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ICTP 40th Anniversary

H4.SMR/1574-27

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Atmospheric Neutrino Oscillations

Giorgio Giacomelli

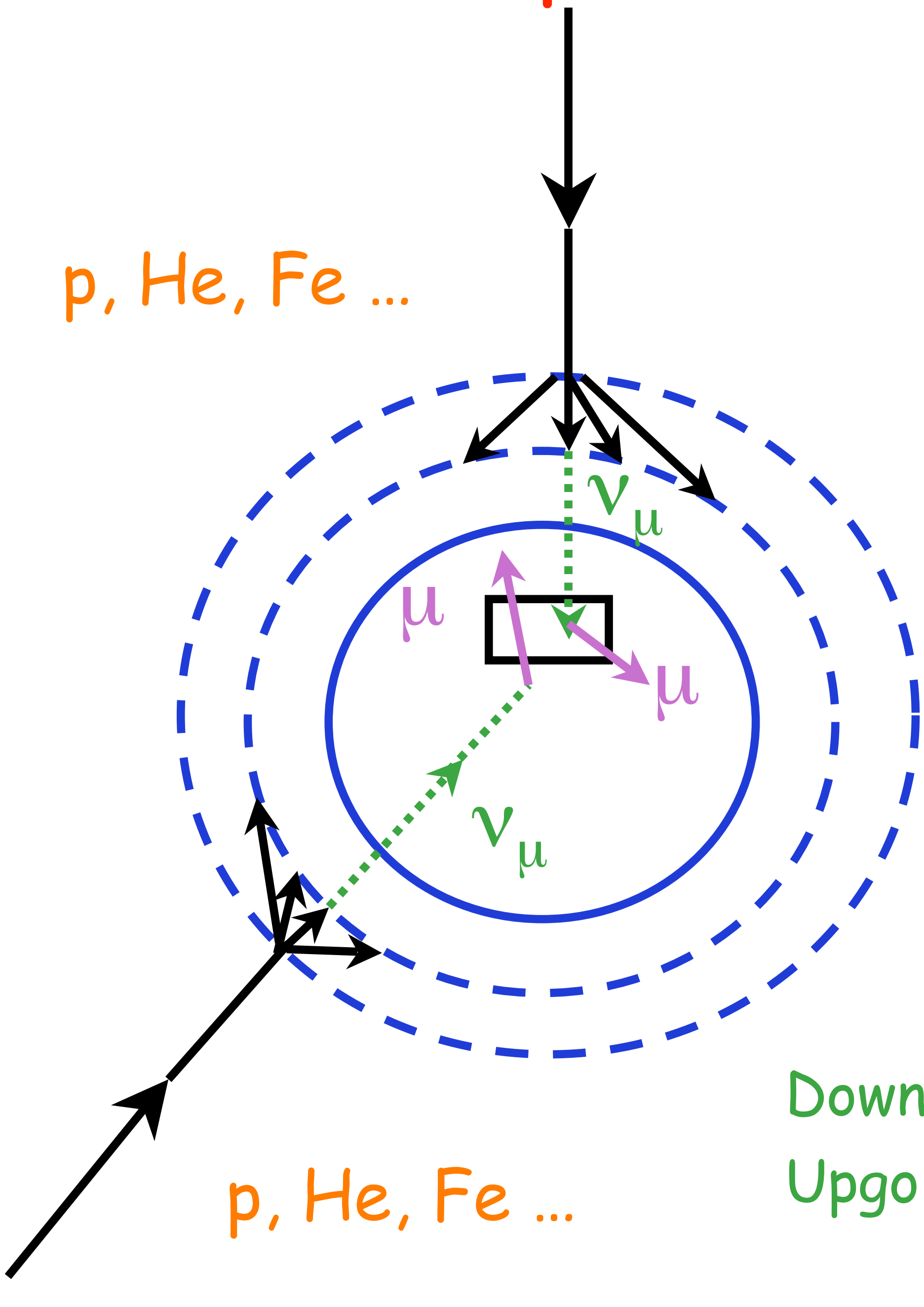
University of Bologna and INFN

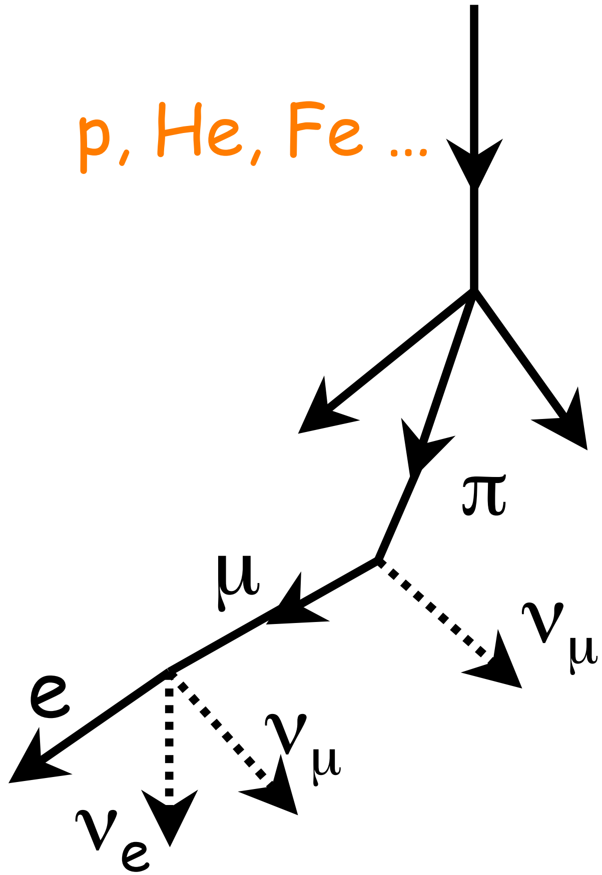
Atmospheric Neutrino Oscillations

G. Giacomelli
University of Bologna and INFN
7th School, ICTP, Trieste, 26/7-6/8 2004

1. Atmospheric neutrinos
2. Neutrino oscillations
3. Soudan 2
4. MACRO
5. SuperKamiokande
6. Discussion, Conclusions and Outlook

1. Atmospheric neutrinos





E_ν: 0.1 GeV → 100 GeV

L: 20 km → 13000 km

L/E_ν: 1 km/GeV → 10^5 km/GeV

Downgoing ν_μ: "near" neutrino source

Upgoing ν_μ: "far" neutrino source

2. ν-Oscillations (in vacuum)

Weak flavor eigenstates ν_e, ν_μ, ν_τ

Mass eigenstates ν_1, ν_2, ν_3

Decays, Interactions $\pi^+ \to \mu^+ \nu_\mu$, $\nu_\mu\, n \to \mu^- p$

Propagation $\nu_1(t) = \nu_1(0)\, e^{-Et}$

Mixing $\nu_f = \Sigma^3_{m=1} U_{fm} \nu_m$

If only 2 flavors (ν_μ, ν_τ) , (ν_1, ν_2) :

Oscillation probability (appearance) over a distance L:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2 (1.27\, \Delta m^2_{23}\, L/E_\nu)$$

Disappearance over a distance L:

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_\tau)$$

Simple formulae modified by : Additional flavor oscillations

Matter effects

In case of oscillations: $m_\nu \neq 0$

L_e, L_μ, L_τ violation

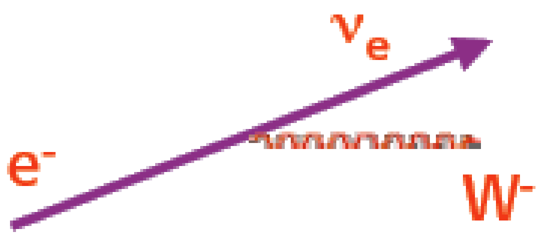
Neutrino decays ?

3-ν Models

Petcov
Feruglio

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavour   mass



Pontecorvo
Maki, Nakagawa, Sakata

In basis where e^-, μ^-, τ^- are diagonal:

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

s = solar: large

CHOOZ: $|s_{13}| <\sim 0.25$

$$\sim \begin{bmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ \dots & \dots & c_{13}s_{23} \\ \dots & \dots & c_{13}c_{23} \end{bmatrix}$$

atm.: ~ max

G. Altarelli

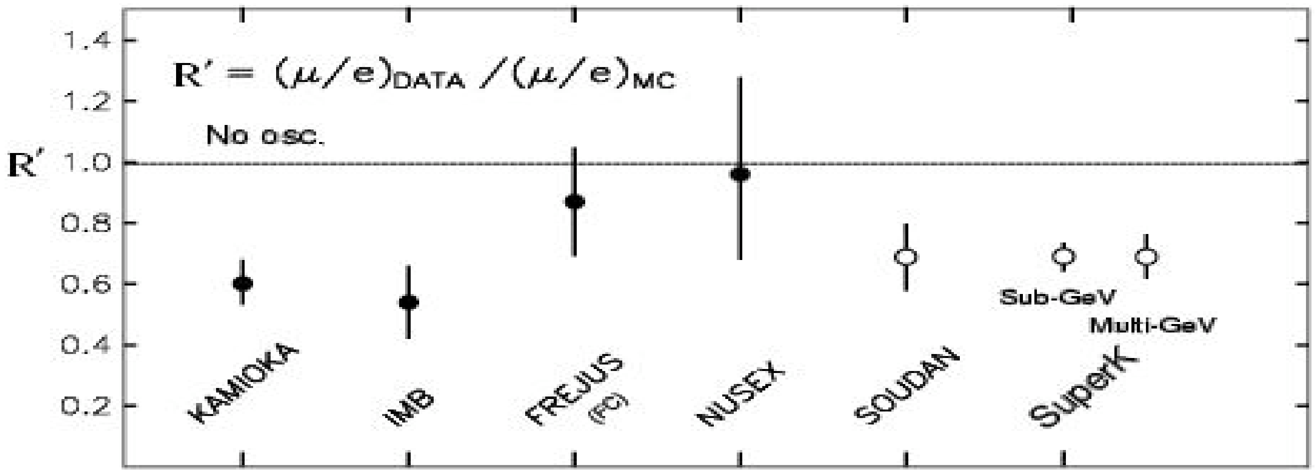
$$U = \begin{bmatrix} c & -s & 0 \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \longrightarrow U = \begin{pmatrix} 0.84 & 0.54 & 0.1 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}$$

Atmospheric Neutrino Anomaly

Summary of results since the mid 1980's:

$$R' = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

Double ratio between the number of detected and expected ν_μ and ν_e



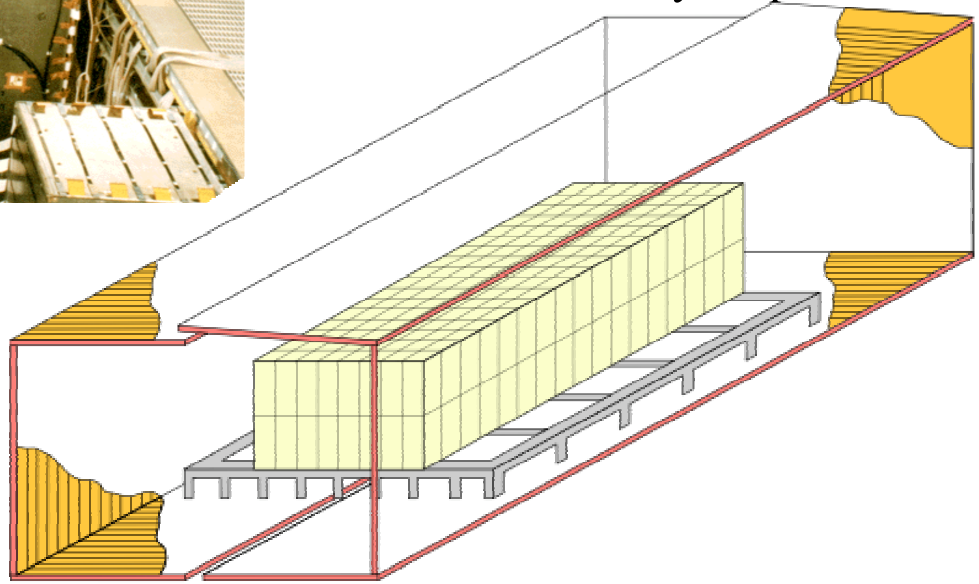
Water Cherenkov

Calorimeters

3. Soudan 2. The Detector

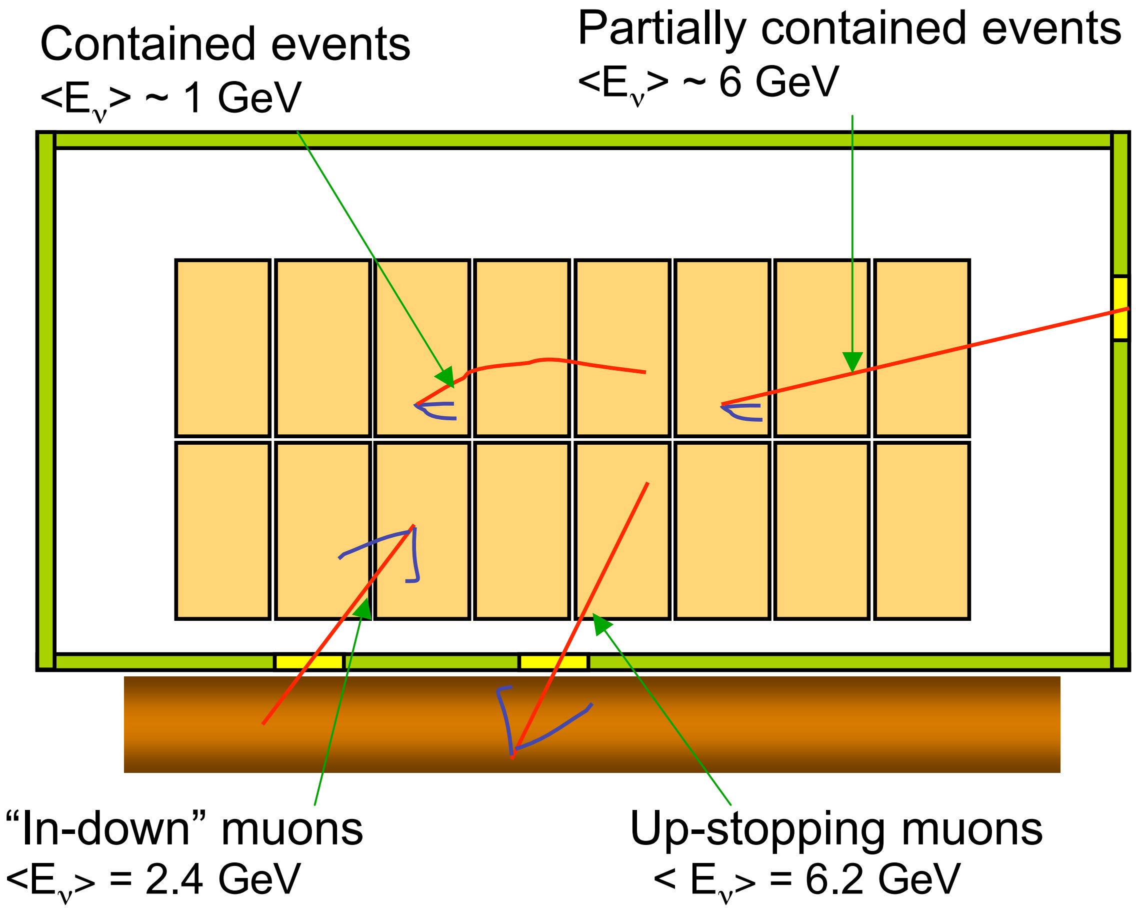
The experiment is located 2340 feet underground in the Soudan State Park, Minnesota.

