Neutrino Physics

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Part 1: Neutrino oscillation in vacuum

- Introduction: neutrino mass, mixing and oscillation
- Atmospheric neutrinos and accelerator neutrinos

Some Historical Remarks

- 1930: neutrino postulated by Pauli (massless, neutral)
- 1956: neutrino ν_e detected by Reines and Cowan

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

- 1957: Wu discovered parity violation in weak interaction
- 1958: Goldhaber experiment neutrinos are left handed anti-neutrinos right handed

3 Neutrino Flavors

- 1960: B. Pontecorvo and M. Schwartz proposed neutrino beam (from accelerated protons)
  → discovery of ν_μ at AGS in Brookhaven by Ledermann, Schwartz and Steinberger

- LEP measurement of Z^0 decay width:
  → 3 active neutrino flavors ($m_\nu < 80$ GeV): $N_\nu = 3.00 \pm 0.06$
  ν_e, ν_μ, ν_τ

- 2000: ν_τ detected by DONUT experiment

Neutrinos in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

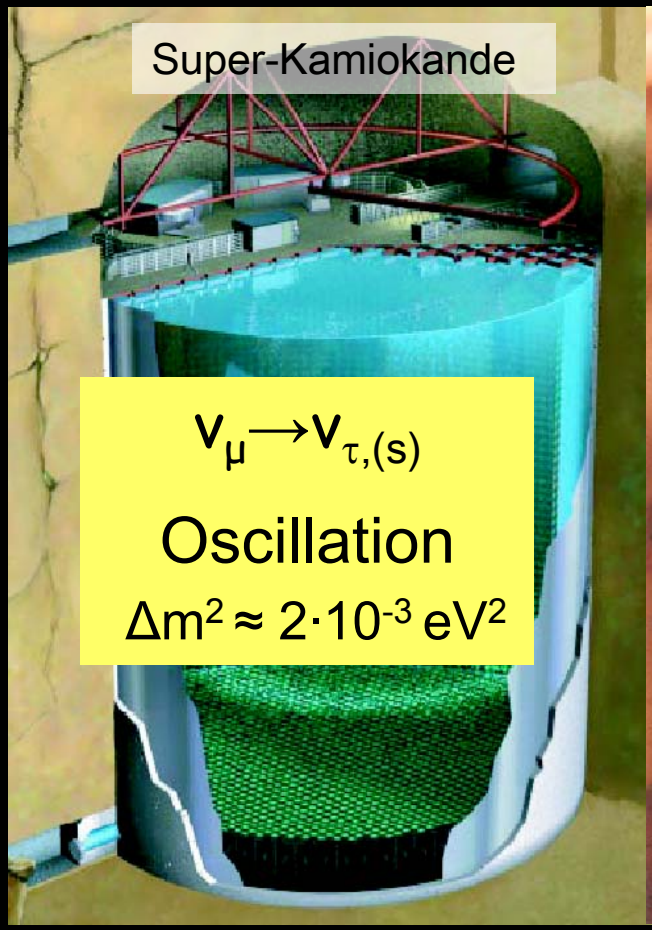
$$(u)_R, (d)_R, (c)_R, (s)_R, (t)_R, (b)_R$$

$$(e^-)_R, (\mu^-)_R, (\tau^-)_R$$

- No right handed neutrinos ?
- Neutrinos are massless
- L_e, L_μ, L_τ conserved

Neutrino Oscillations were observed
→ Neutrinos have mass!

JAPAN

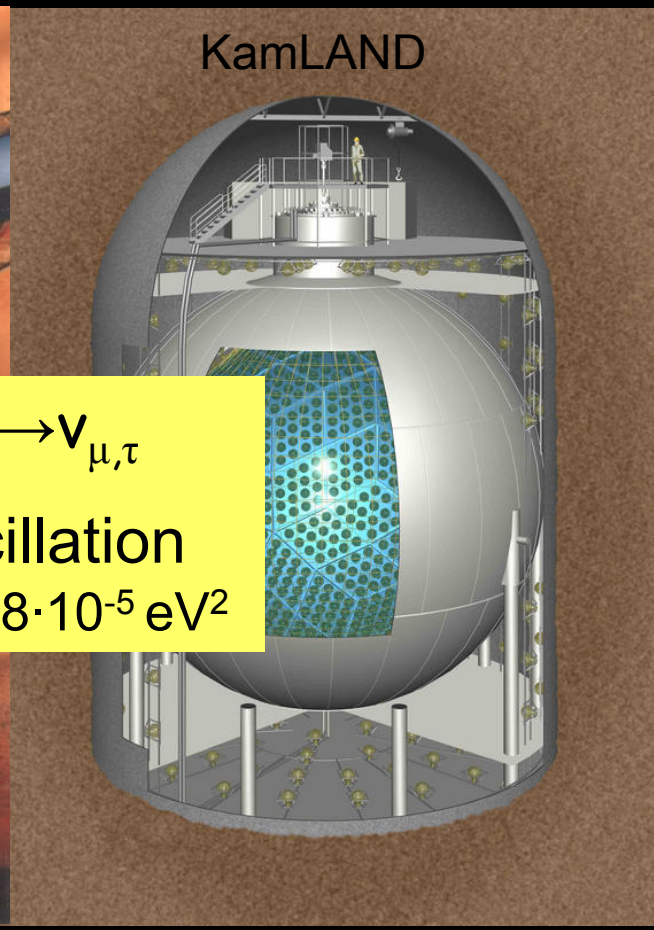


atmospheric neutrinos
accelerator neutrinos

CANADA

solar neutrinos

JAPAN



reactor neutrinos

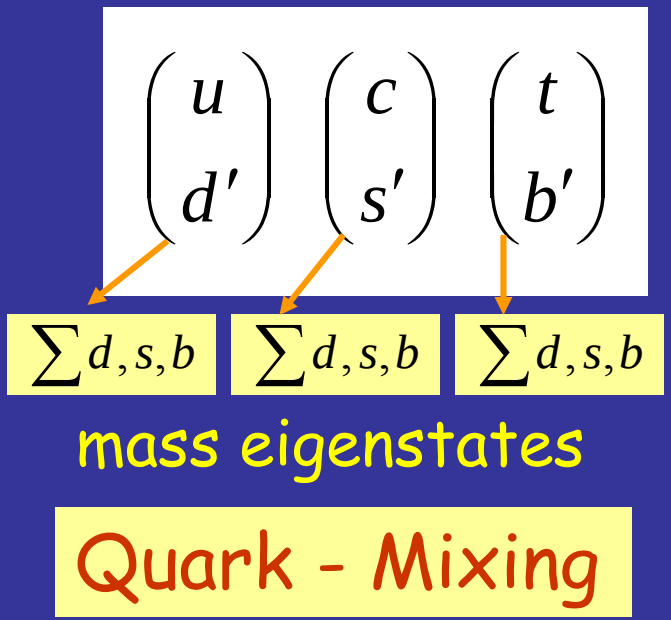
Neutrino Oscillations are a consequence of neutrino mass and mixing

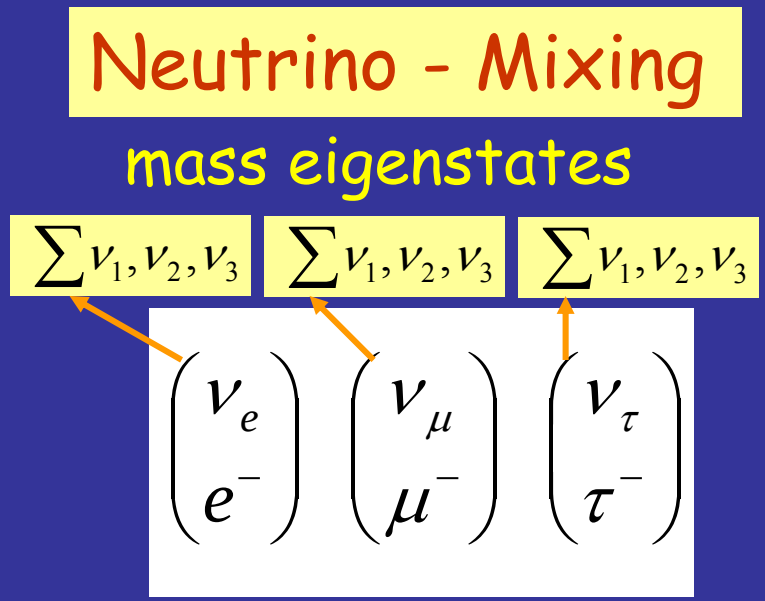
What is neutrino mixing?

→ compare to quark CKM mixing

Quark and Lepton Mixing:

Eigenstates of weak interaction ≠ Eigenstates of mass





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

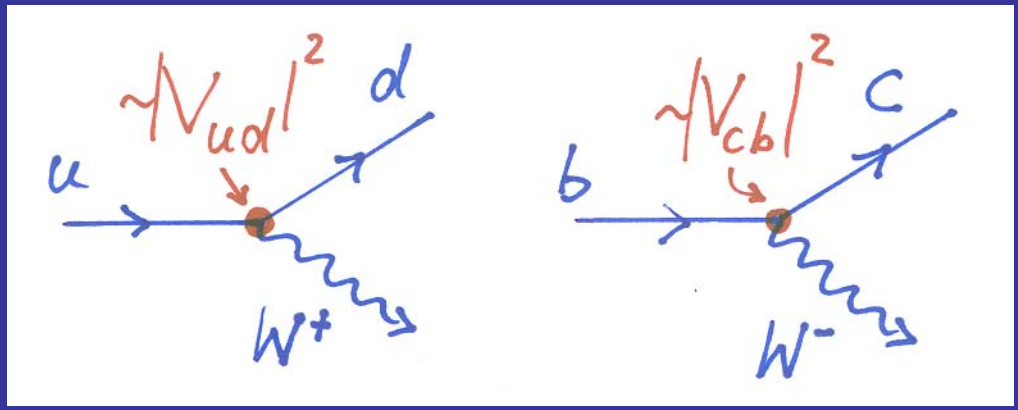
Quark-Mixing

Cabbibo-Kobayashi-Maskawa (CKM) Matrix

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

- 3 mixing angles
- 1 phase: $e^{i\delta}$ CP-violation

BELLE, BABAR, CLEO,...



in precision measurement phase

Hierarchy in Quark Mixing

- of masses: $m_d \ll m_s \ll m_b$
- of mixing angles: $s_{12} = \lambda,\ s_{23} \approx \lambda^2,\ s_{13} \approx \lambda^3$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Neutrino mass and mixing

3 massive neutrinos: ν_1, ν_2, ν_3 with masses: m_1, m_2, m_3

Flavor-Eigenstates $\nu_e, \nu_\mu, \nu_\tau \neq$ Mass-Eigenstates

Neutrino mixing!

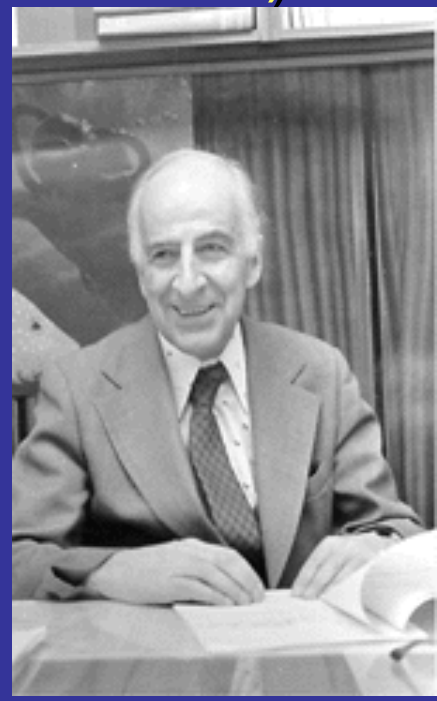
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Historical remark

- 1957-58: B. Pontecorvo proposed neutrino oscillations (because only ν_e was known, he thought of $\nu \leftrightarrow$ anti-ν)

- 1962 Maki, Nakagawa, Sakata described the 2 flavor mixing and discussed neutrino flavor transition

- 1967 full discussion of 2 flavor mixing, possibility of solar neutrino oscillations, question of sterile neutrinos by B. Pontecorvo



Parametrization of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 Mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac-Phase (CP violating): δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

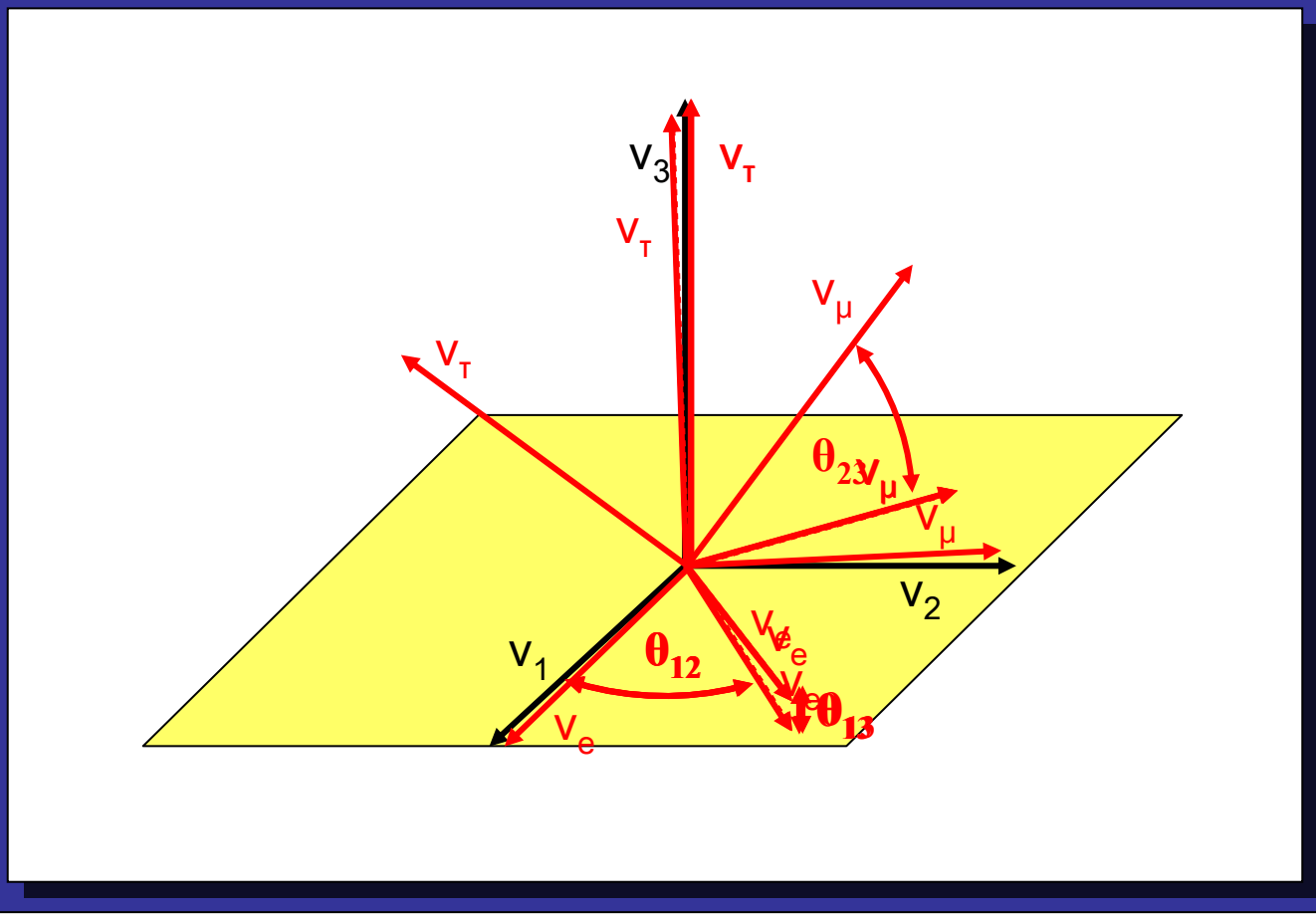
θ_{atm} θ_{13}, δ θ_{sol}

If neutrinos are Majorana particles:

- 2 additional Majorana-Phases (CPV): α_1, α_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_1} & s_{13}e^{-i\delta}e^{i\alpha_2} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & [c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & s_{23}c_{13}e^{i\alpha_2} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & [-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & c_{23}c_{13}e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mixing angles



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Θ_{23}: 34° - 58°

θ_{13}<13°, δ ?

