

Oscillatory Signature in Atmospheric Neutrinos

Danka Kiełczewska

Warsaw University & Institute for Nuclear Studies
University of California, Irvine

for
Super-Kamiokande Collaboration

- Conventional oscillation analysis
based on zenith angle distributions



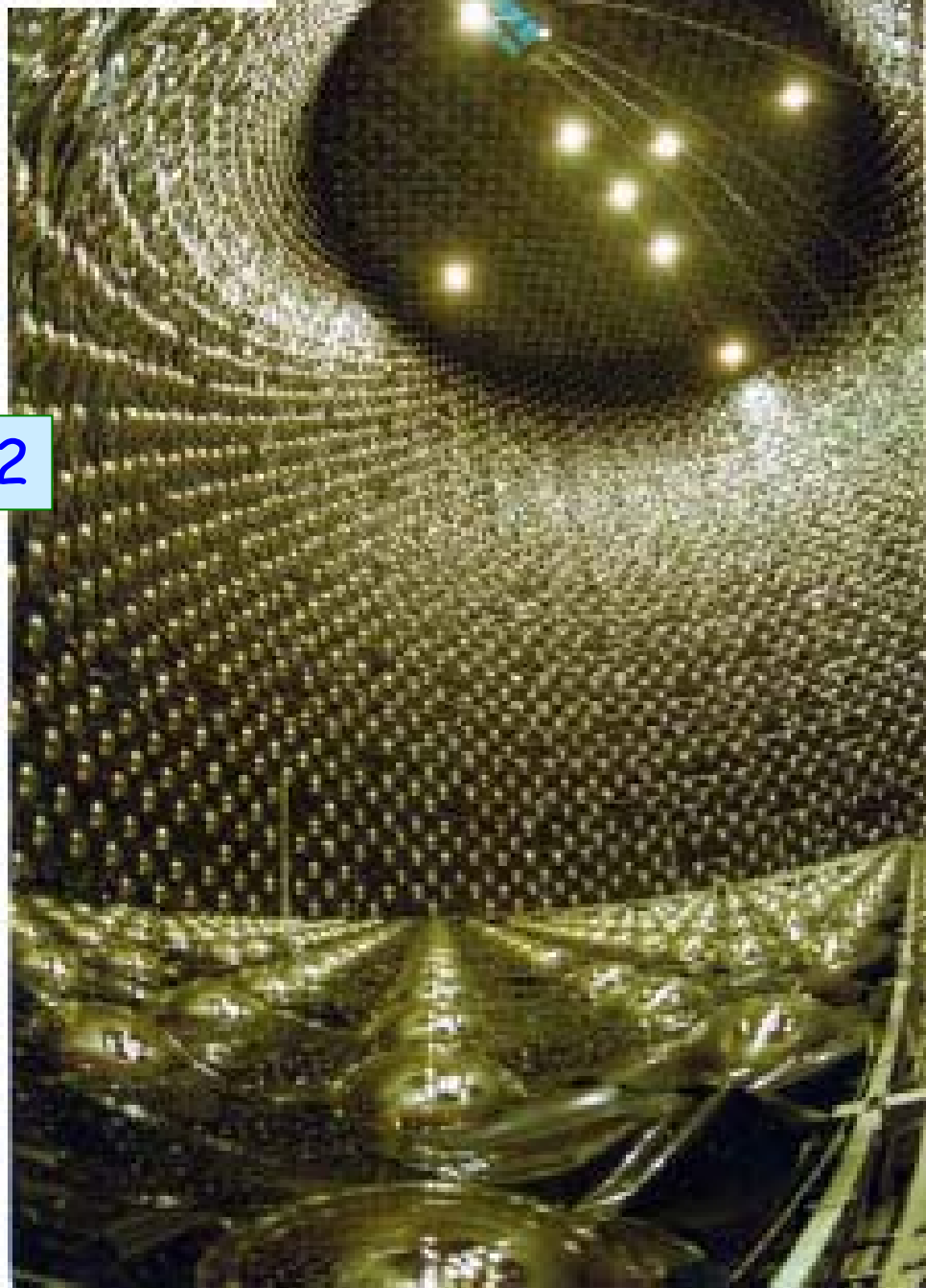
a long paper
soon to be published

- Search for an oscillatory signature
with a high precision sub-sample for L/E studies



hep-ex/0404034
submitted to PRL

October 2002



SK-2

Super-K detector

SK-1: Mar 1996 - Jul 2001

- 22.5 kton fiducial mass
- 11146 50-cm PMTs (inner)
- 40% photocathode coverage
- 1885 20-cm PMTs in (outer)

SK-2: Jan 2003 - Oct 2005

- 5182 PMTs with shields
- ~19% coverage
- outer detector fully restored

SK-3: March 2006 -

- original coverage
- T2K beam from J-PARC

Here: SK- 1 data

JAPAN

ICRR, Kamioka

ICRR, Kashiwa

Gifu University

KEK, Tsukuba

Kobe University

Kyoto University

Miyagi Univ. of Educ, Sendai

Nagoya University

Niigata University

Osaka University

Shizuoka Seika College

Shizuoka University

Tohoku University, Sendai

The University of Tokyo

Tokai University, Kanagawa

Tokyo Institute for Technology

USA

Boston University

Brookhaven National Laboratory

University of California, Irvine,

Calif. State Univ., Dominguez Hills

George Mason University

University of Hawaii

Indiana University

Los Alamos National Laboratory

Louisiana State University

University of Maryland

MIT, Cambridge

University of Minnesota

SUNY, Stony Brook

University of Washington, Seattle

Super-Kamiokande Collaboration

~ 140 authors
~ 35 institutions

KOREA

Chonnam National
University

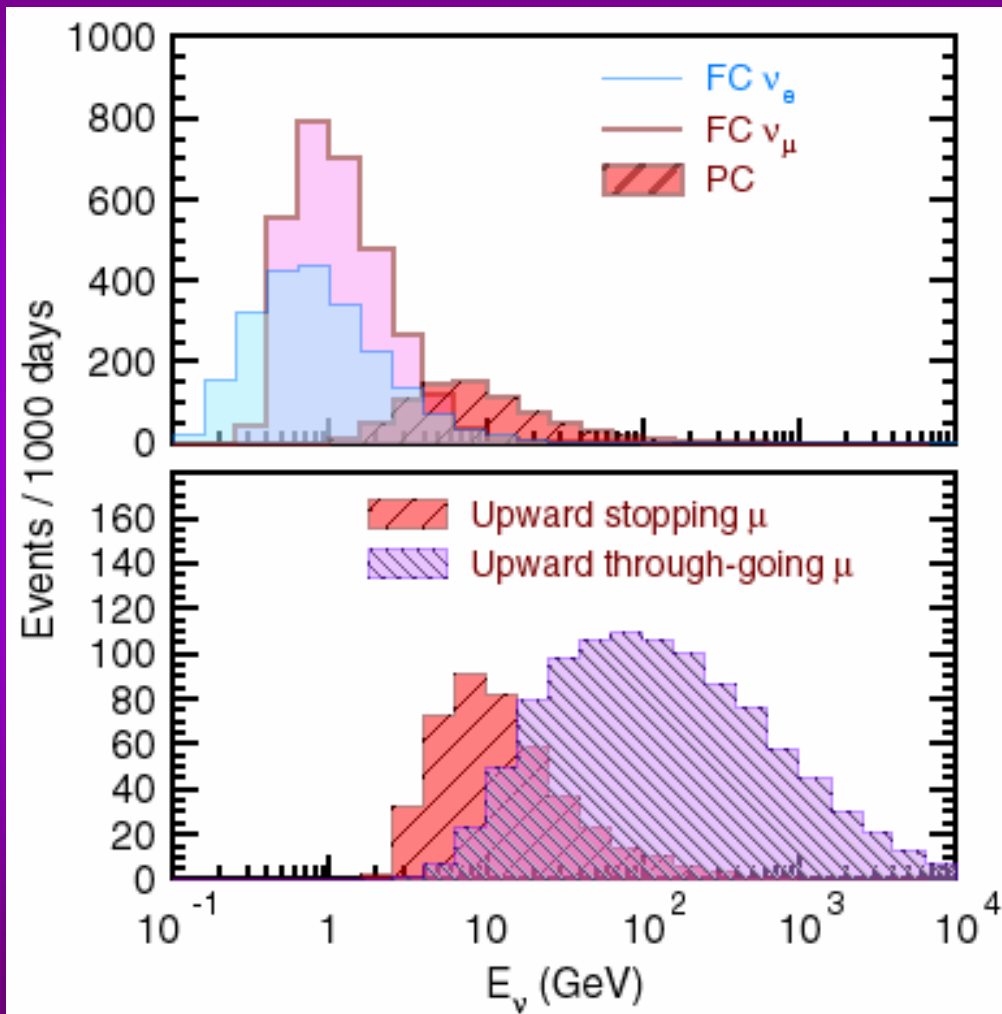
Seoul National University

Sungkyunkwan University

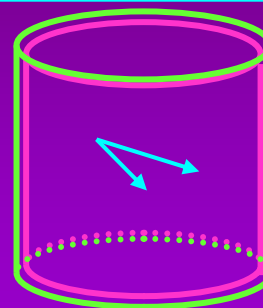
POLAND

Warsaw University

Energy spectrum

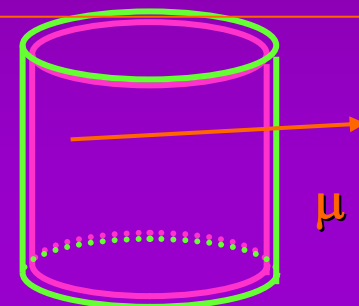


Fully contained
FC



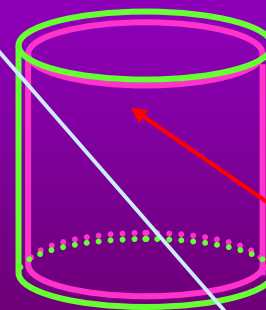
e/μ
identification

Partially contained
PC



all assumed
to be μ

Up μ thru



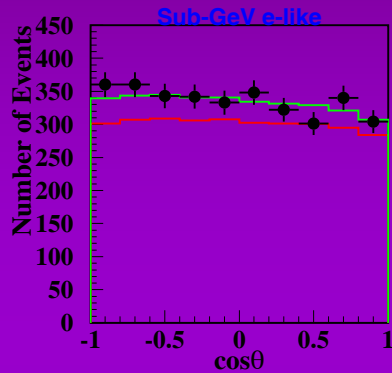
Up μ stop

Interactions in rocks

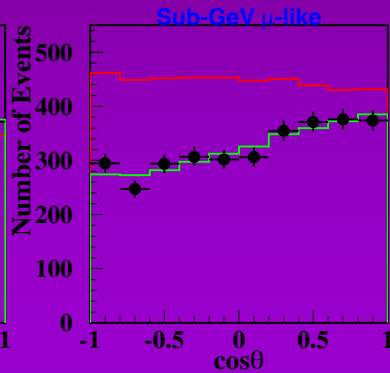
ν_μ

Zenith angle distributions

e-like
1 ring

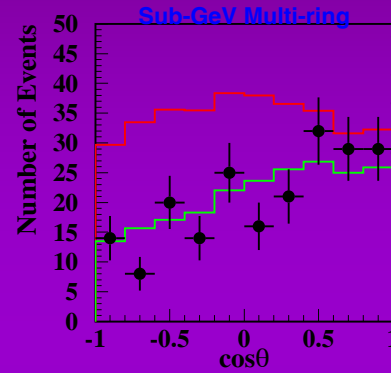


μ -like
1 ring

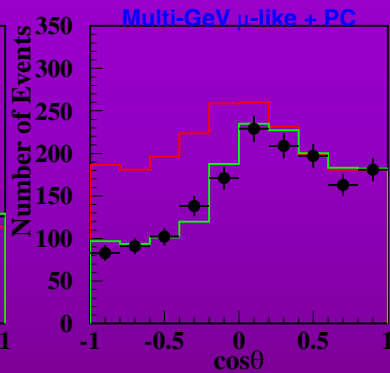
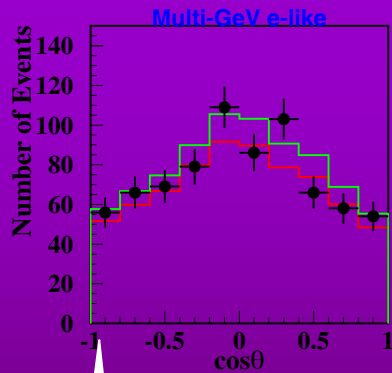
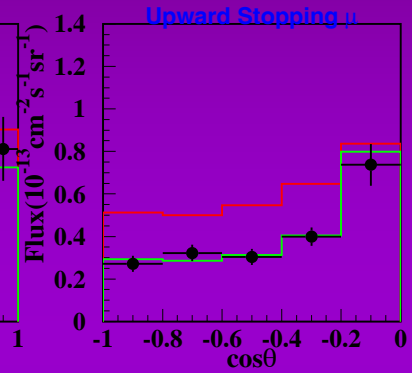