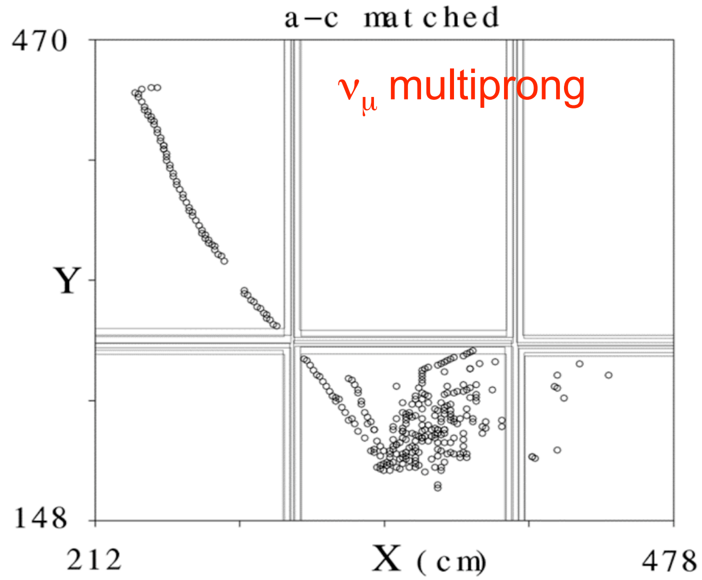
224 1m x 1m x 2.7 m modules
963 ton total mass
5.90 fiducial kton-yr exposure

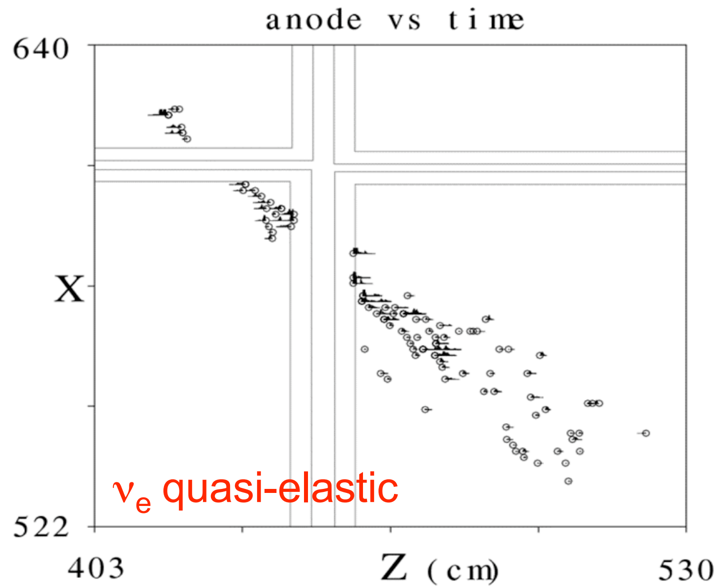


The detector is surrounded by a ~1700 m^2 “veto shield” which provides nearly 4π coverage for the identification of charged particles entering / exiting the detector cavern.

Soudan 2

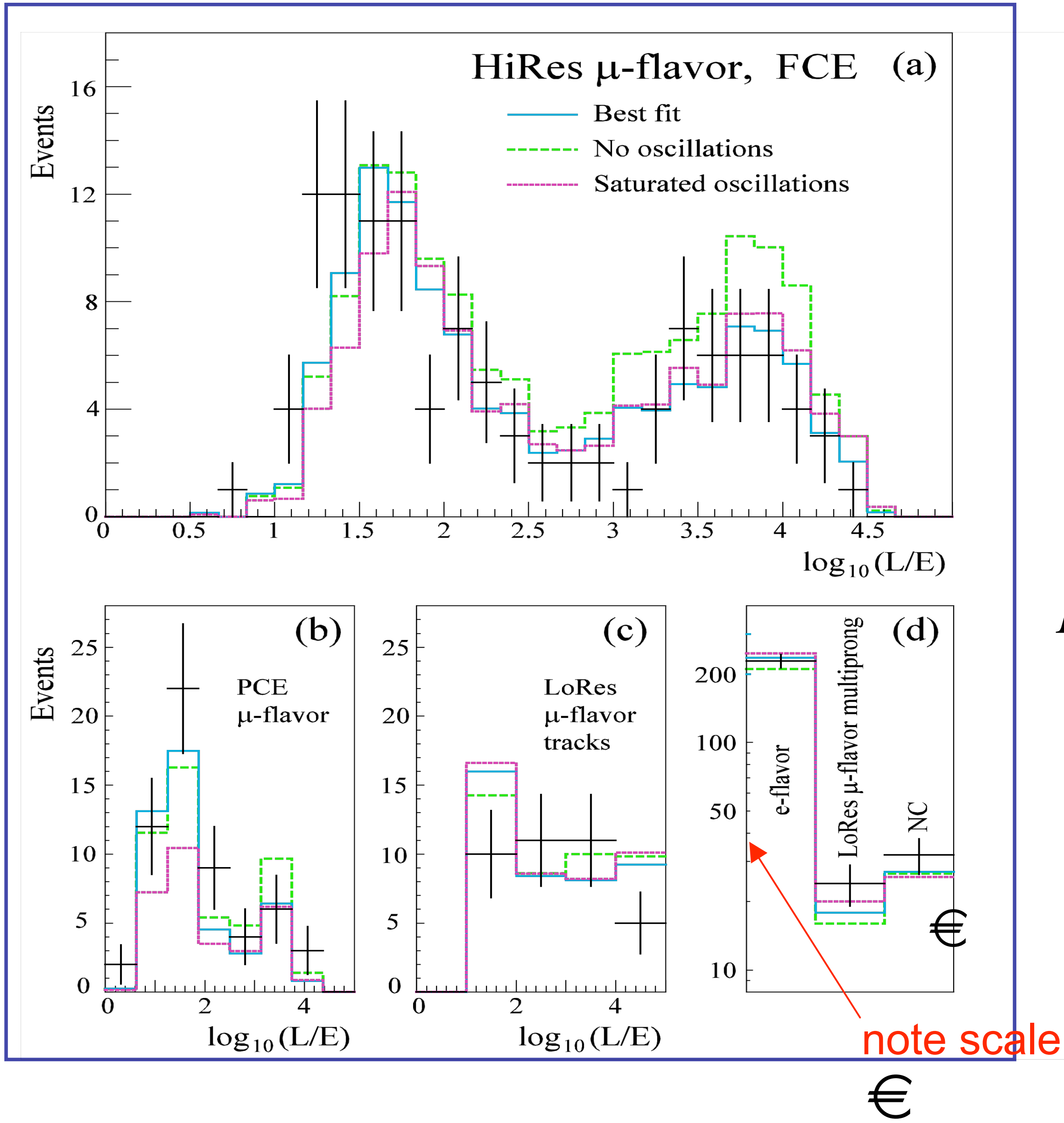






- 3 flavor categories (ν_e CC, ν_μ CC, NC)
- 2 bins of resolution (“hi” and “low” resolution)
- Data corrected for neutral backgrounds (6% in hi-resolution samples)

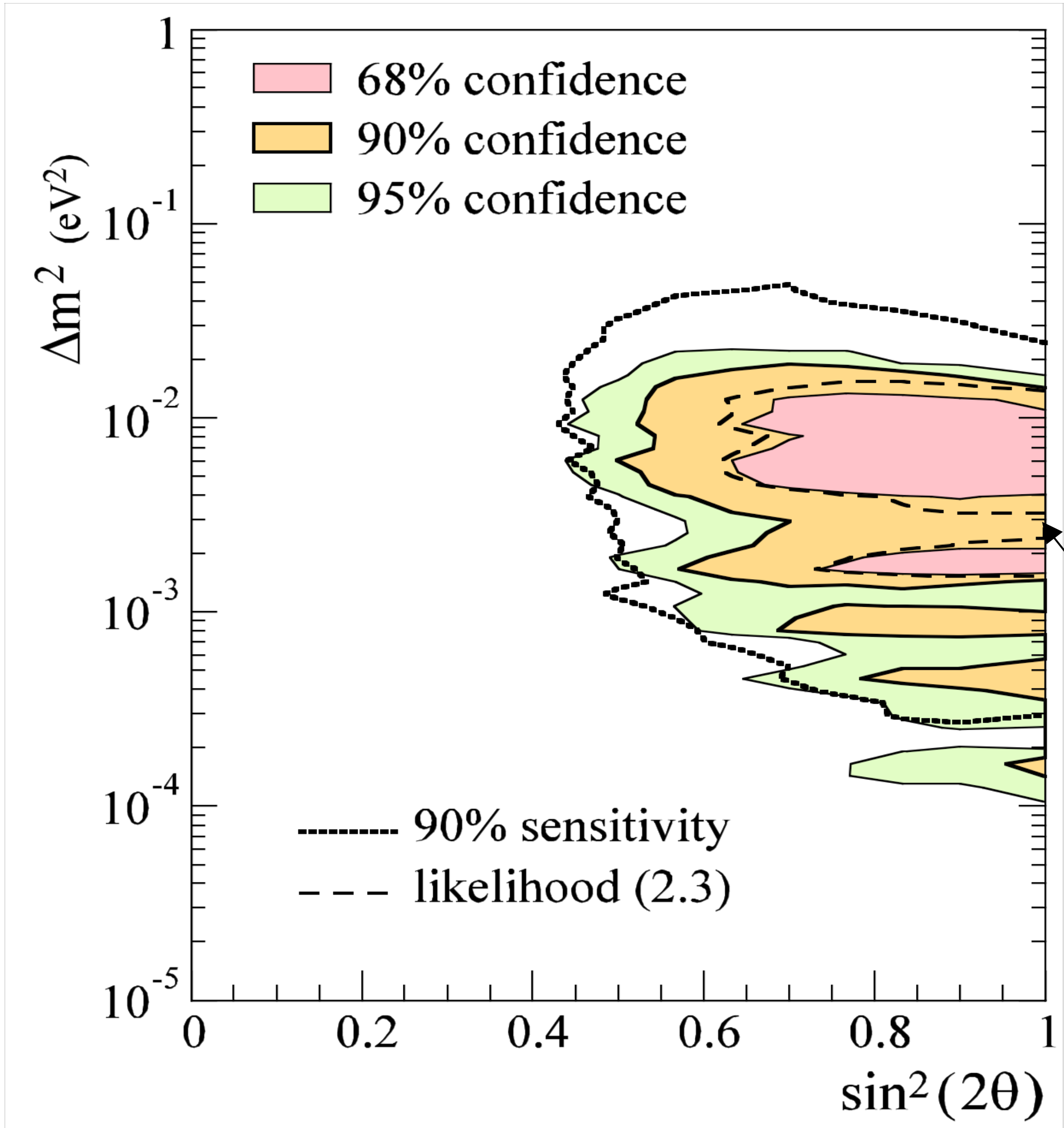
Soudan 2



$$R_{\nu_\mu/\nu_e} = \frac{(\mu - like / e - like)_{DATA}}{(\mu - like / e - like)_{MC}}$$

$$= 0.69 \pm 0.12$$

Soudan 2: Results



Best Fit:

$\Delta m^2 = 0.0052$ eV^2

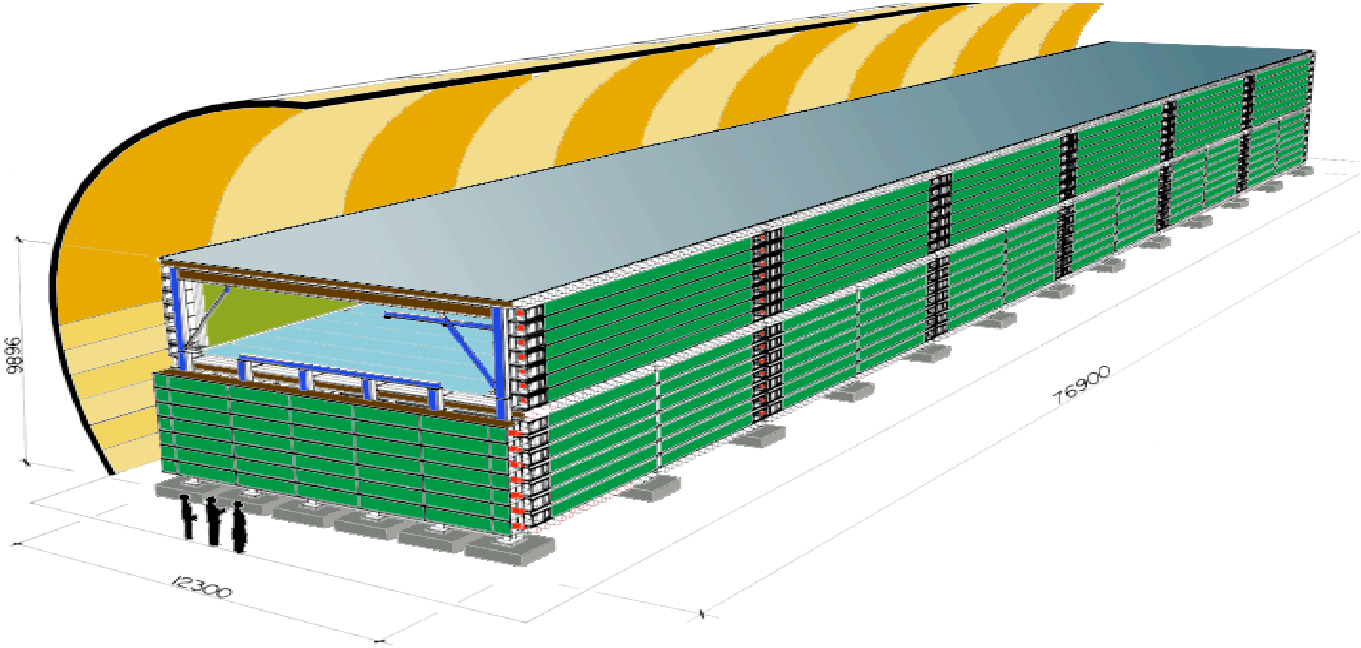
$\sin^2 2\theta = 0.97$

f_ν(data/mc) = 0.90

MC ⇔ Bartol '96

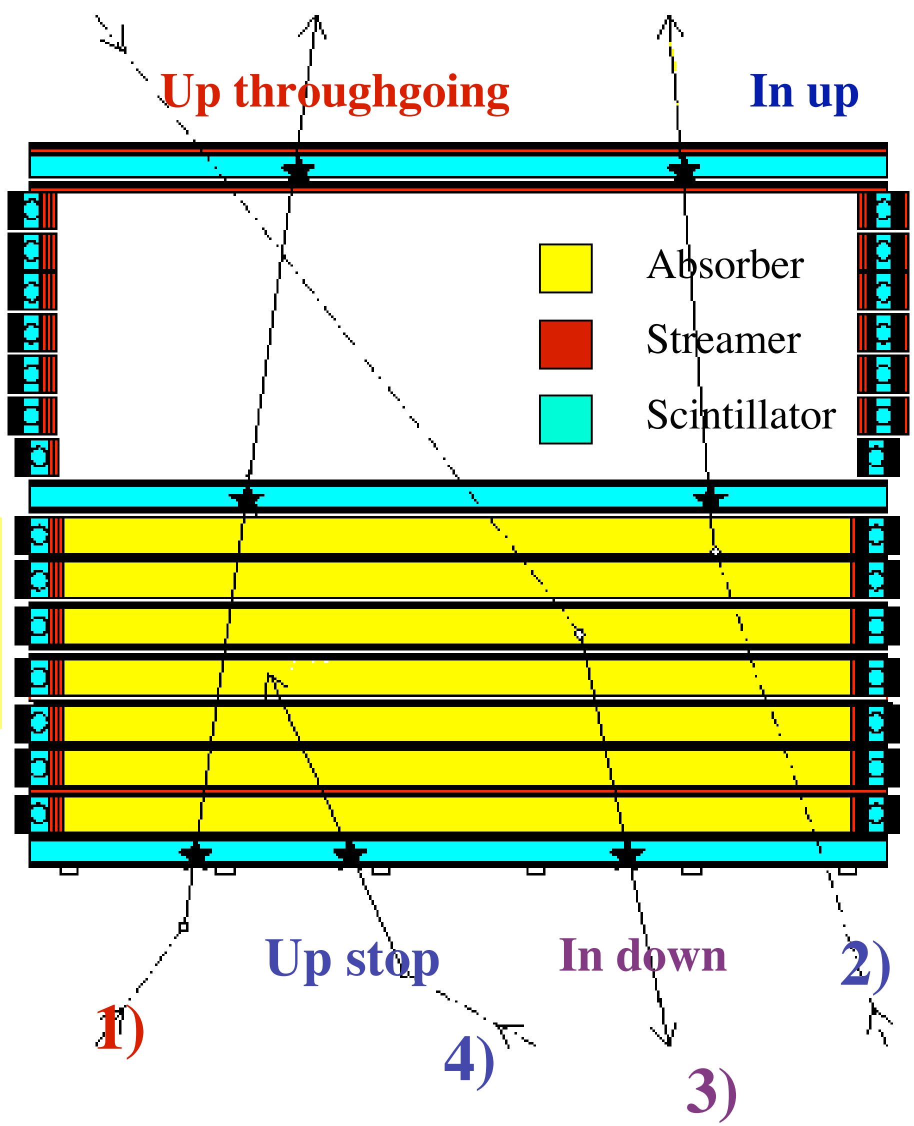
Inclusion of systematic errors and application of Feldman-Cousins technique substantially increases the size of the 90% CL region.

