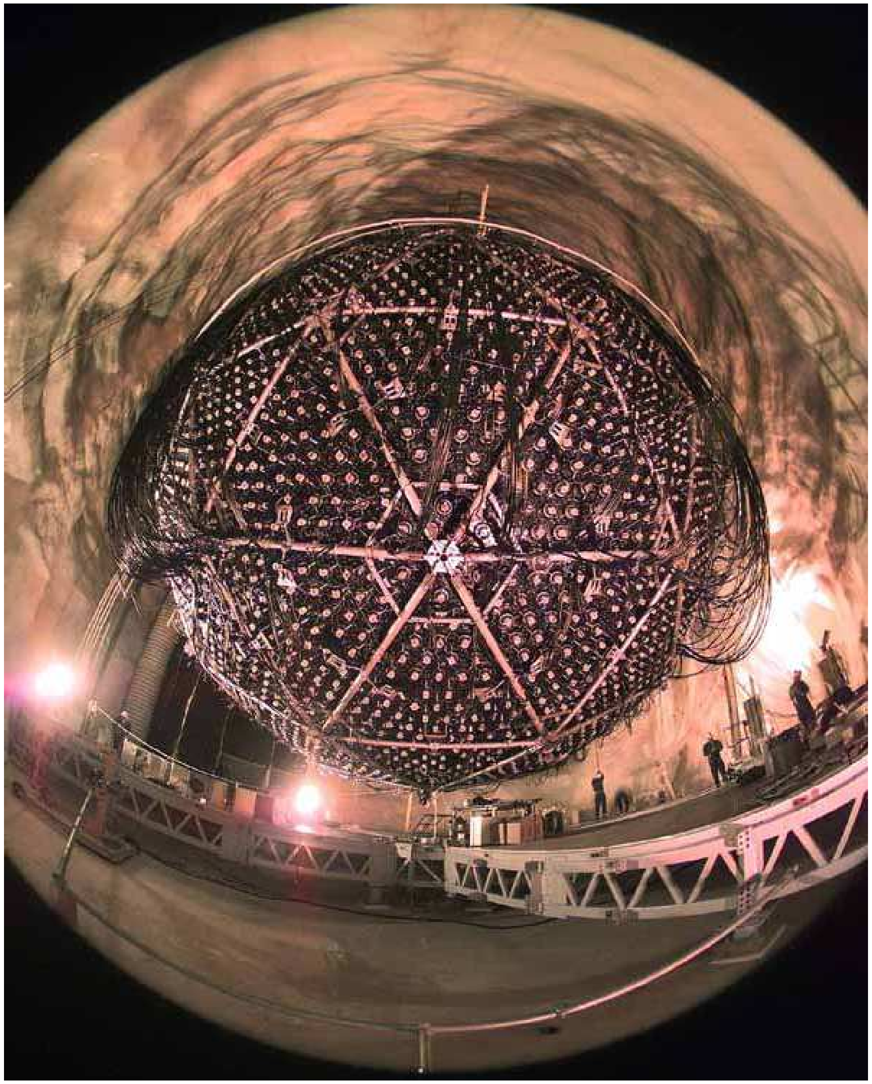
Neutrino Physics, Part 1

Neutrinos in the

Standard Model, and

Why The Standard

Model is Wrong



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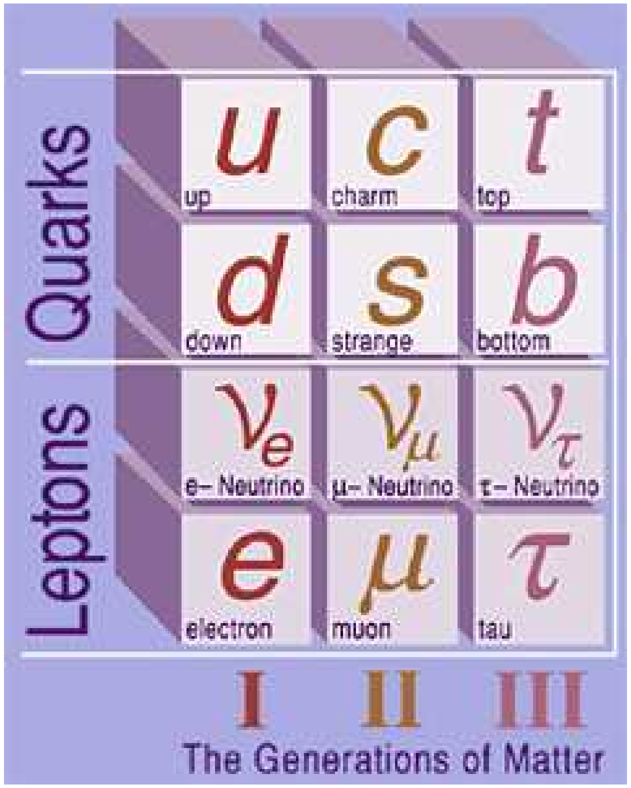
February 2006

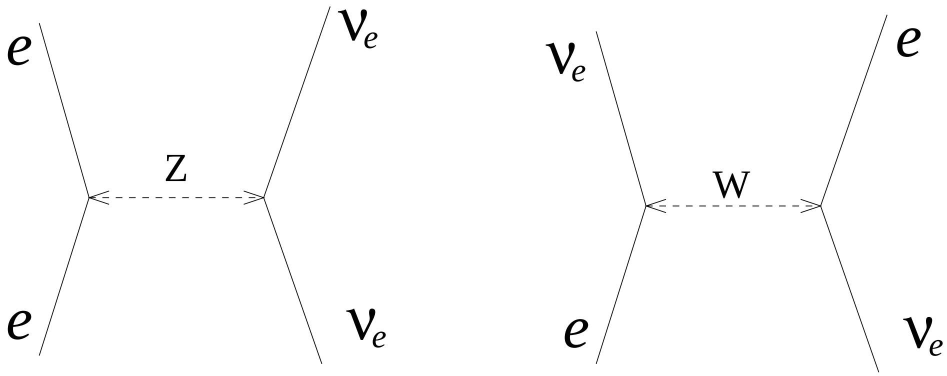
Outline

1. Neutrinos In The Standard Model
2. Neutrino Mixing And Oscillation
3. The Solar Neutrino Problem, With Solution
4. Atmospheric Neutrino Oscillations
5. Results from Long Baseline Neutrino Experiments

Neutrinos in the Standard Model



A neutrino is a neutral cousin of the electron and the other charged leptons.



Only weak interactions — carried by very heavy W, Z particles with short ranges

In the Standard Model, $m_\nu \equiv 0$. (The current limit on the sum of the three masses is ~ 0.6 eV). Neutrinos are many orders of magnitude lighter than the other fermions.

Why are ν's so light? Why 3 kinds?

What's the relationship between leptons and quarks?

Different Kinds of Neutrinos: “Flavours”

Each charged lepton (e, μ, τ) has its own kind of neutrino. For example, in these reactions you get:

$$\begin{aligned} p + e^- &\longrightarrow \nu_e + n \\ p + \mu^- &\longrightarrow \nu_\mu + n \end{aligned}$$

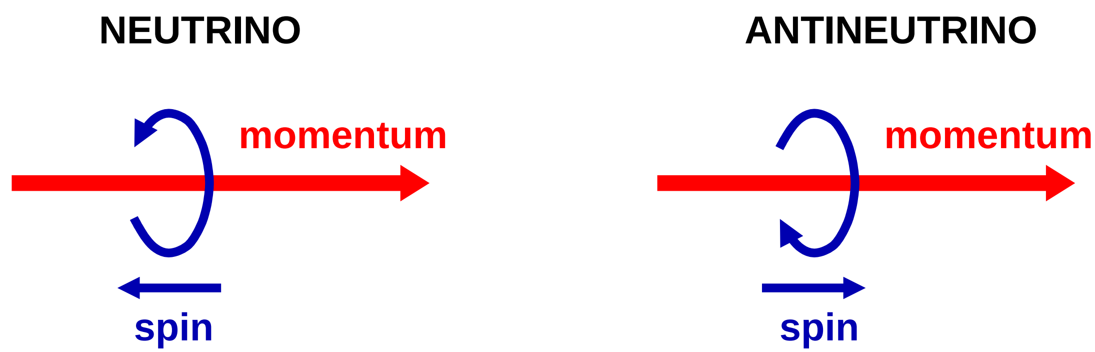
Note that the number of particles of each flavour type seems to be conserved in each reaction.

Flavour is also conserved in the other direction:

$$\begin{aligned} \nu_e + n &\longrightarrow p + e^- \\ \nu_\mu + n &\longrightarrow p + \mu^- \end{aligned}$$

In the Standard Model lepton flavour is rigorously conserved, but is not protected by any symmetry of the Lagrangian.

The Left and the Right of the Matter



Weak interactions only couple to left-handed ν's, or right-handed $\bar{\nu}$'s

This is a pure V-A interaction (maximally parity violating). Weak current has the form:

$$j_\mu = \bar{\psi}\gamma_\mu(1 - \gamma_5)\psi$$

Right-handed ν's either don't exist, or are sterile (don't interact).

A plausible, but wrong, argument ...

1. Ockham's Razor: the simplest solution is if right-handed ν's don't exist.
2. In Standard Model, mass couples left-handed and right-handed states.
3. Therefore, to avoid right-handed states, neutrinos should have no mass.

Neutrino Flavour Mixing

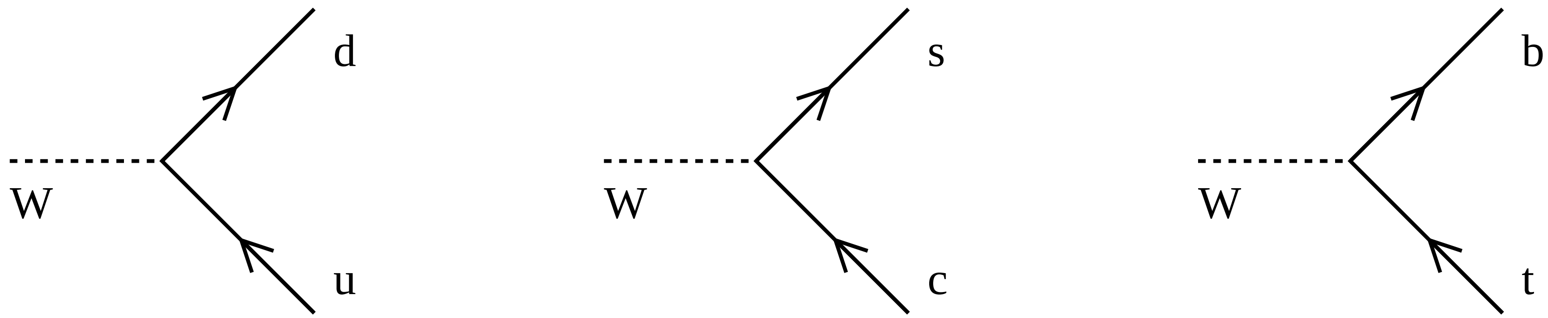
In Standard Model, neutrinos are rather boring ... they have no mass, and only seem to be there to conserve lepton number, flavour number, and energy/momenta/spin.

In 1962, Maki, Nakagawa, and Sakata proposed, on the basis of *zero* experimental evidence, a new phenomenon called neutrino oscillation.

To understand what led MNS to this, let's look at quark mixing first.

Weak Interactions with Quarks

The simple version: W particle couples $u \leftrightarrow d$, $c \leftrightarrow s$, $t \leftrightarrow b$,



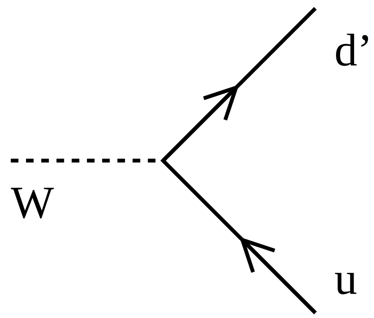
But this can't be complete, since we see weak decays such as:

$$\Lambda(uds) \rightarrow p(uud) + \pi^{-}(d\bar{u})$$

Somehow the strange quark in the Λ gets turned into an up quark!

Quark Flavour Mixing

In reality, W particle couplings mix quark generations:



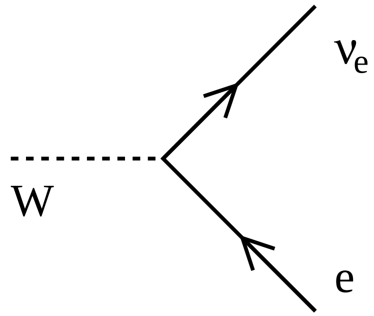
We say that flavour eigenstates (eg. d,s,b) are *rotated* with respect to weak eigenstates (d’,s’,b’)

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

This allows generation-mixing decays such as $\Lambda(uds) \rightarrow p\pi^-$

Neutrino Mixing



Since ν's have only weak interactions, flavour eigenstates are defined as those states that couple to W

What if the flavour eigenstates are rotated relative to the *mass* eigenstates (eigenstates of Hamiltonian with well-defined mass)?

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

How does superposition of mass eigenstates evolve in vacuum?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Each term evolves with a phase factor of $e^{i(px-Et)}$

If $m_1 \neq m_2$, then arguments of exponential will be different! For example, if we consider p to be fixed, then

$$E = \sqrt{p^2 + m^2} = p\sqrt{1 + m^2/p^2} \approx p + m^2/(2p)$$

As neutrino propagates, a phase difference develops between terms!

$$|\nu(t)\rangle \propto \cos\theta\,|\nu_1\rangle + e^{i\phi}\sin\theta\,|\nu_2\rangle$$

with

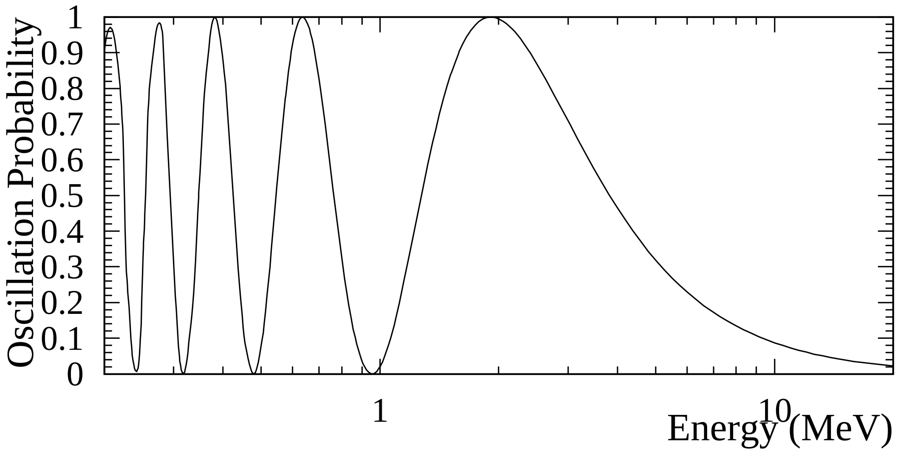
$$\phi = \left(\frac{m_1^2}{2p} - \frac{m_2^2}{2p}\right)t$$

Neutrino Oscillation

Net result: at some later time, $|\nu(t)\rangle \neq |\nu_e\rangle$.

Probability that the original ν_e is detected as a ν_μ at some later time:

$$P(\nu_e \to \nu_\mu) = |\langle \nu_\mu | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$



θ	=	neutrino mixing angle
Δm^2	=	$m_1^2 - m_2^2$ (in eV^2)
L	=	distance ν has travelled (in km)
E	=	neutrino energy (in GeV)

Neutrino oscillation:

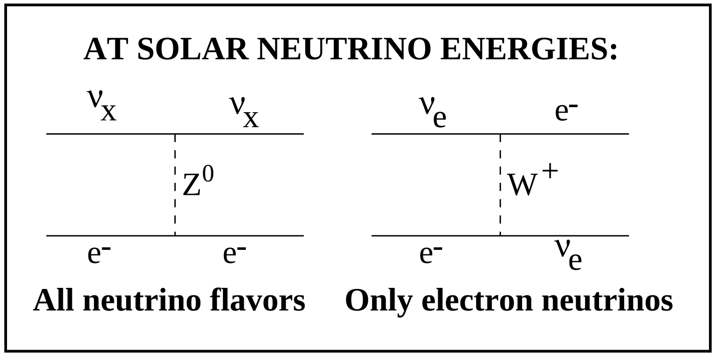
- requires at least one non-zero neutrino mass
- requires non-zero mixing elements
- results from the QM of the propagation, *not* from an interaction

Matter Effects On Neutrino Oscillation

Surprisingly the oscillation formula can be dramatically altered in matter!

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

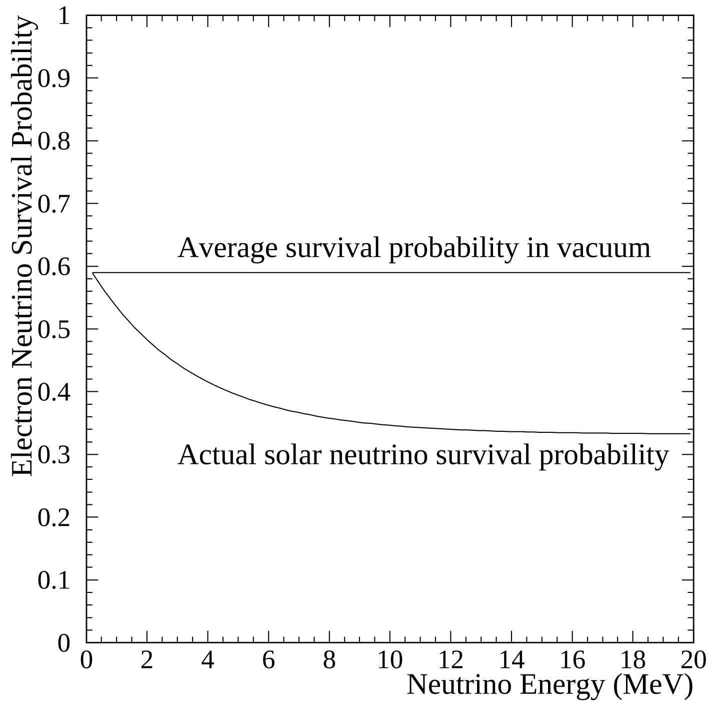
The relevant process is forward scattering, in which no momentum is exchanged. In matter, ν_e's have a different forward scattering amplitude than the other flavours:



This produces a matter-induced potential that is different for ν_e. Effectively ν_e's have a different "index of refraction" in matter.

