Neutrino Oscillations

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Early History

- 1930: To explain the continuous electron spectrum in nuclear decay, W. Pauli proposes the existence of a light, neutral, hardly interacting particle
- 1953: (Reines and Cowan) First experimental evidence at a nuclear reactor by detection of

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

Three Generations

- 1962: First neutrino “beam” and discovery of a second kind of neutrino: the muon neutrino (Lederman, Schwartz, Steinberger et al.):

$$p + Be \rightarrow \pi$$
$$\pi \rightarrow \mu\ \nu$$
$$\nu + N \rightarrow \mu + X$$

- 1975: Discovery of the tau
- Since then, a wealth of indirect evidence for the existence of the tau neutrino:

- From studies of the Z decay, LEP deduces there are 2.989±0.012 species of light neutrinos
- The tau neutrino is not the muon neutrino ($\nu_\mu + N \rightarrow \mu + X$ but not $\tau + X$)
- The tau and its decay properties are the same as those of its fellow charged leptons, the muon and the electron

The Standard Model

	ν_e,ν_μ,ν_τ	e,μ,τ	u,c,t	d,s,b
mass	$<15 eV/c^2$, $<170 KeV/c^2$, $<18.2 MeV/c^2$	$511 KeV/$ $105 MeV/$ $1.8 GeV/c$	$2 MeV/c^2$, $1.5 GeV/c^2$, $174 GeV/c^2$	$5 MeV/c^2$, $100 MeV/c^2$, $5 GeV/c^2$
charge	0	-1	+2/3	-1/3
spin	1/2	1/2	1/2	1/2
color	none	none	one	one
Couples to	W,Z	W,Z,γ	W,Z,γ gluon	W,Z,γ gluon

- In the Standard Model, neutrinos are massless $\Rightarrow$ only left-handed neutrinos exist.
- In just about every extension to the Standard Model, right-handed neutrinos exist, and therefore, in these models, neutrinos have mass!

Neutrino Oscillations

- Basic idea of neutrino oscillations was suggested in 1957 (!) by B. Pontecorvo
- It is a remarkable phenomenon allowed by quantum mechanics
- So, take a simplified two generation world, and suppose the neutrinos interacting with the W and Z are linear combinations of the neutrinos propagating in the vacuum (called "mass eigenstates")

- This can be written:

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

- After a time *t* :

$$|\nu_e(t)> = \cos\theta e^{-iE_1 t}\,|\nu_1> + \sin\theta e^{-iE_2 t}\,|\nu_2>$$
$$|\nu_\mu(t)> = -\sin\theta e^{-iE_1 t}\,|\nu_1> + \cos\theta e^{-iE_2 t}\,|\nu_2>$$

- Since

$$|a(t)> = e^{-iHt}\,|a(0)> = e^{-iE_a t}\,|a(0)>$$

- We can now check the probability that an electron neutrino becomes a muon neutrino after a time *t* :

$$P(\nu_e(0) \rightarrow \nu_\mu(t)) = |< \nu_\mu(t) \,|\, \nu_e(0) >|^2$$
$$= \sin^2 2\theta \sin^2\left(\frac{1}{4}\Delta m^2 \frac{L}{E}\right)$$

- Where L is the distance traveled (=ct) and

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

Properties of Oscillations

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 (eV^2) \frac{L(km)}{E(GeV)}\right)$$

- An experiment's sensitivity to Δm^2 is determined by its L/E value (L/E is small for accelerator experiments, but huge for solar neutrinos)
- For large Δm^2

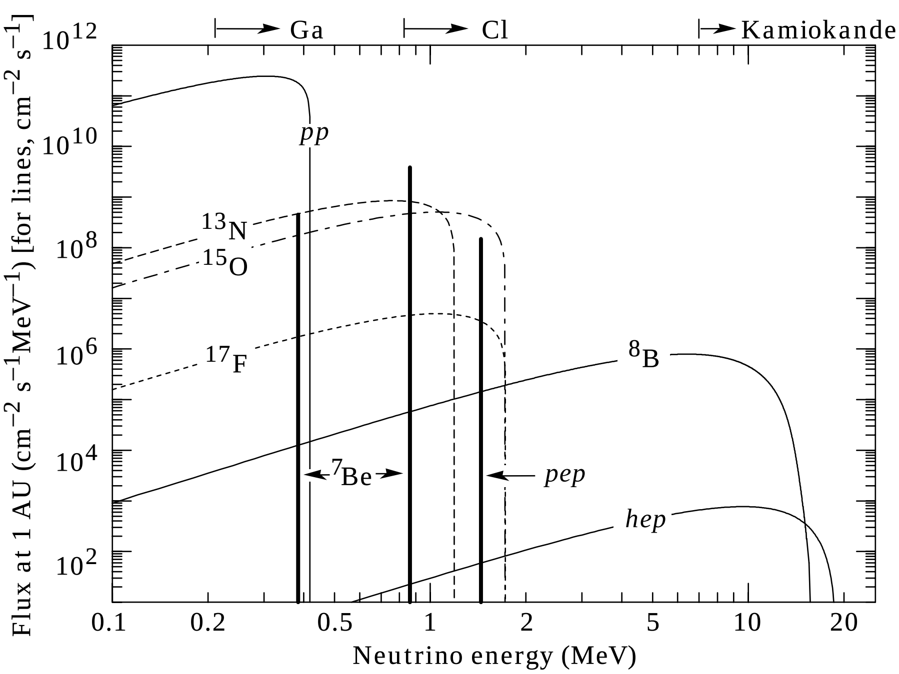
$$P(\nu_e \to \nu_\mu) = \frac{1}{2}\sin^2 2\theta$$

