March,2001

Super-Kamiokande atmospheric neutrino

@ Moriond EW 2001

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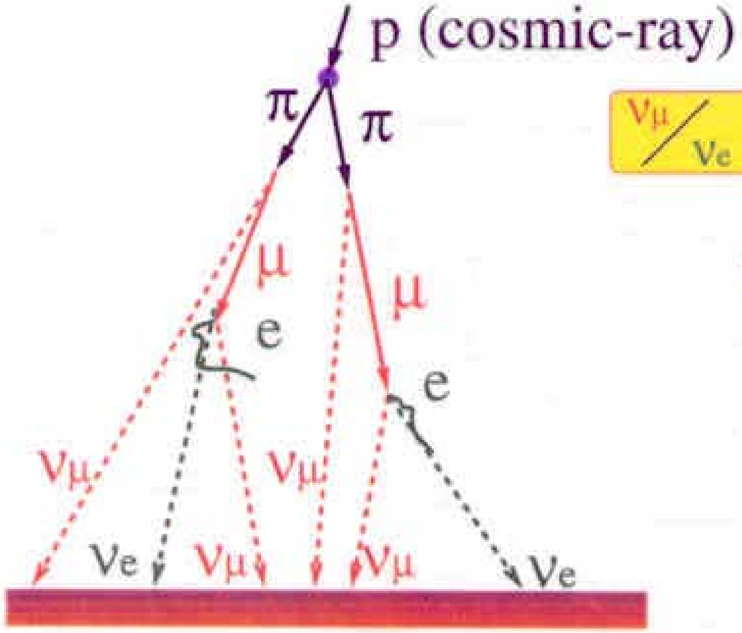
for the Super-Kamiokande collaboration

recent results of

- $\nu_\mu \rightarrow \nu_\tau$ 2 flavor oscillation analysis
- $\nu_\mu \rightarrow \nu_\tau$ vs $\nu_\mu \rightarrow \nu_s$
- A search for CC ν_τ events

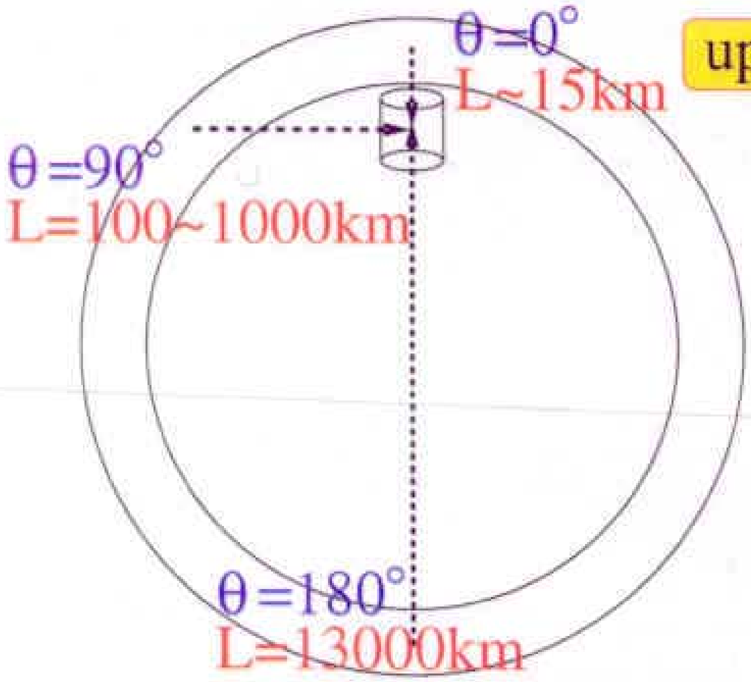
Atmospheric neutrino



$\nu_\mu / \nu_e = 2$ @ low energy ($E_\nu < 1$GeV)

>2 @ higher energy

δ ~5%



up/down symmetry

@ high energy (E_ν > a few GeV)

δ < a few %

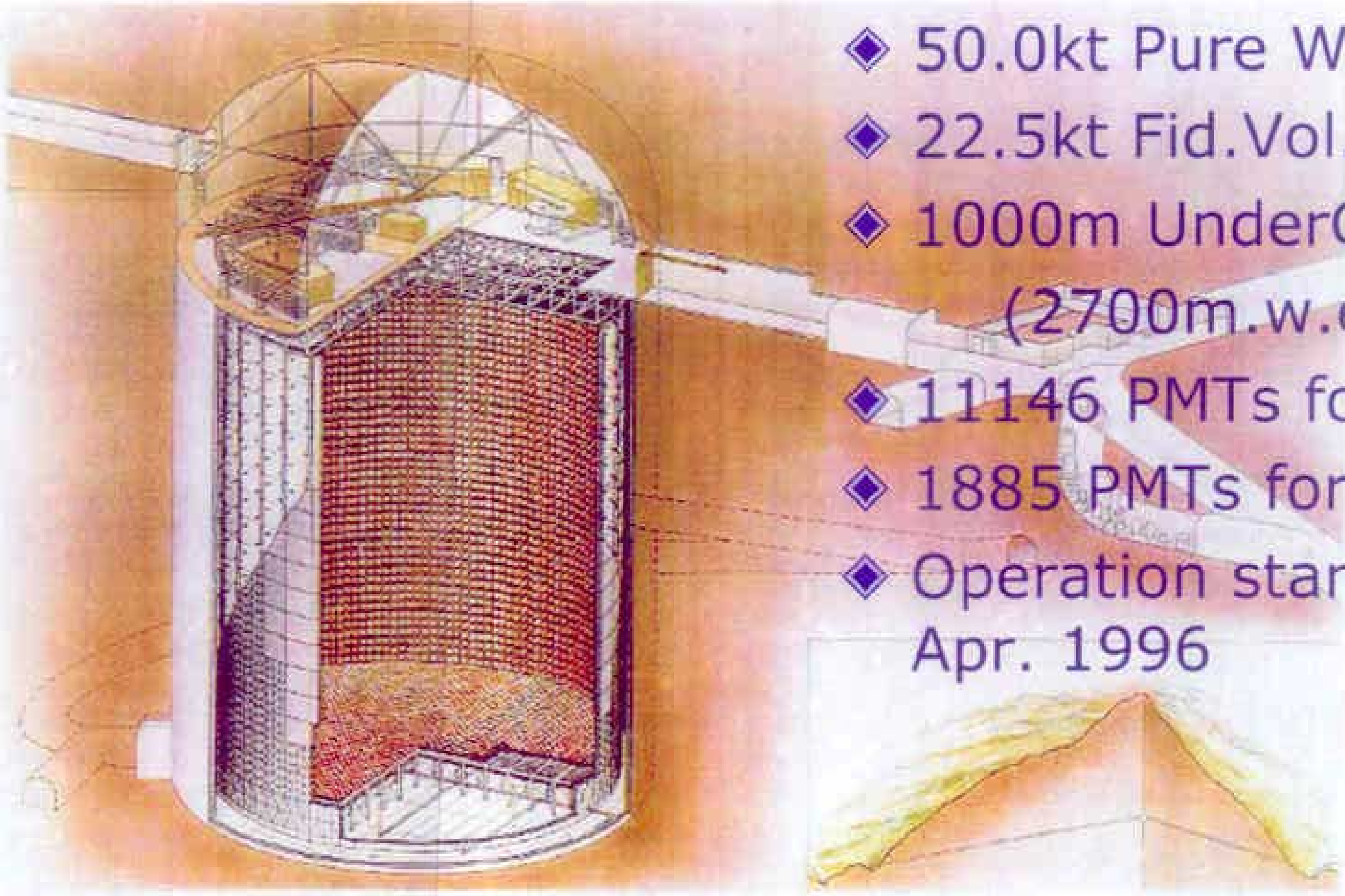
θ(zenith angle)

→ L(flight length)

