN, A.M. LITKE, D. LÜKE[2], B.A. LULU, V. LÜTH, R.J. MADARAS, C.C. MOREHOUSE[3], H.K. NGUYEN[4], J.M. PATERSON, I. PERUZZI[5], M. PICCOLO[5], F.M. PIERRE[6], T.P. PUN, P. RAPIDIS, B. RICHTER, B. SADOULET, R.F. SCHWITTERS, W. TANENBAUM, G.H. TRILLING, F. VANNUCCI[7], J.S. WHITAKER and J.E. WISS

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, USA

Received 15 July 1976

We present the properties of 105 events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. The simplest hypothesis compatible with all the data is that these events come from the production of a pair of heavy leptons, the mass of the lepton being in the range 1.6 to 2.0 GeV/c^2

When the second paper (Fig. 14) was written the following summer, it continued with a tight argument, which is outlined in Fig. 15. If the decays were three-body, there were two missing particles in each decay. Could they be K_L's, photons, or charged particles? By comparing $e\mu$ events with these particles (and using K_S's as a substitute for K_L's, since they had to be the same), we could determine an upper limit on the number of anomalous $e\mu$ events which had missing hadrons or photons. This very conservative limit, obtained by adding all of the upper limits linearly, was 39%. Thus, missing particles had to be neutrinos, because that was the only thing left. Thus, each decay had to have a lepton and two missing neutrinos. The only particle with this signature was a heavy lepton.

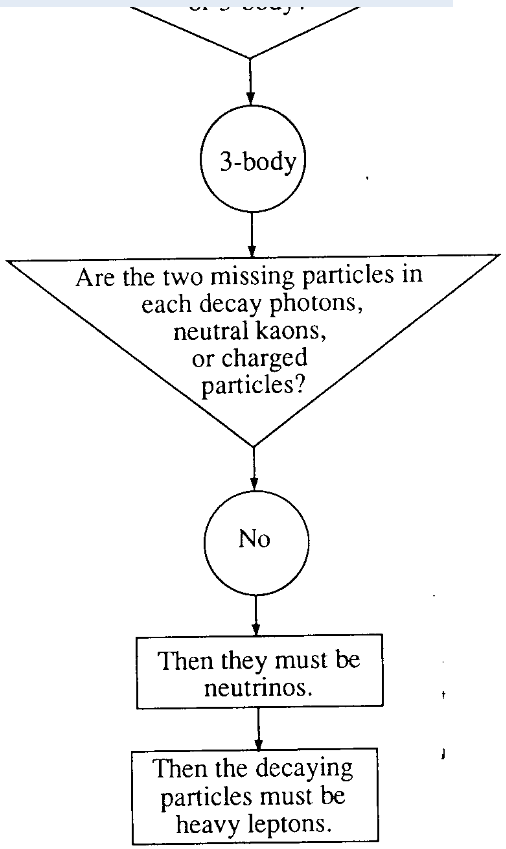


Figure 15. Outline of the second paper (Ref. 13).

The name ‘τ’ appears in 1977, very carefully chosen

Volume 70B, number 4 PHYSICS LETTERS 24 October 1977

PROPERTIES OF THE PROPOSED τ CHARGED LEPTON*

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

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, USA

Received 17 August 1977

The anomalous $e\mu$ and 2-prong μx events produced in e^+e^- annihilation are used to determine the properties of the proposed τ charged lepton. We find the τ mass is 1.90 ± 0.10 GeV/c^2; the mass of the associated neutrino, ν_τ, is less than 0.6 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 μx events where the first error is statistical and the second is systematic.

it had to be greek, like ‘μ’, and τ was chosen for ‘τριτον’, third

.. and ‘ν_τ‘ just… appears

Measurements of τ cross-section and decays by MarkI, MarkII, DELCO, at SPEAR PLUTO and DASP at DORIS quickly showed that

1. the tau lepton was a spin ½ particle
   tau pair cross section as muon pair →
1. the tau decays into leptons and two neutrinos
   and the decay is V-A
2. the tau decays into hadron and one neutrino
   e.g. **Two body decay** $\tau^- \rightarrow \pi^- \nu_\tau$

also ρ, K*, A1, etc… consistent with the weak current

All this implying the existence in tau decays of
a spin ½ weakly interacting neutral particle with mass below measurement limit.
<u>This is what we call a ‘neutrino’.</u>

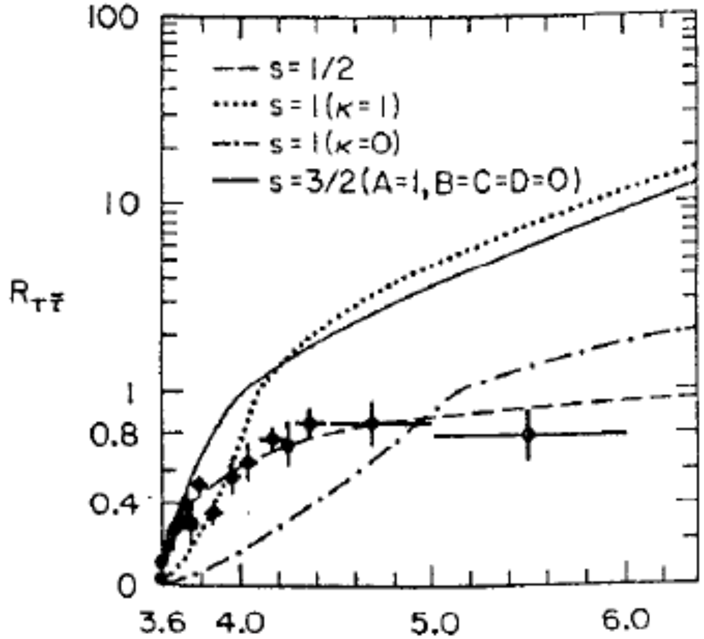


Fig. 2. The cross-sections expected for a pair of point-like particles according to several spin assignments. The constants κ, A, B, C and D are related to the gyromagnetic ratio and multipole values of the particles (see Ref. 2 for details). The data points are the DELCO eX events, normalized to the spin ½ curve. Note that the vertical scale changes from linear to logarithmic at 1.0.

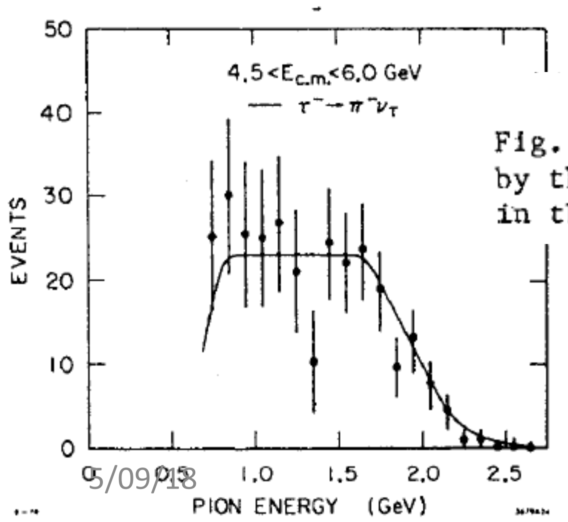


Fig. 7. The π energy spectrum observed by the Mark II for the decay $\tau^- \rightarrow \pi^- \nu_\tau$ in the energy range, $4.5 < E_{cm} < 6.0$ GeV.

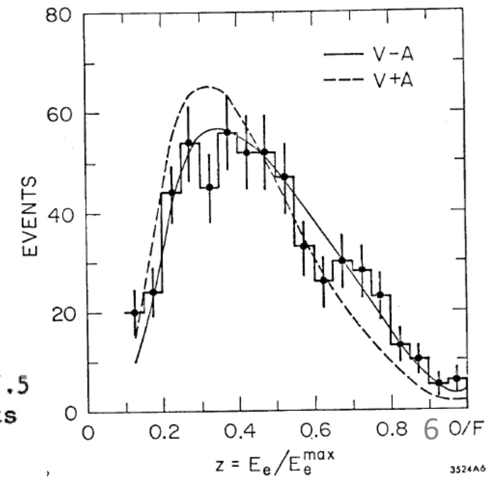


Fig. 4. The normalized electron energy spectrum obtained by DELCO in the energy range, $3.57 < E_{cm} < 7.5$ GeV (excluding ψ''). The radiatively-corrected fits for V − A (solid) and V + A (dashed) show χ^2/dof of 15.9/17 and 53.7/17, respectively.

A STUDY OF THE DECAY $\tau^- \to \pi^- \nu_\tau$ ☆

C.A. BLOCKER [1], J.M. DORFAN, G.S. ABRAMS, M.S. ALAM [2], A. BLONDEL [3], A.M. BOYARSKI, M. BREIDENBACH, D.L. BURKE, W.C. CARITHERS, W. CHINOWSKY, M.W. COLES [4], S. COOPER [4], W.E. DIETERLE, J.B. DILLON, J. DORENBOSCH [5], M.W. EATON, G.J. FELDMAN, M.E.B. FRANKLIN, G. GIDAL, G. GOLDHABER, G. HANSON, K.G. HAYES [5], T. HIMEL [5], D.G. HITLIN [6], R.J. HOLLEBEEK, W.R. INNES, J.A. JAROS, P. JENNI [5], A.D. JOHNSON, J.A. KADYK, A.J. LANKFORD, R.R. LARSEN, M. LEVI [1], V. LÜTH, R.E. MILLIKAN, M.E. NELSON, C.Y. PANG, J.F. PATRICK, M.L. PERL, B. RICHTER, A. ROUSSARIE, D.L. SCHARRE, R.H. SCHINDLER [5], R.F. SCHWITTERS [1], J.L. SIEGRIST, J. STRAIT, H. TAUREG [5], M. TONUTTI [7], G.H. TRILLING, E.N. VELLA, R.A. VIDAL, I. VIDEAU [3], J.M. WEISS and H. ZACCONE [8]

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, CA 94720, USA and Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

Received 19 October 1981

We present a high statistics measurement of the branching ratio for the decay $\tau^- \to \pi^- \nu_\tau$ using data obtained with the Mark II detector at the SLAC e^+e^- storage ring SPEAR. We have used events from the center-of-mass energy region 3.52 to 6.7 GeV to determine that $B(\tau^- \to \pi^- \nu_\tau) = 0.117 \pm 0.004 \pm 0.018$. From electron–muon events in the same data sample, we have determined that $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 0.66 \pm 0.03 \pm 0.11$. We present measurements of the mass and spin of the τ and the mass of the τ neutrino based, for the first time, on a hadronic decay mode of the τ.

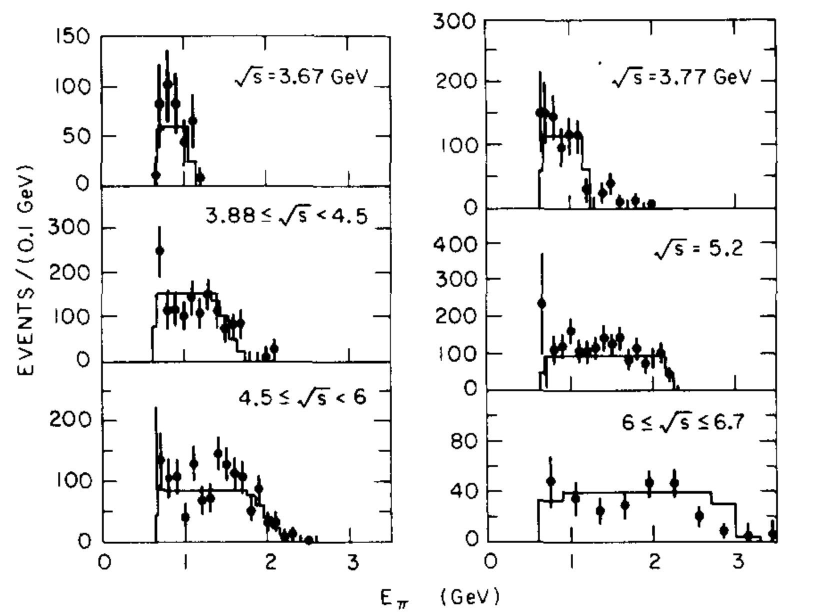


Fig. 3. Pion energy spectrum for π–X events with bin-by-bin background subtraction and efficiency corrections. The curves are the expected spectra for $m_\tau = 1.782\ \mathrm{GeV}/c^2$, $m_\nu = 0$, and $B_\pi = 0.117$.

Two body decay $\tau^- \to \pi^- \nu_\tau$ with $m(\nu_\tau) < 250$ MeV

The ratio $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 0.66 \pm 0.03 \pm 0.11$. is consistent with the tau being coupled to the hadronic weak axial-vector current

The question was not whether there was a neutrino produced in tau decays, but whether this neutrino was a new one!

this situation is very similar to that of 1962

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

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(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 produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β 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-

The question was not whether there was a neutrino produced in pion decays, but whether this neutrino was a new one!

Could the «ν_τ» be different from the weak isospin partner of the tau?

At the same epoch, the b-quark had been discovered, decaying into charm – and not 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 lifetime much longer than would be expected given its mass**.

The same thing could happen with the tau lepton, if for some reason the tau could not decay into its weak isospin partner (by definition '$\nu_{\tau'}$').
This hypothesis would imply that i) the tau lifetime would be very long,
and that, because the tau couples to ν_e & ν_μ ,
taus could be produced in neutrino beams.

To demonstrate that the tau neutrino was a new particle and the weak isospin partner of the tau one should demonstrate:

1. that the coupling of the tau to its neutrino has the full weak interaction strength
   → tau lifetime **or** W→ $\tau\ \nu_\tau$ decay with the same rate as W→ e ν_e and W→ $\mu\ \nu_\mu$

2. that neither ν_e nor ν_μ couple to the tau.

Gary feldman explained in 1981 that the first measurements of the tau lepton lifetime combined with the absence of tau production in e.g. the CERN neutrino beam dump experiment, excluded this scenario.

SLAC-PUB-2839
October 1981
(T/E)

THE LEPTON SPECTRUM*

Gary J. Feldman
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

... ...

DOES THE ν_τ EXIST?