Neutrino Oscillation Experiments

- Solar neutrinos
- Atmospheric neutrinos
- Reactor neutrinos
- Accelerator neutrinos
- Neutrinoless double beta decay

Solar Neutrinos

- Solar Models predict the spectrum and flux of neutrinos observed on Earth:



Solar Neutrino Detection

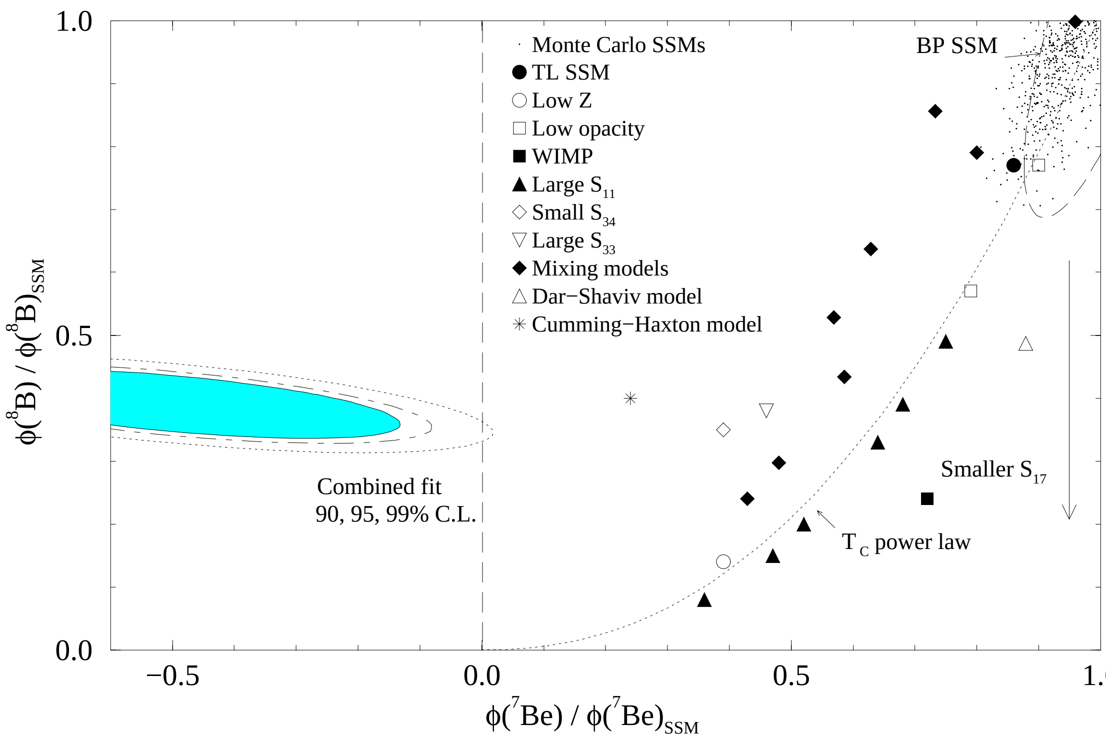
- Three types of experiments are sensitive to different parts of the spectrum:
- Water Čerenkov (neutrino-electron scattering: Super-) Kamiokande), sensitive to neutrinos above 7 MeV (neutrino-electron scattering)
- Chlorine (ν+Cl $\rightarrow$ e + Ar: Homestake), > 814 keV
- Gallium (ν+Ga $\rightarrow$ e + Ge: Gallex and Sage) > 233 keV

Solar Neutrino Results

Exp.	Observed Flux	SSM Prediction	Ratio
Homestake	2.14± 0.2 SNU	9.3±1.4 SNU	0.273± 0.021
Sage	72±13 SNU	137±8 SNU	0.526± 0.089
Gallex	69.7±8 SNU	137±8 SNU	0.509± 0.089
(Super)-Kamio-kande	2.59±0.2	6.62± 1.12	0.391± 0.029

