NOON2004 Feb.11, 2004

Direct oscillatory evidence from L/E analysis in Super-Kamiokande

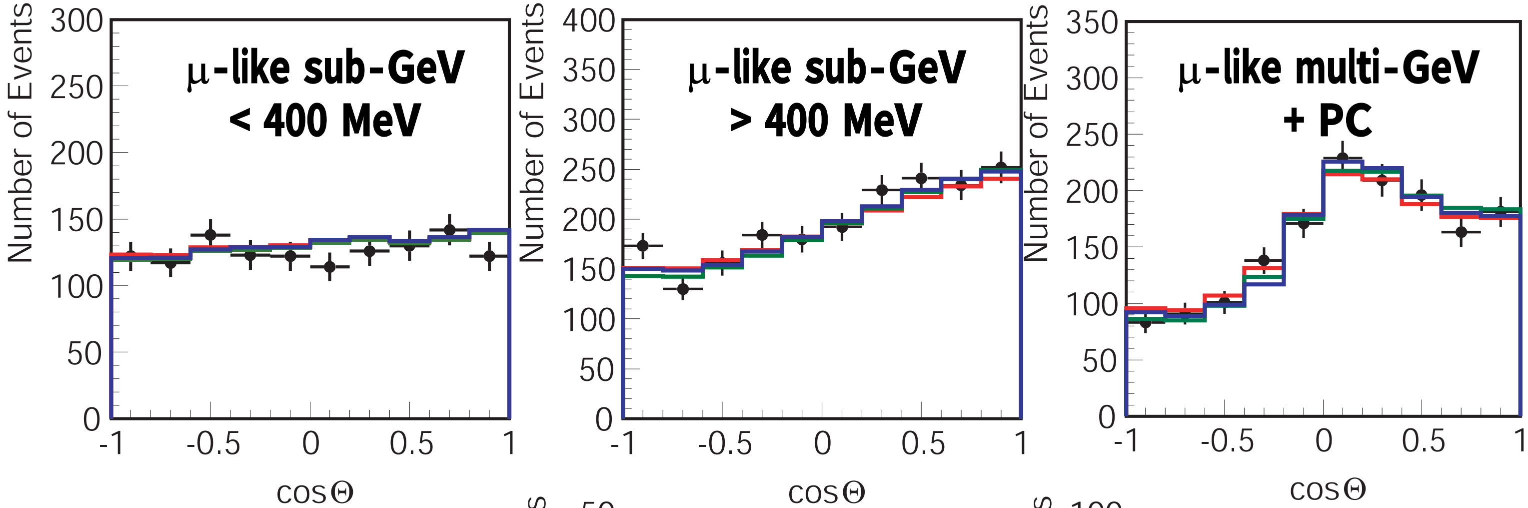
Masaki Ishitsuka

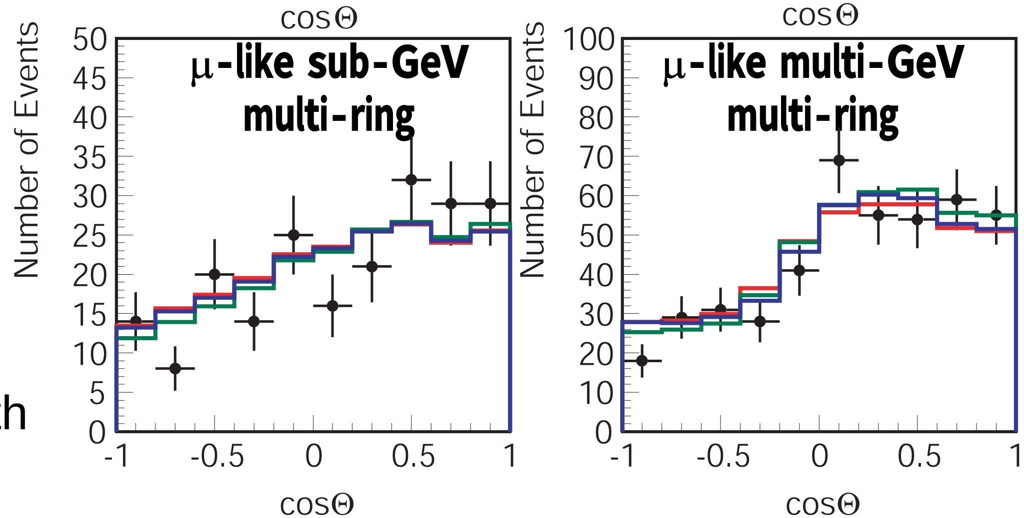
ICRR

for Super-Kamiokande collaboration

Motivation

Zenith angle distributions





Other models can explain zenith angle dependent muon deficit.