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

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

and from the absence of apparent excess neutral currents in the BEBC beam dump experiment,[41]

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

Combining (15) and (16),

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

but from either the Mark II or TASSO τ lifetime measurement,

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

reviews the tau decay demonstrating
-- the spin of the missing neutral,
-- early tau life time meas'ts
and the results of a beam dump experiment at CERN

➔ conclude that the tau neutrino is distinct from nue and numu.

The statistical significance of the argument is still relatively weak.

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	$I^G(J^P)C_n$ [a]	Mass [b] (MeV) Mass^2 (GeV^2)	Mean life [b] (sec) $c\tau$ (cm)	Partial decay mode: Mode	Fraction [b]	p or p_{max} [c] (MeV/c)
				PHOTON		
γ	$0,1(1^-)-$	$(<6\times10^{-22})$	-------	stable		
				LEPTONS		
ν_e	$J=\frac{1}{2}$	$(<0.000046)^d$	stable $(>3\times10^8 m_{\nu_e}$ (MeV))	stable		
e	$J=\frac{1}{2}$	0.5110034 $\pm$0.0000014	stable $(>2\times10^{22}$y)	stable		

ν_e	$J=\frac{1}{2}$	$(<0.000046)^a$	stable $(>3\times10^8 m_{\nu_e}$ (MeV))	stable		
e	$J=\frac{1}{2}$	0.5110034 ±0.0000014	stable $(>2\times10^{22}$y)	stable		
ν_μ	$J=\frac{1}{2}$	0(< 0.52)	stable $(>1.1\times10^5 m_{\nu_\mu}$ (MeV))	stable		
μ	$J=\frac{1}{2}$	105.65943 ±0.00018 $m^2=0.01116392$	2.19714×10^{-6} ±0.00007 $c\tau=6.5868\times10^4$	$\mu^- \rightarrow$ (or $\mu^+ \rightarrow$CC)		
				$e^-\bar{\nu}\nu$	(98.6 ± 0.4)%	53
				$e^-\bar{\nu}\nu\gamma$	^{e}(1.4)%	53
				†[$e^-\nu_e\bar{\nu}_\mu$	(<9)%]	53
				$e^-\gamma$	(<1.9)$\times10^{-10}$	53
				$e^-e^+e^-$	(<1.9)$\times10^{-9}$	53
				$e^-\gamma\gamma$	(<5)$\times10^{-8}$	53
ν_τ	$J=\frac{1}{2}$	< 250				
τ	$J=\frac{1}{2}$	1784.2 ±3.2 $m^2=3.18$	$(4.6\pm1.9)\times10^{-13}$ $c\tau=0.014$	$\tau^- \rightarrow$ (or $\tau^+ \rightarrow$CC)		
				$\mu^-\bar{\nu}\nu$	(18.5 ± 1.2)%	889
				$e^-\bar{\nu}\nu$	(16.2 ± 1.0)%	892
				$hadron^-$ neutrals	(37.0 ± 3.2)%	
				3($hadron^\pm$) neutrals	(28.4 ± 3.0)%	
				5($hadron^\pm$) neutrals	(<6)%	
				†[3($hadron^\pm$)ν	(13 ± 8)%	
				3($hadron^\pm$)$\nu(\geq1\gamma)$	(15 ± 7)%]	
				†[$\pi^-\nu$	(10.7 ± 1.6)%	887
				$\rho^-\nu$	(21.6 ± 3.6)%	726
				K^- neutrals	(small)	
				$\pi^-\pi^-\pi^+\nu$	(7 ± 5)%	864
				$\pi^-\pi^-\pi^+(\geq0\pi^0)\nu$	(18 ± 7)%]	864
				†[$K^{*-}(892)\nu$	(1.7 ± 0.7)%	669
				$K^{*-}(1430)\nu$	(<0.9)%	316
				$\pi^-\rho^0\nu$	(5.4 ± 1.7)%]	718

(continued next page)

1982: the tau neutrino is listed as established

J=1/2 , m<250 (from πν decay)

NB1 the life time measurement is still poor

NB2 large number of hadronic decays reported.
K*/ρ ratio is consistent with the Cabbibo angle
(this is a trademark of weak decay).

NB3 not listed: decay proceeds as V-A, leading
conclusion: tau neutrino is (mainly) left handed.

Review of particle properties S83

Stable Particles

μ, ν_τ

ν_τ

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.

The existence of the tau neutrino as a J=1/2 quantum state distinct from electron & muon neutrinos is considered established since 1981 (1982 PDG)

Why is it considered 'indirect' ?
The detection of the neutral particle from e.g. $\tau\rightarrow\pi\nu$ is perfectly «direct»
(in e+e-, the neutrino is well reconstructed from missing energy and momentum).
'Indirect' may refer to the fact that the assignment of lepton flavour is done
by default (it is not a nu_e or a nu_mu)

Unfortunately….
➔ This note was left unchanged until PDG 2002 although much happened in-between.

SUMMARY TABLES OF PARTICLE PROPERTIES

April 1986

Particle Data Group

M. Aguilar-Benitez, R.M. Barnett, R.L. Crawford, R.A. Eichler, R. Frosch, G.P. Gopal, K.G. Hayes, J.J. Hernandez, I. Hinchliffe, G. Höhler, G.R. Lynch, D.M. Manley, L. Montanet, F.C. Porter, J. Primack, A. Rittenberg, M. Roos, L.D. Roper, R.H. Schindler, K.R. Schubert, T. Shimada, R.E. Shrock, N.A. Törnqvist, T.G. Trippe, W.P. Trower, C.G. Wohl, G.P. Yost, and B. Armstrong and G.S. Wagman (Technical Associates)

(Closing date for data: Dec. 1, 1985) .

Stable Particle Summary Table

(stable under strong decay)

For additional parameters, see Addendum to this table.

Quantities in italics are new or have changed by more than one (old) standard deviation since April 1984

Particle	$I^G(J^{PC})$ [a]	Mass [b] (MeV)	Mean life [b] τ (sec) $c\tau$ (cm)	Partial decay modes: Mode	Fraction [b]	p (MeV/c) [c]
ν_τ	$J=\frac{1}{2}$	<70				
				$\tau^- \to$ (or $\tau^+ \to$ chg. conj.)		
τ	$J=\frac{1}{2}$	1784.2 ± 3.2	$(3.3\pm0.4)\times10^{-13}$	particle$^-$ neutrals	(*86.5* ± *0.3*)%	
				$\mu^-\bar{\nu}\nu$	(17.6 ± 0.6)%	889
			$c\tau=0.010$	$e^-\bar{\nu}\nu$	(17.4 ± 0.5)%	892
				hadron$^-$ $\geqslant 0\pi^0\nu$	(*51.6* ± *0.7*)%	
				hadron$^-$ ν	(*10.8* ± *1.1*)%	
				$\pi^-\nu$	(10.1 ± 1.1)%	887
				$K^-\nu$	(*0.67* ± *0.17*)%	824
				hadron$^-$ $\geqslant 1\pi^0\nu$	(*40.8* ± *1.3*)%	
				$\rho^-\nu$	(21.8 ± 2.0)%	726
				$\pi^-\pi^0$ (non-res.) ν	(*0.3* ± *0.3*)%	881
				$\pi^-\pi^0\pi^0\nu$	(*6.0* ± *3.5*)%	866
				$\pi^-\pi^0\pi^0\pi^0\nu$	(*3.0* ± *2.7*)%	840
				$K^-\geqslant 1\pi^0\nu$	(*1.0* ± *0.3*)%	
				$\pi^-\pi^-\pi^+\geqslant 0\pi^0\nu$	(*13.4* ± *0.3*)%	
				$\pi^-\pi^-\pi^+\geqslant 1\pi^0\nu$	(*5.3* ± *0.8*)%	
				$\pi^-\pi^-\pi^+\nu$	(8.1 ± 0.7)%	865
				$\pi^-\rho^0\nu$	(5.4 ± 1.7)%	718
				$\pi^-\pi^-\pi^+$ (non-res.) ν	(*<1.4*)%	865
				$\pi^-\pi^-\pi^+K^0\geqslant 0\gamma\nu$	(*<0.27*)%	
				K^- 2charged $\geqslant 0\pi^0\nu$	(*<0.6*)%	
				$K^-\pi^+\pi^-\geqslant 0\pi^0\nu$	(*0.2* ± *0.2*)%	
				$K^+K^-\pi^-\nu$	(*0.2* ± *0.2*)%	690

by 1986 the tau life time is known to ±13% and consistent with full G_F coupling)

Mode	Fraction		p (MeV/c)
$\tau^- \to$ (or $\tau^+ \to$ chg. conj.)			
e^- chgd.parts. + μ^- chgd.parts.	(<4)%		
$\mu^-\gamma$	(<5.5)$\times10^{-4}$	*LF*	889
$e^-\gamma$	(<6.4)$\times10^{-4}$	*LF*	892
$\mu^-\mu^+\mu^-$	(<4.9)$\times10^{-4}$	*LF*	876
$e^-\mu^+\mu^-$	(<3.3)$\times10^{-4}$	*LF*	886
$\mu^-e^+e^-$	(<4.4)$\times10^{-4}$	*LF*	889
$e^-e^+e^-$	(<4.0)$\times10^{-4}$	*LF*	892
$\mu^-\pi^0$	(<8.2)$\times10^{-4}$	*LF*	884
$e^-\pi^0$	(<2.1)$\times10^{-3}$	*LF*	887
μ^-K^0	(<1.0)$\times10^{-3}$	*LF*	819
e^-K^0	(<1.3)$\times10^{-3}$	*LF*	823
$\mu^-\rho^0$	(<4.4)$\times10^{-4}$	*LF*	722

VOLUME 57, NUMBER 23 PHYSICAL REVIEW LETTERS 8 DECEMBER 1986

Limits to $\nu_\mu, \nu_e \to \nu_\tau$ Oscillations and $\nu_\mu, \nu_e \to \tau^-$ Direct Coupling

strongly improved limit in the search for tau neutrino appearance in a beam of muon neutrinos (and 3% ν_e), no event seen in 1870 (53) ν_μ (ν_e) and showed that 'most tau decays must contain a neutral lepton other than ν_μ or ν_e'

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 τ^- decays yielded no candidate, resulting in an upper limit of 0.002 (0.073) for direct coupling of ν_μ (ν_e) to τ^-. The ν_μ (ν_e) to ν_τ limits to mass differences and mixing angles (α) 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 τ^- decays must contain a neutral lepton other than ν_μ or ν_e.

PACS numbers: 14.60.Gh, 12.15.Ff, 13.10.+q, 13.35.+s

Neutrino oscillations were predicted qualitatively in 1957 as an analog to the K^0-$\bar{K}^0$ system and later as an explanation for the solar-neutrino problem.[1] After evidence for neutrino oscillations was reported,[2] numerous experiments searched for oscillations among all neutrino types. Because of problems in the tagging of ν_τ interactions, few have obtained limits on oscillations into ν_τ.[3-5] Indirect limits[6] have also been set by looking for the disapperance of ν_μ or ν_e; such experiments are more uncertain because they rely more on the knowledge of their neutrino spectrum.

This experiment (E531) was designed to measure the lifetimes of charmed particles produced by the Fermilab neutrino beam and has obtained the lifetimes[7] of the D^0, $D^\pm$, $F^\pm$, and Λ_c^+. Since the τ lepton has a similar lifetime,[8] it should also be seen in an emulsion target. We have previously published limits[3] on ν_μ-to-ν_τ oscillations and direct coupling of ν_μ to τ^-; we now report new limits, using new data from a second run of the experiment, and also include our ν_e results.

charged-current interactions; any decaying particle in these events is unlikely to be τ^-. To remove background from interactions, scattering, and decays of low-momentum particles, a 2.5-GeV/c momentum cut was applied to the τ candidates. These cuts removed all the decay candidates, as shown in Table I. Overall, 95% of found real τ^- would survive all of the above cuts.

Since there are no candidates left, this corresponds to a 90%-confidence-level (C.L.) limit of 2.3 events.[8] There are 1870 events with an identified μ^- and an estimated 53 e^- events,[11] yielding uncorrected upper limits of $R_{raw}(\mu^-) < 2.3/1870 = 0.0012$ (90% C.L.) and $R_{raw}(e^-) < 2.3/53 = 0.043$ (90% C.L.), where R is the probability that ν_μ/ν_e oscillates into ν_τ, or equivalently the relative coupling (direct coupling) of ν_μ/ν_e to τ^-.

Because of differences in ν_τ, ν_μ, and ν_e interactions, these limits are subject to corrections which depend on the relative cross sections, acceptances, and reconstruction and finding efficiencies:

The direct-coupling limits can also be used to indicate that τ^- decays produce ν_τ. If we use the description of τ^- decay implied by Fig. 3, in which it is assumed that the τ^- couples directly to a neutrino, the semileptonic decay width[16] of the τ^- is given (on the assumption of universal Fermi coupling) by

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

Combining the measured[8] τ semileptonic branching ratios and lifetime gives an average semileptonic decay width of $(3.5^{+0.5}_{-0.4}) \times 10^{-10}$ MeV, which is consistent with the above calculation.

current τ lifetime expressed in MeV!

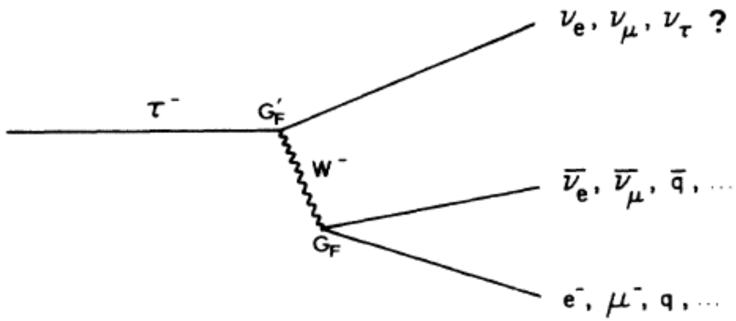


FIG. 3. τ-decay diagram.

