L/E analysis and constraints on exotics of the atmospheric neutrino data from Super-Kamiokande

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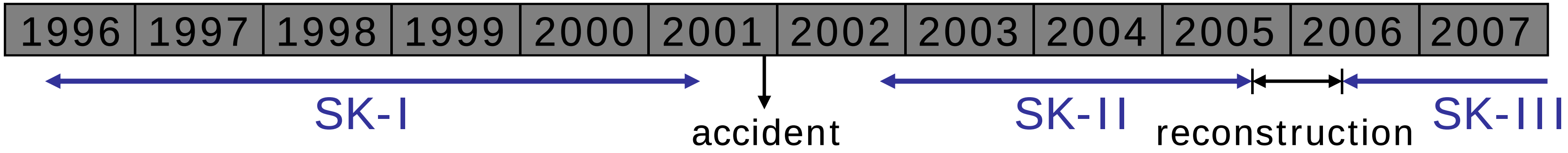
Introduction

- We presented SK-I+II combined L/E ν_{μ} ™ ν_{τ} oscillation analysis result.
- And we presented test of exotic model (neutrino decoherence, neutrino decay) separately.
- But, neutrino decoherence (decay) and oscillation can coexist. We can constrain decoherence (decay) parameter, if we test L/E oscillation analysis with exotic models.
- We report the L/E oscillation analysis with exotic models.

Super-Kamiokande



1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

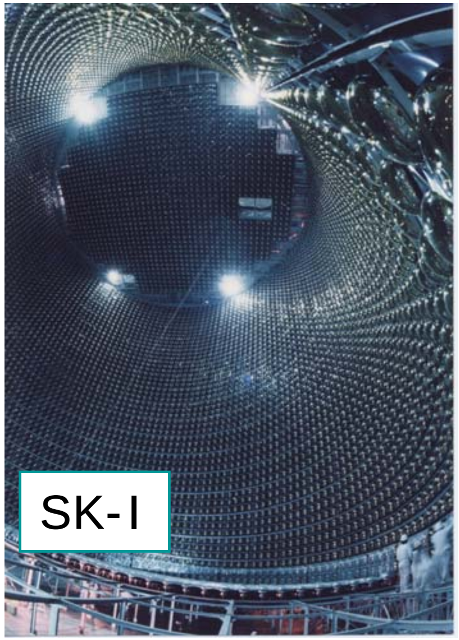
SK-I

accident

SK-II

reconstruction

SK-III



- 50kton cylindrical water Cherenkov detector (22.5kt fiducial vol.)
- 1000m underground (2700m water equiv.)
- optically separated into ID and OD

PMT enclosure : Acrylic (front) and Fiberglass (back)

11146	Num. of inner detector PMTs	5182
40 %	Photocathod coverage	19 %

SK-I (1489days) + SK-II (804days)

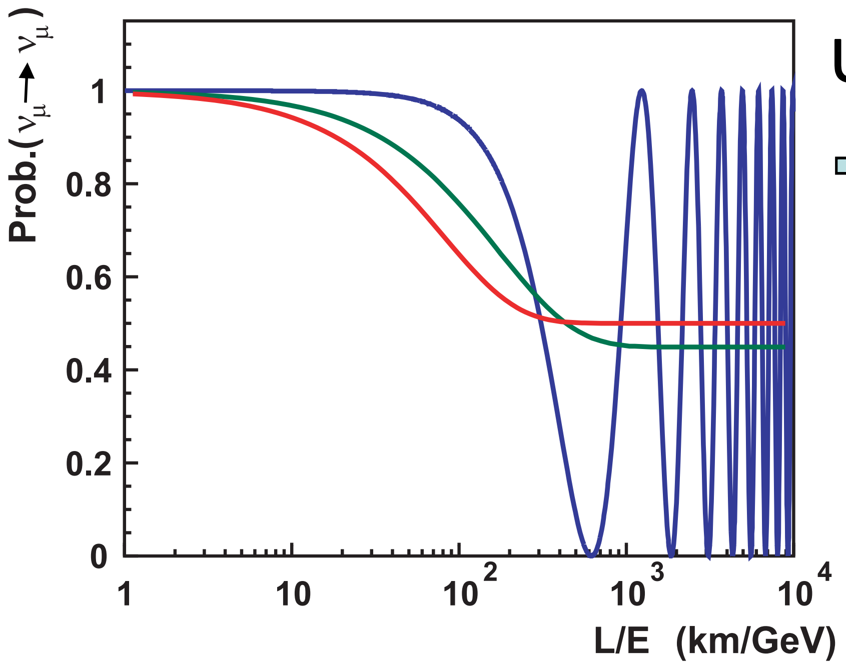
SK-III physics started in July 2006.