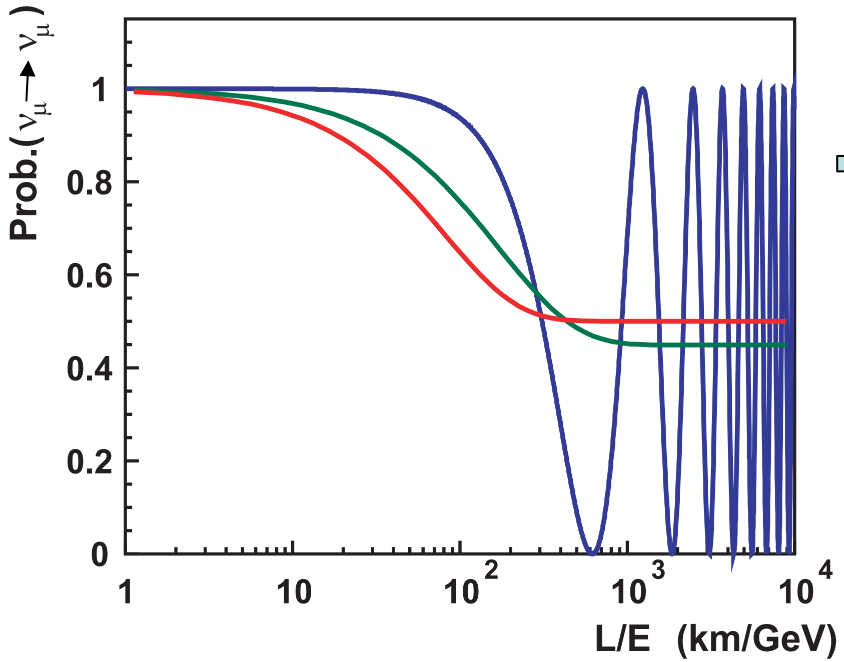
⇨ **How can we distinguish oscillation from other hypotheses ?**