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

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

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

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_e) < 3.0 \times 10^{-11} \text{ MeV},$$

as compared with the experimental average of $(3.5^{+0.5}_{-0.4}) \times 10^{-10}$ MeV mentioned above.[18] Thus, direct coupling to ν_e and ν_μ cannot dominate the τ-decay diagram shown in Fig. 3, indicating that the τ decays into something else, most likely the ν_τ.[19]

this now is about 8 σ exclusion for either ν_μ and ν_e, or the sum

Comment:

the hypothesis that e.g. $\tau \to \pi \nu_e$ or ν_μ in part or in total was not absurd:

-- this could happen if the third family neutrino (e.g. ν_3) would be heavier than the tau lepton itself. In that case the mixing of mass eigenstates with the weak eigenstates would lead to a decay into a $\nu_1 \nu_2$ combination.
The lifetime of the tau would be longer than that calculated using V-A theory for a massless neutrino.

-- this is what happens for quarks: the b quark does not decay into top (which is too heavy) so it decays into c and u quarks, and indeed the life time of the b was found to be considerably longer than expected for a particle of this mass.
NB these measurements were contemporary to those of the tau lifetime.

Consequently the fact that the tau decays into (and thus couples to) a left-handed, spin ½ particle consistent with being massless was established without any doubt. Still it could be a mix of ν_e or ν_μ . This was excluded by neutrino experiments proving that no tau production was seen in the (ν_μ / ν_e) beams -- up to very small fractions. Combined with the measurement of the tau lifetime consistent with that predicted from the muon life-time, **this establishes the neutral particle observed in tau decays is the ν_τ (weak isospin partner of the tau lepton), which was listed as «established stable particle» as of PDG 1982.**

by <u>1986</u> the tau neutrino was solidly known and established

The demonstration required putting together several informations
-- tau decays
-- tau lifetime
-- negative result from neutrino interactions
and… writing a few equations.
several (mostly neutrino-) physicists continued to request that one should ‘directly’ observe the tau neutrino interaction with matter to be convinced.

(not realizing that the observation of $\tau^- \to \pi^-$ «ν_τ» implies that if one can make a beam of «ν_τ» one will certainly see τs appear, also if the «ν_τ» is a combination/superposition of ν_μ or ν_e !)

I conclude that the difference between direct and indirect is related to how many equations good understanding requires.

Indirect requires > 1 equation, direct 0 or 1.

A scientific organization like PDG should prefer to refrain from using these subjective words.

> **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**
>
> $$\nu_\tau N \to \tau N.$$

K. Winter 1991
-- ??? –
no ref. to elaborate model

The quarks and leptons observed so far can be organized into three families (or generations) of weak isodoublets (for left-handed states), as follows:

u	c	t	quark doublets
d′	s′	b′	
ν_e	ν_μ	ν_τ	lepton doublets
e	μ	τ	

Each leptonic doublet contains a distinct type of neutrino, labelled ν_e, ν_μ, and ν_τ. One of the basic questions is, Are there more families than the three observed so far? In view of the regularity prevailing in the first three generations, counting the number of neutrino types may also mean counting the number of fundamental fermion generations.

Until now, the direct detection of neutrinos has been achieved only for the neutrinos ν_e and ν_μ. The third generation ν_τ has not yet been detected directly through its characteristic interactions with matter. The evidence for ν_τ as an independent species, with the same (universal) Fermi coupling to its third-generation charged-lepton partner τ as is the case for the two lighter generations, is indirect . It is obtained from the τ lifetime (Hitlin, 1987; Braunschweig et al., 1988), or from the tests of e–μ–τ universality based on the W partial production cross-section ratios $\sigma(W \to e\nu)/\sigma(W \to \mu\nu)/\sigma(W \to \tau\nu)$ measured at the SPS Collider by the UA1 Collaboration (Albajar et al., 1987a). Whilst the τ lifetime tests the hypothesis of universality of weak charged currents at a low $Q^2 \leq m_\tau^2$, the Collider results test it at $Q^2 \approx m_W^2$.

Denegri, Sadoulet and Spiro «The number of neutrino species» (1989) (an excellent paper!)
AB -- note that the argument is incomplete
(the observations in tau decays and neutrino beam observations are missing)

In 1985 the observation of the W decay W→ $\tau\,\nu_\tau$ was reported.

5. EXPERIMENTAL EVIDENCE FOR THE HEAVY LEPTON DECAY $W \to \tau\nu_\tau$

With the observation of the $W \to \tau\nu$ decay, the 'programme' on the leptonic decay channels of the IVB is complete.

In the case of a $W \to \tau\nu$ event where the τ decays in the hadronic mode, what we measure is a jet including charged tracks and the corresponding energy deposition in some calorimeter cells (both hadronic and electromagnetic). The measured jet represents the charged and neutral π's of ν from the W deca... and that from the τ decay. Therefore, events with missing transv... and one trigger jet were selected in the data recorded... 1983 runs (corresponding to an integrated l...).

As a consequence of the e... the weak current, the $W \to \tau\nu$ rate is expect... abundant. Almost half of the τ's decay into one charge... without neutrals and 38% with) and a neutrino[13]. This suggests a clear signature with a reasonable rate: an isolated high-p_T track of a hadronic type and some missing transverse energy. In this sense,

yes…. and it is also the first time that a tau neutrino is observed, that is not produced in tau decay!

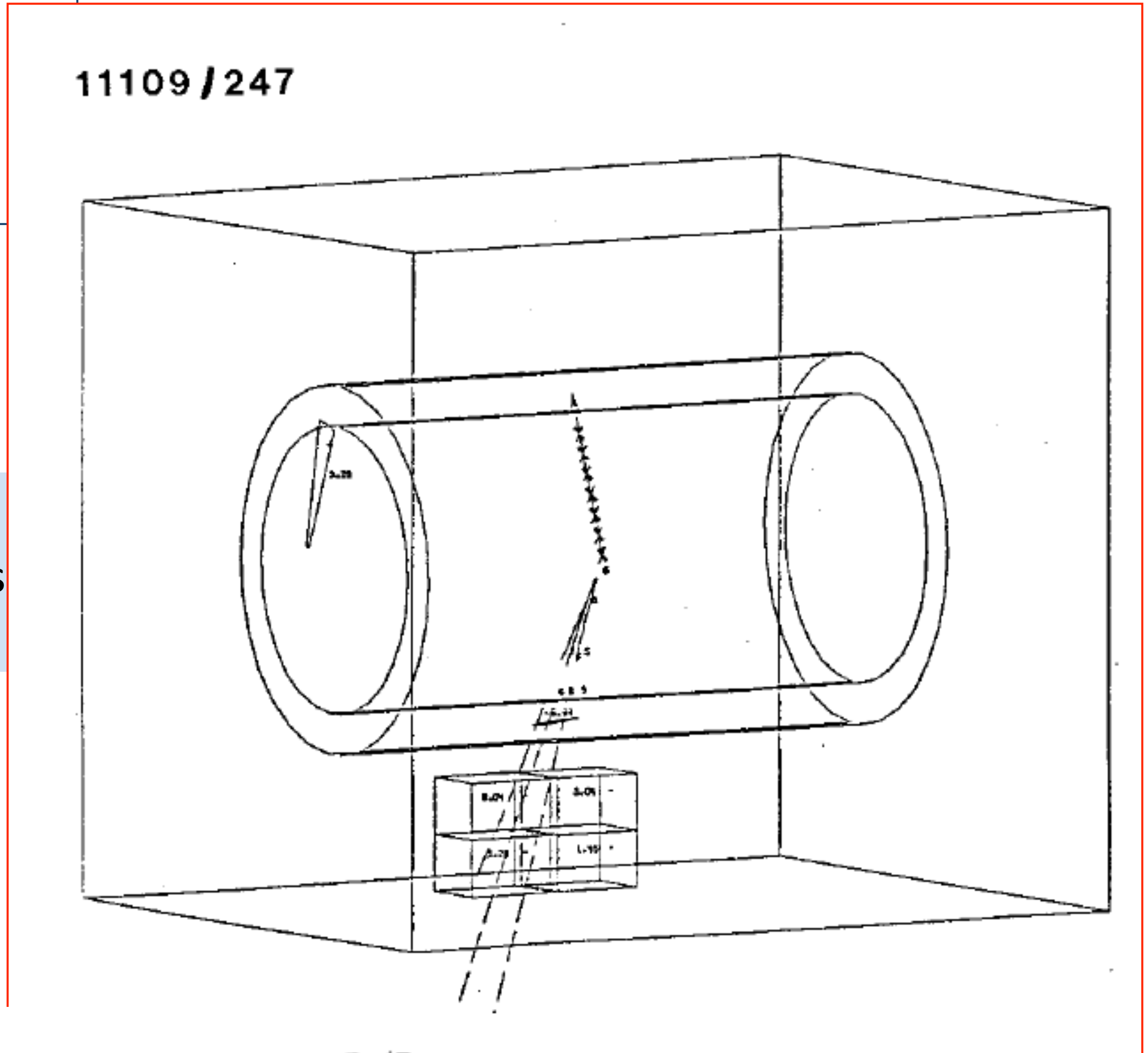
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1985

CERN-EP/85-29
5 March 1985

$W^{\pm}$ AND Z^{0} PRODUCTION IN THE UA1 EXPERIMENT
AT THE CERN PROTON-ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland



UA1 observation of $W \rightarrow \tau \nu_\tau$
- low mass jet of 3 charged tracks
- missing transverse momentum

** Mass not restricted to W mass.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_5/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.02±0.20±0.12	32	ALBAJAR	89	UA1	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.02±0.20±0.10	32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

by 1987 the CC coupling of the tau is established to equal that of the electron to ±20%

by 1987 the CC coupling of the tau
is established to equal that of the electron to 20%

** Mass not restricted to W mass.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_5/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.02±0.20±0.12	32	ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}}$ = 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.02±0.20±0.10	32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

W decay is precisely what we use to define the neutrino flavours.

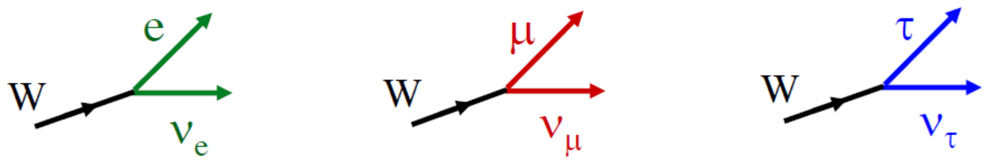
e.g. B. Kayser,
VIIth Pontecorvo School, 2017

The Neutrino Flavors

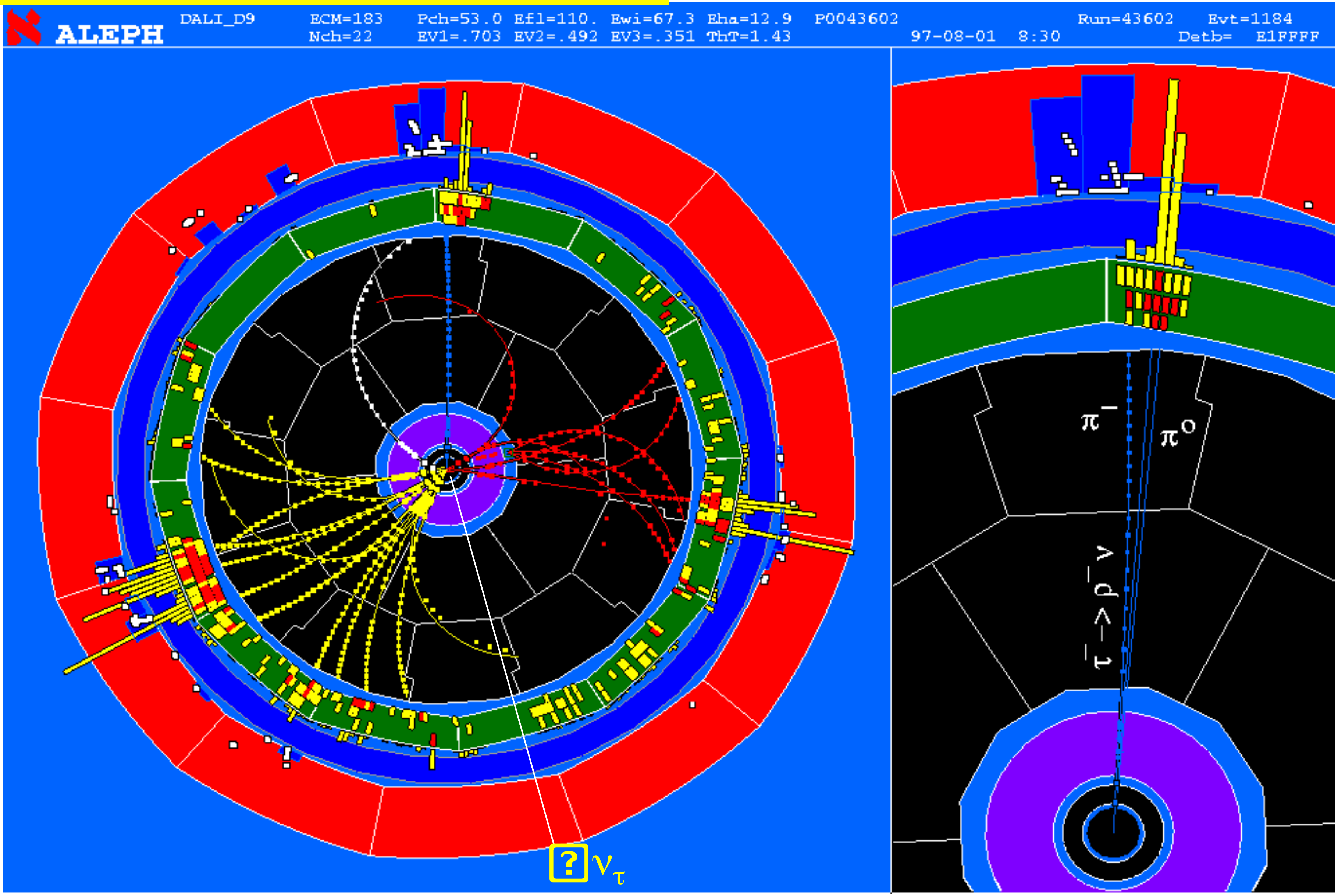
There are three flavors of charged leptons: e , μ , τ

There are three known flavors of neutrinos: ν_e, ν_μ, ν_τ

We ***define*** the neutrinos of specific flavor, ν_e, ν_μ, ν_τ, by W boson decays:



the existence of the three W decay modes with similar branching ratios establishes the tau and its neutrino as a new sequential heavy lepton doublet kinematic reconsruction of two tau neutrinos



Observation of tau-neutrino in ALEPH at LEP (183 GeV E_{cm})

$e+e- \to W+ W- \to (hadrons)^+ + \tau^- \nu_\tau$

LEP saw several 1000's of those in the 90's.

in the 1990s

-- experiments at LEP observed 100'000s of tau pairs and sereval 10000's of W pairs from which the charged current coupling τ-ν_τ was measured, and universality tests at few permil performed in tau decays and percent level in W decays.