Sub-GeV

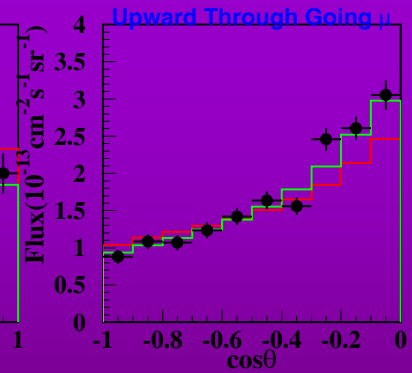
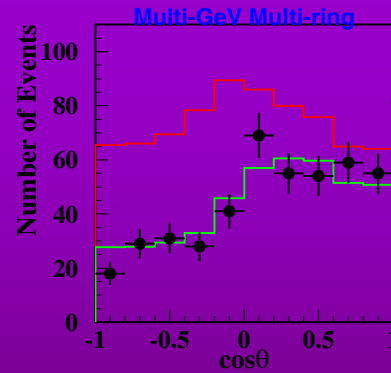
μ -like
multi-ring



upward going μ



Multi-GeV



up

down

1489 days - updated Nov 2003

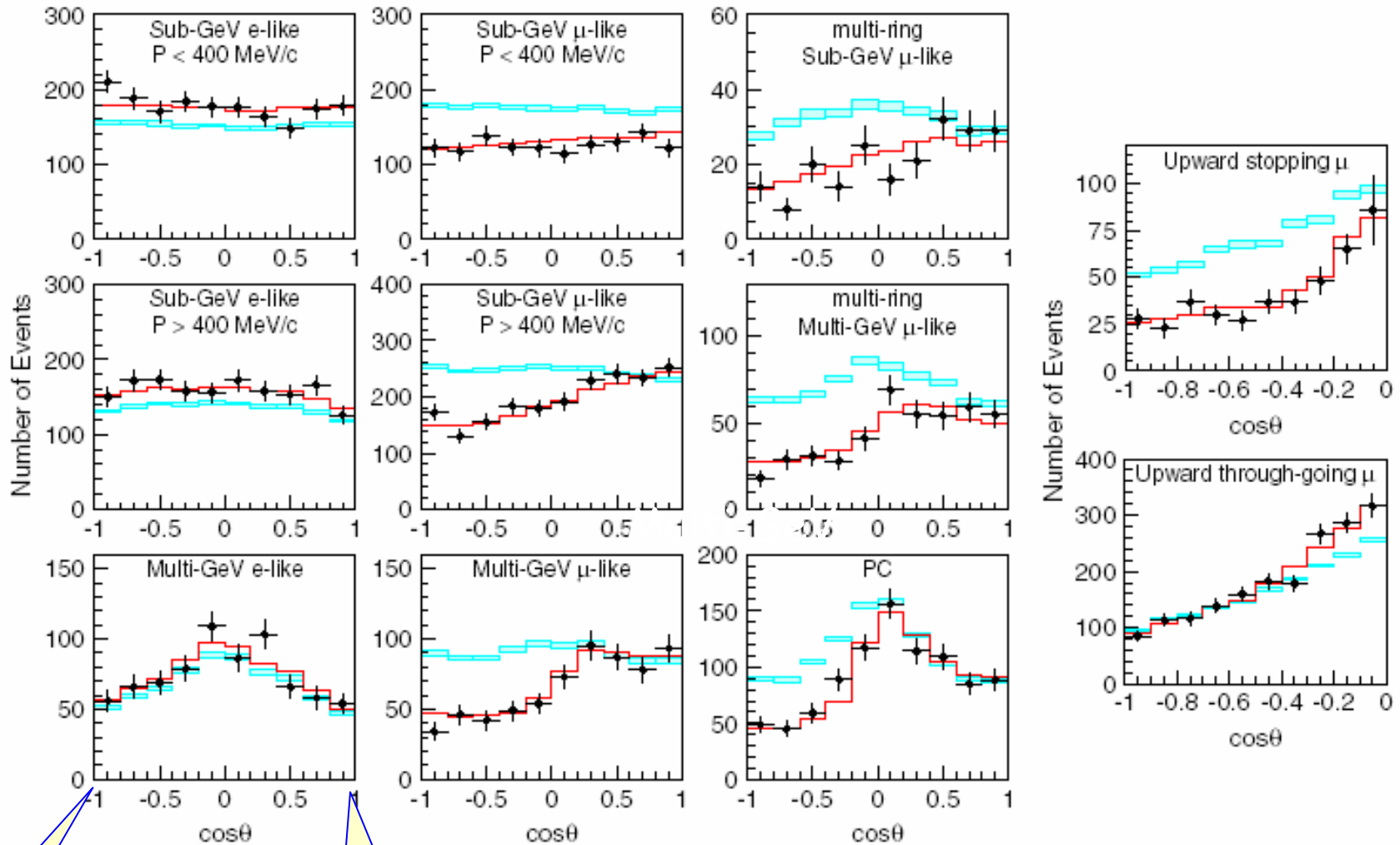
Zenith angle distributions

e-like 1 ring

μ -like 1 ring

μ -like
multi-ring

upward going μ



up

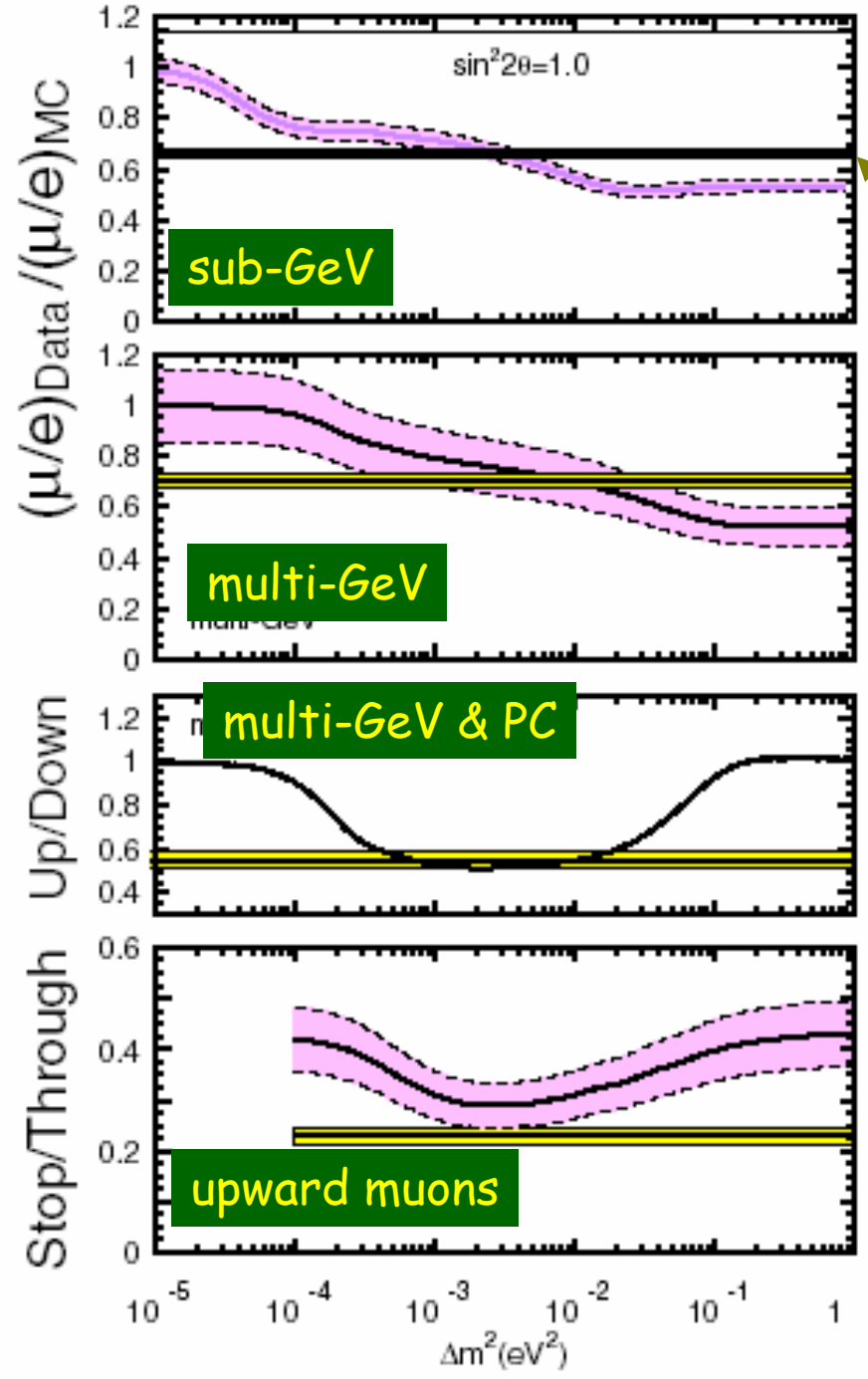
down

Ratios vs Δm^2

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

$$\frac{N_{up}}{N_{down}}$$

$$\frac{\Phi_{\mu-stop}}{\Phi_{\mu-thru}}$$

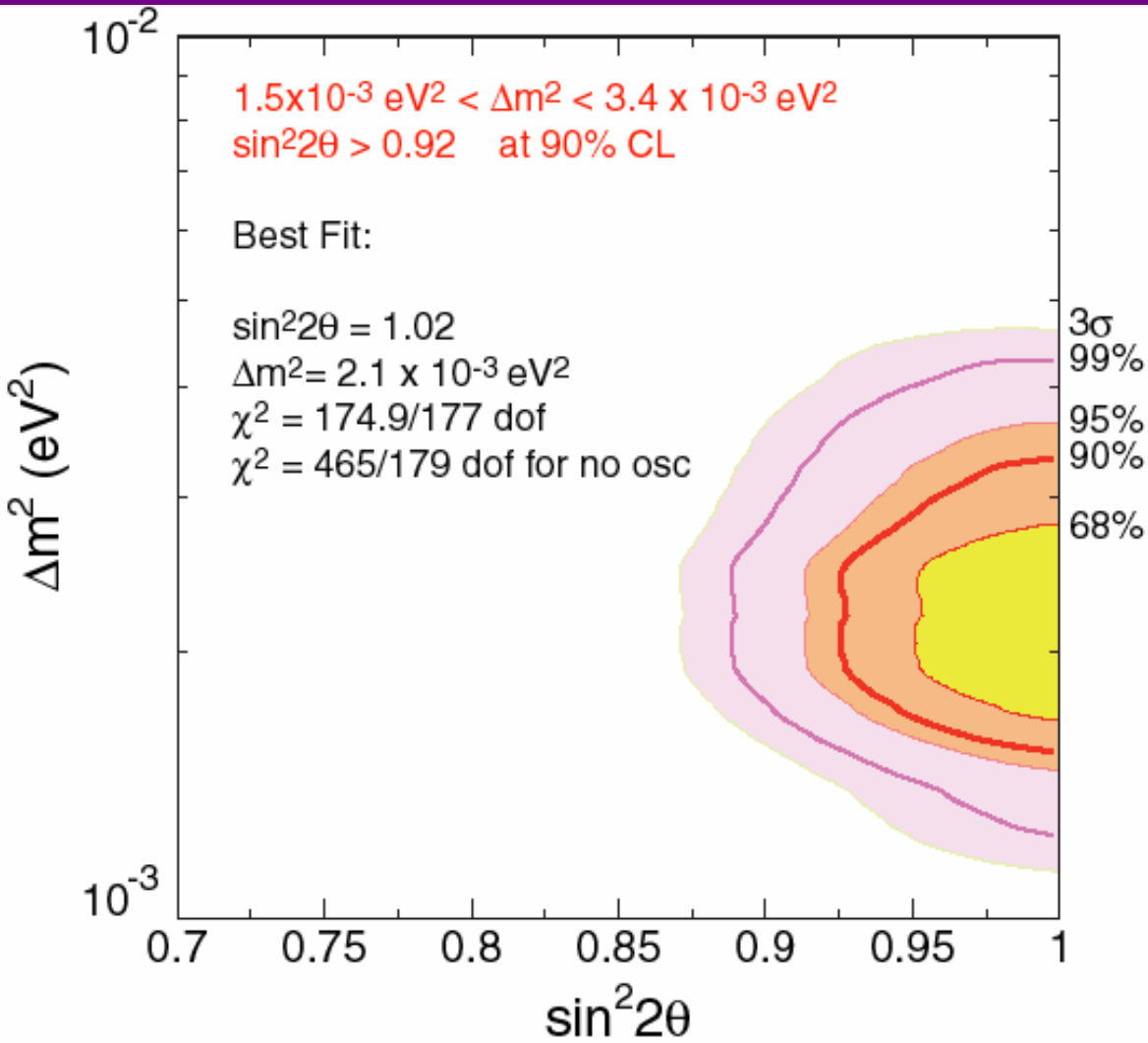


Data with stat. errors

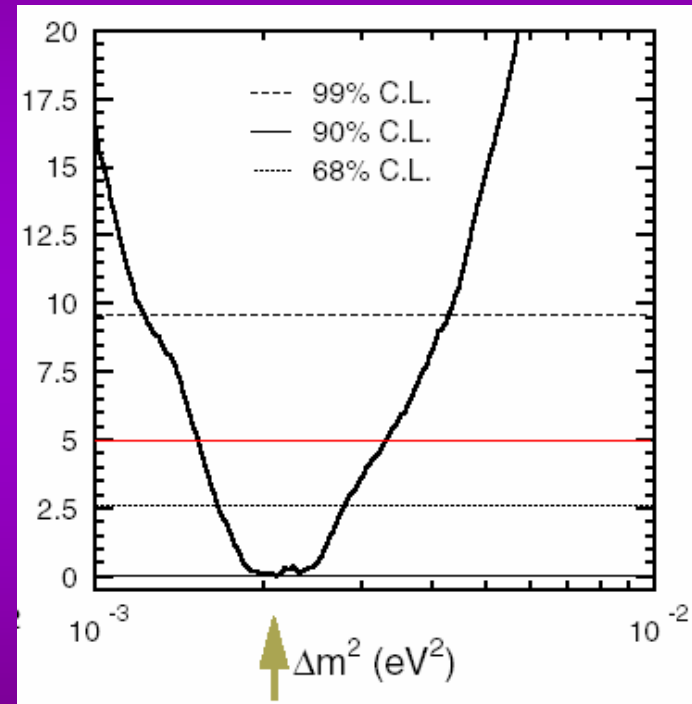
MC with syst. errors

Results of combined fit

$$\nu_{\mu} \leftrightarrow \nu_{\tau}$$

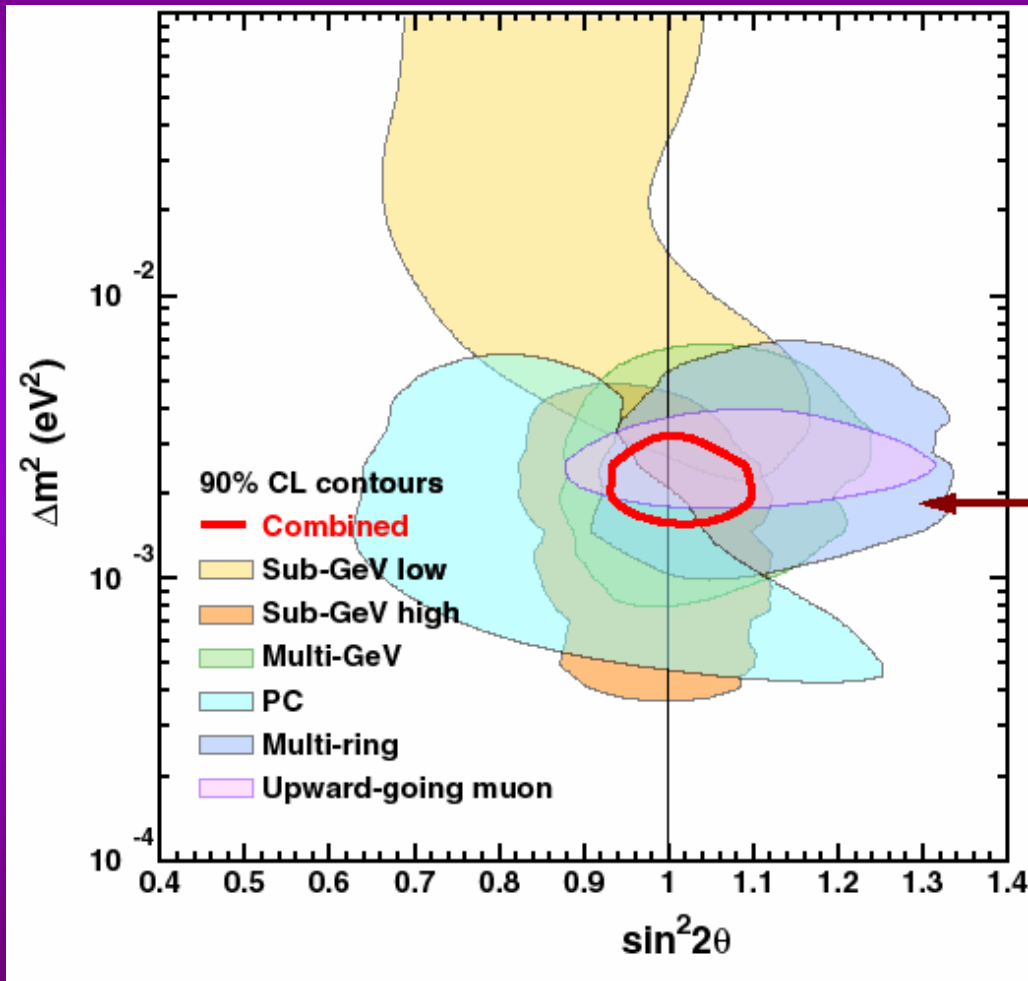


χ^2 vs Δm^2



flat between
0.0019 and 0.0025

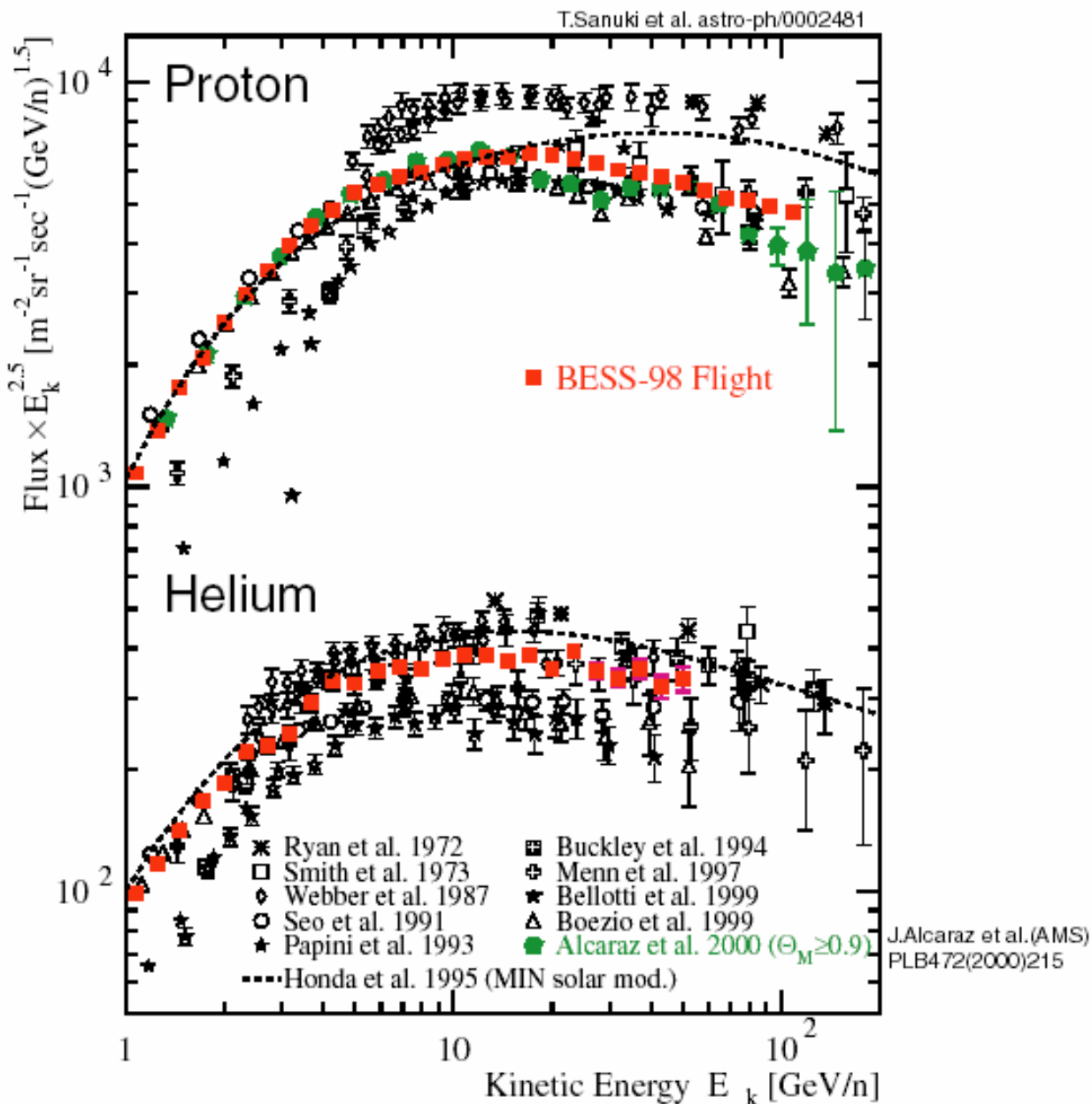
Contours for different subsamples



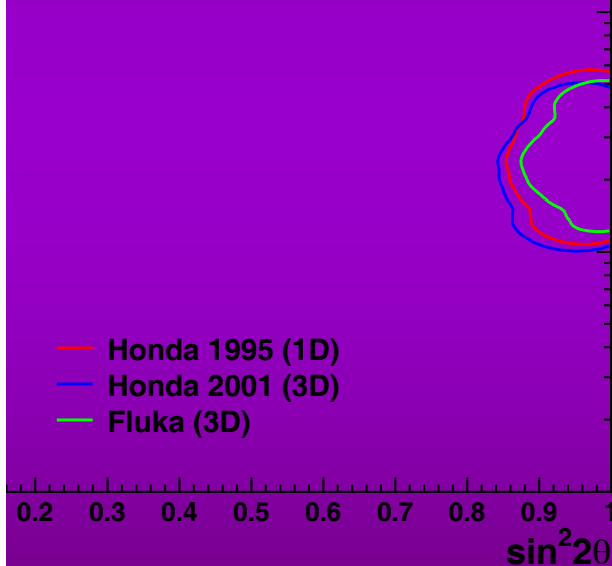
Sub-GeV 1-ring e-like	3353
Sub-GeV 1-ring μ -like	3227
Multi-GeV 1-ring e-like	746
Multi-GeV 1-ring μ -like	651
PC μ -like	647
Multi-ring	647
Upward muons	2259

All	11530

Contours for different neutrino flux models



3d calculations is not a major factor



Primary spectrum shape is not well constrained

However:

Non-oscillation hypotheses

can also describe the zenith angle distributions

Neutrino decay hypothesis

Let's consider: $\nu_3 \rightarrow \nu_x + K$

where x is mostly
a sterile state

mass m , lifetime τ

Survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu) \equiv P_{\mu\mu} = \sin^4 \mathcal{G} + \cos^4 \mathcal{G} \exp\left(-\frac{mL}{\tau E}\right) \\ + 2 \sin^2 \mathcal{G} \cos^2 \mathcal{G} \exp\left(-\frac{mL}{2\tau E}\right) \cos\left(\frac{\Delta m^2 L}{2E}\right)$$

$\Delta m^2 \rightarrow 0$:

$$P_{\mu\mu} = \left(\cos^2 \mathcal{G} + \sin^2 \mathcal{G} \cdot \exp\left(-\frac{m_3}{2\tau_3} \frac{L}{E}\right)\right)^2$$

$\Delta m^2 \rightarrow \infty$

$$P_{\mu\mu} = \sin^4 \mathcal{G} + \cos^4 \mathcal{G} \exp\left(-\frac{mL}{\tau E}\right)$$

excluded even by CC events

Neutrino decay hypothesis

Let's consider: $\nu_3 \rightarrow \nu_x + K$

where x is mostly
a sterile state

mass m , lifetime τ

Survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu) \equiv P_{\mu\mu} = \sin^4 \mathcal{G} + \cos^4 \mathcal{G} \exp\left(-\frac{mL}{\tau E}\right) \\ + 2 \sin^2 \mathcal{G} \cos^2 \mathcal{G} \exp\left(-\frac{mL}{2\tau E}\right) \cos\left(\frac{\Delta m^2 L}{2E}\right)$$

$\Delta m^2 \rightarrow 0$:

$$P_{\mu\mu} = \left(\cos^2 \mathcal{G} + \sin^2 \mathcal{G} \cdot \exp\left(-\frac{m}{2\tau_3} \frac{L}{E}\right) \right)^2$$

Decoherence effects

Due to quantum fluctuations of space a coherent system of 2 neutrino states is not isolated and the coherence can be destroyed by interactions with the fluctuations.

Generally decoherence can be described:

$$P_{\mu\mu}(\Delta m^2, \theta, \mu^2) = 1 - \frac{\sin^2 2\theta}{2} \left[1 - e^{-\frac{\mu^2 L}{2E_\nu}} \cos\left(\frac{\Delta m^2 L}{2E_\nu}\right) \right]$$

i.e. $P_{\mu\mu} < 1$ even for massless neutrinos

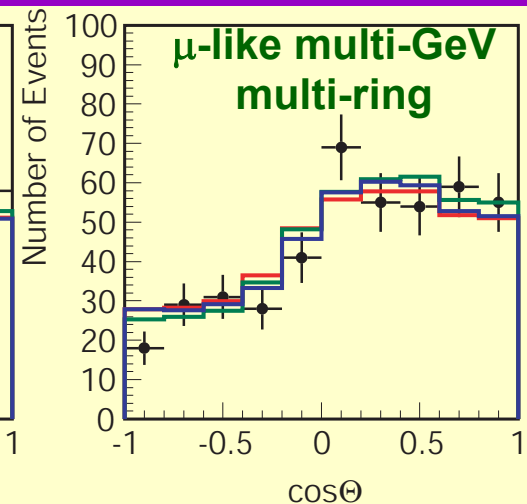
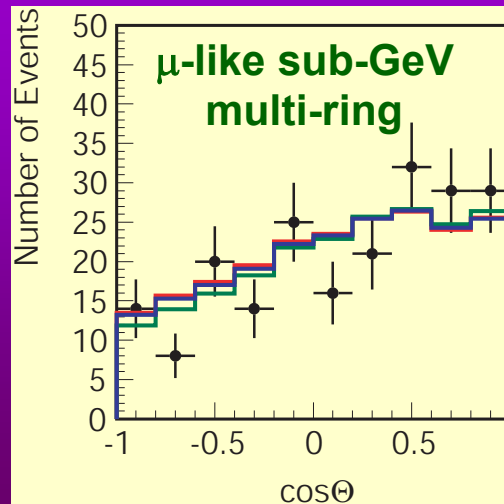
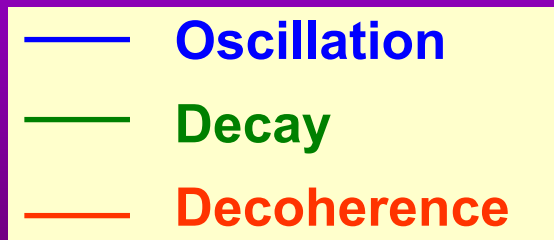
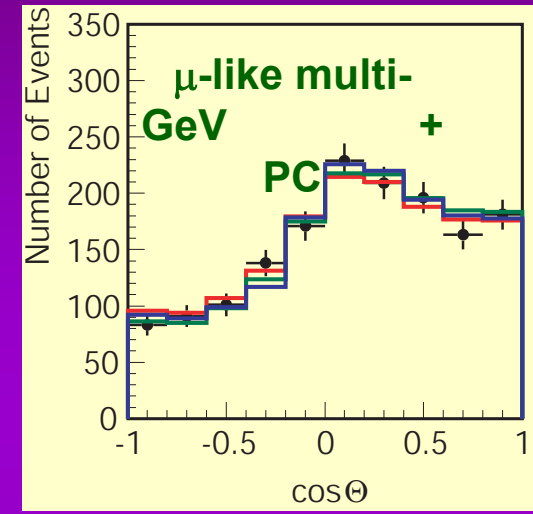
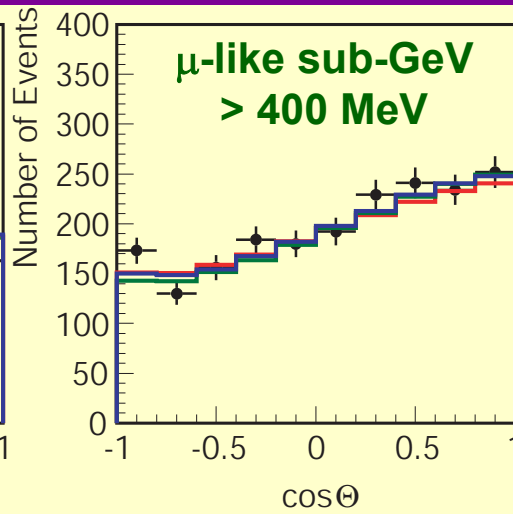
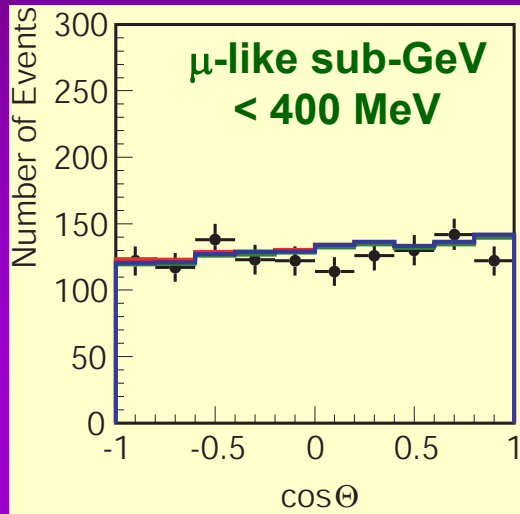
Distributions of zenith angle could be described by decoherence effects.

hep-ph/0105303 Benatti and Floreanini (Trieste)

hep-ph/0005220 Adler

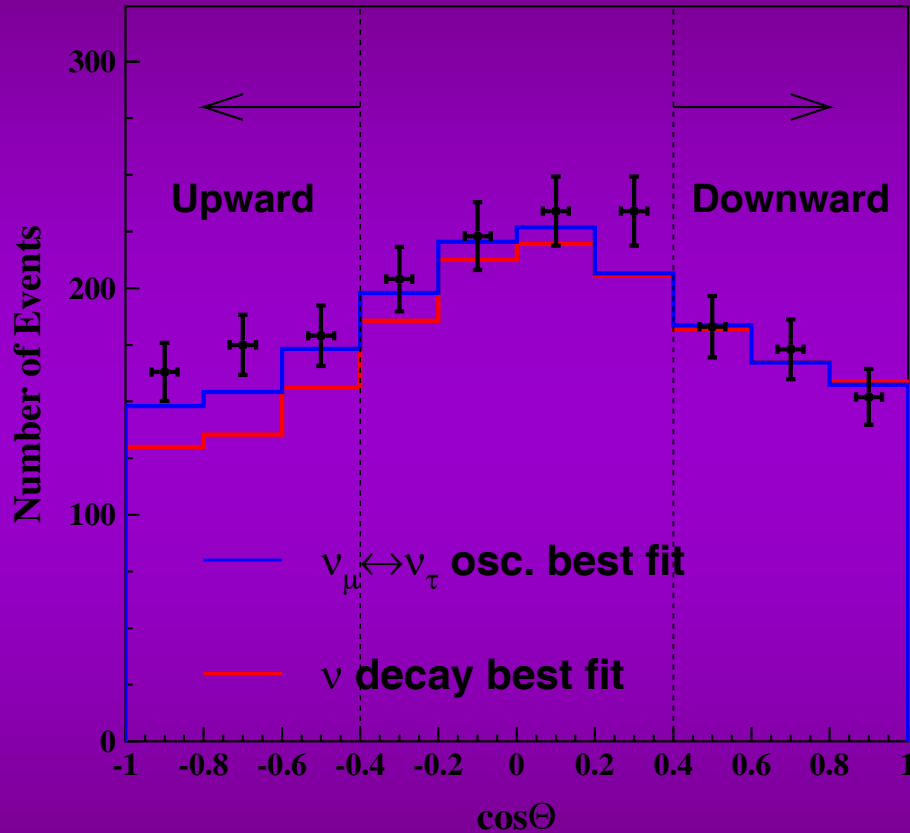
hep-ph/0303064 Fogli et al..