Survive probability

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

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

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



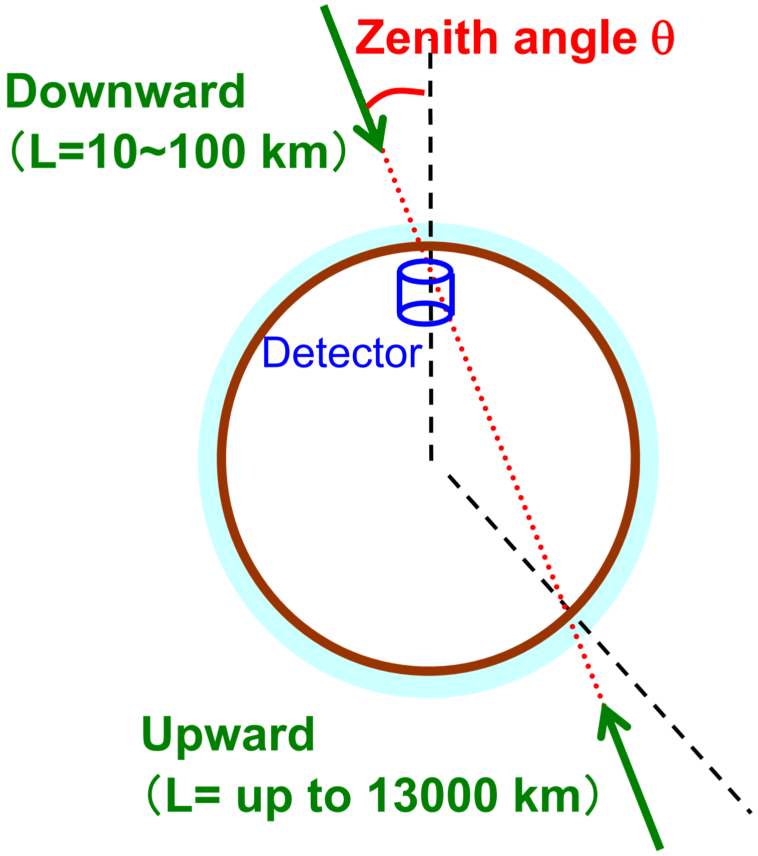
Use events with high resolution in L/E

→ **The first dip can be observed**

→ Direct evidence for oscillations

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

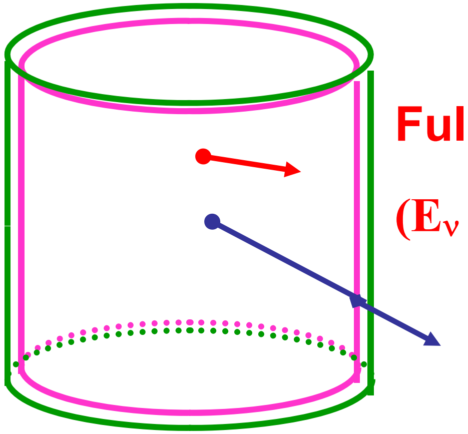
L/E oscillation analysis method



- We use full data set
  SK-I (1489days)
  SK-II (804days)
- Reconstruct flight length and energy.
- Vary parameters ($\sin^2 2\theta, \Delta m^2, \gamma^0$(or m/τ)), fit each model and compare the χ^2

Event samples in L/E analysis

Data set:SK-I(1489)
SK-II(804)



Fully Contained

(E_ν ~1GeV)