The size of the potential is proportional to the electron density N_e.

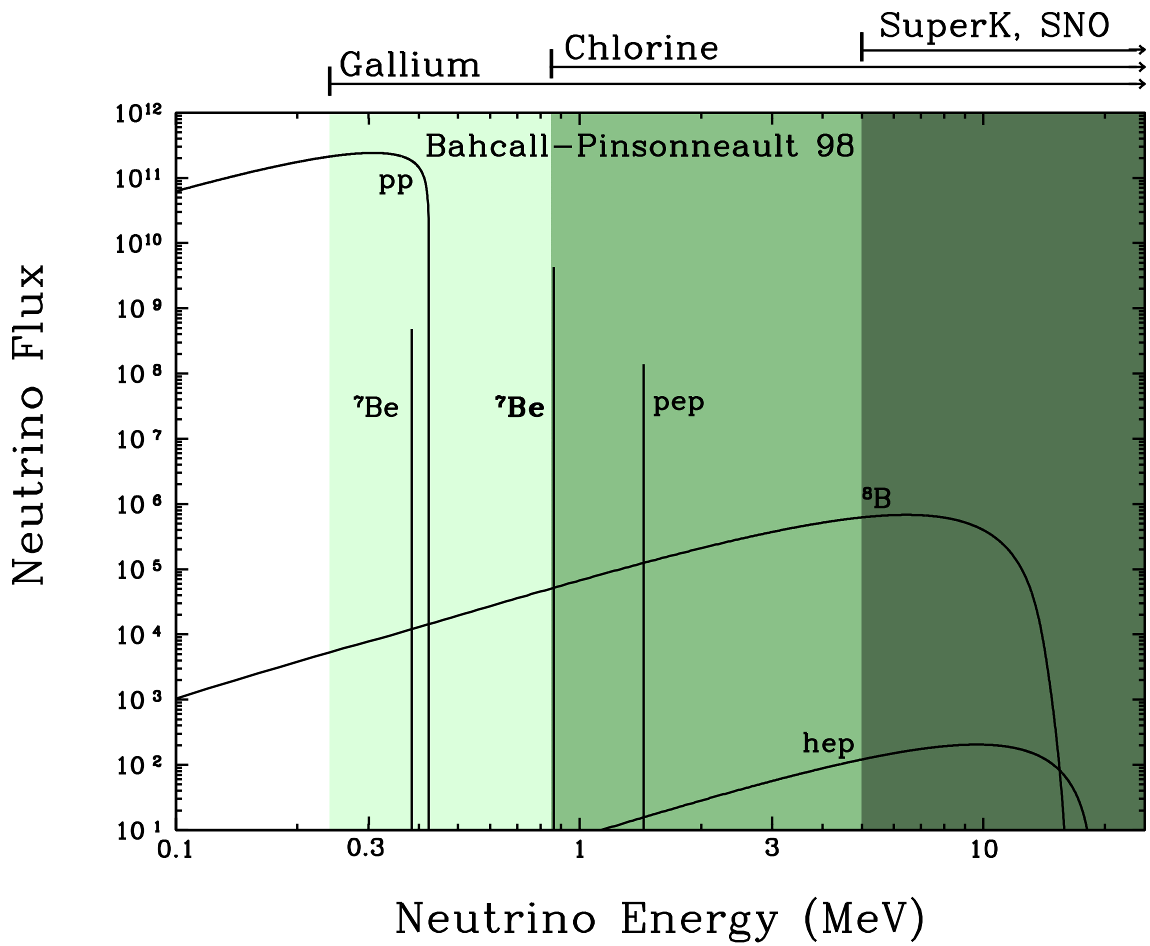
For solar ν's, matter effects are dominant.



Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

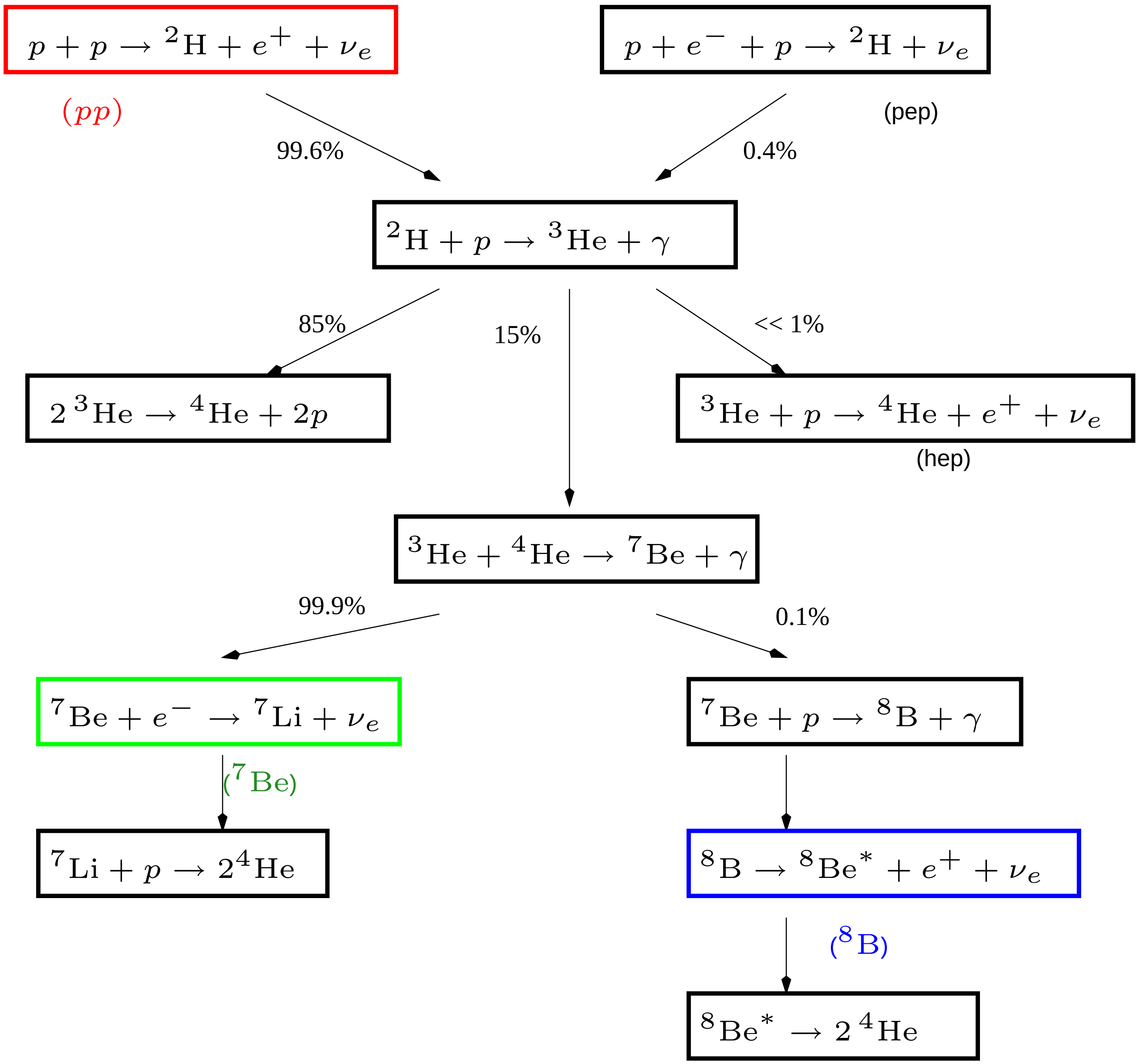
$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.731\ \text{MeV}$$



Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.

The pp Chain


$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$
(pp)
$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$
(pep)
99.6%
0.4%
${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
85%
15%
<< 1%
$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$
${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
(hep)
${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$
99.9%
0.1%
${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$
(${}^7\mathrm{Be}$)
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$
(${}^8\mathrm{B}$)
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

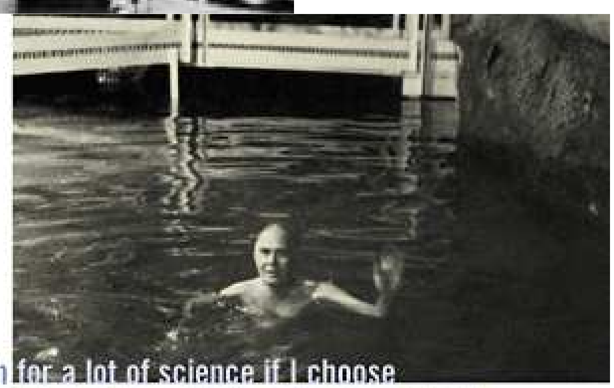
The Pioneers

The ^{37}Cl experiment started in the 1960's

Ray Davis and John Bahcall with the tetrachloroethylene tank.

100,000 gallons of cleaning fluid!

$$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$$



"There's room for a lot of science if I choose this route and just start doing things."

A setback ...

Predicted rate: $7.6^{+1.3}_{-1.1}$ SNU's

Measured rate: 2.56 ± 0.23 SNU's

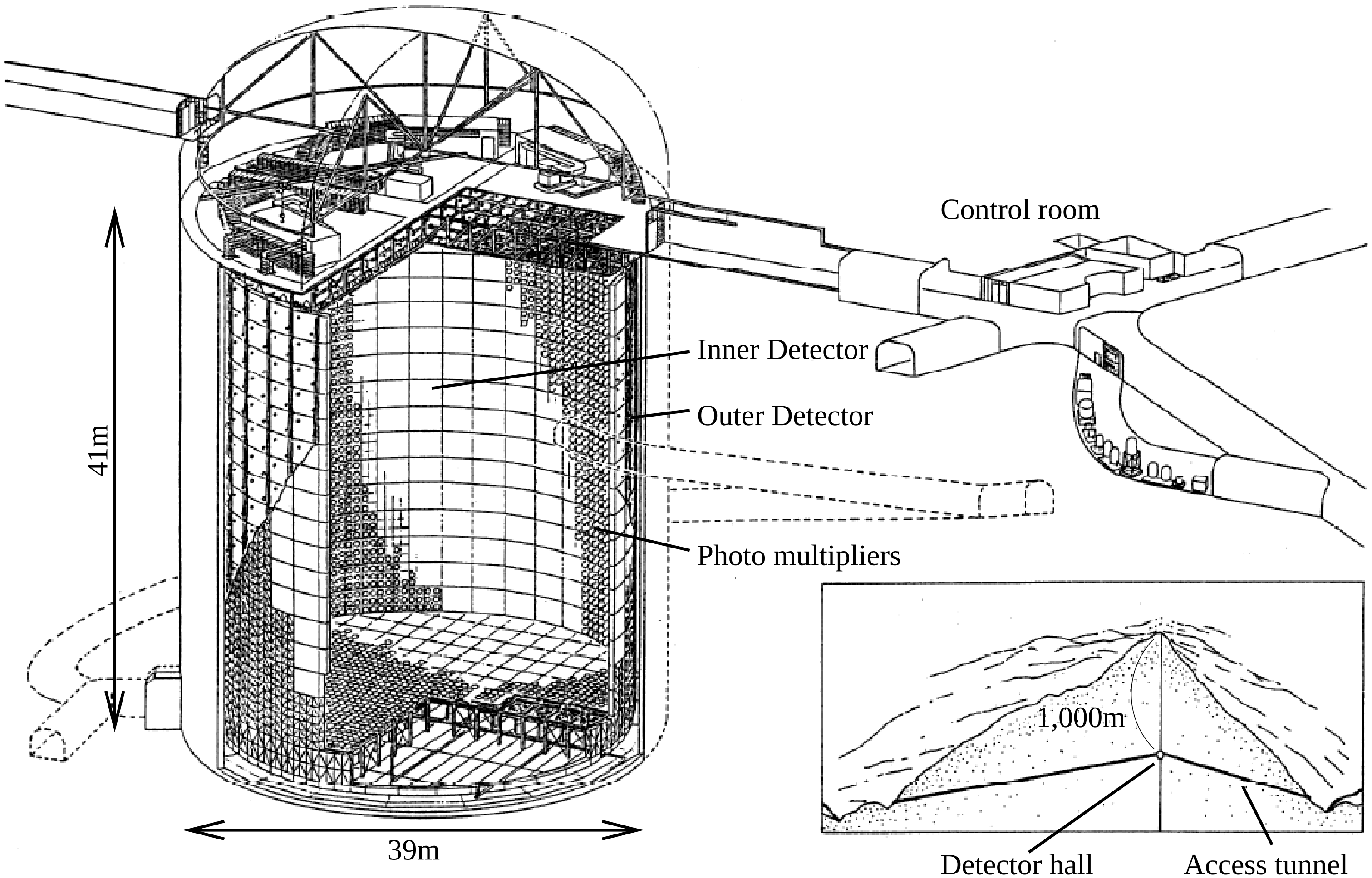
Most people reacted in two ways ...

- Experiment must be wrong. No one can look for 50 Ar atoms in 600 tons of cleaning fluid and expect to find them all!
- Theory must be wrong. The solar models are too complicated to take seriously. The flux changes with solar temperature by T^{25}. Even a tiny mistake could change fluxes greatly!

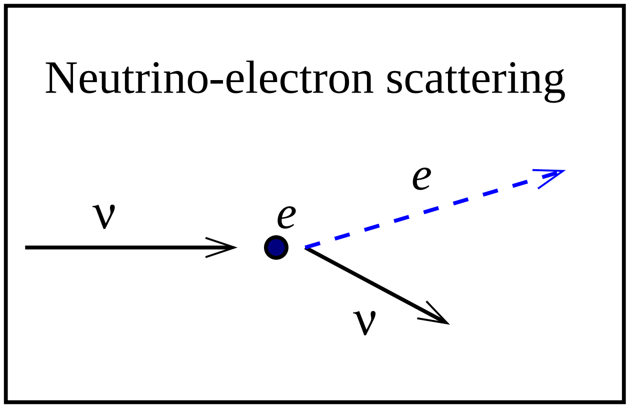
Ray Davis checked and rechecked his experiment. John Bahcall refined astrophysical calculations. Both stuck to their guns.

Others began planning new experiments ...

Super-Kamiokande



Water Cherenkov Detectors



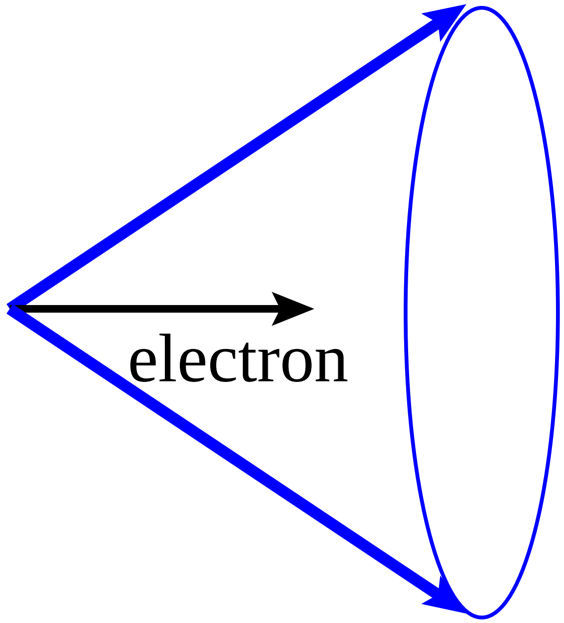
Elastic scattering of electrons by ν's

Scattered electron can move faster than light in water (since water has slowed down light).

Get *Cherenkov light*—an electromagnetic sonic boom!

- Light is blue
- Comes out in cone
- More energy$\longrightarrow$ more light!