θ_{12}: 29° - 39°

Atmospheric and accelerator | **Unknown (CHOOZ)** | **Solar and reactor experiments**

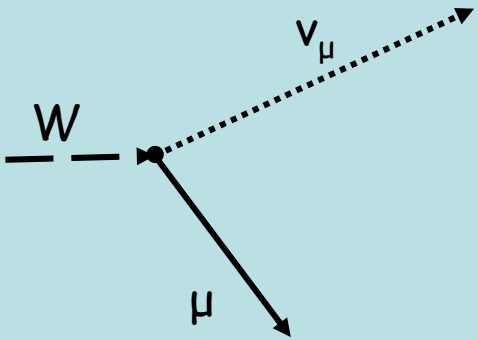
Neutrino Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

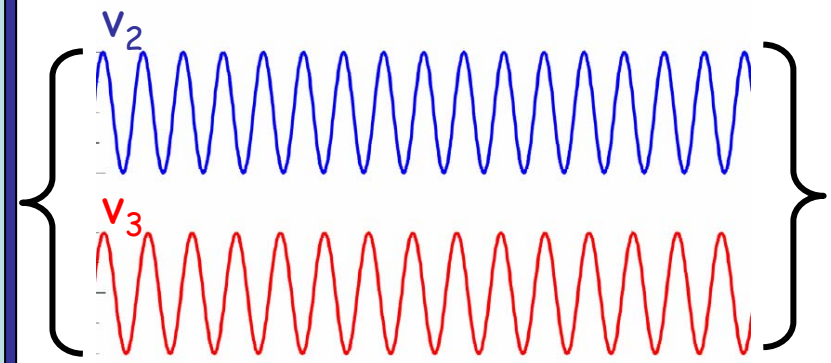
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2,ν_3 with m_2, m_3

source creates flavor-eigenstates



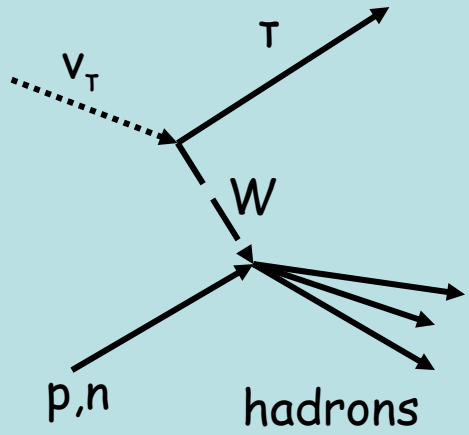
propagation determined by mass-eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates



General derivation of oscillation formula:

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U_{\alpha k} |\nu_k\rangle$$

α = e, μ, τ

k = 1, 2, 3

$|\nu_k\rangle$ neutrinos with negative helicity, mass m_k, momentum p and energy

$$E_k = \sqrt{p^2 + m_k^2} \cong p + \frac{m_k^2}{2p}$$

$$|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{k=1}^{3} U_{\alpha k} e^{-iE_k t} |\nu_k\rangle$$ now change to flavor base →

$$|\nu_\alpha(t)\rangle = \sum_{\beta} \left(\sum_{k=1}^{3} U^*_{\beta k} e^{-iE_k t} U_{\alpha k} \right) |\nu_\beta\rangle$$

$A_{\nu_\alpha \to \nu_\beta}$ is the amplitude for the transition $\nu_\alpha \to \nu_\beta$ at time t

General derivation of oscillation formula:

$$P_{\nu_\alpha \to \nu_\beta} = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \left| \sum_{k=1}^{3} U^*_{\beta k} e^{-iE_k t} U_{\alpha k} \right|^2$$

using $\sum_{k=1}^{3} U^*_{\beta k} U_{\alpha k} = \delta_{\alpha\beta}$ and $\Delta m^2_{kj} = m^2_k - m^2_j$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E} \right)$$

$$+ 2 \sum_{i>j} \Im(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E} \right)$$

2 Flavor Neutrino Oscillations

Oscillation probability

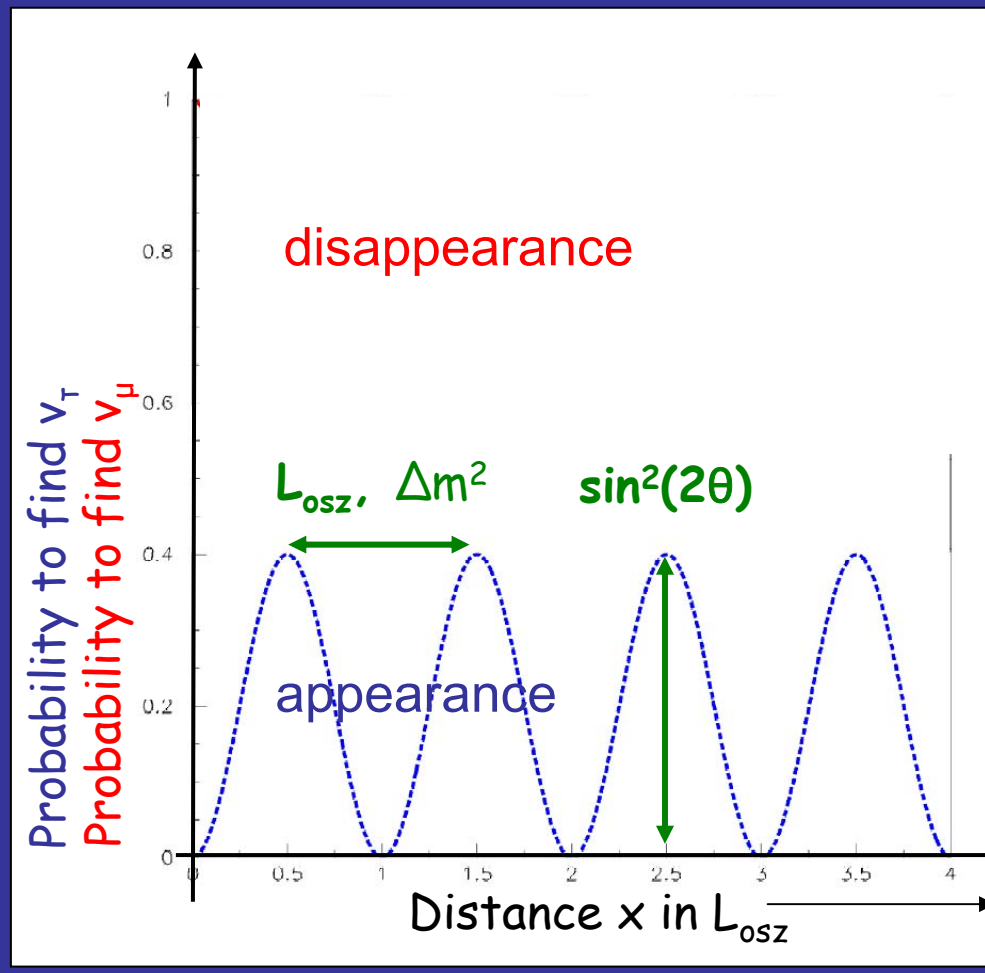
$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

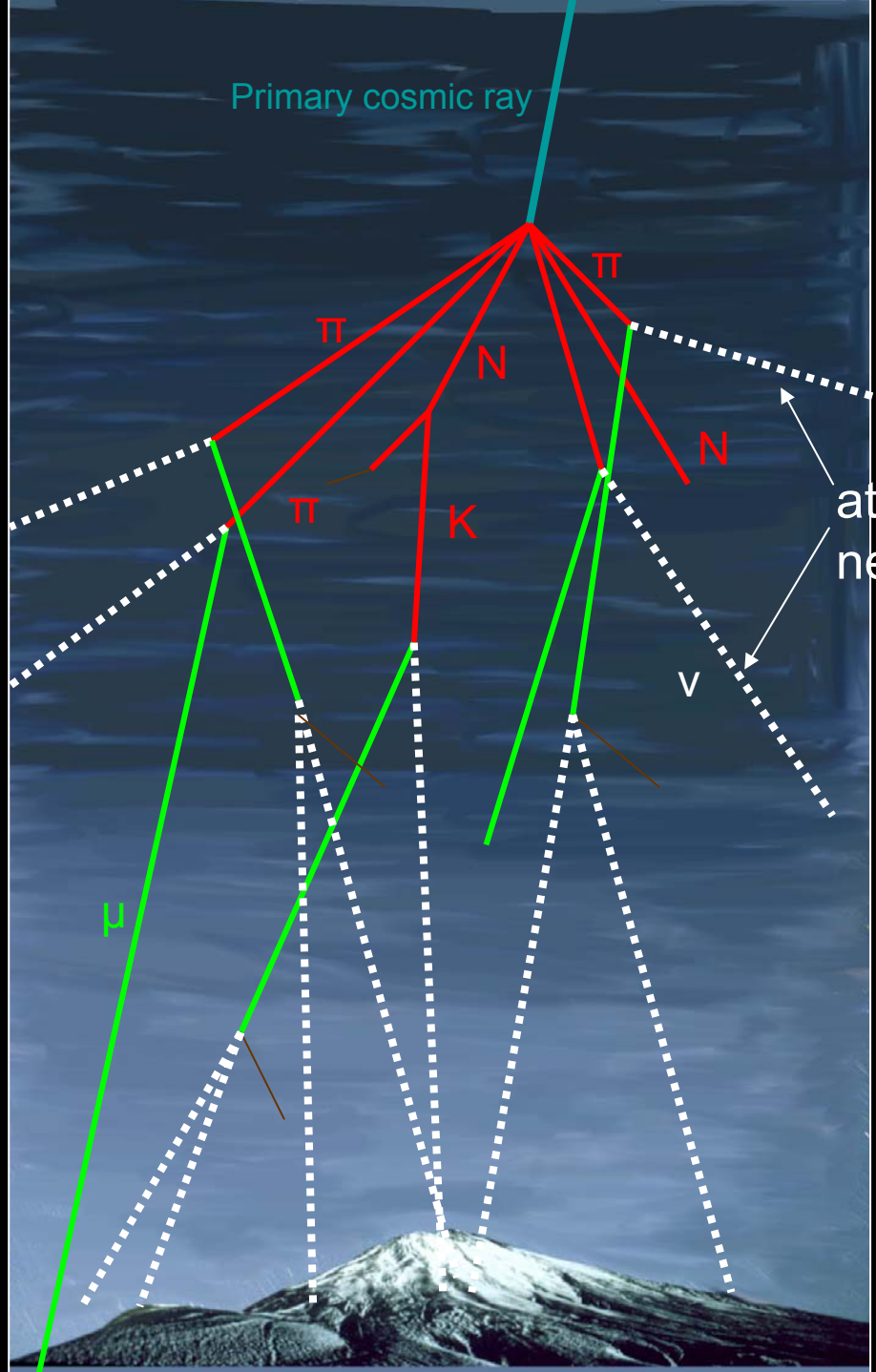
Survival probability

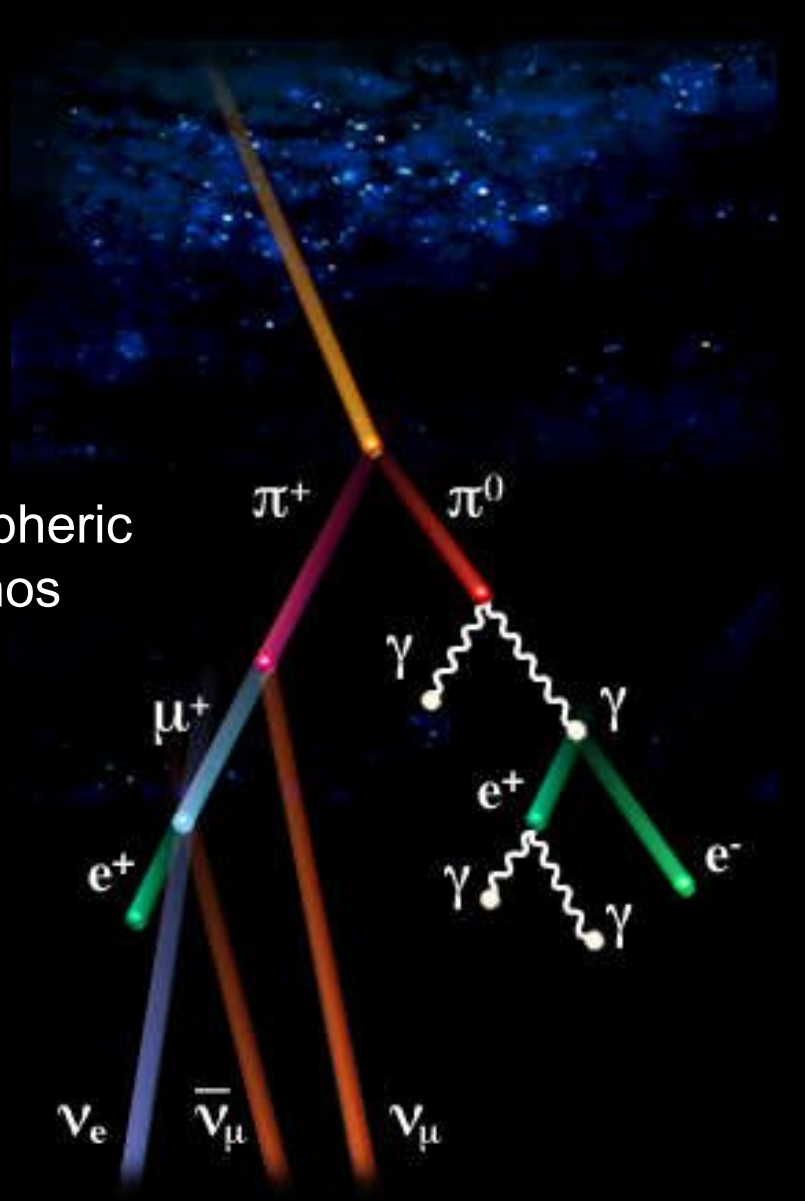
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