Zenith angle distributions - different hypotheses



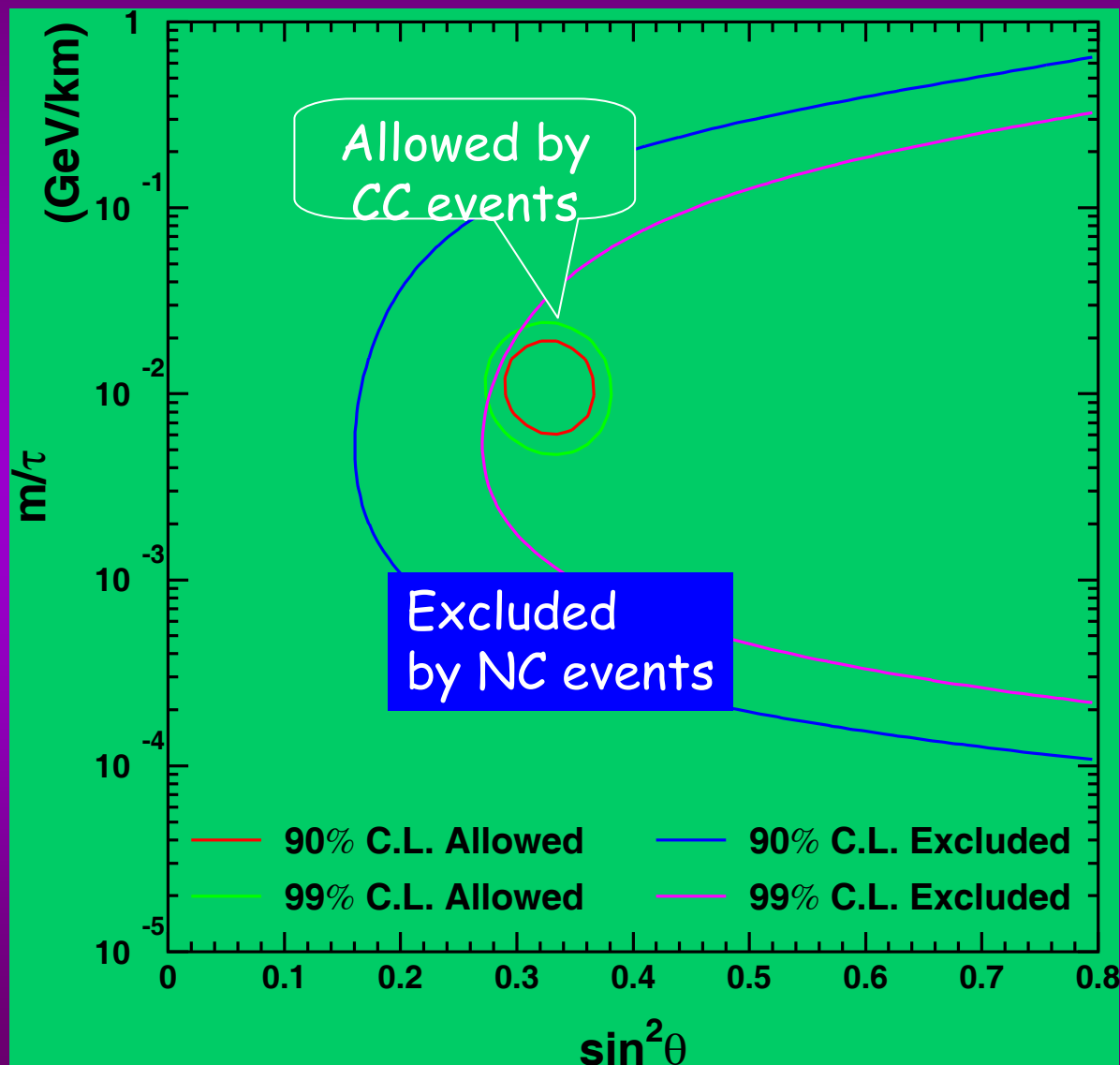
Neutrino decay - NC test

NC enriched sample



Best fit parameters
from CC samples
(FC 1R + PC + upmu)

Test of neutrino decay by NC events



How to test non-oscillation hypotheses

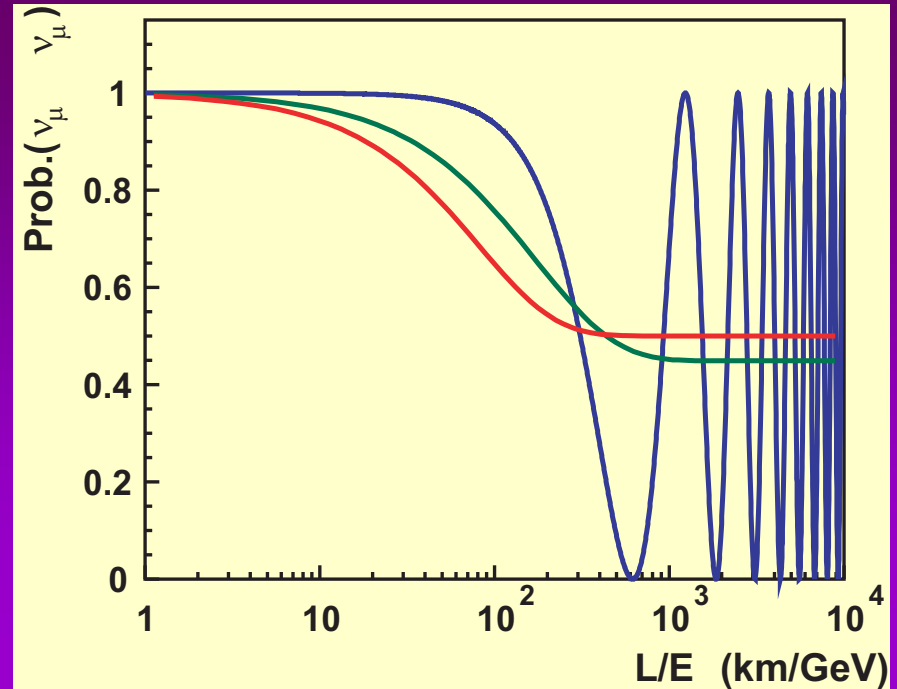
Neutrino oscillation :

$$P_{\mu\mu} = 1 - \sin^2 2\mathcal{G} \sin^2 \left(1.27 \frac{\Delta m^2 L}{E} \right)$$

Neutrino decay:

If $\Delta m^2 = E / L$

$$P_{\mu\mu} = \left(\cos^2 \mathcal{G} + \sin^2 \mathcal{G} \exp\left(-\frac{mL}{2\tau E}\right) \right)^2$$



Neutrino decoherence :

If $\Delta m^2 = E / L$

$$P_{\mu\mu} = 1 - \frac{1}{2} \sin^2 2\mathcal{G} \left[1 - \exp\left(-\gamma_0 \frac{L}{E}\right) \right]$$

Let's try to select events with best precision in L/E

Specials in L/E analysis

FC single-ring, multi-ring μ -like

Expand fiducial volume

→ More statistics for high energy muons

1.5m from top & bottom

1m from barrel

22.5kt

→ 26.4kt

PC

Classify PC events using OD charge

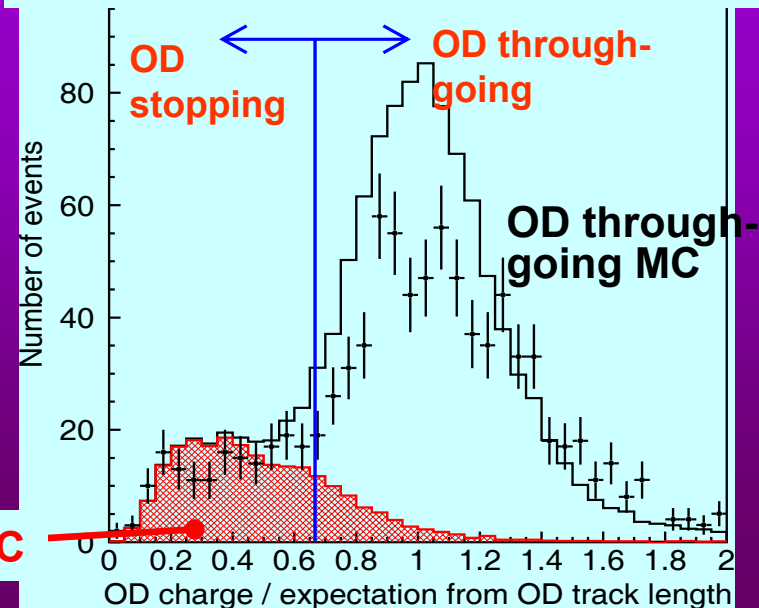
- OD stopping
- OD through going

→ Different L/E resolution

OD stopping MC

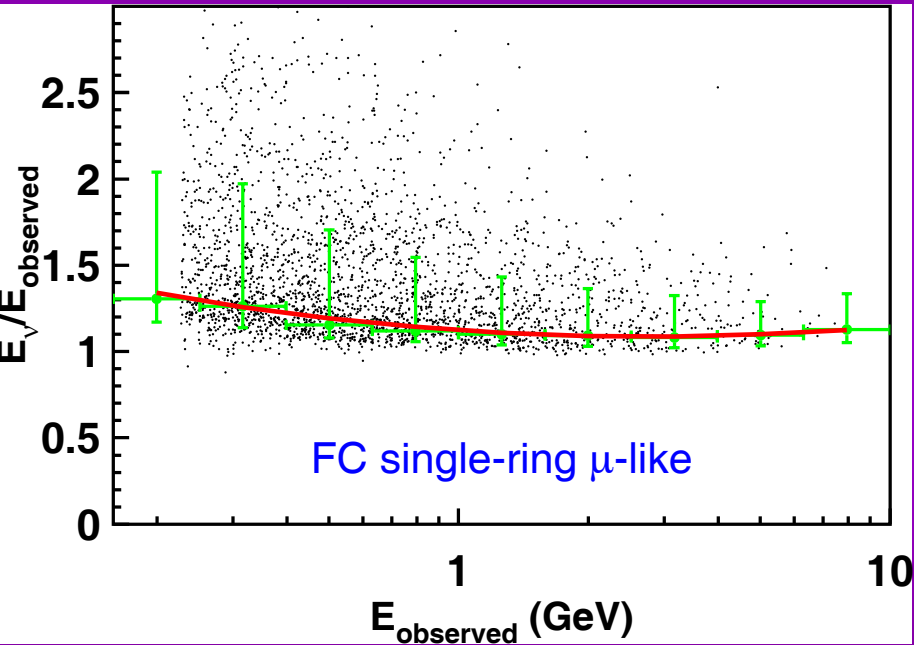
observed charge / expectation

from through-going



Reconstruction of E and L

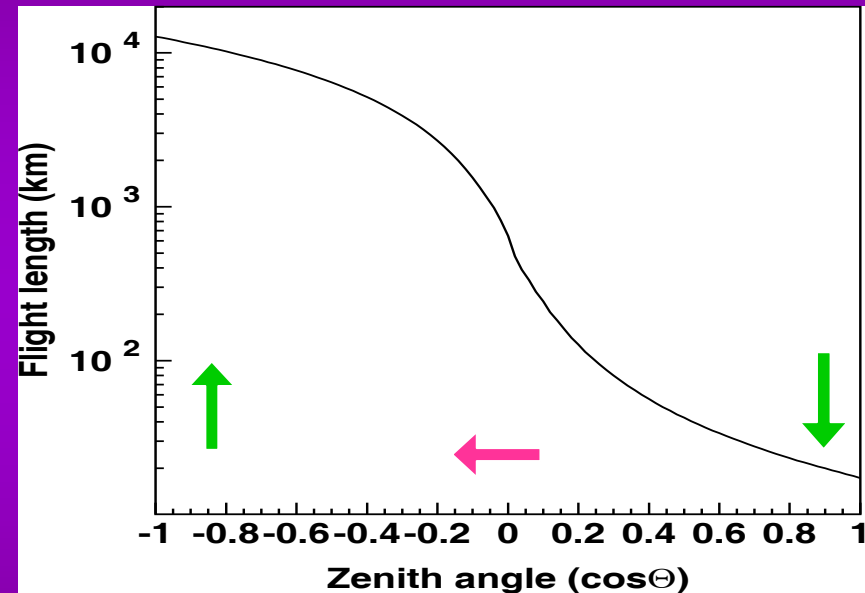
Neutrino energy



$$E_{\text{observed}} \rightarrow E_{\nu}$$

Neutrino energy is reconstructed from observed energy using relations based on MC simulation

Neutrino direction



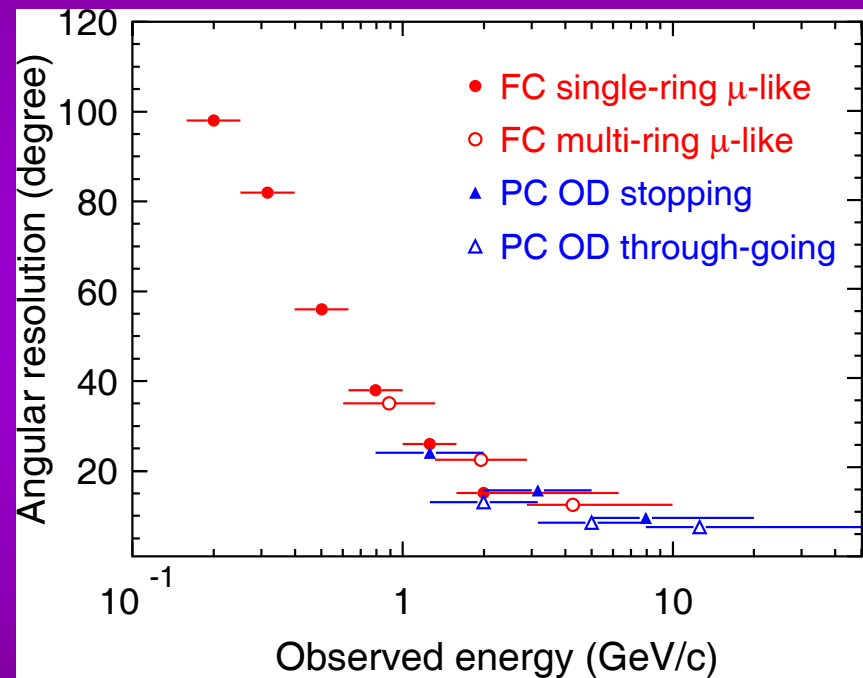
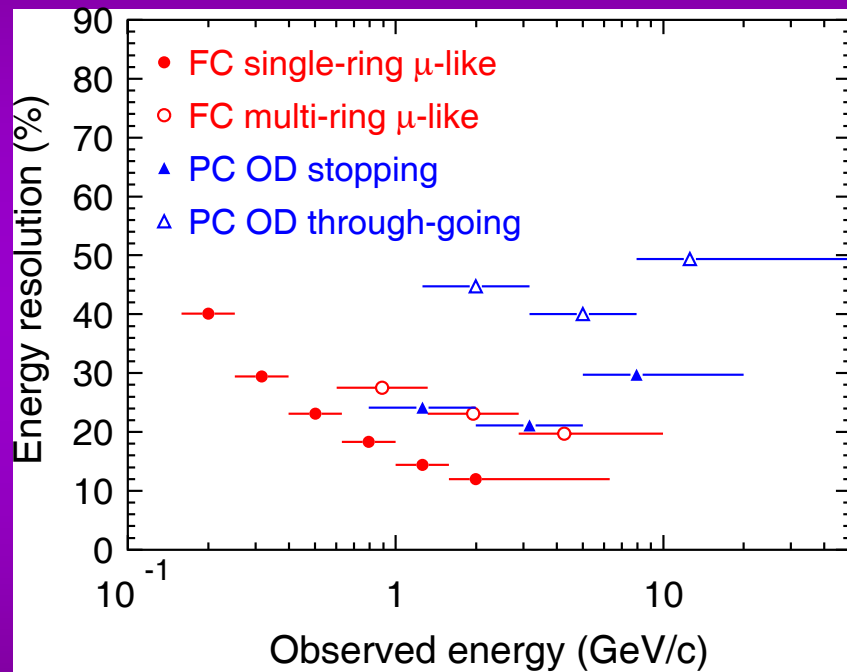
$$\text{Zenith angle} \rightarrow \text{Flight length}$$

