Neutrino Physics

Alain Blondel   Geneva and Paris-Sorbonne

1. Discovery : missing Energy and Momentum
2. Lepton number, lepton flavour, neutrinos and antineutrinos
   → charged current neutrino interactions
3. Neutrinos and the Standard Model: Neutral Currents
4. The three families of neutrinos
5. Neutrinos from the Universe: solar neutrinos, atmospheric neutrinos

5'. Supernova neutrinos

6. Neutrino properties: measuring the neutrino mass?
7. Neutrino oscillations and CP violation
8. On-going and future neutrino experiments on oscillations
9. What is the origin of neutrino masses?
10. Neutrino-less double-beta experiments
11. See-saw, sterile neutrinos
12. Conclusions

Selected questions in Neutrino Physics

Alain Blondel Geneva and Paris-Sorbonne

Today

How do we know there are three (and only three) families of light active neutrinos

How do we know neutrinos have negative helicity (and are left-handed) ?

How do we know neutrinos have mass?

Why do neutrinos oscillate?

Tomorrow

Can neutrino masses be different from those of other fermions?

How can we discover that neutrinos have a Majorana mass term?

Neutrinos at colliders

(If time permits: is there a eV-scale sterile neutrino?)

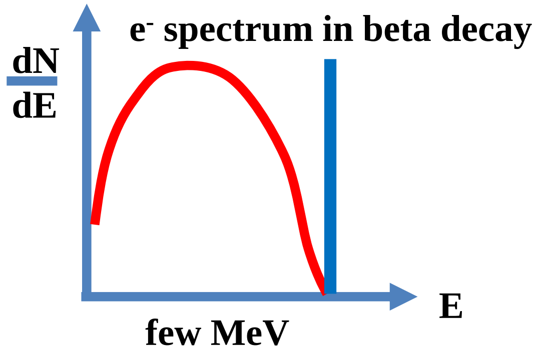
Why neutrinos are central in pushing the limits of the 'Standard Model'

Experimentally:
Neutrinos
=
MISSING ENERGY and MOMENTUM

Consider $^{6}He^{++} \to {}^{6}Li\ \bar{\nu}_e\ e^-$

$Q = 3.5078$ MeV $T/2 \approx 0.8067$ s

1930 Neutrinos: *the birth of the idea*



Pauli's letter of the 4th of December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

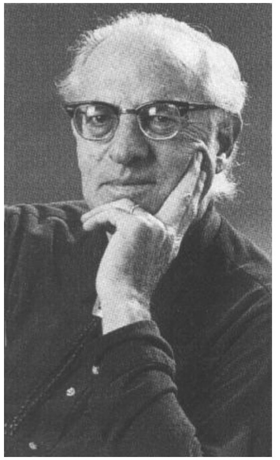
Wolfgang Pauli

Experimentally:
Neutrinos
=
Neutrino interactions

Neutrinos: *direct detection*

Reines and Cowan **1953**

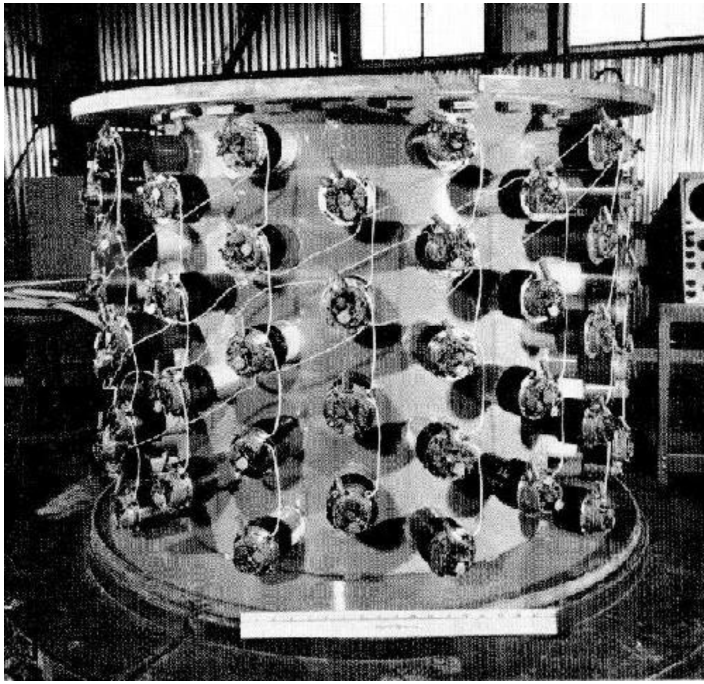
The target is made of about 400 liters of water mixed with cadmium chloride



The anti-neutrino coming from the nuclear reactor interacts with a proton of the target, giving a positron and a neutron.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

The positron annihilates with an electron of target and gives two simultaneous photons ($e^+ + e^- \rightarrow \gamma\gamma$) .
The neutron slows down before being eventually captured by a cadmium nucleus, that gives the emission of 2 photons about 15 microseconds after those of the positron.



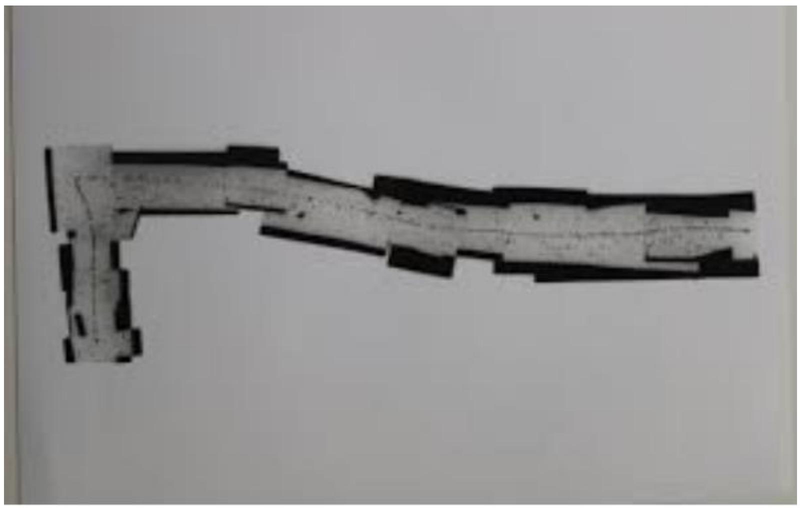
All those 4 photons are detected and the 15 microseconds identify the "neutrino" interaction.

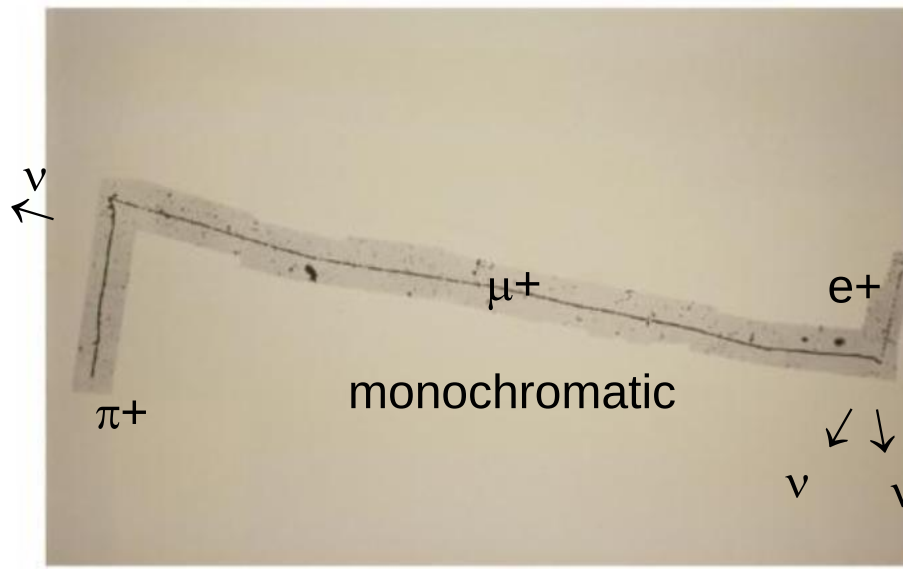
4-fold delayed coincidence

The second « family »

Another neutrino was detected in **1947** with the discovery of the pion. (Powell et al, 1947). Maybe it was the same neutrino than in beta decay?

These emulsions were made of photographic gel and stacked.
Placed in high altitude balloons at up to 10km altitude, they allowed the observation of strongly interacting particles which are otherwise stopped by the atmosphere.



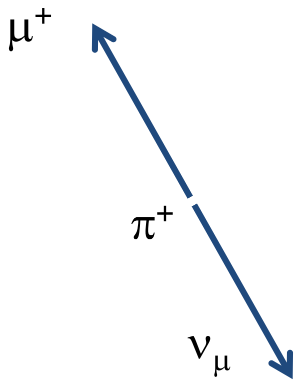


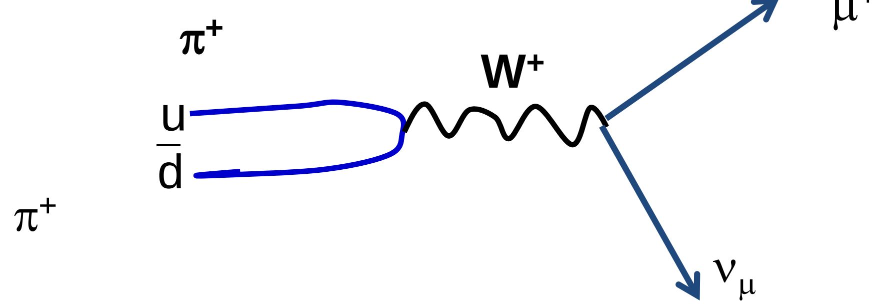
Emulsions played an important role in establishing the nature of the tau neutrino (**E531, 1986**)
and detection of ν_τ interactions (DONUT and OPERA experiments)

Unrelated Preamble

Why do pions decay into $\pi^+ \rightarrow \mu^+ \nu_\mu$ much much more than into $\pi^+ \rightarrow e^+ \nu_e$?

Imagine the π decay at rest. (obviously the decay fraction is Lorentz invariant)



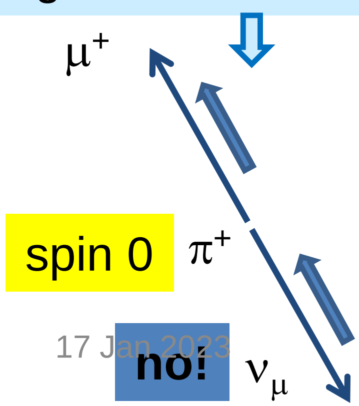


momenta are equal and opposite: $(P_{\mu,\nu})^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

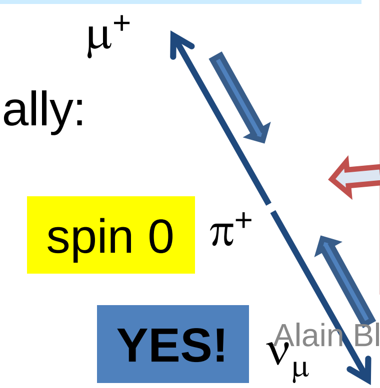
How are the spins? The μ^+ and ν_μ originate from weak interaction

➔ μ^+ is right-handed and ν_μ is left-handed … however the pion has spin 0

If helicity and chirality were identical
we would have violation of
angular momentum conservation!



really:



However they are not.
|R>, |L> chirality states; |+ >, |- > helicity states
$| L > = | - > + m/E\ |+ >$
$| R > = |+ > + m/E\ | - >$
thus the decay rate is proportional to
$||\langle R|-\rangle||^2 = (m_\mu / E_\mu)^2$
Also multiply by the phase space factor
proportional to $(P\mu)^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

However they are not.
|R>, |L> chirality states; |+ >, |- > helicity states
| L > = | - >   +   m/E |+ >
| R > = |+ > +   m/E | - >
thus the decay rate is proportional to
$||\langle R|-\rangle||^2 = (m_\mu / E_\mu)^2$
Also multiply by the phase space factor
proportional to $(P\mu)^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

So we can derive the ratio $R_\pi = \frac{\pi \to e\nu}{\pi \to \mu\nu}$

$$R_\pi = (m_e/m_\mu)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} \right)^2 =$$

1.2351(2) 10^{-4} (theory)

1.230(4) 10^{-4} (exp)

Neutrinos
the properties

1960

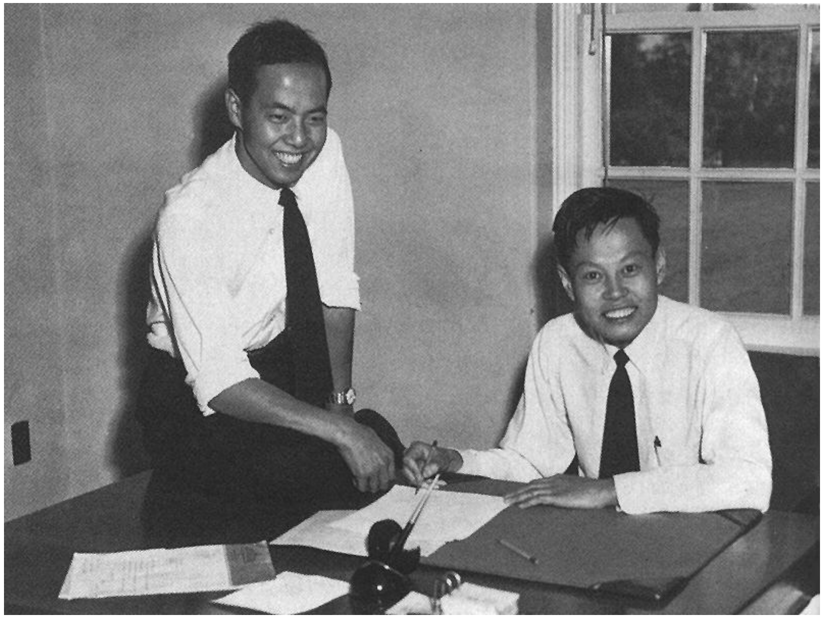
In 1960, Lee and Yang realized that if a reaction like

$$\mu^- \rightarrow e^- + \gamma$$

is not observed, this is because two types of neutrinos exist ν_μ and ν_e

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

otherwise $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ has the same Quantum numbers as $\mu^- \rightarrow e^- + \gamma$



Lee and Yang

1962 discovery of the muon neutrino

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:

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

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!

1962 discovery of the muon neutrino

This also was the first neutrino beam!

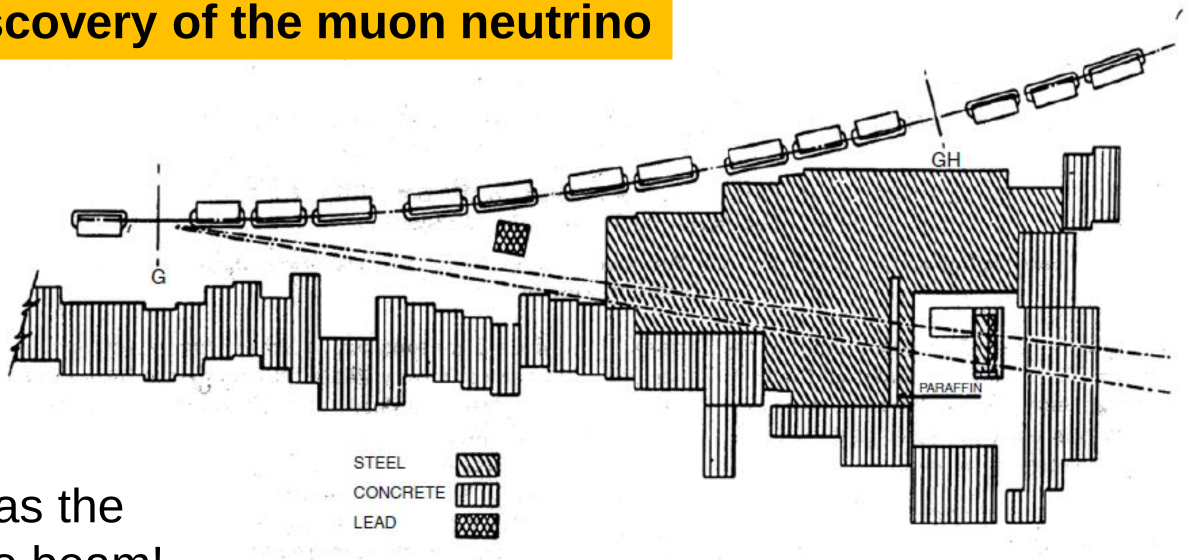


Fig. 11. Plan view of the 2nd neutrino experiment.

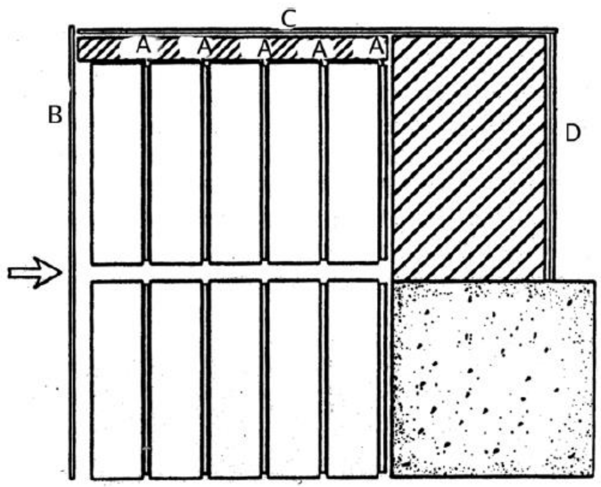


Fig. 12. Spark chamber and counter arrangement. A are triggering counters; B, C, and D are anticoincidence counters.

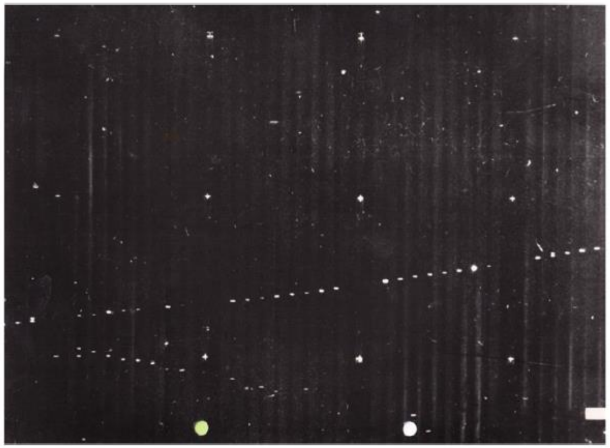


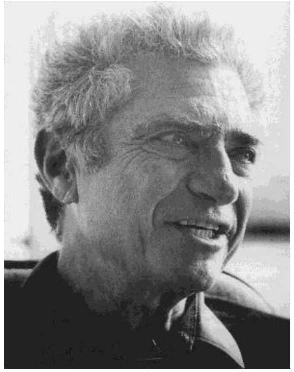
Fig. 14. Event with penetrating muon and hadron shower.

Two Neutrinos

1962

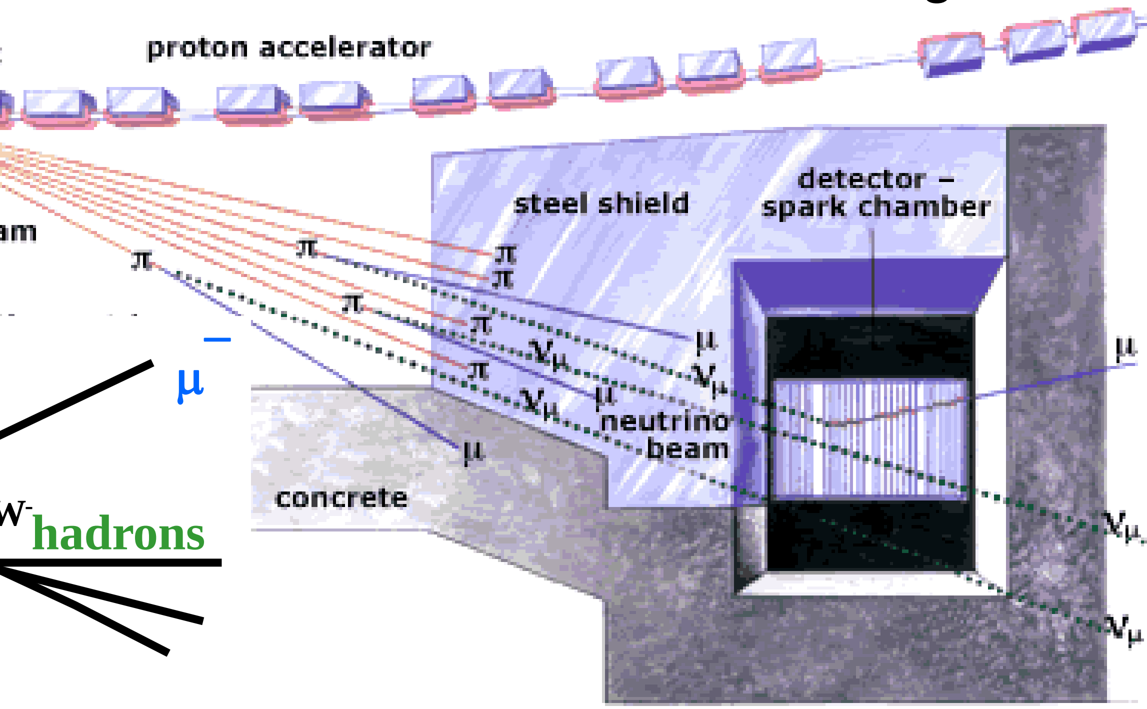
Schwartz

Lederman

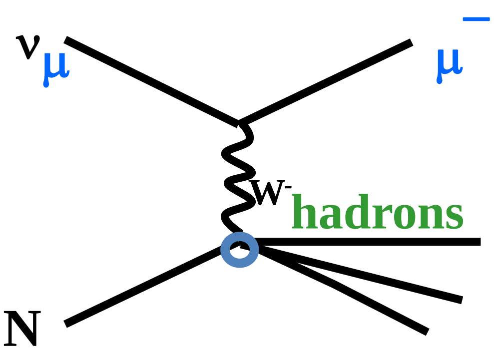


Steinberger

AGS Proton Beam



Neutrinos from π-decay only produce muons (not electrons)

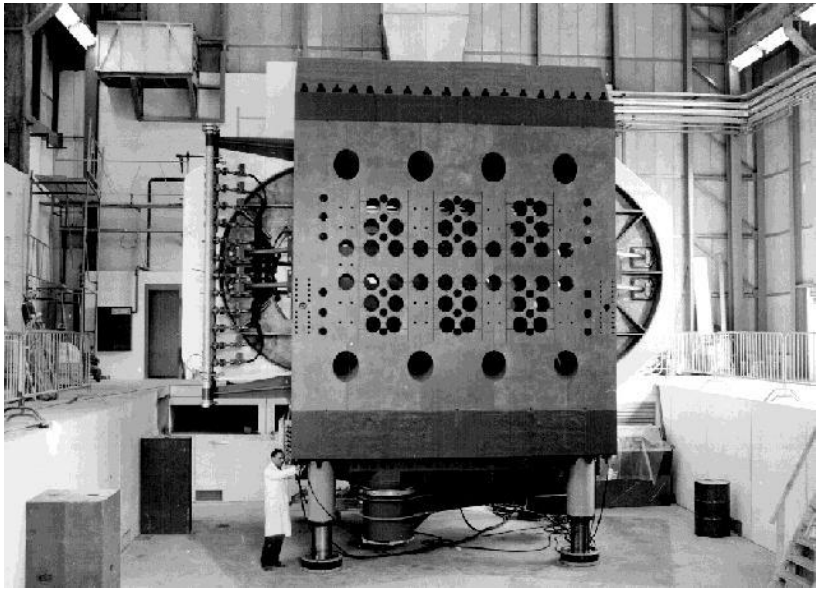


when they interact in matter

SPARK CHAMBERS:
HeNe+ HV Al plates +scintillators

Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN

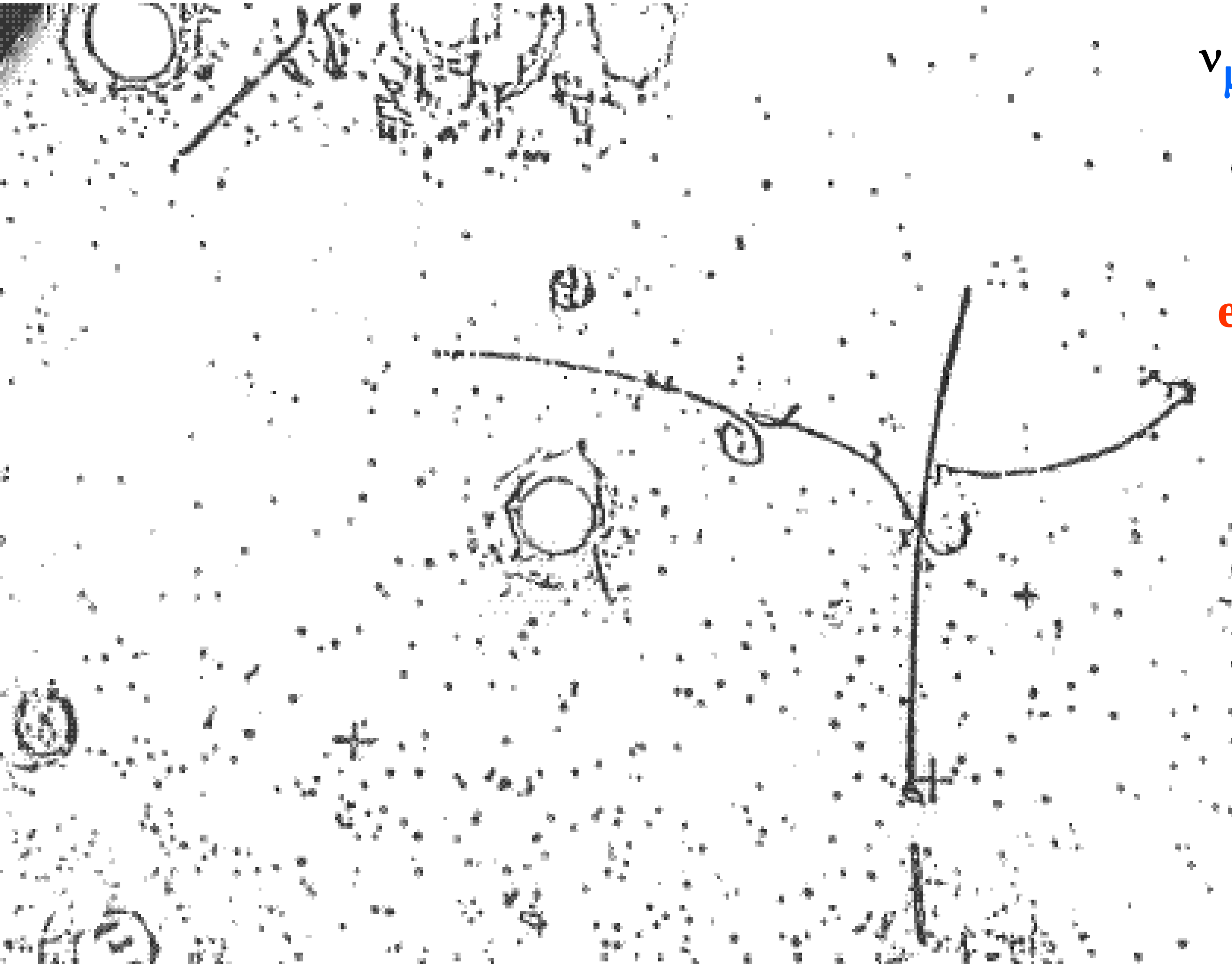
Discovery of weak neutral current

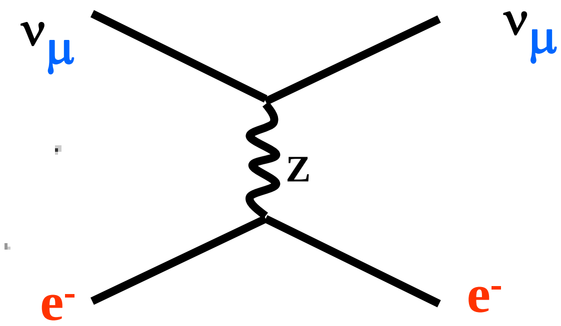
$\nu_\mu + e \rightarrow \nu_\mu + e$

$\nu_\mu + N \rightarrow \nu_\mu + X$ **(no muon)**

previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \to \mu\mu$) leading to extremely stringent limits (10^{-7} or so)

early neutrino experiments had set their trigger on final state (charged) lepton!

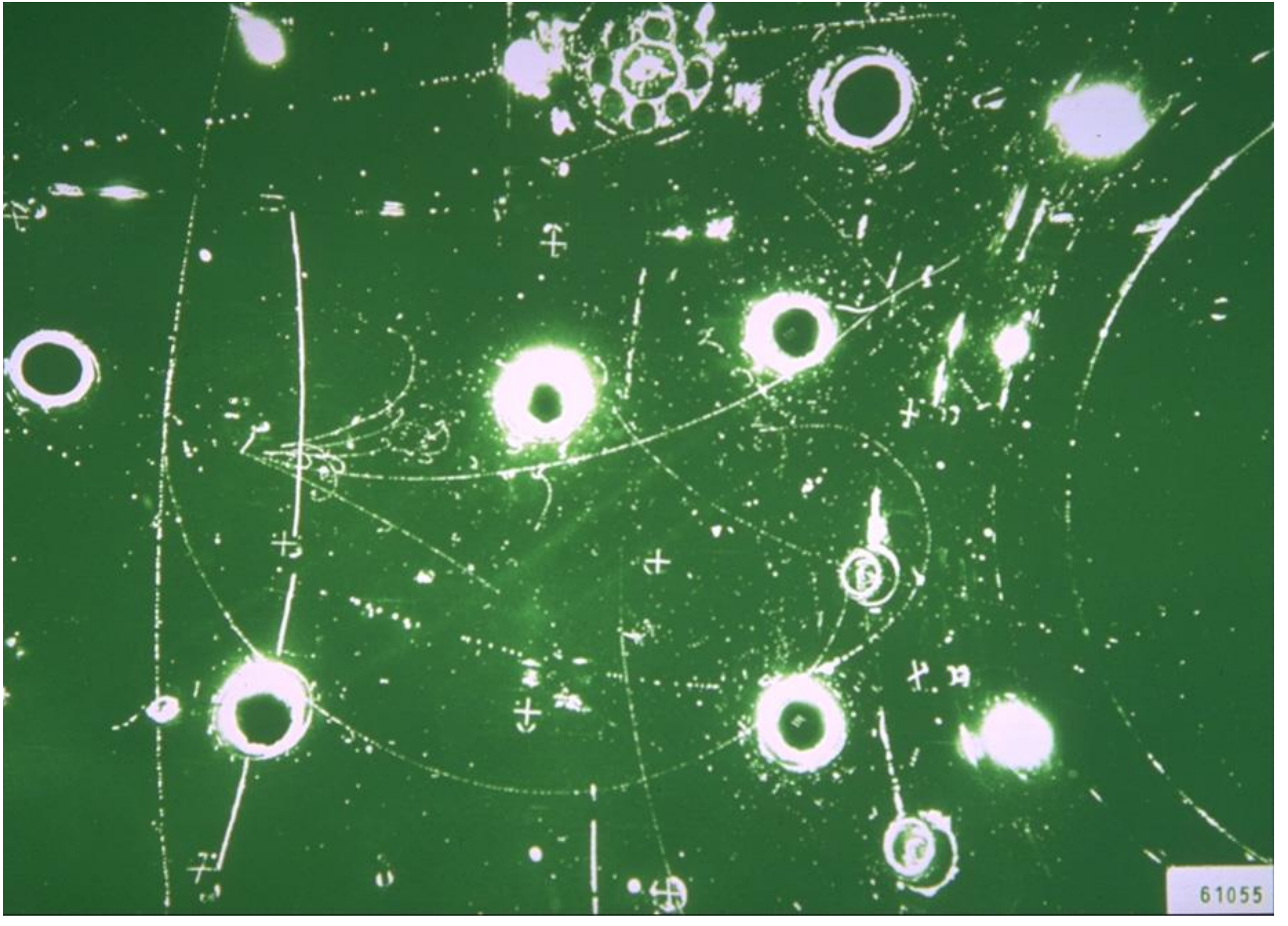




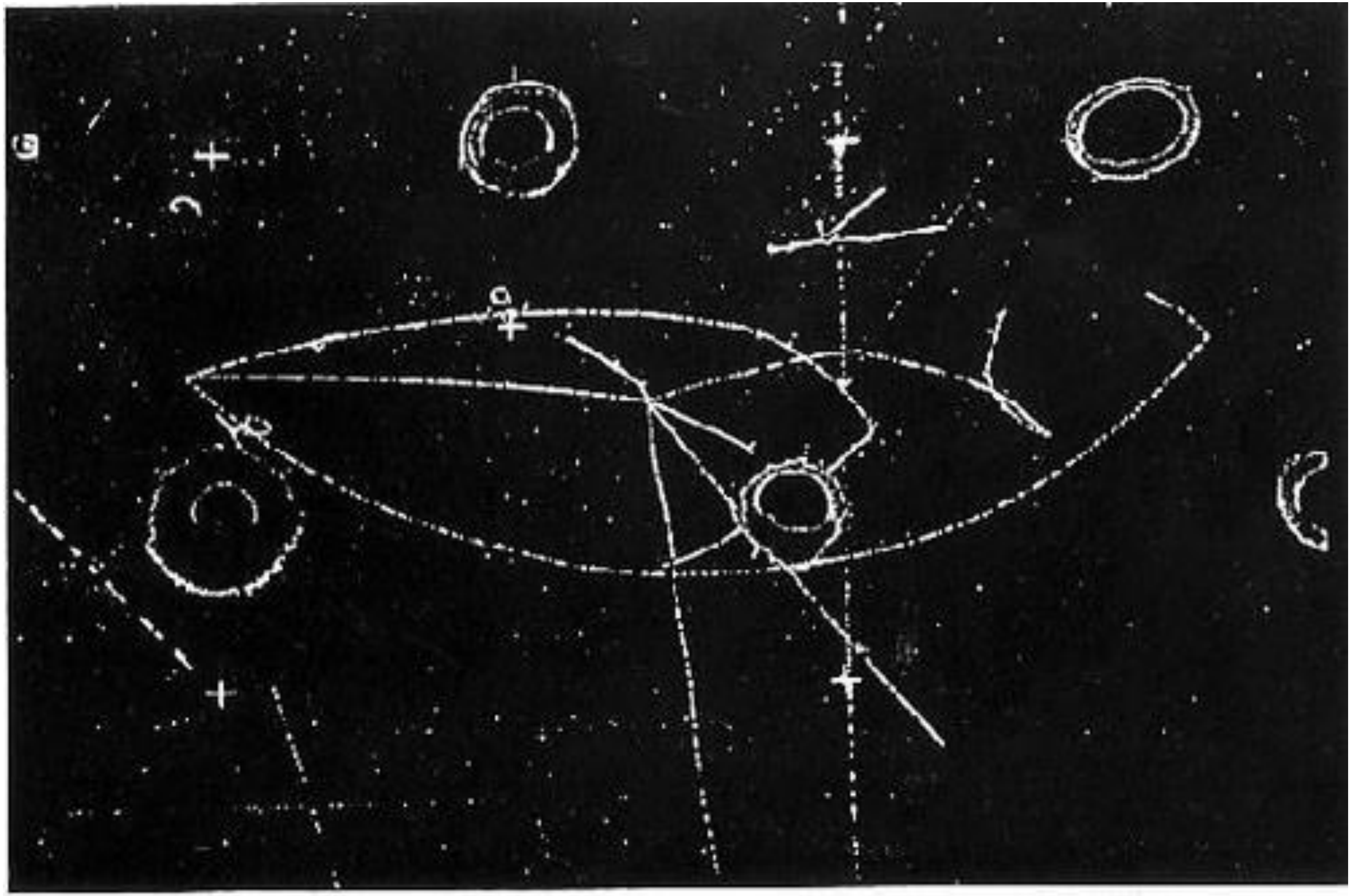
elastic scattering of neutrino off electron in the liquid

1973 Gargamelle

First manifestation of the Z boson experimental birth of the Standard model



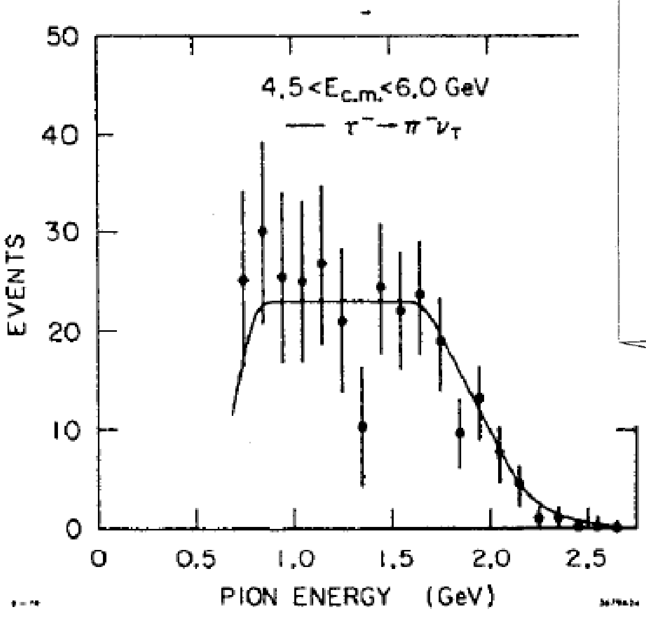
Gargamelle Charged Current event

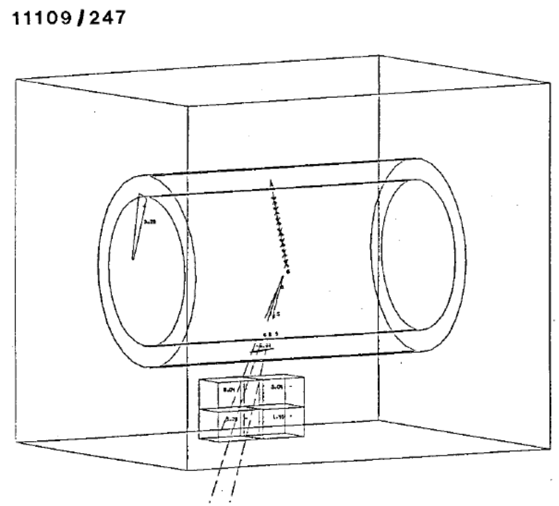


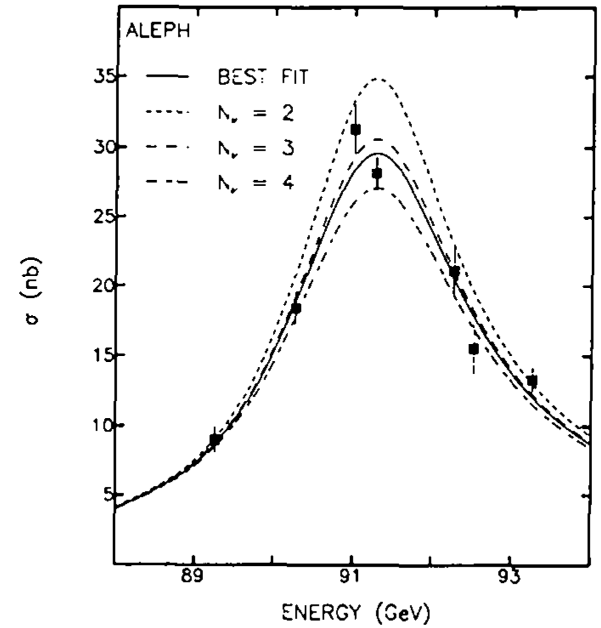
Gargamelle neutral current event (all particles are identified as hadrons)

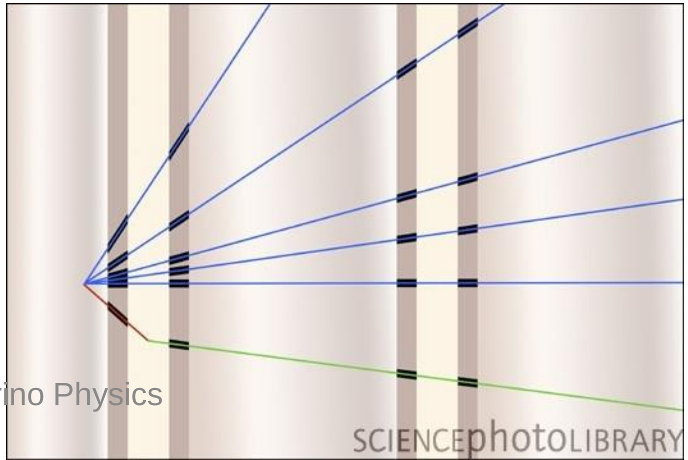
The Third Family of Neutrinos

arXiv:1812.11362









The discovery of the third family of neutrinos begins with

The discovery of a new lepton

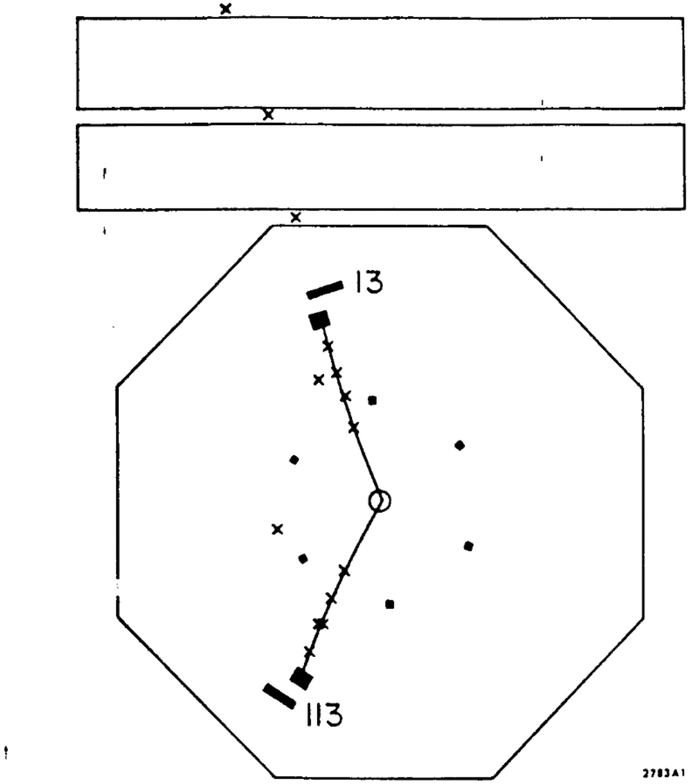


Figure 12. An eμ event in which the muon penetrates both layers of the muon tower. Shown at the Stanford conference, August 1975 (Ref. 37).