Cherenkov cone



Super-Kamiokande

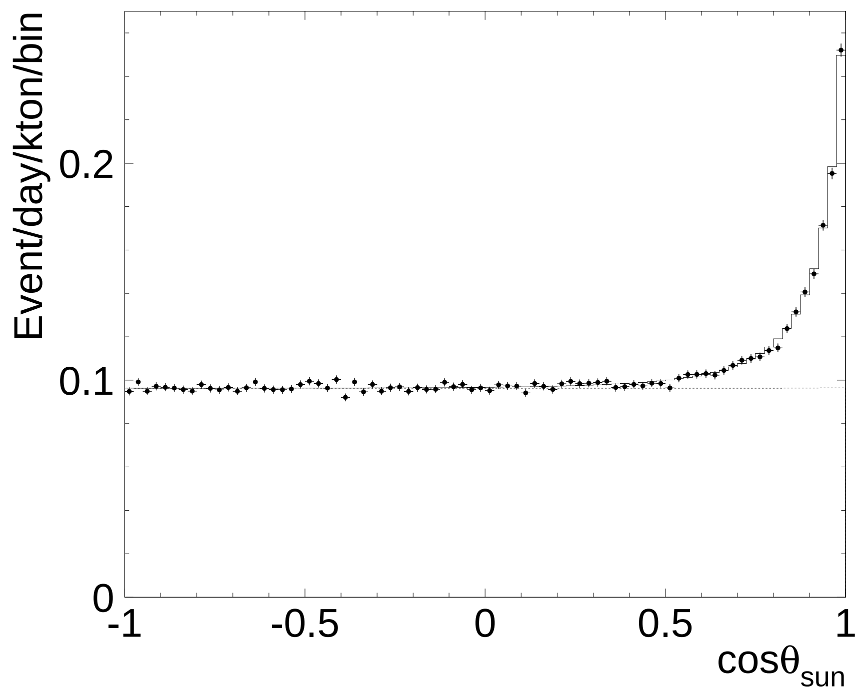
$$\nu_x + e^- \to \nu_x + e^-$$

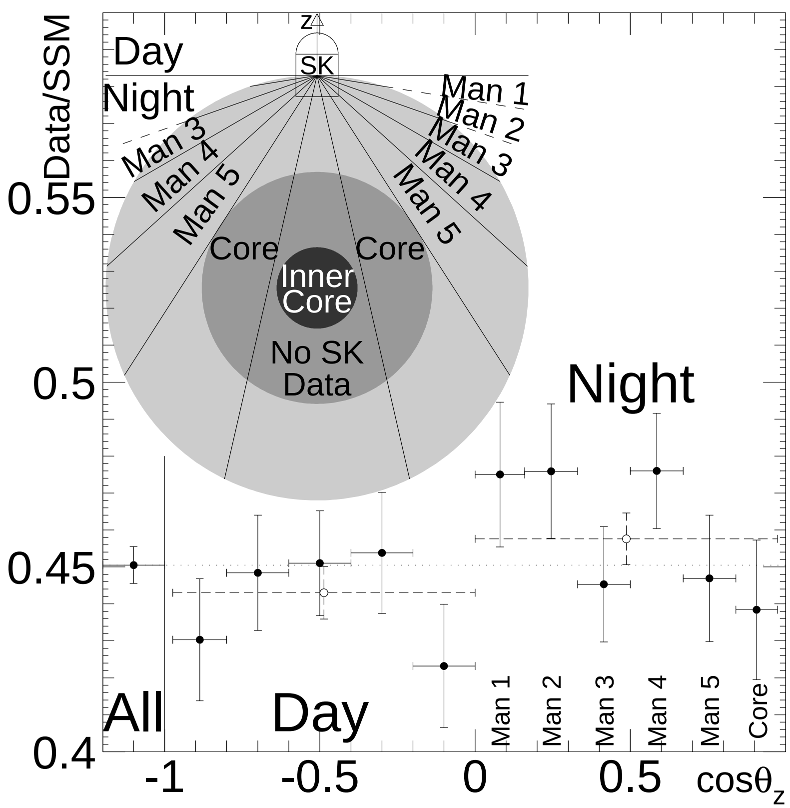
Rate $\propto \phi(\nu_e) + \frac{1}{6}\phi(\nu_{\mu\tau})$

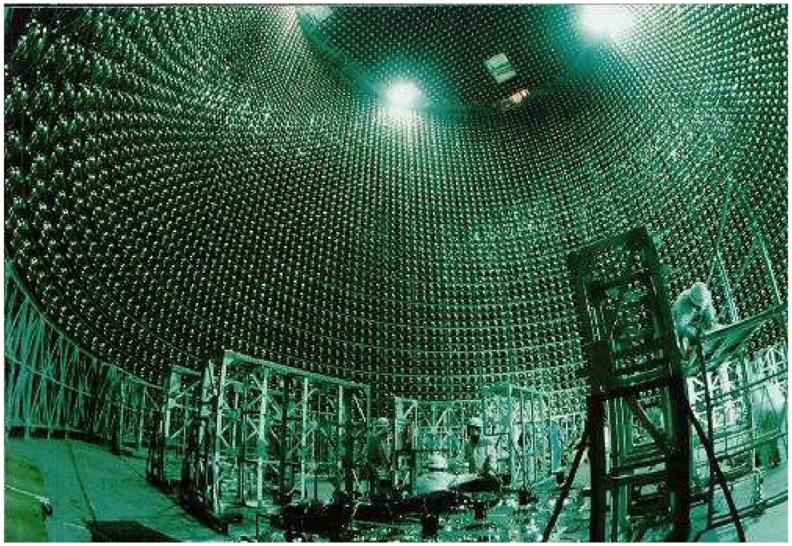
$$R_{exp} = 0.465 \pm 0.005^{+0.014}_{-0.012} \times \text{SSM}$$

(hep-ex/0106064, hep-ex/0206075)

Clear directional ν signal from Sun!



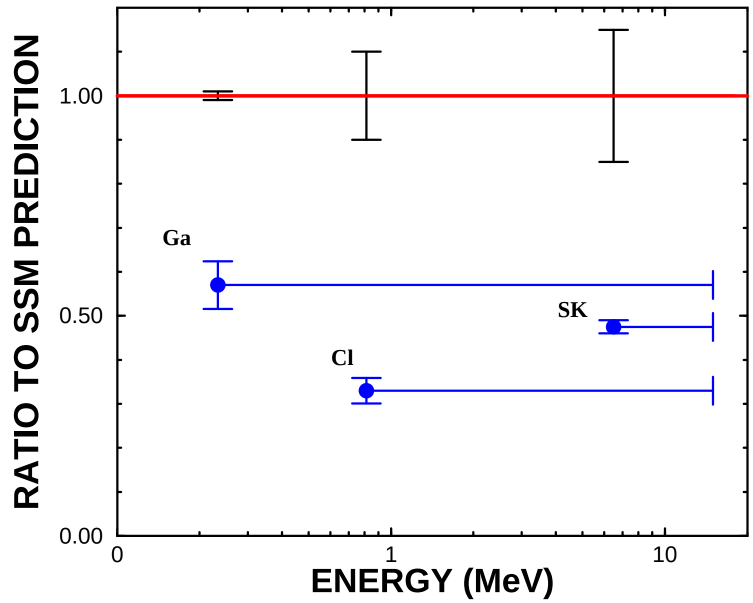




Solar Neutrino Flux Measurements

Two Classes of Experiment (so far)

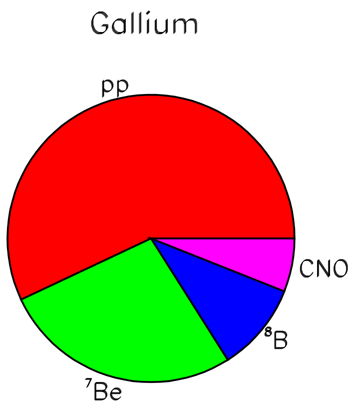
- Radiochemical
  - ν_e interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time
- Water Cerenkov
  - Real-time detection of scattered atomic e^-'s
  - Mixed CC and NC sensitivity

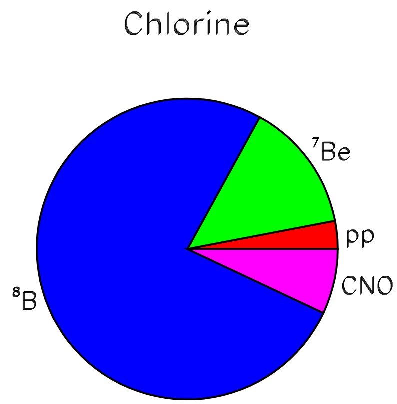


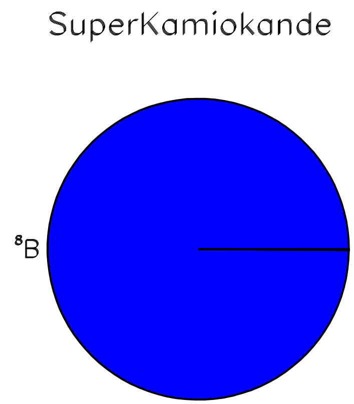
Experiment	Detection Reaction	Threshold	Primary Sources
Homestake	$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$	0.8 MeV	${}^{7}\text{Be}, {}^{8}\text{B}$
Kamiokande	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	7.3 MeV	${}^{8}\text{B}$
SAGE, GALLEX/GNO	$\nu_e + {}^{71}\text{Ga} \rightarrow e^+ + {}^{71}\text{Ge}$	0.23 MeV	$pp, {}^{7}\text{Be}, {}^{8}\text{B}$
Super-K	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	5 MeV	${}^{8}\text{B}$

The Solar Neutrino Problem

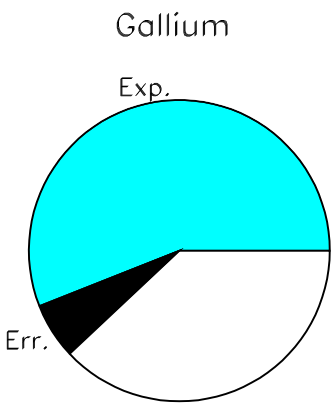
- Standard Solar Model Predictions:

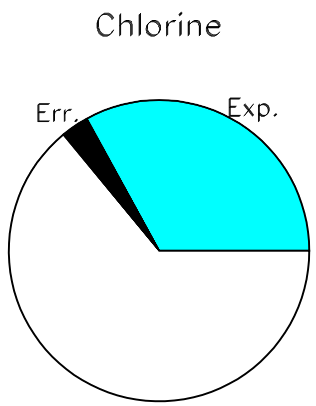


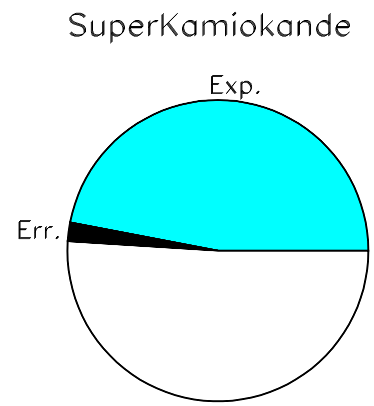




- Measurements:







Sudbury Neutrino Observatory

2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

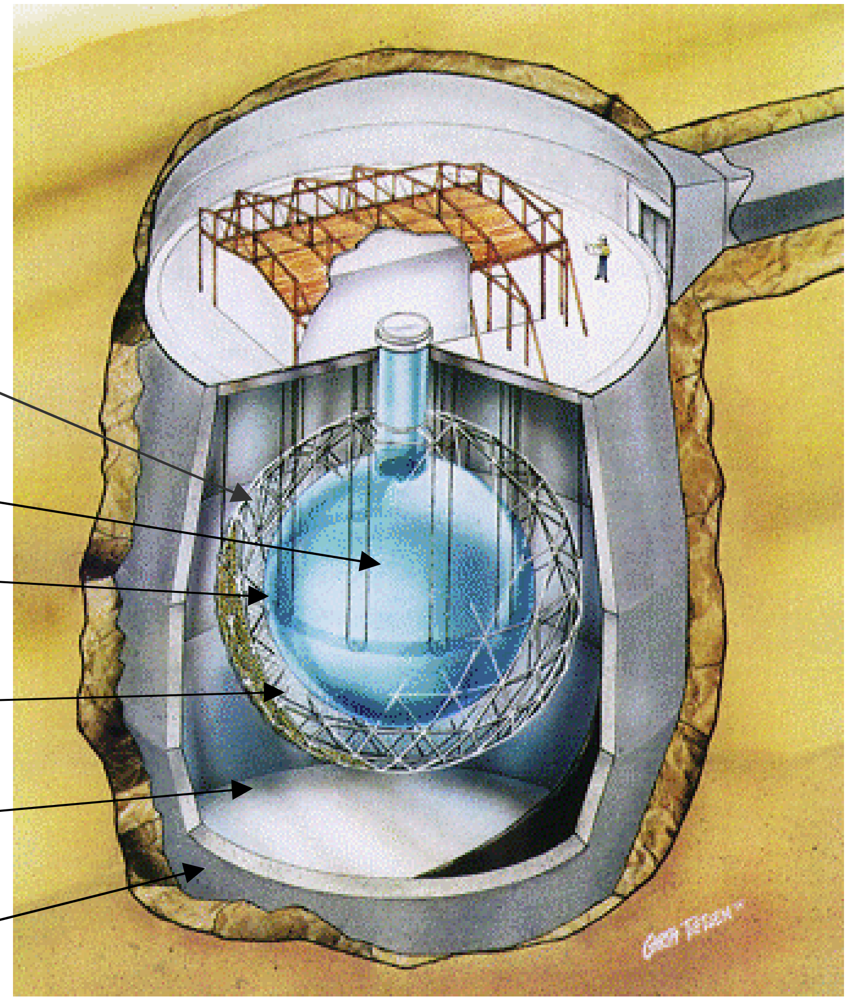
1000 Tonnes D_2O

12 m Diameter Acrylic Vessel

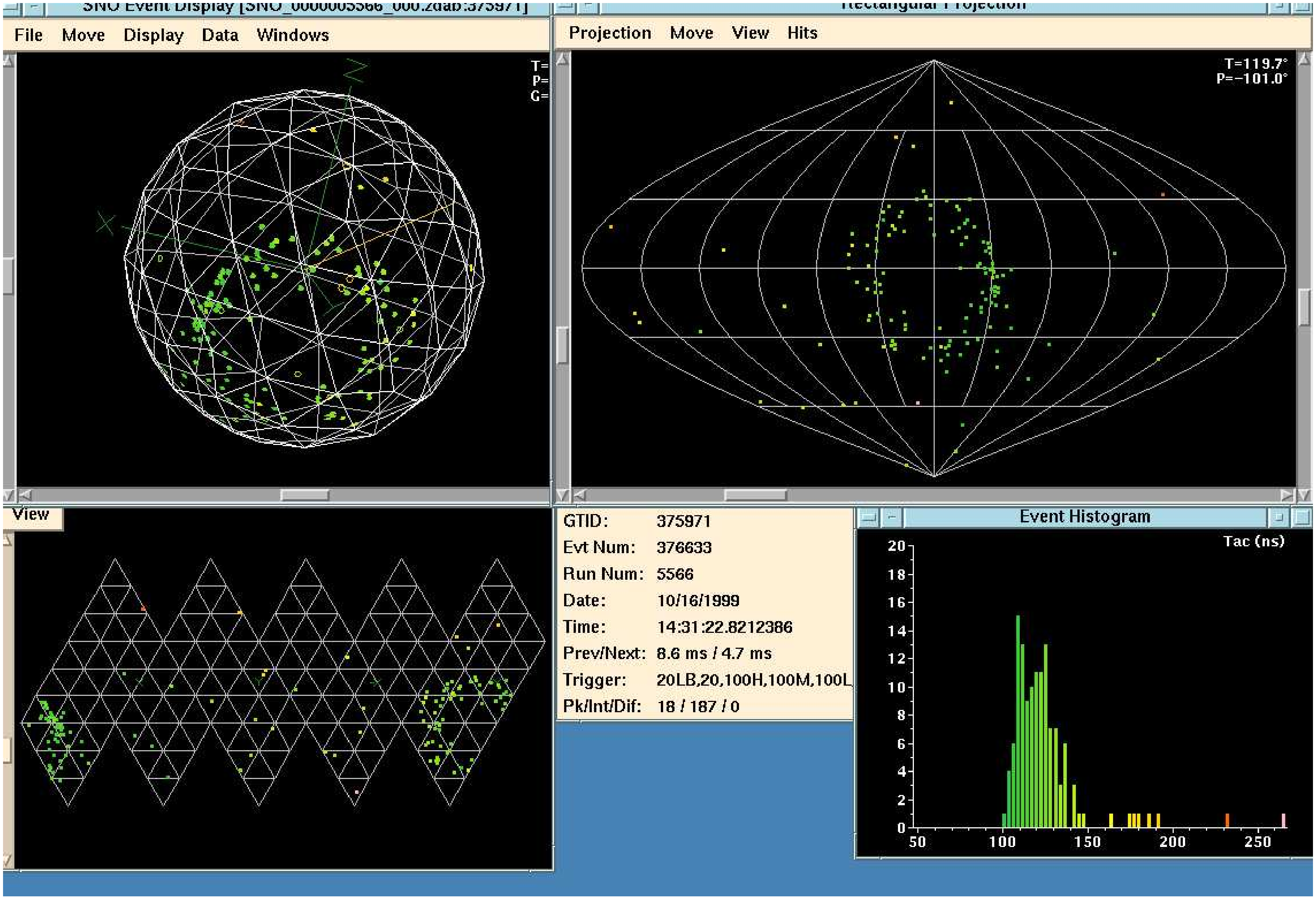
1700 Tonnes Inner Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Event Display–Neutrino Event



Solar ν Interactions in SNO

SNO measures primarily ^{8}B neutrinos by three interactions:

Charged Current:

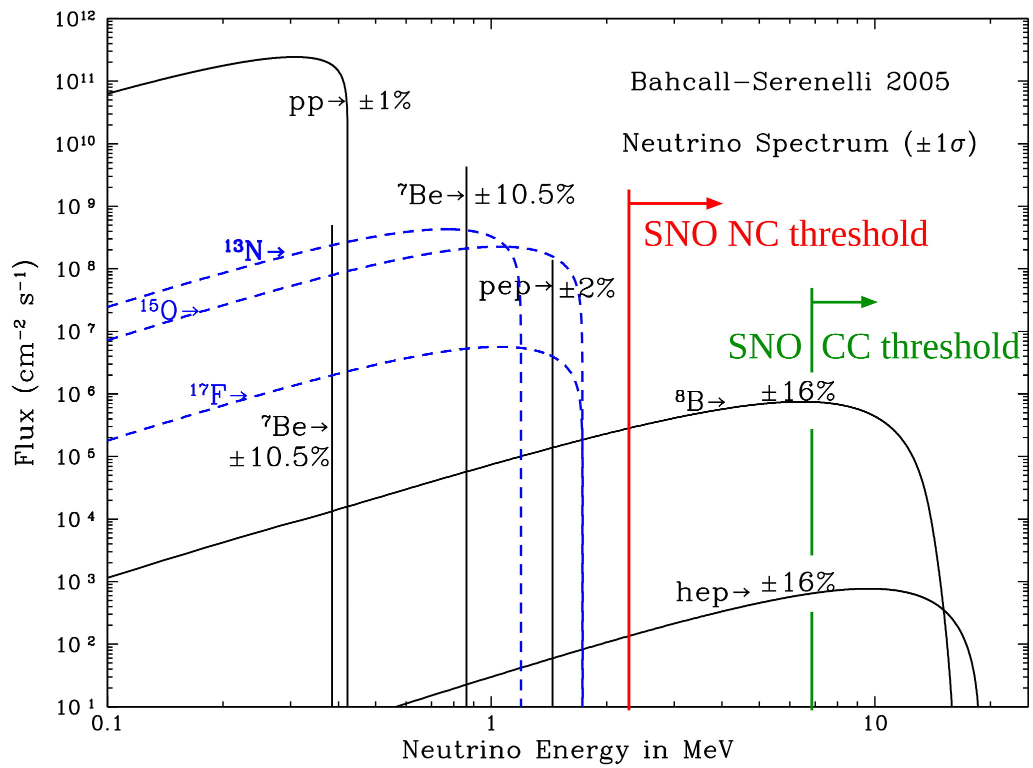
$$\nu_e + d \rightarrow p + p + e^-$$

Neutral Current:

$$\nu_x + d \rightarrow p + n + \nu_x$$

Elastic Scattering:

$$\nu_x + e \rightarrow \nu_x + e^-$$



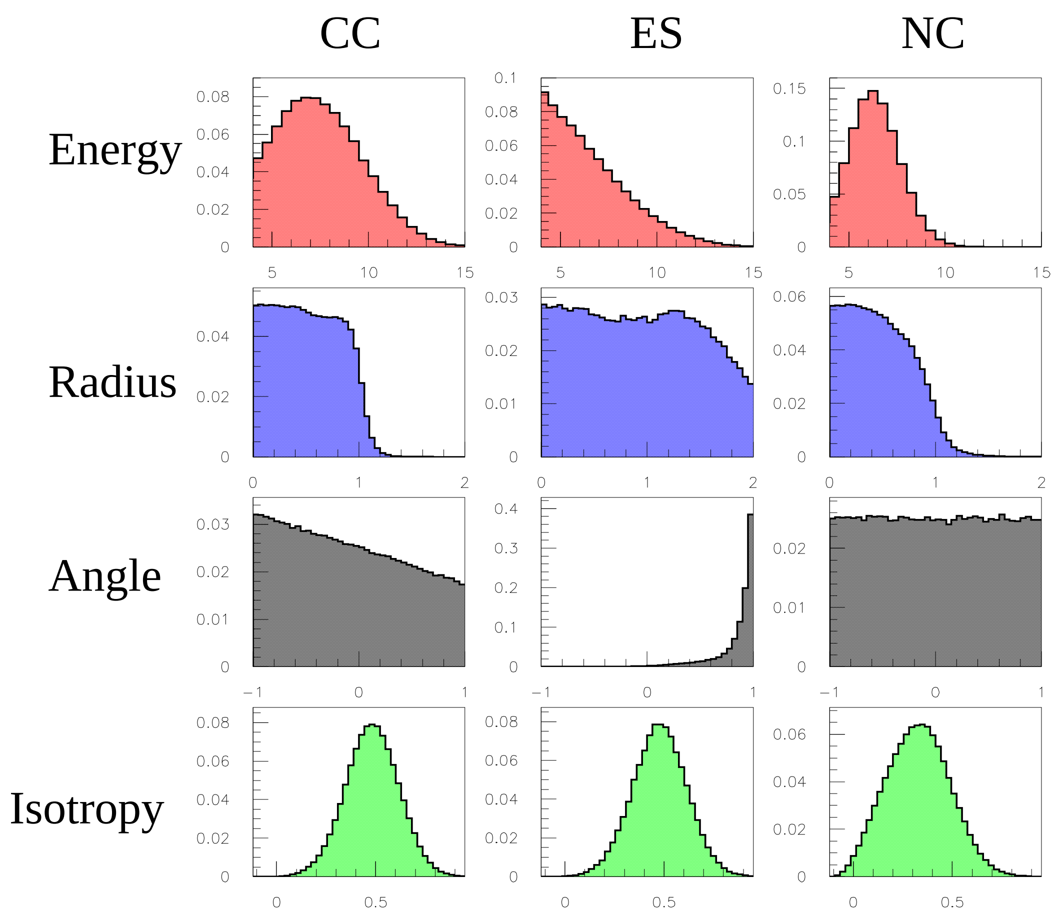
For the Large Mixing Angle (LMA) solution to solar neutrino problem:

$$|U_{e2}|^2 \approx \sin^2\theta_{12} \approx \frac{\phi_{CC}}{\phi_{NC}}$$

Three Phases of the SNO Experiment

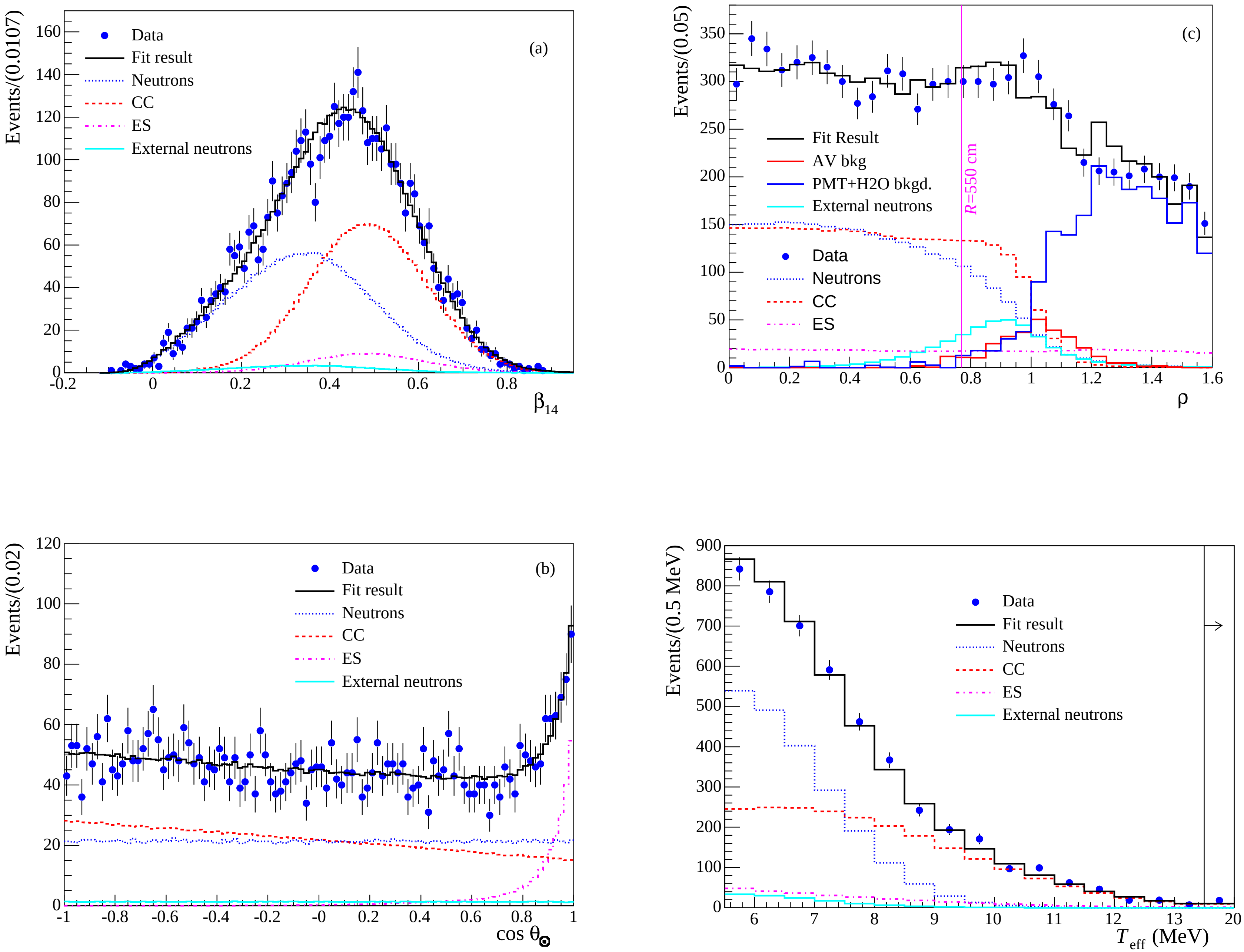
D$_2$O Phase	Salt Phase	NCD Phase
(pure D$_2$0)	(D$_2$O + 0.2% NaCl)	(^{3}He counters)
Nov 1999 - May 2001	July 2001 - Sept 2003	Dec 2004 - Dec 2006
$n + d \rightarrow t + \gamma$	$n + {}^{35}$Cl $\rightarrow {}^{36}$Cl $+ \gamma$'s	$n + {}^3$He $\rightarrow p + t$
$(\sigma = 0.0005\, b)$	$(\sigma = 44\, b)$	$(\sigma = 5330\, b)$
Detect a Compton-scattered electron from a 6.25 MeV γ	Detect Compton-scattered electrons from multiple γ's totalling 8.6 MeV	Detect 764 keV of ionization from the charged particles in ^{3}He proportional counters
PRL 87, 071301 (2001) PRL 89, 011301 (2002) PRL 89, 011302 (2002) PRD 70, 093014 (2004)	PRL 92, 181301 (2004) PRL 92, 102004 (2004) PRC 72, 055502 (2005) PRD 72, 052010 (2005)	

Signal Probability Distributions



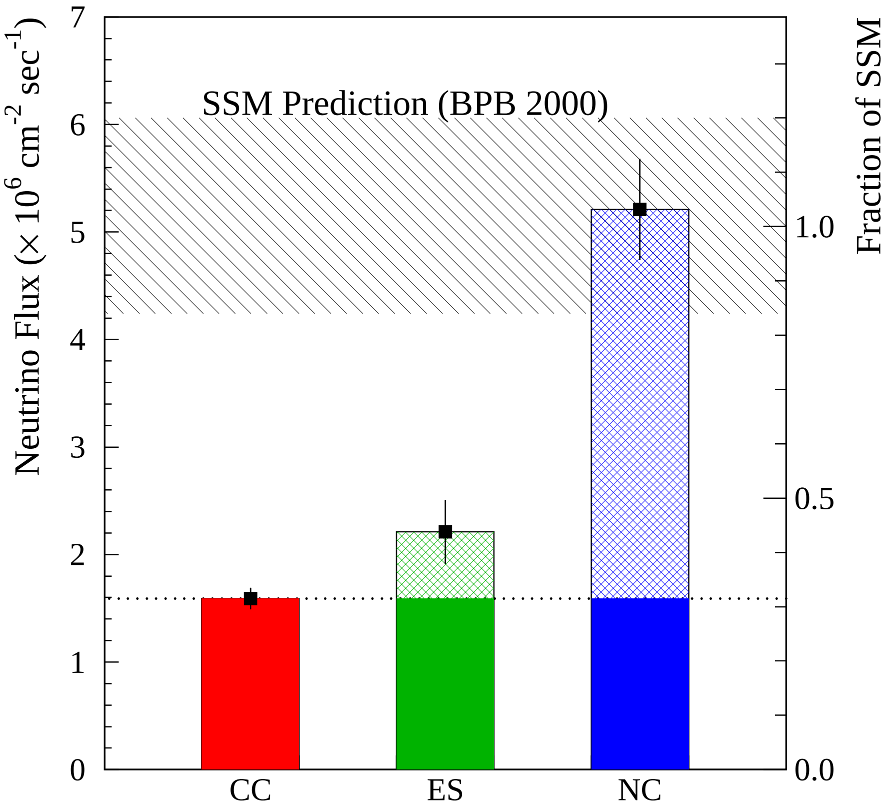
Fit the PDFs to the data to determine fluxes. Leave out the energy PDFs to fit for the spectral shapes.

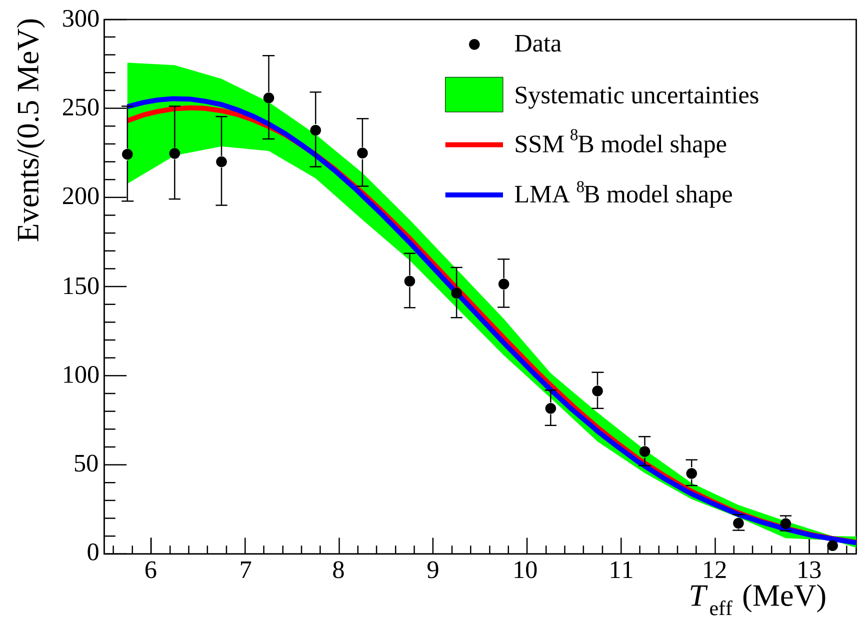
Results for the full 391-day Salt Phase



Evidence for Solar Neutrino Oscillation

Phys Rev C 72, 055502 (2005)





No evidence of spectral distortion.

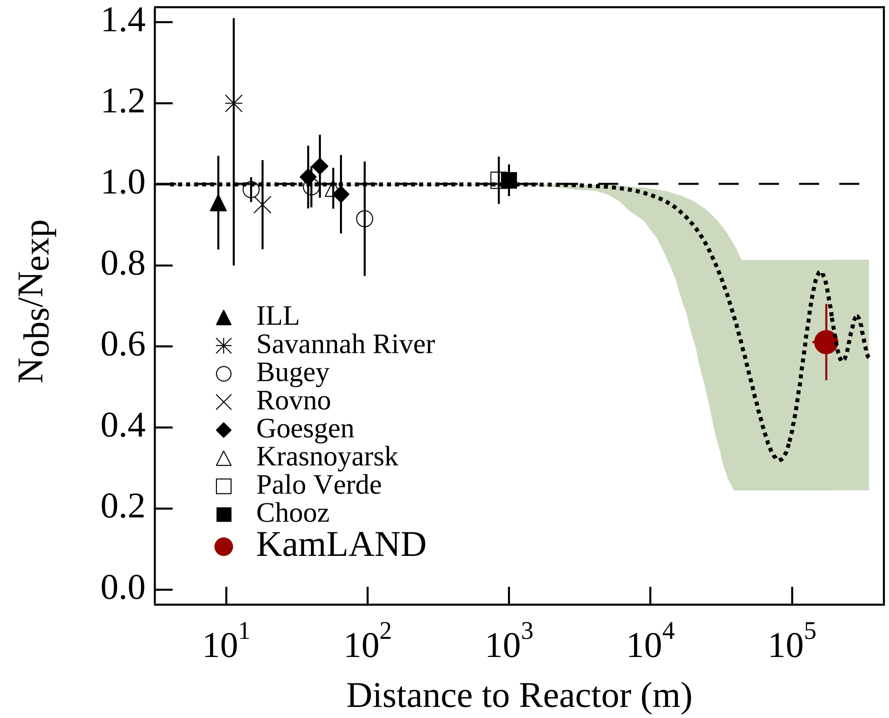
$$A_{DN} = 0.037 \pm 0.040$$

SNO: Direct evidence that

$$\phi(\nu_e) < \phi(\nu_{tot})$$

Self-consistent picture of results from Homestake, SAGE/GALLEX/GNO, and Super-K.