-- the tau neutrino helicity was determined (ARGUS first)

$$\tau_\tau = 290.1 \pm 1.5\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst})\,\mathrm{fs}, \quad (7)$$

with $\chi^2 = 9.1$ for 15 degrees of freedom (CL = 87%). This result, the most precise measurement of the mean τ lifetime, is consistent with other recent measurements [18].

The ALEPH measurements of the τ lifetime and branching fractions may be used to test lepton universality. For $B(\tau \to e\nu\bar{\nu}) = (17.79 \pm 0.12 \pm 0.06)\%$ [15], $B(\tau \to \mu\nu\bar{\nu}) = (17.31 \pm 0.11 \pm 0.05)\%$ [15], and other quantities from [5], the ratios of the effective coupling constants [19] are

$$\frac{g_\tau}{g_\mu} = 1.0004 \pm 0.0032 \pm 0.0038 \pm 0.0005 \quad (8)$$

and

$$\frac{g_\tau}{g_e} = 1.0007 \pm 0.0032 \pm 0.0035 \pm 0.0005, \quad (9)$$

where the first uncertainty is from the τ lifetime, the second is from the τ leptonic branching fraction ($B(\tau \to e\nu\bar{\nu})$ in Eq. 8 and $B(\tau \to \mu\nu\bar{\nu})$ in Eq. 9), and the third is from the τ mass. The measured ratios are consistent with the hypothesis of lepton universality.

Observation of Tau Neutrino Interactions

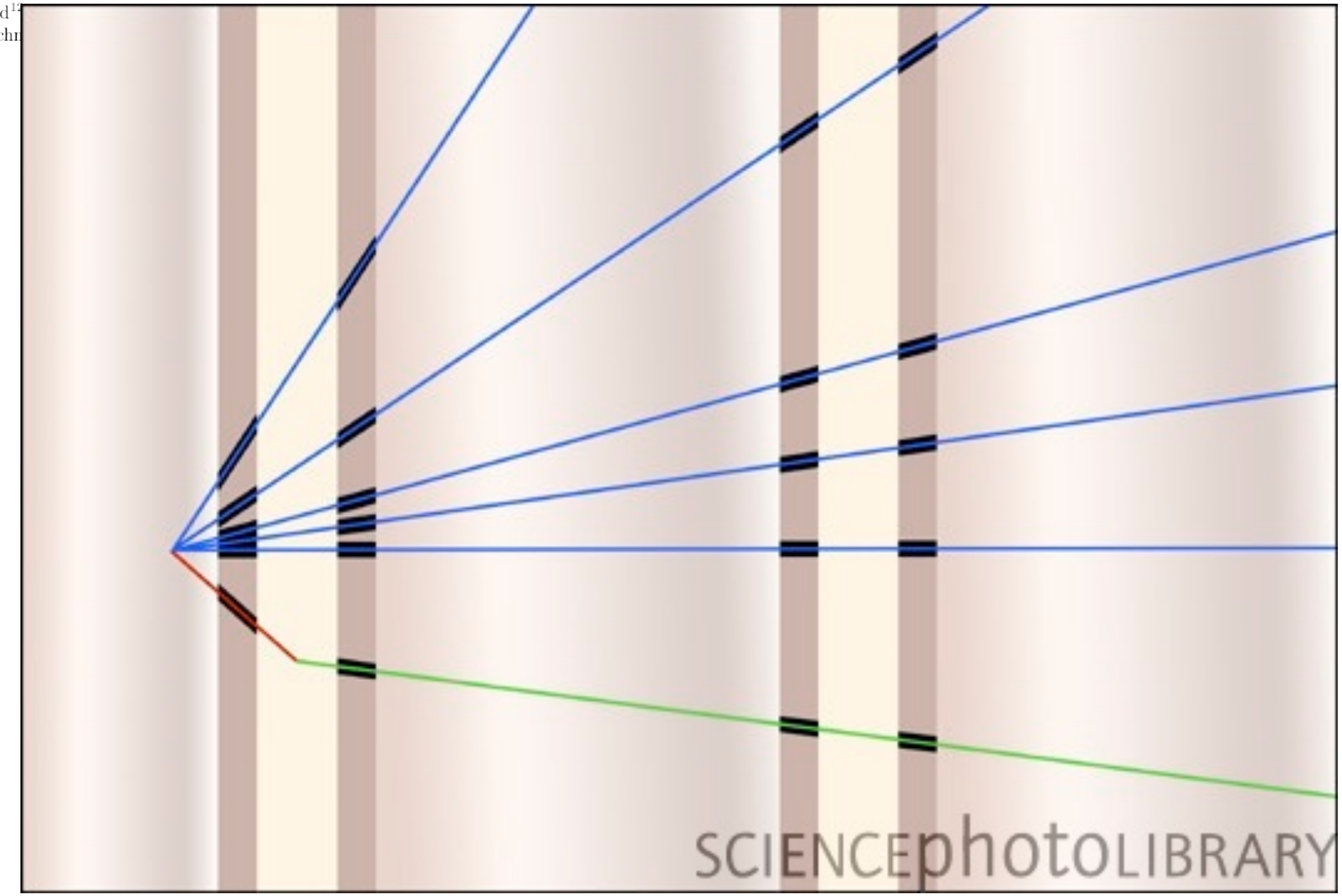
DONUT Collaboration
K. Kodama[1], N. Ushida[1], C. Andreopoulos[2], N. Saoulidou[2],
G. Tzanakos[2], P. Yager[3], B. Baller[4], D. Boehnlein[4],
W. Freeman[4], B. Lundberg[4], J. Morfin[4], R. Rameika[4],
J.C. Yun[4], J.S. Song[5], C.S. Yoon[5], S.H.Chung[5], P. Berghaus[6],
M. Kubanstev[6], N.W. Reay[6], R. Sidwell[6], N. Stanton[6],
S. Yoshida[6], S. Aoki[7], T. Hara[7], J.T. Rhee[8],
D. Ciampa[9], C. Erickson[9], M. Graham[9], K. Heller[9], R. Rusack[9],
R. Schwienhorst[9], J. Sielaff[9], J. Trammell[9], J. Wilcox[9]
K. Hoshino[10], H. Jiko[10], M. Miyanishi[10], M. Komatsu[10], M. Nakamura[10],
T. Nakano[10], K. Niwa[10], N. Nonaka[10], K. Okada[10],
O. Sato[10], T. Akdogan[11], V. Paolone[11], C. Rosenfeld[12]
A. Kulik[11,12], T. Kafka[13], W. Oliver[13], T. Patzak[13], J. Schn
[1] *Aichi University of Education, Kariya, Japan*
[2] *University of Athens, Greece*
[3] *University of California/Davis, Davis, California*
[4] *Fermilab, Batavia, Illinois 60510*
[5] *Gyeongsang University, Chinju, Korea*
[6] *Kansas State University, Manhattan, Kansas*
[7] *Kobe University, Kobe, Japan*
[8] *Kon-kuk University, Korea*
[9] *University of Minnesota, Minnesota*
[10] *Nagoya University, Nagoya 464-8602, Japan*
[11] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[12] *University of South Carolina, Columbia, South Carolina*
[13] *Tufts University, Medford, Massachusetts 02155*

December 14, 2000

Observation of Tau Neutrino Interactions
DONUT

Beautiful observation of neutrino interations producing taus!

there is ‘small print’…



Tau Neutrino interaction in DONUT experiment (Fermilab) 2000

The neutrino beam was created using 800 GeV protons from the Fermilab Tevatron interacting in a meter long tungsten beam dump, which was 36 m upstream from the emulsion target. Most of the neutrinos that interacted in the emulsion target originated in the decays of charmed mesons in the beam dump. The primary source of ν_τ is the leptonic decay of a D_S meson into τ and $\overline{\nu}_\tau$, and the subsequent decay of the τ to a ν_τ. All other sources of ν_τ are estimated to have contributed an additional 15%. $(5 \pm 1)\%$ of all neutrino interactions detected in the emulsion were predicted to be from ν_τ with the dominant uncertainty from charm production and $D_S \to \tau\nu$ branching ratio measurements[4]. The mean energies of the detected neutrino interactions were calculated to be 89 GeV, 69 GeV, and 111 GeV, for ν_e, ν_μ, and ν_τ respectively.

It should be noted that since the neutrino flux had only an estimated 5% ν_τ component, the possibility that the ν_τ is a superposition of ν_e and ν_μ cannot be eliminated using the results of this experiment. Results from other experiments [9] [10] [11], which were sensitive to τ leptons, show that the direct coupling of ν_μ to τ is very small (2×10^{-4}). The upper limit (90% CL) for ν_e to τ is much larger, 1.1×10^{-2} (90% CL). Assuming this upper limit, the estimated number of τ events from this hypothetical source is 0.27 ± 0.09 (90% CL).

[9] E531 Collaboration, N. Ushida *et al.*, Phys. Rev. Lett. **57**, 2897 (1986).

[10] CHORUS Collaboration, E. Eskut *et al.*, Nucl. Phys. **A663**, 807 (2000).

[11] NOMAD Collaboration, P. Astier *et al.*, Phys. Lett. **B483**, 387 (2000).

this is very different from the 1962 experiment in which neutrinos from pion decay are >99% muon neutrinos…

Are there more families of neutrinos?

the SM can accommodate more families of quarks and leptons and in the 70/80's this was a question of great importance for nucleosynthesis and cosmology

The construction of LEP was decided by CERN council in 1981, **before** the W and Z were observed at the proton-antiproton collider! Construction started in 1983.

A big scare of the time was the **number of neutrinos**

LEP was on mission to find out!

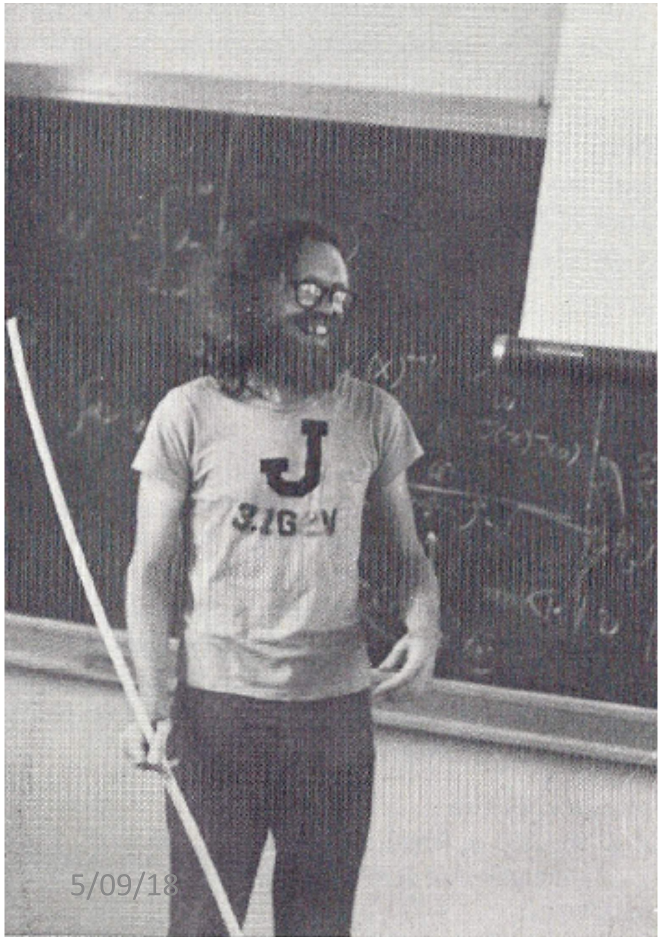
the appearance of a word

PROCEEDINGS OF THE LEP SUMMER STUDY

Les Houches and CERN

10-22 September 1978

CERN 79-01
Volume 2
14 February 1979



- 615 -

Zedology

John Ellis

CERN, Geneva

exercise: google up 'zedology'

we find the formulae that we all know and love....

For an arbitrary Z^o, the formulae (1) and (2) correspond to decay widths

no ρ !

$$\Gamma(Z^o \to f\bar{f}) \approx \frac{G_F m_Z^3}{24\sqrt{2}\pi}(v_f^2 + a_f^2) \quad (14)$$

for $m_f << m_{Z/2}$. For the favoured range of values of m_Z and v_f, a_f of order unity, equation (14) implies that $\Gamma(Z^o \to f\bar{f}) = 0(100)$ MeV. Including 3 generations of fermions one would therefore expect a total Z^o decay width

$$\Gamma(Z^o \to \text{all}) = 0(2 \text{ to } 3)\ \text{GeV} \quad (15)$$

and a little drama...

(...)

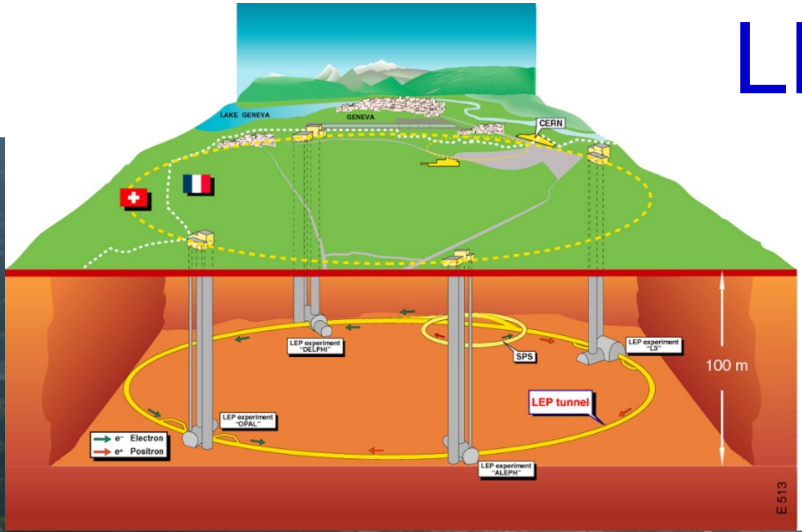
disappearance of the Z boson?

