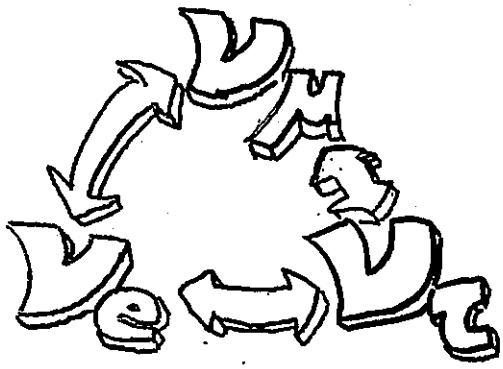
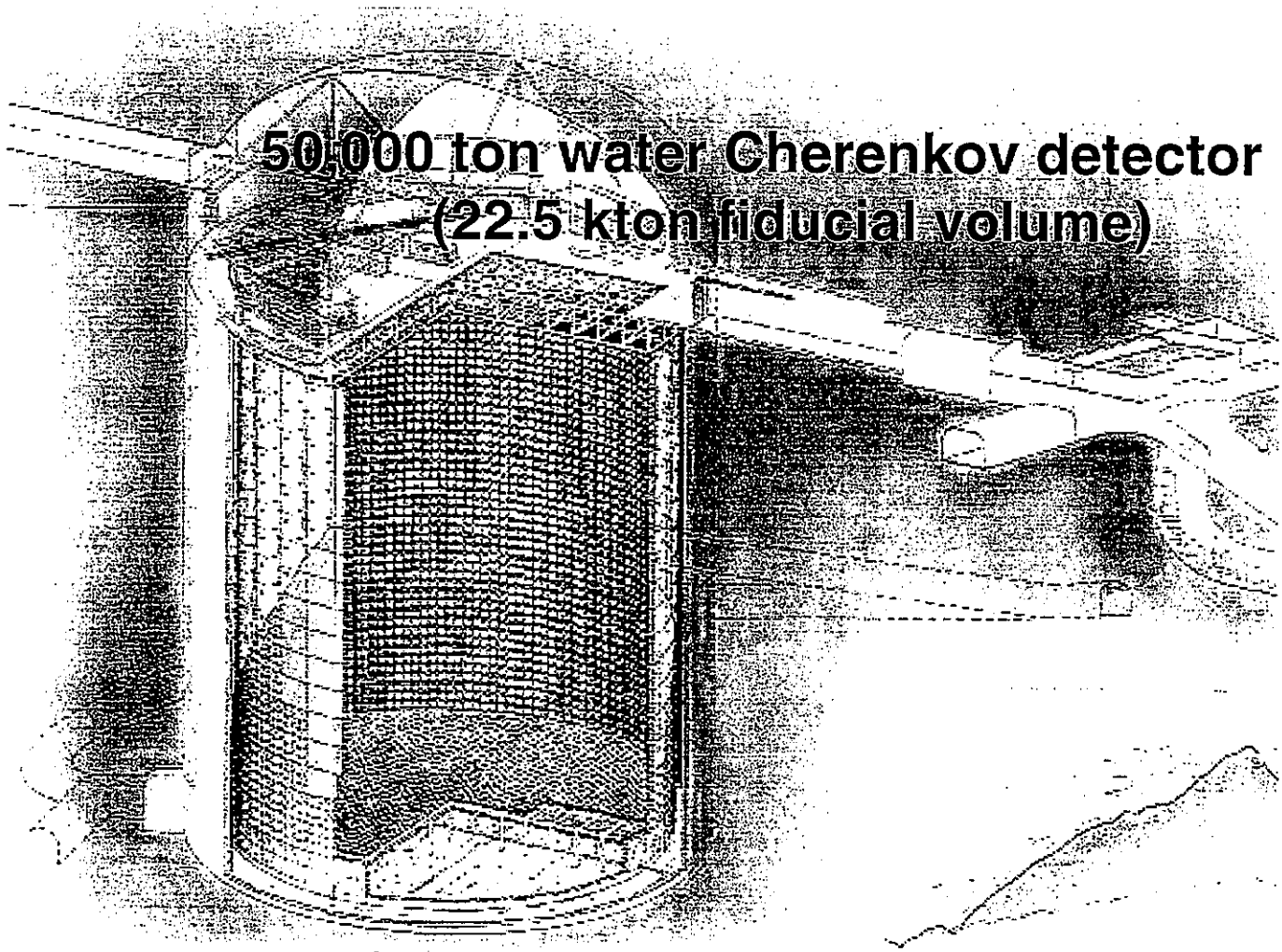
May 12, 2000 @ ICRR-Kashiwa

Three Flavor Oscillation Analysis on Atomospheric Neutrinos @ Super-Kamiokande



Y.OBAYASHI (ICRR, Kamioka)

Super-Kamiokade detector



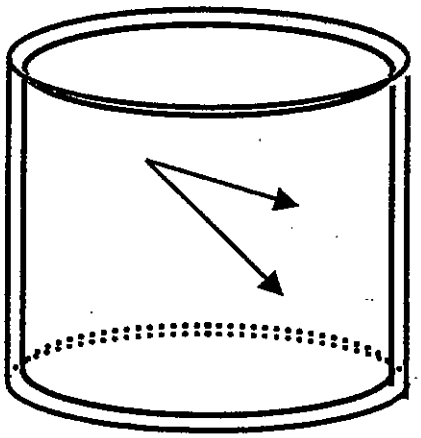
SUPERKAMIOKANDE

11,146 20-inch PMTs for inner detector

1,885 8-inch PMTs for outer detector

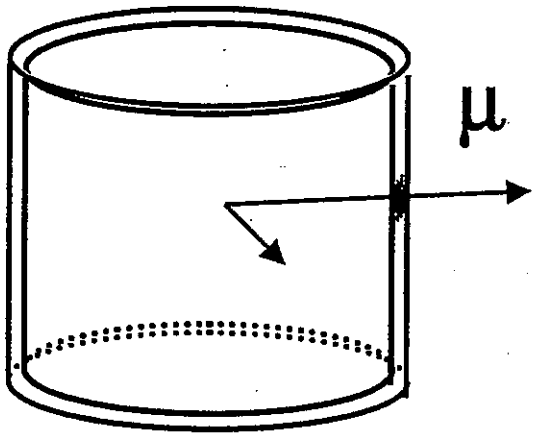
Event classfication of Atm. neutrino

Fully Contained (FC)



e/μ

Partially Contained (PC)

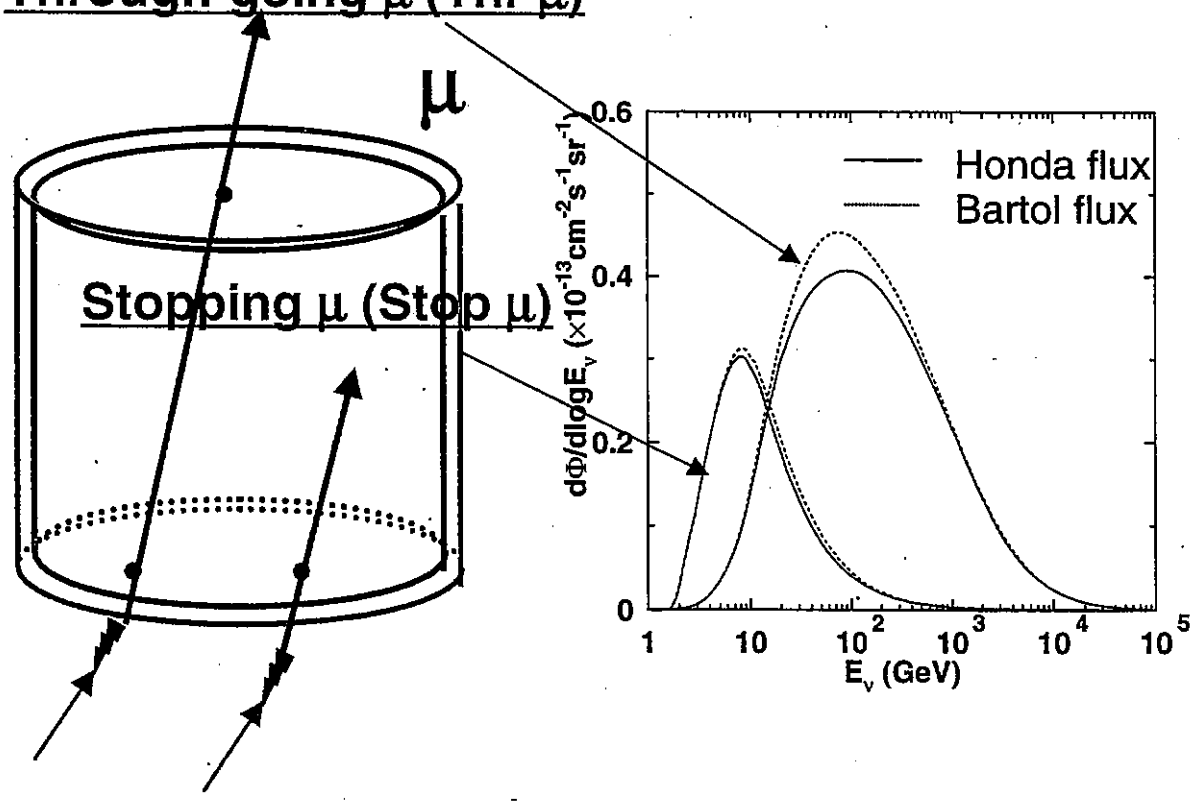


μ

Through-going μ (Thr μ)