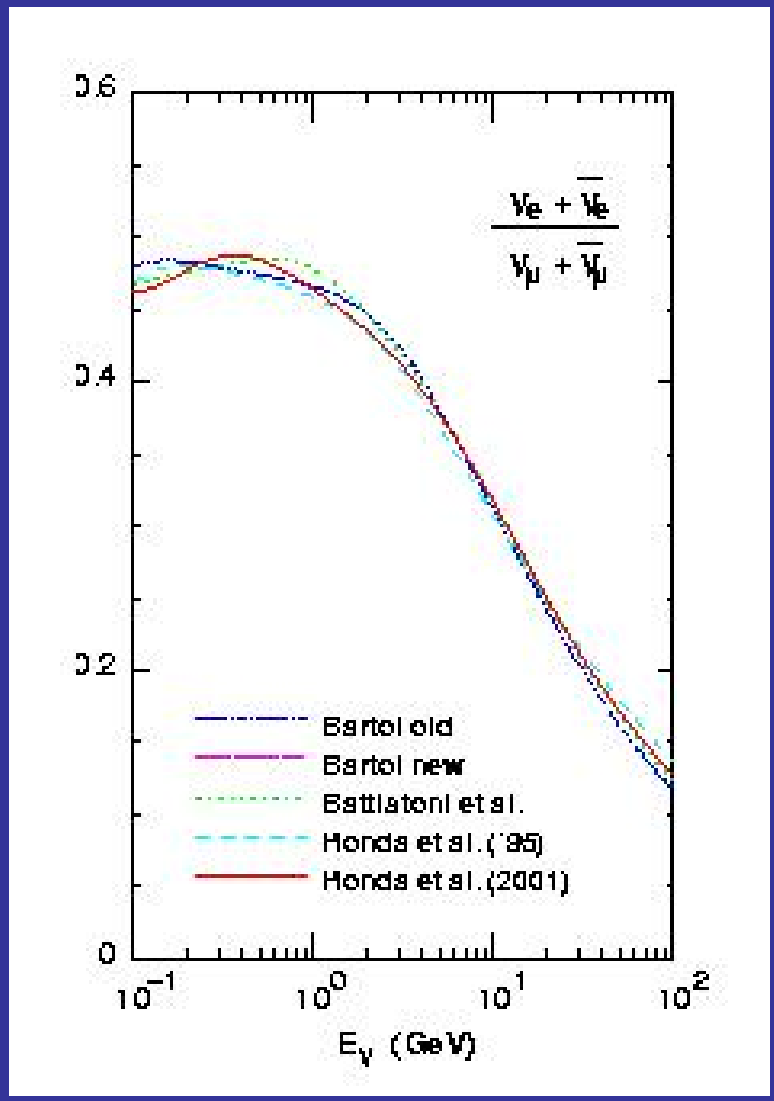
$$\Delta m^2 = m_2^2 - m_3^2$$





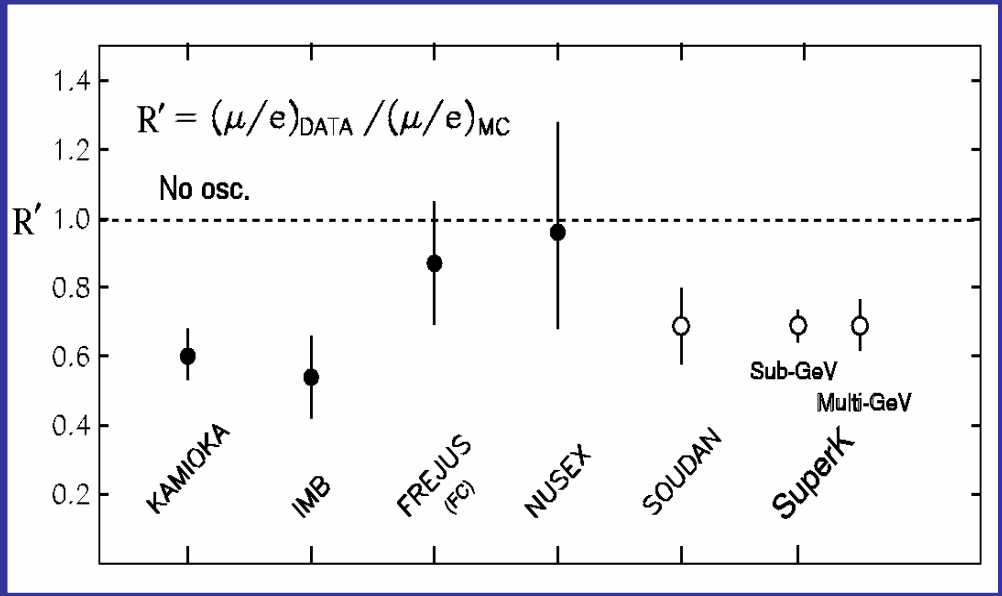


$\#(\nu_\mu) / \#(\nu_e) \approx 2$


0.6
0.4
0.2
0
$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu}$
Bartol old
Bartol new
Battistoni et al.
Honda et al.('95)
Honda et al.(2001)
10^{-1}
10^{0}
10^{1}
10^{2}
E_ν (GeV)

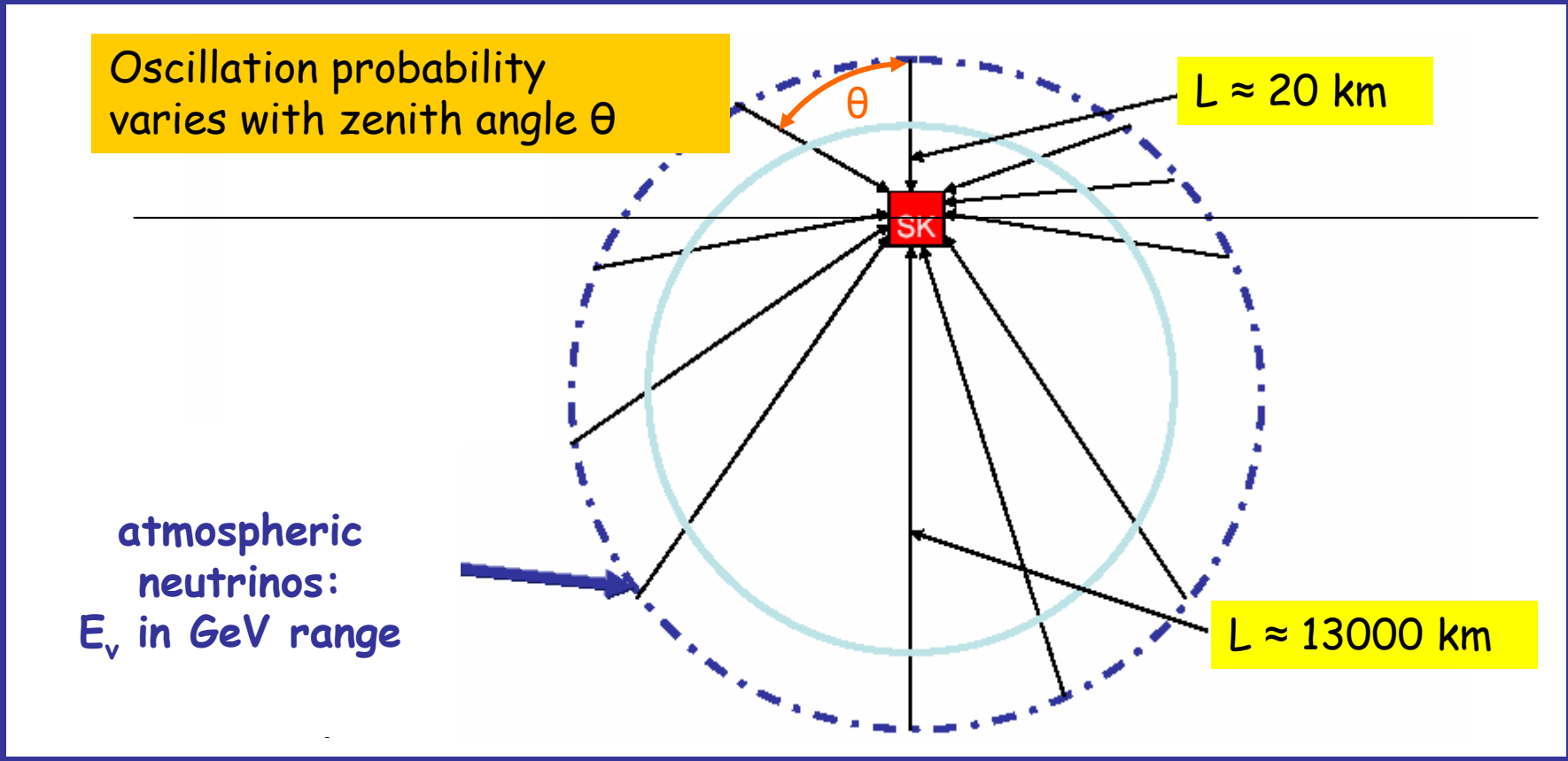
Atmospheric Neutrino History

•In less than two decades, atmospheric neutrinos have gone from being “anomalous” to being one of our main tools for the exploration of the lepton sector.

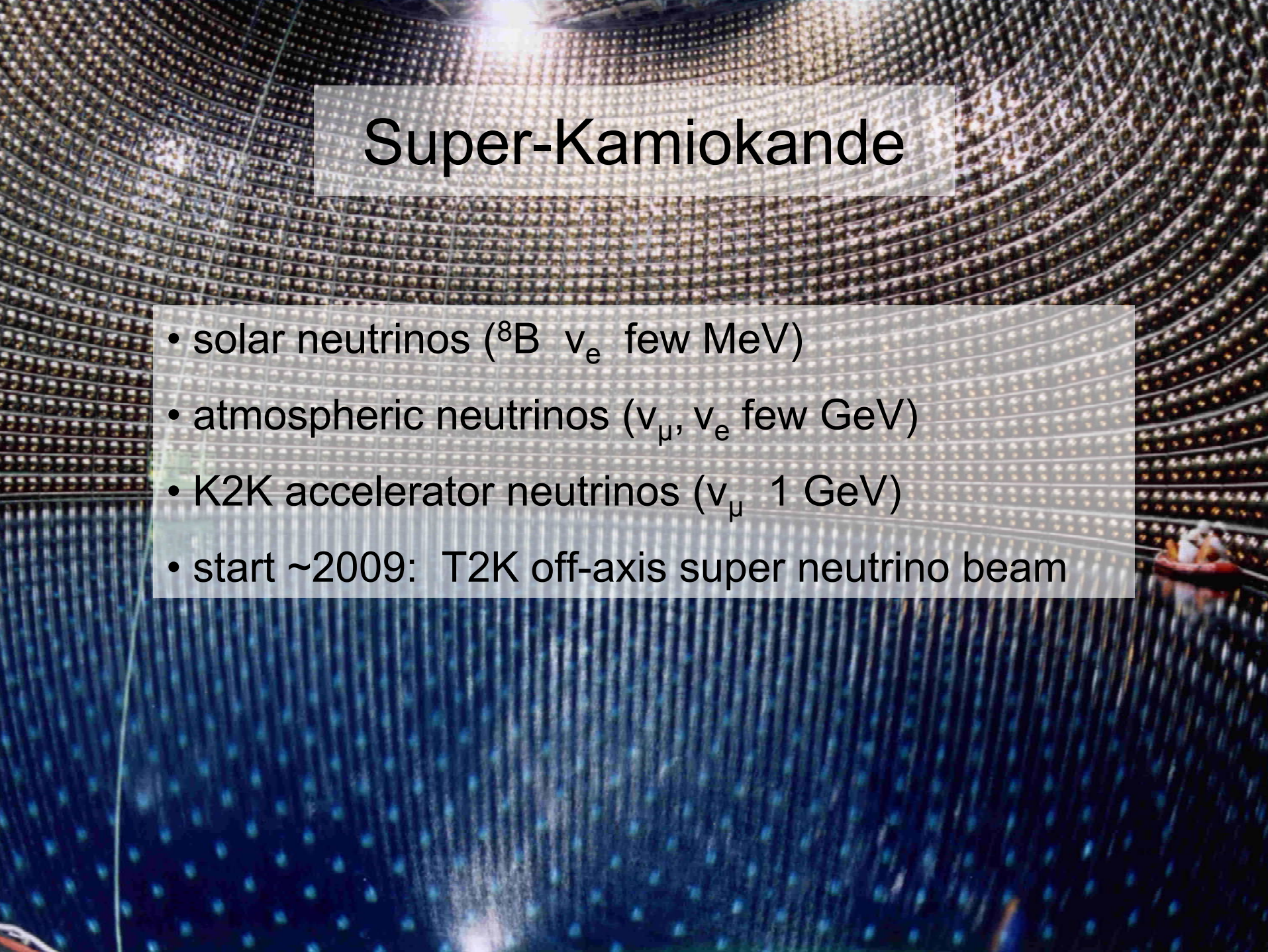


- *1980s – 1990s: Skepticism was rampant!*
- “Neutrino experiments are hard!”
- “Cosmic ray experiments are hard!”
- “Oscillation experiments are hard!”

Oscillation of atmospheric neutrinos

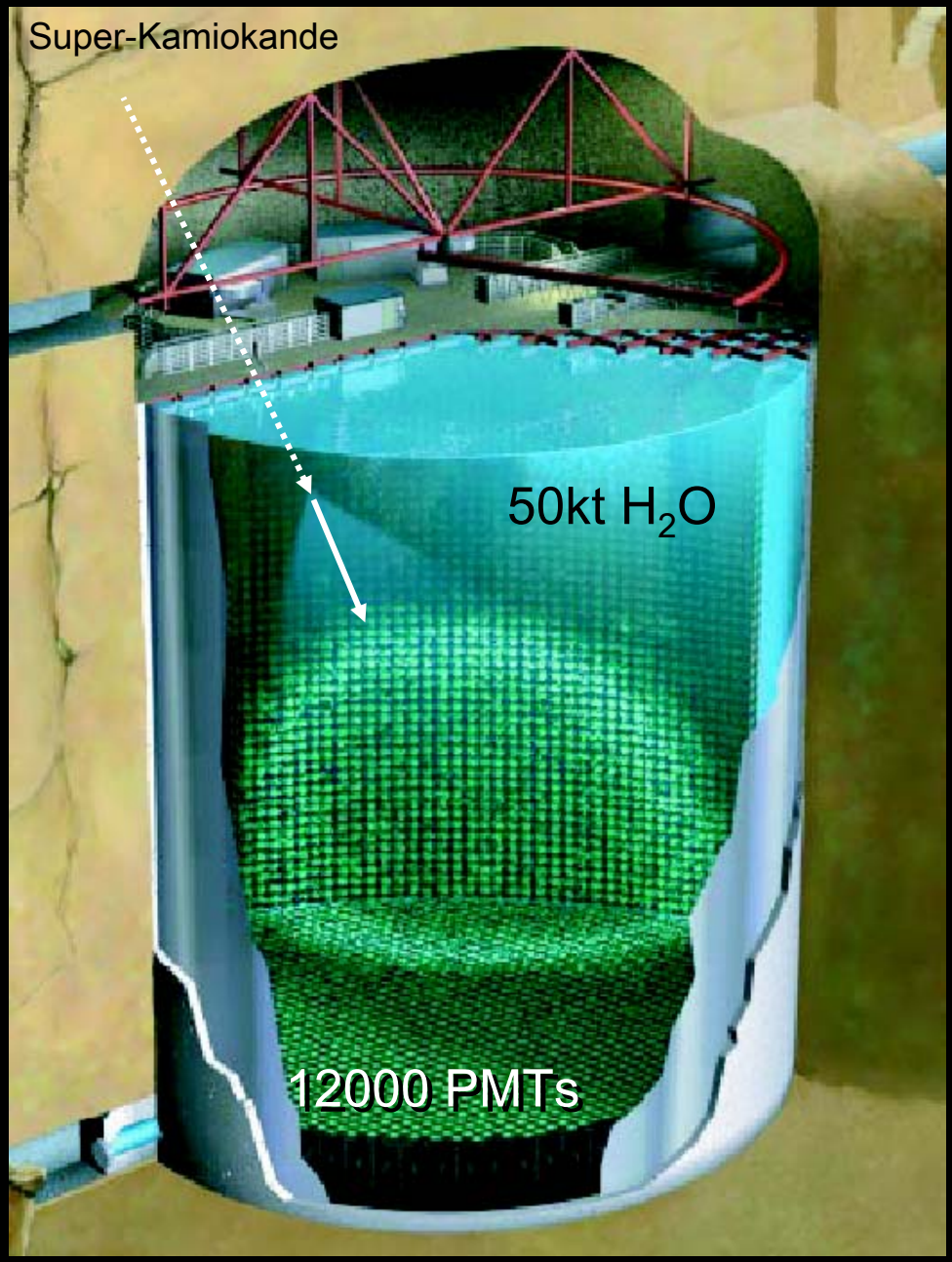


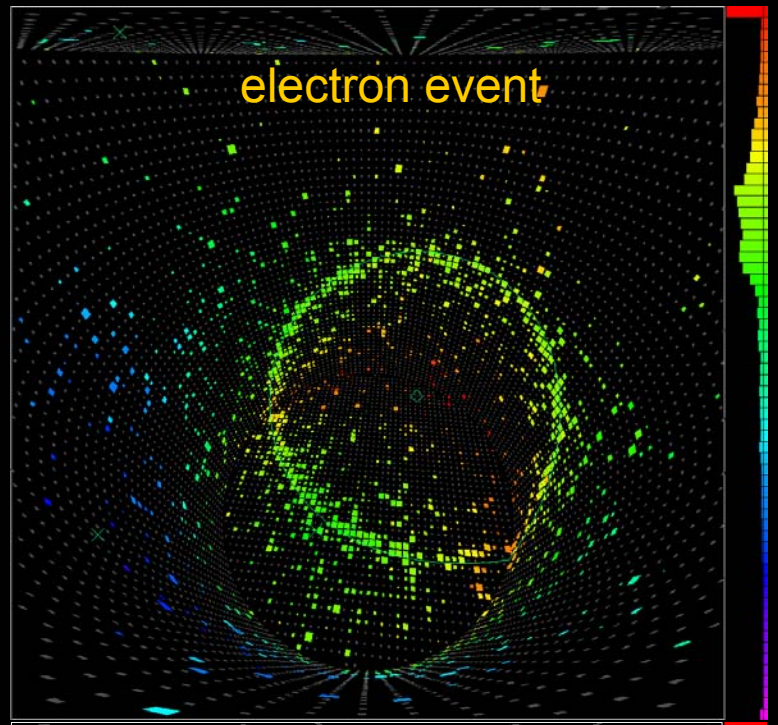
$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{atm} \sin^2\left(\frac{1.27\Delta m^2_{atm}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