E_ν=100MeV~100GeV

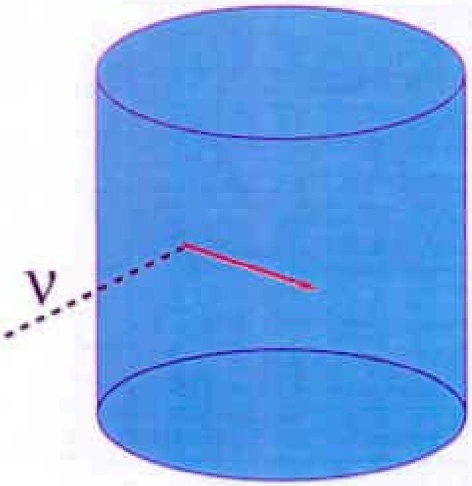
sensitive to neutrino oscillation with $\Delta m^2 > 10^{-4} eV^2$

Super-Kamiokande



- 50.0kt Pure Water
- 22.5kt Fid.Vol.
- 1000m UnderGround (2700m.w.e.)
- 11146 PMTs for ID
- 1885 PMTs for OD
- Operation started in Apr. 1996

Fully Contained (FC)



8ev/day

<Eν>~1GeV

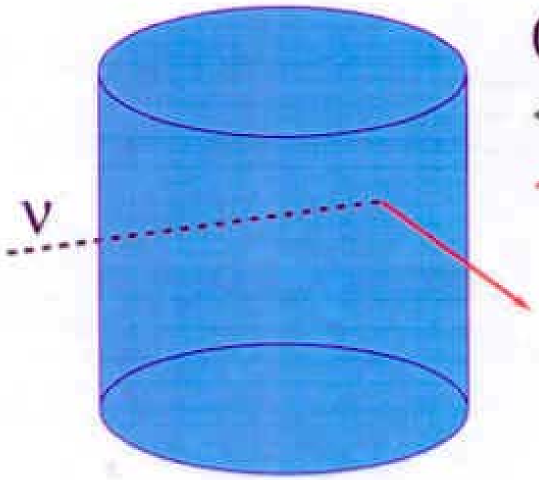
sub-GeV (Evis<1.33GeV)

multi-GeV(Evis>1.33GeV)

→ Particle ID

e-like or μ-like

Partially Contained (PC)



0.6ev/day

<Eν>~10GeV

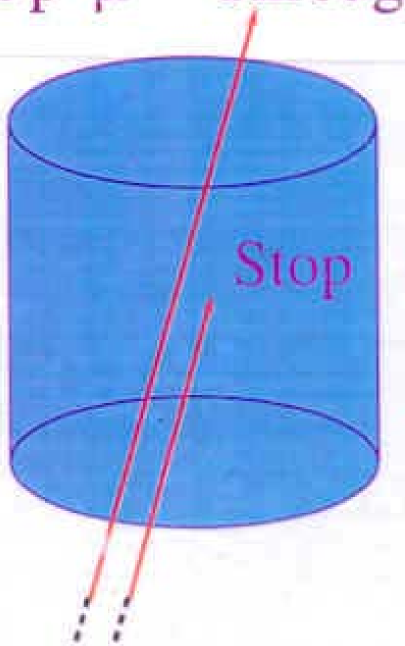
~97% ν_μ C.C.

Up-μ

Through 1.1ev/day

<Eν>~100GeV

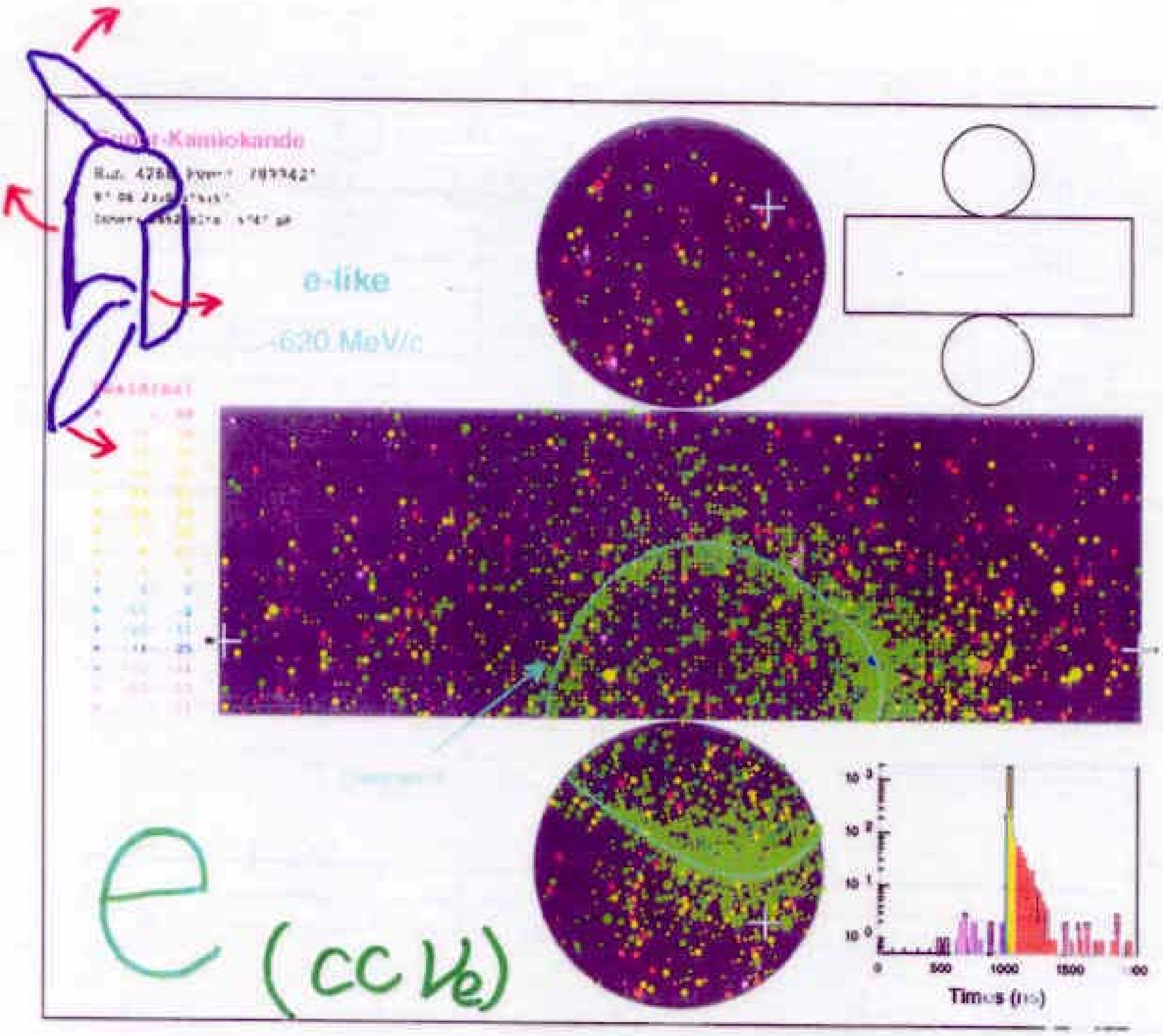
~pure ν_μ C.C.