Neutrino flight length is estimated from zenith angle of particle direction

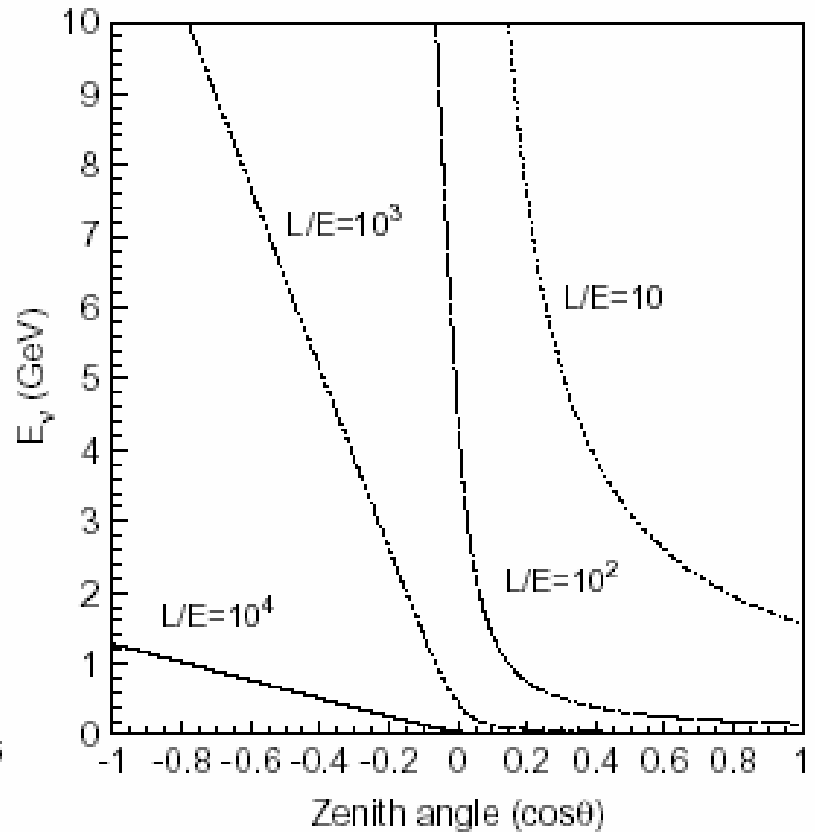
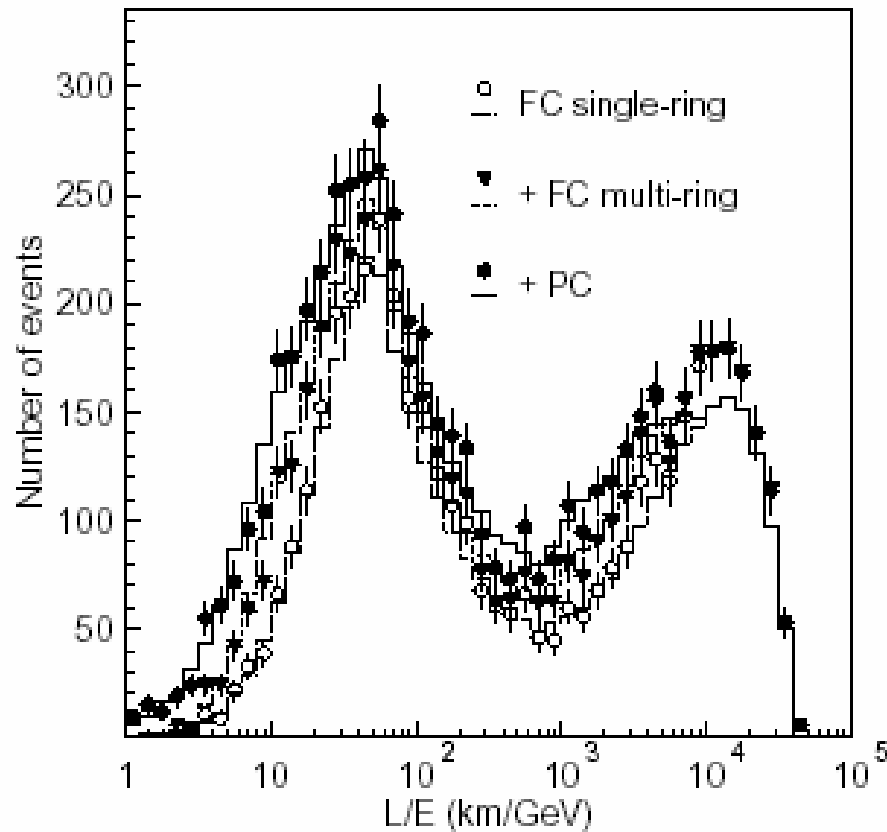
Event samples: μ -like contained events only

FC	Data	MC	CC ν_μ
single-ring	1619	2105.6	(98.3%)
multi-ring	502	813.0	(94.2%)
PC			
stopping	114	137.0	(95.4%)
through-going	491	670.1	(99.2%)
<hr/>			
Total	2726	3725.7	

Energy and angular resolution



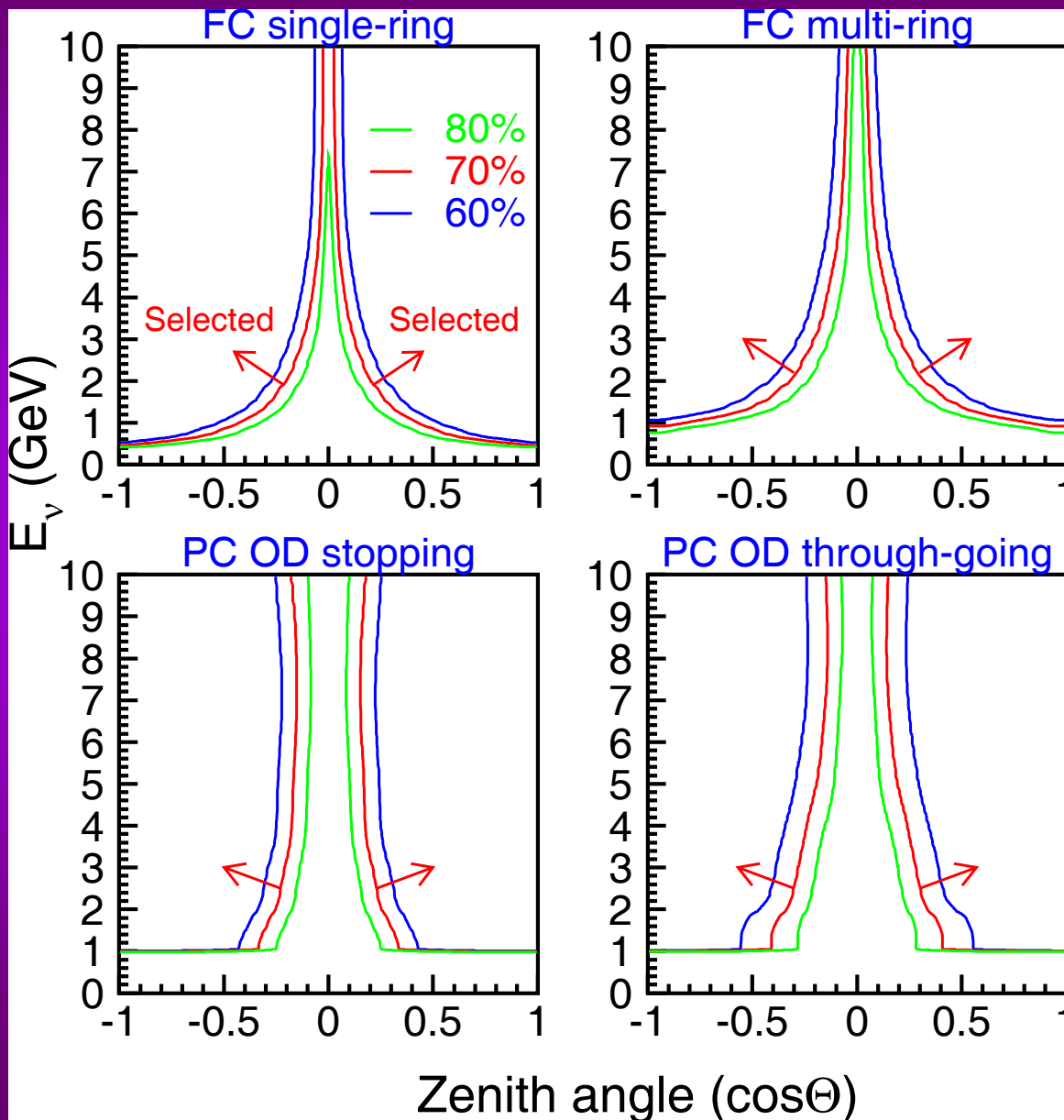
L/E distribution w/out resolution cuts



Histograms: oscillated MC
(100 y)

$$\left\{ \begin{array}{l} \nu_\mu \leftrightarrow \nu_\tau \\ \text{with} \\ \Delta m^2 = 0.002 \text{eV}^2, \quad \sin^2 2\theta = 1 \end{array} \right.$$

Resolution of L/E and cuts



$$\Delta\left(\frac{L}{E}\right)$$

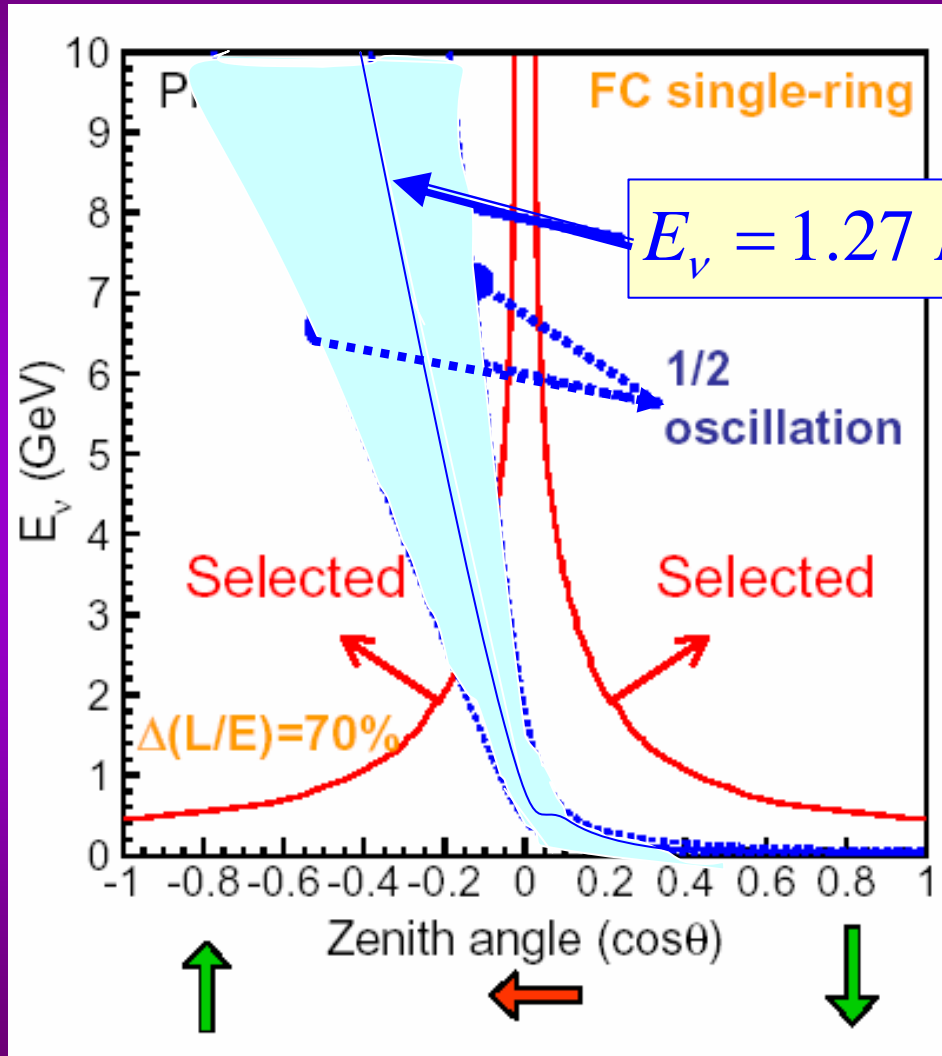
is calculated at every point of the plots

Large $\Delta\left(\frac{L}{E}\right)$ for:

- horizontal neutrinos
because of: $\frac{dL}{d \cos\Theta}$
- low neutrino energy
because of kinematics