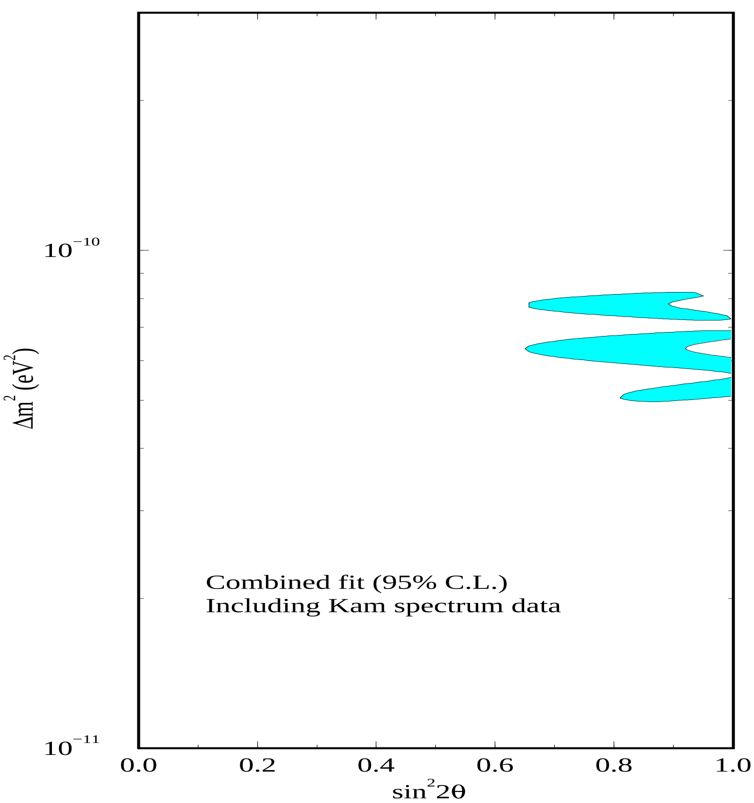
Combined Analysis

- Hata and Langacker have combined all of this:



In Terms of Oscillations

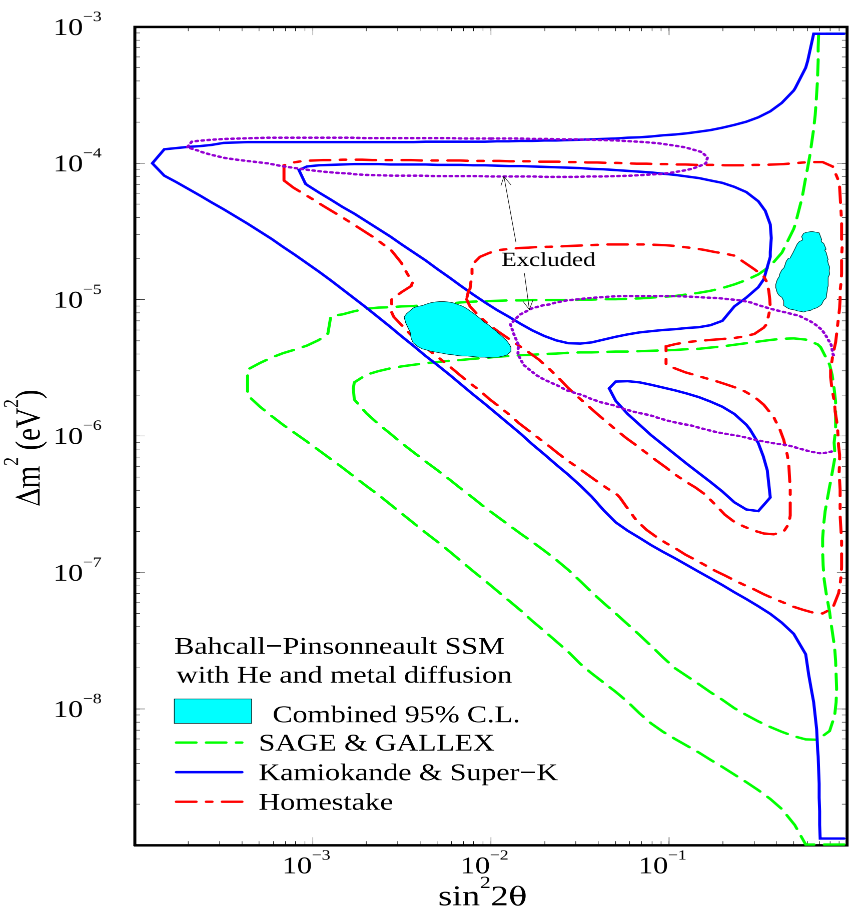
- “Vacuum Oscillations”:



- But in matter

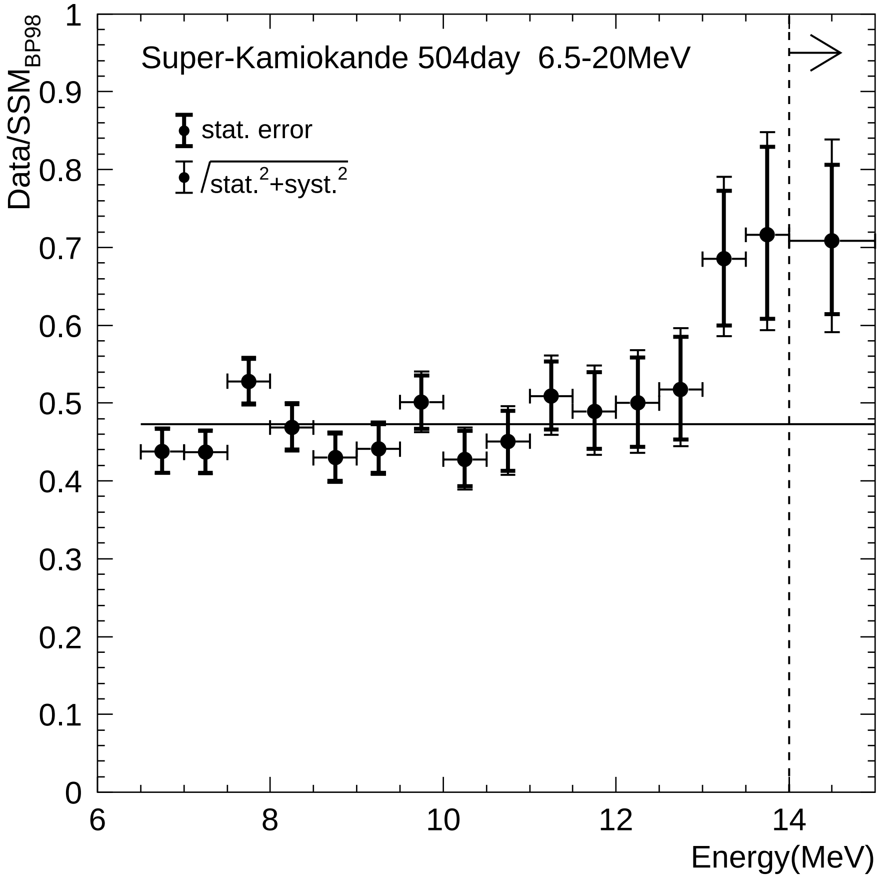
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\cos 2\theta - 2\sqrt{2}EG_F N_e / \Delta m^2\right)^2 + \sin^2 2\theta}$$

- so we get additional solutions



Solar Neutrino Spectrum

- SuperK measures the solar neutrino spectrum:



Atmospheric Neutrinos

- Cosmic rays interact with the upper atmosphere, producing mainly pions and kaons
- The decay sequence from pions is:

$$\pi \rightarrow \mu + \nu_\mu$$

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

- So that we should see two muon-like neutrinos for each electron-like neutrino
- The neutrino flux is about 1 per square cm per second (peaking around 1 GeV)