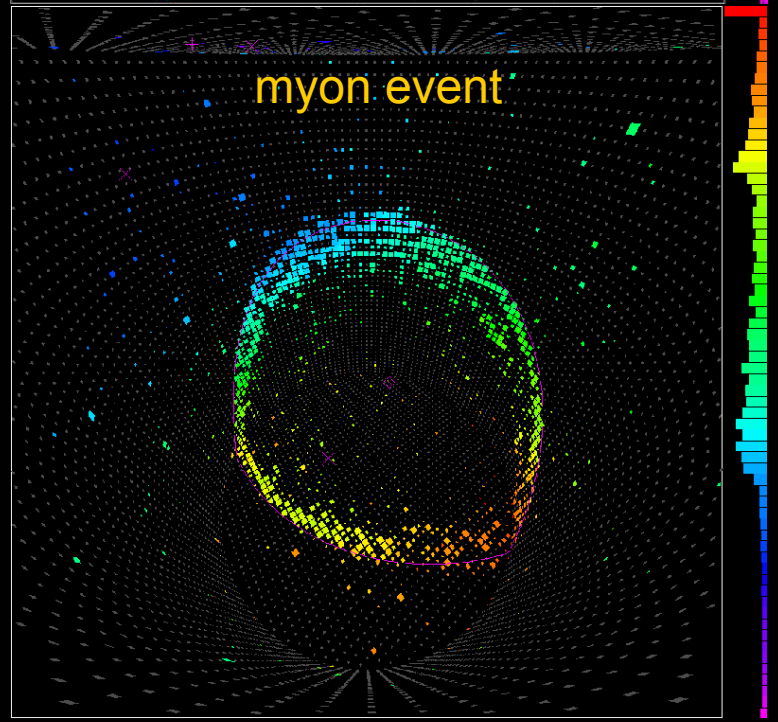


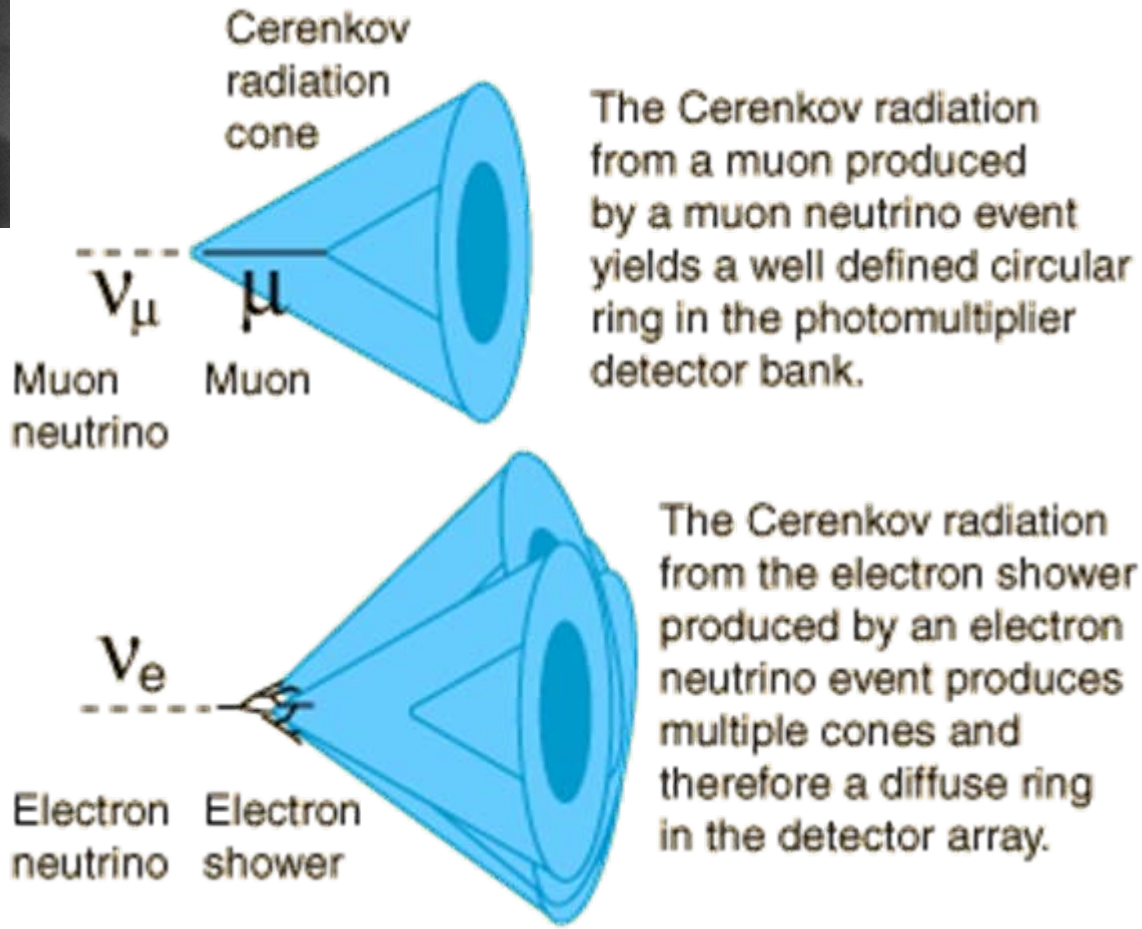
Super-Kamiokande

- solar neutrinos (^{8}B ν_e few MeV)
- atmospheric neutrinos (ν_μ, ν_e few GeV)
- K2K accelerator neutrinos (ν_μ 1 GeV)
- start ~2009: T2K off-axis super neutrino beam


Super-Kamiokande
50kt H_2O
12000 PMTs

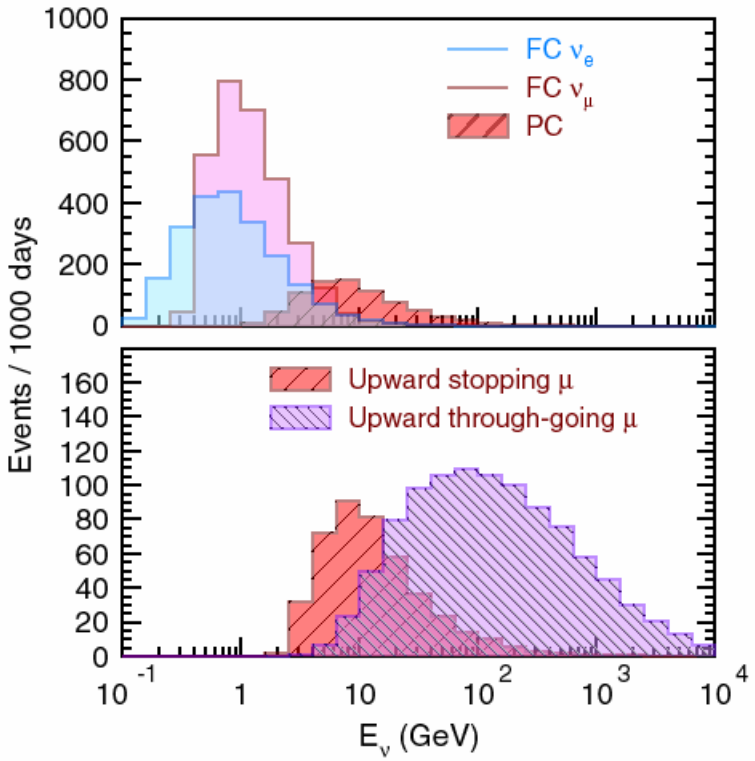

electron event


myon event


Cerenkov
radiation
cone
ν_μ
μ
Muon
neutrino
Muon
The Cerenkov radiation
from a muon produced
by a muon neutrino event
yields a well defined circular
ring in the photomultiplier
detector bank.
ν_e
Electron
neutrino
Electron
shower
The Cerenkov radiation
from the electron shower
produced by an electron
neutrino event produces
multiple cones and
therefore a diffuse ring
in the detector array.

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

Ratios

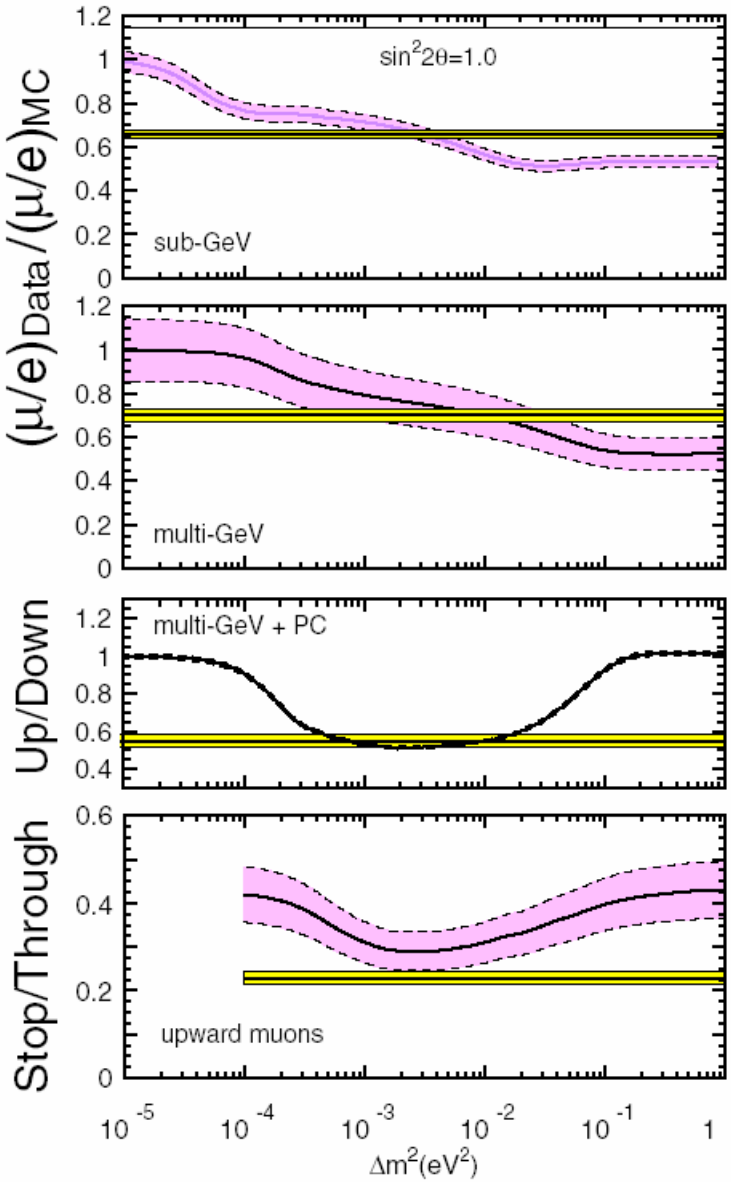
$$R_{sub-GeV} = 0.658 \pm 0.016(stat) \pm 0.032(sys)$$

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

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

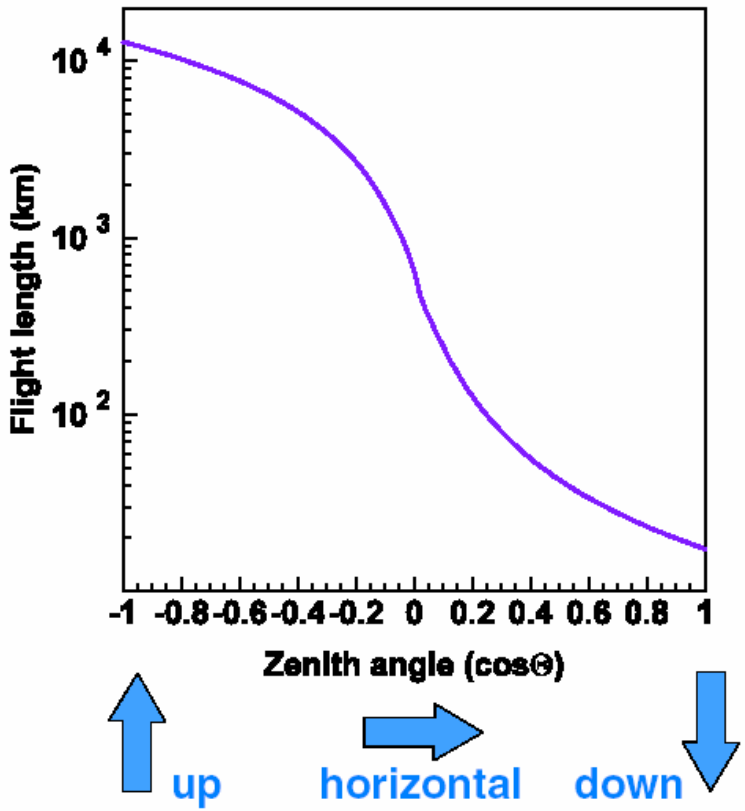
$$\left(\frac{N_{UP}}{N_{DOWN}}\right)_{Multi-GeV+PC} = 0.55^{+0.035}_{-0.033}(stat) \pm 0.005(sys)$$

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

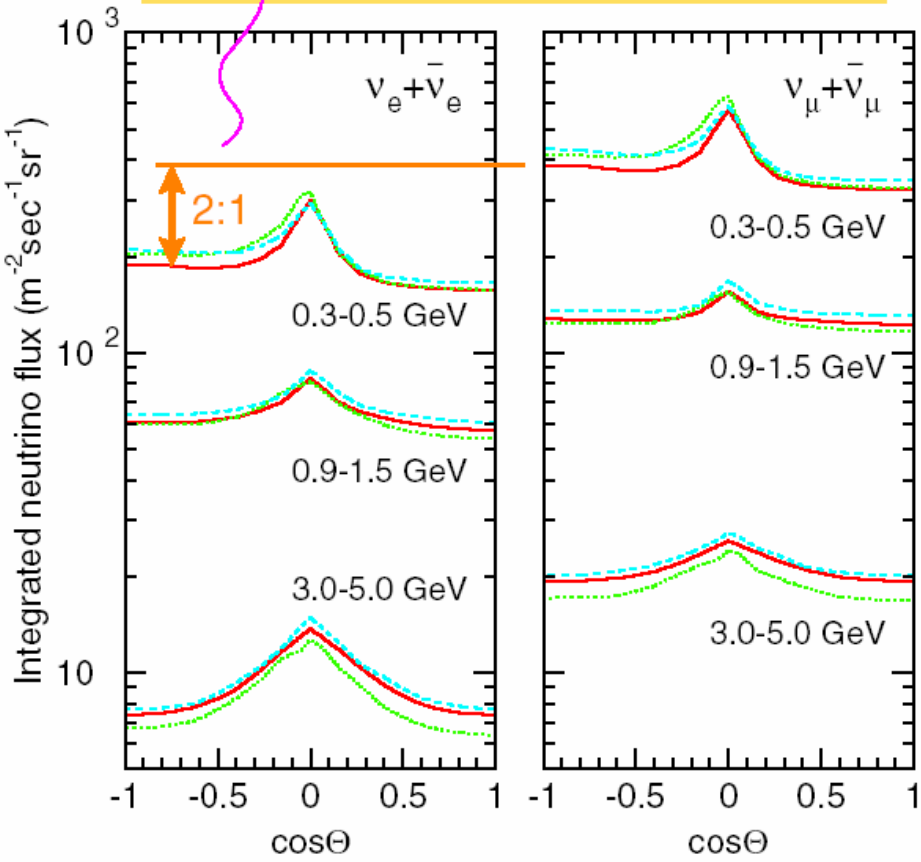


Features of the Atmospheric Neutrino Flux

Three decades of pathlength



Mixed beam of ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$
Well predicted flux ratio