Regions with
 $\Delta\left(\frac{L}{E}\right) < 70\%$
are selected

L/E resolution and first oscil. minimum

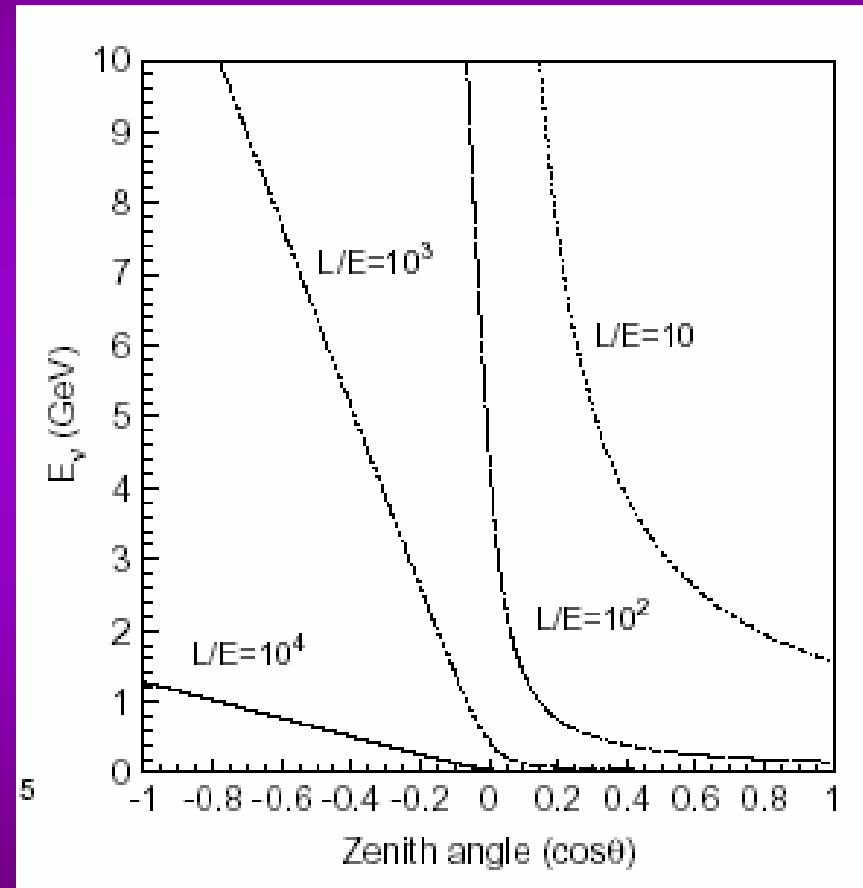
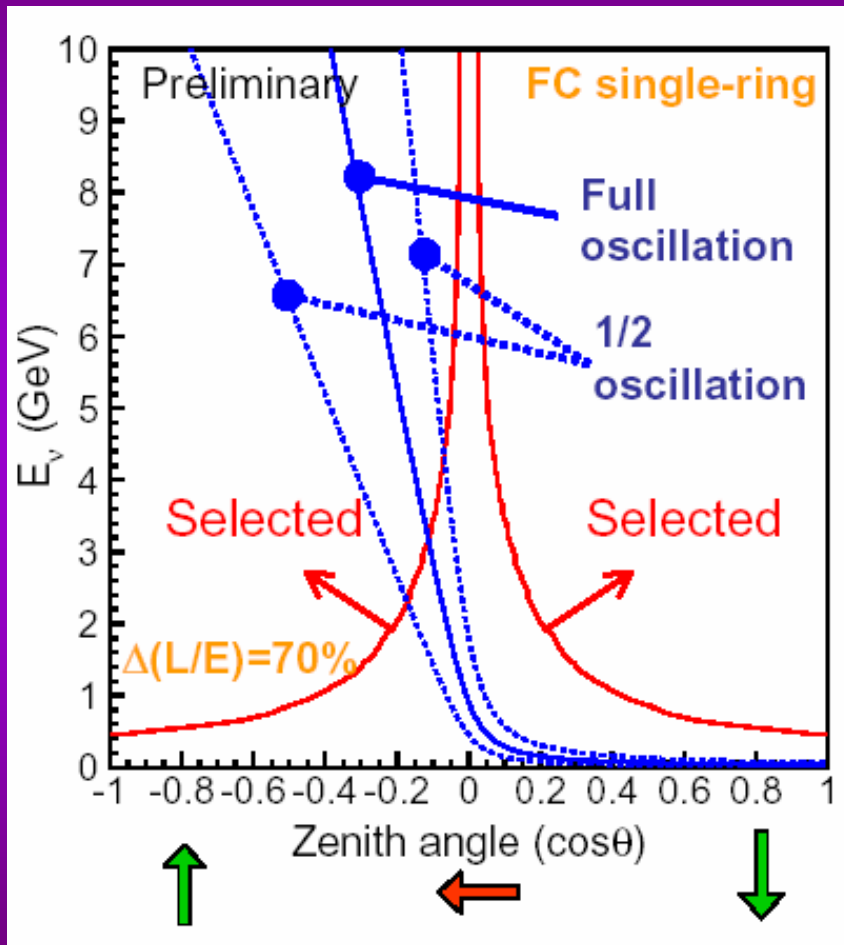


Oscil. max for:

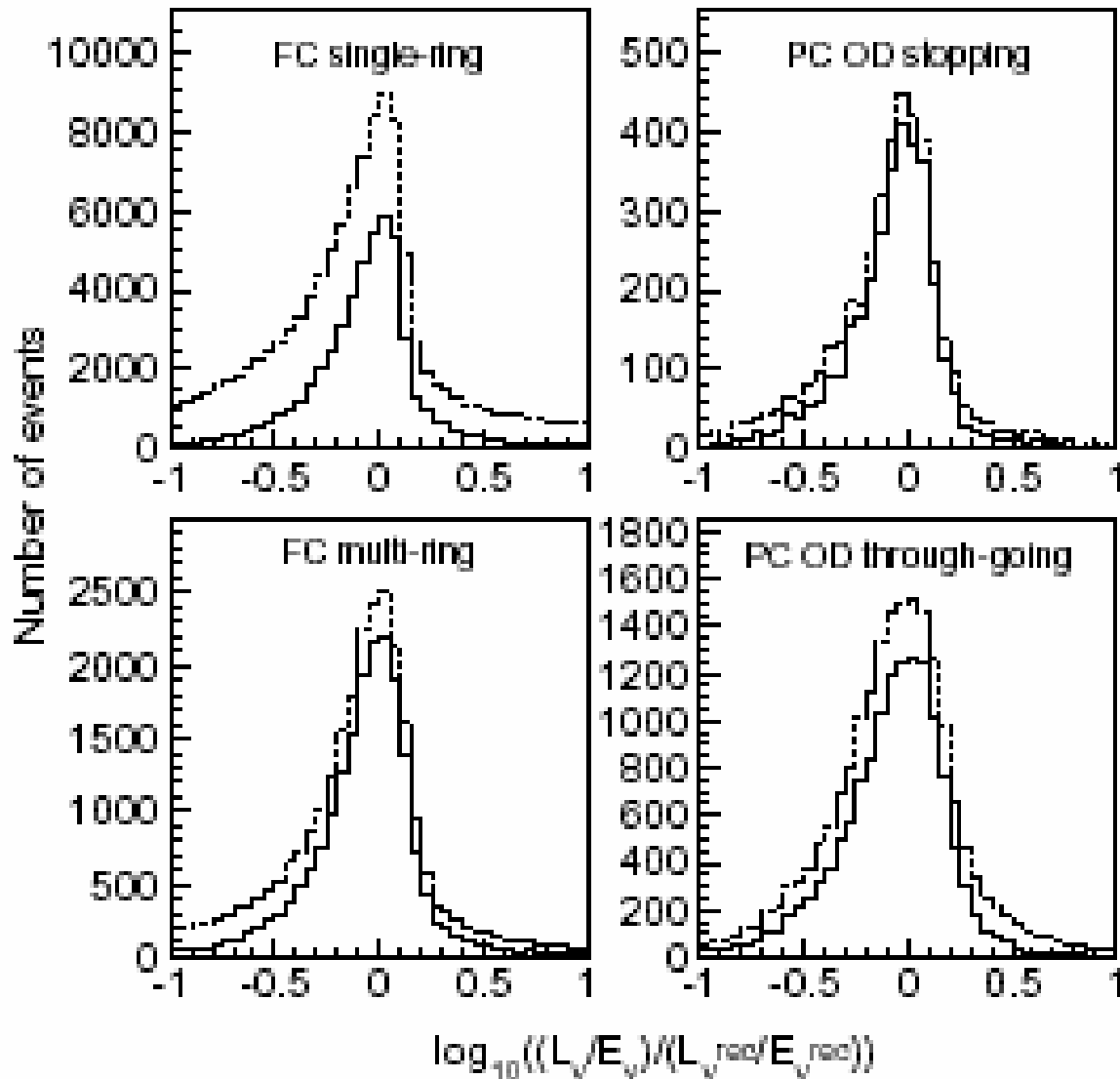
$$\nu_\mu \leftrightarrow \nu_\tau$$

$$\text{with } \Delta m^2 = 0.002 \text{eV}^2$$

L/E resolution and first oscil. minimum



Reconstruction of L/E after resolution cut



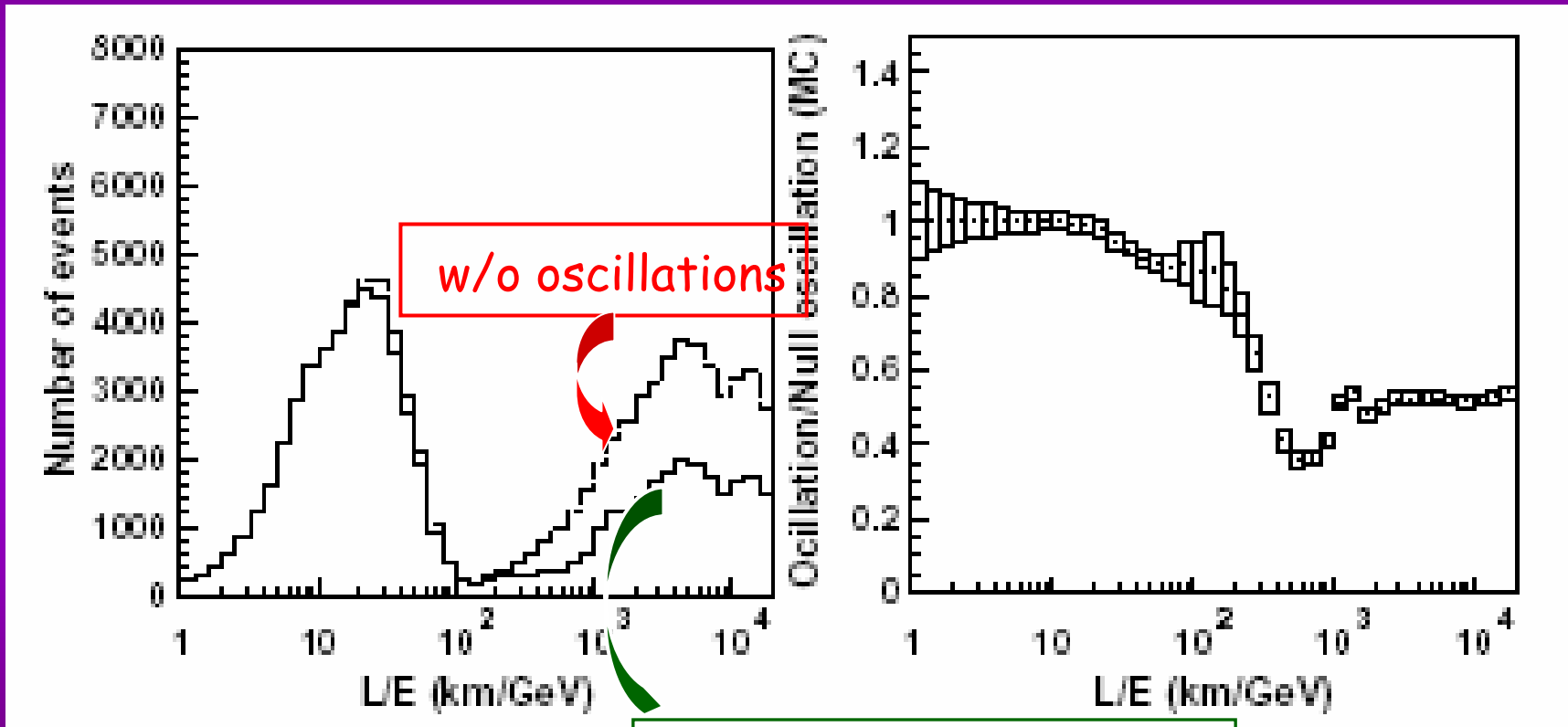
➤ dashed
- no cuts

➤ solid
 $\Delta(L/E) < 70\%$

L/E distributions with cut

MC only

$$\Delta\left(\frac{L}{E}\right) < 70\%$$

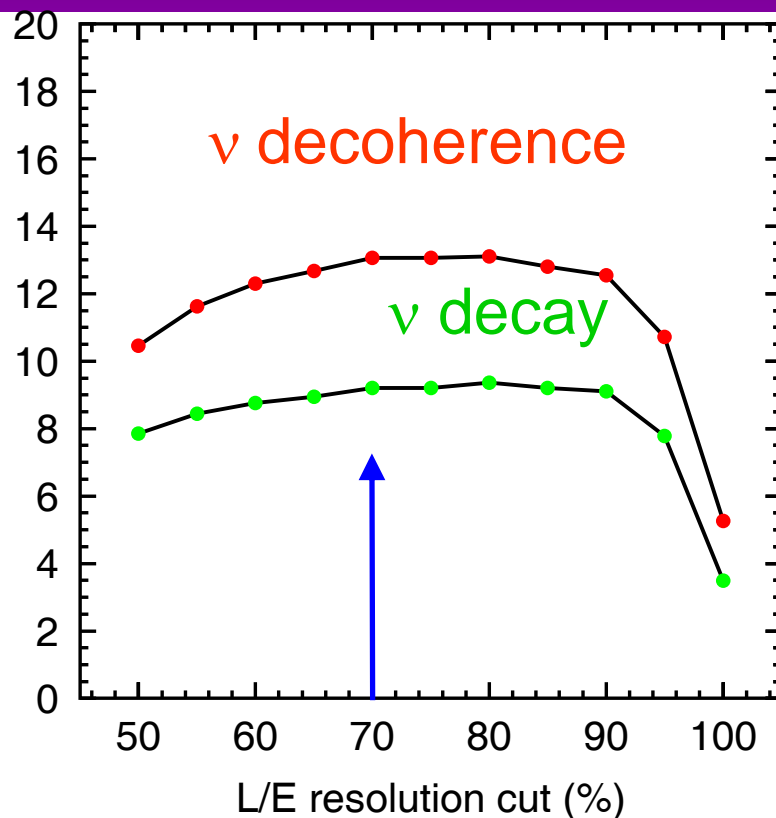
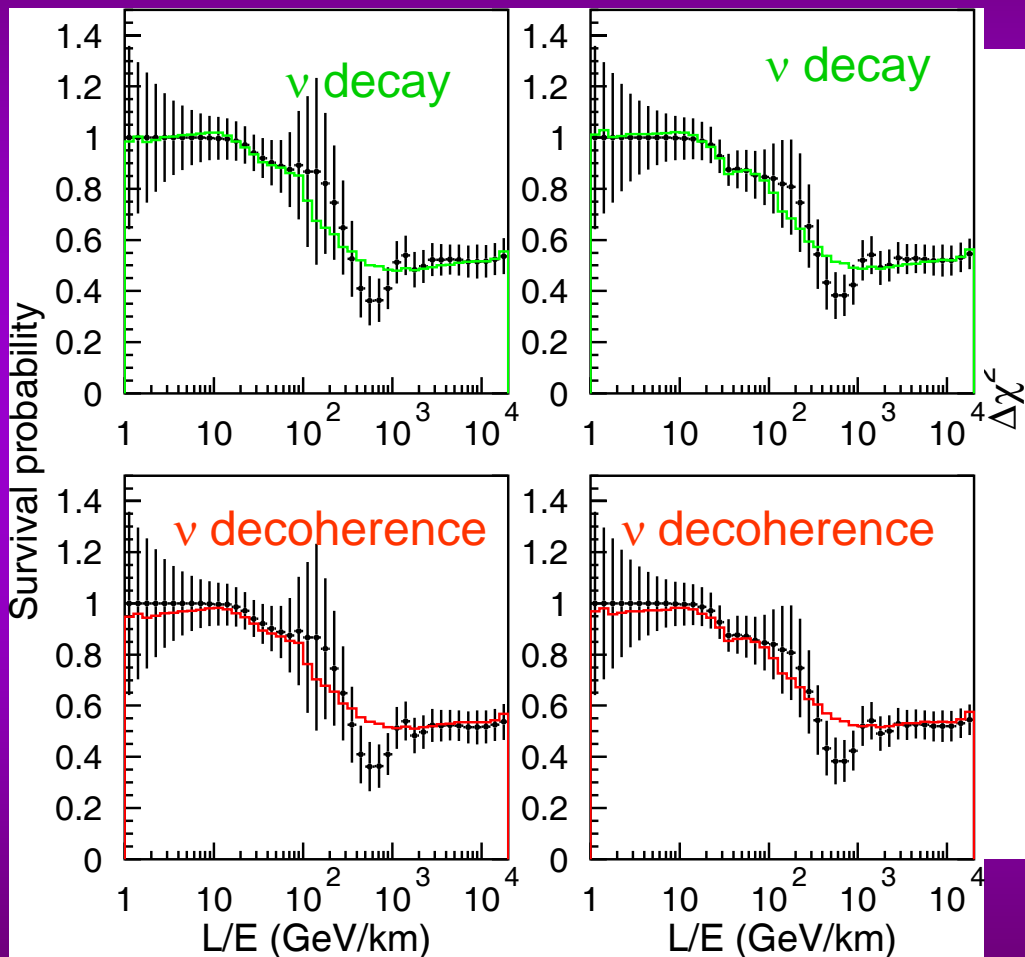


$$\nu_{\mu} \leftrightarrow \nu_{\tau} \text{ with}$$
$$\Delta m^2 = 0.002 \text{eV}^2, \quad \sin^2 2\theta = 1$$