4. MACRO

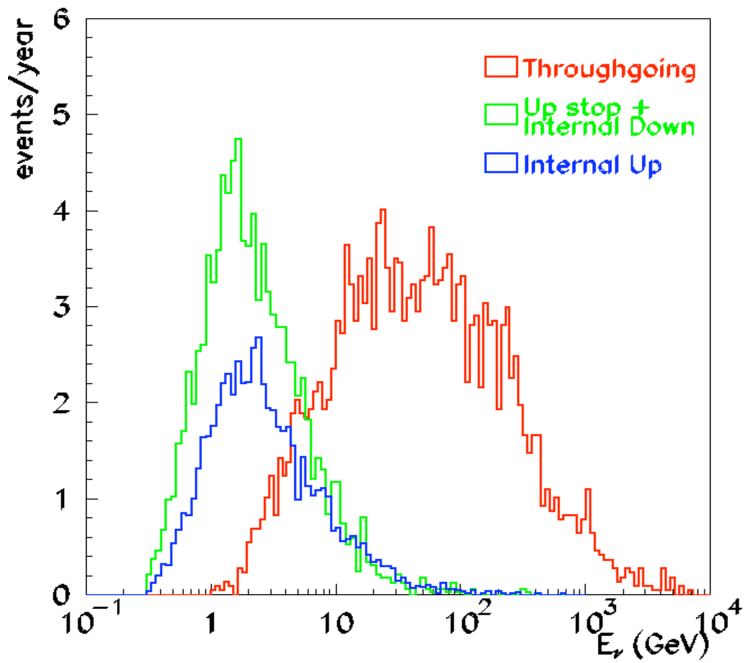


- Large acceptance (~10000 m^2sr for an isotropic flux)
- Low downgoing μ rate (~10^{-6} of the surface rate)
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 m^2 of streamer tubes (3cm cells) for tracking (angular resolution < 1°)

MACRO

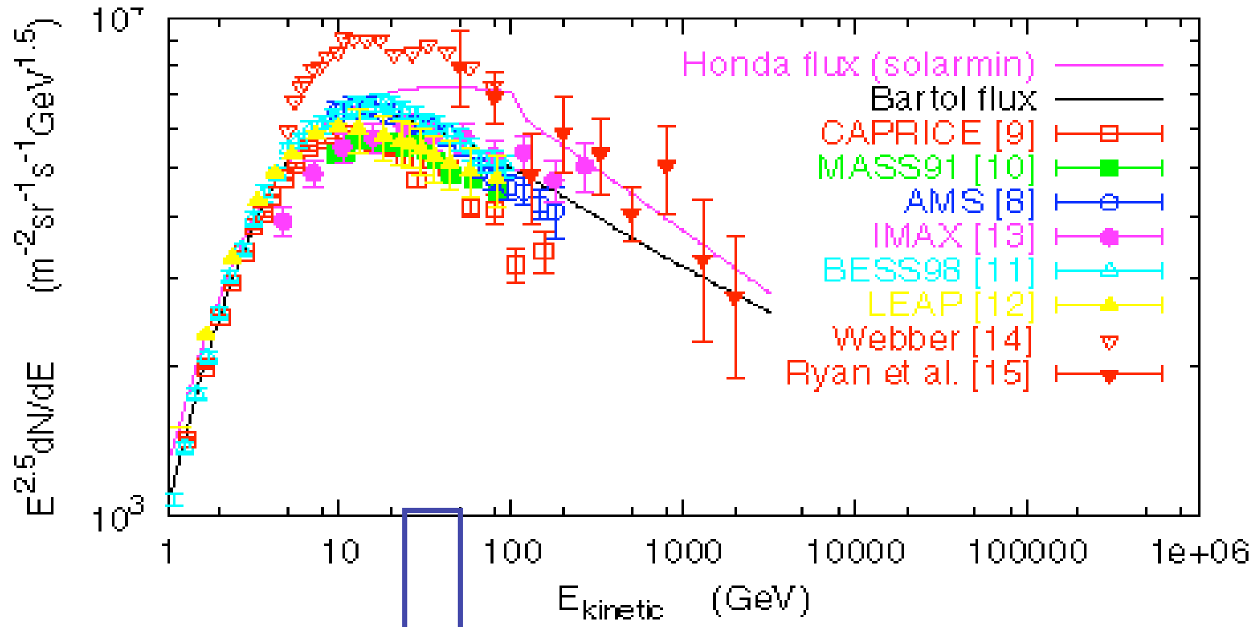


Detector mass ~ 5.3 kton



DATA SAMPLES (measured)
(Bartol96 expected)

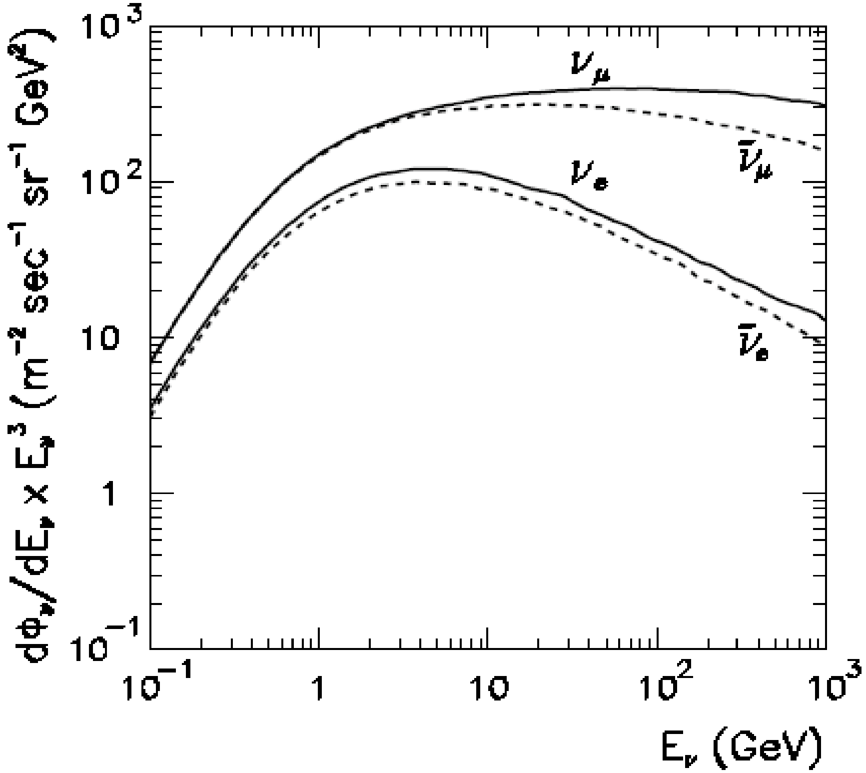
Up through(1)	857
	1169
Internal UP(2)	157
	285
In DOWN(3)+ Stop(4)	262
	375



primary CR

Atmospheric neutrino spectrum from primary CR

neutrinos

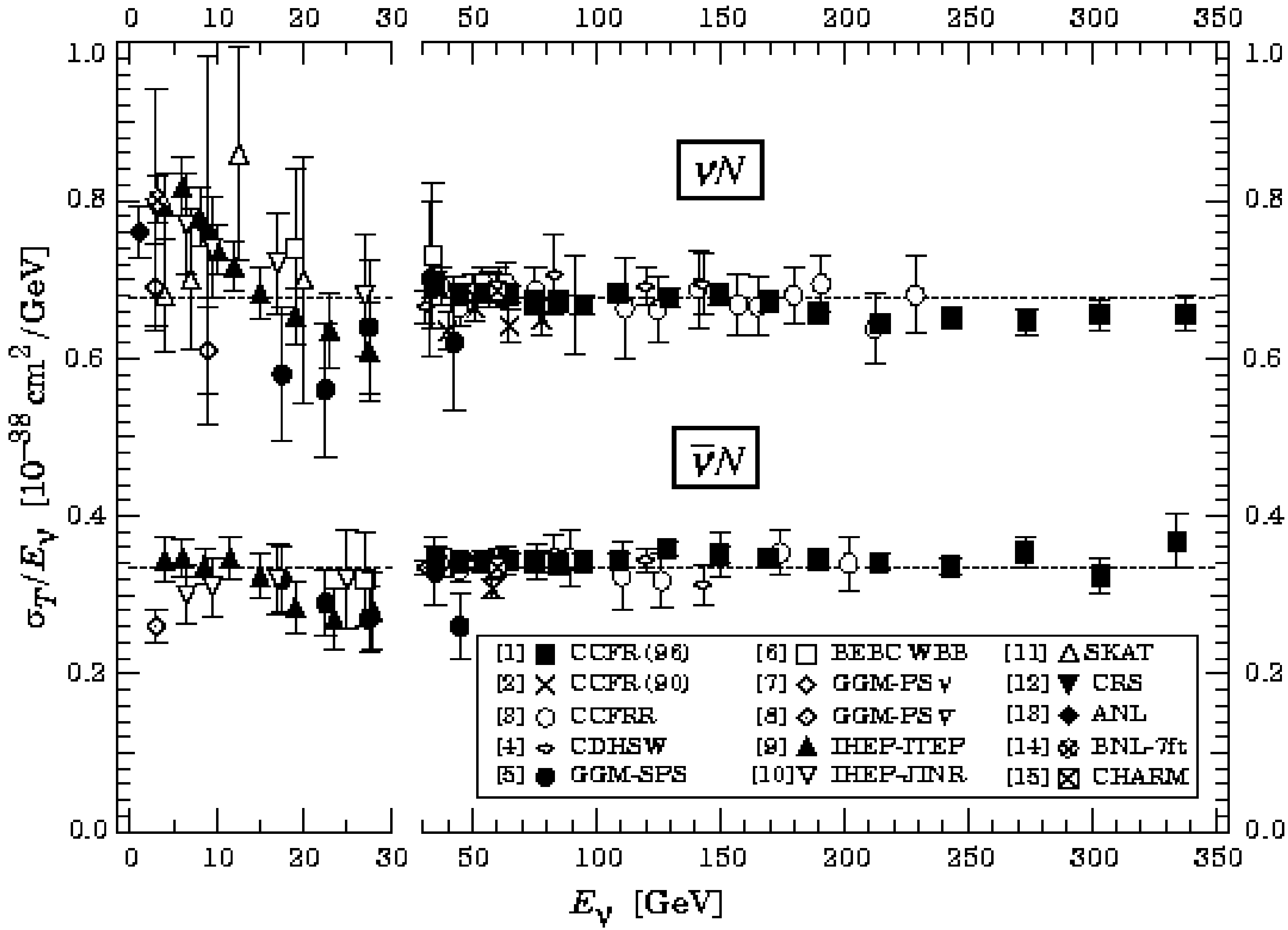


Many ingredients in the **Monte Carlo simulation**:

- CR flux
- ν cross sections
- secondary multiplicity distributions
- atmosphere model

Monte Carlo

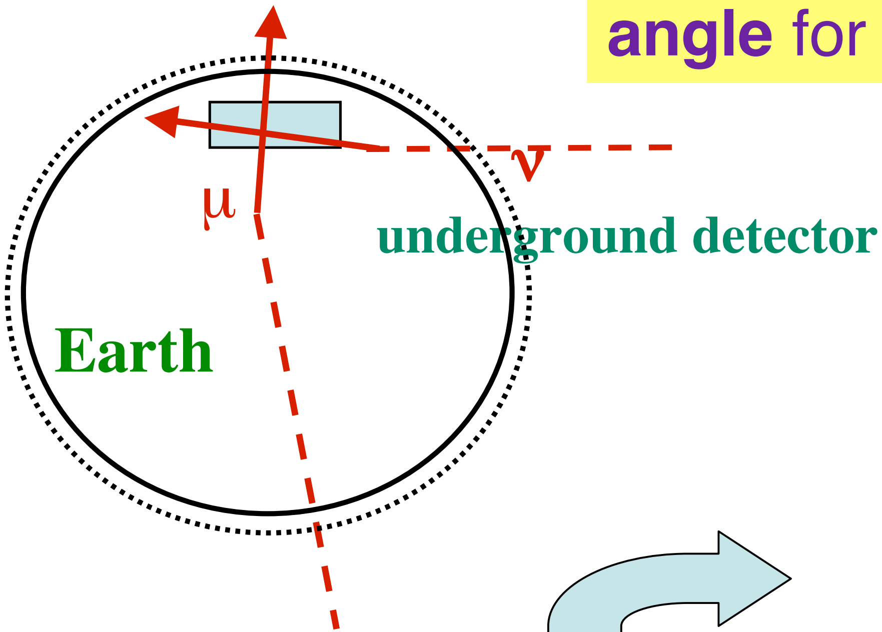
Neutrino cross sections



MC

Effects of ν_μ oscillations on upthroughgoing events

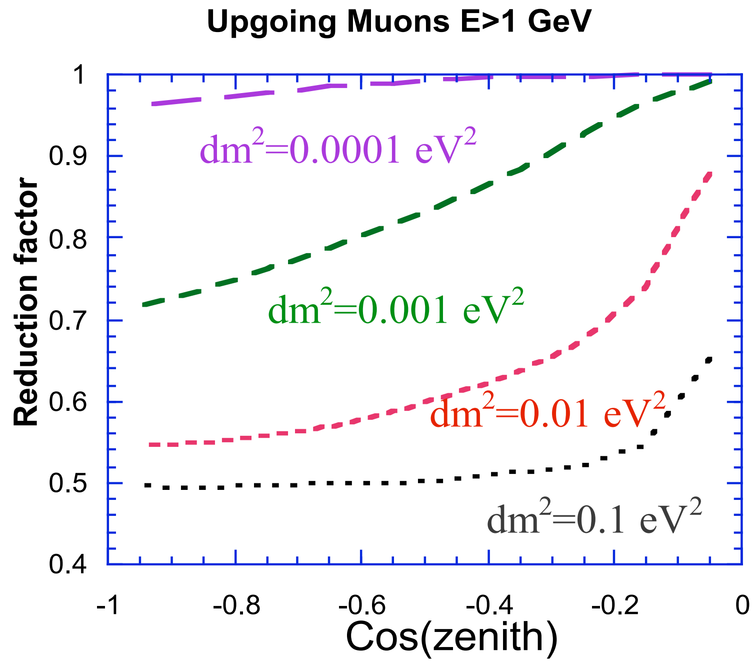
Flux reduction depending on **zenith angle** for the high energy events



$$P_{\nu_\mu\nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27\frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