Partially Contained

(E_ν ~10GeV)

FC (tracks are contained inside the ID)

- **I. Single-ring , μ-like**
- **II. Multi-ring , μ-like**

PC (deposits visible energy in the OD)

μ-like

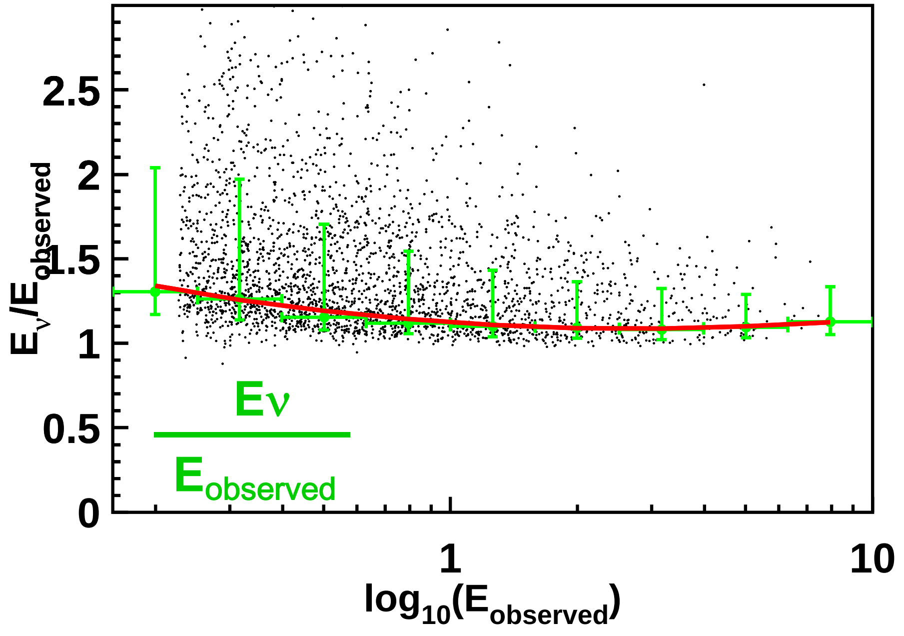
Classify PC events using OD charge

- **I. OD stopping**
- **II. OD through going**

We apply resolution cut.