Sensitivity to other models (determination of L/E resolution cut)

70%

80%



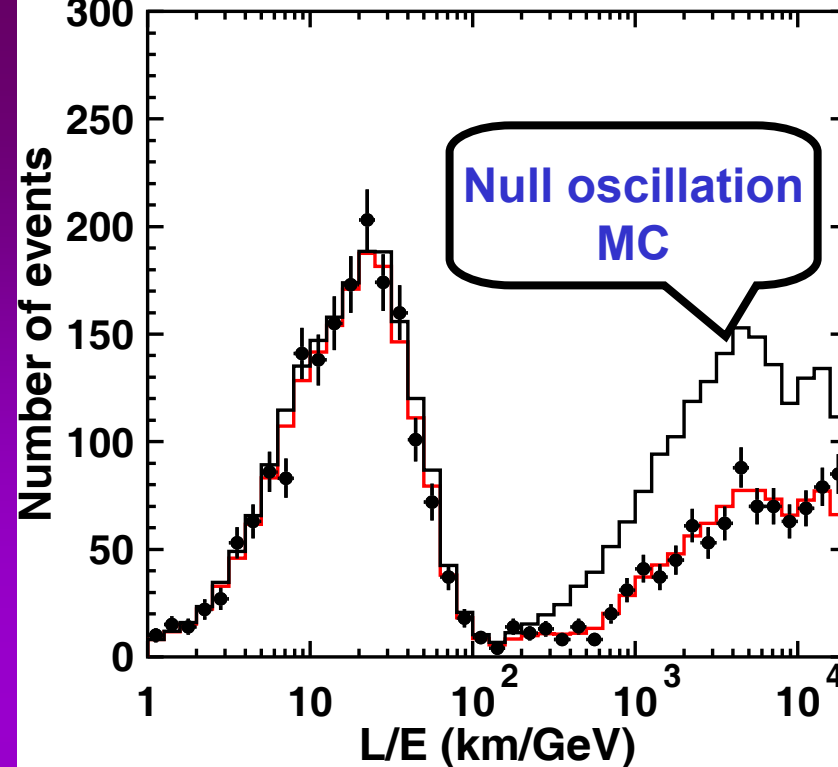
L/E resolution cut at 70%

Data sample for L/E analysis (after cut)

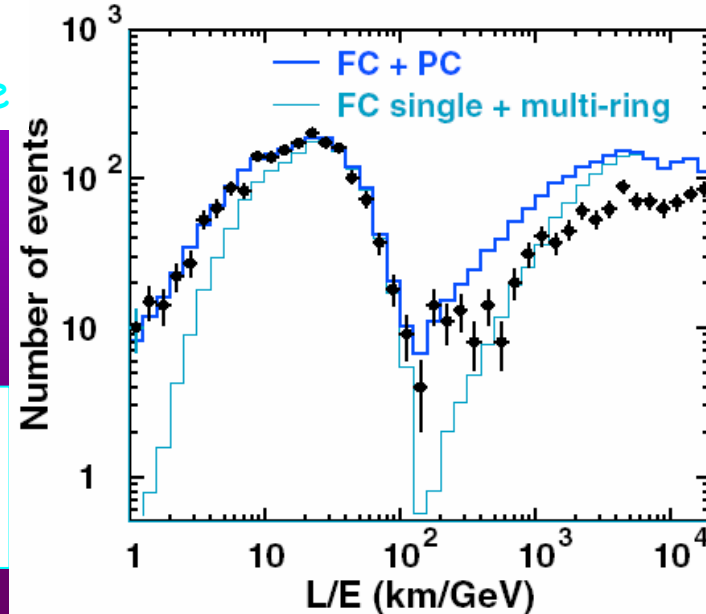
	Data	MC	CC ν_μ
FC			
single-ring	1619	2105.6	(98.3%)
multi-ring	502	813.0	(94.2%)
PC			
stopping	114	137.0	(95.4%)
through-going	491	670.1	(99.2%)

All	2726	3725.7	

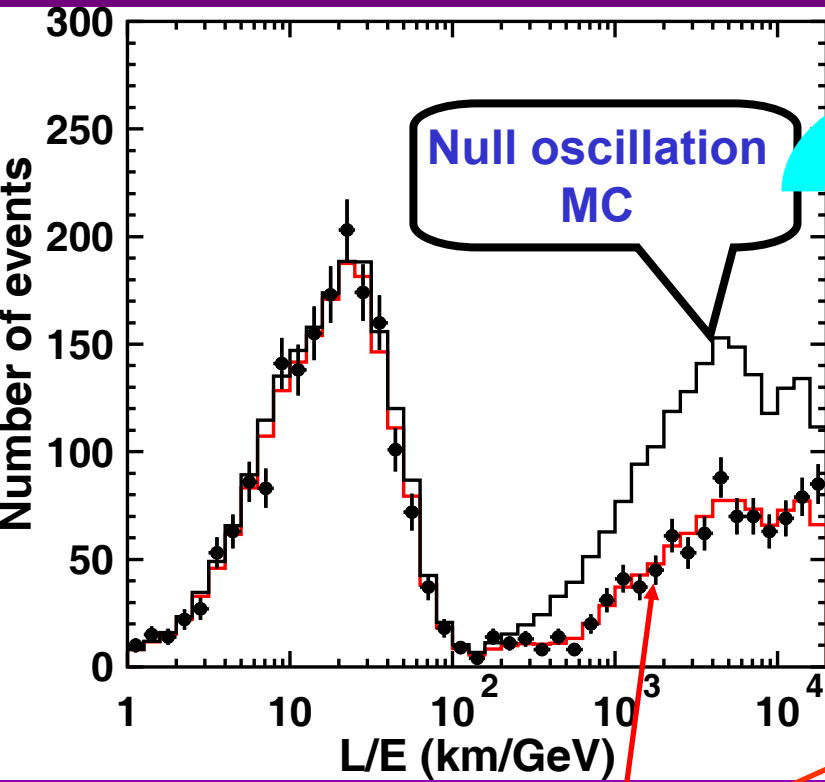
Contribution of
FC and PC



log
scale

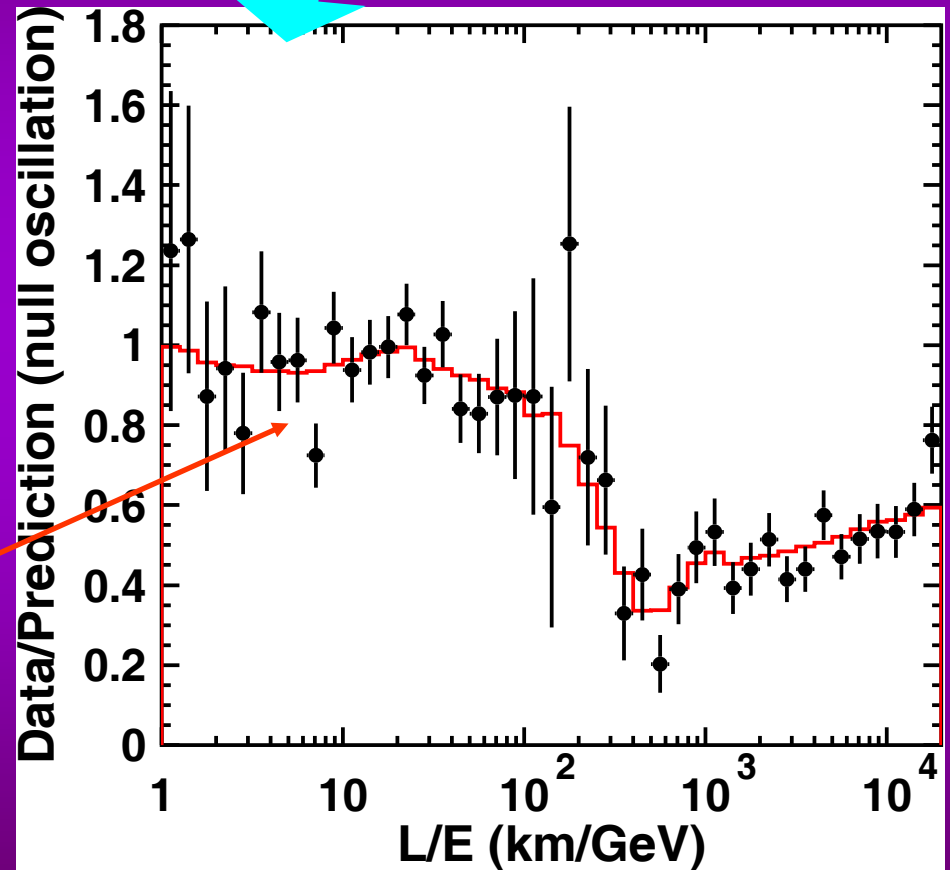


Survival probability



Best-fit expectation

divide DATA/MC

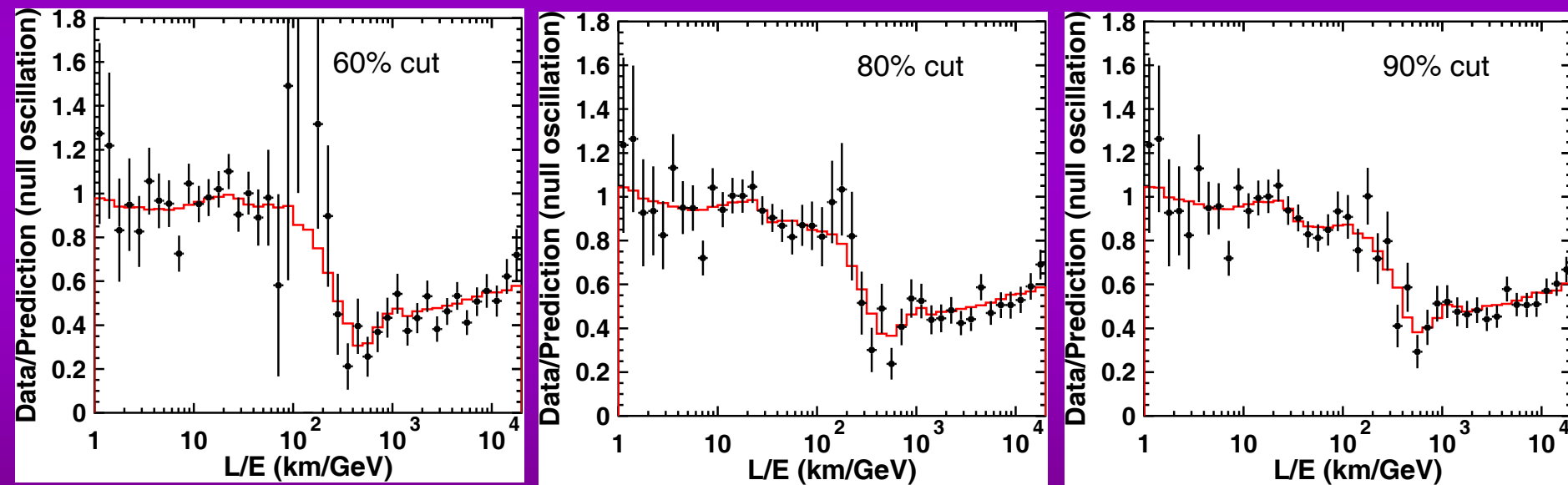


1489.2 days FC+PC

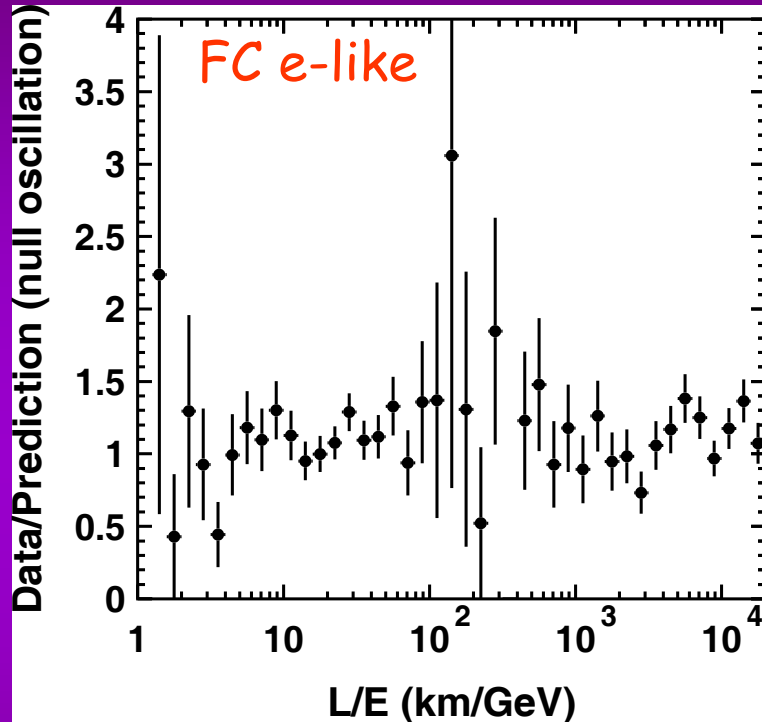
A dip just where oscil. min expected

Does the dip depends on $\Delta(L/E)$?