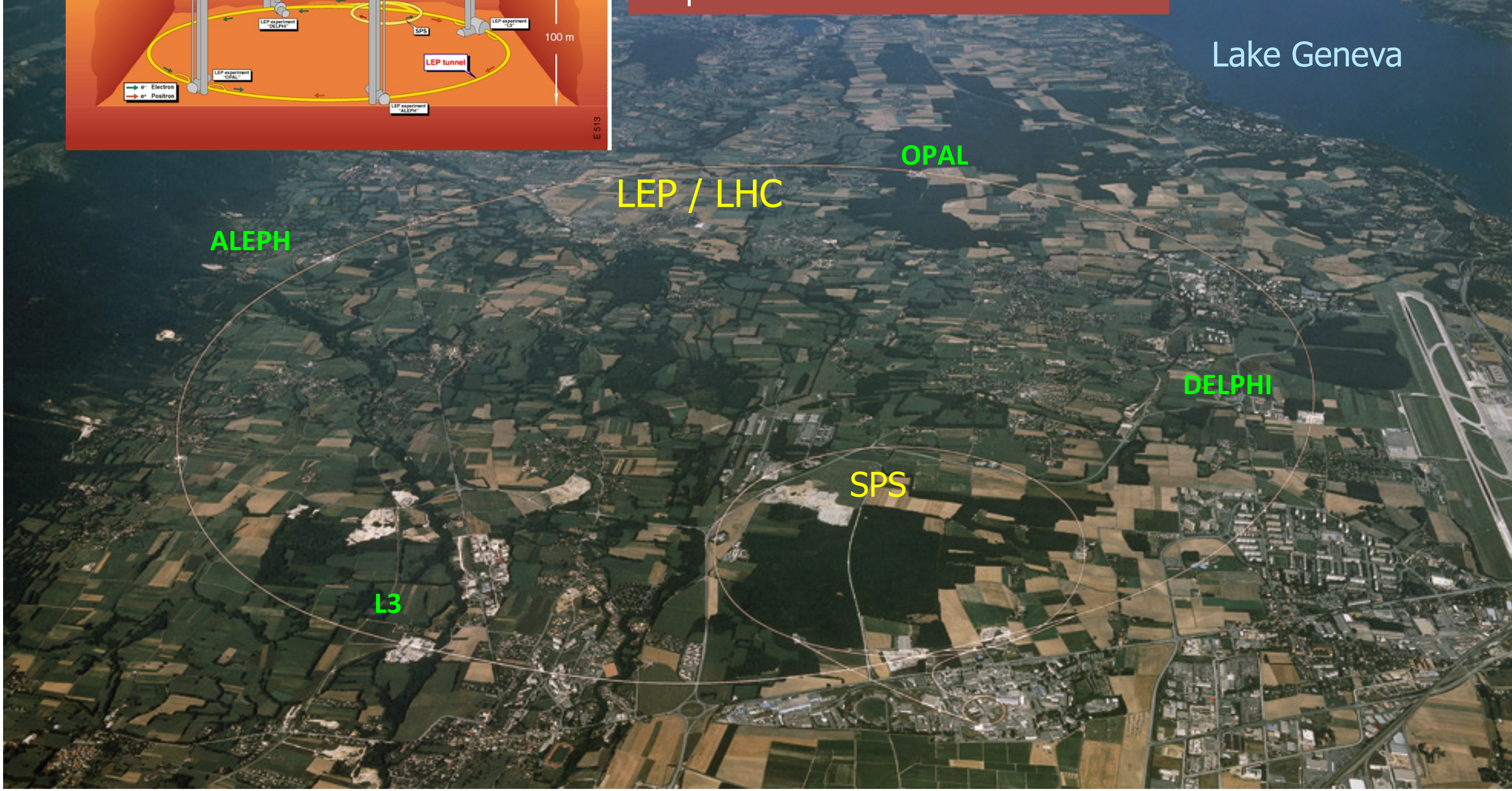
3. Determining the Fermion Spectrum

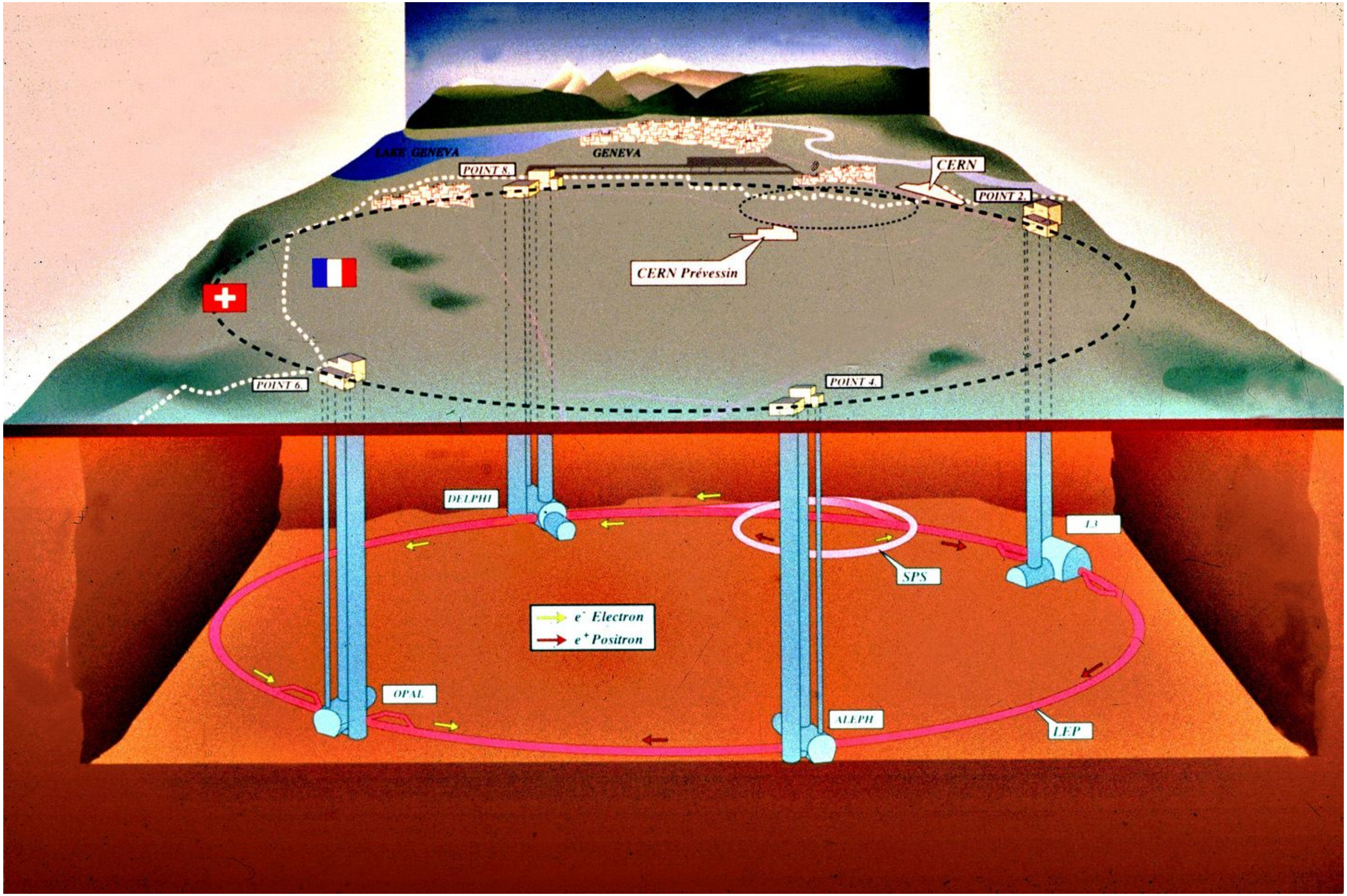
The above results are encouraging, in the sense that the Z^o peak is large and dramatic, as long as there are not too many generations of fermions. Is it conceivable that there might be so many fermions as to wash out the Z^o peak?

build LEP .... and find no Z! (imagine to build LHC and find no Higgs, huh?)

LEP / LHC Layout






LAKE GENEVA
GENEVA
POINT 8.
CERN
POINT 2.
CERN Prévessin
POINT 6.
POINT 4.
DELPHI
L3
SPS
e^- Electron
e^+ Positron
OPAL
ALEPH
LEP

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1989

BEFORE LEP STARTED

CERN-EP/89-72
LBL 26014
DPhPE 88-12
6 June 1989

CDF collab. rec 19 July $M_Z = 90.9 \pm 0.3 \pm 0.2$ GeV
Phys Rev. Lett. 63 (1989) 720

MARK II at SLC rec. 24 July $M_Z = 91.11 \pm 0.23$ GeV
Phys Rev Lett 63 (1989) 724 $N_\nu = 3.8 \pm 1.4$
Phys Rev Lett 63 (1989) 2173 $M_Z = 91.14 \pm 0.12$
rec. 12 october $N_\nu = 2.8 \pm 0.6$ 3.9 @ 95% CL

THE NUMBER OF NEUTRINO SPECIES

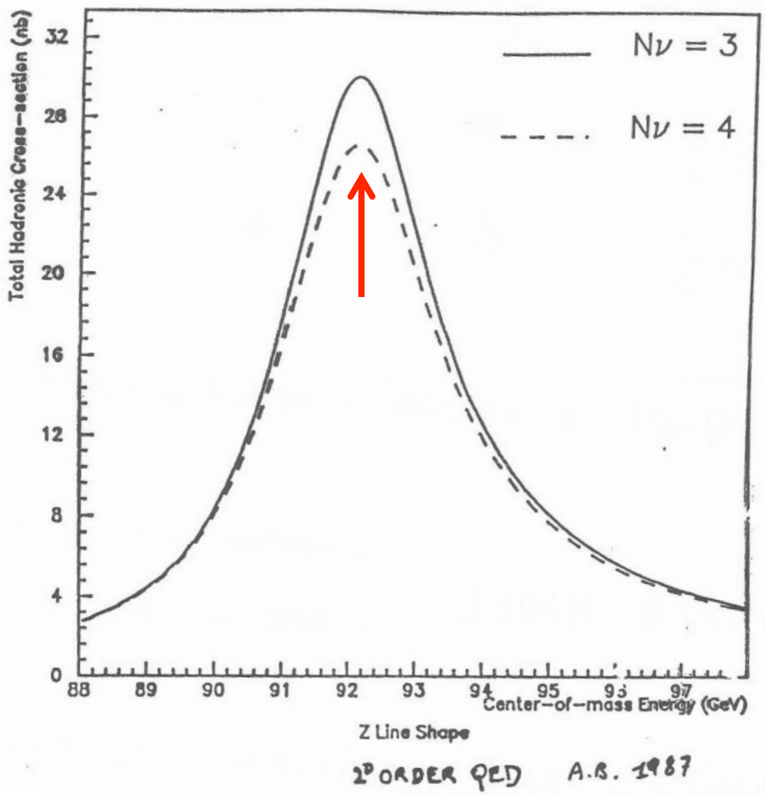
D. Denegri, CERN, Geneva, Switzerland
and DPHPE, CEN-Saclay, Gif-sur-Yvette, France

B. Sadoulet, Center for Particle Astrophysics, Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, USA

M. Spiro, DPhPE, CEN-Saclay, Gif-sur-Yvette, France

We discuss the methods used to determine the number of neutrino species N_ν, or an upper limit on this number, within the framework of the Standard Model. The astrophysical limit based on the neutrino burst from SN1987A is discussed first. Next we proceed with the discussion of the cosmological constraint based on the observed He/H abundance ratio. Finally, we discuss the particle physics methods based on single-photon production in e^+e^- collisions, on the production of monojets in $p\bar{p}$ collisions, and on the determination of N_ν from the ratio of the $W \to \ell\bar{\nu}$ to $Z \to \ell\bar{\ell}$ partial cross-sections in $p\bar{p}$ collisions. The various sources of uncertainty and the experimental backgrounds are presented, as well as an idea of what may be expected on this subject in the future. There is remarkable agreement between the various methods, with central values for N_ν between 2 and 3 and with upper limits $N_\nu < 6$. The consistency between the laboratory determinations of N_ν and those from the supernova SN1987A or cosmology represents an astounding success for the Standard Model and for the current description of stellar collapse and of the Big Bang primordial nucleosynthesis. Combining all determinations, we obtain a central value $N_\nu = 2.1^{+0.6}_{-0.4}$ for $m_t = 50$ GeV and $N_\nu = 2.0^{+0.6}_{-0.4}$ if $m_t \geq m_W$. At present, $N_\nu = 3$ is perfectly compatible with all data. Although the consistency is significantly worse, four families still provide a reasonable fit. In the framework of the Standard Model, a fifth light neutrino is, however, unlikely.

