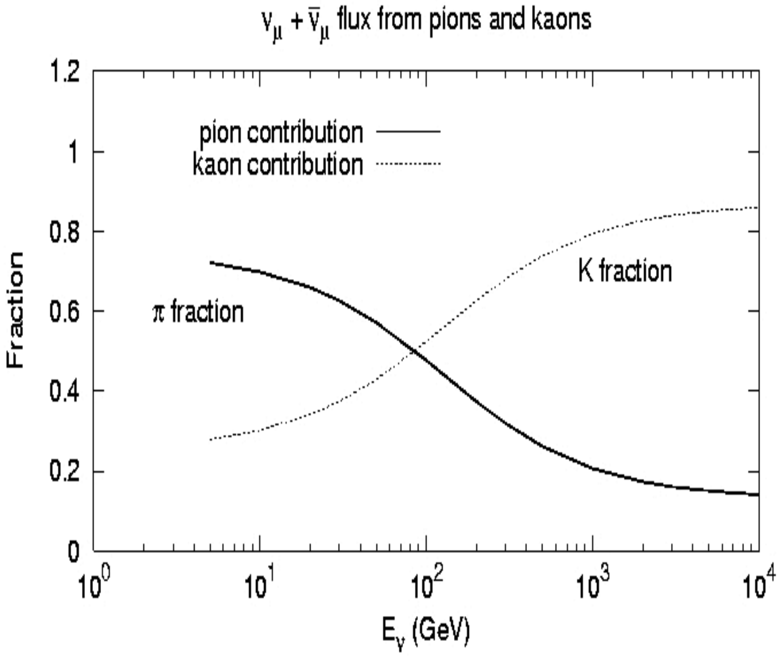
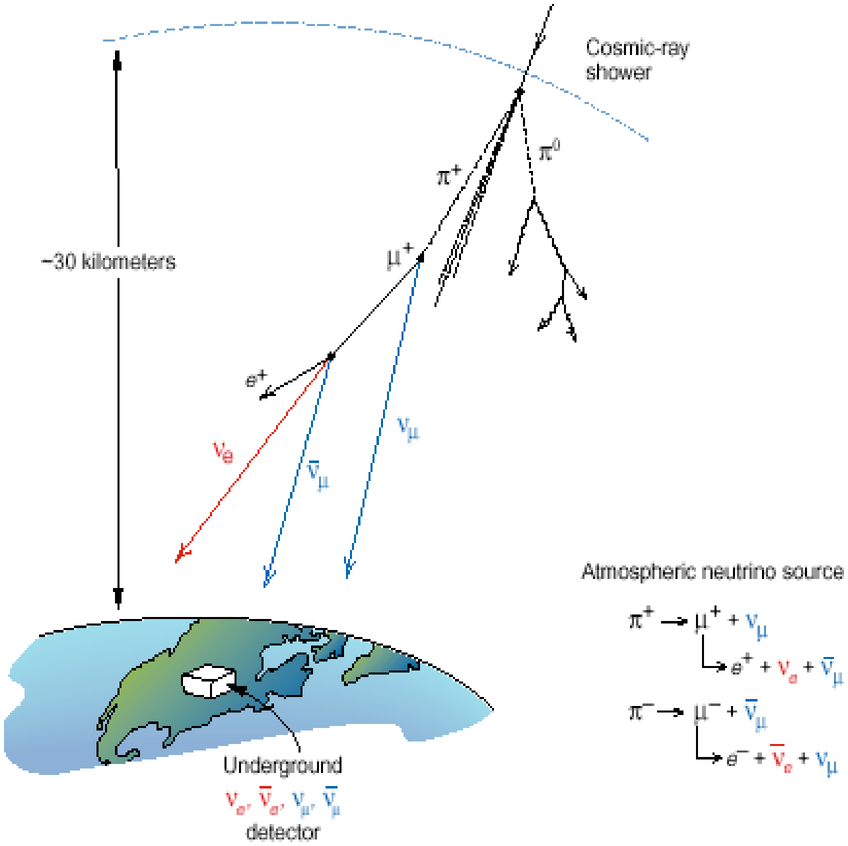
ATMOSPHERIC NEUTRINOS

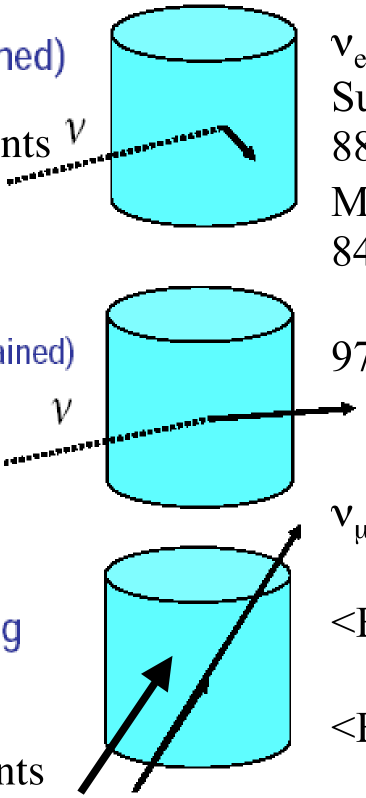
Large uncertainties ~20% on
absolute normalization but useful
well known quantities can be singled out





Atmospheric ν events

$$\overset{(-)}{\nu}_{\mu(e)} + N \rightarrow \mu^{\pm}(e^{\pm}) + X$$



FC
(fully contained)

Volume events

ν_e and ν_μ
Sub-GeV: $E_{vis} < 1.33$ GeV
88% CCν_e 96% CCν_μ
Multi-GeV: $E_{vis} > 1.33$ GeV
84% CCν_e 99% CCν_μ

PC
(partially contained)

