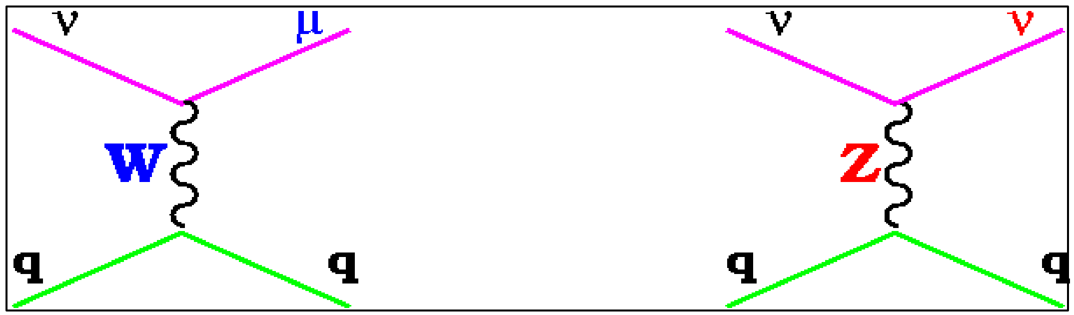
PHYS 5326 – Lecture #11

Monday, Feb. 24, 2003
Dr. Jae Yu

1. Brief Review of $\sin^2\theta_W$ measurement
2. Neutrino Oscillation Measurements
   1. Solar neutrinos
   2. Atmospheric neutrinos
3. A lecture on neutrino mass (Dr. Sydney Meshkov from CalTech)

- **Next makeup class is Friday, Mar. 14, 1-2:30pm, rm 200.**

How is $\sin^2 q_W$ measured?



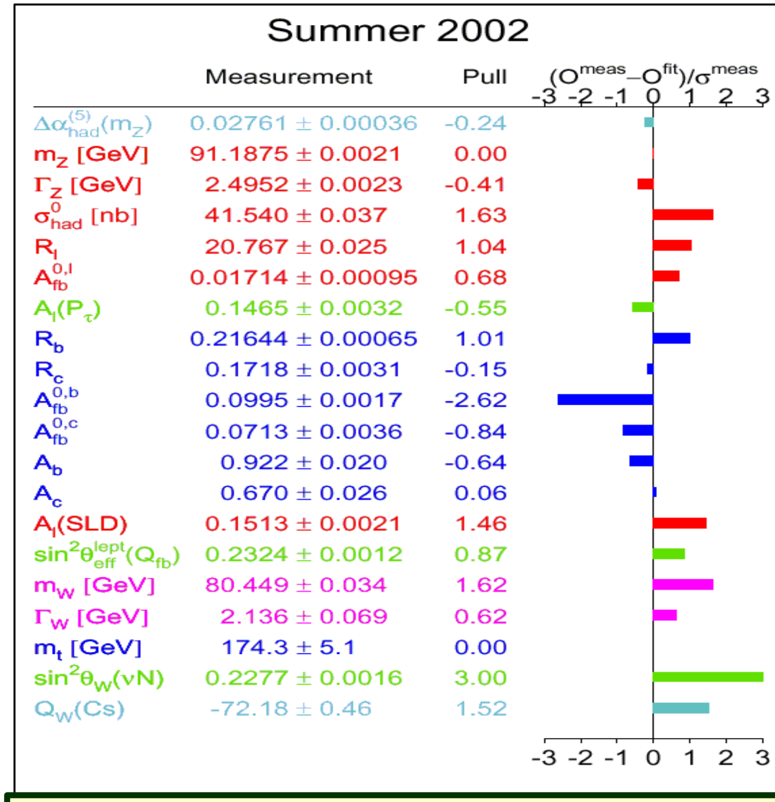
$$coupling \propto I^{(3)}_{weak}$$

$$coupling \propto I^{(3)}_{weak} - Q_{EM}\sin^2 q_W$$

- Cross section ratios between NC and CC proportional to $\sin^2\theta_W$
- Llewellyn Smith Formula:

$$\mathbf{R}^{n(\bar{n})} = \frac{\mathbf{s}^{n(\bar{n})}_{\mathbf{NC}}}{\mathbf{s}^{n(\bar{n})}_{\mathbf{CC}}} = \mathbf{?}^2\left(\frac{\mathbf{1}}{\mathbf{2}} - \mathbf{sin}^2\,\mathbf{?}_{\mathbf{W}} + \frac{\mathbf{5}}{\mathbf{9}}\,\mathbf{sin}^4\,\mathbf{?}_{\mathbf{W}}\left(\mathbf{1} + \frac{\mathbf{s}^{\bar{n}(n)}_{\mathbf{CC}}}{\mathbf{s}^{n(\bar{n})}_{\mathbf{CC}}}\right)\right)$$

SM Global Fits with New Results



Summer 2002

	Measurement	Pull	$(O^{meas}-O^{fit})/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24	
m_Z [GeV]	91.1875 ± 0.0021	0.00	
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41	
σ^0_{had} [nb]	41.540 ± 0.037	1.63	
R_l	20.767 ± 0.025	1.04	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68	
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55	
R_b	0.21644 ± 0.00065	1.01	
R_c	0.1718 ± 0.0031	-0.15	
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62	
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84	
A_b	0.922 ± 0.020	-0.64	
A_c	0.670 ± 0.026	0.06	
A_l(SLD)	0.1513 ± 0.0021	1.46	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87	
m_W [GeV]	80.449 ± 0.034	1.62	
Γ_W [GeV]	2.136 ± 0.069	0.62	
m_t [GeV]	174.3 ± 5.1	0.00	
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00	
$Q_W(Cs)$	-72.18 ± 0.46	1.52	

