Critical Neutrino Experiments Establishing the Standard Model

Ed Kearns – Boston University

The Contest Question: Every year we ask the students to answer a broad-based question depending on the SSI subject. This year the question is:

" What experiment or set of experiments will demonstrably discover new physics beyond the SM & what will be the nature of the theory that replaces it ? "

NB: the existence of DM or neutrino masses doesn't count !

Weinberg (in response to a question):

"Neutrino masses clearly take us beyond the standard model …"

Critical Neutrino Experiments Establishing Our Understanding of the Standard Model with Massive Neutrinos

Early history (pre-Standard Model)

Prediction

Detection

Helicity

Two neutrino experiment

Neutral currents

More modern history (Standard Model Era)

Weak mixing angle

Neutrino as a probe

Three generations

Neutrino puzzles

Solar

Atmospheric

Neutrino Mass

Discovery of neutrino oscillations

Confirmations & Precision measurements

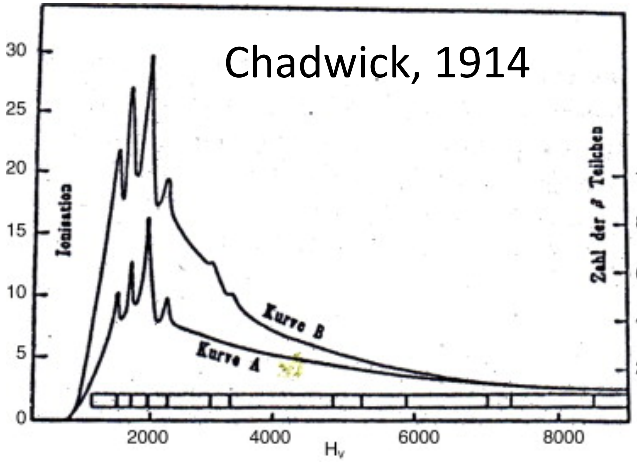
The Neutrino Matrix

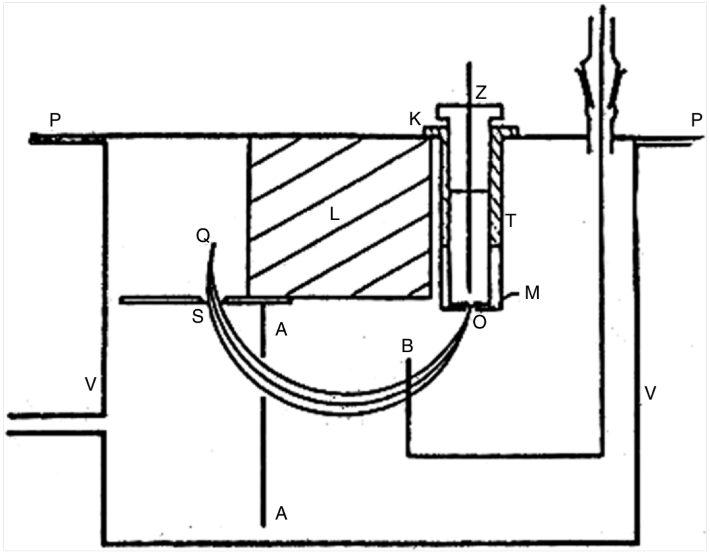
The road ahead

recurring theme of this lecture:

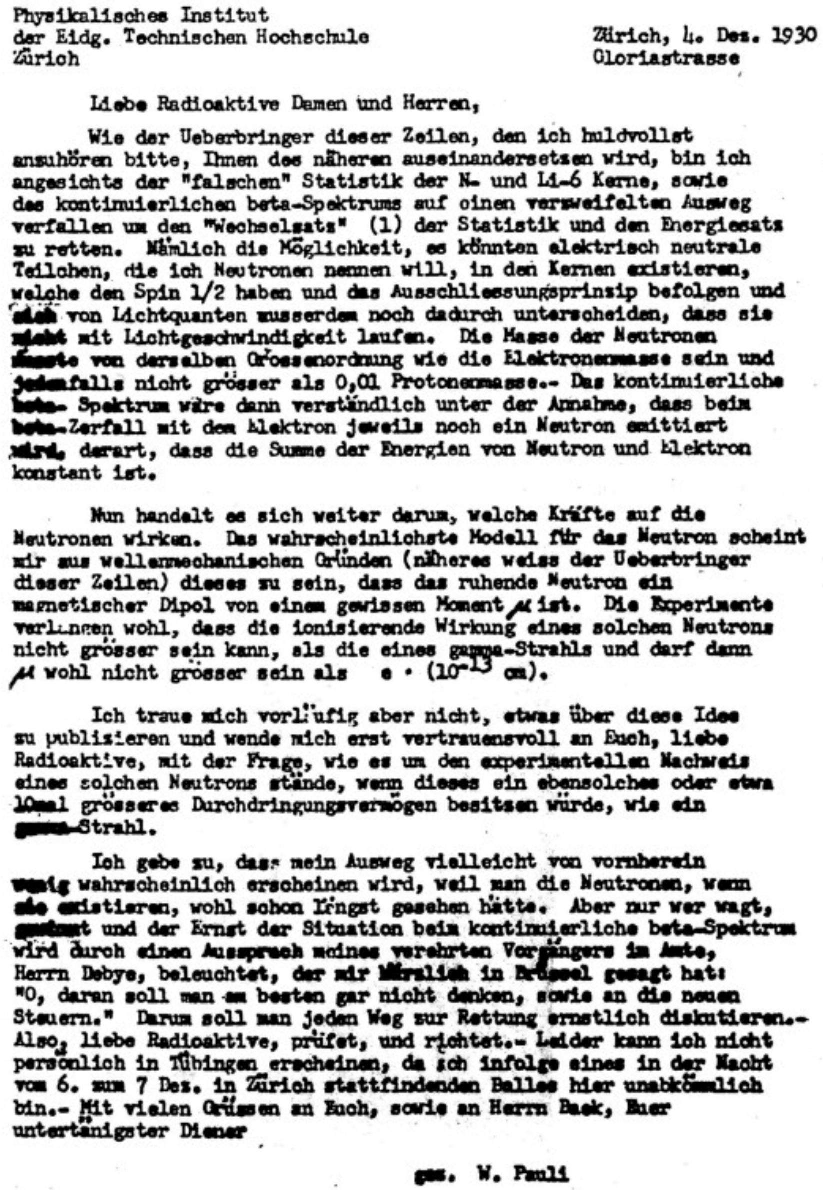
CELEBRATE THE DATA POINTS

Origin Story of the Neutrino





… a desperate remedy …



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. 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 ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Theoretical Insights

Versuch einer Theorie der β-Strahlen. I[1]**).**

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Fermi theory of beta decay

Nuclear Capture of Mesons and the Meson Decay

B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

Muons K-capture like electrons

Interaction of Mesons with Nucleons and Light Particles

T. D. LEE, M. ROSENBLUTH, AND C. N. YANG
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
January 7, 1949

Nuclear beta decay, muon capture, muon decay are universal

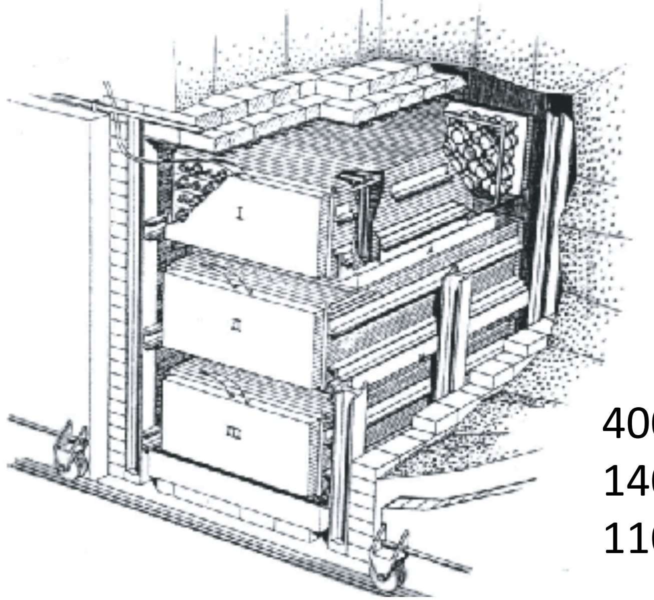
1956

Detection of the Neutrino

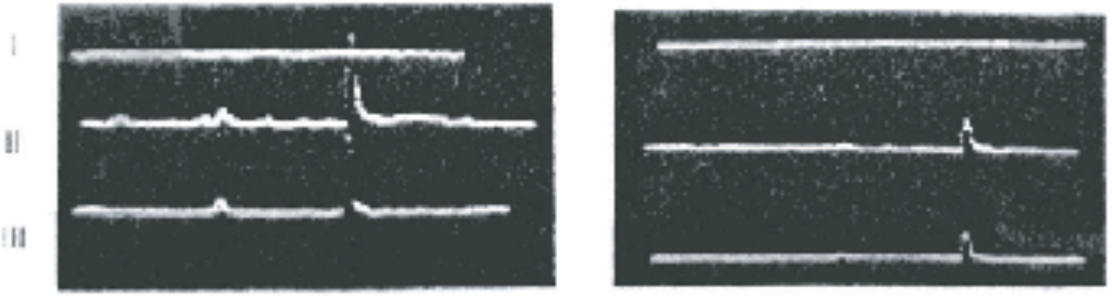
NATURE September 1, 1956 Vol. 178

THE NEUTRINO

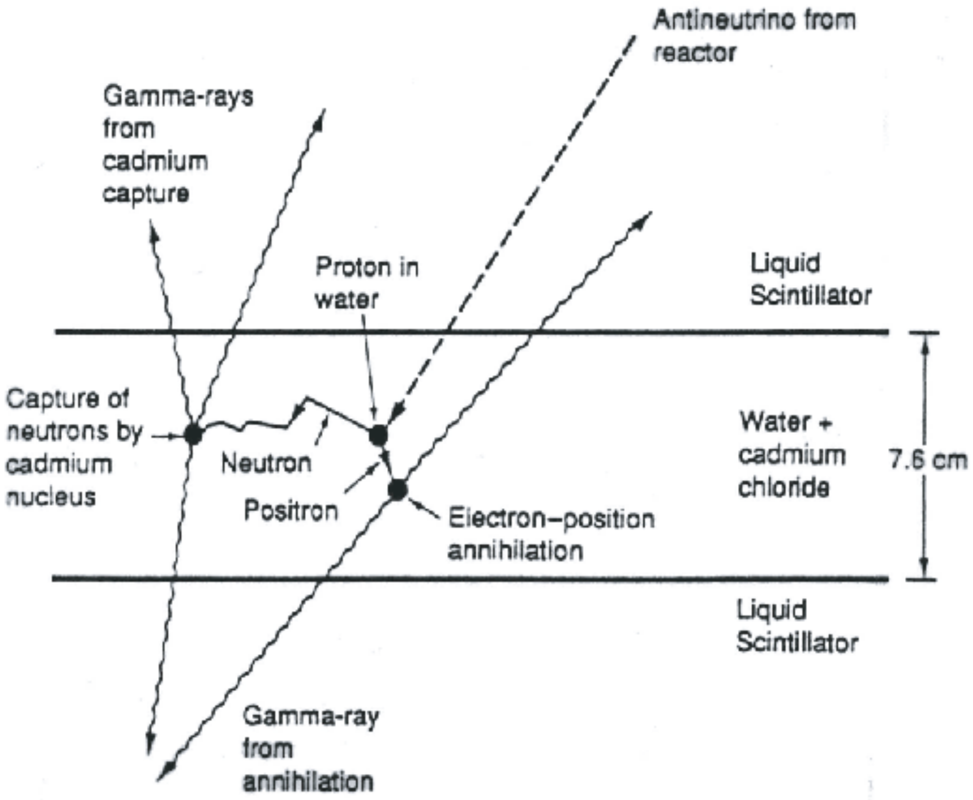
By Dr. FREDERICK REINES and Dr. CLYDE L. COWAN, jun.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico



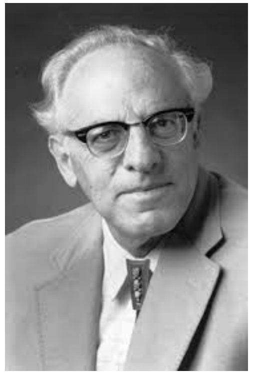
400 L water
1400 L Liq. Sc.
110 PMTs



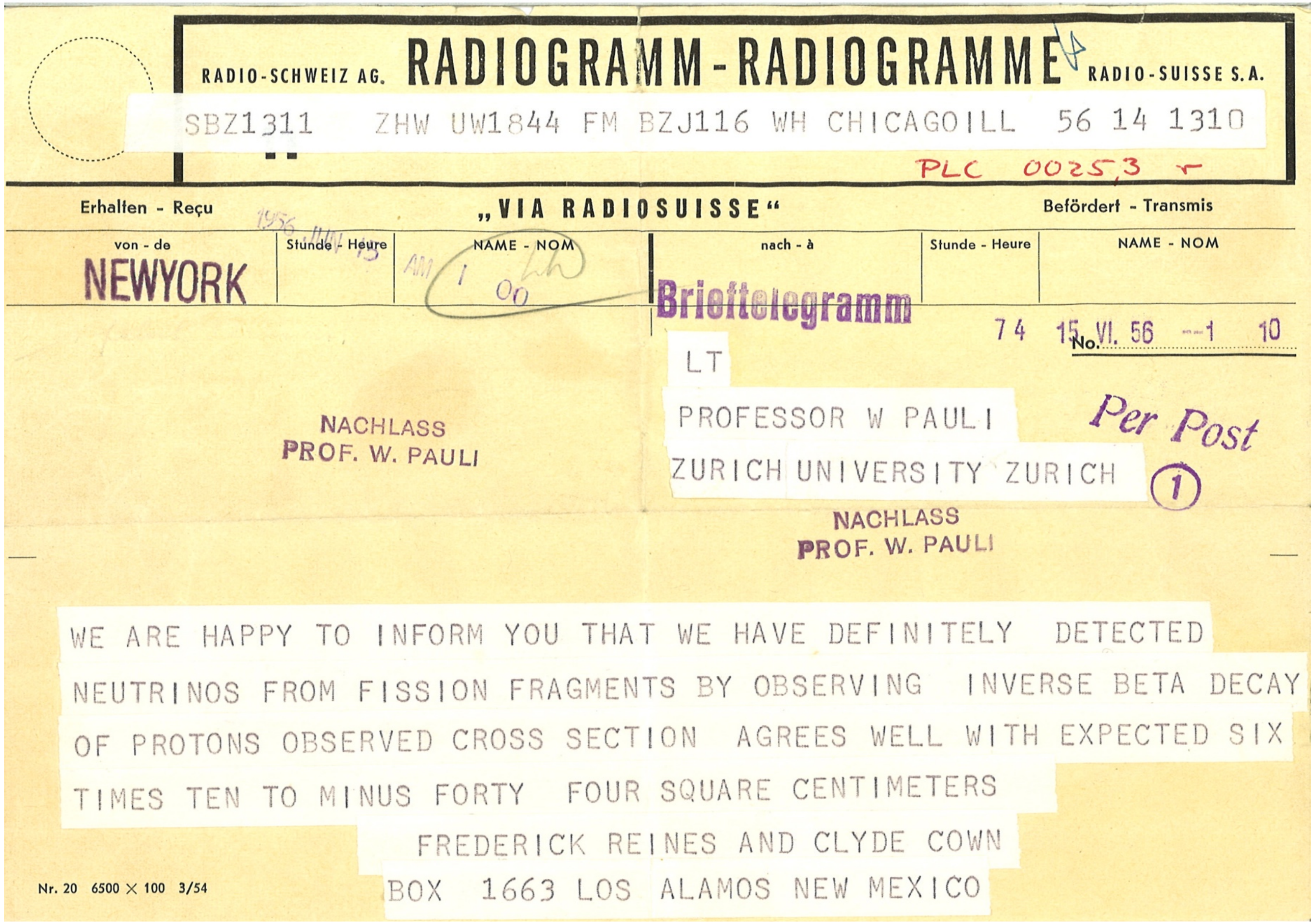
(b) Positron scope   Neutron scope



(1) A signal dependent upon reactor-power, 2·88 ± 0·22 counts/hr. in agreement with the predicted[20] cross-section (6×10^{-44} cm.^{2}), was measured with a signal-to-reactor associated accidental background in excess of 20/1. The signal-to-reactor independent background ratio was 3/1.



1995 Nobel Prize: F. Reines



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LT

PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

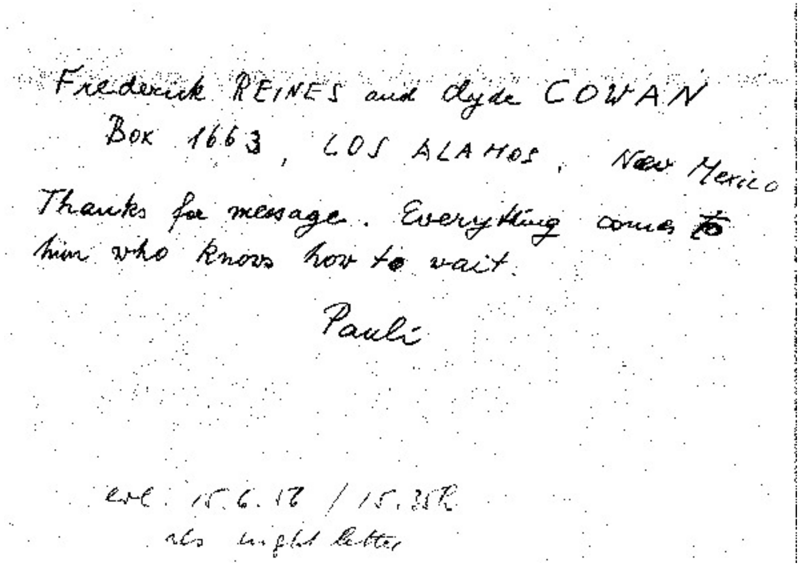
Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54



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

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

Pauli

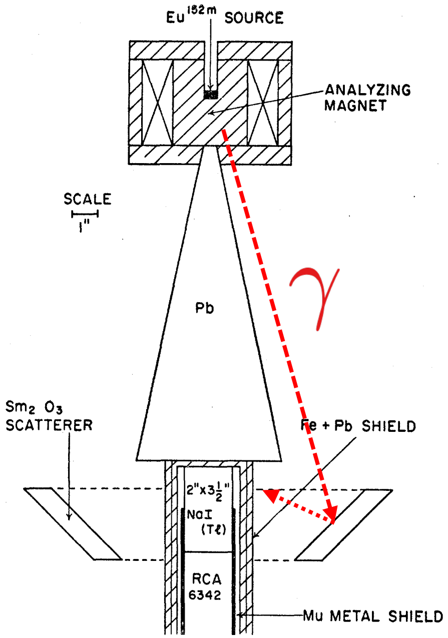
1957

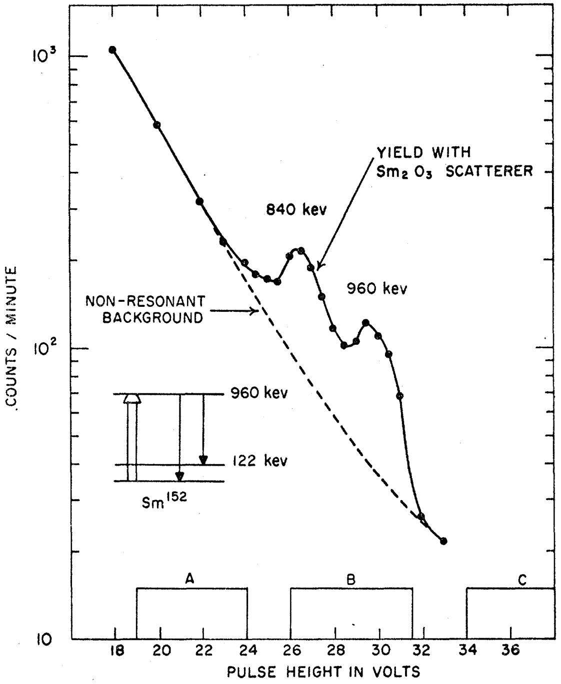
Helicity of the Neutrino

$$h = \sigma \cdot \hat{p}$$

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)





Thus our result seems compatible with spin 0− for Eu^{152m}, and 100% negative helicity of the neutrinos emitted in orbital electron capture.[3]

$$\frac{(N_- - N_+)}{\frac{1}{2}(N_- + N_+)} = +0.017 \pm 0.003$$

$$^{152}\mathrm{Eu}(0^-) + e^- \rightarrow {}^{152}\,\mathrm{Sm}^*(1^-) + \nu$$

$$^{152}\mathrm{Sm}^*(1^-) \rightarrow {}^{152}\,\mathrm{Sm}^*(0^-) + \gamma$$

$$\gamma + {}^{152}\,\mathrm{Sm}(0^-) \rightarrow {}^{152}\,\mathrm{Sm}^* \rightarrow {}^{152}\,\mathrm{Sm} + \gamma$$

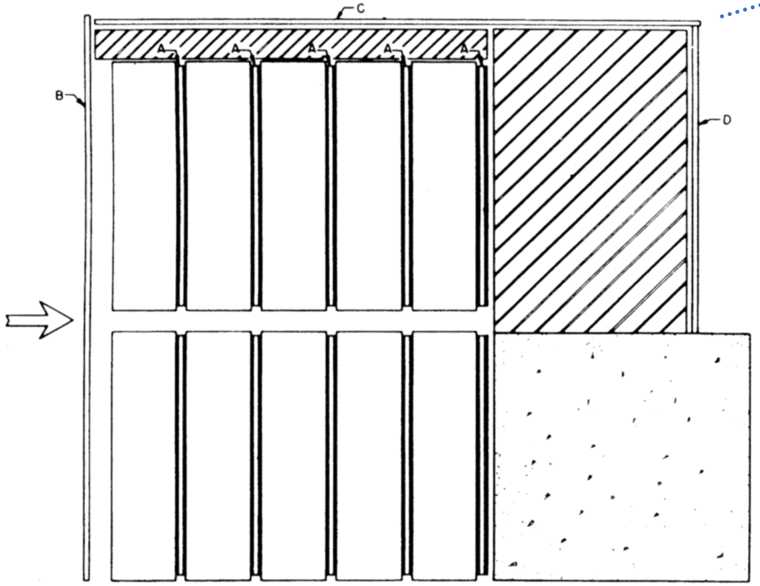
Neutrinos are left handed

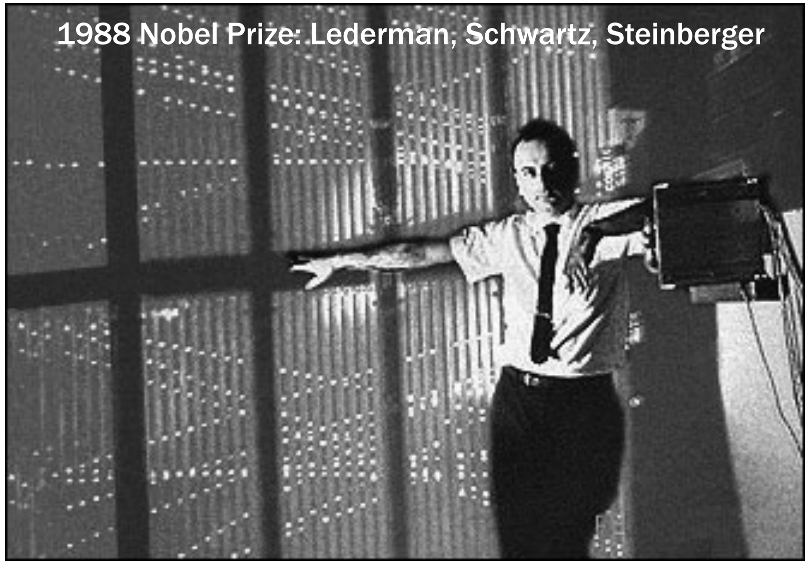
1962

The Two Neutrino Experiment

Fig. 1 Plan view of AGS neutrino experiment.