97% ν_μ CC $\langle E_\nu \rangle \sim 10$ GeV

Upward going muon

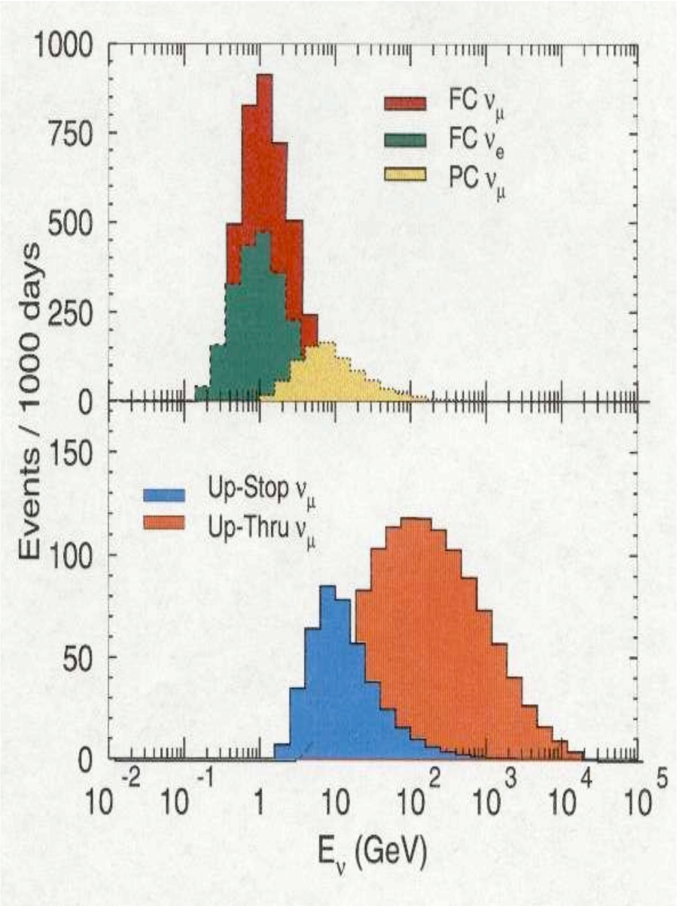
Surface events

ν_μ

$\langle E_\nu \rangle \sim 100$ GeV

$\langle E_\nu \rangle \sim 10$ GeV

Super-Kamiokande response curves

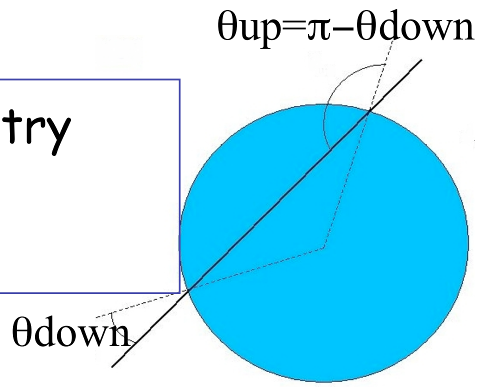


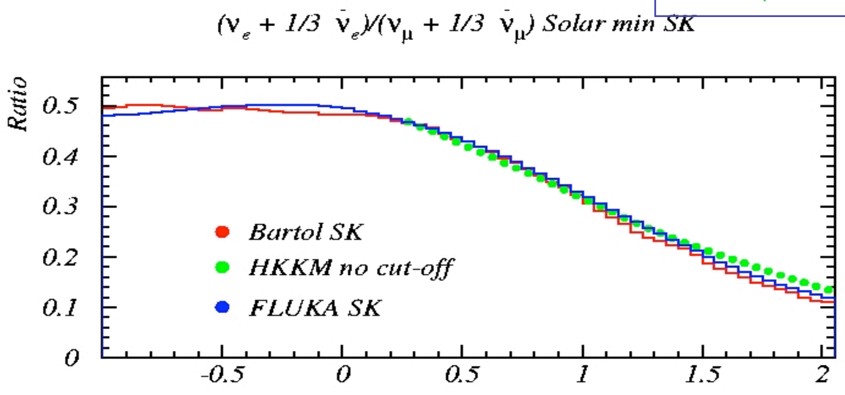
Parameters useful for ν oscillation studies

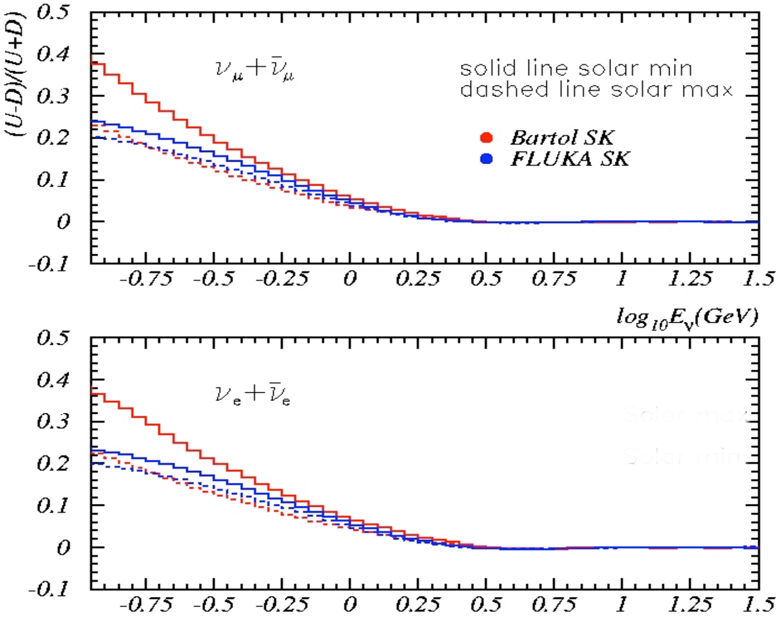
- Flavor ratio **ν_e+1/3anti-ν_e/ν_μ+1/3anti-ν_μ** For Eν < 30 GeV ~5%
- Up/down asymmetry
- Full angular distribution

From full simulations:

Earth spherical symmetry
+CR flux isotropy
$\Phi(E_\nu,\theta) = \Phi(E_\nu,\pi-\theta)$







Shape of the angular distribution of HE neutrinos

Uncertainties:

1) $\delta(V/H)/(V/H) \sim 0.12\ \delta(K/\pi)/(K/\pi)$

$L_{dec} \sim 0.75\ (E(GeV)/100)$ km (K)

$L_{dec} \sim 5.6\ (E(GeV)/100)$ km (π)

almost all K decay up to high energies (> 100 GeV) almost isotropic

competition of interaction/decay for $\pi^{\pm}$: decay more easily at horizon for increasing energy ⇒horizontal > vertical flux.