Reconstruction of E and L

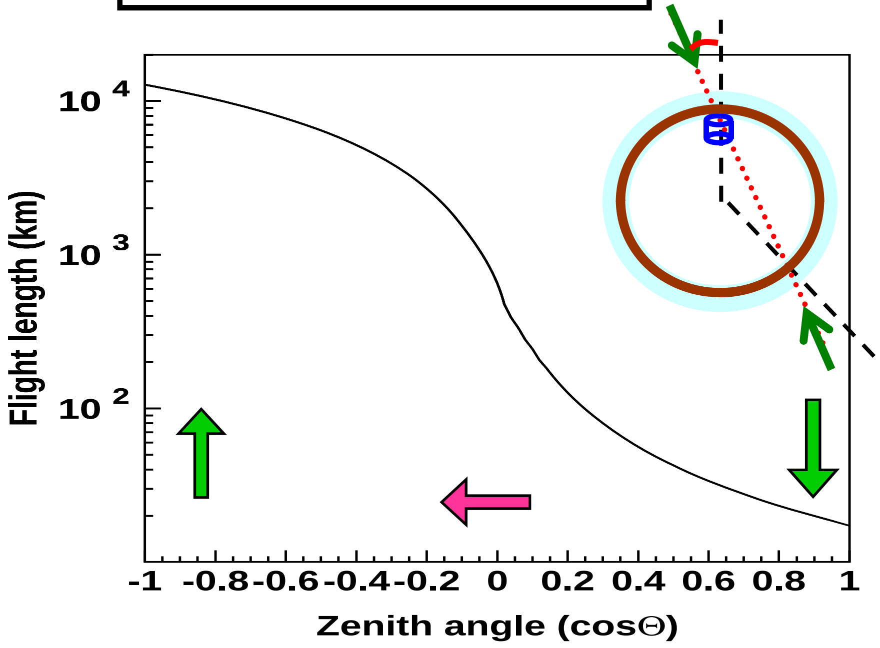
Neutrino energy



$E_{observed} \rightarrow E_\nu$

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

Results of L/E oscillation analysis

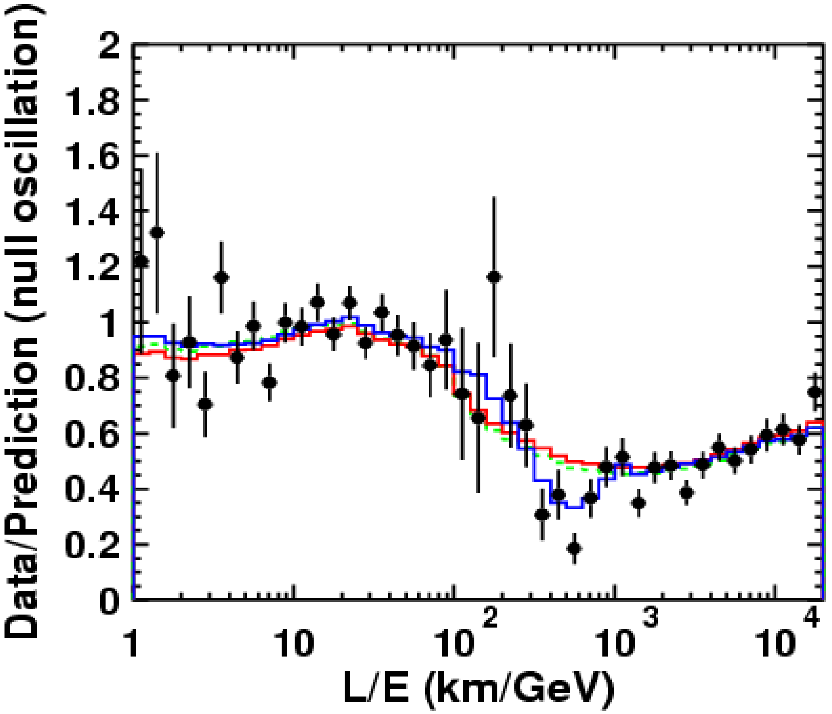
- SK-I+II

Assuming $\nu_\mu \Leftrightarrow \nu_\tau$

χ^2_{min} = 83.9/82 d.o.f

at$(\sin^2 2\theta, \Delta m^2)$

$=(1.00, 2.3\text{x}10^{-3}\text{eV}^2)$



χ^2_{osc} = 83.9/82 d.o.f

χ^2_{dcy} = 107.1/82 d.o.f, $\Delta\chi^2$ = 23.2(**4.8σ**)

χ^2_{dec} = 112.5/82 d.o.f, $\Delta\chi^2$ = 27.6(**5.3σ**)

We exclude neutrino decoherece, decay about 5 σ

oscillation and exotic mode survive probability

$\nu_\mu \Leftrightarrow \nu_\tau$ **Oscillation :**

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

$\nu_\mu \Leftrightarrow \nu_\tau$ **Oscillation+decay :**

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \text{ x } \exp\left(-\frac{m}{\tau}\frac{L}{E}\right)$$

$$+2\sin^2\theta \cos^2\theta \text{ x } \exp\left(-\frac{m}{2\tau}\frac{L}{E}\right)$$

$$\times \cos\left(\frac{\Delta m^2 L}{2E}\right)$$

$\nu_\mu \Leftrightarrow \nu_\tau$ **Oscillation+decoherence :**

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \text{ x } (1 - \exp(- \frac{L}{E}$$