μ

Stopping μ (Stop μ)



Event Summary (991.6 d (61.1 kt·y))

Sub-GeV (Fully Contained)

$E_{vis} < 1.33$ GeV, $P_e > 100$ MeV, $P_\mu > 200$ MeV

		Data	MC(Honda flux)
1ring	e-like	2185	2081.8
	μ-like	2178	3137.4
Multi ring		1637	2011.5
Total		6000	7230.7

$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.661 \pm 0.020 \pm 0.052$$

Multi-GeV

Fully Contained ($E_{vis} > 1.33$ GeV)

		Data	MC(Honda flux)
1ring	e-like	492	481.3
	μ-like	421	640.0
Multi ring		1027	1273.8
Total		1940	2395.1

Partially Contained (assigned as μ-like)

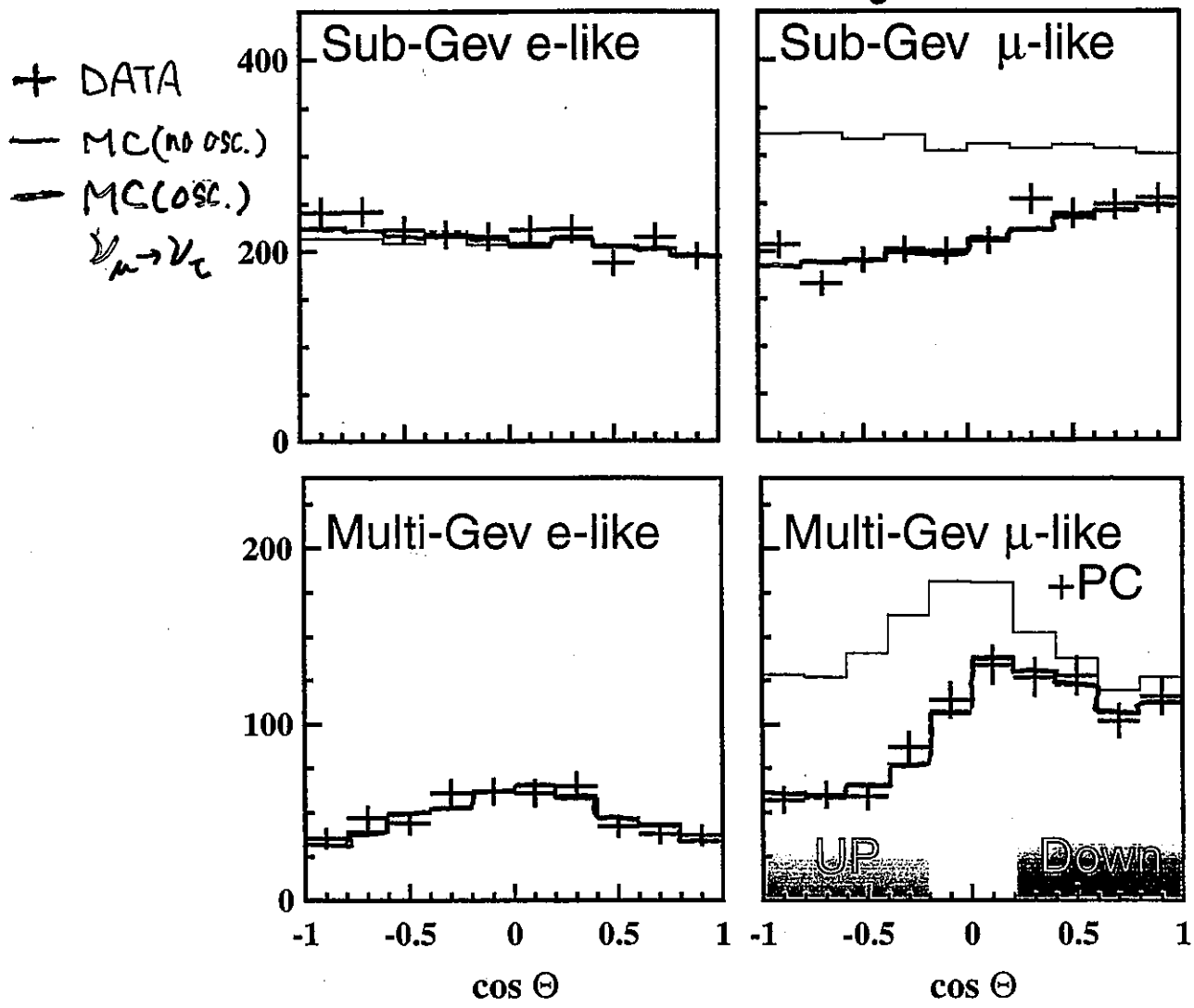
Total	563	818.9

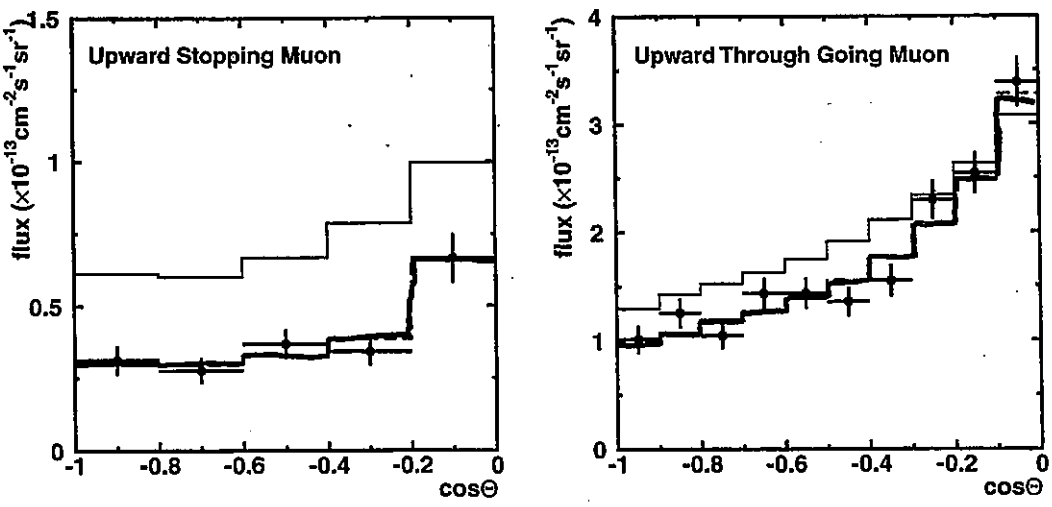
$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.660 \,{}^{+0.038}_{-0.035} \pm 0.078$$

Contents

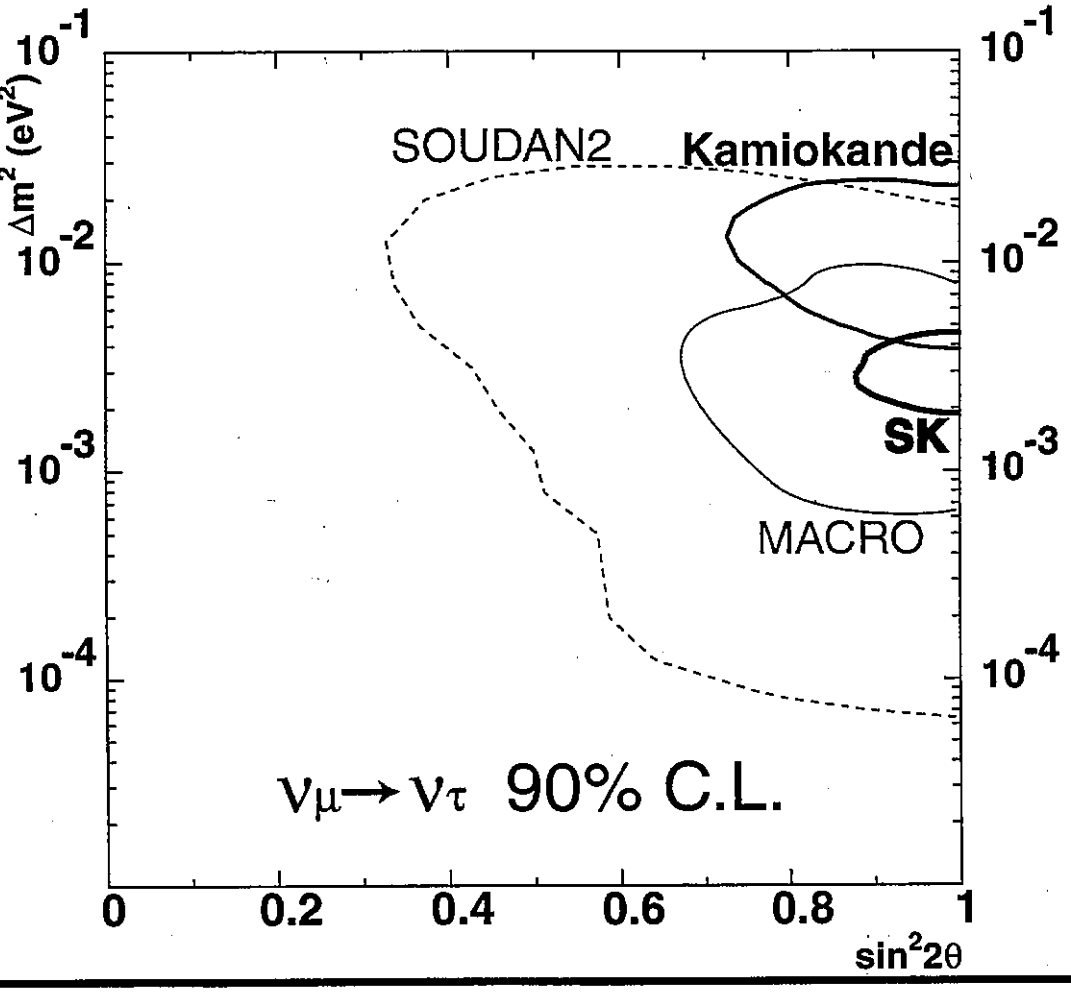
- SK990d $\nu_\mu \to \nu_\tau$ result
- θ_{13} contribution
- How can we see Matter effect?
- Analysis result on SK 990d data
- summary