Flux from Kaons isotropic up to energies higher than pions

2) $\delta(V/H)/(V/H) \sim 0.25\ \delta\alpha$

uncertainty in the slope of primary flux

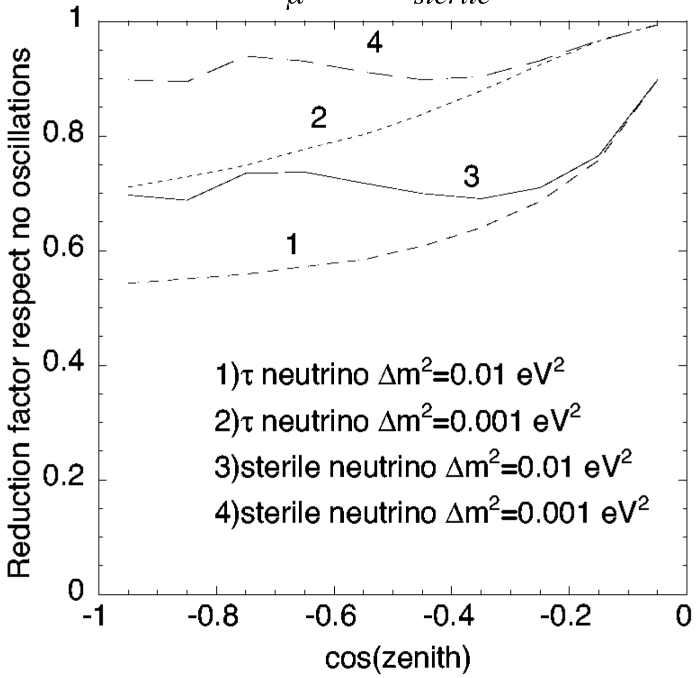
3) Seasonal variations

In quadrature: ~3% error on V/H

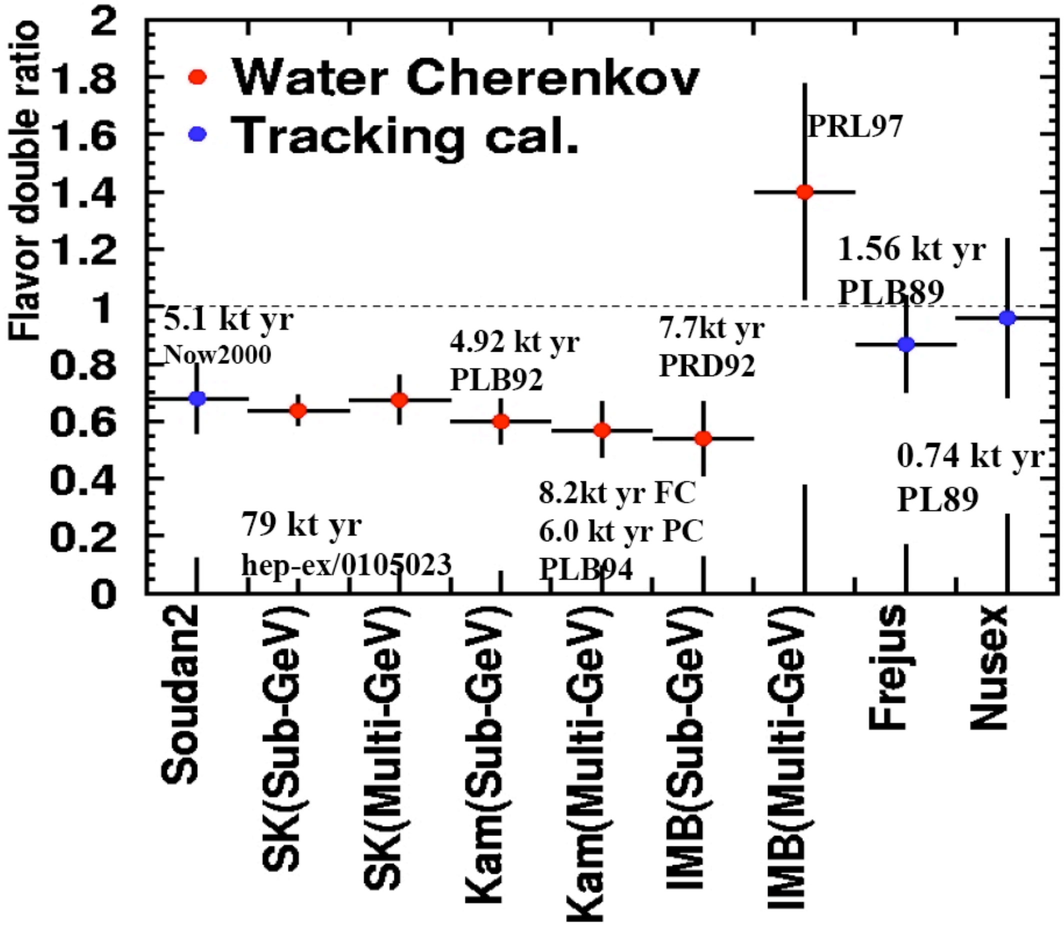
Useful for channel determination

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\mu \rightarrow \nu_{sterile}$$



The atmospheric ν problem: measured flavor ratio



Flavor ratio:

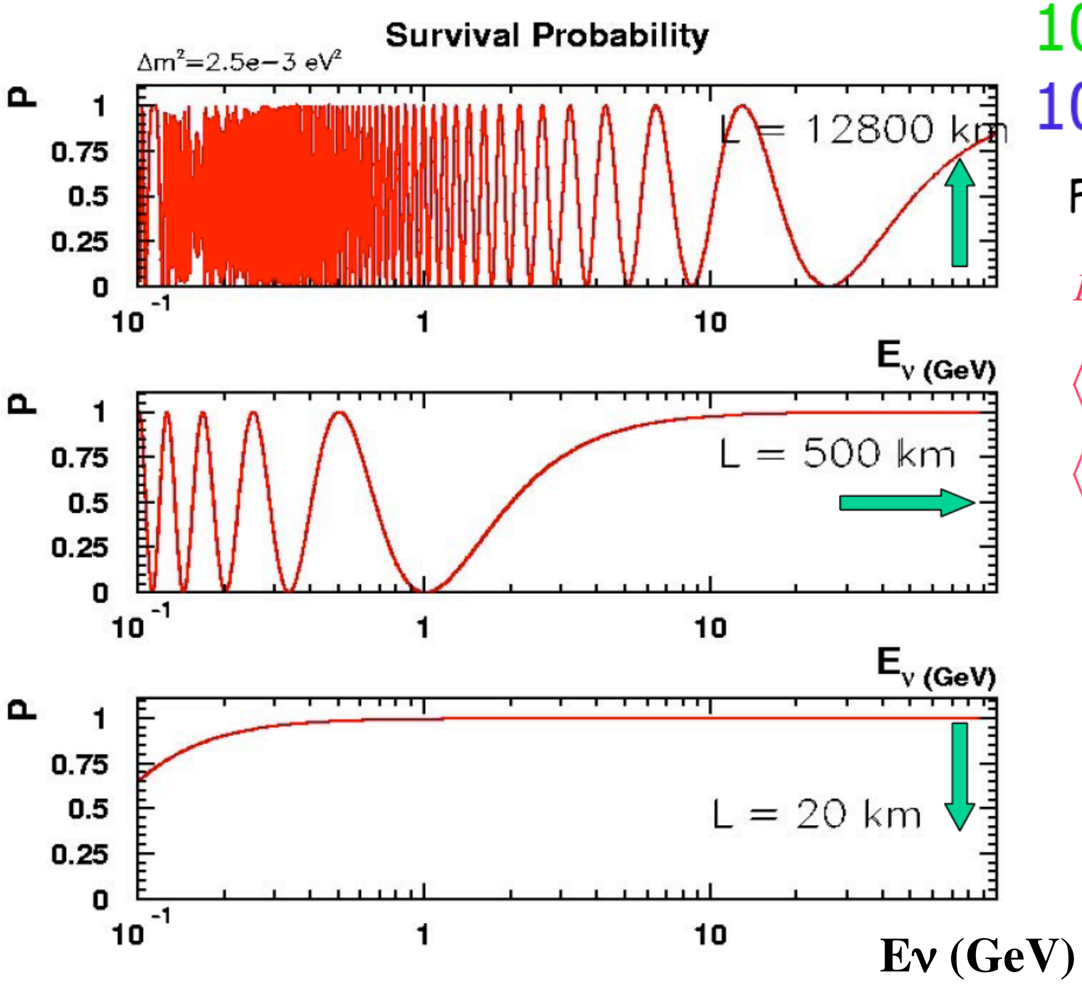
$$R = \frac{\left(\frac{\mu - like}{e - like}\right)_{DATA}}{\left(\frac{\mu - like}{e - like}\right)_{MC}}$$

μ-like (tracks): deficit

e-like (showers): in agreement with expected

Kamiokande Multi-GeV: flavor ratio angular dependence as expected from oscillations

Oscillations in Atmospheric Neutrinos



$100\ \text{MeV} \lesssim E\nu \lesssim 10\ \text{TeV}$

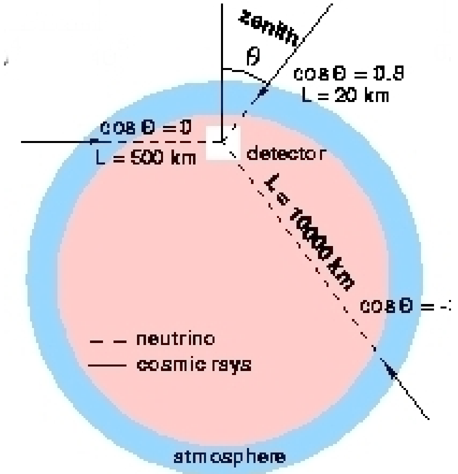
$10\ \text{km} \lesssim L \lesssim 10^4\ \text{km}$