$$E\gamma_0 \quad)$$

$$\times \cos\left(\frac{\Delta m^2 L}{2E}\right))$$

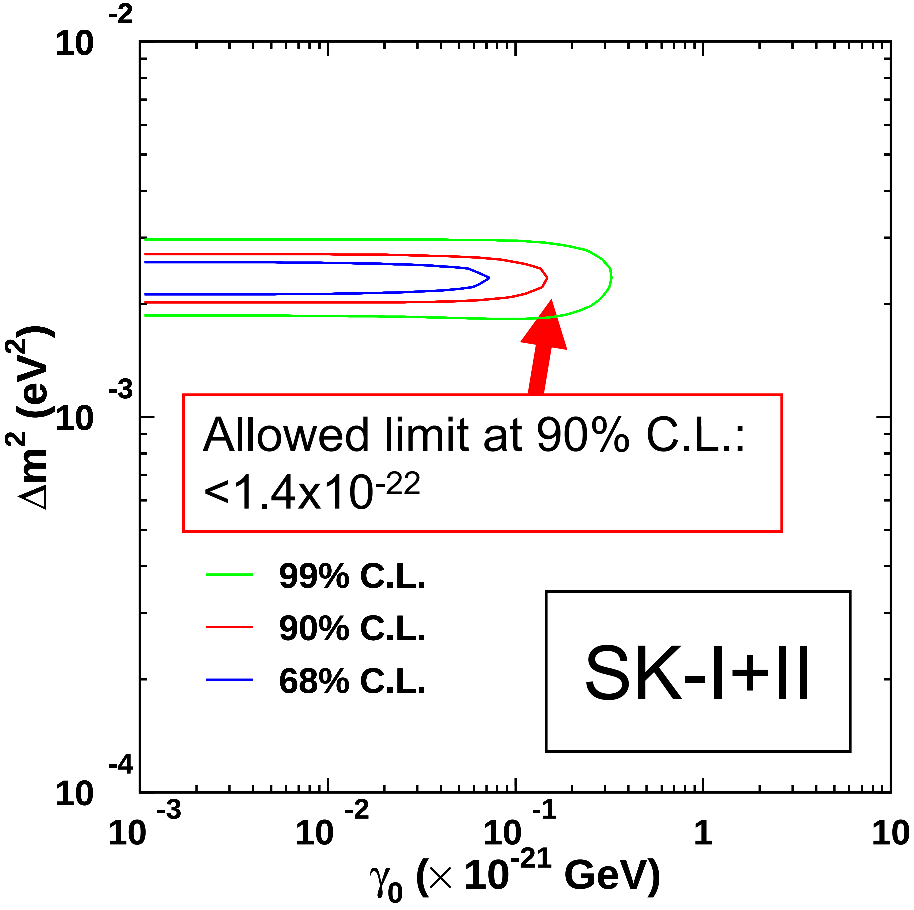
Results of L/E oscillation analysis with decoherence

- SK-I+II

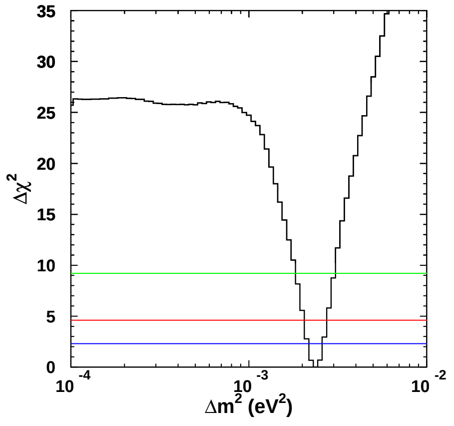
χ^{2min} = 83.8/80 d.o.f

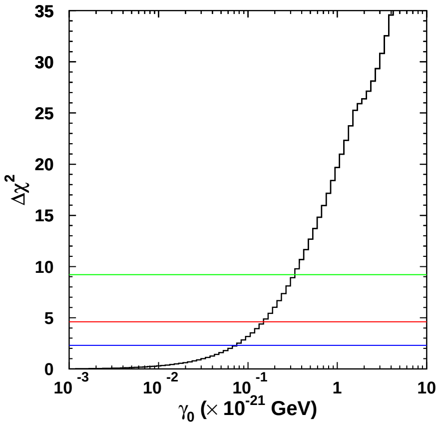
At $(\gamma_0, \Delta m^2, \sin^2 2\theta)$=

(0 GeV^2,2.4x10^{-3}eV^2,1.00)



Allowed limit at 90% C.L.: <1.4x10^{-22}





Compare with the published limit

P.R.L. 85.1166(2000) E.Lisi, A.Marrone, D.Montanino

- Effects of decoherence on the distributions of lepton events as a function of the zenith angle using SK-I data.