The Z width would be made of 1.7 GeV for quarks, 84 MeV for each of 3 leptons and 170 for each neutrino.
One more neutrino would increase the total width by 7% over the known 3 neutrinos.
First studies (AB et al) elaborated a 10 point scan measuring the muon cross-section for a whole year to get a precision of about 20 MeV on the Z width, showing little understanding of the problem



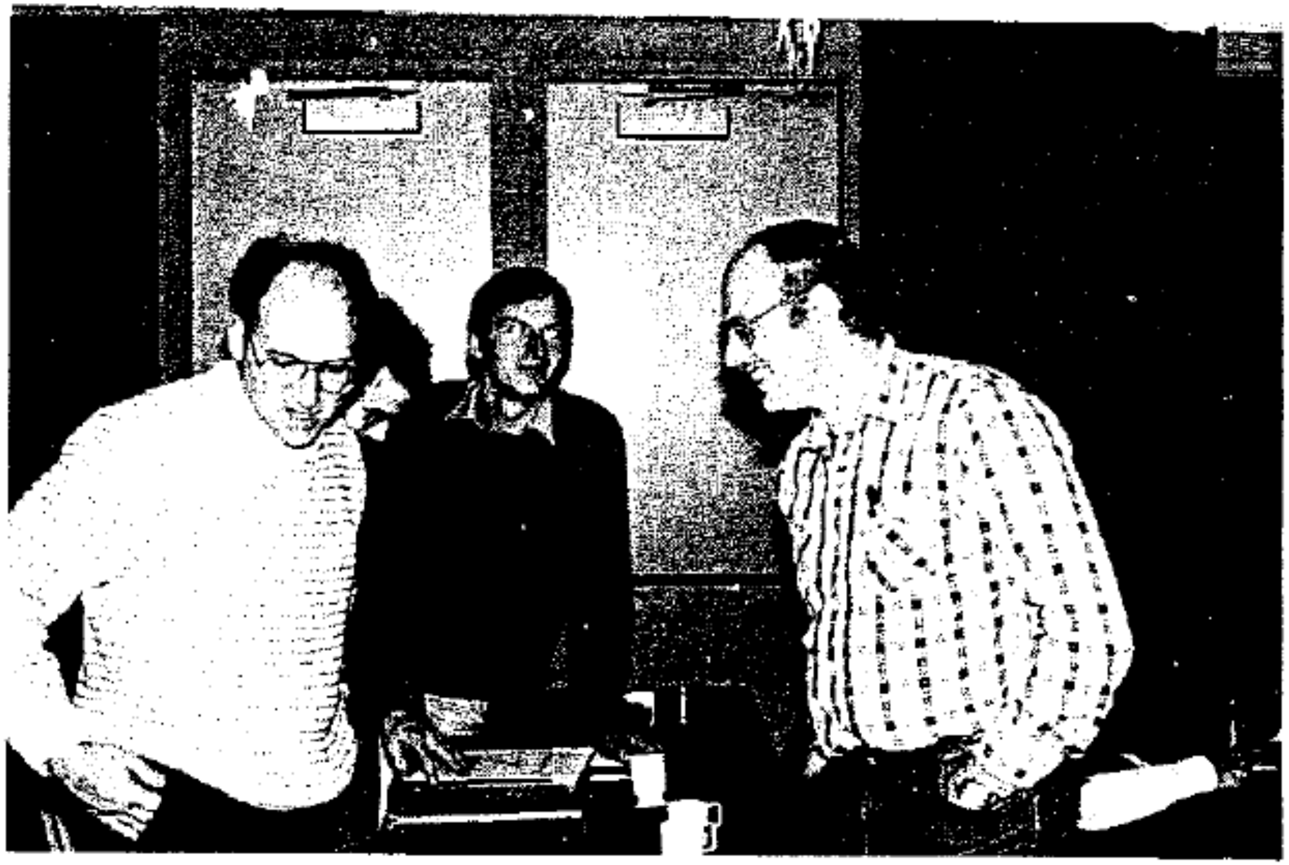
A closer look at a line shape in 1987 revealed that the sensitivity comes almost entirely from the peak cross-section…
and that hadron measurements would be qucker.

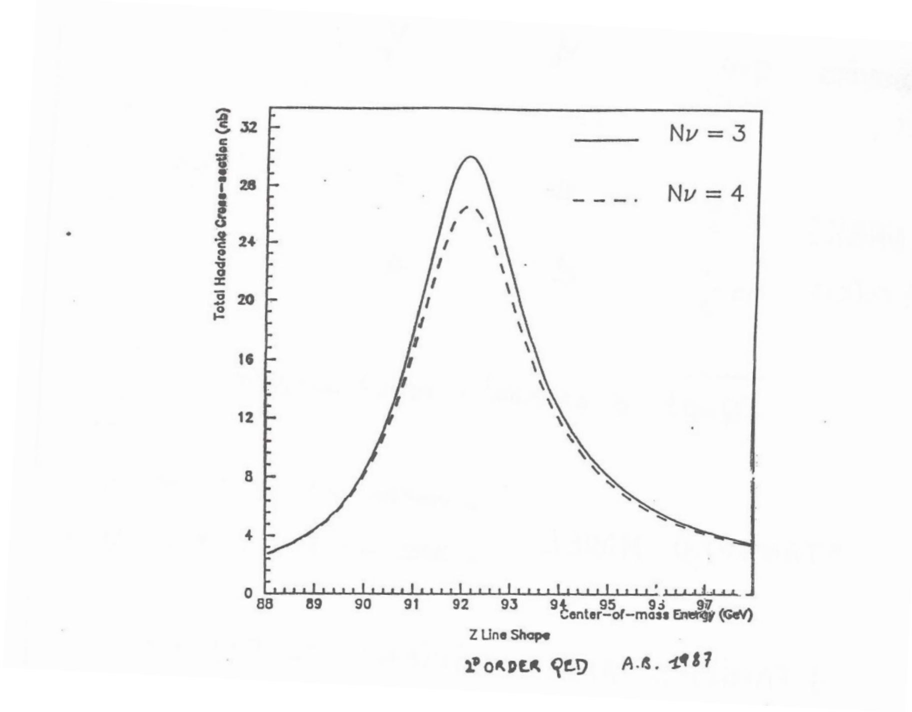
G. Feldman put this all down in equations in the MarkII physics workshop in February 1987.

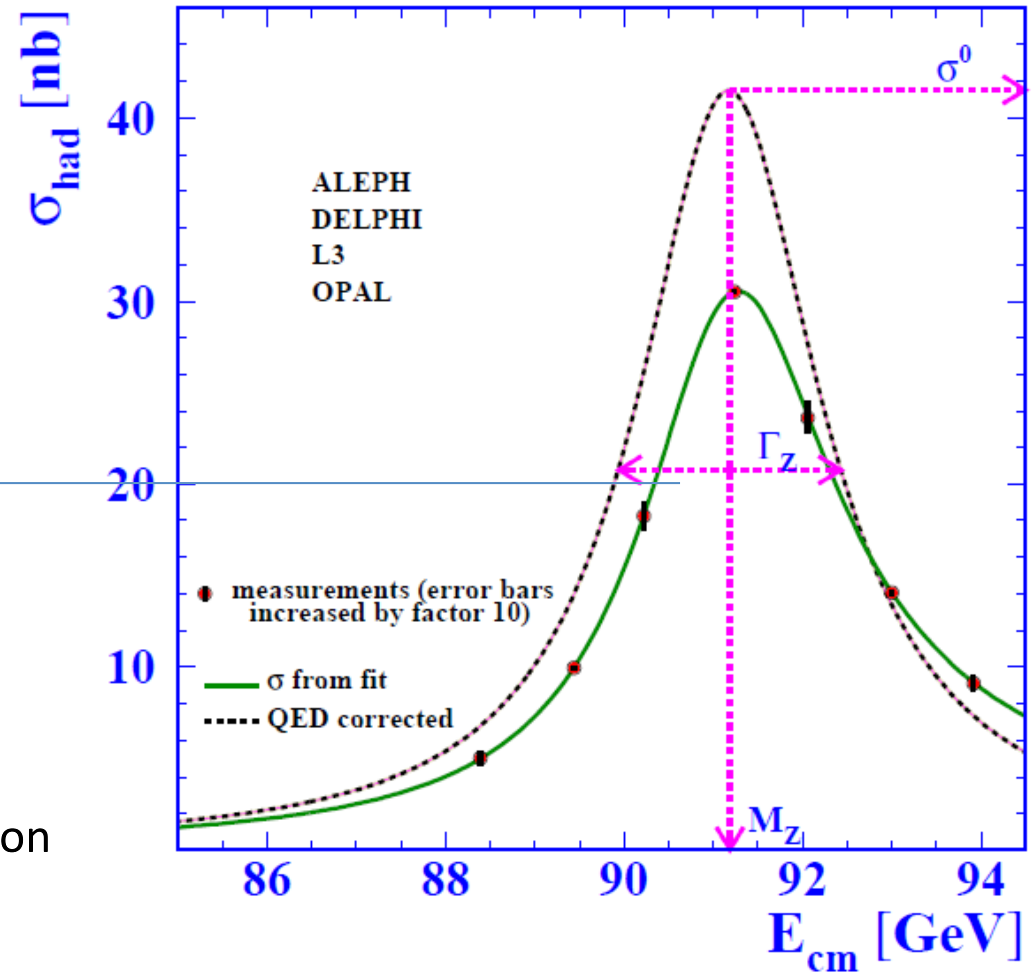
$$\sigma_{\mu\mu} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_{tot}^2} \qquad \sigma_{had} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_{tot}^2}$$

enhancement

N_Z	$\Delta\Gamma_{invis}$, Eq. (11) (MeV)	$\Delta\Gamma_{tot}$, Eq. (12) (MeV)	$\Delta\Gamma_{tot}$, Direct Meas. (MeV)
500	142	215	248
1000	105	156	175
2000	81	115	124
5000	62	82	78
10000	54	67	55







We had figured out that
the quantity that is directly sensitive to the number of neutrinos is the peak cross-section (mostly Z→ ?qq)

➔ the luminosity measurement had been to object of particular attention with a precision of ±1% (in ALEPH)
By the end of LEP it would be precise to ±0.06%.!)

The key to mass and width measurements is the **beam energy calibration**

$$R_\ell \equiv \Gamma_{had}/\Gamma_\ell$$

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

theory

all measured at the peak

Basis for discussion on 1989 running

Proposal for 1989 running

14 May 1989

The $Z \to Q\overline{Q}$ group [1]

PROZ.tex

This note summarizes the present understanding of the $Z \to Q\overline{Q}$ group regarding early measurements of the Z width Γ_Z and of the peak hadronic cross-section, σ_{had}^{peak}. Further details will appear in forthcoming notes. We conclude by the following possible scenario:

I. Measurement of M_Z to $\pm$ 200 Mev. (25 nb^{-1})

II. Measurement of σ_{had}^{peak}. ($\simeq$ 100 nb^{-1})

III. Measurement of Γ_Z. ($\simeq$ 3 pb^{-1})

3 methods

- Using the measurement of the total width: (*method 1*)

$$\Gamma_{inv} = N_\nu \Gamma_\nu = \Gamma_Z^{meas} - \Gamma_Z^{SM}$$

The present knowledge of Γ_Z is ± 25Mev, for a given M_Z, coming form experimental uncertainty on i)$\alpha_s(M_Z^2)$, ii)unknown Standard Model parameters, $m_H, m_t, \rho_{t_{Tee}}$. One neutrino family changes Γ_Z by 170Mev. This method however is sensitive to any new effect, either by direct production or virtual effects (Z')[6].

- Using the peak hadronic cross-section: (*method 2*)

$$\sigma_{had}^{peak} = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{(N_\nu \Gamma_\nu + 3\Gamma_{ee} + \Gamma_{had})^2}(1 - \delta_{rad}) \quad (5)$$

The peak cross-section is insensitive to standard model virtual effects, and to the exact value of Γ_{had} [7]. It changes by -13% for one new family of neutrinos. The invisible width, i.e. the production of anything which is new and not classified as hadronic event, is measured in units of the leptonic width. The only draw-back of this method is that it requires a good understanding of the absolute luminosity.

- using the total width in conjunction with the measurement of $R' = \frac{\Gamma_{had}}{\Gamma_{\mu\mu}} \simeq 20.7$: (*method 3*)

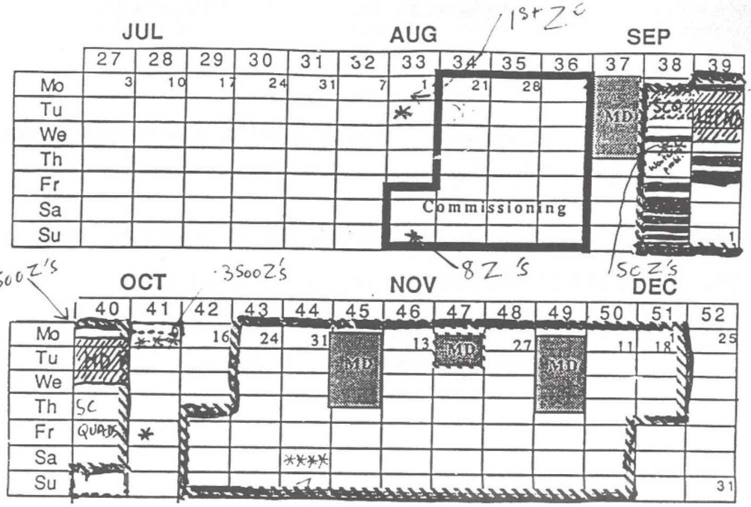
$$\Gamma_{inv} = N_\nu \Gamma_\nu = \Gamma_Z^{meas} - \Gamma_{ee}^{SM}(3 + R') \quad (6)$$

This method requires more statistics but offers the advantage of providing a measurement of the invisible width which is independent on absolute luminosity.

