Neutrino Physics
Accelrator and Reactor Experiments

ICHEP 2000, Osaka

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Kyoto University

- Introduction
- Present situation
- Near Future
- Future

Neutrino Mass & Oscillation

- $m_\nu \neq 0$? Establish ν osci
- Why $m_\nu \ll m_e, m_q$

  see-saw mechanism

  $m_\nu \sim \frac{m_{l,q}^2, \langle\phi_0\rangle}{M}$ $M \sim M_{GUT}$

- why mixing in lepton >> quark

  } Precision meas.

  generations

  lepton-quark symmetry

- CP̸ in lepton $(\Delta L \rightarrow \Delta B)$
- Unexpected

Only neutrino Oscillation can probe $m_\nu \ll 1\,eV$

Flavor oscillation possibility
Maki-Nakagawa-Sakata 1961

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 3\times 3 \\ \text{MNS} \\ \text{Matrix} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

production

$$\Downarrow \; e^{-ipx} = e^{-i(Et - Ex - \frac{m_i^2}{2E} x)} \quad i = 1, 2, 3$$

$$\Downarrow$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

detection

$i, j = 1, 2, 3$
$\alpha, \beta = e, \mu, \tau$

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \cdot \sin^2 \frac{\Delta m^2_{ij}}{4E} \cdot L \overset{+}{\underset{(-)}{}} 2\sum_{i>j} Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\alpha\beta}) \sin \frac{\Delta m^2_{ij}}{2E} \cdot L$$

- Common Δm^2_{ij} for $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$ etc.
- 2 independent Δm^2

Atmospheric ν

$\nu_\mu \to \nu_x \quad (x \neq e)$

$\Delta m^2 \sim (1 \sim 6) \times 10^{-3} eV^2$

Solar ν

$\nu_e \to \nu_x$

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

$\nu_\mu \to \nu_\tau \quad \Delta m^2 \sim 100 eV^2$ CHORUS NOMAD

$\bar{\nu}_\mu \to \bar{\nu}_e \quad \Delta m^2 \sim eV^2$ LSND KARMEN

$\bar{\nu}_e \to \bar{\nu}_x \quad \Delta m^2 > 10^{-3} eV^2$ Chooz Palo Verde

[$\Delta m^2_{\nu atm} \neq \Delta m^2_{\nu sol}$

@ Low energy accelerators

Main source : Decay at Rest

$$p + N \to \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\to \pi^- \to \text{absorbed}$$

Look for

$$\bar{\nu}_\mu \to \bar{\nu}_e + A \to e^+ + n$$
$$\downarrow$$
Nuclear Capture γ

LSND full data set reanalysis

decay at rest ⊕ decay in flight

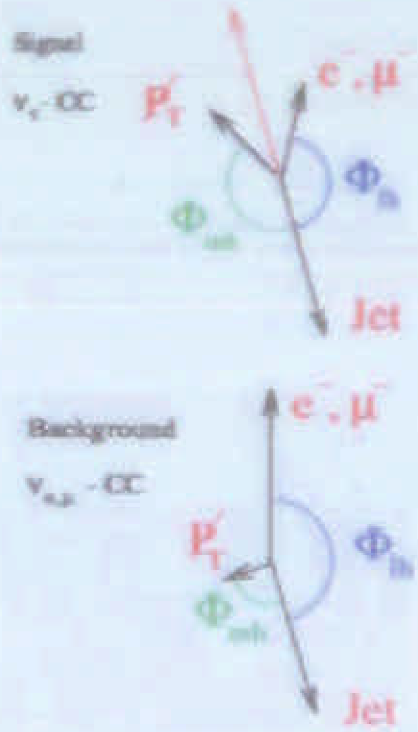
↳ 32.7 ± 9.2 events Excess

KARMEN increased Stat.

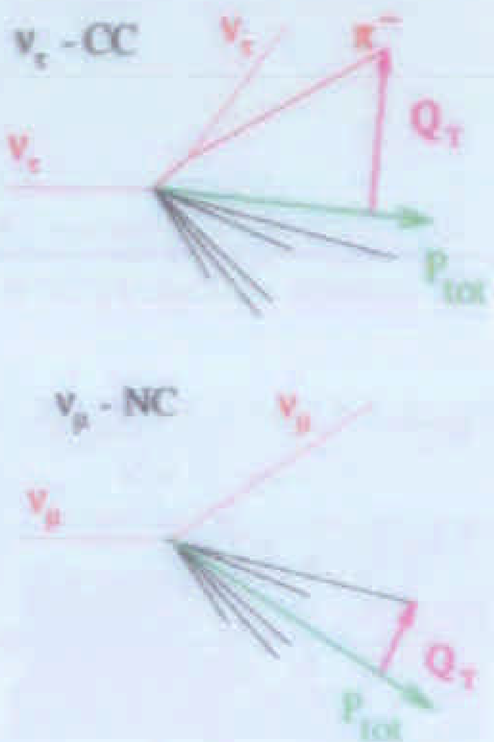
NOMAD 2.7ton, 1.35 M ν_μ CC int.
TRD, Ecal $3.2\%/\sqrt{E} \oplus 1\%$ e
μ

The Basics of Kinematical Criteria

To kill CC use imbalance



To kill NC use isolation



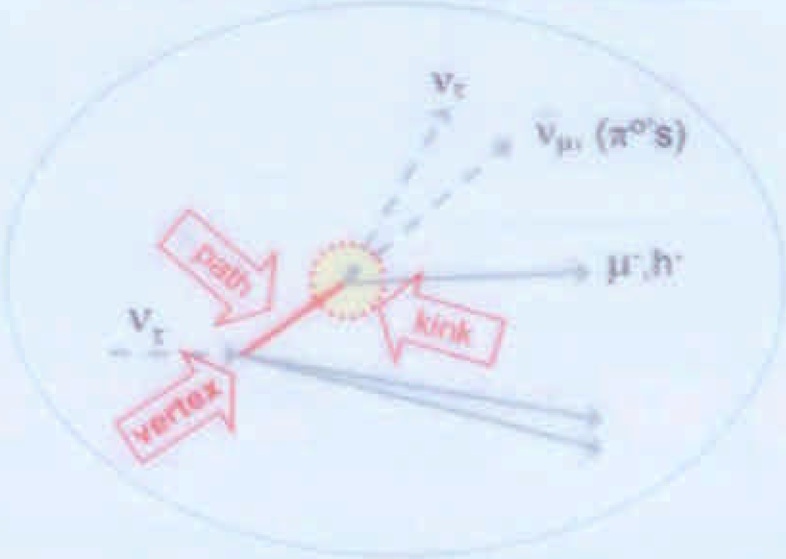
Signal

Background

The Chorus τ "signature"

- The τ lepton is identified by the three-fold simultaneous observation of:

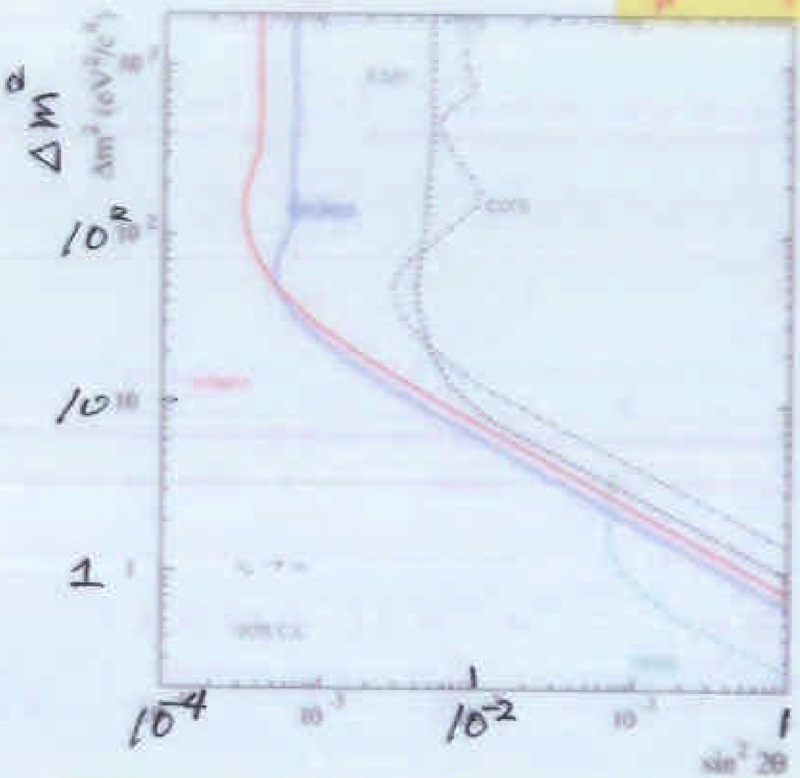
1. the neutrino CC interaction vertex
2. the short τ^- path, $c\tau$=87μm, γ~O(10)
3. the τ^- decay topology: kink



BKG	
1μ	0μ
(c BKG)	(hadronic) int.
0.11	1.1
144k	20k

NOMAD Exclusion Plots

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

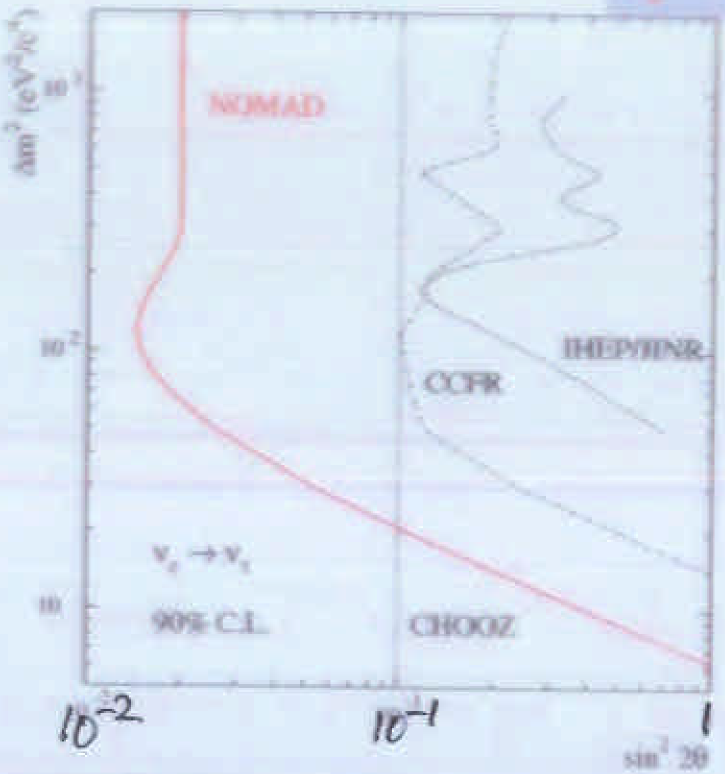


Limit on $P(\nu_\mu \to \nu_\tau) = 2.03 \times 10^{-4}$

Sensitivity on $P(\nu_\mu \to \nu_\tau) = 2.6 \times 10^{-4}$

P(to have this limit or smaller) = 46%

$\nu_e \to \nu_\tau$

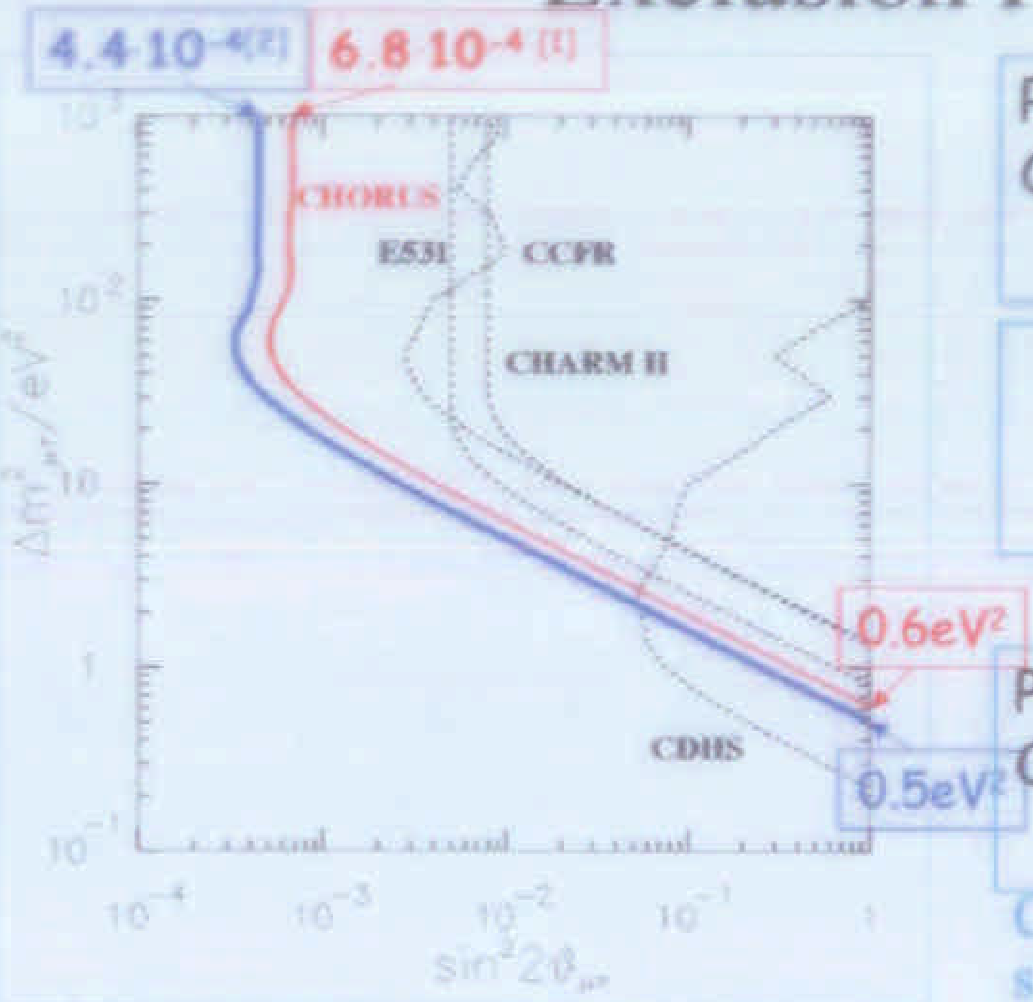


Limit on $P(\nu_e \to \nu_\tau) = 1.0 \times 10^{-2}$

Sensitivity on $P(\nu_e \to \nu_\tau) = 1.3 \times 10^{-2}$

P(to have this limit or smaller) = 48%

CHORUS Exclusion Plot



$P_{\mu\tau} < 3.4 \cdot 10^{-4}$
Or, for large Δm^2
$\sin^2 2\theta_{\mu\tau} < 6.8 \cdot 10^{-4}$

at 90% CL [1]

Our exclusion power (sensitivity) is:
$P_{\mu\tau} = 3.7 \cdot 10^{-4}$

$P_{\mu\tau} = 2.2 \cdot 10^{-4}$
Or, for large Δm^2
$\sin^2 2\theta_{\mu\tau} < 4.4 \cdot 10^{-4}$

at 90% CL [2]

Comparable with NOMAD
$\sin^2 2\theta_{\mu\tau} < 4.1 \cdot 10^{-4}$ @ν2000

[1] T.Junk, NIM A434 (1999) 435
[2] G.J.Feldman and R.D. Cousins, Phys.Rev. D57 (1998) 3873