	90%C.L. upper limit	
	P.R.L.	This result
γ^0(GeV)	2.0x10^{-21}	1.4x10^{-22}

We can improve one order

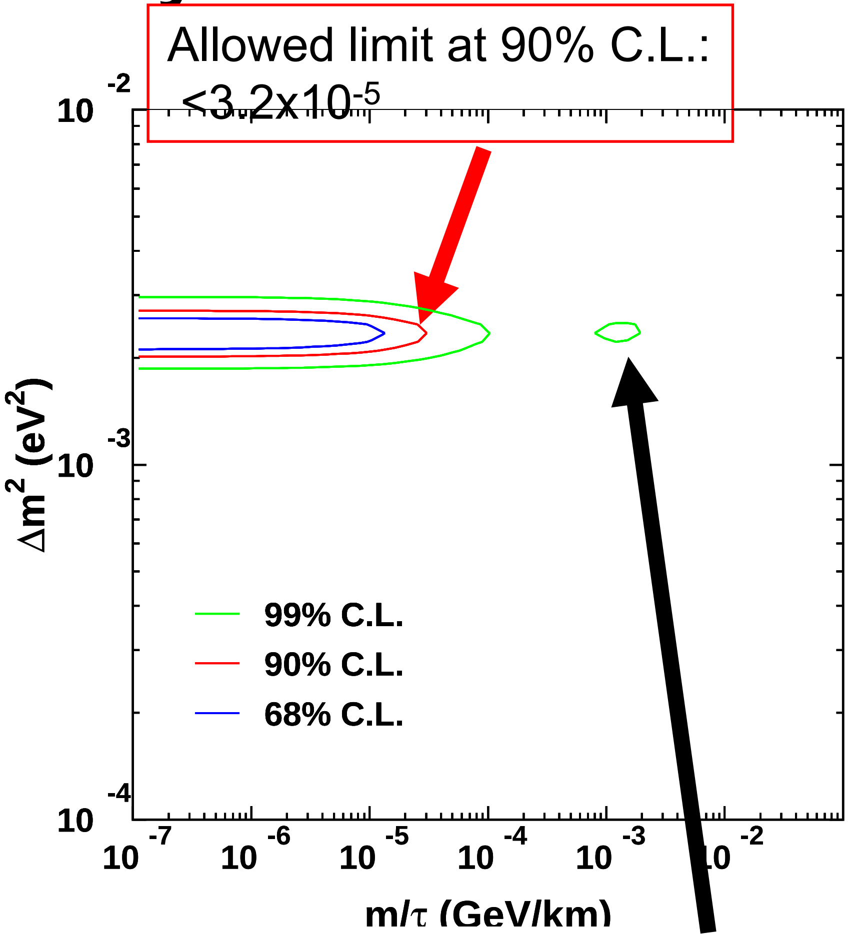
Results of L/E oscillation analysis with decay

- SK-I+II

$\chi^{2\text{min}}$ = 83.8/80 d.o.f

At $(m/\tau, \Delta m^2, \cos^2\theta)$=

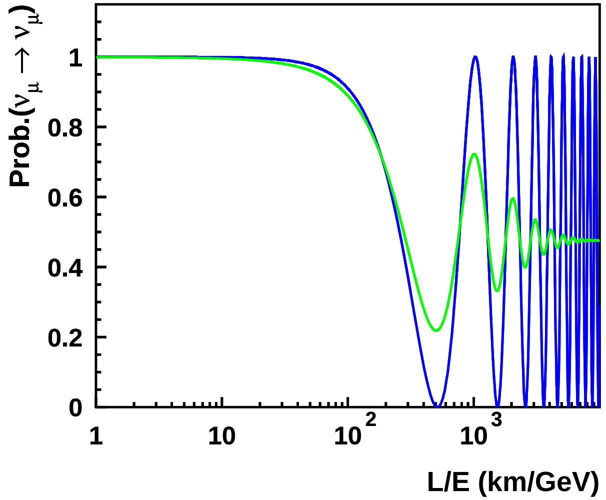
(0 GeV/km, 2.4×10^{-3} eV^2, 0.5)