SK 990day


DATA
MC(no osc.)
MC(osc.)
$\nu_\mu \to \nu_\tau$
Sub-Gev e-like
Sub-Gev μ-like
Multi-Gev e-like
Multi-Gev μ-like
+PC
UP
Down
400
200
0
200
100
0
-1
-0.5
0
0.5
1
cos Θ


Upward Stopping Muon
Upward Through Going Muon
flux (×10⁻¹³cm⁻²s⁻¹sr⁻¹)
cosΘ

$\nu\mu \rightarrow \nu\tau$ analysis



$$\chi^2_{\min} = 61.1/82 d.o.f$$
$$@\ \Delta m^2 = 2.8\times10^{-3} eV^2, \sin^2 2\vartheta = 1.0$$

$$2\times10^{-3} eV^2 < \Delta m^2 < 5\times10^{-3} eV^2,$$
$$0.88 < \sin^2 2\theta < 1.00$$
$$@\ 90\ \%\ \text{C.L.}$$

$$\chi^2(\text{null osc.}) = 232.5/84 d.o.f$$

3 Flavor Oscillation Analysis

- Approximation:

$$\Delta m^2_{23} = \Delta m^2_{\text{atm}} \approx O(10^{-3} eV^2),$$

$$\Delta m^2_{12} = \Delta m^2_{\text{sol}} \leq 10^{-4} eV^2 \ll \Delta m^2_{23}$$

$$P(\nu_\mu \leftrightarrow \nu_e) = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L/E)$$

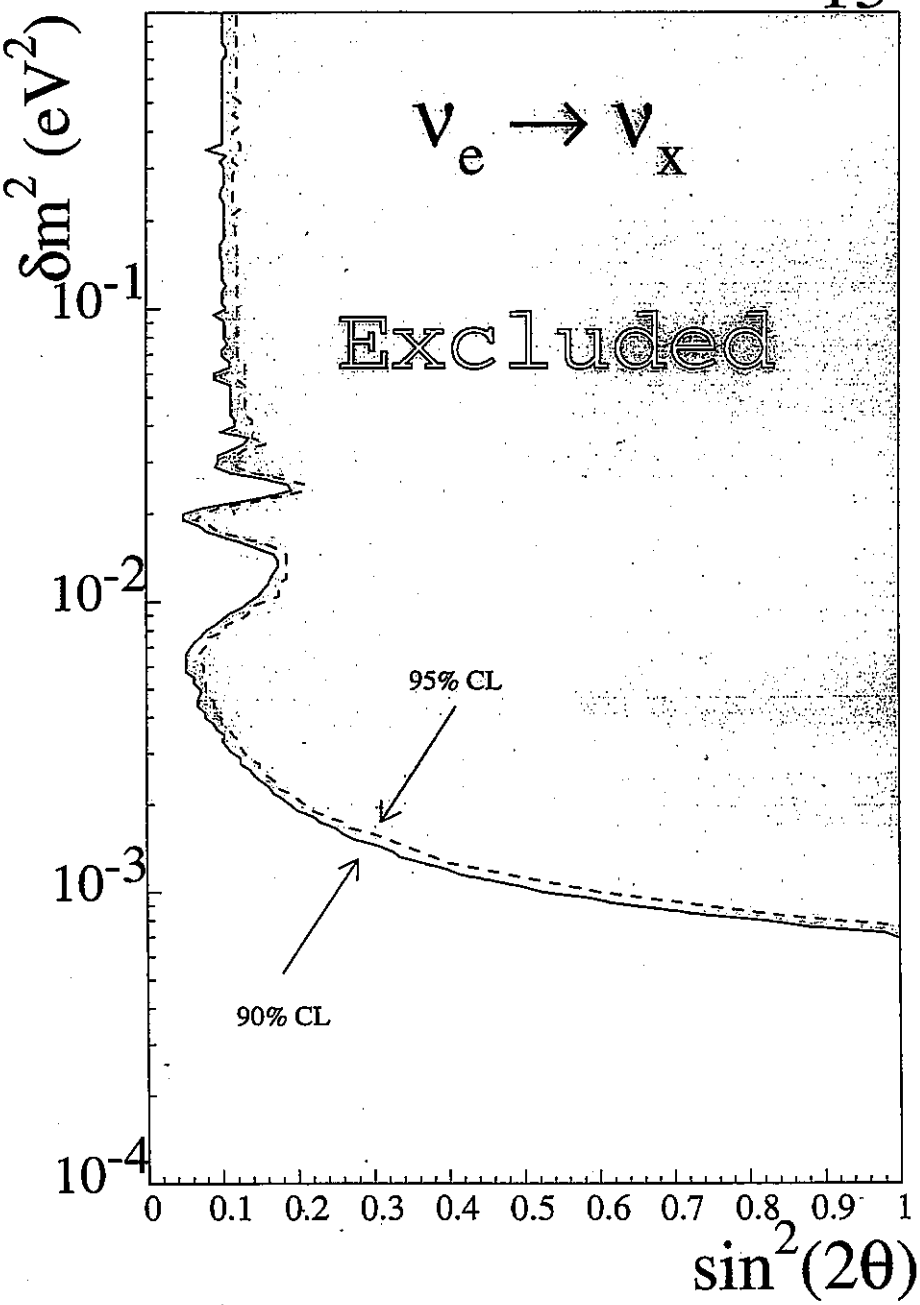
$$P(\nu_\mu \leftrightarrow \nu_\tau) = \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L/E)$$

$$P(\nu_e \leftrightarrow \nu_\tau) = \sin^2 2\theta_{13} \cdot \cos^2 \theta_{23} \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L/E)$$

- P can be described only 3 parameters.

$$(\sin^2 \theta_{13}, \sin^2 \theta_{23}, \Delta m^2_{23} = \Delta m^2_{13})$$

Present limit on θ_{13}



$\sin^2 2\theta_{13} > 0.1$ @ $\Delta m^2 > 2\text{x}10^{-3}$ is excluded by CHOOZ

$\sin^2 2\theta_{13}=0.1$ ➡ $\sin^2\theta_{13}=0.026$

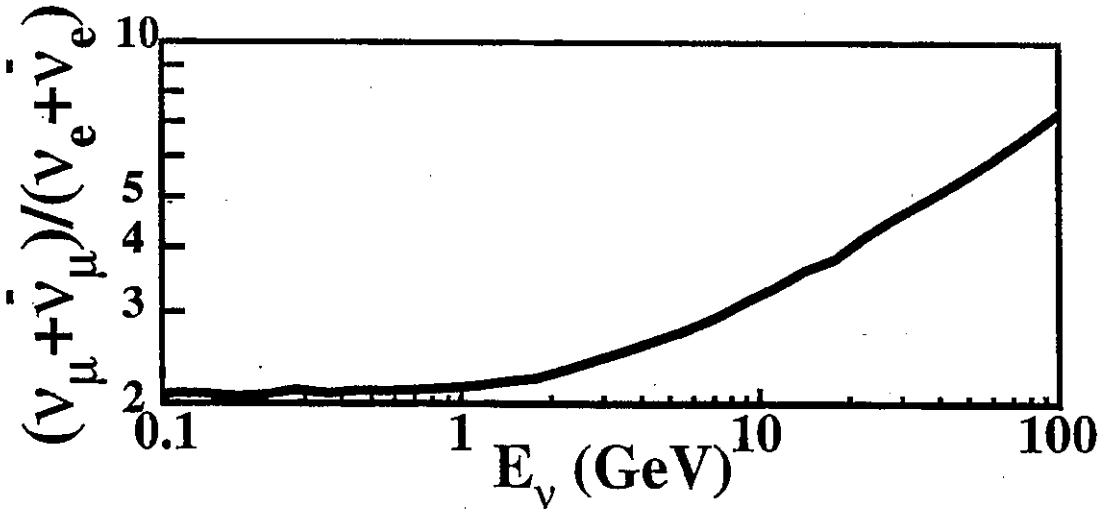
θ_{13} contribution to atomospheric ν_e

$$\Psi = \sin^2(1.27\Delta m^2 L/E)$$

$$\Phi(\nu_e) = \Phi_0(\nu_e)\cdot\{1-\sin^2(2\theta_{13})\Psi\}$$
$$+\Phi_0(\nu_\mu)\cdot\{\sin^2(2\theta_{13})\cdot\sin^2\theta_{23}\Psi\}$$
$$=\Phi_0(\nu_e)\cdot\{1+\sin^2(2\theta_{13})(\sin^2\theta_{23}\frac{\Phi_0(\nu_\mu)}{\Phi_0(\nu_e)}-1)\cdot\Psi\}$$