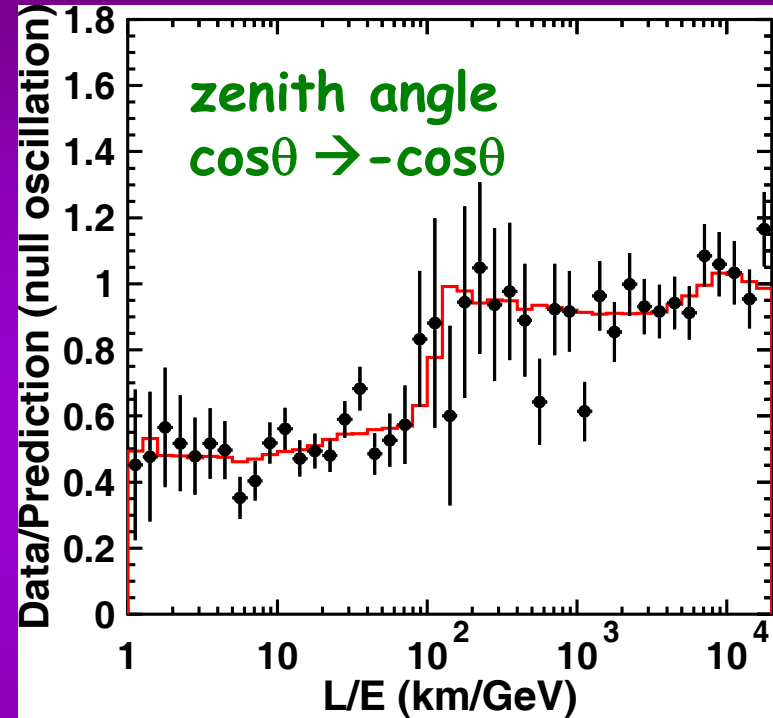
Other L/E resolution cuts:



More checks



Flat L/E distribution is expected.

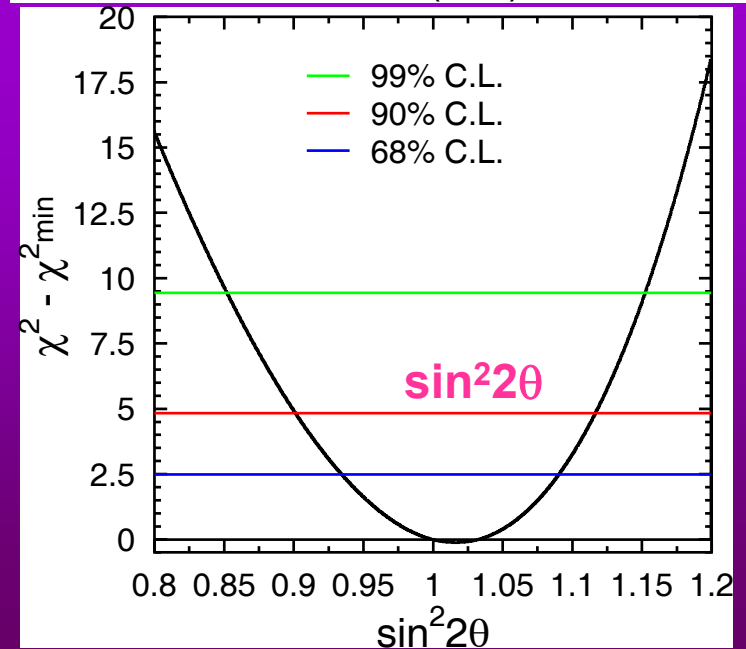
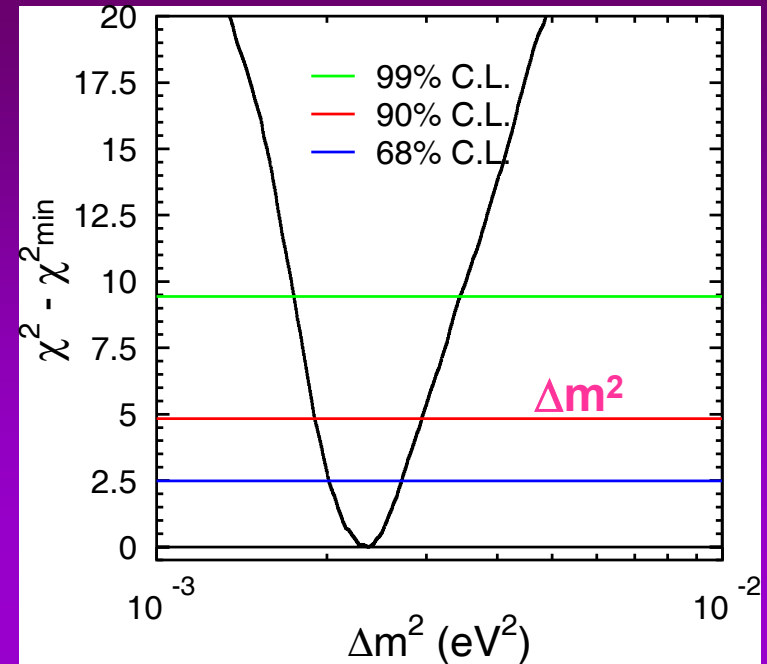
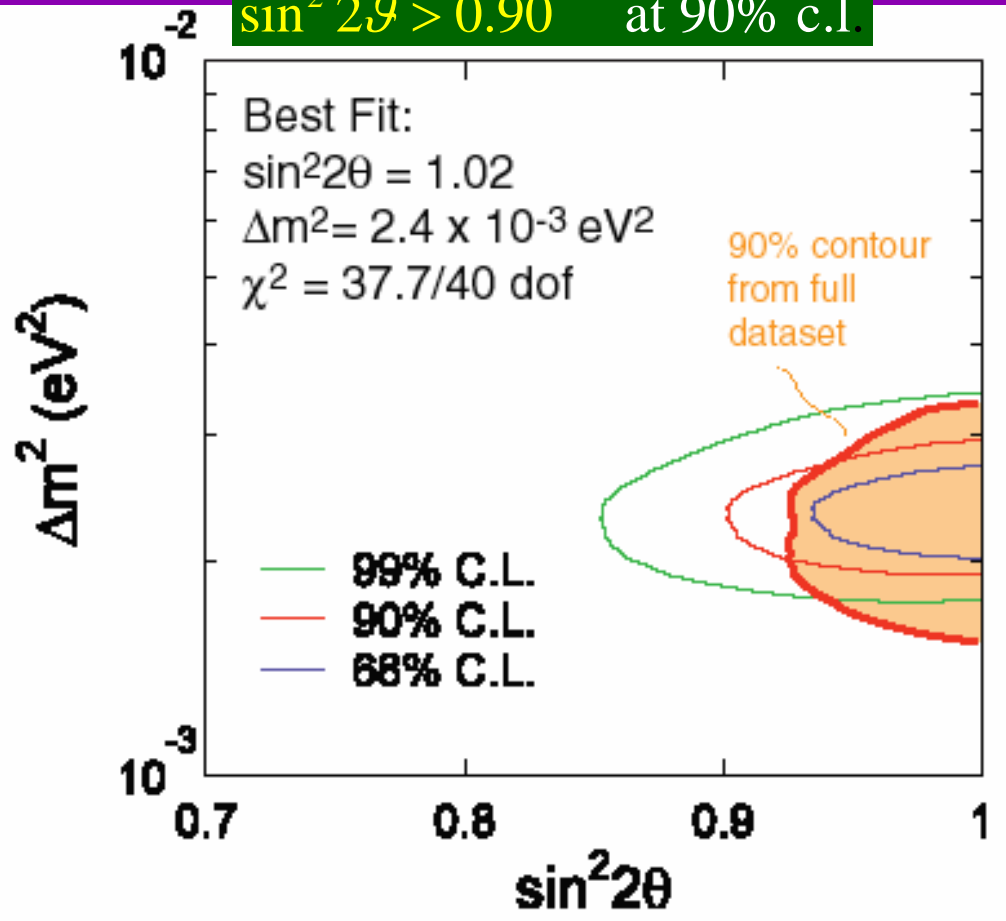


Zenith angle of each event is inverted. Because of the wrong assignment of L, no dip is expected.

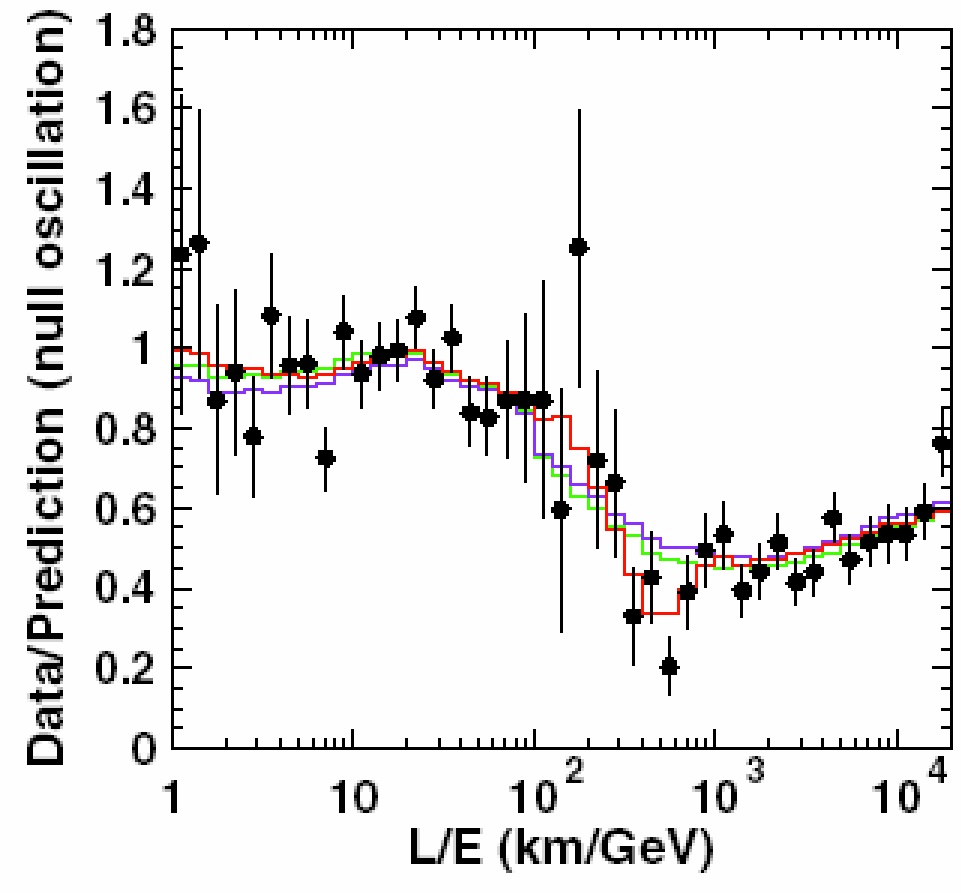
Oscillation analysis - fitting L/E distribution

$$0.0019 < \Delta m^2 < 0.0030 \text{ eV}^2$$

$$\sin^2 2\theta > 0.90 \text{ at 90\% c.l.}$$



Oscillation signature vs neutrino decay or decoherence

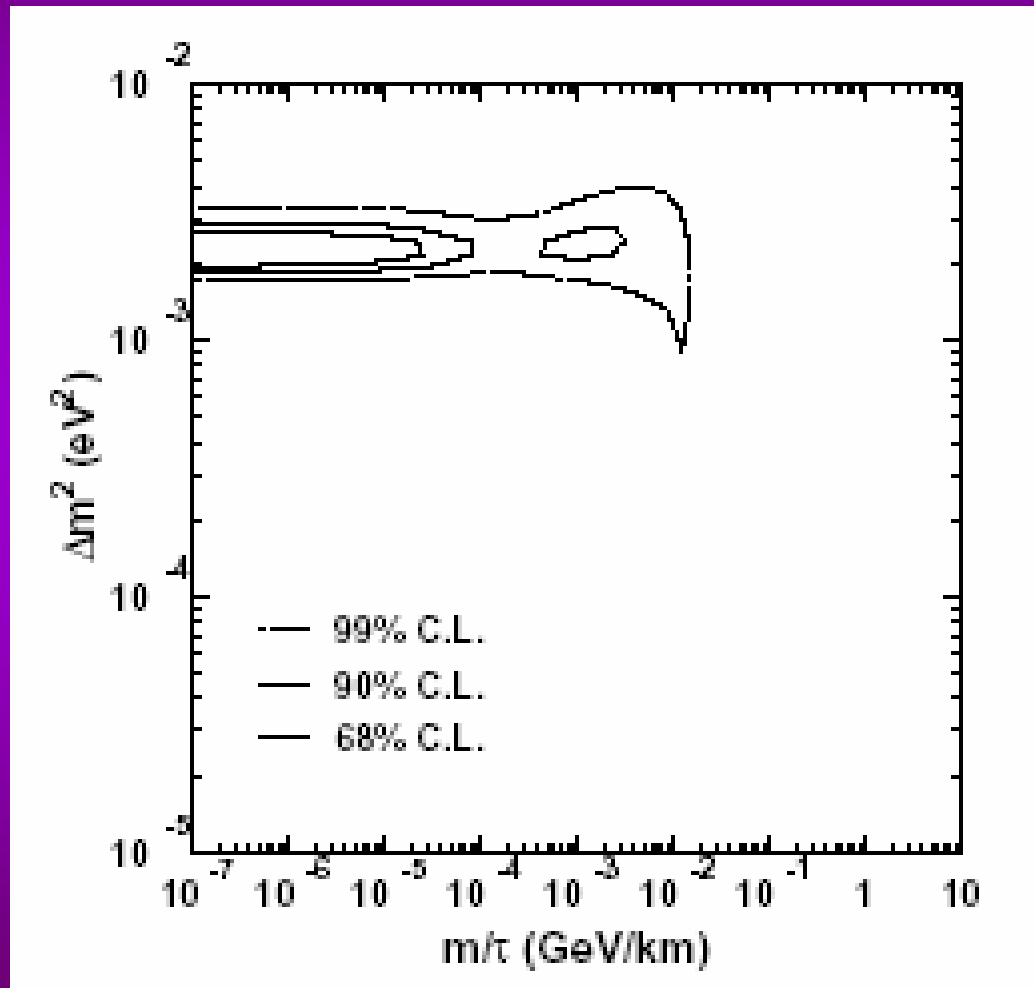


Statistical test of oscillation hypothesis (the dip)
vs
alternative („exponential”) hypotheses

$$\chi_{\min}^2 / \text{d.o.f}$$

—	Oscillations	38/40
—	Decay	49/40
—	Decoherence	52/40

Contours for neutrino decays



Summary

- Conventional oscillation analysis based on 80% of atmospheric neutrino data:

$$\nu_{\mu} \leftrightarrow \nu_{\tau}$$

$$0.0015 < \Delta m^2 < 0.0034 \text{ eV}^2$$

$$\sin^2 2\theta > 0.92 \quad \text{at 90\% c.l.}$$

- High precision sub-sample (20% of the total) displays a dip just where the oscillation minimum expected from the conventional analysis
an oscillatory signature

- The oscillation analysis of high precision subsample leads to
 - more restricted region:
 - disfavors other hypotheses

$$0.0019 < \Delta m^2 < 0.0030 \text{ eV}^2$$

$$\sin^2 2\theta > 0.90 \quad \text{at 90\% c.l.}$$

- Together with the solution of solar neutrino puzzle
we move from fact findings to precision measurements

e.g. Tokai to Kamioka