For Sub-GeV and Multi-GeV

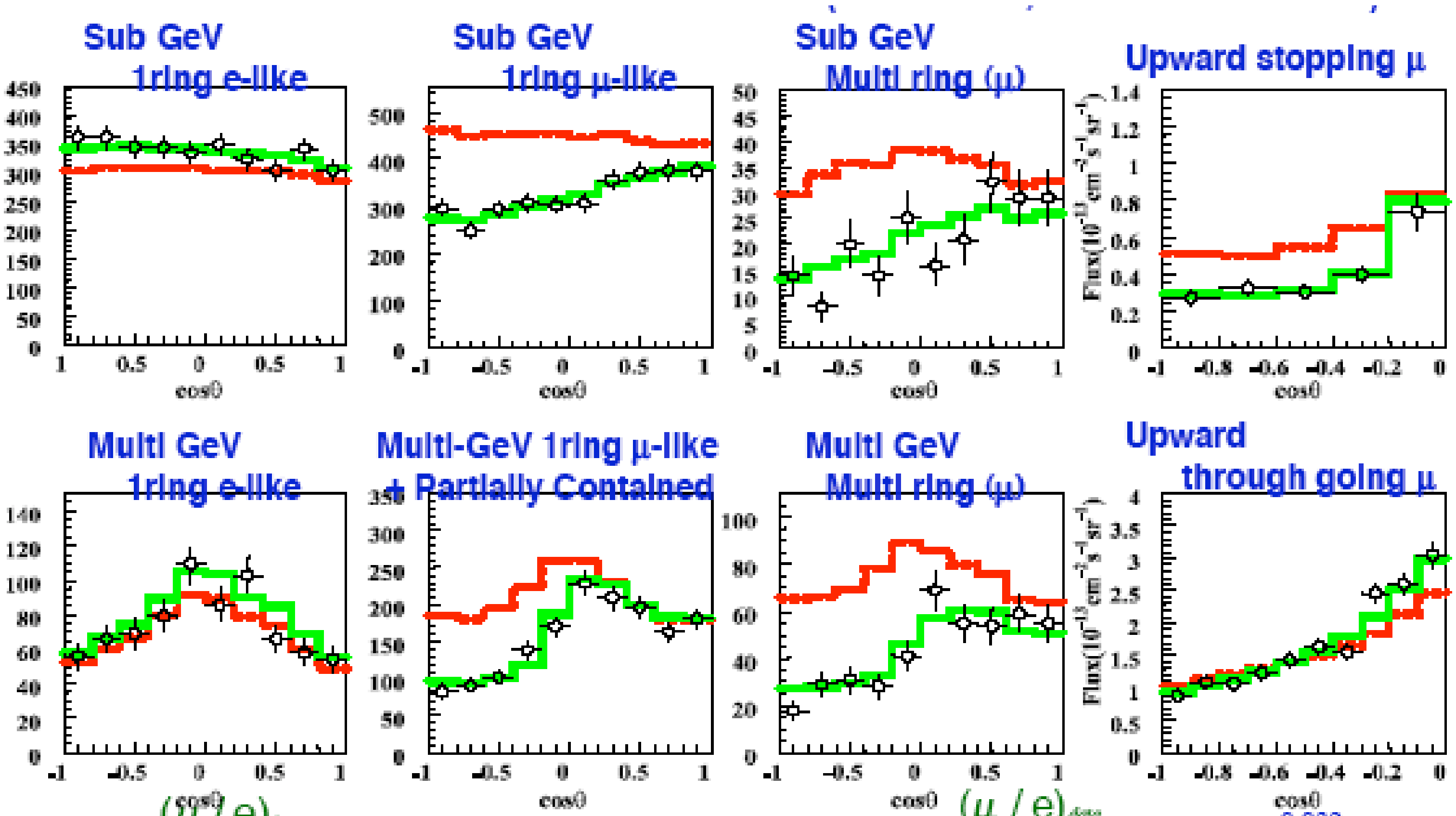
$$P(\nu_\ell \to \nu_\ell) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\langle P(L \le 100\ km)\rangle \to 1$$

$$\langle P(L \ge 2000\ km)\rangle \to 1 - \frac{\sin^2 2\theta}{2} \Rightarrow \frac{1}{2}$$



SK results



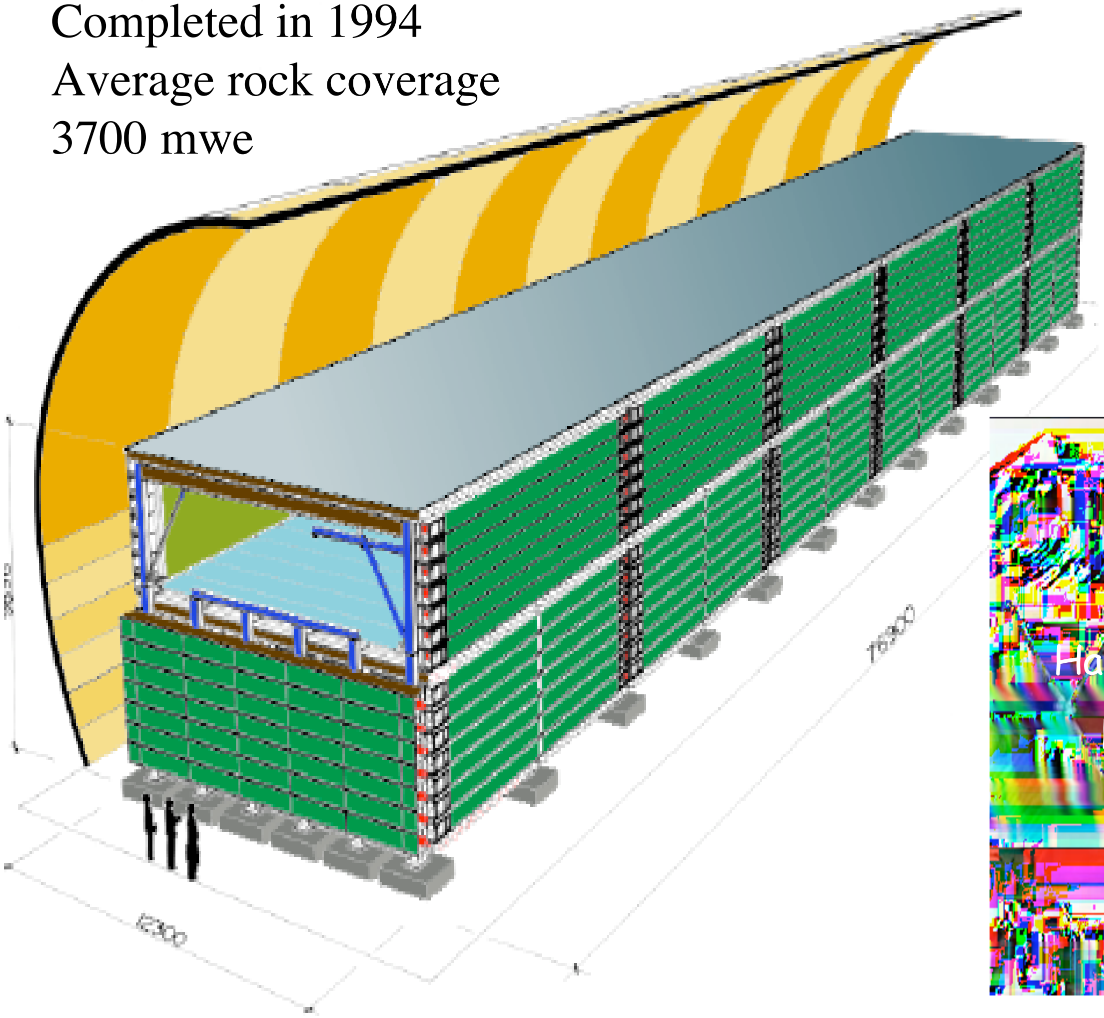
Sub-GeV $\frac{(\mu / e)_{data}}{(\mu / e)_{MC}} = 0.649 \pm 0.016 \pm 0.051$

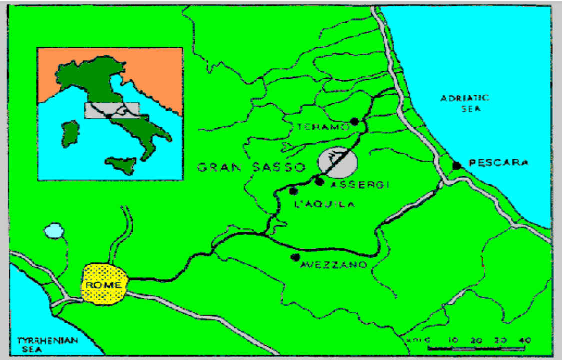
Multi GeV+PC $\frac{(\mu / e)_{data}}{(\mu / e)_{MC}} = 0.699 \pm^{0.032}_{0.030} \pm 0.08$

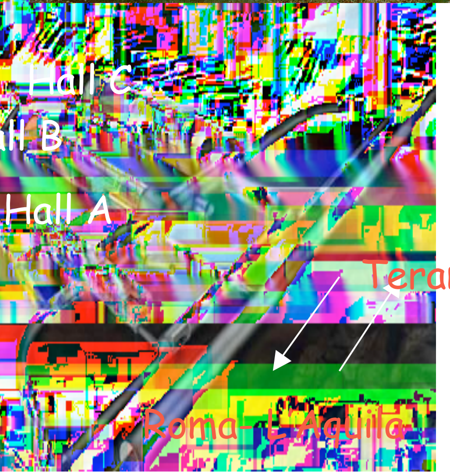
Observed $A_{\mu\text{-like}}$ 9.5σ from no-oscillation prediction!