$\sin^2\theta_{23} \sim 0.5$; $\frac{\Phi_0(\nu_\mu)}{\Phi_0(\nu_e)} \sim 2$

Neutrino flavor ratio



$$\frac{(\nu_\mu+\bar{\nu}_\mu)}{(\nu_e+\bar{\nu}_e)}$$

~2 @Eν<1GeV

↗ @High Eν

Matter Effect

In the earth:

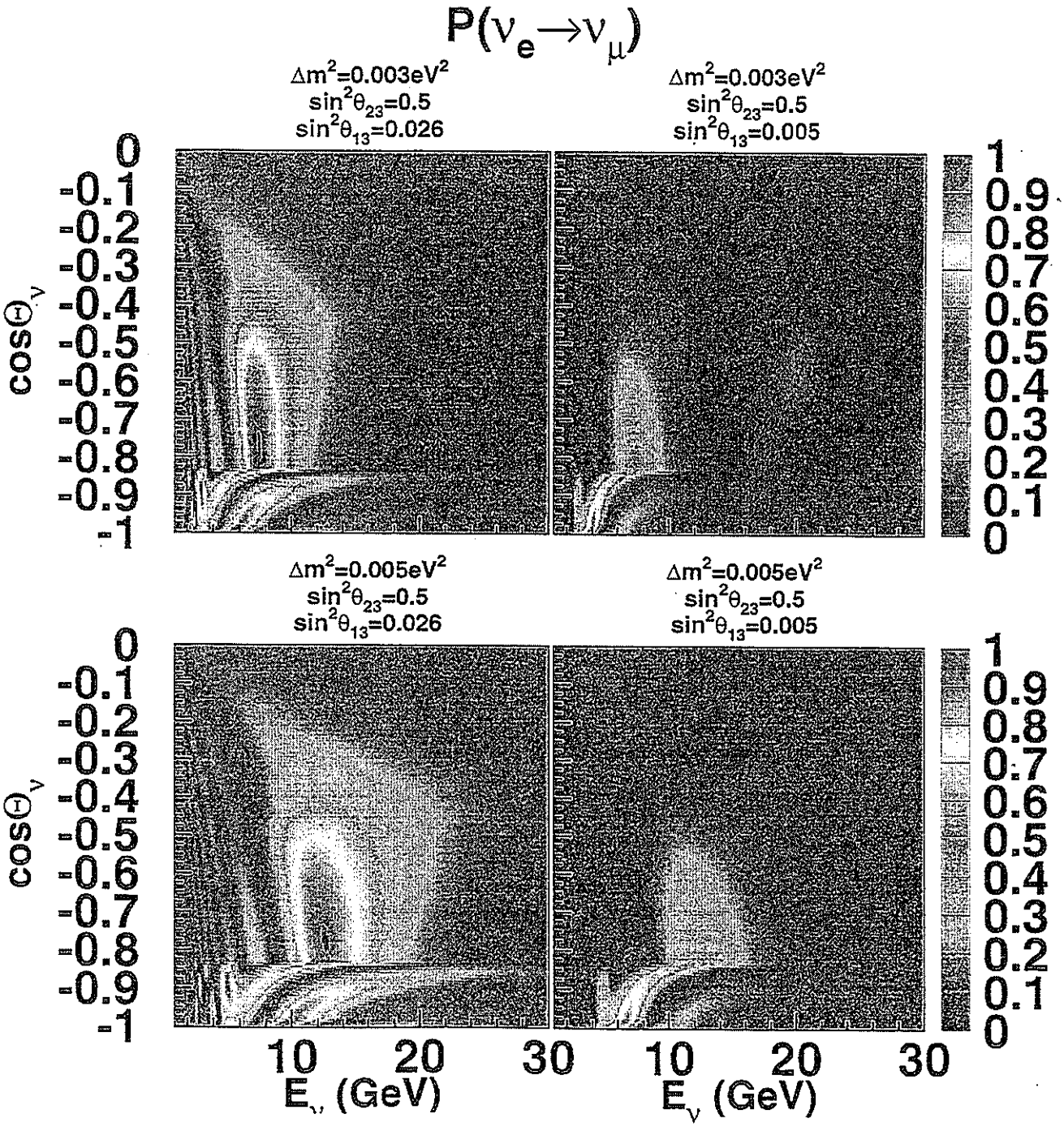
$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{[\xi - \cos 2\theta]^2 + \sin^2 2\theta},$$

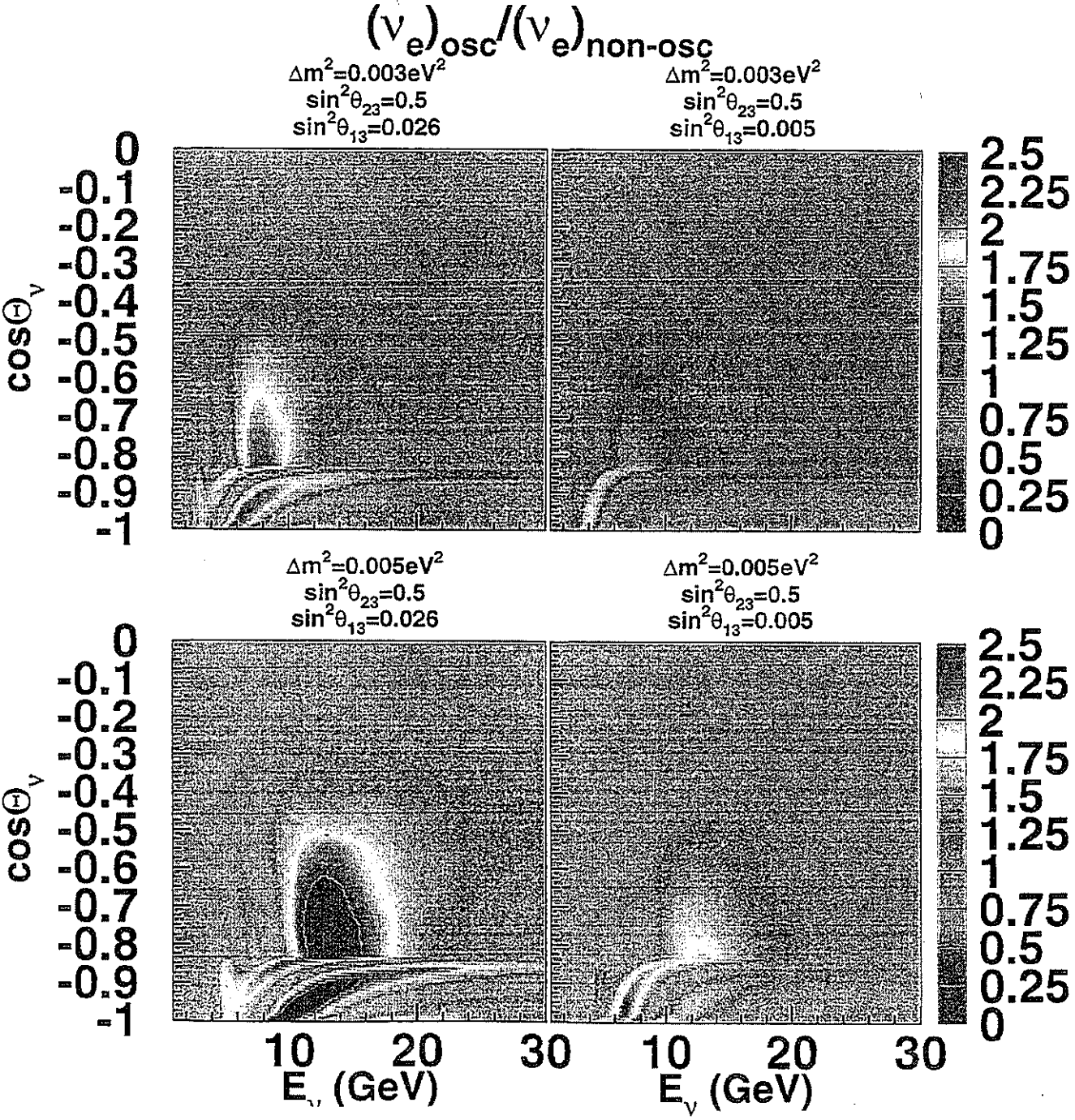
$$(\xi = 2\sqrt{2} G_F N_e \frac{E}{\Delta m^2})$$

