50 Years Neutrino

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1. Birthdate
2. Neutrino Hypothesis
3. Lesson from muon decay
4. Neutrino beam
5. $2\,\nu$-Race
6. Neutrino and Standard Model
7. Neutrino Astronomy

NOVE

February 7, 2006

Birthdate

Cowan and Reines wrote a telegram to Pauli (14/6/1956) :

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

Pauli's Answer

Thanks for message.

Everything comes to him

who knows how to wait.

Pauli's ν-Hypothesis

Puzzle in β-decay experiments : the energy spectrum is continuous

- Energy conservation not valid
- Pauli's desperate way out in a letter (Zürich, 4.Dezember 1939) to the group of the Radioactives at Tübingen

> Liebe Radioaktive Damen und Herren!
> ...nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschließungsprinzip befolgen und sich von Lichtquanten noch dadurch unterscheiden, daß sie nicht mit Lichtgeschwindigkeit laufen...

Remark to a friend

Anecdote told by Herbert Pietschmann:

Pauli said to his astronomer friend Walter Baade

> Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally!

Baade bet, that one day it will be detected. After the discovery, Pietschmann asked Fred Reines during a meeting at Aachen. Reines furiously confirmed that Pauli paid his bet (a case of champagne), but the Champagne was drank by the theoreticians alone and he and Cowan did not get any drop of it.

Highlights

- 1930 Pauli's Neutrino Hypothesis
- 1934 Fermi's theory of Weak Interactions
- 1956 Observation by Cowan and Reines
- 1957 helicity of neutrino (V-A)
- 1958 Lesson from muon decay
- 1959 Idea of a neutrino beam
- 1961 The 2-ν race
- 1968 The solar neutrino problem
- 1973 Weak neutral current in Gargamelle
- 1983 $W^+ \to l^+\nu_l$ and $Z \to \nu_l\overline{\nu}_l$
- 1987 Supernova burst
- 1991 LEP: 3 light neutrinos
- 1993 HERA $ep \to \nu_e + anything$
- 1998 Kamioka claims neutrino oscillations
- 2000 DONUT observes the tau-neutrino
- 2001 SNO solves solar puzzle

Fermi's Theory

- 1930: Pauli's neutrino hypothesis
- Known particles : $e \quad p \quad \gamma$
- 1932: Chadwick discovers the neutron
- 1933: Solvay conference
  Pauli suggests the existence of a neutrino
- Fermi picks up Pauli's *new view* and formulates a quantum theory of β decay within two months
- Fermi's letter submitted to *Nature* was rejected because of abstract speculations too far from physical reality to be of interest to the readers
- 1934 Publication in Zeitschrift für Physik
  Versuch einer Theorie der β-Strahlen
- The $e - \nu$ pair acts like a field coupled to the charge changing $p - n$ current

From Fermi to V-A

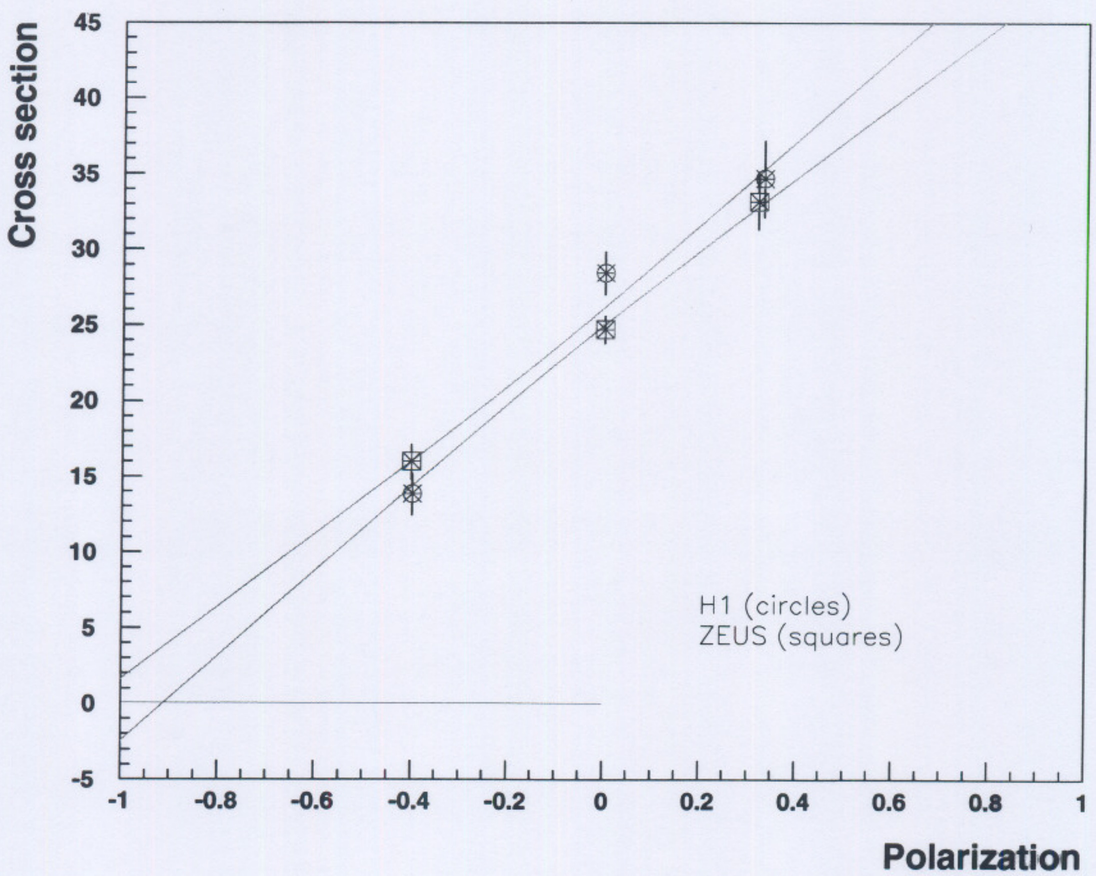
- 1934-1956: Structure of 4-fermion interaction is (V,A) or (S,P,T)
- 1956: $\theta - \tau$ puzzle and parity
- 1957: Experiment by Wu et al demonstrates parity violation
- ν is a left-hander $\Rightarrow$ 2-component theory
- 1958: V-A (Sudarshan & Marshak and Feynman & Gell-Mann)
- Current-Current formulation of weak interactions with universal coupling

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

- Firm theoretical basis for the first ν experiments opening the GeV range
- ep collider HERA: a recent test of V-A