From MC: **distortion of the angular distribution**

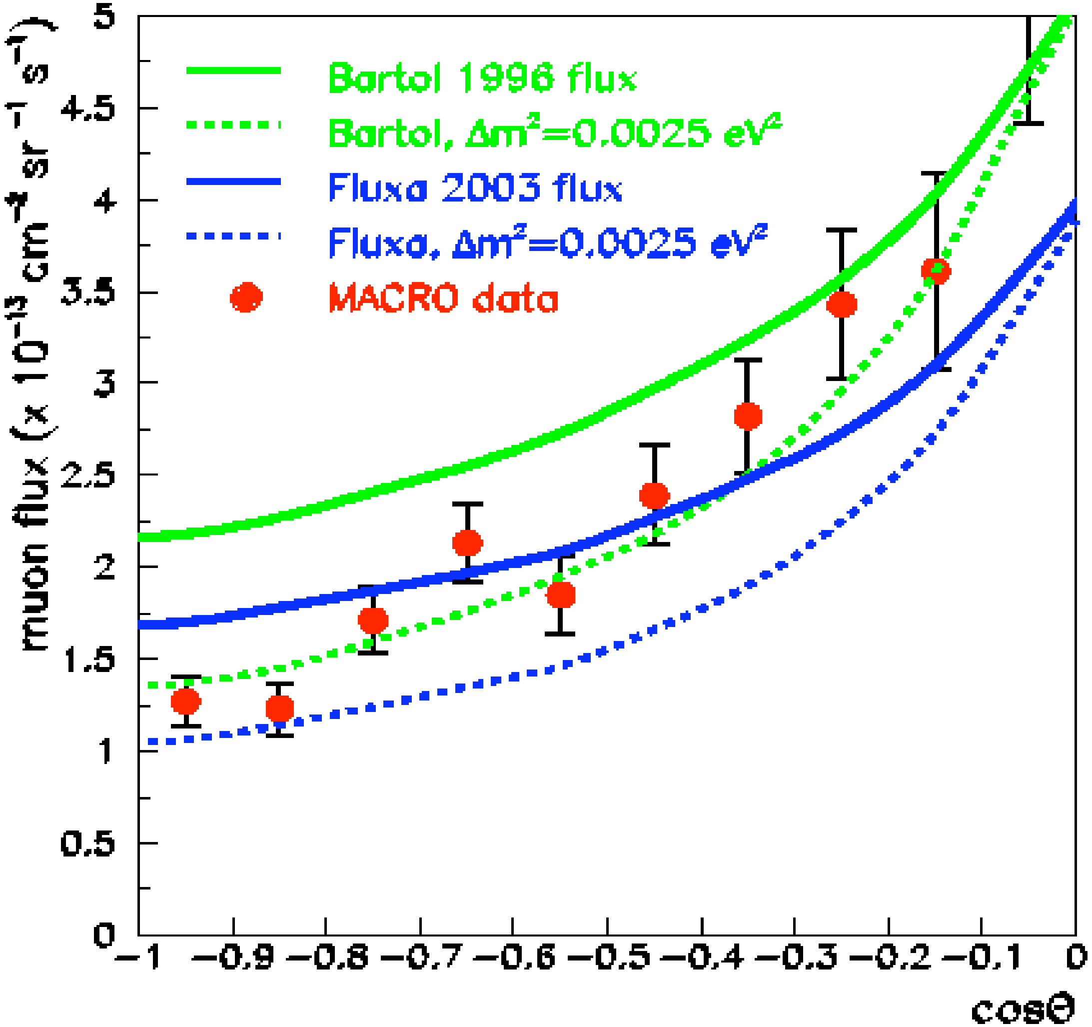
$E_\nu \sim 100$ GeV
$L_\nu \sim 10 - 10^4$ km



$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2 \left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu} \right]$$

*Through the measurement of **the shape** of the muon zenith angle distribution.*

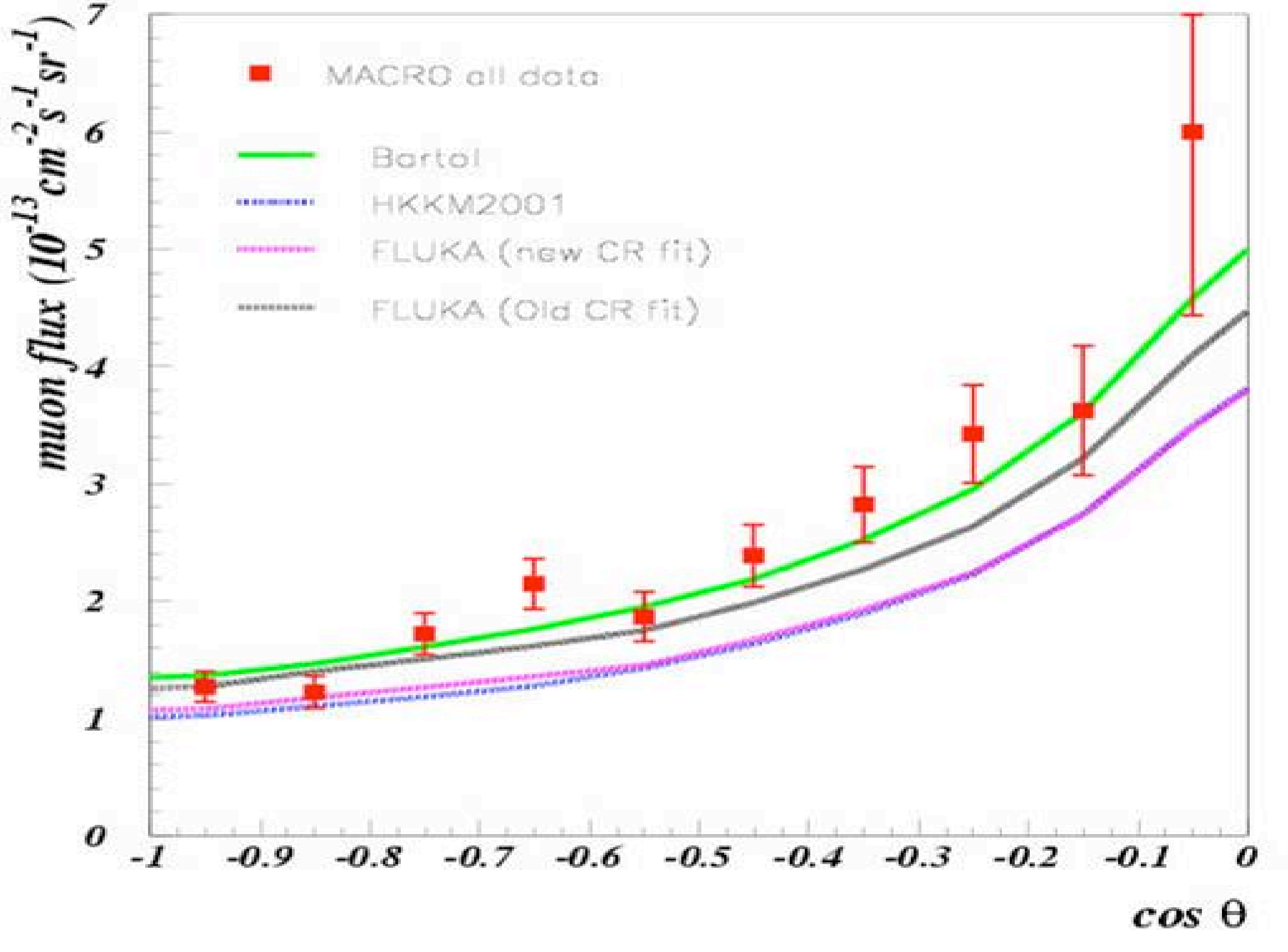
L(cosΘ=-1)~13000 km
L(cosΘ=0)~500 km



MACRO

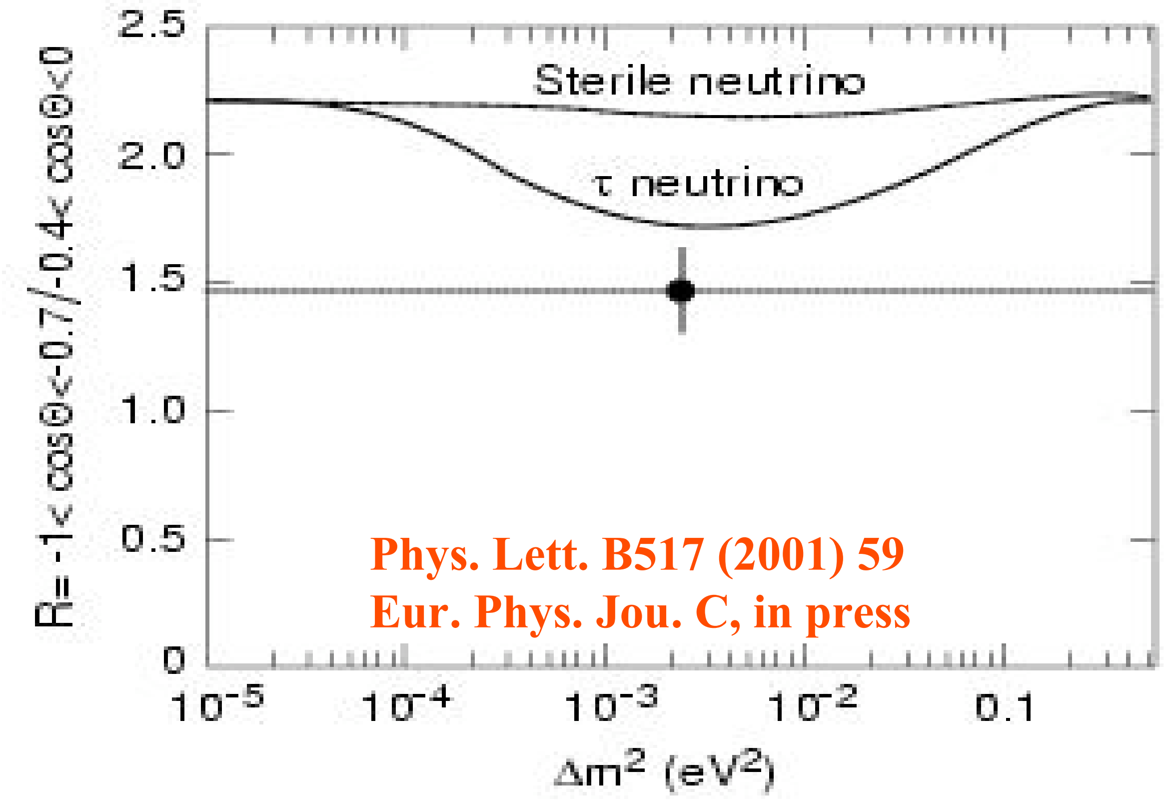
MonteCarlo

MACRO-MonteCarlo



$\nu_\mu \longleftrightarrow \nu_\tau$ or $\nu_\mu \longleftrightarrow \nu_{sterile}$?

MACRO



OSCILLATION HYPOTHESIS

Minimum value for $\nu_\mu \longleftrightarrow \nu_\tau$: R_τ^{min} =1.61

Minimum value for $\nu_\mu \longleftrightarrow \nu_{sterile}$: R_{st}^{min} =2.03

PROBABILITY FOR R < R^{min} :

P_τ = 7.2% ; $P_{sterile}$ = 0.015% $\longrightarrow$ $P_\tau/P_{sterile}$ = 480

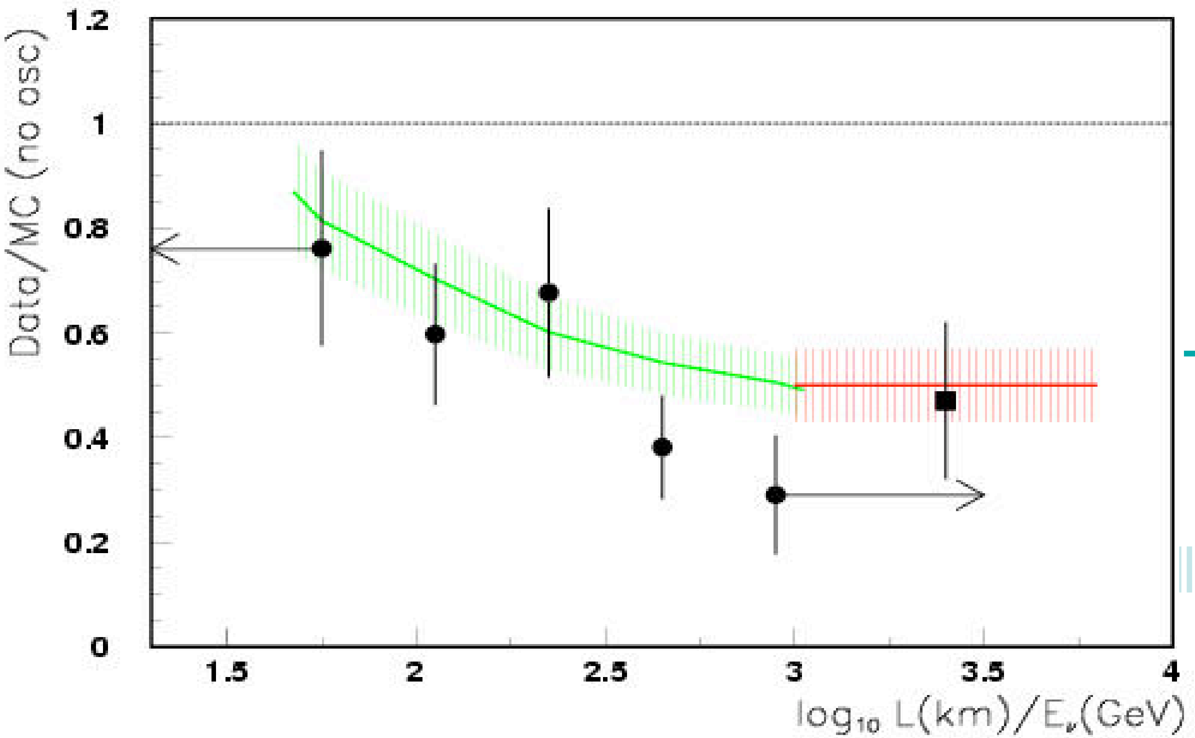
$\nu_\mu \longleftrightarrow \nu_{sterile}$ hypothesis disfavoured at 99.8 % C.L. with respect to $\nu_\mu \longleftrightarrow \nu_\tau$

MACRO : L/E$_\nu$ distribution

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2 \left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu} \right]$$

From the shape of the muon zenith distribution

From the measurement of the muon energy using Multiple Coulomb Scattering



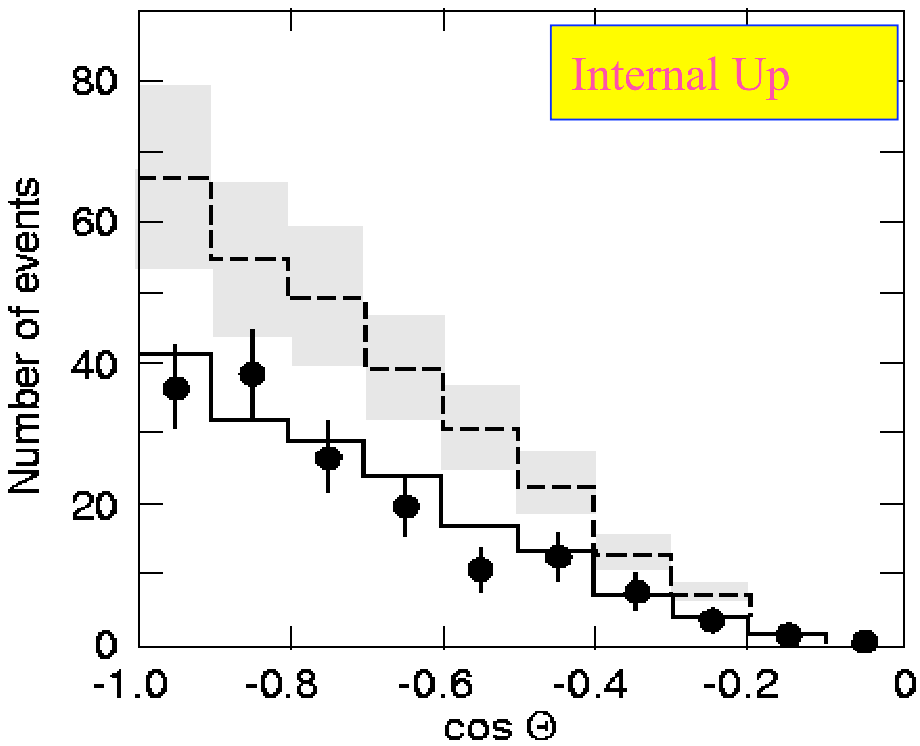
● **Upthr. μ data**

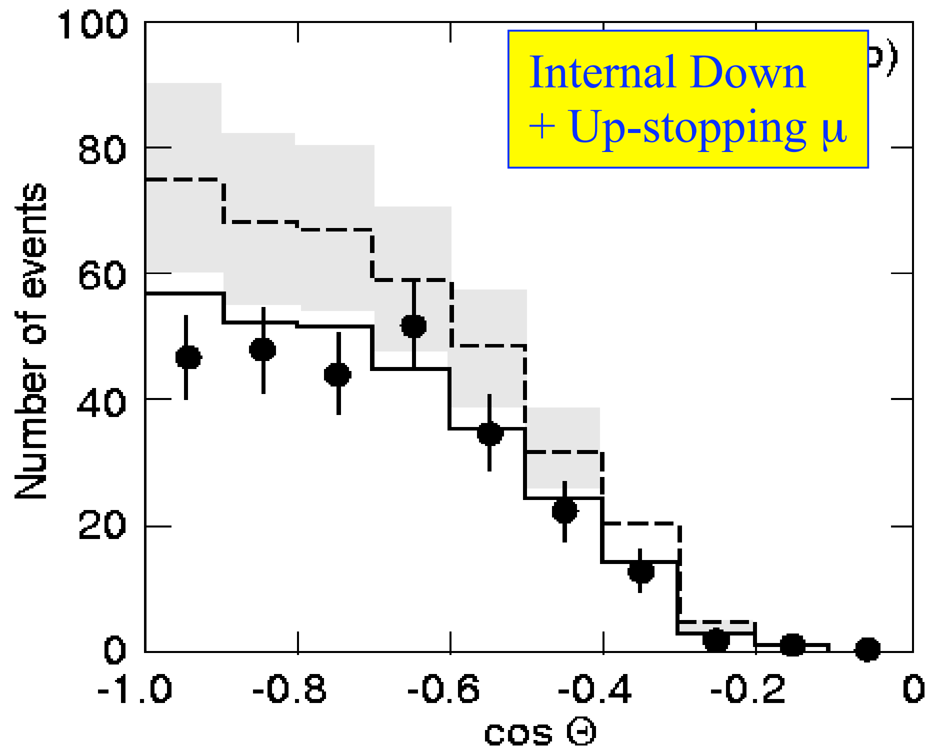
■ **IU μ data**

MC predictions for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the best MACRO parameters

12% point-to-point syst. error

MACRO : Low Energy Neutrino Events





Measured (points) and expected number (dashed lines) of upgoing semicontained events (left) and up-stopping plus downgoing semicontained μ (right).