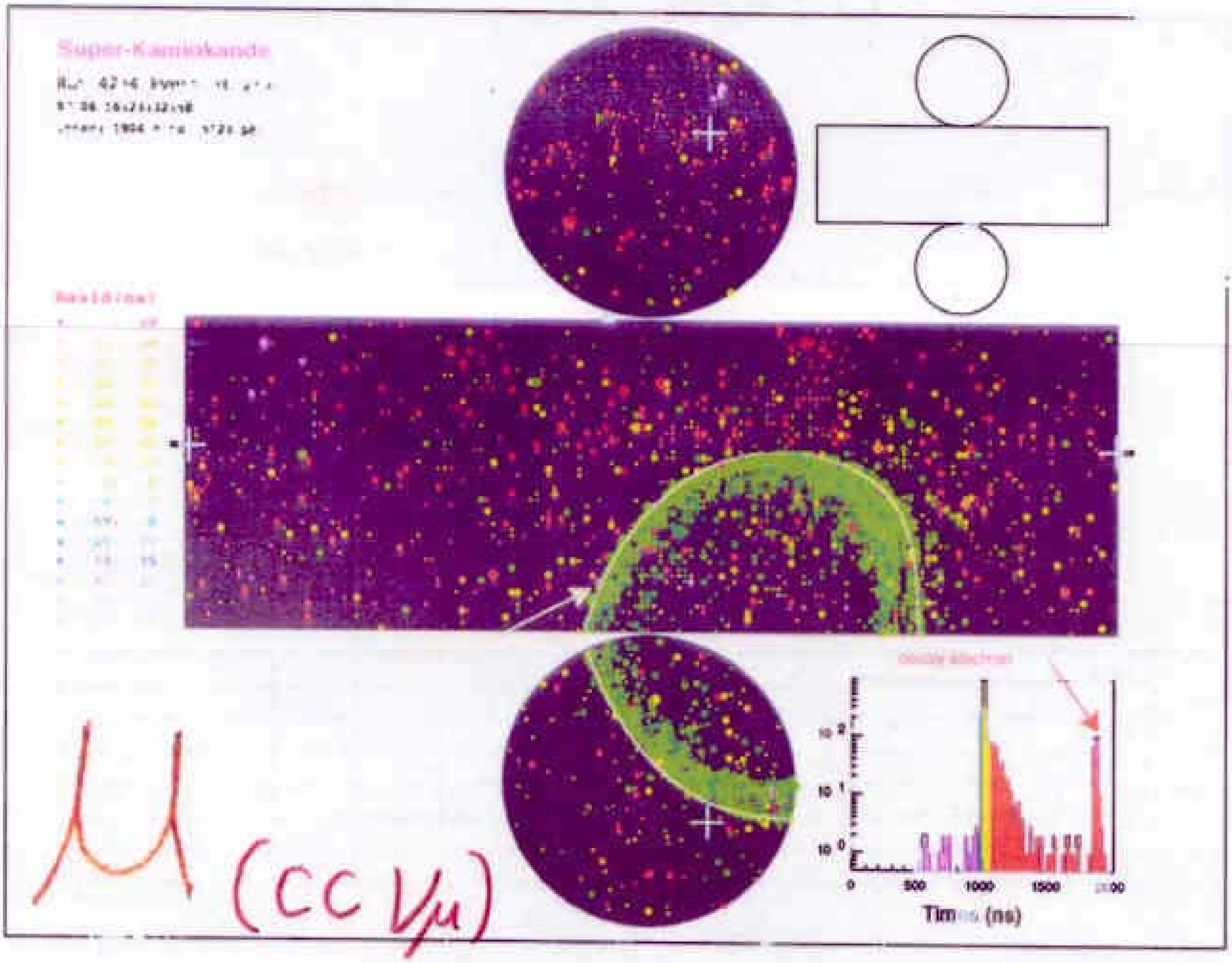
0.3ev/day

<Eν>~10GeV

~pure ν_μ C.C.



e (CC ν_e)



μ (CC ν_μ)

Event summary (79kton year)

Contained events (1289days)

sub-GeV Evis<1.33GeV Pe>100MeV/c,P_{μ}>200MeV/c

		DATA	MC	
single ring	e-like	2864	2668	ν_eC.C. 87%
	μ-like	2788	4073	ν_μC.C. 95%
multi-ring		2159	2585	

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.638^{+0.017}_{-0.017} \pm 0.050$$

multi-GeV Evis>1.33GeV(FC)+PC → μ-like

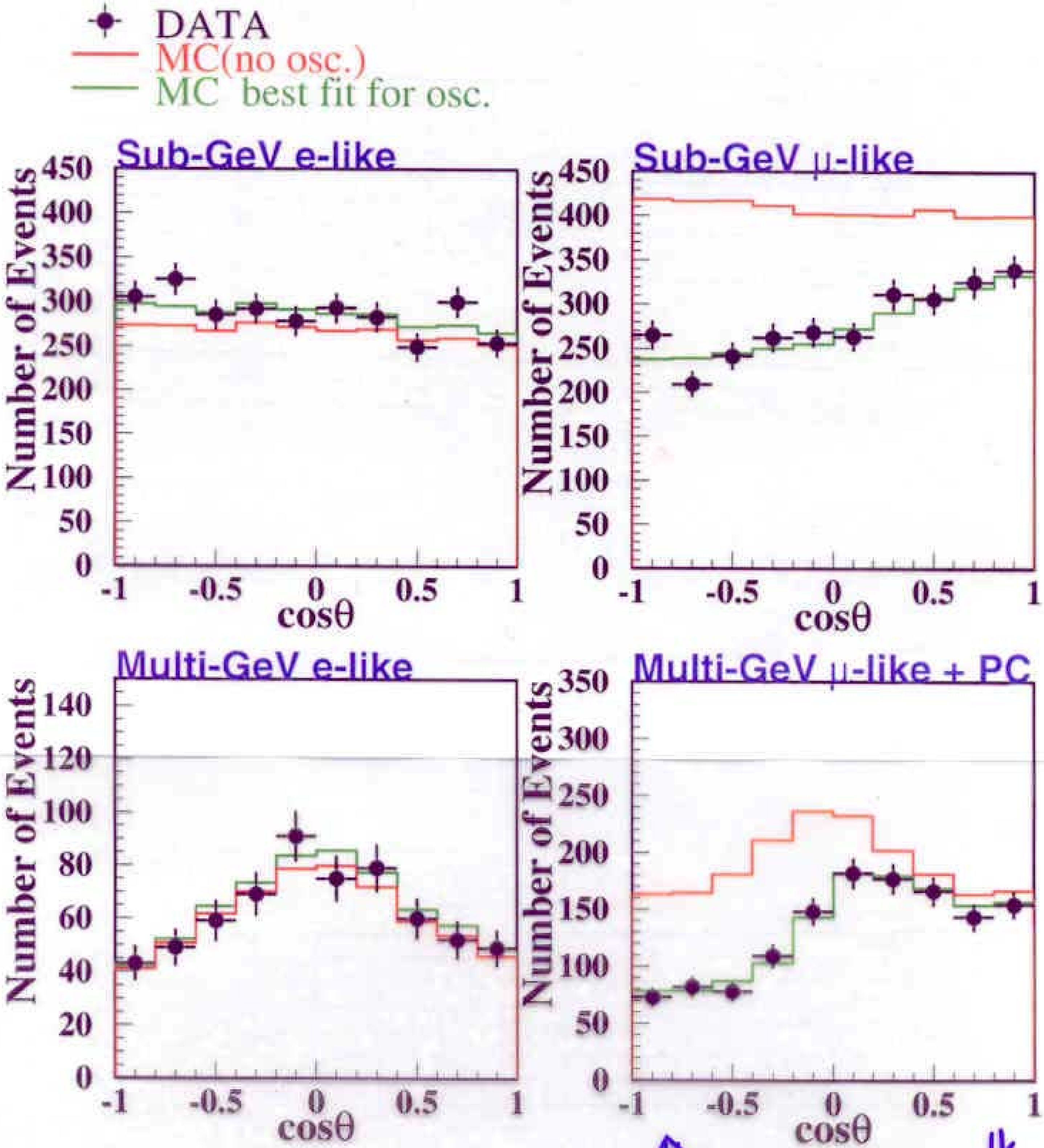
		DATA	MC	
single ring	e-like	626	613	ν_eC.C. 84%
	μ-like	558+754	838+1065	ν_μC.C. 98%
multi-ring		1318	1648	

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.675^{+0.034}_{-0.032} \pm 0.080$$