$\mathcal{L}_{tot}$	0.1 pb^{-1}	0.3 pb^{-1}	1 pb^{-1}	3 pb^{-1}
N_{peak}	1200	3600	12000	36000
N_{tot}	1800	5400	18000	54000
method 1				
$\Delta\Gamma_Z$(Mev), statistical	160	88	48	28
$\Delta\Gamma_Z$(Mev), total	162	92	54	38
ΔN_ν	0.96	0.56	0.35	0.25
method 2				
$\frac{\Delta\sigma_{had}^{peak}}{\sigma_{had}^{peak}}$, statistical	0.040	0.024	0.013	0.007
$\frac{\Delta\sigma_{had}^{peak}}{\sigma_{had}^{peak}}$, total	0.050	0.038	0.032	0.031
ΔN_ν	0.42	0.32	0.27	0.26
method 3				
$\Delta R'$	2.7	1.6	0.9	0.6
ΔN_ν	1.6	0.95	0.55	0.38
ΔM_Z(Mev)	100	70	55	48

J. WOTSCHACK, EP

1989 LEP SCHEDULE



Machine Stop — MD CPS+SPS — Physics

12000 Z's

Commissioning

*: $\mathcal{L} \approx 2\ 10^{28}$ cm²/s

**: $\mathcal{L} = 5\ 10^{29}$ cm²/s

***: $\mathcal{L} = 1.5\ 10^{30}$ cm²/s

****: $\mathcal{L} = 4\ 10^{30}$ cm²/s

Aim for end of this year (1989)
$\langle \mathcal{L} \rangle \sim 10^{30}$, eg $\mathcal{L} = 3\ 10^{30}$
100 000 Z's per experiment

NOTES

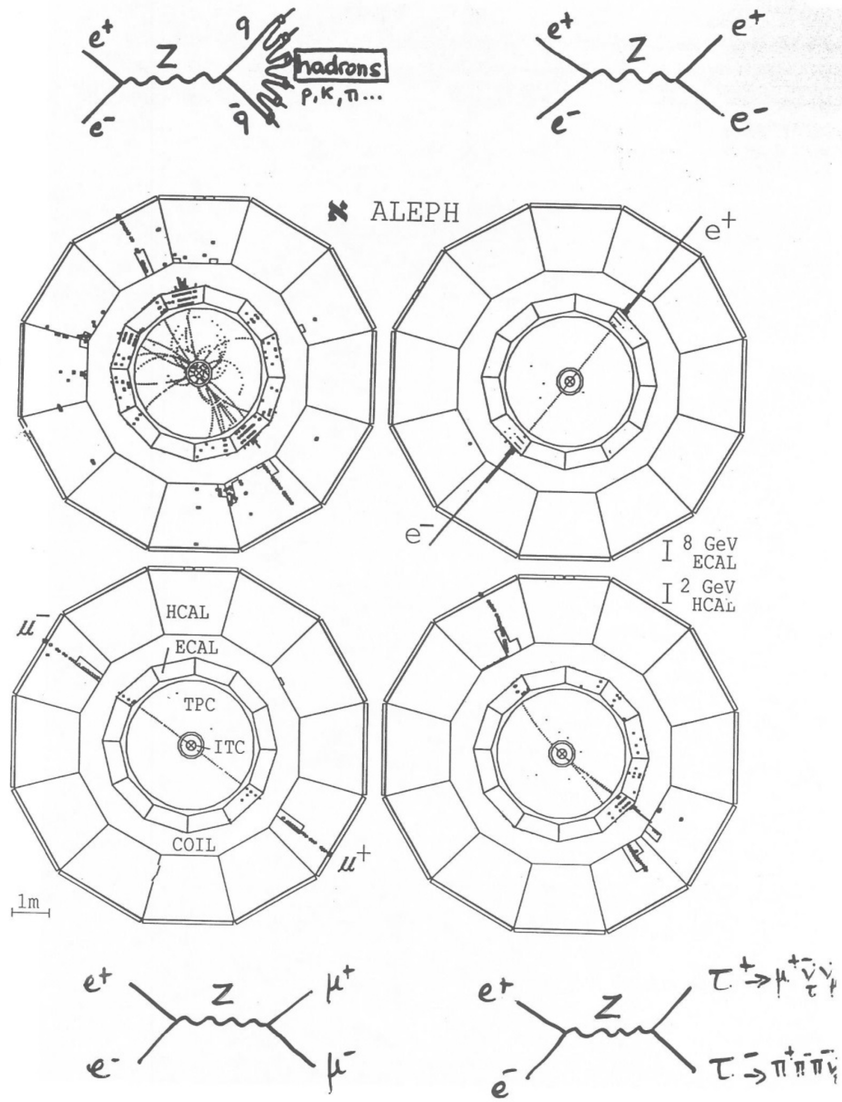
a) The LEP stop due to the PS and SPS MD of 11-14 Sept. will be extended to the 18th Sept. at noon to allow the repair of the L3 TEC.

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.

* CERN Seminar: First results from LEP i.e. 8th Sept 89.
13 october 1989



The thirc

L3 hadrons

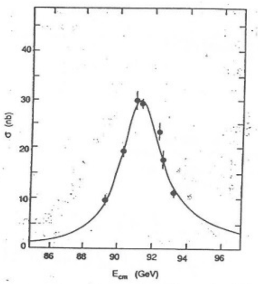


Fig. 7. Measured cross section for $e^+e^- \to$ hadrons as a function of $\sqrt{s}$. Data are shown with statistical errors only. The curve shows a fit to the Cahn formula [13] in which M_{Z^0} and $\Gamma_{invisible}$ were left free. The normalization was floated within the quoted 6% systematic error.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

L3 muons

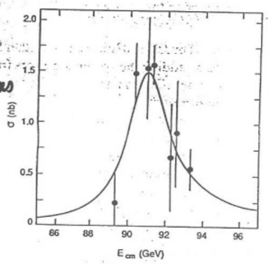


Fig. 8. Measured cross section for $e^+e^- \to \mu^+\mu^-$ as a function of $\sqrt{s}$. The solid line is the standard model fit. Data are shown with statistical errors only.

ALEPH hadrons.

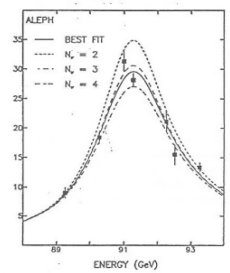
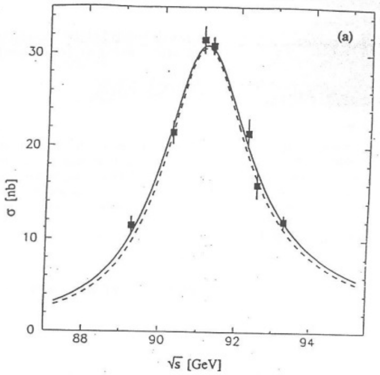


Fig. 5. The cross-section for $e^+e^- \to$ hadrons as a function of centre-of-mass energy and result of the three parameter fit.

OPAL



"My line-shape is the prettiest of all"

Tatiana Fabergé
Theory christmas Party 1989

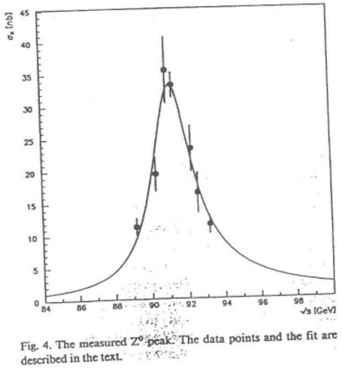


Fig. 4. The measured Z^0 peak. The data points and the fit are described in the text.

DELPHI hadrons

ne 231, number 4 PHYSICS LETTERS B 16 November 1989

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z^0

L3 Collaboration

Received 12 October 1989

We report the results of first physics runs of the L3 detector at LEP. Based on 2538 hadron events, we determined the mass m_{Z^0} and the width Γ_{Z^0} of the intermediate vector boson Z^0 to be $m_{Z^0}=91.132\pm0.057$ GeV (not including the 46 MeV LEP machine energy uncertainty) and $\Gamma_{Z^0}=2.588\pm0.137$ GeV. We also determined $\Gamma_{invisible}=0.567\pm0.080$ GeV, corresponding to 3.42 ± 0.48 number of neutrino flavors. We also measured the muon pair cross section and determined the branching ratio $\Gamma_{\mu\mu}/\Gamma_h=0.056\pm0.006$. The partial width of $Z^0 \to e^+e^-$ is $\Gamma_{ee}=88\pm9\pm7$ MeV.

2538 $Z \to q\bar{q}$
95 e^+e^- 97 $\mu^+\mu^-$

$N_\nu = 3.42 \pm 0.48$
$M_Z = 91.132 \pm 0.057 \pm 0.046$ LEP
$\Gamma_Z = 2.588 \pm 0.137$

DETERMINATION OF THE NUMBER OF LIGHT NEUTRINO SPECIES

ALEPH Collaboration

Received 12 October 1989

The cross-section for $e^+e^- \to$ hadrons in the vicinity of the Z boson peak has been measured with the ALEPH detector at the CERN Large Electron Positron collider, LEP. Measurements of the Z mass, $M_Z=(91.174\pm0.070)$ GeV, the Z width $\Gamma_Z=(2.68\pm0.15)$ GeV, and of the peak hadronic cross-section, $\sigma^{peak}_{had}=(29.3\pm1.2)$ nb, are presented. Within the constraints of the standard electroweak model, the number of light neutrino species is found to be $N_\nu=3.27\pm0.30$. This result rules out the possibility of a fourth type of light neutrino at 98% CL.

3112 $Z \to q\bar{q}$

$N_\nu = 3.27 \pm 0.30$
$M_Z = 91.174 \pm 0.055 \pm 0.045$
$\Gamma_Z = 2.68 \pm 0.15$

MEASUREMENT OF THE Z^0 MASS AND WIDTH WITH THE OPAL DETECTOR AT LEP

OPAL Collaboration

Received 13 October 1989

1350 $Z \to q\bar{q}$

We report an experimental determination of the cross section for $e^+e^- \to$ hadrons from a scan around the Z^0 pole. On the basis of [redacted] hadronic events collected over seven energy points between 89.26 GeV and 93.26 GeV we obtain a mass of $m_Z=91.01\pm0.05\pm0.05$ GeV, and a total decay width of $\Gamma_Z=2.60\pm0.13$ GeV. In the context of the standard model these results imply 3.1 ± 0.4 neutrino generations.

$N_\nu = 3.1 \pm 0.4$
$M_Z = 91.01 \pm 0.05 \pm 0.05$
$\Gamma_Z = 2.60 \pm 0.13$

MEASUREMENT OF THE MASS AND WIDTH OF THE Z^0-PARTICLE FROM MULTIHADRONIC FINAL STATES PRODUCED IN e^+e^- ANNIHILATIONS

DELPHI Collaboration

1066 $Z \to q\bar{q}$

Received 16 October 1989

First measurements of the mass and width of the Z^0 performed at the newly commissioned LEP Collider by the DELPHI Collaboration are presented. The measurements are derived from the study of multihadronic final states produced in e^+e^- annihilations at several energies around the Z^0 mass. The values found for the mass and width are $M(Z^0)=91.06\pm0.09$ (stat.) ±0.045 (syst.) GeV and $\Gamma(Z^0)=2.42\pm0.21$ (stat.) GeV respectively, from a three-parameter fit to the line shape. A two-parameter fit in the framework of the standard model yields for the number of light neutrino species $N_\nu=2.4\pm0.4$ (stat.) ±0.5 (syst.).

13 October 1989:

$N_\nu = 3.16 \pm 0.20$ $\chi^2 = 1.8/3$
$M_Z = 91.094 \pm 0.029 \pm 0.045$ $\chi^2 = 5.5/3$

$N_\nu = 2.4 \pm 0.4 \pm 0.5$
$M_Z = 91.06 \pm 0.09 \pm 0.045$
$\Gamma_Z = 2.42 \pm 0.21$

Three weeks of data at LEP…
and there were only three neutrinos

W.A. : 3.11±0.16

$$N_\nu = 3.27 \pm 0.30. \quad (5)$$

The hypothesis $N_\nu = 4$ is ruled out at 98% confidence level. This measurement improves in a decisive way upon previous determinations of the number of neutrino species from the UA1 [16] and UA2 [17] experiments, from PEP [18] and PETRA [19], from cosmological [20] or astrophysical [21] arguments, as well as from a similar determination at the Z peak [22].

The demonstration that there is a third neutrino confirms that the τ neutrino is distinct from the e and μ 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 masses in excess of $\sim$ 30GeV.

ALEPH collaboration 'determination of the number of light neutrino species'
Physics Letters B Volume 231, Issue 4, 16 November 1989, Pages 519-529

by 1989 (and before the measurement at LEP)
the first three families of neutrinos (ν_e ν_μ ν_τ) were «already known»

In October 1989 LEP determined that the number of neutrino families was 3.11±0.15

In Feb 1990 Cecilia Jarlskog commented that this number could smaller than 3
if the left handed neutrino(s) has a component of (a) heavy sterile neutrino(s)
which is kinematically suppressed or forbidden

Volume 241, number 4 PHYSICS LETTERS B 24 May 1990

NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

C. JARLSKOG
CERN, CH-1211 Geneva 23, Switzerland
and Department of Physics, University of Stockholm, S-113 46 Stockholm, Sweden

Received 20 February 1990

We consider the implications of extending the n
an arbitrary number of right-handed neutrinos, f
effective number of neutrinos, $\langle n \rangle$, satisfies, the i
is the standard width for one massless neutrino. T
is less than three, if there are right-handed neutrin

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(\mathrm{Z} \rightarrow \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \qquad (15)$$

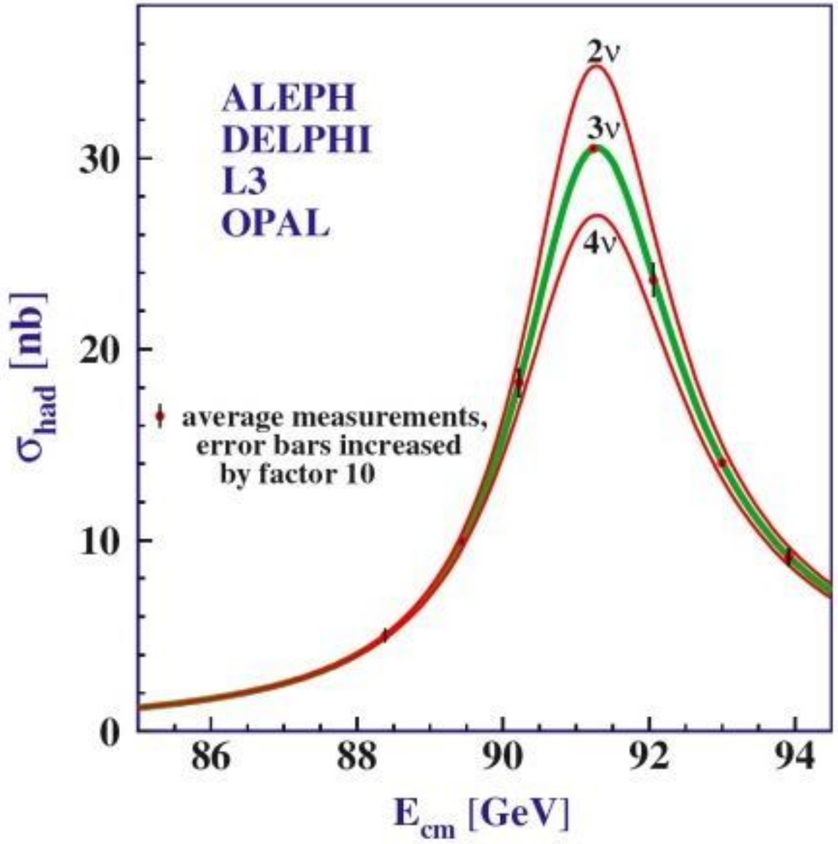
At the end of LEP:

Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

- 2 σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔



The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!