Solid lines: neutrino two flavor oscillations, with the best fit parameters **$\sin^2 2\Theta = 1$ and $\Delta m^2 = 0.0023$ eV^2.** (Phys. Lett. B478 (2000) 5)

MACRO : Combined analysis

H.E. { Zenith distribution; E_ν estimate

L.E. IU, ID and UGS μ

R_1= N(cos Θ < -0.7) /N(cosΘ > -0.4)

R_2= N(low E_ν) / N(high E_ν)

R_3= N(ID+UGS) / N(IU)

NO OSCILLATION HYPOTHESIS
RULED OUT BY ~ 5 σ

Best fit parameters for $\nu_\mu \rightarrow \nu_\tau$
$\Delta m^2 = 2.3\ 10^{-3}\ eV^2$; $\sin^2 2\theta = 1$

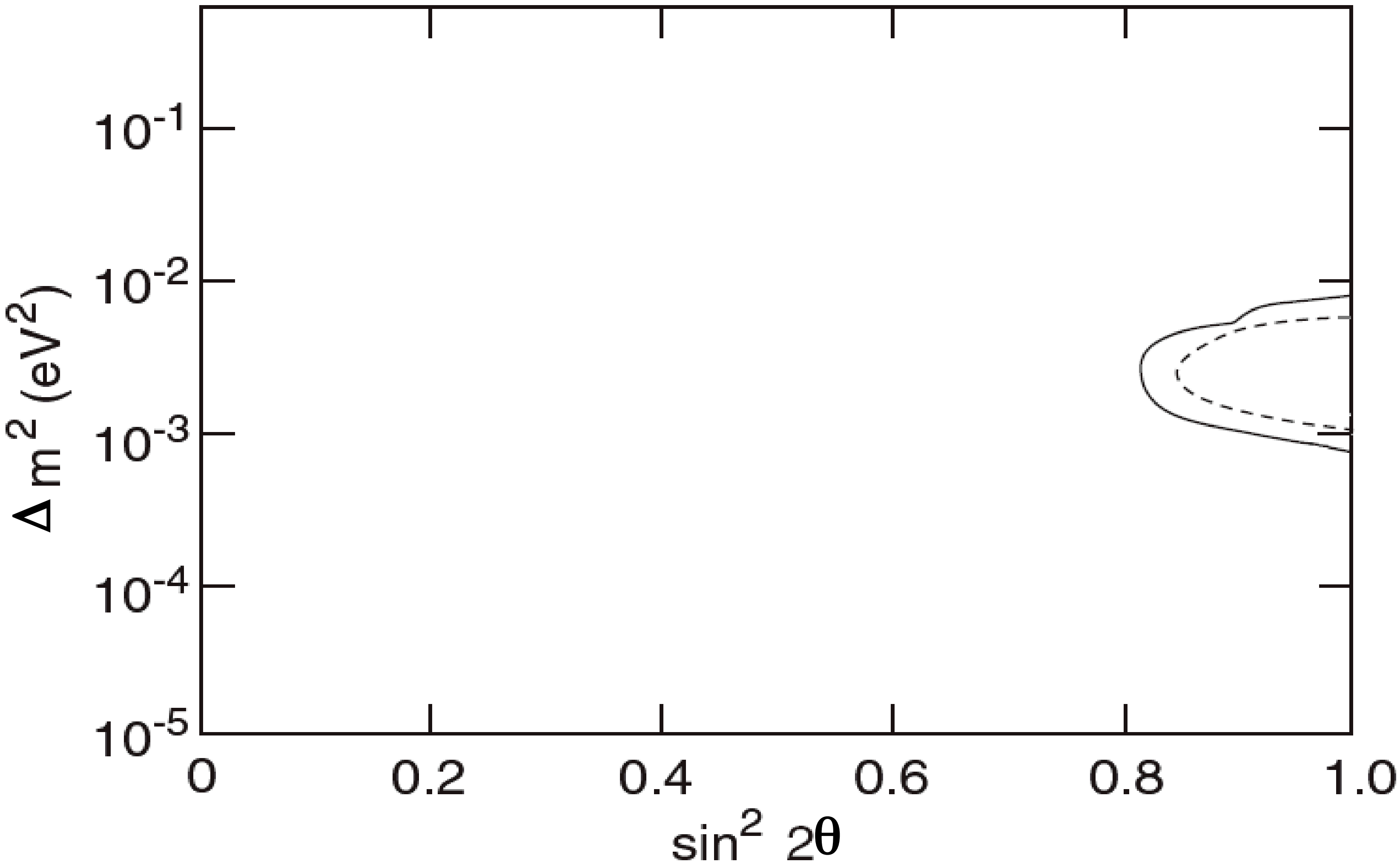
Predictions of the FLUKA and Honda Monte Carlo
H.E. 25% low ; L.E. 12% low

Bartol96 may give additional evidence for oscillations:
Absolute values referred to Bartol96 MC:

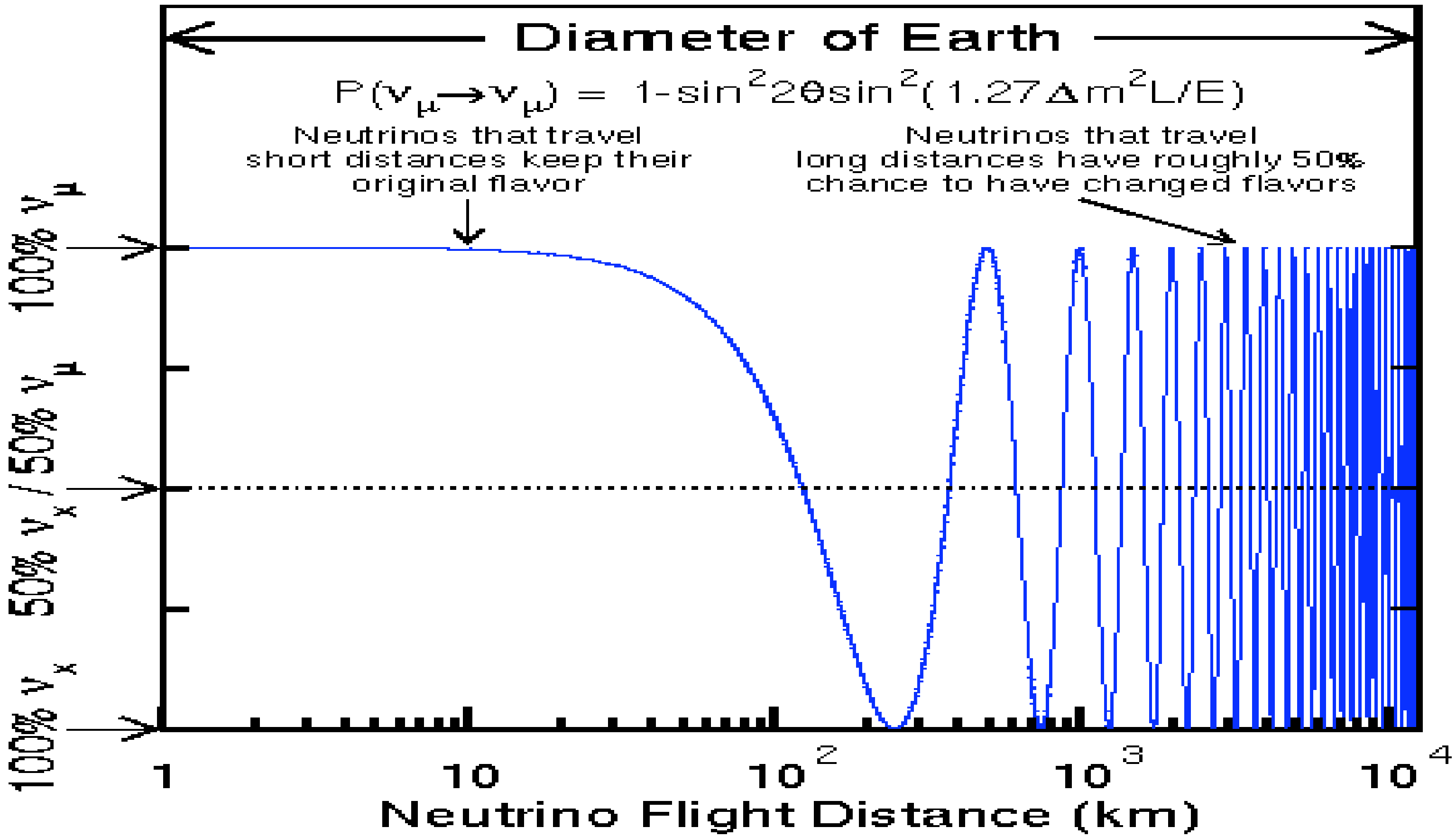
$$R_4=(Data/MC)_{H.E.} \quad ; \quad R_5=(Data/MC)_{L.E.}$$

With these informations, the no oscillation hypothesis is ruled out by ~ 6 σ

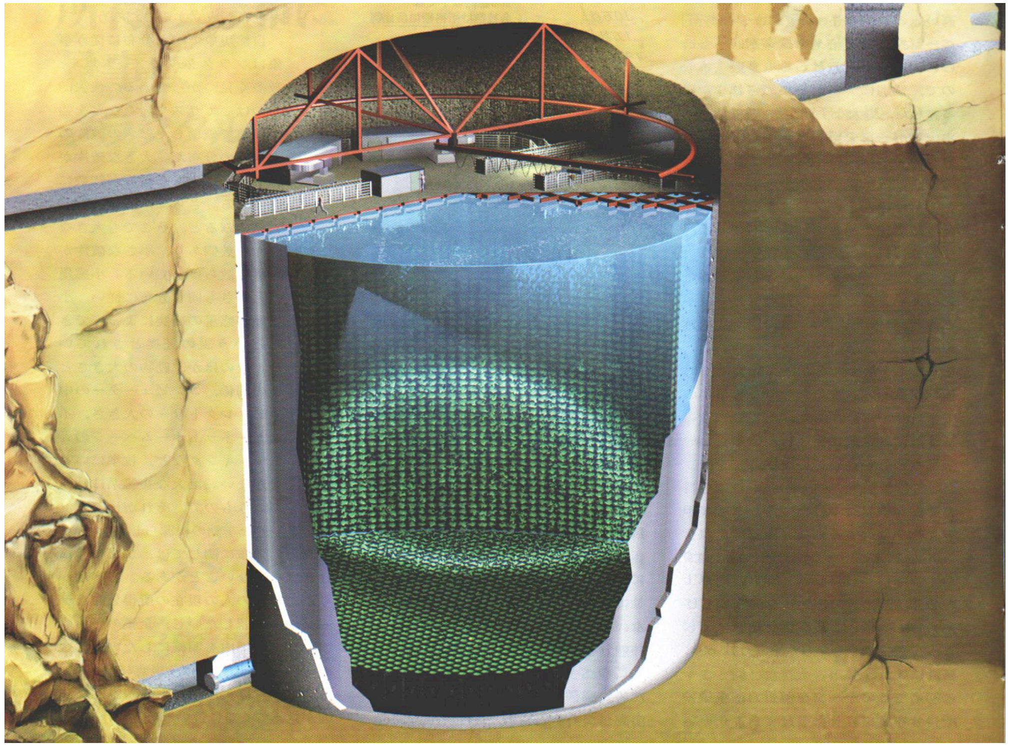
MACRO

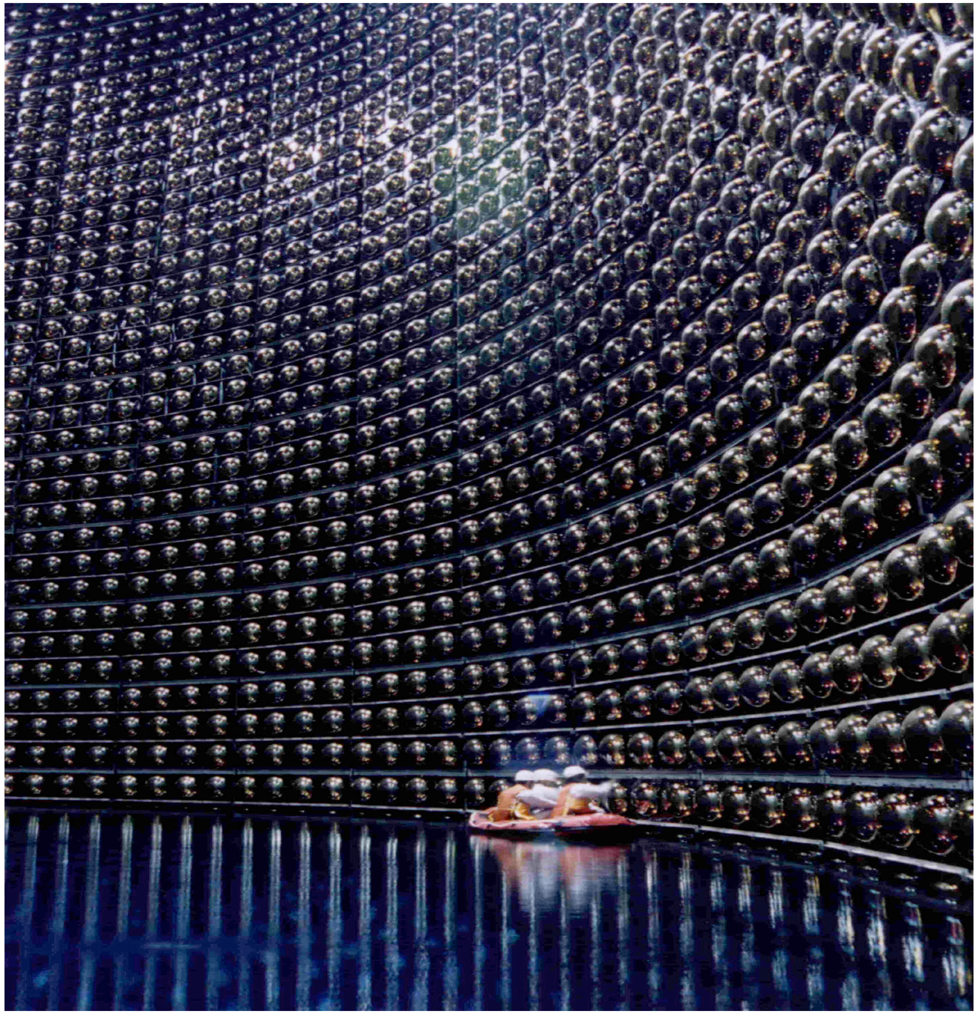


Oscillation probability vs L (at fixed E_ν)