MACRO at Laboratori Nazionali del Gran Sasso

77 x 12.3 x 9 m^3
Run time: 1989-2000
Completed in 1994
Average rock coverage
3700 mwe





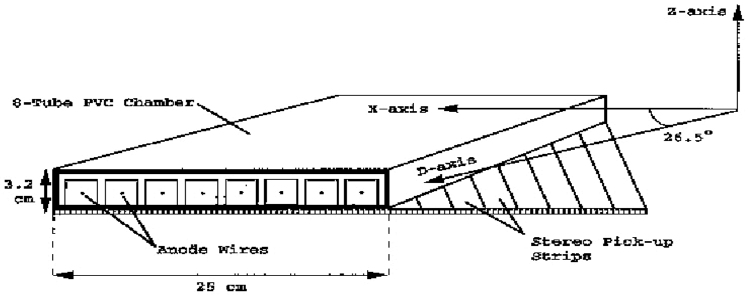


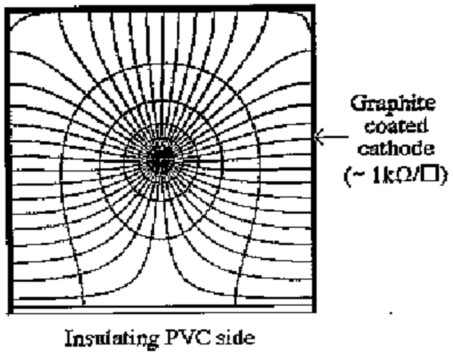
11 km-long highway tunnels

Tracking with Streamer Tubes

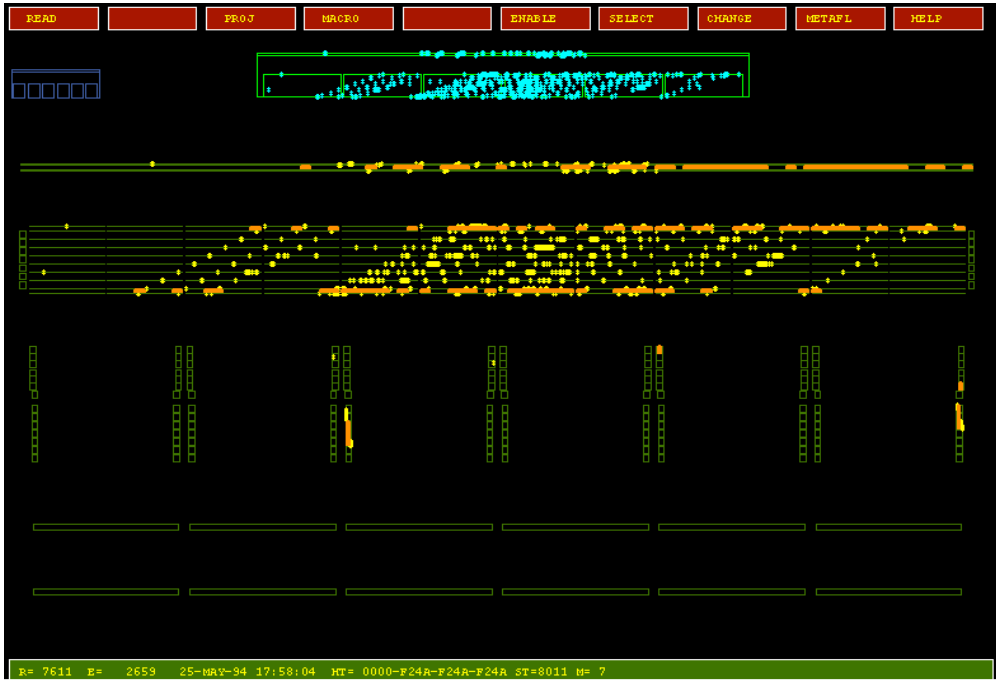
Streamer tube chambers:

- 20000 m^2 of 3x3 cm^2 x 12 m cells with 100μm Cu-Be wire
- Gas mixture: He + n-pentane (27%)
- Pick-up strips for stereo track reconstruction
- Intrinsic angular resolution ~0.2°



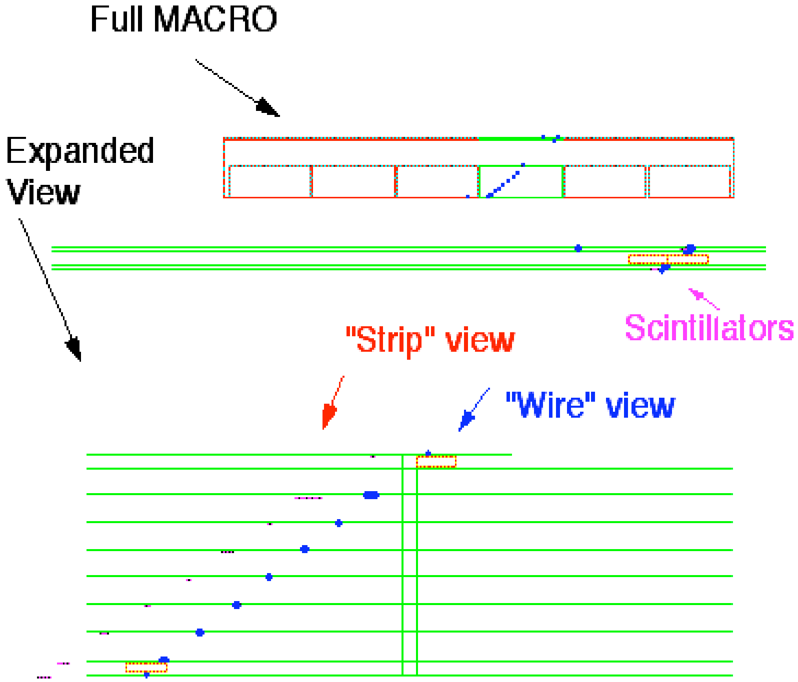


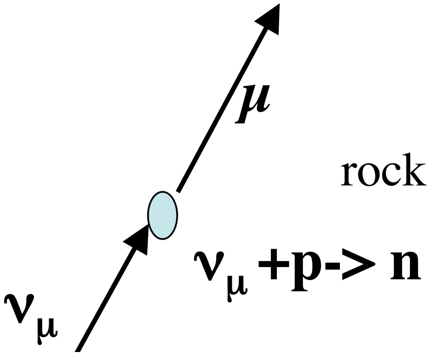
Field configuration



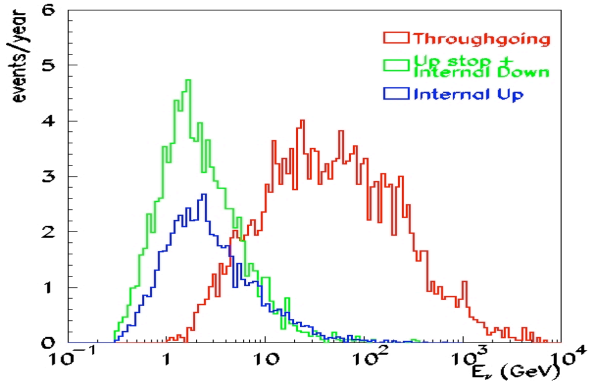
```
R= 7611  E=    2659   25-MAY-94 17:58:04  HT= 0000-F24A-F24A-F24A ST=8011 M= 7
```