→ resonance at

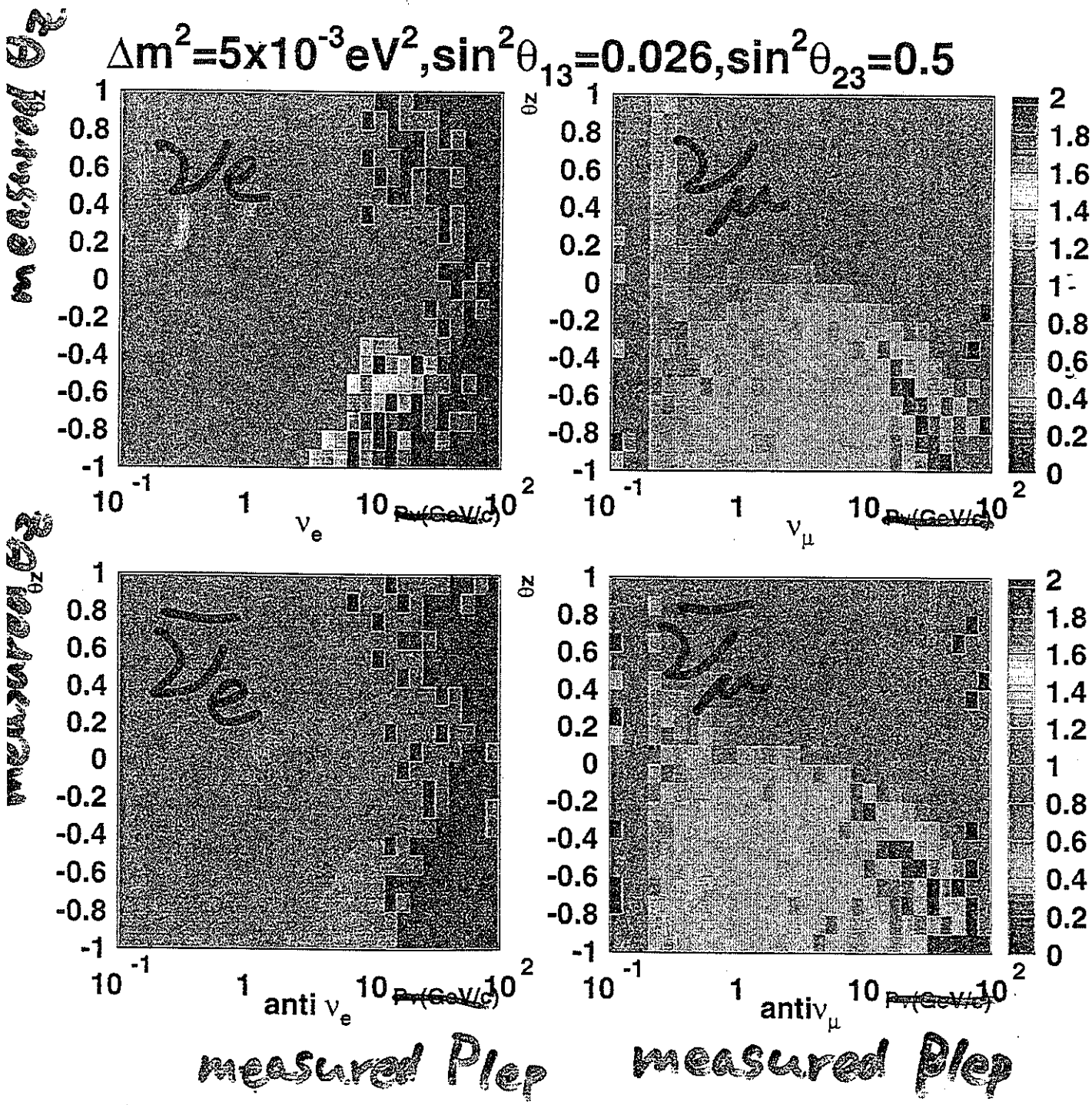
$$\frac{E(GeV)}{|\Delta m^2|(eV^2)} = \frac{6.55\times 10^3}{\frac{Z}{A}\rho(g/cm^3)} \cos 2\theta$$

$\Delta m^2 = 5\times 10^{-3}$:	
Mantle(ρ~5)	E~12GeV
Core(ρ~13)	E~ 5GeV


$P(\nu_e \rightarrow \nu_\mu)$
Δm^2=0.003eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.026
Δm^2=0.003eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.005
Δm^2=0.005eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.026
Δm^2=0.005eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.005
$\cos\Theta_\nu$
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
E_ν (GeV)


$(\nu_e)_{osc}/(\nu_e)_{non\text{-}osc}$
Δm^2=0.003eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.026
Δm^2=0.003eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.005
Δm^2=0.005eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.026
Δm^2=0.005eV^2
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{13}$=0.005
$\cos\Theta_\nu$
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
10
20
30
E_ν (GeV)