10× 1-ton modules
1” Aluminum plates with spark gap
Coincidence counters (A) and
Anticoincidence counters (B,C,D)

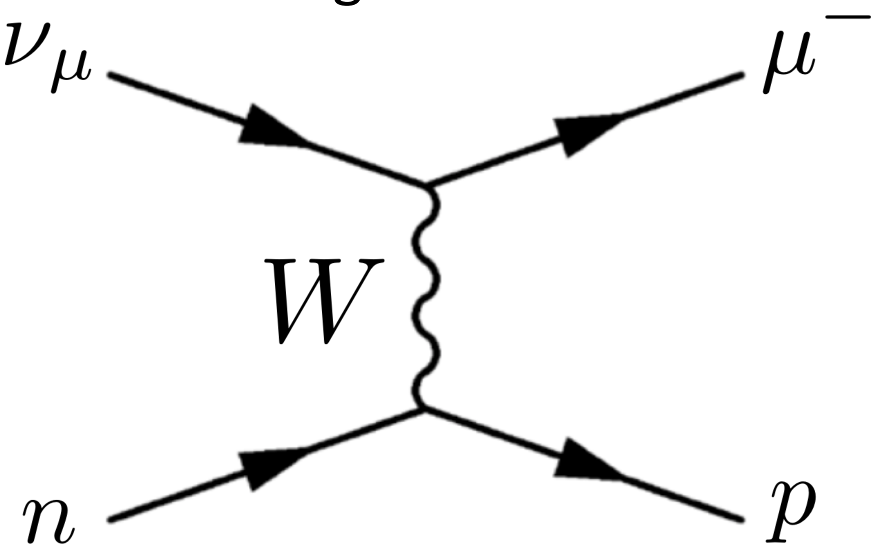




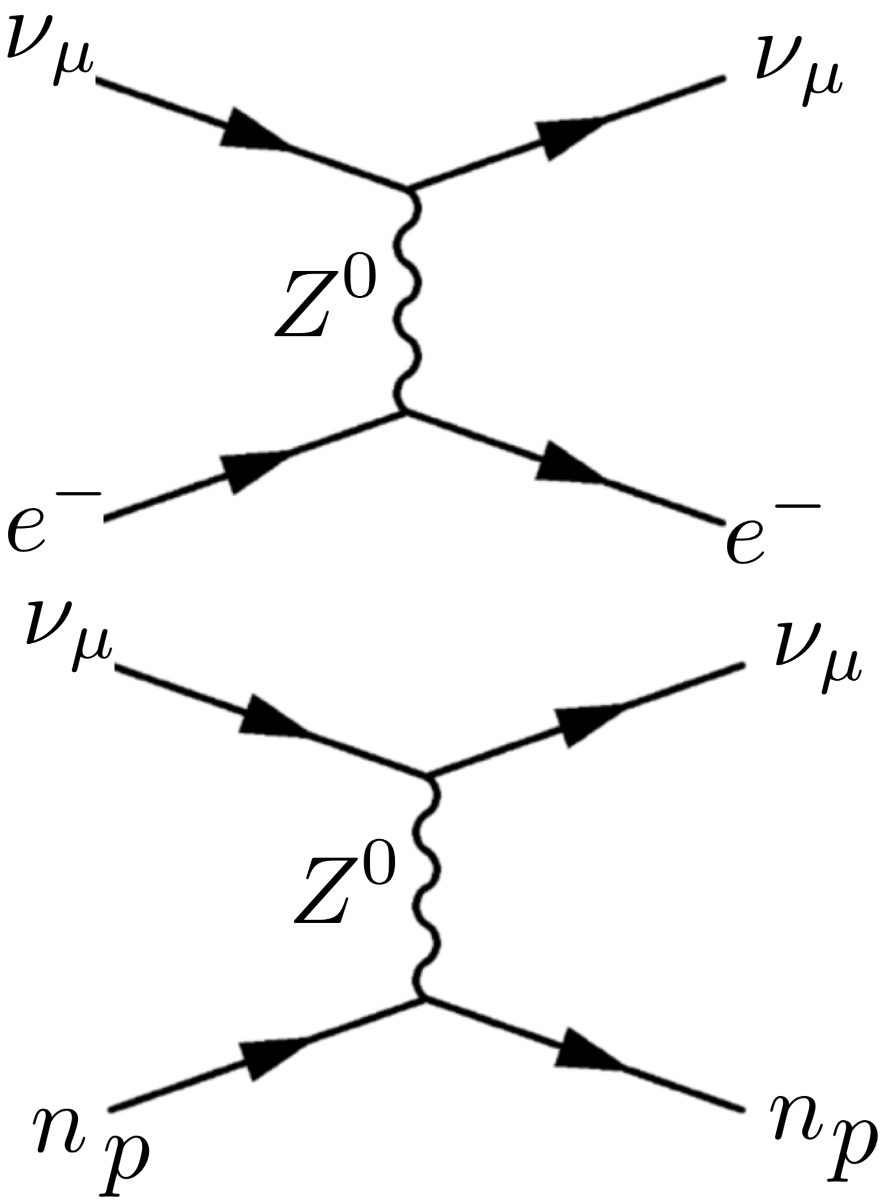
34 single muon events and only 6 showers ⇒ $\pi \to \mu\nu$ is ν_μ not ν_e

Muon neutrino reactions:

Charged current



Neutral current



In the Standard Model:
No flavor changing neutral currents! (FCNC)

1973 Discovery of Neutral Currents

Gargamelle (CERN)

Single event discovery … background estimate 0.03 ± 0.02

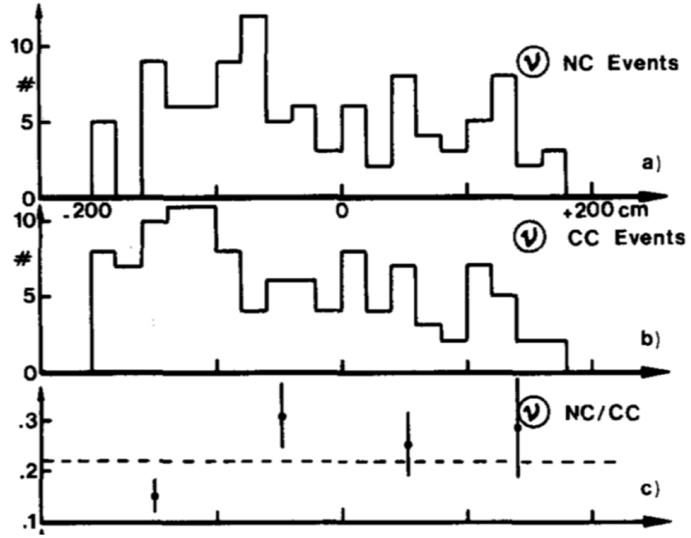
Received 2 July 1973

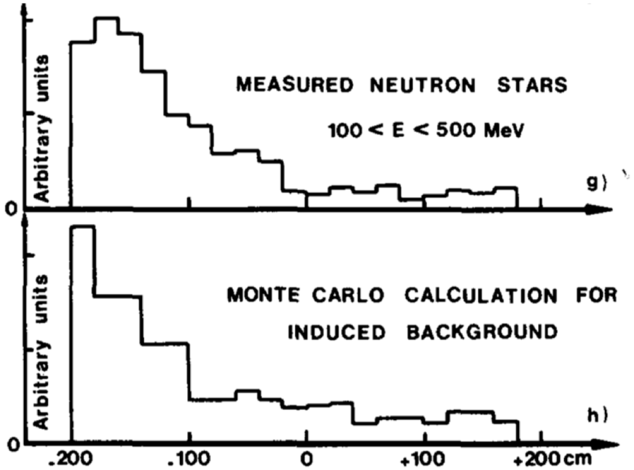
One possible event of the process $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$ has been observed. The various background processes are discussed and the event interpreted in terms of the Weinberg theory. The 90% confidence limits on the Weinberg parameter are $0.1 < \sin^2\theta_W < 0.6$.

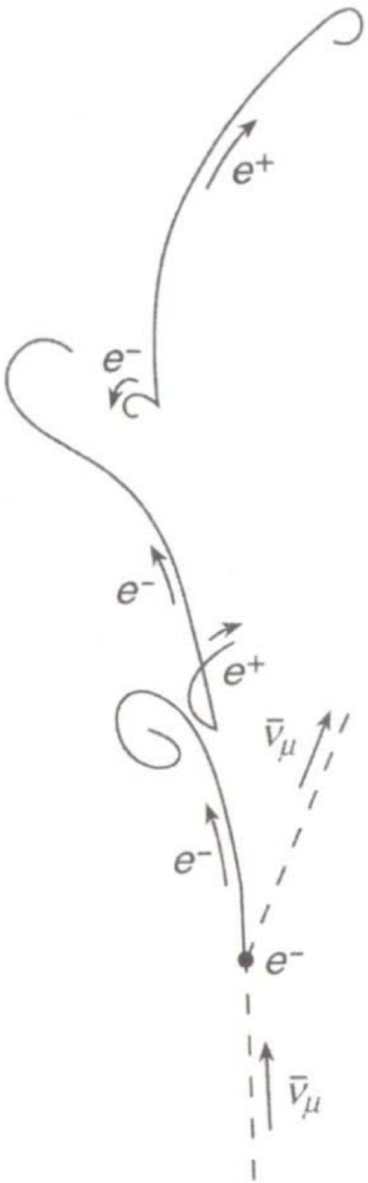
Statistical analysis (including Monte Carlo) …

Received 25 July 1973

Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.





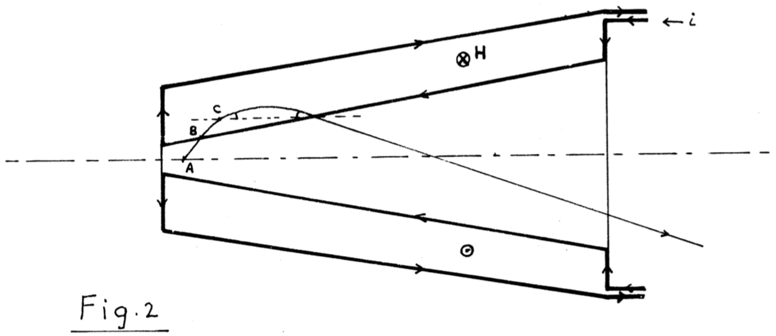


https://home.cern/about/experiments/gargamelle

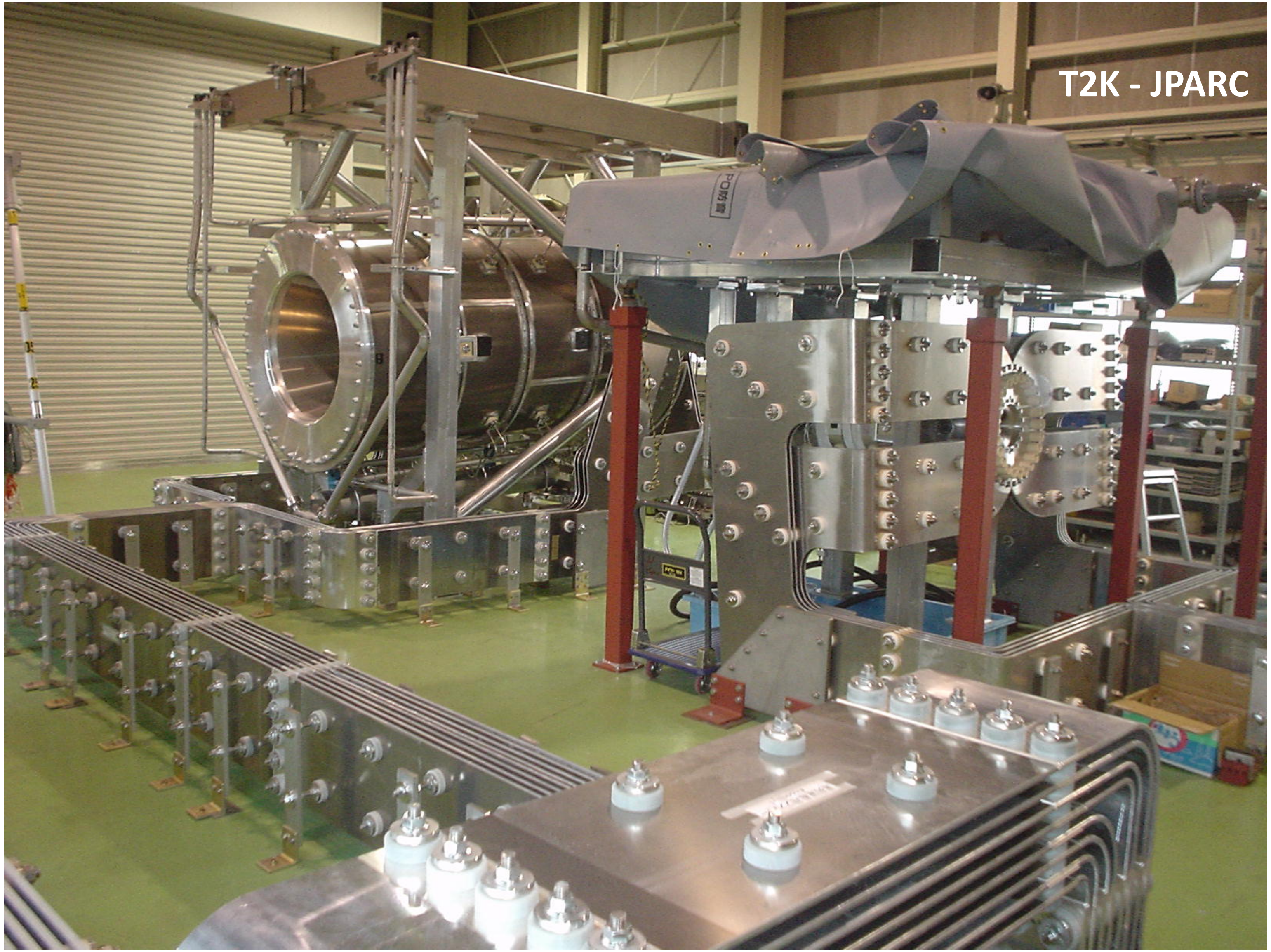
Magnetic Horn

Fig. 1: Simon van der Meer, 37 years old, explaining the principles of a magnetic horn, June 1962

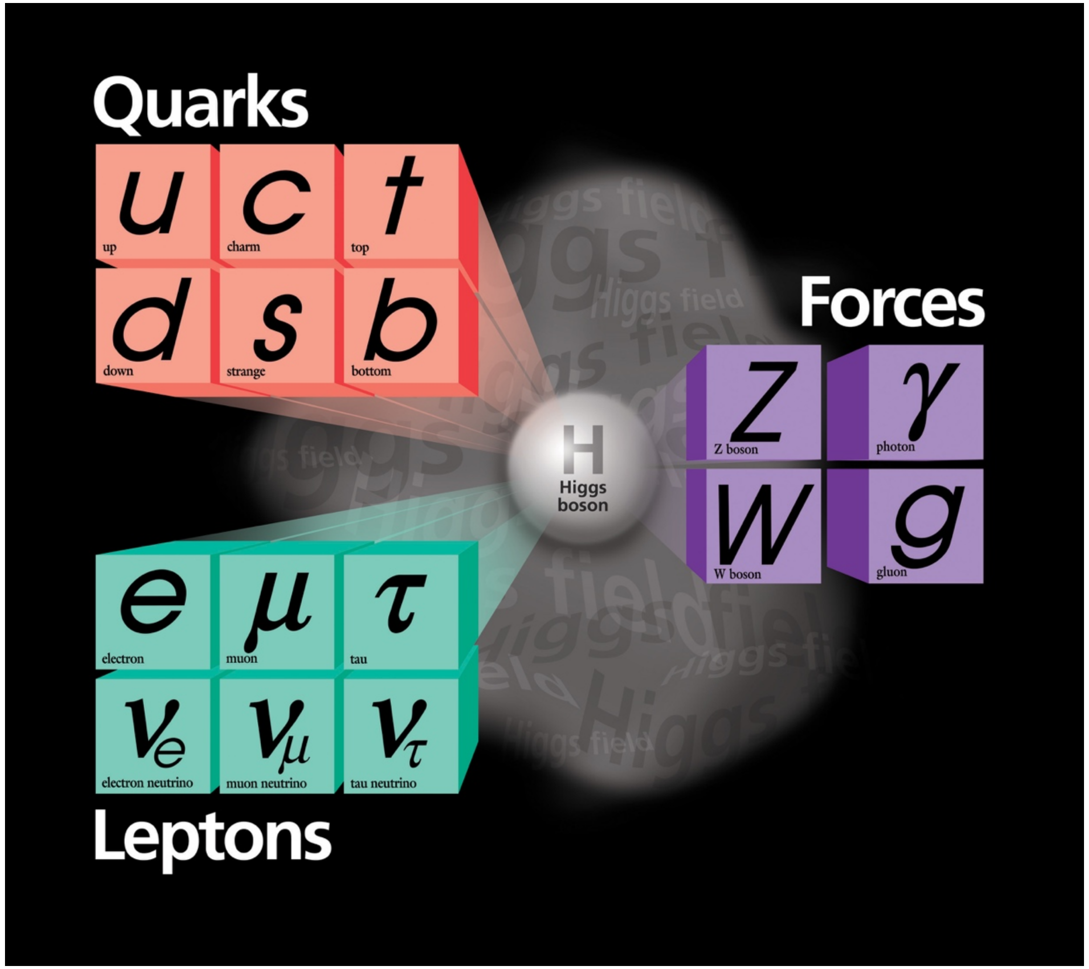
CERN–2012–008
31 October 2012



CERN-62-07



The Massless Neutrino in the Standard Model



$$SU(2)_L \times U(1)_Y$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

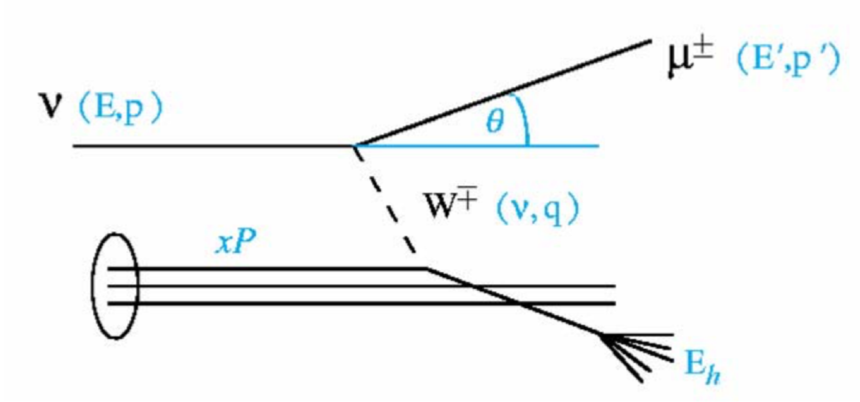
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

universal coupling e.g. $g, \ g'$

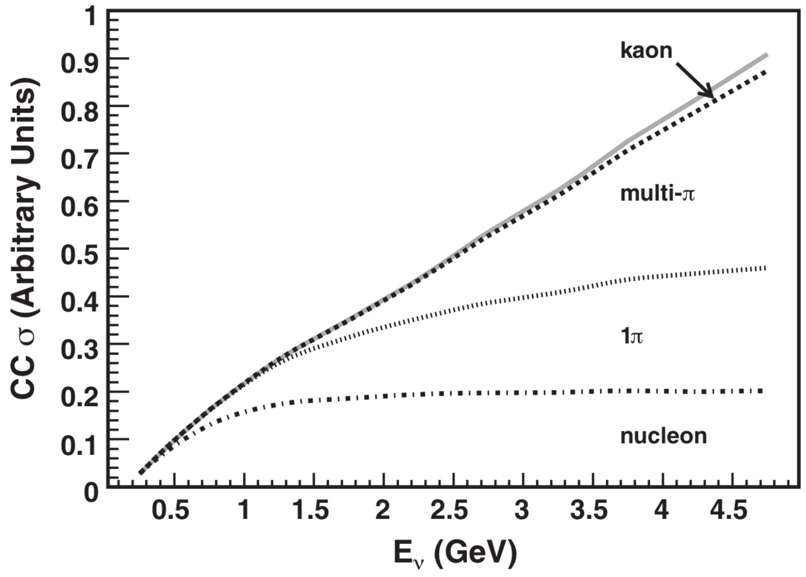
$$u_R, d_R, e_R$$

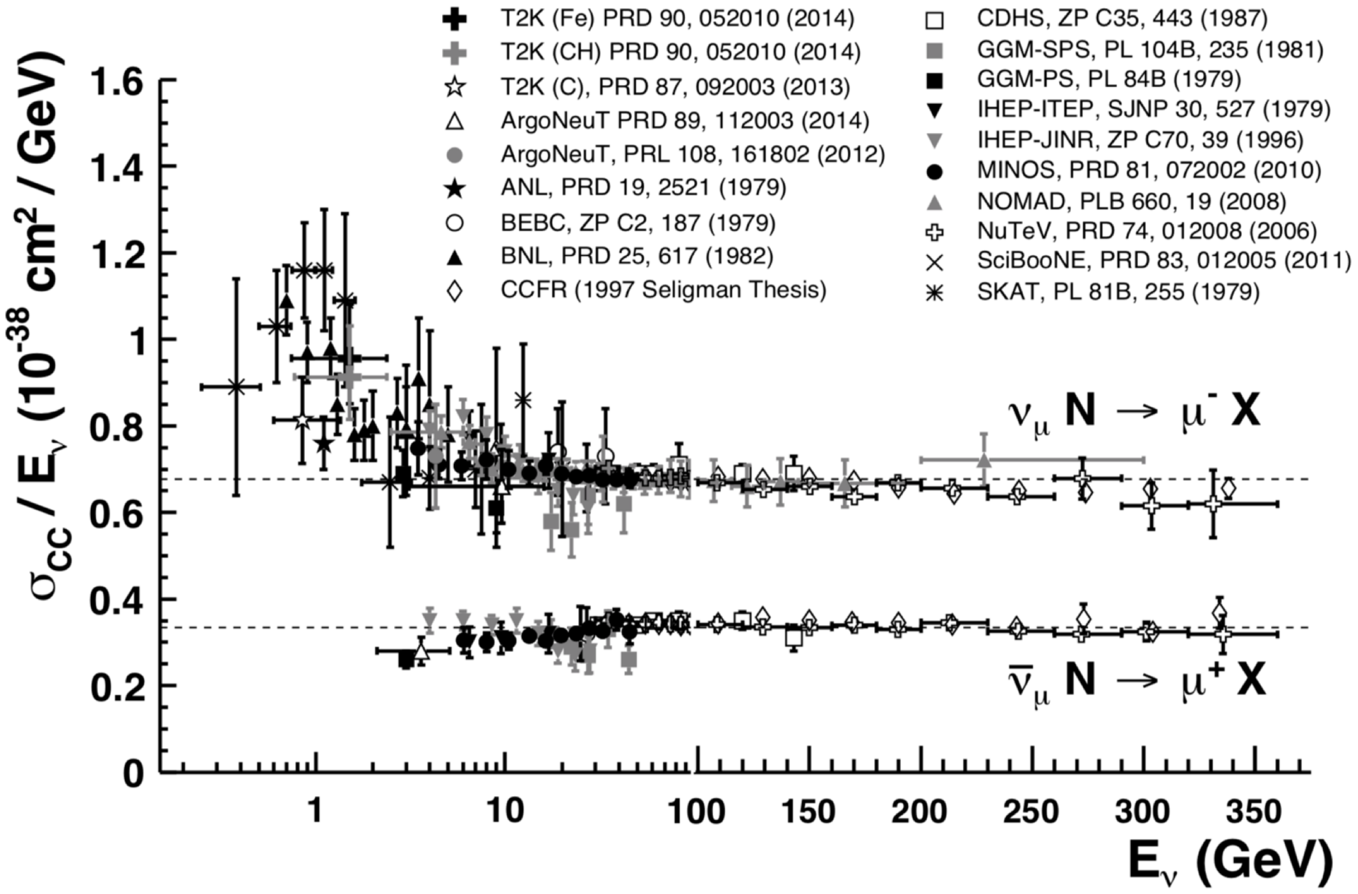
~~$-m(\bar{\nu}_R \nu_L + h.c.)$~~

The Neutrino as a Probe



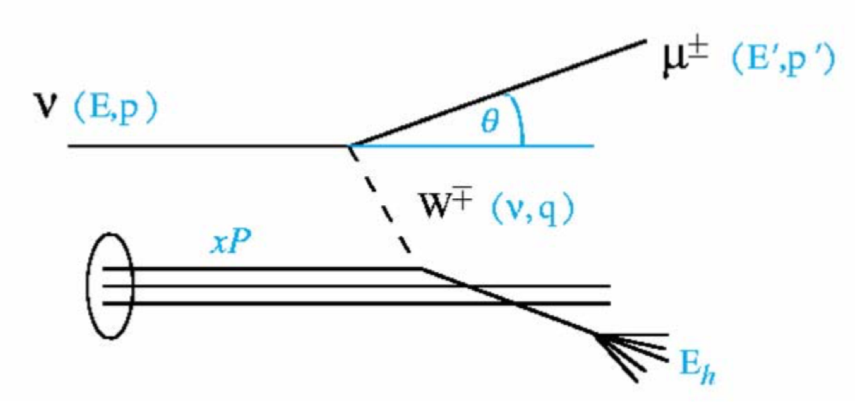
Neutrino cross section grows with energy





1975

The Neutrino as a Probe



Demonstration that the weak coupling to quarks and leptons is universal

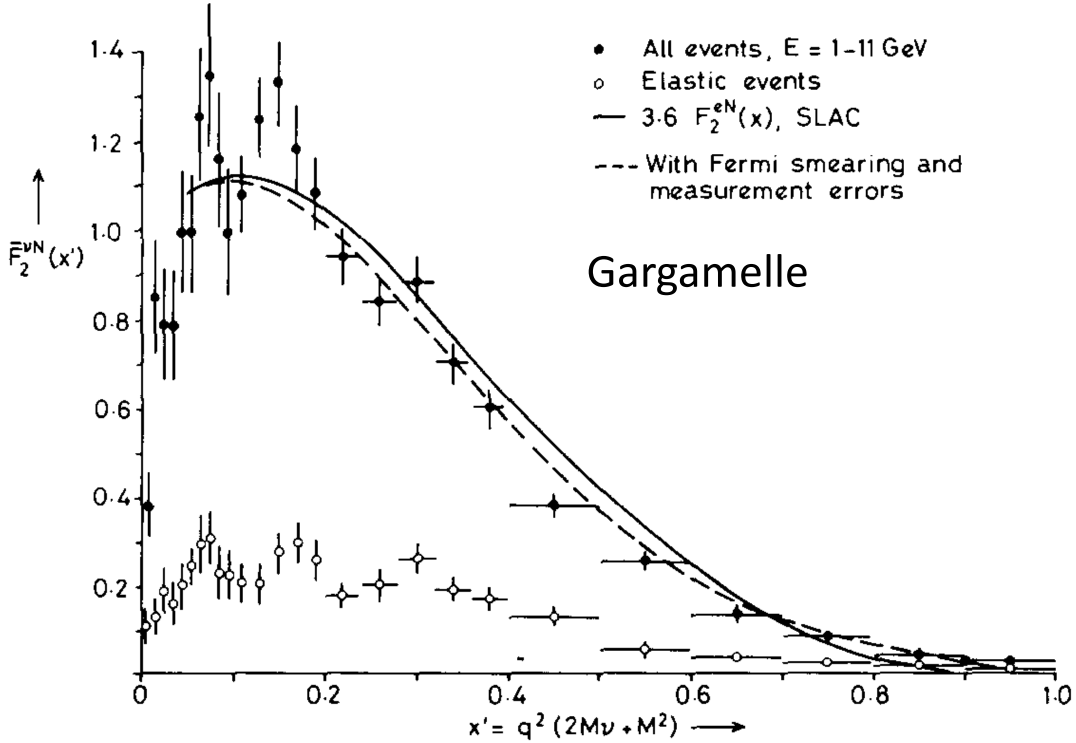
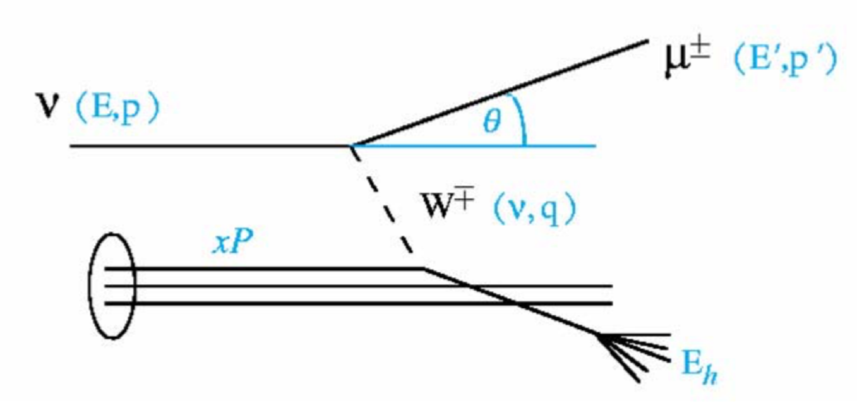


Fig. 4. $\bar{F}_2^{\nu N}(x')$ computed from all events irrespective of neutrino/antineutrino energy. At small x', the data are binned in small intervals $\Delta x'$ to indicate the fall in $\bar{F}_2$. Within the statistical errors, the form of $\bar{F}_2$ for $x' < 0.1$ is independent of energy.