Up-μ events

through	**(1268days)**	1416
stop	**(1247days)**	345

Zenith angle distributions FC,PC



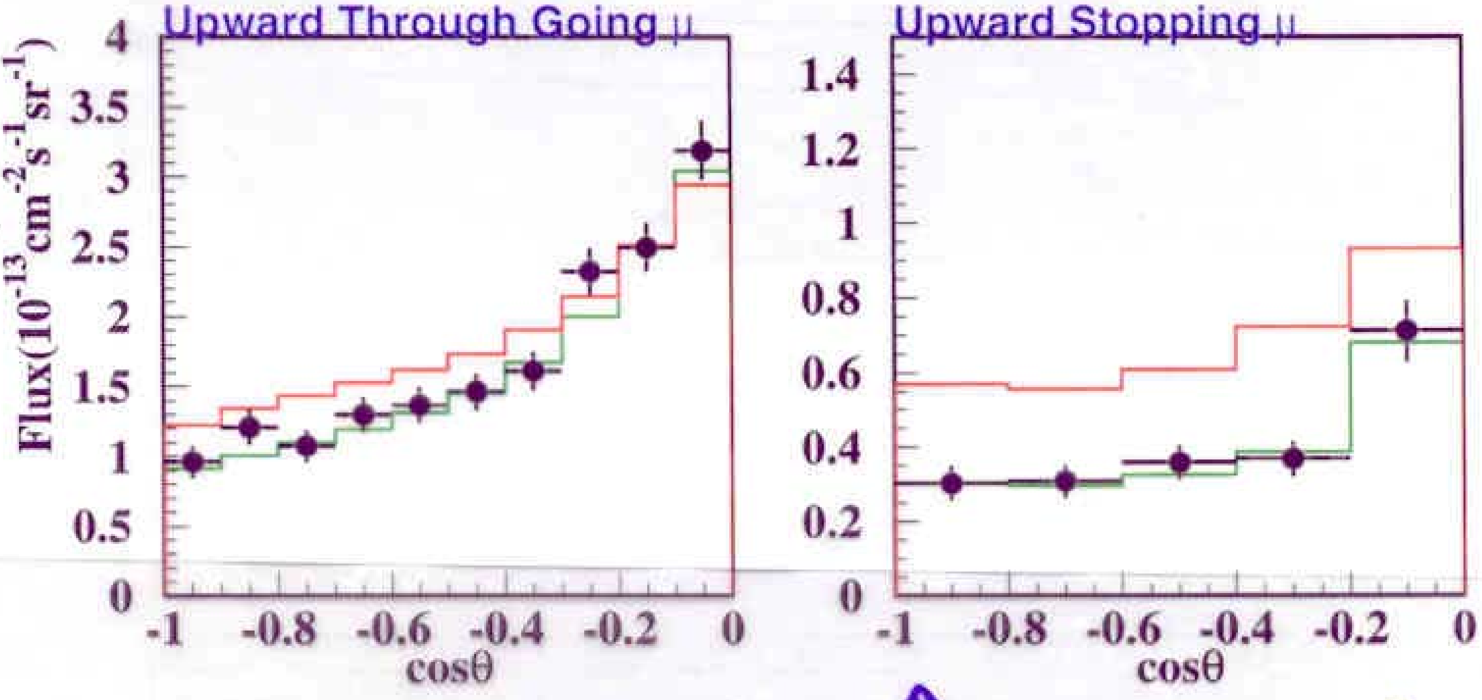
⇑ Up

⇓ Down

Zenith angle distributions

upward going muons

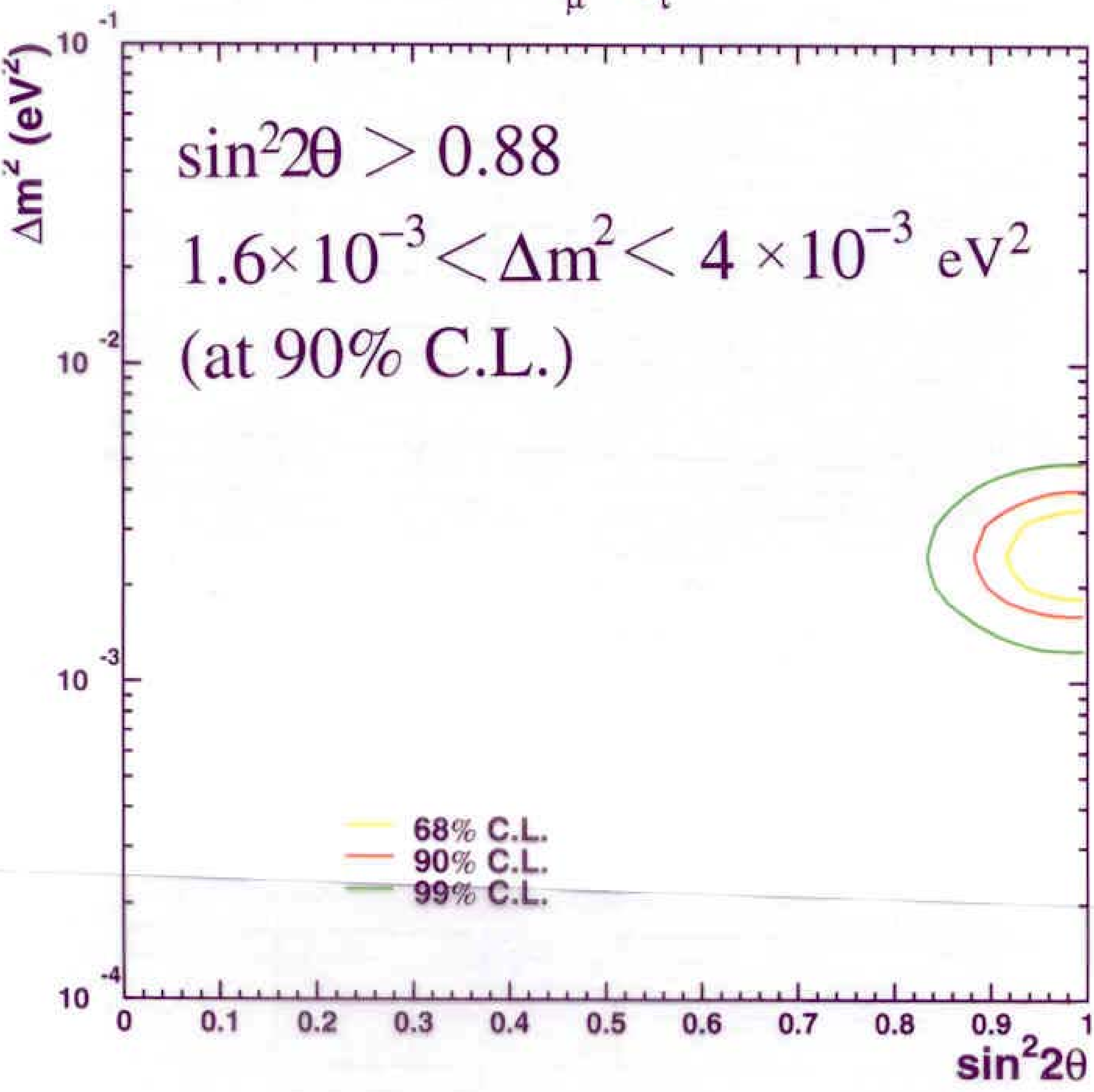
● DATA
— prediction(no osc.)
— prediction best fit for osc.



⇑ Vertical

⇐ Horizontal

Allowed region (FC+PC+upmu)


$\nu_\mu - \nu_\tau$

$\sin^2 2\theta > 0.88$

$1.6\times 10^{-3} < \Delta m^2 < 4 \times 10^{-3}$ eV^2

(at 90% C.L.)

Best fit $\chi^2_{min} = 142.1/152$ d.o.f

$(\sin^2 2\theta\ ,\Delta m^2)=(1.00, 2.5\times 10^{-3}\,\mathrm{eV}^2)$

No oscillation

$\chi^2 = 344.1/154$ d.o.f

$\nu_\mu \leftrightarrow \nu_\tau$ vs $\nu_\mu \leftrightarrow \nu_s$

Neutral current

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

$\downarrow \nu_\mu$

$\nu_\mu \uparrow \; \uparrow \nu_\tau$

$\nu_\mu \leftrightarrow \nu_s$

$\downarrow \nu_\mu$

$\nu_\mu \uparrow \; \uparrow \cancel{\nu_s}$

does not interact with matter
even through neutral current

Fewer upward going N.C. events

Matter effect

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

No

$\nu_\mu \leftrightarrow \nu_s$

Yes

mixing angle in matter

effective potential

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2V_{\mu s} E\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