L/E analysis

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



Use events with high resolution in L/E

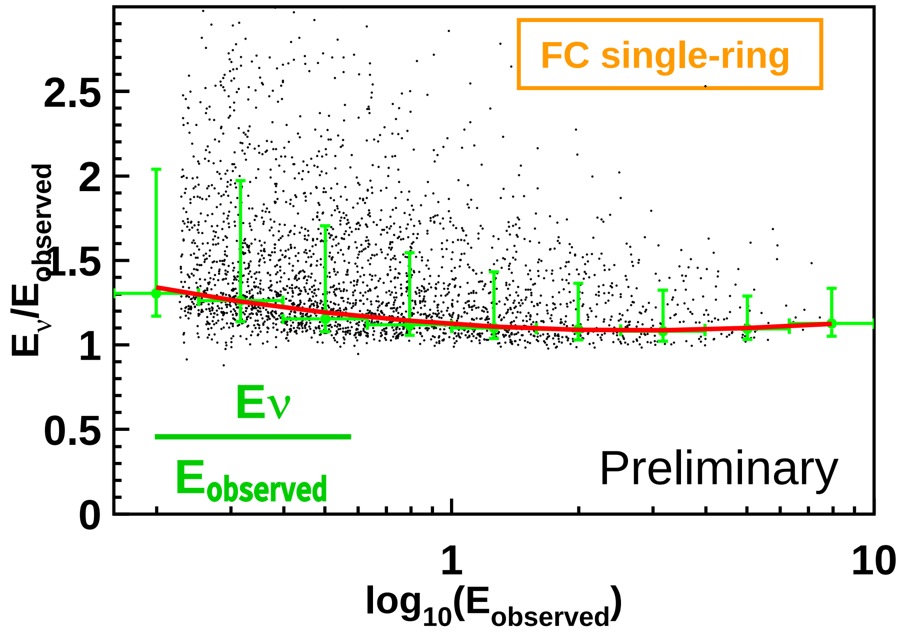
→ **The first dip can be observed**

→ Direct evidence for oscillations

→ Strong constraint to oscillation parameters, especially Δm^2 value

Reconstruction of E and L

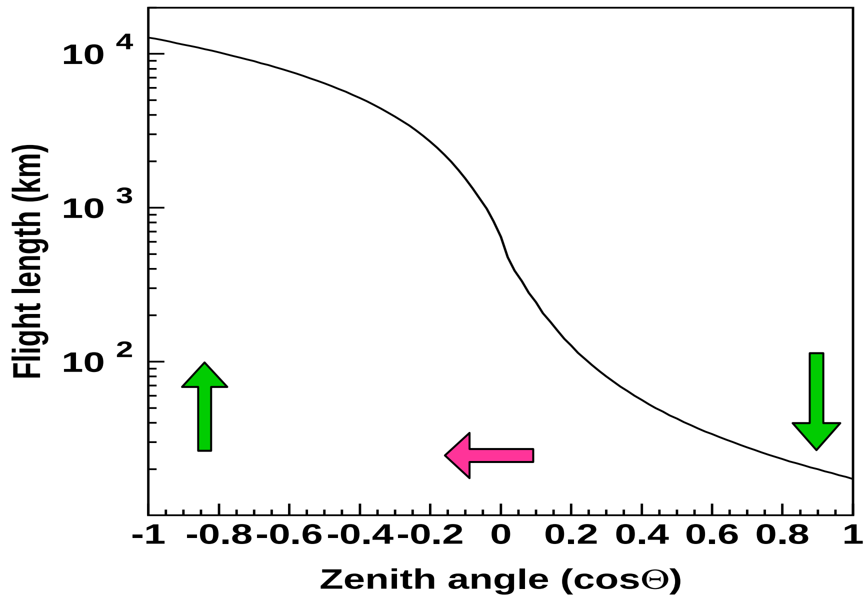
Neutrino energy



$E_{observed} \rightarrow E_\nu$

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

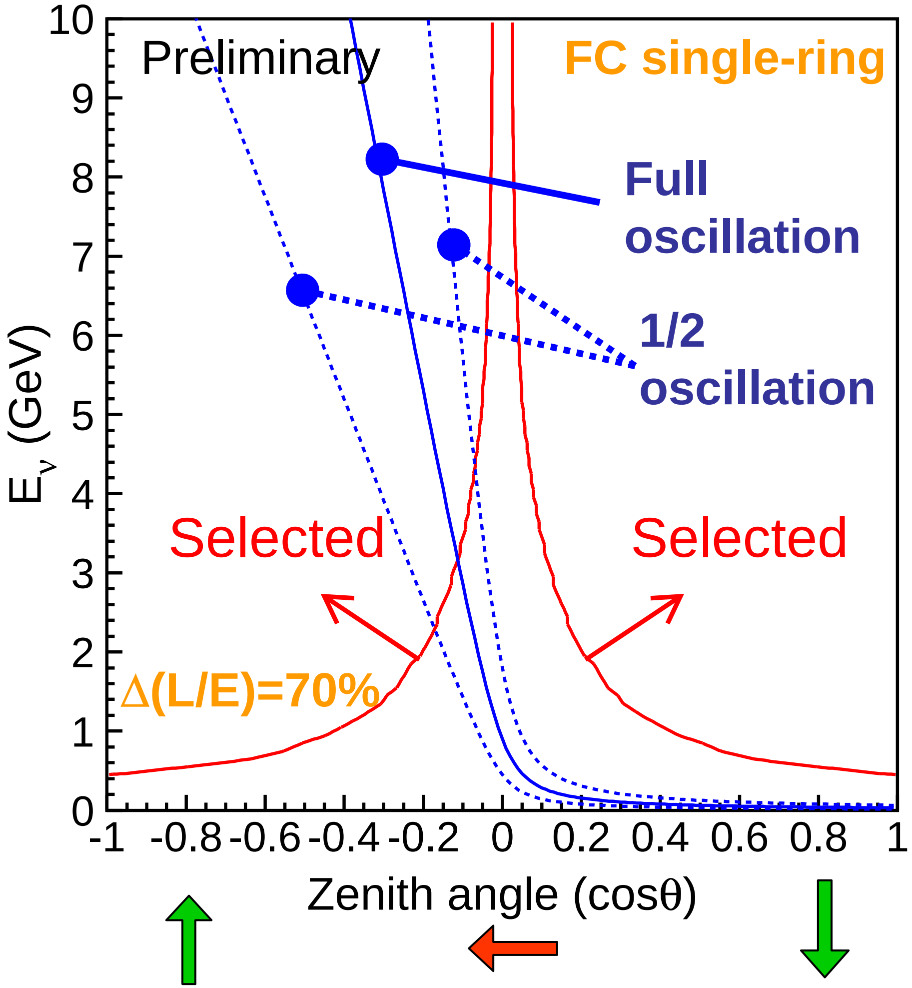
Neutrino flight length



Zenith angle
→ Flight length

Neutrino flight length is estimated from zenith angle of particle direction

L/E resolution cut



Select events with high resolution in L/E

Bad L/E resolution for

horizontally going events
→ due to large dL/dcosθ

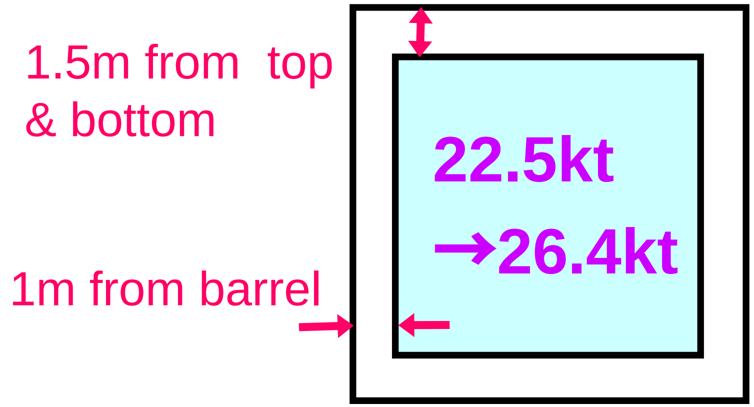
low energy events
→ due to large scattering angle