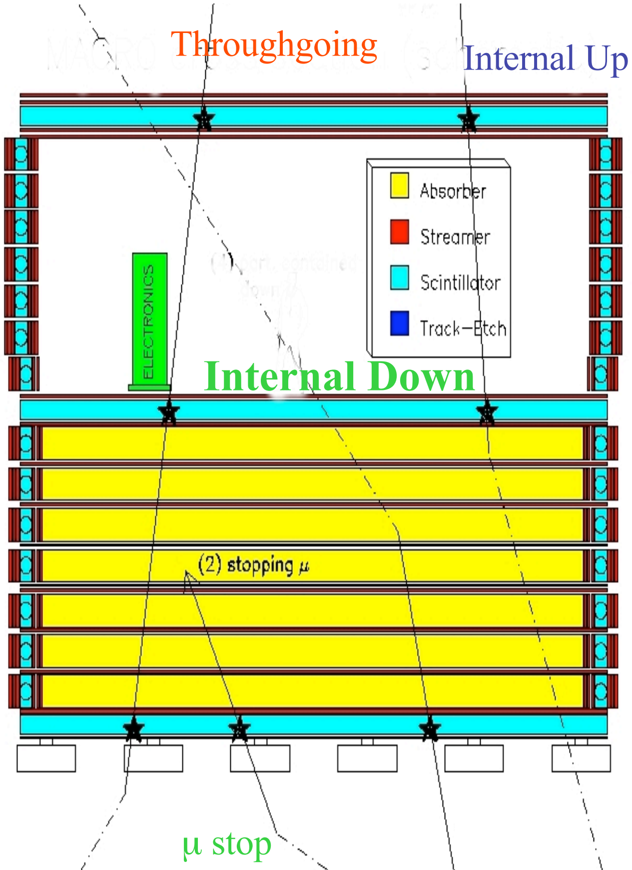
Neutrino events





$\nu_\mu + p \to n + \mu^+$



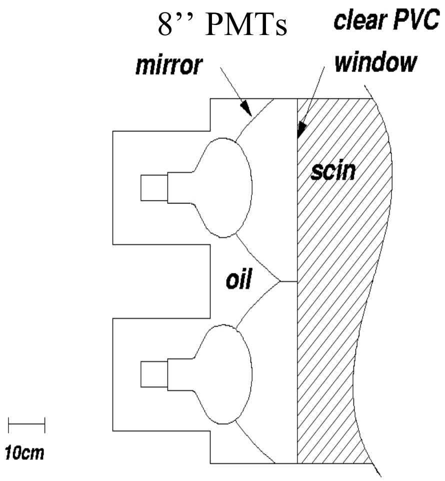


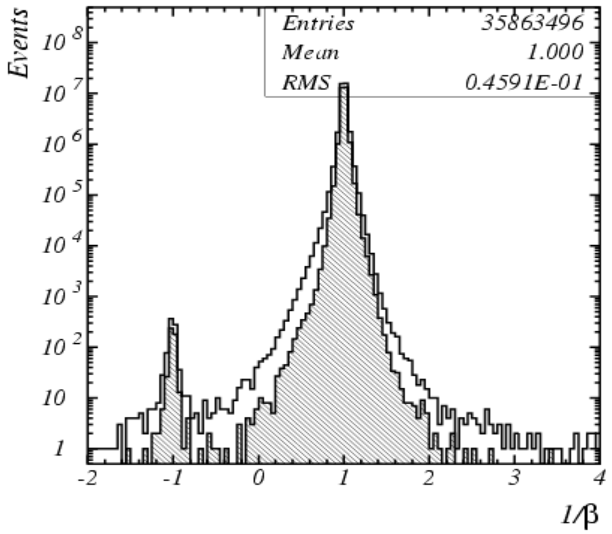
Detector mass ~ 5.3 kton

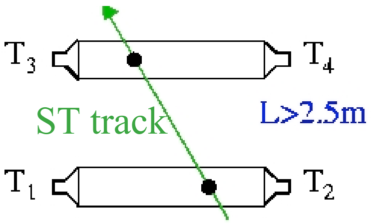
Time Of Flight technique

Scintillators:

- 600 tons of liquid scintillator (mineral oil+ pseudocumene+ wls) in 12 m-long boxes;
- time resolution ~700 ps;
- calibration tools: atmospheric μs, Light Emitting Diodes, laser light;
- 200 MHz Wave Form Digitizers for pulse shape analysis;

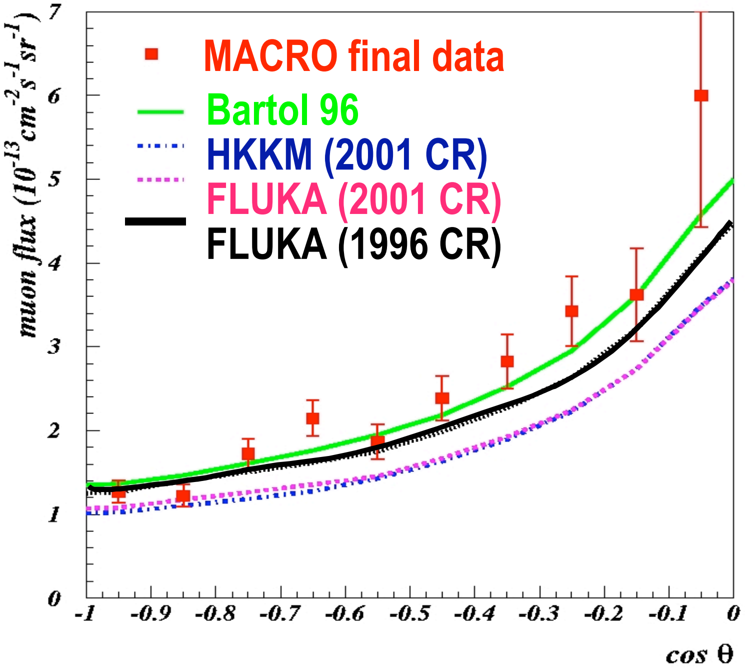


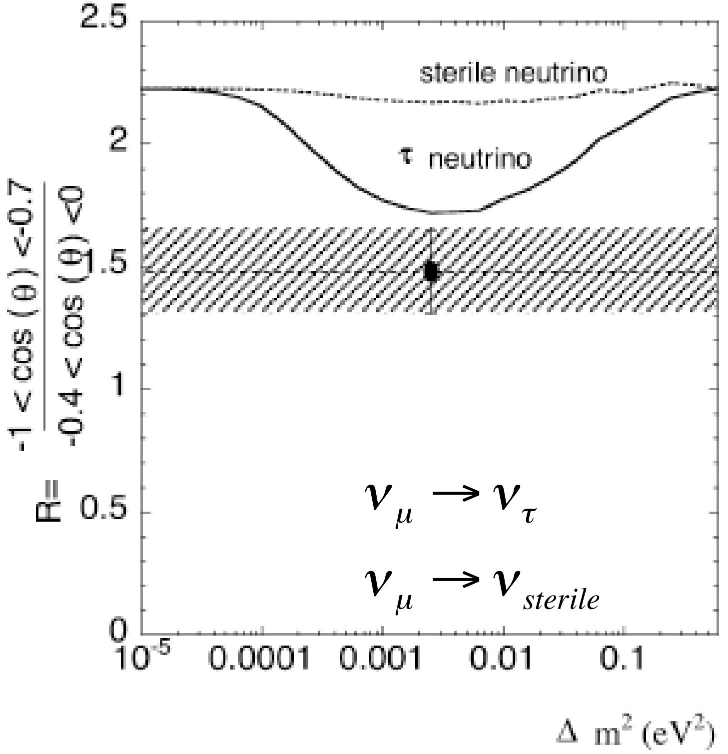




$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu\downarrow \\ -1 & \mu\uparrow \end{cases}$$