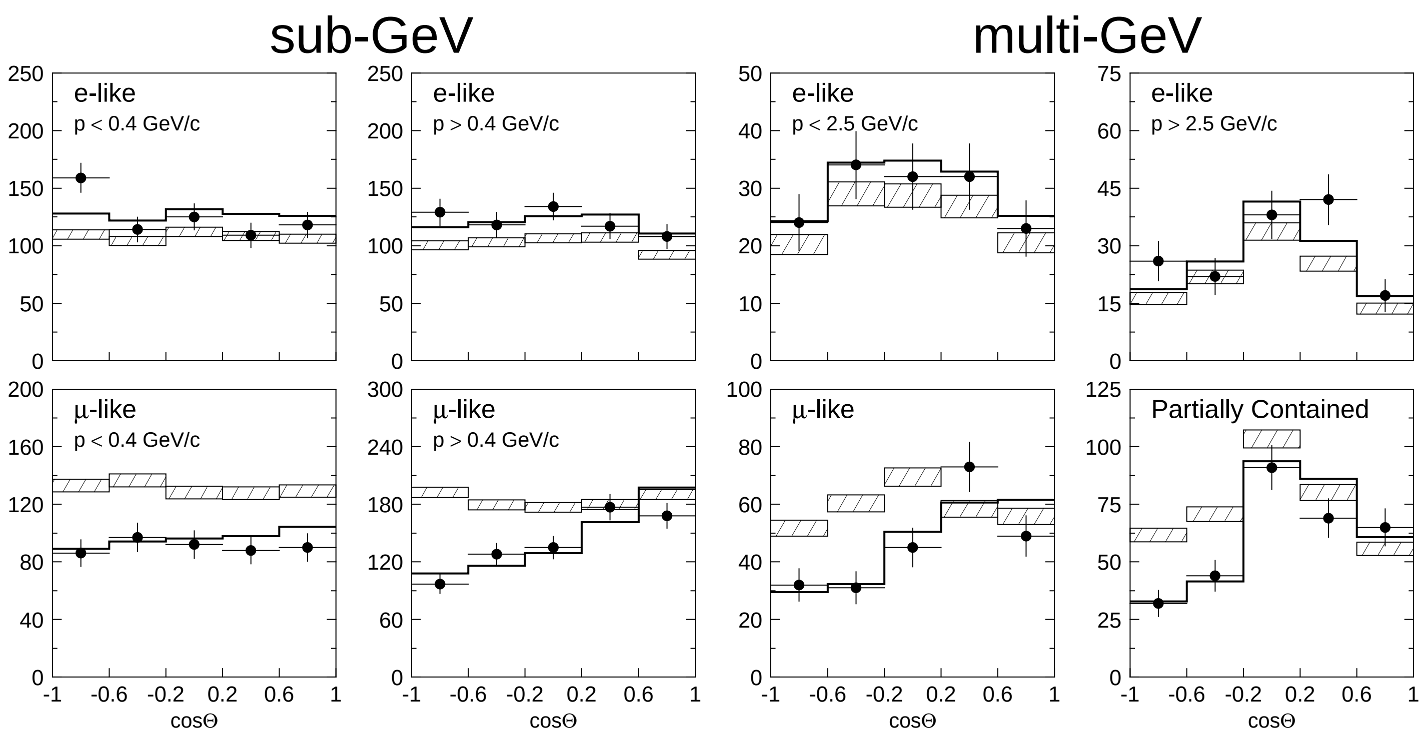
Atmospheric Neutrino Detection

- Measure

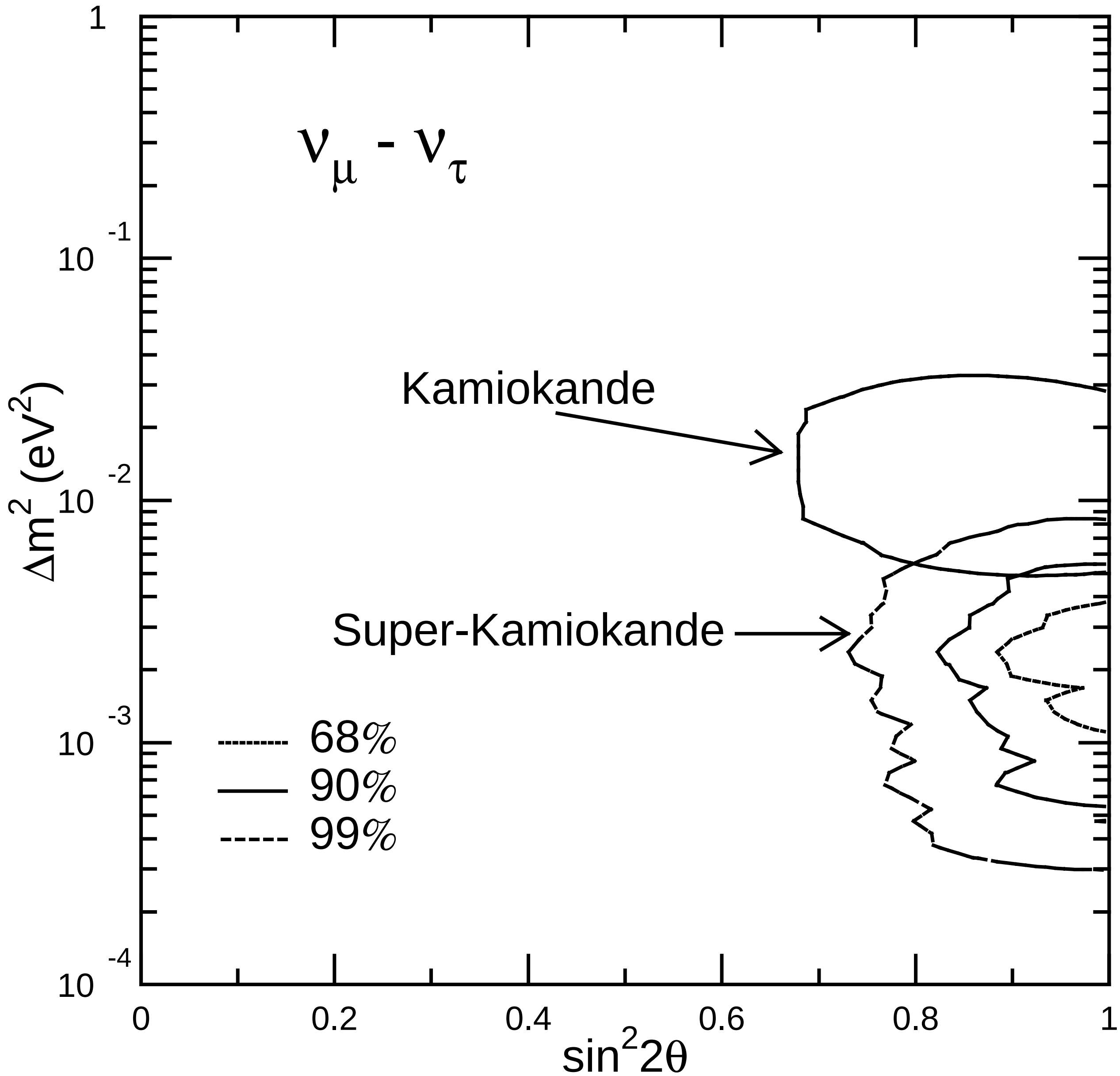
$$R = \frac{\left(\nu_\mu + \overline{\nu_\mu} / \nu_e + \overline{\nu_e}\right)_{Data}}{\left(\nu_\mu + \overline{\nu_\mu} / \nu_e + \overline{\nu_e}\right)_{MC}}$$