Allowed limit at 90% C.L.: $<3.2\times10^{-5}$

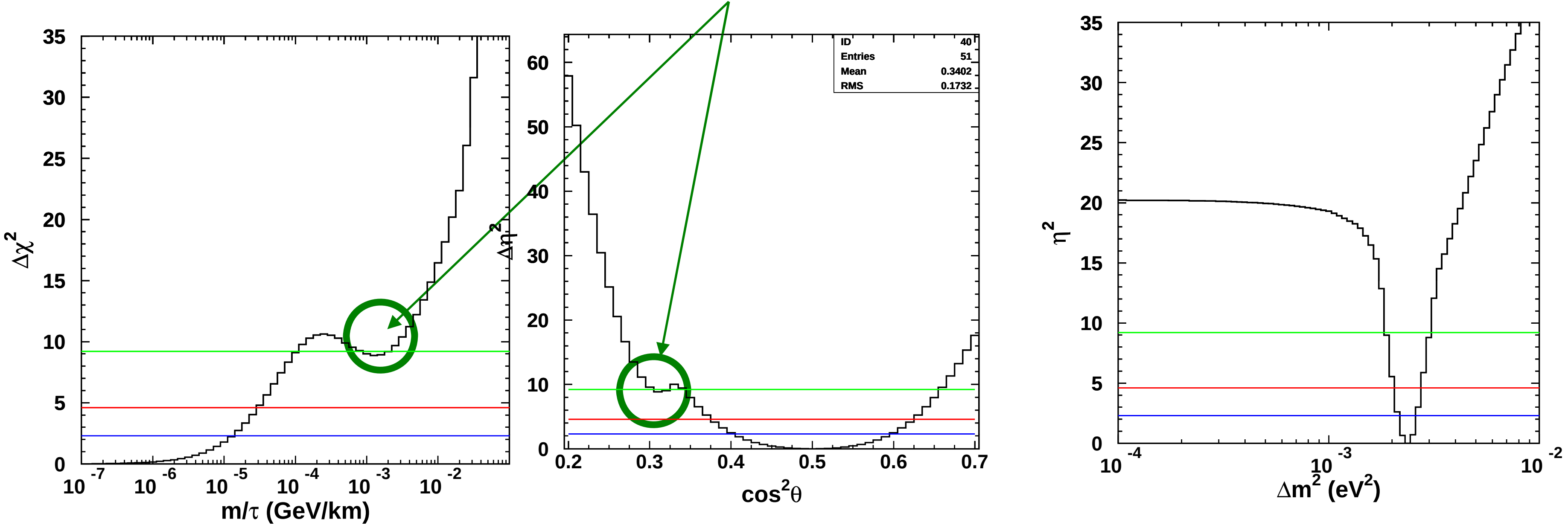
Local minimum due to neutrino decay

Contour and $\Delta\chi^2$ distribution



	$\cos^2\theta$	Δm^2	m/τ
Best fit	0.50	2.4×10^{-3}	0.0
Local minimum	0.31	2.4×10^{-3}	1.3×10^{-3}

Local minimum



Compare with the published limit

P.R.L. 82.2640(1999) V.Barger, J.G.Learned, S.Pakvasa,T.J.Wiler

- Fit to the L/E distribution modeled neutrino decay.
- We use SK-I+II, PC event and high resolution sample.

	90%C.L. upper limit	
m/τ	P.R.L	This result
GeV/km	$7.8\text{x}10^{-5}$	$3.2\text{x}10^{-5}$

summary

- We reported L/E oscillation analysis with exotics.
- We get chi2 minimum at $\nu_\mu \Leftrightarrow \nu_\tau$ oscillation.
- SK constrains on exotics mode.

$\gamma^0 < 1.4 \times 10^{-22}$ GeV at 90% C.L. for decoherecen

$m/\tau < 3.2 \times 10^{-5}$ GeV/km at 90% C.L. for decay