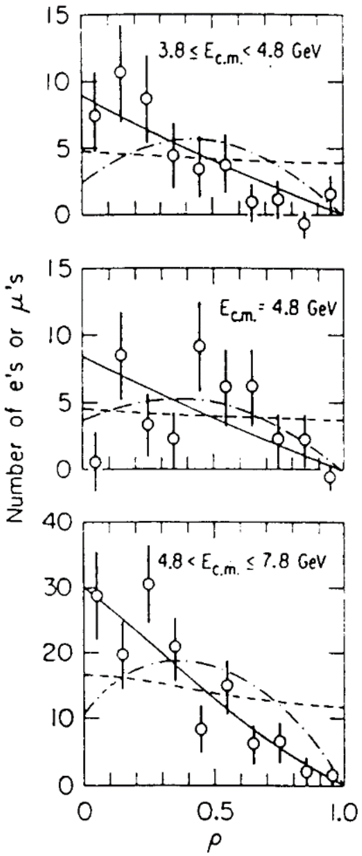


Figure 13. The scaled momentum spectrum of leptons from eμ events in three energy regions. The solid curve represents the expectation of a 1.8 GeV/c^2 lepton with V-A interactions. The dashed and dot-dashed curves represent the expectations from a 1.8 GeV/c^2 boson with spin 0 and spin 1, helicity 0,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

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 $e^+ + e^- \to e^\pm + \mu^\mp$ + 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.

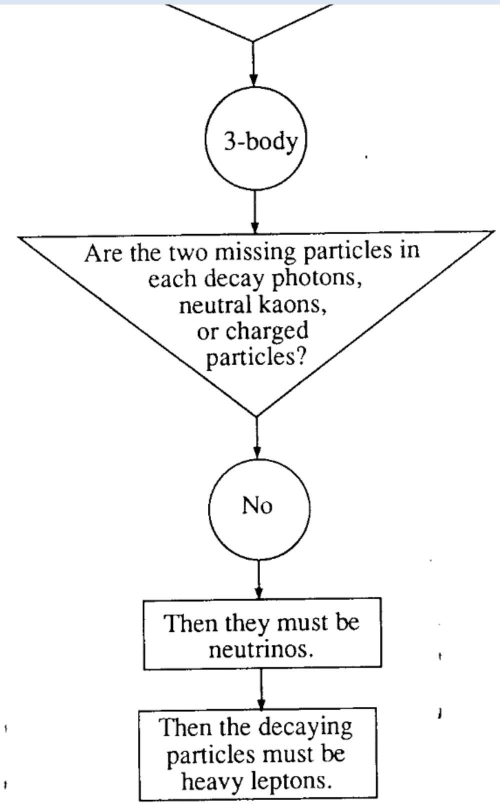


Figure 15. Outline of the second paper (Ref. 13).

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 eμ 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 eμ 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

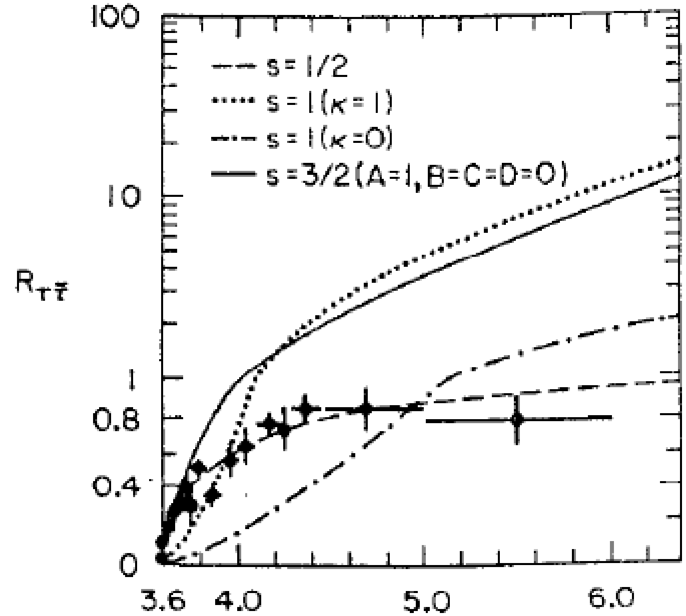


Fig. 2. The cross-sections expected for a pair of point-like particles according to several spin assignments. The constants κ, A, B, C and D are related to the gyromagnetic ratio and multipole values of the particles (see Ref. 2 for details). The data points are the DELCO eX events, normalized to the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

All this implying the existence in tau decays of
a spin ½ weakly interacting neutral particle with mass below measurement limit.
This, is what we call a 'neutrino'.

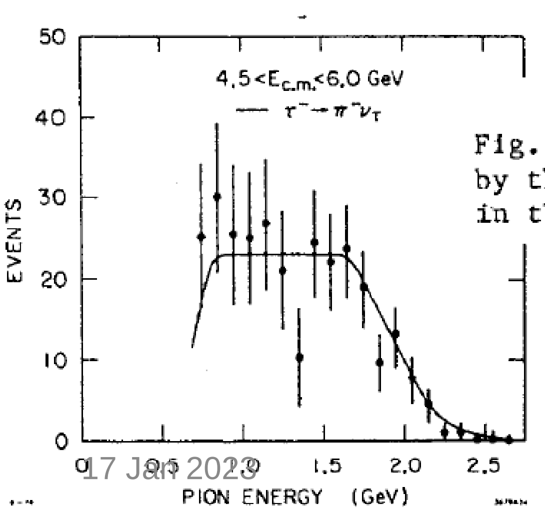


Fig. 7. The π energy spectrum observed by the Mark II for the decay $\tau^- \rightarrow \pi^- \nu_\tau$ in the energy range, $4.5 < E_{cm} < 6.0$ GeV.

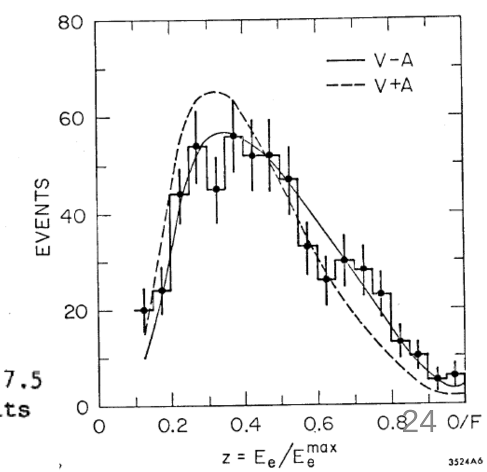


Fig. 4. The normalized electron energy spectrum obtained by DELCO in the energy range, $3.57 < E_{cm} < 7.5$ GeV (excluding ψ''). The radiatively-corrected fits for V-A (solid) and V+A (dashed) show χ^2/dof of 15.9/17 and 53.7/17, respectively.

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

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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 decav mode of the τ.

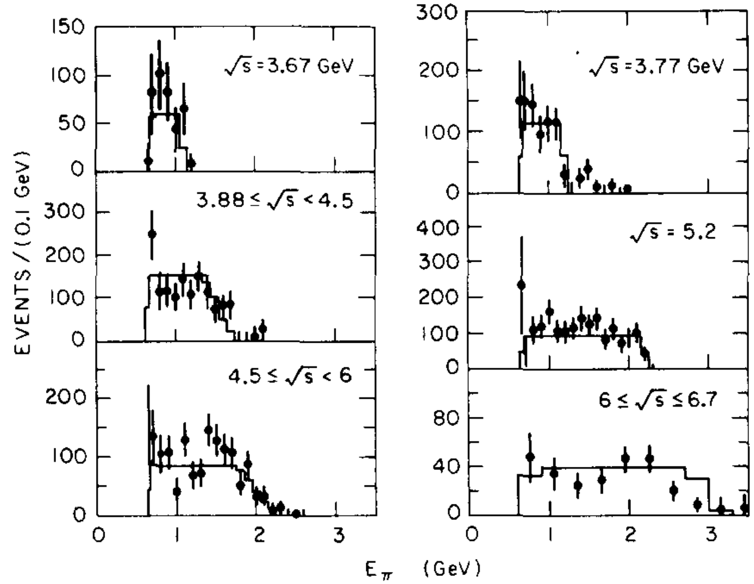

Fig. 3. Pion energy spectrum for π–X events with bin-by-bin background subtraction and efficiency corrections. The curves are the expected spectra for $m_\tau = 1.782$ GeV/c^2, $m_\nu = 0$, and $B_\pi = 0.117$.

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!

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 'ν_τ').
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 both:

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
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... ...

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		
	$J=\frac{1}{2}$	0.5110034	stable	stable		

$(>5\times10\ m_{\nu_e}\ (\mathrm{MeV}))$

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 $c\tau=6.5868\times10^{4}$	μ^- ↴ (or $\mu^+\to$CC)		
				$e^-\bar{\nu}\nu$	(98.6 ± 0.4)%	53
				$e^-\bar{\nu}\nu\gamma$	(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 $m^2=3.18$	$(4.6\pm1.9)\times10^{-13}$ $c\tau=0.014$	τ^- ↴ (or $\tau^+\to$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 Cabibbo 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				
τ	$J=\frac{1}{2}$	1784.2 $\pm$ 3.2	$(3.3\pm0.4)\times10^{-13}$ $c\tau=0.010$	τ^- → (or τ^+ → chg. conj.)		
				particle$^-$ neutrals	(*86.5* ± *0.3*)%	
				$\mu^-\bar{\nu}\nu$	(17.6 ± 0.6)%	889
				$e^-\bar{\nu}\nu$	(17.4 ± 0.5)%	892
				dron$^-$ $\geq 0\pi^0\nu$	(*51.6* ± *0.7*)%	
				adron$^-$ ν	(*10.8* ± *1.1*)%	
				$\pi^-\nu$	(10.1 ± 1.1)%	887
				$K^-\nu$	(*0.67* ± *0.17*)%	824
				nadron$^-$ $\geq 1\pi^0\nu$	(*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
				$K^-\geq 1\pi^0\nu$	(*1.0* ± *0.3*)%	
				$\pi^-\pi^-\pi^+\geq 0\pi^0\nu$	(*13.4* ± *0.3*)%	
				$\pi^-\pi^-\pi^+\geq 1\pi^0\nu$	(*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
				$\pi^-\pi^-\pi^+K^0\geq 0\gamma\nu$	(*<0.27*)%	
				K^- 2charged $\geq 0\pi^0\nu$	(*<0.6*)%	

Mode	Fraction		p (MeV/c)
τ^- → (or τ^+ → 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

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

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.

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!

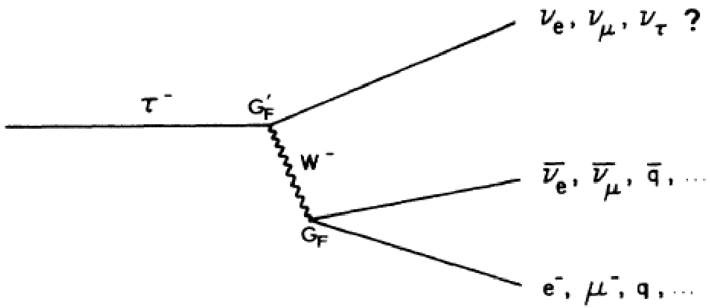


FIG. 3. τ-decay diagram.

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

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 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 $\tau^- \rightarrow \pi^- «\nu_\tau»$ implies that if one can make a beam of $«\nu_\tau»$ one will certainly see τs appear, also if the $«\nu_\tau»$ 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

$$\nu_\tau N \rightarrow \tau N.$$

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 $W \rightarrow \tau\nu_\tau$

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

In the case of a $W \rightarrow \tau\nu$ 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 $W \rightarrow \tau\nu$ 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!

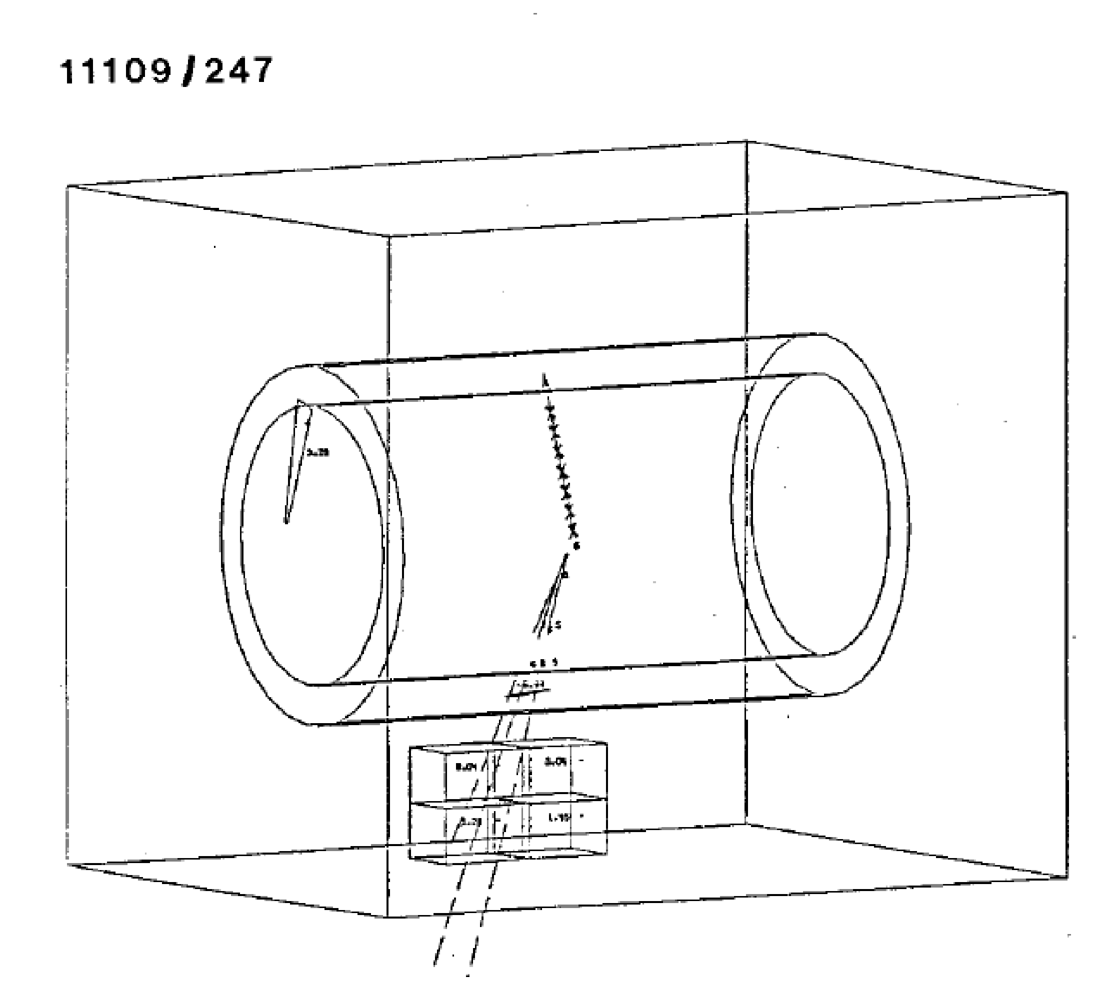
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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 → $\tau\ \nu_\tau$

- low mass jet of 3 charged tra
- missing transverse momentu

** Mass not restricted to W mass.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ $\qquad\qquad$ 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

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%

[22] 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.

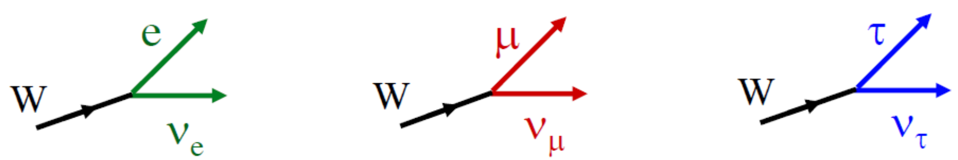
e.g. B. Kayser,
VII[th] Pontecorvo School, 2017

The Neutrino Flavors

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

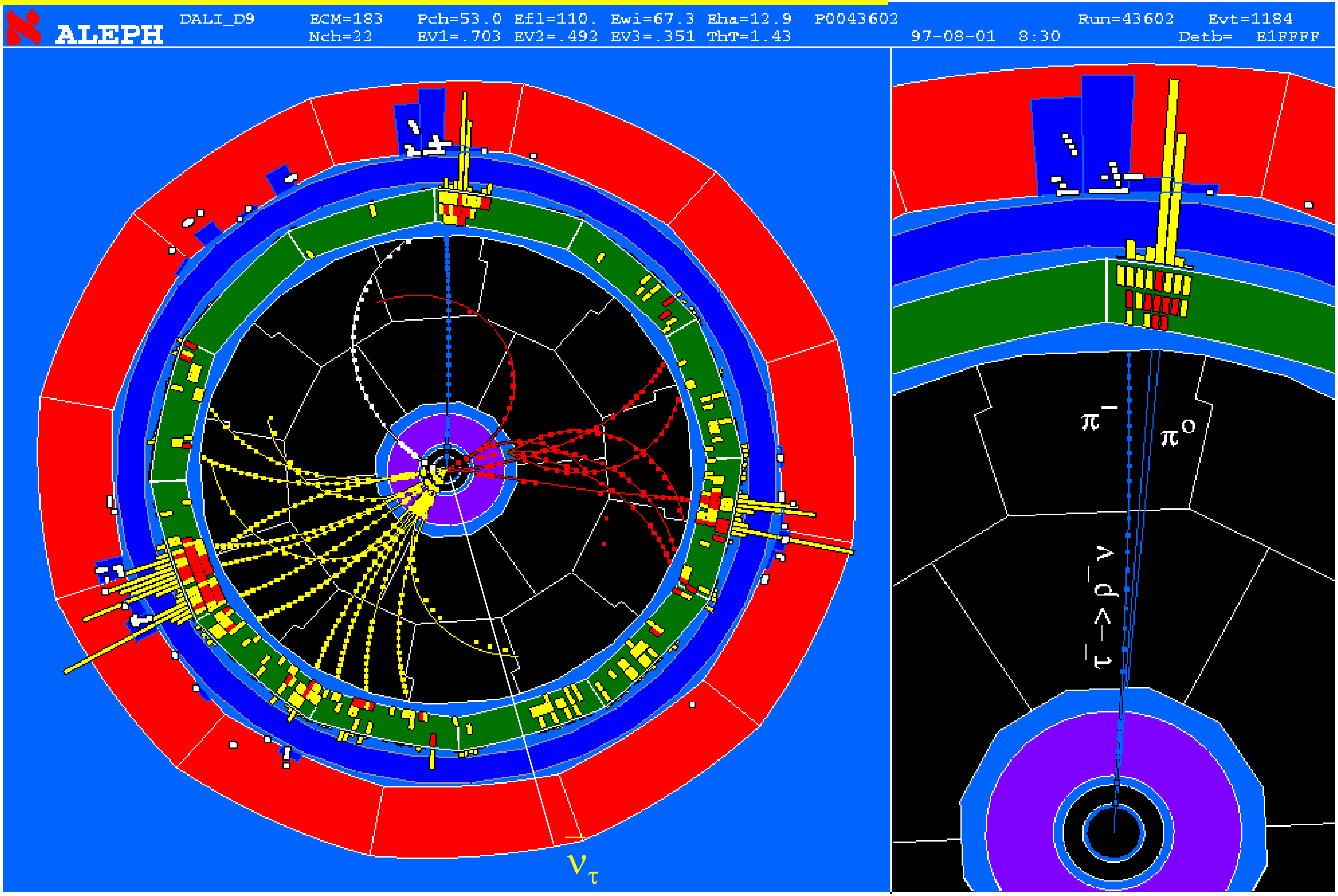
There are three known flavors of neutrinos: ν_e, ν_μ, ν_τ

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})

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

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

in the 1990s

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

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

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

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

$$\frac{g_\tau}{g_\mu} = 1.0004 \pm 0.0032 \pm 0.0038 \pm 0.0005 \tag{8}$$

and

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

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.

NB these are the weak couplings of both e/mu/tau and their neutrinos!

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
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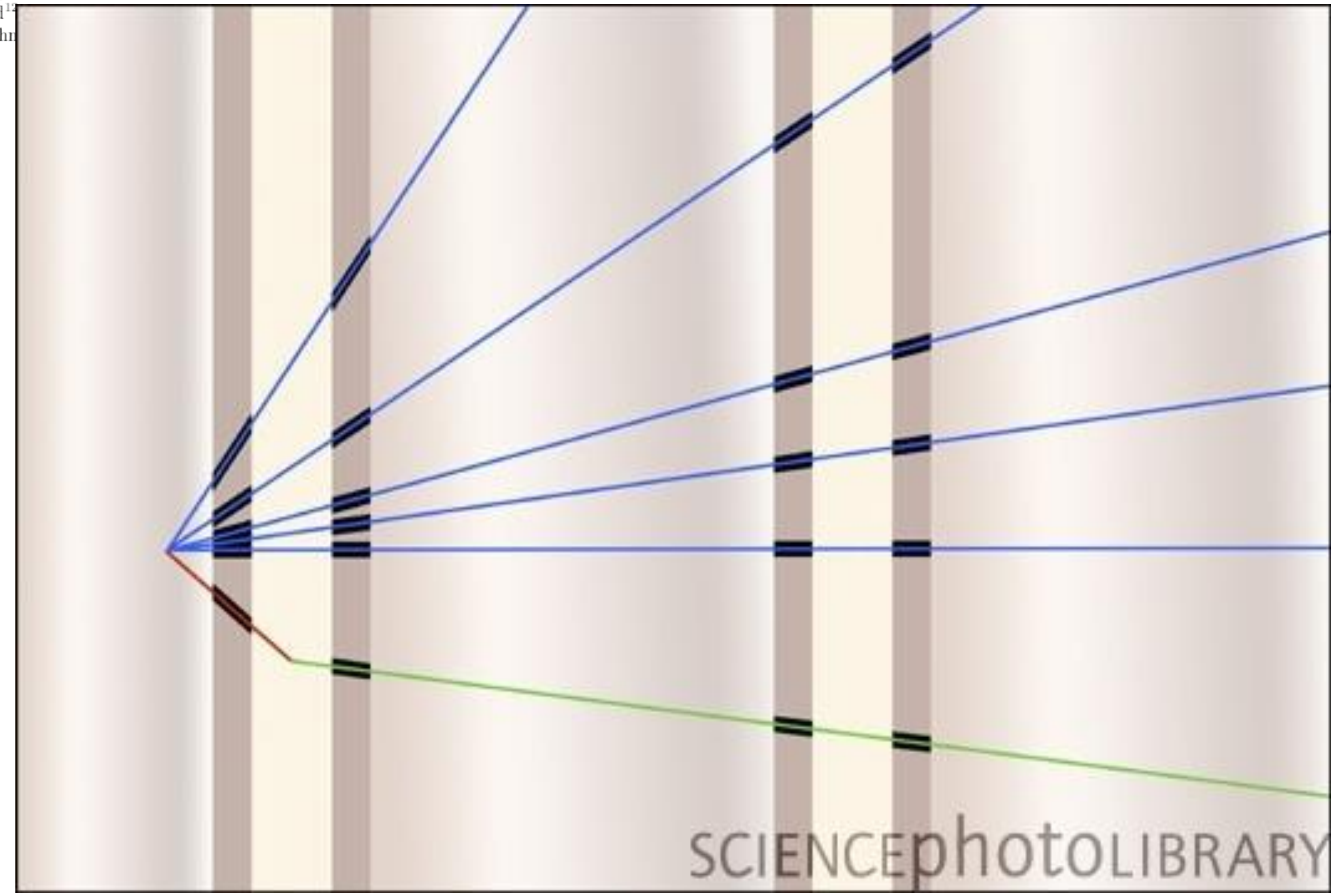
[6] *Kansas State University, Manhattan, Kansas*
[7] *Kobe University, Kobe, Japan*
[8] *Kon-kuk University, Korea*
[9] *University of Minnesota, Minnesota*
[10] *Nagoya University, Nagoya 464-8602, Japan*
[11] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[12] *University of South Carolina, 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'…



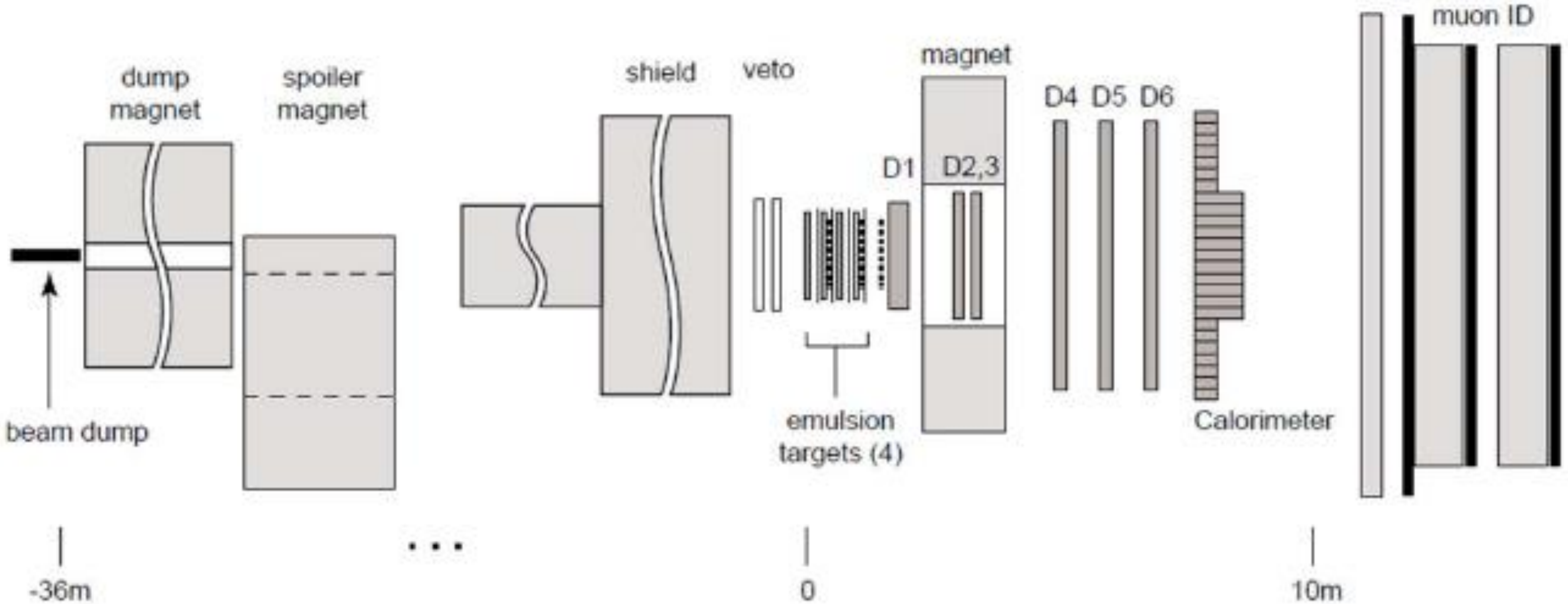
Tau Neutrino interaction in DONUT experiment (Fermilab) 2000

Observation of Tau Neutrino Interactions

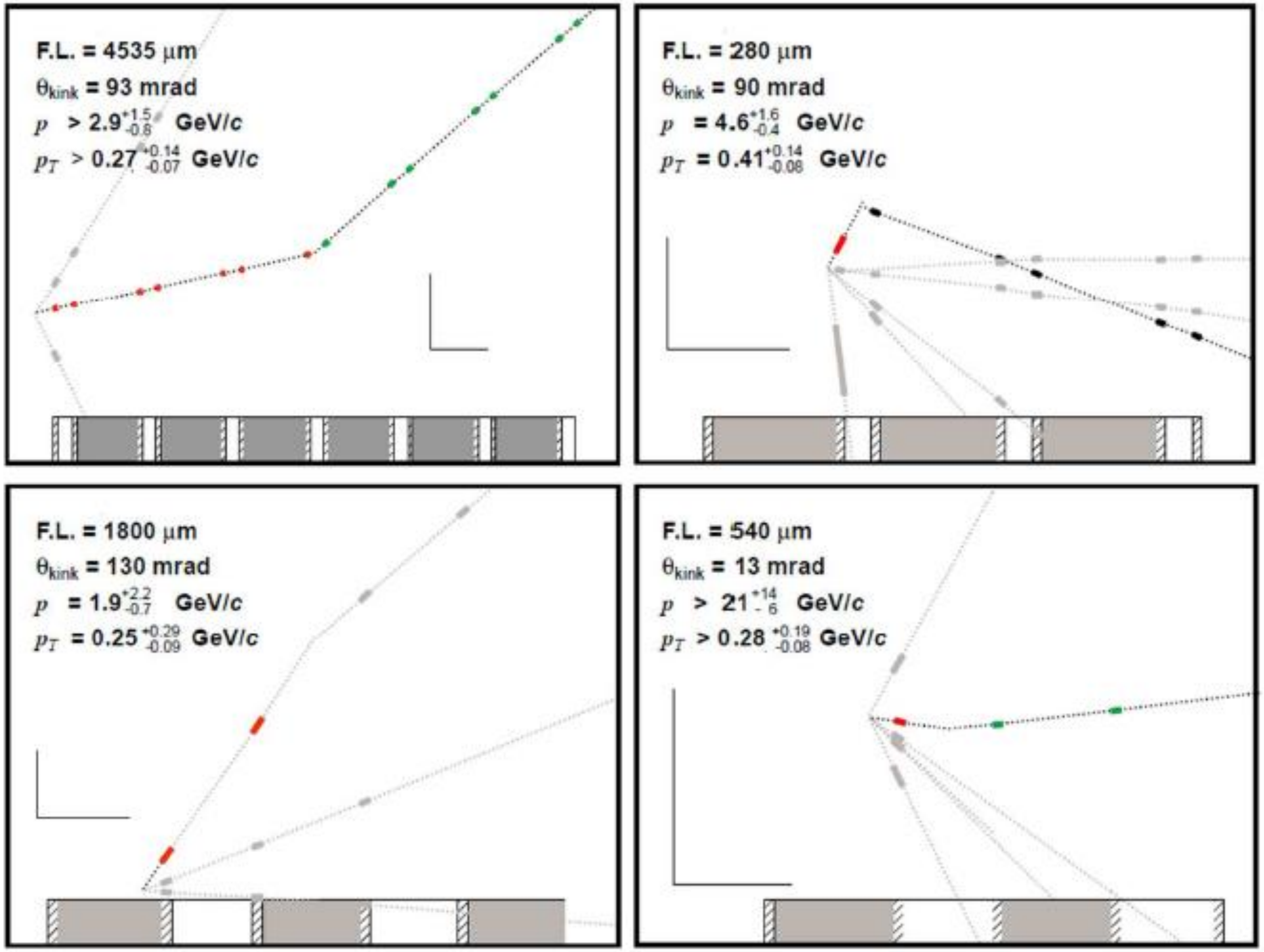
The **DONUT** experiment

DONUT Collaboration

Phys. Lett., B504:218–224, 2001
+ Phys. Rev., D78:052002, 2008.



800 GeV protons from Fermilab Tevatron
beam dump suppresses π and K decays, spoiler magnet sweeps muons away
result is a beam with 5% tau neutrinos from mainly $D_s \rightarrow \tau\ \nu_\tau$
Emulsions combined with scintillators and spectrometer facilitate the search for events.



F.L. = 4535 μm
θkink = 93 mrad
p > 2.9 +1.5 -0.8 GeV/c
pT > 0.27 +0.14 -0.07 GeV/c
F.L. = 280 μm
θkink = 90 mrad
p = 4.6 +1.6 -0.4 GeV/c
pT = 0.41 +0.14 -0.08 GeV/c
F.L. = 1800 μm
θkink = 130 mrad
p = 1.9 +2.2 -0.7 GeV/c
pT = 0.25 +0.29 -0.09 GeV/c
F.L. = 540 μm
θkink = 13 mrad
p > 21 +14 -6 GeV/c
pT > 0.28 +0.19 -0.08 GeV/c

first paper

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!

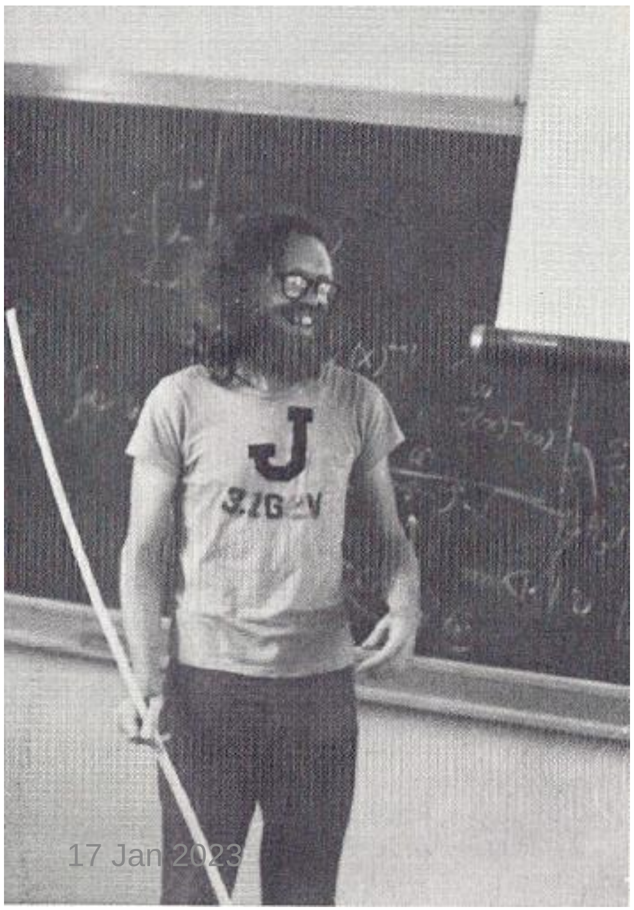
the appearance of a word

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

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

no ρ !