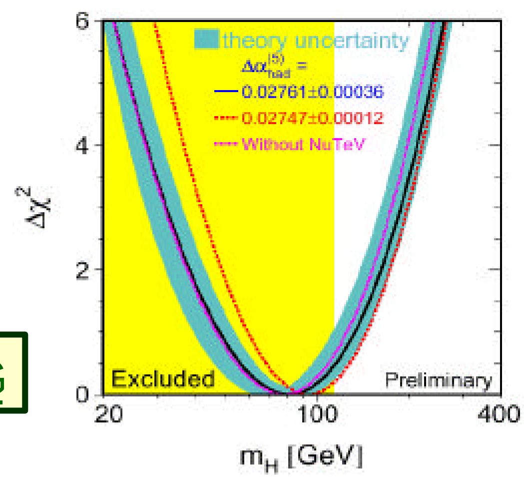
Without NuTeV

χ^2/dof=20.5/14: *P=11.4%*

With NuTeV

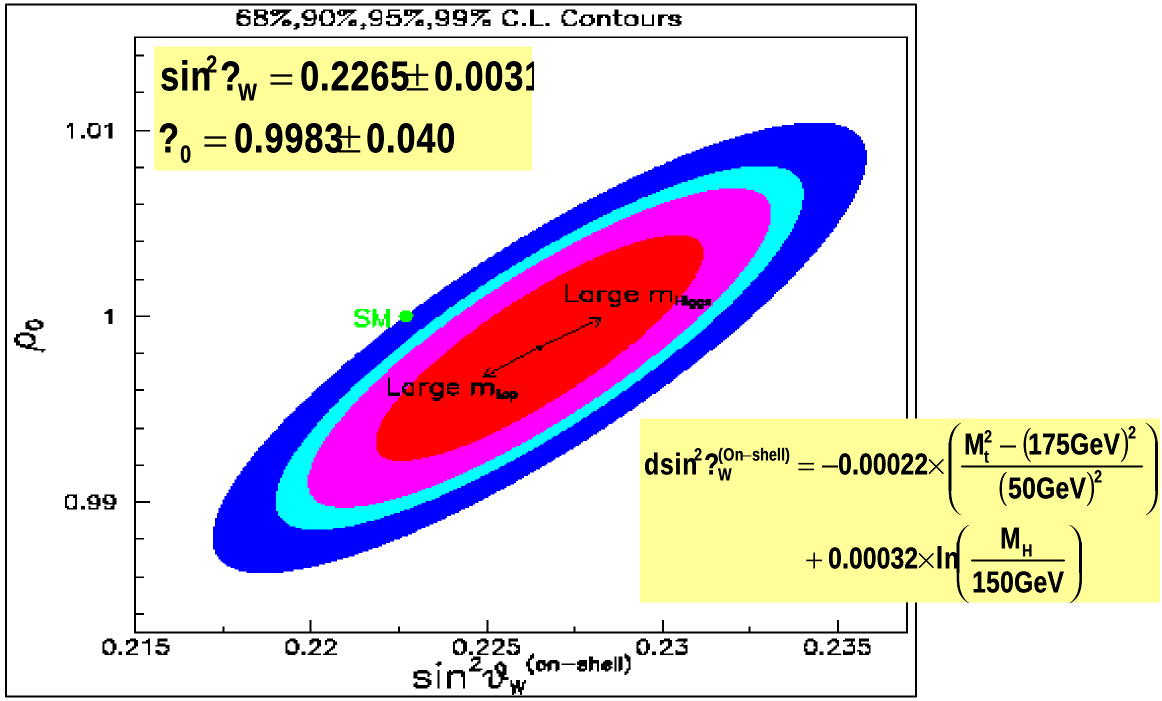
χ^2/dof=29.7/15: *P=1.3%*

Confidence level in upper M_{higgs} limit weakens slightly.



LEP EWWG: http://www.cern.ch/LEPEWWG

Tree-level Parameters: ρ_0 and $\sin^2\theta_W^{(on\text{-}shell)}$



- Either $\sin^2\theta_W^{(on\text{-}shell)}$ or ρ_0 could agree with SM but both agreeing simultaneously is unlikely

Model Independent Analysis

- $R^{\nu(\bar{\nu})}$ can be expressed in terms of quark couplings:

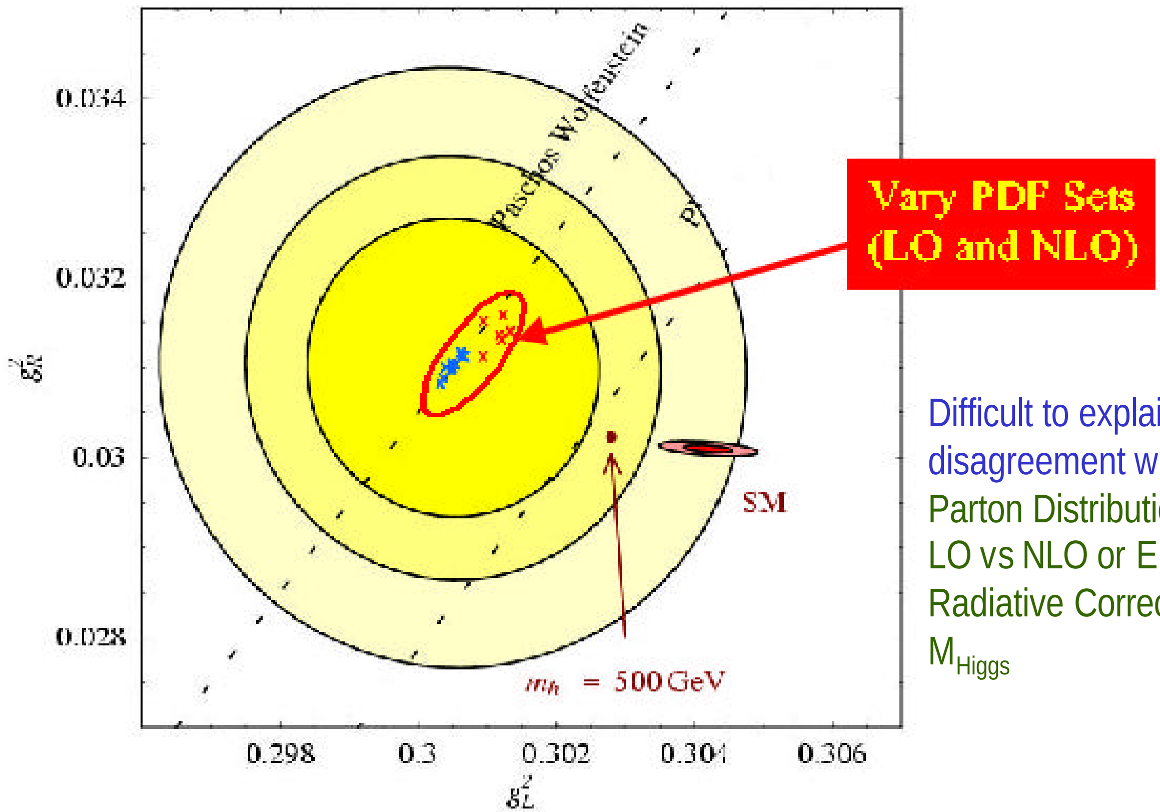
$$R^{n(\bar{n})} \equiv \frac{s\left(\overset{(-)}{n} N \to \overset{(-)}{n} X\right)}{s\left(\overset{(-)}{n} N \to \ell^{-(+)} X\right)} = g_L^2 + r^{(-1)} g_R^2$$

Where $$r \equiv \frac{s\left(\bar{?}N \to \ell^{+} X\right)}{s\left(?N \to \ell^{-(+)} X\right)} \approx \frac{1}{2}$$

Paschos-Wolfenstein formula can be expressed as

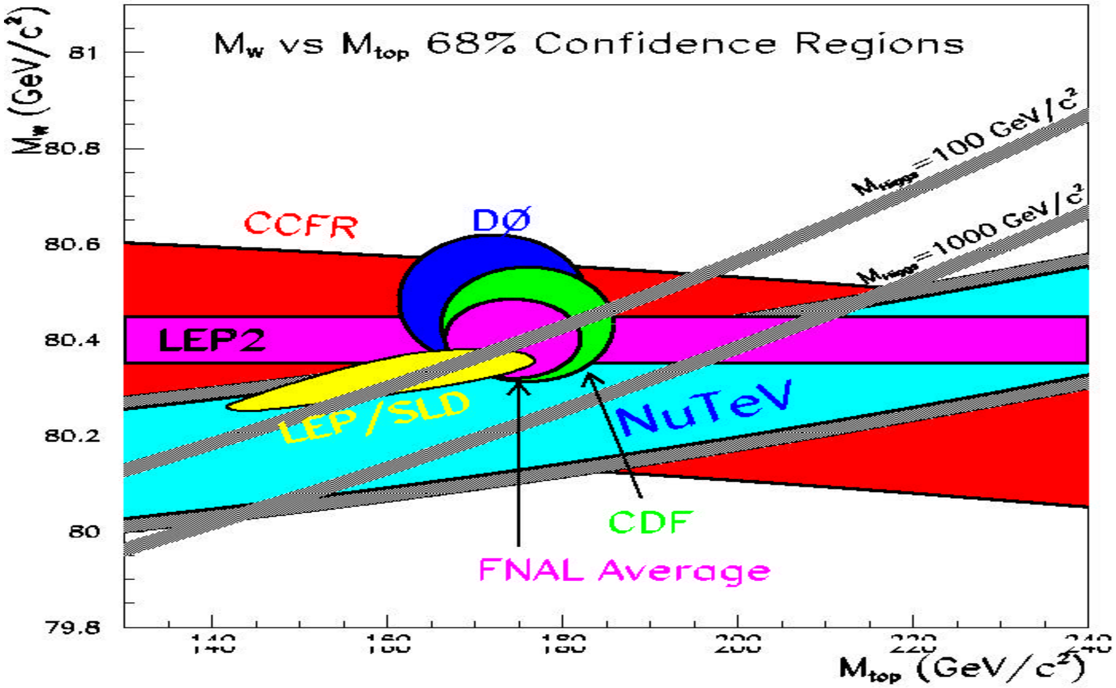
$$R^{-} = \frac{s^{?}_{NC} - s^{\bar{?}}_{NC}}{s^{?}_{CC} - s^{\bar{?}}_{CC}} = ?^2\left(\frac{1}{2} - \sin^2 ?_W\right) = \frac{R^{?} - rR^{\bar{?}}}{1 - r} = g_L^2 - g_R^2$$

Model Independent Analysis



Difficult to explain the disagreement with SM by: Parton Distribution Function or LO vs NLO or Electroweak Radiative Correction: large M_{Higgs}

Linking $\sin^2\theta_W$ with Higgs through M_{top} vs M_W



One-loop correction to $\sin^2\theta_W$

$$d\sin^2 ?_W^{(\text{On-shell})} = -0.00022\times\left(\frac{M_t^2-(175GeV)^2}{(50GeV)^2}\right)+0.00032\times\ln\left(\frac{M_H}{150GeV}\right)$$

Oscillation Probability

- Substituting the energies into the wave function:

$$\left|n_m(t)\right\rangle = \exp\left[-it\left(p + {m_1^2}/{2E_n}\right)\right]\left[-\sin q\left|n_1\right\rangle + \cos q\left|n_2\right\rangle \exp\left[{i\Delta m^2 t}/{2E_n}\right]\right]$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$ and $E_n \cong p$.

- Since the ν's move at the speed of light, t=x/c, where x is the distance to the source of ν_μ.
- The probability for ν_μ with energy E_ν oscillates to ν_e at the distance *L* from the source becomes

$$\boxed{P\left(n_m \rightarrow n_e\right) = \sin^2 2q \sin^2\left(\frac{1.27\Delta m^2 L}{E_n}\right)}$$

Why is Neutrino Oscillation Important?

- Neutrinos are one of the fundamental constituents in nature
  - Three weak eigenstates based on SM
- Left handed particles and right handed anti-particles only
  - Violates parity ➔ Why only neutrinos?
  - Is it because of its masslessness?
- SM based on massless neutrinos
- Mass eigenstates of neutrinos makes flavors to mix
- SM in trouble…
- Many experimental results showing definitive evidences of neutrino oscillation
  - SNO giving 5 sigma results

ν Sources for Oscillation Experiments

- Must have some way of knowing the flux
  - Why?
- Natural Sources
  - Solar neutrinos
  - Atmospheric neutrinos
- Manmade Sources
  - Nuclear Reactor
  - Accelerator

Oscillation Detectors

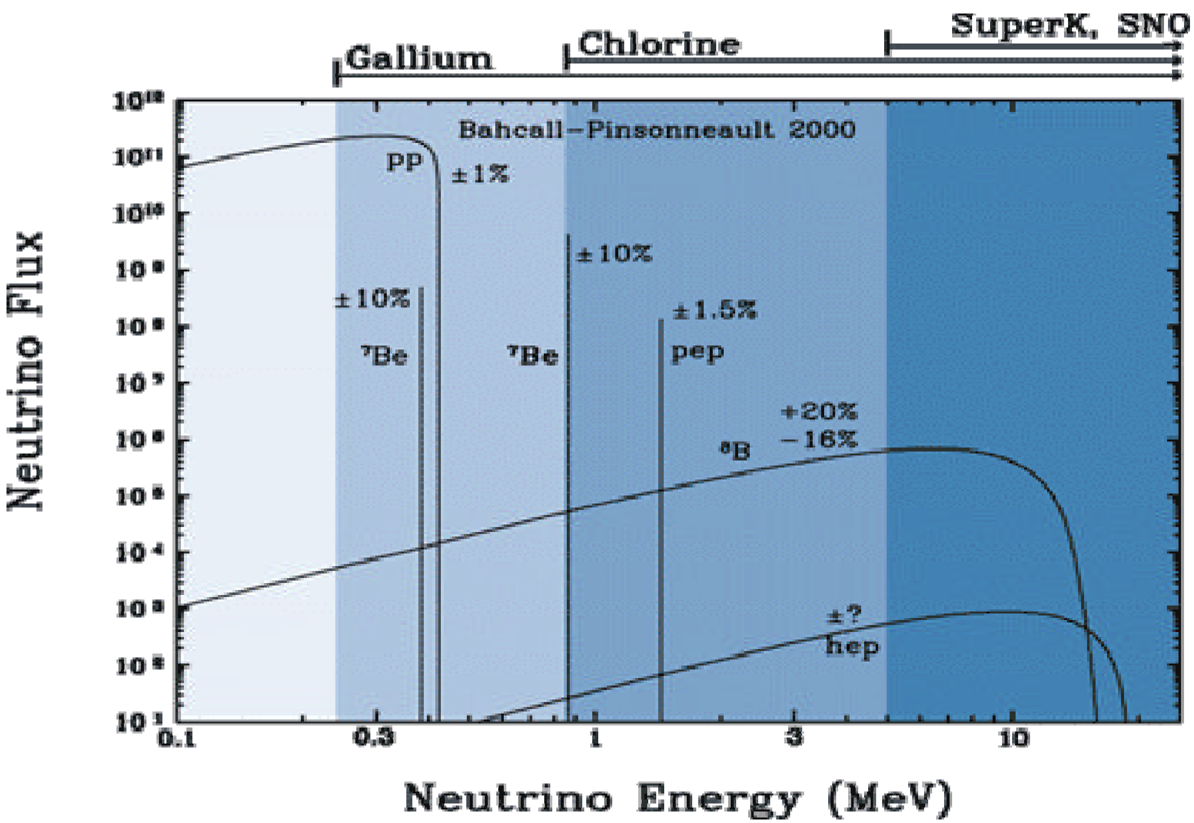
- The most important factor is the energy of neutrinos and its products from interactions
- Good particle ID is crucial
- Detectors using natural sources
  - Deep under ground to minimize cosmic ray background
  - Use Cerenkov light from secondary interactions of neutrinos
    - $\nu_e + e \rightarrow e + X$: electron gives out Cerenkov light
    - ν_μ CC interactions, resulting in muons with Cerenkov light
- Detectors using accelerator made neutrinos
  - Look very much like normal neutrino detectors
    - Need to increase statistics