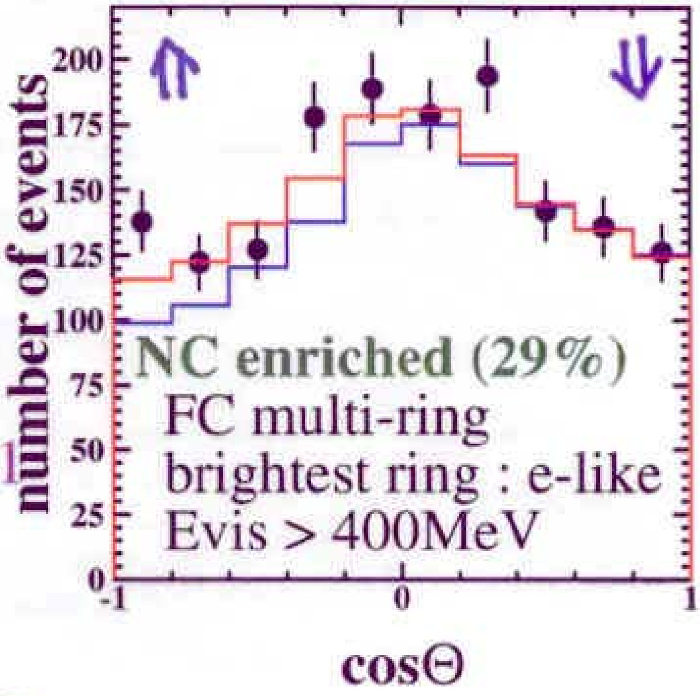
For high Eν ($\gtrsim$15GeV)
oscillation is significantly suppressed.

Zenith angle distributions

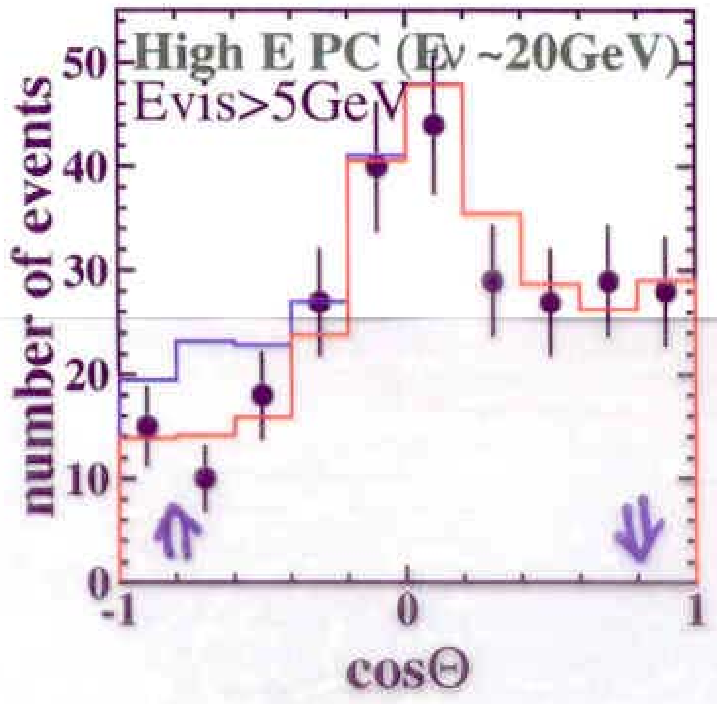
Neutral current

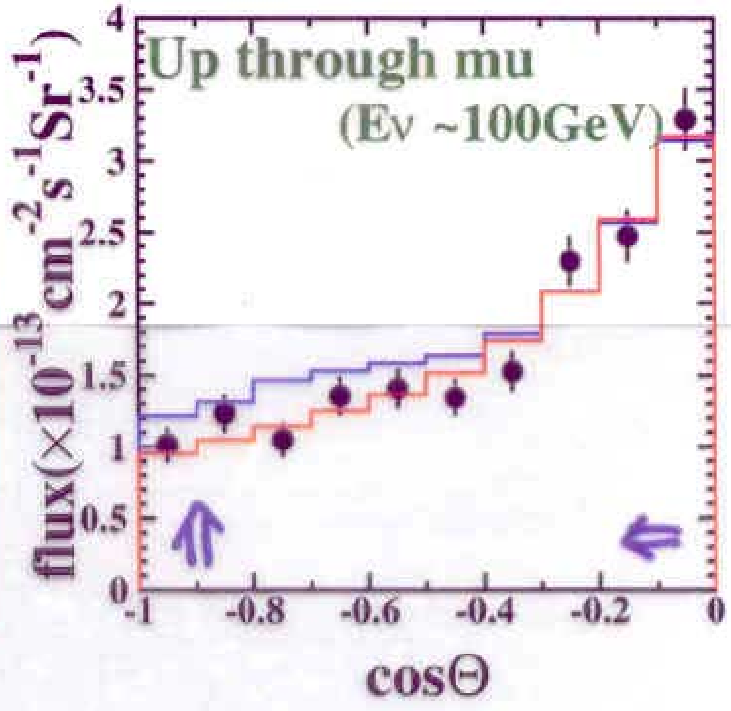
- ● DATA
- — $\nu_\mu \rightarrow \nu_\tau$
- — $\nu_\mu \rightarrow \nu_s$

$@\Delta m^2 = 3 \times 10^{-3} eV^2, \sin^2 2\theta = 1$

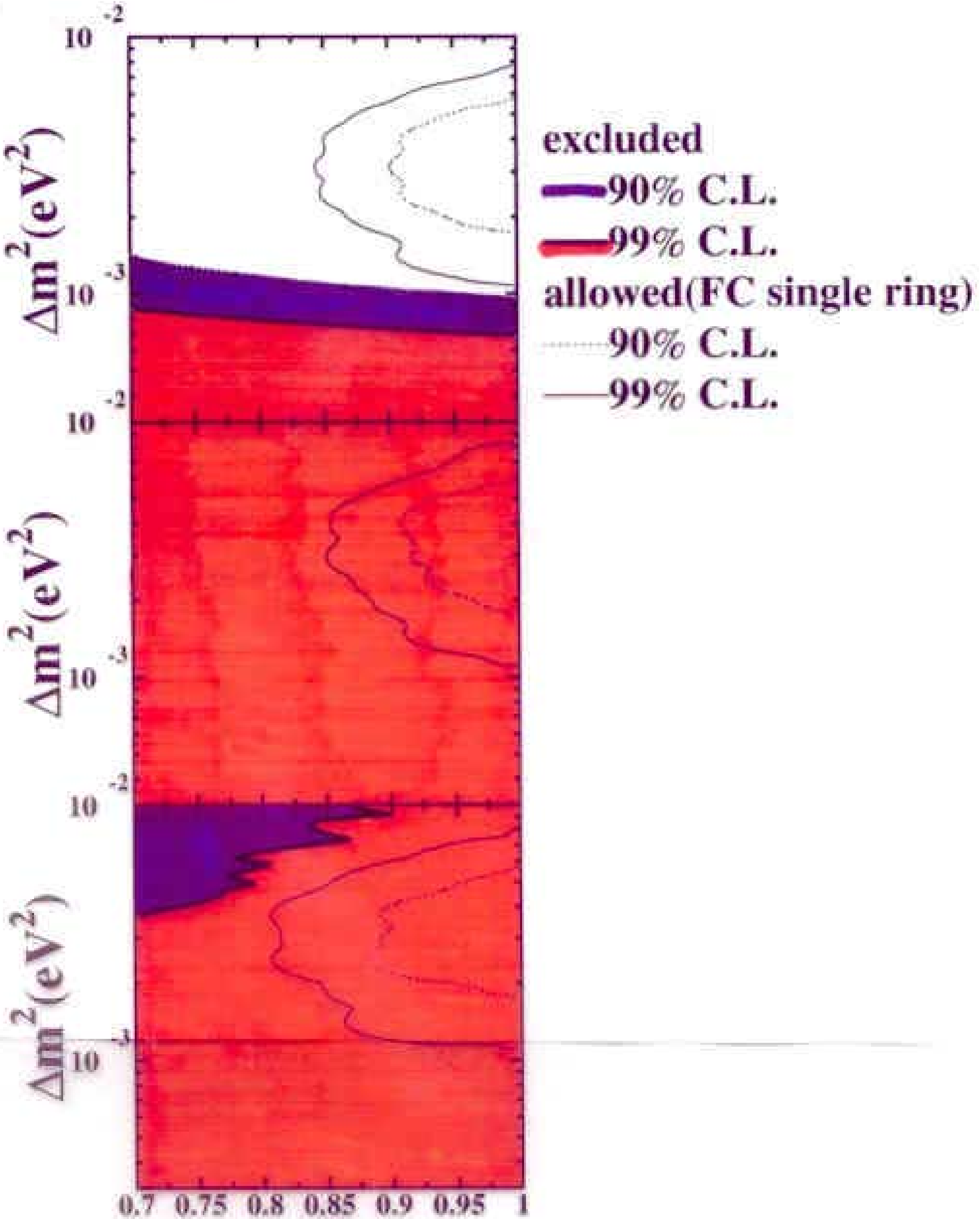


Matter effect





Excluded region by combined analysis



$\nu_\mu \to \nu_\tau$

$\nu_\mu \to \nu_s$

($\Delta m^2 > 0$)

$\nu_\mu \to \nu_s$

($\Delta m^2 < 0$)

$\Longrightarrow$ pure $\nu_\mu \to \nu_s$ is disfavored at 99% C.L.