Event samples in L/E analysis

FC single-ring, multi-ring μ-like

Expand fiducial volume

→ **More statistics for high energy muons**

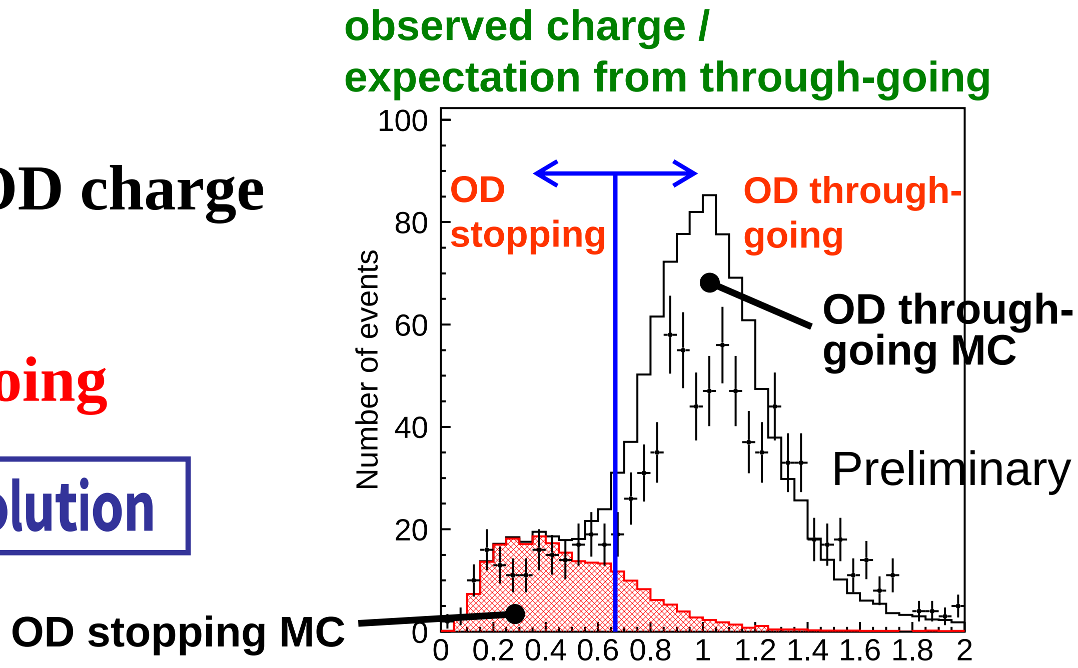


PC

Classify PC events using OD charge

- I. OD stopping
- II. OD through going

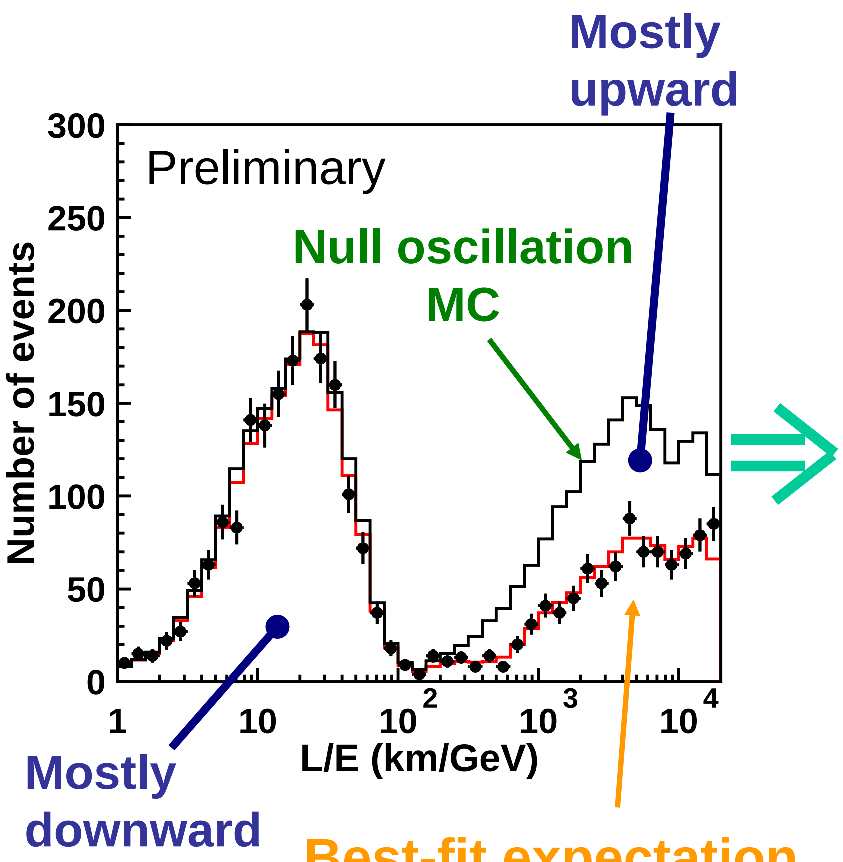
→ **Different L/E resolution**