The Neutrino as a Probe



Demonstration that the weak coupling to quarks and leptons is universal

$$\frac{d\sigma}{dy} = \frac{2G_F^2 m E_\nu}{\pi}$$ neutrino

$$\frac{d\sigma}{dy} = \frac{2G_F^2 m E_{\bar{\nu}}}{\pi}(1-y)^2$$ antineutrino

CDHS

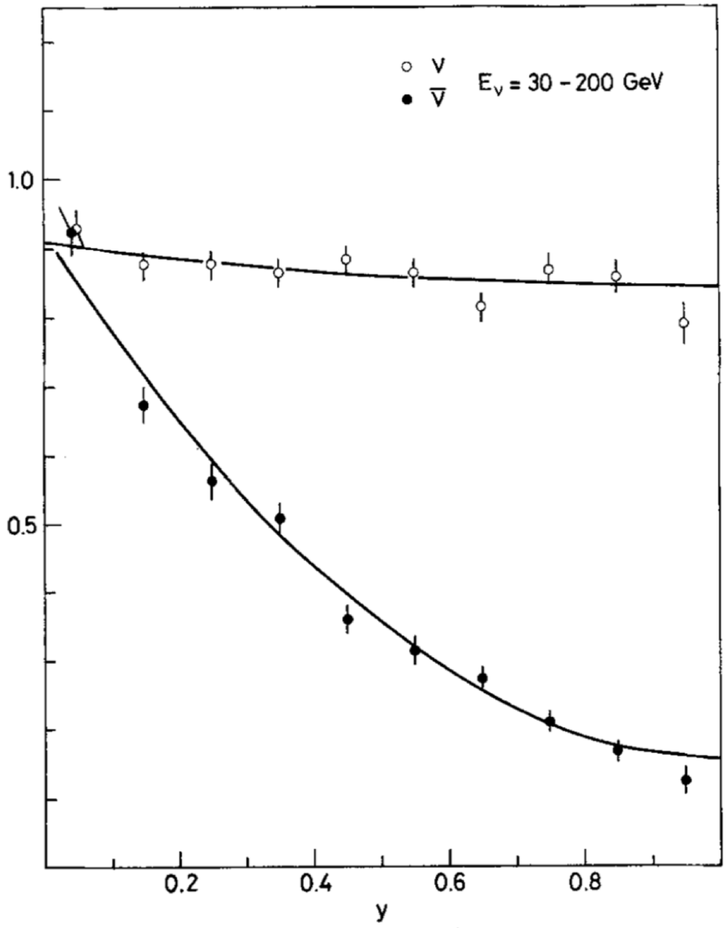
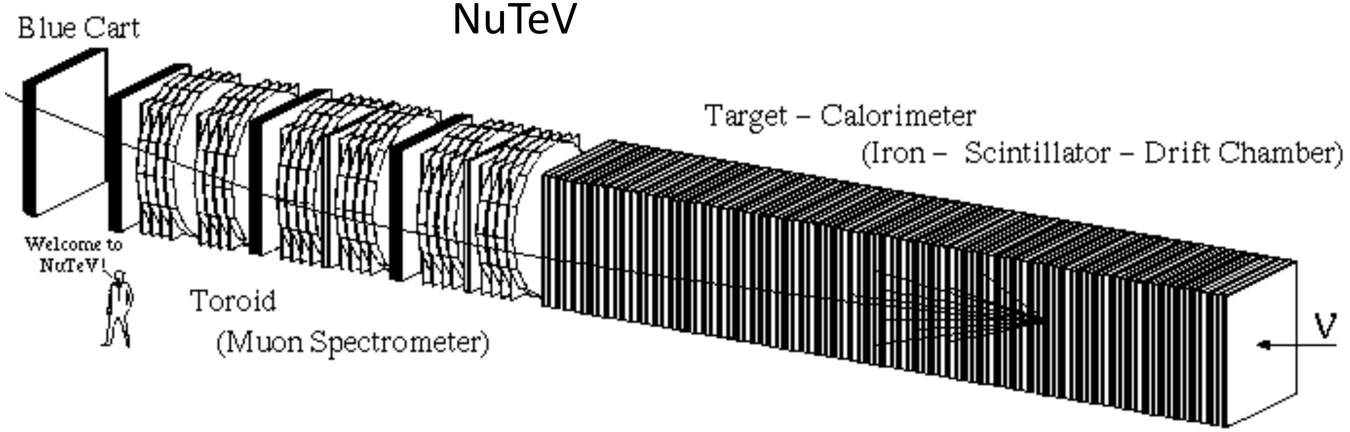
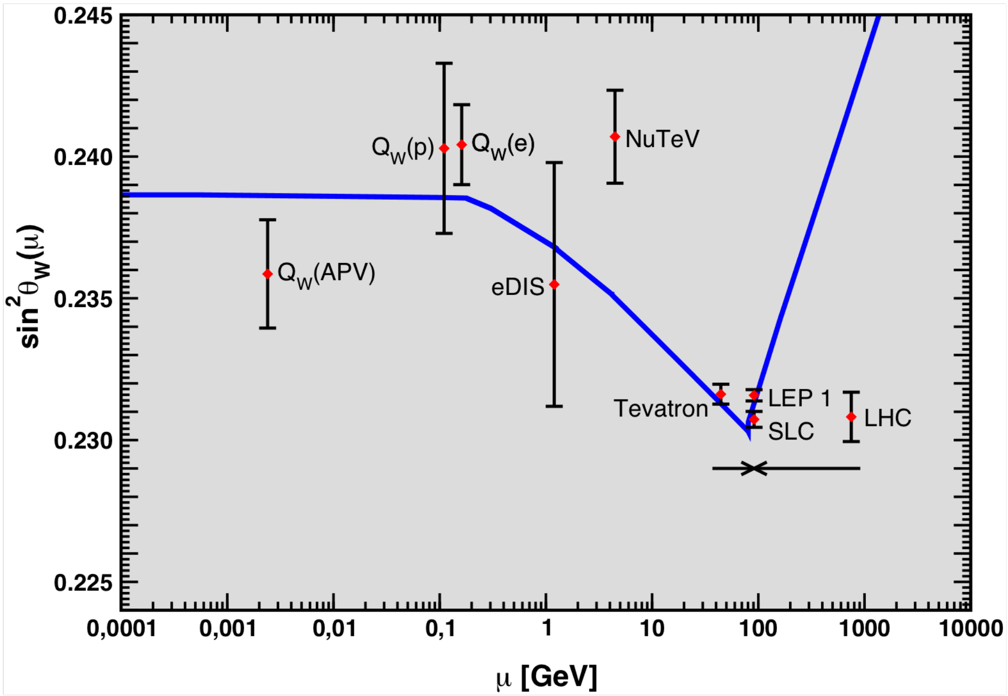


Fig. 12. Distributions in y for neutrinos and antineutrinos, after corrections for acceptance, resolution and flux

The Neutrino as a Probe

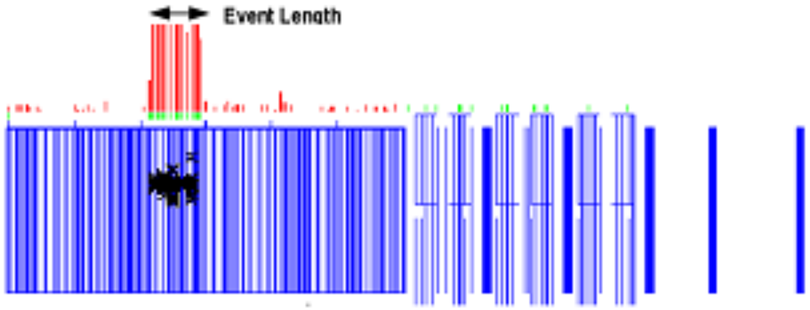
NuTeV

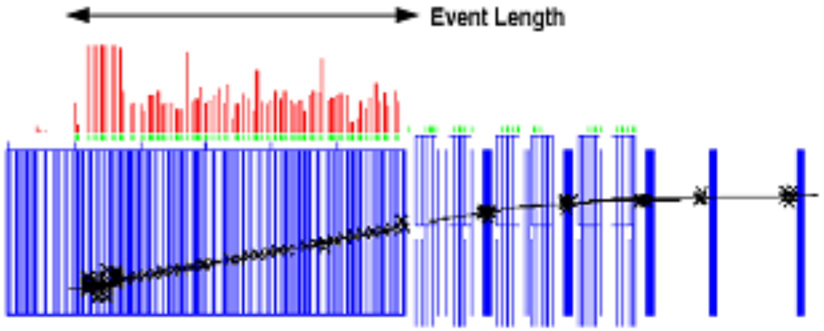




Paschos-Wolfenstein

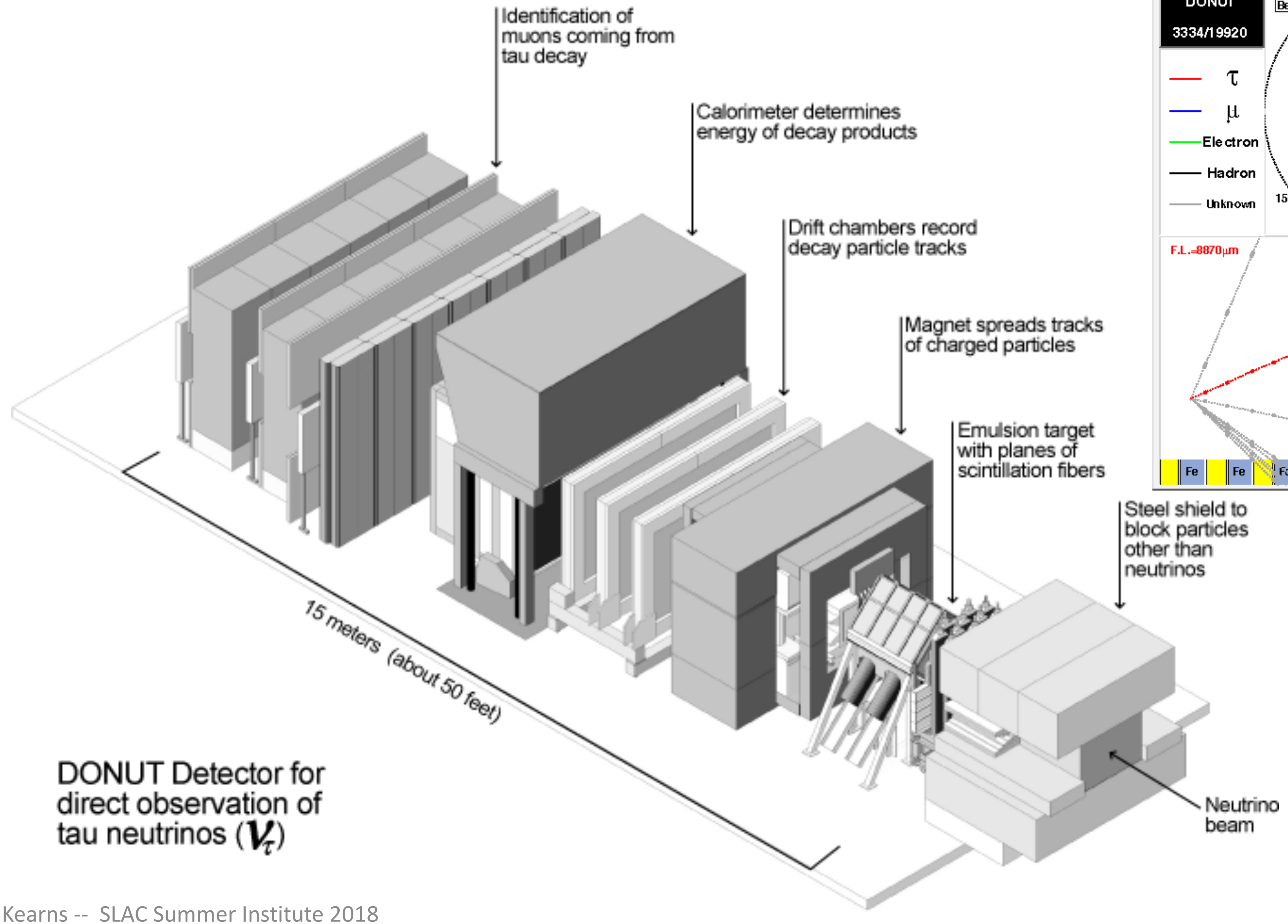
$$\frac{\sigma(NC,\nu)-\sigma(NC,\bar{\nu})}{\sigma(CC,\nu)-\sigma(CC,\bar{\nu})}=\frac{1}{2}-\sin^2\theta_W$$



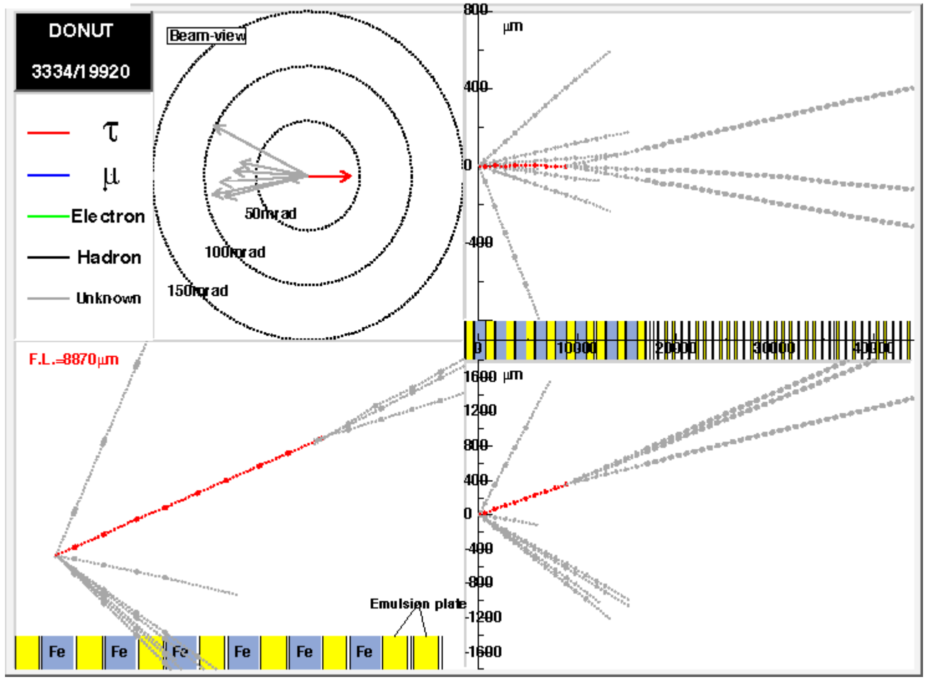


2000 Detection of the Tau Neutrino

One of four…



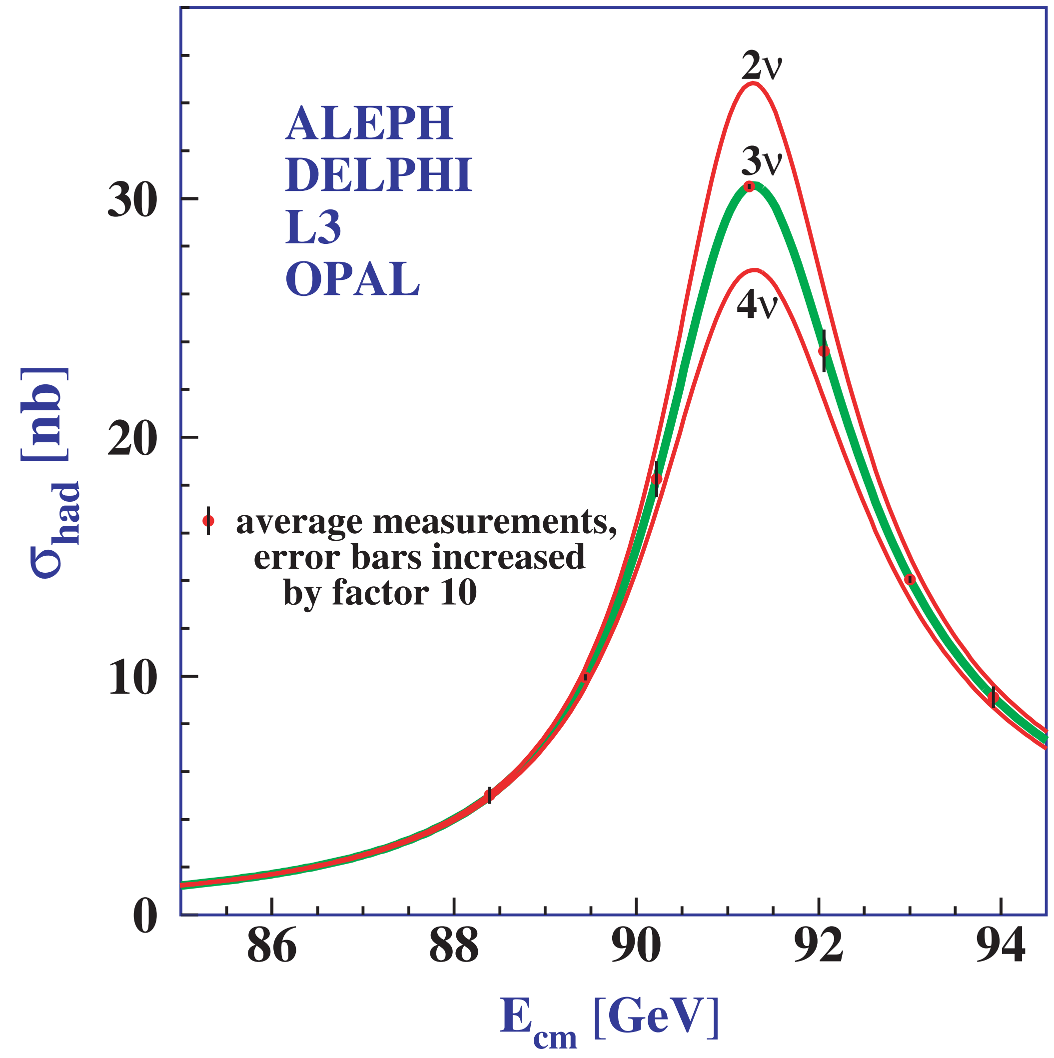
DONUT Detector for direct observation of tau neutrinos (ν_τ)



$$\nu_\tau \, N \rightarrow \tau \;\; X$$
$$\hookrightarrow 3h \, \nu_\tau \;\; (X)$$

1989 - 2000

Three Neutrinos



This result is critical to interpreting observations of neutrino oscillation.

Neutrino Puzzles

Solar Neutrino Puzzle

Too few neutrinos
from the Sun

First puzzle found,
second one solved

Atmospheric Neutrino Anomaly

Ratio of muon neutrinos
to electron neutrinos
Is wrong

Second puzzle found,
first one solved

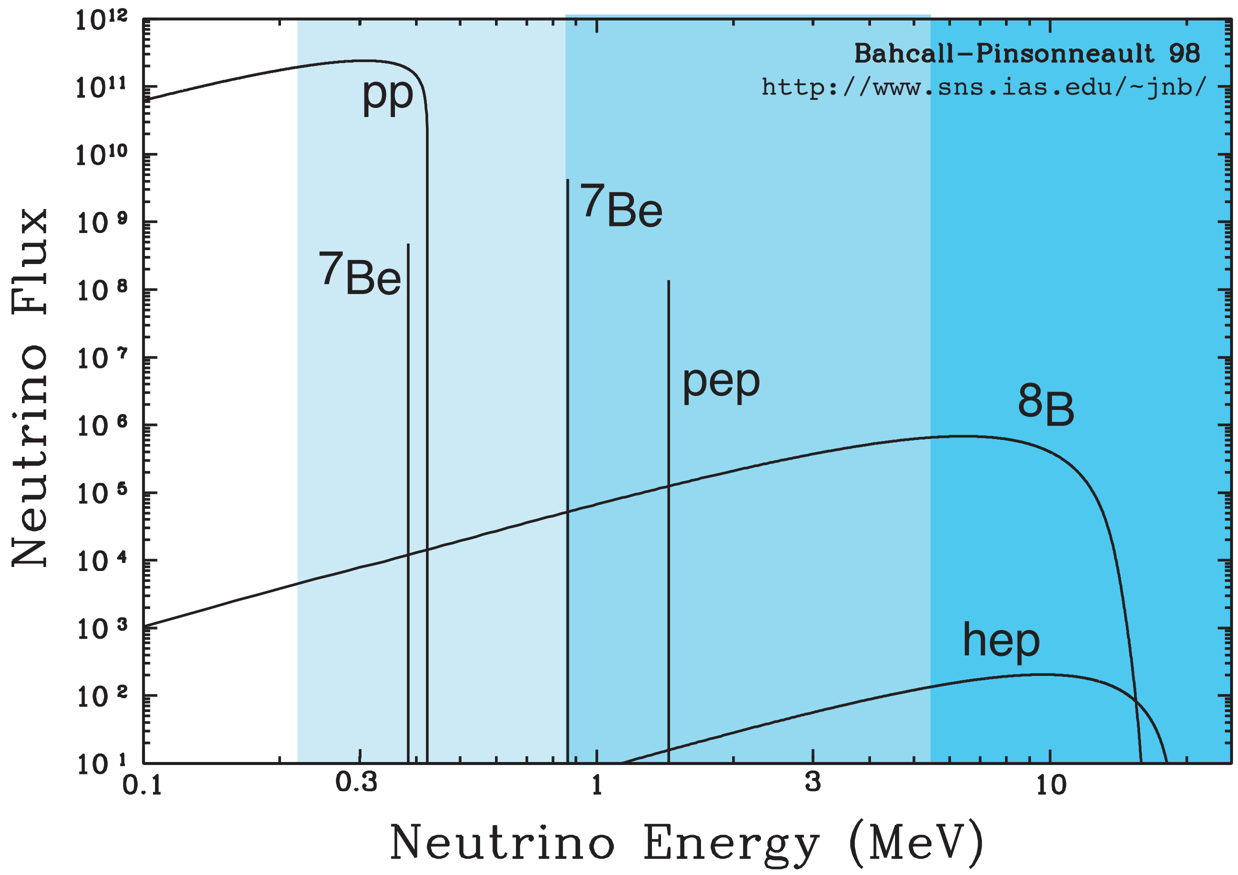
Solar Neutrinos

$$4p \rightarrow {}^4\text{He} + 2e^+ + \gamma + 2\nu_e$$

$$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$$

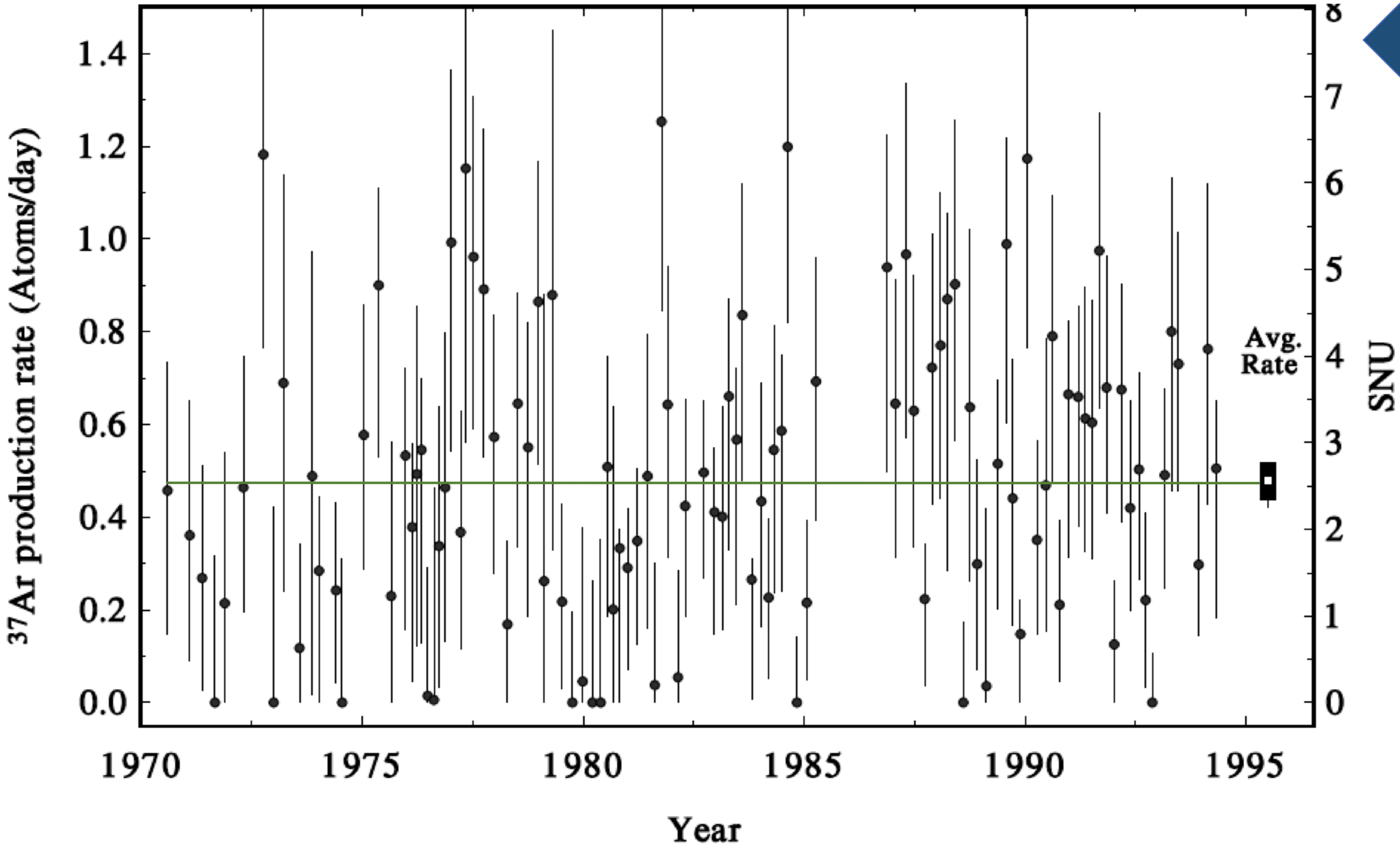
$$^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$$