Search for CC ν_τ

Assumption

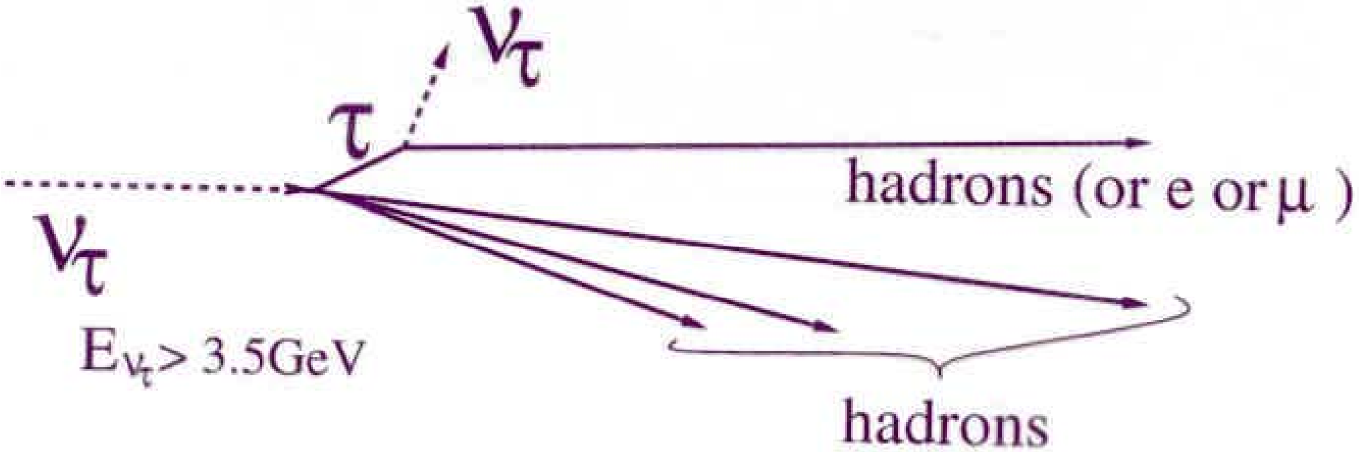
$\nu_\mu \rightarrow \nu_\tau$ oscillation

at $\Delta m^2 = 3 \times 10^{-3} eV^2$, $\sin^2 2\theta = 1$

~20 events/year

S/N ~ 0.7%

CC ν_τ CCν_e ,CCν_μ ,NC



Many hadrons are produced!

Three different analyses to enrich CCν_τ

1)likelihood method using Evis,# of decay-e,rings etc

2)neural network method

3)likelihood method using energy flow and event shape such as sphericity

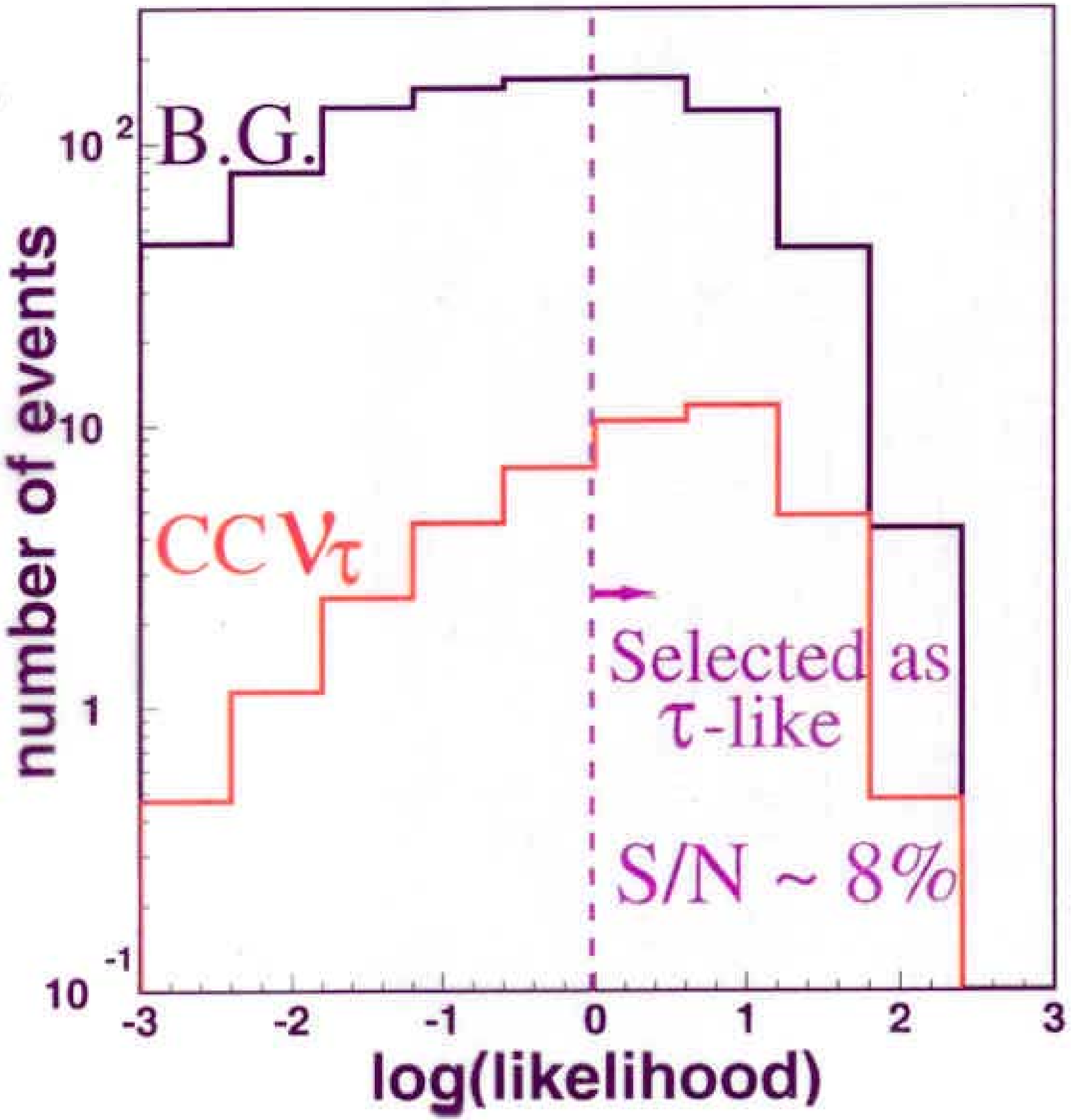
Analysis(1)

basic cuts;

FC,Evis>1.33GeV,brightest ring:e-like

likelihood analysis with;

- Evis
- # of decay-e
- # of rings
- max(E of a ring)/Etot
- max distance from 1ry to decay-e
- max P_{μ}
- Pt
- PID likelihood of brightest ring