Evidence for Reactor Neutrino Oscillations

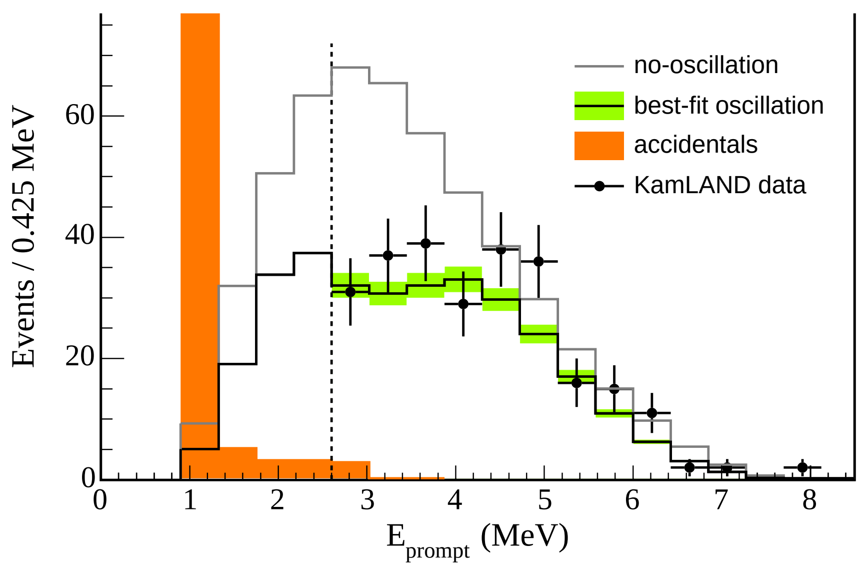


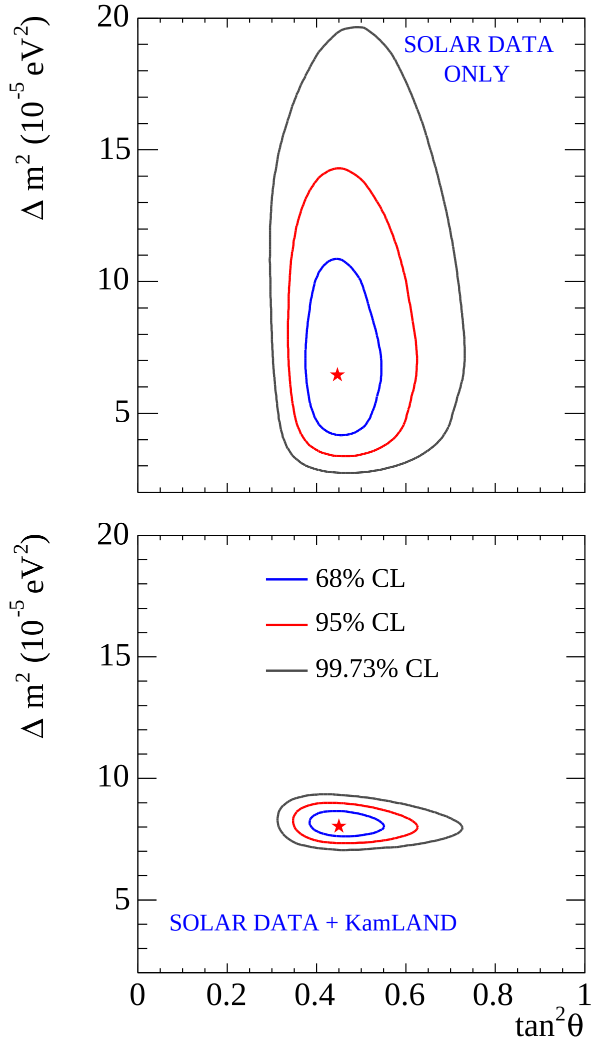
KamLAND: Observation of reactor neutrino disappearance at L/E value where solar neutrino effect occurs.

Evidence for Reactor Neutrino Oscillations

(PRL 94, 081801, 2005)

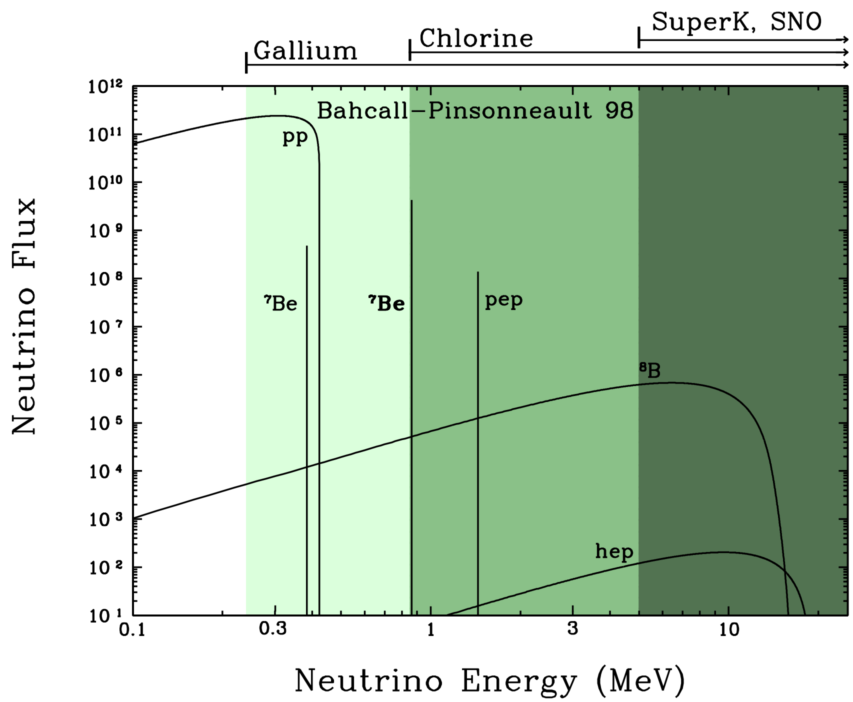
Spectral distortion seen in reactor neutrino energy spectrum

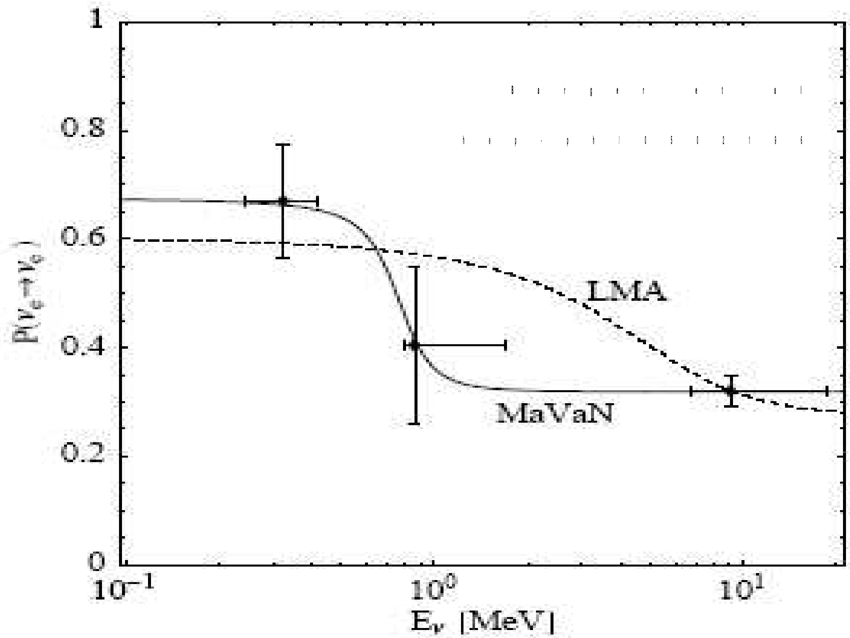




Solar data constrains θ_{12}, while reactor data constrains Δm^2—extreme complementarity!

Future Solar Neutrino Experiments





Barger *et al*, hep-ph/0502196

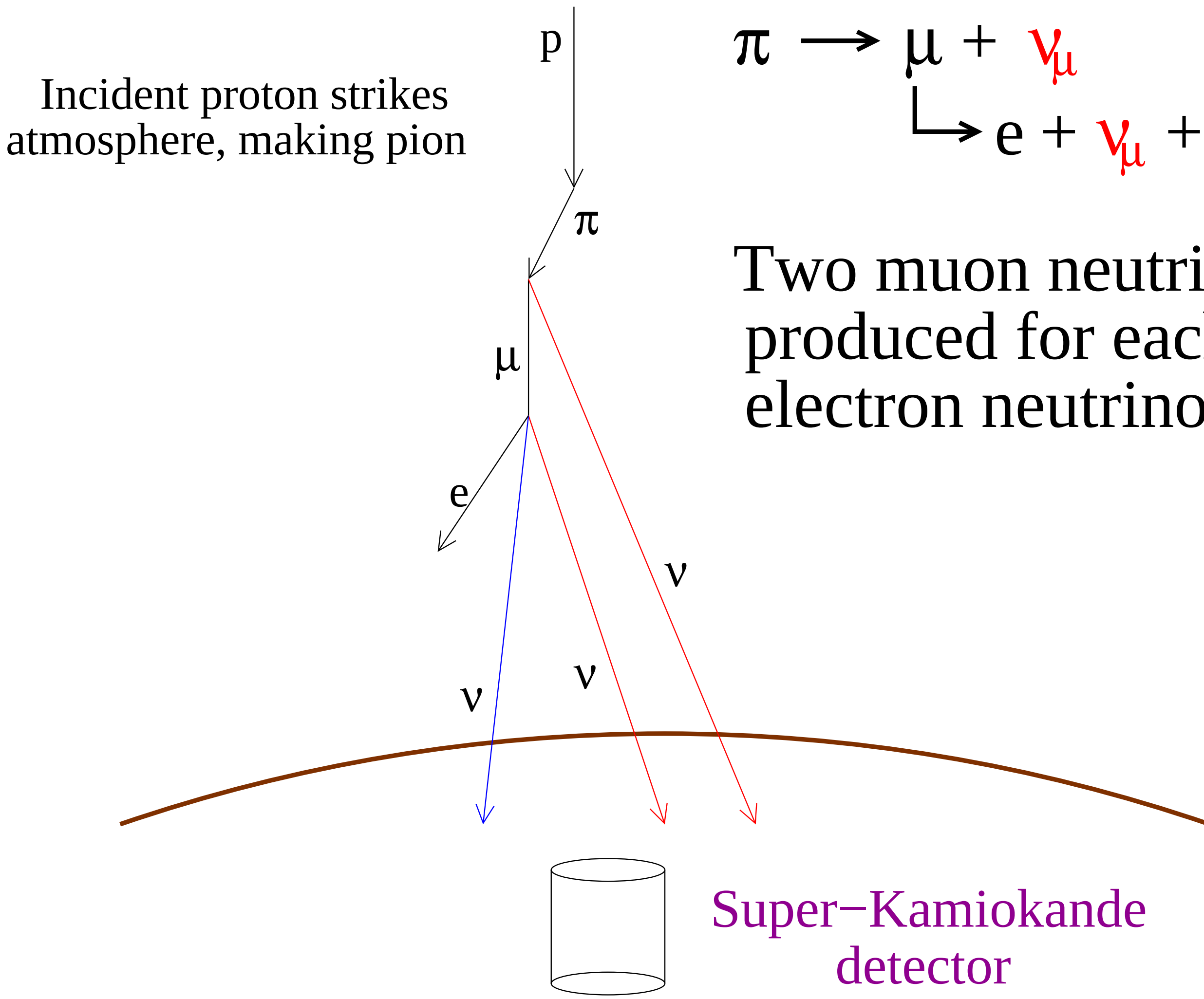
There are various ideas for precision measurement of ^{7}Be and pep neutrinos by low-background scintillator detectors:

- Borexino
- KamLAND
- SNO+
- liquid noble gas detectors

Possible Motivations:

- Observe turn-up in LMA survival probability
- Constrain solar models
- Test exotic scenarios

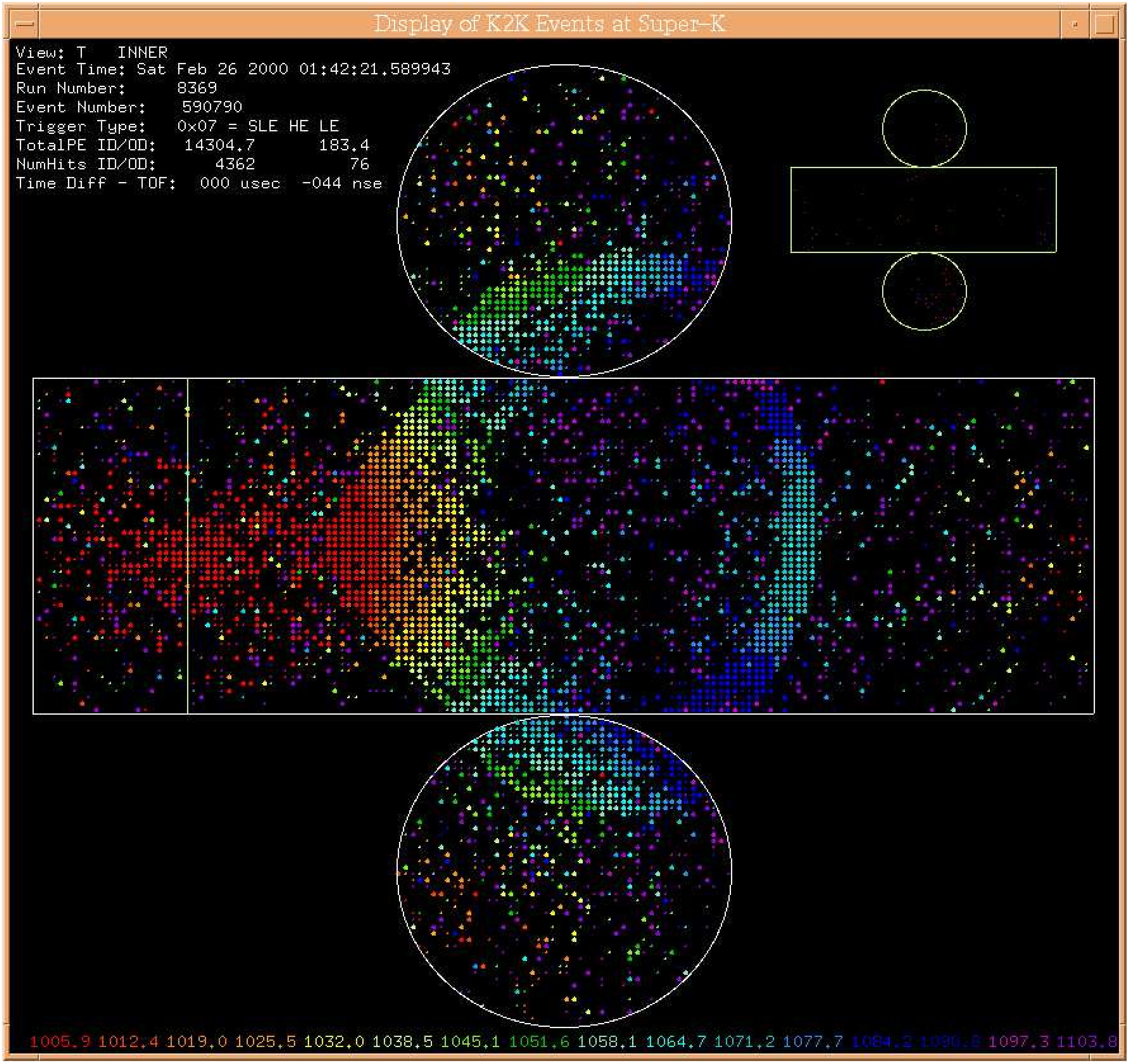
Atmospheric Neutrinos



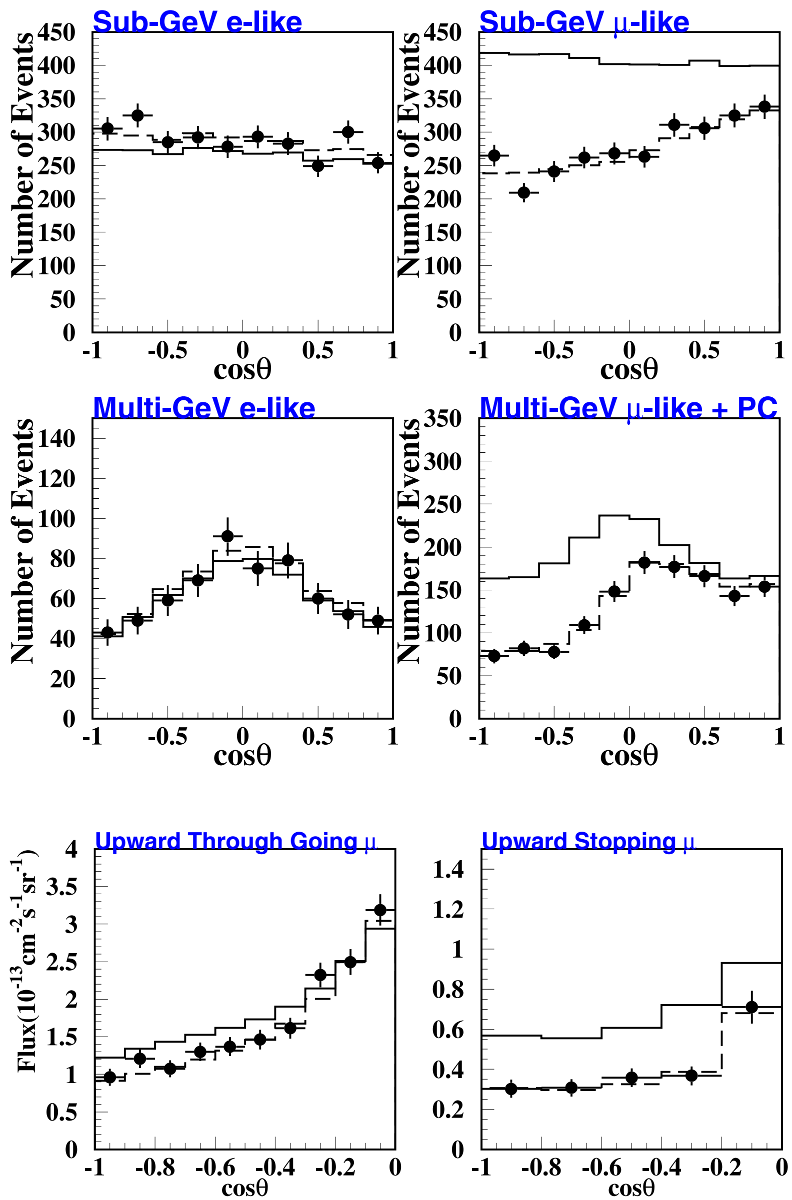
$$\pi \longrightarrow \mu + \nu_\mu$$
$$\quad\quad \llcorner\!\!\longrightarrow e + \nu_\mu + \nu_e$$

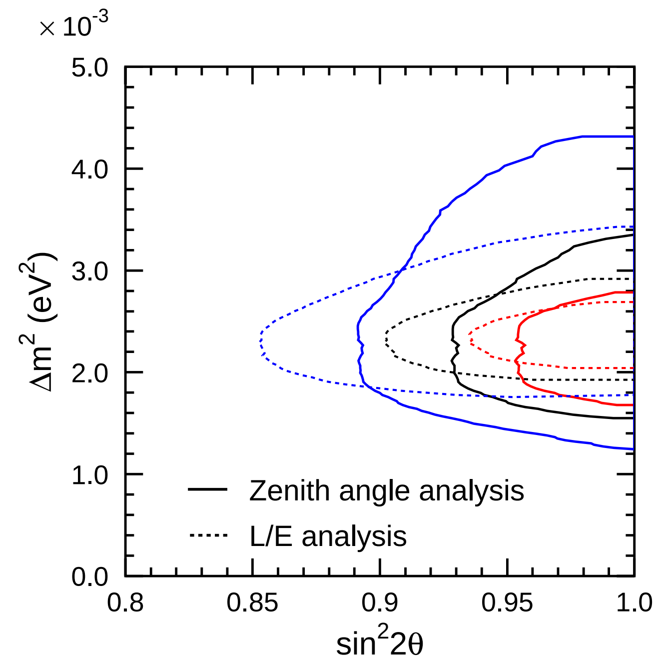
Two muon neutrinos produced for each electron neutrino!