Event summary of L/E analysis

	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%)
Total	2726	3725.7	

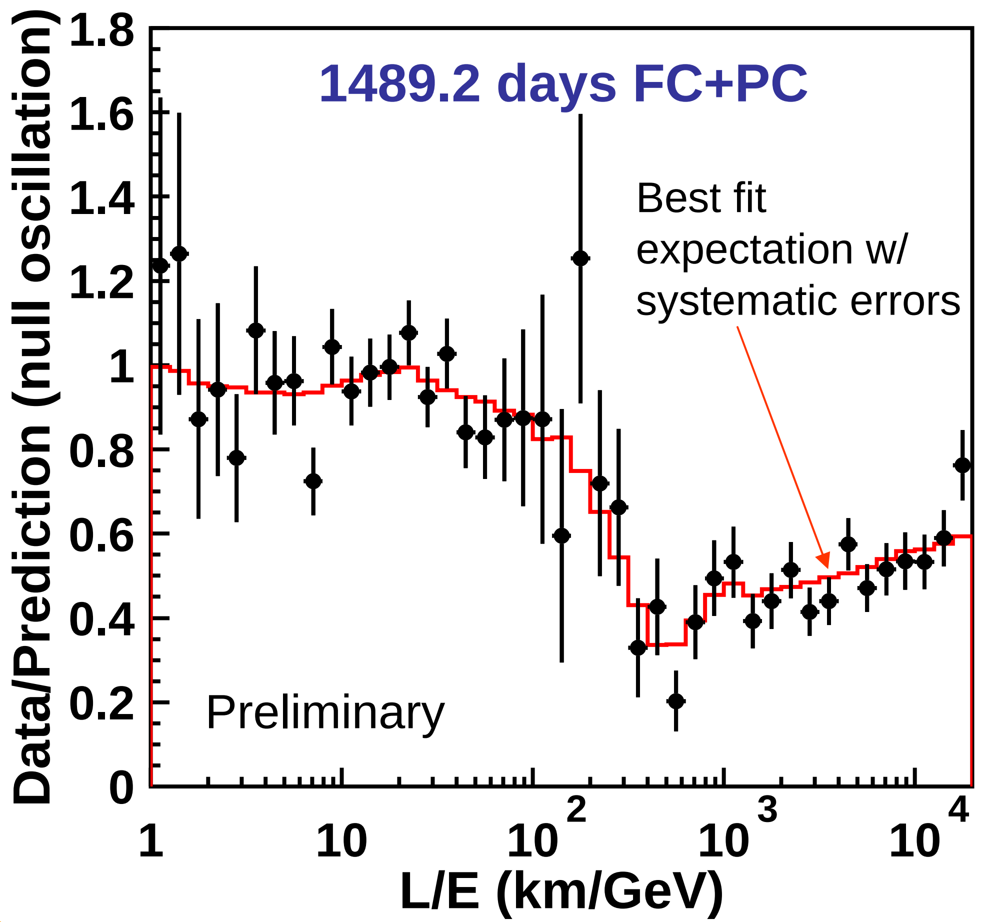
L/E in atmospheric neutrino data



Best-fit expectation

$\Delta m^2=2.4\times10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{min}=37.8/40$ d.o.f