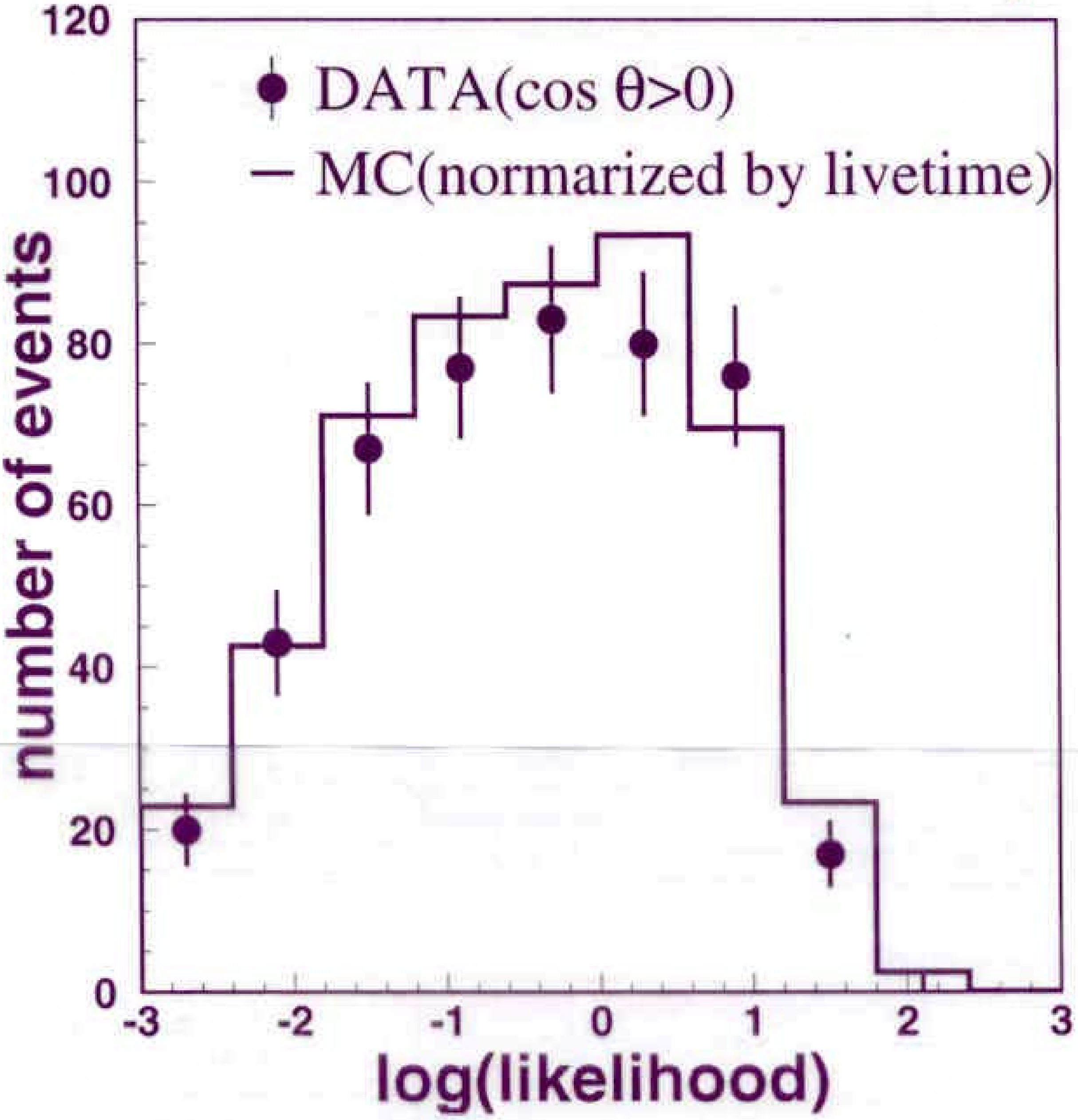


ν_τ events apper as upward going.

Analysis is optimized by MC.

Analysis is checked
by looking at only downward going data.

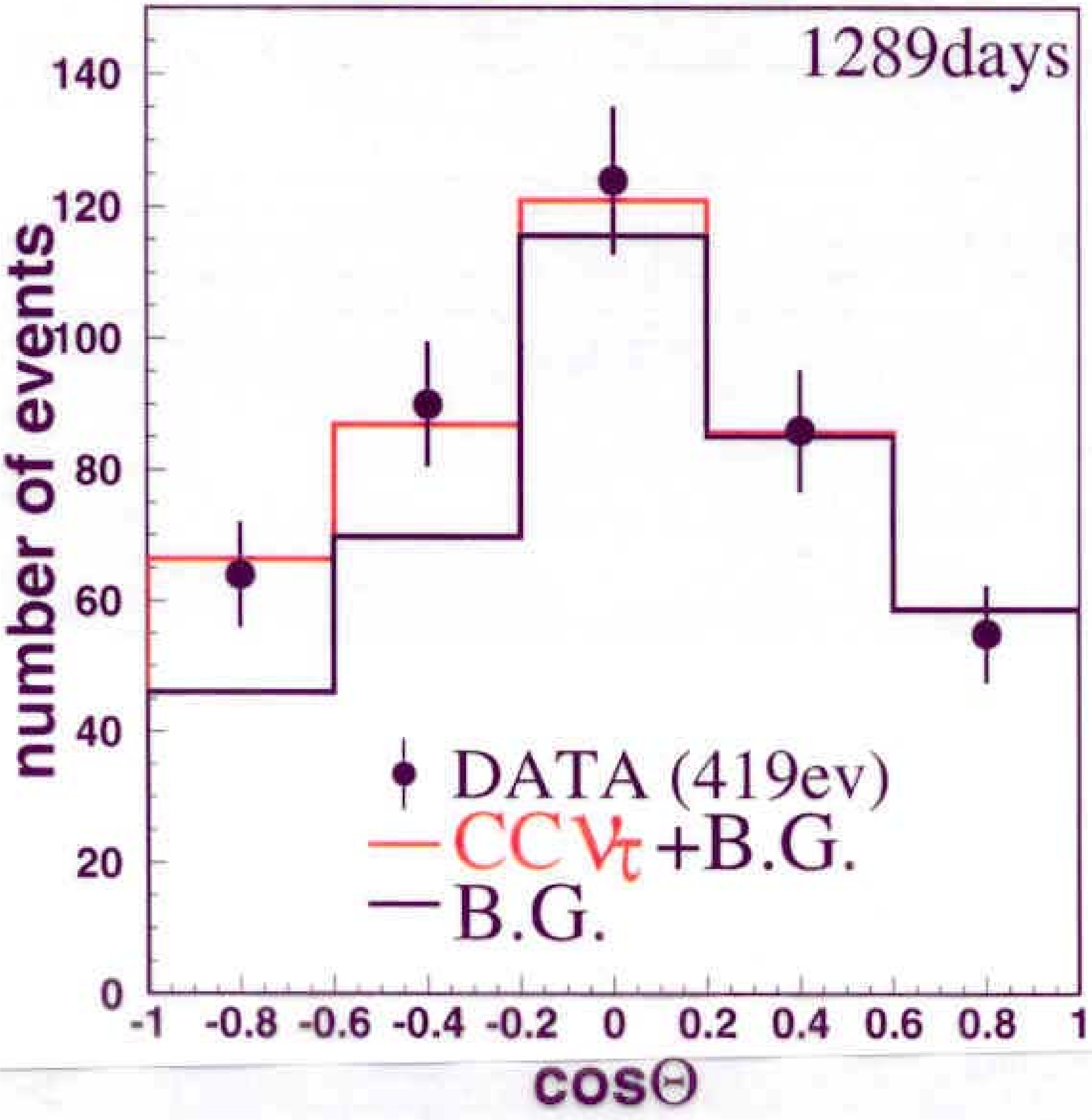
Blind analysis!



DATA and MC agree well in dawnward going.