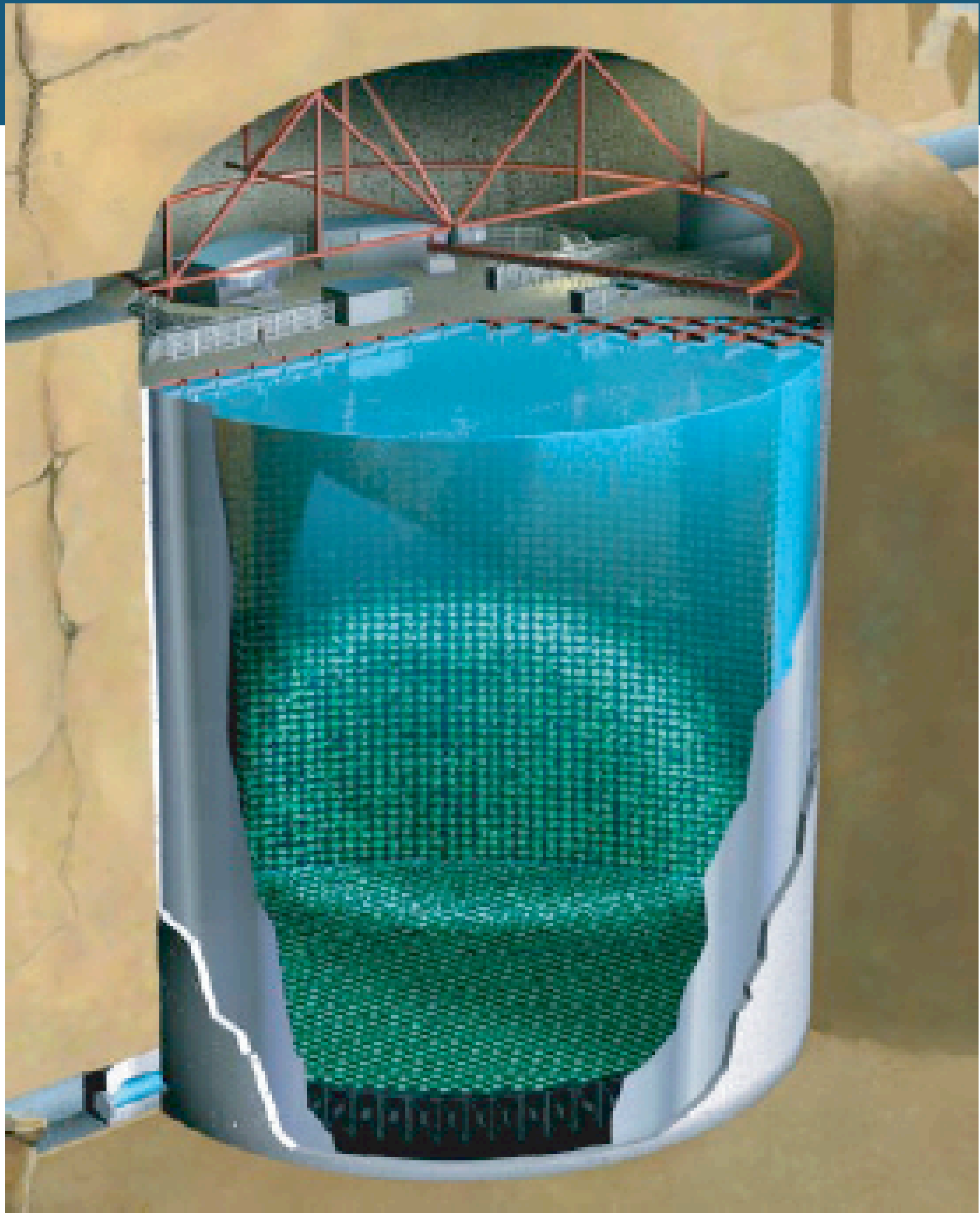
5. SuperK





- 1000 m Deep Underground
- 50,000 ton of Ultra-Pure Water
- 11000 +2000 PMTs

Super-Kamiokande



SK-1 1996 - 2001

- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

SK-2 January 2003 - October 2005

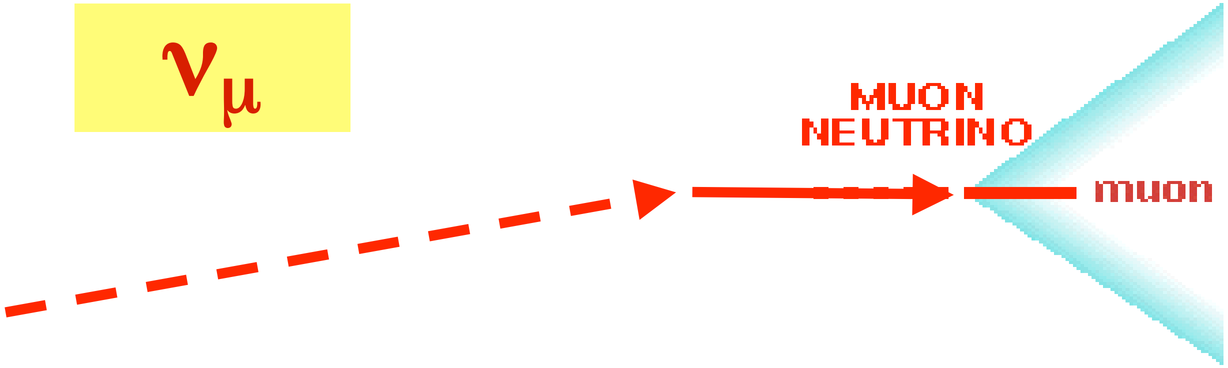
- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

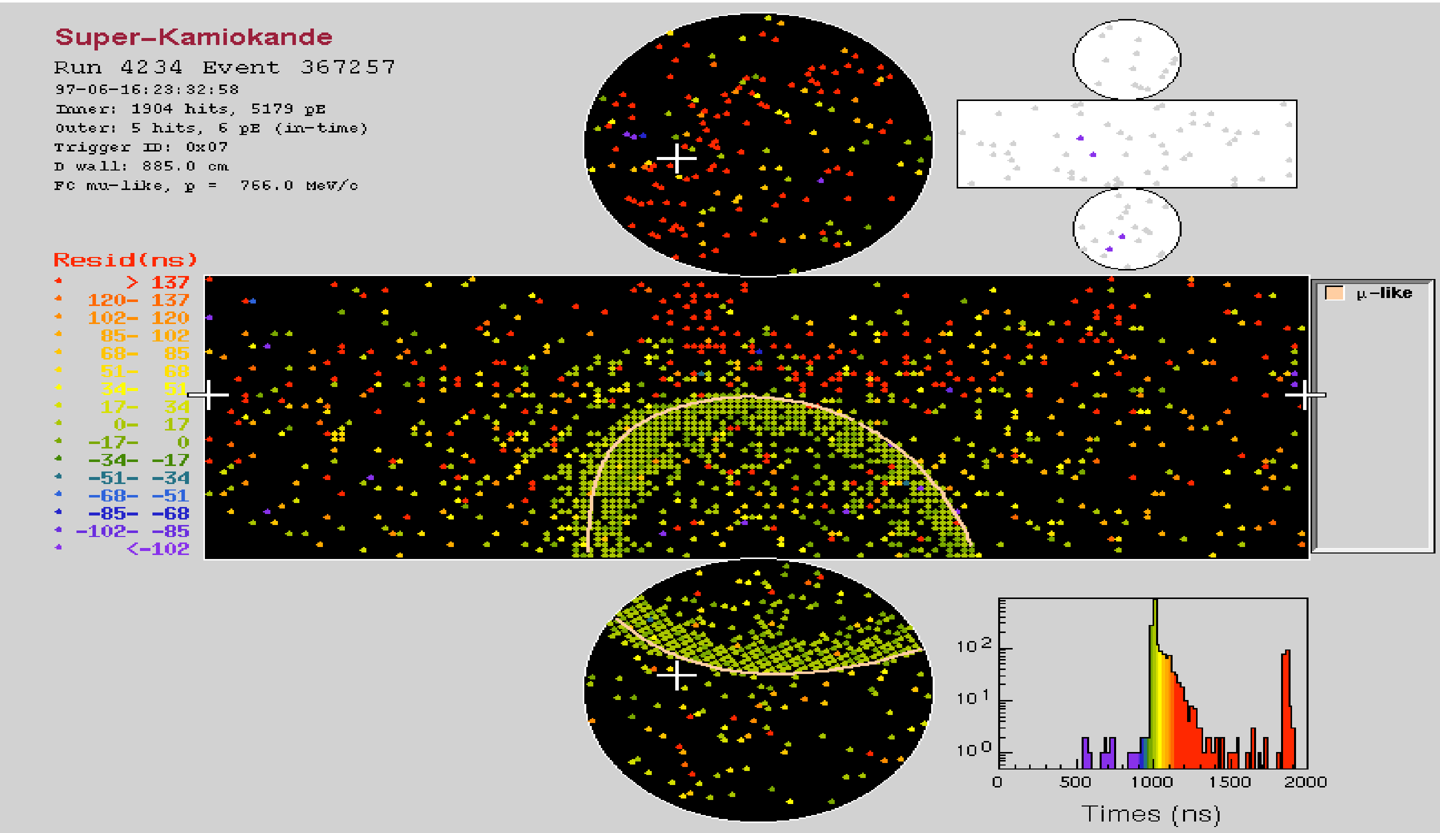
SK-3 March 2006 +

- original coverage to be restored
- T2K off-axis beam from J-PARC

SK

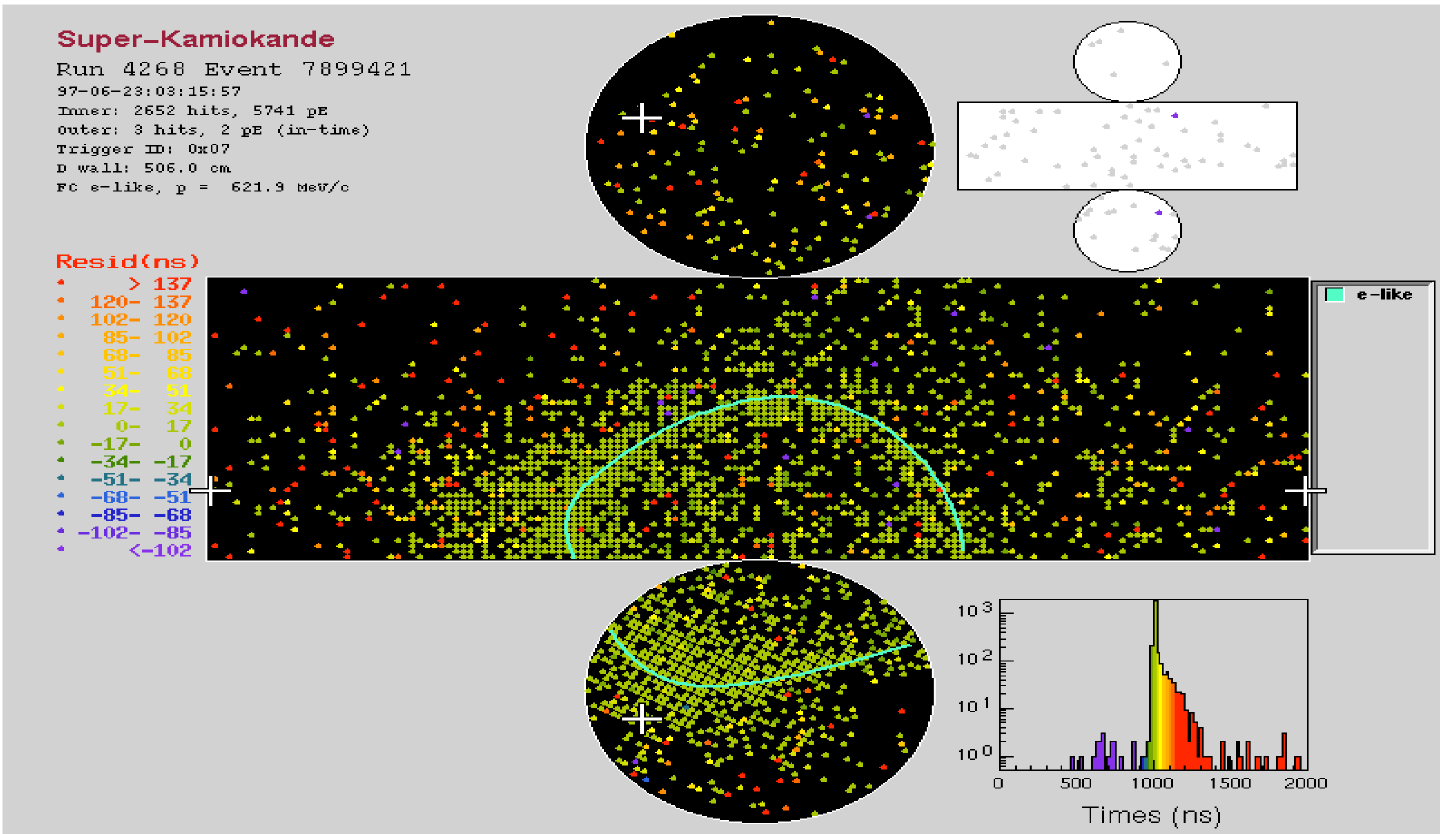
ν_μ


MUON
NEUTRINO
muon


Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p = 766.0 MeV/c
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
μ-like
10^2
10^1
10^0
0
500
1000
1500
2000
Times (ns)

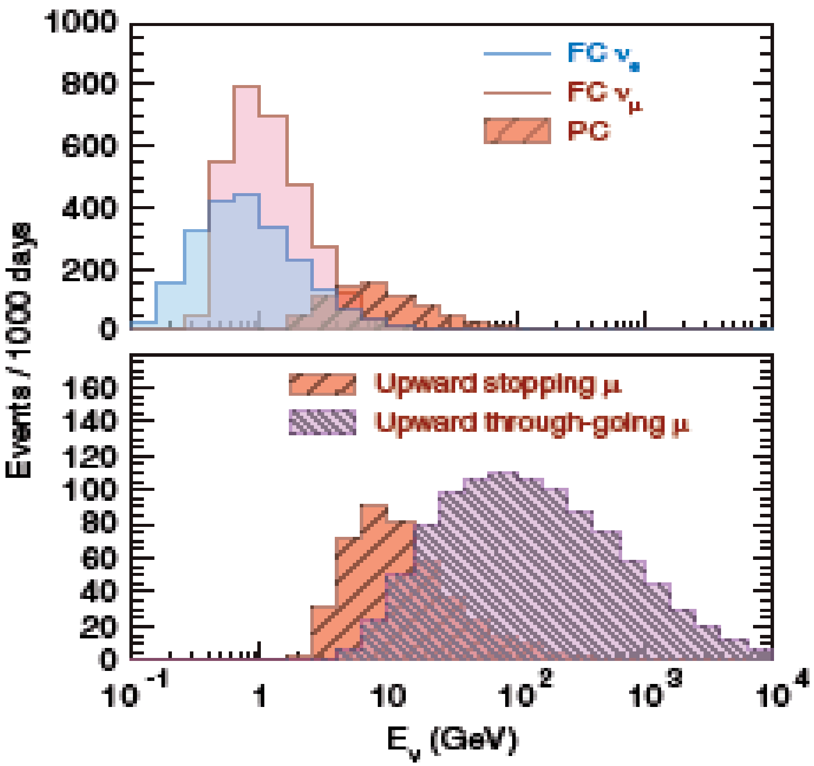
SK


ν_e
ELECTRON NEUTRINO
electron shower


Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p = 621.9 MeV/c
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
e-like
10^3
10^2
10^1
10^0
0 500 1000 1500 2000
Times (ns)