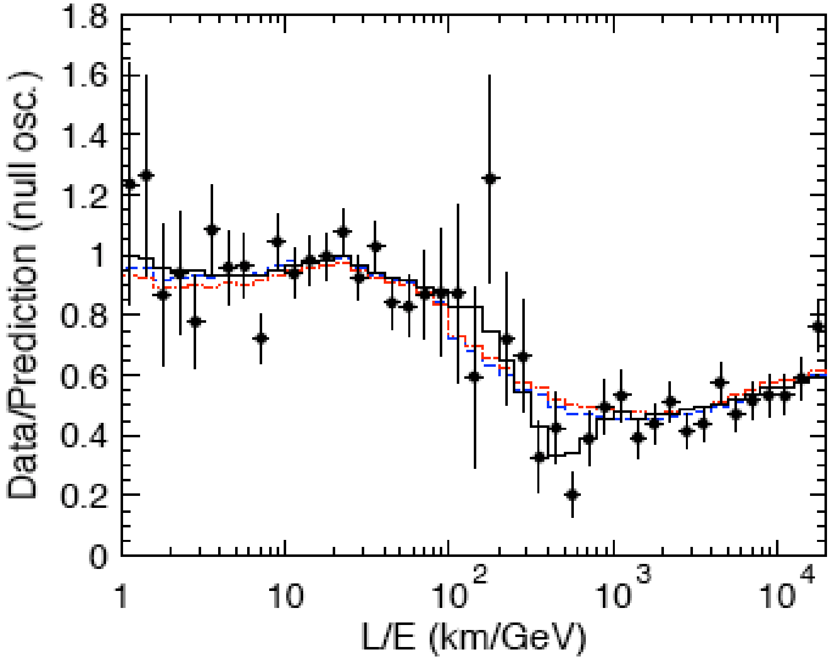
Through going muons





Similar results for
SK

The oscillation pattern



The binning choise is critical

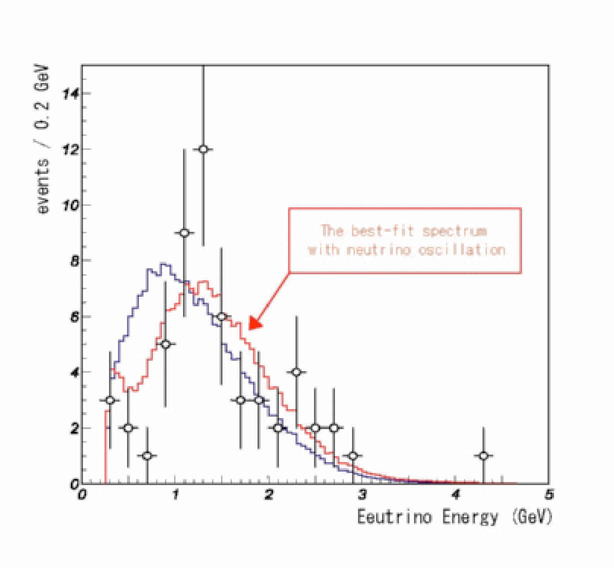
SK ν_μ compared to predictions for oscillations

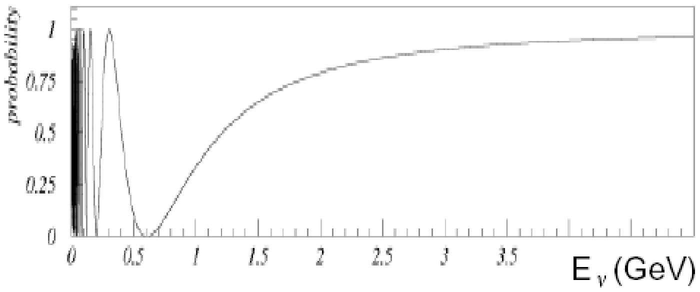
νdecay and decoherence

Hep-ex/0404034

K2K

KEK to Kamioka (L = 250 km): ν beam from 12 GeV protons accelerated by the KEK proton synchrotron on alluminium target
98% pure muon neutrinos with mean energy 1.3 GeV



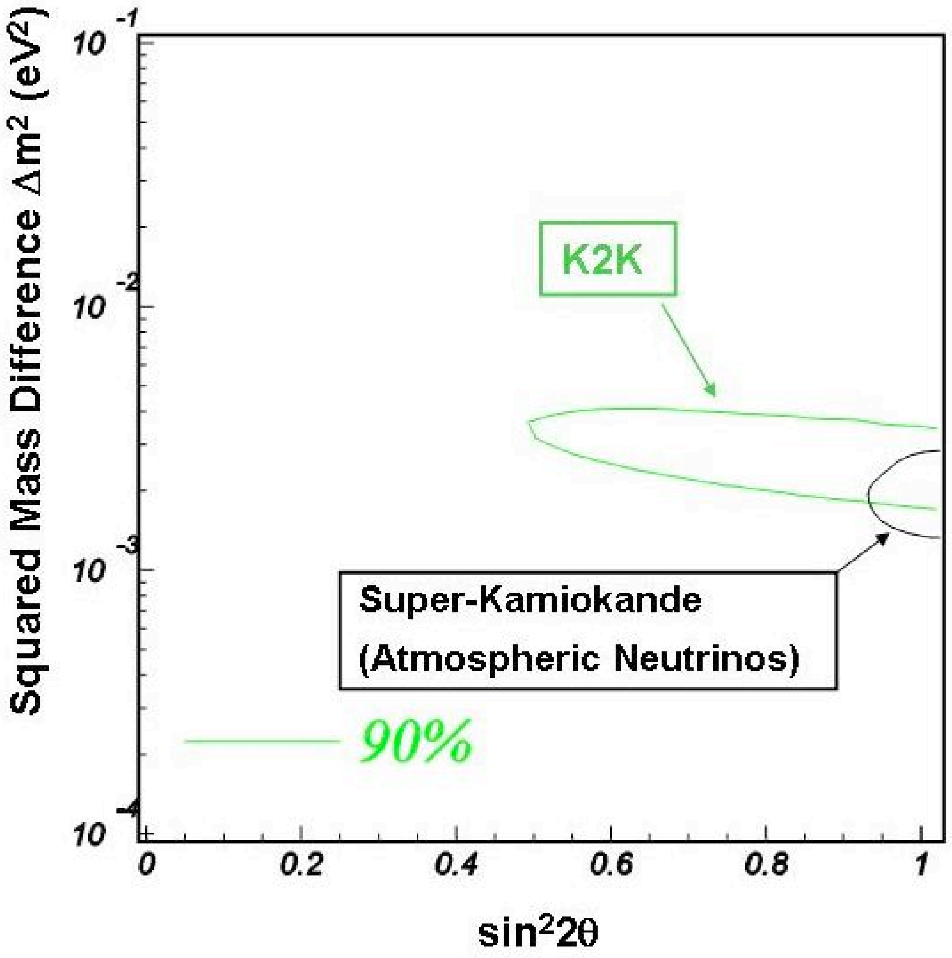


Neutrino oscillation probability for $\Delta m^2=0.003eV^2$ and at 250km.