- One detector significantly more accurate than the others: SuperKamiokande
- They find R(sub_GeV)=0.63±0.06 and R(multi_GeV)=0.65±0.09

- It is even more powerful to look at R versus cosθ (where θ is the incoming neutrino's azimuthal angle). cosθ determines the distance L traveled by the neutrino:

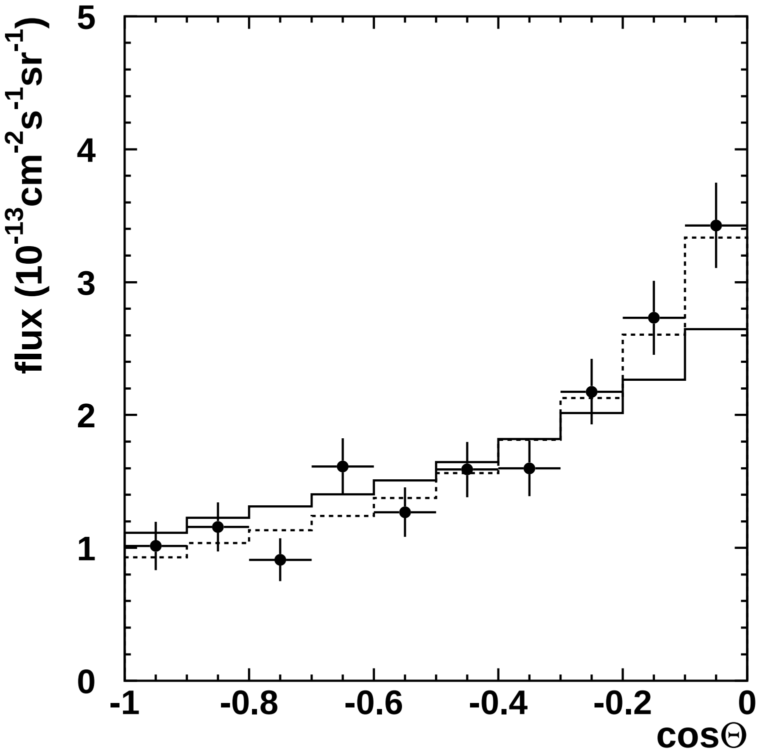


- Interpreted in terms of neutrino oscillations, the data yield



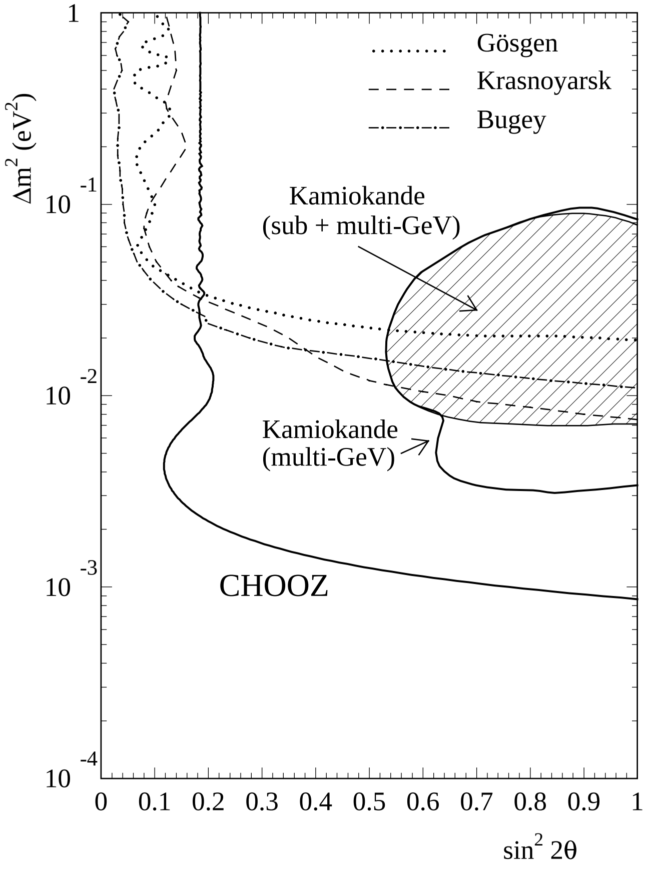
Upward-going Muons

- Neutrinos interact in the Earth, producing muons (dashed = with oscillations):