First dip is observed as expected from neutrino oscillation

Definition of χ^2

$$L\left(N_{\exp}, N_{obs}\right) = \prod_{n=1}^{43} \frac{\exp(-N_{\exp}^{n})(N_{\exp}^{n})^{N_{obs}^{n}}}{N_{obs}^{n}!} \times \prod_{i=1}^{25} \exp\left(\frac{-\varepsilon_i^2}{2\sigma_i^2}\right)$$

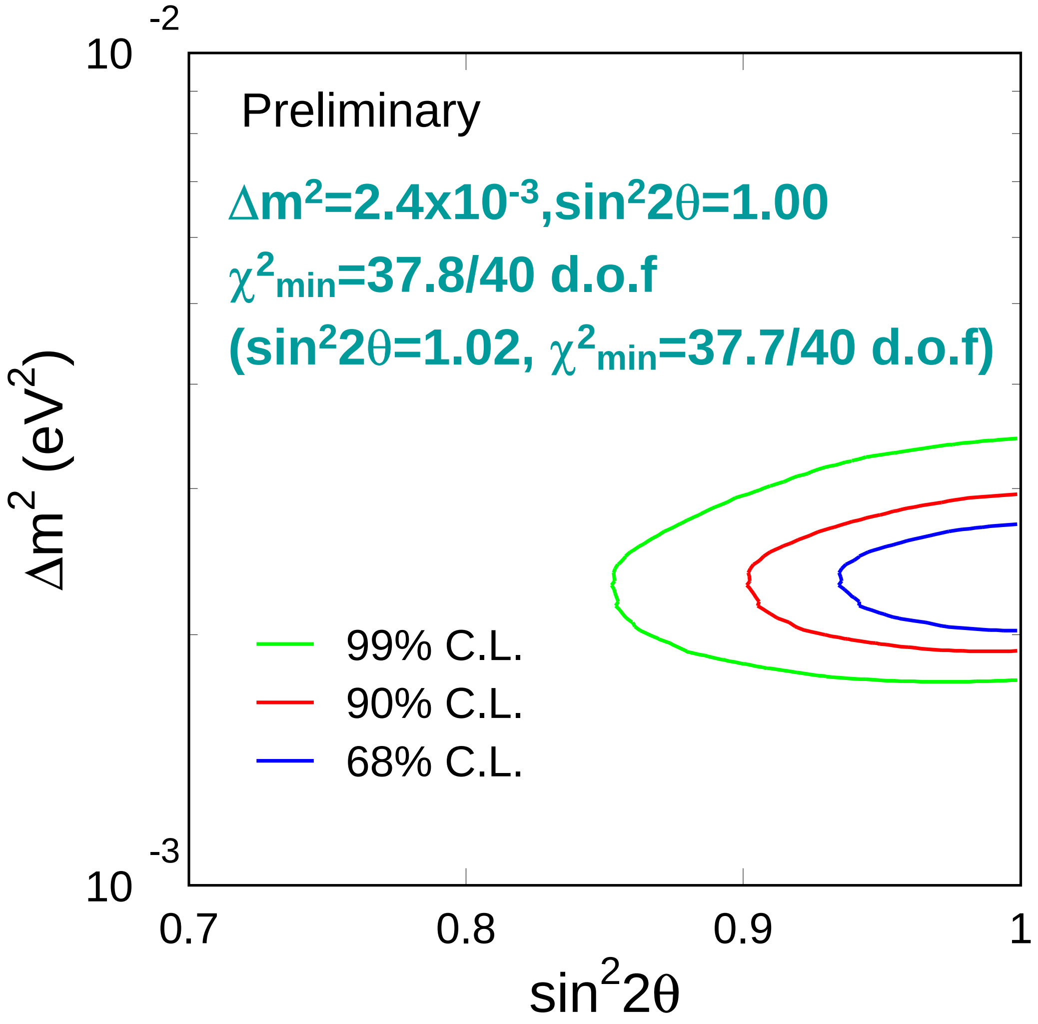
Poisson with systematic errors

$$\chi^2 \equiv -2\ln\left(\frac{L\left(N_{\exp}, N_{obs}\right)}{L\left(N_{obs}, N_{obs}\right)}\right) = \sum_{n=1}^{43}\left[2(N_{\exp}^{n} - N_{obs}^{n}) + 2N_{obs}^{n}\ln\left(\frac{N_{obs}^{n}}{N_{\exp}^{n}}\right)\right] + \sum_{i=1}^{25}\left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