Another solution:

determine the number of neutrinos from the radiative returns

$$e^+e^- \rightarrow \gamma\ Z\ (\rightarrow \nu ? \nu)$$

CERN-TH.5528/89

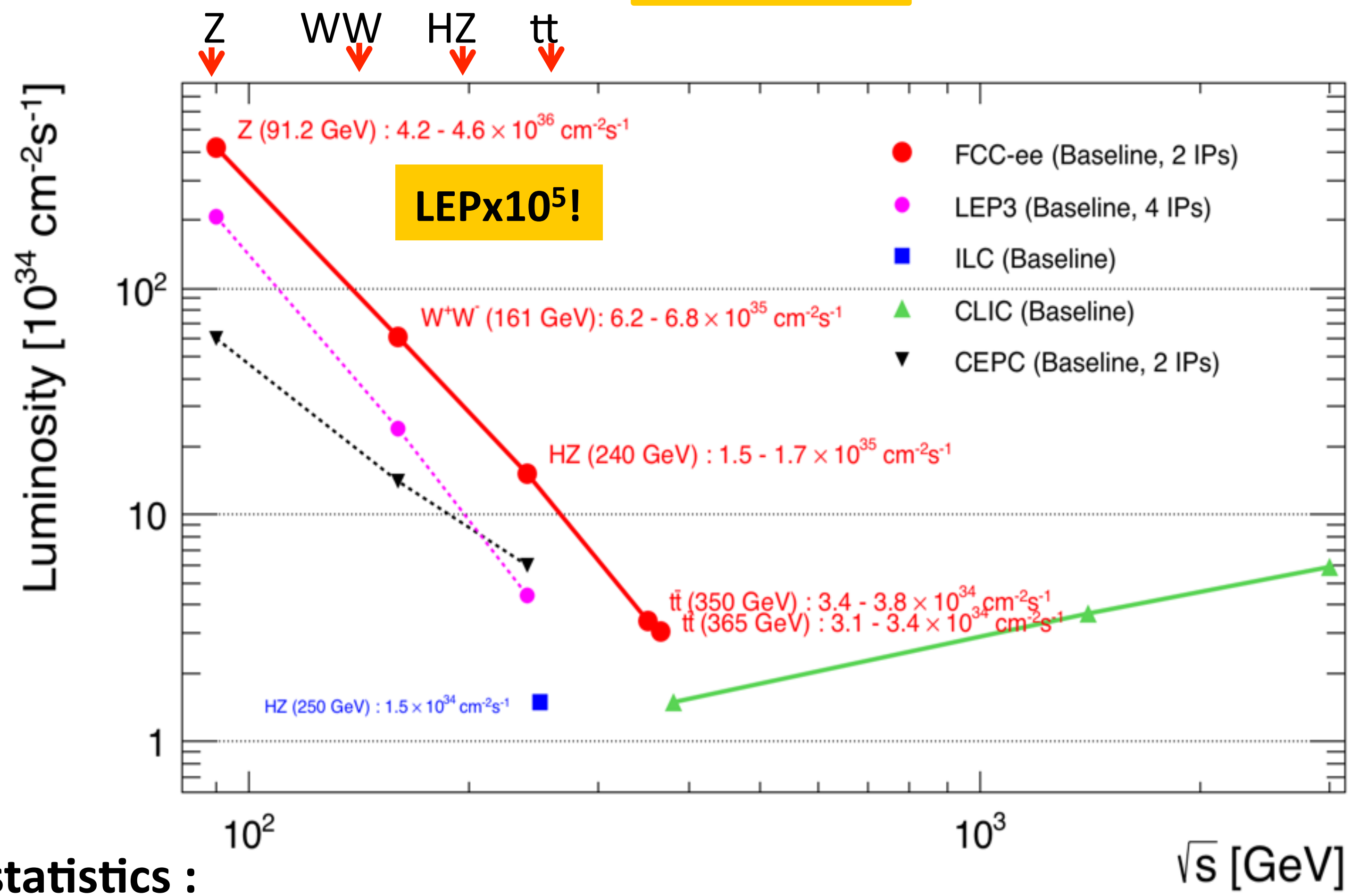
NEUTRINO COUNTING

G. Barbiellini[1], X. Berdugo[2], G. Bonvicini[3], P. Colas[4], L. Mirabito[4], C. Dionisi[5], D. Karlen[6], F. Linde[7], C. Luci[8], C. Mana[8], C. Matteuzzi[9], O. Nicrosini[10], R. Ragazzon[1], D. Schaile[11], F. Scuri[1] and L. Trentadue*),[12]

in its original form (Karlen) the method only counts the 'single photon' events and is actually less sensitive than claimed. It has poorer statistics and requires running ~10 GeV above the Z pole. Systematics on photon selection are not small.

present result: $N_\nu = 2.92 \pm 0.05$

FCC-ee



Event statistics :

E_{CM} errors:

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	1 MeV
?tt threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → ?tt**	**Never done**	2 MeV

Great energy range for the heavy particles of the Standard Model.

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\frac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\frac{\Gamma_\nu}{\Gamma e,\mu}\,(SM)}$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availanbility of O(10^{12}) Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}\,(SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for |cosθ_γ| <0.95

161 GeV (10^7 s) running at 1.6x10^{35}/cm^2/s x 4 exp ➔ 3x10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

A better point may be 105 GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?

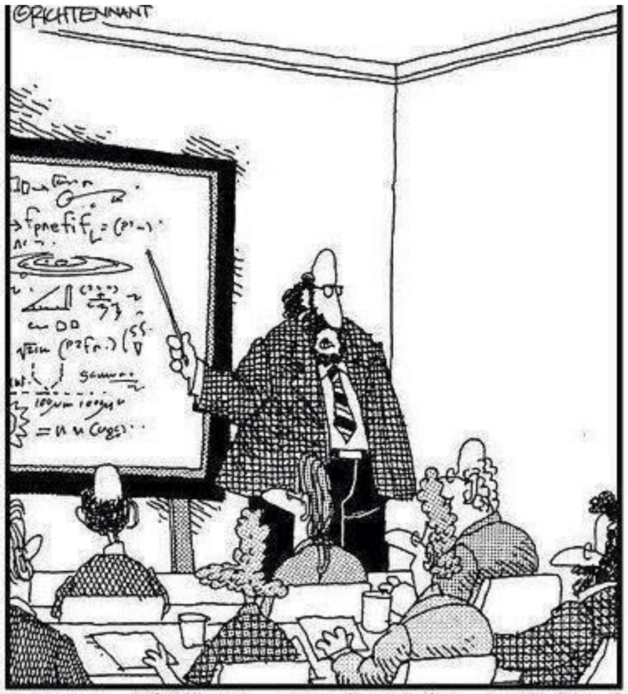
Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

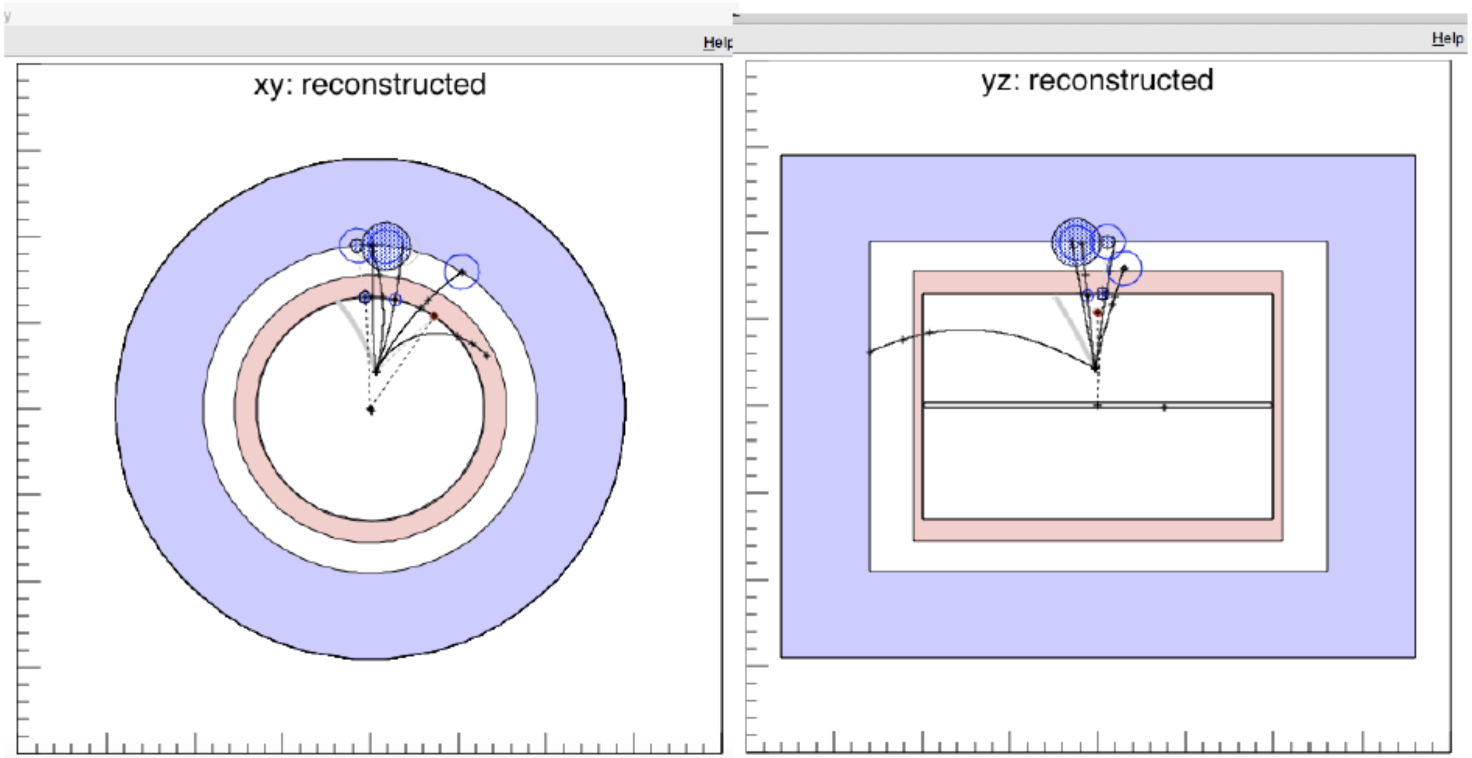
can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'



" Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Simulation of heavy neutrino decay in a FCC-ee detector

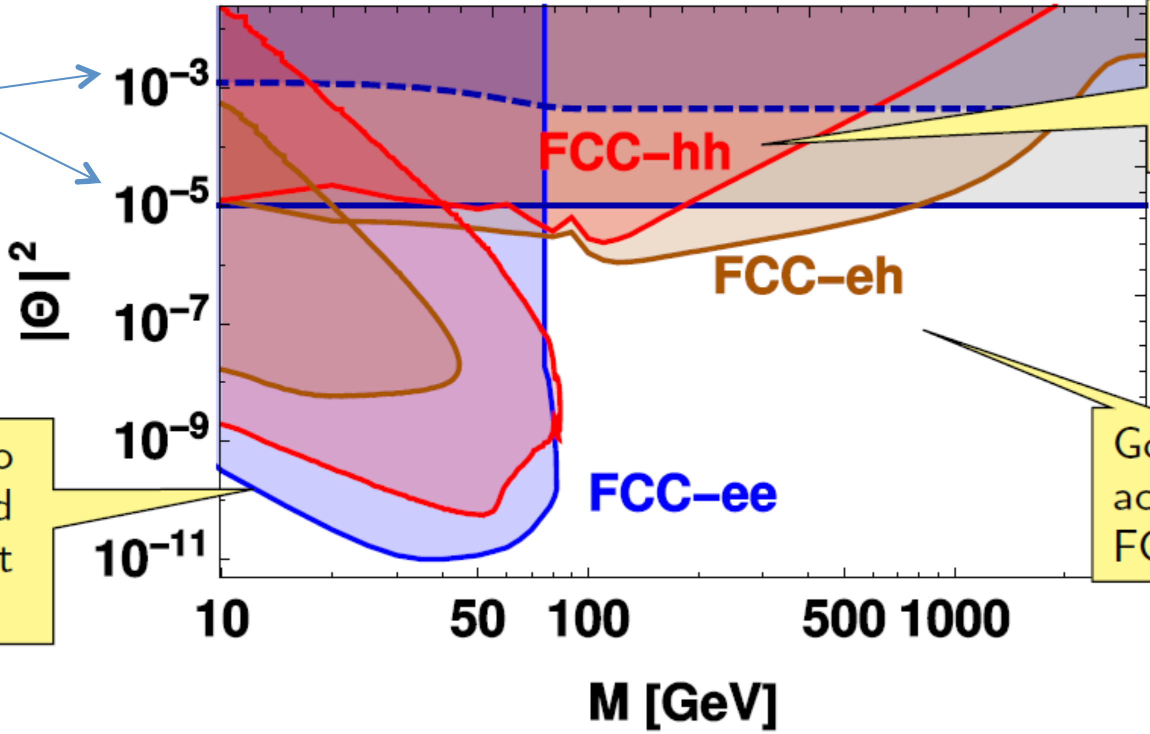


Summary

Another example of Synergy and complementarity
while ee covers a large part of space very cleanly ,
its either 'white' in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO sensitivity up to very high mass scales



FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

CONCLUSIONS

The tau neutrino was discovered in the wake of the tau lepton discovery as the spin ½ neutral particle produced in tau decays

It took until 1981-**1986 to establish** that it was indeed the isospin partner of the tau.

In 1989 it took only three weeks for the LEP and SLC experiments to demonstrate that there are **only three families of active neutrinos.**

This was due to extraordinary preparation and the careful measurement of luminosity
this number became very precise $N_{\nu} = 2.984 \pm 0.008$
This can be seen as a test of unitarity.

Charged Couplings of the neutrinos were measured to permil accuracy at LEP from tau decays

These results stress the important contribution of colliders to neutrino physics.

We are now planning a fantastic Z factory (FCC-ee) to hunt for signs of further neutrinos the right-handed ones.