Reactor Neutrinos

- Experiments measure the neutrino flux at several distances



- → atmospheric anomaly cannot be muon to electron

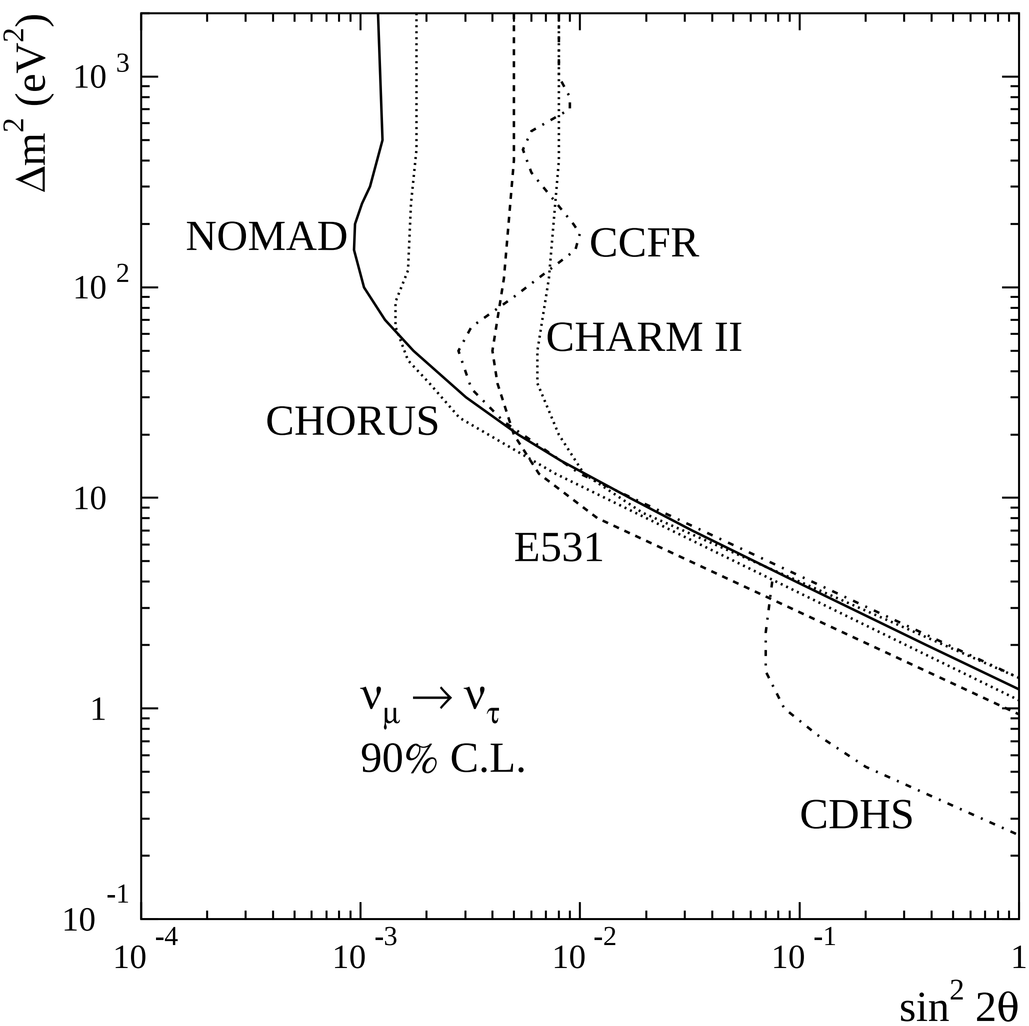
Accelerator Neutrinos

- Experiments have the advantage of using a fairly well understood beam
- But suffer from rather high energy and short distance
- So, with high statistics (O(million events)), sensitive to small mixing angles but only large Δm^2

Chorus and Nomad

- Search for tau neutrinos in a high-energy muon neutrino beam
- Nomad uses precise tracking to identify an excess of events with missing transverse momentum (neutrino from tau decay)
- Chorus uses a nuclear emulsion target (1 micron resolution) to tag the tau before its decay

- Analysis ongoing:



LSND

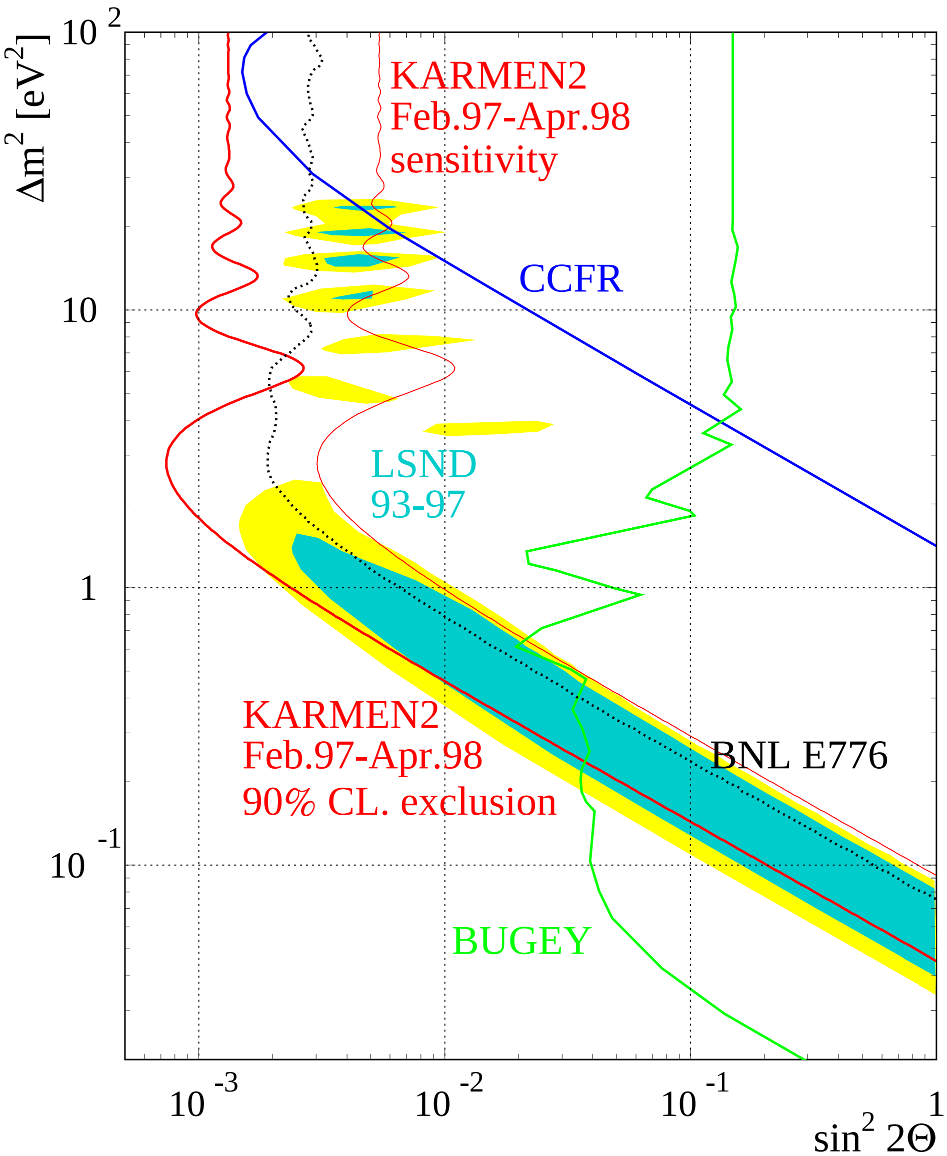
- Liquid Scintillator Neutrino Detector - at Los Alamos
- Beam contains mostly positive pions which decay through

$$\pi^+ \to \mu^+ + \nu_\mu,$$
$$\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu}$$

- Search for electron antineutrinos, detected through

$$\overline{\nu_e} + p \to e^+ + n$$

- LSND sees a net excess of 17.4±4.7 events, leading to



Summary of experimental results

- Solar: need disappearance of electron neutrinos with

$$\Delta m^2 \leq 10^{-5} eV^2$$

- Atmospheric: disappearance of muon neutrinos (and not into electron neutrinos) with

$$\Delta m^2 \approx 10^{-3} eV^2$$

- LSND: sees muon-to-electron antineutrino oscillations with

$$\Delta m^2 \approx 1 eV^2$$

- However, with three light neutrino generations there can only be two independent values of Δm^2
- Therefore, if all experimental results are correctly interpreted, require the existence of at least one additional light neutrino, which has to be sterile!
- Otherwise, can live with three neutrinos, and now know all 5 mixing parameters (2 mass differences and 3 angles)

Let's Speculate!

- LSND's a difficult experiment, if it's wrong, then long baseline accelerator experiments should see a signal (LBL searches for tau neutrinos in a muon neutrino beam with $E \approx 15$ GeV and $L \approx 1000$)
- SuperK could be wrong, then …
- There's a mountain of phenomenology papers with such speculations

Future Experiments

- SNO: will detect solar neutrinos through neutral currents (able to tell if total flux is ok) - 2000?
- (Mini)Boone: check LSND - 2001
- Minos: Fermilab-Soudan, check atmospheric neutrinos - 2002
- CERN-Gran Sasso: like Minos
- CERN-PS: like MiniBoone
- K2K: KeK to SuperKamiokande - can only see disappearance - end 1999

Closing Comments

- Neutrinos are an open window to physics beyond the Standard Model
- Many experimental results are not compatible with the SM, indicating neutrinos are probably massive
- BTW, there's much more to neutrino physics than just oscillations.

- To keep up to date, check out the "Neutrino Oscillation Industry" page at: http://www.hep.anl.gov/NDK/Hypertext/nuindustry.html