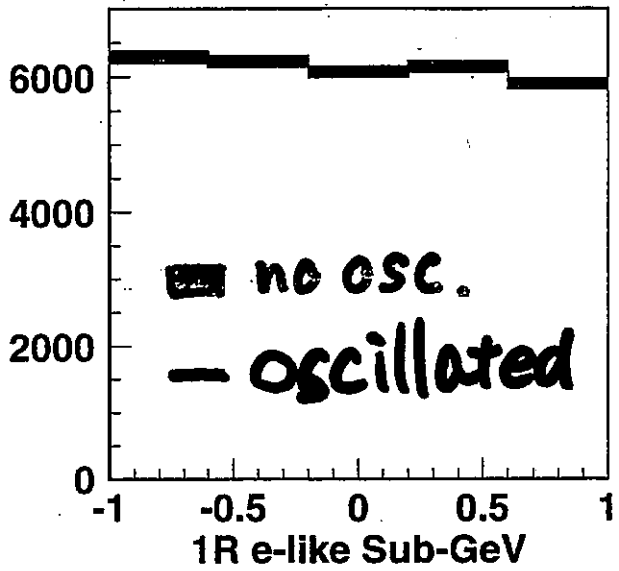
oscillated / no oscillated

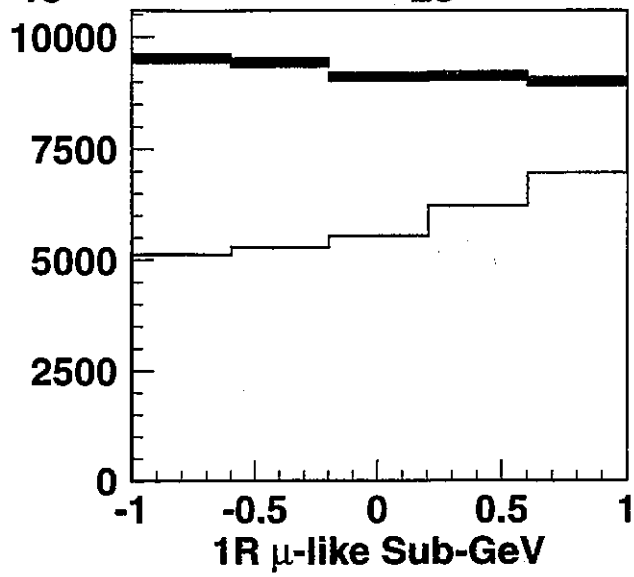


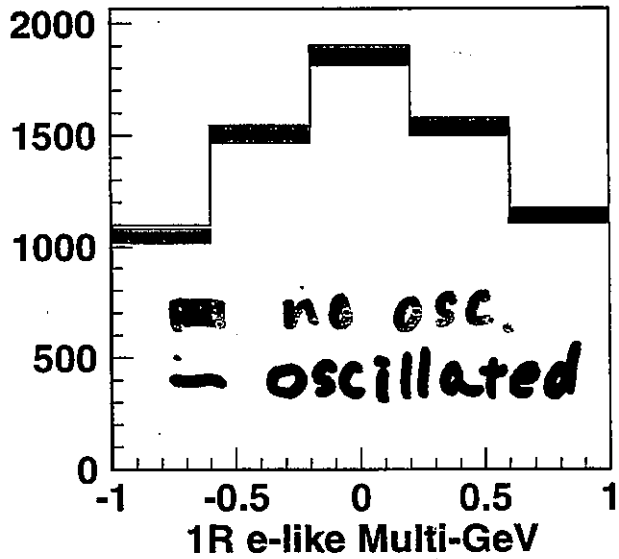
SK 40yr MC

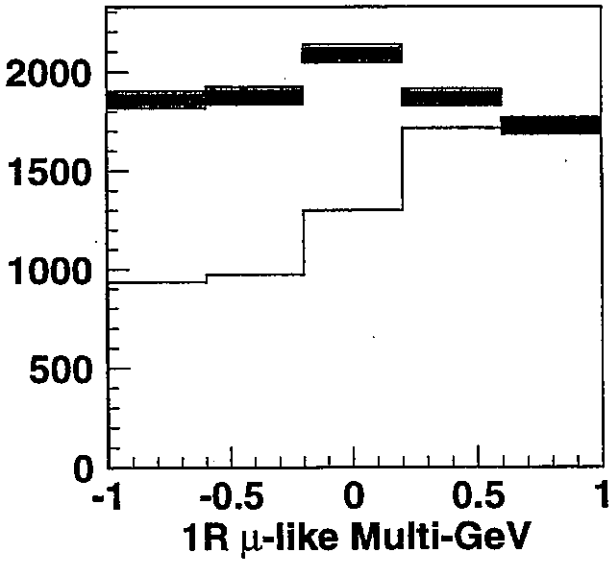
:0/05/11 16.19

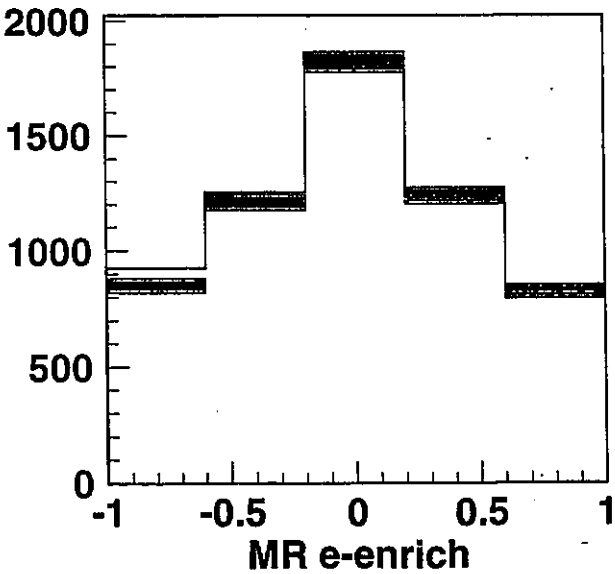
$\log(\Delta m^2)=-2.3$, $\sin^2\theta_{13}=0.026$, $\sin^2\theta_{23}=0.5$

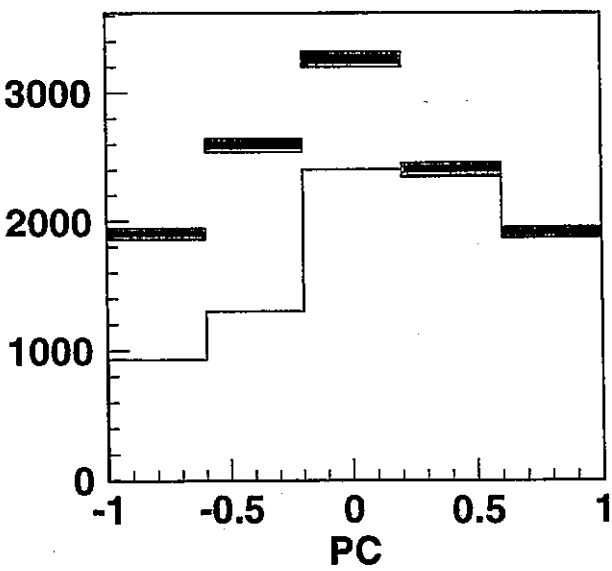








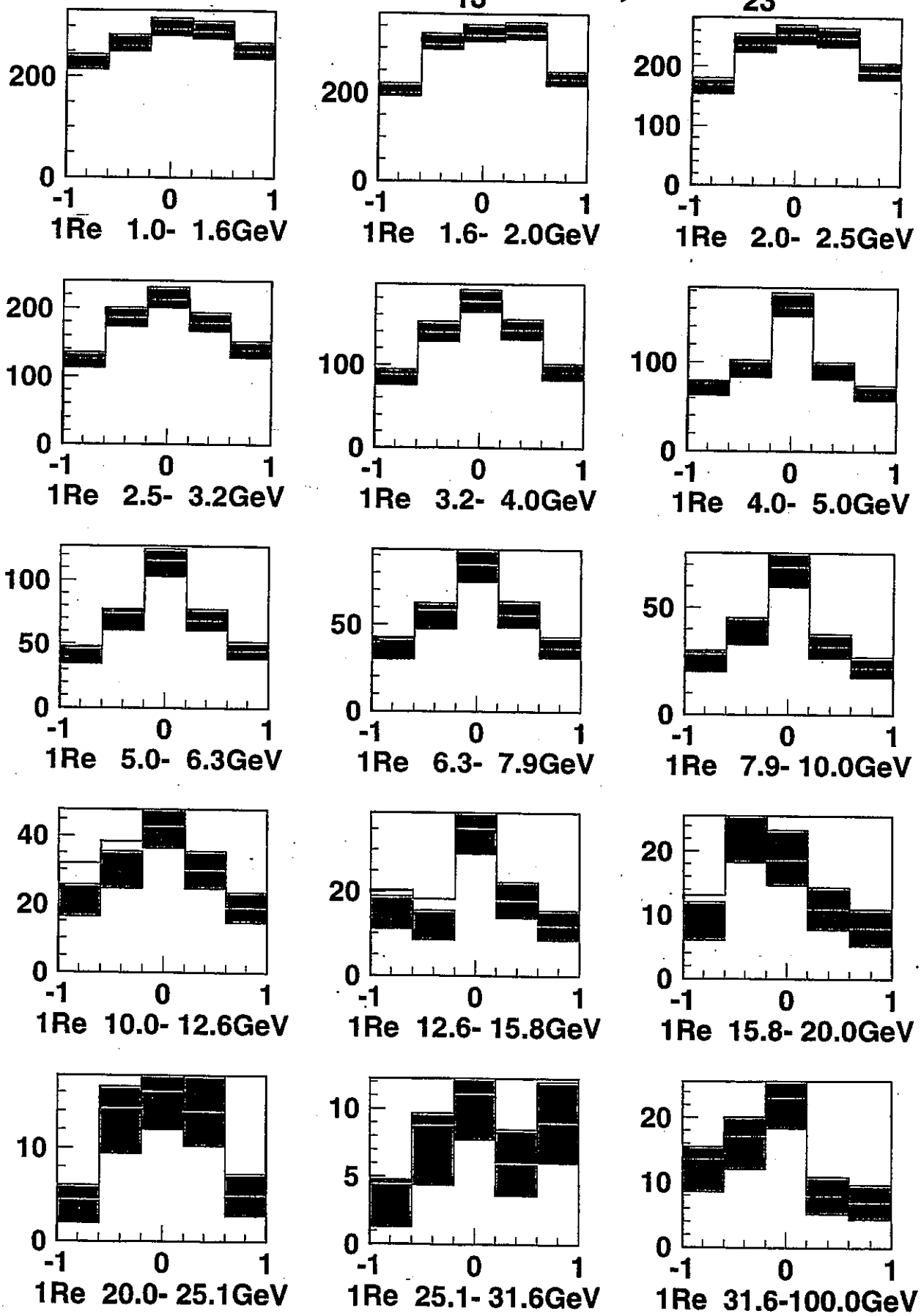




SK 40yr MC 1ring e-like

:0/05/11 16.19

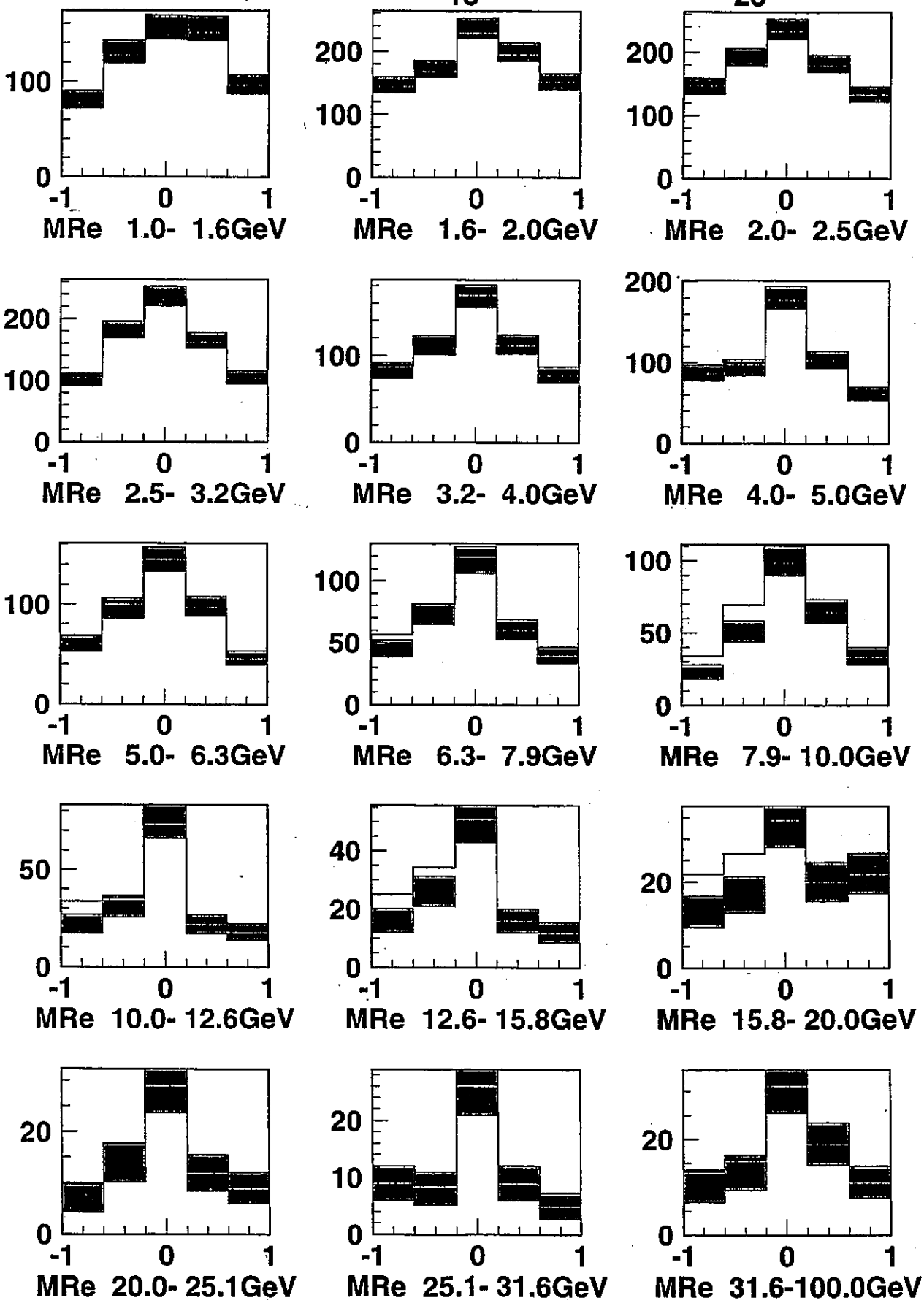
$\log(\Delta m^2)=-2.3$, $\sin^2\theta_{13}=0.026$, $\sin^2\theta_{23}=0.5$