N_{obs} : observed number of events
N_{exp} : expectation from MC
ε_i : systematic error term
σ_i: sigma of systematic error

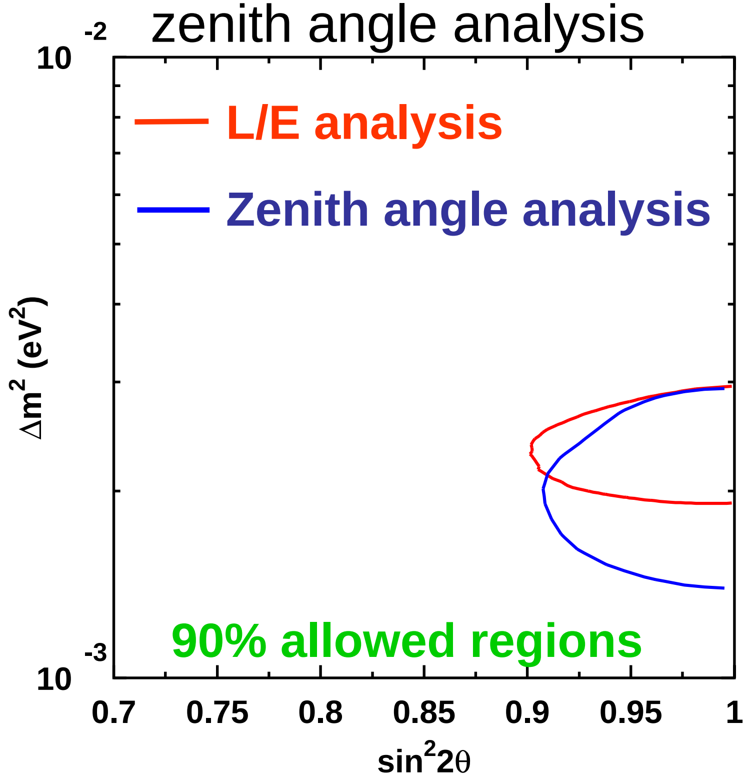
Various systematic effects in detector, flux calculation and neutrino interaction are taken into account

Constraint to neutrino oscillation parameters



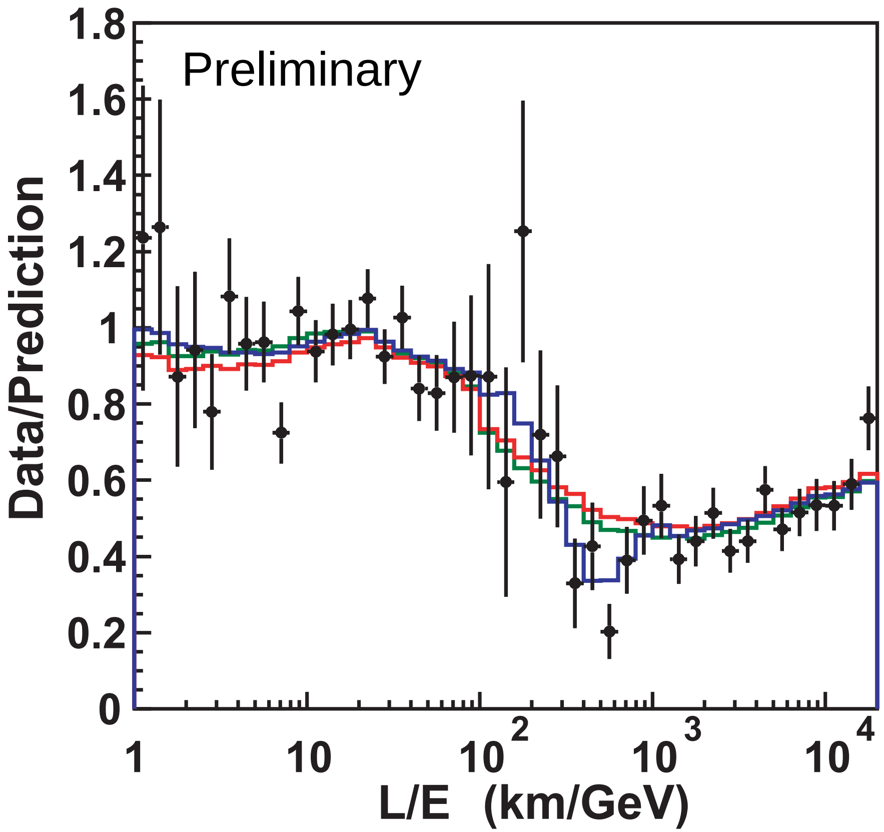
$1.9\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2
$0.90 < \sin^2 2\theta$ at 90% C.L.