First results: PRL 90 (2003)041801 (data from Jun 1999-Jul 2001 4.8 10^{19} P.O.T.)
Events in SK in time coincidence inside 1.5 μs (reduce atm ν background in 22.5 kton SK fiducial volume to 10^{-3})
Measured: 56 (Expected: $80.1^{+6.2}_{-5.4}$) and in Feb 2004 108 measured 150.9 ±11 predicted

Observables to infer oscillations: energy spectrum and normalization

Atmospheric neutrino results



Results for atmospheric neutrinos

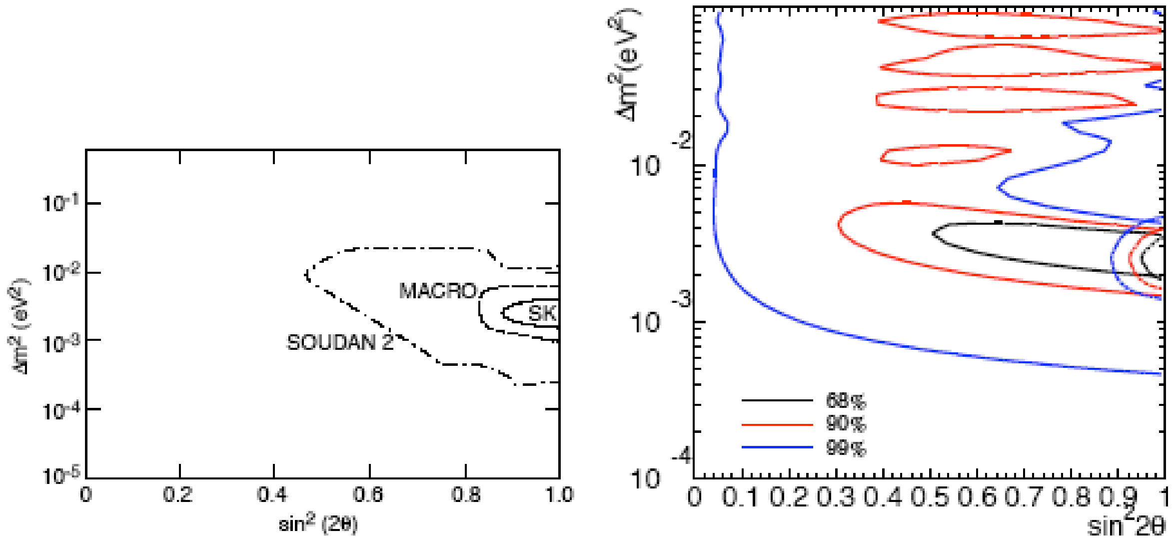


Figure 7: Left: 90% C.L. allowed region contours for $\nu_\mu \to \nu_\tau$ oscillations obtained by the Super-Kamiokande, MACRO and Soudan-2 experiments [29]. Right: Allowed region contours for ν_μ disappearance obtained in the K2K experiment confronted with the allowed regions for $\nu_\mu \to \nu_\tau$ oscillations obtained in the Super-Kamiokande experiment [151].

Astrophysical Neutrino Oscillations

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

If $\theta_{13} = 0 \Rightarrow c_{13} = 1$ and $s_{13} = 0$ and $\delta = 0$ and for normal hierarchy

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}s_{23} & c_{23} \end{pmatrix} = \begin{pmatrix} c_{sol} & s_{sol} & 0 \\ -s_{sol}c_{atm} & c_{sol}c_{atm} & s_{atm} \\ s_{sol}s_{atm} & -c_{sol}s_{atm} & c_{atm} \end{pmatrix}$$

$$\theta_{12} \approx 35\deg \Rightarrow c_{sol} = 0.82 \text{ and } s_{sol} = 0.57$$

$$\theta_{23} \approx 45\deg \Rightarrow s_{atm} = c_{atm} = 1$$

$$U = \begin{pmatrix} c & s & 0 \\ -sx & cx & x \\ sx & -cx & x \end{pmatrix} = \begin{pmatrix} 0.82 & 0.57 & 0 \\ -0.4 & 0.58 & 1/\sqrt{2} \\ 0.4 & -0.58 & 1/\sqrt{2} \end{pmatrix}$$

Astrophysical Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha,i} U^*_{\beta,i} U^*_{\alpha,j} U_{\beta,j} e^{-i\Delta m^2_{i,j} L/2E}$$

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

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

If CP is conserved ($\delta = 0$) this expression can be written as (U is a real matrix):

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2 + 2 \sum_{i<j} U_{\alpha,i} U_{\beta,i} U_{\alpha,j} U_{\beta,j} \cos\left(\frac{\Delta \mathrm{m}^2_{ij} L}{2\mathrm{E}}\right).$$

For astrophysical sources L>kpc and Δm^2 L/2E » 1.
Let's give a typical number to the phase factor for a source at a distance of 1 kpc emitting neutrinos of 10 TeV:

$$\varphi = \frac{1.27 L(km) \Delta m^2_{12} (eV^2)}{E(GeV)} \approx \frac{1.27 \cdot 3.1 \cdot 10^{16} \cdot 8 \cdot 10^{-5}}{10^4} \approx 3 \cdot 10^8$$

$$\varphi \sim 3 \cdot 10^8 \left(\frac{\Delta m^2}{8 \cdot 10^{-5}\ \mathrm{eV}^2}\right) \left(\frac{D}{1\ \mathrm{kpc}}\right) \left(\frac{10\ \mathrm{TeV}}{E_\nu}\right)$$

⇨ Let us assume that an experiment measures the events in a small energy bin so that we can consider approximately constant the energy E, then the oscillating term is given by const x cosL, so the term averages to zero. As a matter of fact, his value means that if the distance of the source (or eventually the energy) of the emitted neutrinos is not known with a precision of 10^8 the oscillating term averages to zero. Since sources have extensions of about 1 pc and their distance is > 1 kpc their distance are known with precision 1/1000!! Also the energy is about 30% uncertain.

Astrophysical Neutrino Oscillations

Hence for astrophysical sources L>kpc: the uncertainties on distances to sources and on their dimensions eliminate the effect of the phase term.

⇨ $$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

Eg.

$$P(\nu_e \to \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \to \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 + |U_{e3}|^2 |U_{\mu 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \to \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 + |U_{e3}|^2 |U_{\tau 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

Astrophysical Neutrino Oscillations

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

So for $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$: for ν_e 60% comes from ν_e survival and 2*20% from 2 ν_μ conversion =>100%. For 2 ν_μ 2*40% =80% comes from ν_μ survival, then 20% from ν_e that become ν_μ => 100%

ν_τ will appear after 20% of ν_e + 2*40% of ν_μ = 100%

For n decay $n \rightarrow p + e^- + \bar{\nu}_e$ from the Galactic Centre at L~10 kpc anti-electron neutrinos convert according the same matrix into 20% muon neutrinos and 20% tau neutrinos. And 60% electron neutrinos will remain such.

Suggested Readings

- Textbooks

Halzen and Martin, Quarks and Leptons, An Introductory Course to Modern Physics, Wiley 1984

B.R. Martin and G. Shaw, Particle Physics, Manchester Physics Series (1987)

Perkins, Introduction to High Energy Physics, Addison-Wesley, 1987

L. Bergstrom and A. Goobar, Cosmology and Particle Astrophysics (2nd edition), Springer 2004 cap 6

Neutrino people do not miss

http://www.nu.to.infn.it/

http://www.nu.to.infn.it/pap/0310238/ (neutrino mixing)

Feldamn and Cousins, Unified approach to the classical statistical

analysis of small signals, Phys. Rev. D 57 (1998) 3873

http://prola.aps.org/abstract/PRD/v57/i7/p3873_1

http://pdg.lbl.gov/2005/reviews/solarnu_s005313.pdf (solar neutrinos)