$$^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$$



1970 – 1994

30 years of Ray Davis' Homestake experiment - 800 solar neutrinos



SSM

2002 Nobel Prize: Ray Davis

Quarks

J/ψ

τ

W/Z

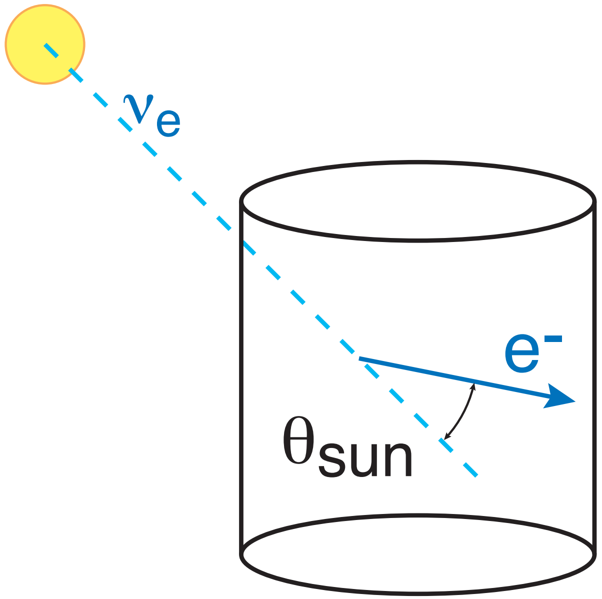
SN1987a

top quark

neutrino oscillation

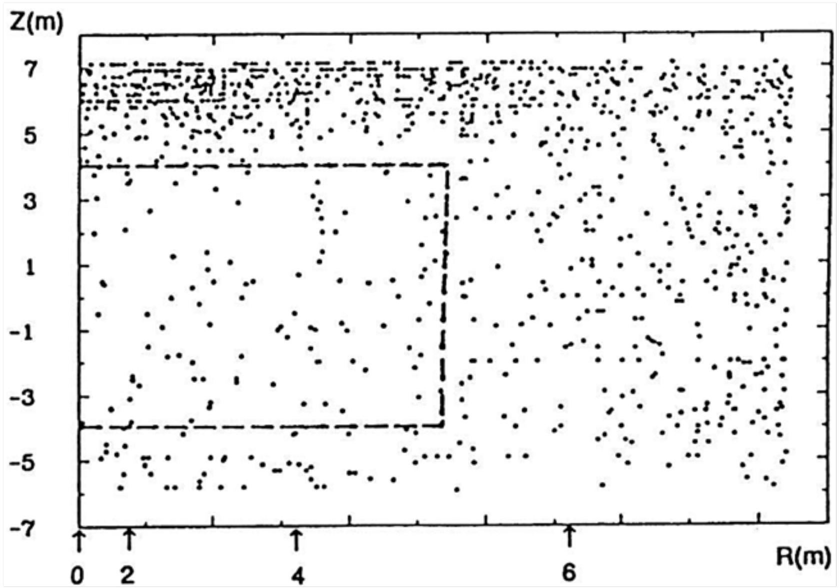
Higgs boson

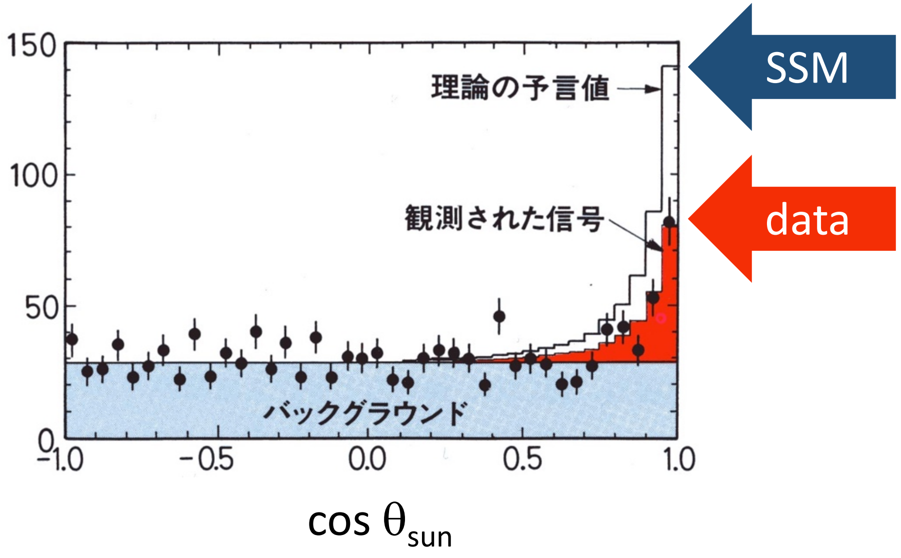
Kamiokande



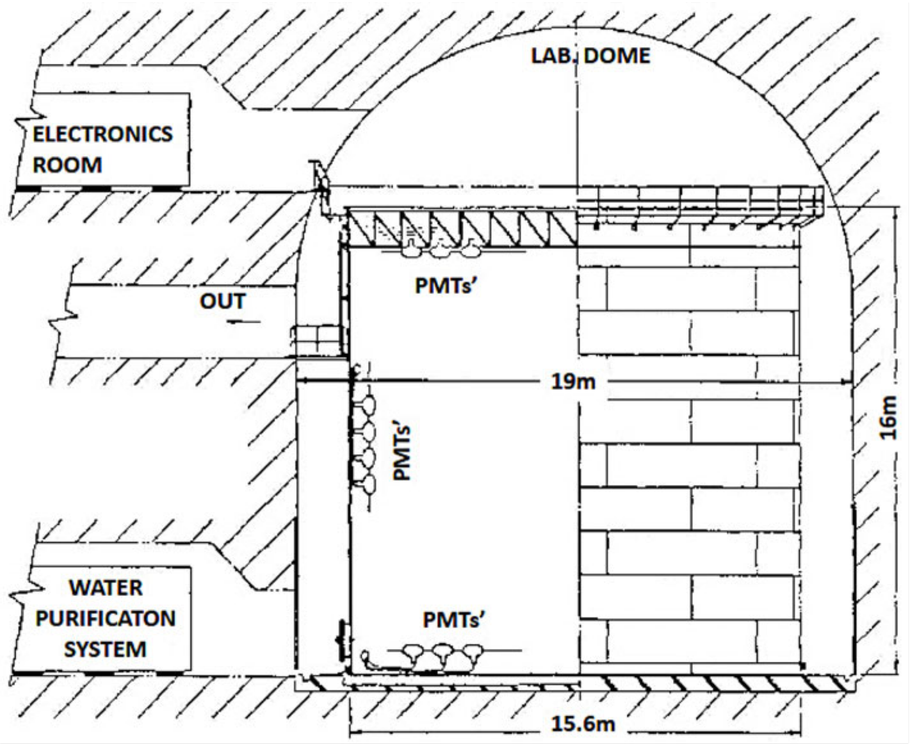
neutrino scattering
off atomic electrons

directional detection

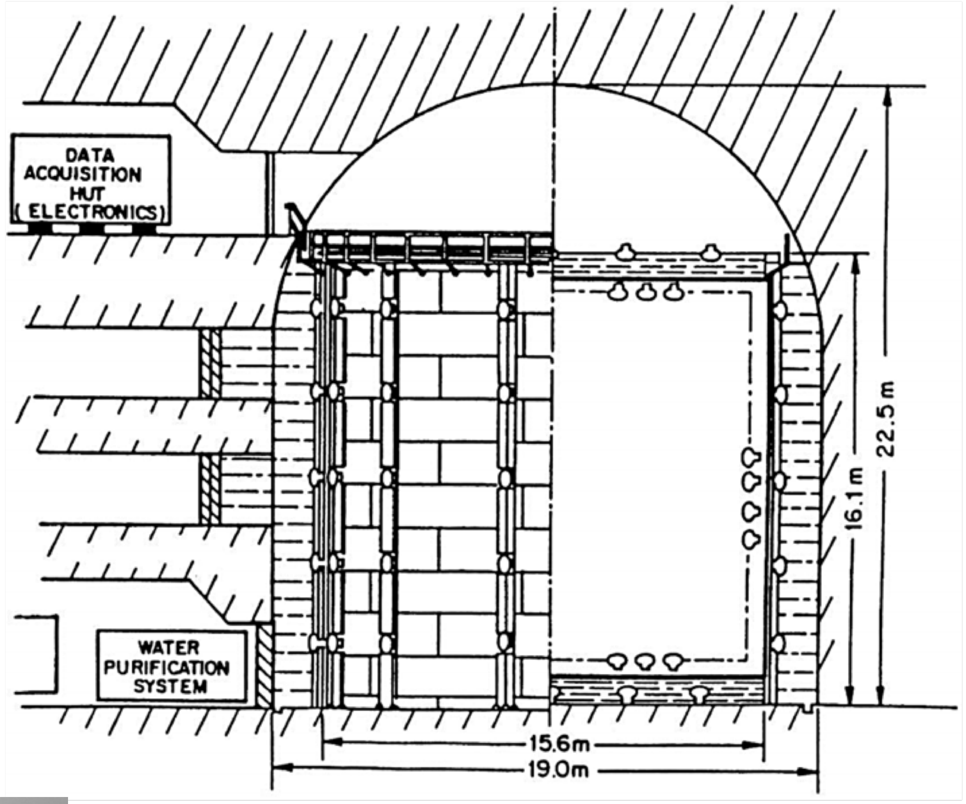


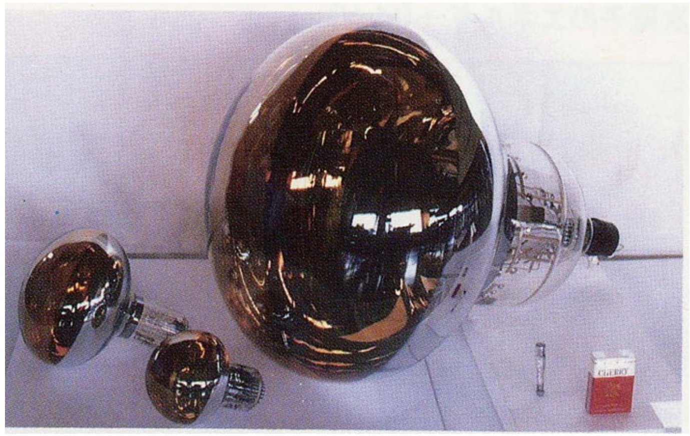


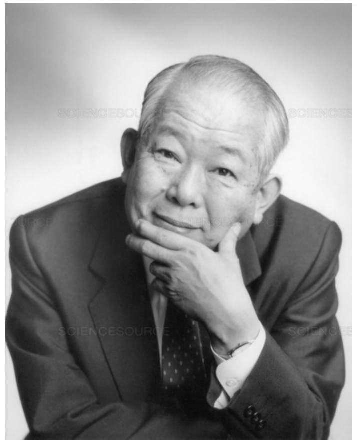
1982 Kamiokande-I



1985 Kamiokande-II







2002 Nobel Prize:
Masatoshi Koshiba

1990's

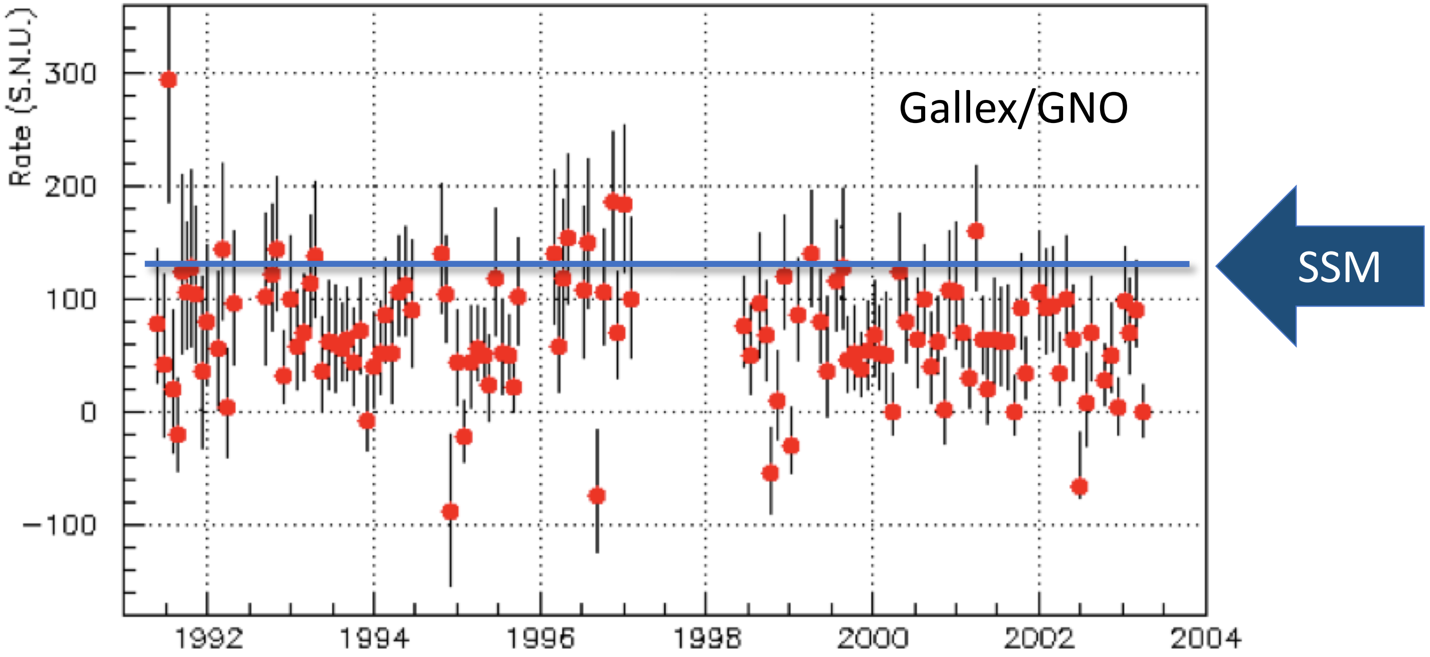
Gallex/GNO &SAGE

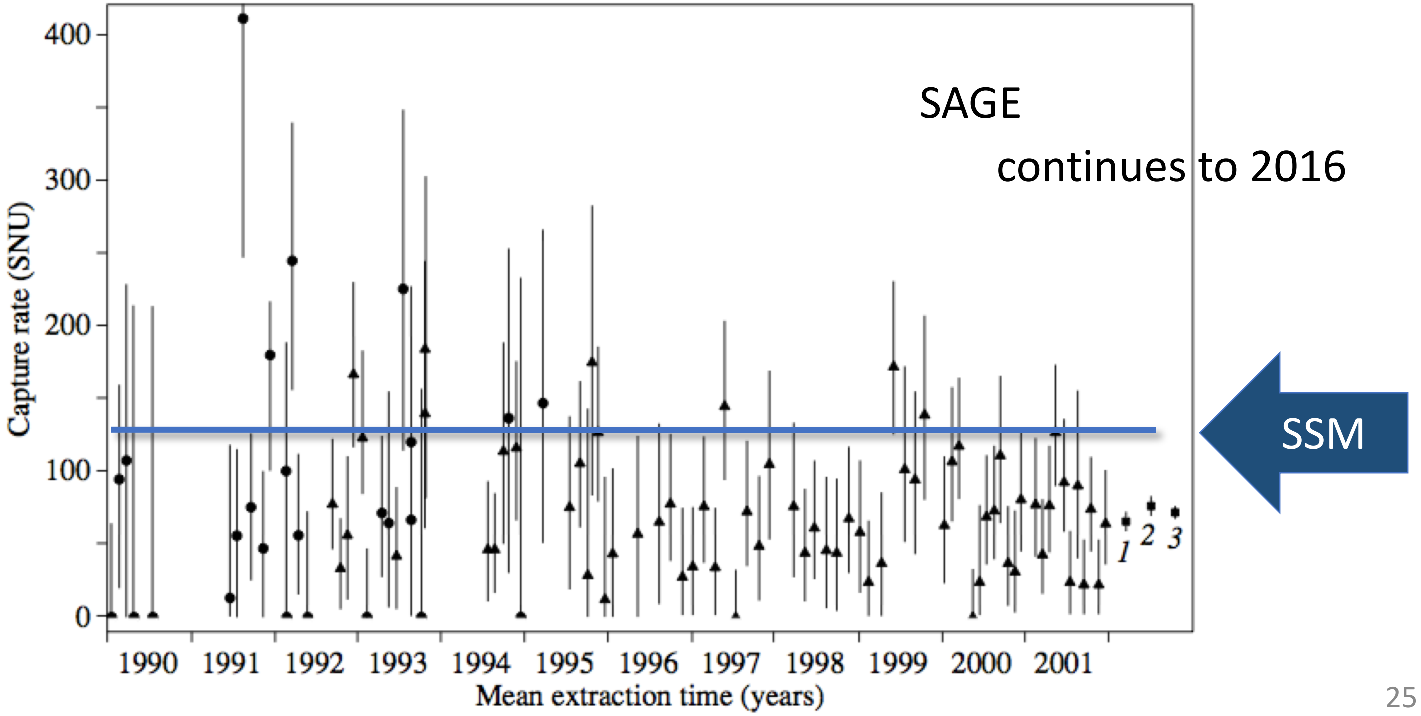
30-60 tons of gallium

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

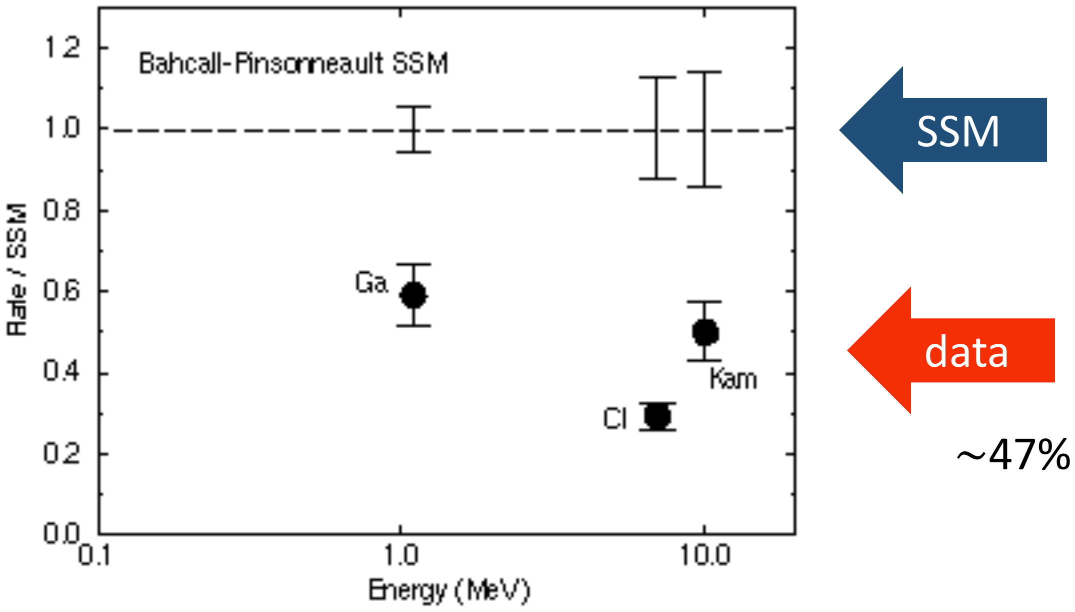
$E_\nu > 0.23$ MeV

pp neutrino flux predicted to ~2%





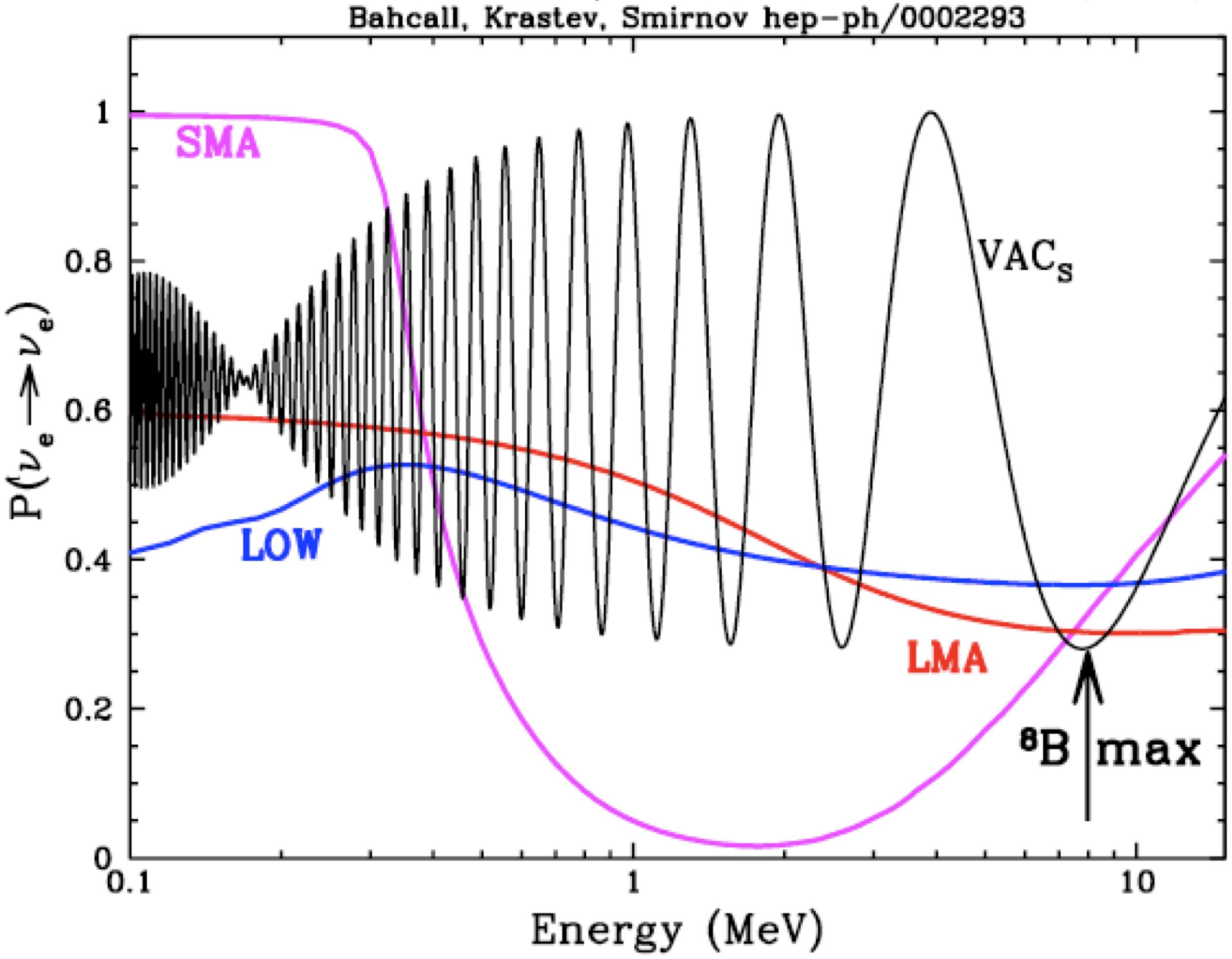
Solar Neutrinos – circa 1995

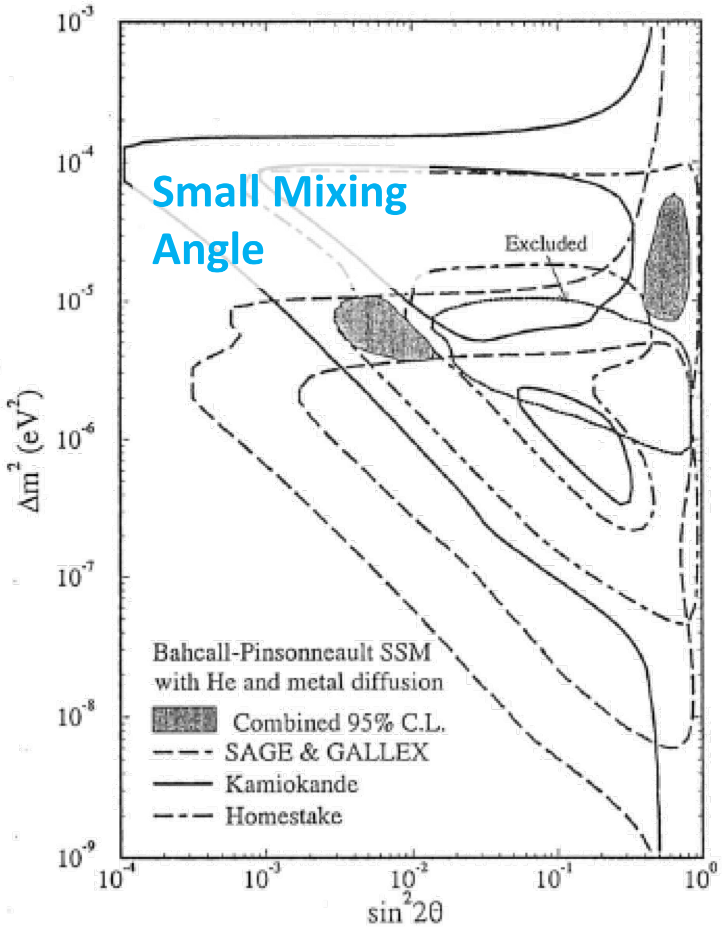


~47% of SSM

Neutrino Flavor Mixing?