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

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

and a little drama...

(…)

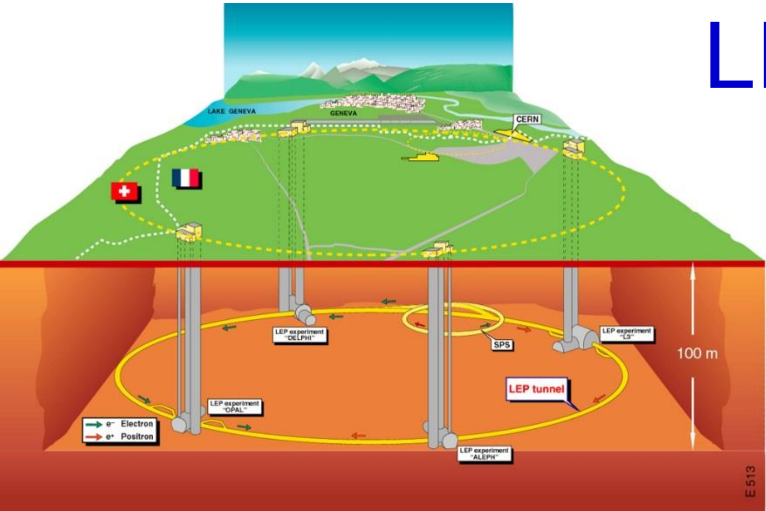
disappearance of the Z boson?

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?

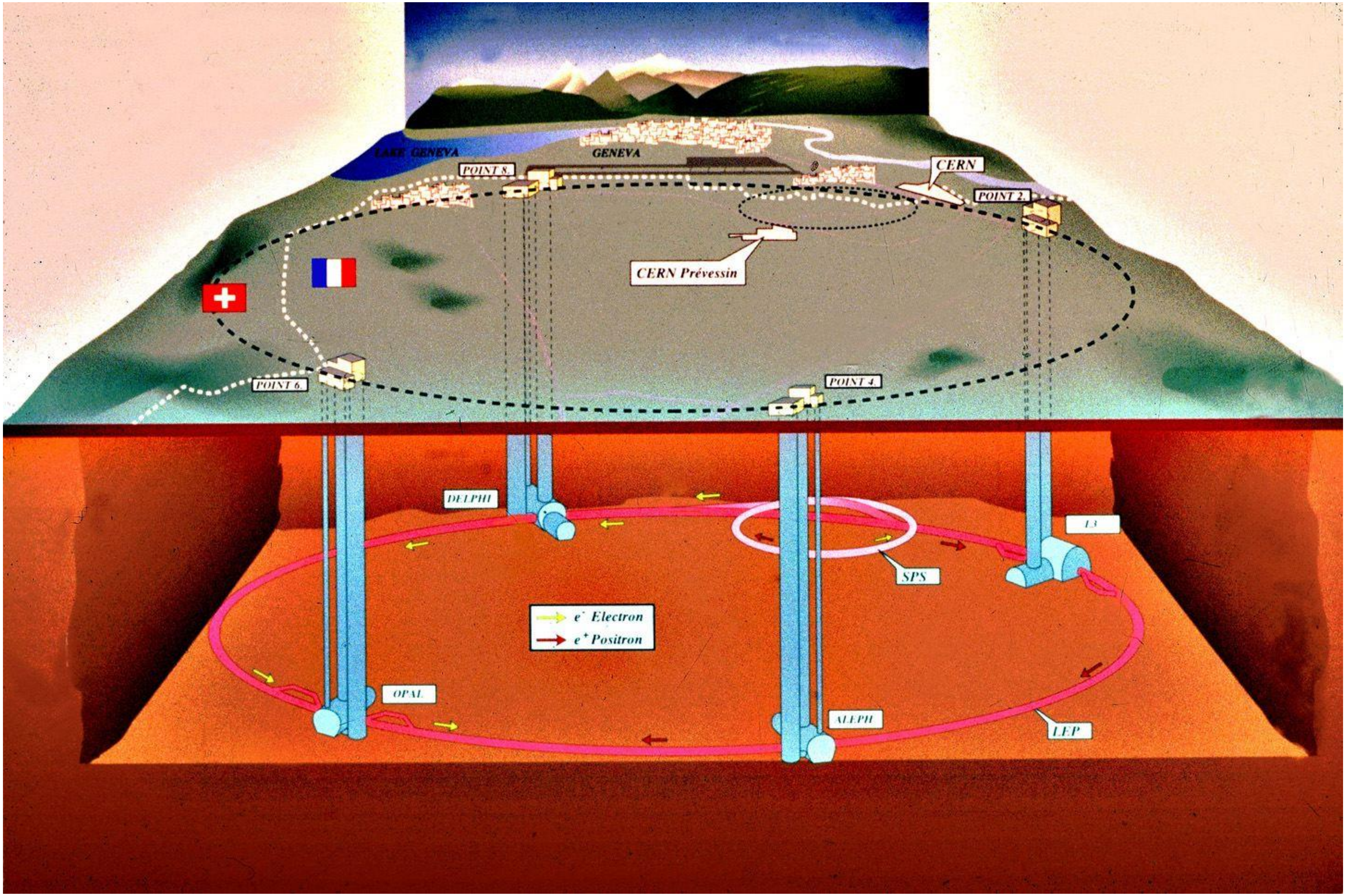
build LEP …. and find no Z! (imagine to build LHC and find no Higgs, huh?)

LEP / LHC Layout



The 26.7 km LEP / LHC tunnel

Depth: 70-140 m


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

BEFORE LEP STARTED

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

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

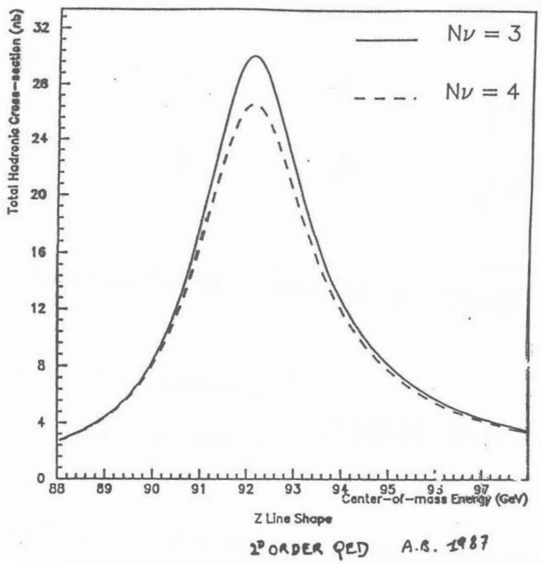
THE NUMBER OF NEUTRINO SPECIES

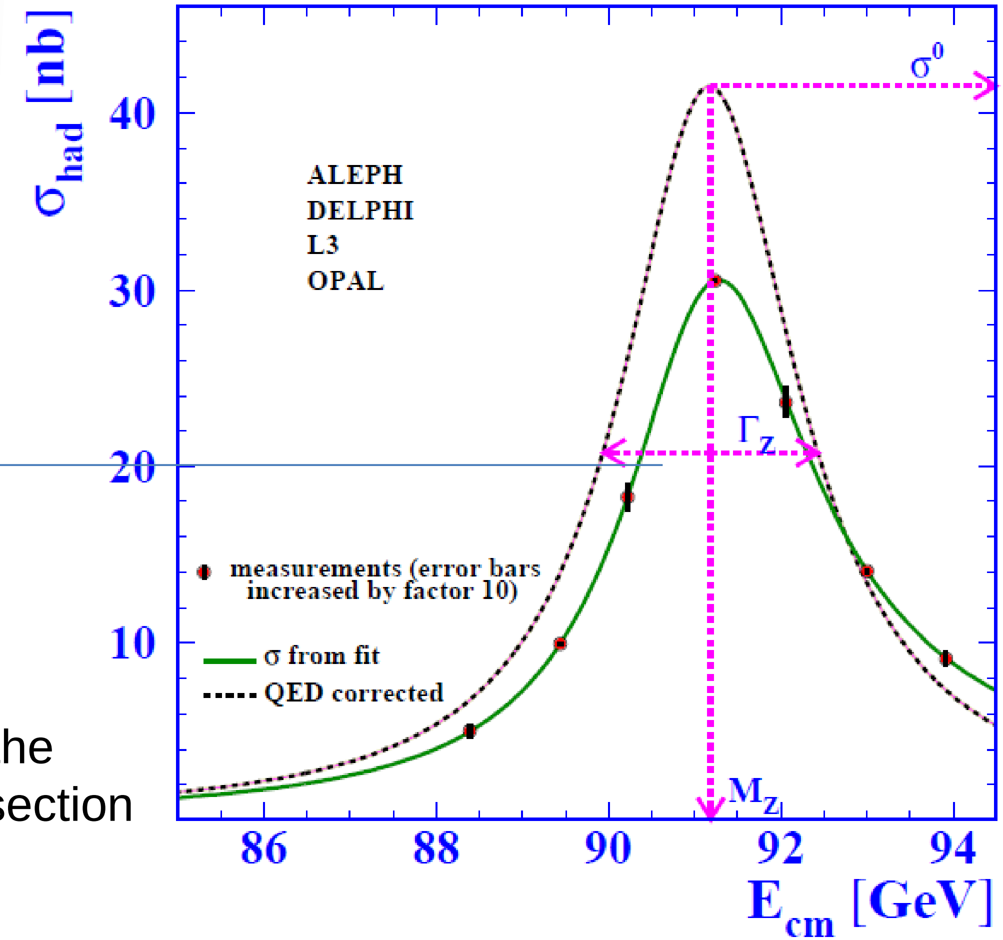
D. Denegri, CERN, Geneva, Switzerland
and DPHPE, CEN-Saclay, Gif-sur-Yvette, France

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 $W \rightarrow \ell\bar{\nu}$ to $Z \rightarrow \ell\bar{\ell}$ 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.





We had figured out that
the quantity that is directly sensitive to the number of neutrinos is the peak cross-section (mostly Z→ $q\bar{q}$)

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

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

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

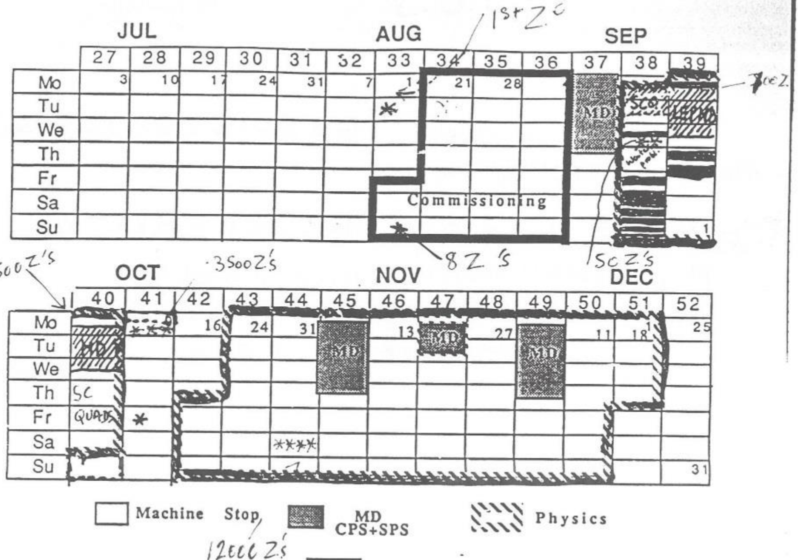
$$N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu} \cdot \left(\sqrt{\frac{12\pi R_\ell}{M_Z^2 \sigma_{had}^{peak,0}}} - R_\ell - 3 \right).$$

theory

all measured at the peak

J. WOTSCHACK, EP

1989 LEP SCHEDULE



*: $\mathcal{L} \simeq 2\ 10^{29}$ 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

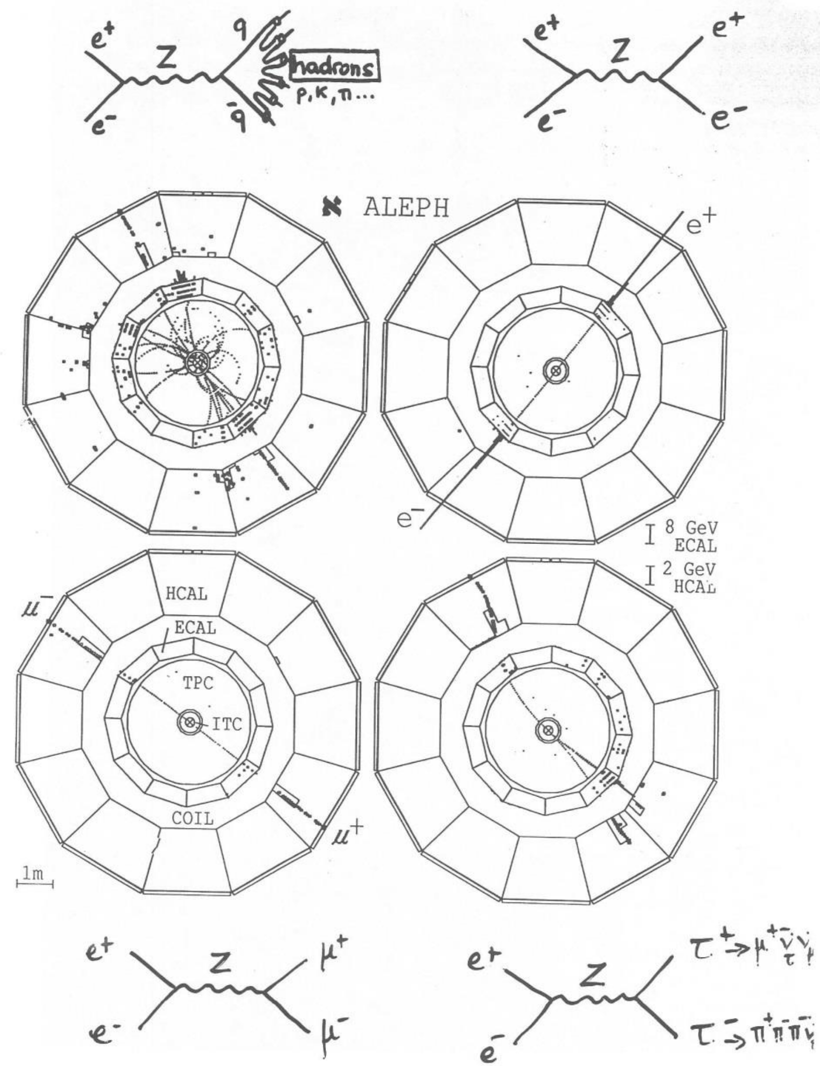
a) The LEP stop due to the PS and SPS MD of 11-14 Sept. will be extended to the 18th Sept. at noon to allow the repair of the L3 TEC.

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



L3 hadrons

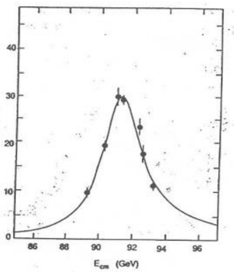


Fig. 7. Measured cross section for $e^+e^- \to$ hadrons as a function of $\sqrt{s}$. Data are shown with statistical errors only. The curve shows a fit to the Cahn formula [13] in which M_{Z^0} and $\Gamma_{invisible}$ were left free. The normalization was floated within the quoted 6% systematic error.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

L3 muons

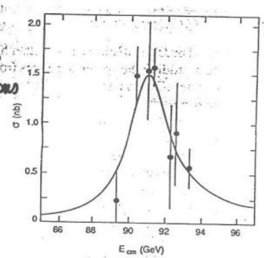


Fig. 8. Measured cross section for $e^+e^- \to \mu^+\mu^-$ as a function of $\sqrt{s}$. The solid line is the standard model fit. Data are shown with statistical errors only.

ALEPH hadrons.

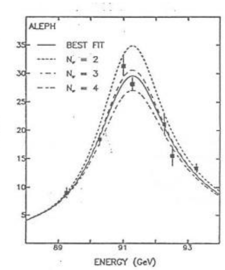
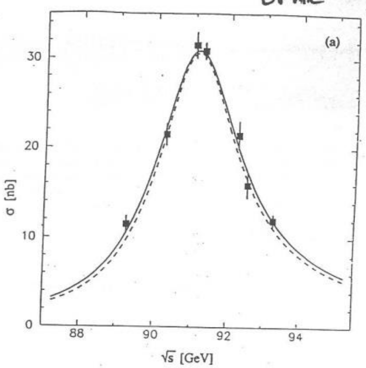


Fig. 5. The cross-section for $e^+e^- \to$ hadrons as a function of centre-of-mass energy and result of the three parameter fit.

OPAL



"My line-shape is the prettiest of all"

Tatiana Fabergé
Theory christmas Party 1989

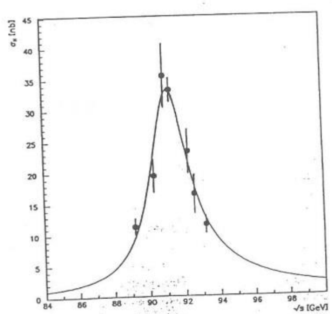


Fig. 4. The measured Z^0 peak. The data points and the fit are described in the text.

DELPHI hadrons

me 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 $m_{Z^0} = 91.132 \pm 0.057$ GeV (not including the 46 MeV LEP machine energy uncertainty) and $\Gamma_{Z^0} = 2.588 \pm 0.137$ GeV. We also determined $\Gamma_{invisible} = 0.567 \pm 0.080$ GeV, corresponding to 3.42 ± 0.48 number of neutrino flavors. We also measured the muon pair cross section and determined the branching ratio $\Gamma_{\mu\mu} = \Gamma_h = 0.056 \pm 0.006$. The partial width of $Z^0 \to e^+e^-$ is $\Gamma_{ee} = 88 \pm 9 \pm 7$ 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, $M_Z = (91.174 \pm 0.070)$ GeV, the Z width $\Gamma_Z = (2.68 \pm 0.15)$ GeV, and of the peak hadronic cross-section, $\sigma^{peak}_{had} = (29.3 \pm 1.2)$ nb, are presented. Within the constraints of the standard electroweak model, the number of light neutrino species is found to be $N_\nu = 3.27 \pm 0.30$. 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 $m_Z = 91.01 \pm 0.05 \pm 0.05$ GeV, and a total decay width of $\Gamma_Z = 2.60 \pm 0.13$ GeV. In the context of the standard model these results imply 3.1 ± 0.4 neutrino generations.

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

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

ELPHI Collaboration

066 $Z \to q\bar{q}$

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 $M(Z^0) = 91.06 \pm 0.09$ (stat.) ± 0.045 (syst.) GeV and $\Gamma(Z^0) = 2.42 \pm 0.21$ (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 $N_\nu = 2.4 \pm 0.4$ (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

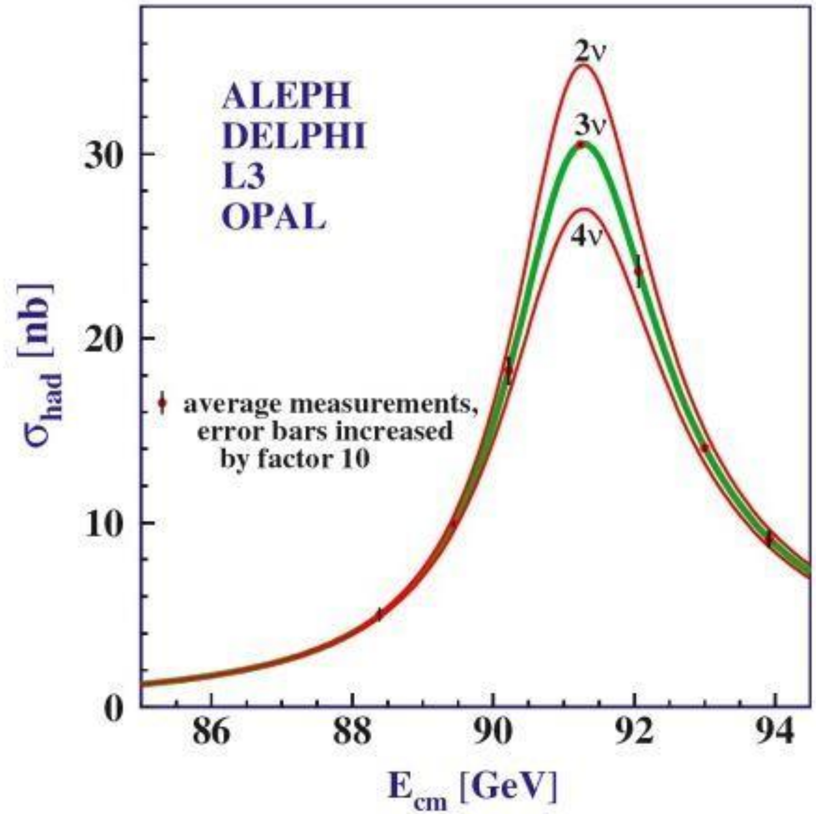
by 1989 (and before the measurement at LEP)
the first three families of neutrinos (ν_e ν_μ ν_τ) were «already known»

At the end of LEP:

Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

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!

1956 Parity violation in Co beta decay: electron is left-handed (C.S. Wu et al)

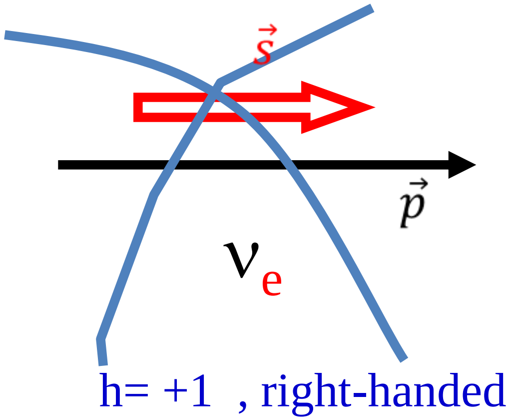
1957 Neutrino helicity measurement

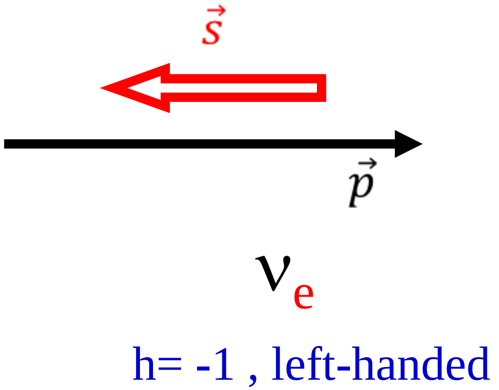
M. Goldhaber et al Phys.Rev.109(1958)1015

$$h = \frac{\vec{s}.\vec{p}}{|\vec{s}|.|\vec{p}|}$$

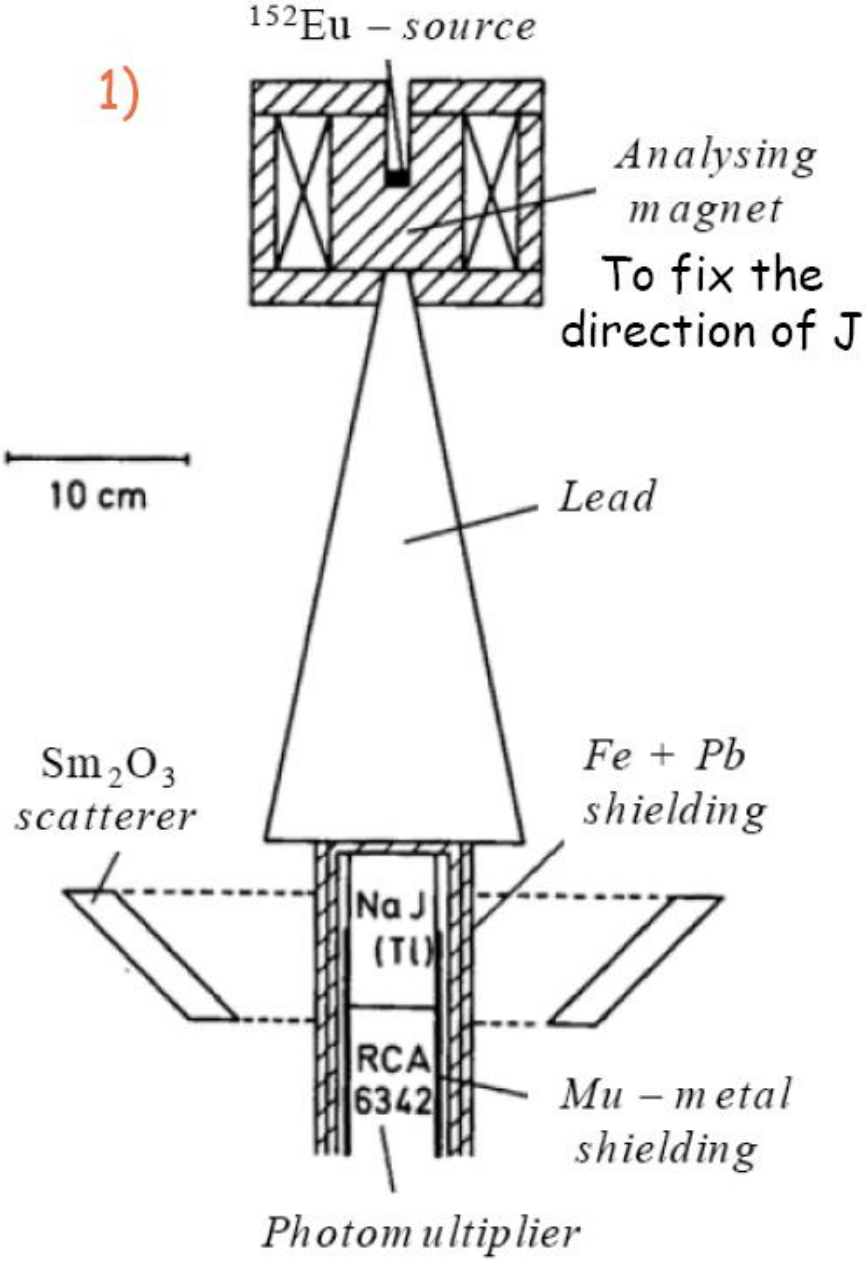
neutrinos have <u>negative helicity</u>

(If massless this is the same as left-handed)

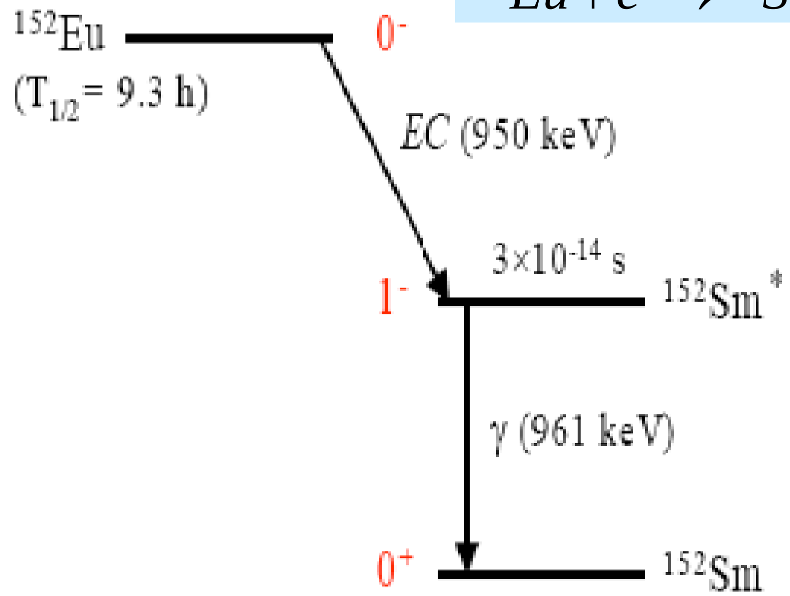


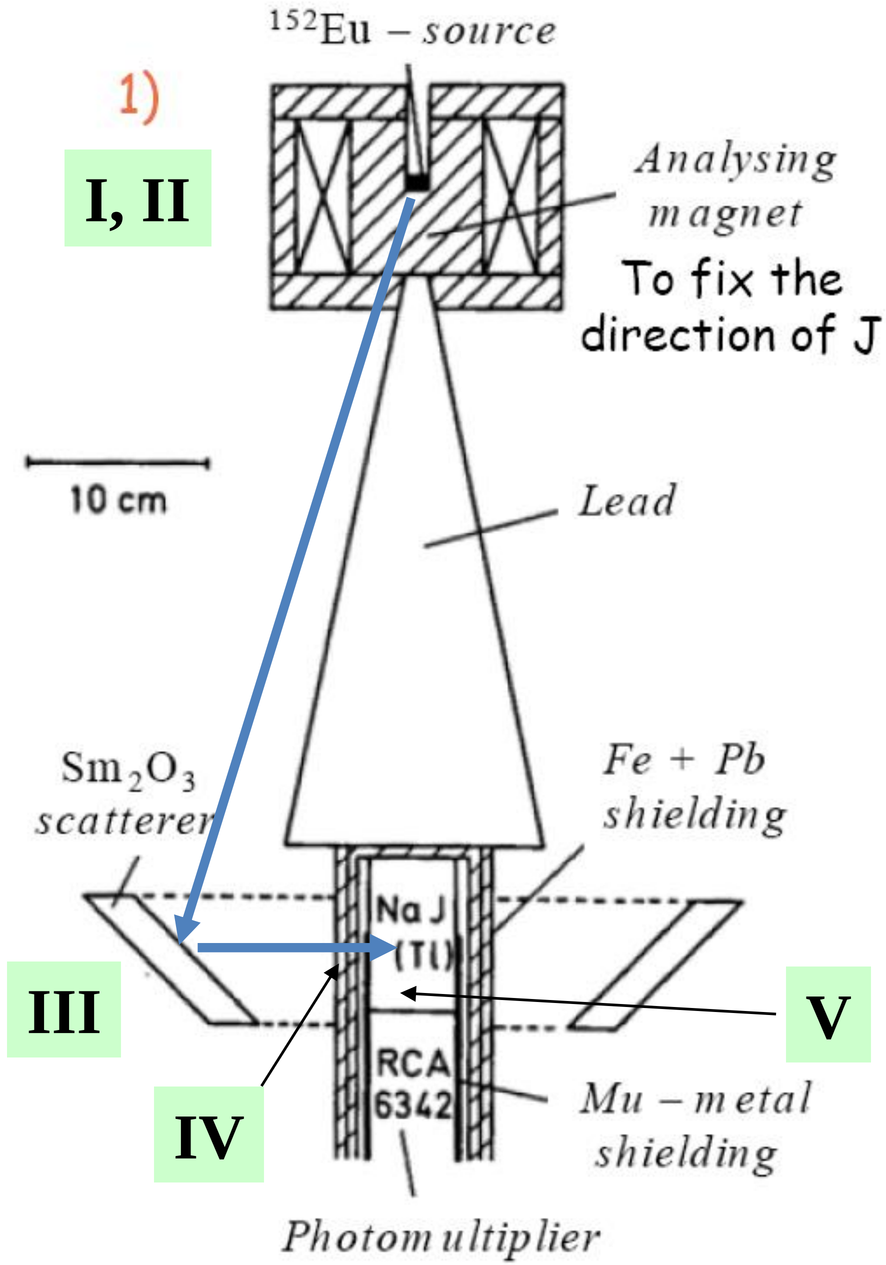


1)



$$^{152}Eu + e^{-} \rightarrow {}^{152}Sm^{*} + \nu$$





Step I neutrino emission

$$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu$$

Step II photon emission

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

E_γ = 961 keV/c (1 ± v (Sm*) /c)

Step III photon absorption/emission

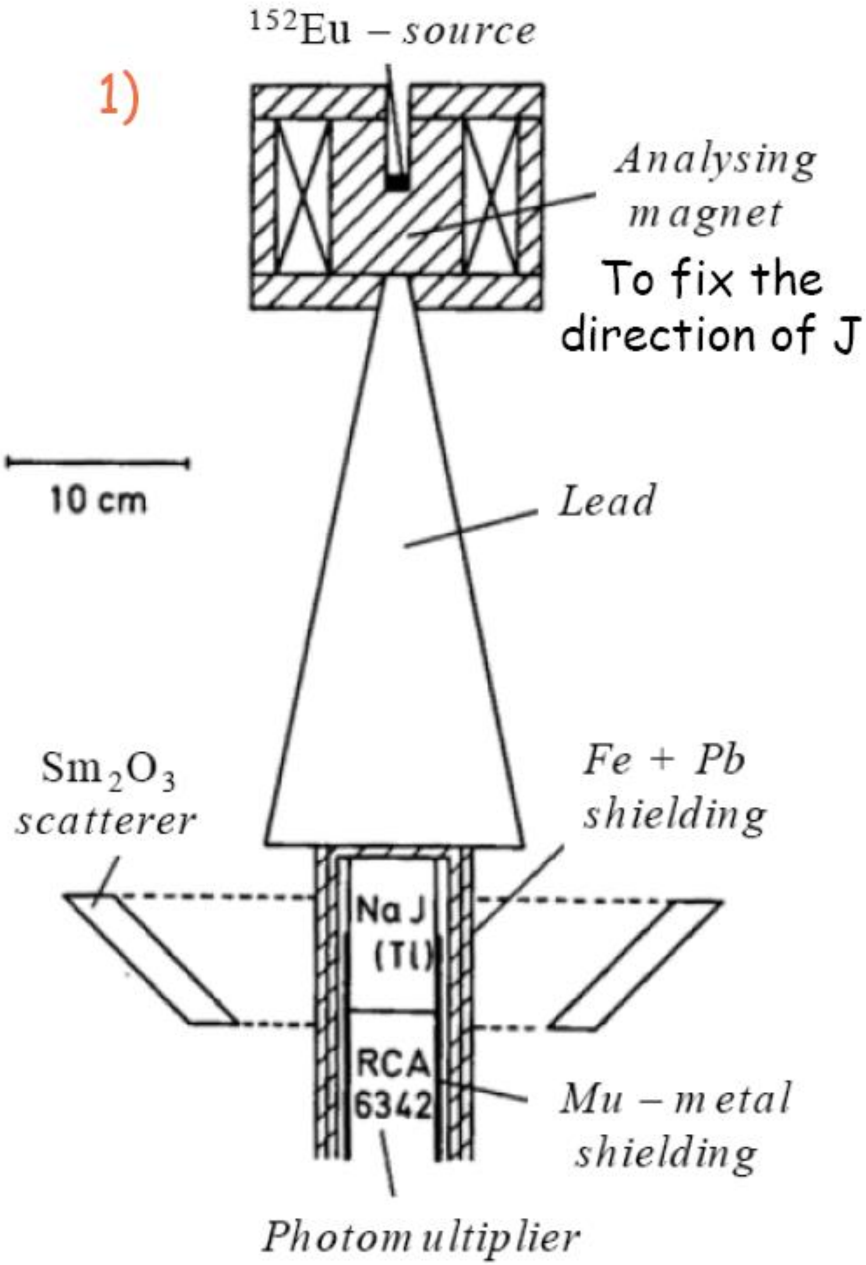
$$\gamma + {}^{152}Sm \rightarrow {}^{152}Sm^*$$

E_γ > 961 keV/c

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

Step IV photon filter through magnetic iron

Step V photon detection in NaI cristal



Step I -- source

$$^{152}Eu(J=0)+e^-(s=1/2)\rightarrow ^{152}Sm^*(J=1)+\nu_e(s=1/2)$$

electron spin oriented opposite magnetic field

e^- $^{152}Sm^*$ ν_e

B ↓ ↑ ↑ ↓

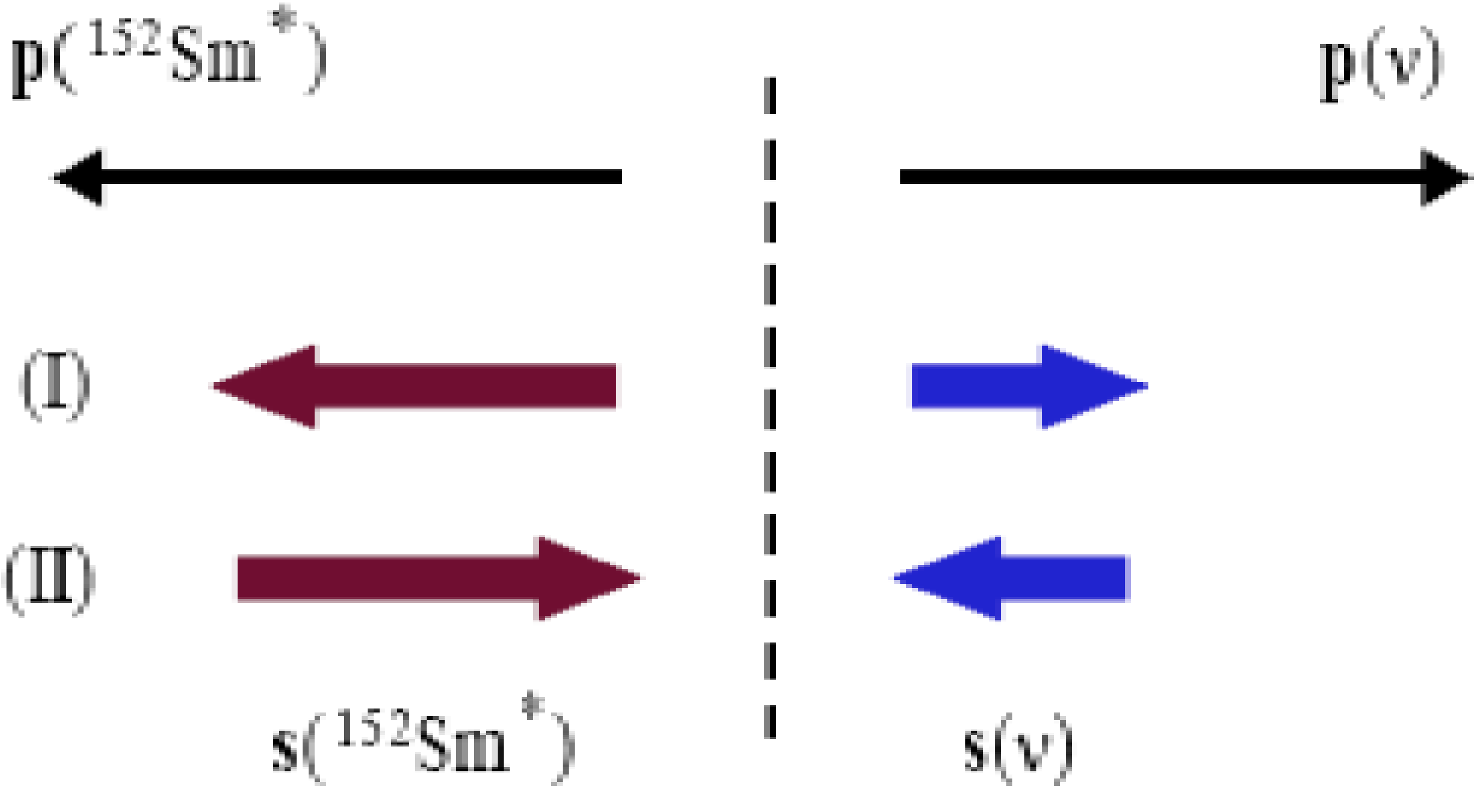
$J_z = +1/2 = +1 \quad -1/2$

B ↑ ↓ ↓ ↑

$J_z = -1/2 = -1 + 1/2$

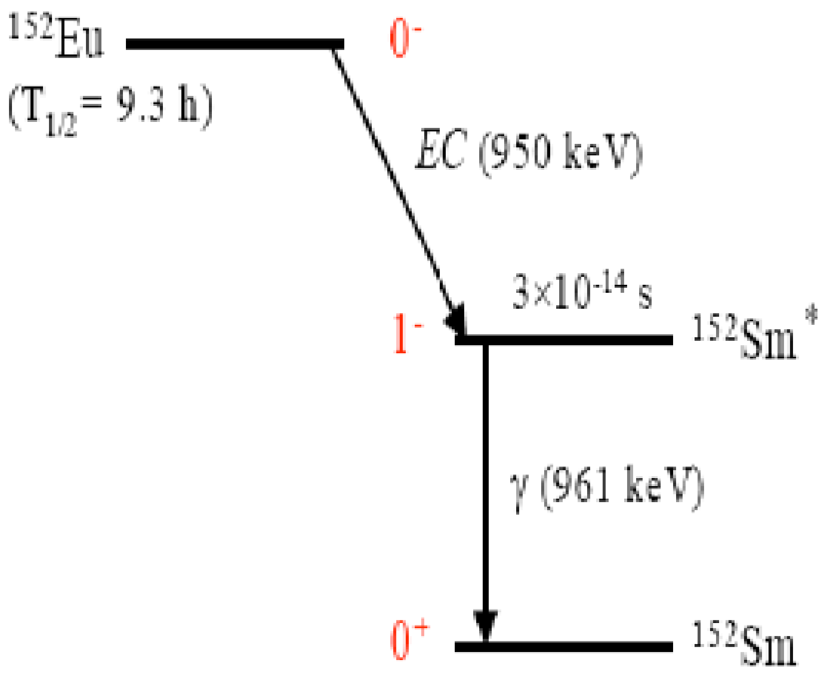
neutrino spin is in direction of magnetic field (conservation of angular momentum)

$$^{152}Eu(J=0)+e^{-}(s=1/2)\rightarrow^{152}Sm^{*}(J=1)+\nu_e(s=1/2)$$



Sm* and neutrino have the same helicity
photon from Sm* carries that spin too.