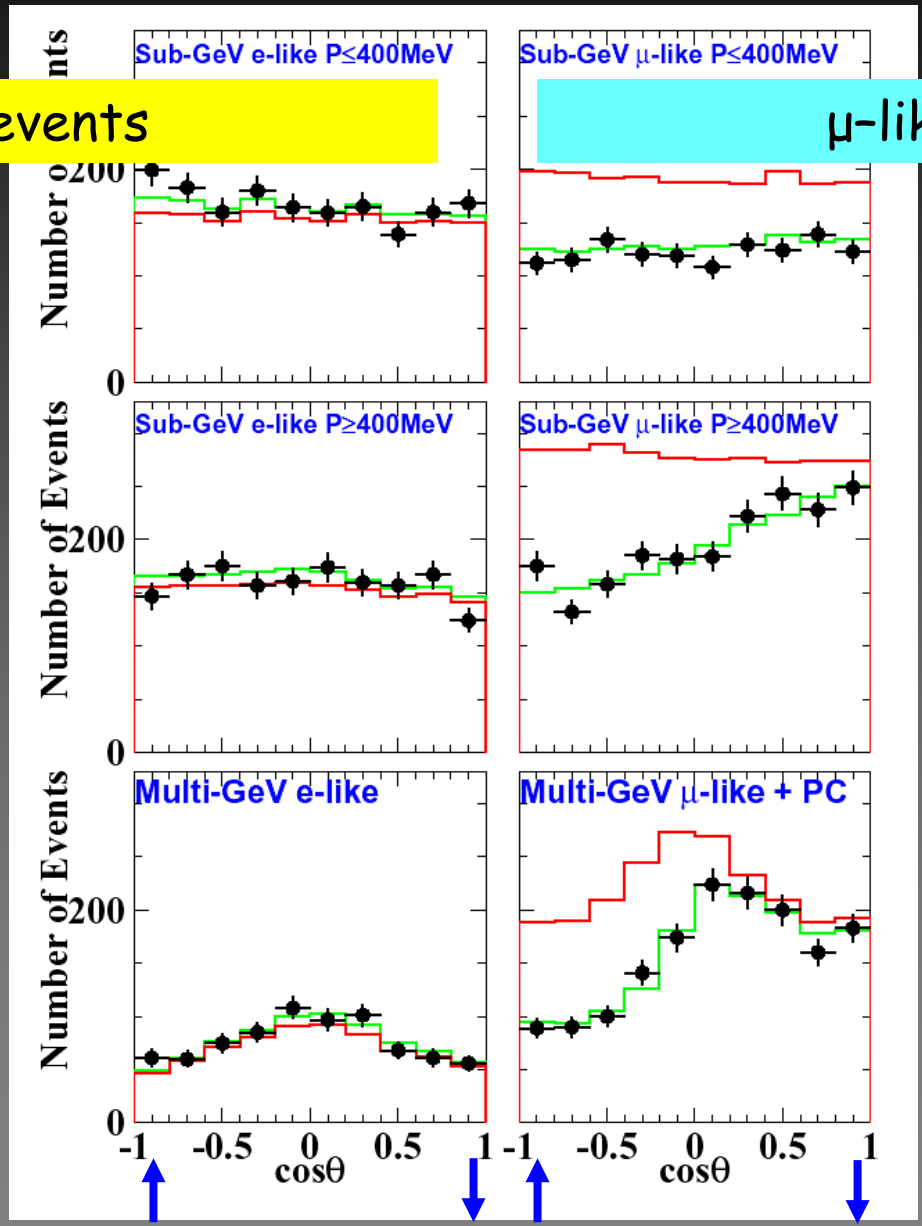


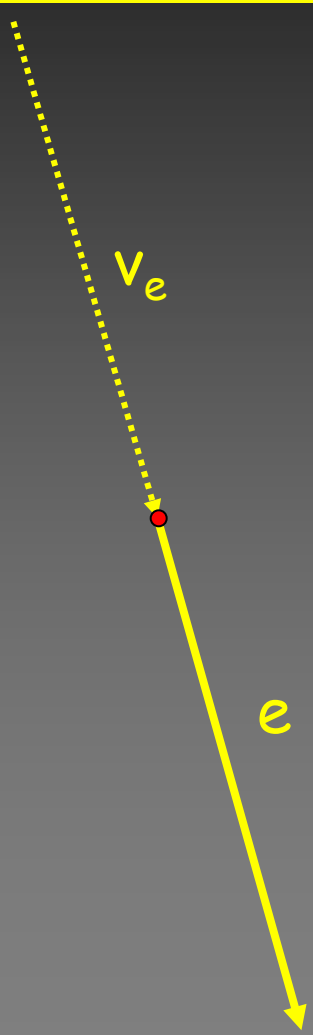
up-down symmetry at high energy

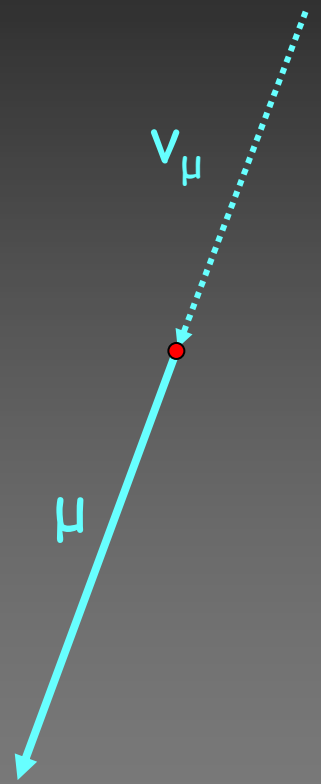
SuperK – atmospheric neutrinos

e-like events

μ-like events





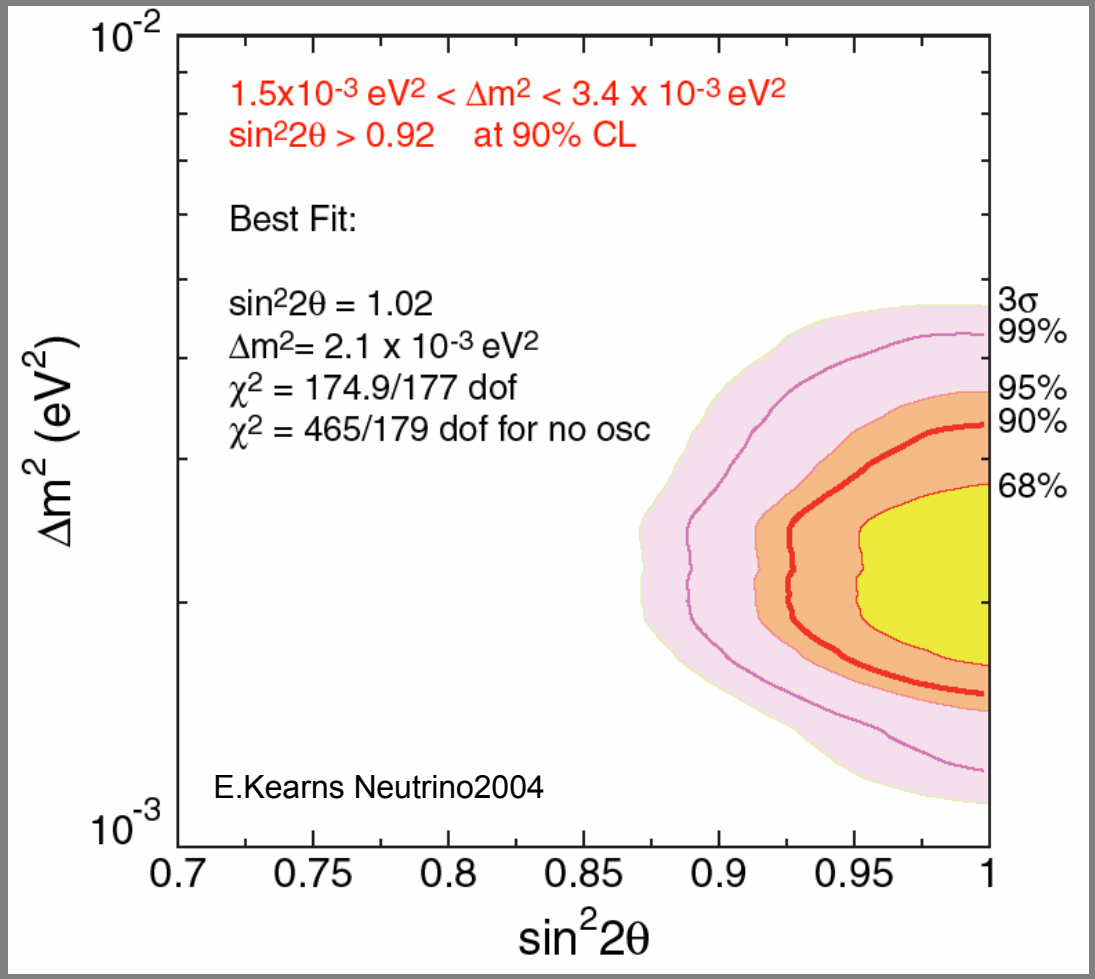


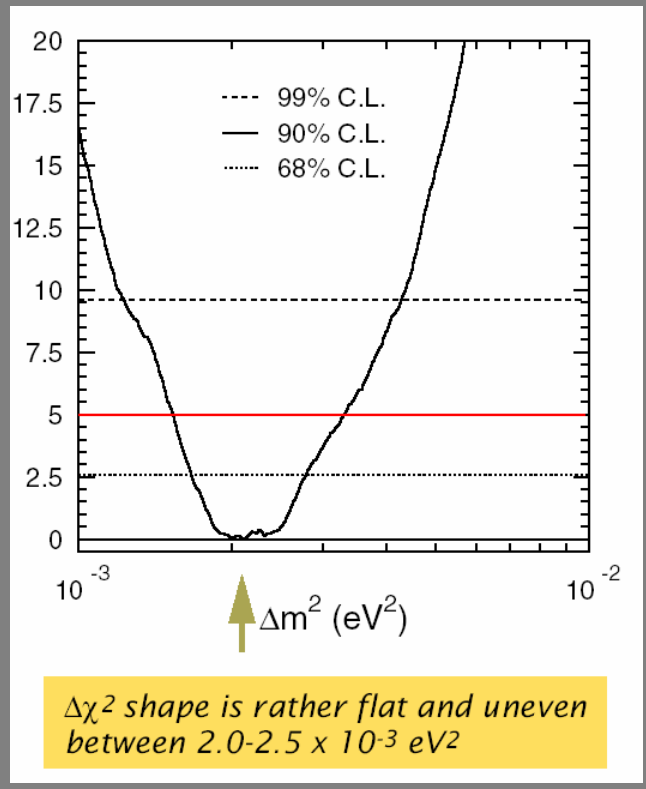
without oscillation

oscillation (best fit)

data

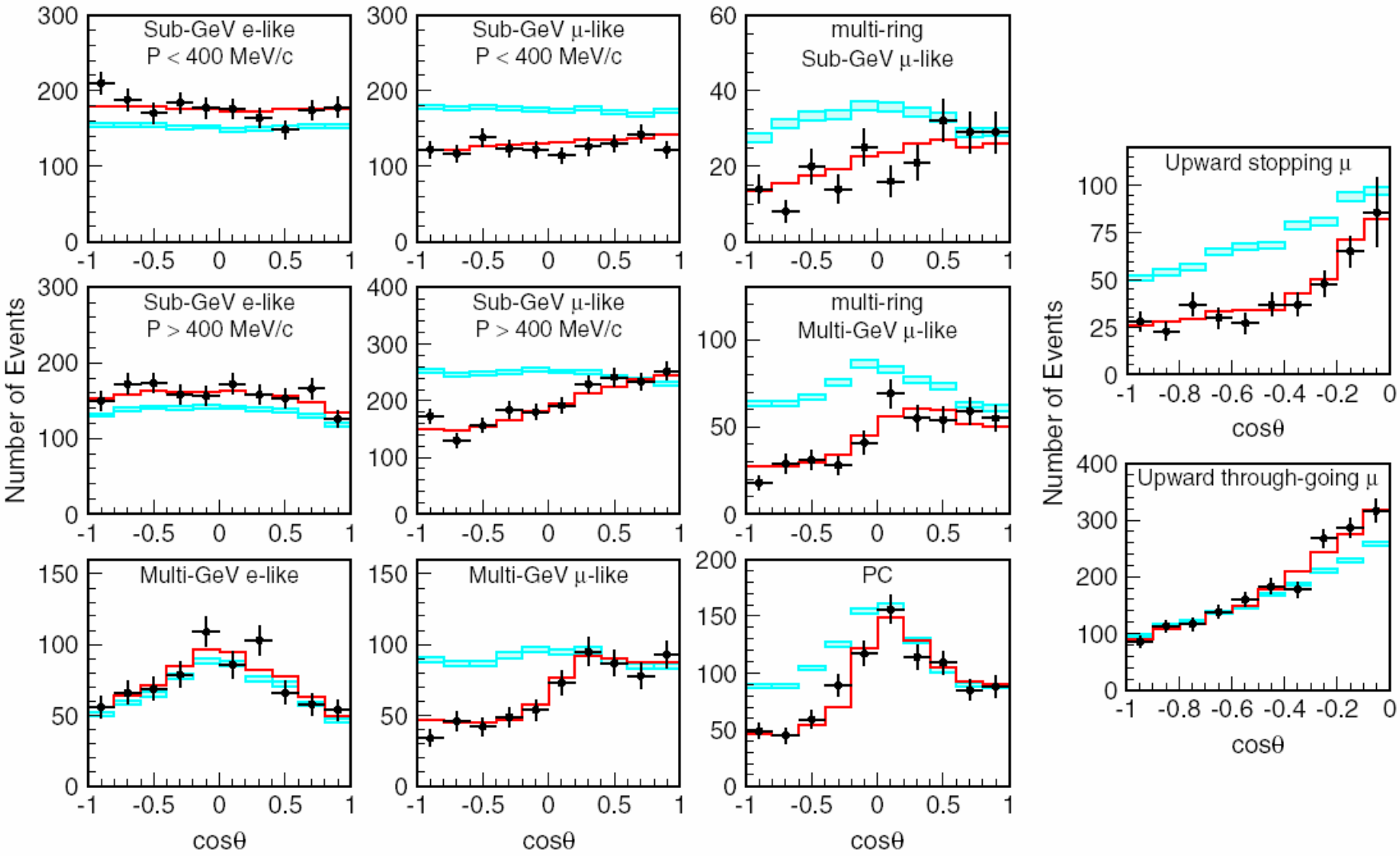
Atmospheric neutrinos:
Analysis neutrino oscillation (full SK-I data set)