Solar Neutrinos

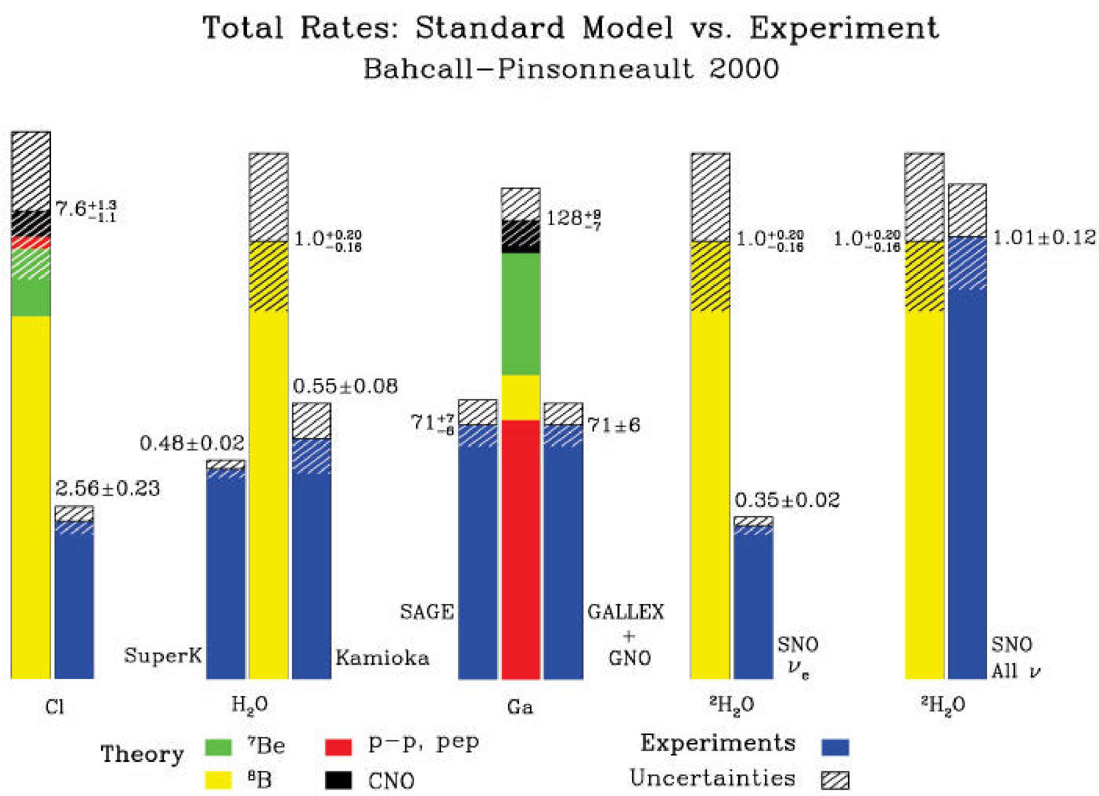
- Result from nuclear fusion process in the Sun
- Primary reactions and the neutrino energy from them are:

Name	Reaction	E_ν End point (MeV)
pp	$p+p \rightarrow D+e^{+}+n_e$	0.42
pep	$p+e^{-}+p \rightarrow D+n_e$	1.44
^{7}Be	$^{7}Be+e^{-} \rightarrow {}^{7}Li+n_e$	0.86
^{8}B	$^{8}B \rightarrow 2\left({}^{4}He\right)+e^{+}+n_e$	15

Solar Neutrino Energy Spectrum



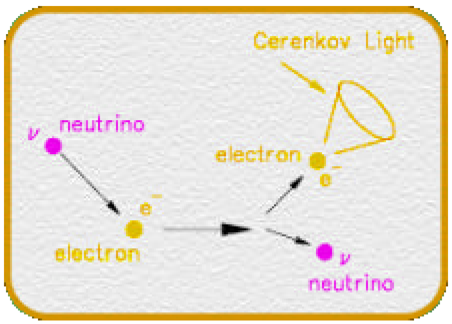
Comparison of Theory and Experiments



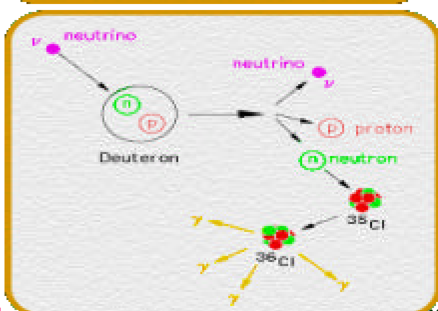
Sudbery Neutrino Observatory (SNO)

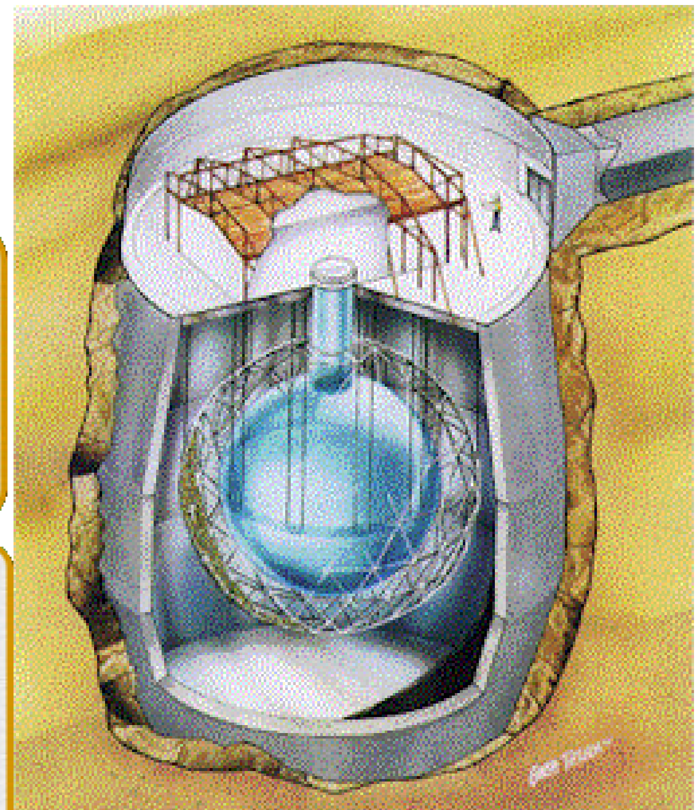
- •Sudbery mine, Canada
- •6800 ft underground
- •12 m diameter acrylic vessel
- •1000 tons of D_2O
- •9600 PMT's

Elastic Scattering

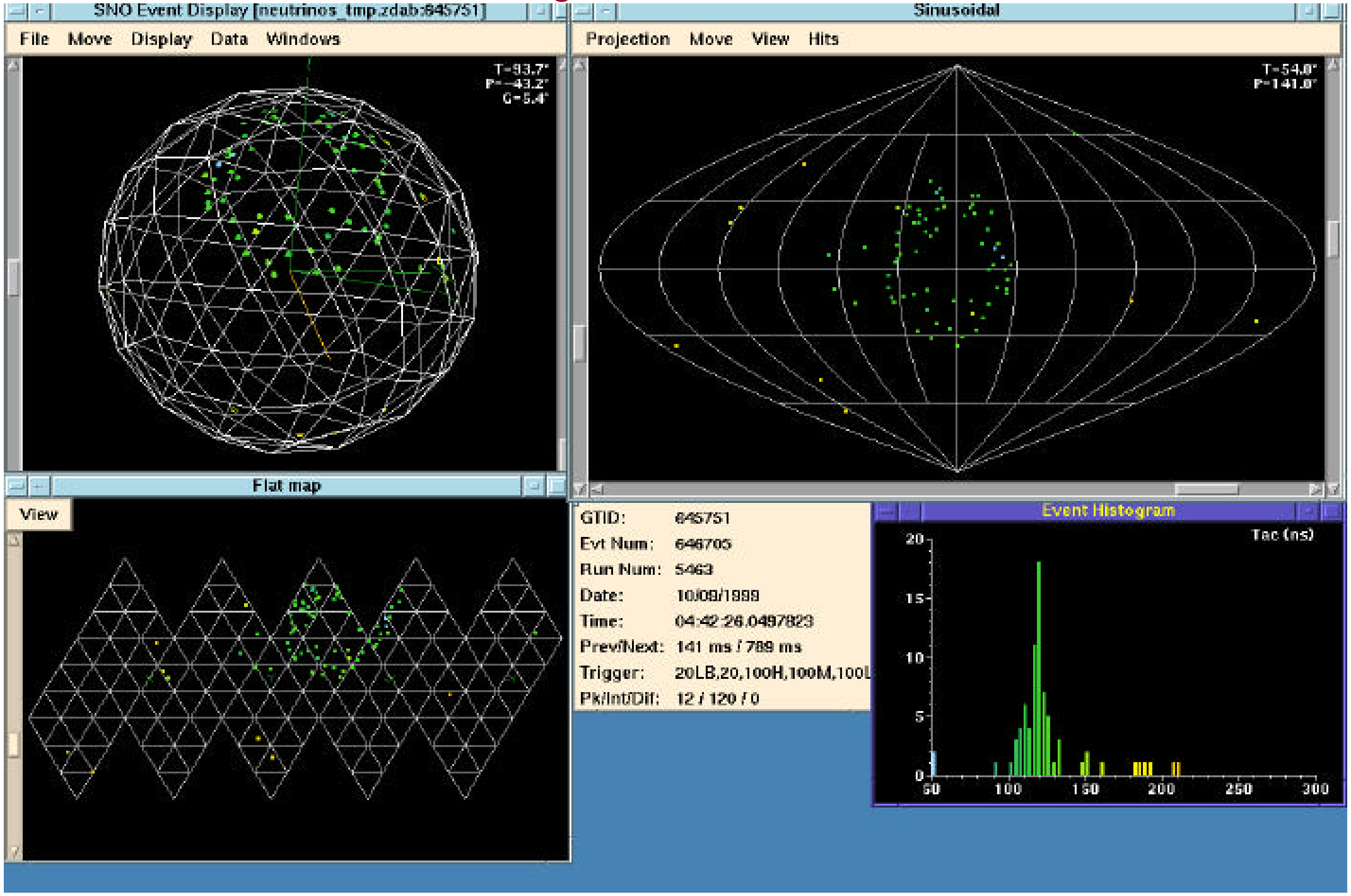


Neutral Current

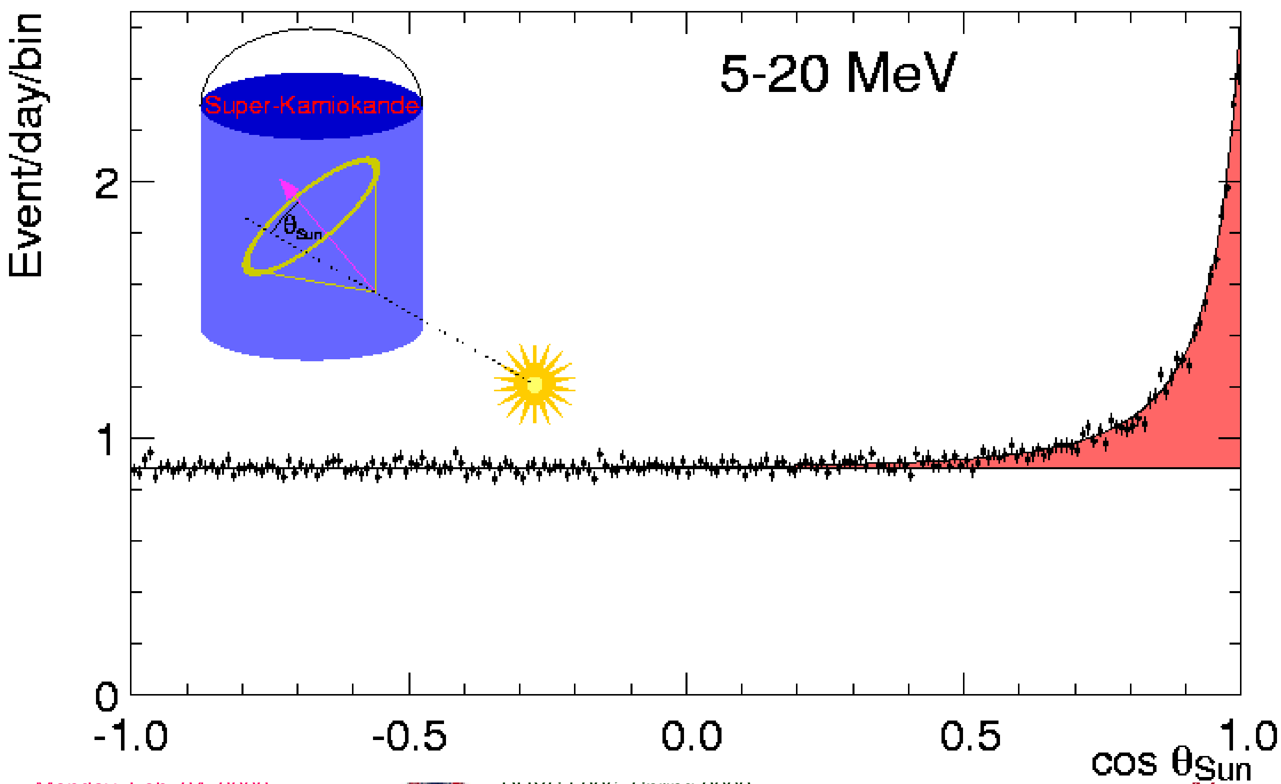




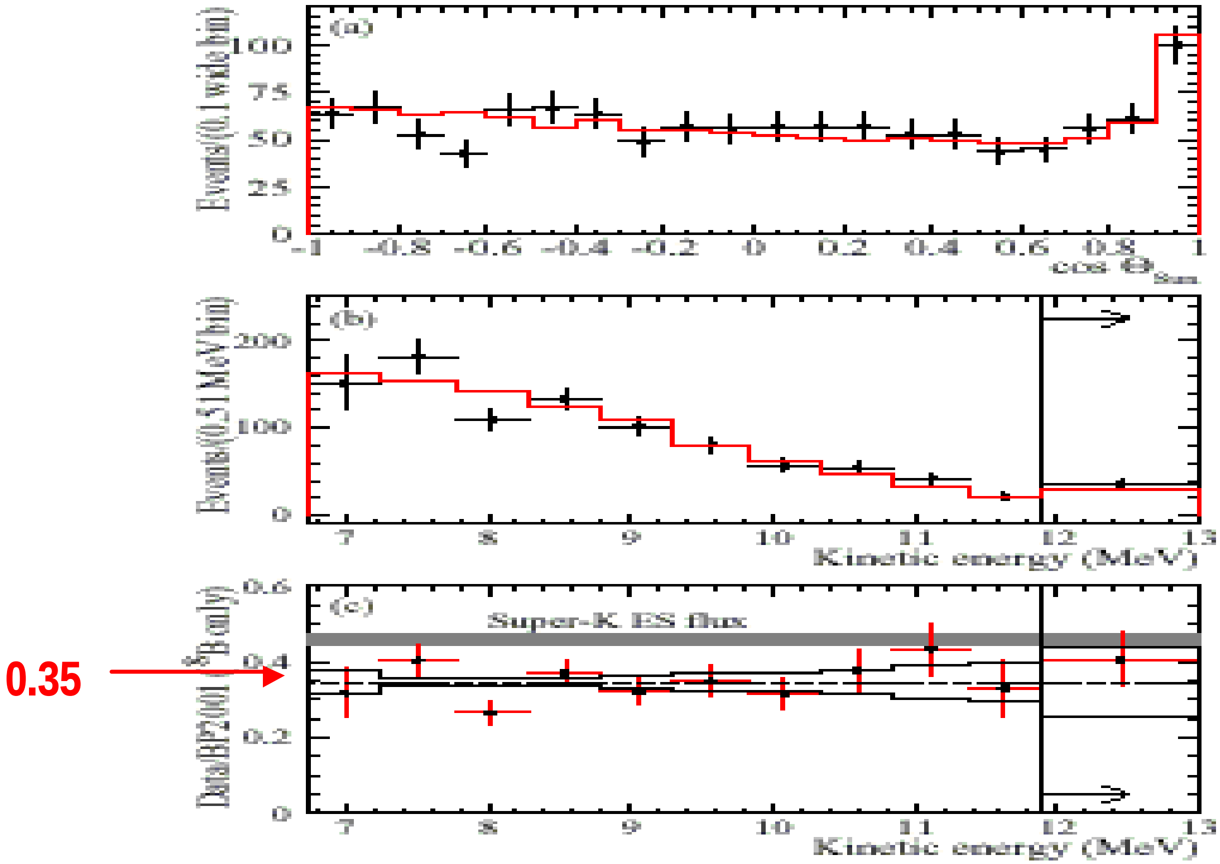
SNO ν_e Event Display



Solar Neutrino Flux



SNO First Results



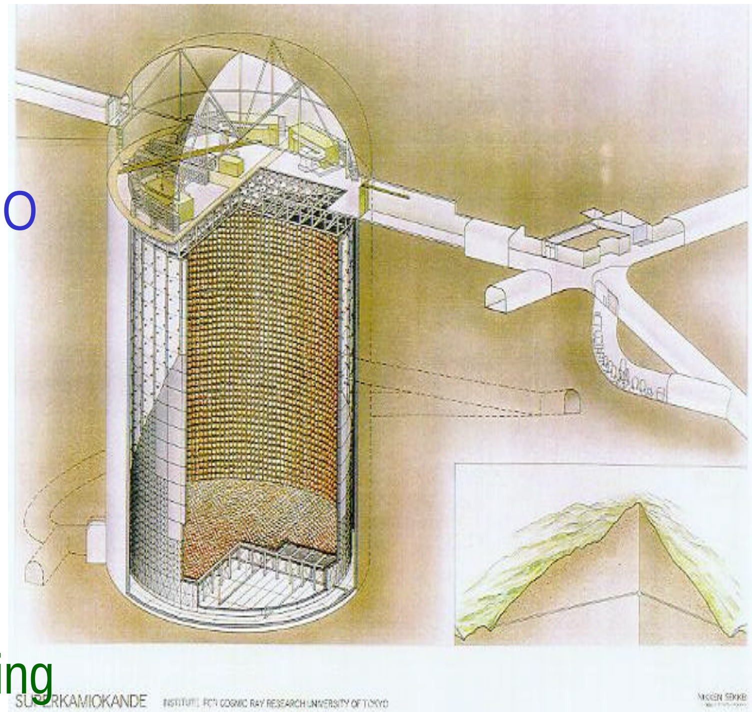
Atmospheric Neutrinos

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - ν_μ to ν_e is about 2 to 1
  - He, p, etc + N $\rightarrow$ π,K, etc
    - $\pi \rightarrow \mu + \nu_\mu$
    - $\mu \rightarrow e + \nu_e + \nu_\mu$
  - This reaction gives 2 ν_μ and 1 ν_e
- Expected flux ratio between ν_μ and ν_e is 2 to 1
- Form a double ratio for the measurement

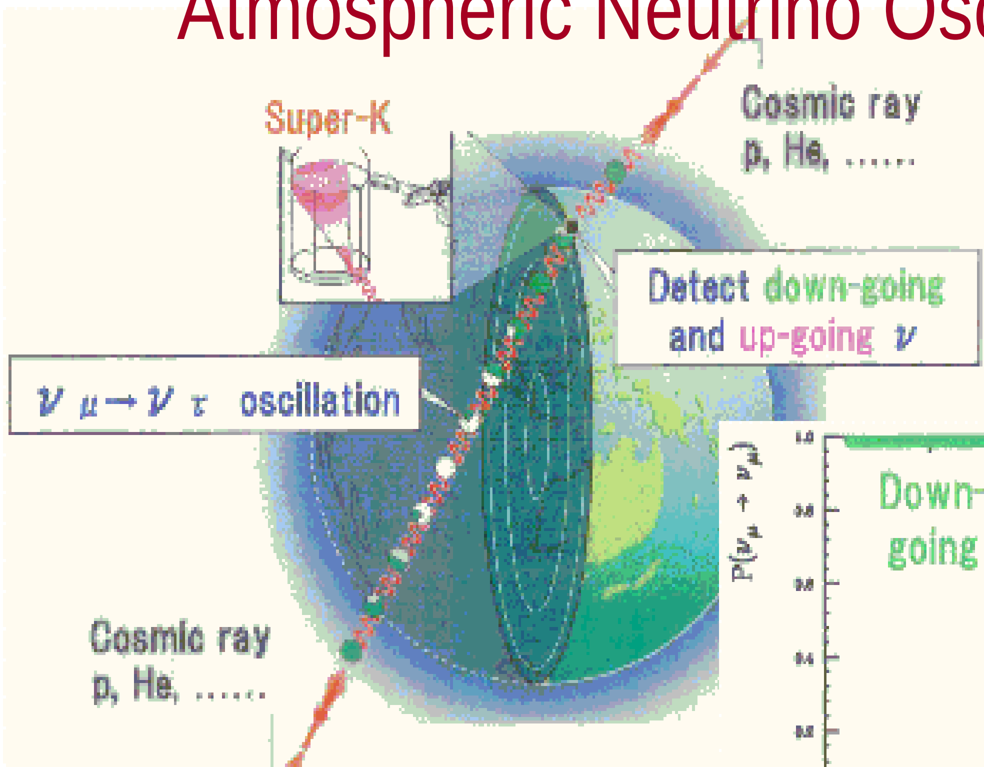
$$R \equiv \frac{\left(N_{\nu_e} / N_{\nu_\mu} \right)^{Exp}}{\left(N_{\nu_e} / N_{\nu_\mu} \right)^{The}}$$

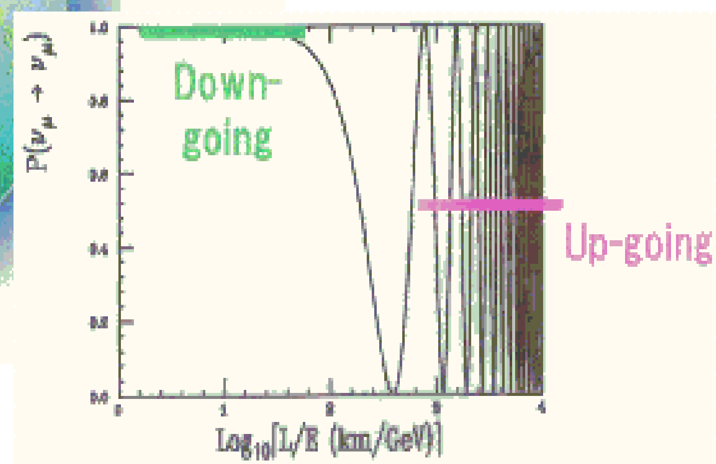
Super Kamiokande

- Kamioka zinc mine, Japan
- 1000m underground
- 40 m (d) x 40m(h) SS
- 50,000 tons of ultra pure H_2O
- 11200(inner)+1800(outer) 50cm PMT's
- Originally for proton decay experiment
- Accident in Nov. 2001, destroyed 7000 PMT's
- Dec. 2002 resume data taking

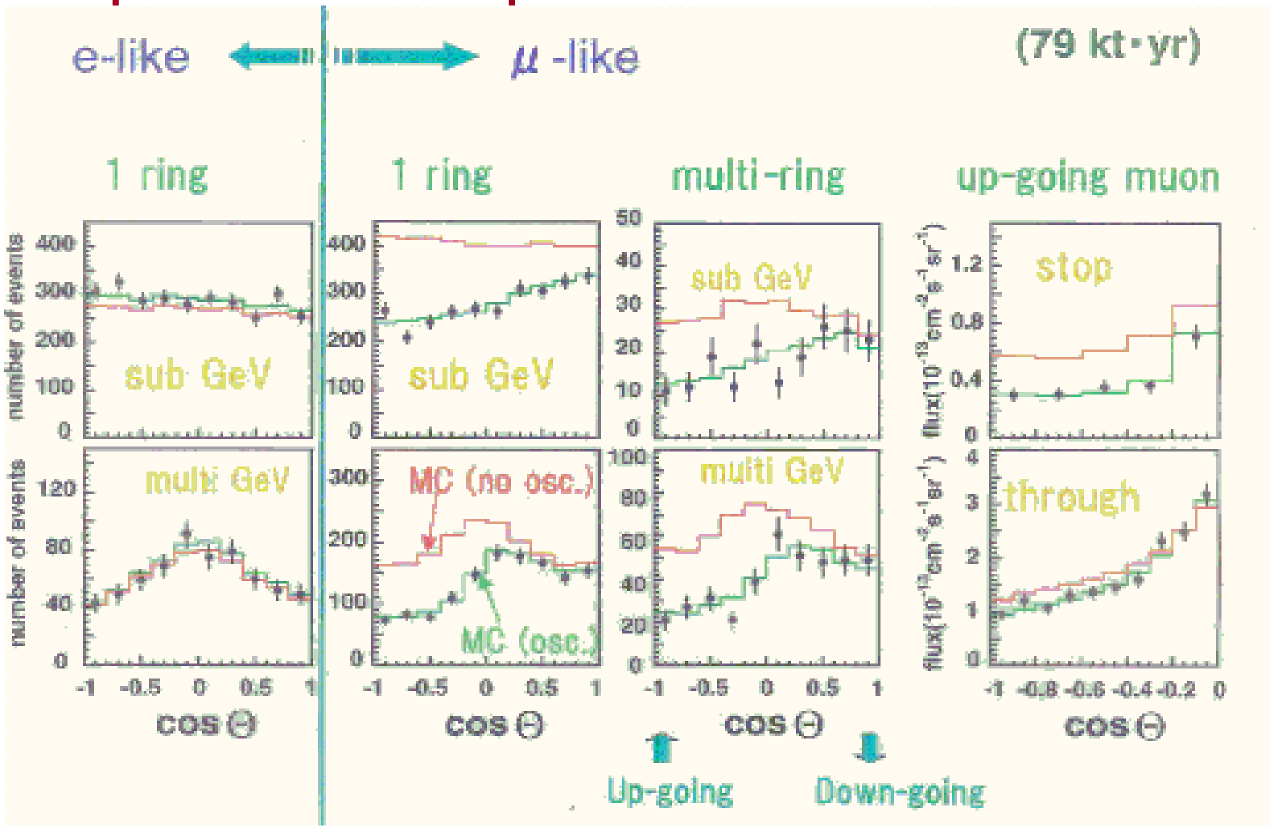


Atmospheric Neutrino Oscillations

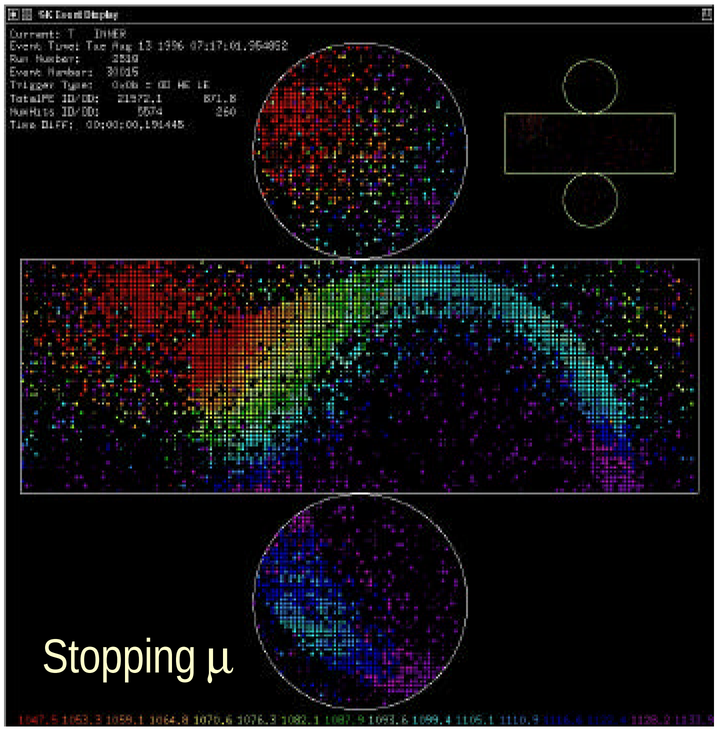


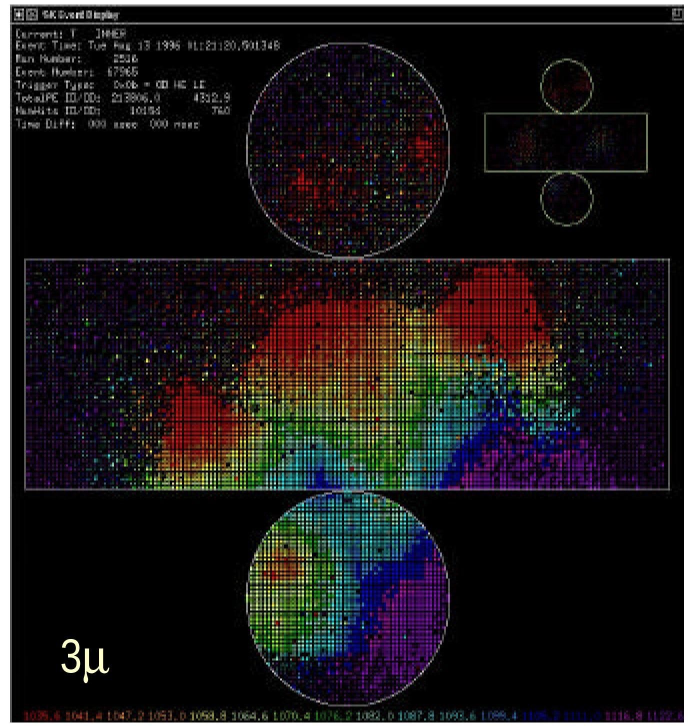


Super-K Atmospheric Neutrino Results

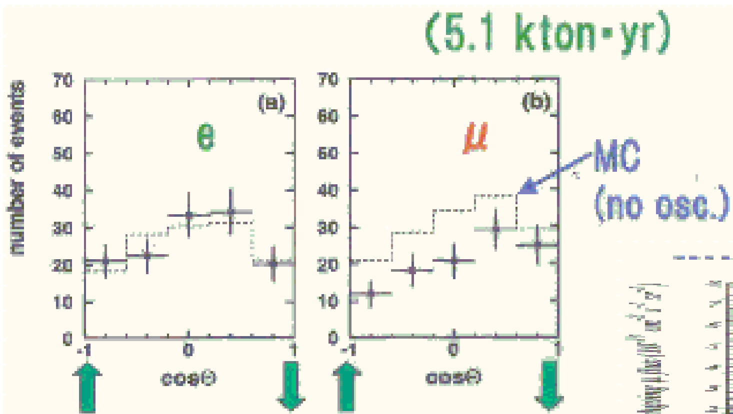


Super-K Event Displays



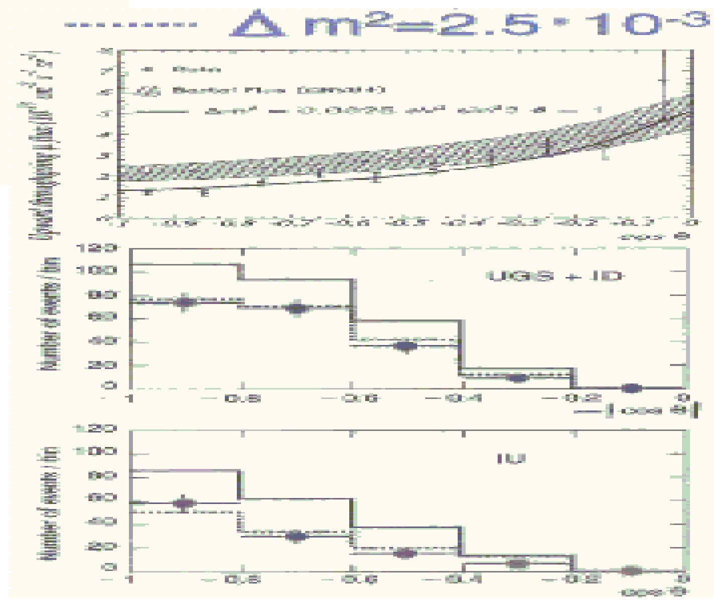


Other Experimental Results



Soudan 2 experiment

Macro experiment



Accelerator Based Experiments

- Mostly ν_μ from accelerators
- Long and Short baseline experiments
  - Long baseline: Detectors located far away from the source, assisted by a similar detector at a very short distance (eg. MINOS: 370km, K2K: 250km, etc)
    - Compare the near detector with the far detector, taking into account angular dispersion
  - Short baseline: Detectors located at a close distance to the source
    - Need to know flux well