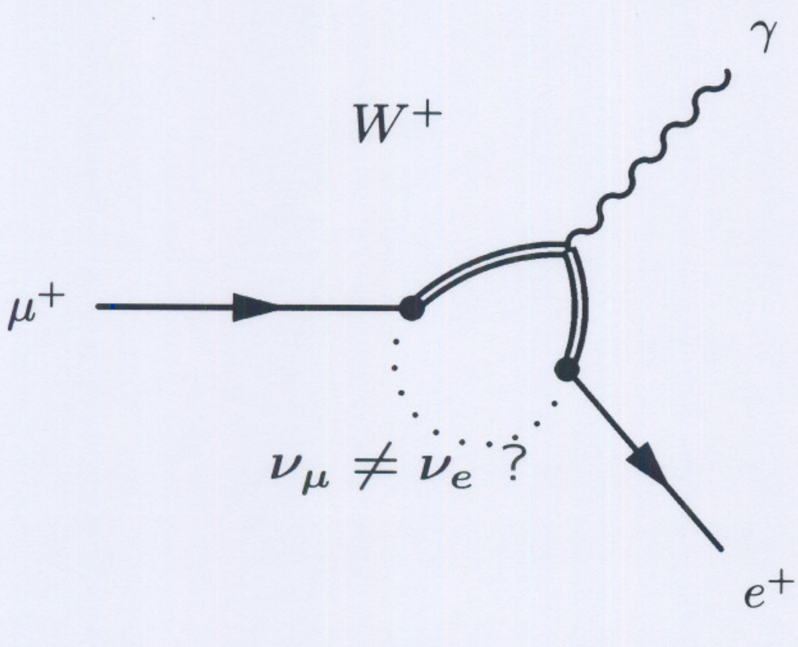
HERA: polarized positrons

- Purely weak process $e^+ + p \rightarrow \overline{\nu}_e + anything$ at HERA ($\sqrt{s} = 300$ GeV)
- e^+ is massive $\Rightarrow$ two helicity states : $(e^+)_R$ and $(e^+)_L$
- Weak process : only $(e^+)_R$ participates $\Rightarrow$ show $(e^+)_L + p \rightarrow \overline{\nu_e} + anything$ vanishes
- H1 and ZEUS with polarized e^+ beams:



Feinberg's Argument (1958)

- $V - A$ suggests Intermediate Vector Boson $W^{\pm}$ analogous to γ
- The decay $\mu^+ \to e^+\gamma$ is known to be strongly suppressed
- If IVB exists, then sizeable decay rate expected unless two neutrino species

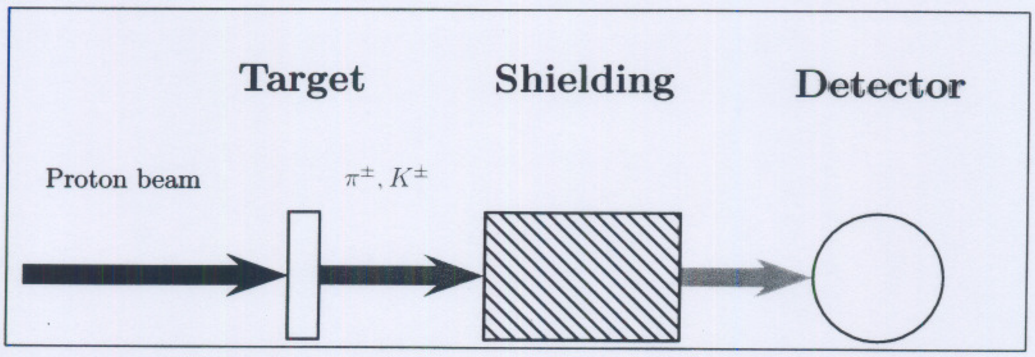


Pontecorvo (1959) : test both ideas with high energy neutrino beam

Accelerator Neutrino Beams

Two proton synchrotrons under construction at CERN (24 GeV) and BNL

Idea by Bruno Pontecorvo (1959) and Melvin Schwartz (1960) for multi-GeV ν-beam



- p-beam: $p + nucleus \rightarrow \pi^+ + anything$
- main decay mode $\pi^+ \rightarrow \mu^+ + neutrino$
- $\pi^+ \rightarrow e^+ + neutrino$ suppressed

Aim:

- $\nu_\mu \neq \nu_e$? Observe ν-induced interactions and count events with μ and e
- W ? Search for dilepton events

T.D.Lee's Catalog

- V-A theory describes all known (low energy) weak phenomena
- T.D.Lee's to-do list (Phys.Rev.Lett. 4 (1960) 307)

  #1 : Identity of neutrinos

  #3 : Neutral lepton current

  #8 : The intermediate vector boson W

- Bad high energy behaviour : cure with *neutral currents* or *heavy leptons*

The 2-ν Race

- Bernardini picks up Pontecorvos's idea
- Early 1960 feasibility study : Krienen,Steinberger and Salmeron (ν flux and shielding), BC (EP and Ramm) and counter-cloud chamber(Faissner)
- SPC in May 1960 : very promising
- AGS at BNL completed in summer 1960 : Lederman, Schwartz and Gaillard propose 10 t spark chamber
- CERN decides in November 1960 to carry out ν experiment
- April 1961 CERN Seminar : T.D.Lee lecture on neutrino questions
- Alarm in May 1961 : Dardel measures secondary π flux and concludes that ν flux was overestimated by factor 10
- BNL finds two ν species (publ.June 1962)
- CERN Council in June 1962: race lost, now ν more than ever

The ν_τ

- From $(e\ \mu\ \nu)\ (p\ n\ \Lambda) \to \begin{pmatrix}\nu_e \\ e\end{pmatrix}\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}\begin{pmatrix}u \\ d\end{pmatrix}\begin{pmatrix}c \\ s\end{pmatrix}$
- 1975: heavy lepton τ observed at SLAC
- Data on $e^+e^- \to \tau\overline{\tau}$ show: τ in iso-doublet $\Rightarrow$ where is the neutral partner ?
- LEP 1991: Three light neutrinos from Z-decay width
- 2000: First observation reported by DONUT to Sudbury Conference in Canada
- DONAT at FNAL:

  a. beam dump : $p + N \to D_s + anything$

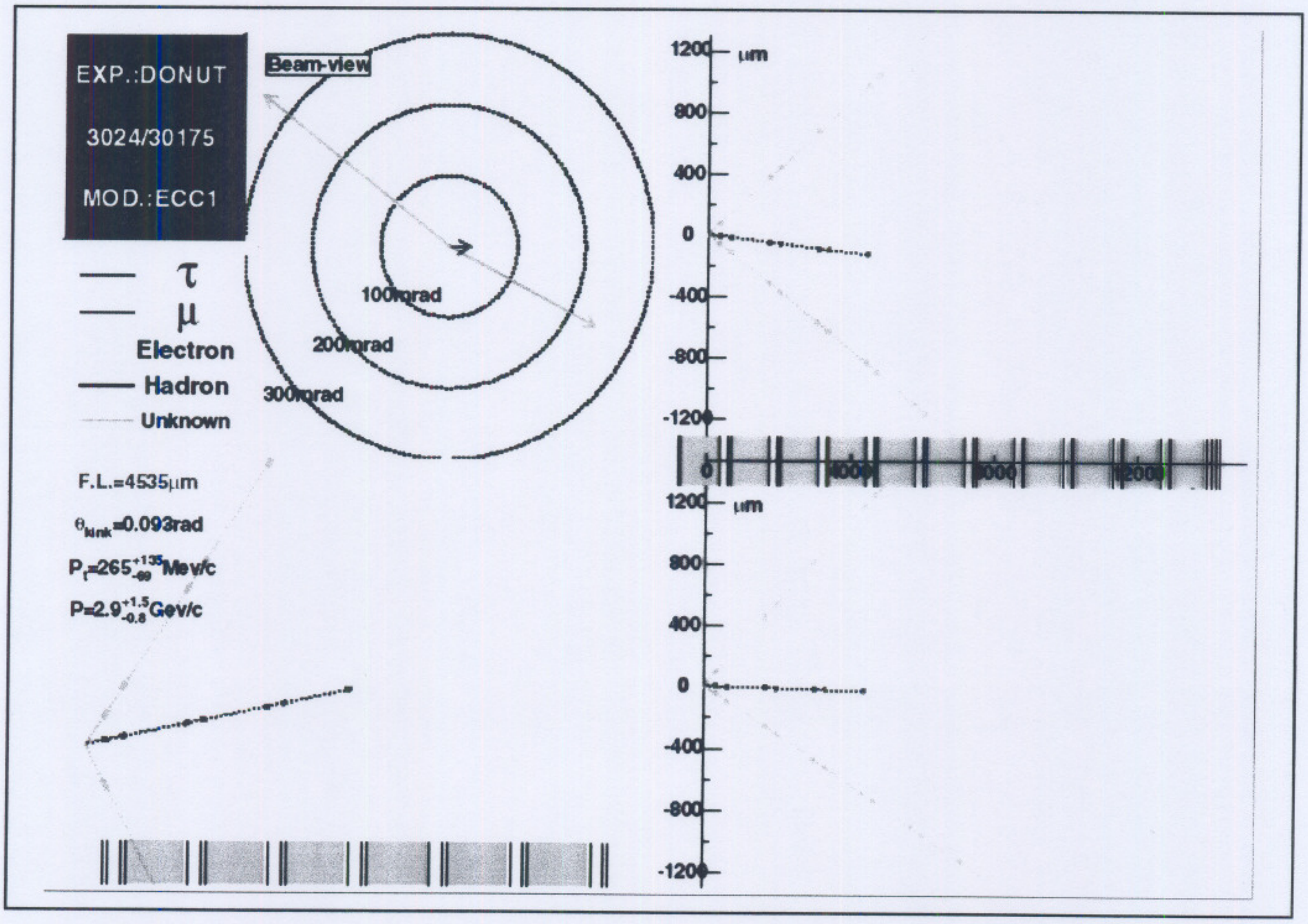
  b. $c\overline{s} \to \tau^+ + \nu_\tau$ and $\tau^+ \to \bar{\nu}_\tau + X$

  c. search in emulsion for $\nu_\tau + N \to \tau + anything$

  d. choose 1-prong τ-decays (86 %)

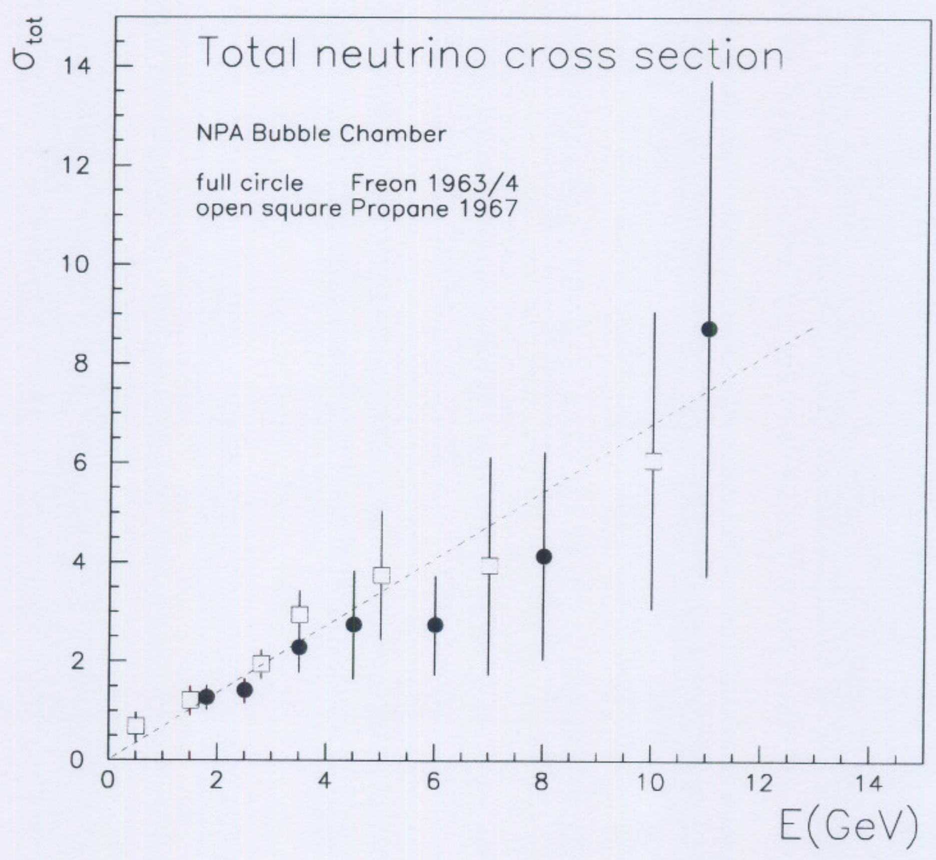
A ν_τ-event in DONUT

- $\nu_\tau + N \to \tau + hadrons$
- $\tau \to \nu_\tau + e + \overline{\nu}_e$



Searching for W

- Siena 1963 : dilepton signature; observe one event in BC $\nu_\mu + p \to \mu^- e^+ + p$ (interpretation as W production with $W^+ \to e^+ + \nu$) and several $\mu^+\mu^-$ events in SC
- Attribute events to background (charm ?)
- Search for W-propagator in $\sigma_{tot}(\nu N)$



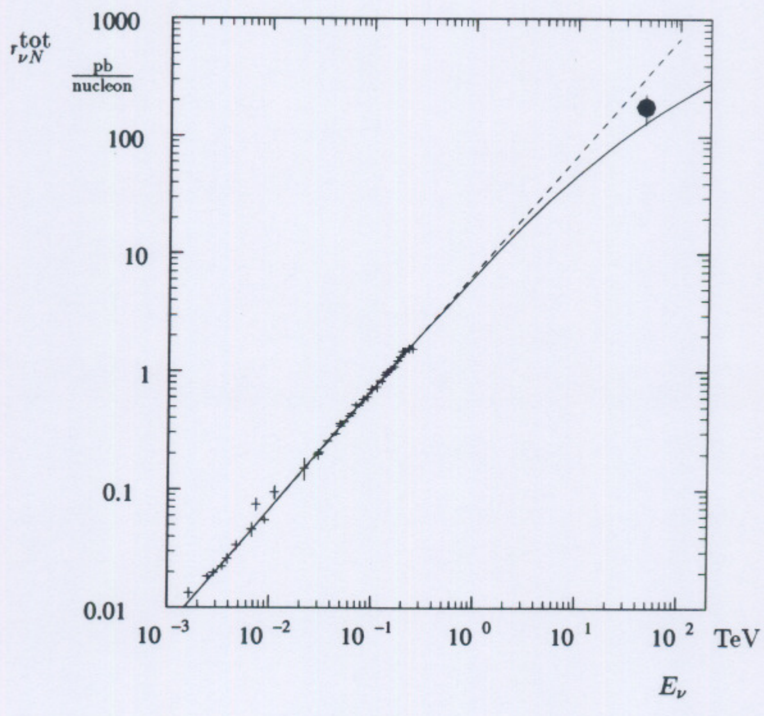
- Gradual increase every few years until HERA

W Propagator

- 1993 : First observation of the CC process $e^+ + p \rightarrow \overline{\nu}_e + anything$ at HERA
- Now $Q^2 = \mathcal{O}(M_W^2) \Rightarrow$ feel propagator

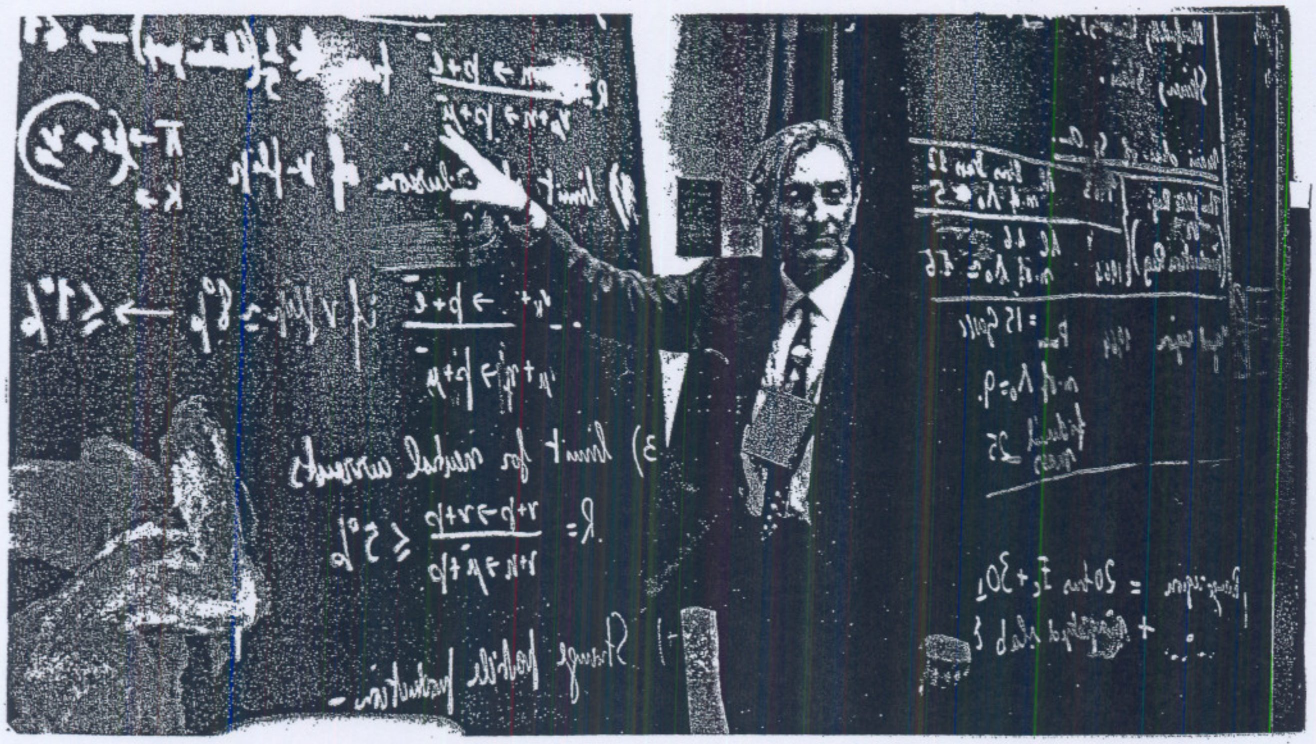
$$\frac{1}{1 + Q^2/M_W^2}$$

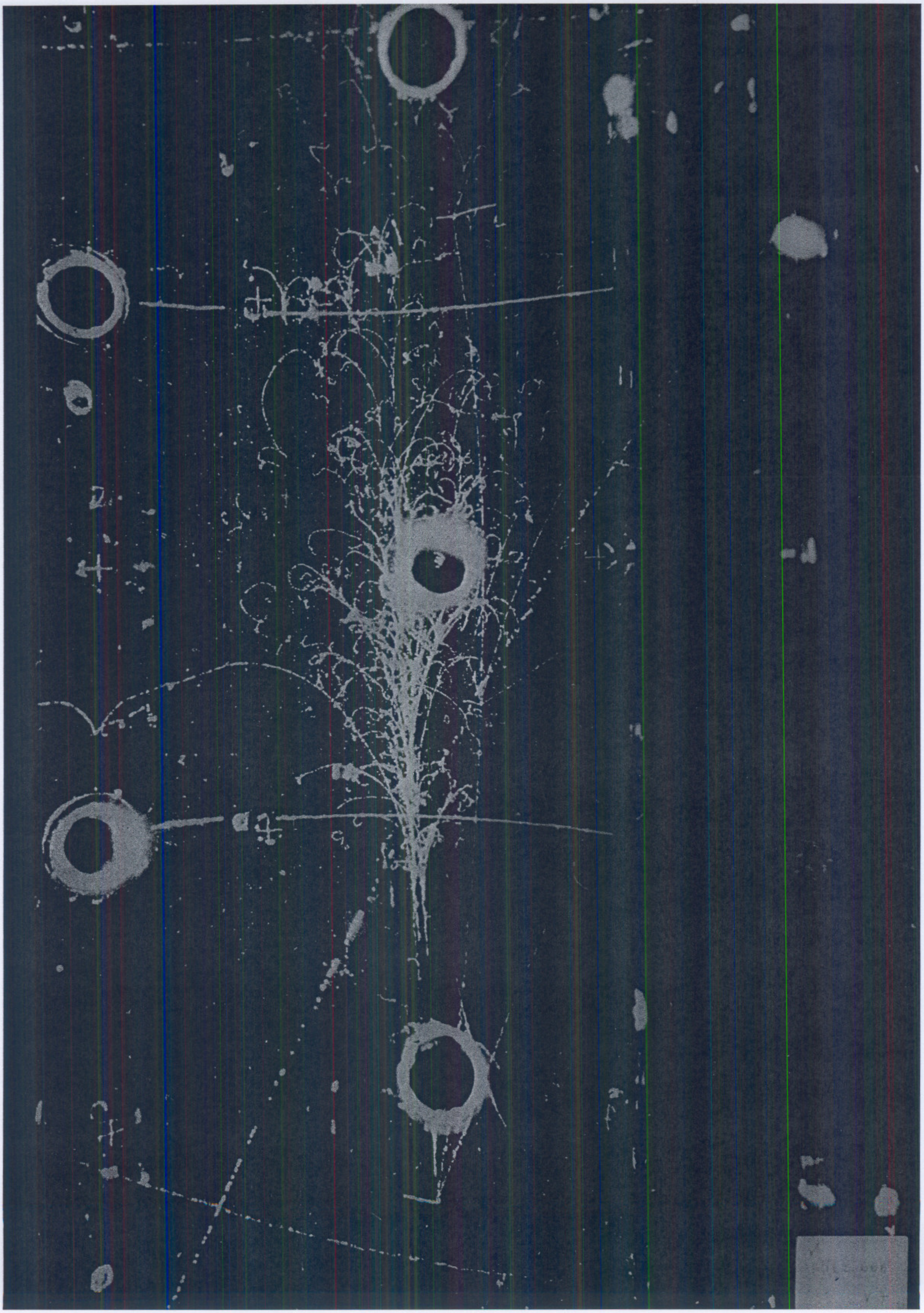
- Interpret as fixed target experiment, i.e. projectile energy of $\mathcal{O}$(50 TeV)



Discovery of Weak Neutral Currents

- CERN starts a long term neutrino program
- Improved ν beam : Van der Meer's horn
- Runs 1963/4 in Ramm NPA 1m HLBC (Freon, later Propane) and SC
- NC in Lee's catalog, Seminar by John Bell and Martinus Veltman
- Theory : Weak Interactions renormalizable ?
- Search for NC: in elastic and 1 π channels
  Problem : neutron-background
  Low upper limits $\Rightarrow$ consensus: no NC
- Next generation of HLBC: Gargamelle 1970-1978
- Physics aims: W and proton substructure (SLAC 1967)
- Turnover: 't Hooft's proof and n^* distribution $\Rightarrow$ NC-dedicated search





Key to W-mass

- GSW relates G_F and $\alpha \Rightarrow$ predicts W-mass

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

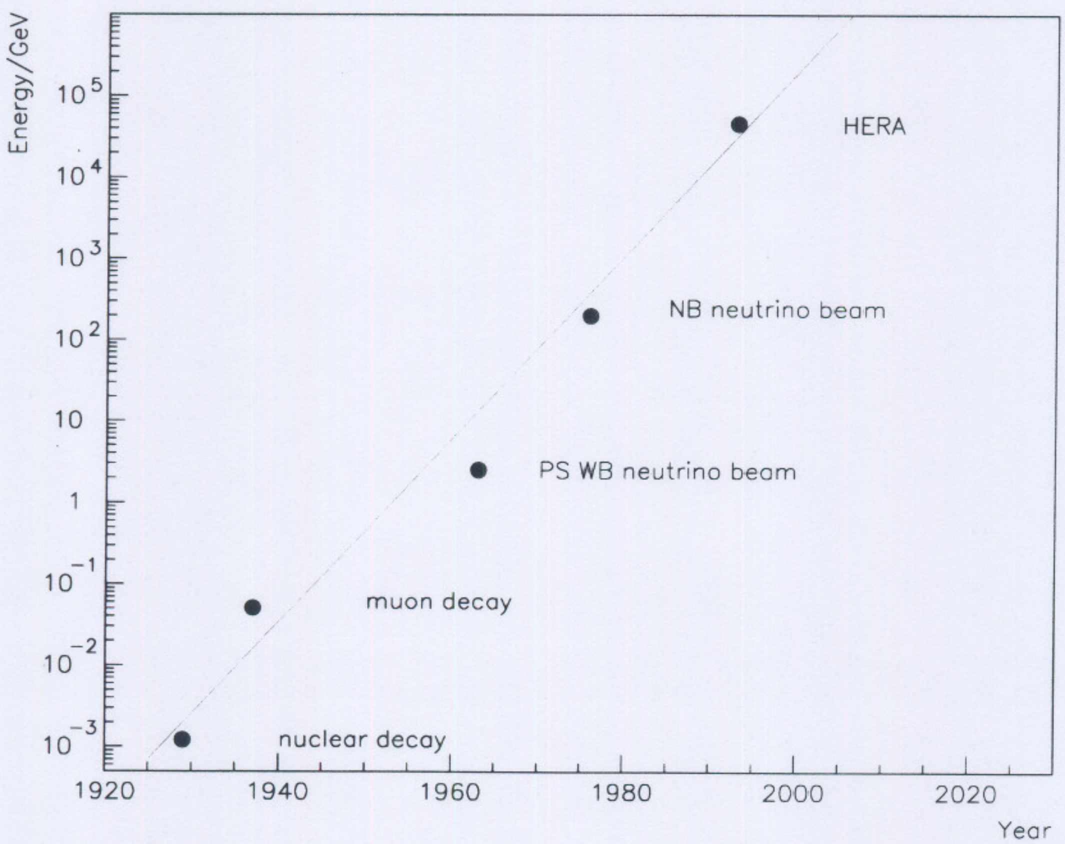
- 1973-1976 : neutrino experiments yield $\sin^2\theta \approx 0.3 \pm 0.05 \Rightarrow m_W \approx 70$ GeV
- Fixed target neutrino experiment cannot see W propagator
- Aachen 1976 : Cline, Rubbia and McIntyre propose $p\overline{p}$ project
- 1983 : UA1 and UA2 observe W and Z hermetic detectors: physics with missing momentum
- Test quantum corrections of GSW: Measure M_W and predict M_W through $\sin^2\theta_w$; need accuracy $\pm$ 0.005

Neutrino and Standard Model

- 1973 discovery of weak neutral currents in Gargamelle neutrino experiment
- Breakthrough to models with NC, e.g. GSW
- New era : worldwide program to study NC with impact on accelerators and colliders, omnipurpose detectors, sociology of collaborations, astrophysics
- New term electroweak
- 1976 : neutrinos yield key to W-mass $\Rightarrow$ start $p\overline{p}$ project
- $\nu + p \rightarrow \nu + N + \pi$ (Δ via NC)
- APV, SLAC ed; PETRA/PEP A_l
- ν-physics at high precision: test quantum corrections with $\sin^2\theta$ to $\pm$ 0.005
- High Q^2 region: SLC/LEP and HERA

From β decay to its inverse

- Nuclear Decay (End 1920ies) $n \rightarrow p + e + \nu$
- Reactor (1956) $\overline{\nu}_e + p \rightarrow e^+ + n$
- Proton Accelerators $\nu_l + N \rightarrow l + anything$
- HERA Collider (1993) $e^+ + p \rightarrow \overline{\nu}_e + anything$



Factor 10 increase per decade

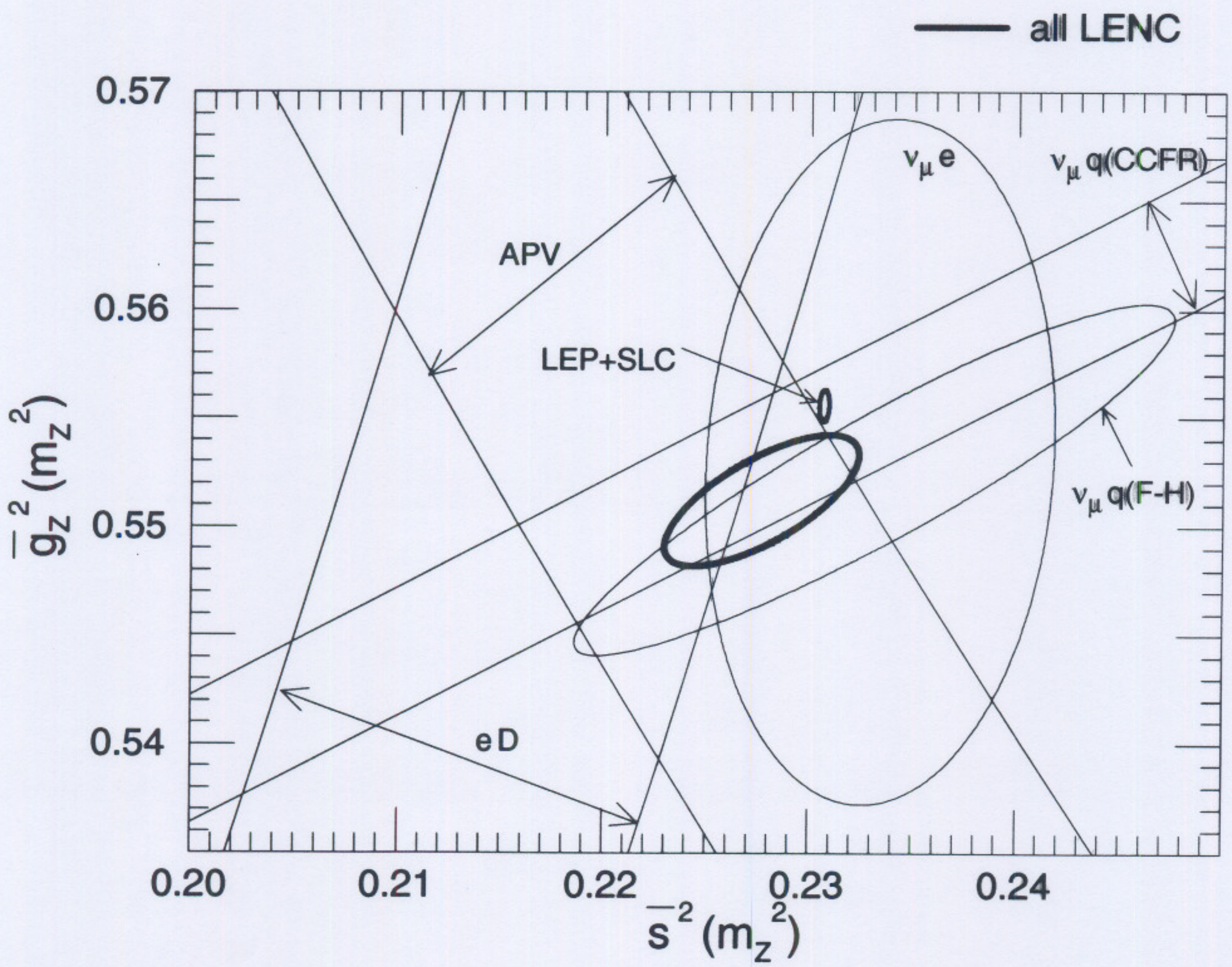
Fit to NC data

ν-experiments: NC($\nu,\overline{\nu}$) and $\nu_\mu e$, $\overline{\nu}_\mu e$

Atomic parity violation : Cs atom

SLAC ed : polarisation asymmetry

All data in ($\overline{s}^2(0)$,$\overline{g}_z^2(0)$)-plane shifted to $Q^2 = M_Z^2$
(note: $\sin^2\Theta_{eff} \approx \overline{s}^2(M_Z^2)$+0.0010)



EPJ **C2** (1998) 95

Solar Neutrinos

Pioneered and first observed by Ray Davis.

Attitude of Maurice Goldhaber (BNL,1963) :

> No astrophysicist can calculate anything with sufficient precision to be of any interest to any particle physicist.

Important theoretical work

- Bethe 1938 : energy production of stars,
- Pontecorvo : $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
- Bahcall (1964) : solar ν-flux calculation

Result (1968) : $\Phi(meas)/\Phi(calc) \approx 0.3 \neq 1$
$\Rightarrow$ the solar neutrino problem

Solar Neutrino Problem

Possibilities (1968) :

- Problem in measurement
- Problem in solar nuclear fusion processes
- Problem in particle physics

Trigger new activities on all three frontiers

- New experiments and new techniques : GALLEX/GNO (pp cycle), SAGE, Kamioka (pioneered Water Cerenkov and observed $\nu e \rightarrow \nu e$) later SK, SNO
- He seismography
- Neutrinos massive ?
  GUT : ΔB=0 ? Searches for proton decay (underground experiments); neutrino background decisive

We know today : Neutrinos oscillate

Neutrino Experiments

Any ν-experiment involves three aspects :

ν-**production**	ν-**propagation**	ν-**detection**

Neutrinos interact weakly

- Good : information over cosmic distances
- Bad : Need massive detectors

Sources

- Terrestrial : decays, reactor, accelerator
- Astrophysical : sun, supernova, cosmic rays

Propagation

- in vacuum or matter (Wolfenstein, MSW)

Detection

- Bubble Chambers, omnipurpose detectors
- underground detectors

Neutrino Oscillations

No principle guaranties : $m_\nu = 0$

- Unitary neutrino mixing matrix U

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

- Propagation leads to oscillations

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

- Oscillation length: $\lambda_{j1} = 4\pi \frac{E}{\Delta m^2_{j1}}$
- Sensitivity to $\Delta m \Leftrightarrow$ large L, small E
- No hint : need many experiments to restrict the multi-parameter phase space

The long way to ν oscillations

Oscillation condition

$$\frac{L}{\lambda} = 0.4 \frac{\Delta m^2}{eV^2} \frac{L/km}{E/GeV} = \mathcal{O}(1)$$

Short base line L

- Systematic searches in reactor and accelerator experiments in the 70s and 80s
- Reach Δm^2 down to 10^{-2} : null results restrict Δm^2-$\sin^2 2\theta$ plot
- Excitement from 30 eV ν_e-mass and LSND

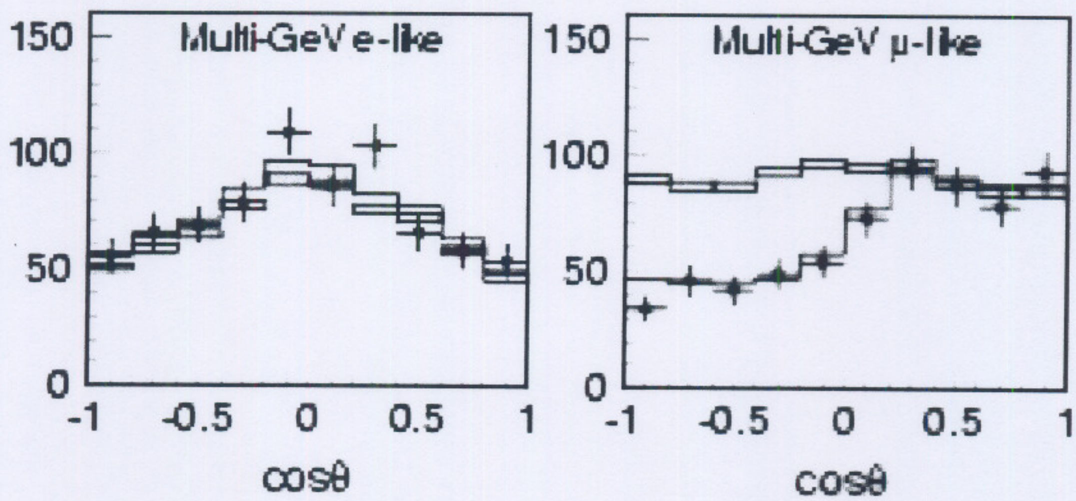
Long base line L

- GUT Theories (1980) motivate search for proton decay
- NUSEX,IMB,Kamioka,Fréjus,Soudan
  ↓
- New technique: water Cerenkov detector
- Change focus on atmospheric ν:
  $R(\mu/e) < 1$? sensitive to $\Delta m^2 < 10^{-2}$ eV^2
  oscillation hypothesis disfavours small $\sin^2\theta$

Evidence for oscillations

Takayama 1998 : SK claims ν oscillations

- Compelling case : comparing atmospheric $\nu, \overline{\nu}$ rate from above ($L/E \approx 15$ km/GeV) and below through earth ($L/E \approx 15000$ km/GeV)

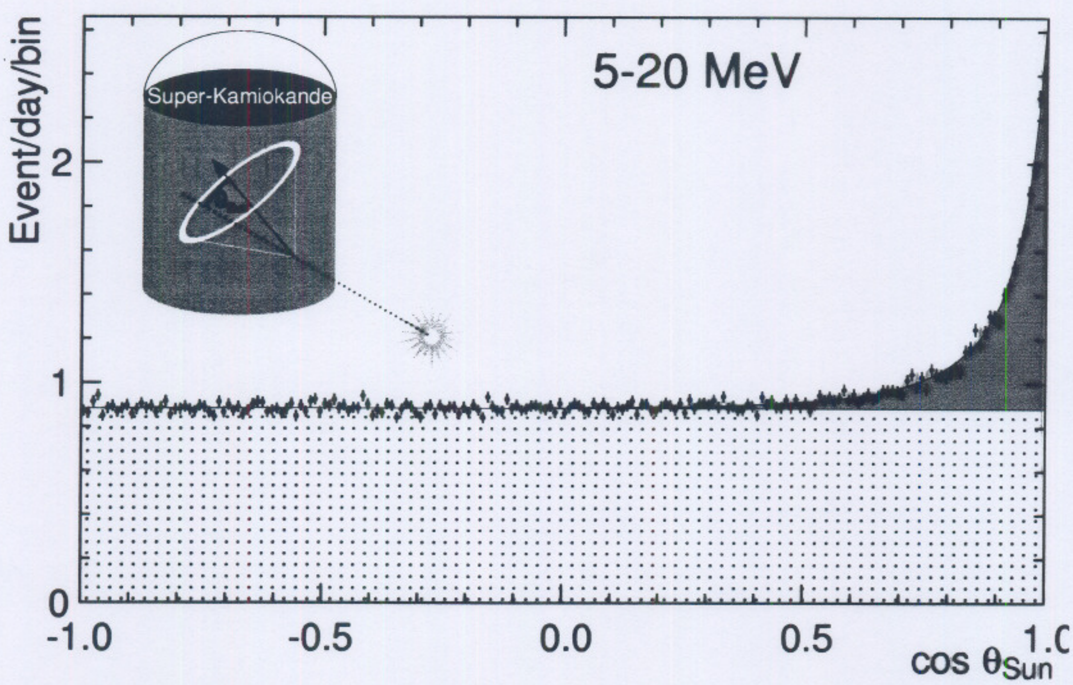


- up/down ratio is robust against systematics
- Conclusion :
  clear deficit for ν_μ and no deficit for ν_e
- Interpretation as oscillation $\nu_\mu \leftrightarrow \nu_\tau$ with large mixing angle

Neutrinos from the sun

SuperKamiokande has small energy threshold and directional information

- Collect high statistics solar ν e events (1996-2001):
  $\Phi^B = 2.35 \pm 0.02 \pm 0.08\ 10^6\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$
- Two contributions: $\nu_e + e \rightarrow \nu_e + e$ (CC+NC) and $\nu_{\mu,\tau} + e \rightarrow \nu_{\mu,\tau} + e$ (only NC)

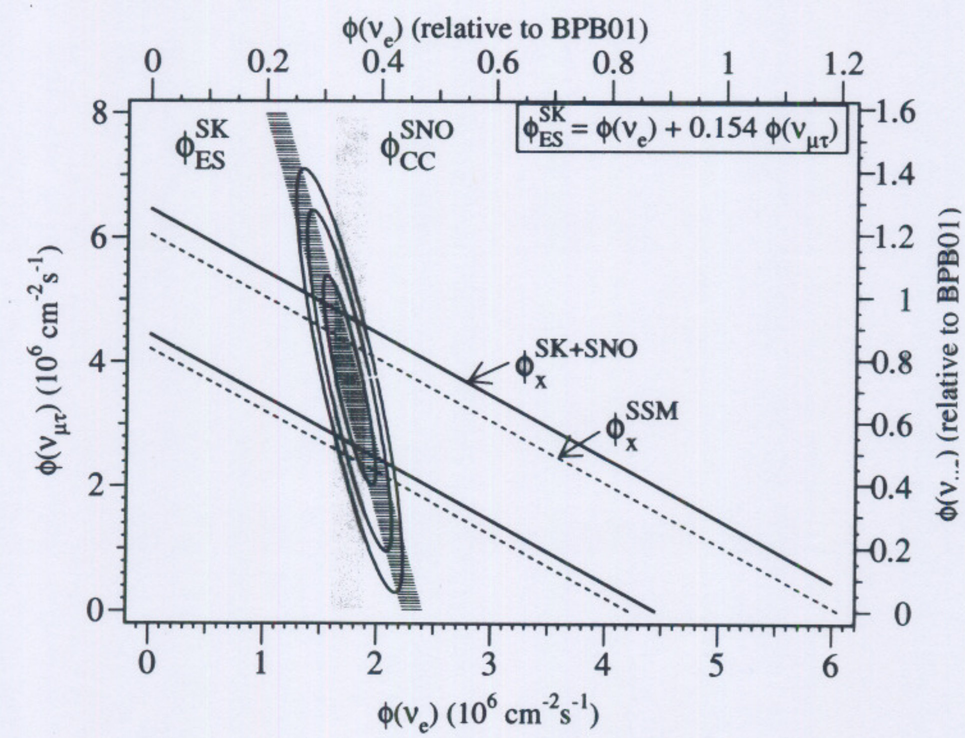


- Compare: first event 1973 $\overline{\nu}_\mu + e \rightarrow \overline{\nu}_\mu + e$ rate 1/year

NO-VE #1

First NO-VE Conference : combine brandnew results from SNO with SK (units 10^6 cm^{-1}sec^{-1})

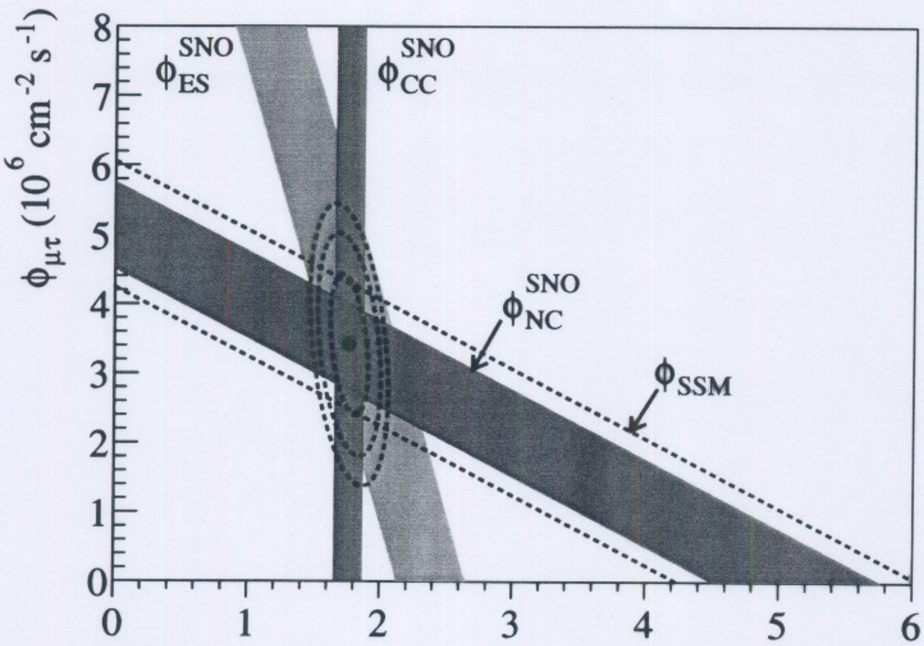
- $\Phi(\nu_e + d \rightarrow e^- + p + p)$ = 1.75±0.07±0.13
- $\Phi(\nu + e^- \rightarrow \nu + e^-)$ = 2.39±0.34±0.16
  agrees with SK 2.35±0.02±0.08
- Note: $\Phi(\nu e) = \Phi(\nu_e e)$ +0.154 $\Phi(\nu_{\mu,\tau})$
- Establish active oscillation component in agreement with solar model



The solar neutrino problem is solved

SNO Update

2002: SNO observes also the NC-reaction:
$\nu + d \rightarrow \nu + p + n.$



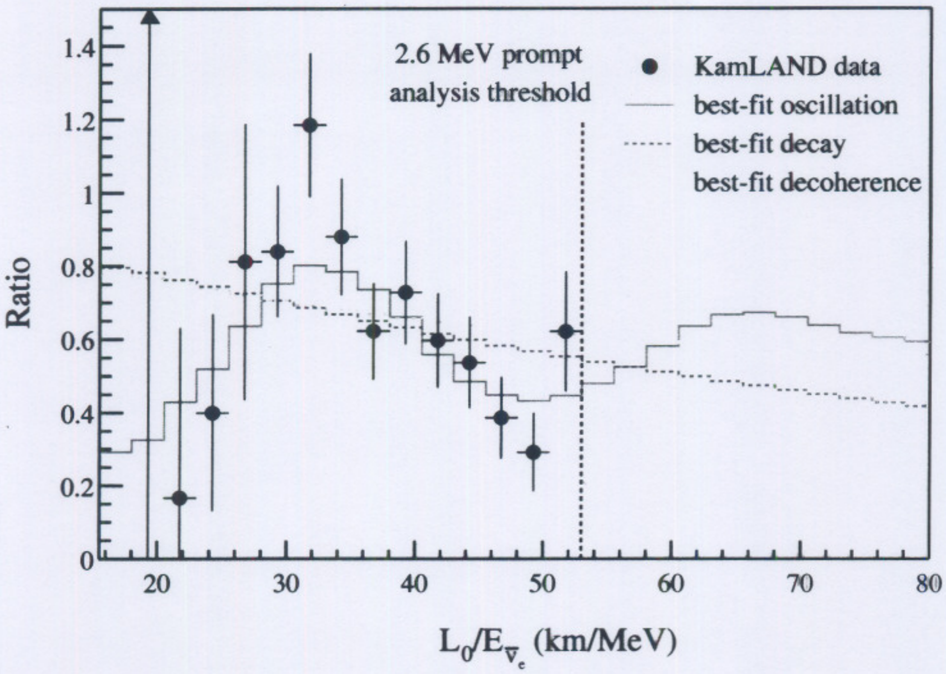
Results from a single experiment :

- $\Phi^{CC}(\nu_e) \approx \frac{1}{3}\ \Phi_{theory}$
- $\Phi^{NC}(\nu)\ \approx\ 3\ \Phi^{CC}(\nu_e)$
- Note the crucial role of weak neutral currents in solving the solar neutrino problem

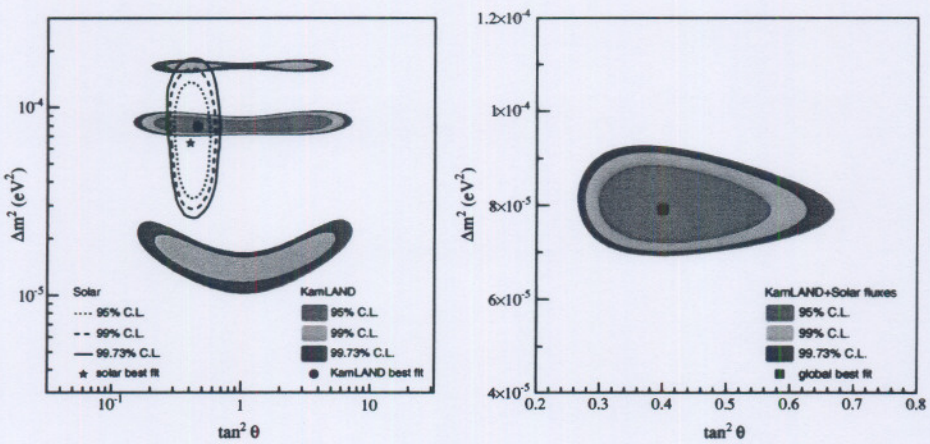
Impact of Kamland

Multi-reactor long baseline experiment

Observe oscillatory behaviour



Solar data + Kamland : LMA solution



SN1987A

An epocal event : Neutrinos from Supernova explosion 1987 observed by Superkamioka and IMB detectors

Wolfenstein's comment :

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

- Cooling mechanism : NC
- Huge flux
- Need worldwide synchronized detector net

Neutrino Haiku

The japanese flavor of the neutrino

Neutrinos reveal
the deep in and the far out
- yet keep their secret

Anonymous

Outlook

We had 50 years of brilliant neutrino physics

- The neutrino joins particle and astroparticle physics and cosmology
- Neutrino oscillations key to new physics
- Precision measurement of U and masses; size of U_{e3} (θ_{13}), CP ?
- ν contribute to mass of universe
- Magnetic moment ?
- Majorana or Dirac ? $\beta\beta$-experiments
- Clarify NUTEV $\sin^2\theta$ and LSND
- Many experiments in progress : OPERA, ICARUS, MINOS, T2K, ICECUBE, ANTARES, NESTOR, NEMO, ...

Neutrino physics has a bright future

NO-VE $n \to n+1$

Thanks to Milla

for providing with NOVE

a marvelous forum to meet

experts and to discuss

the latest results and ideas