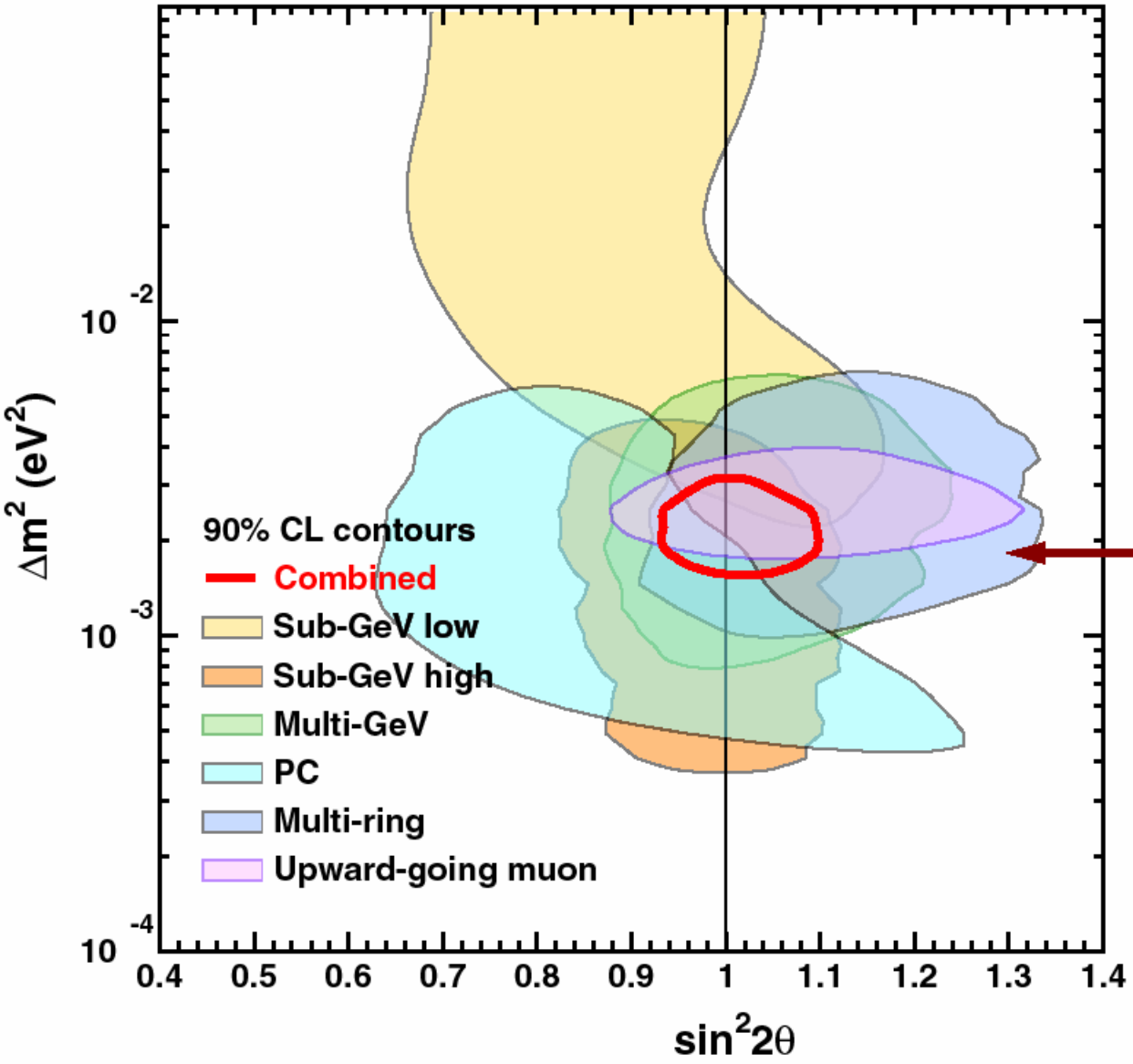


Confirmed by MACRO, SOUDAN

Zenith Angle Distributions

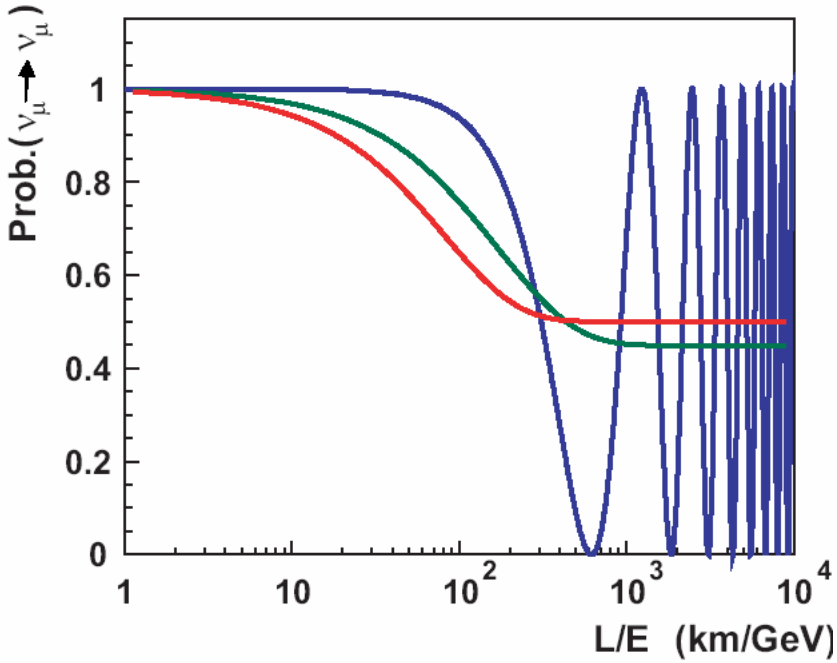


Sub-sample Contours



Upward muons provide strong constraint on minimum Δm^2

Analysis of events with high L/E resolution

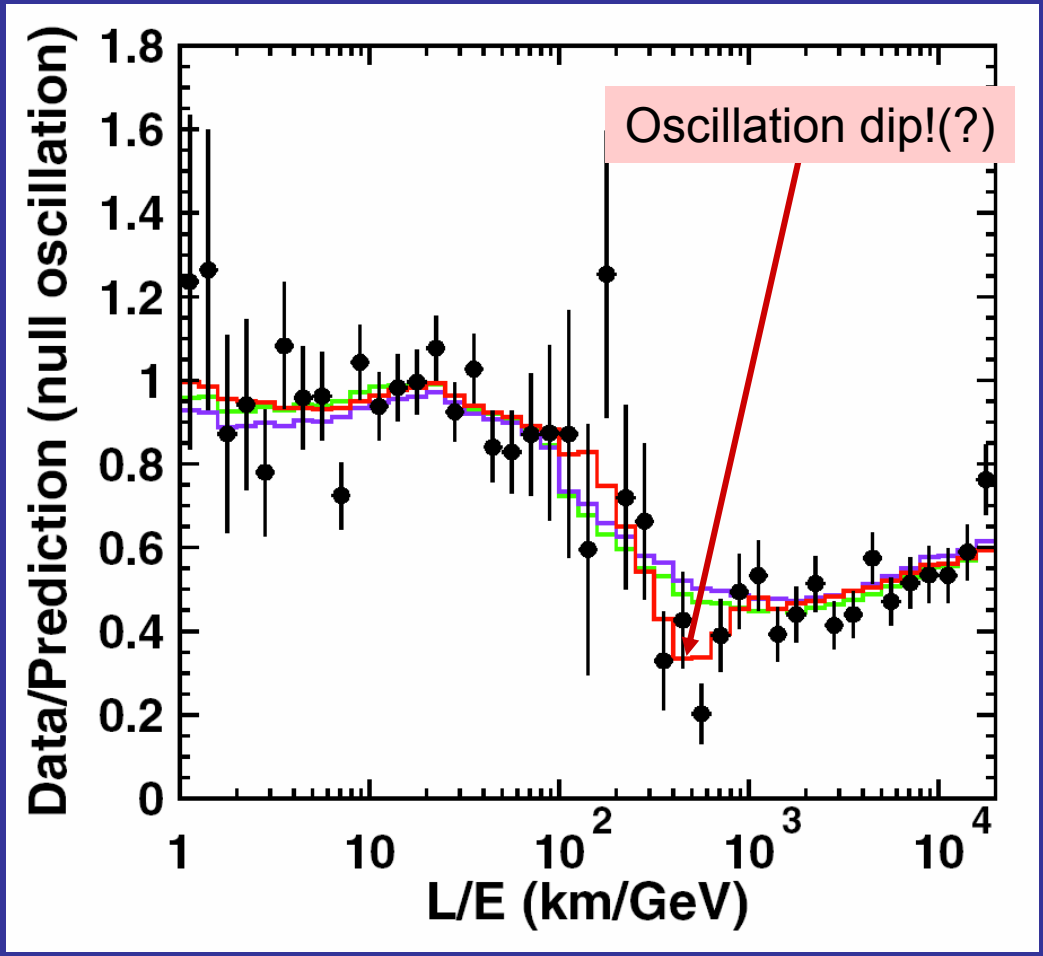


Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$

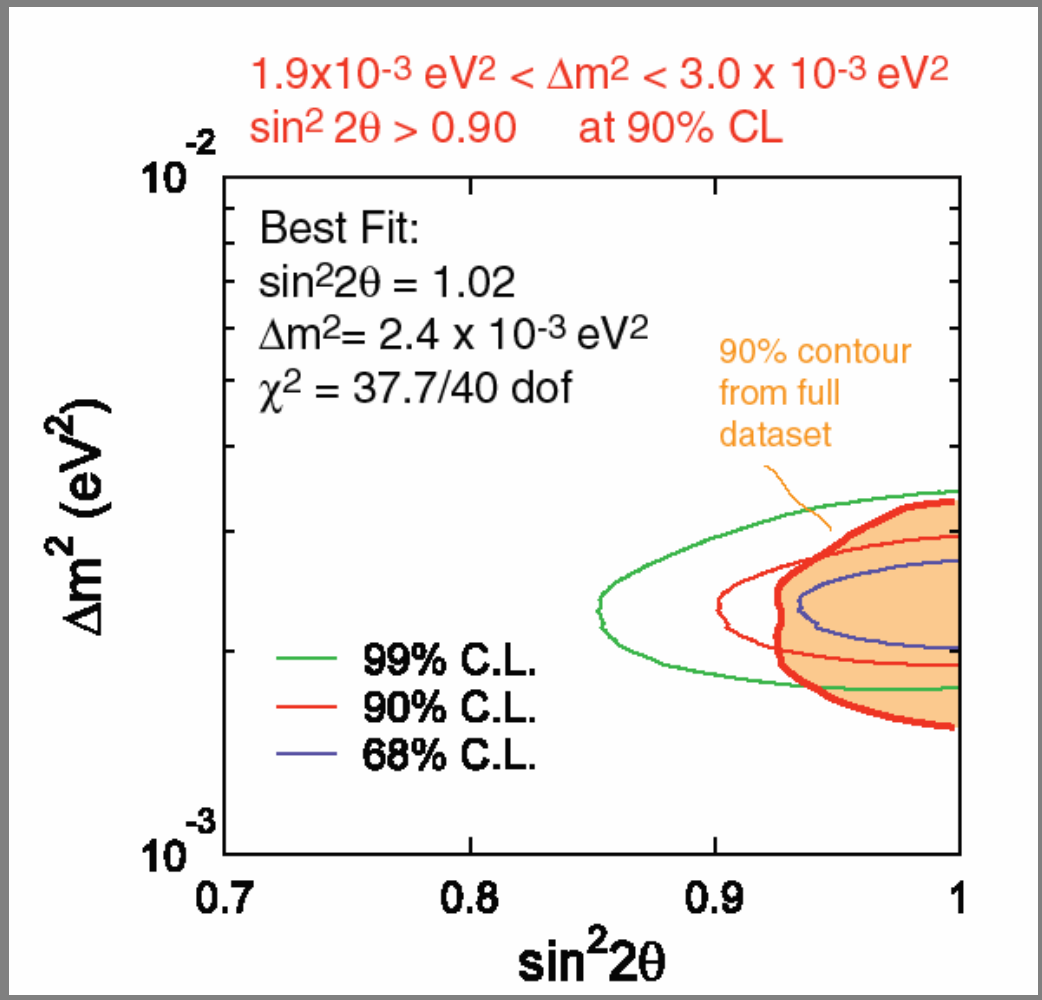
First evidence of oscillation pattern?

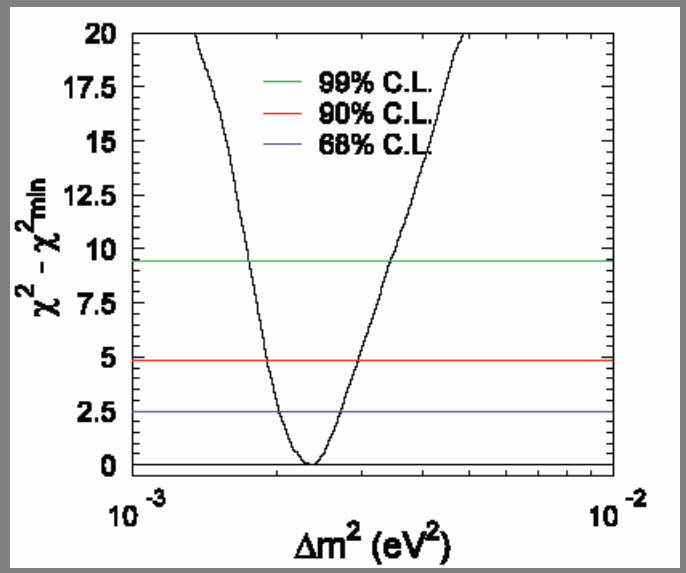


- oscillation
- decay
- decoherence

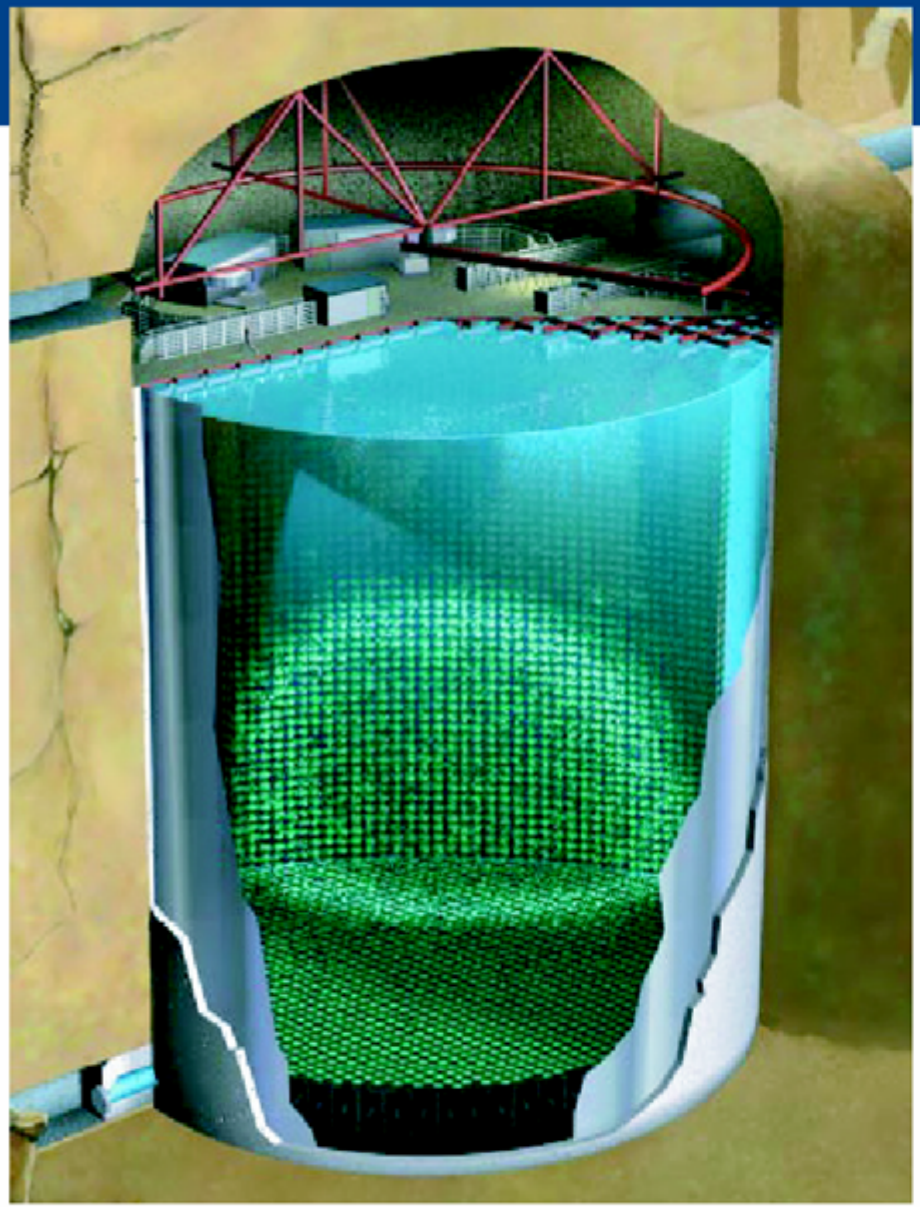
"EVIDENCE FOR AN OSCILLATORY SIGNATURE IN ATMOSPHERIC NEUTRINO OSCILLATION."
Super-Kamiokande Apr 2004., Submitted to Phys.Rev.Lett., **hep-ex/0404034**