Energies



$$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu$$

$$P_\nu = \frac{E^2 - m^2{}_{Sm^*}}{2E} = \frac{(E - m_{Sm^*})(E + m_{Sm^*})}{2E}$$

$$P_\nu \approx E - m_{Sm^*} = 940\ keV/c$$

$$E^{kin}_{Sm*} = \frac{P^2}{2m_{Sm^*}} = 3.12\ eV$$

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

$$P_\gamma \approx m_{Sm^*} - m_{Sm} = 961\ keV/c$$

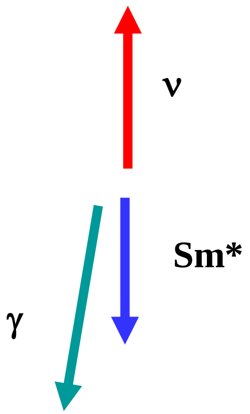
$$E^{kin}_{Sm} = \frac{P^2}{2m_{Sm}} = 3.2\ eV$$

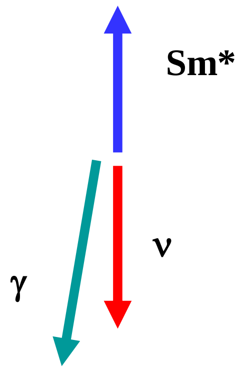
NB:

$$velocity = \sqrt{\frac{2E^{kin}}{m}} = \sqrt{6.4/1.510^{11}} = 610^{-6}c$$

$$\tau = 3 \cdot 10^{-14}\ s \rightarrow \Gamma = \hbar/\tau = 0{,}023\ eV$$

Goldhaber experiment -- STEP II Photon emission





E_γ = 961 keV/c (1 + v (Sm*) /c)

E_γ > 961 keV/c

E_γ = 961 keV/c (1 - v (Sm*) /c)

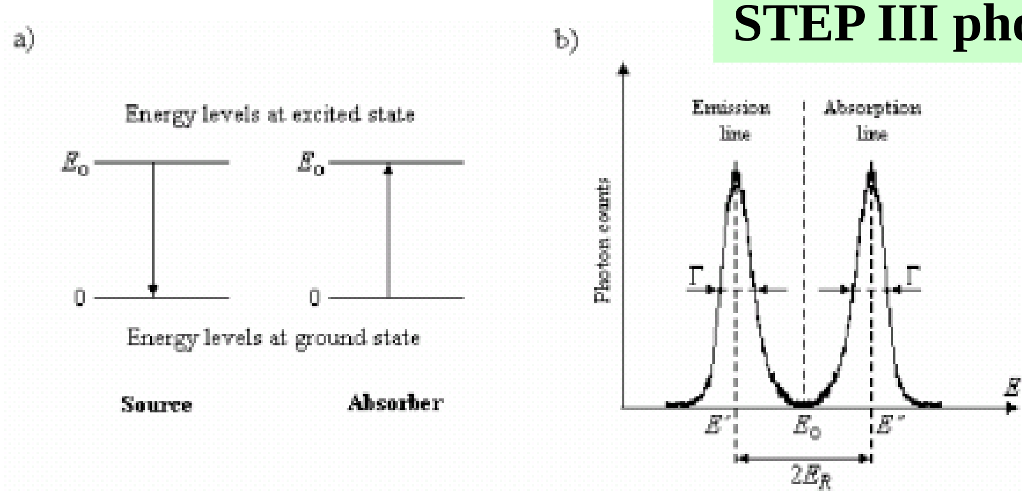
E_γ < 961 keV/c

THIS ↑ is selected by the apparatus

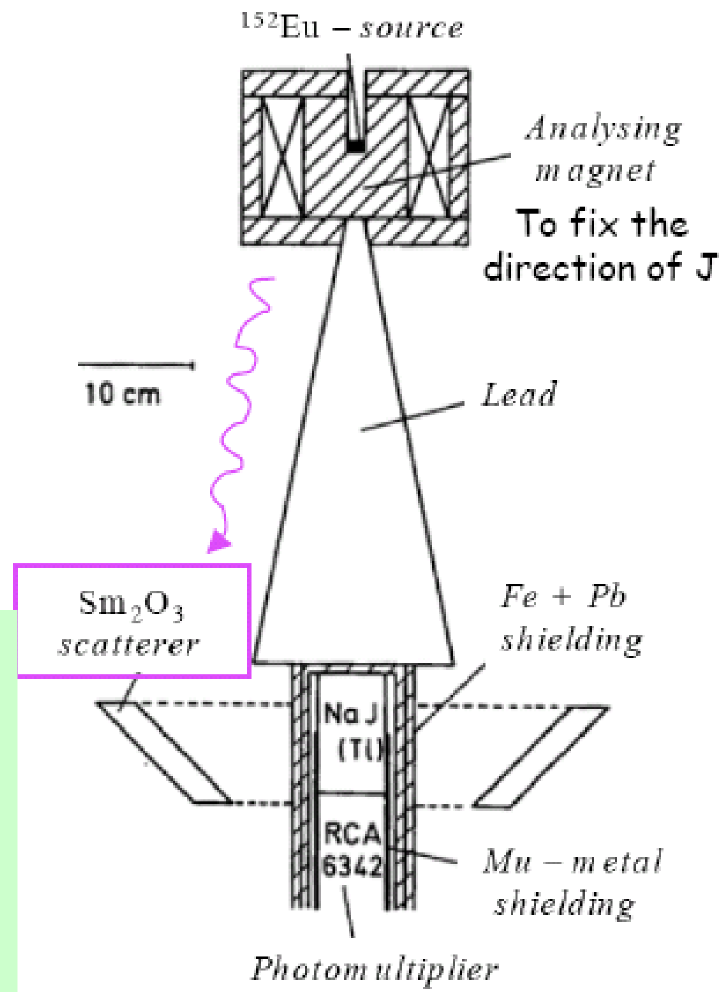
If B is up, then neutrino is right-handed
If B is down, neutrino is left handed

Goldhaber Experiment

STEP III photon absorption and reemission



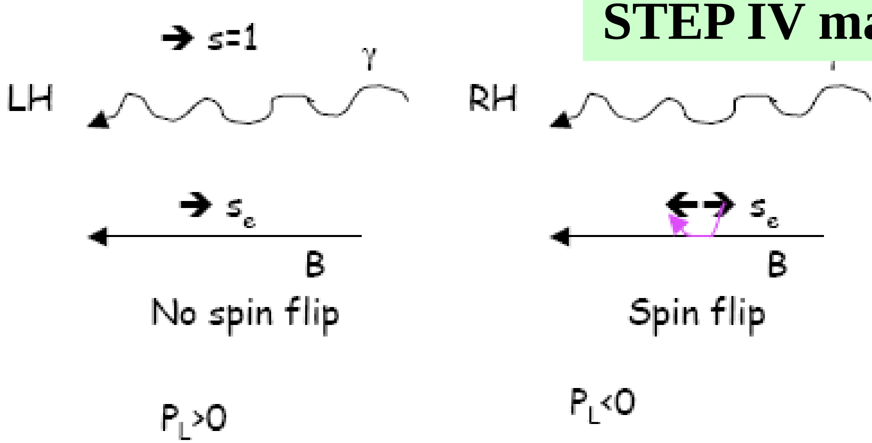
$$E_{Sm} = \frac{(E_\nu - E_\gamma)^2}{2M_{Sm}c^2} = 4\cdot 10^{-4}\,eV$$

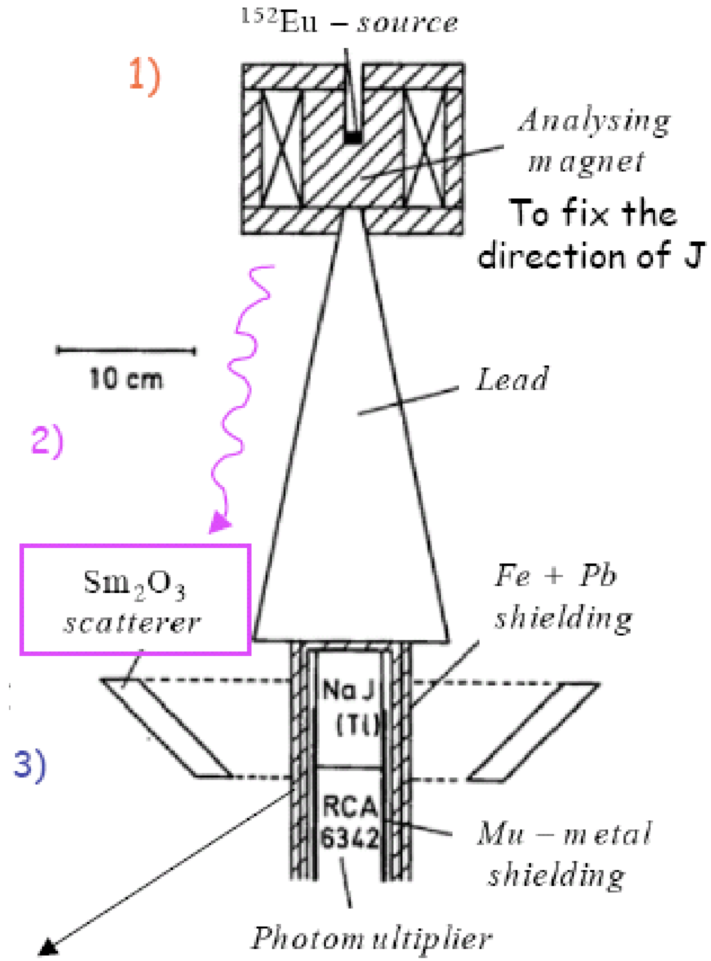


The photon must have enough energy to raise Sm to excited state.
This happens only if the Sm* is emitted in the same direction and thus E_γ > 961 keV/c
(a few eV is enough, 6 eV is Doppler shift)

Goldhaber Experiment :

STEP IV magnetic filter

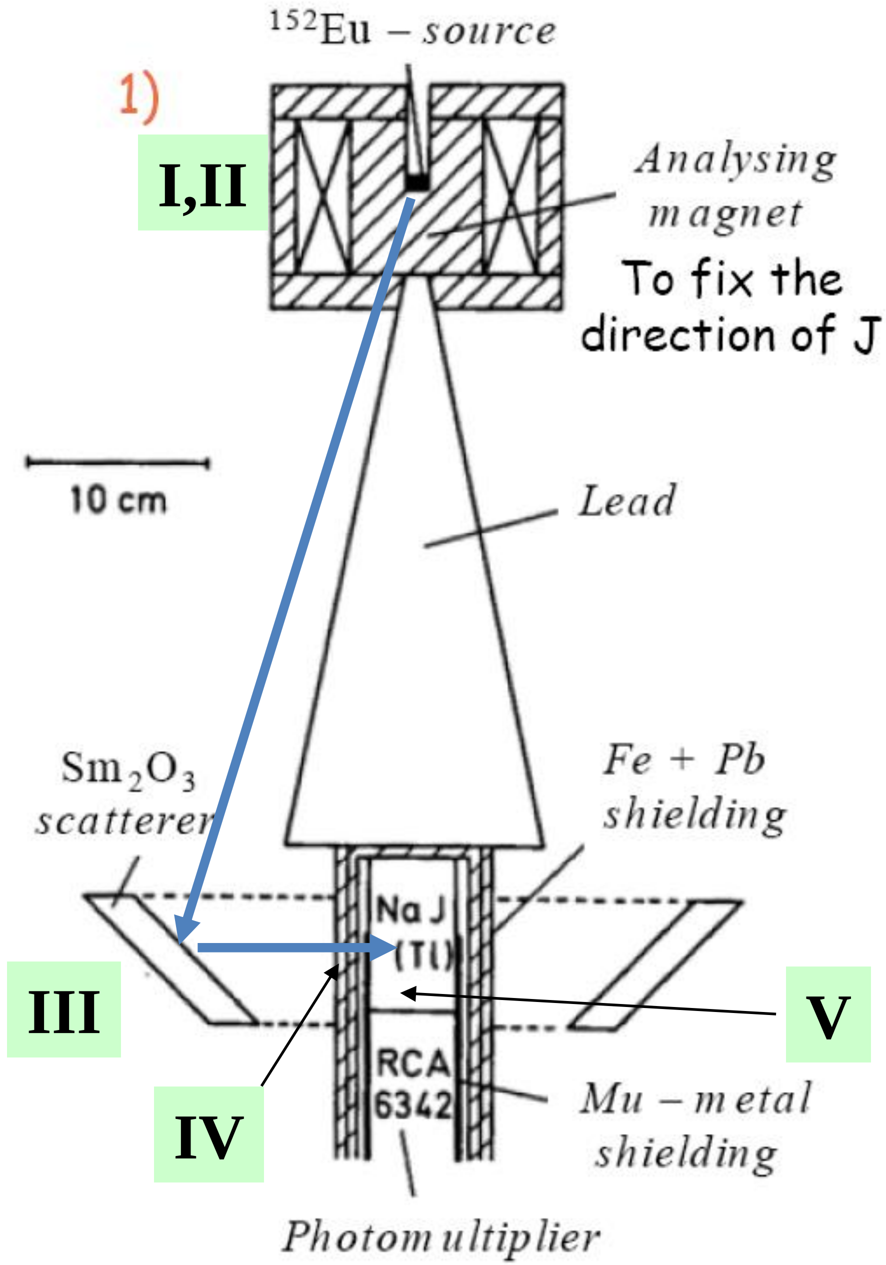




If the spin of γ is opposite to the spin of the e⁻ in the iron the γ can be absorbed via spin-flip

The dependence of signal in the NaI cristal is recorded as function of magnetic field
-- in analyzing magnet and
-- in magnetic filter

Magnetized iron which can generate a B



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E_γ > 961 keV/c

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

Step IV photon filter through magnetic iron

Step V photon detection in NaI cristal

Goldhaber experiment -- Summary --

B	P_ν	S_ν	h_ν	STEP I P_{Sm^*}	STEPII $E_\gamma > 961$?	Photon helicity	Magnetic filter	**Detection**	Neutrino
+	+	+	+	-	**YES**	+	+ (3)	**Consistent with 0**	R-H.
							- (1)		
+	-	+	-	+	no	-	+	No	R-H.
							-	No	
-	+	-	-	-	**YES**	-	+ (1)	Reduced	L-H.
							- (3)	**YES**	L-H.
-	-	-	+	+	no	+	+	No	L-H.
							-	No	L-H.

the positive neutrino helicity situation could be detected if it existed but no signal not.
the negative neutrino helicity situation gices a clear signal

➔The neutrino emitted in K capture is left-handed.

1959 Ray Davis established that
(anti) neutrinos from reactors do not interact with chlorine to produce argon

reactor : n $\rightarrow$ p e$^-$ ν_e or $\bar{\nu}_e$?

these ν_e **don't do** $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

they do this:

they are anti-neutrinos! $\bar{\nu}_e + p \rightarrow e^+ + n$

Introduce a <u>lepton number</u> which is
+1 for e^- and ν_e
and
-1 for e^+ and $\bar{\nu}_e$

which is observed to be conserved in weak/EM/Strong interactions

more about the lepton number conservation later...

Neutrino mysteries

1. **Neutrinos have mass (we know this from oscillations, see later…)**

2. **neutrinos are massless or nearly so (while m_e=5.10^{5}eV/c^2, m_{top}=1.7 10^{11}eV/c^2)**
   mass limit of 0.7eV/c^2 from beta decay (KATRIN)
   mass limit of <~ 1 eV/c^2 from large scale structure of the universe

3. **neutrinos appear in a single helicity (or chirality?)**
   but of course weak interaction only couples to left-handed particles
   and neutrinos have no other known interaction…
   So… even if right handed neutrinos existed,
   they would neither be produced nor be detected!

4. **if they are not massless why are the masses so different from those of other quark and leptons?**

5. **3 families are necessary for CP violation, but why only 3 families?**

…….

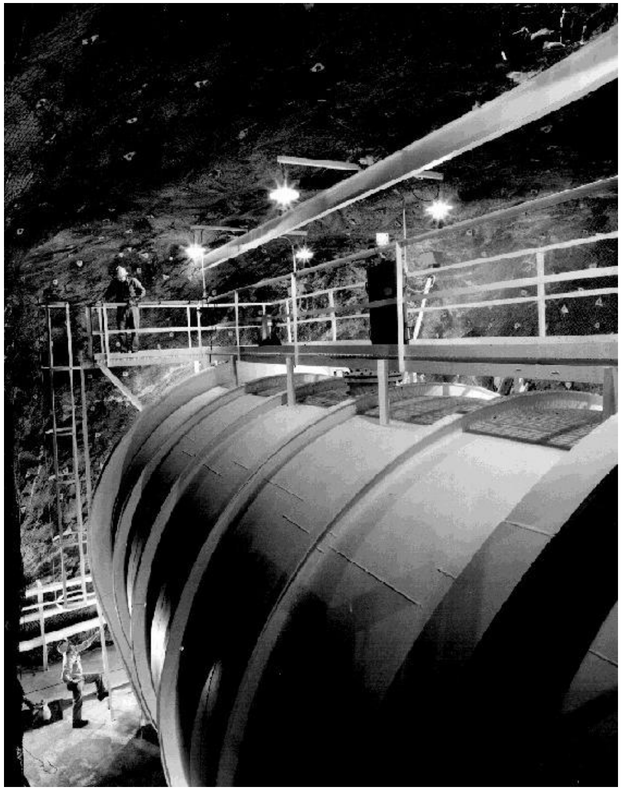
Neutrinos

astrophysical neutrinos

Ray Davis

since ~1968

Homestake Detector



Solar Neutrino Detection
600 tons of chlorine.

- Detected neutrinos E> 1MeV

- fusion process in the sun

solar : pp $\rightarrow$ pn e^+ ν_e (then D gives He etc…)

these ν_e do ν_e + $^{37}Cl \rightarrow {}^{37}Ar$ + e^-

they are neutrinos

- The rate of neutrinos detected is
three times less than predicted!

solar neutrino 'puzzle' since 1968-1975!

solution: 1) solar nuclear model is wrong or 2) neutrino oscillate

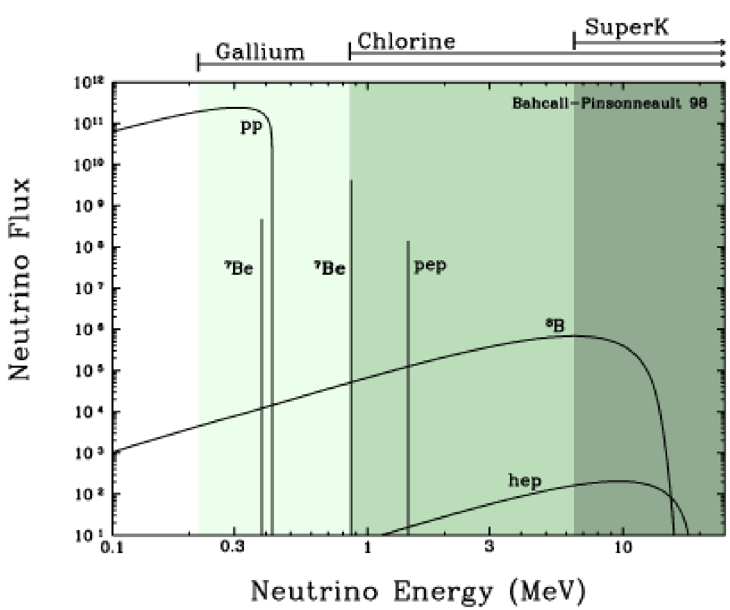
ν_e solar neutrinos

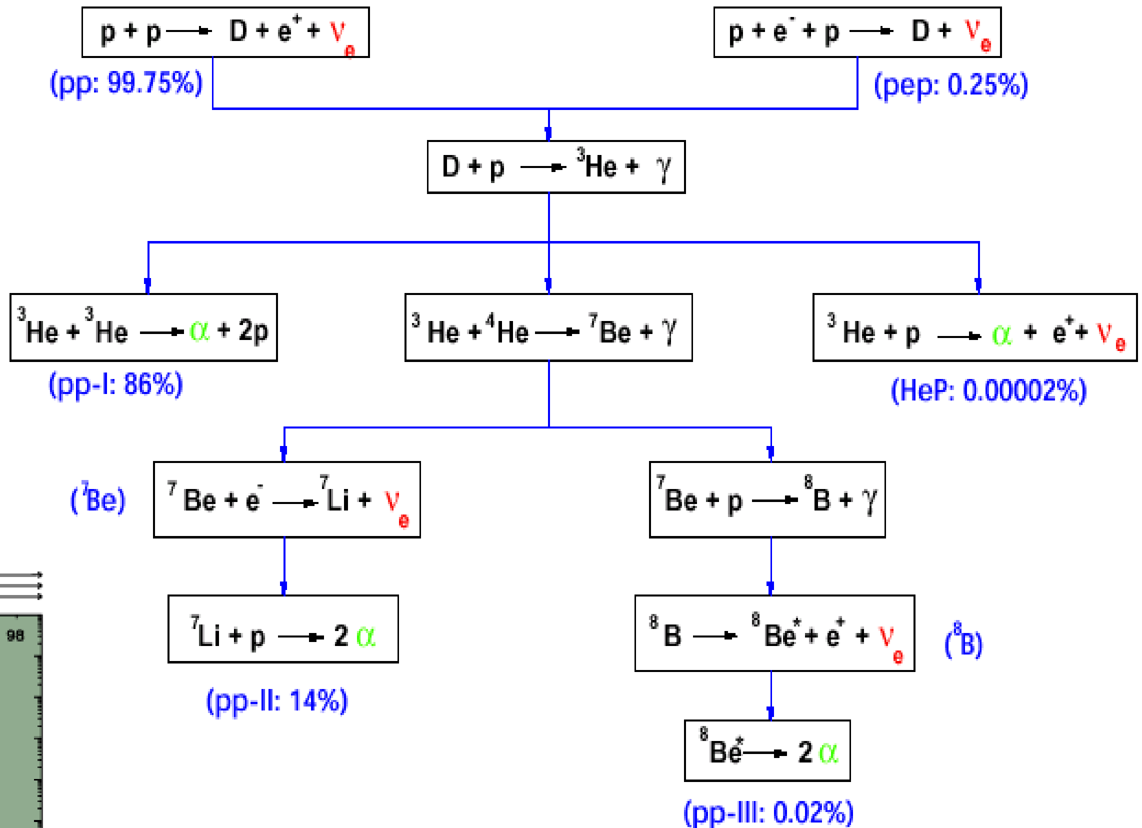
Sun = Fusion reactor

Only ν_e produced

Different reactions

Spectrum in energy





Counting experiments vs flux calculated by SSM

BUT ...

The Pioneer: Chlorine Experiment

The interaction

$^{37}Cl(\nu_e,e)^{37}Ar$ (E_{thr} = 813 keV)

K_{shell} **EC** τ = **50.5** d

^{37}Cl + 2.82 keV (*Auger* e^-, *X*)

ν Signal Composition:
(BP04+N14 SSM+ ν osc)

pep+hep	0.15 SNU	(4.6%)
^{7}Be	0.65 SNU	(20.0%)
^{8}B	2.30 SNU	(71.0%)
CNO	0.13 SNU	(4.0%)
Tot	3.23 SNU ± 0.68 **1σ**	

Expected Signal
(BP04 + N14)

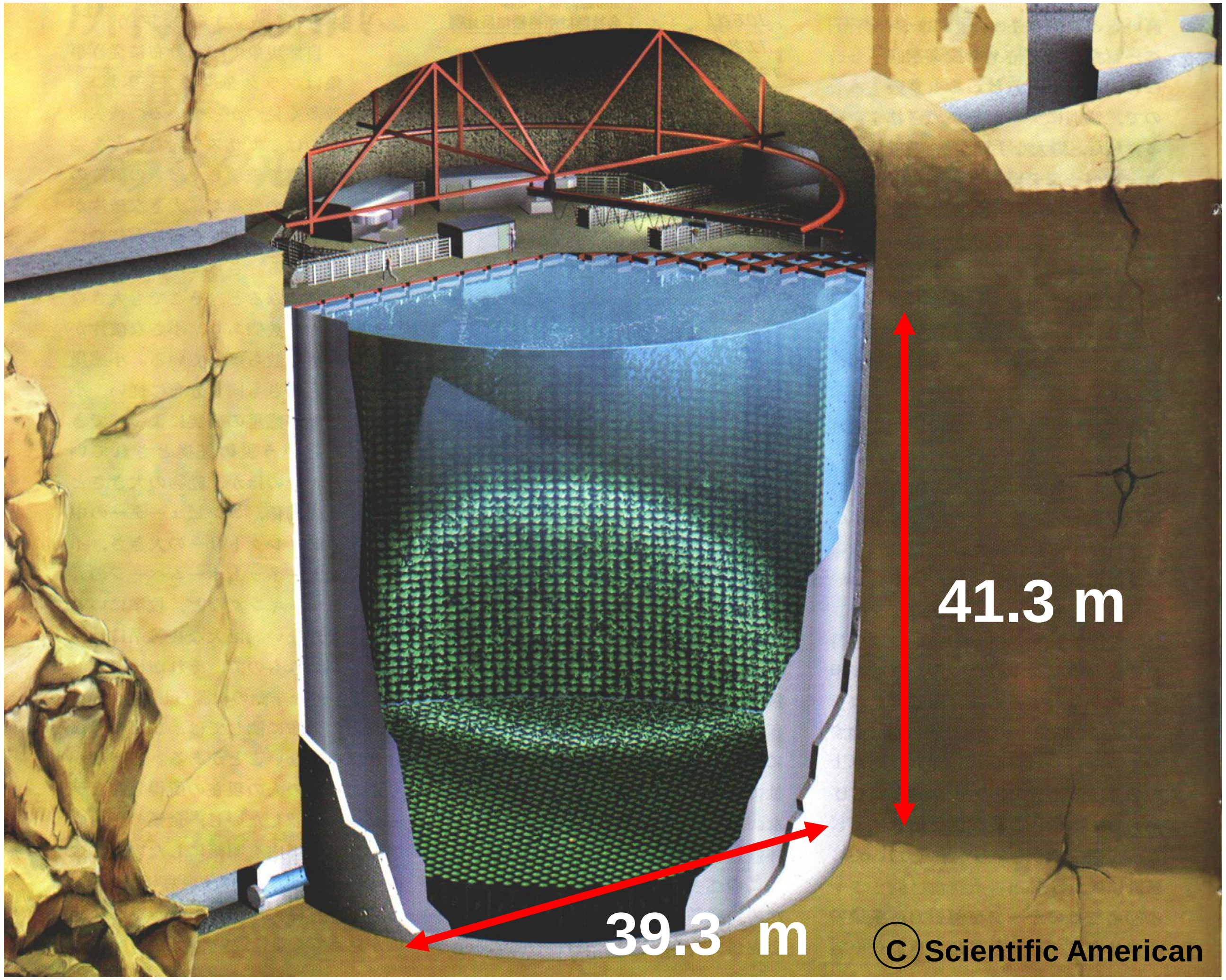
8.2 SNU $^{+1.8}_{-1.8}$ **1σ**

S.N.U. = Solar Neutrino Unit
(electron-) neutrino flux producing 10^{-36} captures per target atom per second

Generalities on radiochemical experiments

	Data used for R determination	N runs	Average efficiency	Hot chem check	Source calib	R_{ex} [SNU] **expected (no osc)**
Chlorine (Homestake Mine); South Dakota USA	1970-1993	106	0.958 ± 0.007	^{36}Cl	No	2.55 ± 0.17 ± 0.18 6.6% 7% **2.6 ± 0.3** **8.5+-1.8**
GALLEX /GNO LNGS Italy	1991-2003	124		^{37}As	Yes twice ^{51}Cr source	69.3 ± 4.1 ± 3.6 5.9% 5% **131+-11**
SAGE Baksan Kabardino Balkaria	1990-ongoing	104		No	Yes ^{51}Cr ^{37}Ar	70.5 ± 4.8 ± 3.7 6.8% 5.2% **70.5 ± 6.0** **131+-11**

Super-K detector



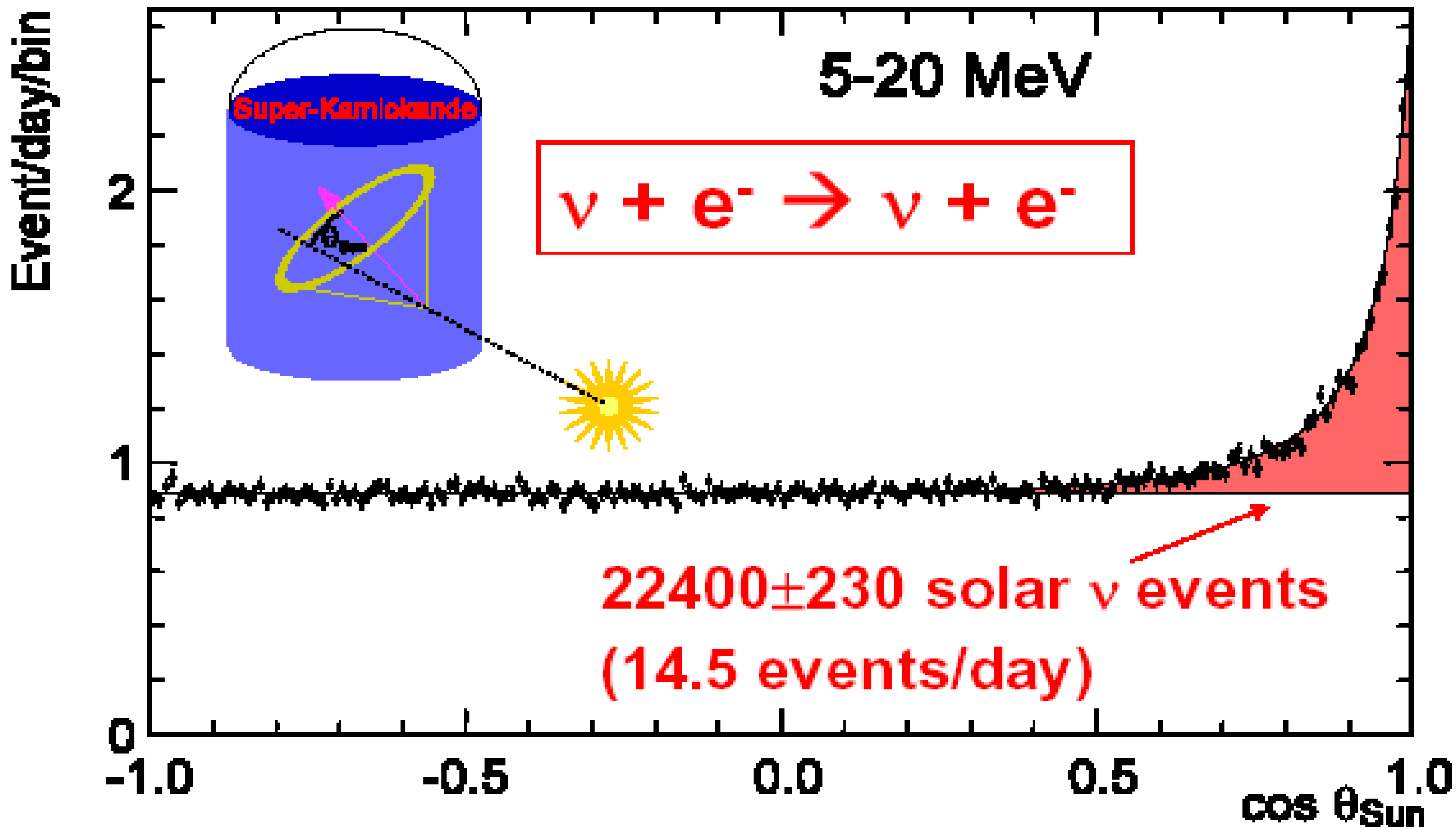
Water Cerenkov detector

50000 tons of pure light water

≈10000 PMTs

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, ^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

Missing Solar Neutrinos

Only fraction of the expected flux is measured !

Possible explications:

wrong SSM

NO. Helio-seismology

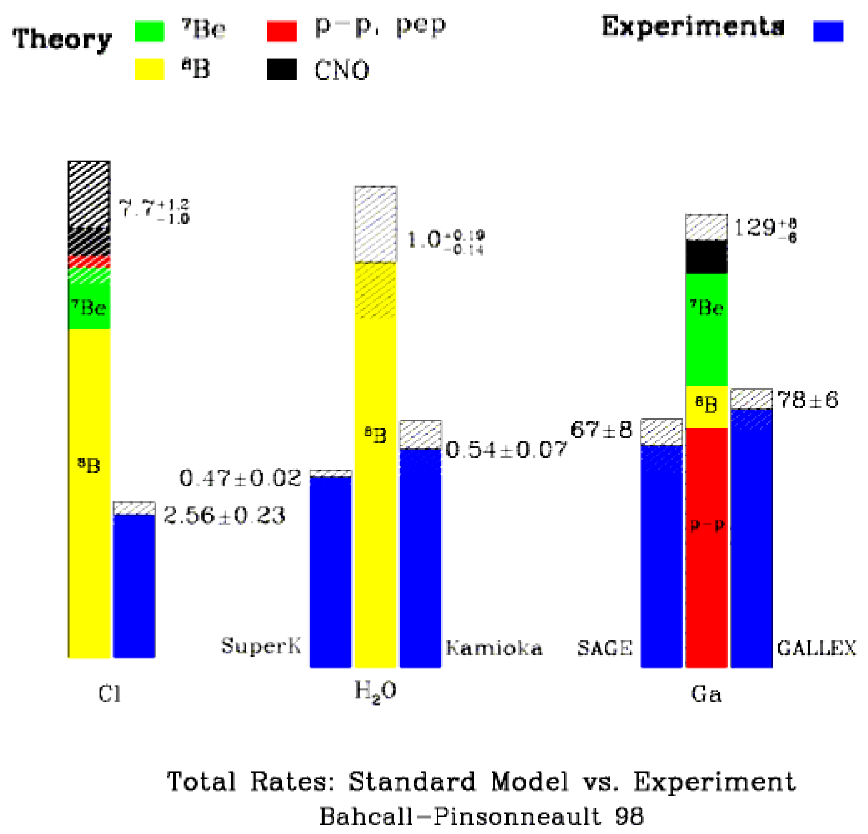
wrong experiments

NO. Agreement between different techniques

or

ν_e's go into something else

Oscillations?



neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \to \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

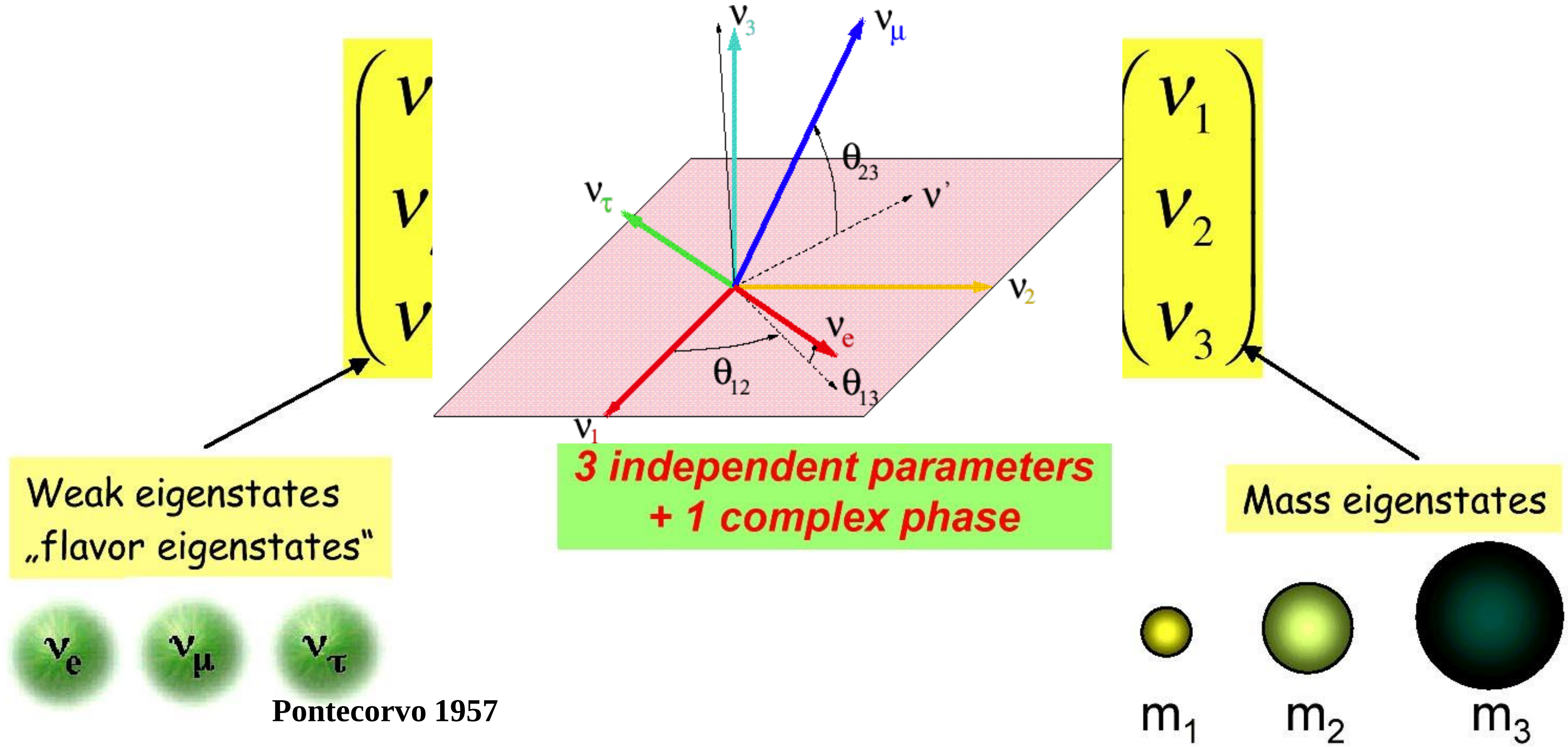
the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

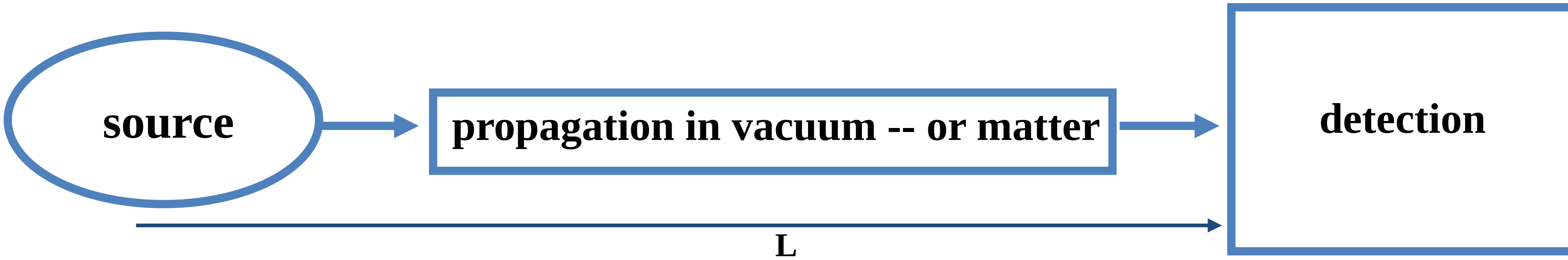
Lepton Sector Mixing

- If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:



Pontecorvo 1957

Neutrino Oscillations (Quantum Mechanics lesson 5)



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \rightarrow \mu\nu$

$|\nu_\mu\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$

α **is noted** $U_{1\mu}$

β **is noted** $U_{2\mu}$

γ **is noted** $U_{3\mu}$ **etc….**

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\,|\nu_1\rangle\ \exp(i E_1 t) + \beta\,|\nu_2\rangle\ \exp(i E_2 t) + \gamma\,|\nu_3\rangle\ \exp(i E_3 t)$$

t = proper time $\propto$ **L/E**

weak interaction: (CC)

$\nu_\mu\ N \rightarrow \mu^-\ X$

or $\nu_e\ N \rightarrow e^-\ X$

or $\nu_\tau\ N \rightarrow \tau^-\ X$

$P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu(t)\rangle|^2$

oscillatory function of time

important: neutral current does not oscillate!

Oscillation Probability

- The case with two neutrinos:
  - → A mixing angle: θ
  - → A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

Dm2 en ev2
L en km
E en GeV

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector
E = neutrino energy

Hamiltonian= E = sqrt($p^2 + m^2$) = p + $m^2 / 2p$
for a given momentum, eigenstate of propagation in free space are the mass eigenstates!

LA MECANIQUE QUANTIQUE DES OSCILLATIONS DE NEUTRINOS

On traitera d'abord un système à deux neutrinos pour simplifier

Propagation dans le vide: on écrit le Hamiltonien pour une particule relativiste
(NB il y a là une certaine incohérence car la mécanique quantique relativiste utilise des méthodes différentes. Dans ce cas particulièrement simple les résultats sont les mêmes.)

On se rappellera du 4-vecteur relativiste Energie Impulsion

$$\begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

Dont la norme est par définition la masse (invariant relativiste) et s'écrit

$(mc^2)^2 = E^2 - (pc)^2$

D'ou l'énergie:

$$E = \sqrt{(pc)^2 + (mc^2)^2} \approx pc\,\left(1 + \frac{(mc^2)^2}{2(pc)^2}\right) = pc + \frac{m^2c^4}{2pc}$$

On considère pour simplifier encore le cas de neutrinos dont la quantité de mouvement est connue ce qui fait que le Hamiltonien va s'écrire ainsi dans la base des états de masse bien définie:

$$H = pc\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \frac{c^4}{2pc}\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}$$

Pour le cas de deux neutrinos, dans la base des états de masse bien définie:

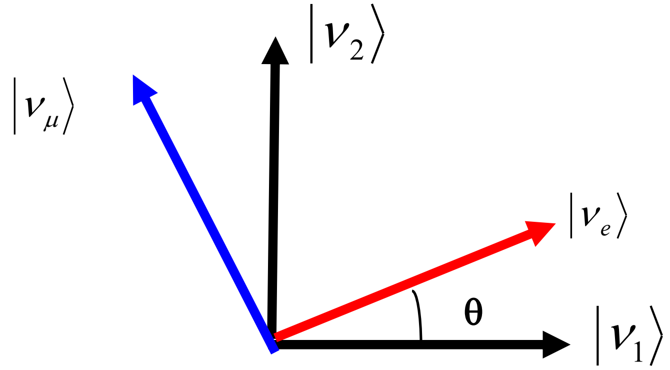
$$H = pc\begin{pmatrix}1 0\\ 0 1\end{pmatrix} + \frac{c^4}{2pc}\begin{pmatrix}m_1^2 & 0\\ 0 & m_2^2\end{pmatrix}$$

L'evolution dans le temps des états propres $|\nu_1\rangle$ **et** $|\nu_2\rangle$ **s'écrit:**

$$|\nu_1(t)\rangle = |\nu_1\rangle e^{iE_1 t/\hbar} \qquad |\nu_2(t)\rangle = |\nu_2\rangle e^{iE_2 t/\hbar}$$

Cependant les neutrinos de saveur bien définie sont des vecteurs orthogonaux de ce sous espace de Hilbert à deux dimensions, mais différents des neutrinos de masse bien définie: $|\nu_e\rangle$ $|\nu_\mu\rangle$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



L'évolution dans le temps s'écrit maintenant

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 e^{iE_1 t/\hbar}\\ \nu_2 e^{iE_2 t/\hbar}\end{pmatrix} = e^{iE_1 t/\hbar}\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2 e^{i(E_2-E_1)t/\hbar}\end{pmatrix}$$

$$\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \end{pmatrix} = e^{iE_1 t/\hbar} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 e^{i(E_2-E_1)t/\hbar} \end{pmatrix}$$

Si nous partons maintenant au niveau de la source (t=0) avc un état $|\nu_e\rangle$
et que nous allons détecter des neutrinos à une distance L (soit à un temps L/c plus tard) la probabilité
Quand on observe une interaction de neutrino d'observer une interaction produisant un electron ou un muon
seront donnés par le calcul de

$$P_e(|\nu_e(t)\rangle) = \| \langle \nu_e | \nu_e(t) \rangle \|^2$$

$$P_\mu(|\nu_e(t)\rangle) = \| \langle \nu_\mu | \nu_e(t) \rangle \|^2$$

$$P_e(|\nu_e(t)\rangle) = \| \langle \nu_e | \nu_e(t) \rangle \|^2 = \| \cos\theta \langle \nu_e | \nu_1 \rangle + \sin\theta \langle \nu_e | \nu_2 \rangle e^{i(E_2-E_1)t/\hbar} \|^2$$

$$P_e(|\nu_e(t)\rangle) = (\cos^2\theta + \sin^2\theta\, e^{-i(E_2-E_1)t/\hbar})(\cos^2\theta + \sin^2\theta\, e^{+i(E_2-E_1)t/\hbar})$$

$$P_e(|\nu_e(t)\rangle) = \left\| \langle \nu_e | \nu_e(t) \rangle \right\|^2 = \left\| \cos\theta \langle \nu_e | \nu_1 \rangle + \sin\theta \langle \nu_e | \nu_2 \rangle e^{i(E_2-E_1)t/\hbar} \right\|^2$$

$$P_e(|\nu_e(t)\rangle) = (\cos^2\theta + \sin^2\theta\, e^{-i(E_2-E_1)t/\hbar})(\cos^2\theta + \sin^2\theta\, e^{+i(E_2-E_1)t/\hbar})$$

$$P_e(|\nu_e(t)\rangle) = \cos^4\theta + \sin^4\theta + \cos^2\theta \sin^2\theta\,(e^{+i(E_2-E_1)t/\hbar} + e^{-i(E_2-E_1)t/\hbar})$$

$$P_e(|\nu_e(t)\rangle) = \cos^4\theta + \sin^4\theta + \cos^2\theta \sin^2\theta\,(2\cos((E_2-E_1)t/\hbar))$$

$$P_e(|\nu_e(t)\rangle) = \cos^4\theta + \sin^4\theta + 2\cos^2\theta \sin^2\theta - 2\cos^2\theta \sin^2\theta\,(1-\cos(E_2-E_1)t/\hbar)$$

$$P_e(|\nu_e(t)\rangle) = 1 - \sin^2 2\theta \sin^2(1/2(E_2-E_1)t/\hbar)$$

$$P_e(|\nu_e(t)\rangle) = 1 - \sin^2 2\theta \sin^2(1/2(E_2-E_1)t/\hbar)$$

$$P_\mu(|\nu_e(t)\rangle) = \sin^2 2\theta \sin^2(1/2(E_2-E_1)t/\hbar)$$

En utilisant:

$$1-\cos x = 2\sin^2 x/2,$$

$$2\sin x \cos x = \sin 2x$$

On a donc trouvé:

$$P_e(|\nu_e(t)\rangle) = 1 - \sin^2 2\theta \sin^2(1/2(E_2 - E_1)t/\hbar)$$

$$P_\mu(|\nu_e(t)\rangle) = \sin^2 2\theta \sin^2(1/2(E_2 - E_1)t/\hbar)$$

mélange **oscillation**

Le terme d'oscillation peut être reformulé:

$$E = pc + \frac{m^2c^4}{2pc}$$

$$E_2 - E_1 = \frac{(m_2^2 - m_1^2)c^4}{2pc} = \frac{\Delta m_{12}^2 c^4}{2pc}$$

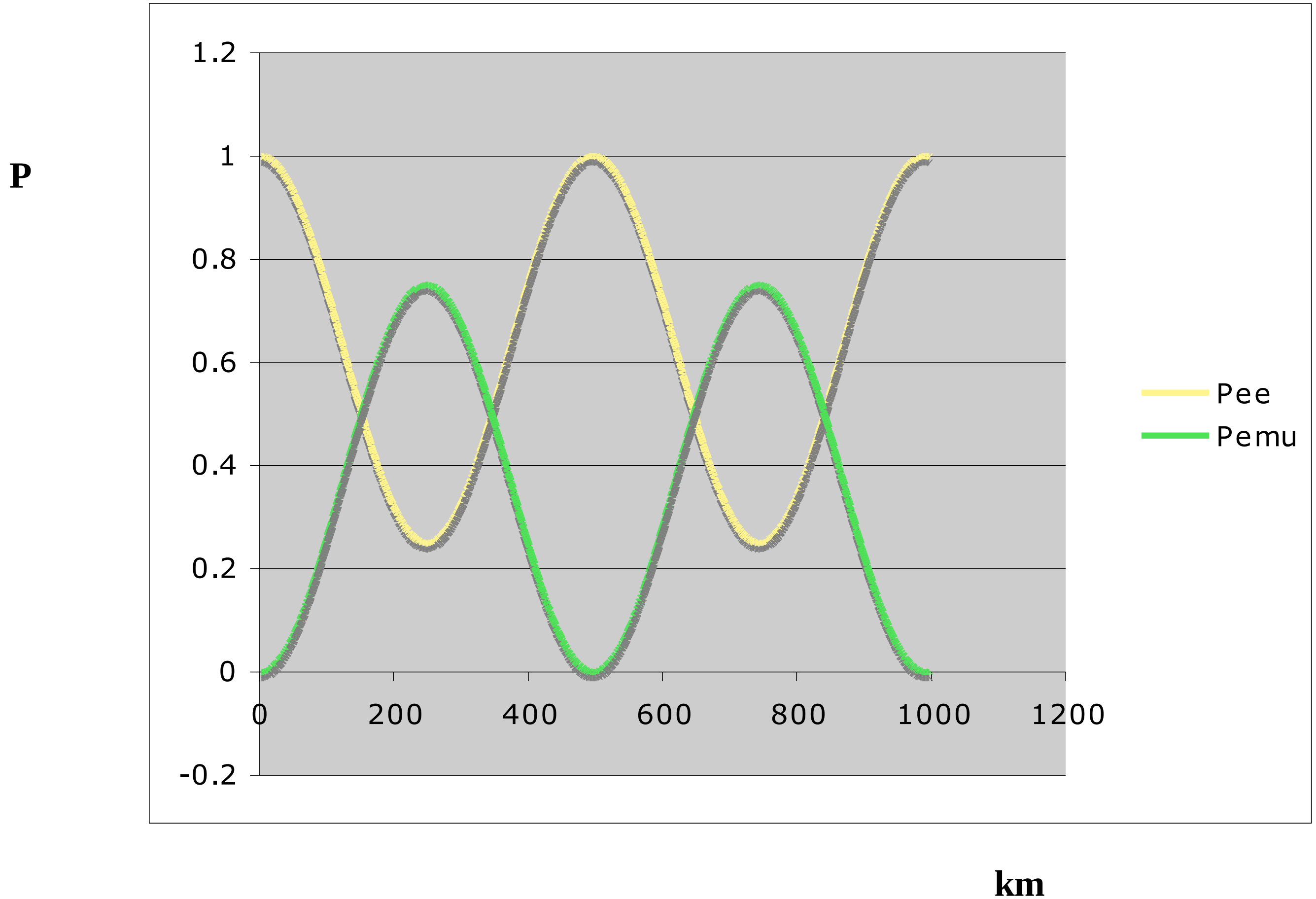
$$\frac{\Delta m^2 c^4}{4p\hbar c} t = \frac{\Delta m^2 c^4}{4pc\hbar c} ct = \frac{\Delta m^2 c^4}{4\hbar c} \frac{L}{E}$$

Les unités pratiques sont
Les énergies en GeV
Les masses mc^2 en eV
Les longeurs en km…

On trouve alors en se souvenant que $\hbar c = 197\ MeV.fm$

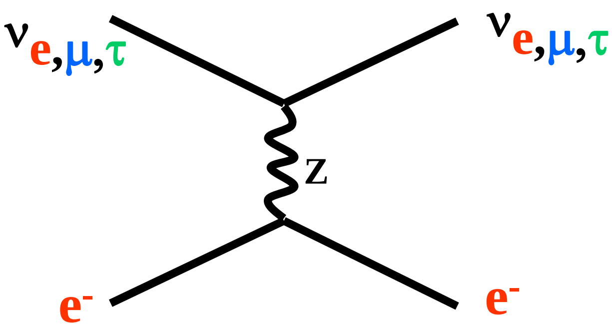
$$P_e(|\nu_e(t)\rangle) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m_{12}^2 L / E)$$

$$P_\mu(|\nu_e(t)\rangle) = \sin^2 2\theta \sin^2(1.27 \Delta m_{12}^2 L / E)$$

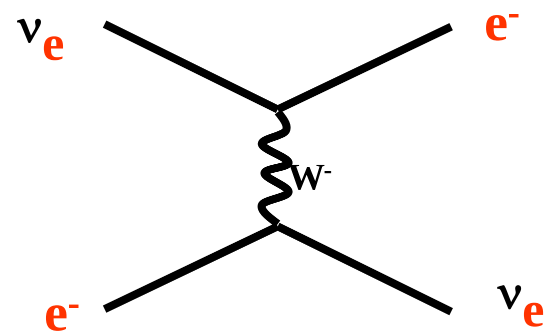


Exemple de probabilité en fonction de la distance à la source pour E= 0.5 GeV,
Δm^2_{12} = 2.5 10-^{3} (eV/c^2)^2

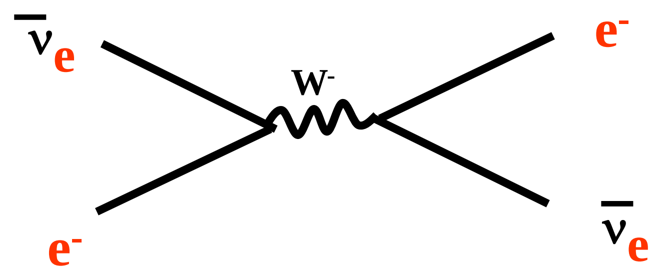
To complicate things further:
matter effects
elastic scattering of (anti) neutrinos on electrons



all neutrinos and anti neutrinos do this equally



only electron neutrinos



only electron anti- neutrinos

These processes add a forward amplitude to the Hamiltonian, which is proportional to the number of elecrons encountered to the Fermi constant and to the neutrio energy.
The Z exchange is diagonal in the 3-neutrino space
this does not change the eigenstates
The W exchange is only there for electron neutrinos
It has opposite sign for neutrinos and anti-neutrinos (s vs t-channel exchange)

$D = \pm 2\sqrt{2}\, G_F\, n_e E_\nu$

THIS GENERATES A FALSE CP VIOLATION

$$D = \pm 2\sqrt{2}\, G_F\, n_e E_\nu$$

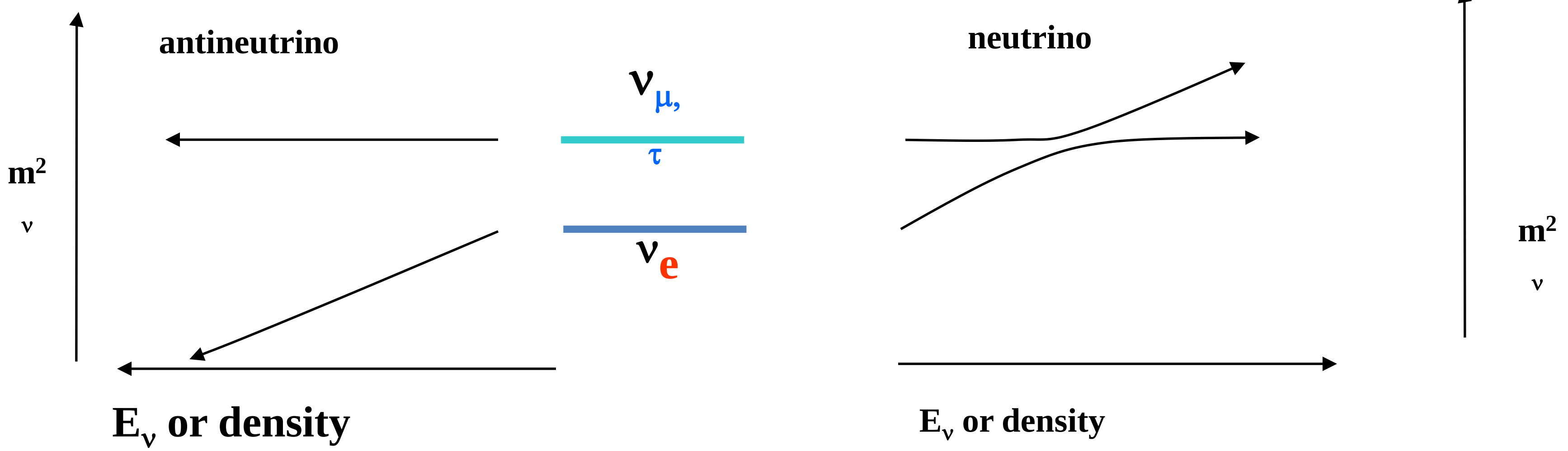
$$\mathbf{H}_{\text{flavour base}} = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} D & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This is how YOU can solve this problem: write the matrix, diagonalize, and evolve using,

$$i\frac{\partial \psi}{\partial t} = H\psi$$

This has the effect of modifying the eigenstates of propagation!

Mixing angle and energy levels are modified, this can even lead to level-crossing. ***MSW effect***



oscillation is further suppressed **resonance… enhances oscillation**

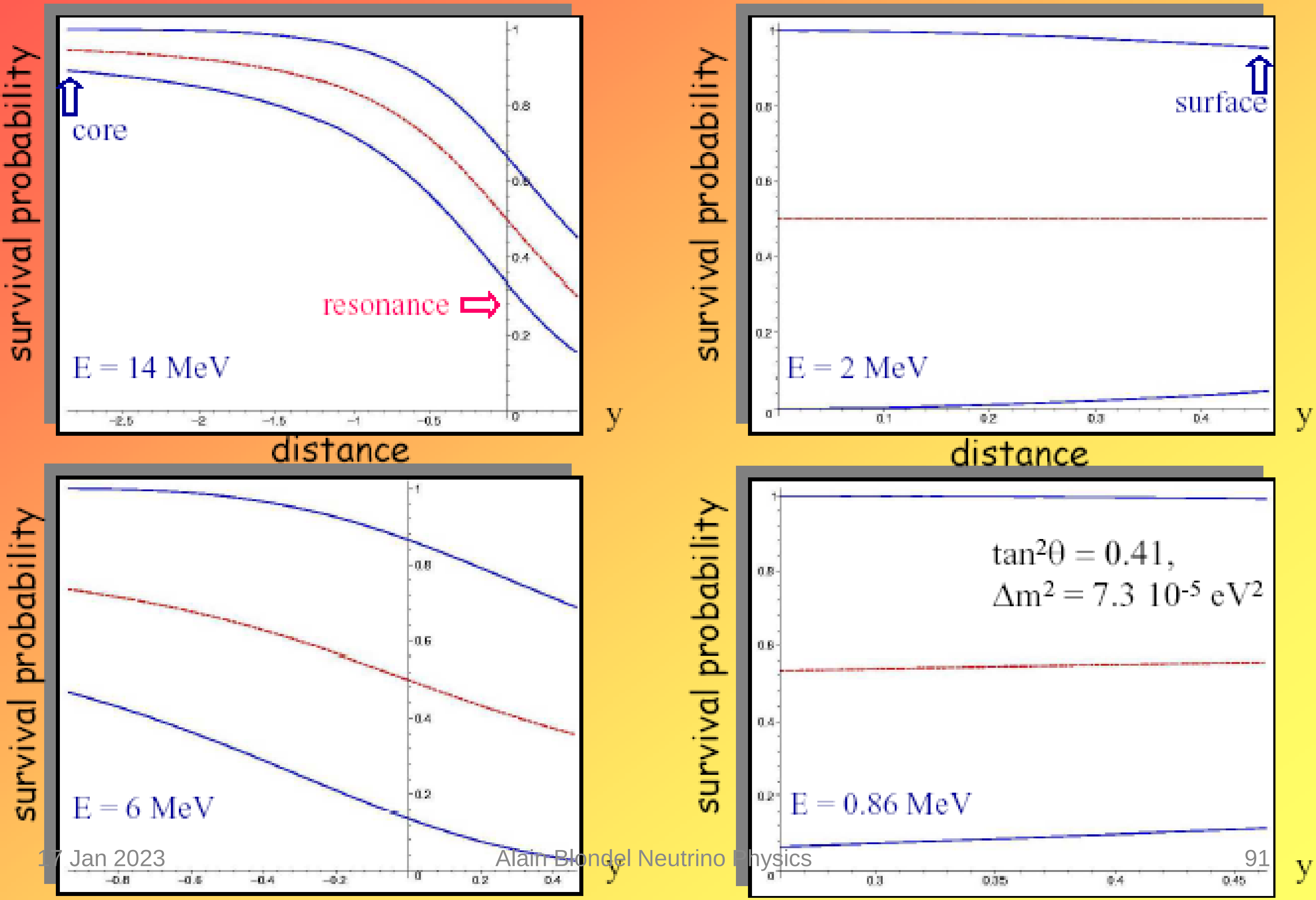
oscillation is enhanced for neutrinos if $\Delta m^2_{1x} > 0$, and suppressed for antineutrinos

oscillation is enhanced for antineutrinos if $\Delta m^2_{1x} < 0$, and suppressed for neutrinos

since T asymmetry uses neutrinos it is not affected

MSW conversion inside the Sun

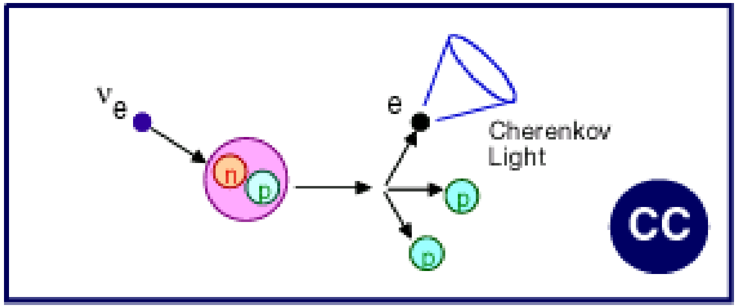
SMIRNOV



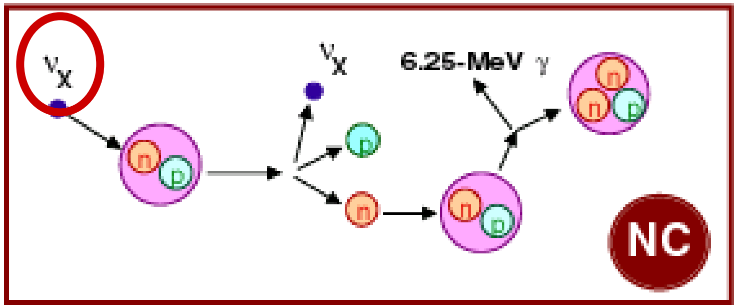
SNO detector

Aim: measuring non ν_e neutrinos in a pure solar ν_e beam

How? Three possible neutrino reaction in heavy water:

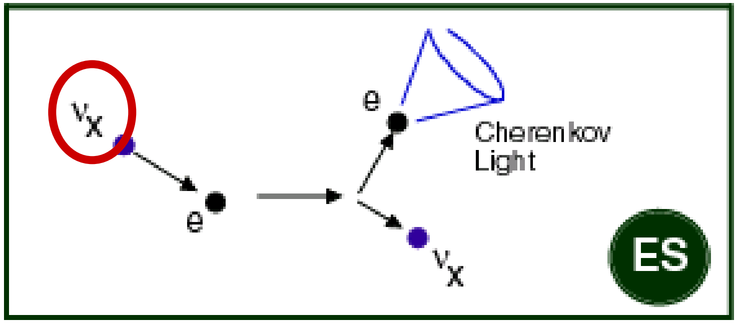


only ν_e



equally

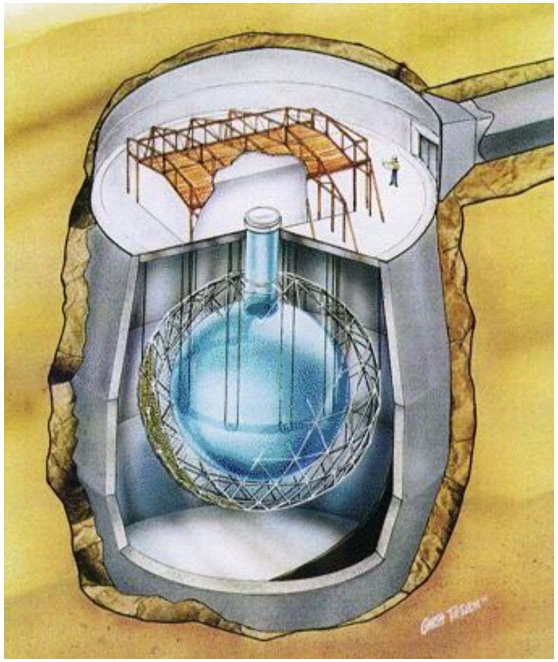
$\nu_e + \nu_\mu + \nu_\tau$



in-equally

$\nu_e +$

$0.1\ (\nu_\mu + \nu_\tau\ )$



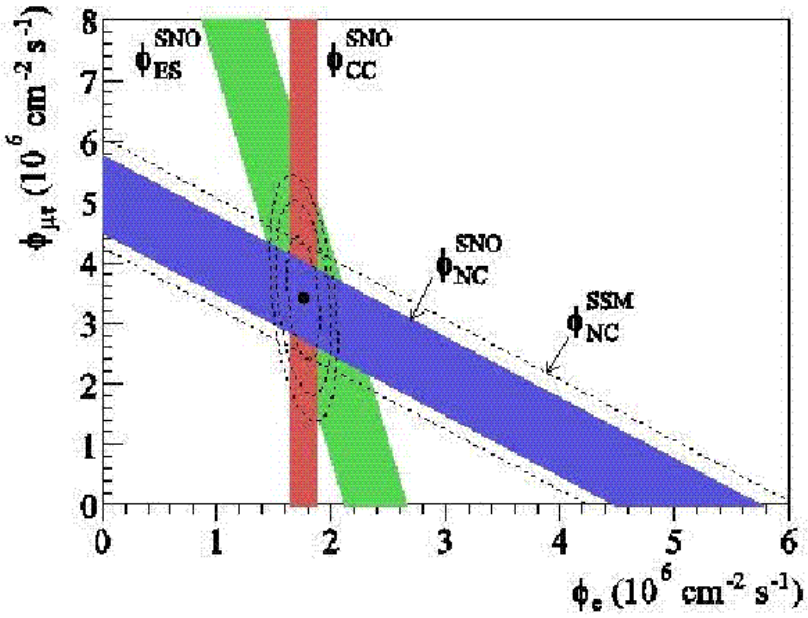
1000 ton of $D_2 0$

12 m diam.

9456 PMTs

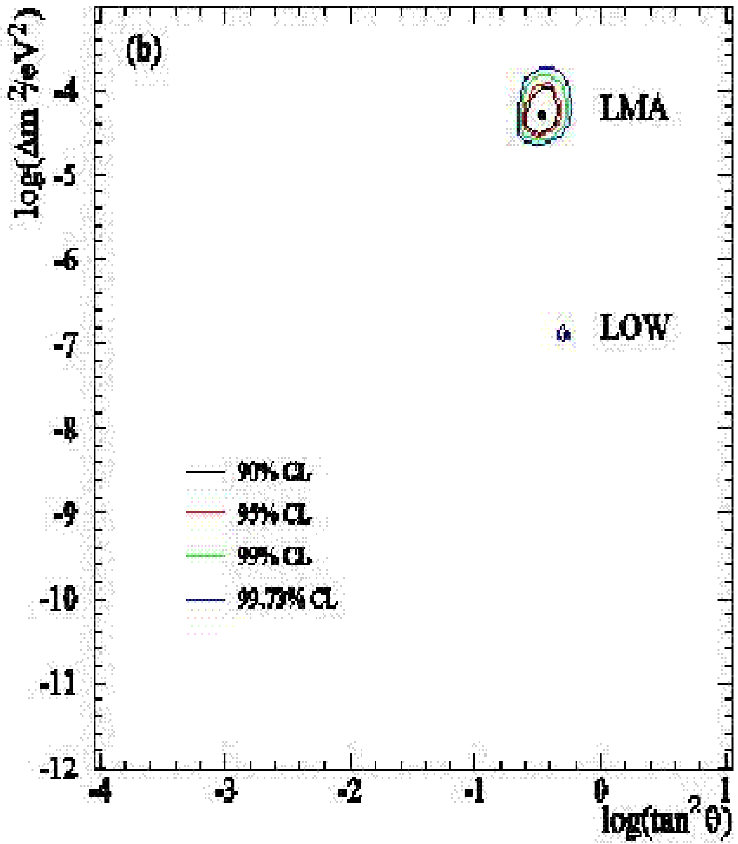
Physics Implication Flavor Content

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$



Strong evidence of flavor change

Combining All Experimental and Solar Model information

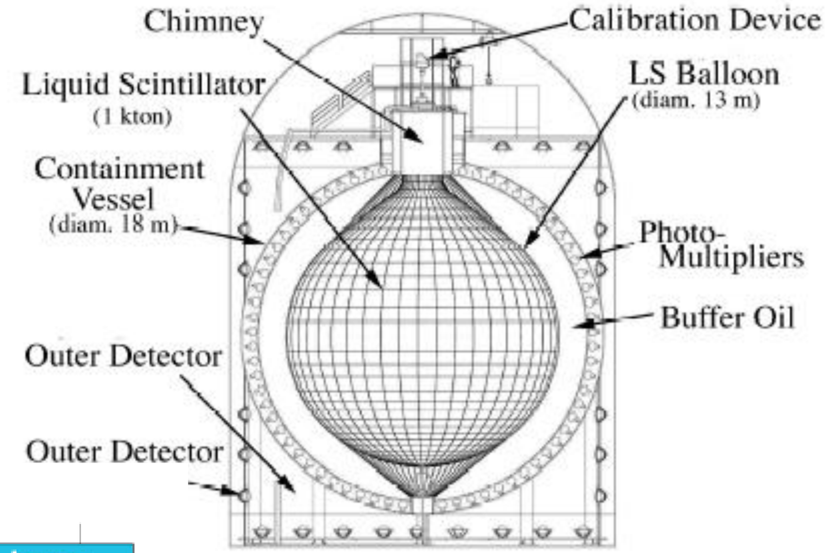


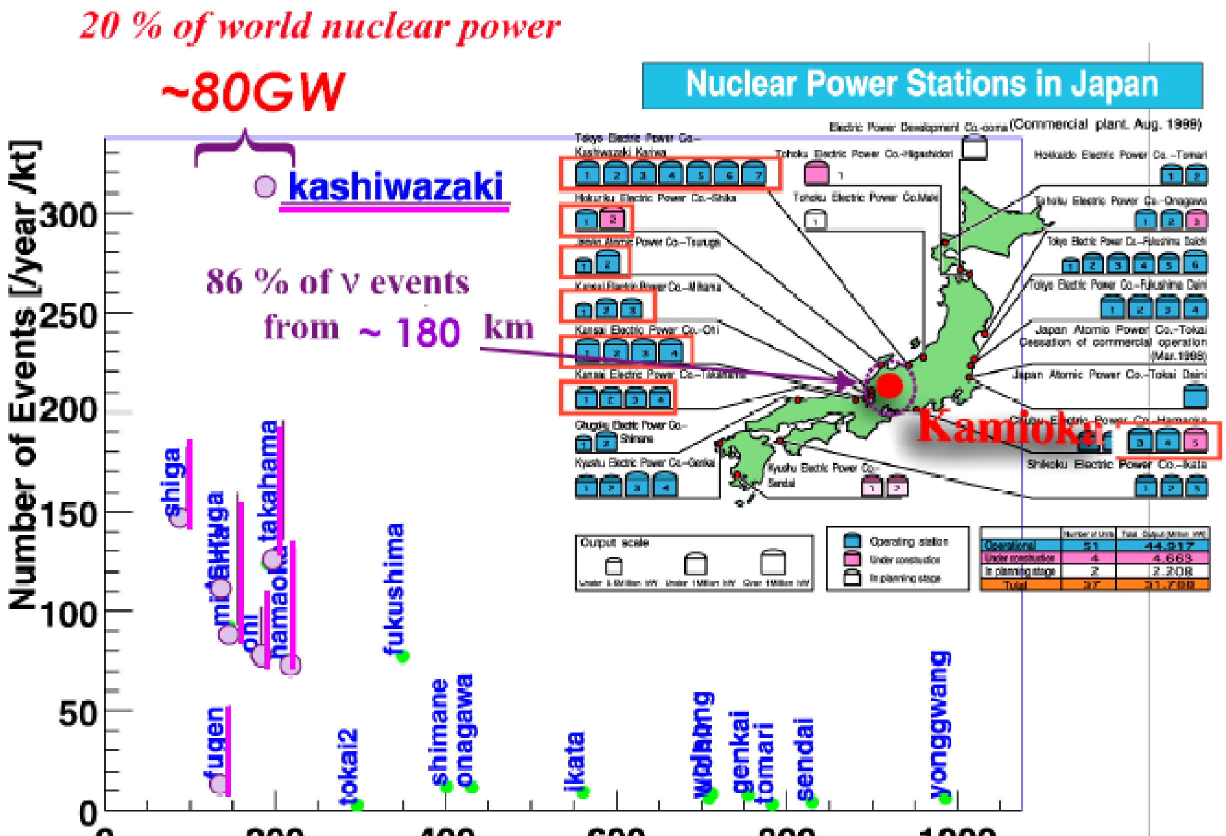
Charged current events are depleted (reaction involving electron neutrinos)

Neutral current reaction agrees with Solar Model (flavour blind)

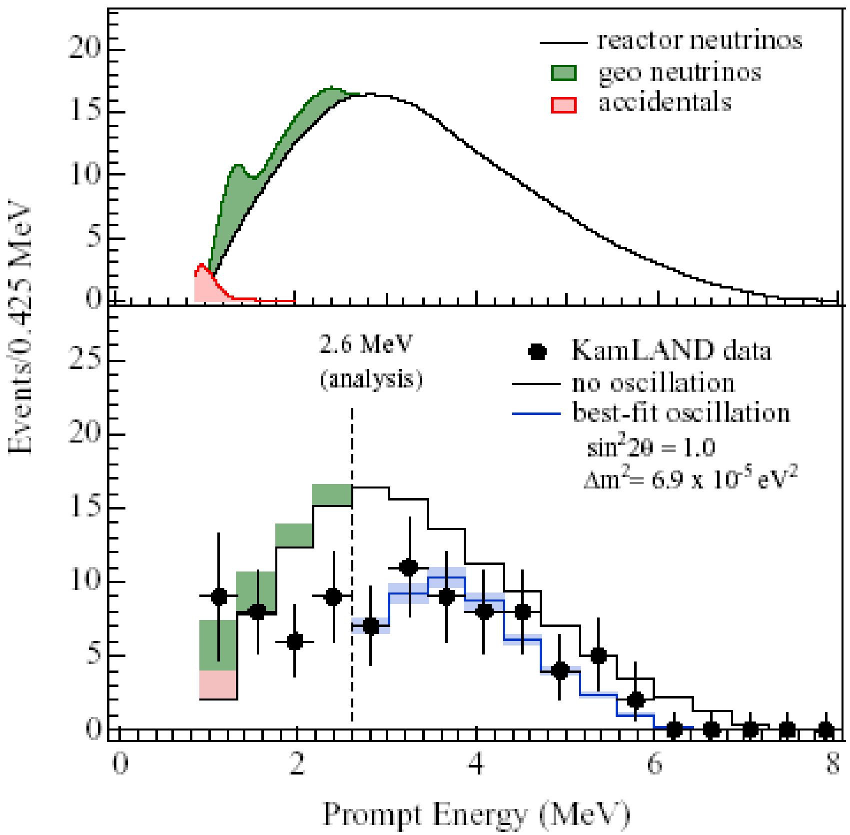
SSM is right, neutrinos oscillate!

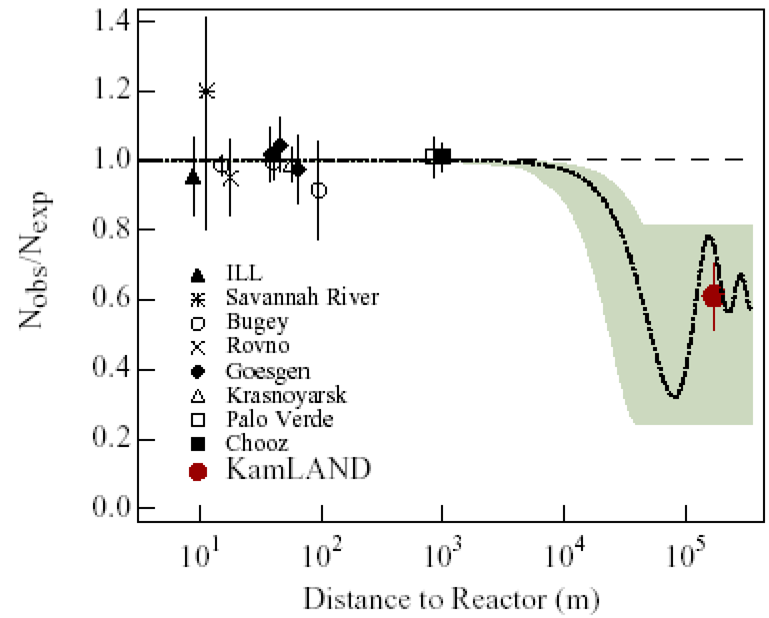
Kamland 2002

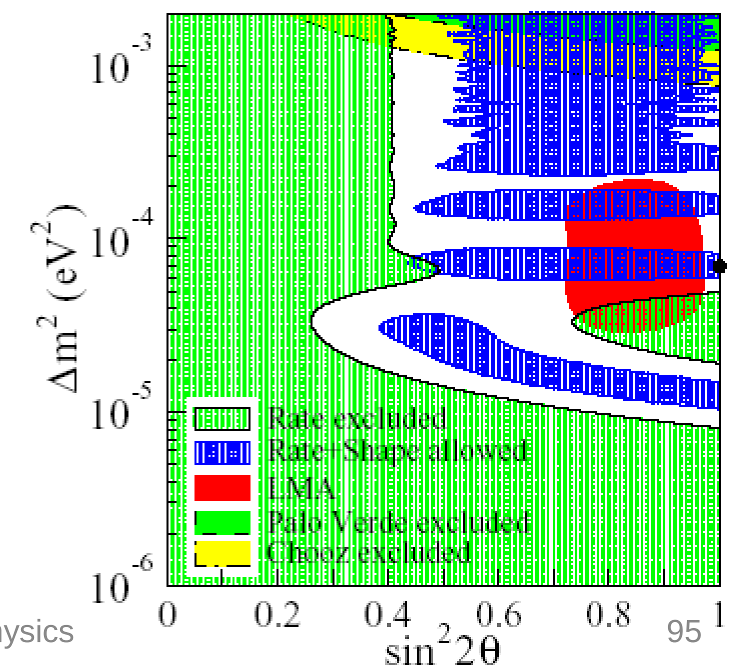




KamLAND: disappearance of antineutrinos from reactor
(few MeV at ~100 km)

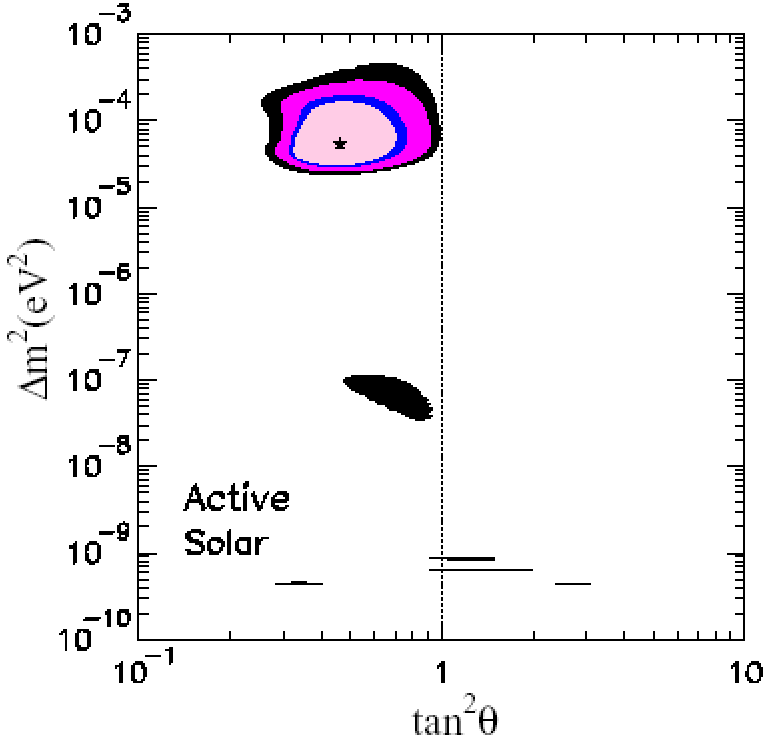




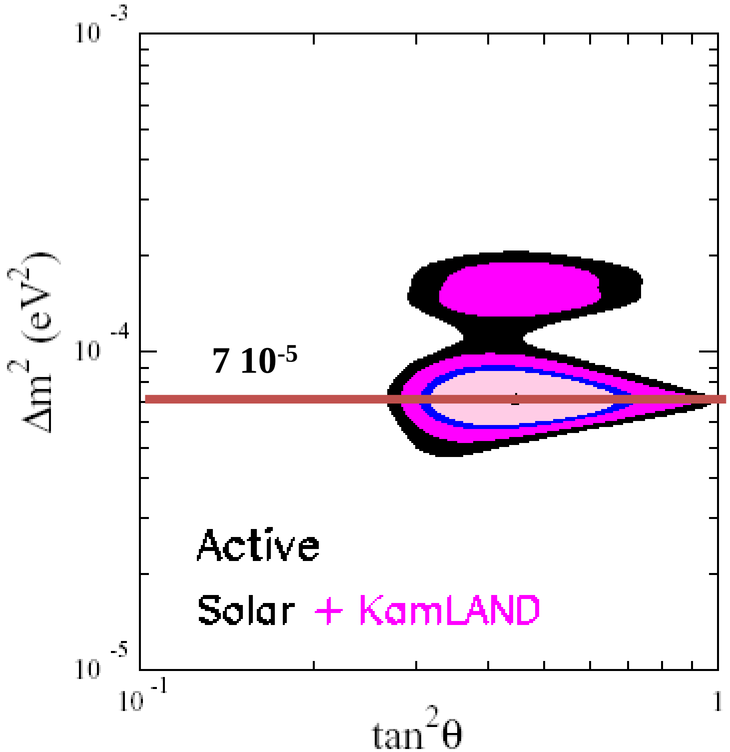


Prerequisite for CP violation in neutrinos: Solar LMA solution

Before KamLAND

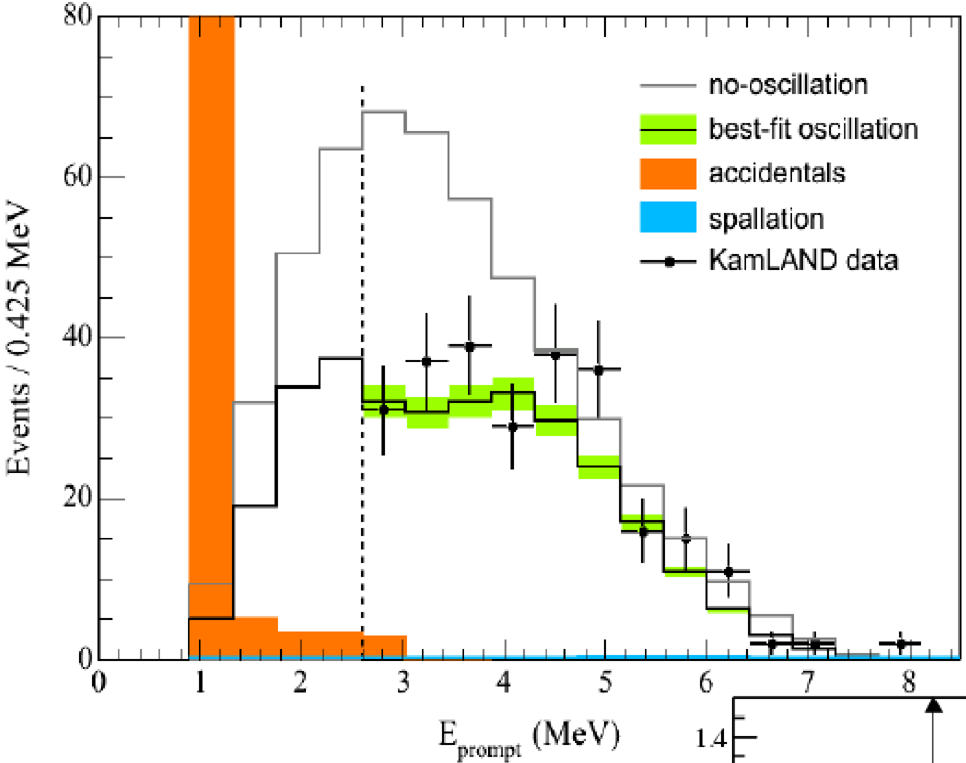


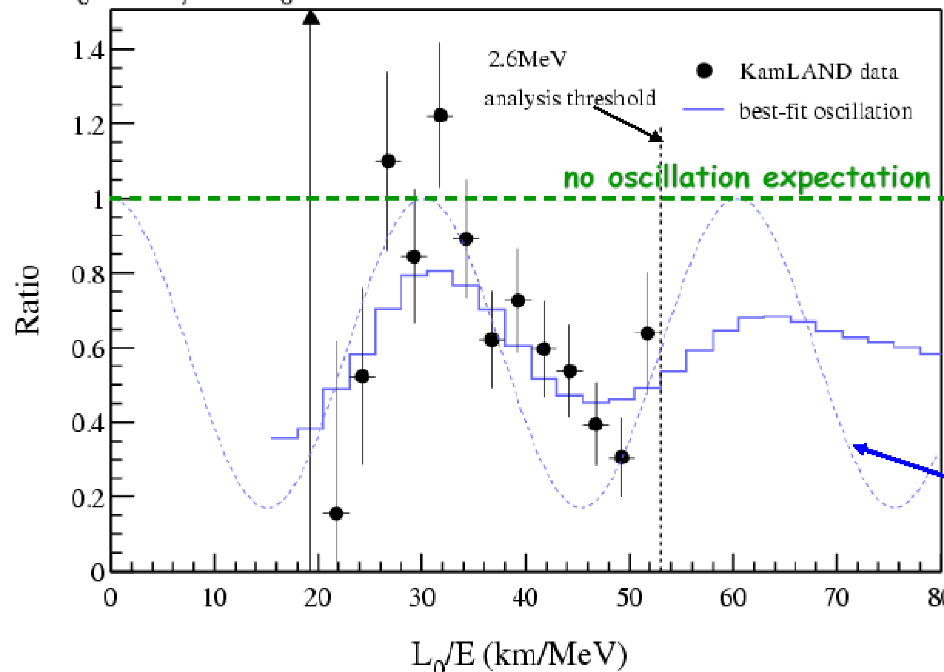
After KamLAND



This will be confirmed and Δm^2_{12} measured precisely by KAMLAND and maybe Borexino in next 2-4 yrs

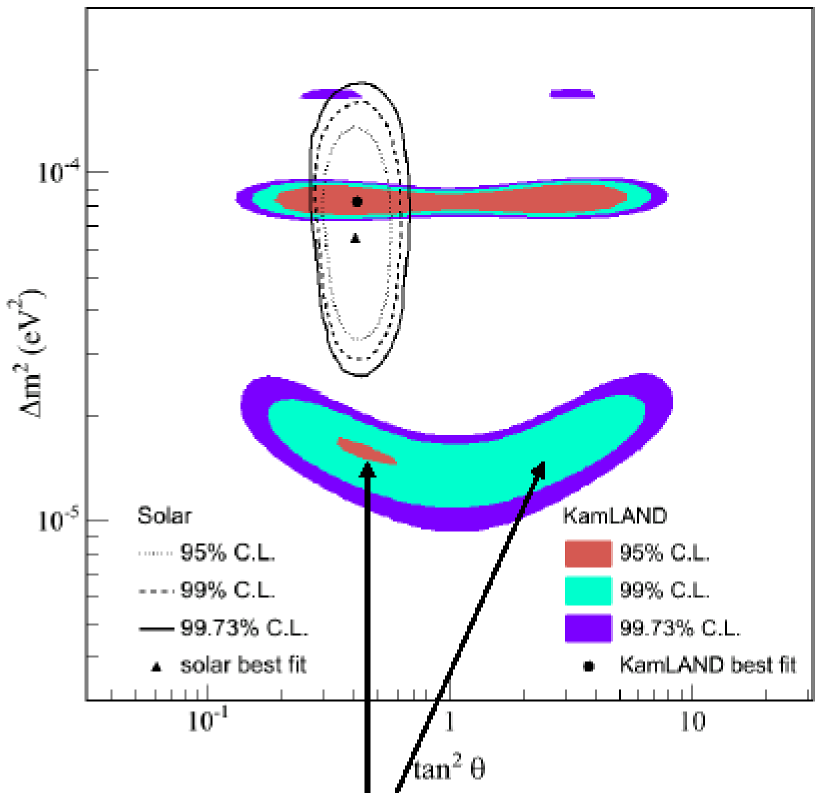
Kamland 2004





Hypothetical single 180km baseline experiment

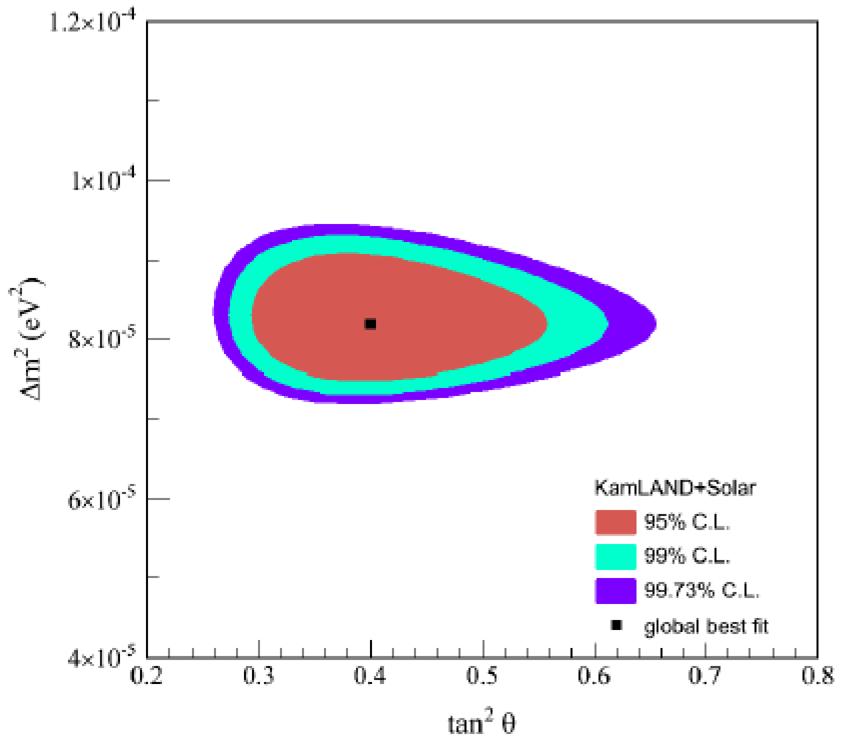
Kamland 2004



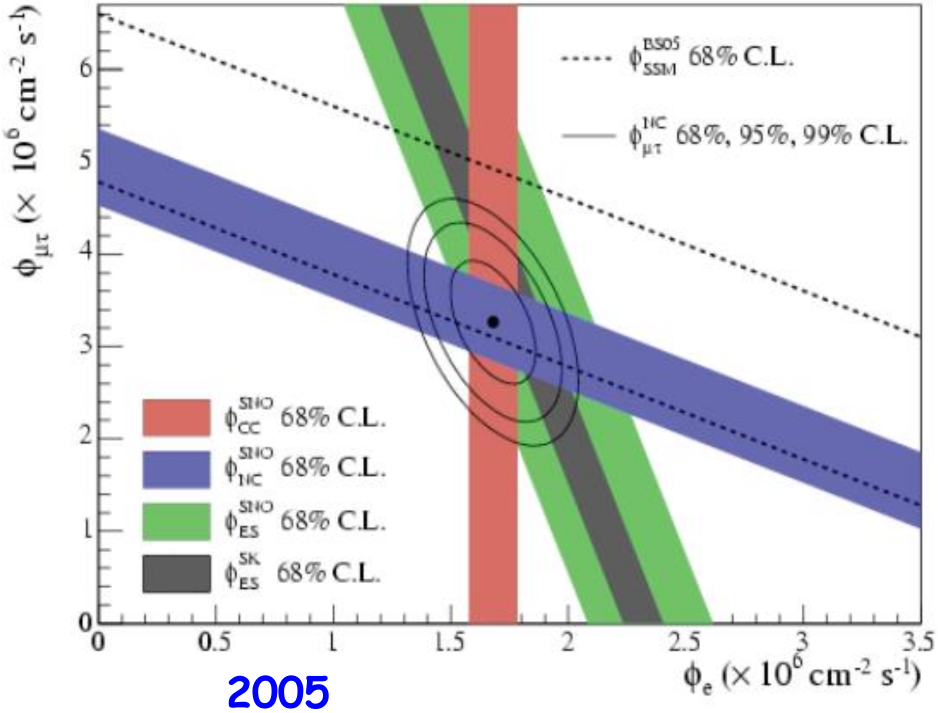
Includes (small) matter effects

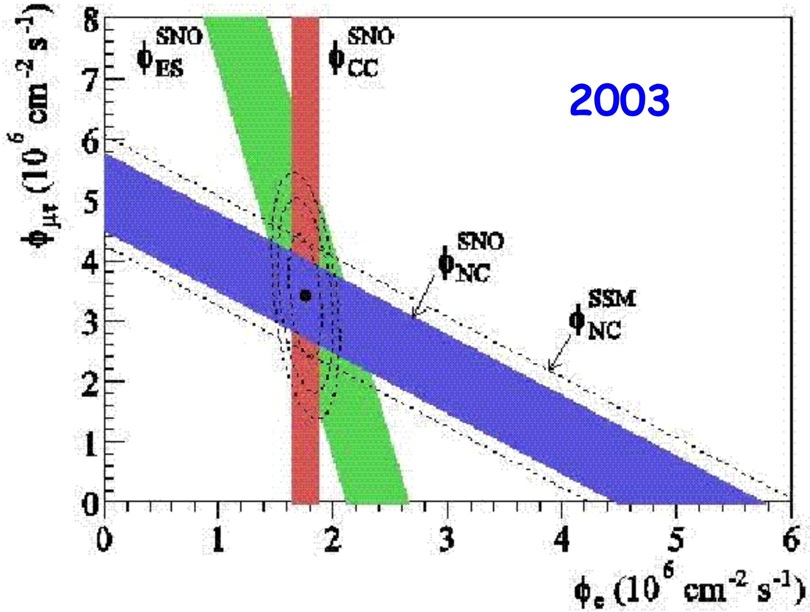
$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

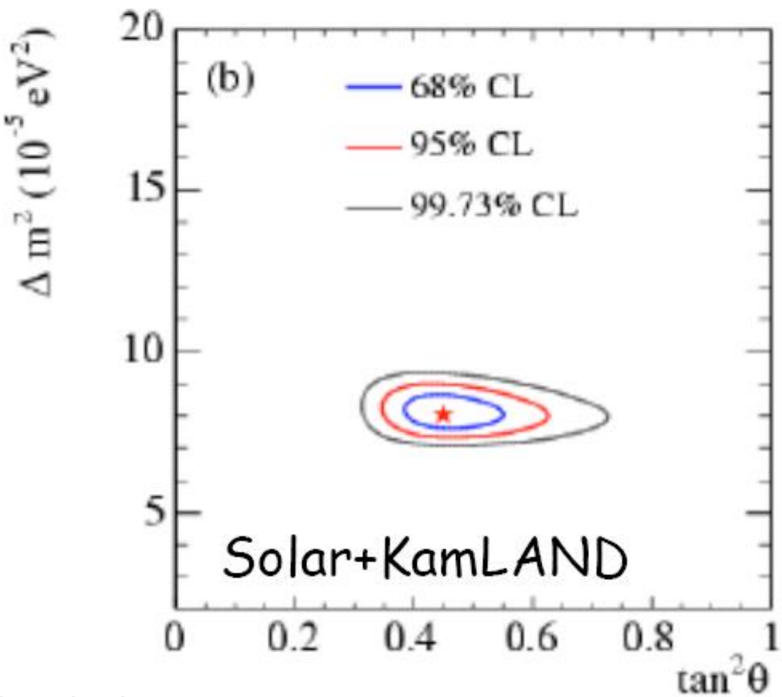
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Flavor content of solar flux.





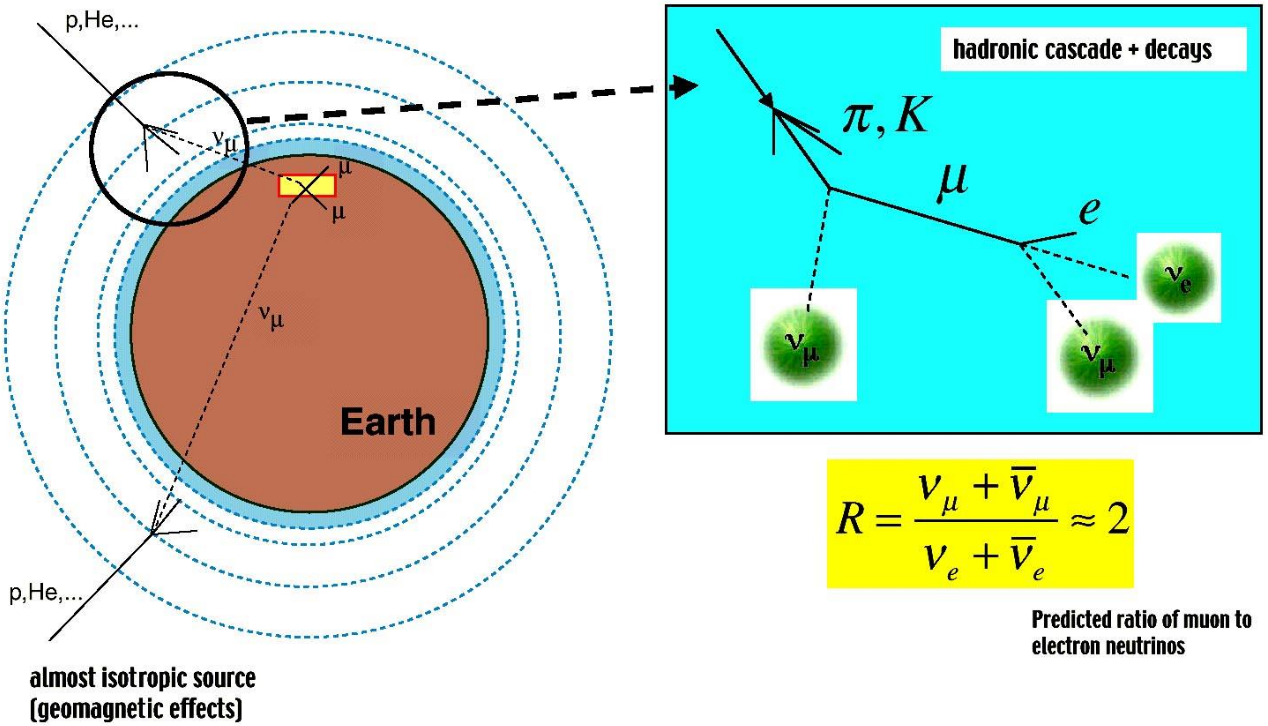


Solar oscillation parameters now at 10-20% precision.

(Maximal mixing excluded at >5 s)

Atmospheric Neutrinos

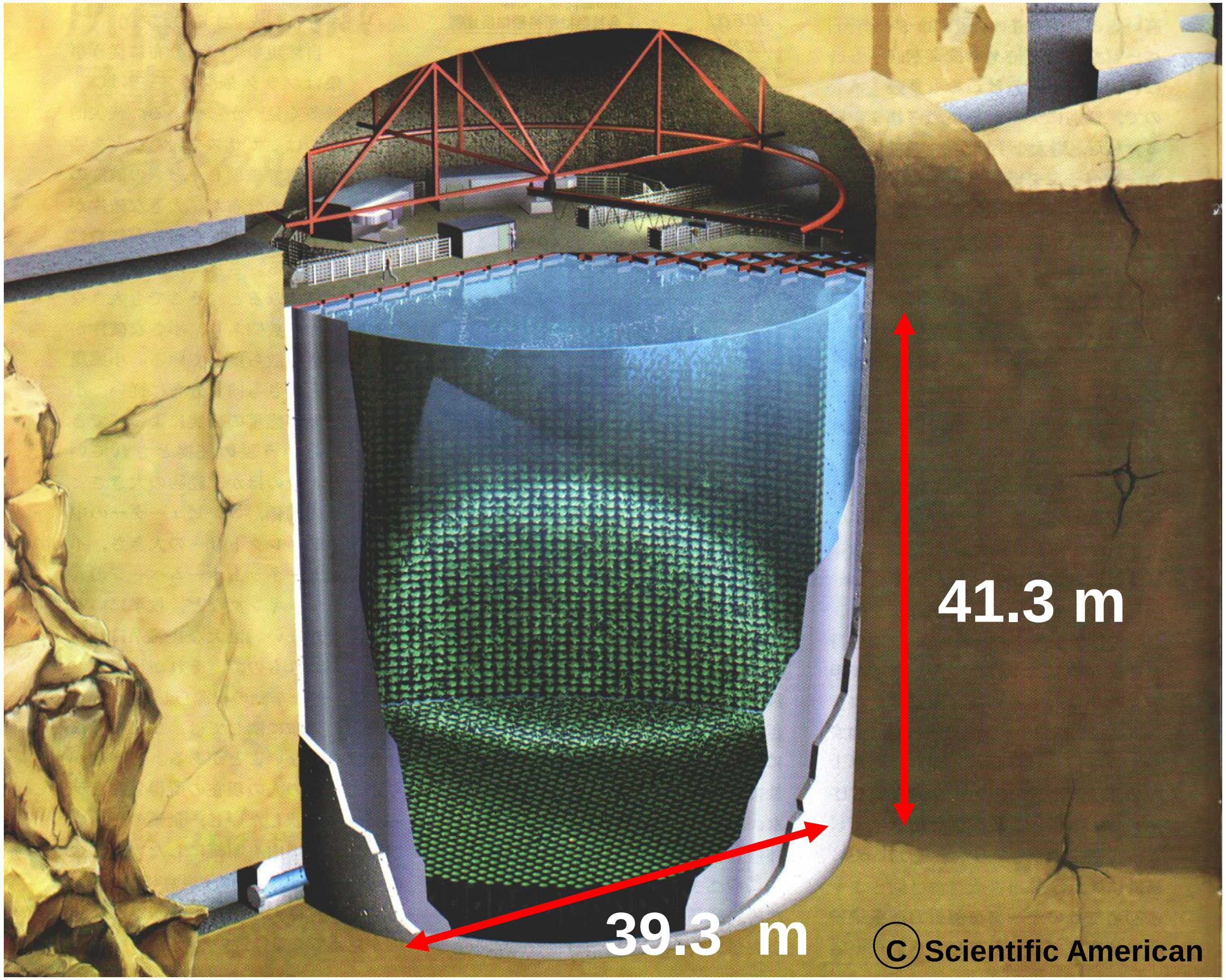
Path length from ~20km to 12700 km



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

Super-K detector



Water Cerenkov detector

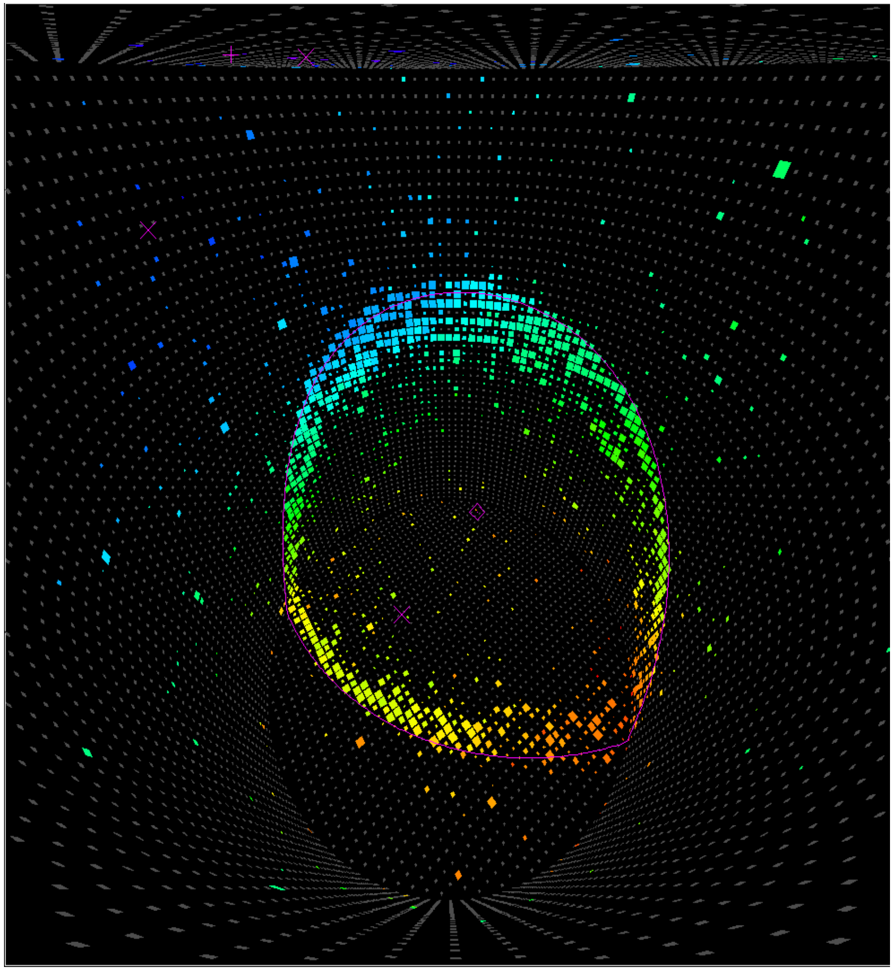
50000 tons of pure light water

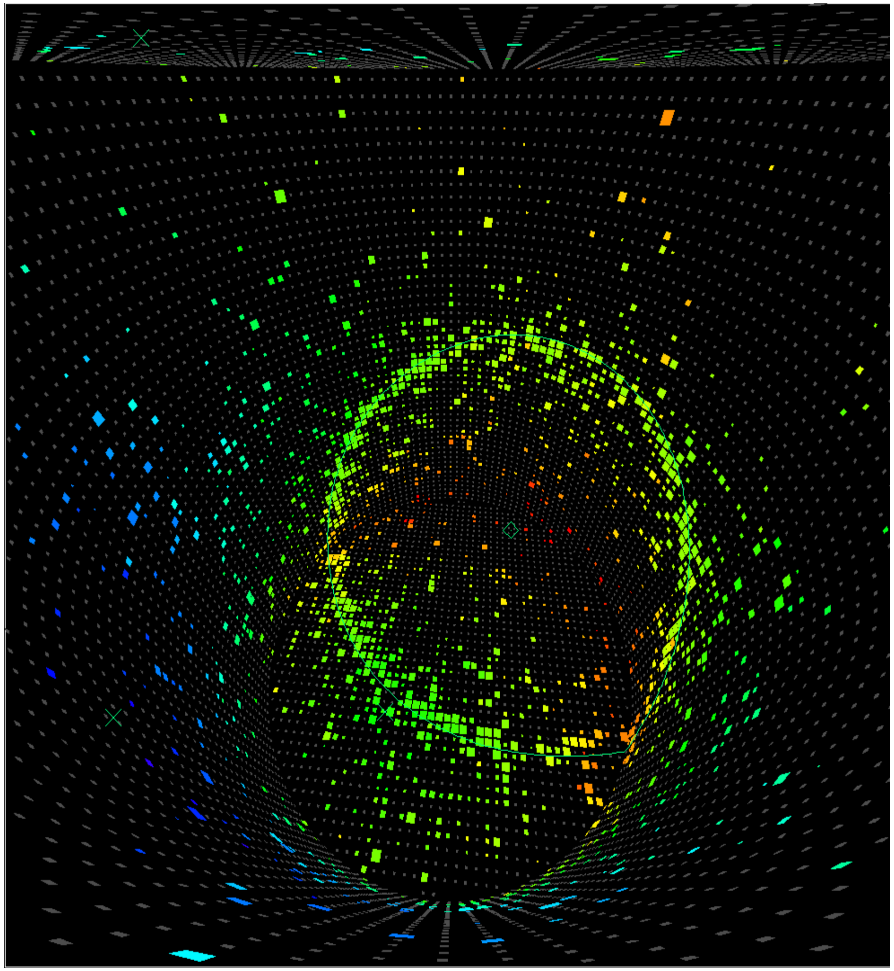
≈10000 PMTs

μ/e Background Rejection

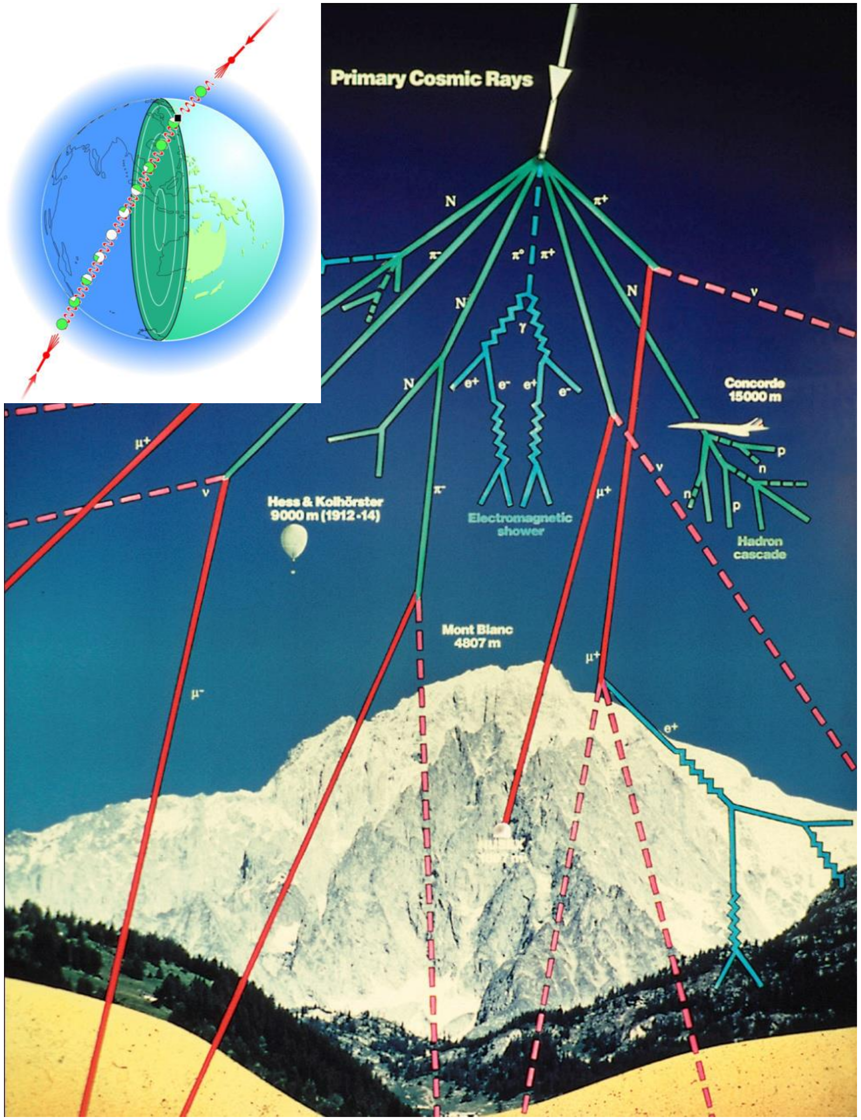
e/mu separation directly related to granularity of coverage.

Limit is around 10^{-3} (mu decay in flight) SKII coverage OKOK, less maybe possible



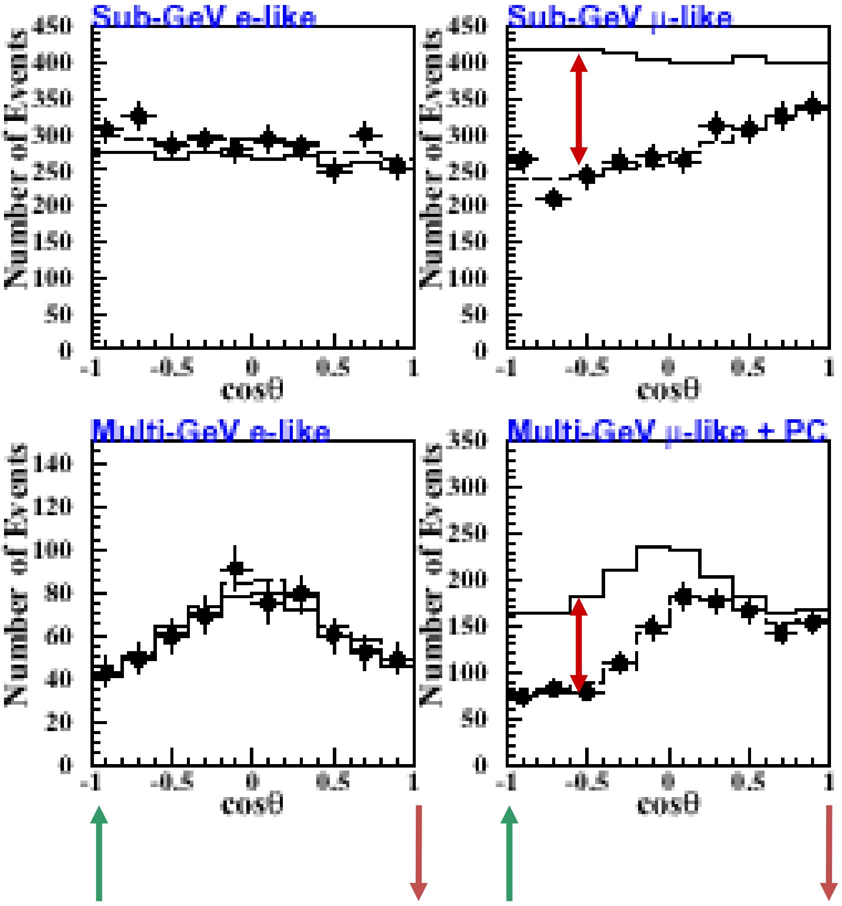


Atmospheric ν : up-down asymmetry



Super-K results

ν_e ν_μ

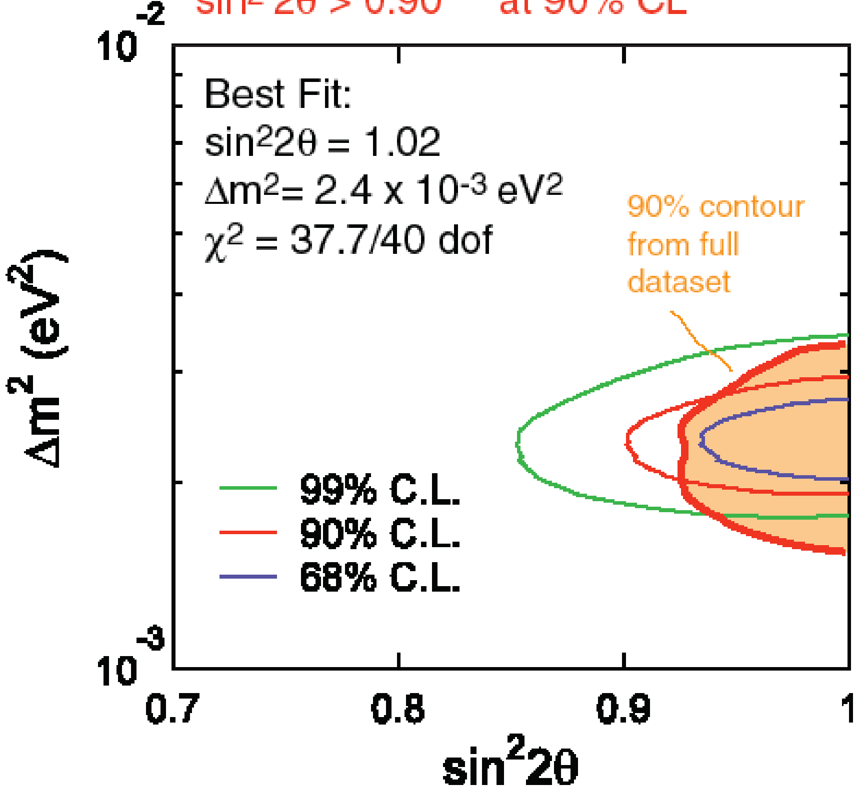


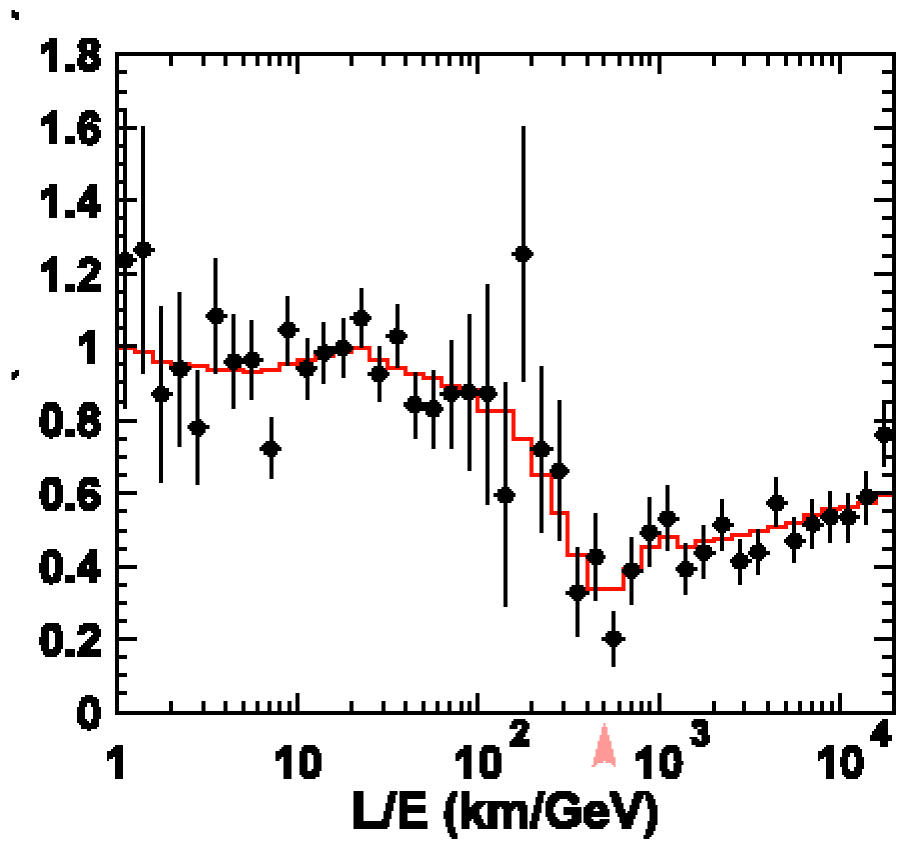
up down

Atmospheric Neutrinos

SuperKamiok

$1.9\times10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$
$\sin^2 2\theta > 0.90$ at 90% CL





General framework :

1. We know that there are three families of active, light neutrinos *(LEP)*
2. Solar neutrino oscillations are established *(Homestake+Gallium+Kam+SK+SNO)*
3. Atmospheric neutrino (ν_μ –>) oscillations are established *(IMB+Kam+SK+Macro+Sudan)*
4. At that frequency, (ν_μ –> ν_e) oscillations are small (5%) and have been observed (T2K, NOVA) and ν_e disappearance has been measured (Daya Bay, Reno, Double Chooz)

This allows a consistent picture with 3-family oscillations preferred:

LMA: $\theta_{12} \sim 30^0$ $\Delta m_{12}{}^2 \sim 8\ 10^{-5} eV^2$, $\theta_{23} \sim 45^0$ $\Delta m_{23}{}^2 \sim \pm 2.5\ 10^{-3} eV^2$, $\theta_{13} = 10^0$

Weak CP violation signal (2-3 sigma) from T2K, not confirmed by NOVA (yet)

=> an exciting experimental program for at least 15 years *)

including leptonic CP & T violations

5. There are phenomena possibly interpreted as higher frequency oscillation (LSND) and confirmed by miniBooNe.
This is not consistent with three families of neutrinos oscillating, and not supported by disappearance experiments. (Sterile neutrino, neutrino decay, photon production by NC?)
And recently completely disproven by microboone experiment at FERMILAB

*)to set the scale: CP violation in quarks was discovered in 1964
and there is still an important program (K0pi0, B-factories, Neutron EDM, BTeV, LHCb..)
to go on for 10 years…i.e. a total of ~50 yrs.
and we have not discovered leptonic CP yet!

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

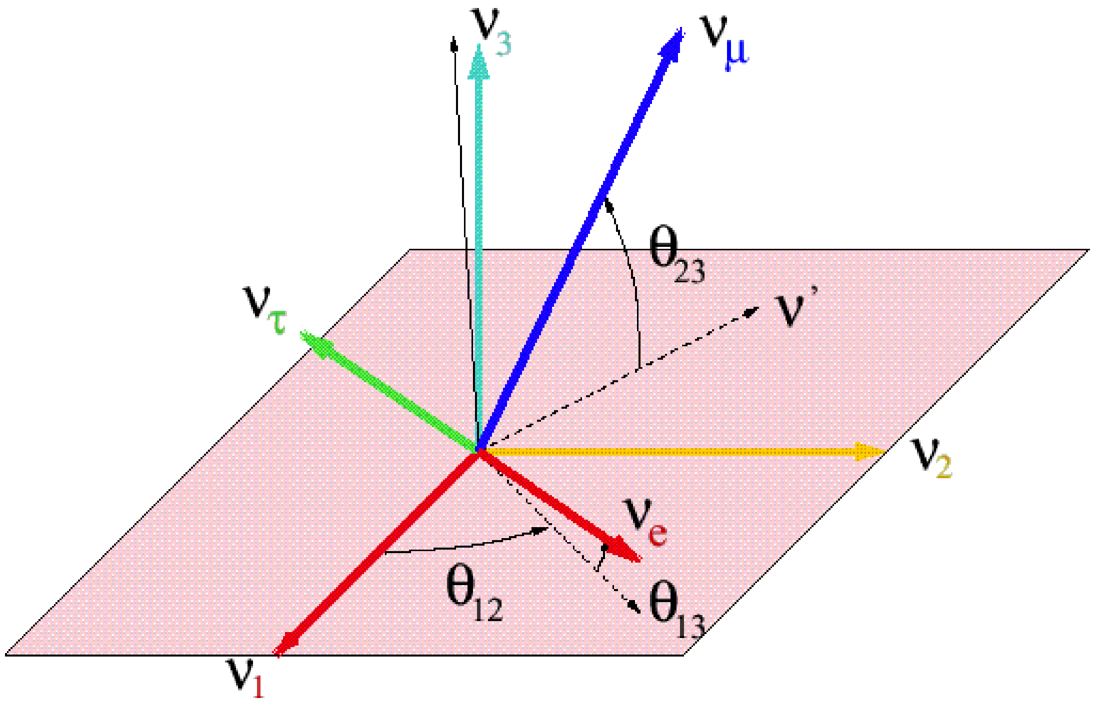
Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

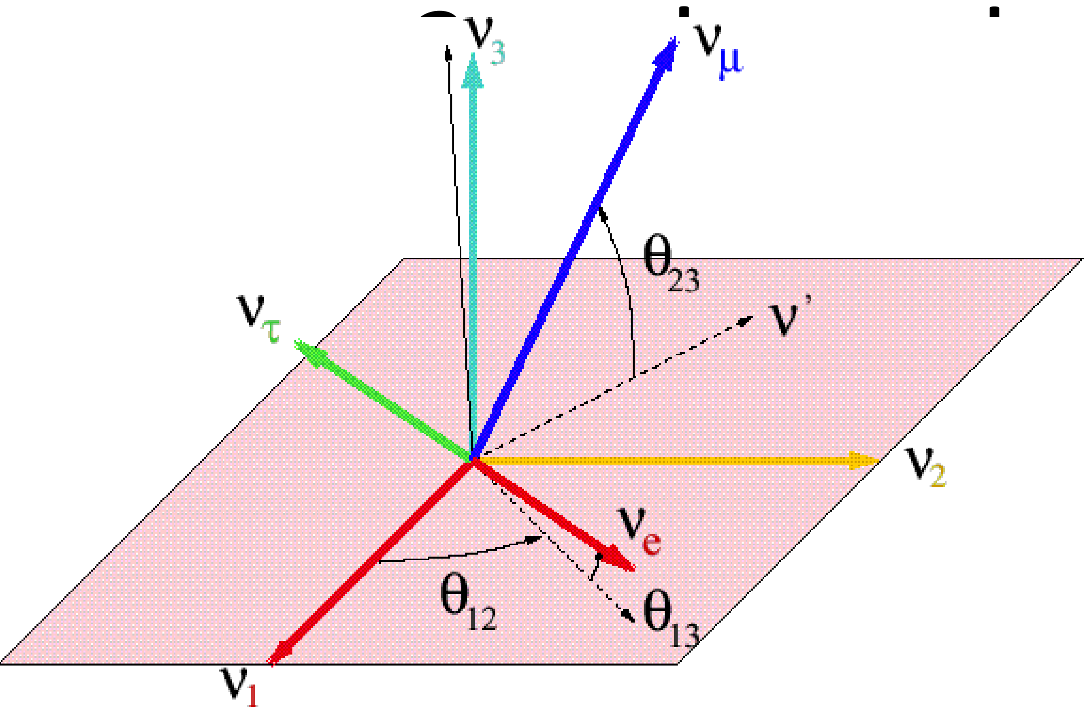
Q | Terms

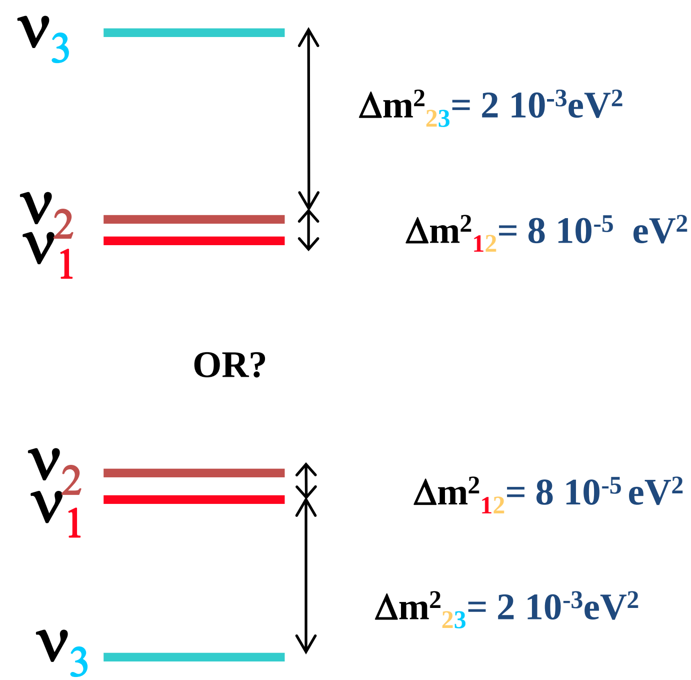


ν3
νμ
θ23
ντ
ν'
ν2
νe
θ12
θ13
ν1

The neutrino mixing matrix:

phase δ



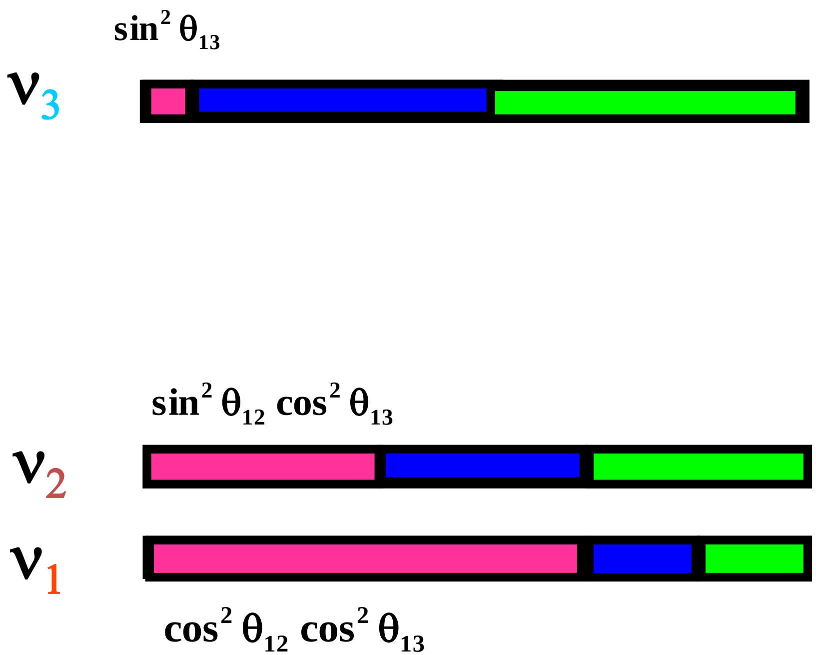


θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 32^0, θ_{13} (Chooz) < 13^0

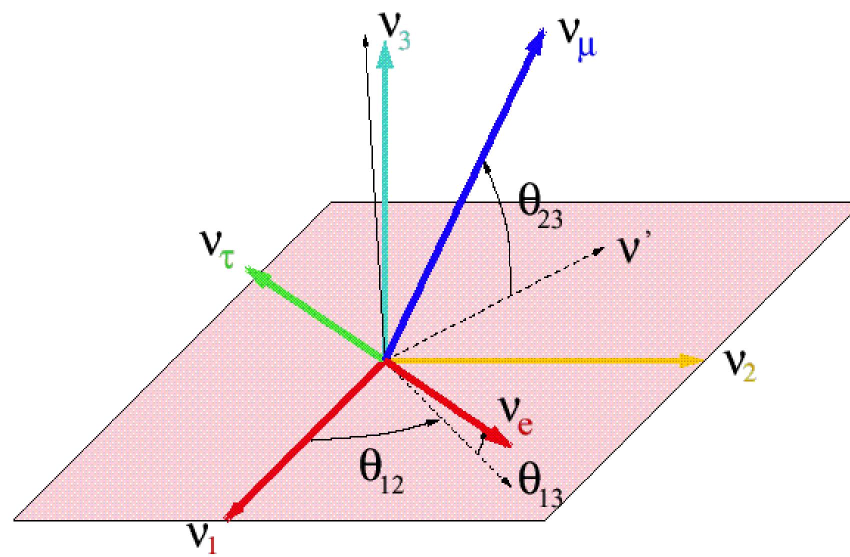
$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known now
phase δ, sign of Δm^2_{13}

neutrino mixing (LMA, natural hierarchy)



m^2_ν



$$U_{MNS}: \begin{pmatrix} \sim\frac{\sqrt{2}}{2} & \sim-\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim-\frac{\sqrt{2}}{2} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim\frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

with a small admixture of ν_3

food for thought:

what result would one get if one measured the mass of a ν_e (in K-capture for instance)?

what result would one get if one measured the mass of a ν_μ (in pion decay)?

Is energy conserved when neutrinos oscillate?

Why do neutrinos oscillate and quarks do not?

food for thought: (simple)

what result would one get if one measured the mass of a ν_e (in K-capture for instance)?

what result would one get if one measured the mass of a ν_μ (in pion decay)?

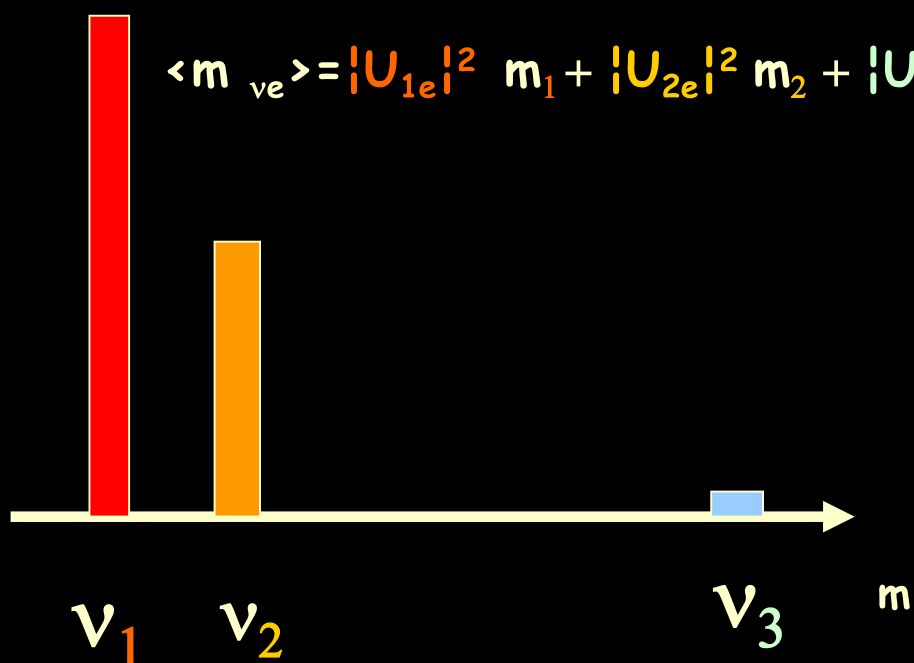
Is energy conserved when neutrinos oscillate?

ν_e

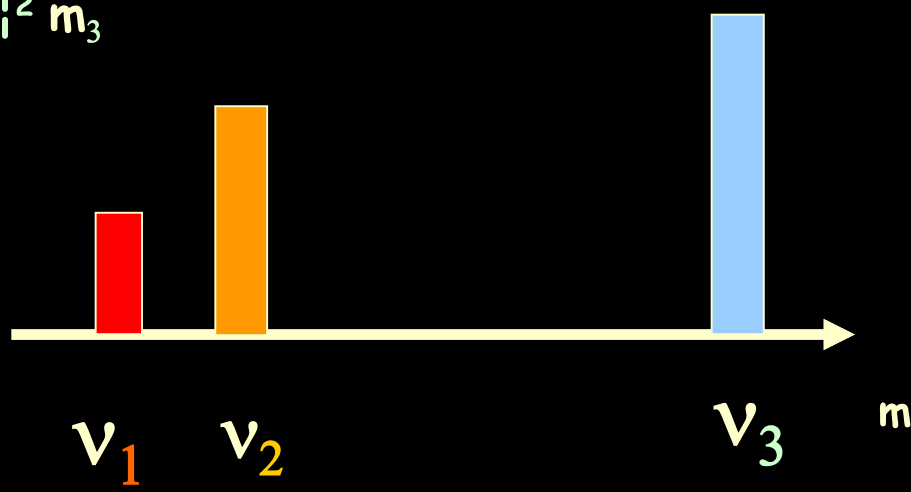
would measure a distribution with three values of mass with the following probabilities

$|U_{1e}|^2$ $|U_{2e}|^2$ $|U_{3e}|^2$

$$\langle m_{\nu e} \rangle = |U_{1e}|^2\, m_1 + |U_{2e}|^2\, m_2 + |U_{3e}|^2\, m_3$$



ν_μ



Is energy conserved when neutrinos oscillate?

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = U_{1e}\,|\nu_1\rangle\ \exp(\,i\,E_1\,t) + U_{2e}\,|\nu_2\rangle\ \exp(\,i\,E_2\,t) + U_{3e}\,|\nu_3\rangle\ \exp(\,i\,E_3\,t)$$

$P(\nu_1) = |U_{1e}|^2$

$P(\nu_2) = |U_{2e}|^2$

$P(\nu_3) = |U_{3e}|^2$

are conserved during propagation

Why do neutrinos oscillate?

take $\pi \to \mu\nu$ decay $M=m_\pi$ $m_1=m_\mu$ $m_2=m_\nu$

muon momentum:

$$\frac{p}{c} = \frac{M^2 - m_1^2 - m_2^2}{2M}$$

variation of muon momentum upon neutrino mass and mass differences

$$\frac{\delta p_\mu}{c} = \left(\frac{p_\mu}{c}\right)_{m_\nu=0} - \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0} \quad , \quad \frac{\delta' p_\mu}{c} = \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0} - \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0'}$$

$$\frac{\delta p_\mu}{c} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} - \frac{m_\pi^2 - m_\mu^2 - m_0^2}{2m_\pi} = \frac{m_0^2}{2m_\pi}$$

$$1.4 \times 10^{-14}\ \mathrm{MeV/c}$$

for $m_\nu = 2\mathrm{eV/c}^2$

$$\frac{\delta' p_\mu}{c} = \frac{m_\pi^2 - m_\mu^2 - m_0^2}{2m_\pi} - \frac{m_\pi^2 - m_\mu^2 - m_0'^2}{2m_\pi} = -\frac{\Delta m^2}{2m_\pi}$$

$$8.9 \times 10^{-18}\ \mathrm{MeV/c}$$

for $\Delta m^2_\nu = 2\ 10^{-3}(\mathrm{eV/c}^2)^2$

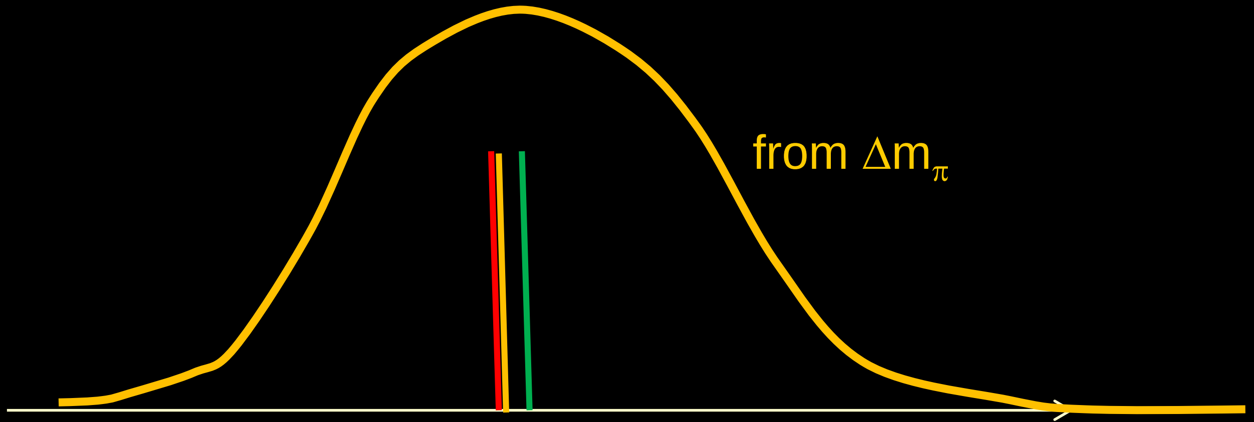
However we need to take into account the width of the pion since it decays with a life time of 26ns or $c\tau$=7.8m (hbar.c = 200 MeV.fm)

Δm_π = hbar/τ ~4 10^{-14} MeV/c^2 ➔ Δp_μ ~ 3 10^{-14} MeV/c (verify)

➔ the uncertainty due to the pion decay width is much larger than the difference in momentum between the neutrino mass eigenstates.

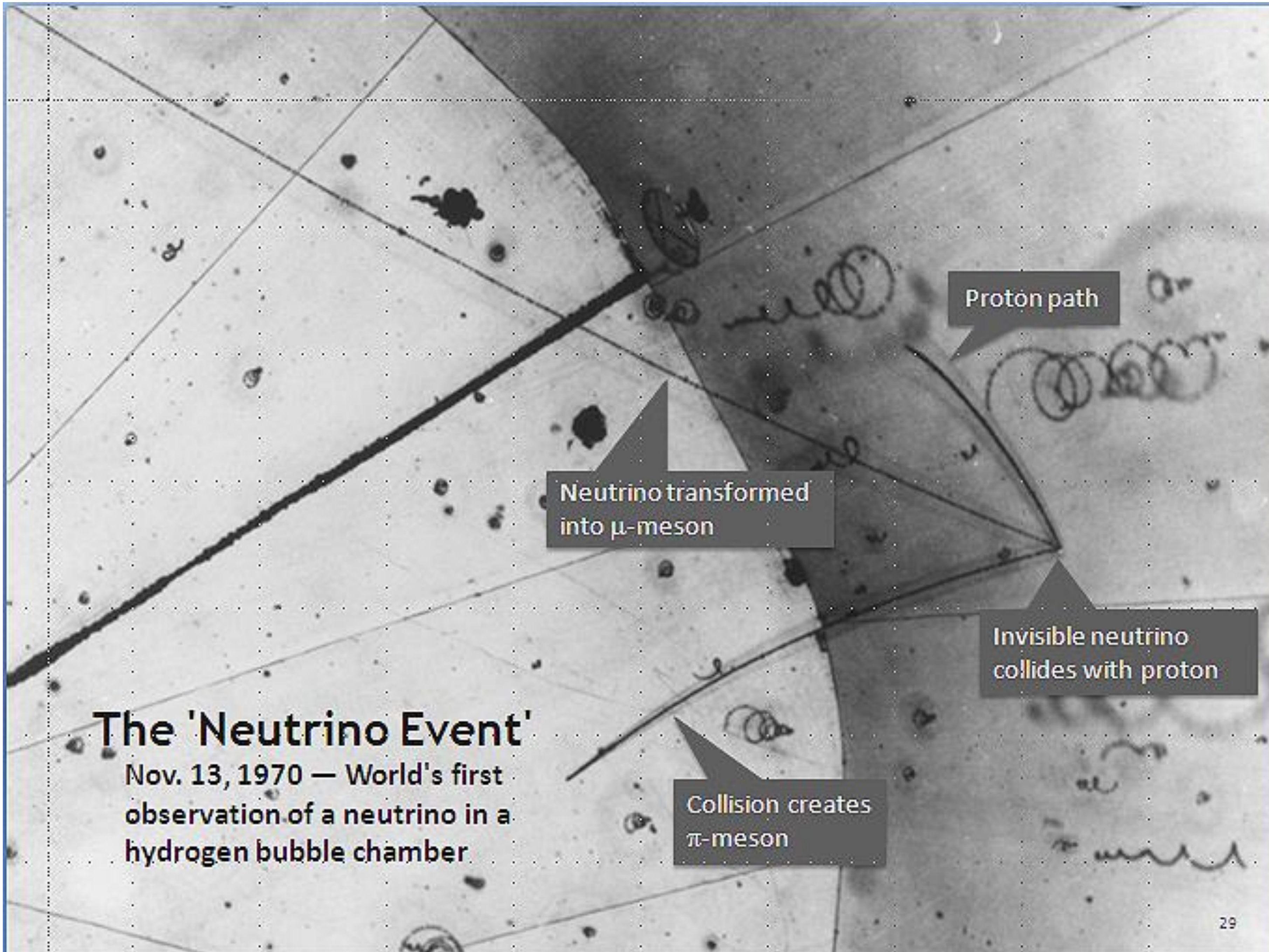
This is the same relationship that ensures that interference happens between light coming from different holes. (can't tell which hole the light went through)

Neutrinos oscillate for the fundamental quantum reason that the width of the decaying parent makes it impossible to tell the neutrino species by measuring its mass from kinematics.



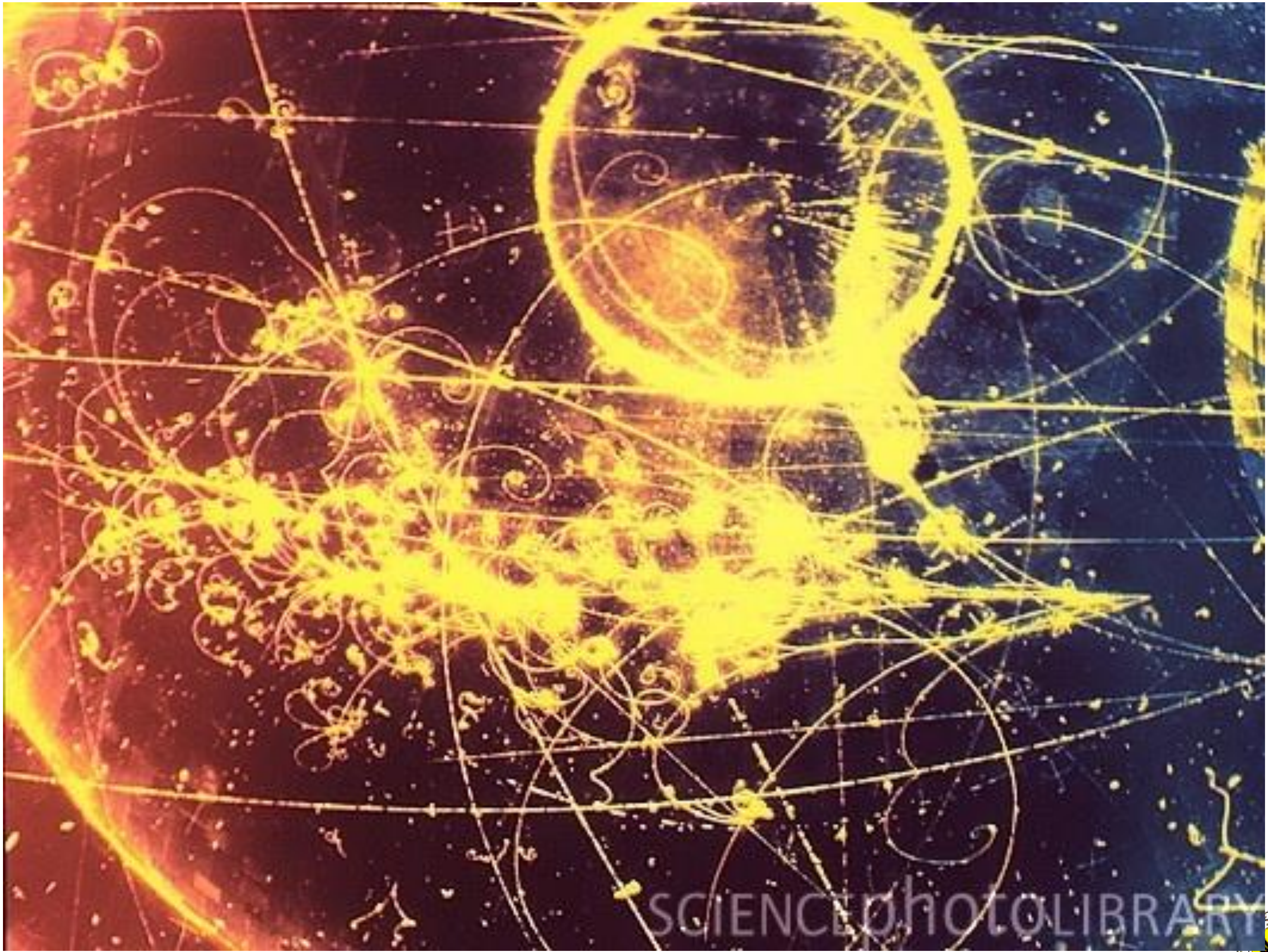
much amplified: the central value of $p_\mu(\nu 1)$, $p_\mu(\nu 2)$, $p_\mu(\nu 3)$ distribution

Neutrino Interactions



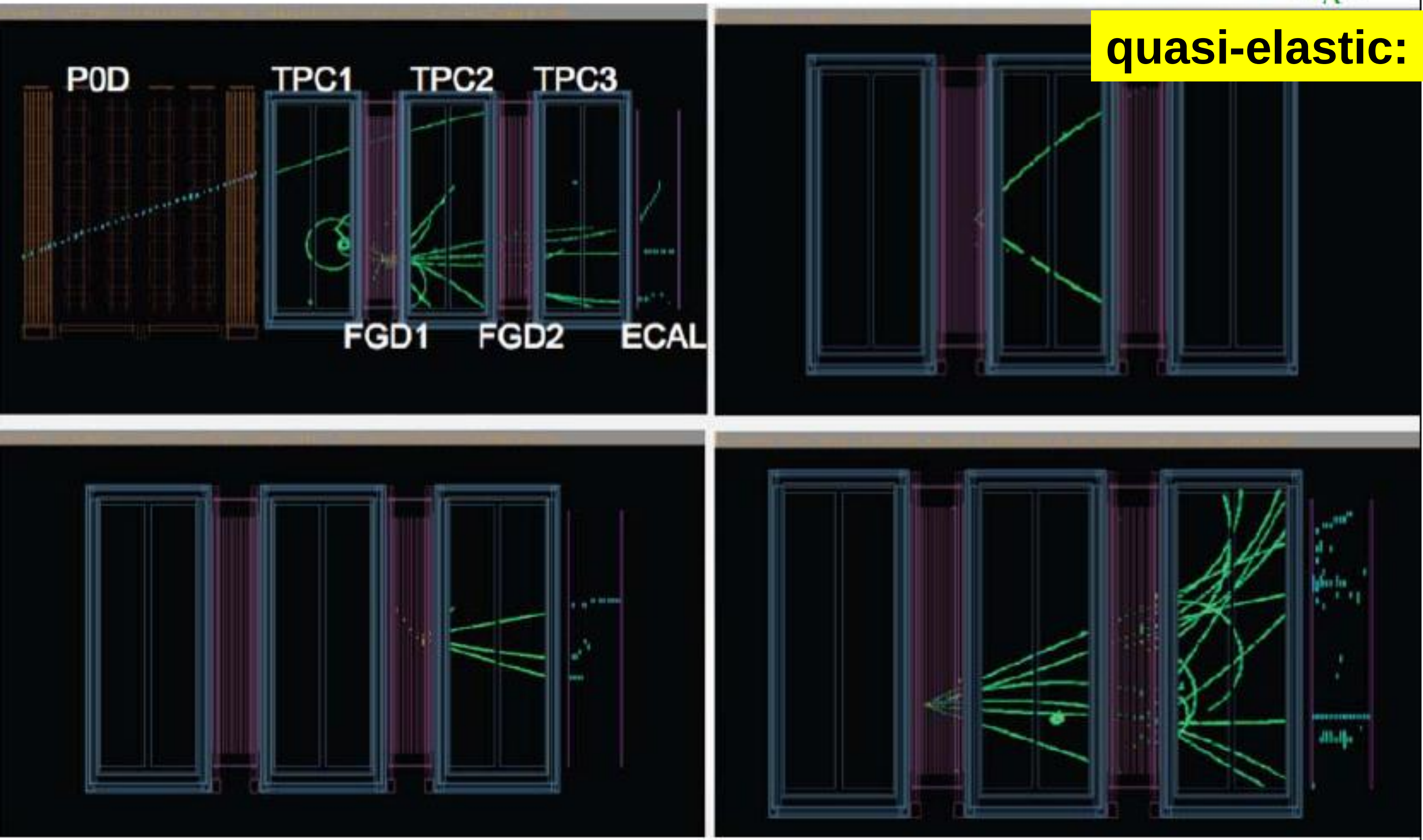
The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber



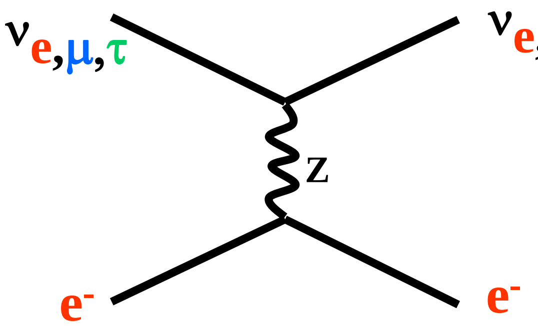
SCIENCEPHOTOLIBRARY

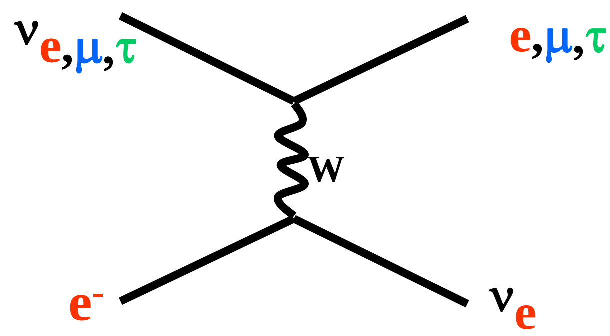
ND280 off-axis neutrino events



Neutrino cross-sections

at all energies NC reactions (Z exchange) are possible for all neutrinos





CC reactions

very low energies(E<~50 MeV): $\nu_e + {}_A^{Z}N \to e^- + {}_A^{Z+1}N$ **inverse beta decay of nuclei**

$\bar{\nu}_e + {}_A^{Z}N \to e^+ + {}_A^{Z-1}N$

medium energy (50<E<700 MeV) quasi elastic reaction on protons or neutrons

$\nu_e + n \to e^- + p$

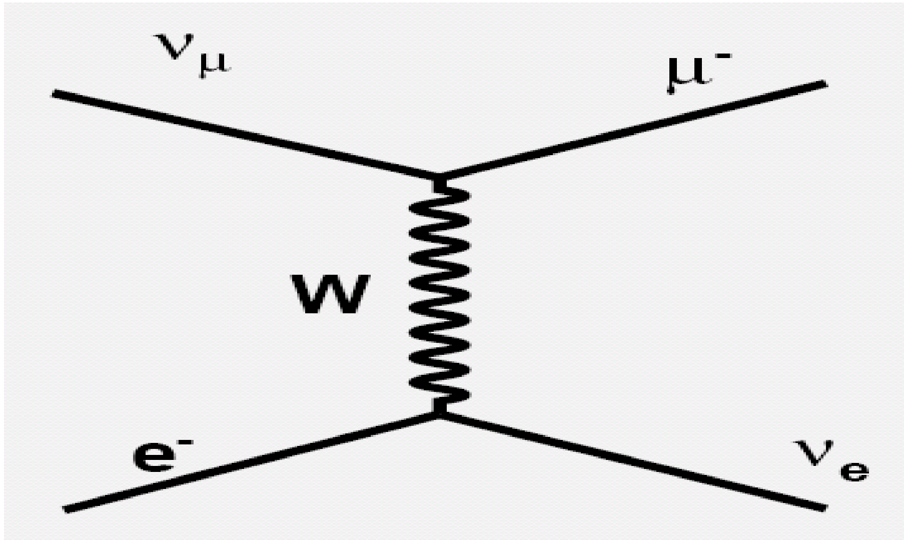
or

$\bar{\nu}_e + p \to e^+ + n$

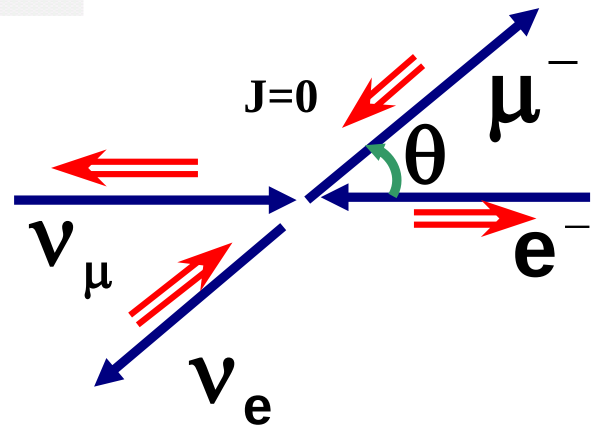
Threshold for muon reaction 110 MeV
Threshold for tau reaction 3.5 GeV

above 700 MeV pion production becomes abundant and
above a few GeV inelastic (diffusion on quark folloed by fragmentation) dominates

Quasielastic scattering off electrons ("Leptons and quarks" L.B.Okun)



$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



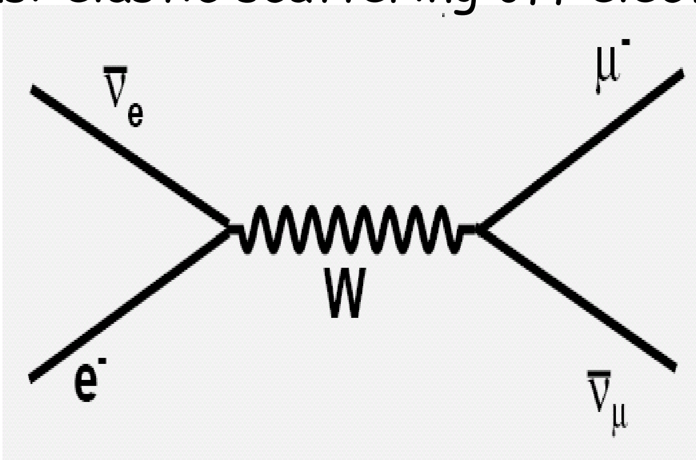
J=0 ==> Cross section is isotropic in c.m. system

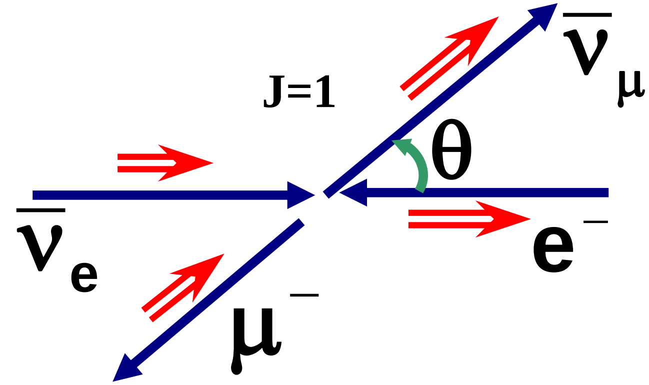
$$\sigma = \frac{G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2}{s}$$

high energy limit
(neglect muon mass)

$$\sigma = \frac{G_F^2}{\pi} s$$

Quasi-elastic scattering off electrons





$$\overline{\nu_e} + e^- \rightarrow \overline{\nu_\mu} + \mu^-$$

Differential cross section in c.m. system

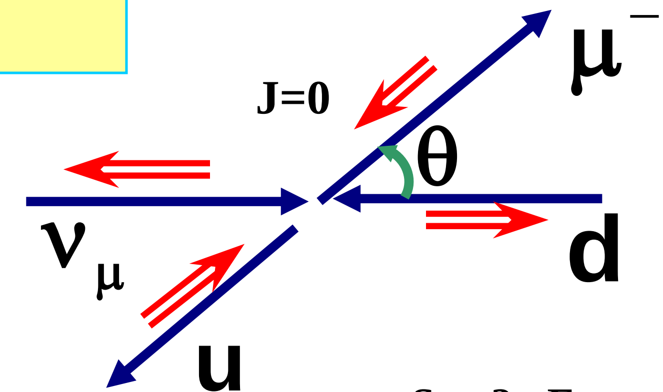
$$\frac{d\sigma}{d\cos\theta} = \frac{2G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2 E_e E_\mu}{s^2} \left(1 + \frac{s - m_e^2}{s + m_e^2} \cos\theta\right) \left(1 + \frac{s - m_\mu^2}{s + m_\mu^2} \cos\theta\right)$$

Total cross section

$$\sigma = \frac{2G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2 (E_e E_\mu + 1/3 E_{\nu 1} E_{\mu 2})}{s^2}$$

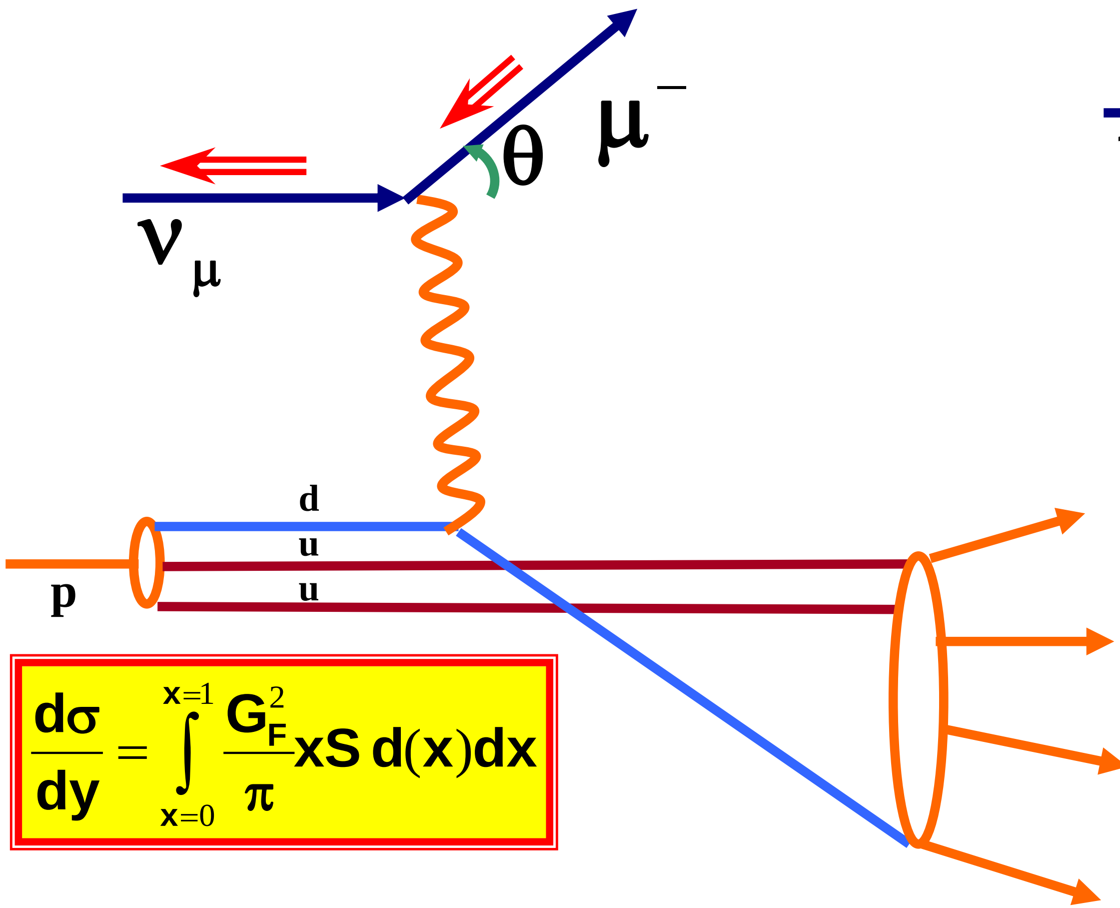
At high energies interactions on quarks dominate: DIS regime: neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
y= (1-cosθ)/2
for J=0 isotropic distribution
d(x)= probability density of quark d with mom. fraction x
<u>neglect all masses!</u>



$s = xS = 2mE_\nu x$

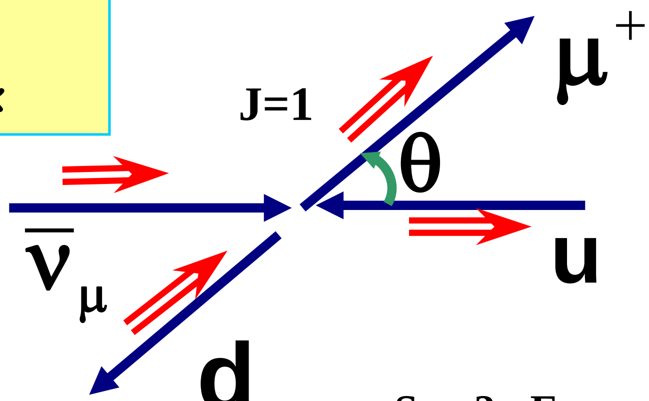
$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS$$



$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\, d(x)dx$$

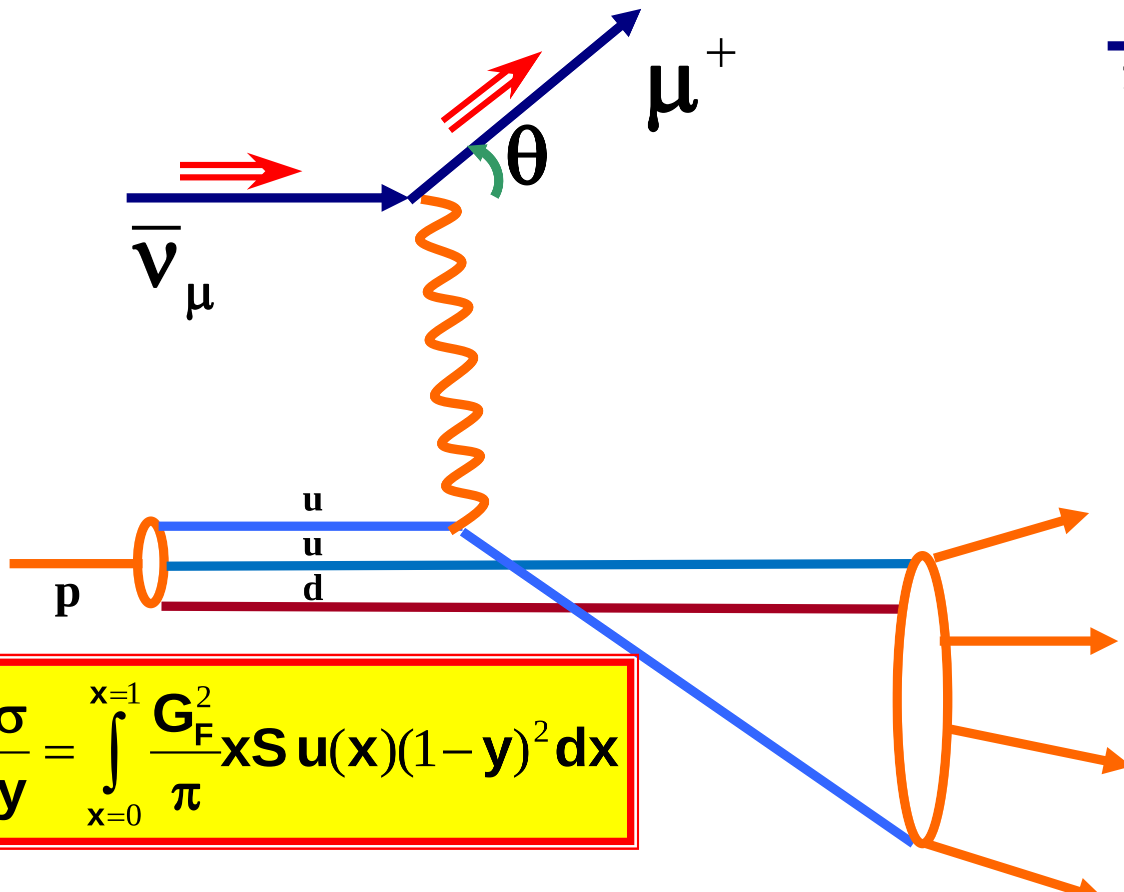
At high energies interactions on quarks dominate:
DIS regime: anti-neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
y= (1-cosθ)/2
for J=1 distribution prop. to $(1-y)^2$ (forward favored)
u(x)= probability density of quark u with mom. fraction x



$s = xS = 2mE_\nu x$

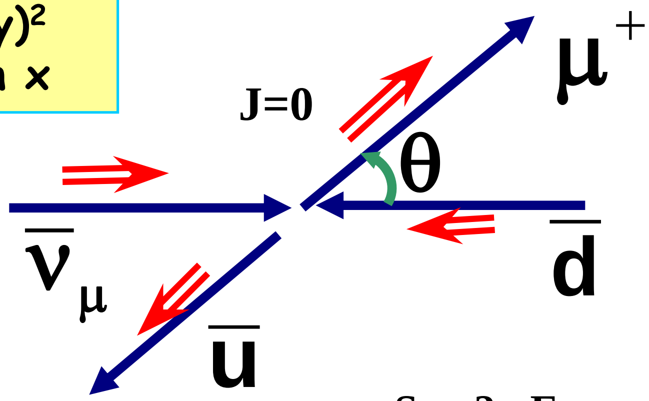
$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS\,(1-y)^2$$



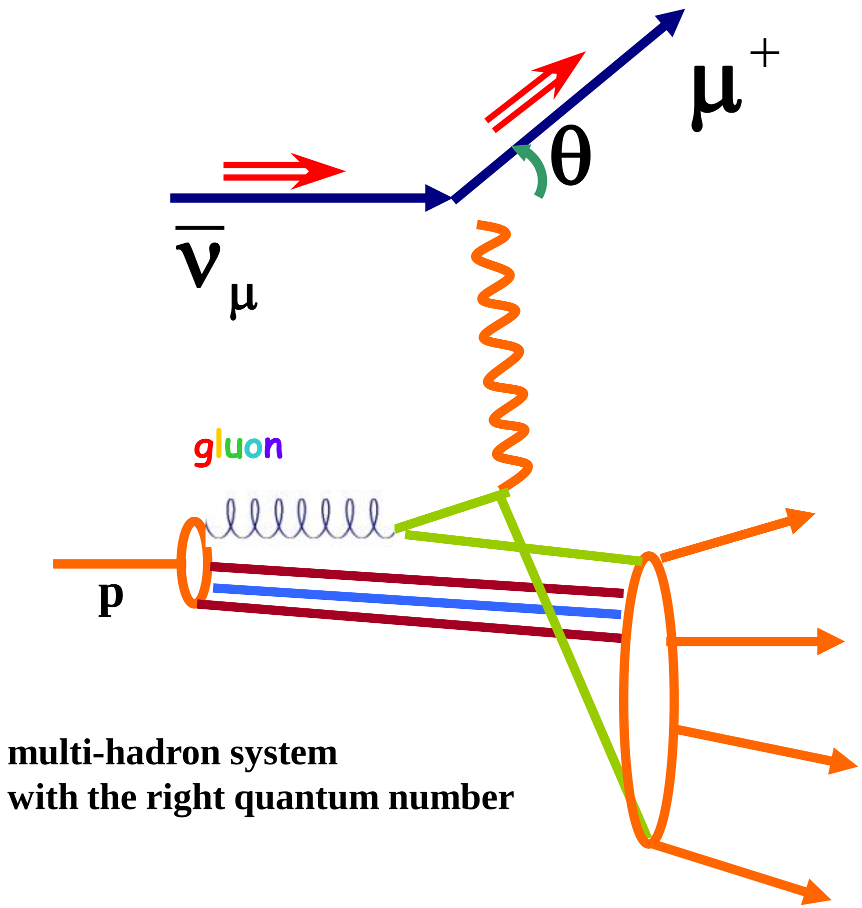
$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,u(x)(1-y)^2 dx$$

there are also (gluons) and anti-quarks at low x (sea)
(anti)neutrinos on sea-(anti)quarks

for J=0 (neutrino+quarks or antineutrino+antiquarks) isotropic
for J=1 (neutrino+antiquarks or antineutrino+quarks) $(1-y)^2$
$q_i(x)$, = probability density of quark u with mom. fraction x



$s = xS = 2mE_\nu x$



$$\frac{d\sigma^{\nu}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,(\bar{q}(x)(1-y)^2 + q(x))dx$$

$q = d, s, (b)$ and $\bar{q} = \bar{u}, \bar{c}, (\bar{t})$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,(q(x)(1-y)^2 + \bar{q}(x))dx$$

$q = u, c, (t)$ and $\bar{q} = \bar{d}, \bar{s}, (\bar{b})$

Neutral Currents

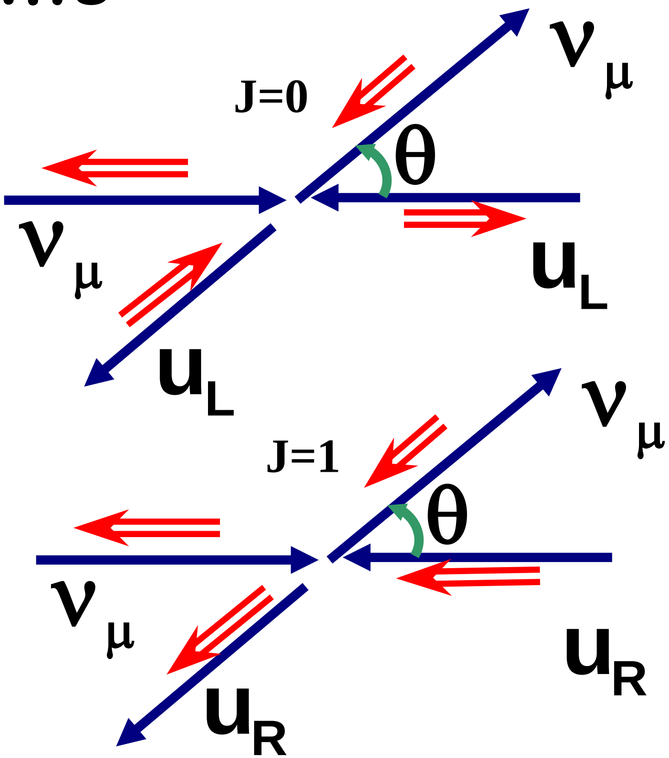
electroweak theory

CC: $g = e/\sin\theta_W$
NC: $g' = e/\sin\theta_W\cos\theta_W$

NC fermion coupling = $g'(I^3 - Q\sin\theta_W)$

I^3= weak isospin =
+1/2 for Left handed neutrinos & u-quarks,
-1/2 for Left handed electrons muons taus, d-quarks
0 for right handed leptons and quarks

Q= electric charge
θ_W= weak mixing angle.



$g_L^u = 1/2 - 2/3 \sin\theta_W$

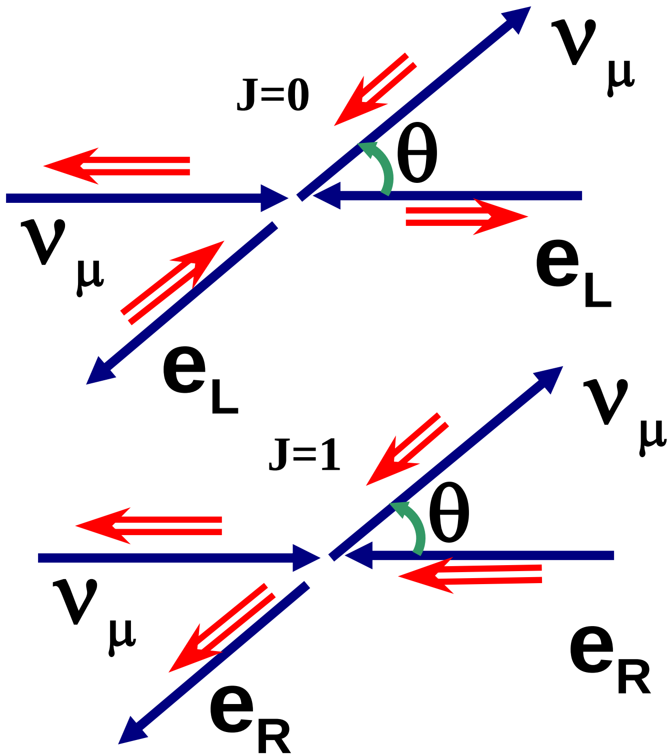
$g_R^u = \quad - 2/3 \sin\theta_W$

$$\frac{d\sigma(x)}{dy} = \frac{G_F^2\rho^2}{\pi} x S\left({g_L^u}^2 + {g_R^u}^2 (1-y)^2\right)$$

(sum over quarks and antiquarks as appropriate)

the parameter ρ can be calculated by remembering that for these cross sections we have the W (resp Z) propagator, and that the CC/NC coupling is in the ratio $\cos\theta_W$
thus $\rho^2 = m_W^4 / (m_Z^4 \cos\theta_W) = 1$ at tree level in the SM, but is affected by radiative corrections sensitive to e.g. m_{top}

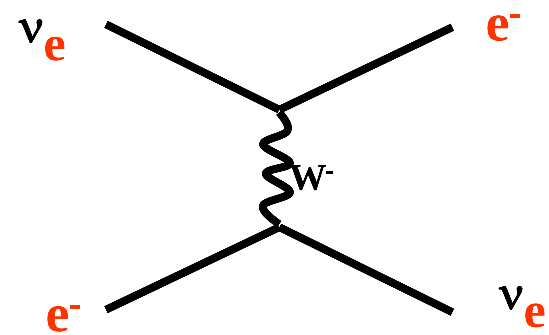
scattering of ν_μ on electrons:
(invert the role of R and L for antineutrino scattering)



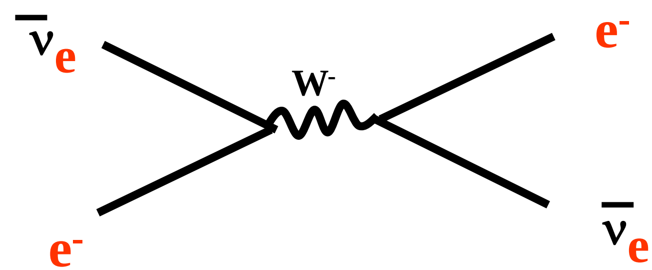
$$\frac{d\sigma}{dy} = \frac{G_F^2 \rho^2}{\pi} S\left(g_L^{e\,2} + g_R^{e\,2}(1-y)^2\right)$$

$$\sigma = \frac{G_F^2 \rho^2}{\pi} S\left(g_L^{e\,2} + 1/3\, g_R^{e\,2}\right)$$

the scattering of electron neutrinos off electrons is a little more complicated (W exchange diagram)

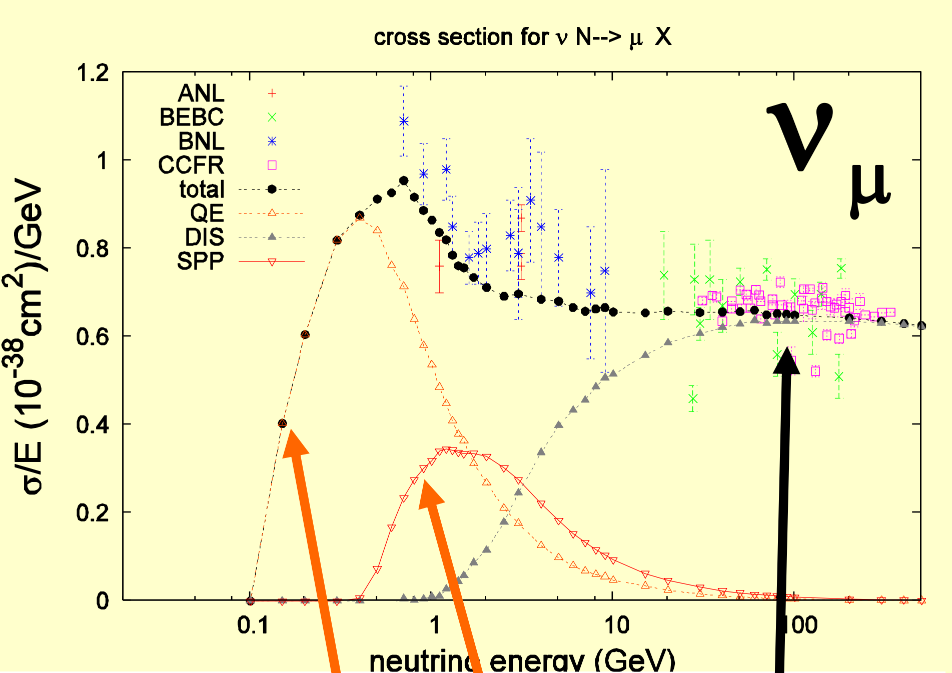


only electron neutrinos

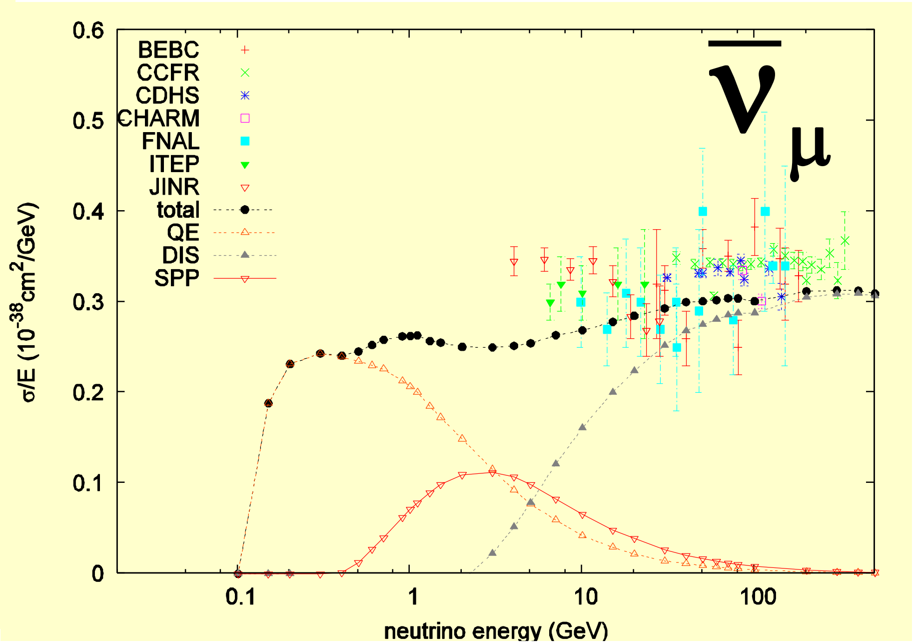


only electron anti- neutrinos

Total neutrino – nucleon CC cross sections



neutrino



anti-neutrino

We distinguish:

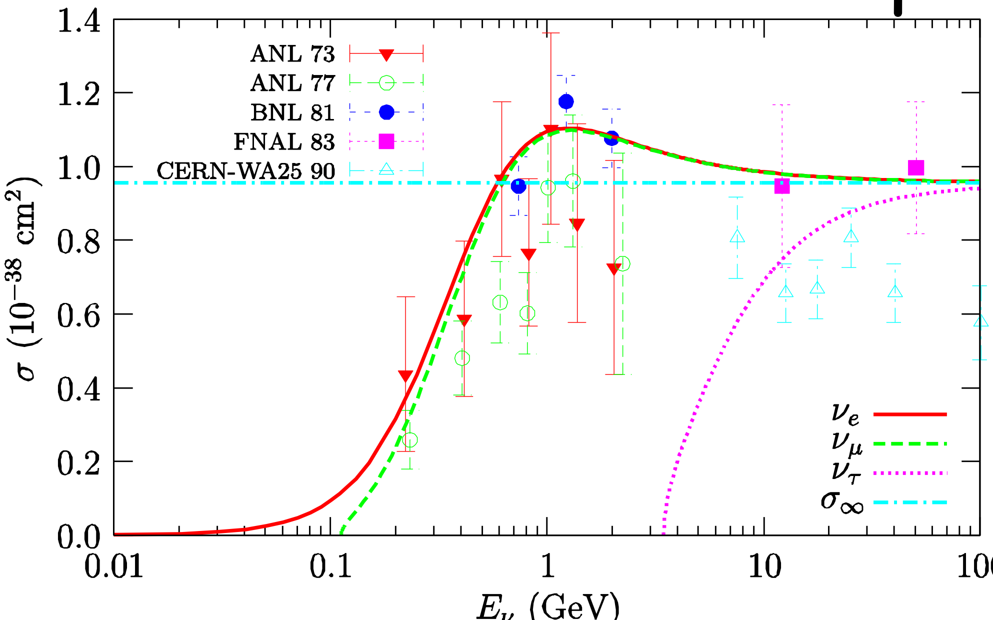
- quasi-elastic
- single pion production („RES region", e.g. W<=2 GeV)
- more inelastic („DIS region")

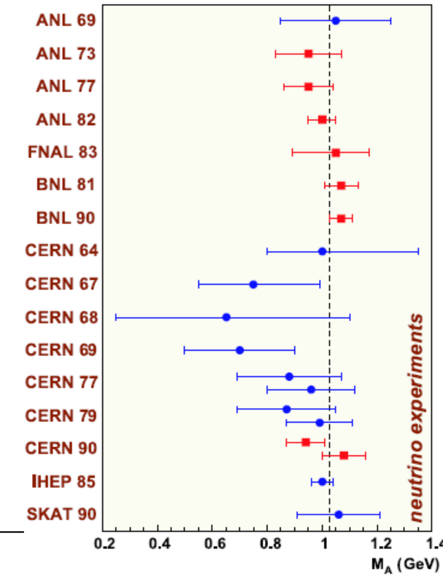
Below a few hundred MeV neutrino energies: quasi-elastic region.

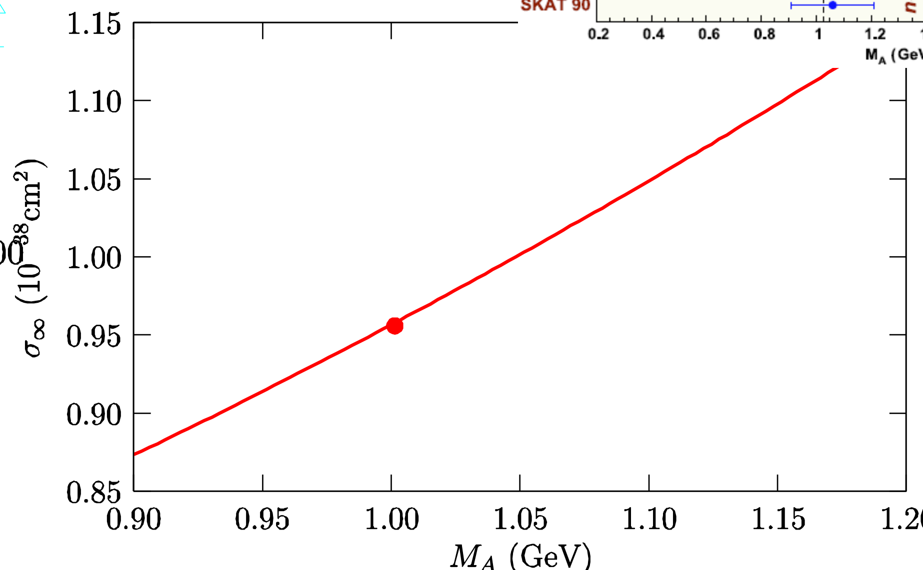
Plots from Wrocław MC generator

Quasi-elastic reaction
ν+n->lepton +p

(from Naumov)







Huge experimental uncertainty

The limiting value depends on the axial mass

Under assumption of dipole vector form-factors:

$$\sigma_\infty = \frac{G_F^2 \cos^2\theta_C}{6\pi}\left[M_V^2 + g_A^2 M_A^2 + \frac{2\xi(\xi+2)M_V^4}{(4M^2-M_V^2)^2}(M^2-M_V^2) + \frac{3\xi(\xi+2)M_V^8}{(4M^2-M_V^2)^3}\left(\frac{4M^2}{4M^2-M_V^2}\ln\frac{4M^2}{M_V^2}-1\right)\right].$$

(A. Ankowski)