SK-I Atmospheric Neutrino Event Sample

5 decades of neutrino energy

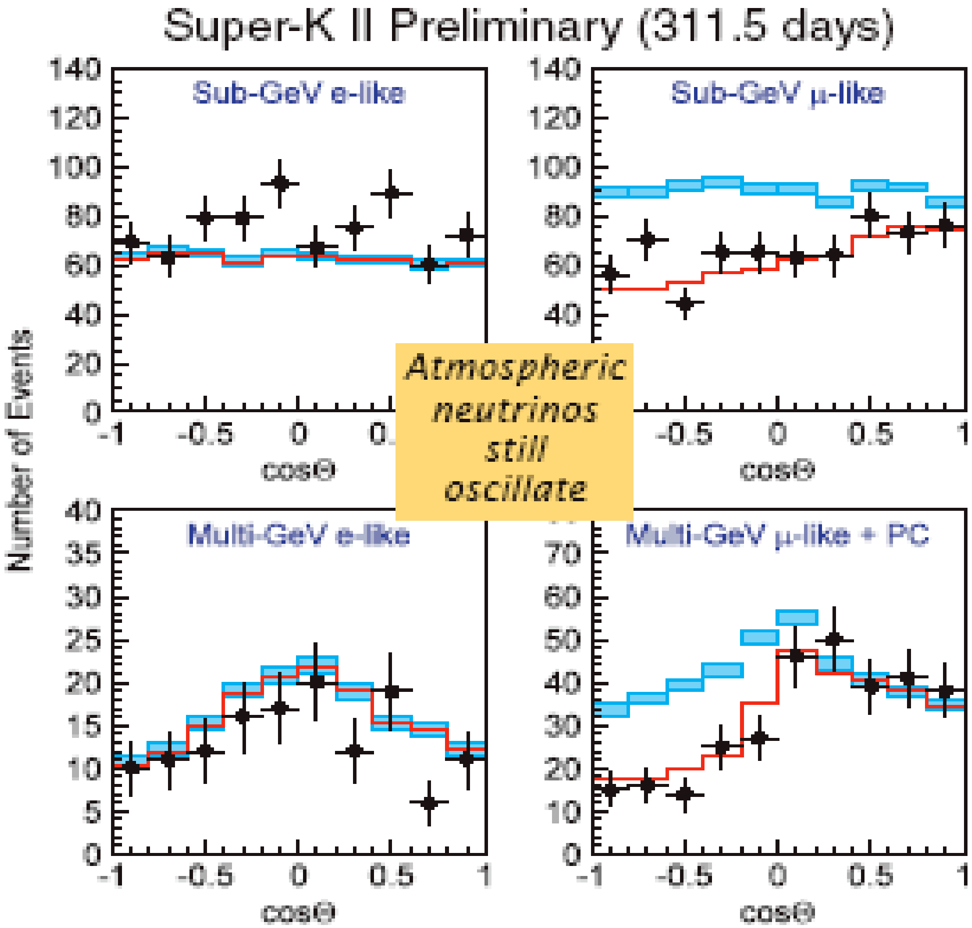


~14000 events total from data reduction

	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%

11530 events used (80%) in oscillation analysis

Status of Super-K II Atmospheric Neutrinos



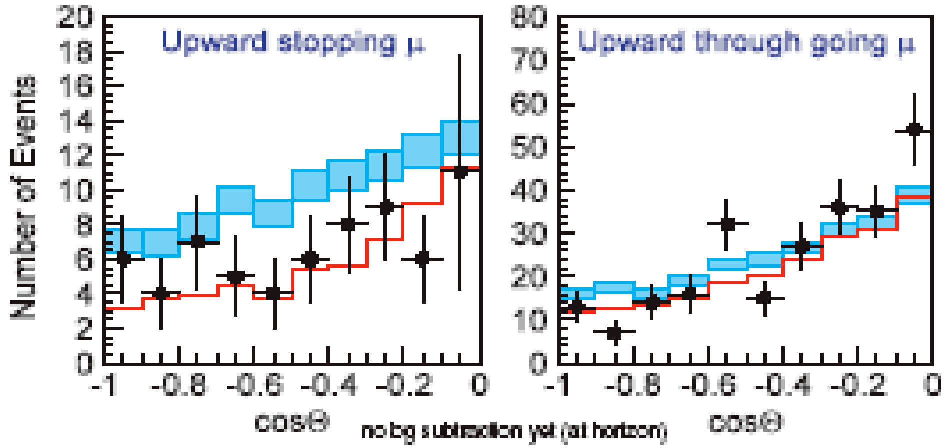
Atmospheric neutrinos still oscillate

FC data reduction:
8.22 ± 0.16 ev/day (cf. 8.17 SK-I)

PC data reduction:
0.51 ± 0.04 ev/day (cf. 0.61 SK-I)

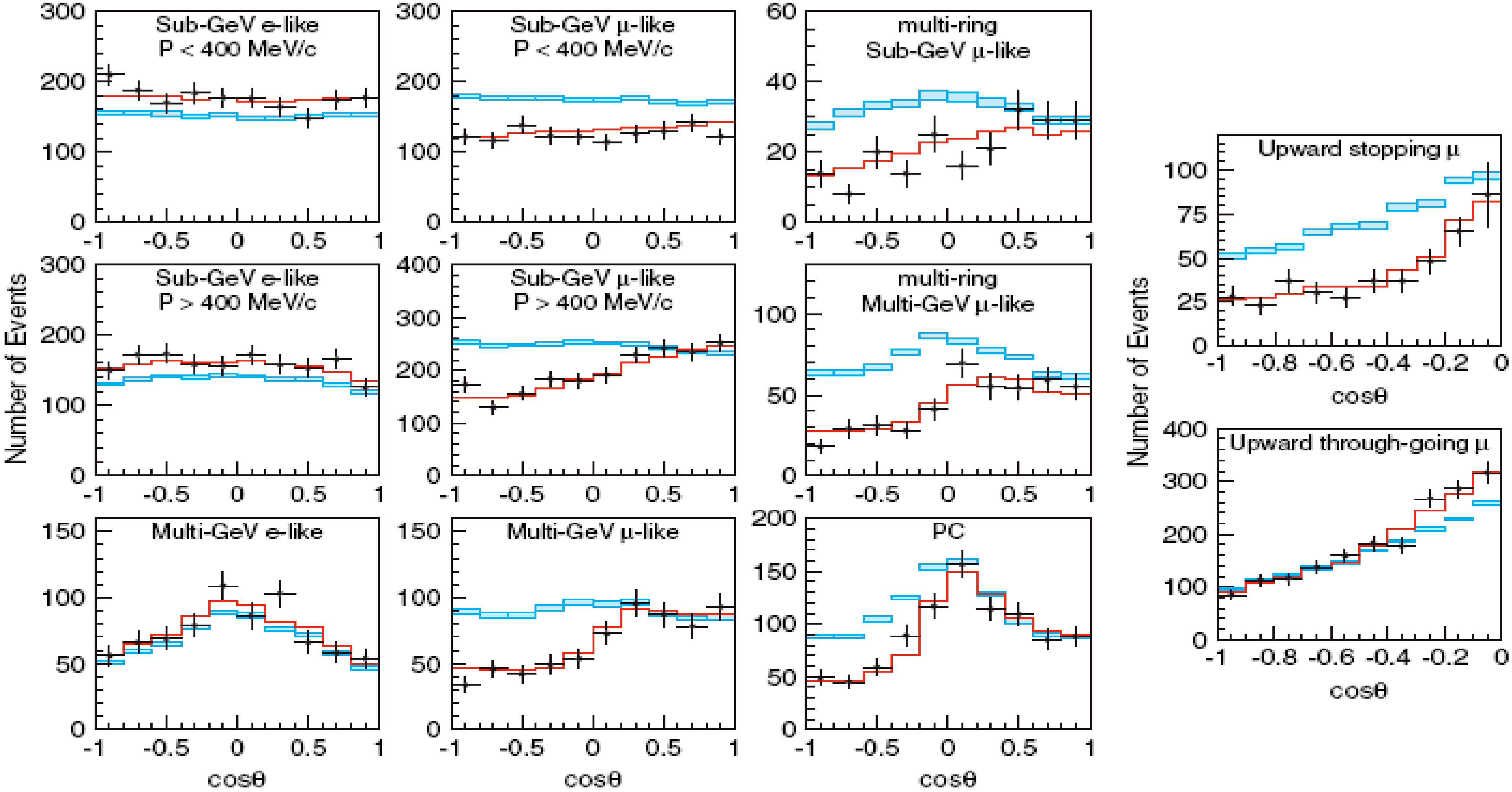
$R_{\text{sub-GeV}} = 0.61 \pm 0.03 \pm 0.05$

$R_{\text{multi-GeV}} = 0.89 \pm 0.10 \pm 0.16$



SK-II data is consistent with SK-I results. e/μ ID, energy scale look very good. Current studies emphasize ring counting, PC reduction, OD simulation.

SK-1 Zenith Angle Distributions

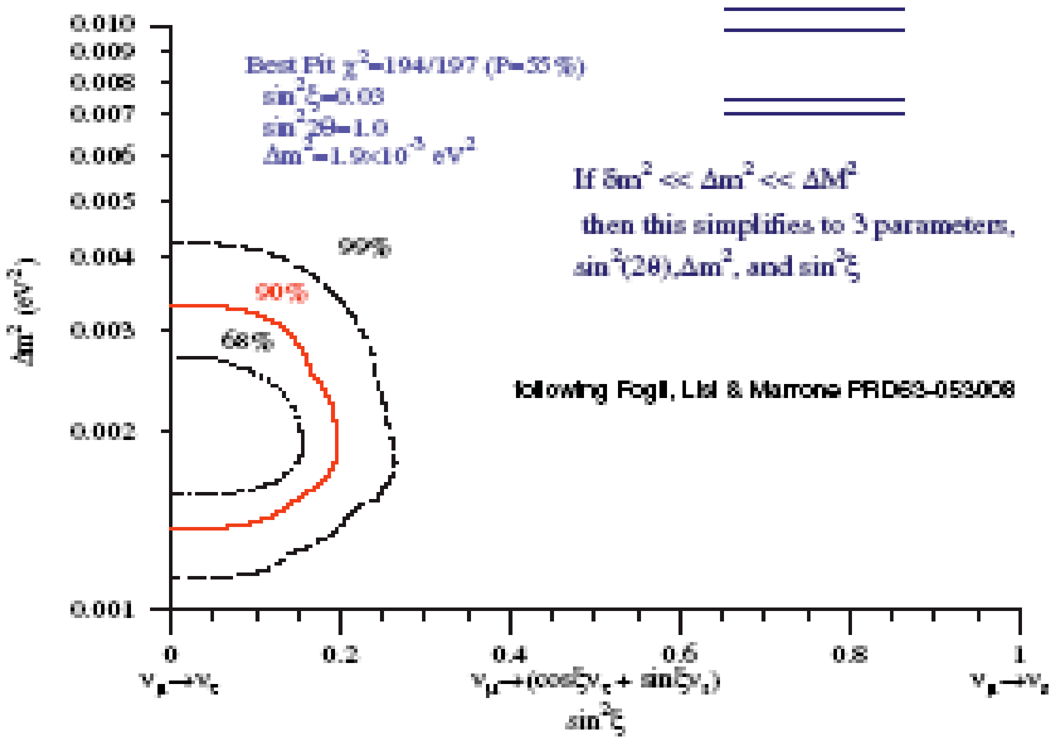


SK. Exotic scenarios

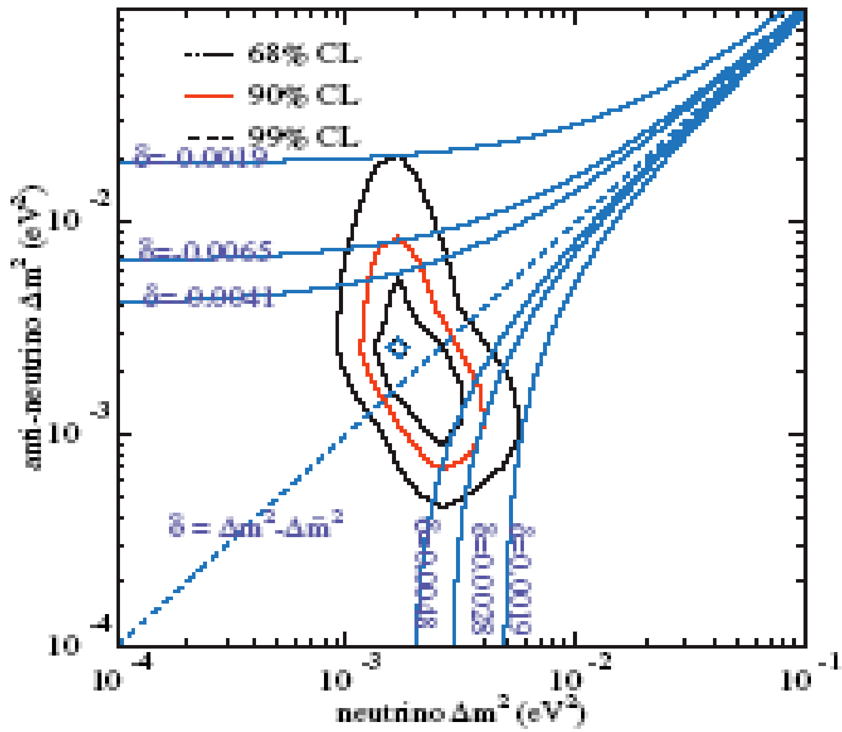
sterile neutrino admixture

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

δm^2 - Solar Neutrinos ($< 10^{-4}$ eV^2)
Δm^2 - Atmosperic Neutrinos ($\sim 10^{-3}$-10^{-2} eV^2)
ΔM^2 - LSND (~ 1 eV^2)



CPT violation



atmospheric neutrino dynamic range
very powerful in limiting neutrino exotica

SK. Ratios

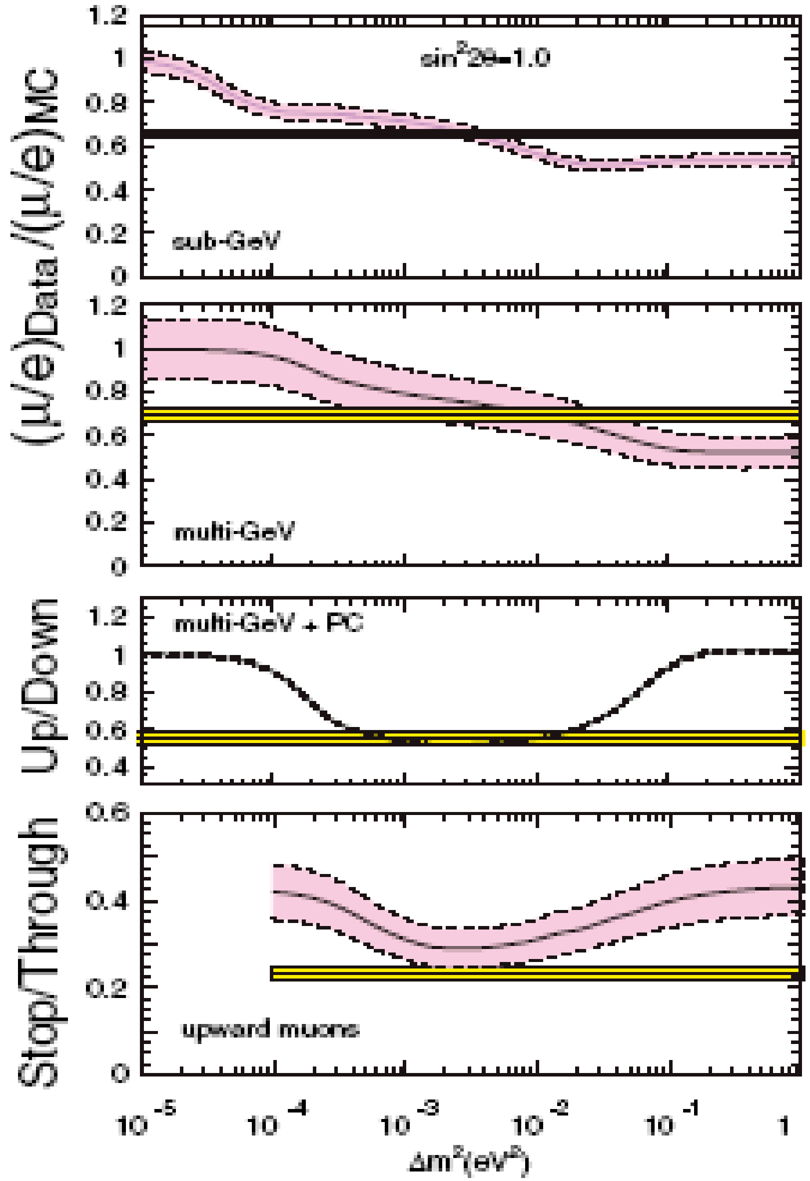
$$R \equiv \frac{(\mu/e)_{DATA}}{(\mu/e)_{M.C.}}$$