from L/E analysis





Super-Kamiokande

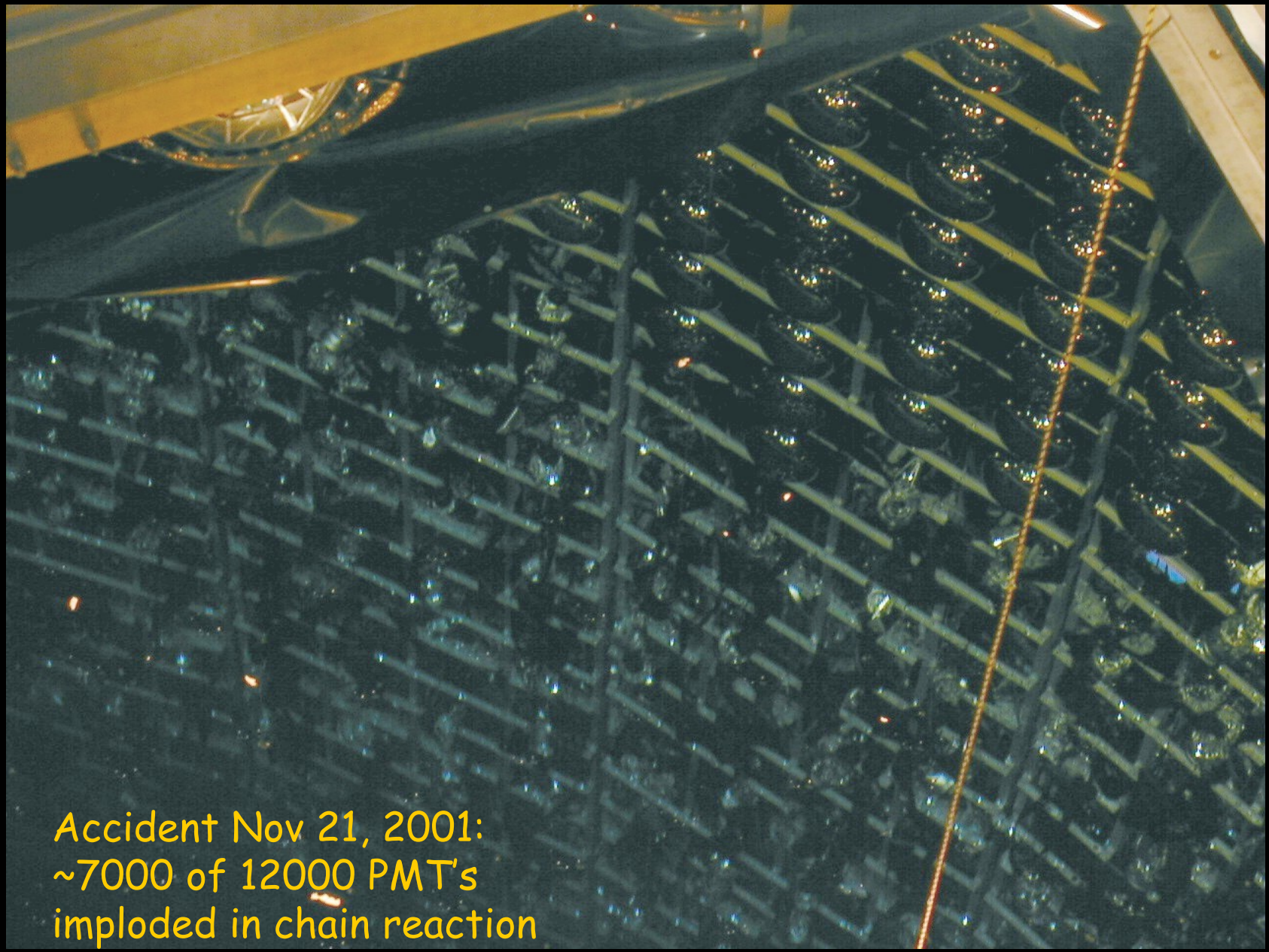


SK-1 1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

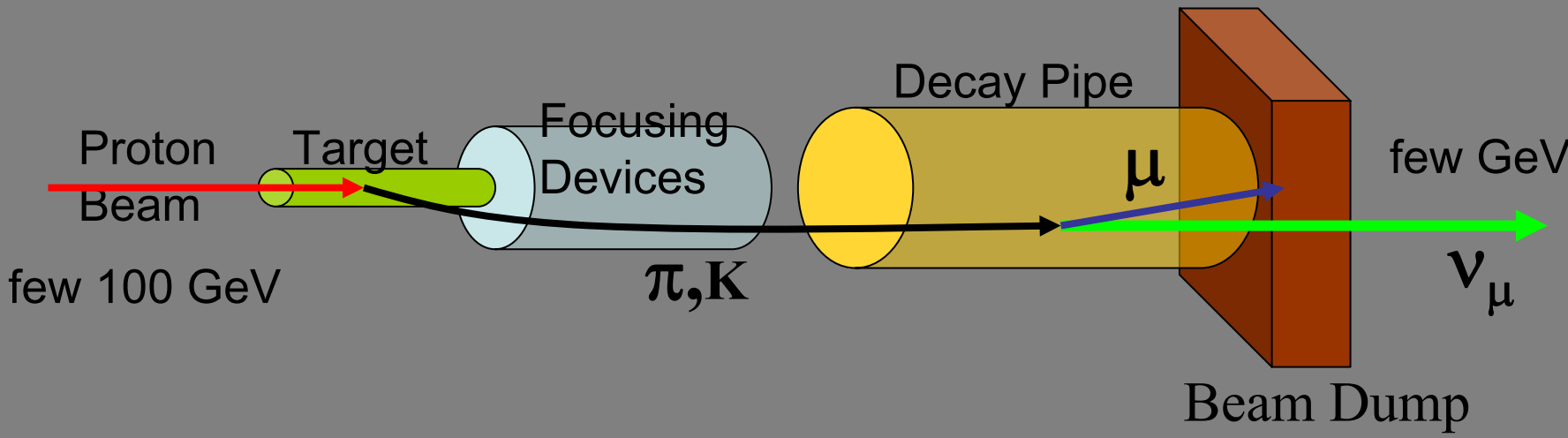
SK-2 January 2003 - October 2005
- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

SK-3 March 2006 +
- original coverage to be restored
- T2K off-axis beam from J-PARC

Super-Kamiokande: Accident 2001



Neutrino beams



Beam composition (typical example):

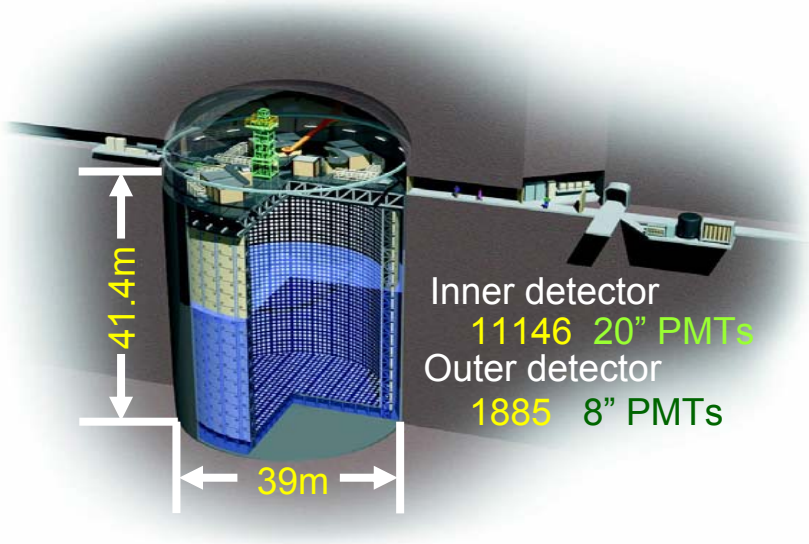
- dominantly ν_μ
- contamination from $\overline{\nu}_\mu$ (≈6%), ν_e (≈0.7%), $\overline{\nu}_e$ (≈0.2%)
- $\nu_\tau \lesssim 10^{-6}$

NEUTRINO OSCILLATION EXPERIMENT
K2K
Toyama
Super-Kamiokande
250km
Nagoya
Mt.Tsukuba
KEK
Mt.Fuji

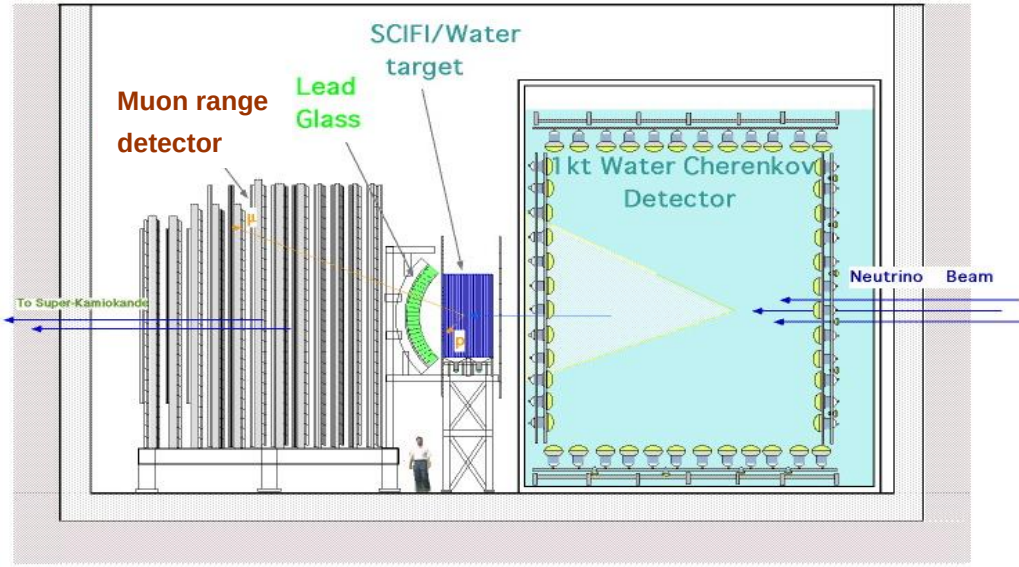
The K2K experiment

K2K-I Mar.1999 ~ Jul.2001

Super-Kamiokande I



near neutrino detectors



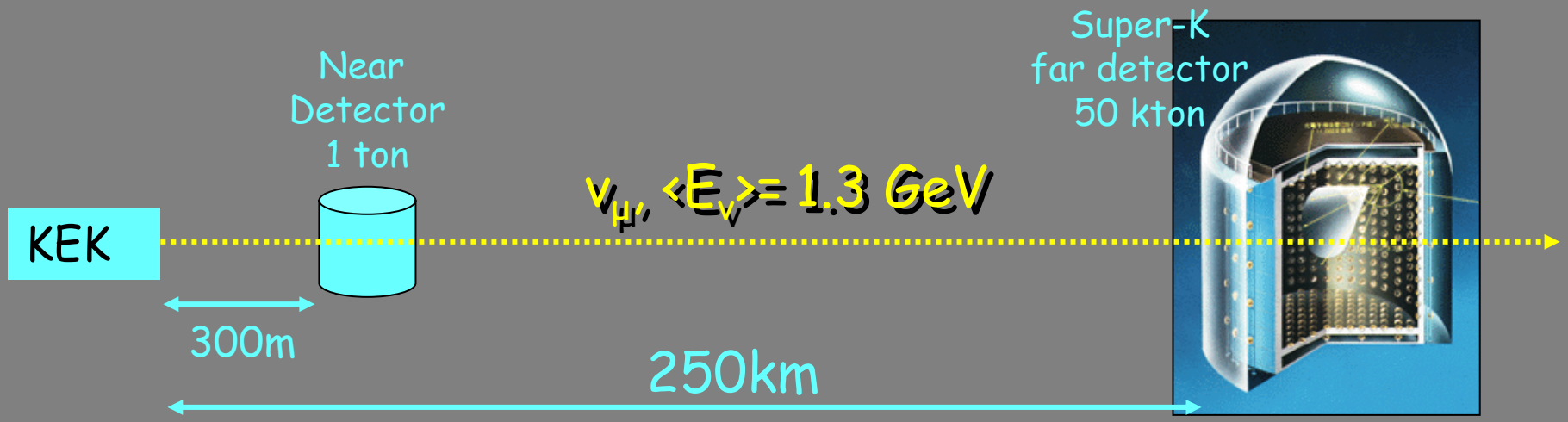
K2K-II Dec.2002~

Super-Kamiokande II

Upgrade of near neutrino detectors

- Removed **Lead Glass** detector
- Installed **SciBar** and **Electron Catcher** (Oct.2003~)

K2K accelerator experiment



Goal: 1.0×10^{20} POT
= 200 neutrino events in SK

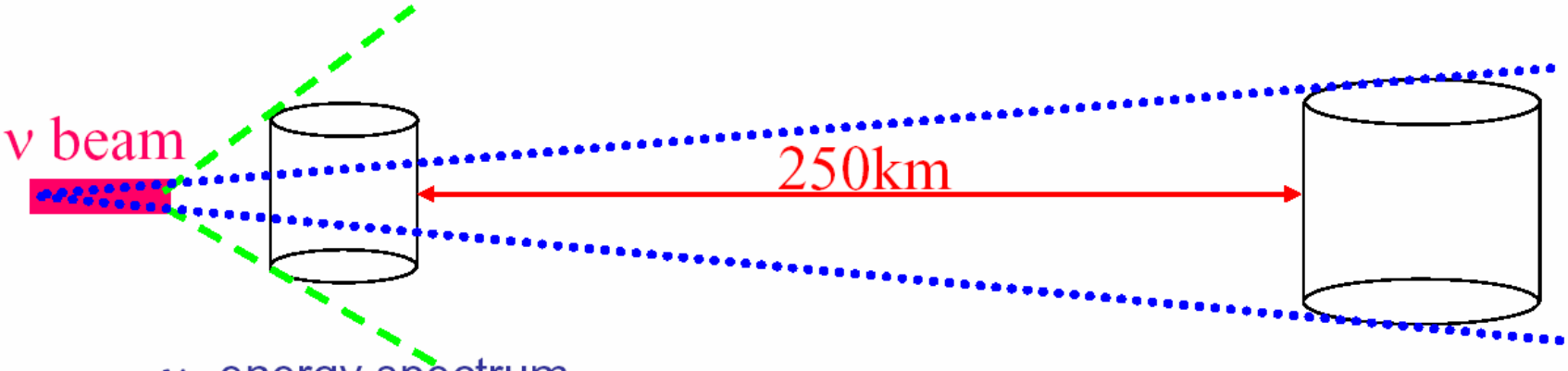
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

