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Atmospheric Neutrinos and Long Baseline Neutrino Oscillation Experiments

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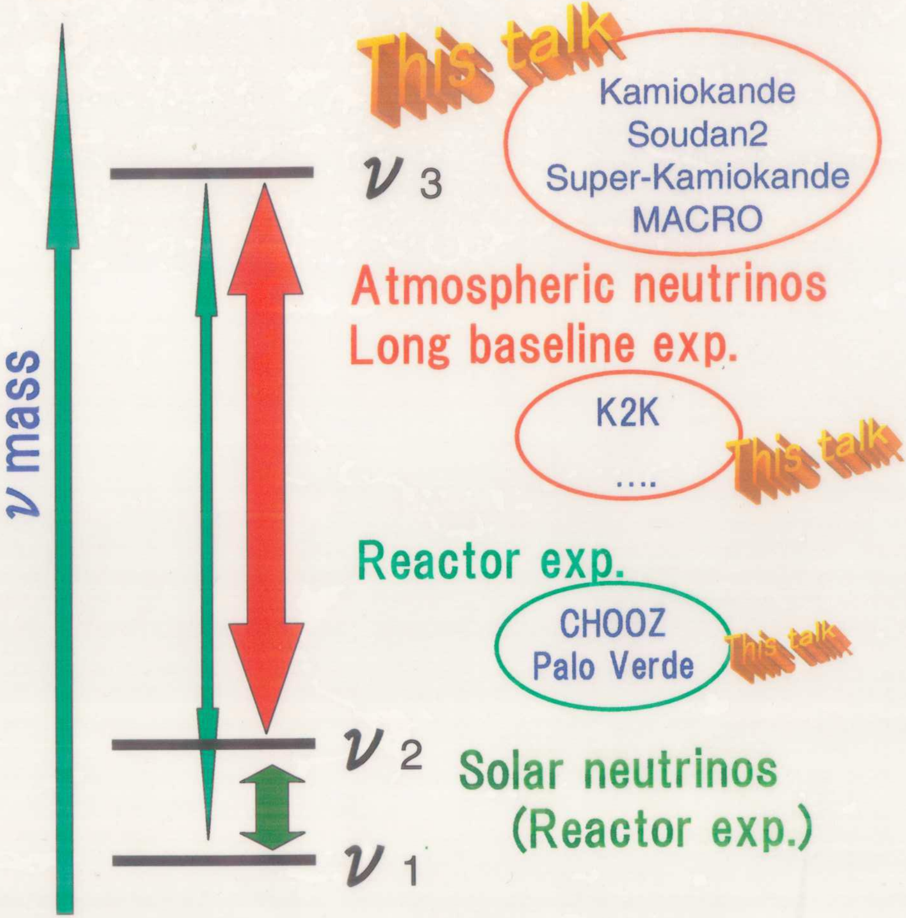
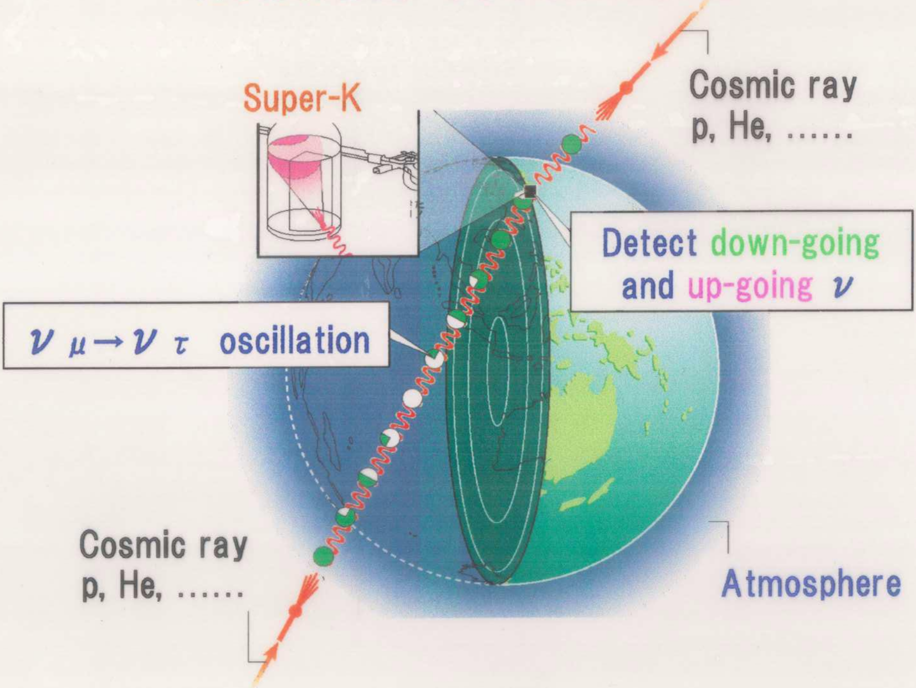
Outline

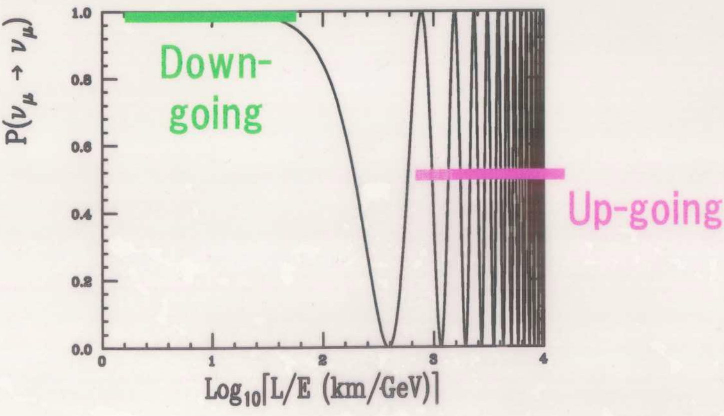
- Introduction
- Atmospheric neutrinos
  - ⇒ data and $\nu_\mu \rightarrow \nu_\tau$ analysis
  - ⇒ 3 flavor oscillation and reactor exp's
  - ⇒ Search for CC ν_τ events
- Long-baseline accelerator experiments
  - ⇒ Status of K2K
  - ⇒ Future experiments
- Summary

Introduction



Atmospheric neutrinos and neutrino oscillations

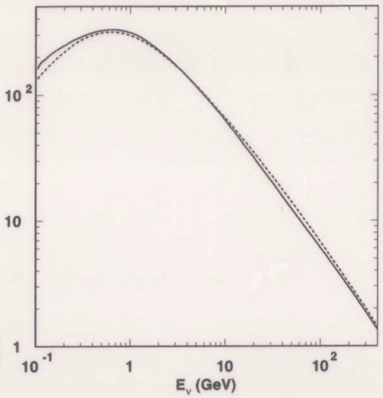




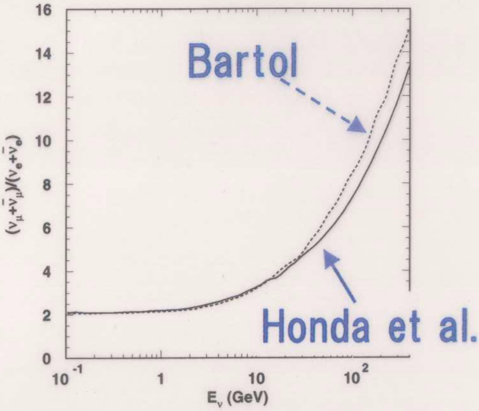
Atmospheric neutrino flux

Overall flux

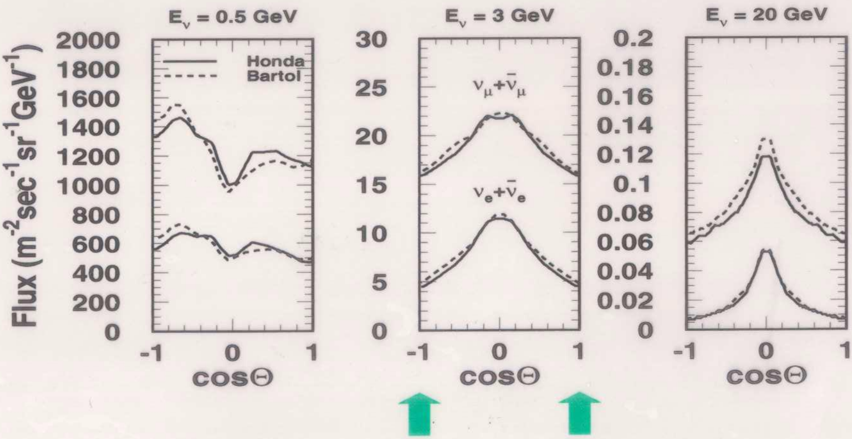
$(\nu_\mu + \overline{\nu}_\mu)$ flux $\times E_\nu^2$



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



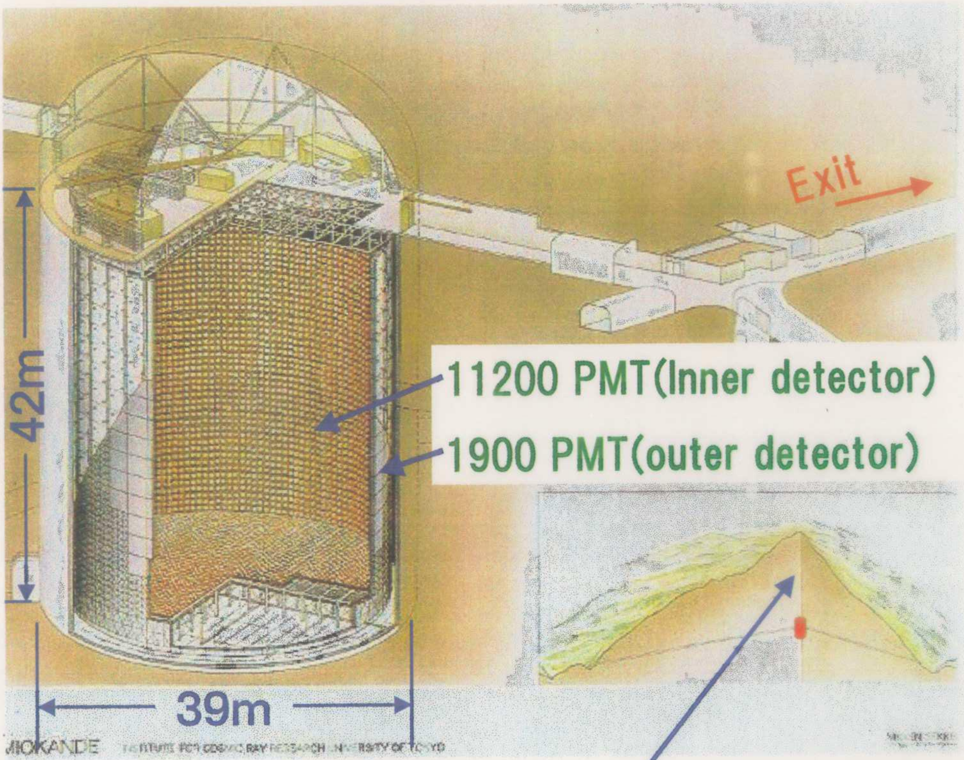
Zenith angle (flight length)



$L\nu =$ 12800 ~20km

Super-Kamiokade detector

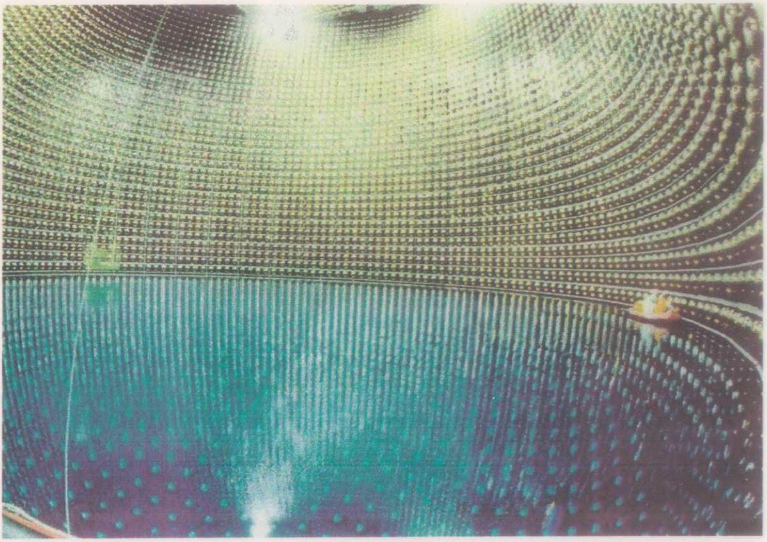
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)



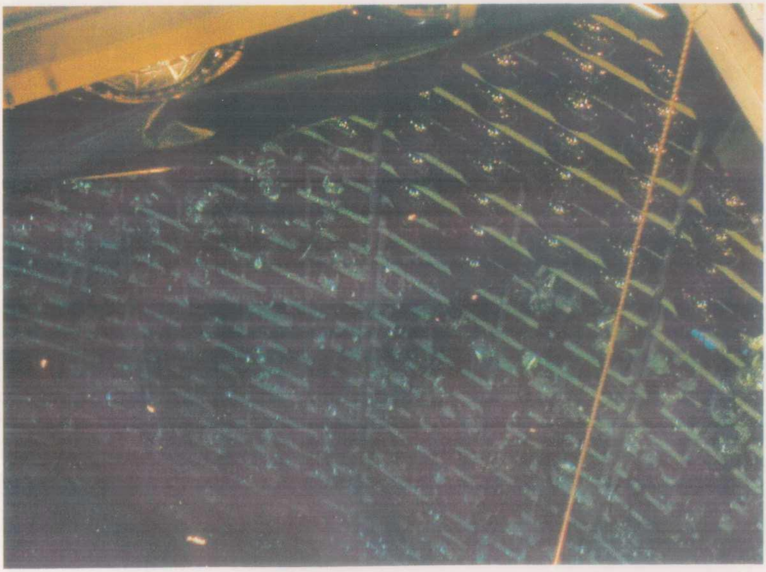
1000m

Super-Kamiokande accident...

Before..



After..



Damage, cause and future…

- **Damage:**

6777/11146 broken ID PMTs
1100/1885 broken OD PMTs
Electronics, HV … are almost OK

- **Cause:**

A PMT at the bottom imploded.
(reason: not sure…)

↓

Shock wave was generated.

↓

Chain reaction.

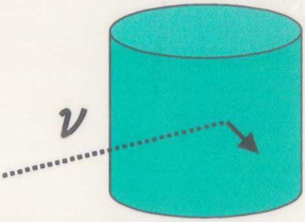
- **Future: (We hope…)**

1) Restart experiment late 2002 with about ½ of PMTs.
2) Full recovery in 2006 before JHF-SK neutrino oscillation experiment.

We need strong and continuous support and encouragement from all of you.

Various types of atmospheric ν events

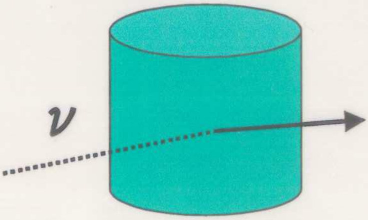
FC (fully contained)



- Both CC ν_e and ν_μ (+NC)
- Need particle identification to separate ν_e and ν_μ

~10300 events (Super-K)

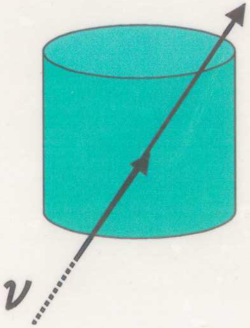
PC (partially contained)



- $\gtrsim$ CC ν_μ

~750 events

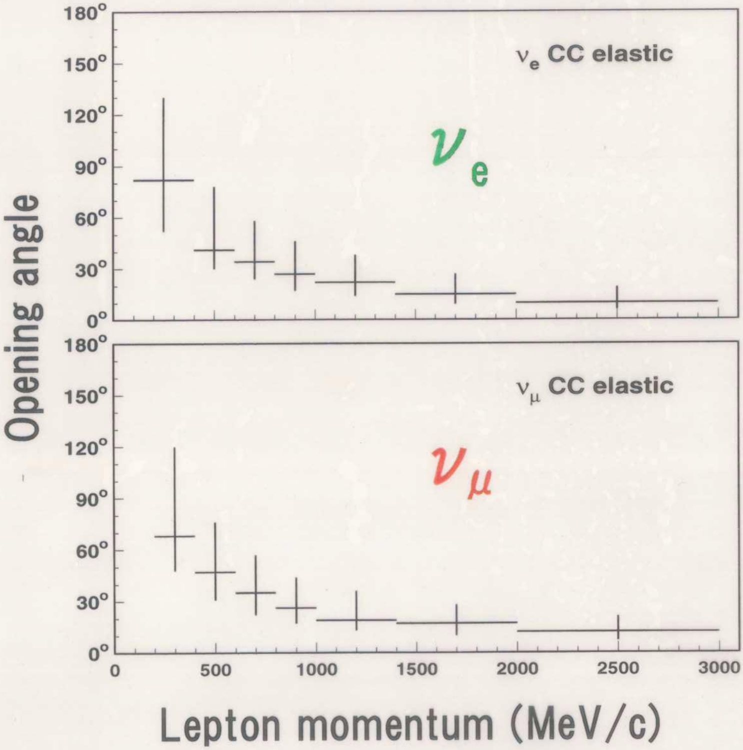
Upward going muon



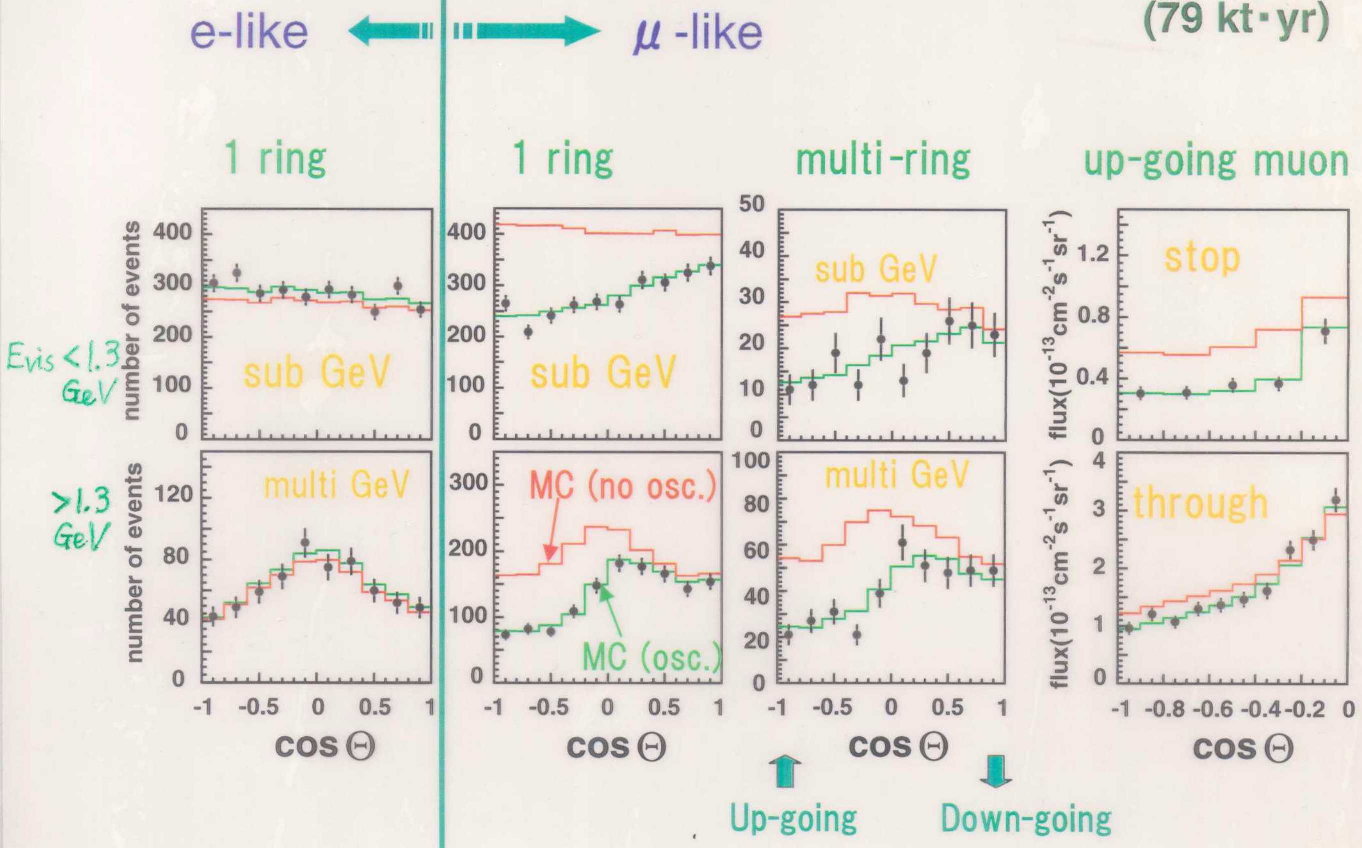
- $\simeq$ CC ν_μ

~1400 events (through)
~320 events (stopping)

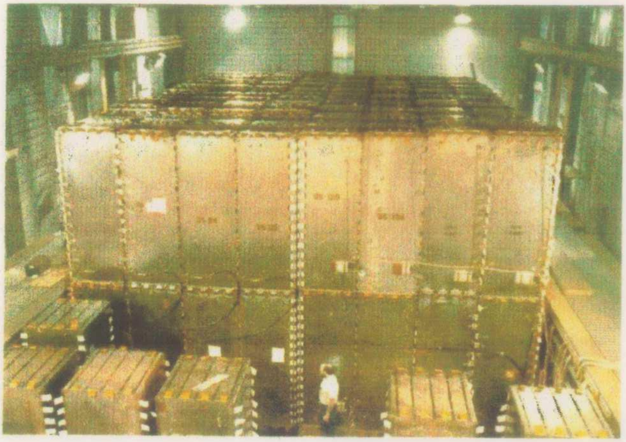
Angular correlation between neutrino and lepton



Zenith angle distribution (Super-K)



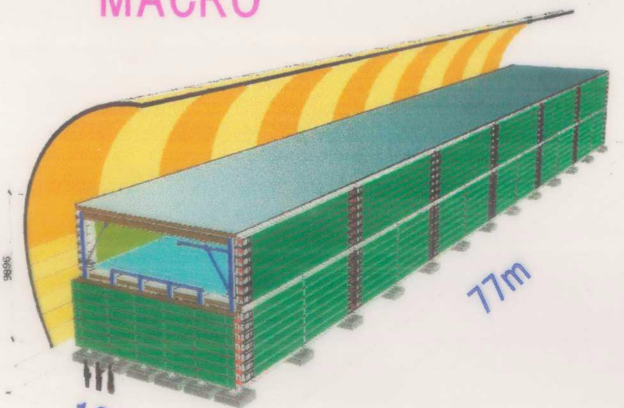
Soudan-2 (1kton tracking calorimeter)



Fully contained events

(~320 ev.)

MACRO



Upward going muons,

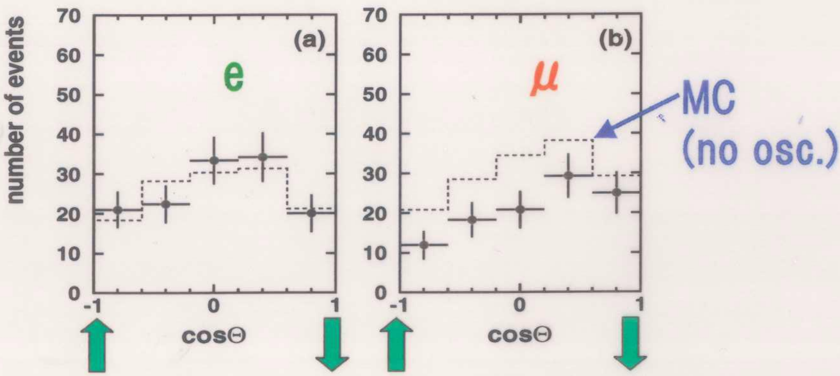
partially contained events

($\gtrsim$1000 ev.)

Soudan-2 data

High { energy / angular } resolution sample

(5.1 kton·yr)

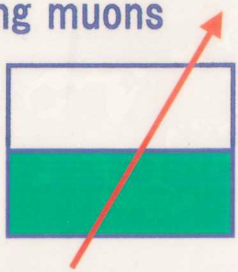


Deficit of upward going muon events.

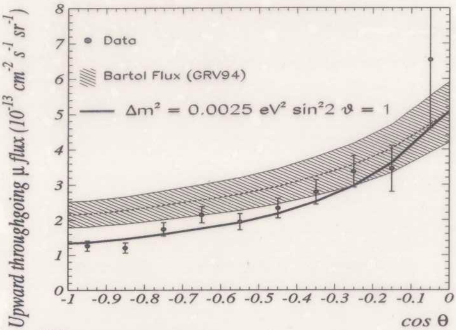
➡ Consistent with Super-K.

MACRO data

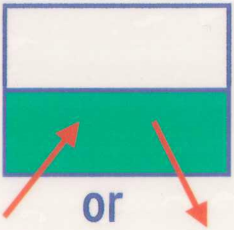
Upward through-going muons

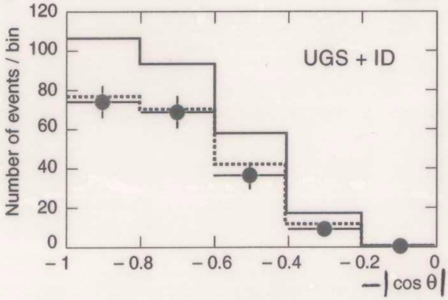


$\cdots\cdots\cdots$ $\Delta m^2=2.5\cdot10^{-3}$

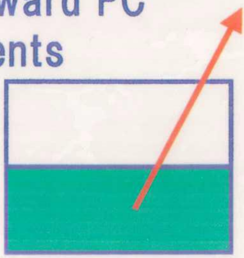


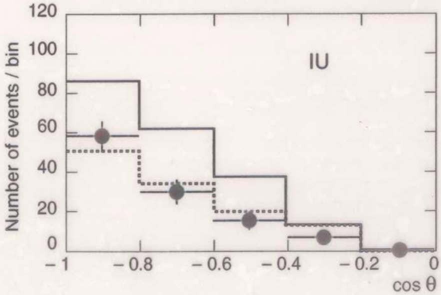
Upward stopping muons + Downward PC events





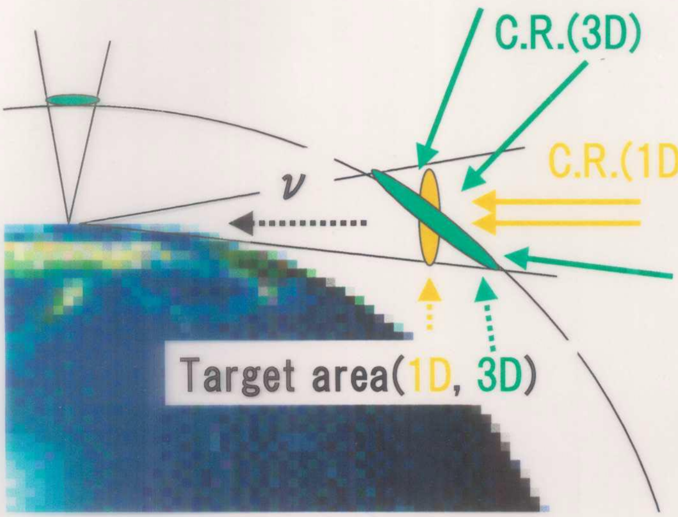
Upward PC events





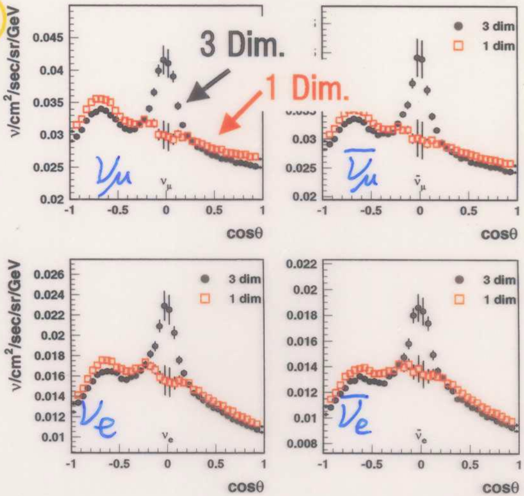
Consistent with $\nu_\mu \rightarrow \nu_\tau$ osc.

New 3 dimensional calculation of the flux



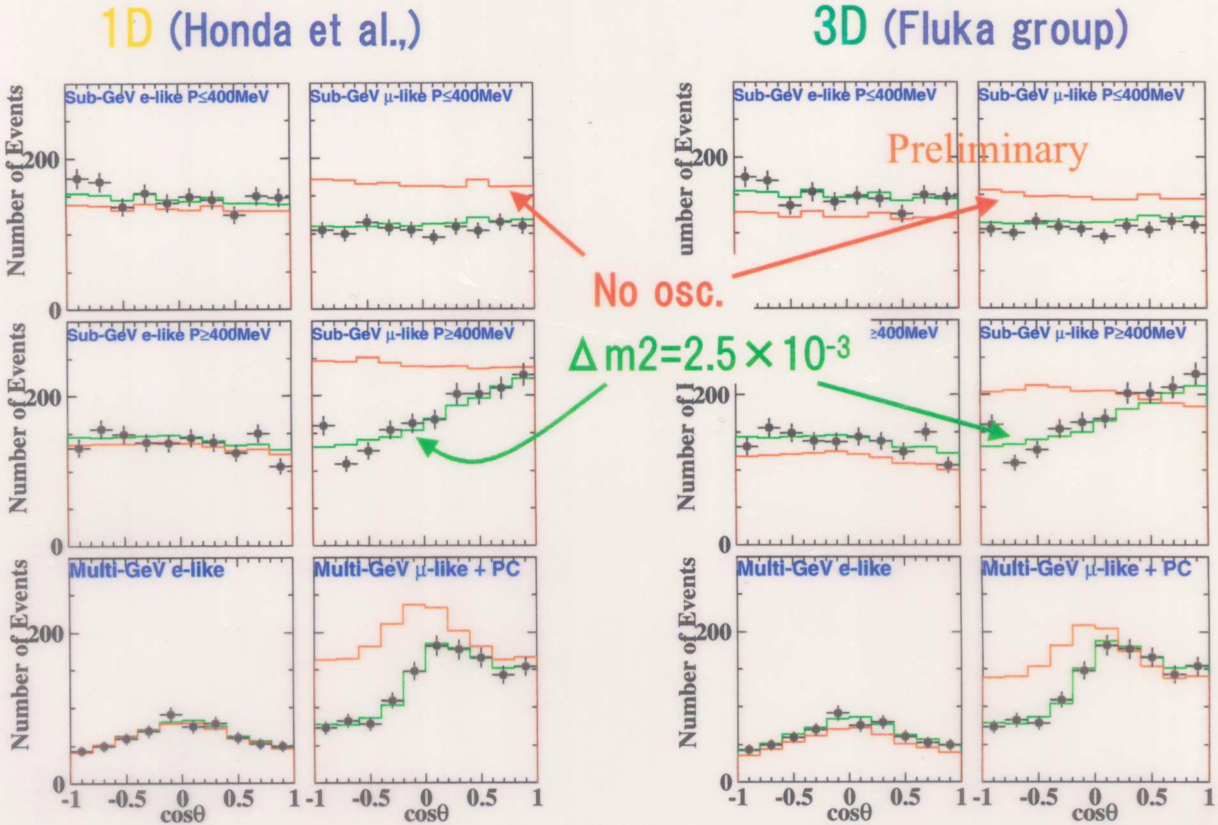
Sub-GeV flux at Kamioka

(Fluka group)



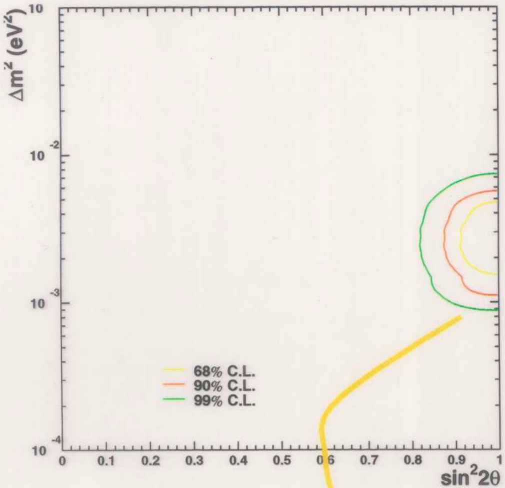
(No big difference for Multi-GeV flux)

Zenith angle distributions (1D vs. 3D)

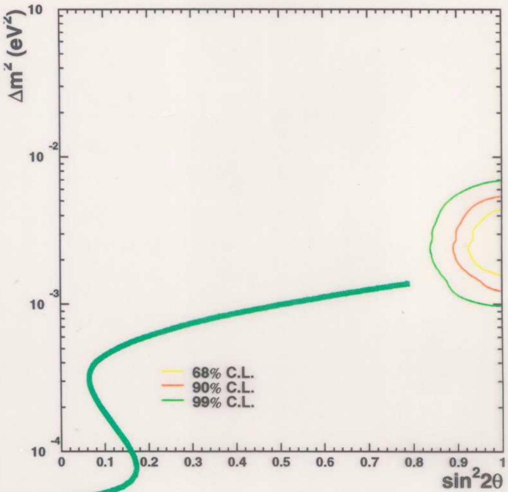


Allowed parameter region (1D vs. 3D) based on FC+PC events

1D (Honda et al.,)



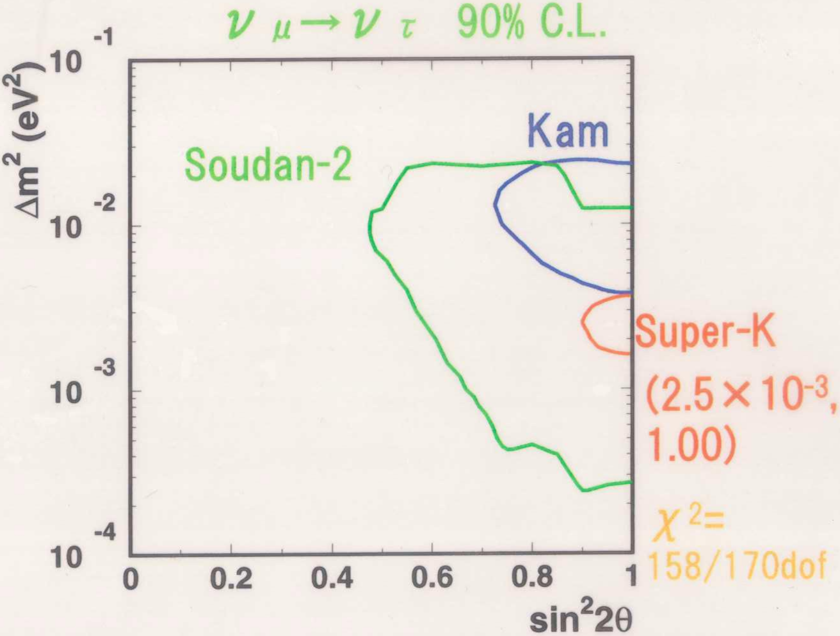
3D (Fluka group)



No big difference! (1D flux in this talk)

(Future: 3D flux will be used.)

Allowed parameter region
(contained events + up-going μ's)



$$\begin{cases} \Delta m^2 = (1.6 \sim 3.6) \times 10^{-3} eV^2 \\ \sin^2 2\theta > 0.90 \end{cases}$$ (90% C.L., Super-K)

3 flavor oscillations

★Approximation

$m_{\nu 3}$

$$\Delta m_{23}^2 = \Delta m_{13}^2 \equiv \Delta m^2$$

$m_{\nu 2}$

$m_{\nu 1}$

$$\Delta m_{12}^2 = 0$$

$$\boxed{\theta_{13},\ \theta_{23},\ \Delta m^2}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = 4|U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2(1.27 \Delta m^2 L/E)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4|U_{\alpha 3}|^2 (1 - |U_{\alpha 3}|^2) \sin^2(1.27 \Delta m^2 L/E)$$

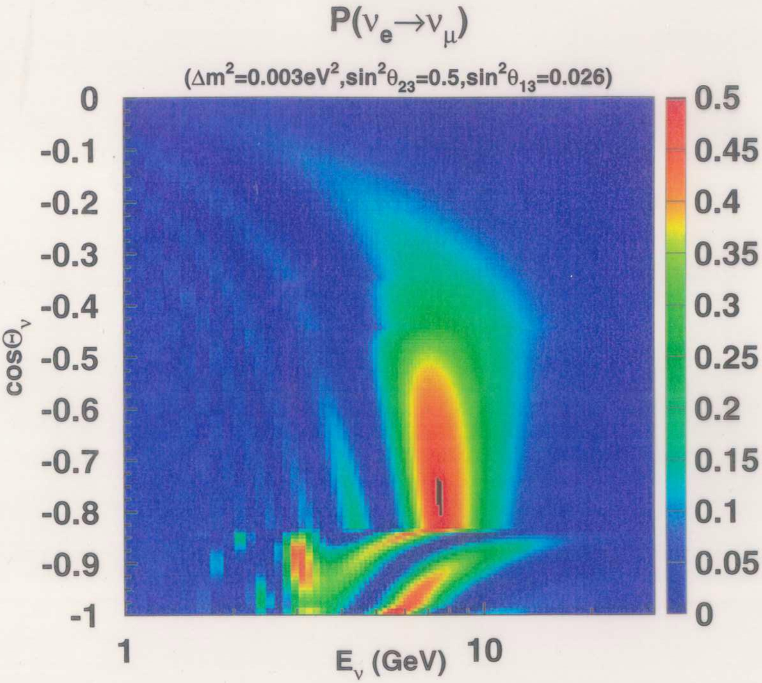
$$|U_{e3}|^2 = \sin^2\theta_{13}$$

$$|U_{\mu 3}|^2 = \cos^2\theta_{13} \sin^2\theta_{23}$$

$$|U_{\tau 3}|^2 = \cos^2\theta_{13} \cos^2\theta_{23}$$

3 flavor analysis

➡ Matter effect

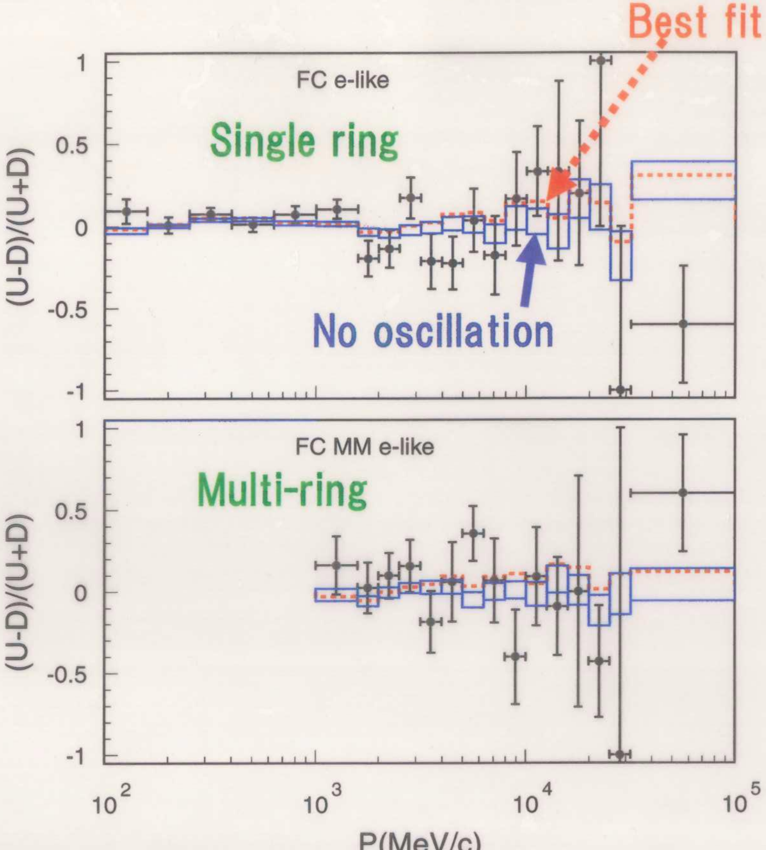


For $\theta_{23} = 45^\circ$;

$P(\nu_\mu \rightarrow \nu_e) = 1/2 \times P(\nu_e \rightarrow \nu_x)$

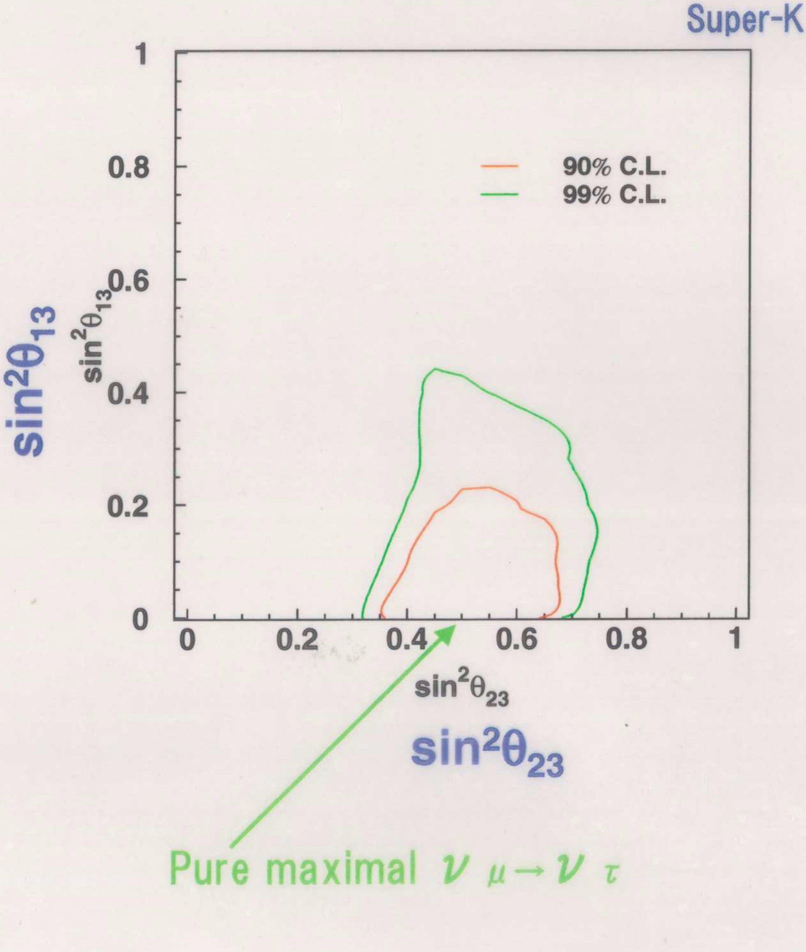
➡ No visible oscillation effect for

e-like data (up-down asymmetry)



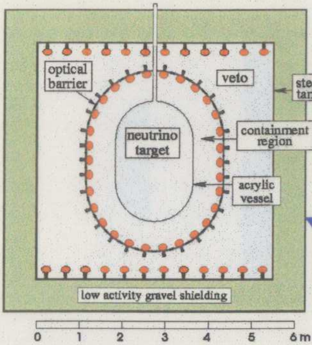
→ No evidence for excess of upward-going e-like events in the 10GeV energy region.

Allowed region for $\sin^2\theta_{13}$ & $\sin^2\theta_{23}$

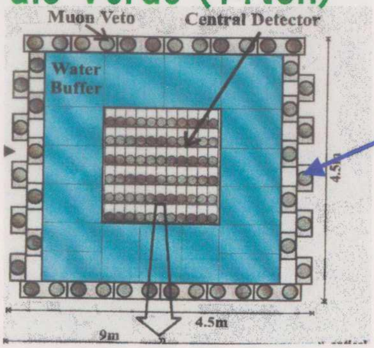


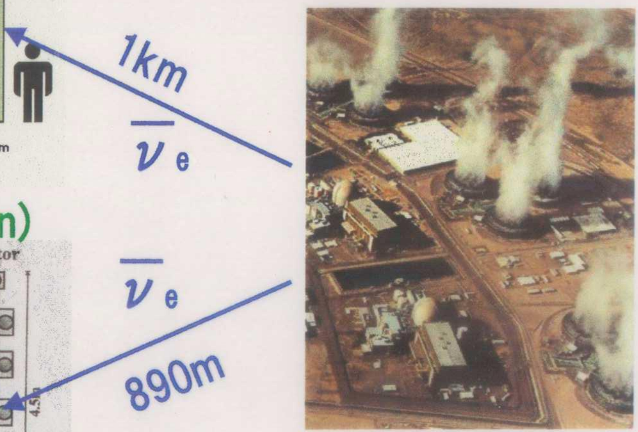
Reactor experiments

CHOOZ (5ton)



Palo Verde (11ton)

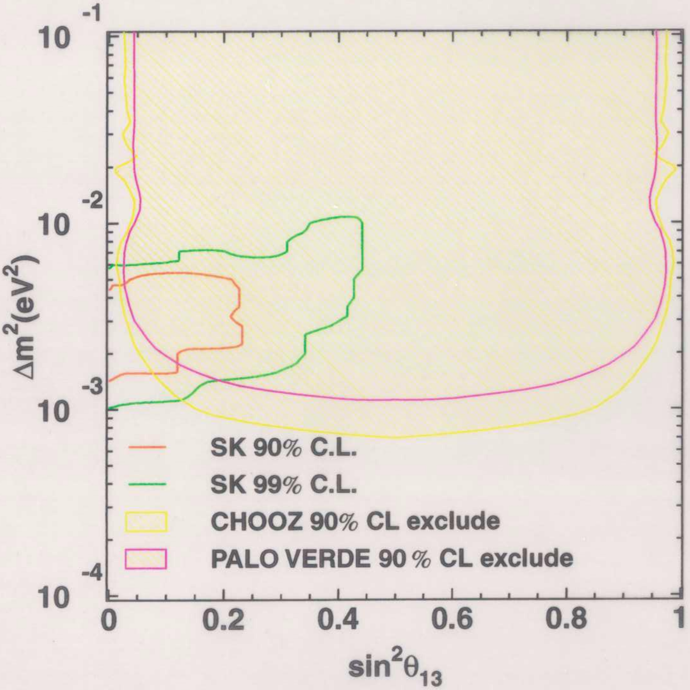




L/E ~ 300 → sensitivity: $\Delta m^2 \gtrsim 10^{-3}$

Information on θ_{13}

3 flavor analysis and reactor experiments



Other proposed scenarios

- Oscillations to sterile neutrinos
- Oscillations generated by new physics such as violation of Lorentz invariance
- Flavor Changing Neutral Current
- Neutrino decay

↓

Disfavored at > 99% C.L.

↓

Only $\nu_\mu \rightarrow \nu_\tau$ oscillations remain

If so, ...

Neutrino decay ?

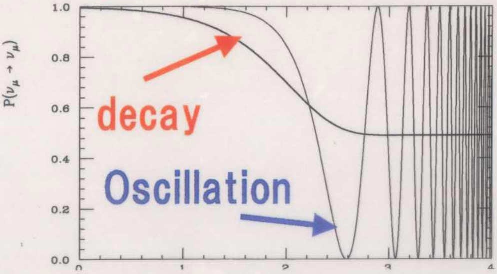
★**Scenario** (V.Barger et al., PLB 462 (1999) 109):

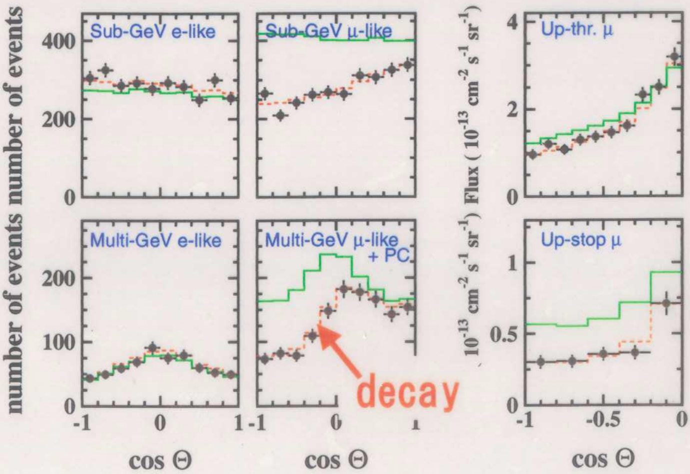
$\nu_\mu = \cos\theta\, \nu_2 + \sin\theta\, \nu_3$ $(\nu_\tau = -\sin\theta\, \nu_2 + \cos\theta\, \nu_3)$

decay: $\nu_2 \rightarrow X$

For $\Delta m^2 \rightarrow 0$; $P(\nu_\mu \rightarrow \nu_\mu) = (\sin^2\theta + \cos^2\theta\, e^{-\alpha L/2E})^2$

$\alpha = m/\tau$





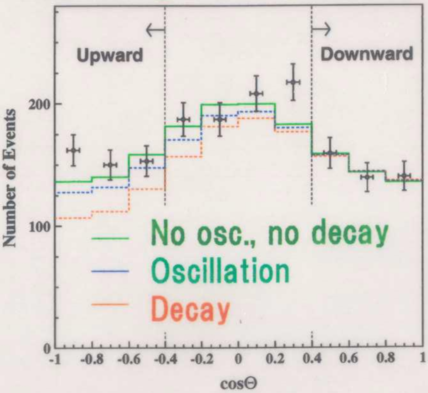
Decay scenario explains the CC data well.

Neutrino decay ?

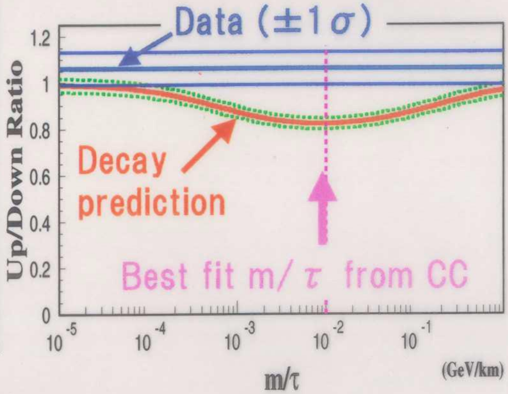
However, NC events should also decrease due to decay.

New!

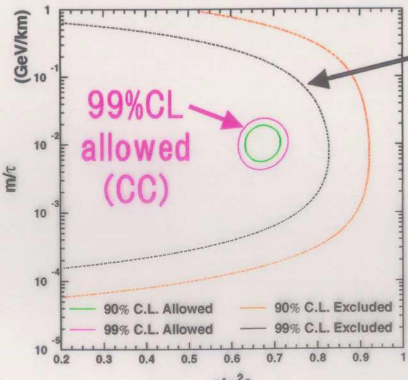
Multi-ring e-like (29% NC)



Up/down ratio vs. m/ τ



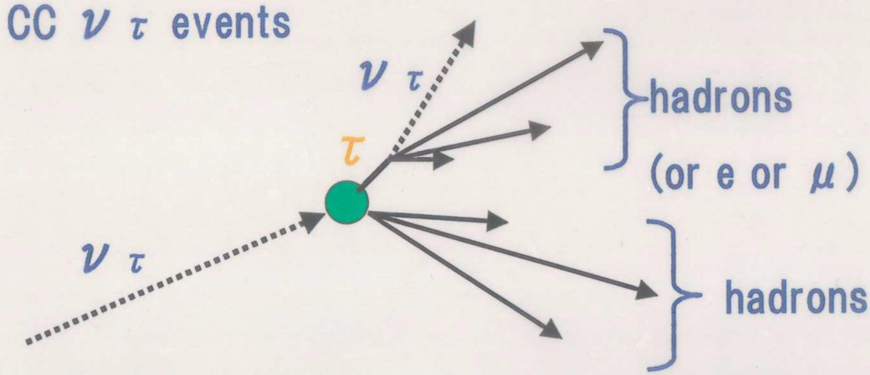
Excluded & allowed regions



99%CL excluded (NC)

Neutrino decay cannot explain CC and NC events simultaneously.

Search for CC ν_τ



- Many hadrons . . . .
(But no big difference with other events .)
↳ BAD ⟹ τ - likelihood analysis

- Upward going only
↳ GOOD ⟹ Zenith angle

Only ~ 1.0 CC ν_τ FC events/kton・yr

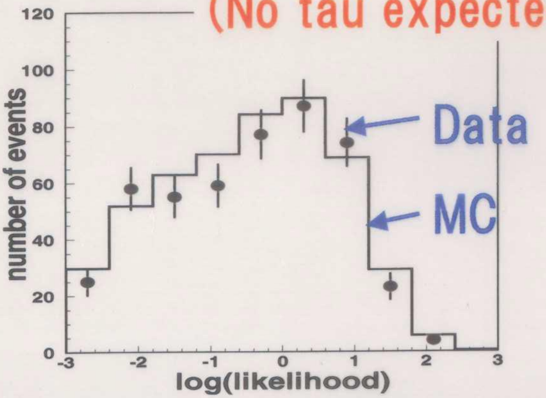
(BG (other ν events) ~ 130 ev./kton・yr)

Tau likelihood distribution

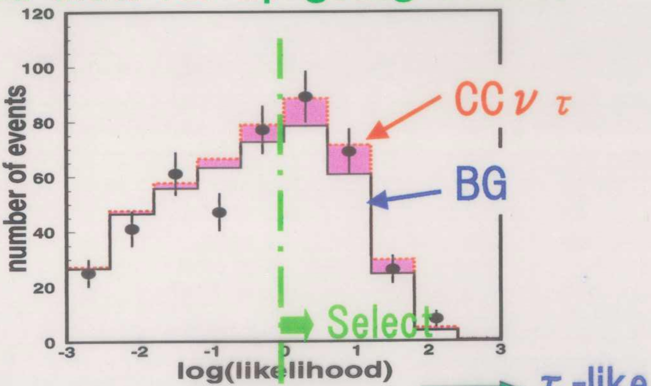
Likelihood dist. for down going events

(No tau expected)

OK!

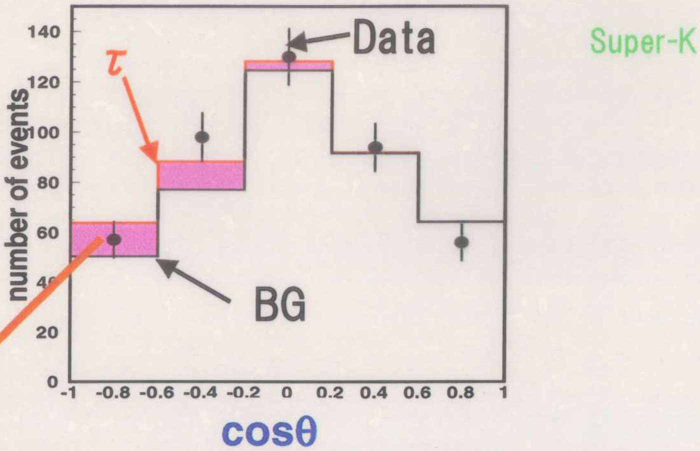


Likelihood dist. for up going events



Zenith angle distribution

Zenith angle for τ enriched sample



ε =44%

τ production: 66 ±41 $^{+25}_{-18}$ **Likelihood method (1)**

Other analyses

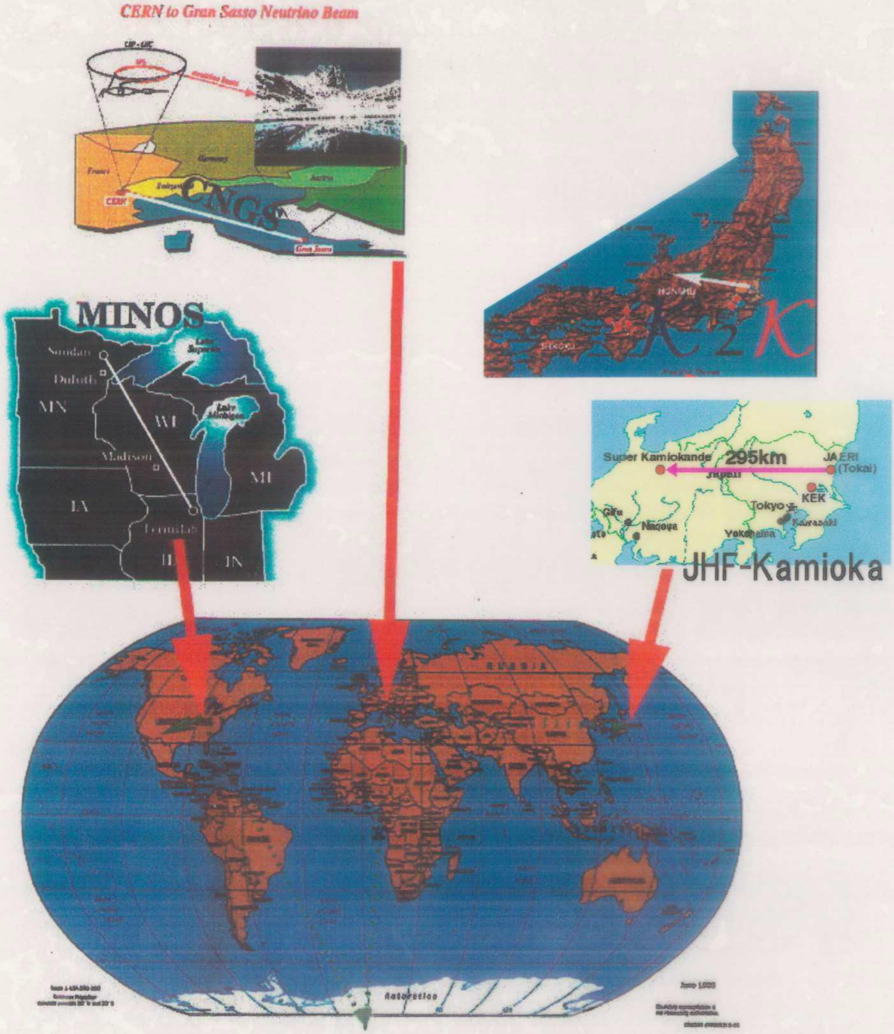
79 $^{+44}_{-40}$ **Likelihood method(2) (Energy flow etc)**

92±35 $^{+17}_{-23}$ **Neural network method**

(Expected tau ev. = 74)

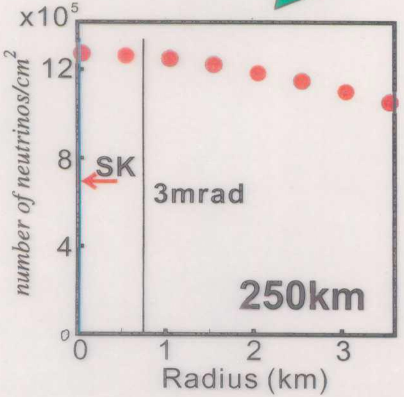
➡ Consistent with τ production at the 1.5～2σ level (VERY preliminary).

Long baseline experiments

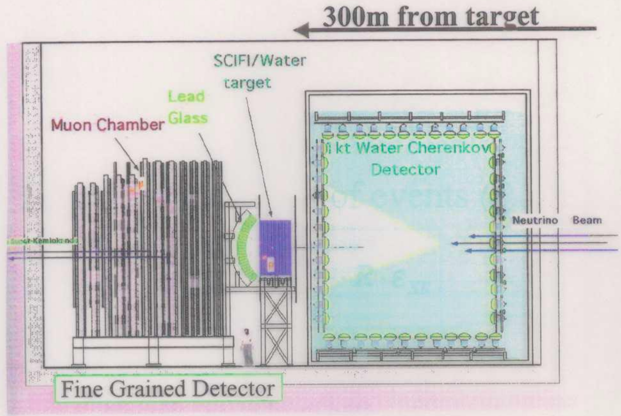


K2K long baseline experiment

L=250km, $\langle E_\nu \rangle$=1.5GeV



Front NeutrinoDetector(FD)



Status of the K2K long baseline experiment

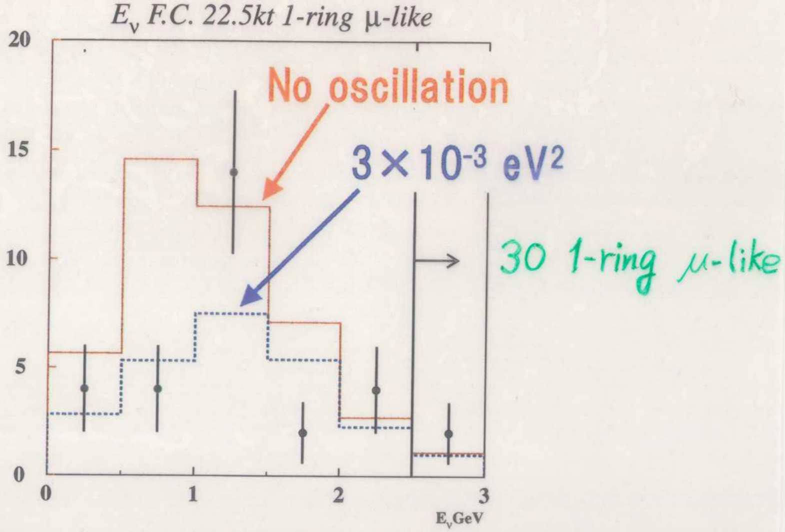
New

4.8×10^{19} p.o.t. (50% of design, 1999 – Jul. 2001)

	Obs.	No Ocsi.	$\Delta m^2 (\times 10^{-3} eV^2)$ 3	5	7
FC 22.5kt	56	$80.6^{+7.3}_{-8.0}$	52.4	34.6	29.2
1-ring	32	48.4±6.7	28.1	17.8	16.6
μ-like	30	44.0±6.8	24.4	14.6	13.5
e-like	2	4.4±1.7	3.7	3.2	3.0
multi ring	24	32.2±5.3	24.3	16.8	12.6

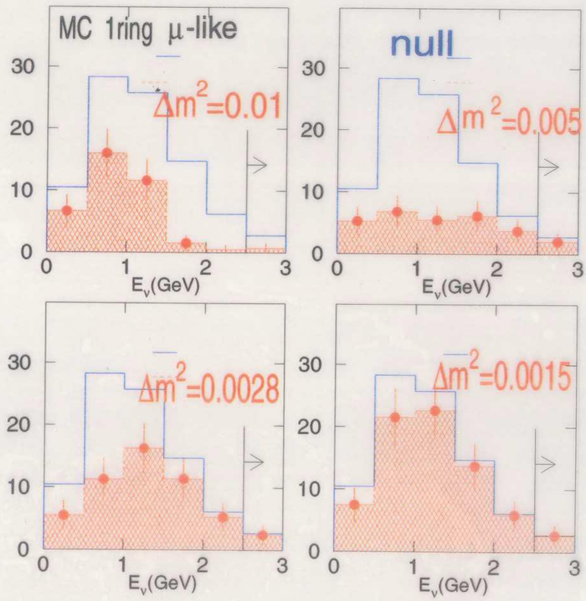
→ Consistent with $\Delta m^2 = 3 \times 10^{-3}$ eV^2

Reconstructed neutrino energy distribution

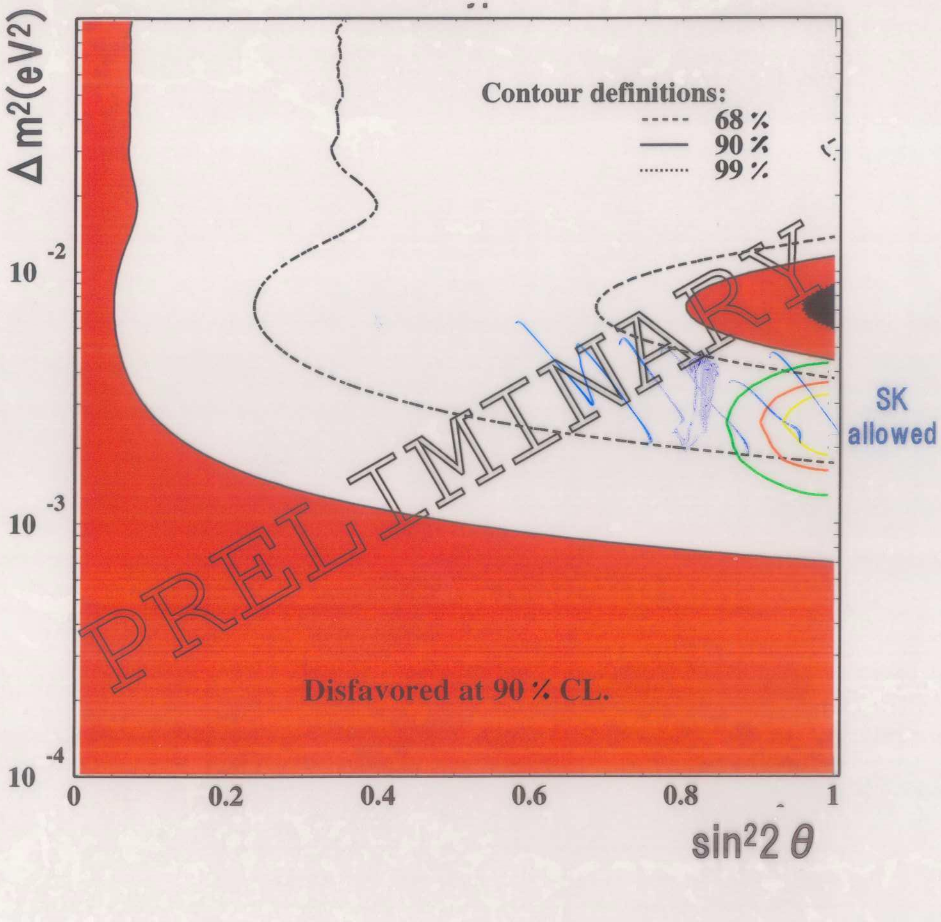


How about the expected distributions....

(1×10^{20} pot)

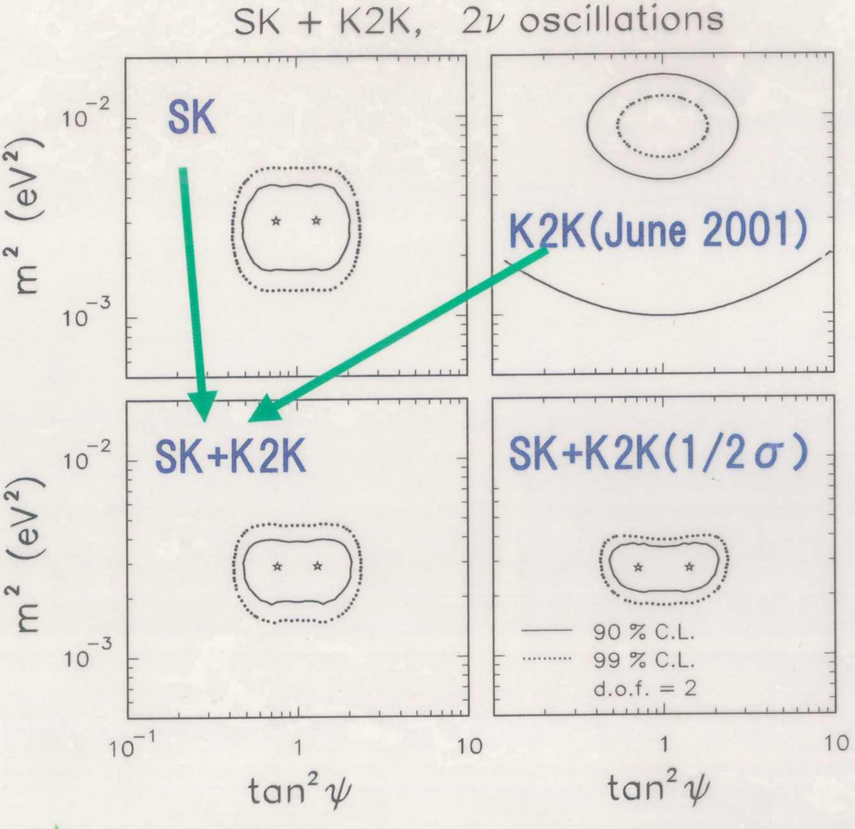


K2K allowed parameter region
(Based on the number of events)



SK + K2K combined analysis

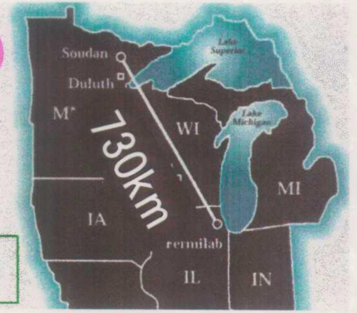
G.L.Fogli et al., hep-ph/0110089



SK+K2K reduces the Δm2 uncertainty by 20-30%.

Important to reduce the K2K total rate uncertainty.

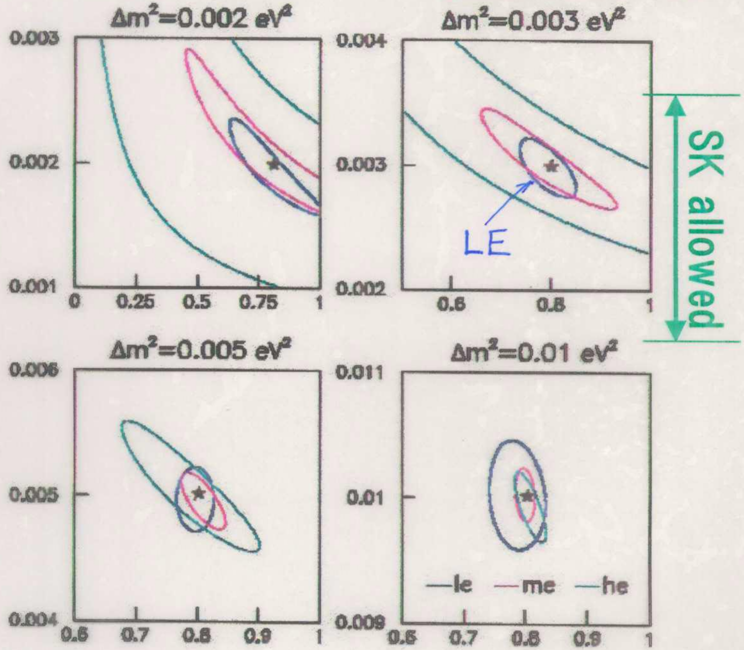
Status of future LBL ν osc. exp's (1)



MINOS Fermilab → Soudan (start: 2004 ?)

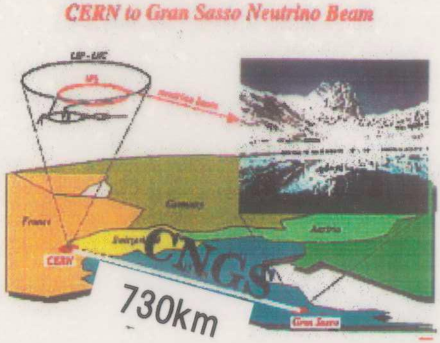
5.4 kton Fe/Plastic scinti. (w/ WLS) detector

Sensitivity (2yrs)

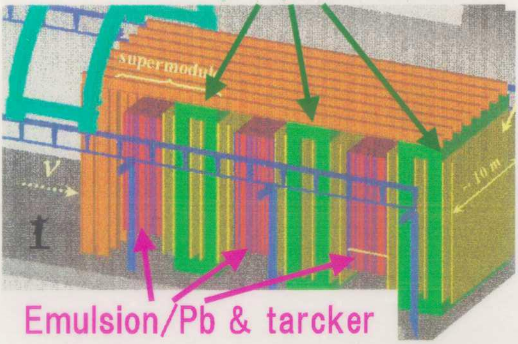


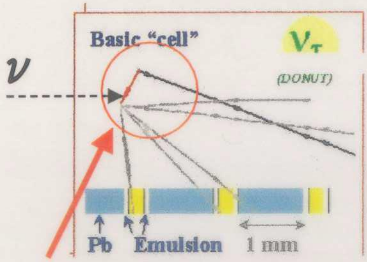
Status of future LBL ν osc. exp's (2)

CNGS main physics goal: Direct detection of CC ν_τ events



OPERA (Start: 2005)





5yr Sensitivity (target mass : 1.8kton)

$\Delta m2$ ($\times$10-3)	1.5	3.0	5.0	Background
Number of ev.	4.1	18.3	44.1	0.57

ICARUS

600ton detector was successfully tested on surface.

μ bundle by Icarus T600

Multi-kton detector was recently proposed. Waiting for approval...

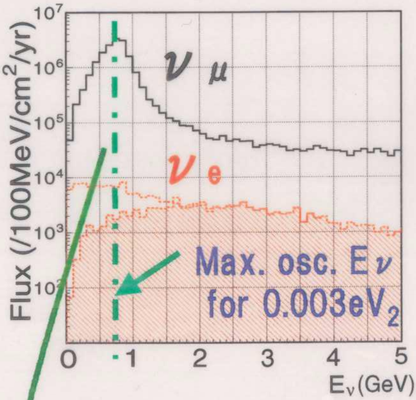
Status of future LBL ν osc. exp's (3)

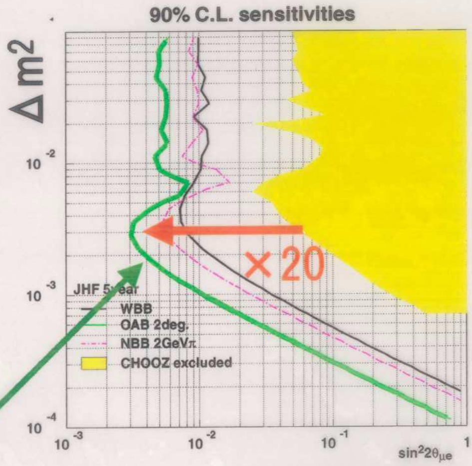
JHF - Kamioka

(start 2007 ?)

×100 more intensity than K2K,
$E\nu$ < 1GeV

Precise measurements of Δm^2, θ_{23}, θ_{13}





Sensitivity to θ_{13}

$0.5 \cdot \sin^2 2\theta_{13}$

(2^{nd} phase: CP violation (w/ Hyper-Kamiokande))

Summary

- Neutrino oscillation signal is consistent with pure $\nu_\mu \rightarrow \nu_\tau$. (atmospheric and reactor experiments)
- Allowed parameter region:

$$\begin{cases} \sin^2 2\theta_{23} > 0.90 \\ 1.6 < \Delta m^2_{23} < 3.6 \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

- Many other possibilities are disfavored.
- Search for CC ν_τ events: in progress.
- K2K data are consistent with SK atmospheric neutrino data.
- In the near future, long baseline experiments will give us much more precise information on neutrino mass and mixing.