$$R_{sub-GeV} = 0.658 \pm 0.016(stat) \pm 0.032(sys)$$

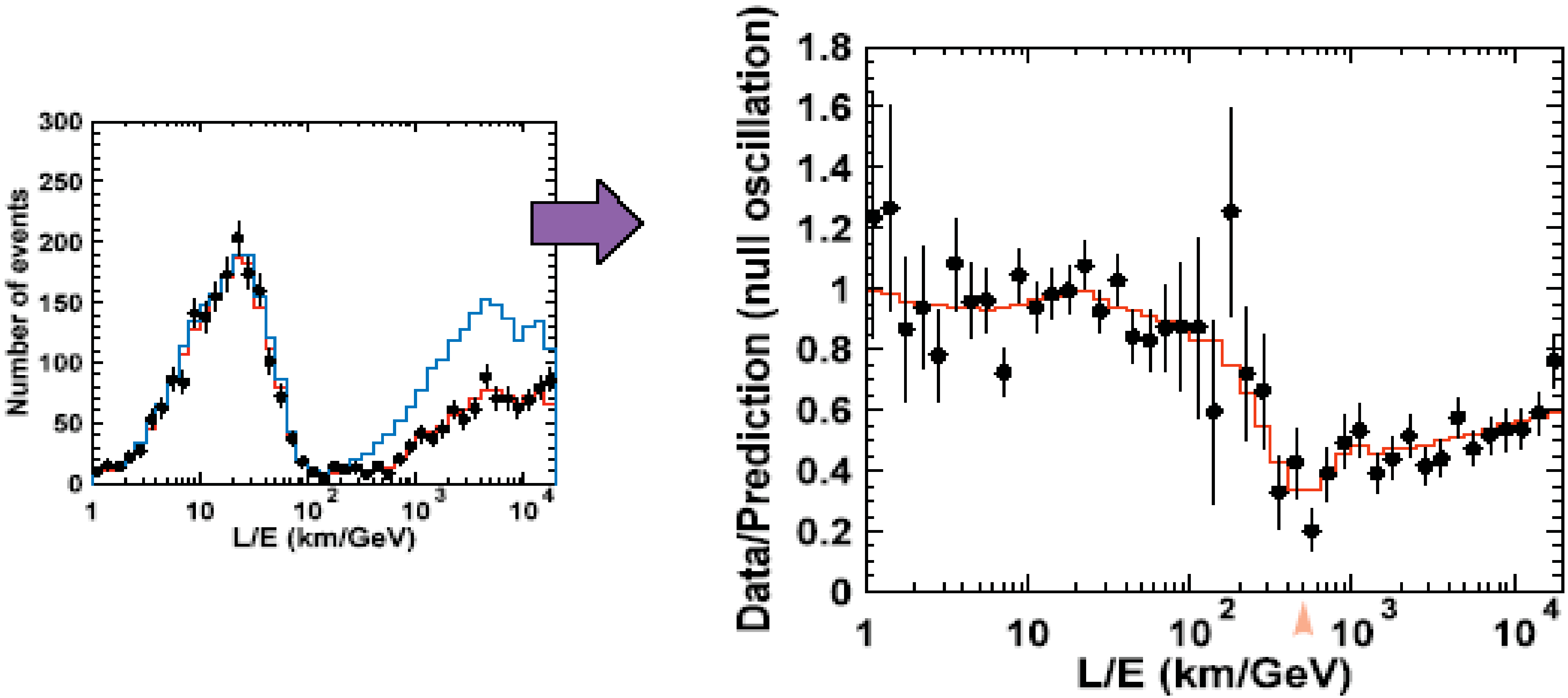
$$R_{multi-GeV} = 0.702^{+0.032}_{-0.030}(stat) \pm 0.099(sys)$$

$$\left(\frac{N_{UP}}{N_{DOWN}}\right)_{Multi-GeV+PC} = 0.55^{+0.035}_{-0.033}(stat) \pm 0.005(sys)$$

$$\frac{\Phi(stop)}{\Phi(through)} = 0.229 \pm 0.015(stat) \pm 0.003(sys)$$



SK. L/E_ν distribution



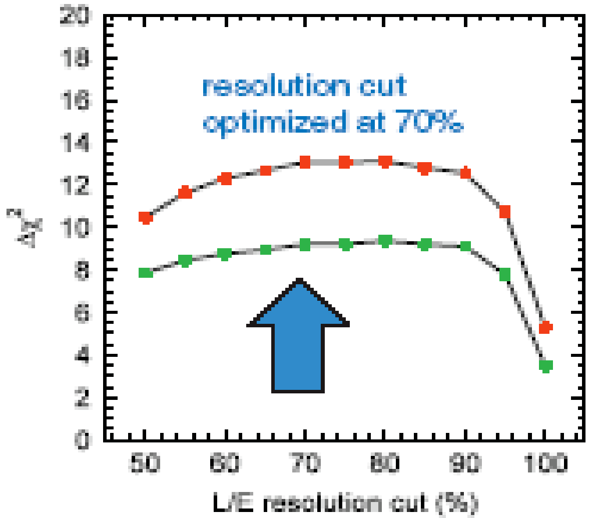
oscillation dip seen at ~500 km/GeV

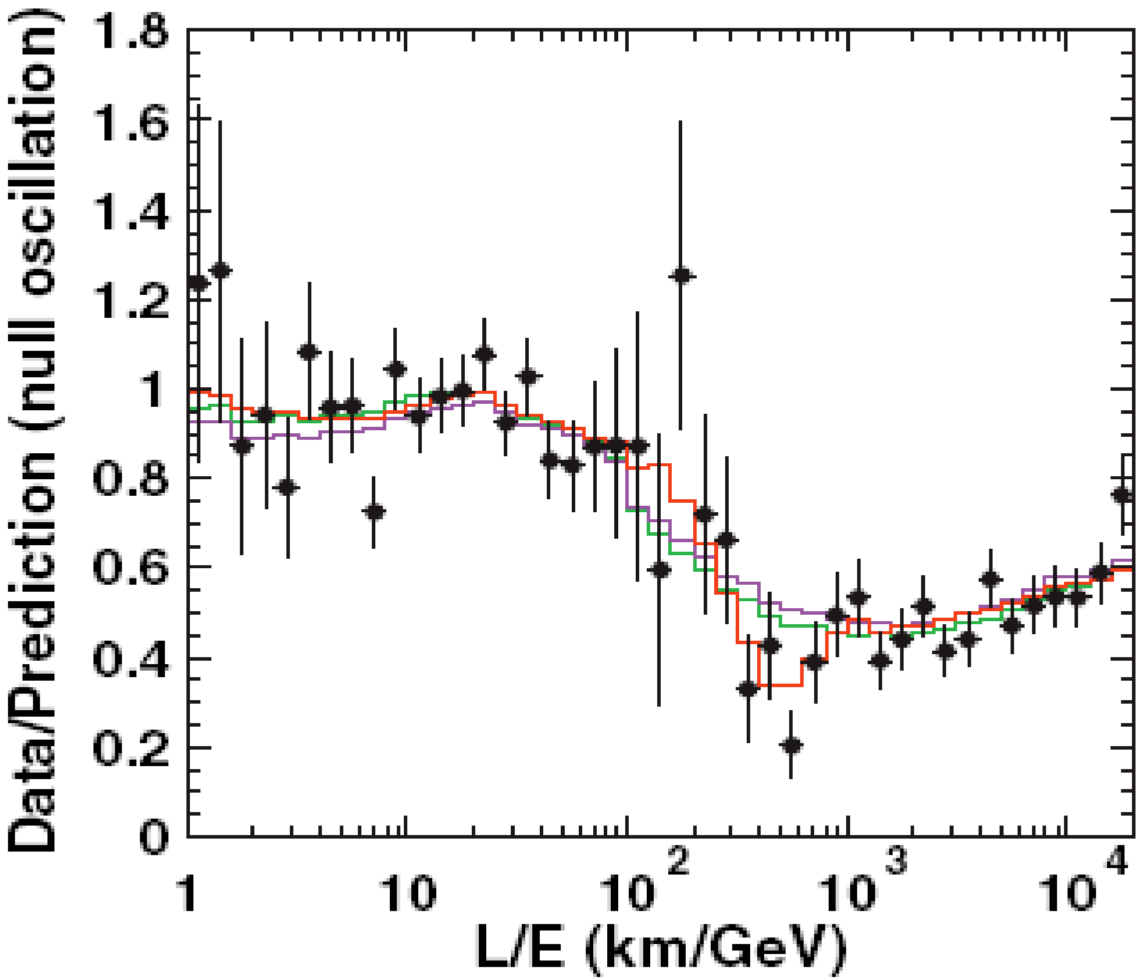
SK - L/E$_\nu$ significance

To evaluate significance of oscillation signature, we need a comparison shape (no oscillations too strongly ruled out by high L/E data)

Fit against: neutrino decay
neutrino decoherence

Barger et al: PRD54 (1996) 1
Barger et al: PLB462 (1999) 462
Grossman and Worah: hep-ph/9807511
Lisi et al: PRL85 (2000) 1166



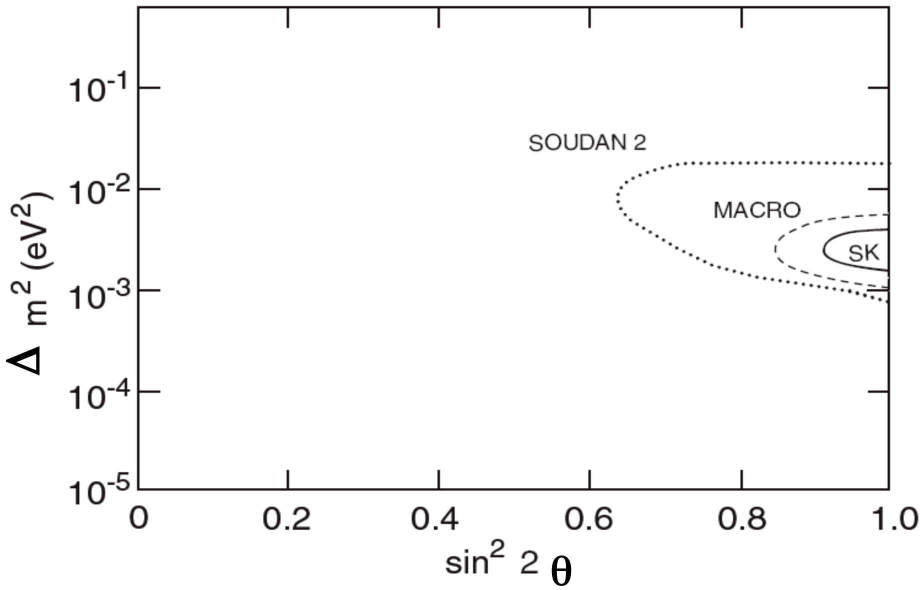


Decay rejected at 3.4σ
Decoherence rejected at 3.8σ

6. Discussion, Conclusions and Outlook

Atmospheric neutrino data favor 2-flavor oscillations with

- **maximal mixing**
- $\Delta m_{23}^2 =$
  - **Soudan2** 5.2 $10^{-3}\,eV^2$
  - **MACRO** 2.3 "
  - **SK** 2.4 "
  - **K2K** 2.7 "



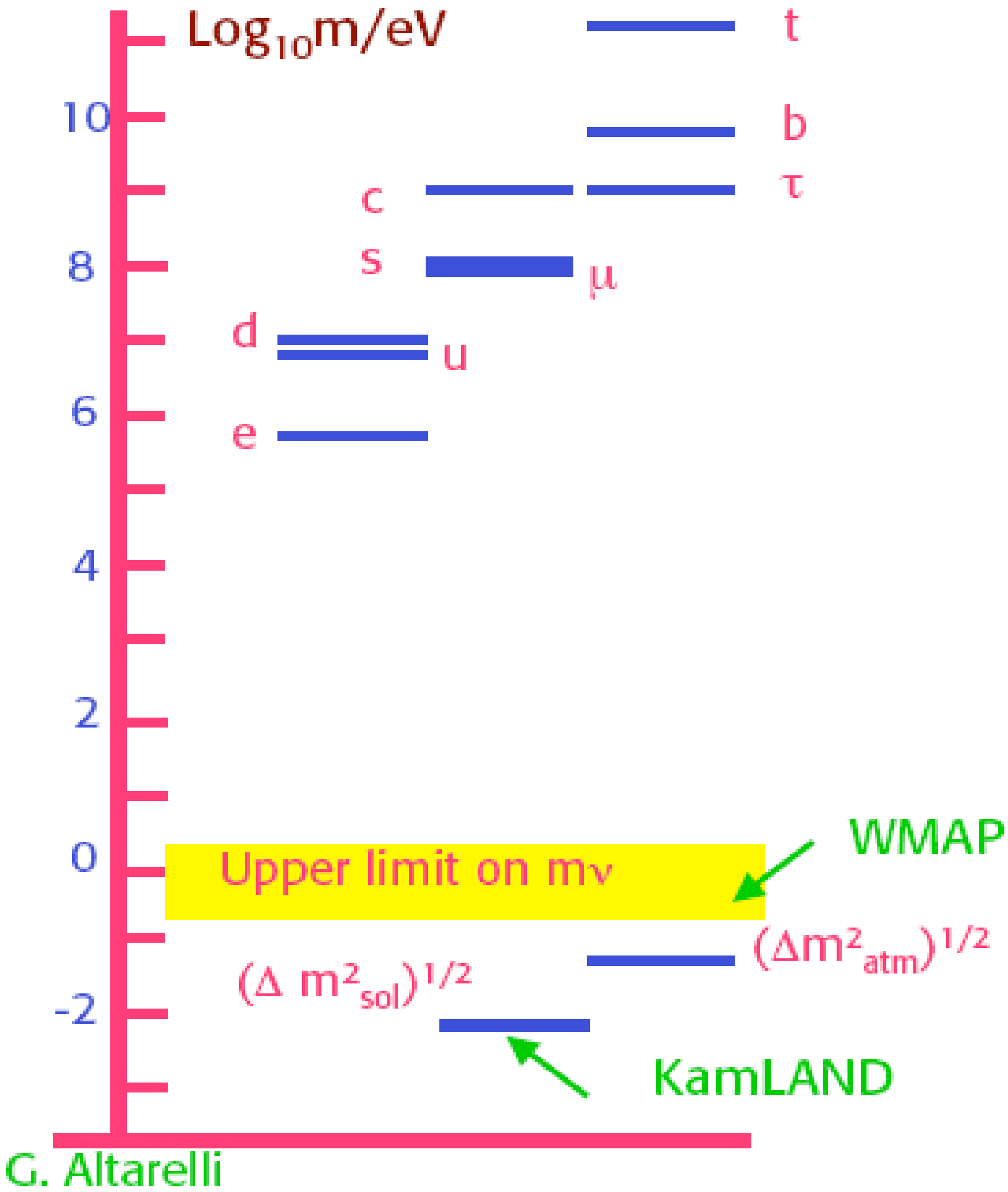
No $\nu_\mu \rightarrow \nu_\sigma$ oscillations (MACRO, SK)

Oscillation pattern in L/E_ν (SK,MINOS)

More exotic scenarios:

- **Lorentz invariance violation : mixing between flavor and velocity eigenstates (MACRO, SK,...)**
- **neutrino radiative decay (NOTTE,...)**

Appearance experiments $\nu_\mu \rightarrow \nu_\tau$ (OPERA, ICARUS,...)



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m \sim m_t \sim v \sim 200$ GeV

M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV

$m \sim v \sim 200$ GeV

$M \sim 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

G. Altarelli