Zenith angle distribution

τ-like events



MC is normarized to minimize χ^2 ;

$$\chi^2 \equiv \sum_{\cos\theta_i}^{5\mathrm{bin}} \left\{ \frac{N_i^{\mathrm{DATA}} - (\alpha N_i^{\tau\mathrm{MC}} + \beta N_i^{\mathrm{B.G.\,MC}})}{\sigma_i} \right\}^2$$

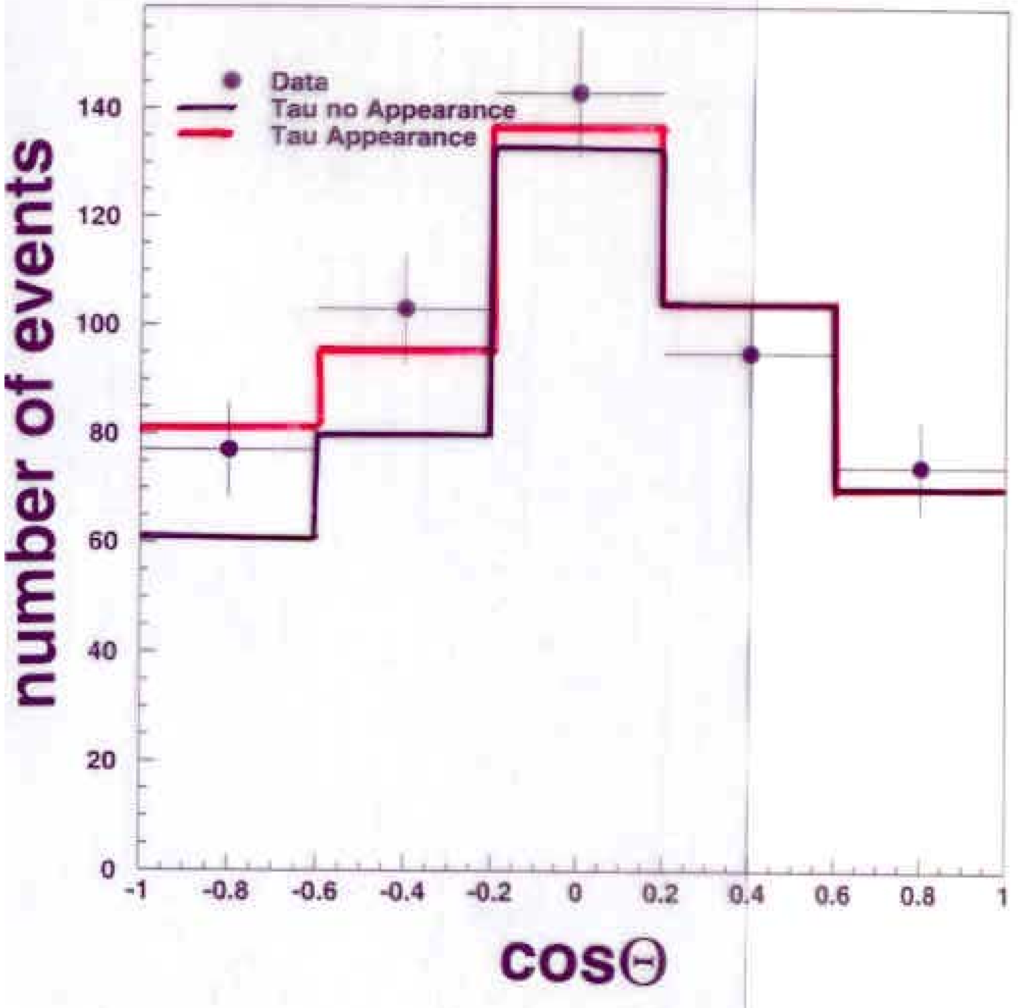
α, β : free

$$\rightarrow N^{\tau\,\mathrm{obs.}} \equiv \alpha N^{\tau\mathrm{MC}}$$

$$= 43 \pm 17$$

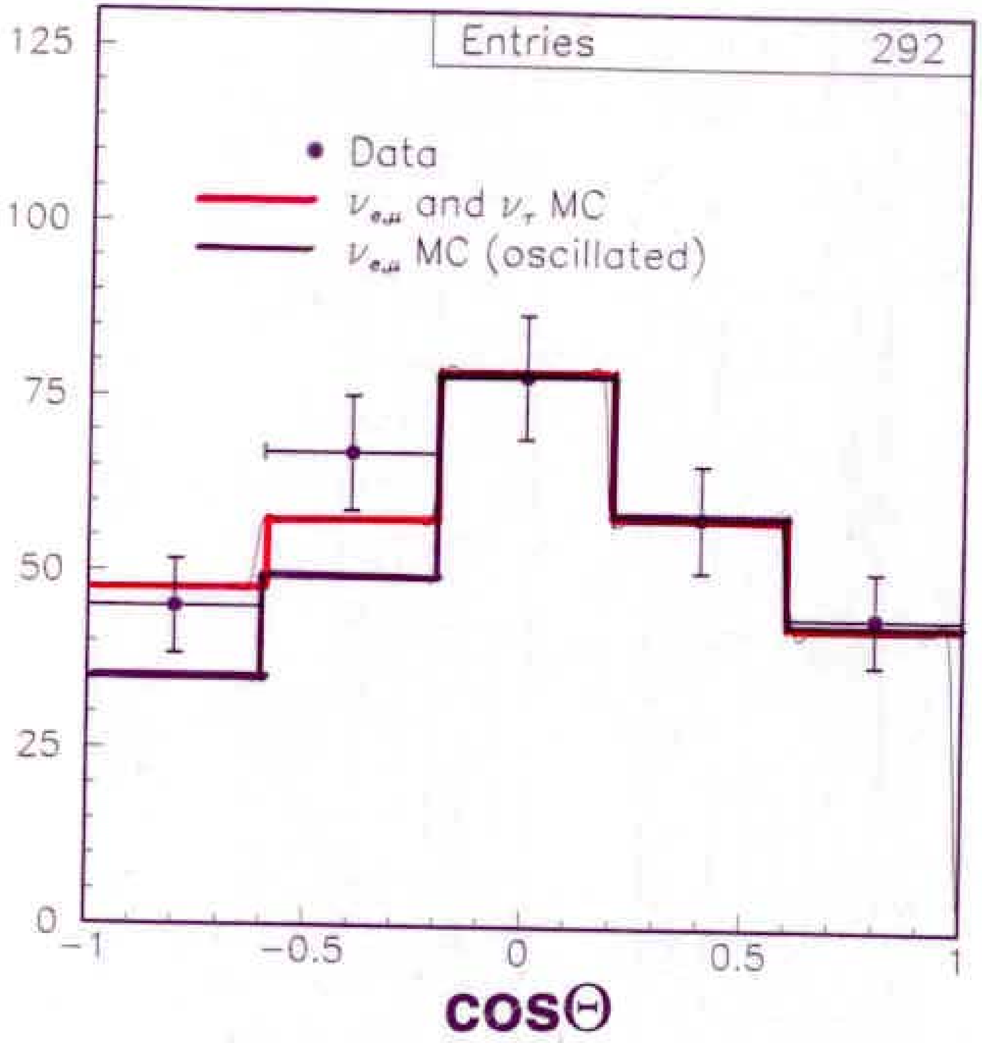
Zenith angle distribution

Analysis(2)



$$N^{\tau obs.} = 44 \pm 20$$

Analysis(3)



$$N^{\tau obs.} = 25.5 \pm^{14}_{13}$$

Results

	1)	2)	3)
Number of CC ν_τ (fitted excess)	$43 \pm 17^{+8}_{-11}$	$44 \pm 20^{+8}_{-12}$	25.5^{+14}_{-13}
Efficiency	42%	45%	32%
Number of CC ν_τ (efficiency corrected)	$103 \pm 41^{+18}_{-26}$	$98 \pm 44^{+18}_{-27}$	79^{+44}_{-40}

Consistent with ν_τ appearance.

74 CC ν_τ events are expected as FC so far.

Summary

79kt year of SK atmospheric neutrino data

- 2-flavor oscillation analysis $\nu_\mu \rightarrow \nu_\tau$

$\sin^2 2\theta > 0.88$, $1.6\times10^{-3} < \Delta m^2 < 4\times10^{-3}$ eV^2
(at 90% C.L.)

- $\nu_\mu \rightarrow \nu_\tau$ vs $\nu_\mu \rightarrow \nu_s$

Pure $\nu_\mu \rightarrow \nu_s$ is disfavored at 99% C.L.

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- Search fot C.C. ν_τ

Consistent with ν_τ appearance