Matter Effects: Mikheyev, Smirnov, Wolfenstein (MSW)

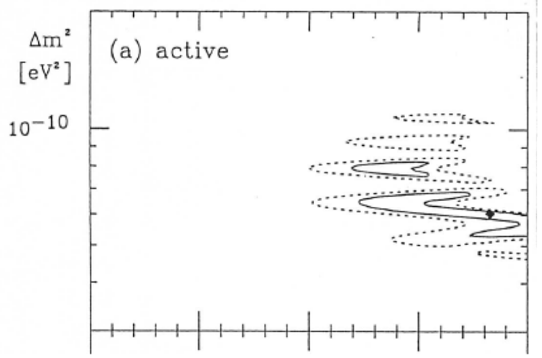




Small Mixing Angle

Large Mixing Angle

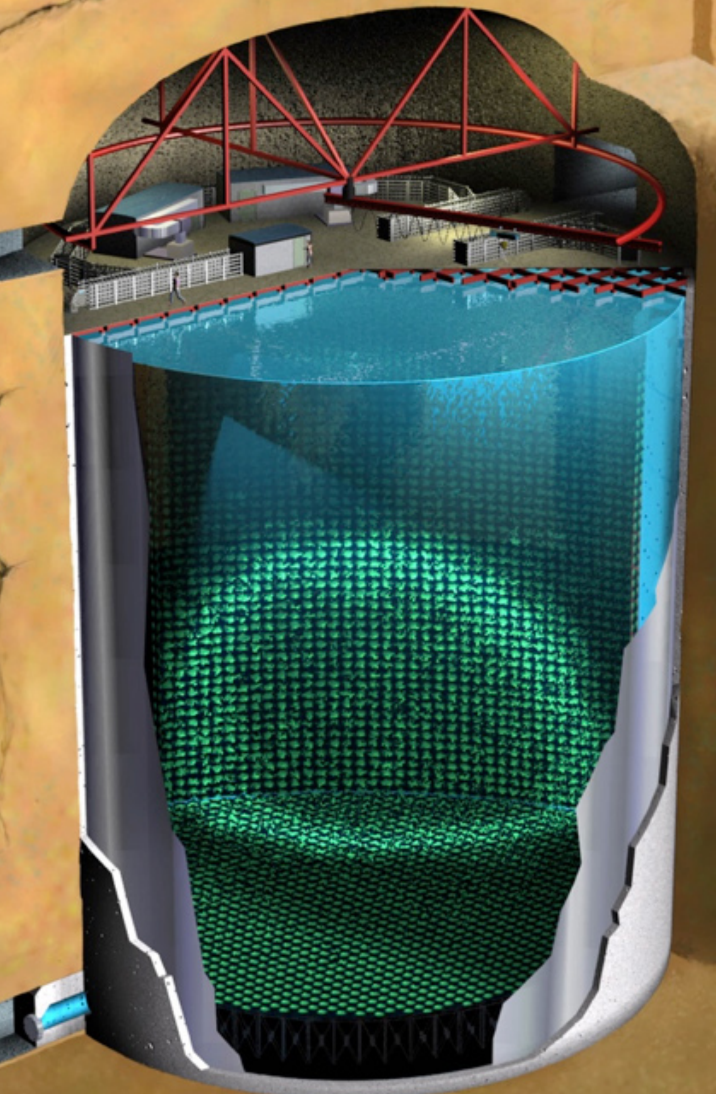
LOW (mass and probability)



Vacuum "Just So"

1996 -

Super-Kamiokande

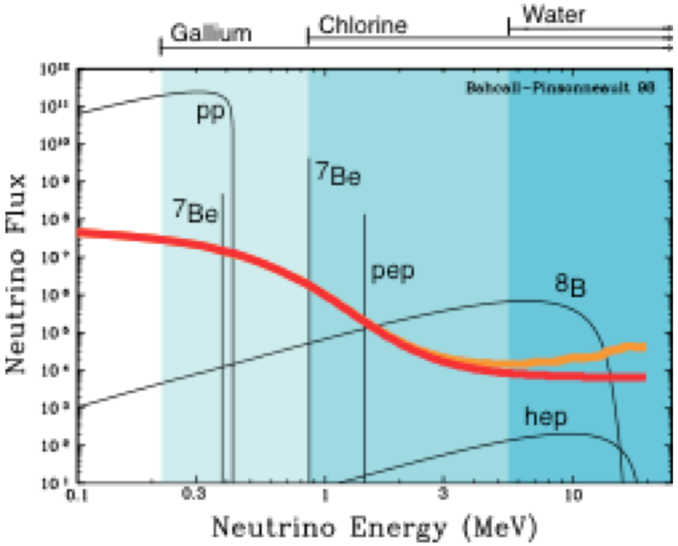


42 m high, 39 m diameter
50000 tons of water (22.5 kton fiducial)
11000 50-cm PMTs
Outer detector (1900 smaller PMTs)
1 km under a mountain
Energy threshold (solar) ~ 5 MeV
10 atmospheric neutrinos per day
Far detector for K2K and T2K

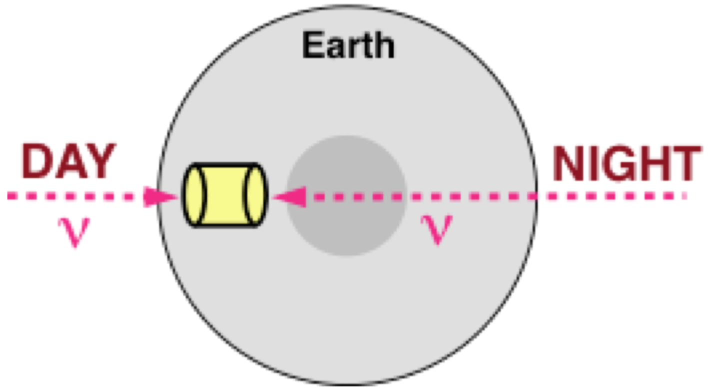
SK-I, II, III, IV and currently preparing for SK-Gd

Smoking Guns

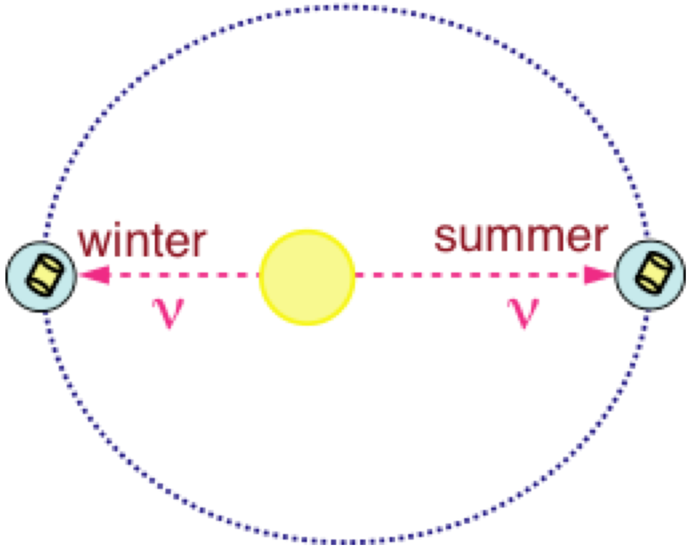
Energy spectrum distortion



Day/Night Effect: Regeneration in Matter

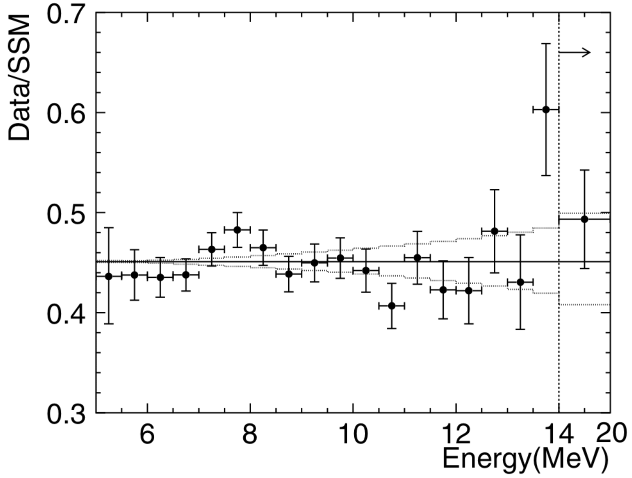


Seasonal Variation

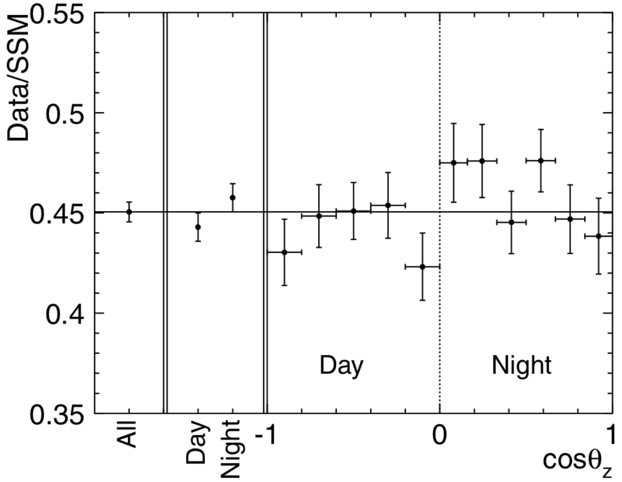


Super-K Solar Result (2001)

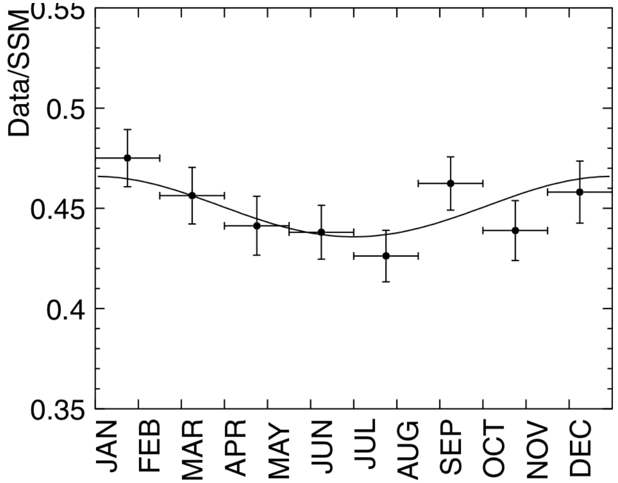
Energy spectrum distortion

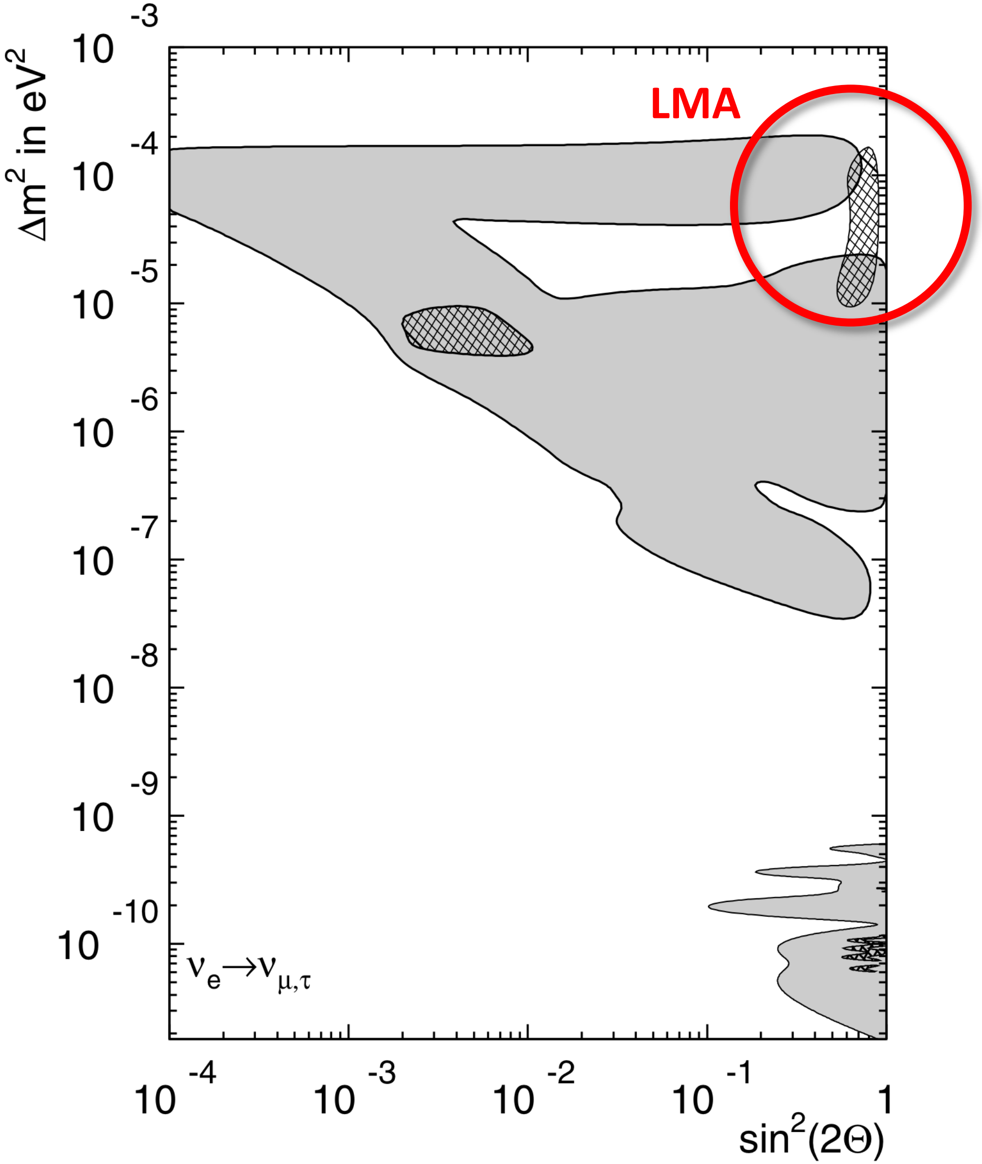


Day/Night Effect



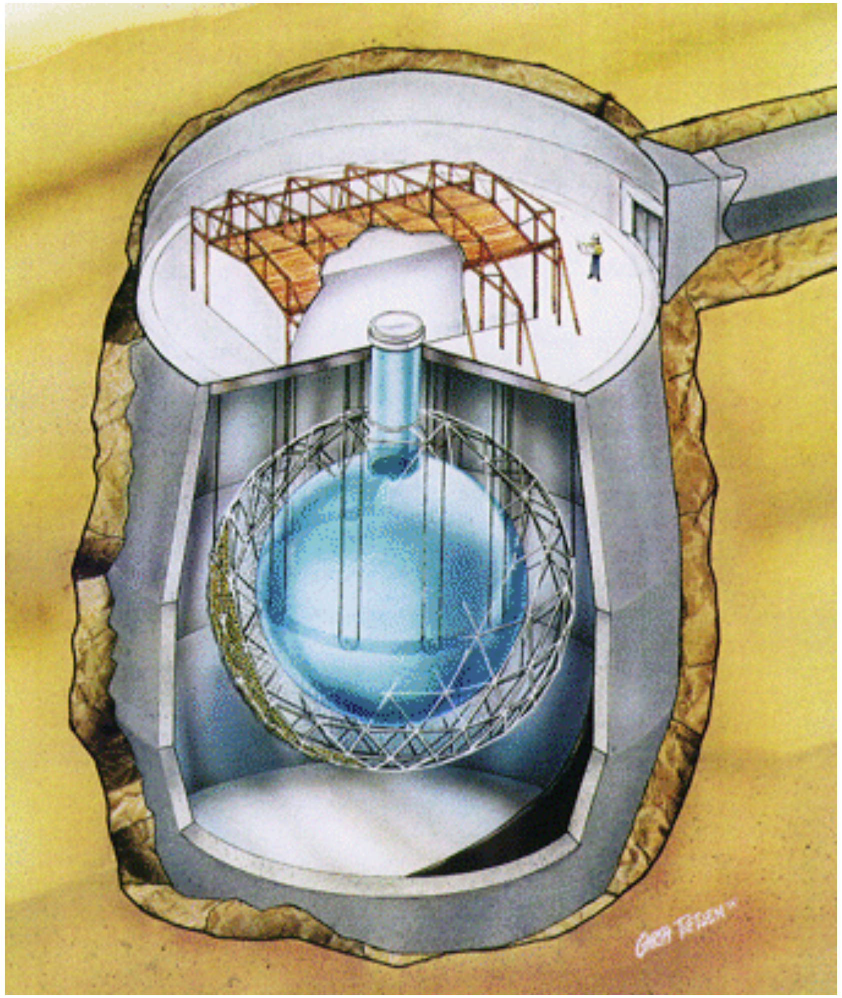
Seasonal Variation

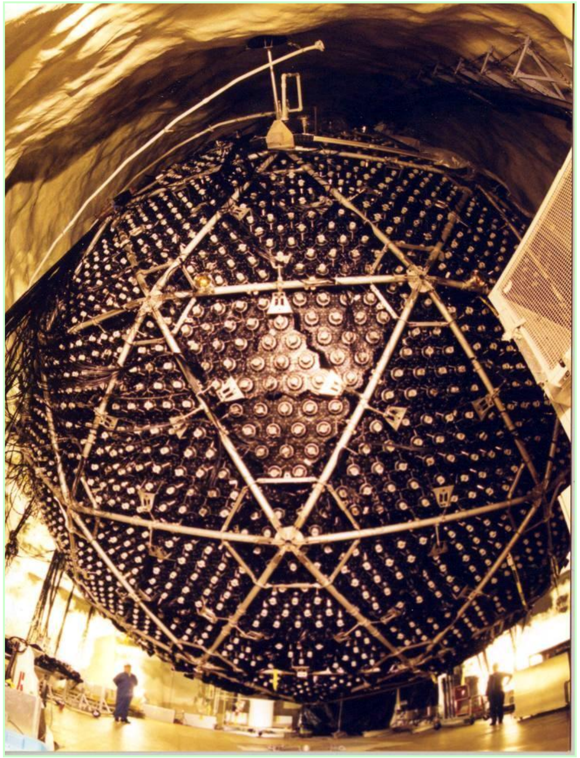




1999 – 2006

SNO – Sudbury Neutrino Observatory

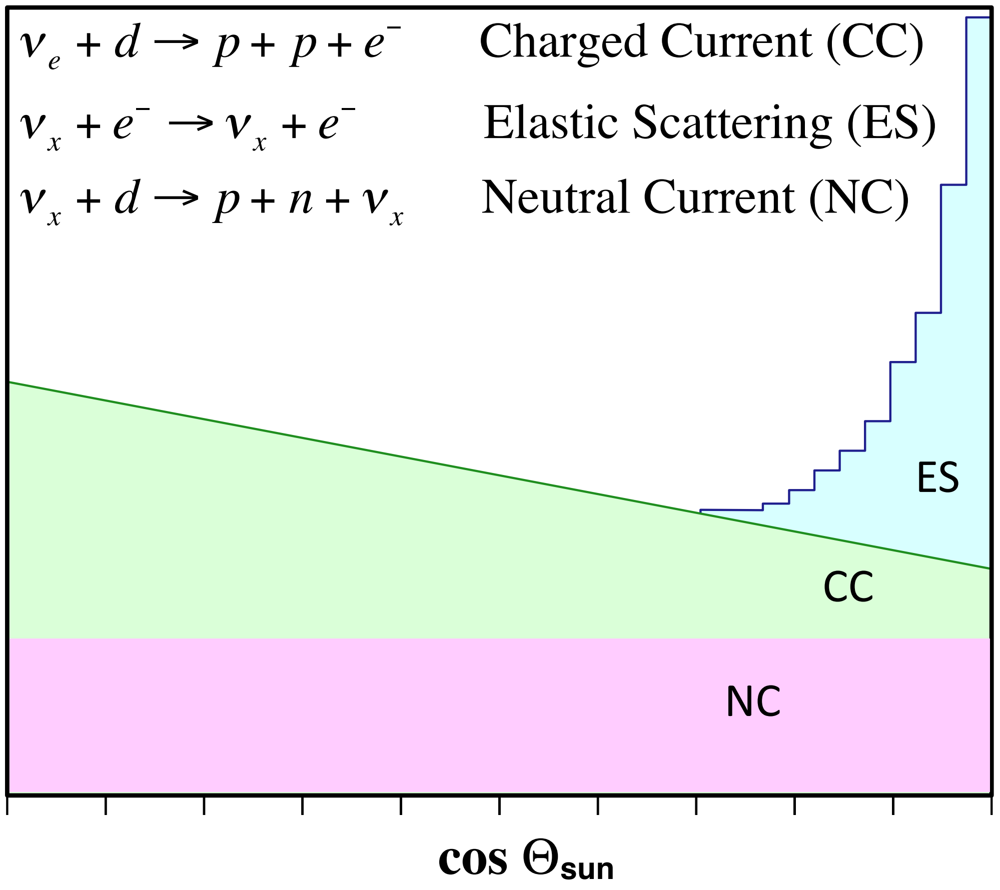


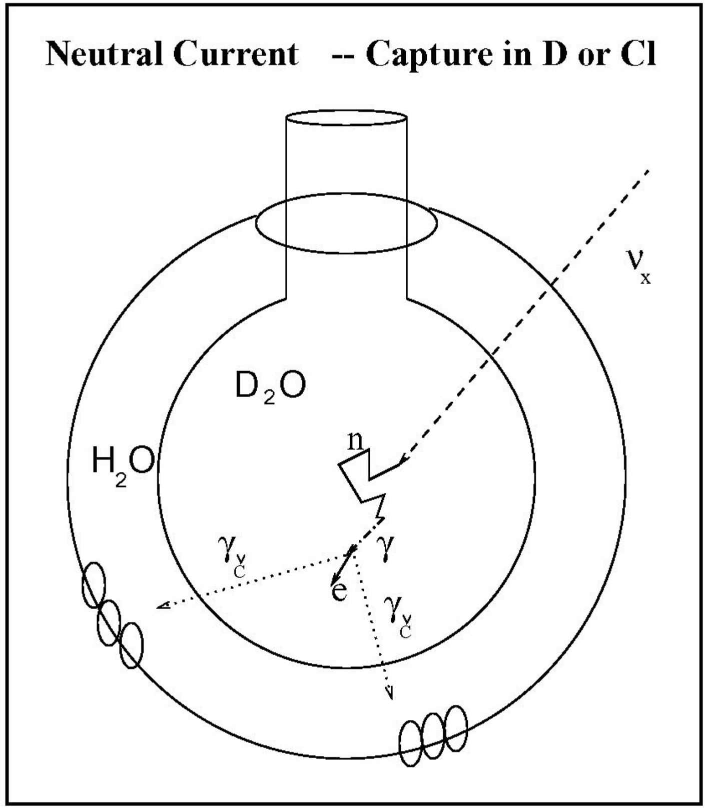


2015 Nobel Prize:
Art McDonald

Creighton Nickel Mine in Sudbury Ontario
1 kton of heavy water (D_2O)
9500 PMTs
2100 meters deep – 6000 mwe **3 muons per hour!**
Clean detector: low radioactivity
Three phases: pure D_2O, NaCl salt, Neutral Current Detectors

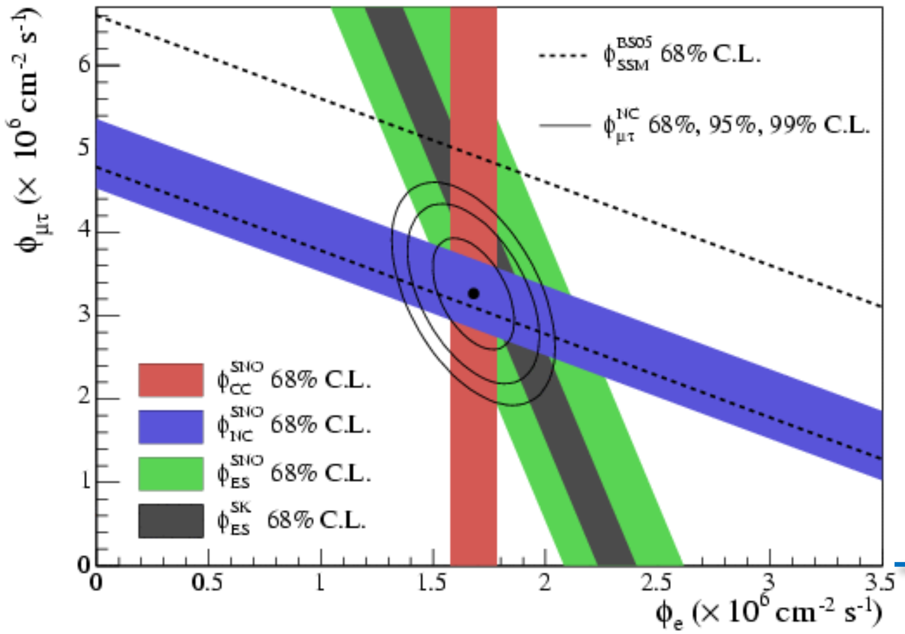
Heavy Water: D_2O

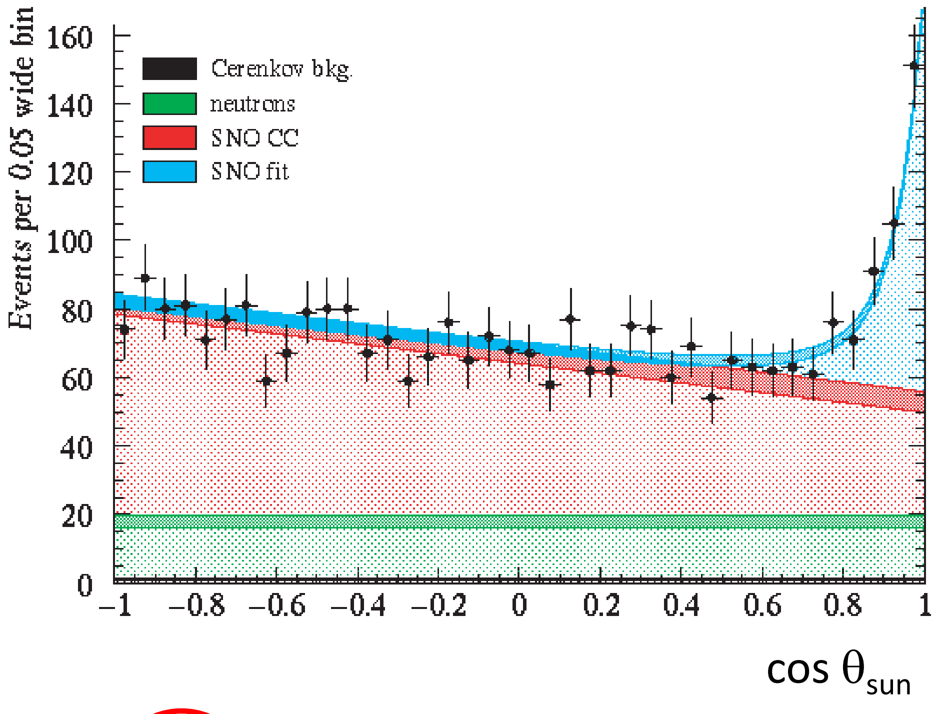




SNO Solar Result (2001)

PRC **72**, 055502 (2005)

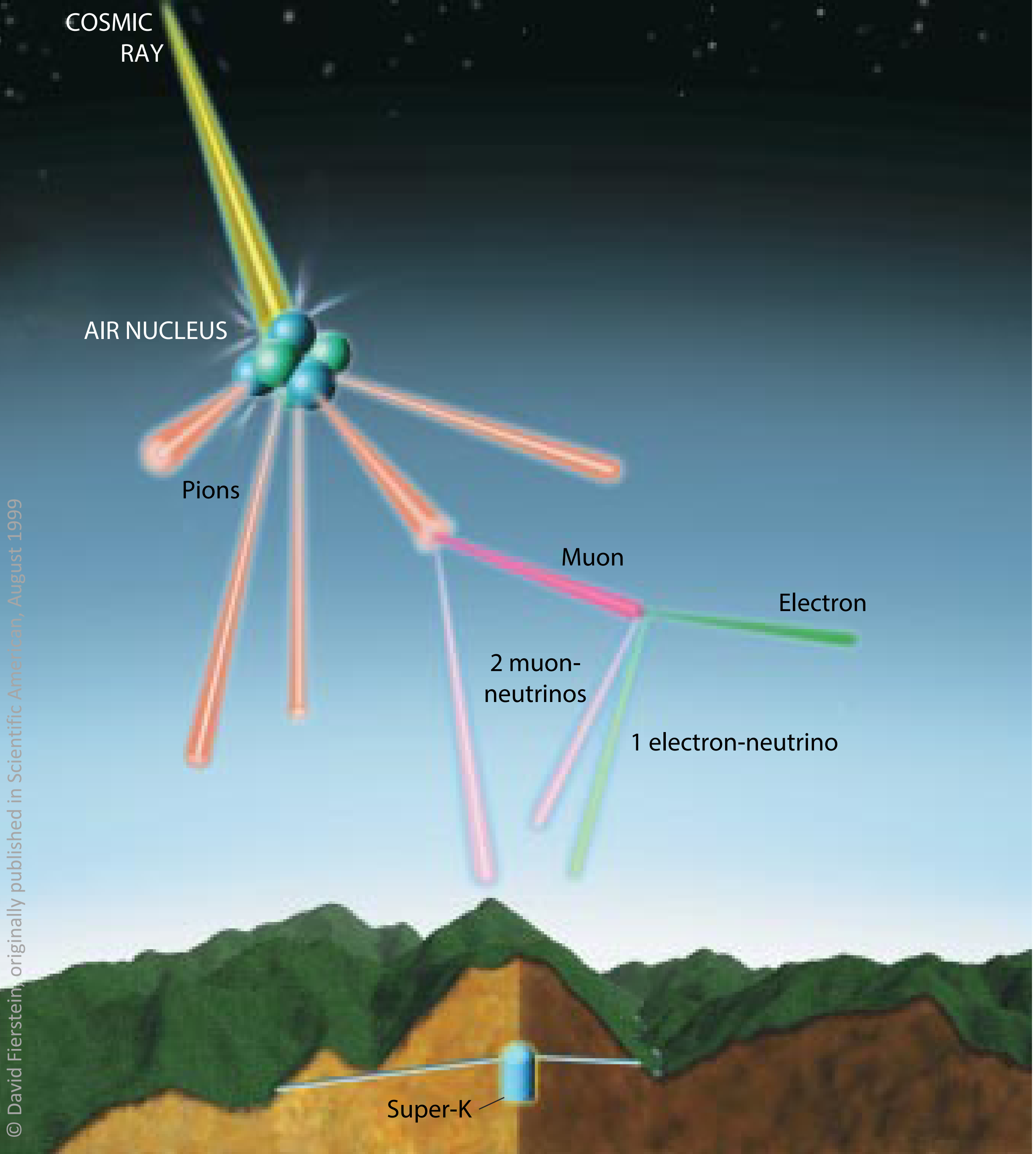




Would measure
here if no ν mixing.
Standard Solar Model prediction.

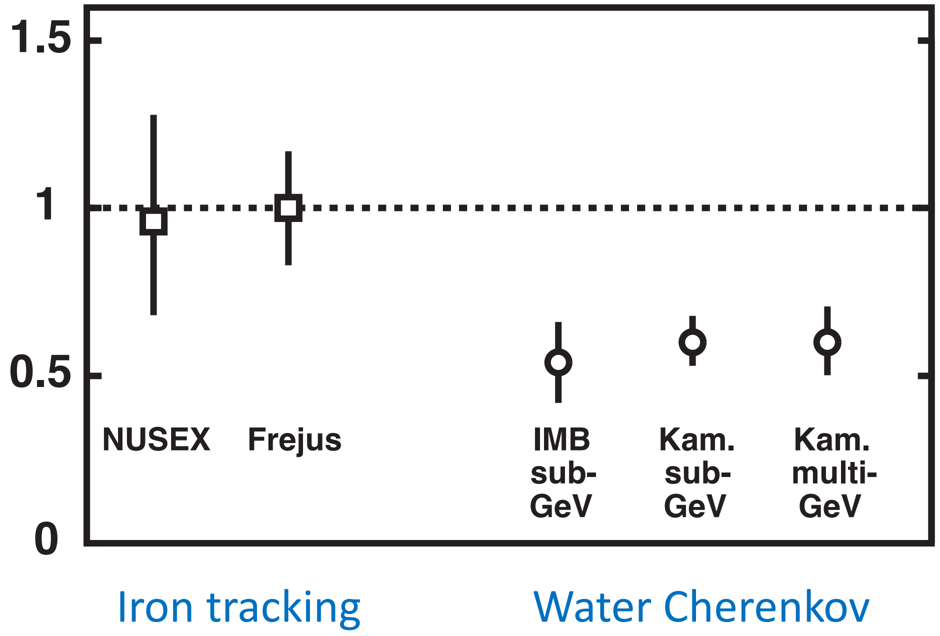
$$\Phi_{CC} = 1.68 \pm 0.11$$

$$\Phi_{NC} = 4.94 \pm 0.43$$



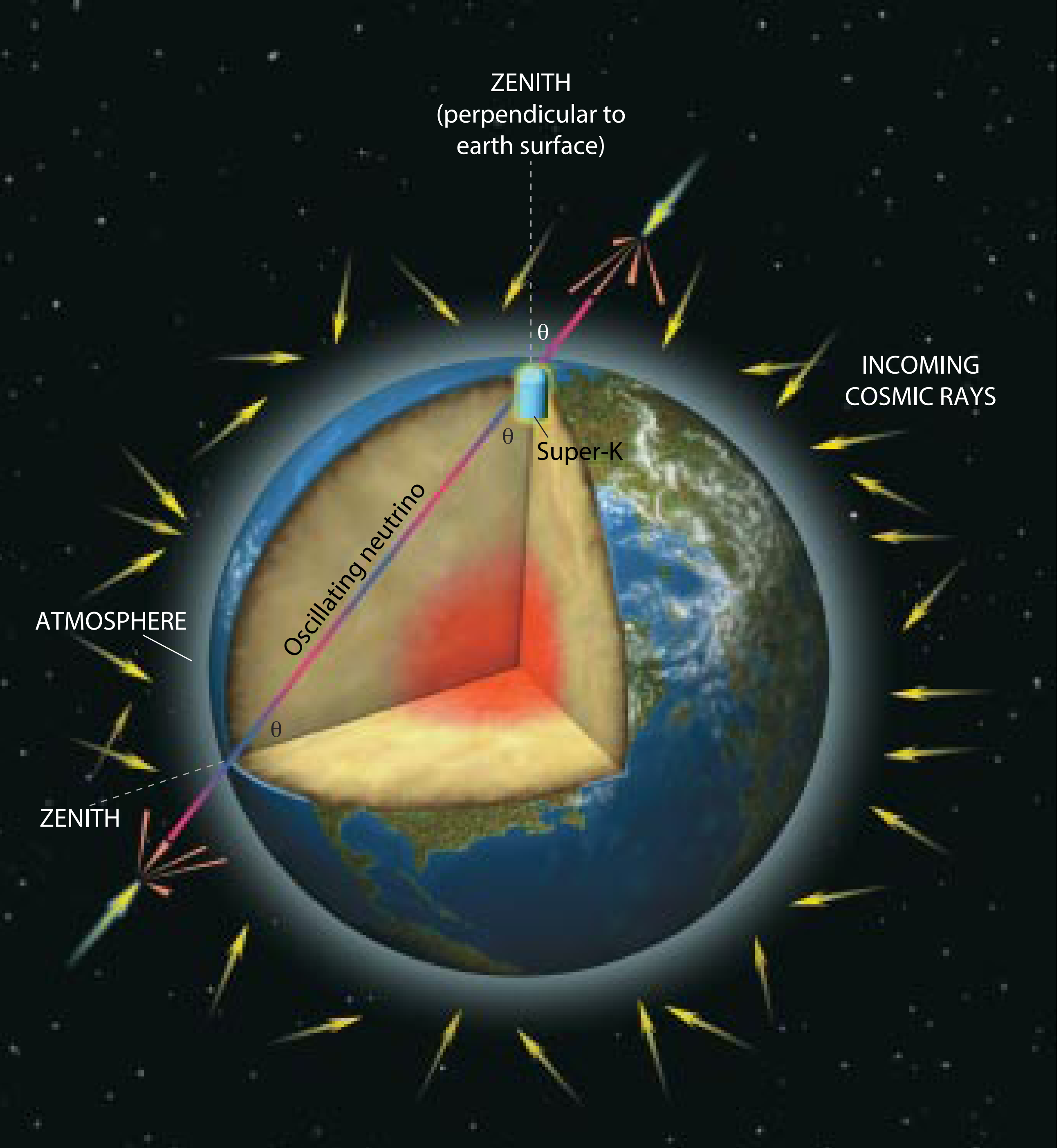
Atmospheric Neutrino Anomaly

$$R = \frac{(\nu_\mu/\nu_e)_{\mathrm{DATA}}}{(\nu_\mu/\nu_e)_{\mathrm{M.C.}}}$$



1986-1998

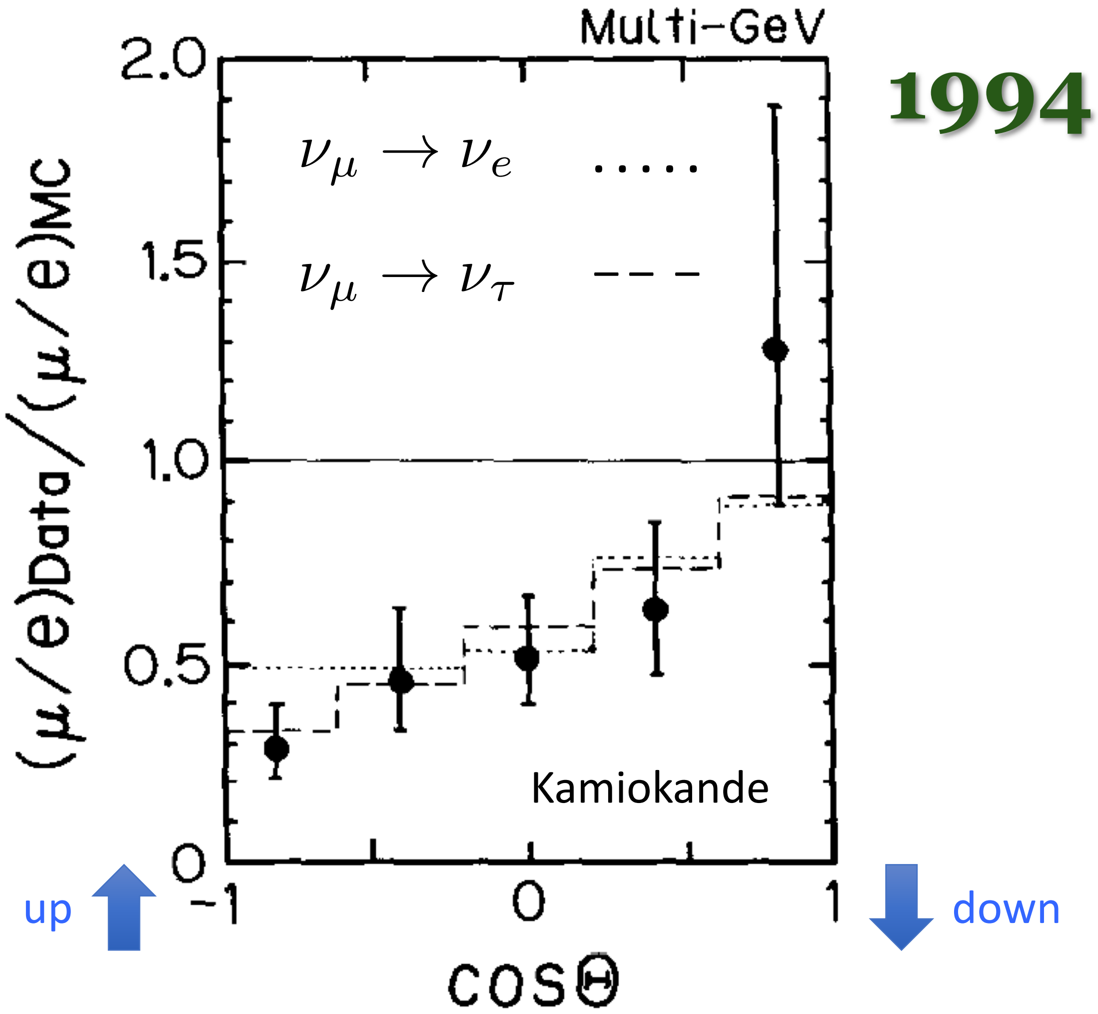
Atmospheric Neutrino Anomaly



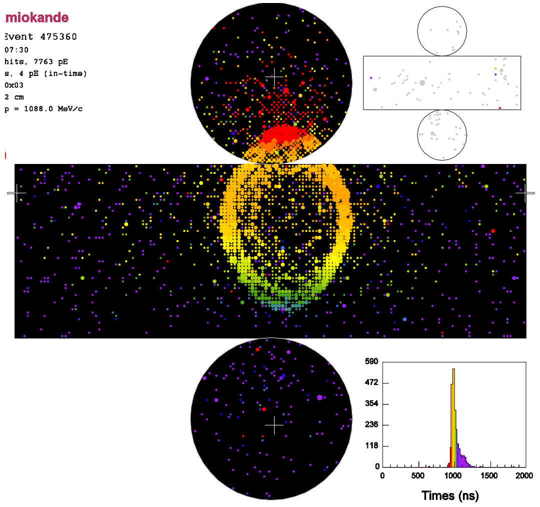
© David Fierstein, originally published in Scientific American, August 1999

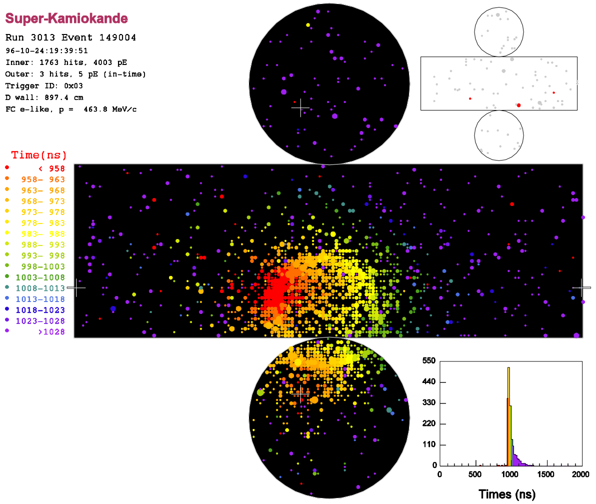
$$R = \frac{(\nu_\mu/\nu_e)_{\mathrm{DATA}}}{(\nu_\mu/\nu_e)_{\mathrm{M.C.}}}$$

1994



1st Super-K paper – March 1998

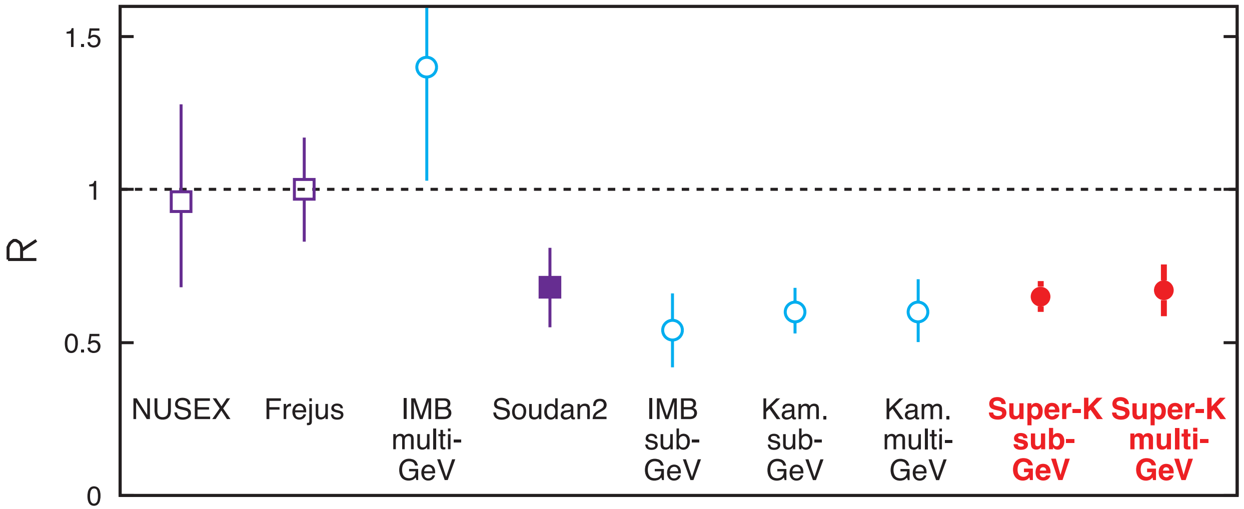




Measurement of a small atmospheric ν_μ/ν_e ratio

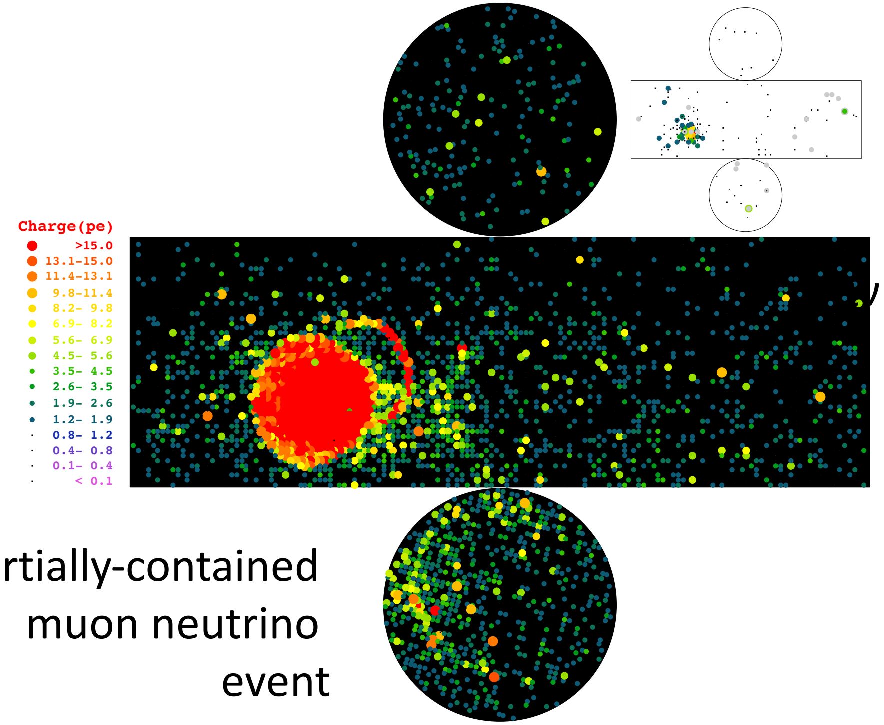
firmed the existence of a smaller atmospheric ν_μ/ν_e ratio than predicted. We obtained $R = 0.61 \pm 0.03(\text{stat.}) \pm 0.05(\text{sys.})$ for events in the sub-GeV range. The Super-Kamiokande detector has much greater fiducial mass and sensitivity than prior experiments. Given the relative certainty in this result, statistical fluctuations can no longer explain the deviation of R from unity.

25.5 kton yr (414 days data)
Sub-GeV only
Two independent analyses

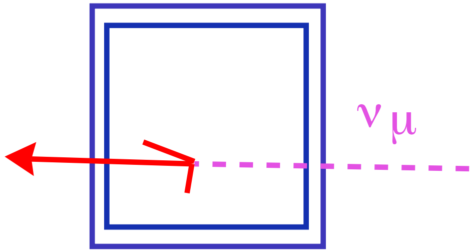


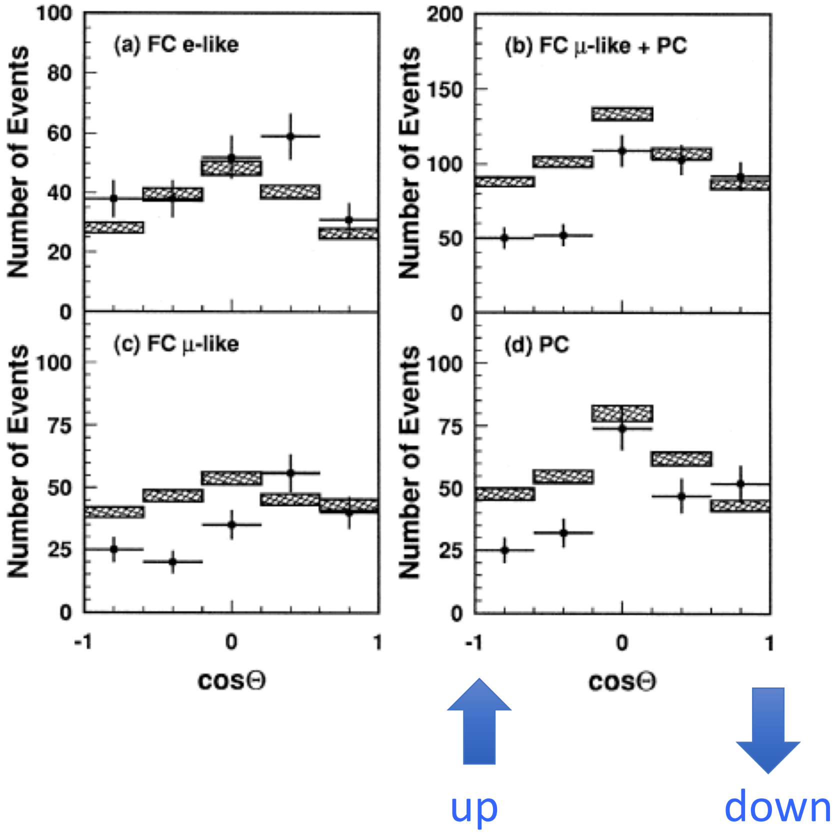
2^{nd} Super-K paper – May 1998

Study of the atmospheric neutrino flux
in the multi-GeV energy range

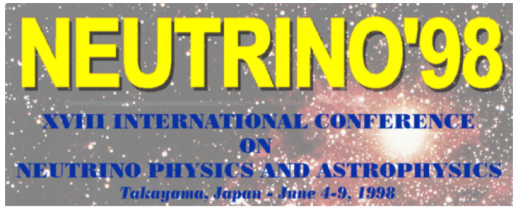


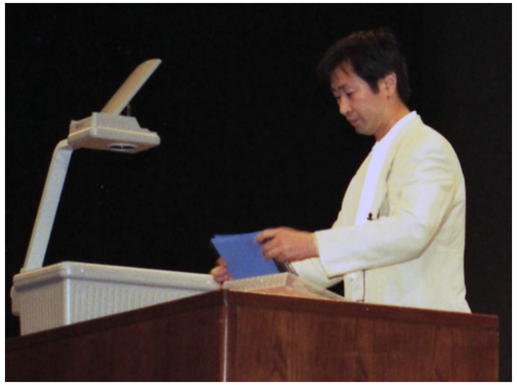
Partially-contained
muon neutrino
event



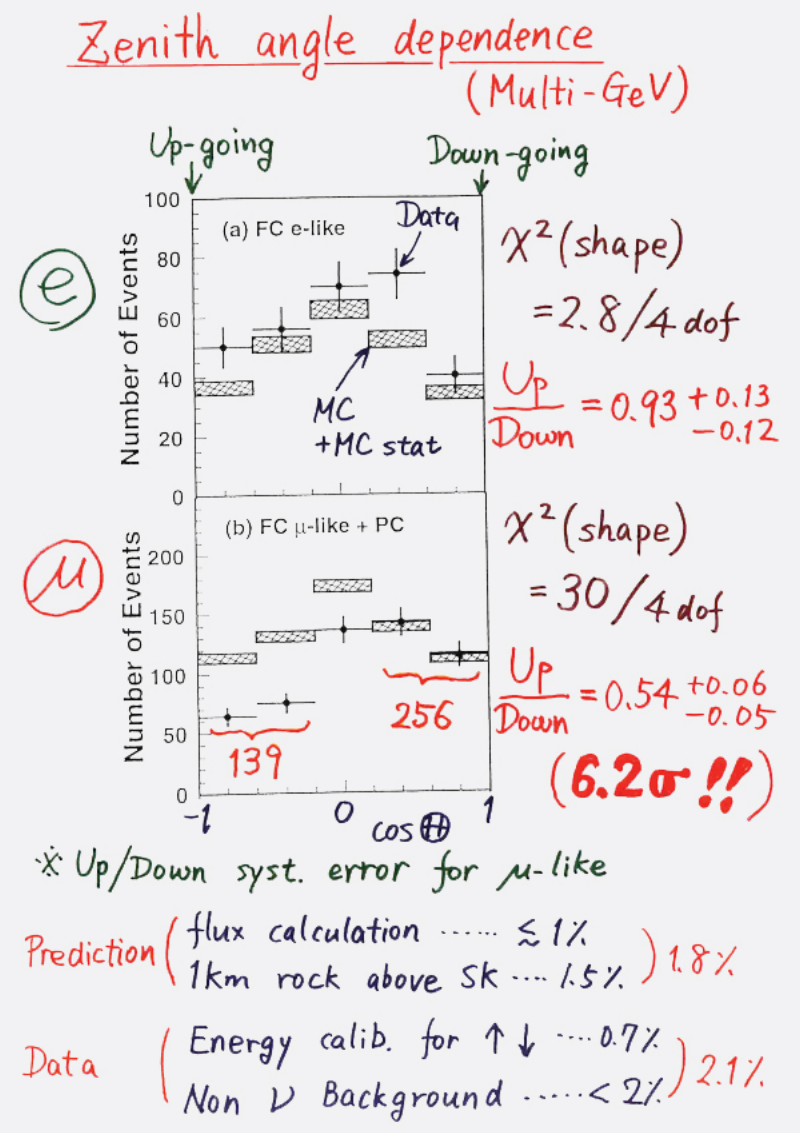


Discovery of Neutrino Oscillations





2015 Nobel Prize:
Takaaki Kajita




The New York Times

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

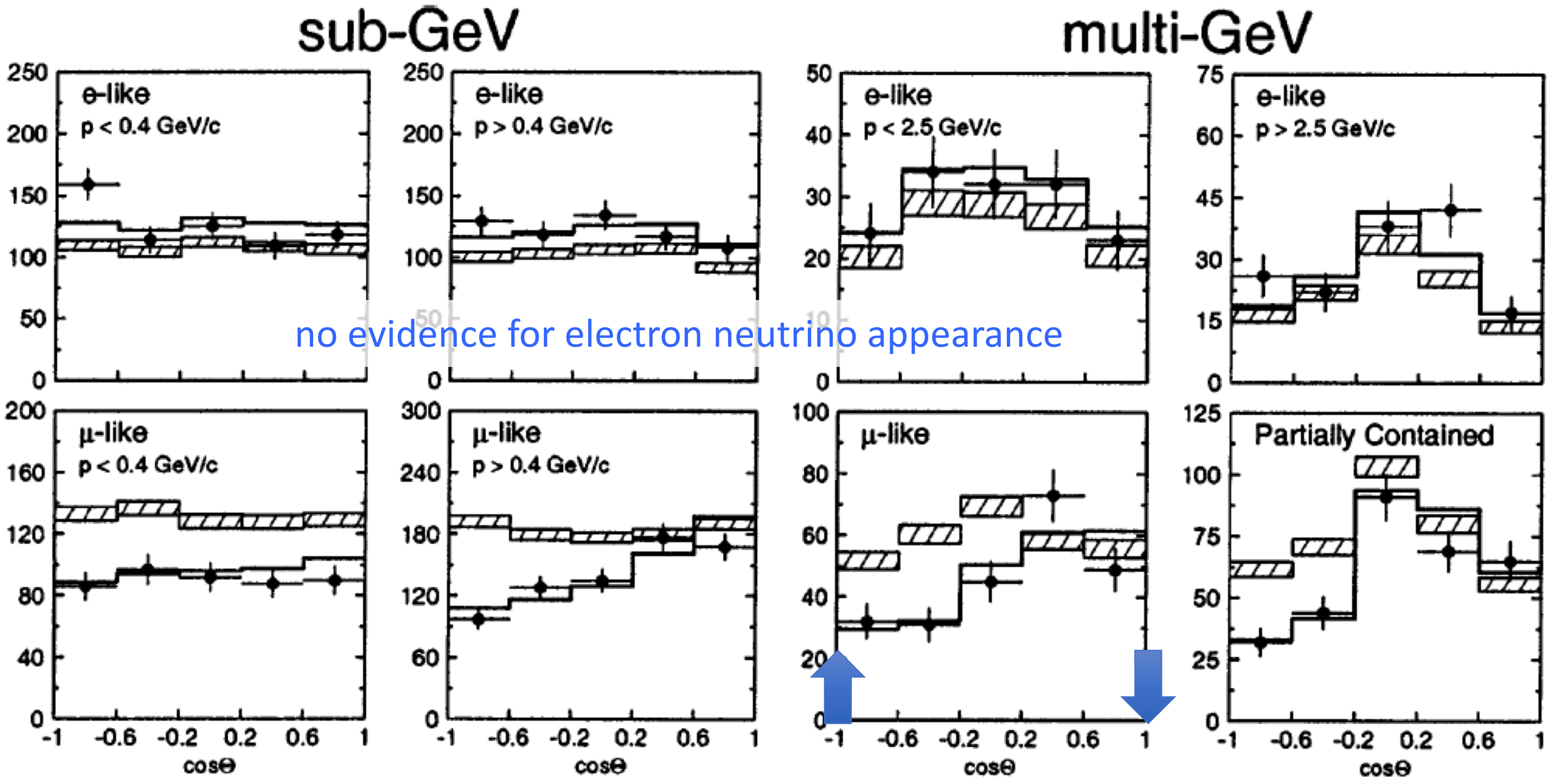
JUSTICES REBUFF STARR'S REQUEST TO SPEED REVIEW

Refugees From Kosovo Cite A Bitter Choice: Flee or Die

Yankee Owner Warns Vallone On Referendum

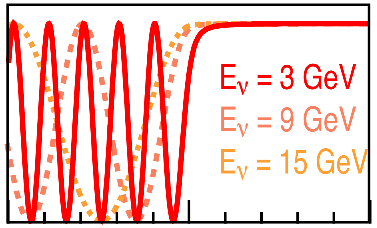
VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos



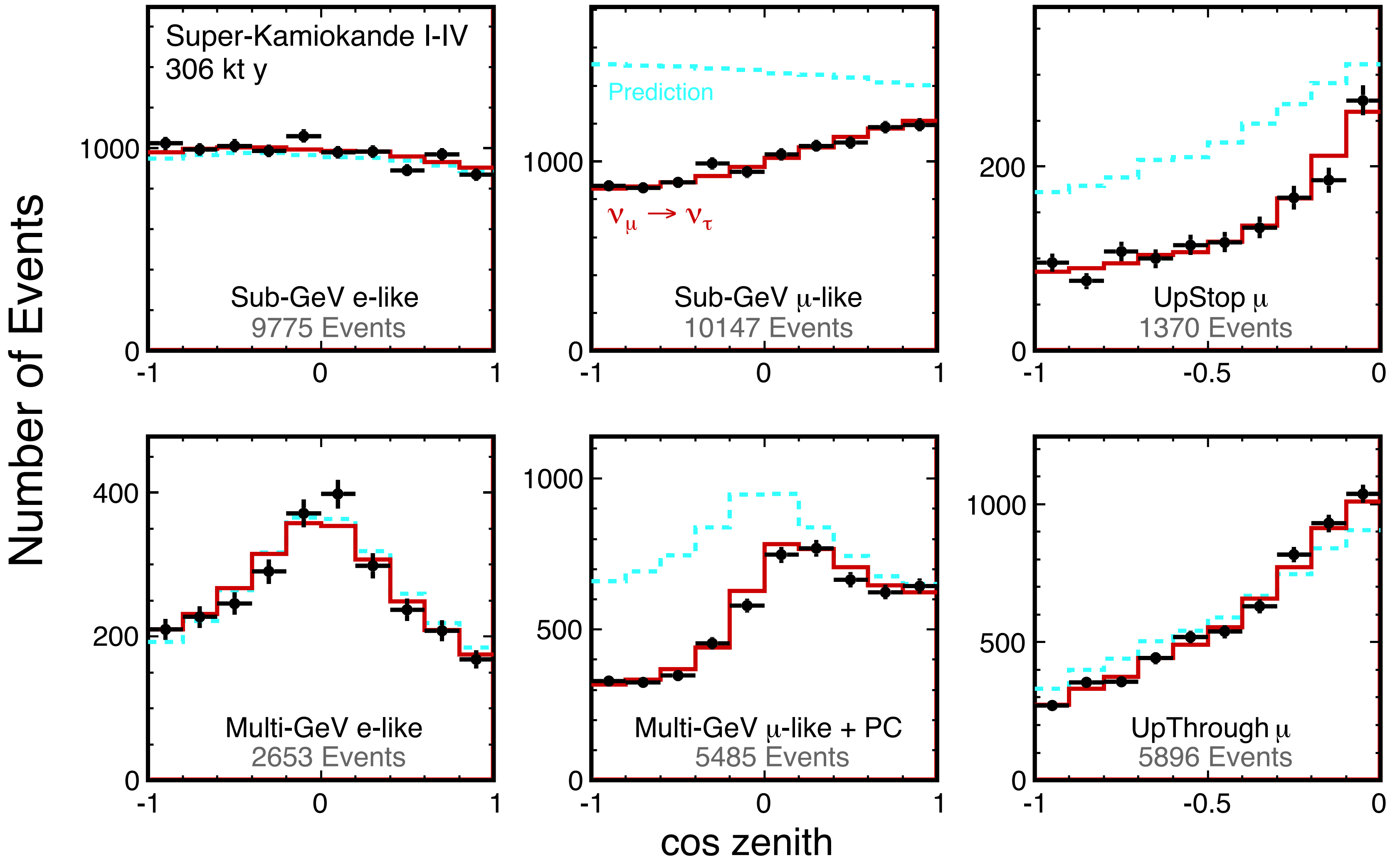
3rd Super-K paper – August 1998

survival probability

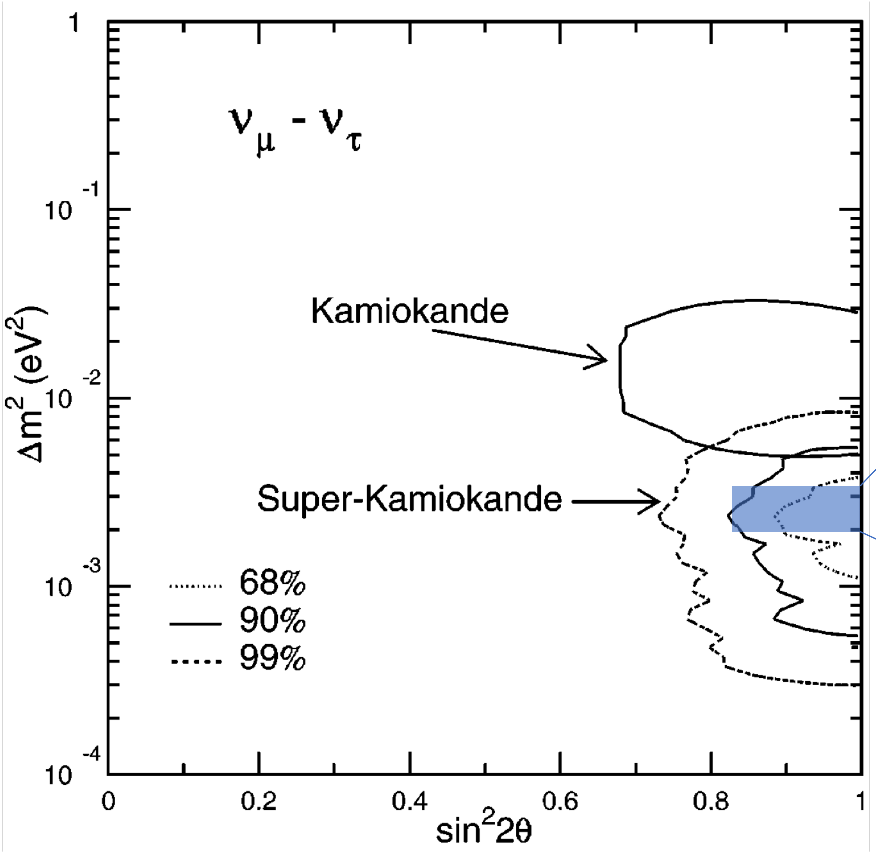


strong evidence for muon neutrino disappearance

2017

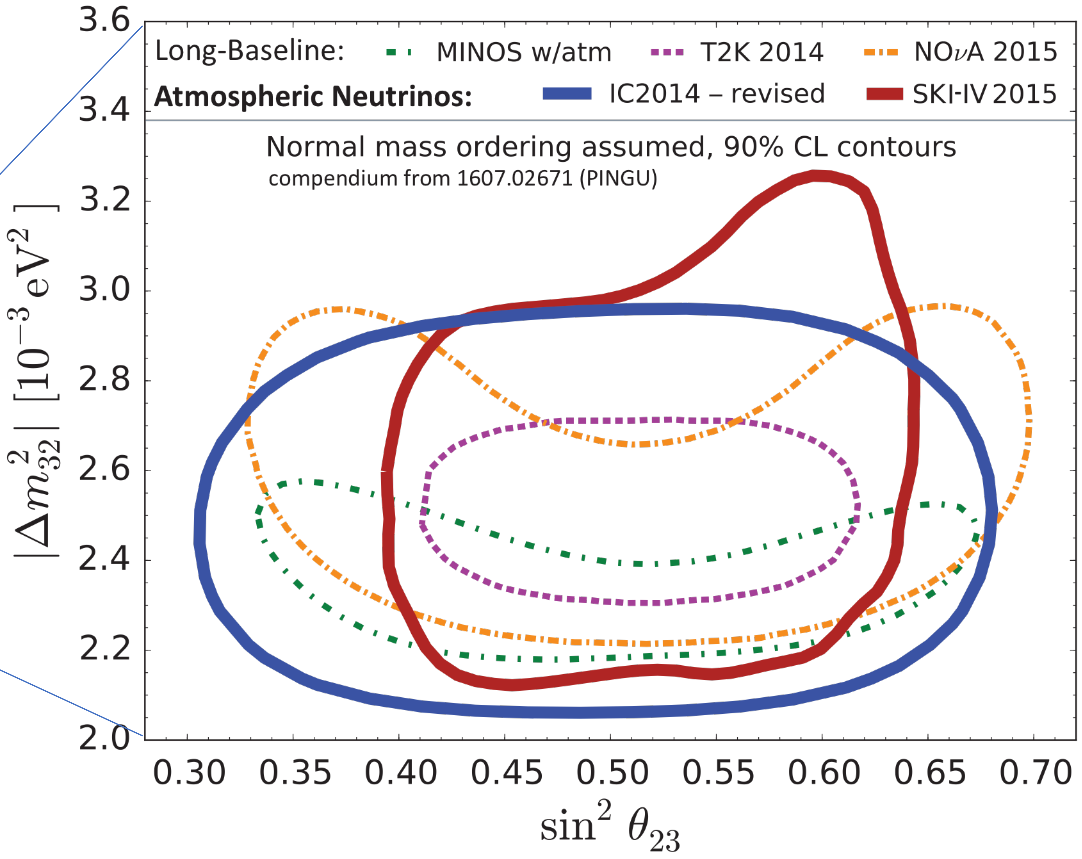

Super-Kamiokande I-IV
306 kt y
Prediction
$\nu_\mu \rightarrow \nu_\tau$
Number of Events
cos zenith
Sub-GeV e-like
9775 Events
Sub-GeV μ-like
10147 Events
UpStop μ
1370 Events
Multi-GeV e-like
2653 Events
Multi-GeV μ-like + PC
5485 Events
UpThrough μ
5896 Events

1998



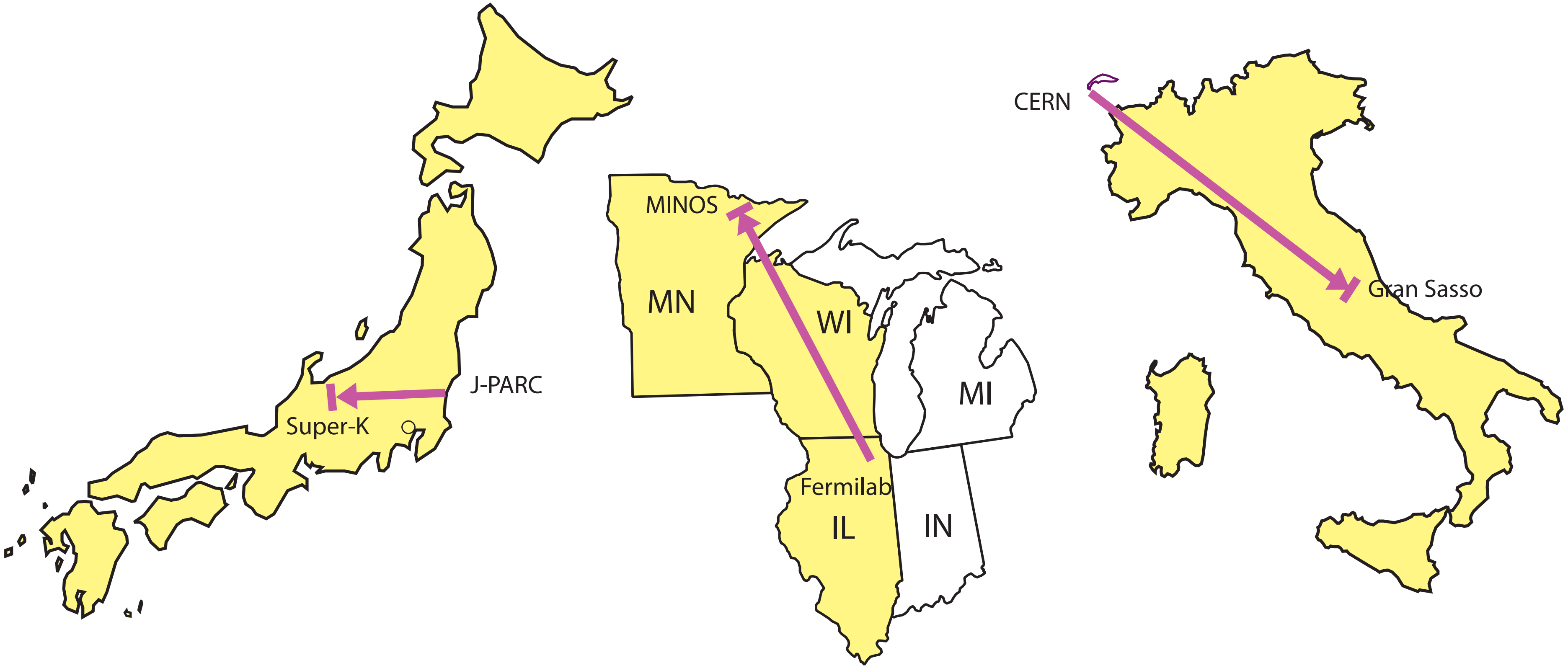
$\nu_\mu - \nu_\tau$
Kamiokande
Super-Kamiokande
68%
90%
99%
Δm^2 (eV^2)
$\sin^2 2\theta$

2017



Long-Baseline: MINOS w/atm T2K 2014 NOνA 2015
Atmospheric Neutrinos: IC2014 – revised SKI-IV 2015
Normal mass ordering assumed, 90% CL contours
compendium from 1607.02671 (PINGU)
$|\Delta m^2_{32}|$ [10^{-3} eV^2]
$\sin^2 \theta_{23}$

1999 - Long-Baseline Neutrino Experiments



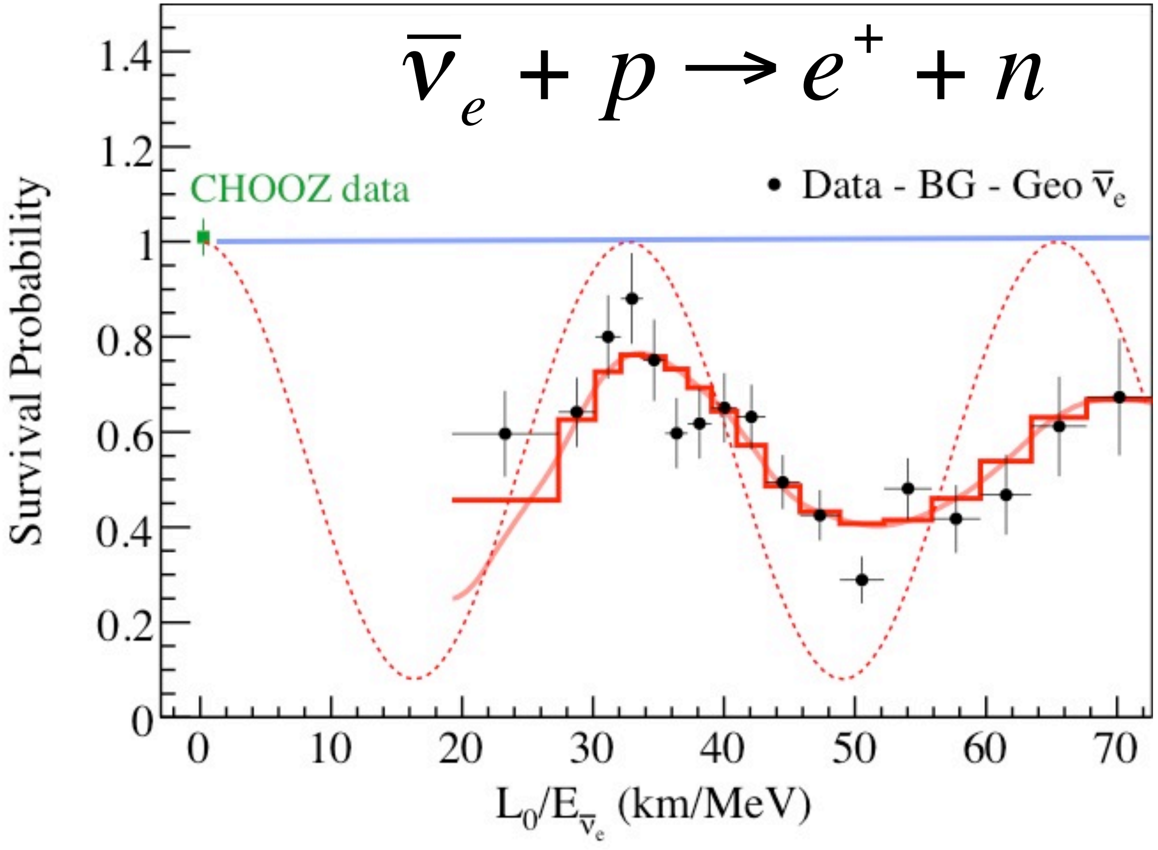
**K2K (1999-2004)
and
T2K (2011+)**

**MINOS (2005-present)
and
NOνA (2013+)**

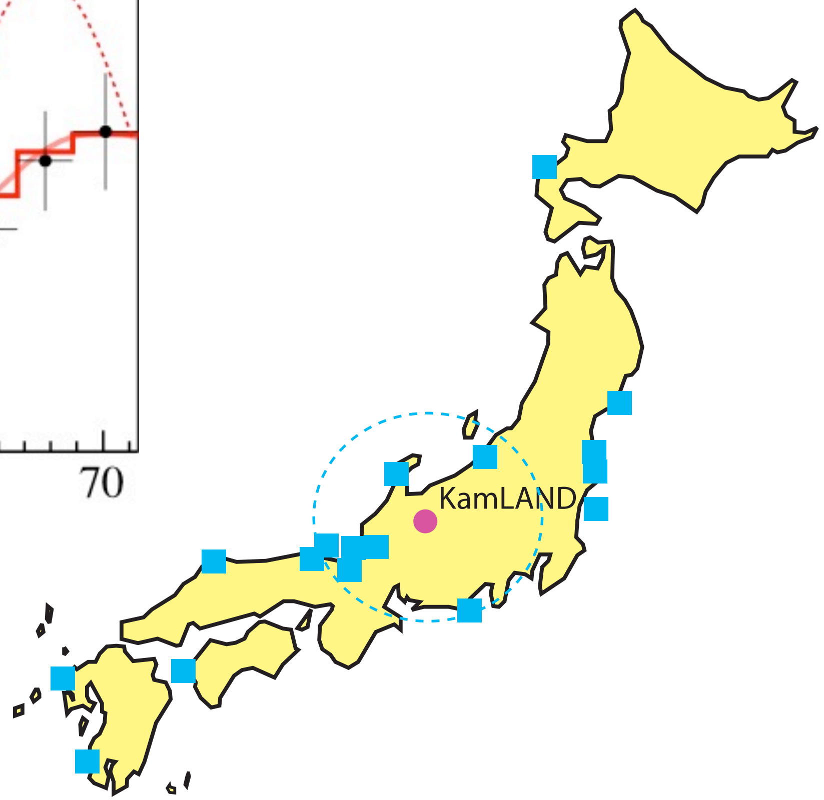
**OPERA and ICARUS
(2008-2012)**

Confirmed (K2K) and precisely measured (MINOS) muon neutrino disappearance
Found electron neutrino appearance (T2K, MINOS)
Studying CP Violation and Mass Ordering with neutrinos and antineutrinos (T2K, NOvA)
Found Tau neutrino appearance (OPERA)

2005 KamLAND – Solar Sector with Antineutrinos



1 kton liquid scintillator
reuse the Kamiokande cavern
sensitive to combined flux
from numerous reactors



The Neutrino Matrix

Pontecorvo-Maki-Nakagawa-Sakata Matrix (PMNS or MNS)

flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass

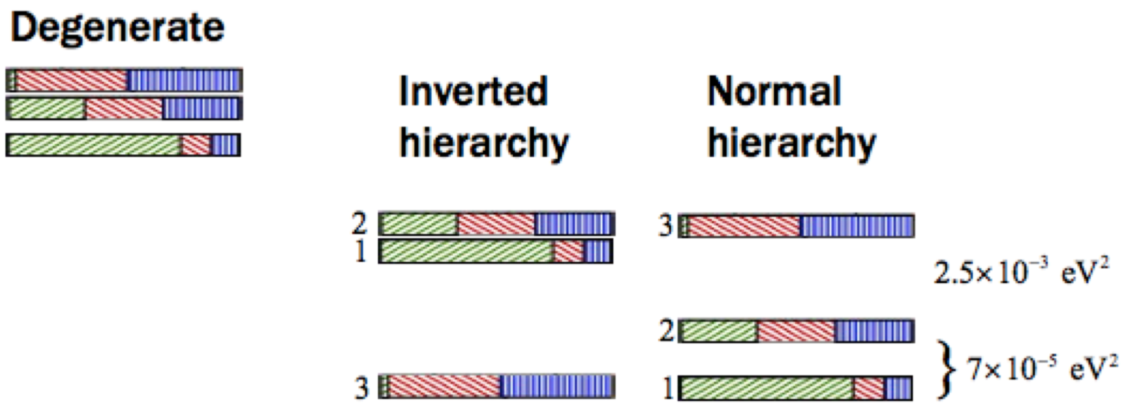
$$U_{PMNS} = \begin{pmatrix} 0.8 & 0.6 & 0.15 \\ 0.5 & 0.5 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

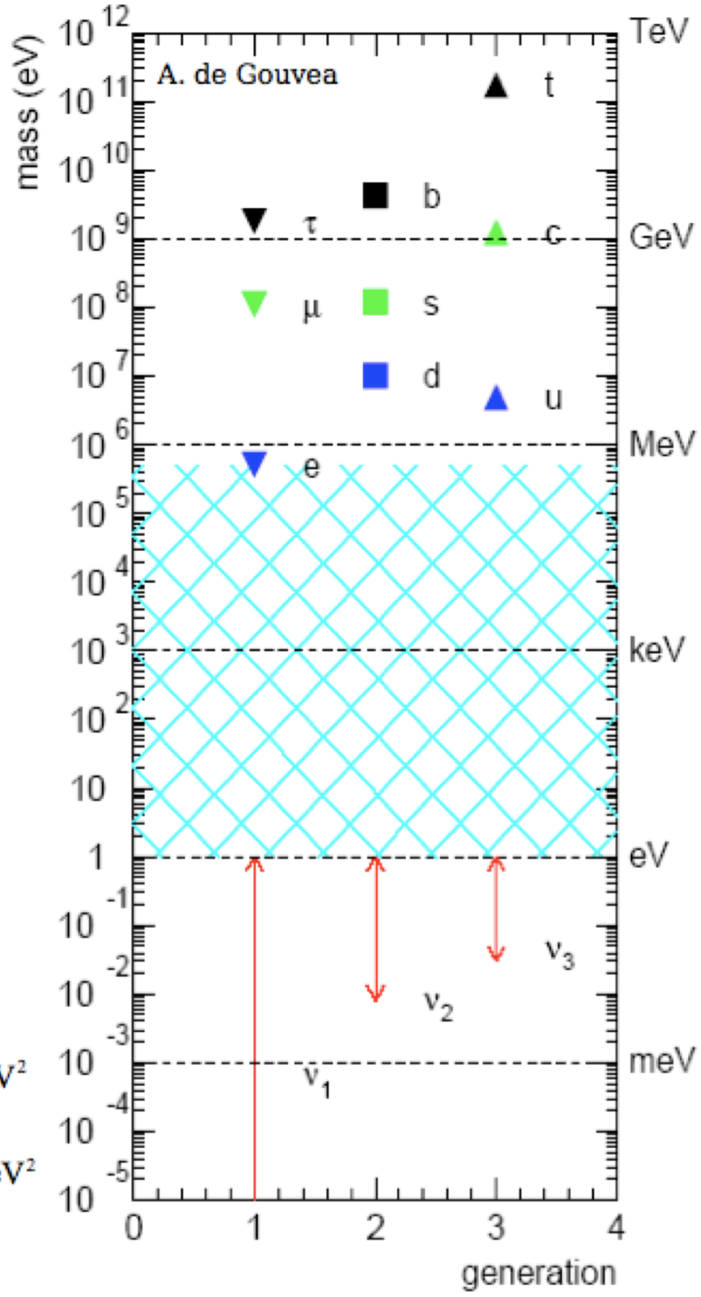
$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.5 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

neutrinos

quarks

Neutrino Mixing
=>
Neutrino Mass





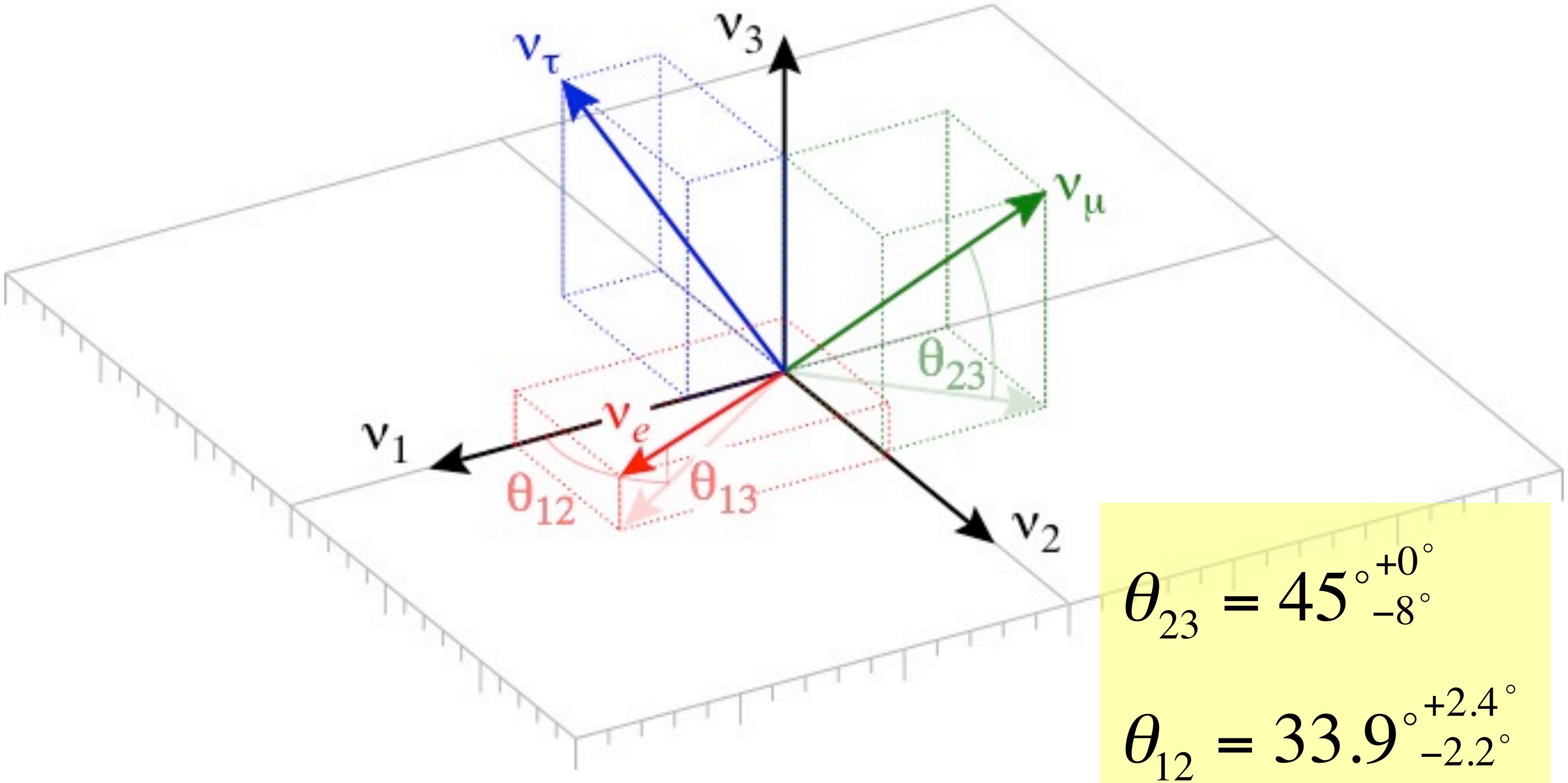
The Neutrino Matrix

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

Three mixing angles plus one complex phase.

Neutrino Mixing Angles



$$\theta_{23} = 45^{\circ}{}^{+0^{\circ}}_{-8^{\circ}}$$

$$\theta_{12} = 33.9^{\circ}{}^{+2.4^{\circ}}_{-2.2^{\circ}}$$

Until summer 2011 $\theta_{13} < 13^{\circ}$

Three Flavor Neutrino Oscillation in Matter

$$P(\nu_\mu \to \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

CP violating

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

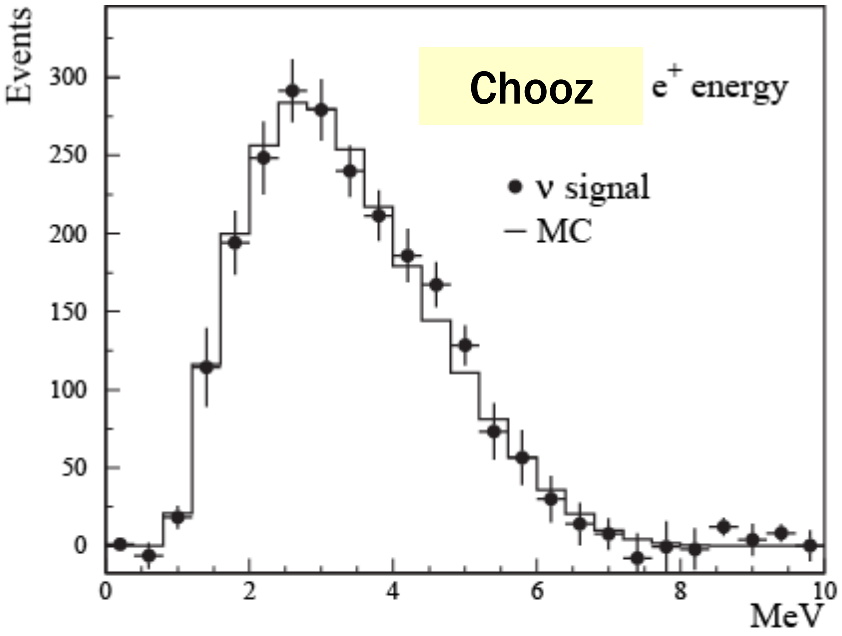
$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \Delta m^2_{31} L/4E \qquad x = 2\sqrt{2} G_F N_e E/\Delta m^2_{31} \cong E/12 \text{ GeV}$$

for anti-neutrinos, sign of x and sin δ_{cp} is changed

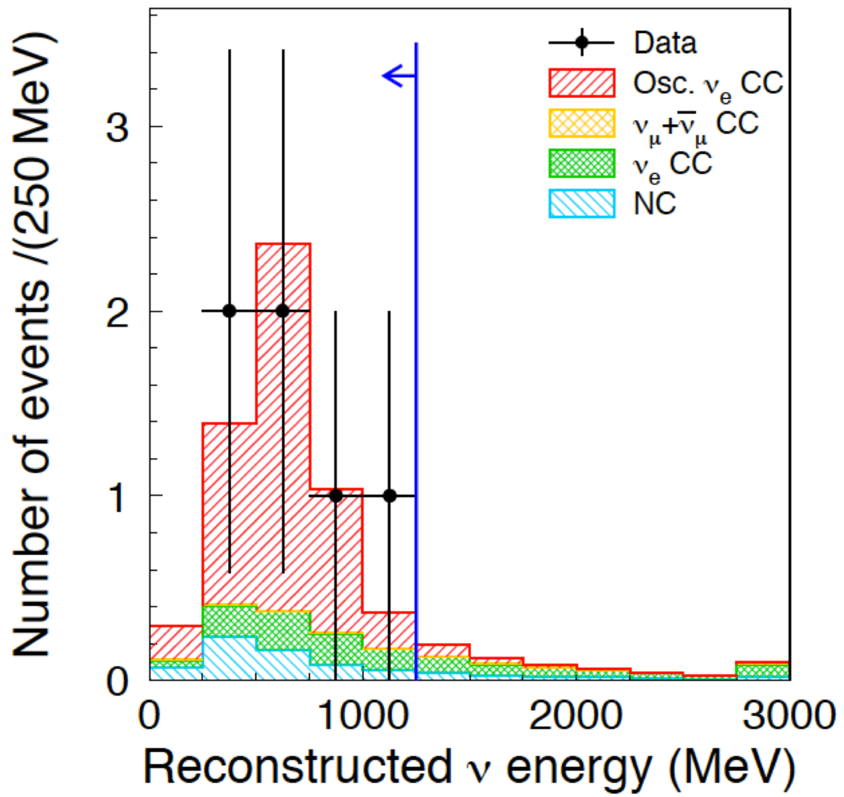
2010



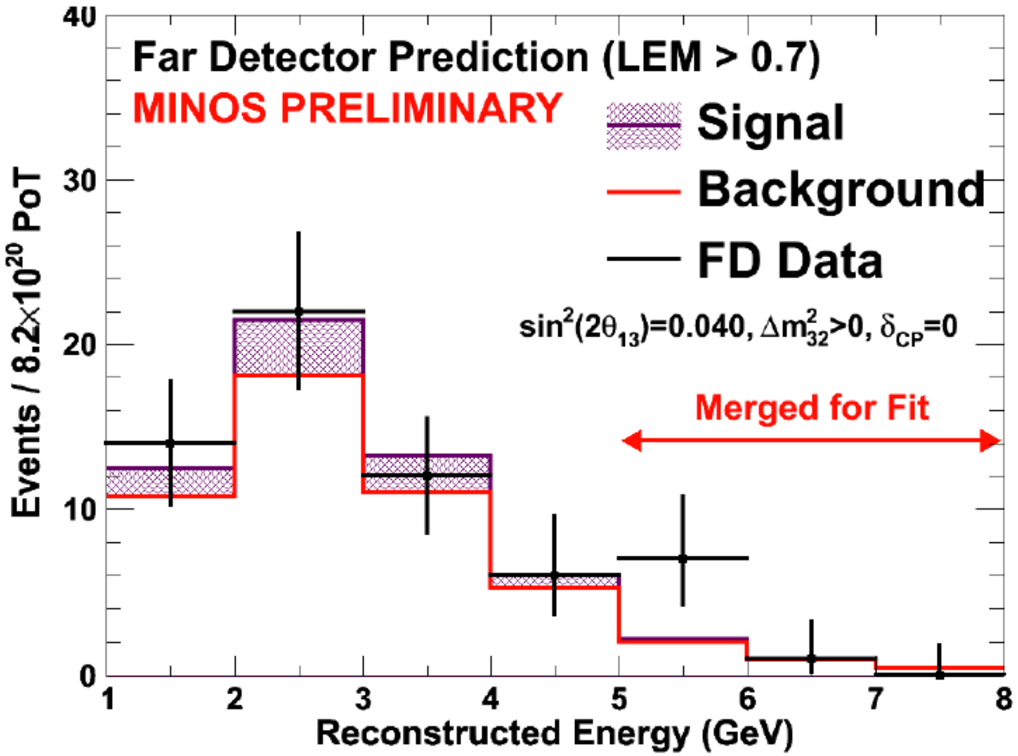
No evidence for reactor neutrino disappearance at short distances (km)

2011

T2K

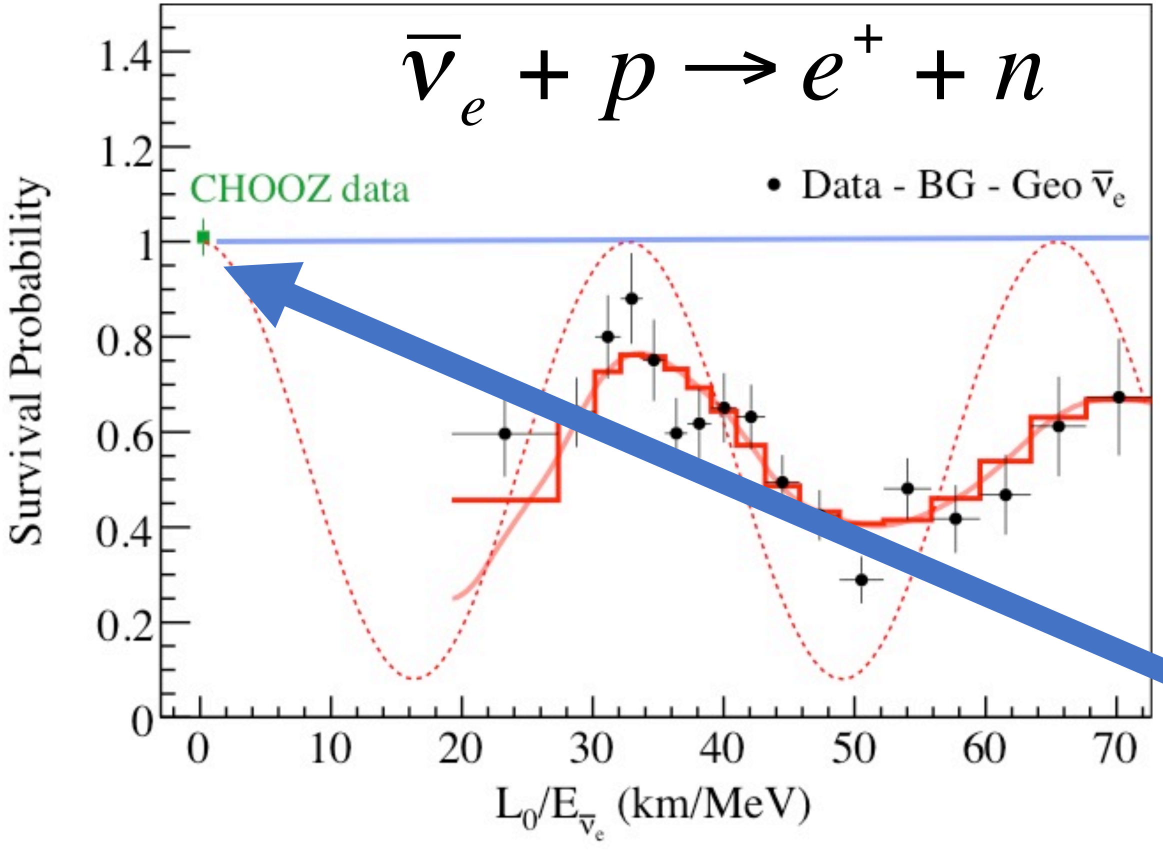


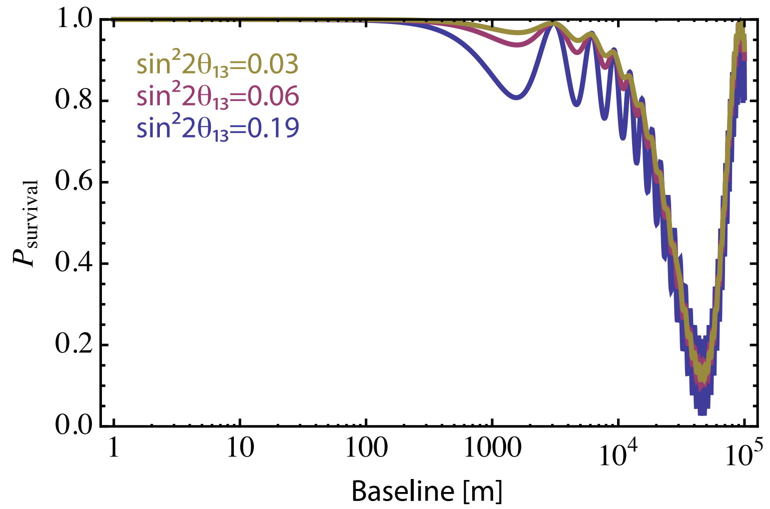
MINOS



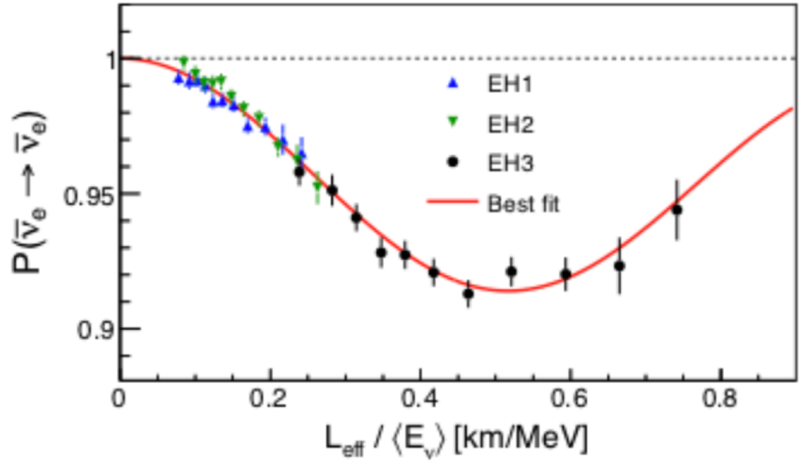
2012

Theta-13 is definitely non-zero!





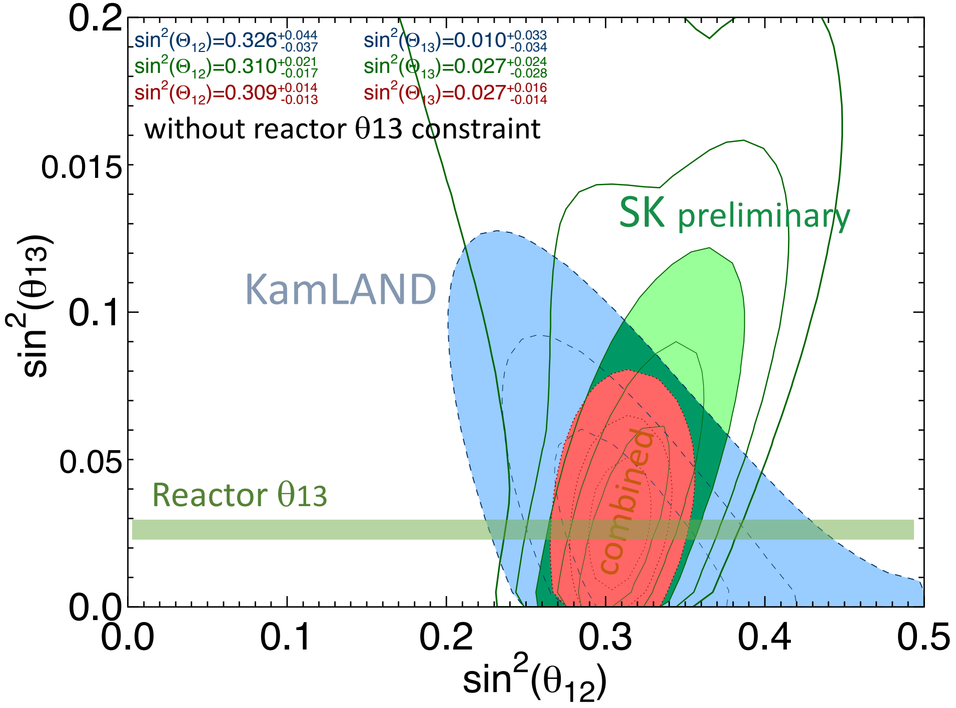
Daya Bay

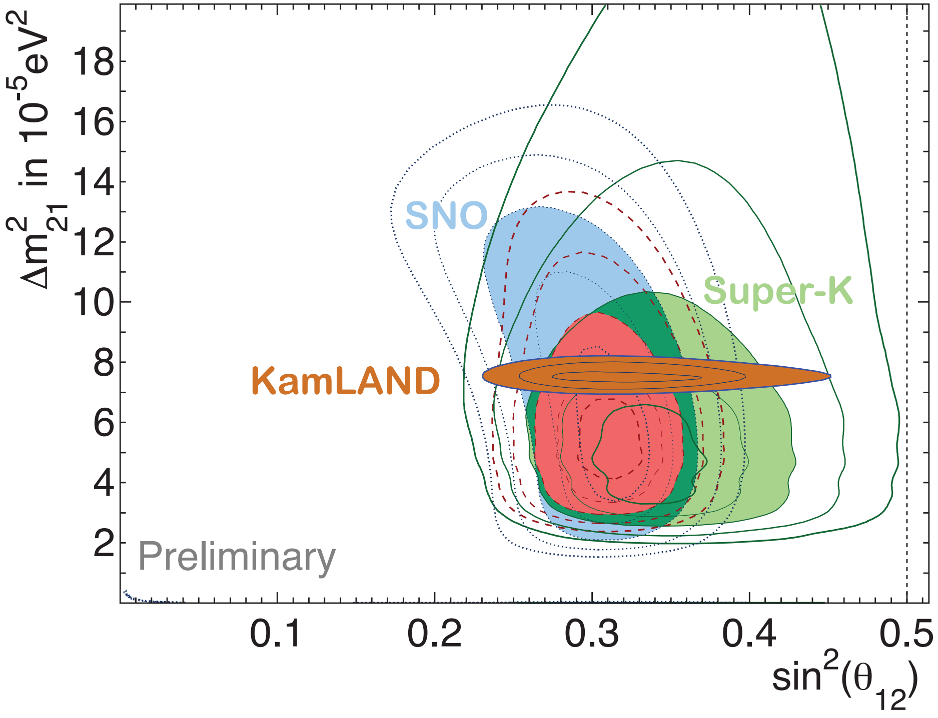


Also RENO and Double Chooz

2017

"Solar" Mixing Parameters



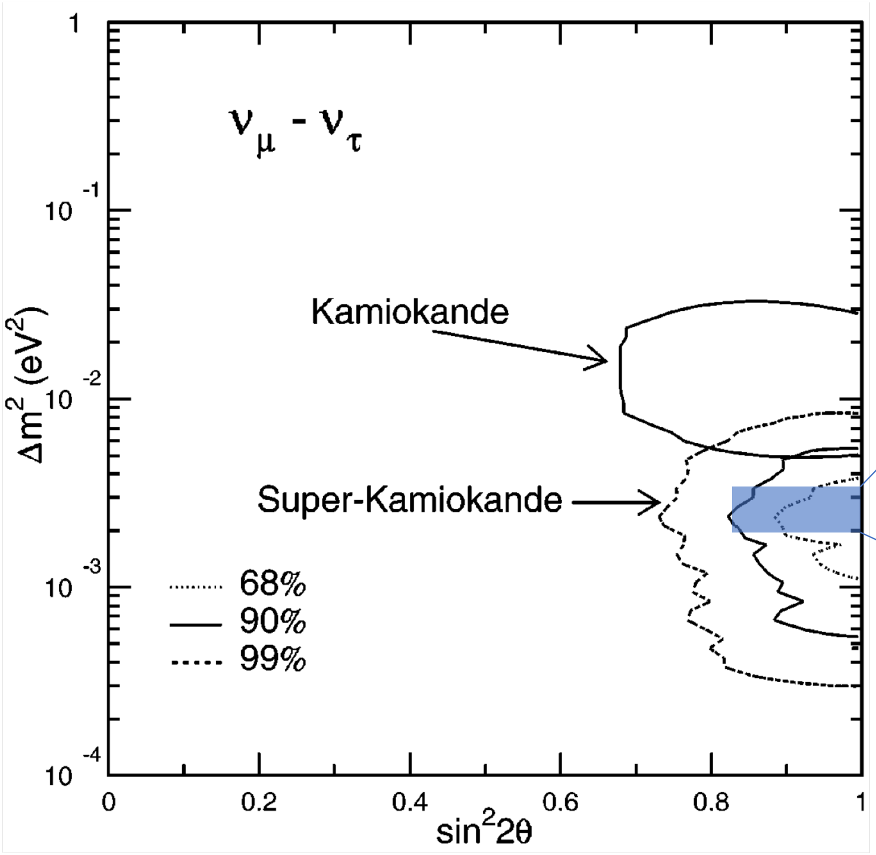


Mixing angles in good agreement
with reactor (Daya Bay, RENO, Double Chooz)

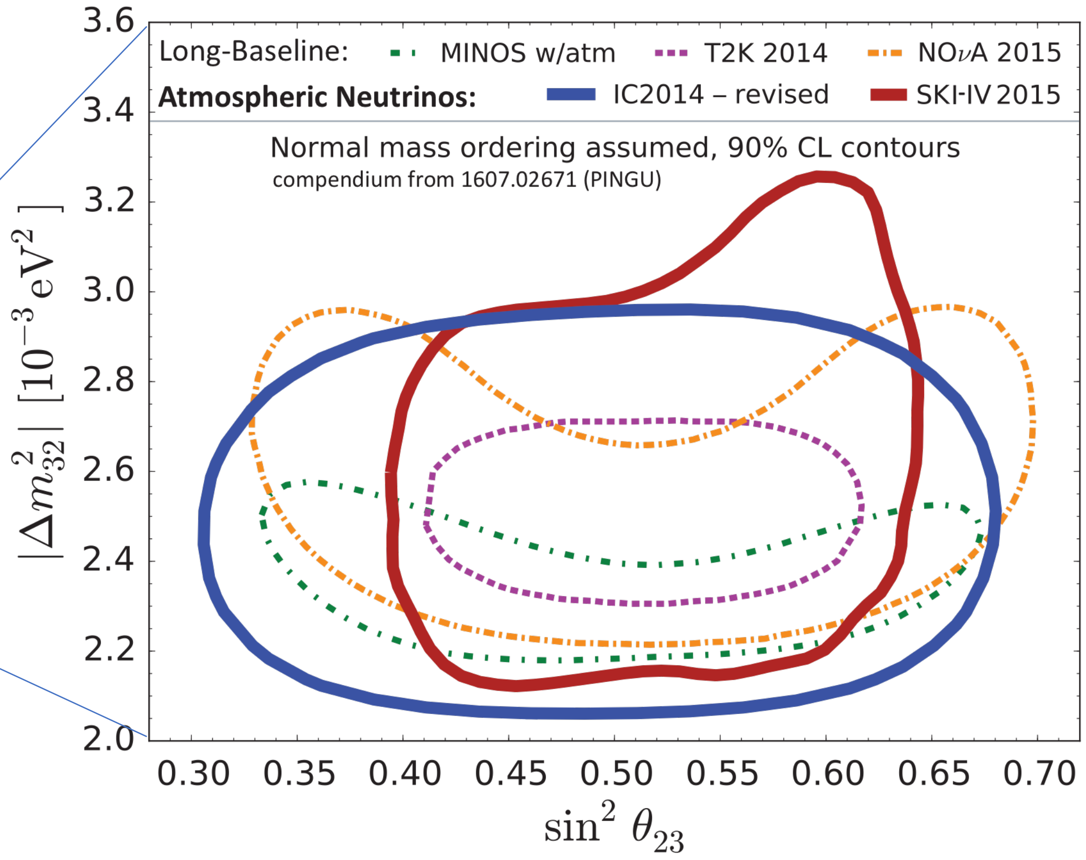
2σ tension in Δm^2_{12}
between solar and KamLAND

"Atmospheric" Mixing Parameters

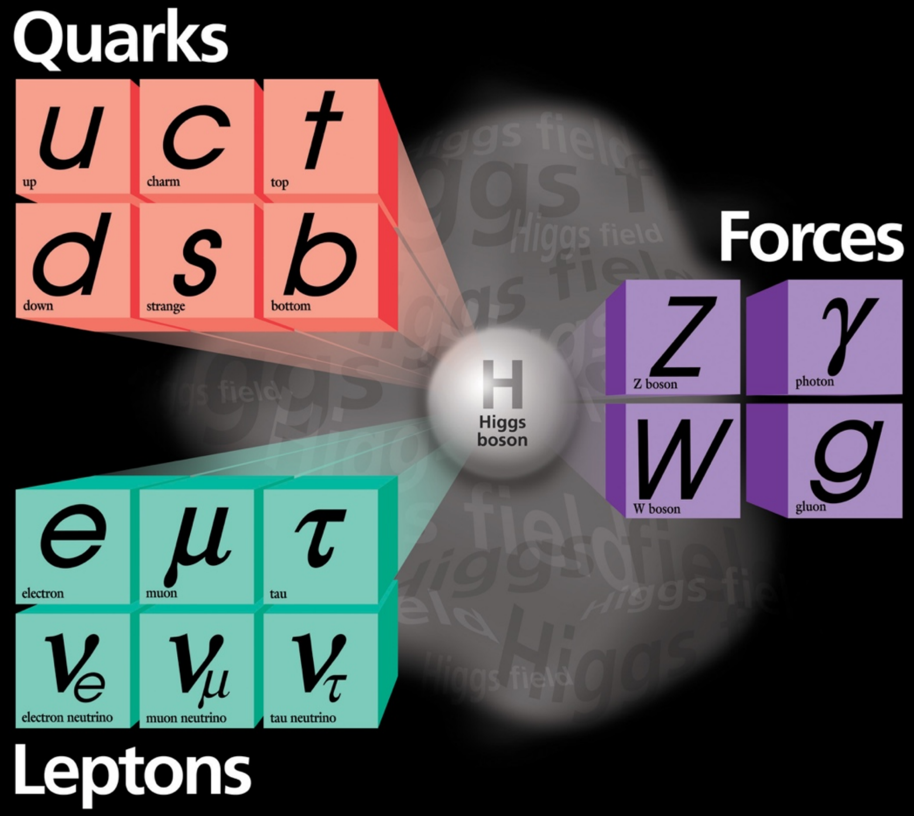
1998



2017



Neutrino history is being written now



- Determine the mass ordering
  - Leaning towards normal ordering
- Measure phase δ – seek CP violation
  - Could be maximal
- Refine measurements, especially: is $\theta_{23} \neq 45°$?
  - Unstable results
- Absolute mass scale
  - Sum masses < 0.3 eV
- Is the neutrino mass term Dirac or Majorana?
  - No idea!
- Resolve current puzzles and anomalies!
  - Get out the popcorn!
- Use the neutrino detectors for other good science: Baryon number violation, astrophysics, dark matter