Consistent with standard zenith angle analysis



Tests for neutrino decay & decoherence

Oscillation	χ^2_{min}=37.8/40 d.o.f
Decay	χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$=11.4
Decoherence	χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$=14.6

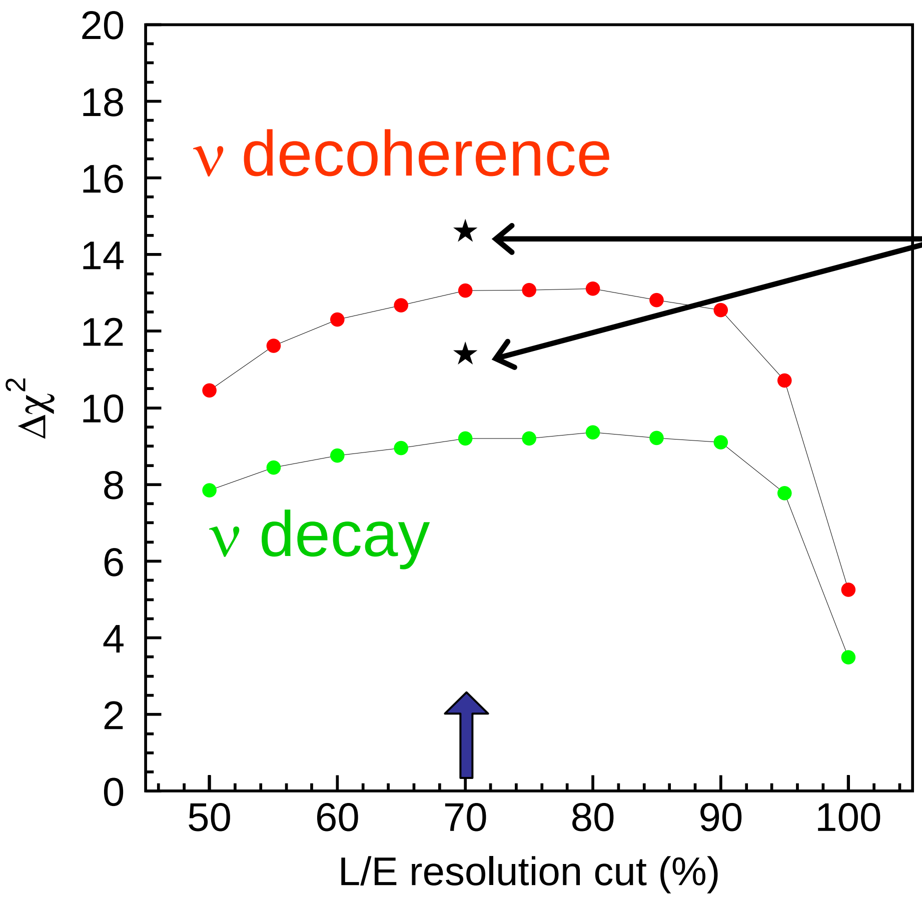


3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

Sensitivities to alternative models



obtained $\Delta\chi^2$

Consistent with the expectation

L/E resolution cut at 70%

Assumption

$\nu_\mu \leftrightarrow \nu_\tau$ 2 flavor oscillation

($\Delta m^2 = 2.0 \times 10^{-3} eV^2, \sin^2 2\theta = 1.0$)

Conclusions

Measurement of L/E dependence of flavor transition probability

First dip was observed as expected from neutrino oscillation

→ cannot be explained by alternative hypotheses (3.4 σ to ν decay, 3.8 σ to ν decoherence)

→ gives strong constraint to neutrino oscillation parameters

$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$

$0.90 < \sin^2 2\theta$ at 90%C.L.

consistent with zenith angle analysis

First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation