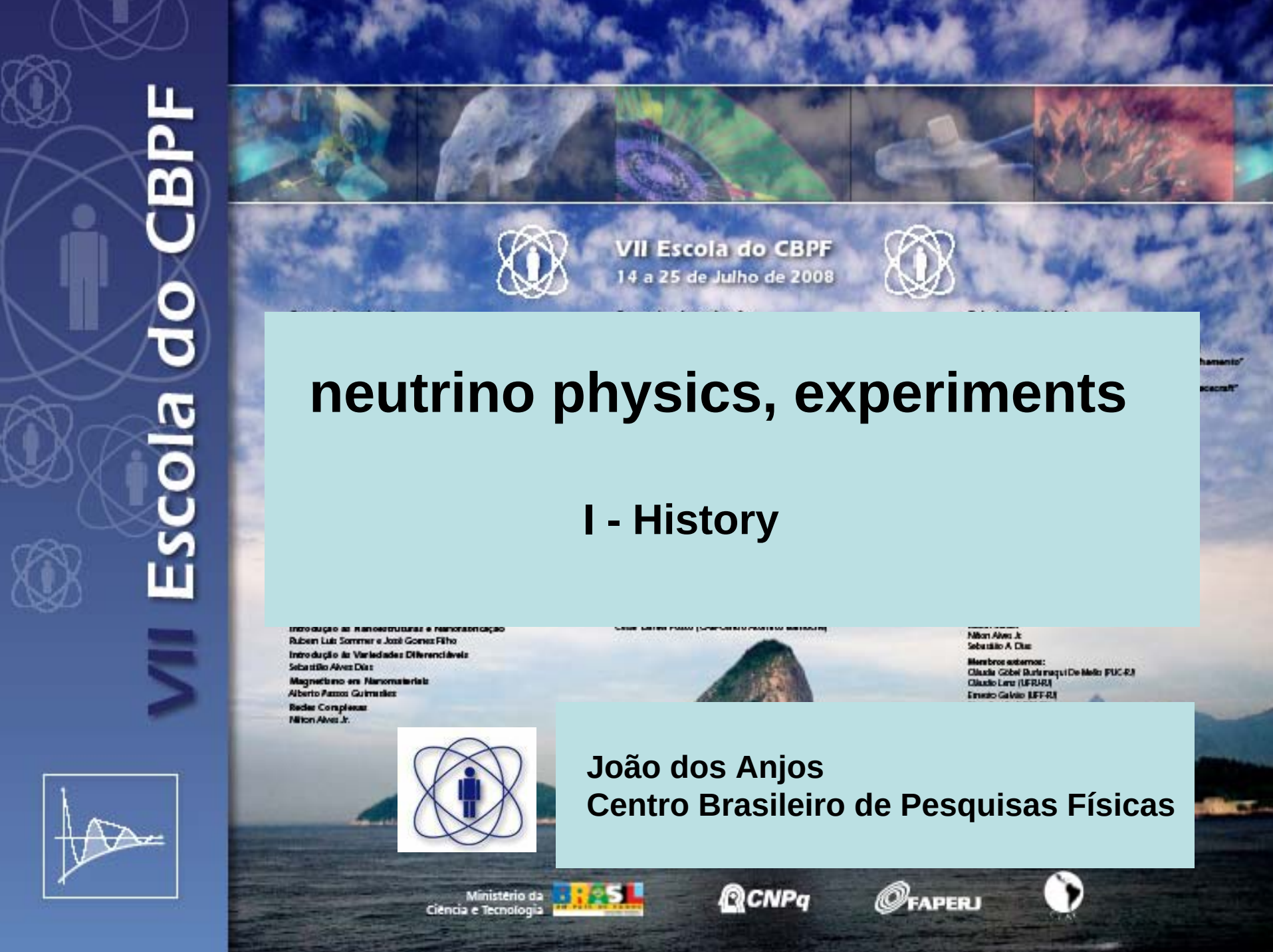


neutrino physics, experiments

I - History

João dos Anjos
Centro Brasileiro de Pesquisas Físicas

Main Sources

- **Recent Conferences presentations:**

- **Neutrino 2008** – Christchurch, New Zealand. – 25 -31 Mai 2008
- **Neutrino 2006** – Santa Fe, U.S.A. – 13-19 June 2006

- **NuFact 08 –** Valencia, Spain – 30 June – 4 July 2008
- **NuFact 06 –** Univ. Irvine, CA, U.S.A. – 24-30 August 2006
- – Workshop on Neutrino Factories, Superbeams & Betabeams

- **ECRS 2006** – 20th European Cosmic Ray Symposium Lisbon, Portugal – 5-8 September 2006

- **CERN Summer Student School 2005**
  J.J. Gómez-Cadenas – IFIC/U. Valencia

References - I

- Richard Wigmans (Texas Tech. University)
- Herald W. Kruse (Neutrino 2006)
- Jack Steinberger (Neutrino 2006)
- Hamish Robertson (Neutrino 2006)
- George Tzanakos (Neutrino 2006)
- J.J Goméz-Cadenas (Cern School 2005)
- Boris Kaiser (PASI 2006)
- H. Nunokawa (CBPF School 2006)
- O.L.G.Peres (CBPF School 2006)
- V.N. Gavrin (Neutrino 2006)
- Karsten Heeger (Neutrino 2006)
- Evgeny Akhmedov (Neutrino 2006)
- Deborah Harris (NuFact 06)
- Alessandro Curione (NuFact 06)
- Patricia Vahle (NuFact 06)
- Malika Meddahi (NuFact 06)

References - II

- S. Zeller (NuFact 06)
- S. Manly (NuFact 06)
- T. Nakadaira (Neutrino 2006)
- P. Shanaham (Neutrino 2006)
- M. Bishai (NuFact 06)
- P. Doe (Neutrino 2006)
- A.S. Barabash (Neutrino 2006)
- Rabi Mohapatra (Neutrino 2006)
- A. Piepke (Neutrino 2006)
- K. Abazajian (NuFact 06)
- M. Cirelli (NuFact 06)
- A. Fabich (NuFact 06)
- C. Rubia (NuFact 06)
- A. Rubia (NuFact 06)
- Leslie Camilliere (Neutrino 2006)

Outline

- History of Neutrino Experiments
- Neutrinos in the Standard Model
- Solar Neutrino Problem – What's wrong?
- Atmospheric neutrinos
- Reactor experiments
- Accelerator experiments
- Neutrino Mass
- Double beta decay experiments
- Astrophysical neutrinos
- Betabeams, Neutrino Factories

History

- The discovery
- Two Flavors
- Three flavors
- Three Families
- Third neutrino discovery

HISTORICAL OVERVIEW:

The problem and its solution

- **1896** Becquerel discovers nuclear β-decay: $A \rightarrow A' + e^-$

- **1914** J. Chadwick measures the electron spectrum in β-decay
  electrons are NOT mono-energetic !!

- **1930** N. Bohr: energy conservation is perhaps not valid for β-decay

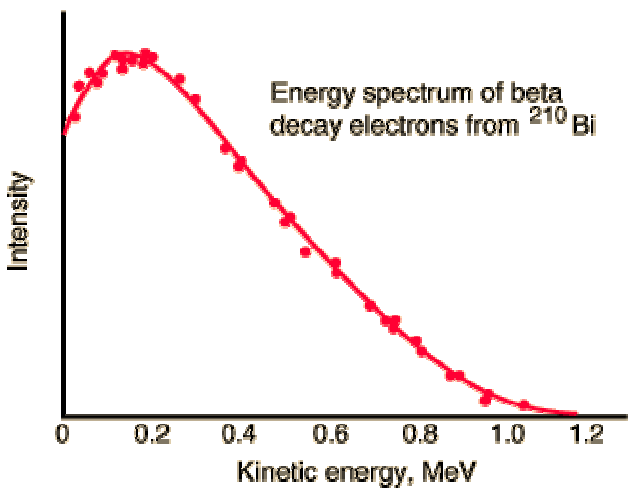
  W. Pauli proposes the existence of the neutrino to solve the problem:
  $n \rightarrow p + e^- + \nu$
  ν : Massless, undetected spin ½ particle

- **1932** J. Chadwick discovers the neutron: too heavy to be Pauli's particle

- **1934** E. Fermi – comprehensive theory of nuclear β-decay
  Call the new particle neutrino
  Distinguishes neutrino (lefthanded) anti-neutrino (righthanded)

The missing energy problem

2 body Nuclear decay drawing

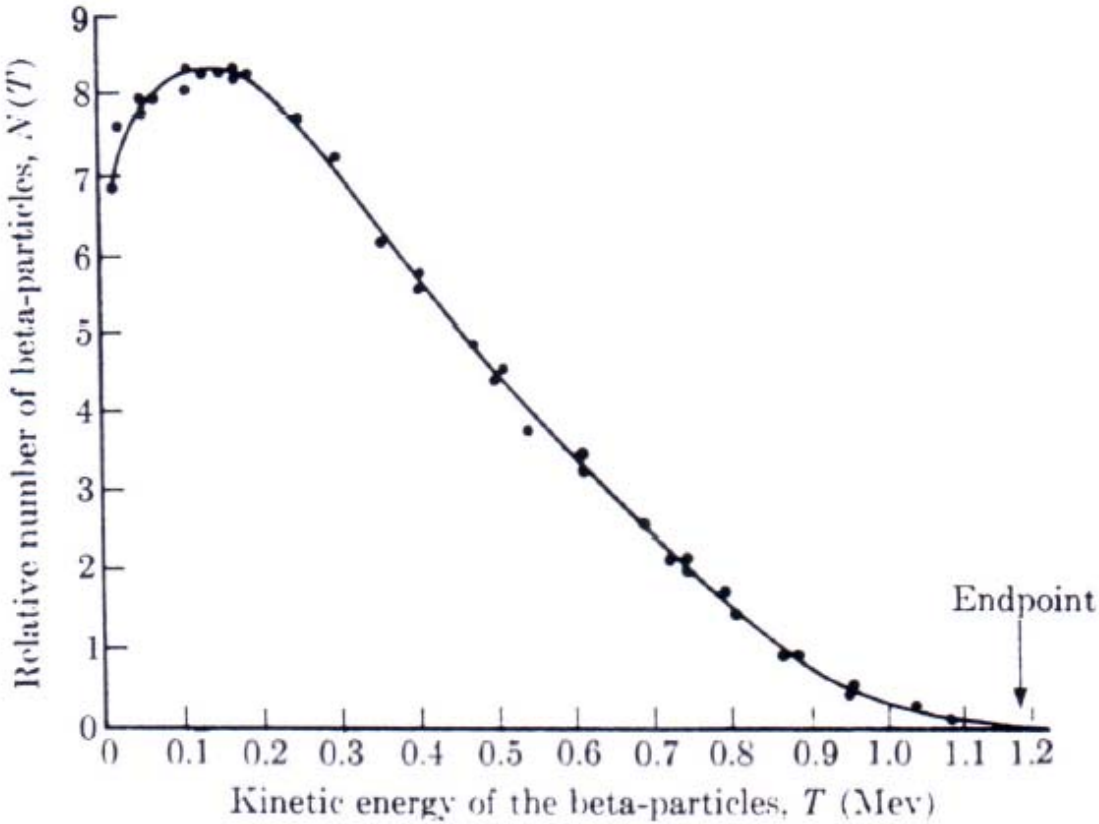


Electron energy distribution

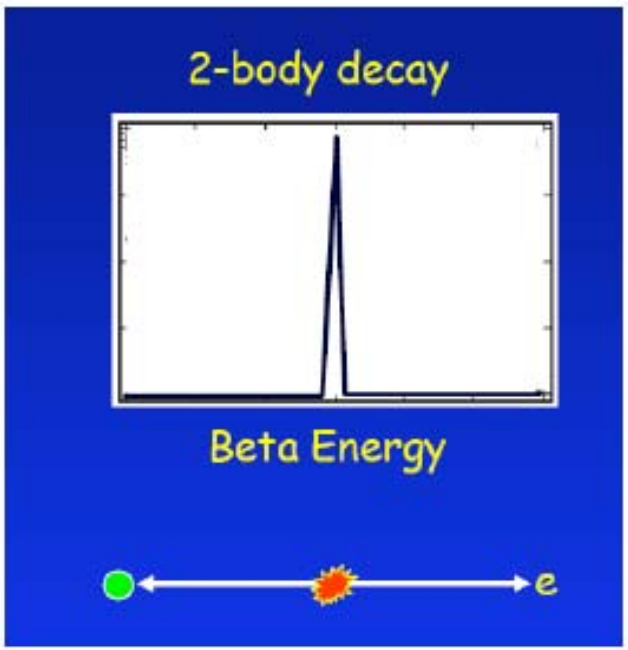
From: G. J. Neary, Proc. Phys. Soc. (London), A175, 71 (1940).

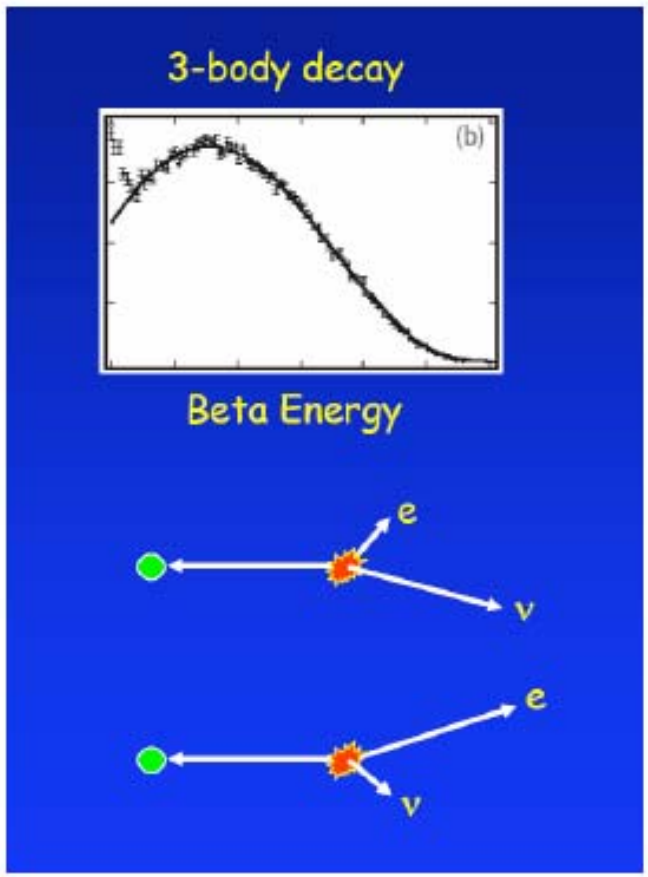
- 1914 Chadwick measures (continuous) nuclear beta decay spectrum
- (A,Z) > (A,Z+1) + e
- E energy expected to be constant.
- Bohr: no conservation of energy!

Electrons from β-decay are not mono-energetic

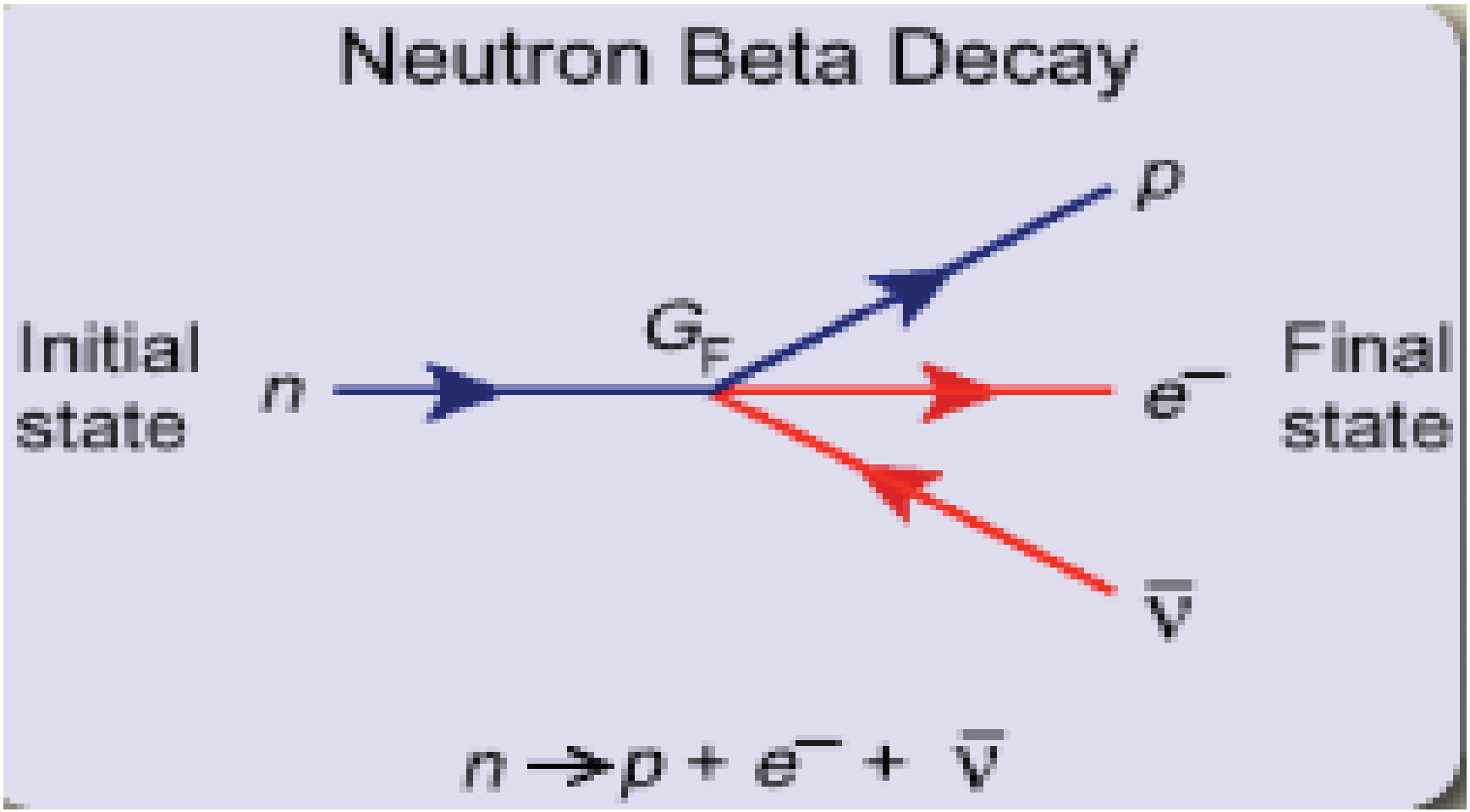


Two and three-body kinematics

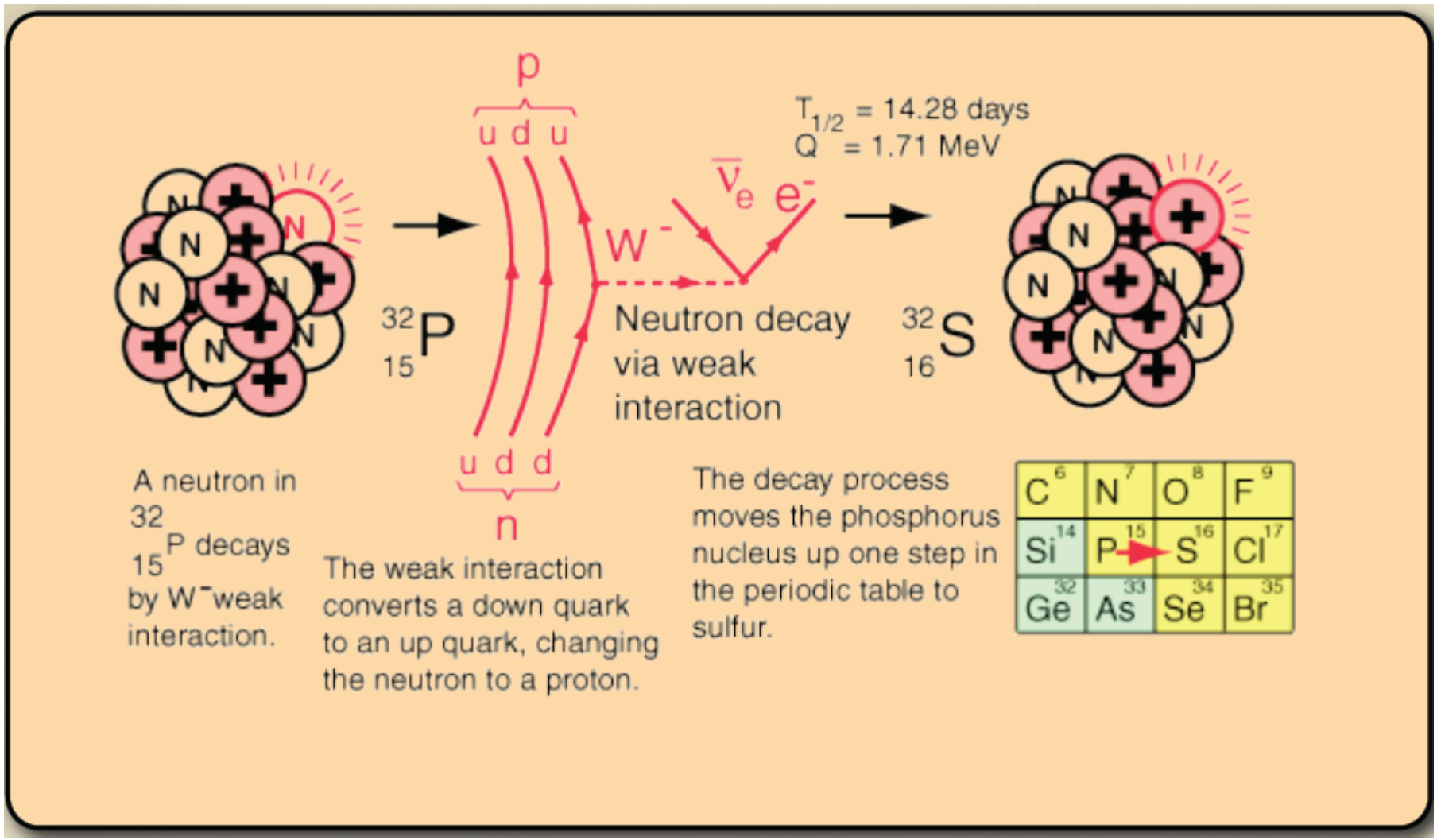




Fermi beta-decay



Today's theory of weak interactions: Interaction mediated by W boson



HISTORICAL OVERVIEW

- 1933 - 1956: *Skepticism*

  In an ordinary way I might say that I do not believe in neutrinos....
  Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos?

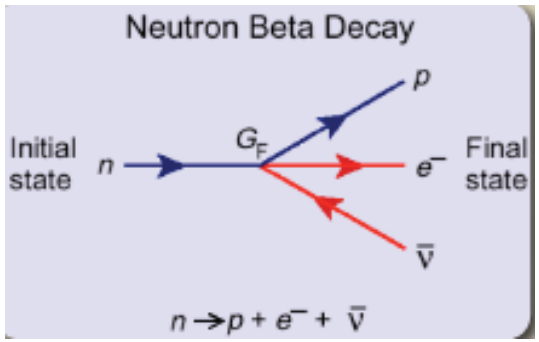
  Sir Arthur Eddington, 1939

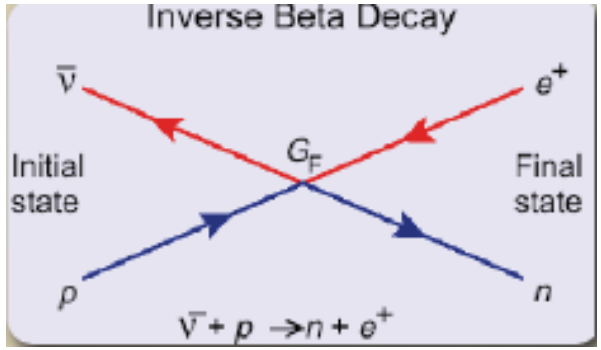
- 1956: Cowan & Reines detect neutrinos (project *Poltergeist*)

  $\bar{\nu} + p \longrightarrow e^+ + n$ *(inverse* β*-decay)*

  Signal: delayed coincidences between neutrons and 511 keV γ's from positron annihilation in a 1400 liter tank of liquid scintillator installed near the core of the Savannah River nuclear reactor

But how to detect neutrinos?





$$\sigma(\bar{\nu}p) \approx 10^{-43} cm^2 \quad E_\nu \sim 3\ MeV$$

$$\lambda = \frac{1}{N_A \rho \sigma}$$

$$\lambda(Pb) \sim \frac{1}{610^{23}(nucleon/g)(7.9\ g/cm^3)(10^{-43}\ cm^2)}$$

$$\sim 4\ light\ years!$$

The mean free path of a neutrino in Pb is 4 light years !!!!

Neutrino- Reines & Cowan



Clyde Cowan Jr.



Frederick Reines

Nobel Lecture, December 8, 1995

by

FREDERICK REINES

Physics Department, University of California, Irvine, California 92717, USA

Detection Technique

According to the Pauli-Fermi theory (1930-1934), the neutrino should be able to invert the process of beta decay as shown in Equation (1):

$$\nu + A^Z \leftrightarrow A^{Z-1} + e^+ \; or \leftrightarrow A^{Z+1} + e^- \tag{1}$$

We chose to focus on the particular reaction

$$\nu + p \rightarrow n + e^+ \tag{2}$$

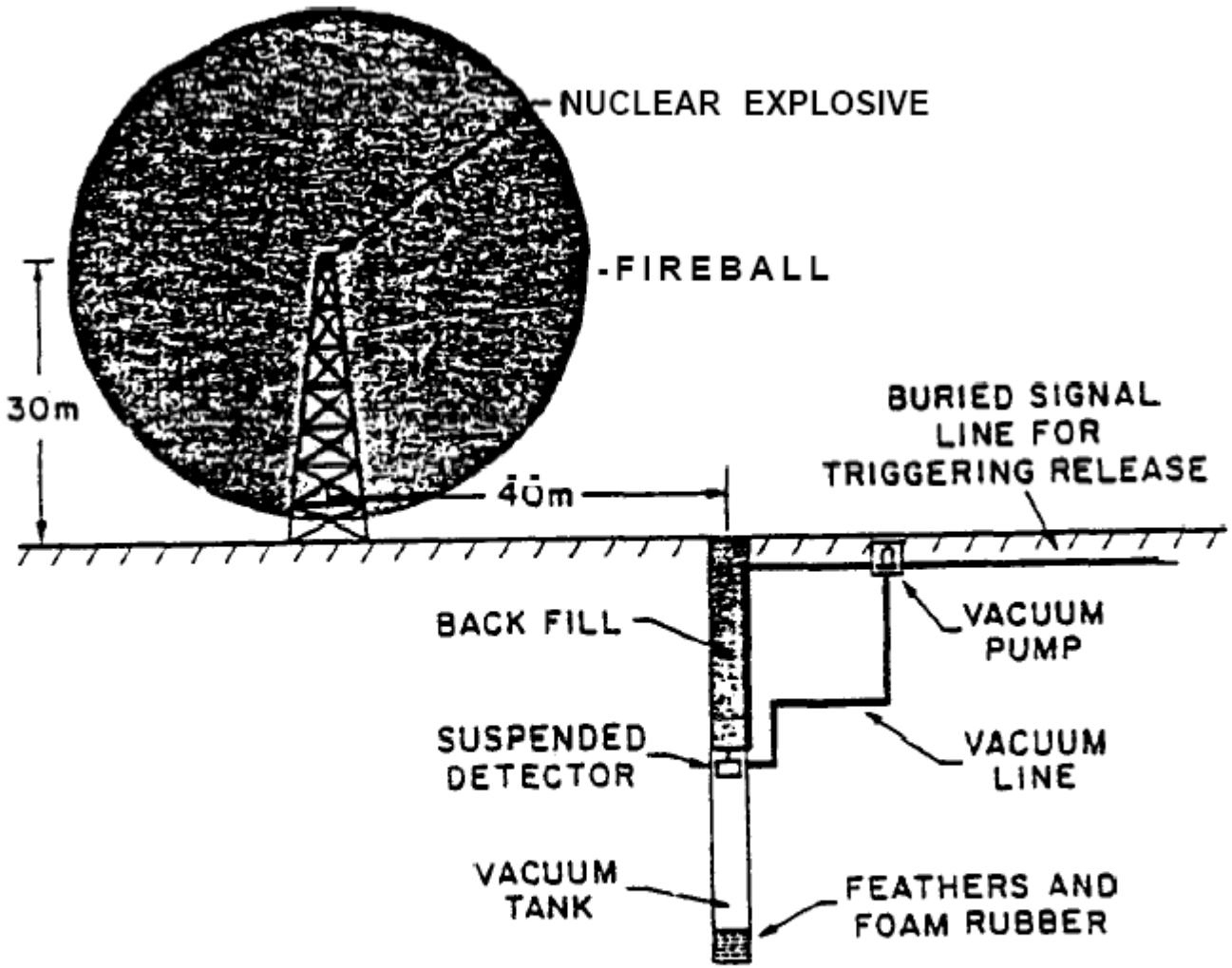
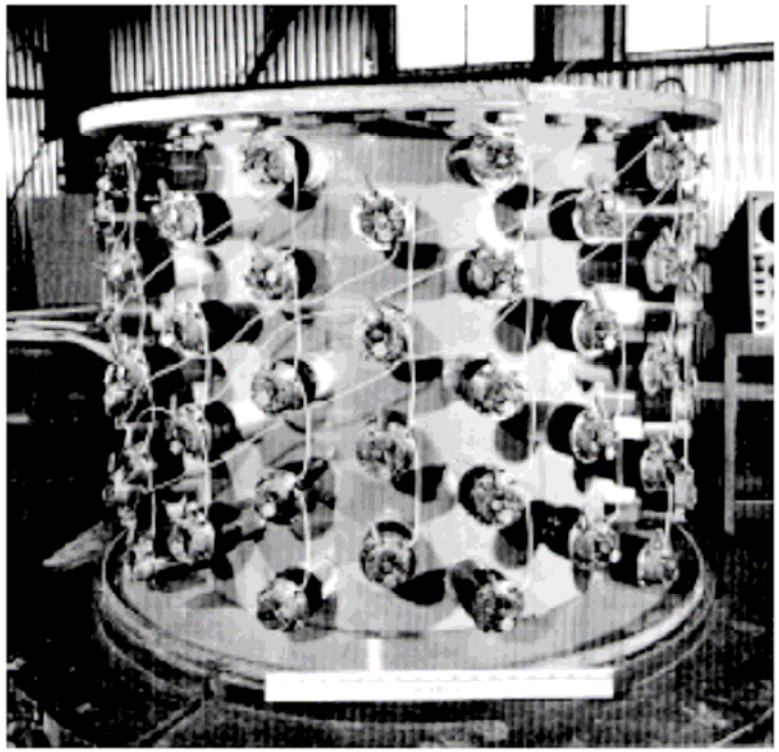
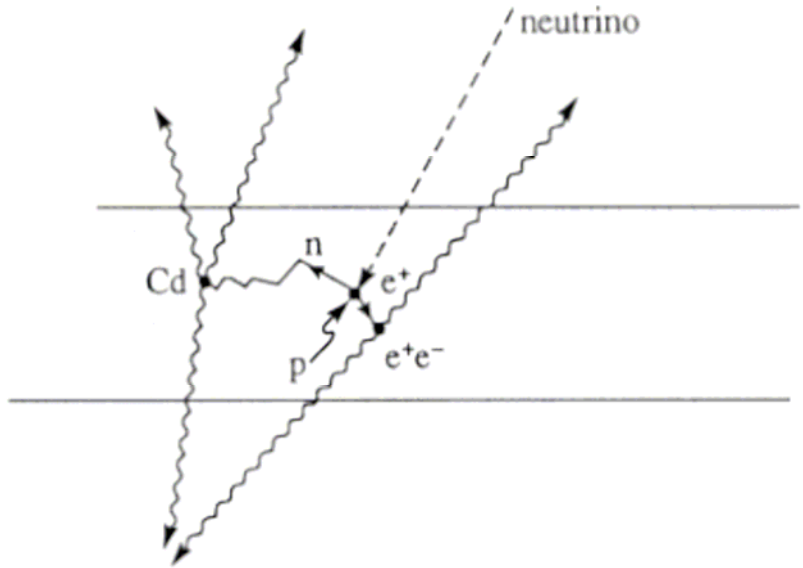


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

Reines and Cowan first detector:

Hanford experiment (1953)





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

Captured by cadmium

Annihilation with electron

"Herr Auge"

(Mr. Eye)

300 liter target, 90 pmt's 2"

H. Nunokawa

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

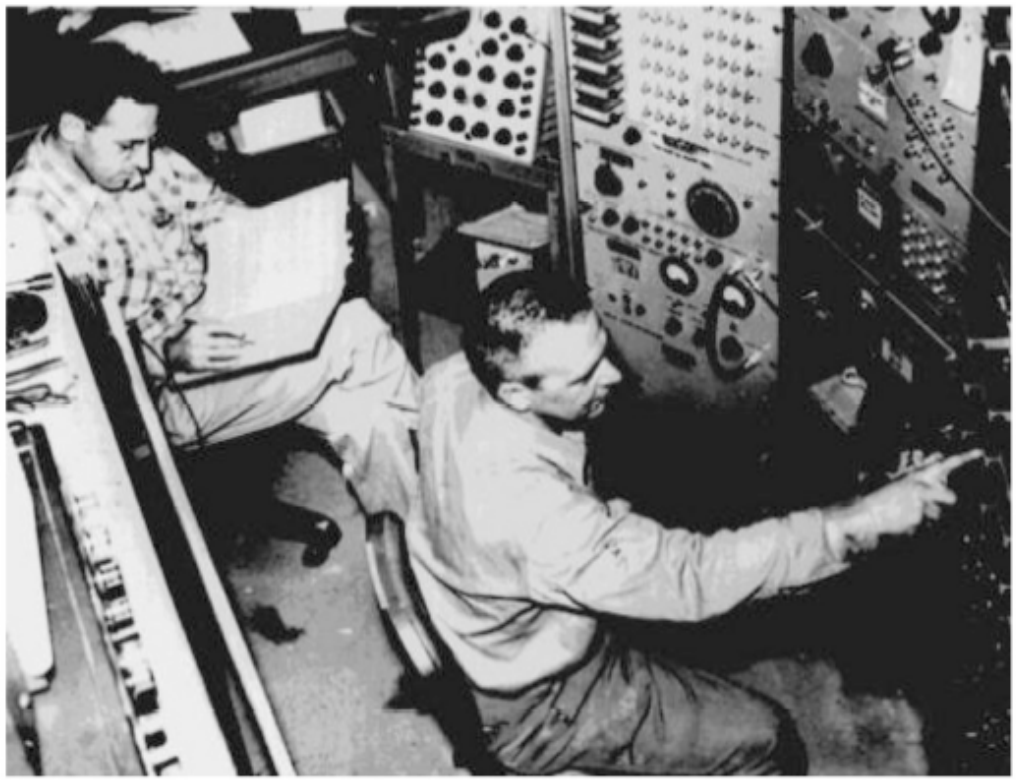
Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,

Enrico Fermi



Fred Reines and Clyde Cowan at the Control Center of the Hanford Experiment (1953)

H.W. Kruse

Neutrino- Savannah River



Savannah National Lab
Reactor K

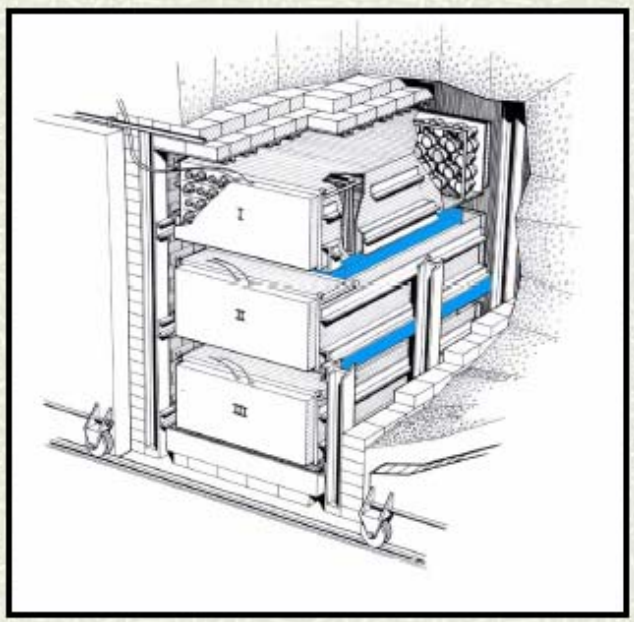


Fall 1955: brand new powerful 700 MW reactor!
11 meters from core, neutrino flux 1.2×10^{13} /cm^{2}sec
12 meters underground, good shielding

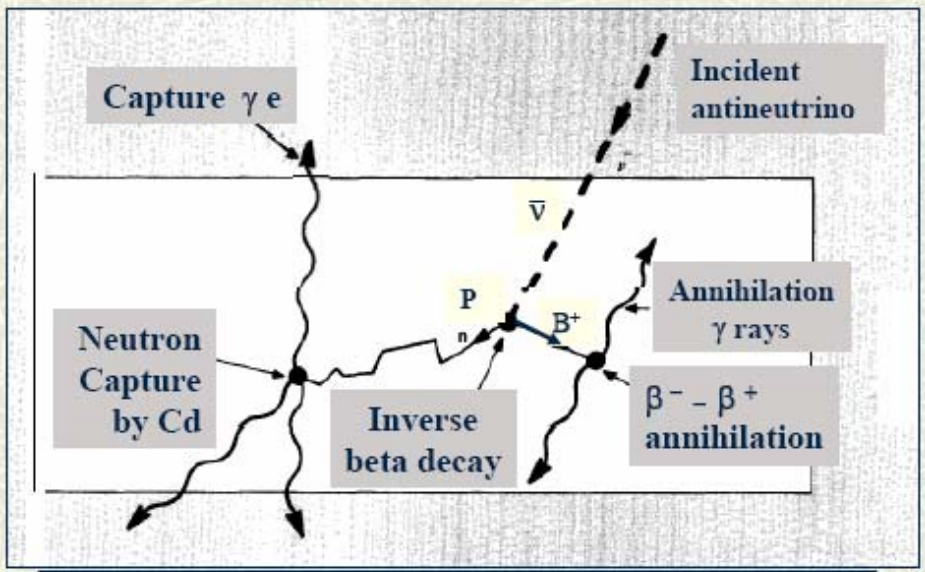
H.W. Kruse

Neutrino –Savannah River

- Detector Design
- Target Tanks (Blue) between Scintillation Detectors (I,II,III)



Neutrino – The Reaction



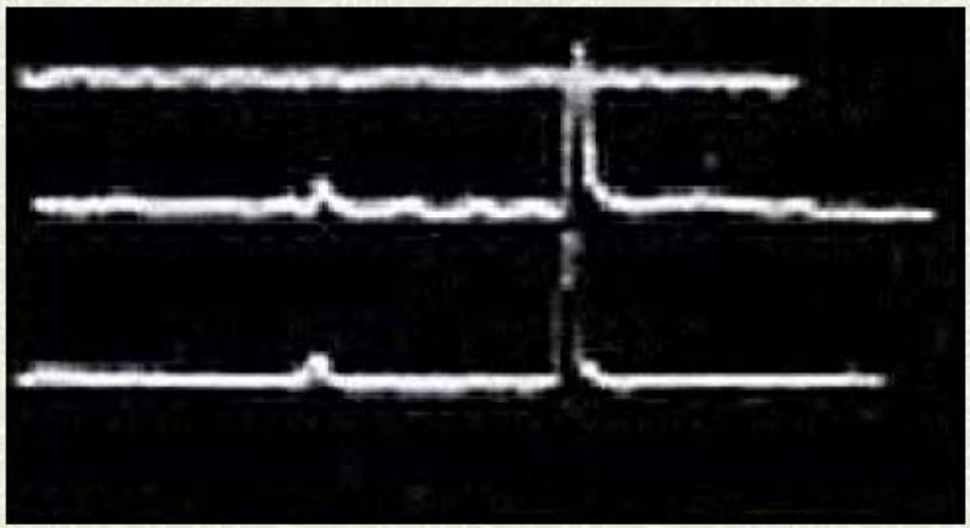
$$\bar{\nu} + p \longrightarrow \beta^+ + n$$

Observation of the neutrino

- Reactor-associated signal rate of 3.0±0.2 events/hour

- Main checks:
- Reactor-associated delayed coincidence signal consistent with theoretical expectations
- First pulse due to positron annihilation
- Second pulse due to neutron capture
- Signal was a function of the number of target protons
- Other type of radiation ruled out

Neutrino – Scope Trace



Delayed-Coincidence Signal

Neutrino- Savannah River



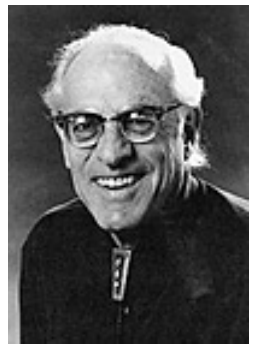
- Shielding, 4 Feet Thick
- Bags of Soaked Sawdust

Nobel prize for neutrino discovery!

- **1995**

  Martin L. Perl, Frederick Reines

"for the detection of the neutrino"



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

Two types of neutrinos!

- End 1940's: Discovery of π, μ, K in cosmic rays.
  These particles have *anomalously long lifetimes*: 26 ns, 2.2 μs, 12 ns
  They decay through the Weak Interaction.

- *Pion decay:* $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  Kaon decay: $K^+ \rightarrow \mu^+ + \nu_\mu$

- *Muon decay:* $\mu^+ \rightarrow e^+ + \gamma$ *not* observed (branching ratio $< 10^{-9}$)
  $\Rightarrow$ Need 3-body decay: $\mu^+ \rightarrow e^+ + \bar{\nu_\mu} + \nu_e$

- *Question:* $\nu_\mu \equiv \nu_e$?
  Answer: **NO!**

- *L. Lederman, J. Steinberger & M. Schwartz (Brookhaven, 1961):*
  Made neutrino beam from pion decay products
  $\nu_\mu + N \rightarrow \mu^- + X$
  $\bar{\nu_\mu} + N \rightarrow \mu^+ + X$

History of BNL 2nd neutrino experiment.

1958 Feinberg: Why $\mu \not\rightarrow e + \gamma$?

1958 Oneda and Pati: is ν_μ different from ν_e?

1959 Pontecorvo: look for $\nu_\mu + p \rightarrow e^+ + n$.

1959 Question of T.D. Lee at friday afternoon Columbia physics department coffee:
How might we study the weak interaction at energies higher than those of particle decays?

J.Steinberger

1959 Answer of Mel Schwartz: make and use neutrino beams at particle accelerators.

1960 Completion of AGS accelerator at BNL and PS accelerator at CERN, following thc invention of the alternate focusing principle in 1952 by Courant, Livingston and Snyder, which for the first time made neutrino beam experiments feasible.

1962 Brookhaven experiment shows that neutrinos from pion and kaon decay produce muons but not clectrons, and so must be different from neutrinos of decay.

J.Steinberger

SOVIET PHYSICS JETP VOLUME 37 (10), NUMBER 6 JUNE, 1960

ELECTRON AND MUON NEUTRINOS

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor July 9, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 1751-1757 (December, 1959)

Some processes due to free neutrinos, not heretofore considered, are discussed. Particular attention is paid to those processes which, in principle, could help decide whether two neutral lepton pairs [electron pair (ν_e and $\bar{\nu}_e$) and muon pair (ν_μ and $\bar{\nu}_\mu$)] exist.

To answer the fundamental question about the identity of ν_μ and ν_e a method is proposed which in essence is analogous to the method used to distinguish neutrinos from antineutrinos or K^0 mesons from $\bar{K}^0$ mesons. In principle the problem is solved when an experiment is carried out showing whether a beam of $\bar{\nu}_\mu$ is capable of initiating transitions which can without any doubt be initiated by $\bar{\nu}_e$ (for example the reaction $\bar{\nu}_\mu + p \rightarrow e^+ + n$).

The suggested experiment, although difficult, should be feasible with accelerators capable of producing more intense beams then those produced by present-day accelerators.

J.Steinberger

FEASIBILITY OF USING HIGH-ENERGY NEUTRINOS TO STUDY THE WEAK INTERACTIONS

M. Schwartz*
Columbia University, New York, New York
(Received February 23, 1960)

For many years, the question to how to investigate the behavior of the weak interactions at high energies has been one of considerable interest. It is the purpose of this note to show that experiments pointed in this direction, though not quite feasible with presently existing equipment, are within the capabilities of present technology and should be possible within the next decade.

We propose the use of high-energy neutrinos as a probe to investigate the weak interactions.

A natural source of high-energy neutrinos are high-energy pions. Such pions will produce

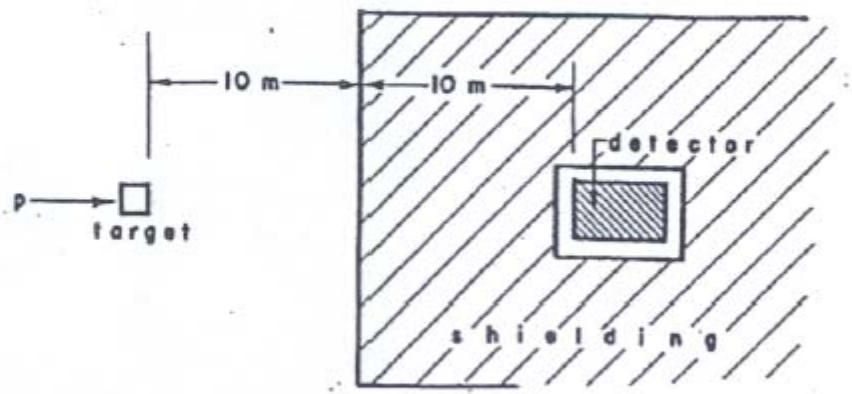


FIG. 1. Proposed experimental arrangement.

J.Steinberger

2nd neutrino discovered in 1962

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

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

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

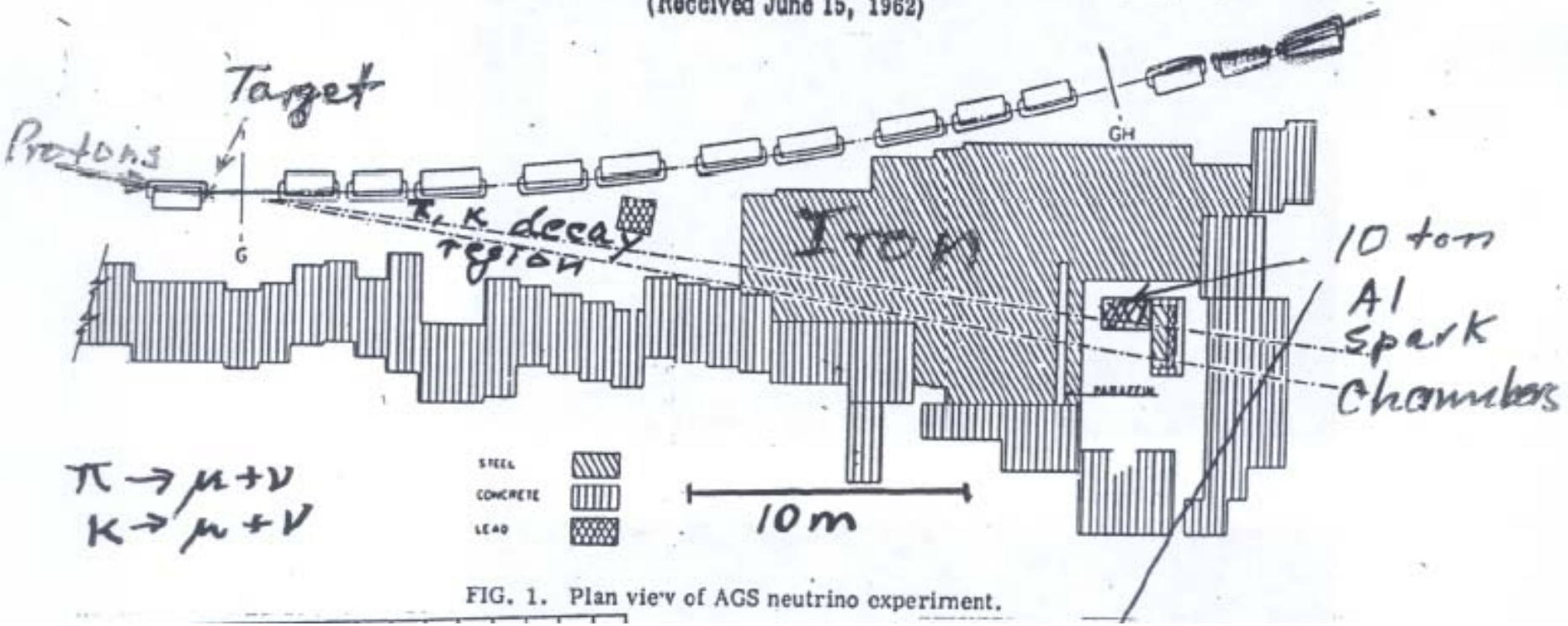
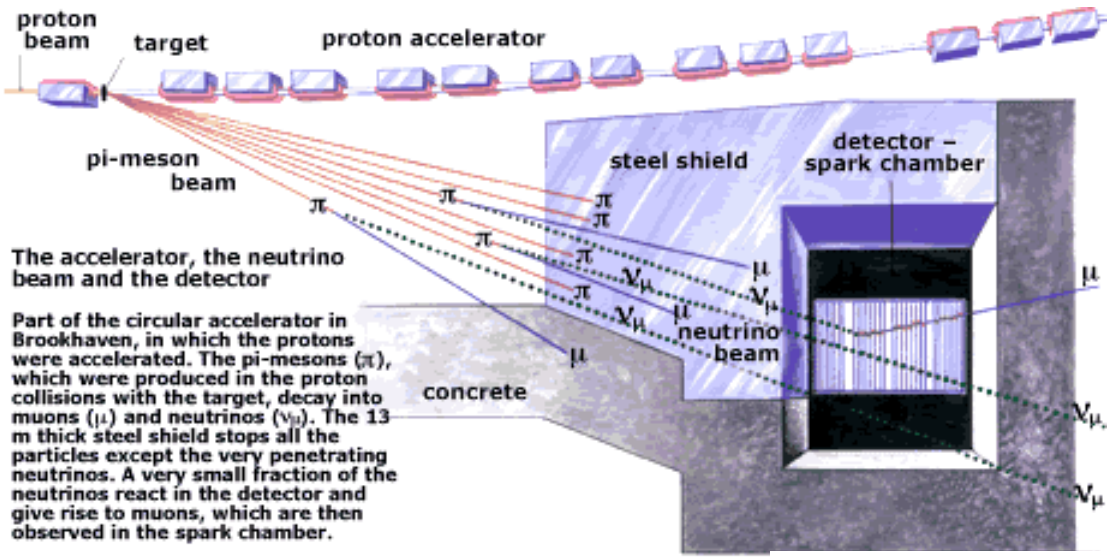


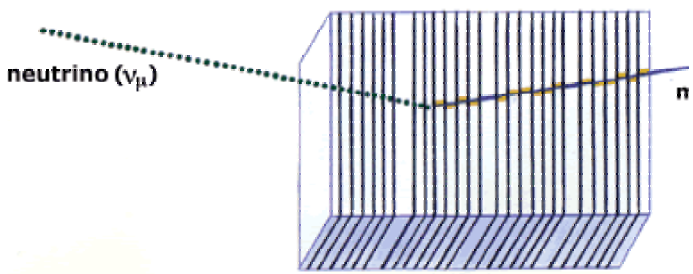
FIG. 1. Plan view of AGS neutrino experiment.

J.Steinberger

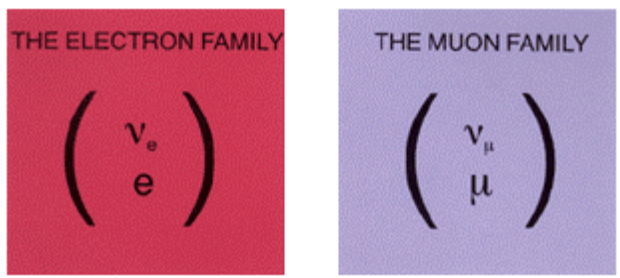
Discovery of distinct flavors…



By far mostly (produced) muons were observed: second nu family



A muon produced in a neutrino reaction gives rise to discharges observed in the spa



The known lepton families after the neutrino experiment; the electron (e) and the electron neutrino (νe), the muon (μ) and the muon neutrino (νμ).

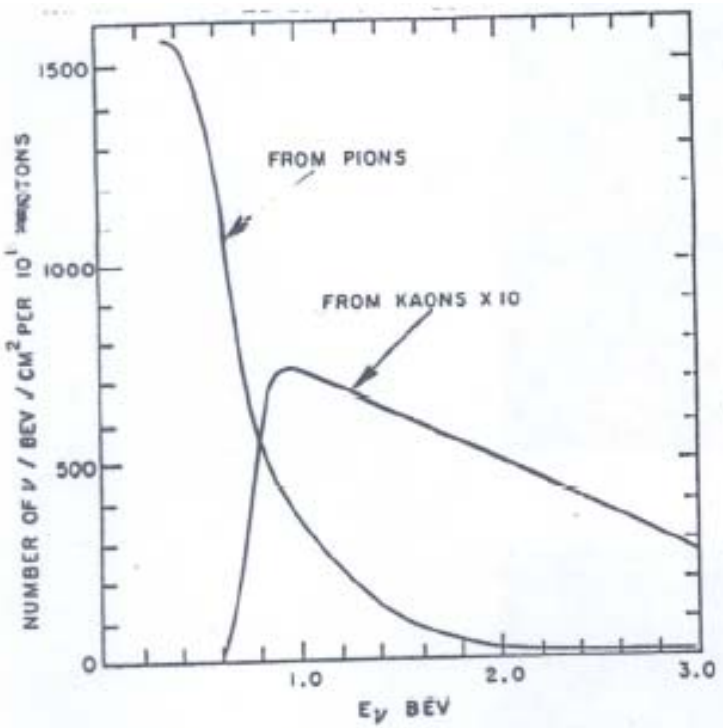


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.

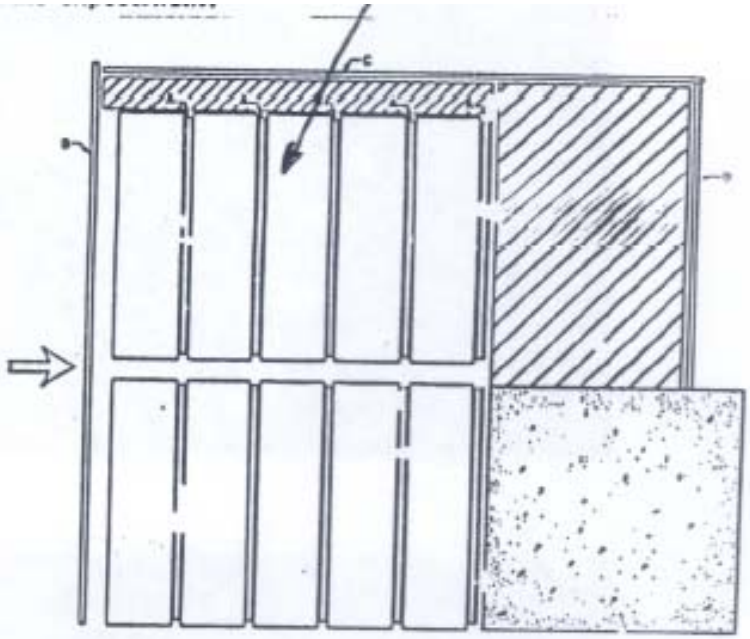
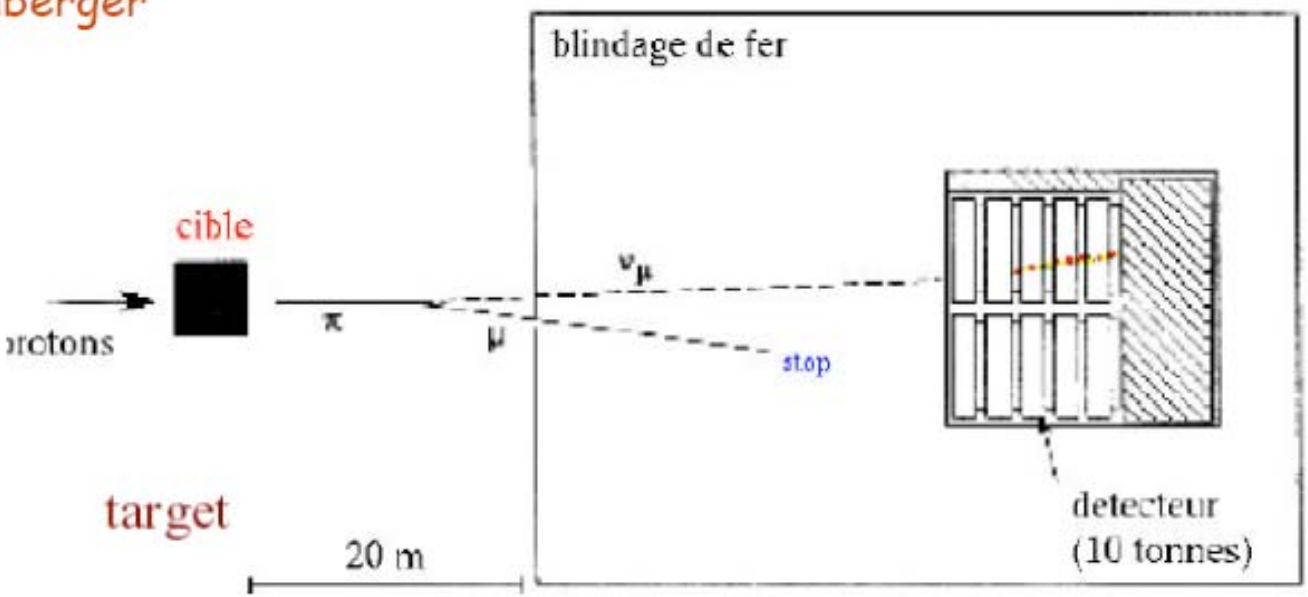


FIG. 3. Spark chamber and counter arrangement. *A* are the triggering slabs; *B*, *C*, and *D* are anticoincidence slabs. This is the front view seen by the four-camera stereo system.

J.Steinberger

The discovery of ν_μ (1962)

Swartz Lederman & Steinberger



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

----- sparks along a muon track



Result: ~ 2 dz events

show $\nu_\mu \neq \nu_e$

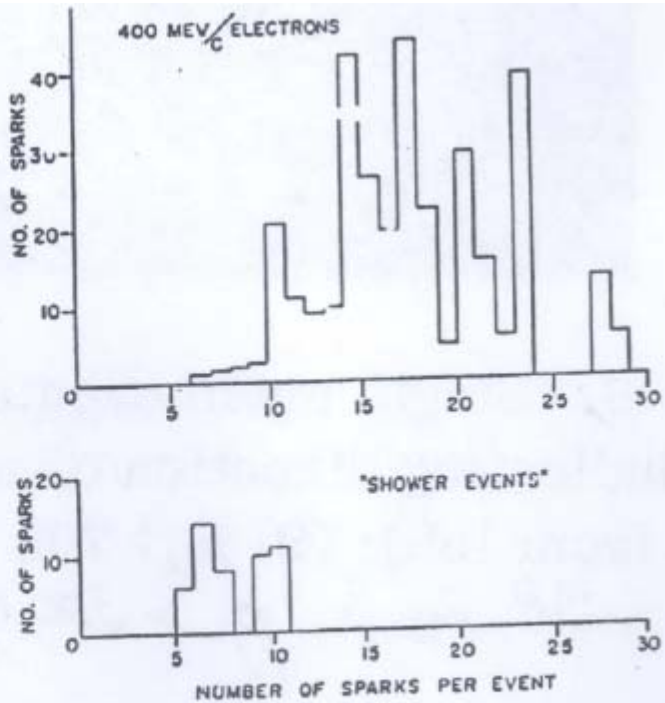


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

J.Steinberger

26 years later



J. Steinberger, M. Schwartz e L. Lerderman



$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad n + \nu_\mu \rightarrow p + \mu^-$$

H. Nunokawa

Postlude: Improved beams and detectors make neutrino beams an important tool for studying the weak interaction and nucleon structure. Some highlights:

1961 Invention of "Neutrino Horn" by Van der Meer, important step forward in intensities of broad band neutrino beams.

1973 Discovery of neutral currents by Gargamelle at CERN.

1975 Comparison of Gargamelle neutrino structure functions with SLAC electron structure functions shows that the sum of the squares of the up and down quark charges is 5/9.

1979 CDHS, CERN. First verification of quantitative predictions of QCD "asymptotic freedom" in scaling violations.

2001 First observation of tau neutrinos in Donut at FNAL.

J.Steinberger

Discovery of Neutral Currents.
Cern - Gargamelle - 1973

This experiment established E.W. theory

University College, London, England

Charged Current Reaction (old)

$$\nu_\mu + n \rightarrow \mu + X$$

Neutral current Reaction (new)

$$\nu_\mu + n \rightarrow \nu_\mu + X$$

muonless.

J.Steinberger

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

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III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

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Interuniversity Institute for High Energies, U.L.B., V.U.B. Brussels, Belgium

U. CAMERINI*[2], D.C. CUNDY, R. BALDI, I. DANILCHENKO*[3], W.F. FRY*[2], D. HAIDT, S. NATALI*[4], P. MUSSET, B. OSCULATI, R. PALMER*[4], J.B.M. PATTISON, D.H. PERKINS*[6], A. PULLIA, A. ROUSSET, W. VENUS*[7] and H. WACHSMUTH
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E. BELOTTI, S. BONETTI, D. CAVALLI, C. CONTA*[8], E. FIORINI and M. R[illegible]LLI[illegible]
Istituto di Fisica dell'Università, Milano and I.N.F.N. Milano, Italy

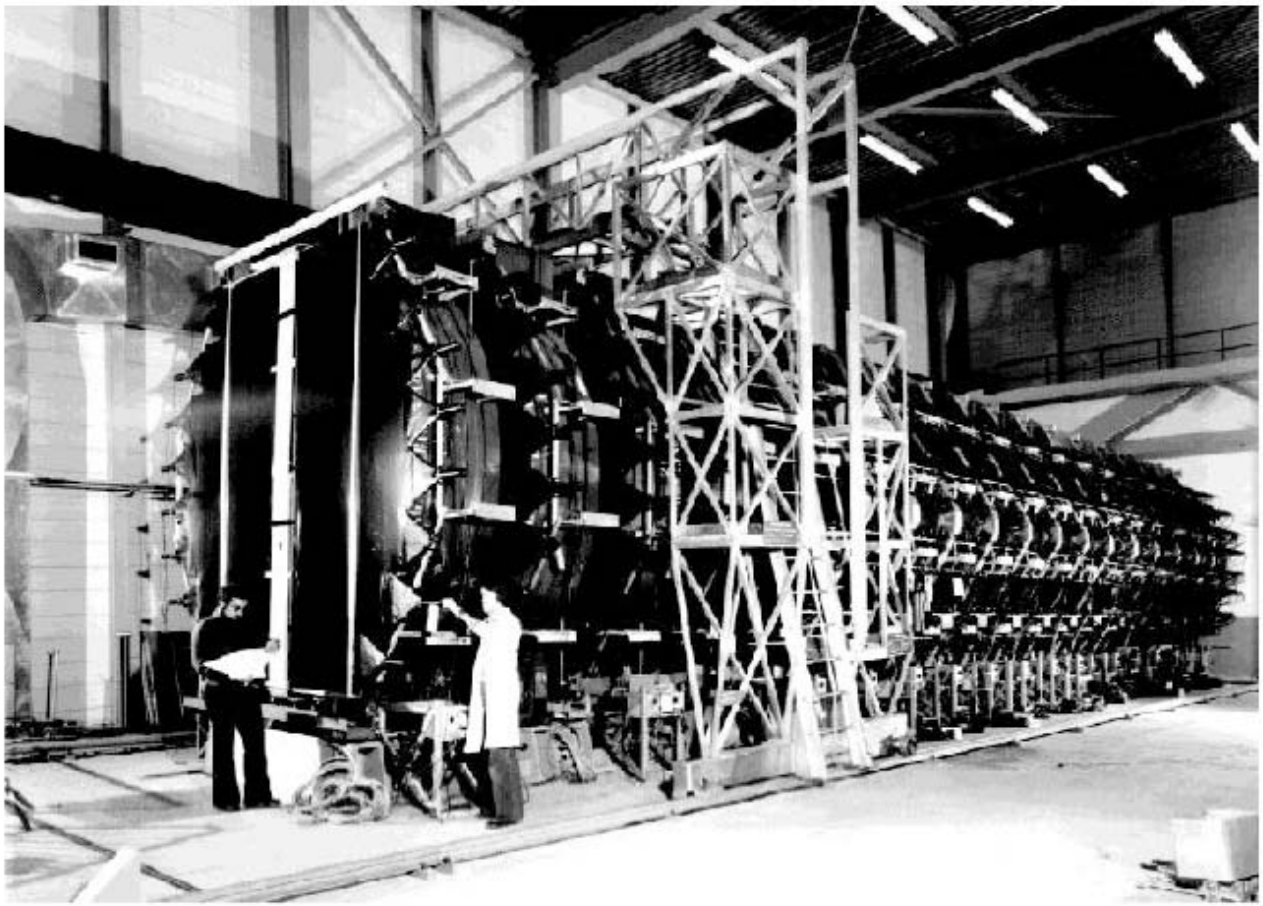
B. AUBERT, D. BLUM, L.M. CHOUNET, P. HEUSSE, A. LAGARRIGUE, A.M. LUTZ, A. ORKIN-LECOURTOIS and J.P. VIALLE
Laboratoire de l'Accélérateur Linéaire, Orsay, France

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University College, London, England

J.Steinberger

J.Steinberger

Neutrino detection at CERN: CDHS (1976 - 1980)



Richard Wigmans

Neutrino interaction in a Bubble Chamber



Figure 1.14 The charmed baryon. The probable interpretation of this event is $\nu_\mu + p \rightarrow \Lambda_c^+ + \mu^- + \pi^+ + \pi^-$. The charmed baryon decays ($\Lambda_c^+ \rightarrow \Lambda + \pi^+$) too soon to leave a track, but the subsequent decay of the Λ is clearly visible. (Photo courtesy of N. P. Samios, Brookhaven National Laboratory.)

Richard Wigmans

The third one!

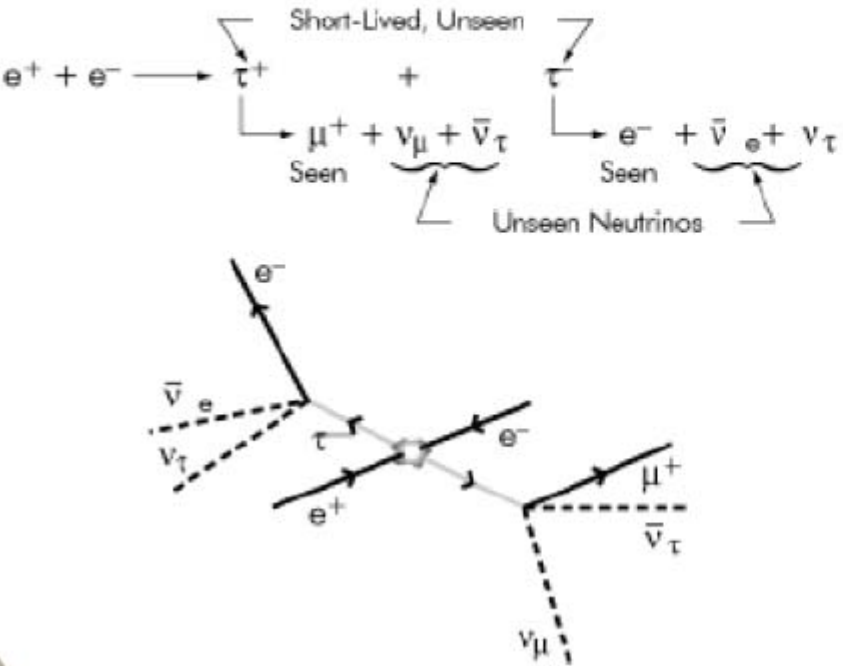
- 1974: History repeats itself
  Discovery of the τ lepton (SLAC) : $e^+e^- \rightarrow \tau^+\tau^-$
  $\tau^- \rightarrow \mu^- + \nu_\tau + \bar{\nu}_\mu$
  $\tau^+ \rightarrow \mu^+ + \bar{\nu}_\tau + \nu_\mu$

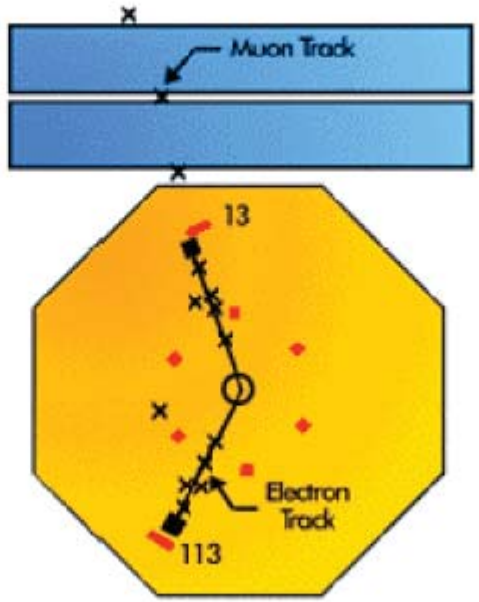
  $\Rightarrow$ **Need yet another quantum number**

- All different ν species seem to be *massless*!

The Third lepton and the third neutrino?

The third heavy electron, tha tau was discovered by M. Perl and collaborators in 1975 at SLAC





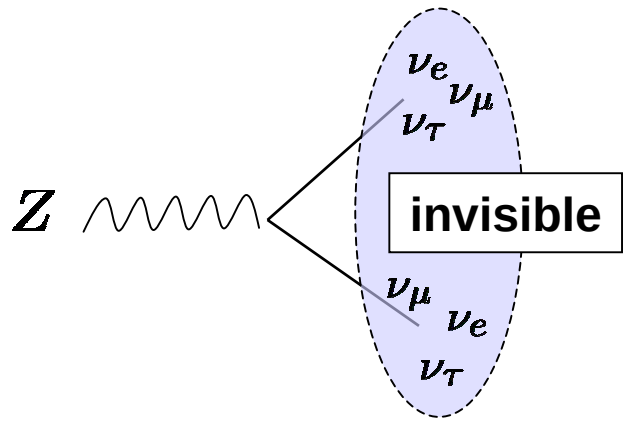


Why not more leptons and more neutrinos?

The experimental constraints 1

~invisible decay width~

LEP @ CERN



Z DECAY MODES	Fraction (Γ_i/Γ)
$e^+ e^-$	(3.363 ±0.004) %
$\mu^+ \mu^-$	(3.366 ±0.007) %
$\tau^+ \tau^-$	(3.370 ±0.008) %
invisible	(20.00 ±0.06) %
hadrons	(69.91 ±0.06) %

LEP/ OPAL, DELPHI,
L3, ALEPH, SLD

➡ ***NO CONSTRAINT***
<u>individual</u> decay

No information is available
on the <u>individual</u> decay widths into each flavor

Three generations of neutrinos, and no more than three

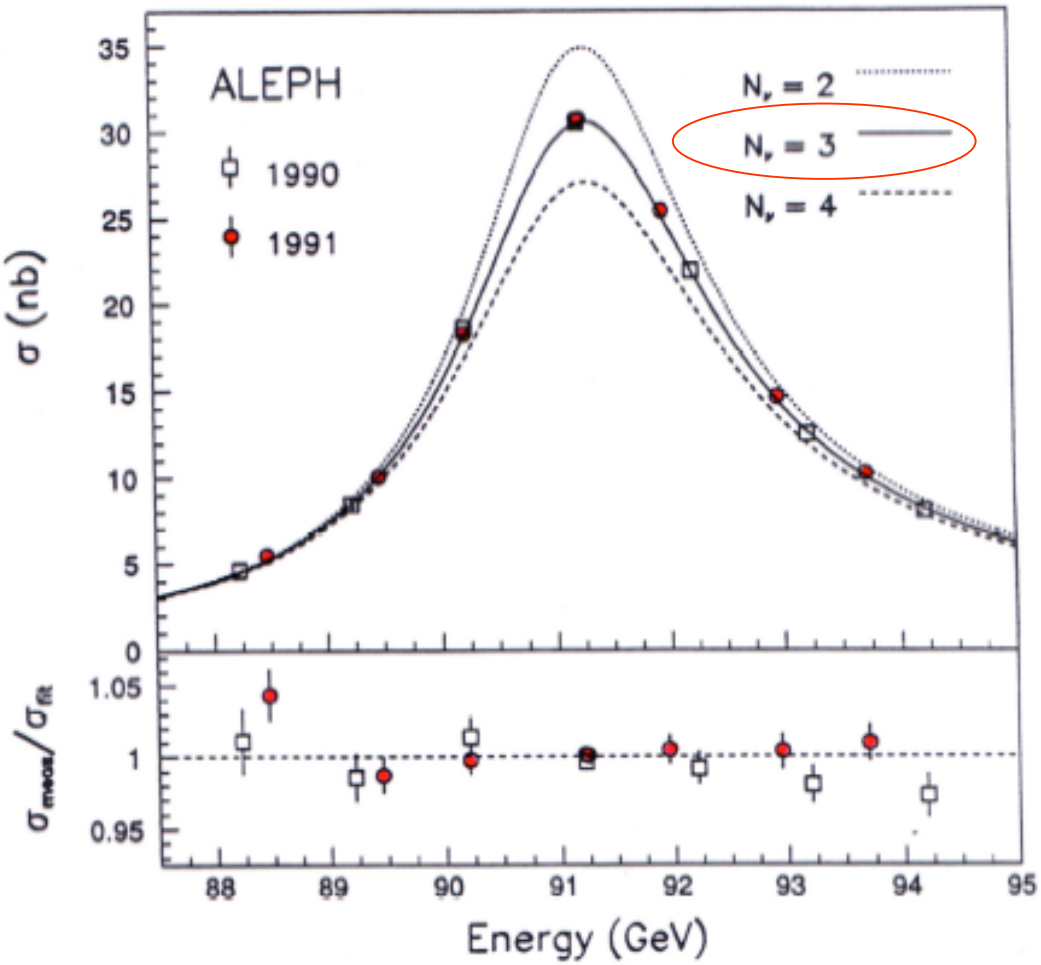
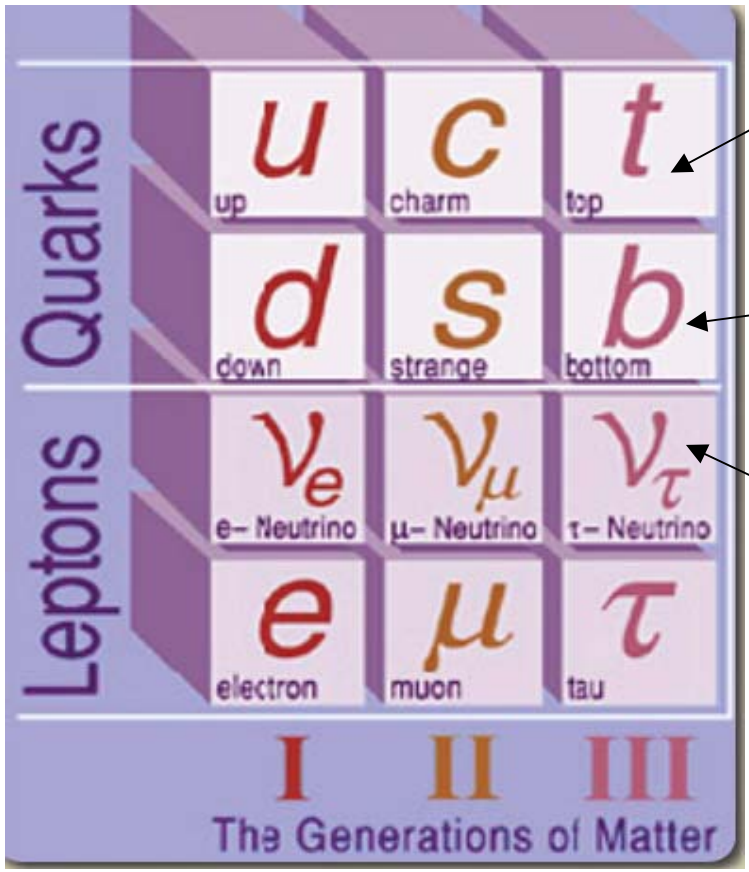


Figure 2: Cross sections for $e^+e^- \rightarrow$ hadrons as functions of the centre-of-mass energy for the 1990 and 1991 data. The Standard Model predictions for $N_\nu = 2,3$, and 4 are shown. The lower plot shows the ratio of the measured points to the best fit values.

Richard Wigmans

Three Generations of leptons and quarks



1995

1977

2001



Direct Observation of NU Tau



(2001)

Observation of tau neutrino interactions

DONUT Collaboration

K. Kodama [a], N. Ushida [a], C. Andreopoulos [b], N. Saoulidou [b], G. Tzanakos [b], P. Yager [c], B. Baller [d], D. Boehnlein [d], W. Freeman [d], B. Lundberg [d], J. Morfin [d], R. Rameika [d], J.C. Yun [d], J.S. Song [e], C.S. Yoon [e], S.H. Chung [e], P. Berghaus [f,*], M. Kubantsev [f], N.W. Reay [f], R. Sidwell [f], N. Stanton [f], S. Yoshida [f], S. Aoki [g], T. Hara [g], J.T. Rhee [h], D. Ciampa [i], C. Erickson [i], M. Graham [i], K. Heller [i], R. Rusack [i], R. Schwienhorst [i], J. Sielaff [i], J. Trammell [i], J. Wilcox [i], K. Hoshino [j], H. Jiko [j], M. Miyanishi [j], M. Komatsu [j], M. Nakamura [j], T. Nakano [j], K. Niwa [j], N. Nonaka [j], K. Okada [j], O. Sato [j], T. Akdogan [k], V. Paolone [k], C. Rosenfeld [l], A. Kulik [k,l], T. Kafka [m], W. Oliver [m], T. Patzak [m], J. Schneps [m]

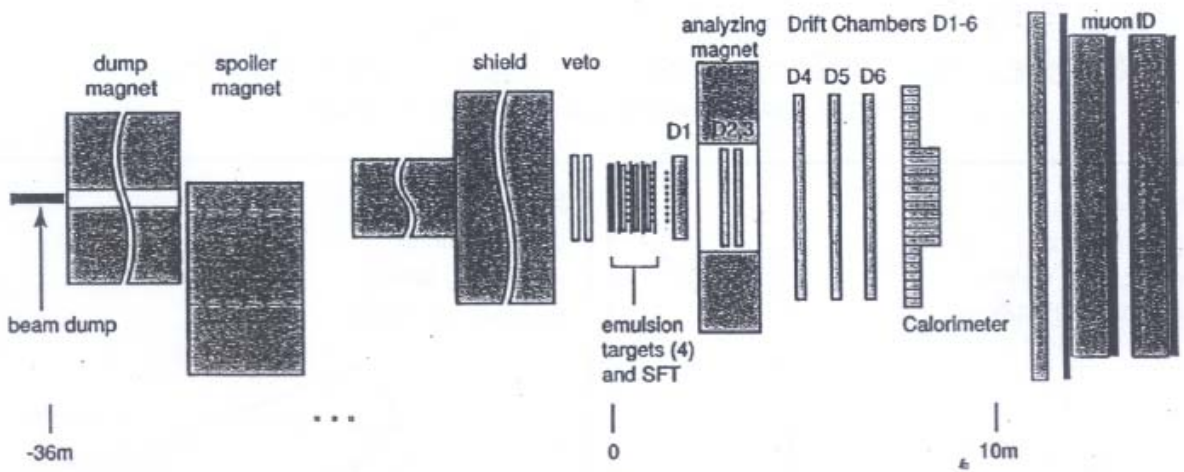
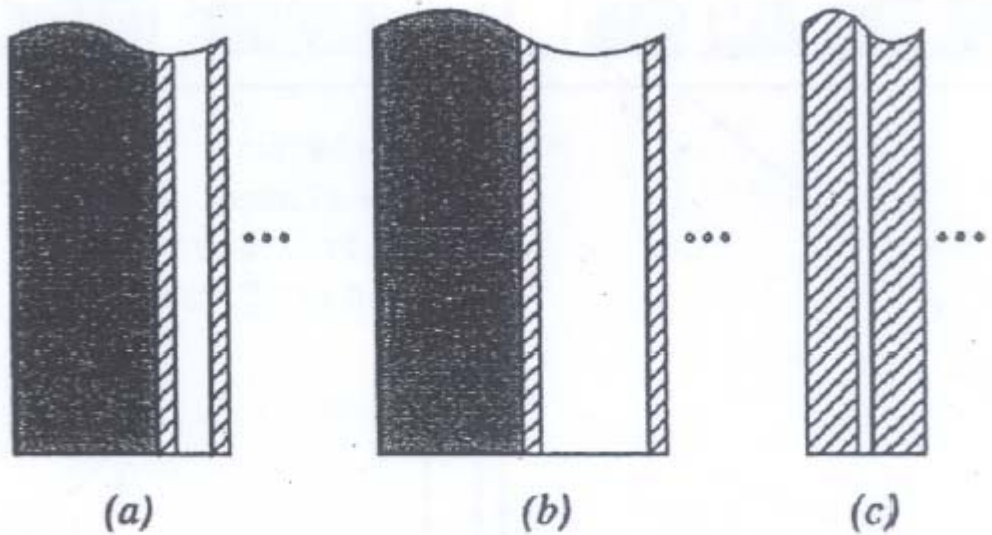


Fig. 1. Experimental beam and spectrometer. At the left, 800 GeV protons were incident on the beam dump, which was 36 m from the first emulsion target. Muon identification was done by range in the system at the right.

Emulsion target design



ig. 2. Emulsion target designs. The ECC designs (a) and (b) used stainless steel sheets interleaved with emulsion plates. Most neutrino nteractions were in the steel. The bulk emulsion type (c) used thicker emulsion layers, without steel. Steel is indicated by shading, emulsion y cross-hatching, the plastic base is unshaded.

"DONUT" demonstration of ν_τ

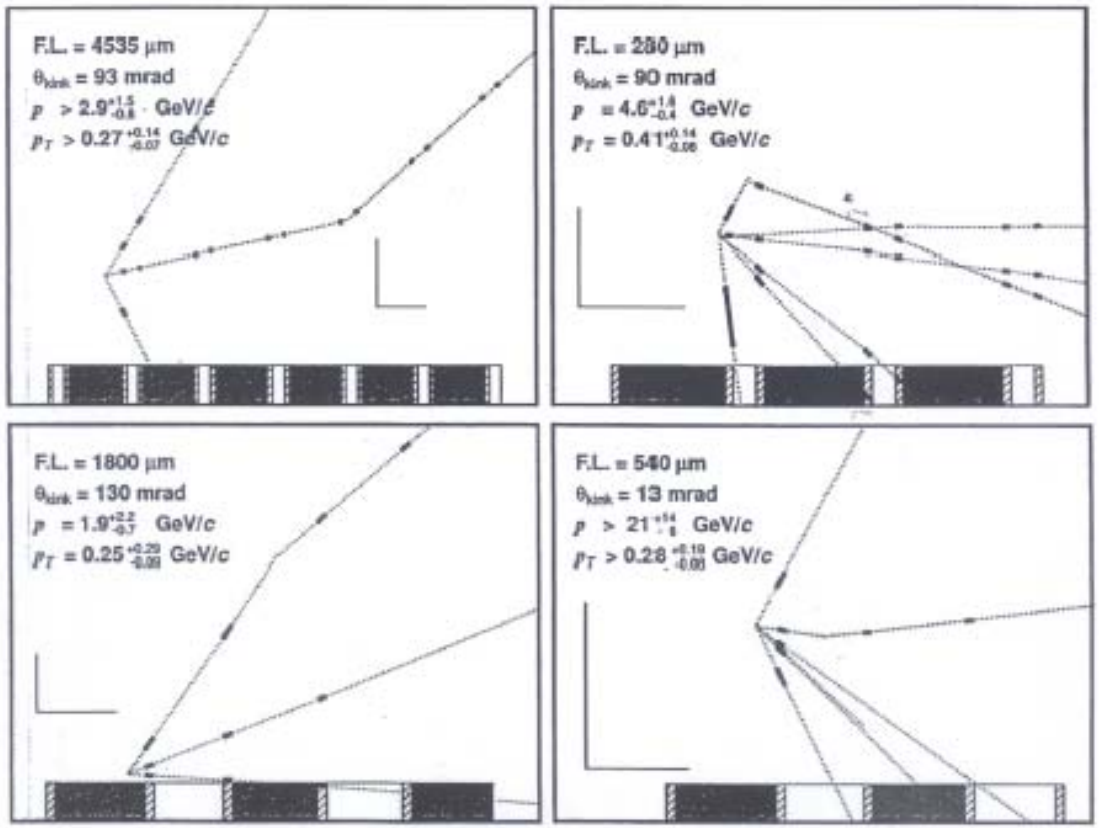


Fig. 3. The four ν_τ CC interaction events. (Top left) 3024-30175, (top right) 3039-01910, (bottom left) 3263-25102, (bottom right) 3333-17665. The neutrinos are incident from the left. The scale is given by the perpendicular lines with the vertical line representing 0.1 mm and the horizontal 1.0 mm. The target material is shown by the bar at the bottom of each part of the figure representing steel (shaded), emulsion (cross-hatched) and plastic (no shading).

J.Steinberger

Search for the Tau-Neutrino



Historical Development

1975- τ - lepton discovered ; 'ν_τ' postulated to exist

Late 70's: DELCO, MARK II, : τ - decay studies, Michel Parameter ρ, τ-lifetime, τ-μ Universality.

1980's - MARK II, TASSO, CLEO, ARGUS, LEP: τ - decay studies, 'ν_τ' helicity = -1, spin = ½.

1986 - E531 : Is 'ν_τ' may be ν_e, ν_μ? No, no direct couplings of the τ-lepton to ν_e,or ν_μ.

1991 - LEP demonstrates 3.00 ν 's

2000 – DONUT: Direct Observation: First 4 ν_τ CC events

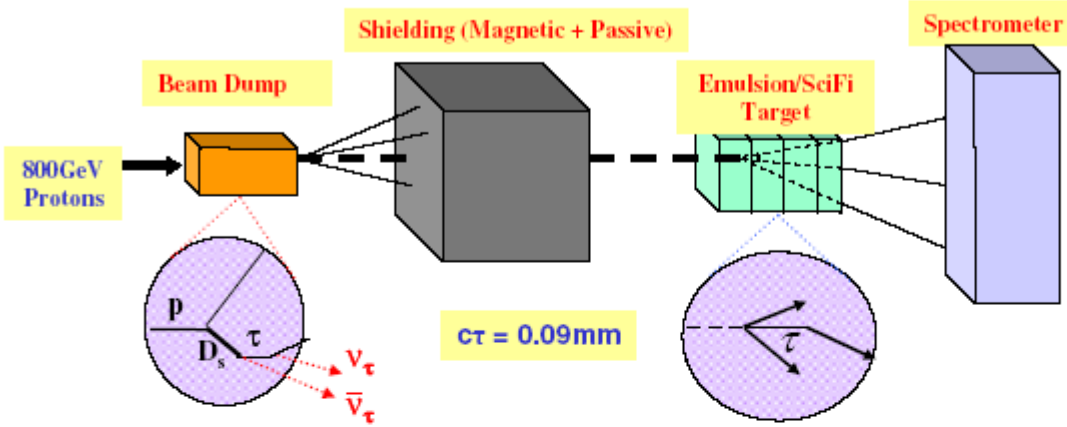
The DONUT Experiment



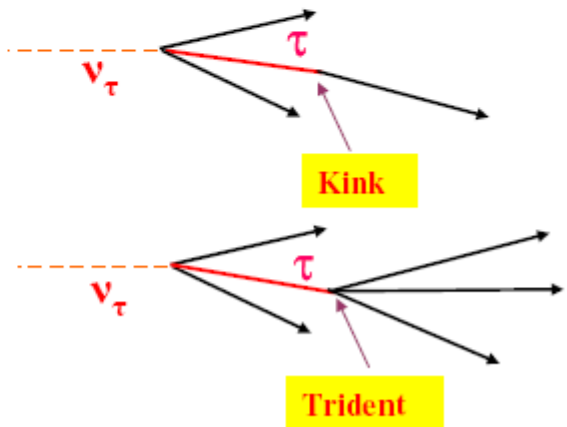
- Designed to observe directly and study the charged-current interactions of the tau-neutrino.
- Uses a hybrid emulsion spectrometer to locate and identify ν_τ – Nucleus CC interactions.
- First 4 events published in Phys. Lett. B 504, 218(2001)

DONUT = Direct Observation of NU Tau

How is it Done?



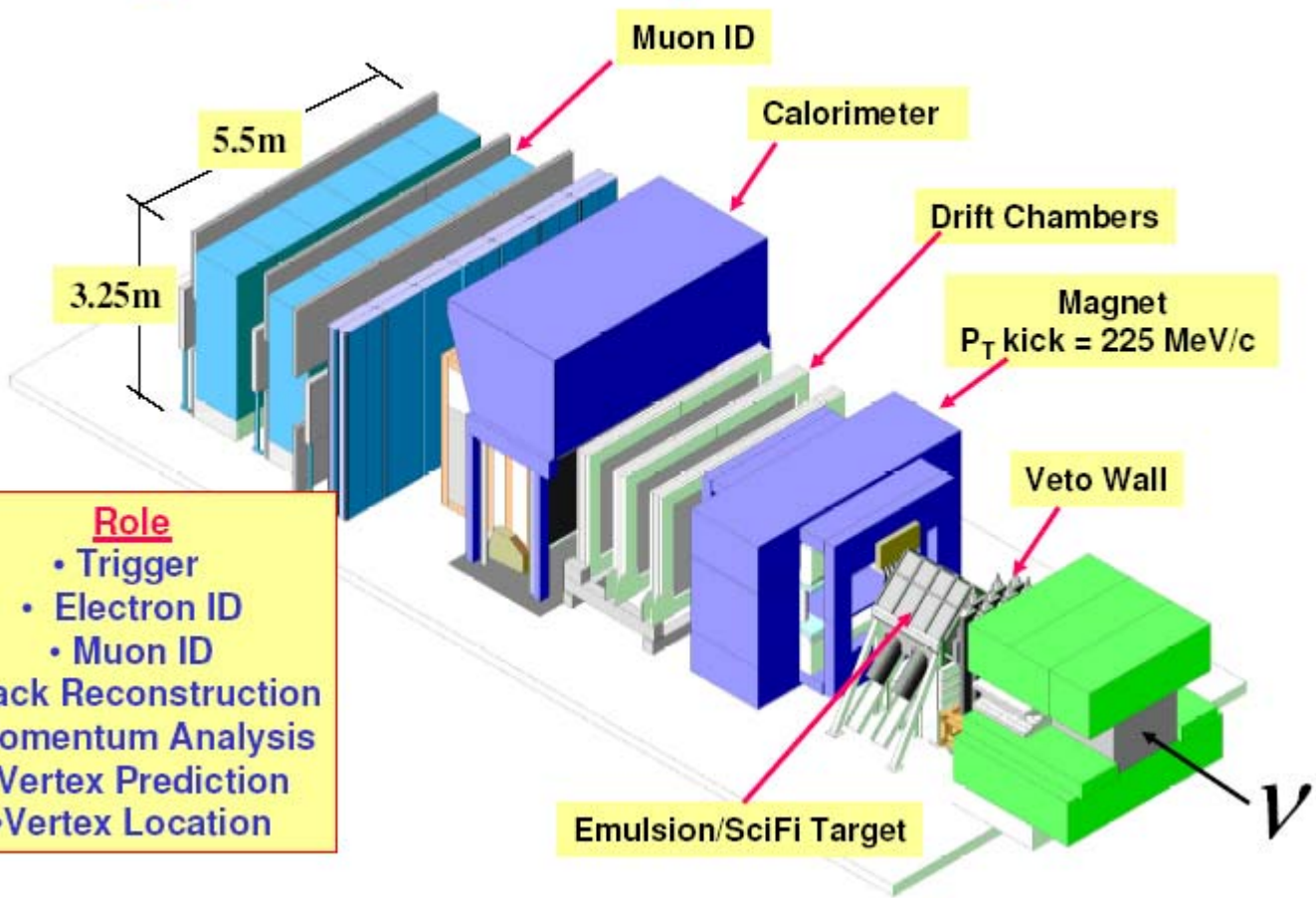
- 800 GeV protons → Beam Dump → ($D_s \rightarrow \nu_\tau$ + ..)
- Magnetic/Passive shield to protect the emulsion
- Emulsion target at 36 m
- Spectrometer: vertex, track ID, P
- Emulsion scanning: Locate vertex, Decay search
- Find ν_τ by topology: Kinks and tridents



G. Tzanakos, Neutrino 2006, Santa Fe, New Mexico, 14-6-2006

The characteristic signature of a tau neutrino event is the observation of a primary interaction track with a bend point or kink, identifying this track as a tau lepton

Hybrid Emulsion Spectrometer



Role

- Trigger
- Electron ID
- Muon ID
- Track Reconstruction
- Momentum Analysis
- Vertex Prediction
- Vertex Location

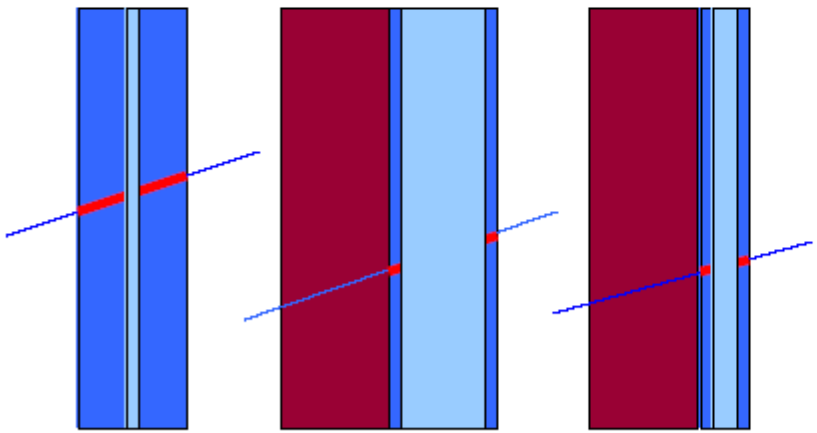
Emulsion Target Technology



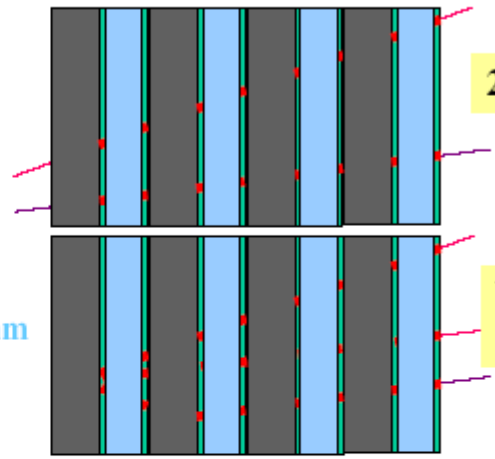
3-D Tracker

Basic Block: Steel / Emulsion / Acrylic / Emulsion

EAE	SEAE	SEAE
BULK	ECC800	ECC200
	1.0 mm	1.0 mm
0.32 mm	0.10 mm	0.10 mm
0.08 mm	0.80 mm	0.20 mm



95% emulsion 5% emulsion

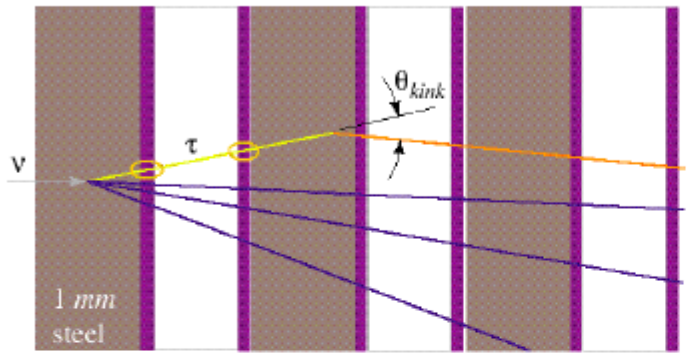


2 tracks

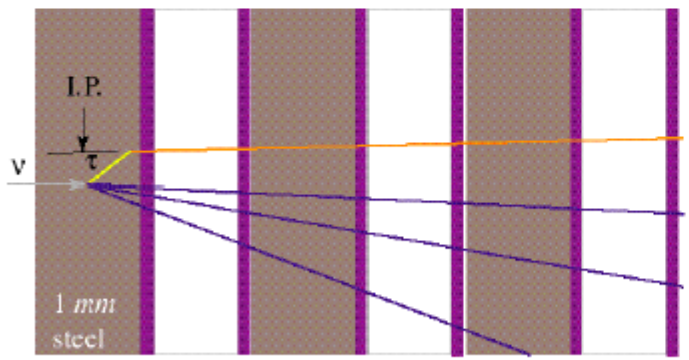
Vertex + 3 tracks

- AgBr suspended in a gel (Fuji ET7C) coated on plastic sheets.
- 29±2 grains per 100 μm for minimum ionizing track
- Spatial Resolution: 0.3 μm
- Vertex Resolution: 0.8 μm
- OPERA: Same idea

Decay Search



1. *Long Decays*
   - parent measured
   - 1-prong (kink)
   - 3-prong (trident)
   - τ ⇒ no 1ry *lepton*
   - ~75% of kinks



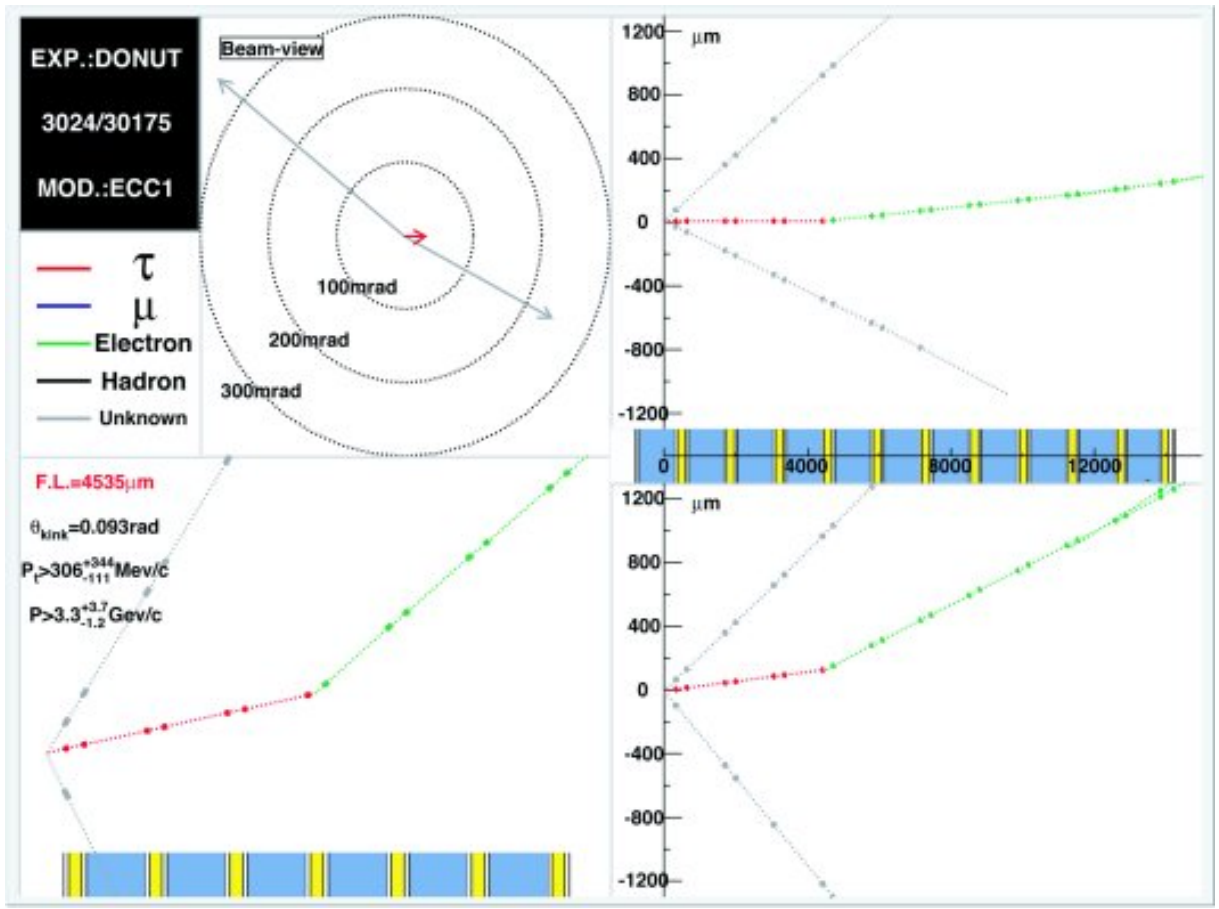
2. *Short Decays*
   - IP wrt 1ry vertex
   - only daughter meas.
   - daughter seen in spect.
   - ~25% of kinks

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

$$\tau^- \rightarrow \left(\mu^- \text{ or } e^-\right) \nu_\mu \nu_\tau \text{ or } \tau^- \rightarrow h^- \nu_\tau$$

TAU DECAY INTO AN ELECTRON

One of the four observed tau neutrino charged current interactions.
The kink signature of the tau decay is clearly visible. The target is represented at the bottom:
steel = blue
emulsions = yellow
In this example the tau decays into an electron.



ν - τau Event List



Kinks

DONUT Preliminary

Run	Event	FL (mm)	θ_{kink} (rad)	IP (μm)	Daug t	P (GeV/c)	P_T (GeV/c)	P_τ	P_c	P_l
3024	30175	4.47	0.093	416.0	e	5.2 ± 0.8	0.48	0.64	0.36	0.0
3039	01910	0.28	0.089	23.5	h	$4.6^{+1.6}_{-1.0}$	0.41	0.96	0.04	0.0
3140	22143	4.83	0.012	60.2	μ^+	$16.8^{+18.4}_{-6.0}$	0.20	0.97	0.03	0.0
3333	17665	0.66	0.011	7.7	e	53 ± 12	0.69	0.99	0.01	0.0
3024	18706	1.7	0.014	22.6	e	50 ± 10	0.70	1.0	0.0	0.0
3139	22722	0.53	0.022	11.8	h	$15.8^{+127}_{-5.1}$	0.35			

Tridents

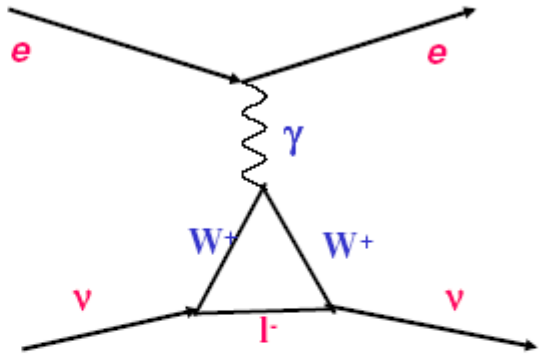
DONUT Preliminary

Run	Event	FL (mm)	θ_d (rad)	IP (μm)	P (GeV/c)	P_T (GeV/c)	P_τ	P_c	P_l
3296	18816	0.78	0.054	38.2	5.0	0.27	0.71	0.29	0.0
			0.190	148.1	$1.3^{+0.6}_{-0.3}$	0.25			
		0.80	0.130	112.0	1.9	0.25			
3334	19920	8.88	0.017	147.4	$11.6^{+5.9}_{-3.0}$	0.20	1.0	0.0	0.0
			0.011	98.0	$15.7^{+17.2}_{-5.6}$	0.17			
			0.011	94.1	$3.2^{+1.1}_{-0.7}$	0.04			
3250	01713	0.83	0.133	109.9	$1.3^{+.03}_{-0.2}$	0.17	0.71	0.03	0.26
			0.192	160.7	$2.4^{+0.8}_{-0.5}$	0.46			
			0.442	354.7	$0.5^{+0.2}_{-0.1}$	0.21			

ν - tau Magnetic Moment



Interaction of ν with e^- via a dipole moment has a distinct signature
- single, forward e^-
- dominates e-w process for $T_e/E_\nu < 0.2$



$$\frac{d\sigma^{\mu}}{dy} \propto \left(\frac{\mu_\nu}{\mu_B}\right)^2 \left(\frac{E_\nu}{T} - 1\right)$$

1 event observed after cuts
2.3 Bgnd events expected

$\mu_\nu < 3.9 \times 10^{-7}\ \mu_B$ 90% CL

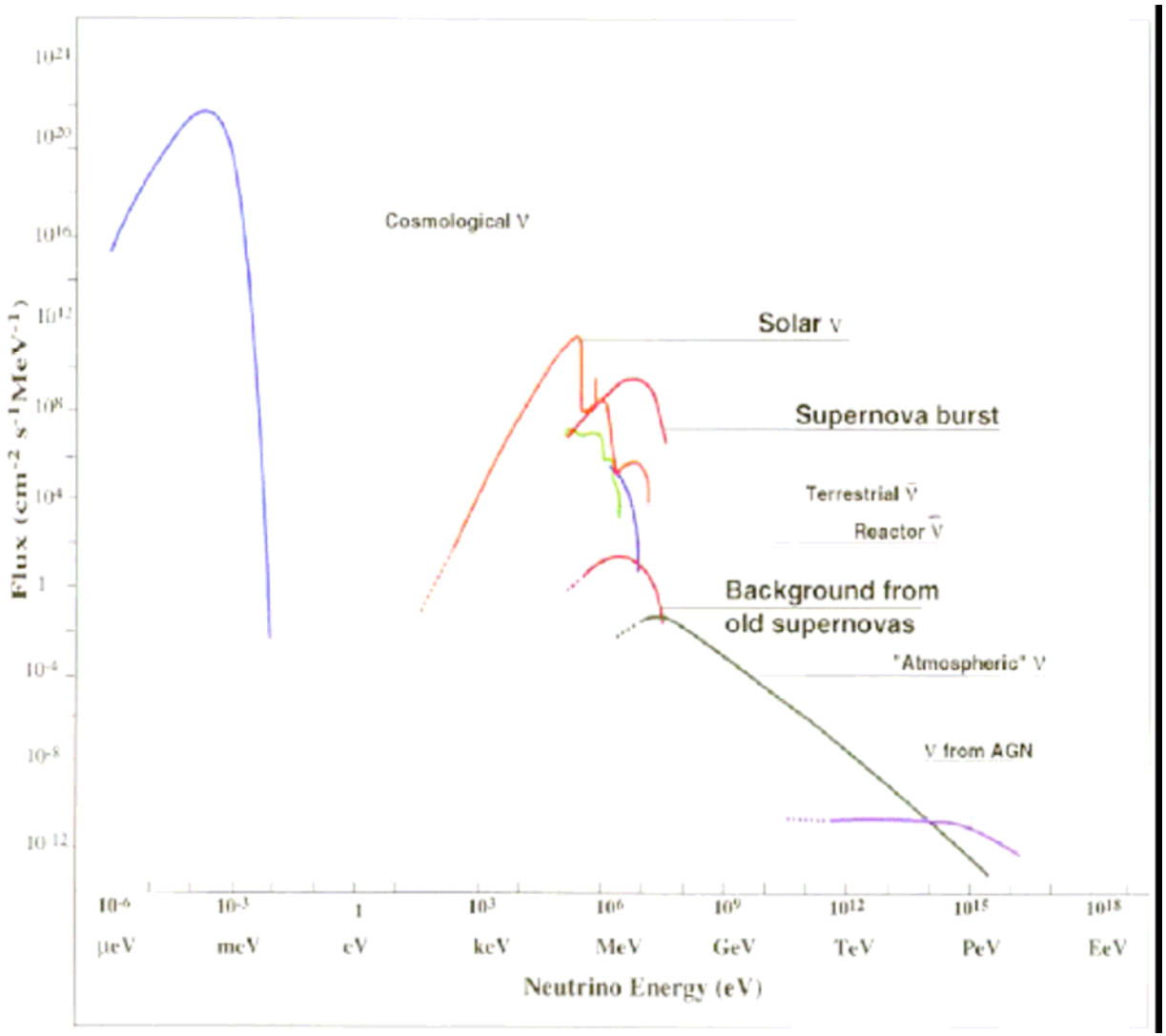
Published in Phys. Lett. B 513, 23 (2001)

Summary and Conclusions



- DONUT has directly observed the tau-neutrino as a particle via its CC interactions with nuclei.
- 9 (CC) tau events have been identified in DONUT. Number consistent with expectations from the S-M. (Also consistent with charm production from prompt ν_μ, ν_e).
- First measurement of ν_τN DIS consistent with S-M.
- We have precise τ – decay studies from collider experiments (Michel parameters, life time) and $N_\nu = 3$ from LEP which are in excellent agreement with the S-M.
- **Conclusion:** Above properties justify assigning this neutral particle of J=1/2, H = -1, as the weak isospin ½ partner of the τ-lepton .

Sources of Neutrinos: Flux vs energy



O.L.G.Peres

SOURCES OF NEUTRINOS

- *Neutrinos from mankind's activity*

  - *Nuclear reactors* produce $\bar{\nu}_e$, typical energy few MeV , flux 10^{20} per second

  - *Particle accelerators (CERN, Fermilab)* produce *beams* of $\nu_\mu, \bar{\nu}_\mu (\bar{\nu}_e, \bar{\nu}_\tau)$
    Energies up to 500 GeV, typical flux 10^{11} per second

- *Neutrinos from the Earth*

  - *Natural radioactivity* provides the Earth with 20 TW of power.
    Generates $\bar{\nu}_e$ of a few MeV, typical flux 10^7 per cm^2 per second

- *Neutrinos from Space*

  - *The Sun* is a prolific source of ν_e (10^{38} per second). Flux on Earth 10^{11} per cm^2 per second
    Typical energy < 1 MeV, but spectrum extends up to 15 MeV

  - *Supernova* explosions produce 10^{57} ν_e in 10 seconds. Flux on Earth depends on distance.

  - *Cosmic rays* (mainly protons) interacting in the atmosphere generate $\nu_\mu, \bar{\nu}_\mu$ $(+\nu_e, \bar{\nu}_e)$
    produced in pion (muon) decay. Typical energy 1 GeV, typical flux 10^3 per m^2 per second

  - *The Big Bang* generated 10^{87} neutrinos of all types. Typical energy today 0.0004 eV
    Average density in Universe 660 per cm^3

Richard Wigmans

RELIC NEUTRINOS

- Most abundant particles in Universe (6 billion ν for each proton)
- How to detect? Weak interaction @ 2 Kelvin?
- Possibly significant astrophysical/cosmological implications of a non-zero neutrino mass

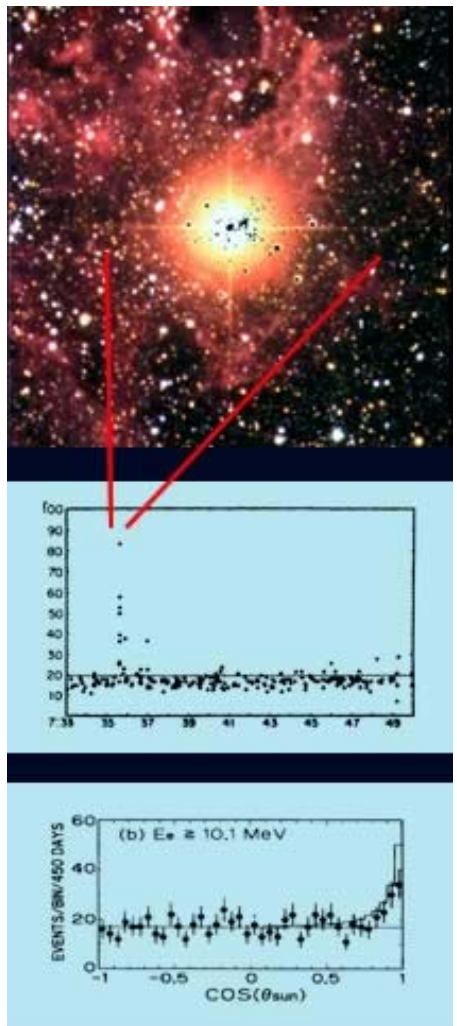
  Indications:

  - Features of high-energy cosmic-ray spectra
  - Large-scale structure of Universe
  - Accelerated expansion of the Universe

Richard Wigmans

Kamioka (II) and IMB see supernova neutrinos

- Kamioka saw a dozen of the 10^58 neutrinos produced when the 1987A supernova exploded, 170,000 light years from the Earth.
- First clear observation of neutrinos produced outside our galaxy



SN1987a



2/21/1987 2/26/1987

Richard Wigmans

Neutrinos from Supernova 1987a

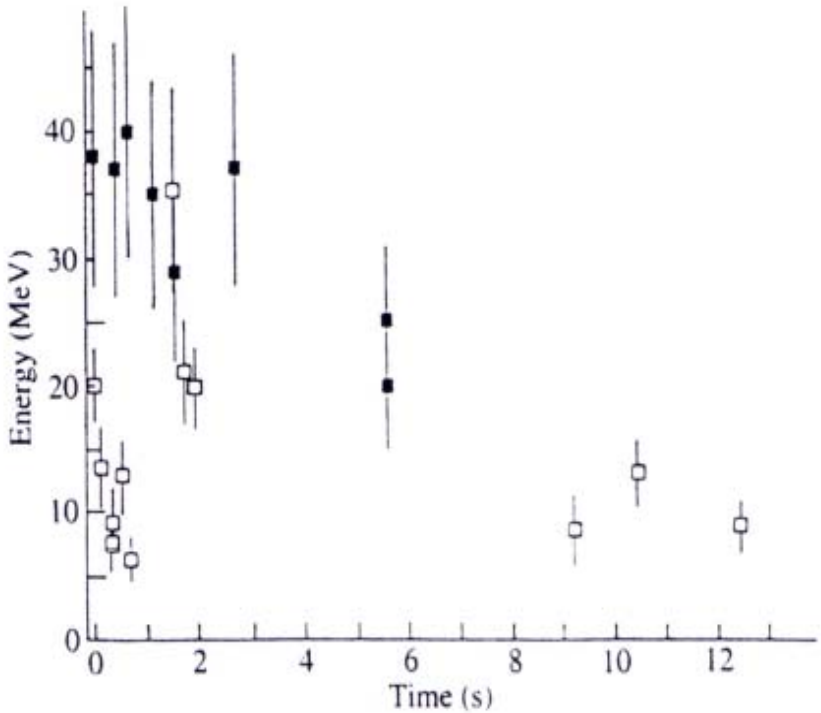


Figure 7.2 Energies vs. time of the Kamiokande (open squares) and IMB (filled squares) neutrino events. The Kamiokande time axis has been shifted as if the first neutrinos arrived simultaneously in both detectors.

Richard Wigmans