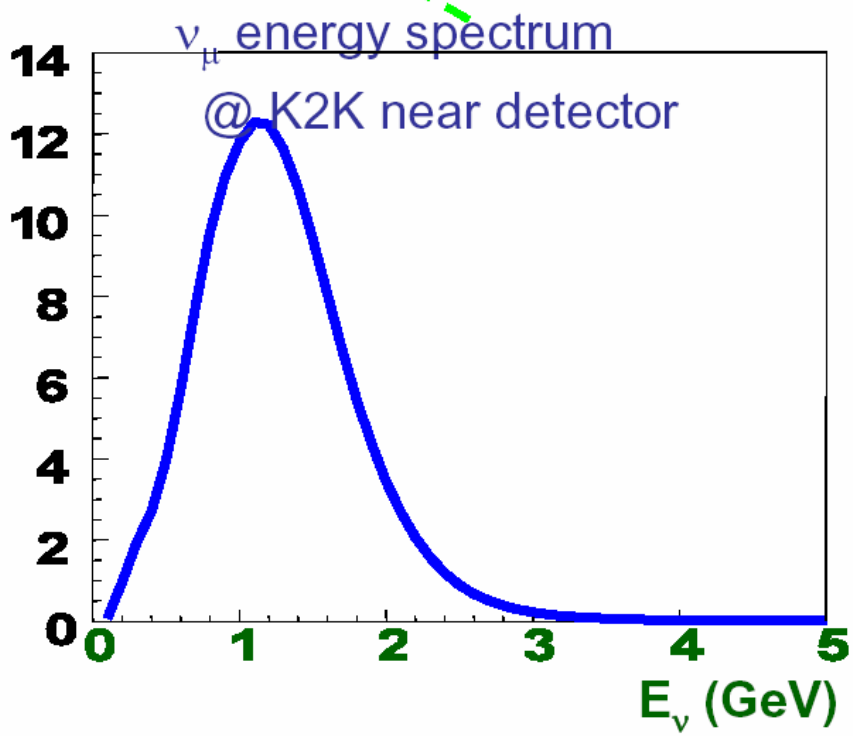
Data (06/1999 – 02/2004):
$8.9 \cdot 10^{19}$ POT

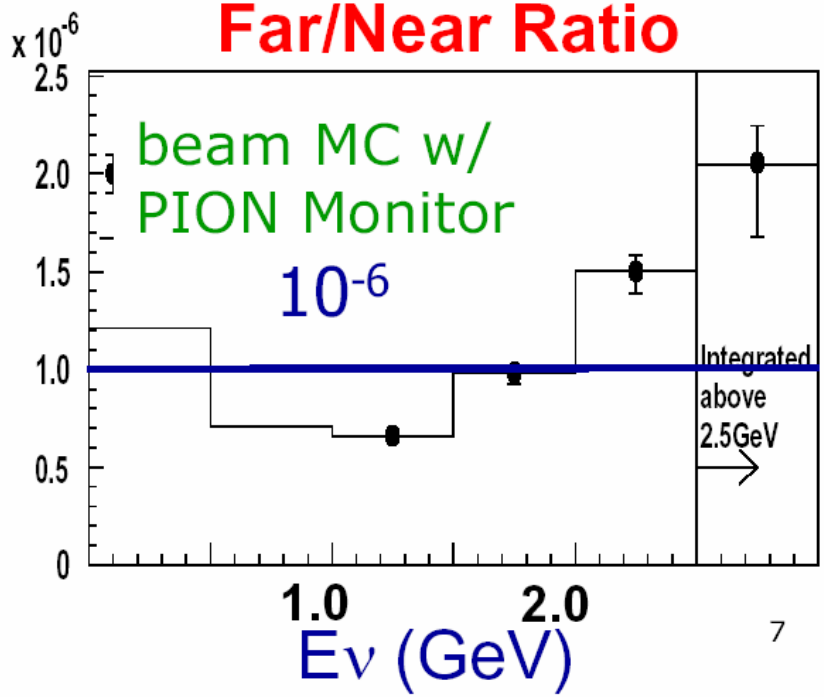
events in "Far Detector" :	108
expected without oscillation:	$150.9^{+11.6}_{-10.0}$

Probability for no oscillation: **<0.01%**
Neutrino oscillation confirmed with 3.9σ!

Neutrino spectrum and the far/near ratio



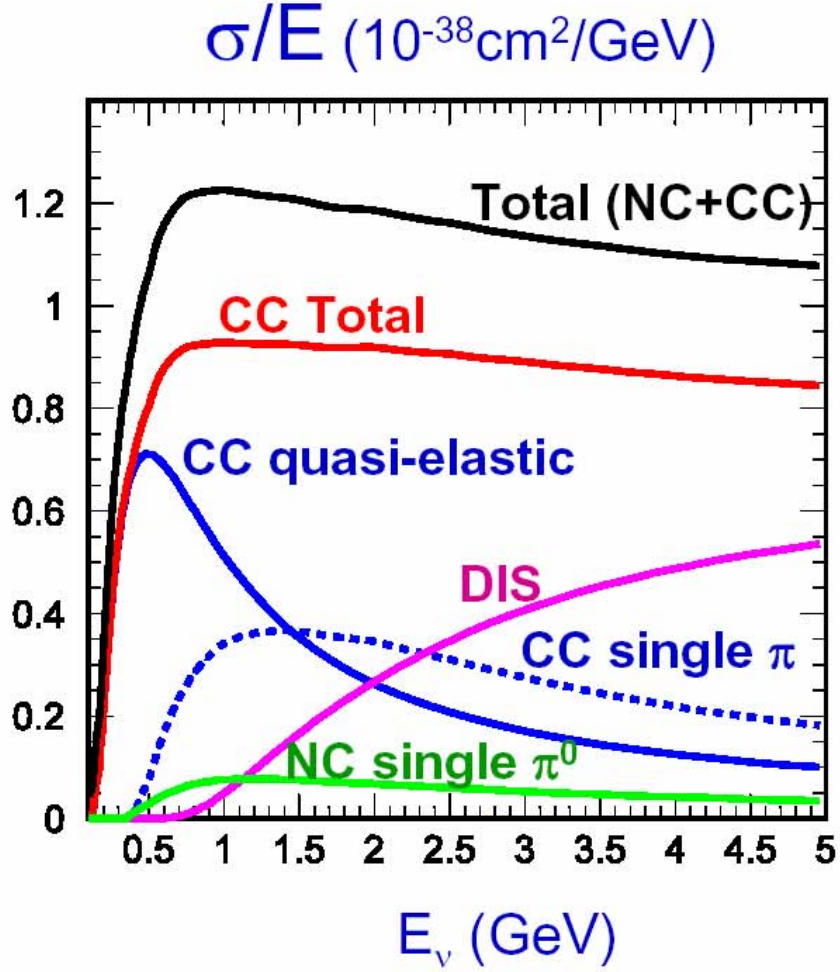




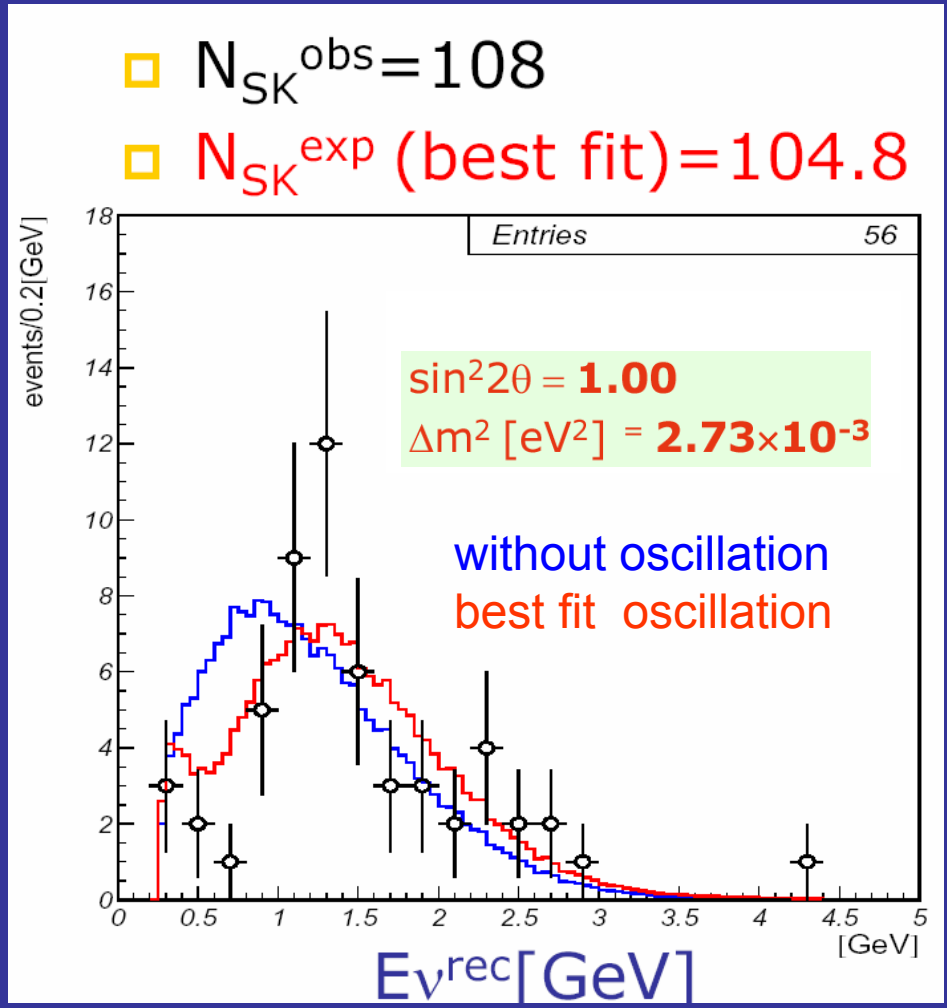
NEUT: K2K Neutrino interaction MC

- **CC quasi elastic (CCQE)**
  - Smith and Moniz with M_A=1.1GeV
- **CC (resonance) single π(CC-1π)**
  - Rein and Sehgal's with M_A=1.1GeV
- **DIS**
  - GRV94 + JETSET with Bodek and Yang correction.
- **CC coherent π**
  - Rein&Sehgal with the cross section rescale by J. Marteau
- **NC**

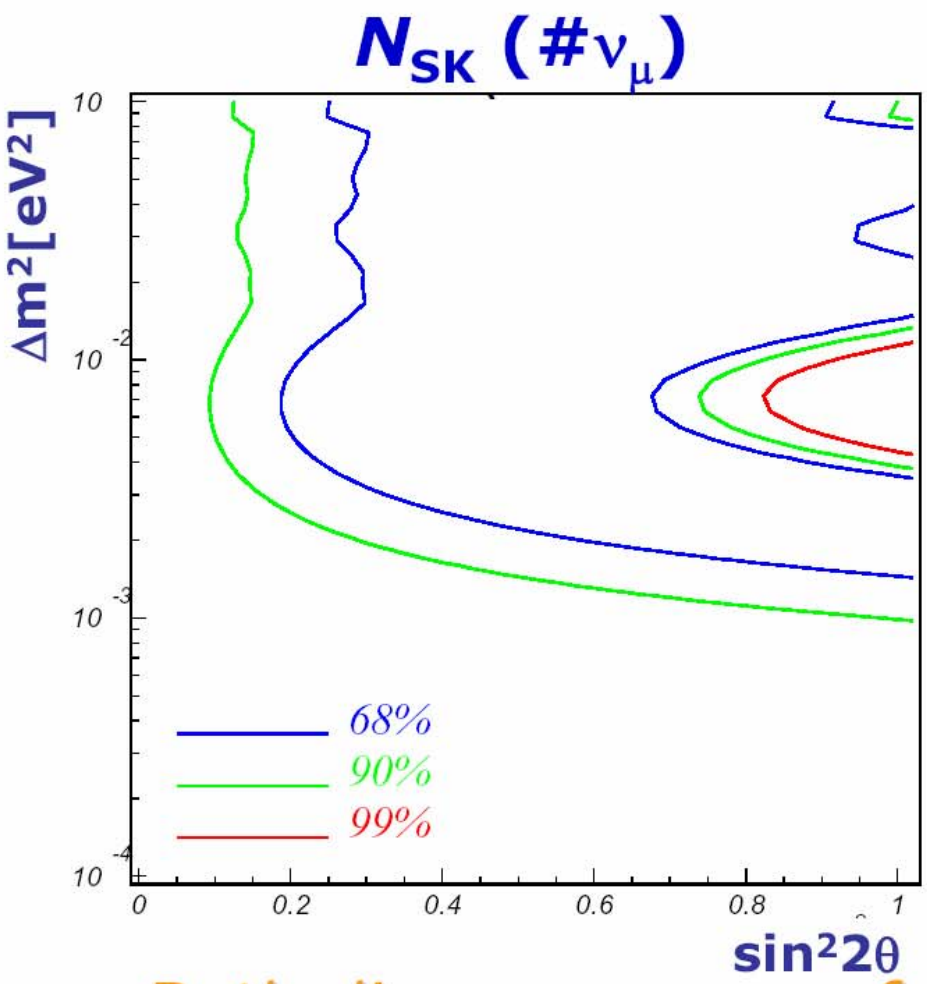
+ Nuclear Effects

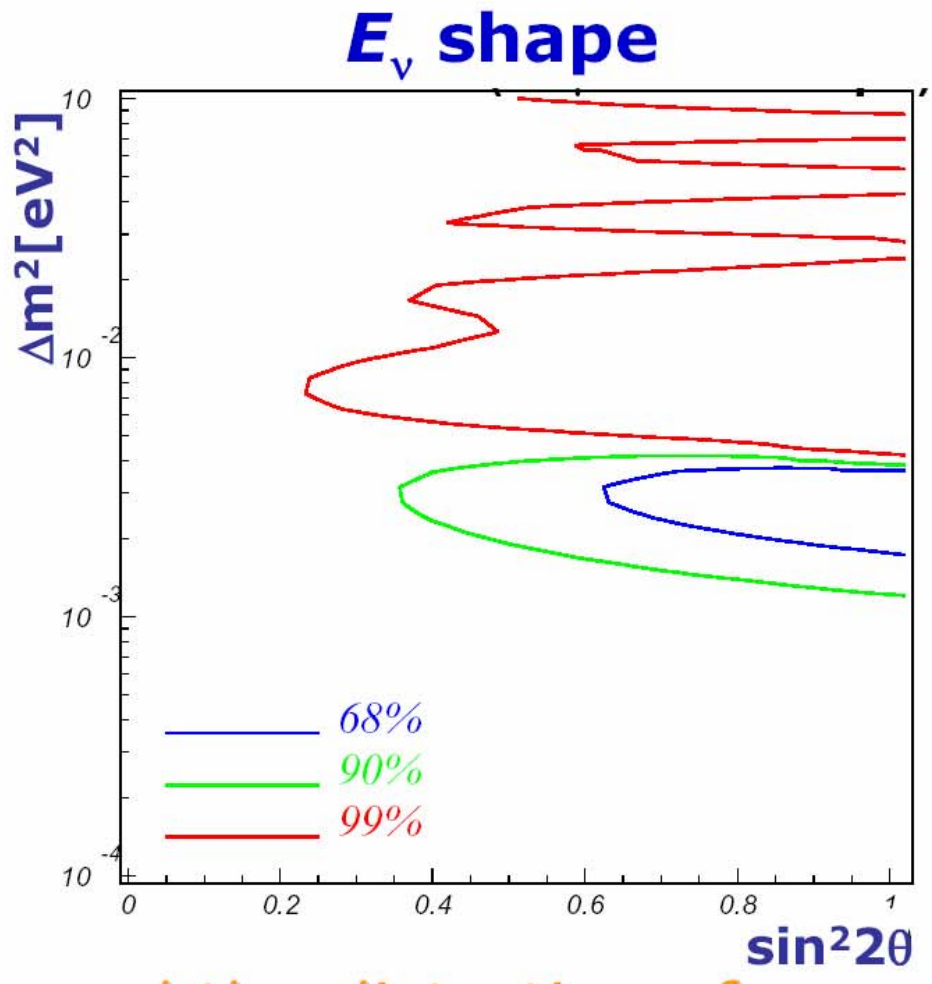


First hint for typical deformation of energy spectrum



ν_μ disappearance versus E_ν shape distortion





Both disappearance of ν_μ and the distortion of E_ν spectrum have the consistent result.