SK 40yr MC Multi ring e-like

:0/05/11 16.19

$\log(\Delta m^2)=-2.3$, $\sin^2\theta_{13}=0.026$, $\sin^2\theta_{23}=0.5$



Summary

- If $\sin^2\theta_{13} \simeq 0.026$ ($^{\text{CHOOZ}}_{\text{limit}}$)

  → A excess @ $\uparrow \nu_e$

  $E\nu \sim 10\,GeV$

  $(\Delta m^2 \sim 5\times10^{-3}\,eV)$

  should be observed

  → Analysis is now in progress on SK data

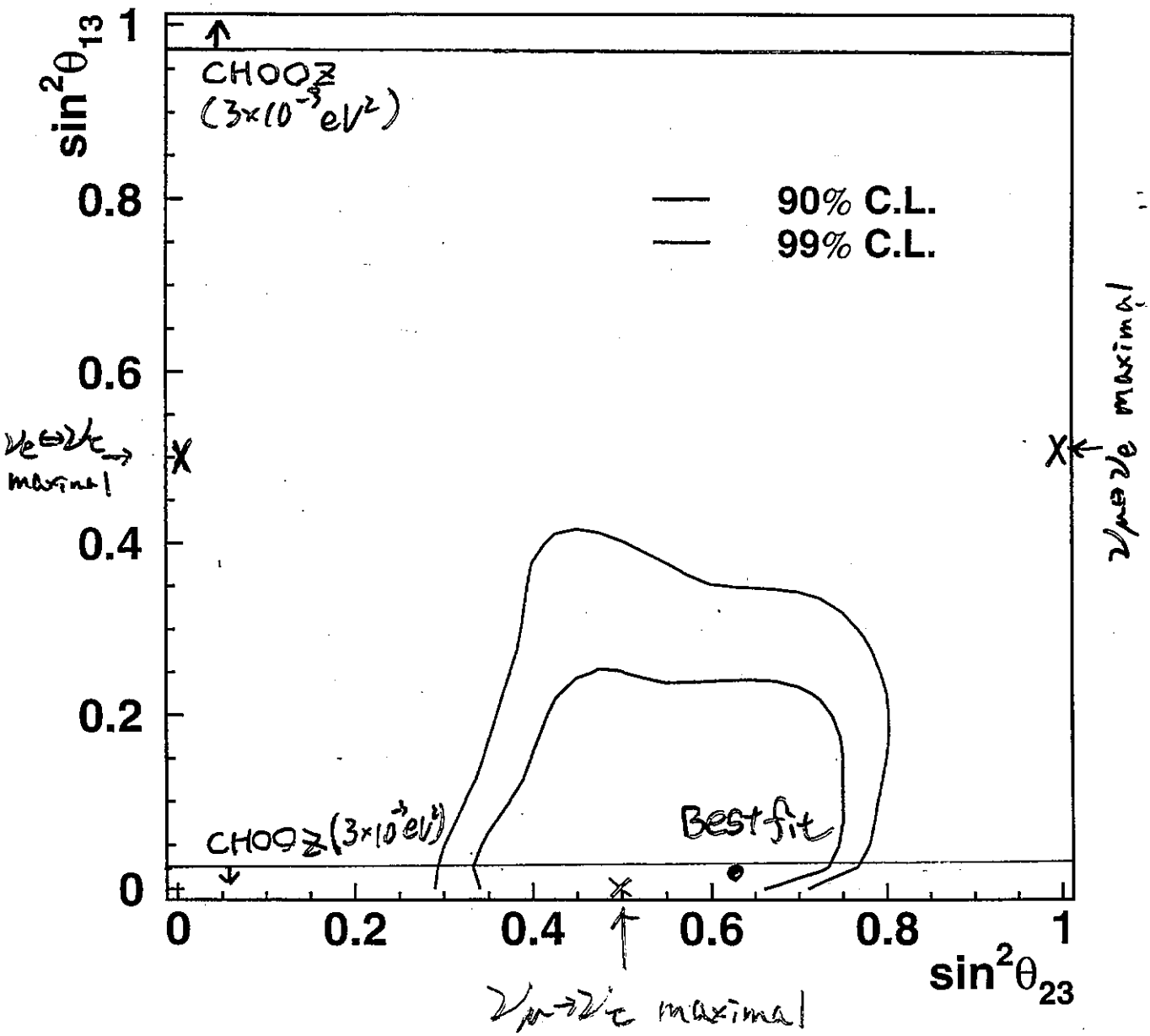
- "Standard" analysis result on SK 990 day data:

  $\sin^2\theta_{13} < 0.25$

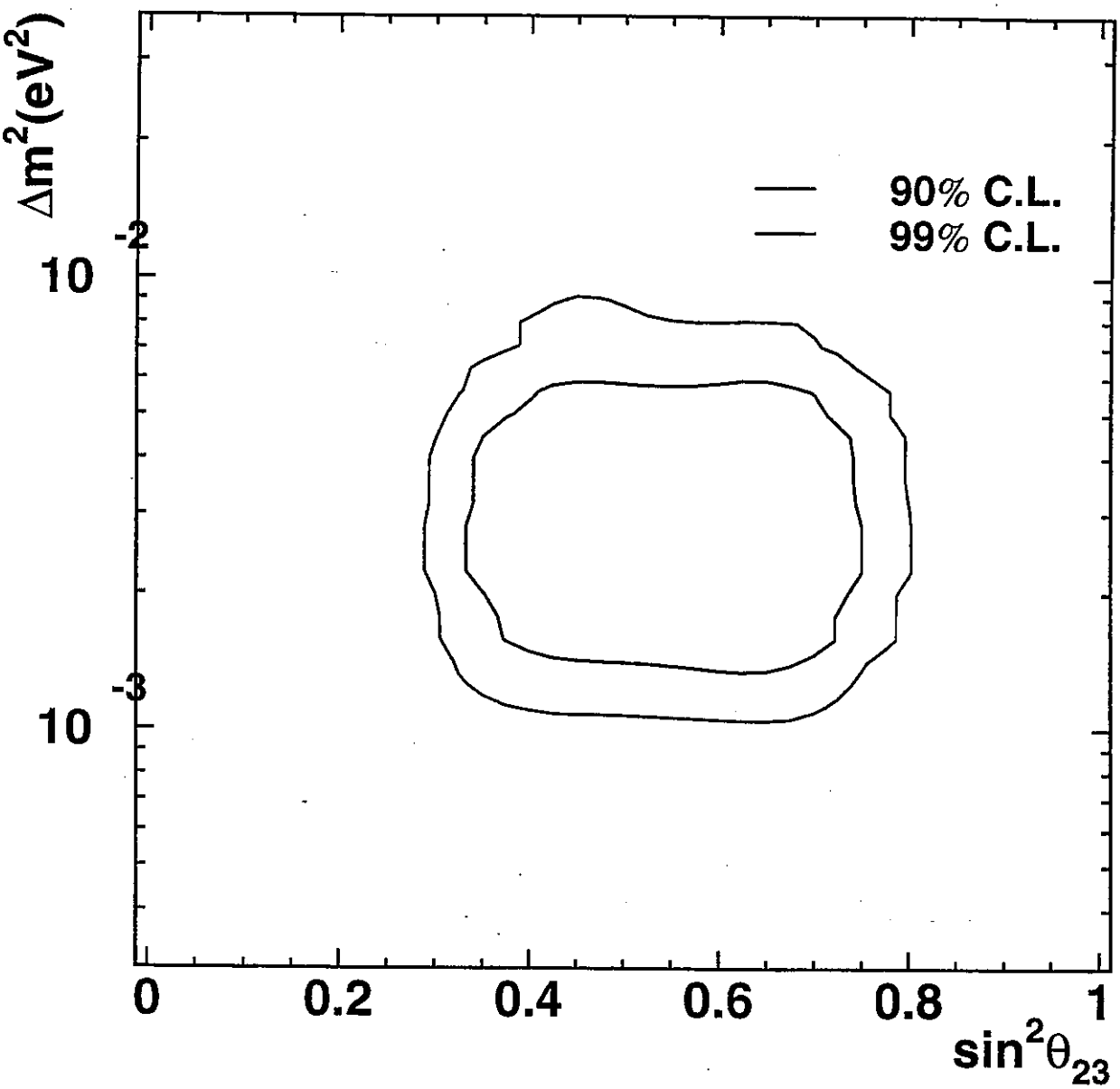
  Best fit: $\sin^2\theta_{13} = 0.025$

  $\sin^2\theta_{23} = 0.625$

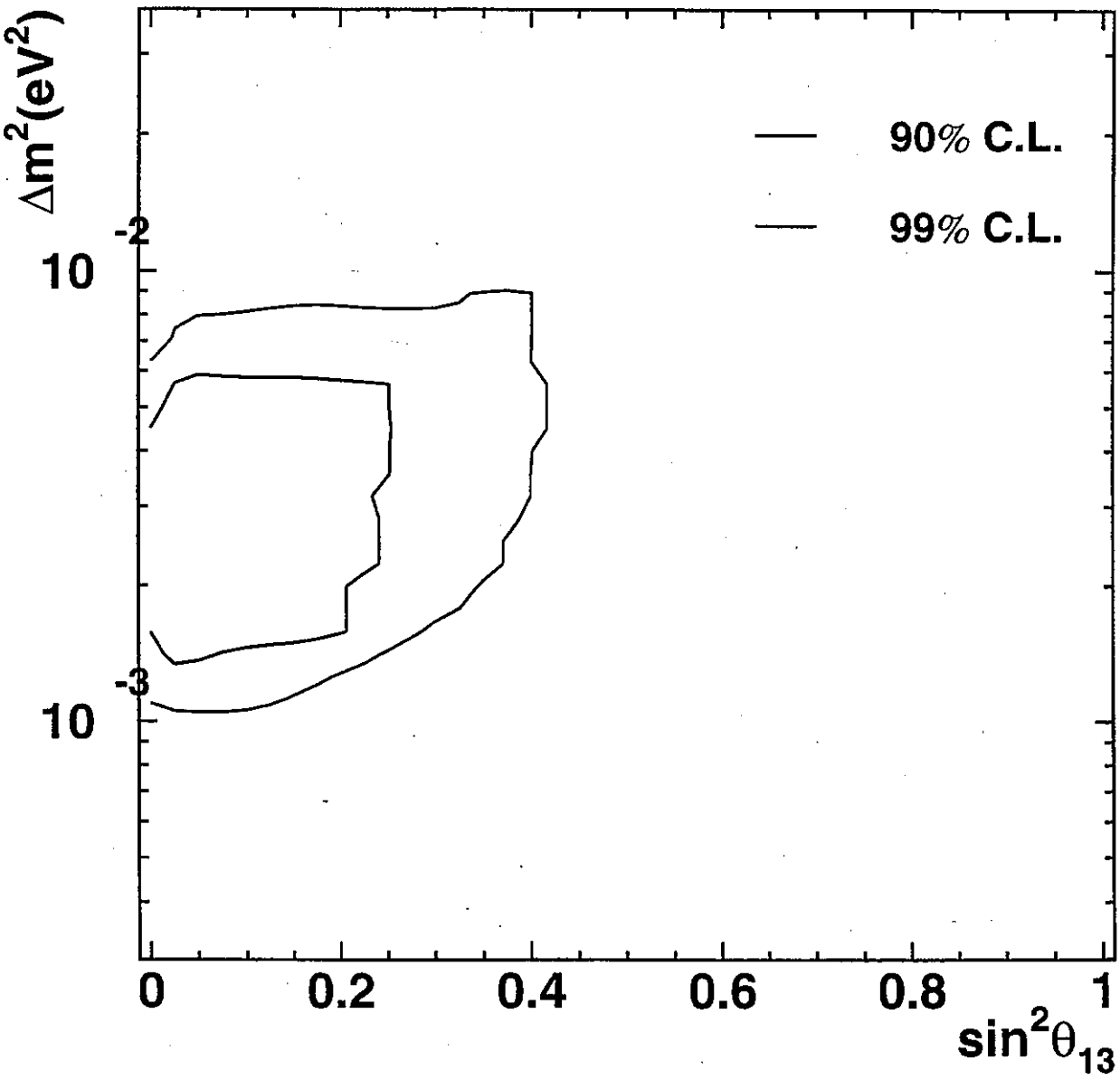
Allowed region for $\sin^2\theta_{13}$, $\sin^2\theta_{23}$ (FC+PC 990 day)

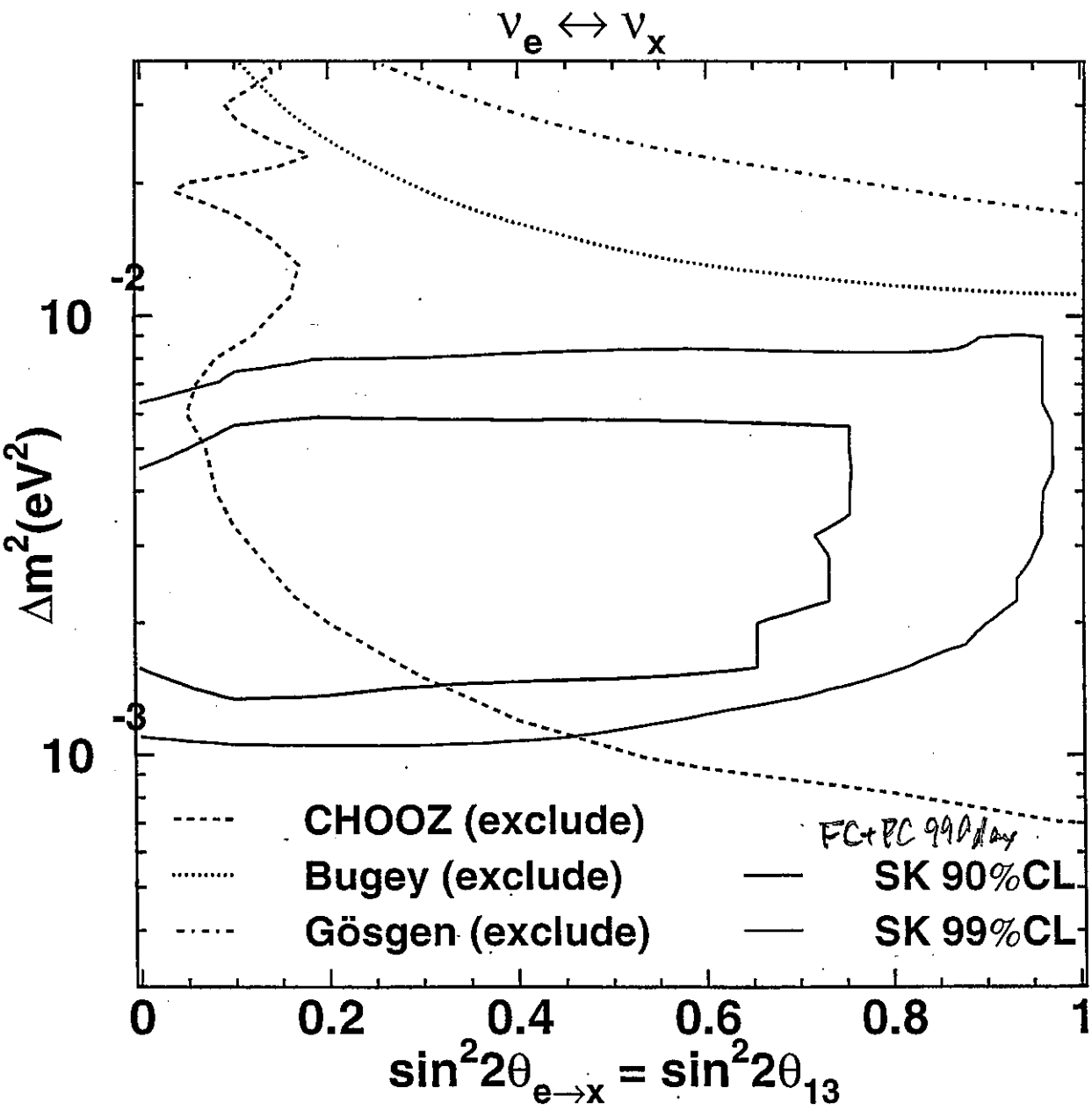


FC+PC 990 day



FC+PC 990day




$\nu_e \leftrightarrow \nu_x$
$\Delta m^2(eV^2)$
10^{-2}
10^{-3}
CHOOZ (exclude)
Bugey (exclude)
Gösgen (exclude)
FC+PC 990day
SK 90%CL
SK 99%CL
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta_{e\to x} = \sin^2 2\theta_{13}$