Super-Kamiokande Event Display



Super-Kamiokande Atmospheric ν Results





PRD 71, 112005 (2005)

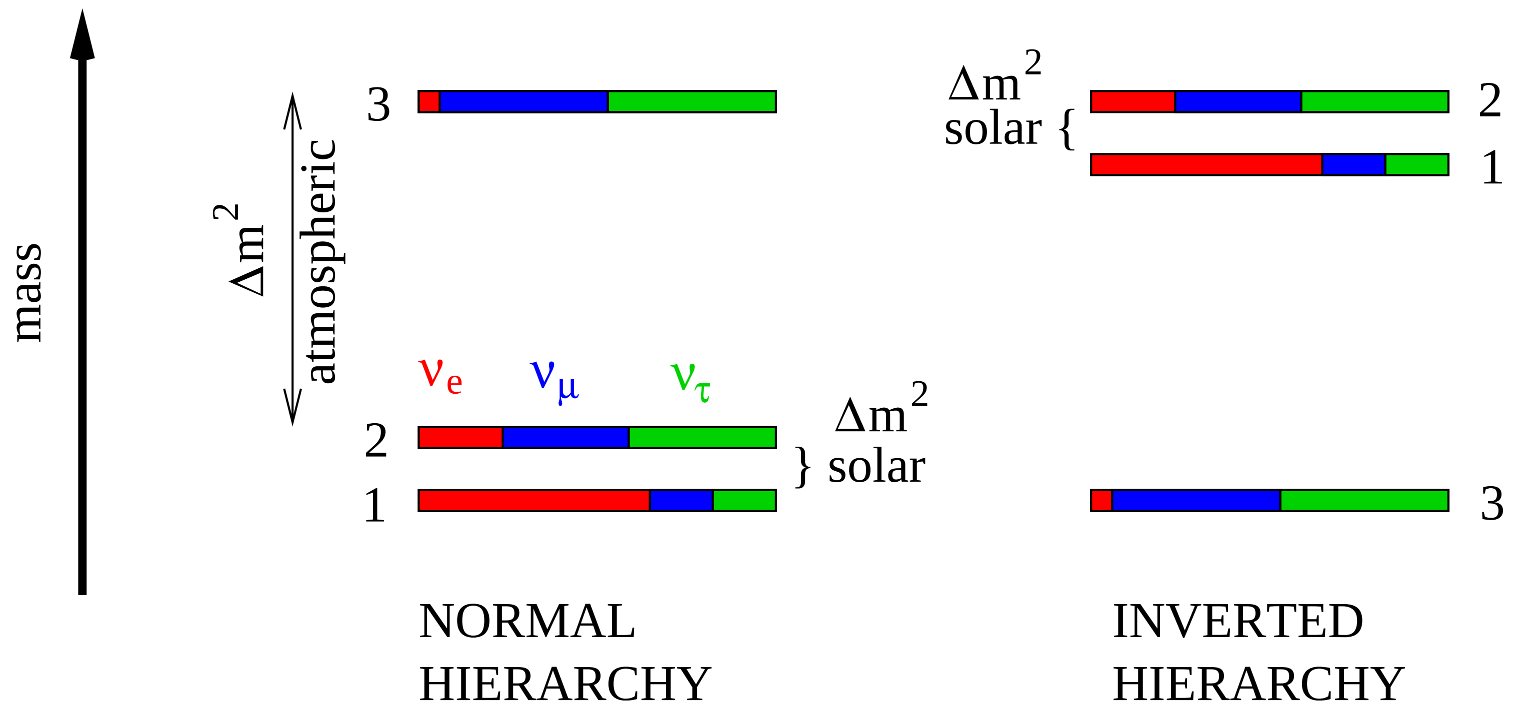
Super-K sees suppression of ν_μ flux at large zenith angles (distances).

ν_e flux is unaffected.

Looks to be $\nu_\mu \rightarrow \nu_\tau$ oscillations

First clear evidence for neutrino oscillations (1998)!

Neutrino Mass Hierarchy



$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}$ eV^2

$\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2

Neutrino Mixing Matrix

Adjust L/E to view oscillations at different Δm^2's

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

Atmospheric ν's:	Short baseline reactor ν's:	Solar ν's:
$\theta_{23} \approx \pi/4$	$\theta_{13} < \pi/20$	$\theta_{12} \approx \pi/6$
Maximal mixing! (?)	Small, quark-like mixing	Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$\theta_{23} \approx \pi/76$ $\qquad$ $\theta_{13} \approx \pi/870$ $\qquad$ $\theta_{12} \approx \pi/14$

Physics of Long Baseline ν Experiments

Basic idea: shoot a man-made neutrino beam through the Earth, and study neutrino oscillations in controlled way

K2K: KEK to Kamioka

T2K: J-PARC to Kamioka ($\times 50$ stats.)

Far detector: Super-K

Measure	Determine
$P(\nu_\mu \to \nu_\mu)$	$\Delta m^2_{23}, \theta_{23}$
$P(\nu_\mu \to \nu_e)$	θ_{13}
$P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$	CPT
$P(\overline{\nu}_\mu \to \overline{\nu}_e)$	δ_{CP}, sign(Δm^2_{23})

K2K: KEK to Kamiokande

250 km baseline, wide-band beam

	Beam
ν_μ	98.2%
ν_e	1.3%
$\bar{\nu}_\mu$	0.5%

K2K-I: March 1999 - July 2001

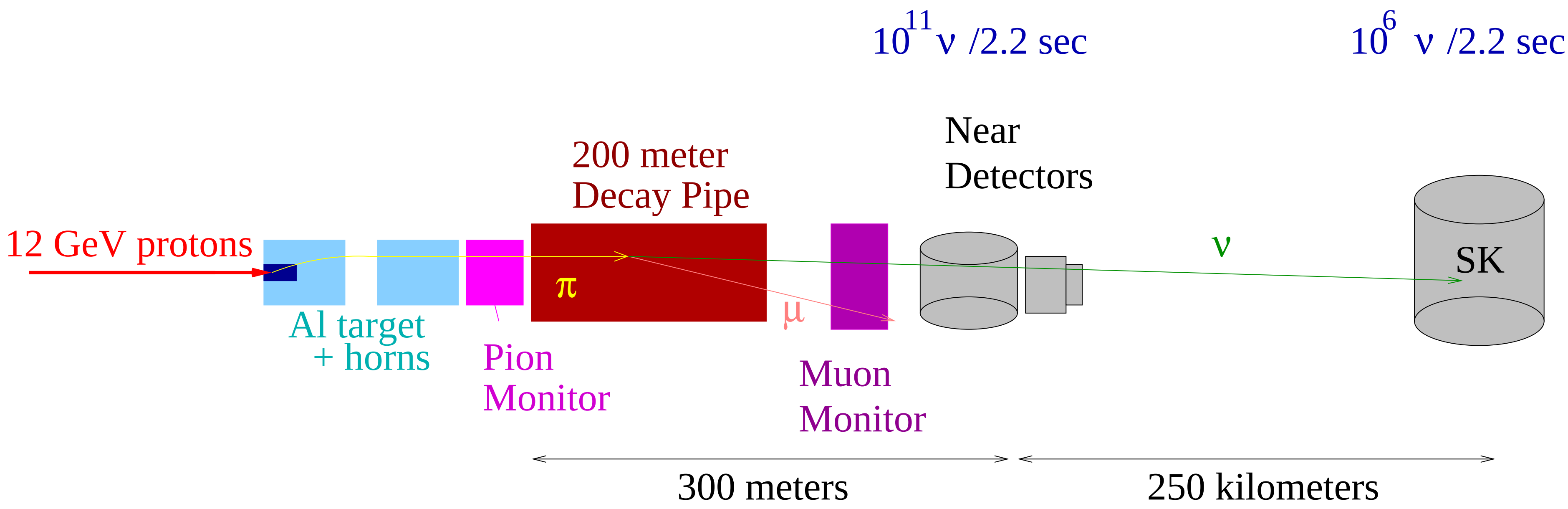
Super-K accident, reconstruction

K2K-II: December 2002 - November 2004

The first long baseline ν experiment

Goal: measure ν_μ disappearance at atmospheric Δm^2

Anatomy of a Long Baseline Experiment



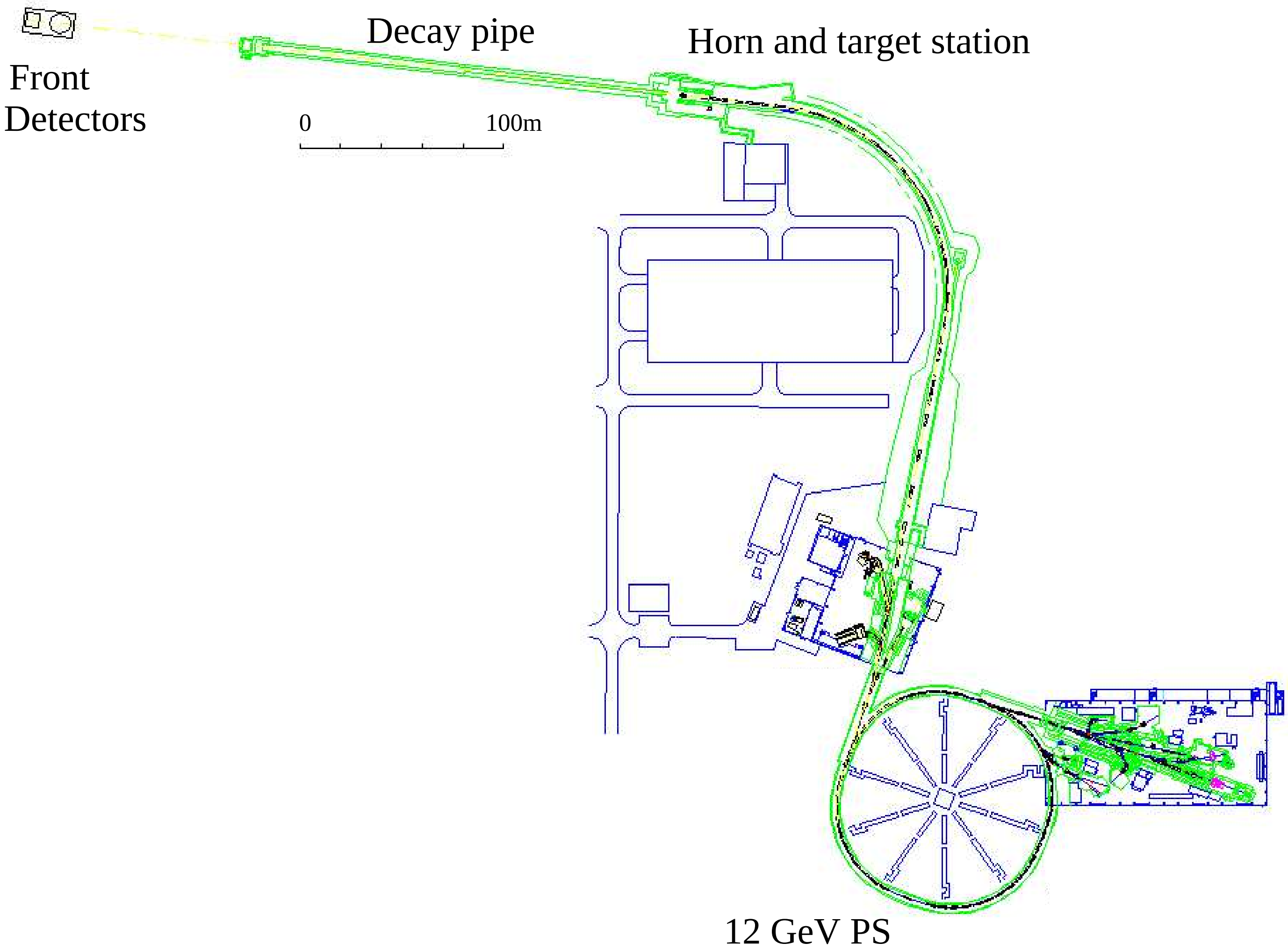
Target: 3cm dia $\times$ 66cm long Al cylinder

Horns: toroidal B fields, pulsed at 250 kA

Pion monitor: gas Cherenkov detector

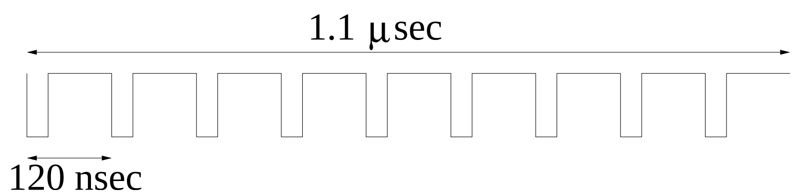
Muon monitor: segmented ionization chamber + array of silicon pad detectors

12 GeV PS Beamline

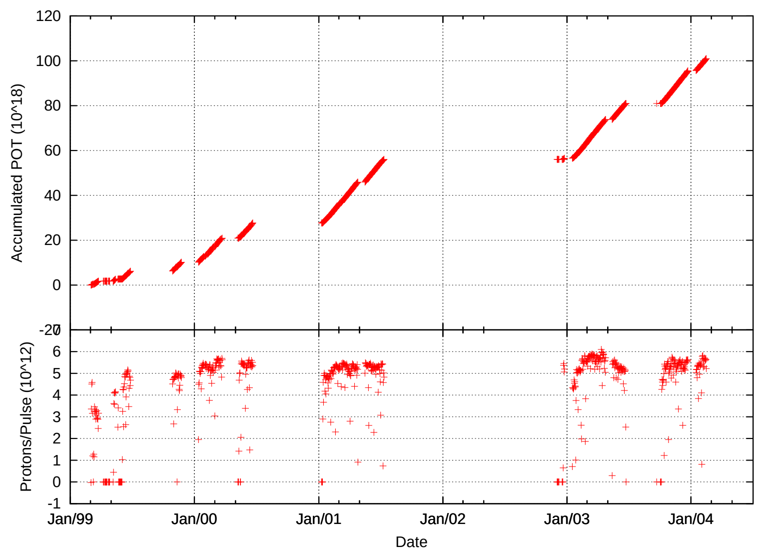


Magnetic horns focus π's, which decay in pipe to produce ν_μ

K2K Beam Statistics

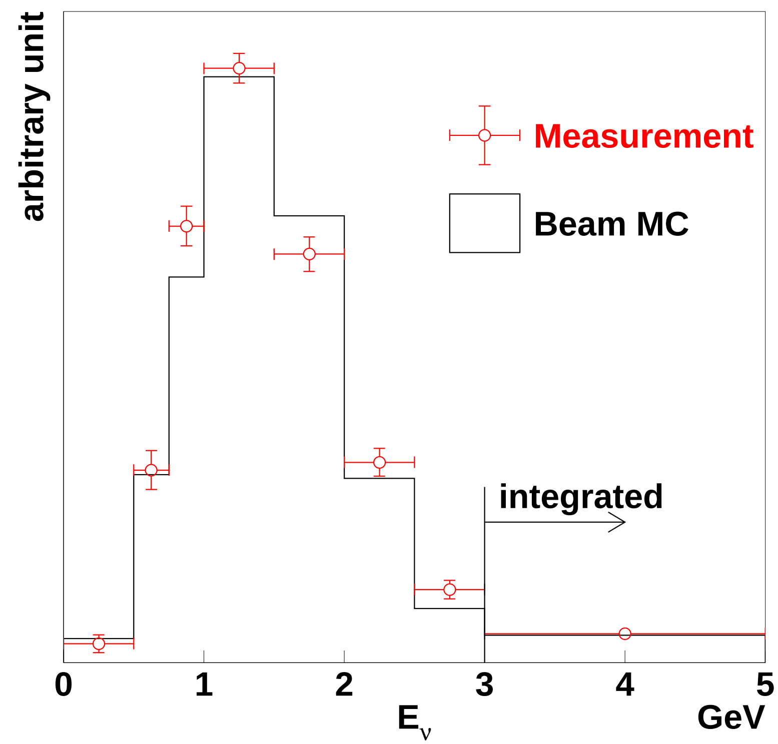


$\sim 6 \times 10^{12}$ p.o.t. in 9 bunches



89.1×10^{18} POT usable data

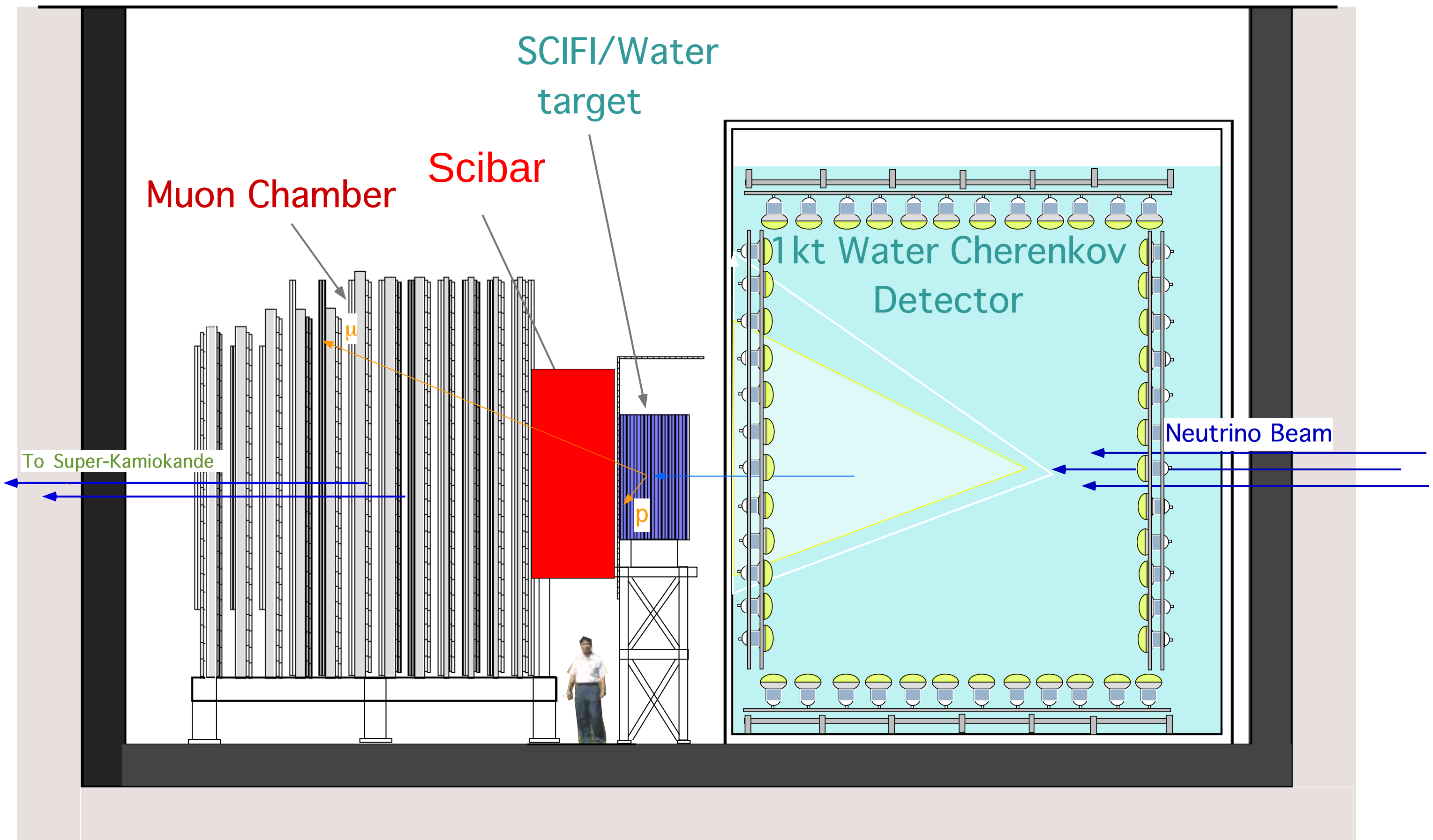
Neutrino Energy Spectrum at KEK



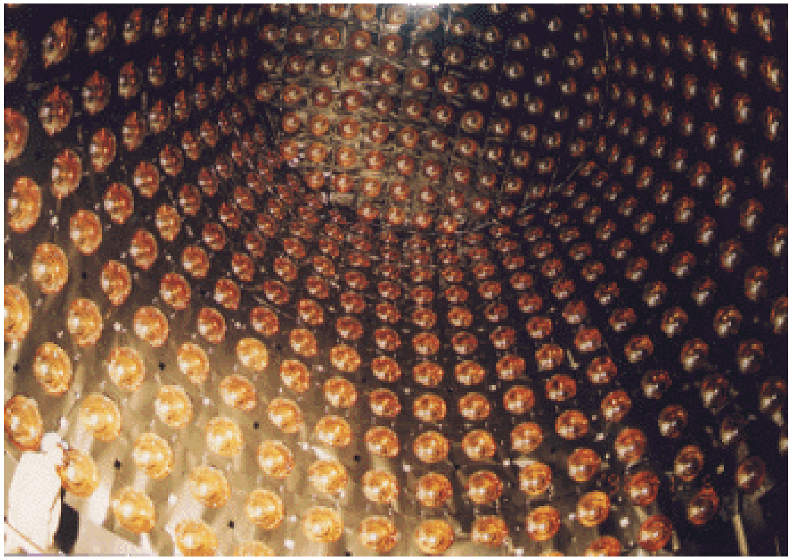
On-axis beam

Relatively wide energy spectrum

K2K Near Detectors



Kiloton Water Cherenkov Detector



8.6 m diameter $\times$ 8.6 m high cylinder

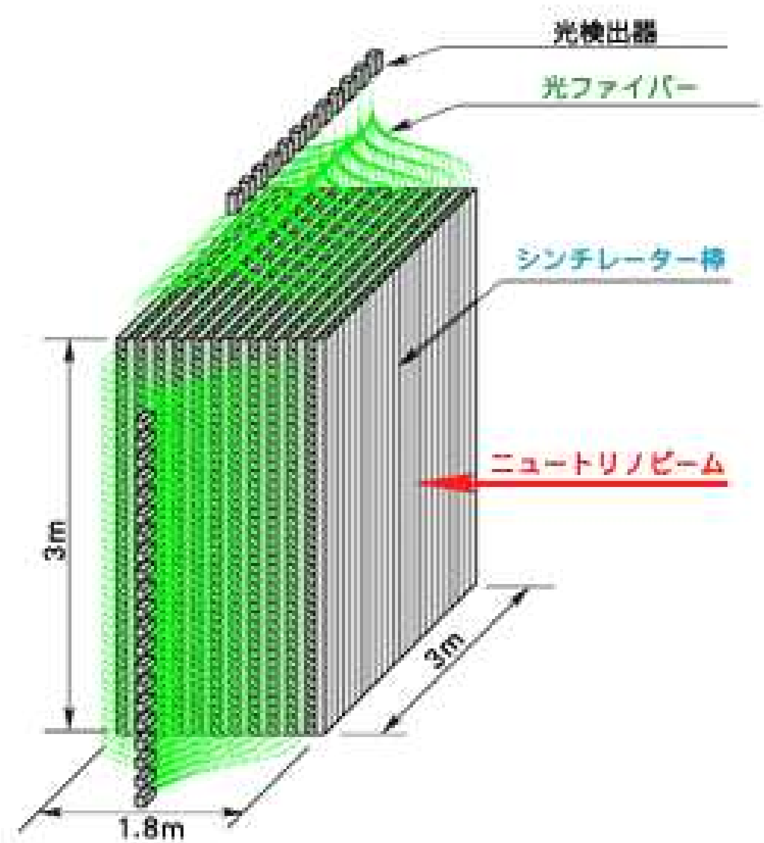
680 Super-K PMTs with electronics—a miniature Super-K

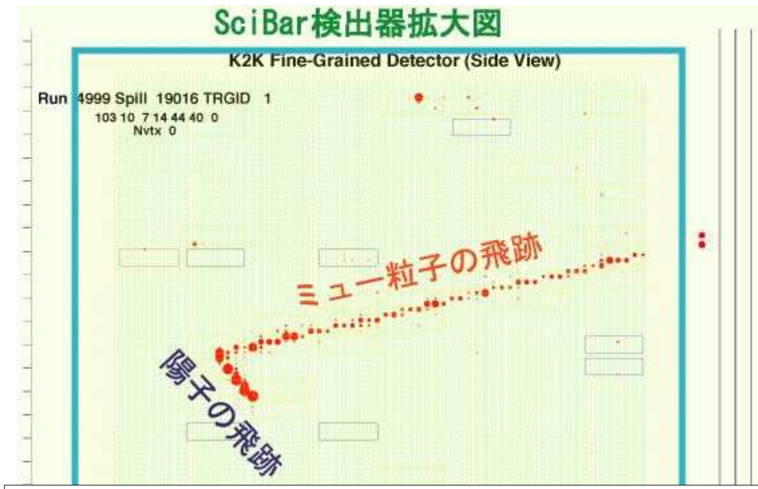
1 kton water Cherenkov detector normalizes beam interactions on water target.

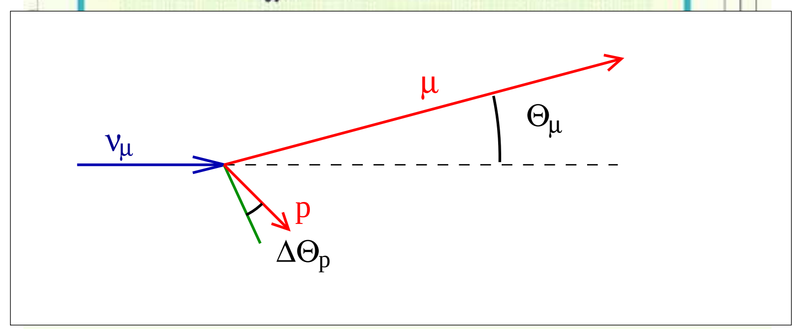
Measure ν spectrum and backgrounds before oscillation

Used to predict event rate at Super-K

Scibar Detector





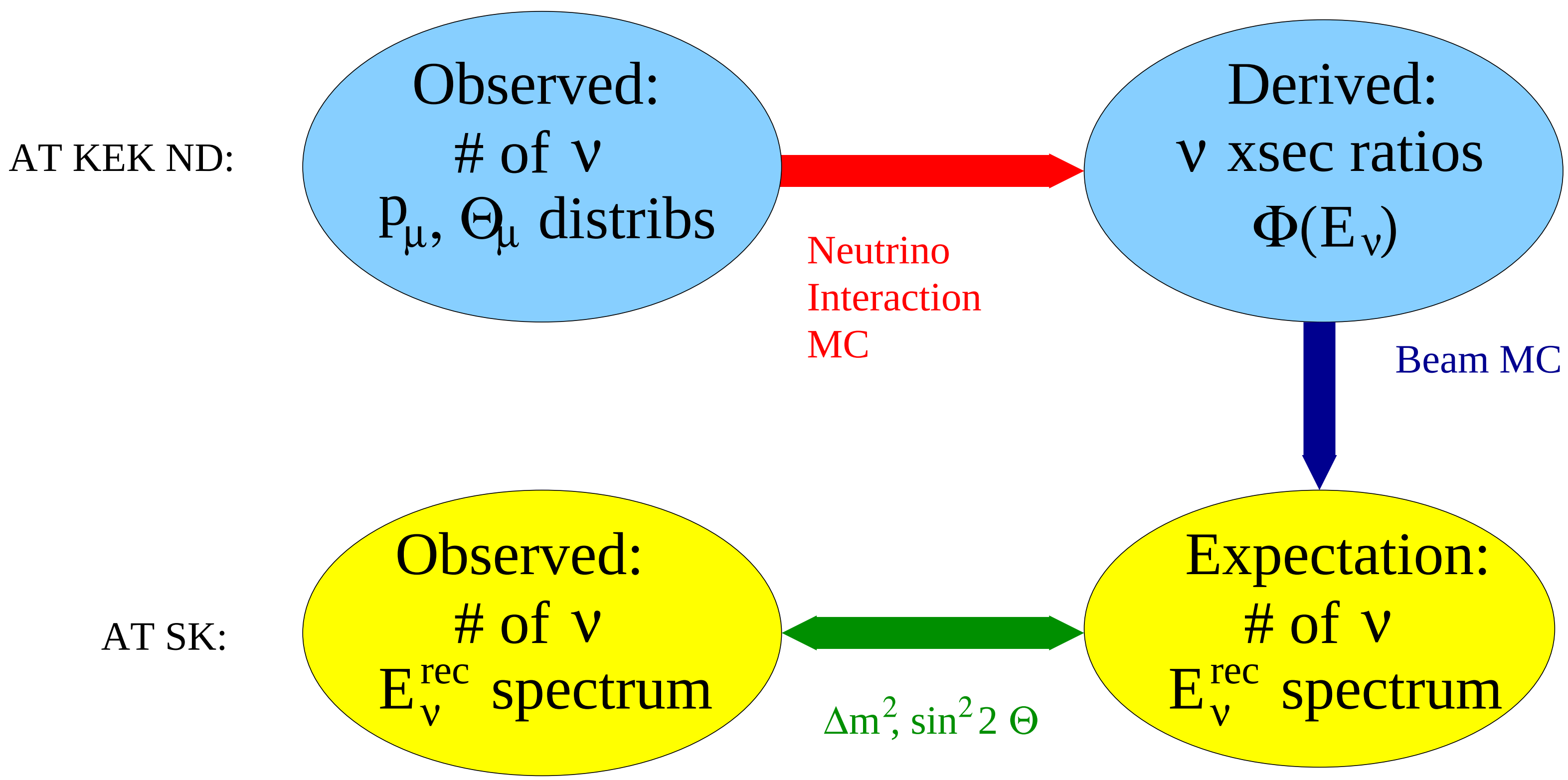


14848 extruded scintillator strips

Read out by 1.5mm diameter WLS fibres with multi-anode PMTs

Compare measured proton recoil direction to quasielastic prediction to identify or reject CCQE events ($\nu_\mu + n \rightarrow \mu + p$).

Analysis Flowchart



Main Interaction Types

Processes modelled with the NEUT Monte Carlo

CC Quasi-Elastic (CCQE)

- Smith & Moniz with $M_A = 1.1$ GeV

CC Resonant Single Pion (CC-1π)

- Rein & Sehgal with $M_A = 1.1$ GeV

CC Multiple Pion (DIS)

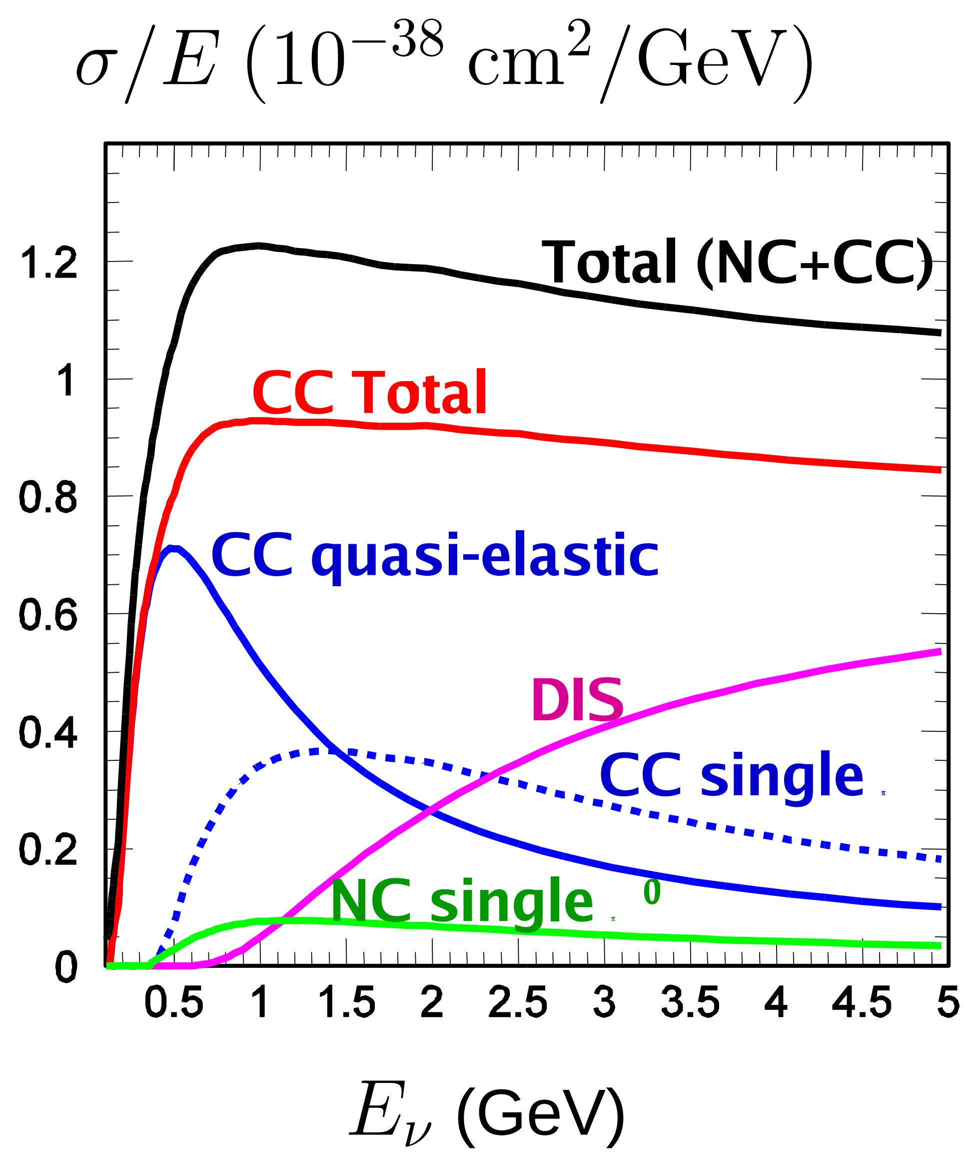
- GRV94 + JETSET with Bodek & Yang correction

CC Coherent Pion

- Rein & Sehgal with cross-section rescaling by J. Marteau

NC

+ Nuclear Effects



Low q^2 Anomaly

K2K observes a deficit of forward-going μ relative to MC in all near detectors

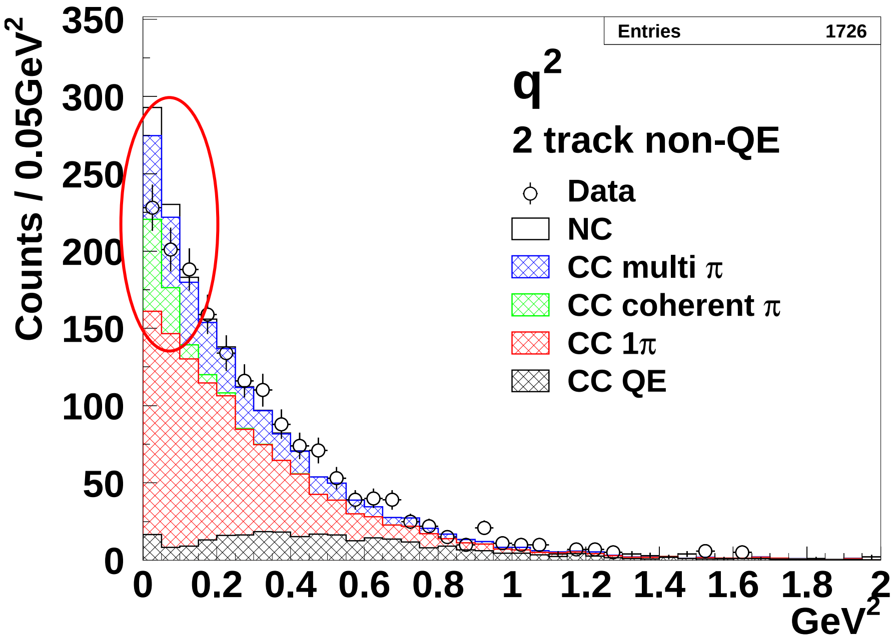
- Seen in non-QE events

Two possible explanations:

- Suppression of CC-1π at $q^2 < 0.1$ GeV^2
- Absence of CC coherent π production

Significant nuclear effects (poorly understood).

Scibar data



Data favours coherent pion suppression (PRL 95, 252301 (2005)).

Oscillation analysis is insensitive to how q^2 deficit is modelled.

Flux measurement with the kiloton detector

The kiloton near detector, like SK, is water Cherenkov detector. So cross-section systematics cancel in far-near ratio.

$$N_{SK}^{exp} = N_{KT}^{obs} \cdot \left[\frac{\int dE_\nu \Phi_{SK}(E_\nu)\sigma(E_\nu)}{\int dE_\nu \Phi_{KT}(E_\nu)\sigma(E_\nu)} \cdot \right] \frac{M_{SK}}{M_{KT}} \cdot \frac{\epsilon_{SK}}{\epsilon_{KT}}$$

[Far-near ratio (from MC) $\approx 1 \times 10^{-6}$]

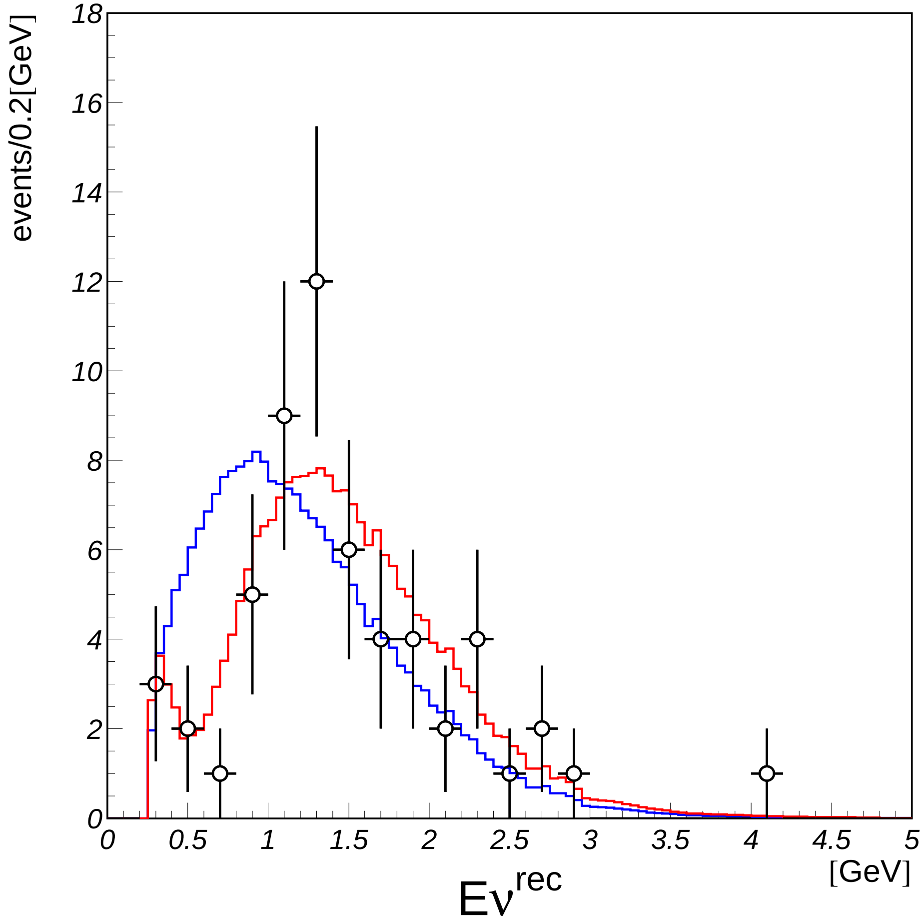
$N_{SK}^{obs} = 107$ $N_{SK}^{exp} = 150.9^{+11.5}_{-10.1}$

Null oscillation probability: $P = 0.0025\ (3.02\sigma)$

(PRL 94, 081802 (2005))

Reconstructed Neutrino Spectrum at Super-K

Reconstructed energy spectrum from 1-ring μ events



Kolgomorov-Smirnov test probability (no oscillation): 0.08%

Kolgomorov-Smirnov test probability (best-fit oscillation): 36%

Allowed K2K Mixing Parameters

Consistency with null oscillation hypothesis:

Normalization only	0.26%
Spectrum only	0.74%
Spectrum + normalization	0.005%

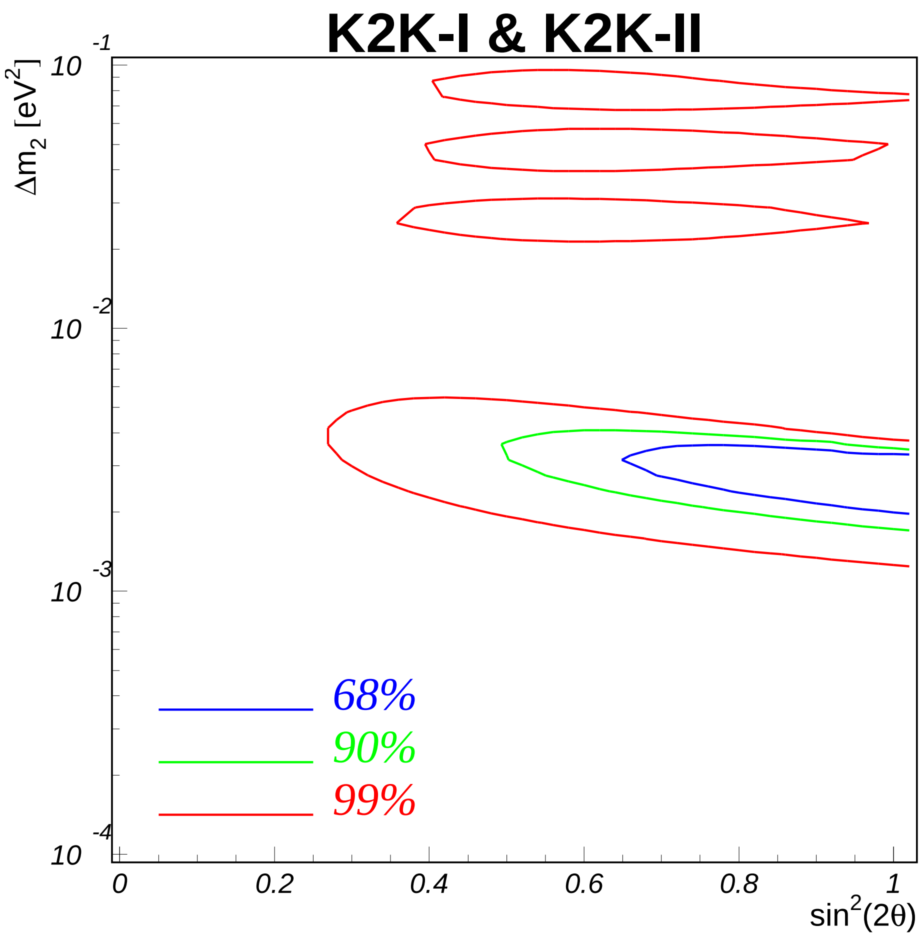
Favored mixing parameters:

$$\Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta = 1$$

90% CL at $\sin^2 2\theta = 1$:

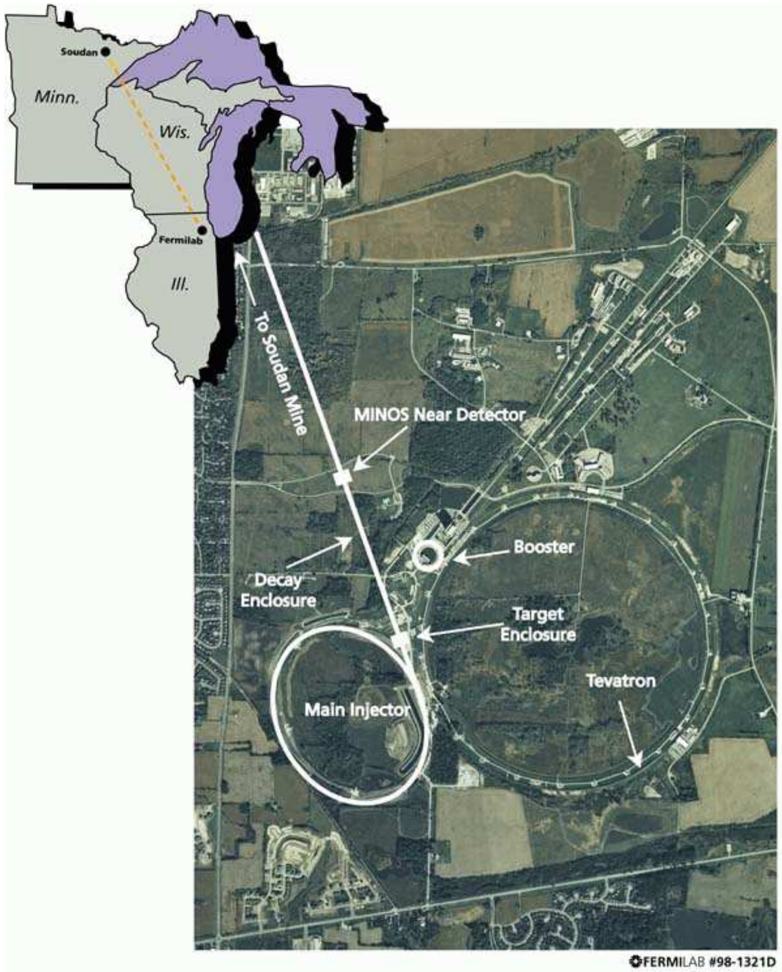
$$1.9 - 3.6 \times 10^{-3} \text{ eV}^2$$

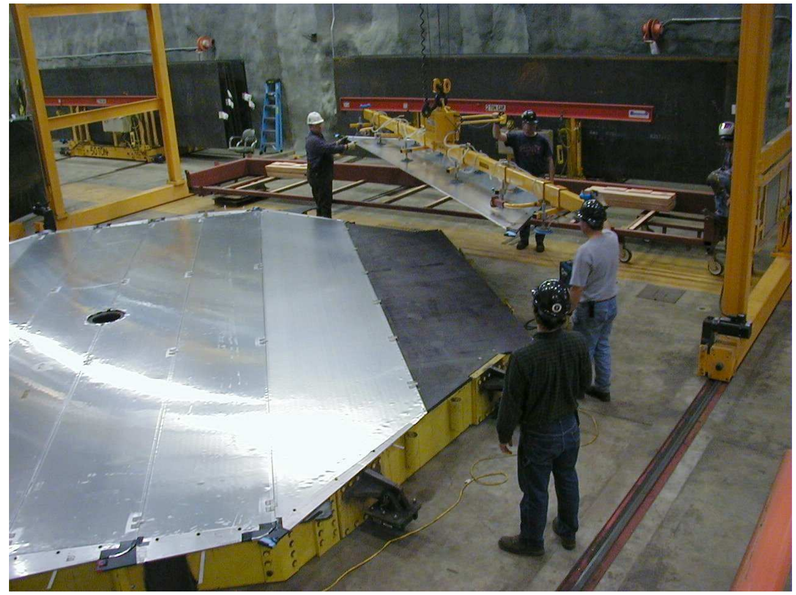


Null oscillation hypothesis rejected at 4.0σ level

(PRL 94, 081802 (2005))

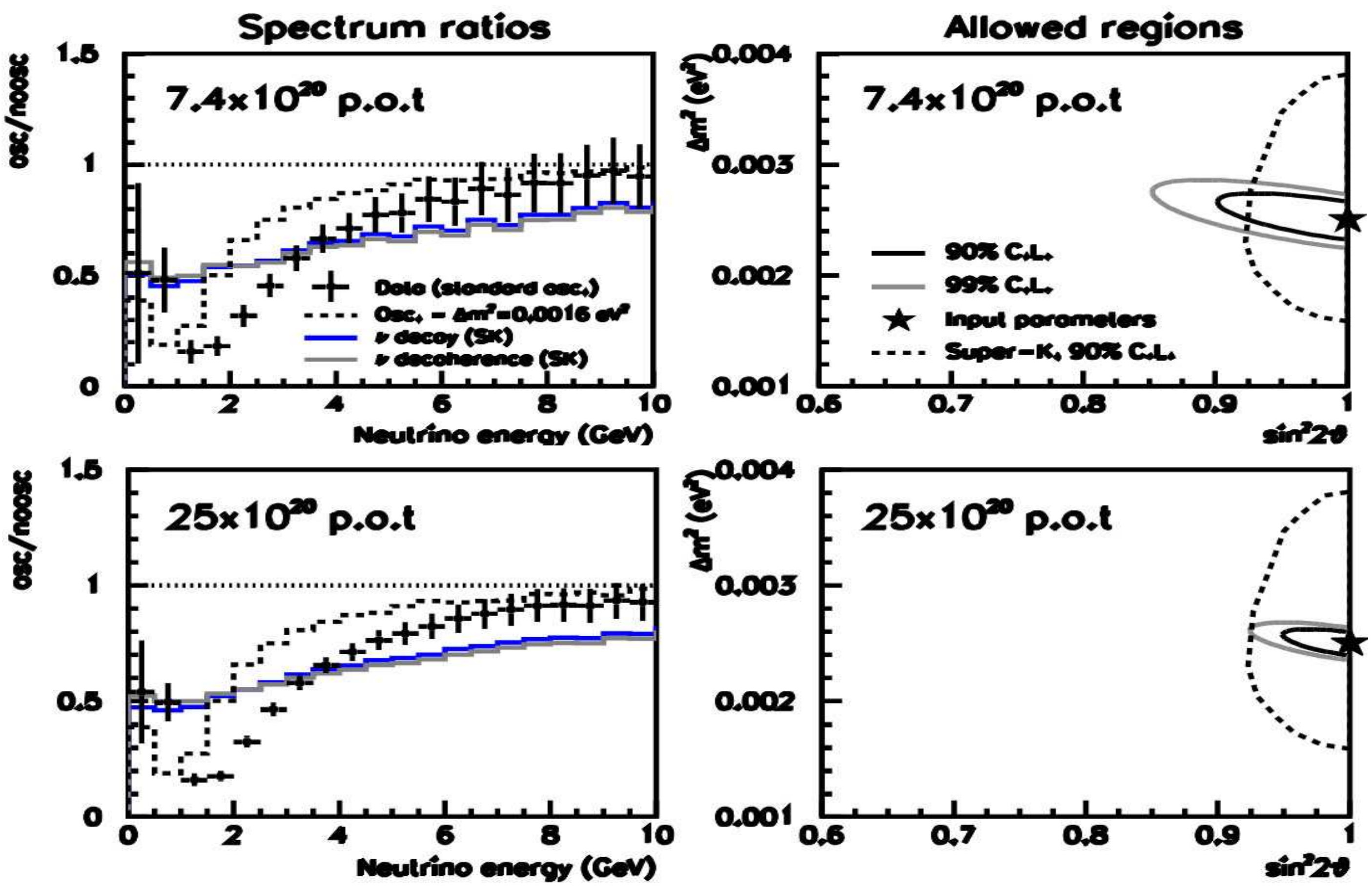
The MINOS Experiment





A beam from Fermilab's Main Injector to the Soudan mine located 720 km away

Expected MINOS Sensitivity



Goals of MINOS;

- precise measurement of Δm^2
- test alternatives of oscillation model (eg. neutrino decay)

Conclusions

- Neutrinos have mass and oscillate. Compelling evidence from four different kinds of experiments
  1. solar neutrinos
  2. reactor neutrinos
  3. atmospheric neutrinos
  4. long baseline neutrino beams
- Neutrino mixing opens a whole new area of lepton flavour physics. *This is new physics beyond the Standard Model, involving new fields and new fundamental constants!*
- Next time:
  1. How many neutrinos are there really?
  2. What are the theoretical implications?
  3. How do we complete our map of the neutrino mixing matrix?
  4. How might we determine the *absolute* mass of neutrinos?
  5. Are neutrinos the reason we're all here?