25

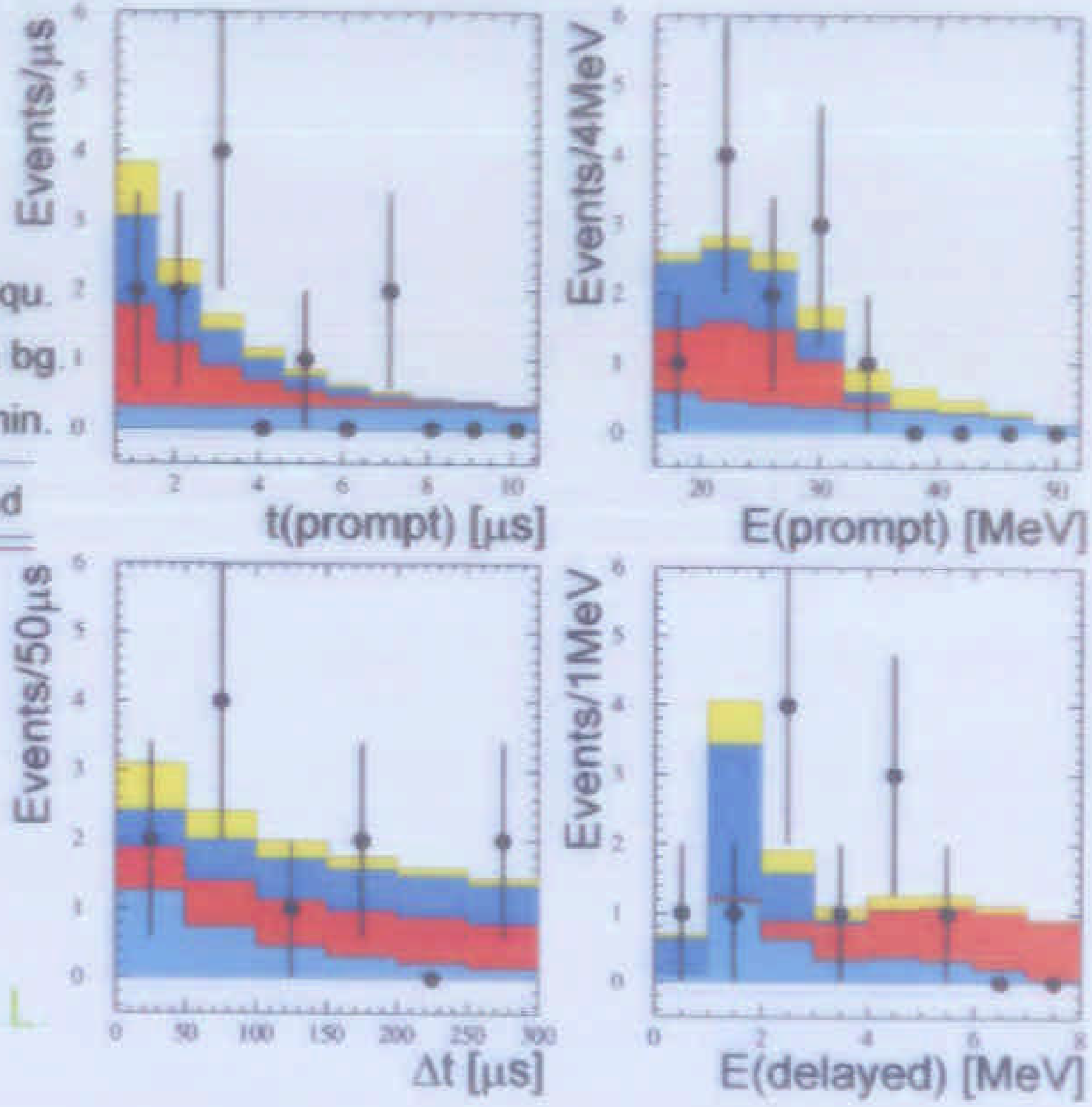
data set after final cuts

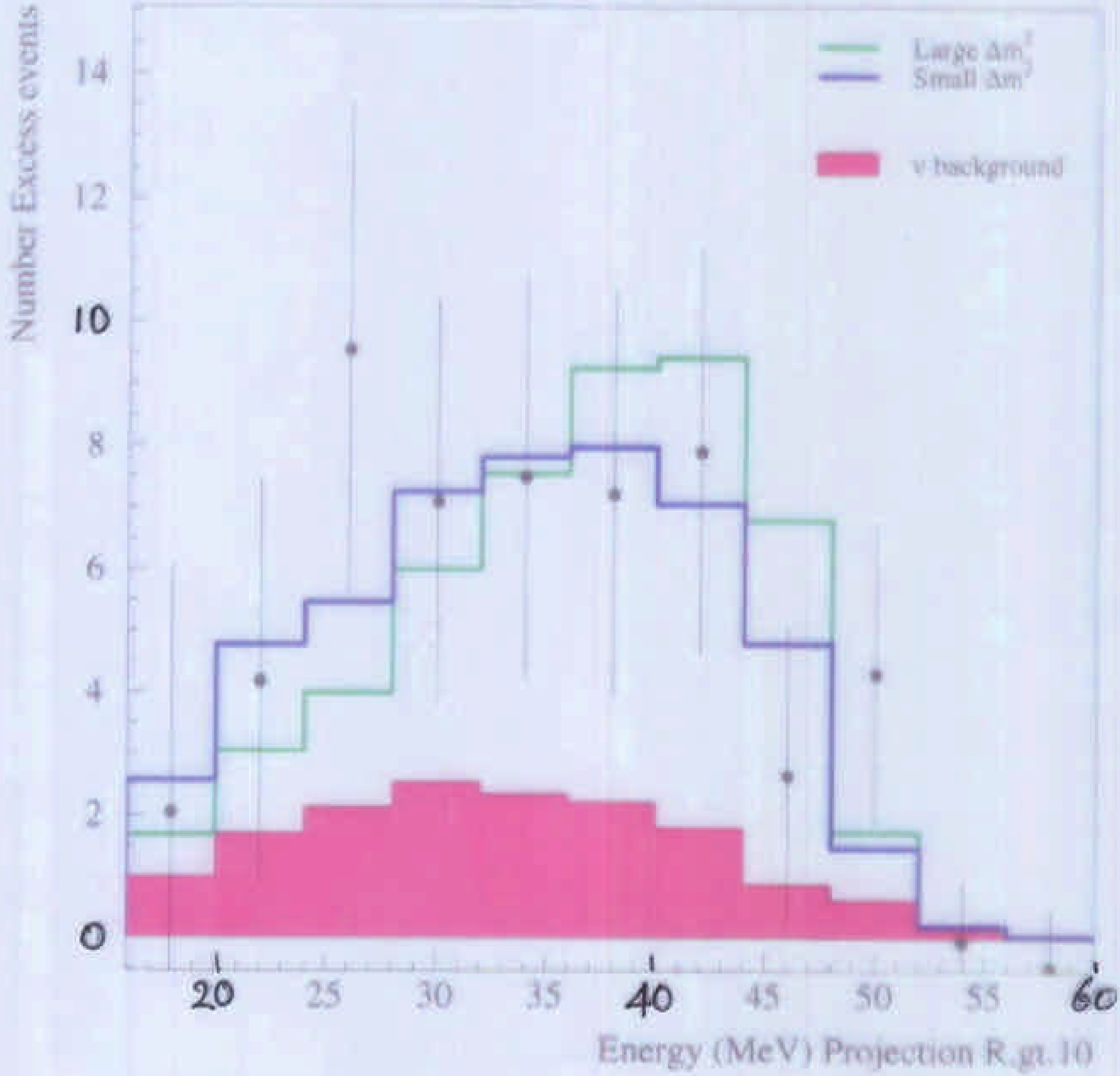
11 candidates

3.94 +- 0.51	red	ν_e-induced CC sequ.
3.52 +- 0.30	blue	ν-induced random bg.
1.67 +- 0.17	yellow	$\bar{\nu}_e$ intrinsic contamin.
3.17 +- 0.17	light blue	cosmic background
12.29 +- 0.63		total background

→ **no osci signal**

Bayes:
signal > 6.3 evts
excluded @ 90% C.L.

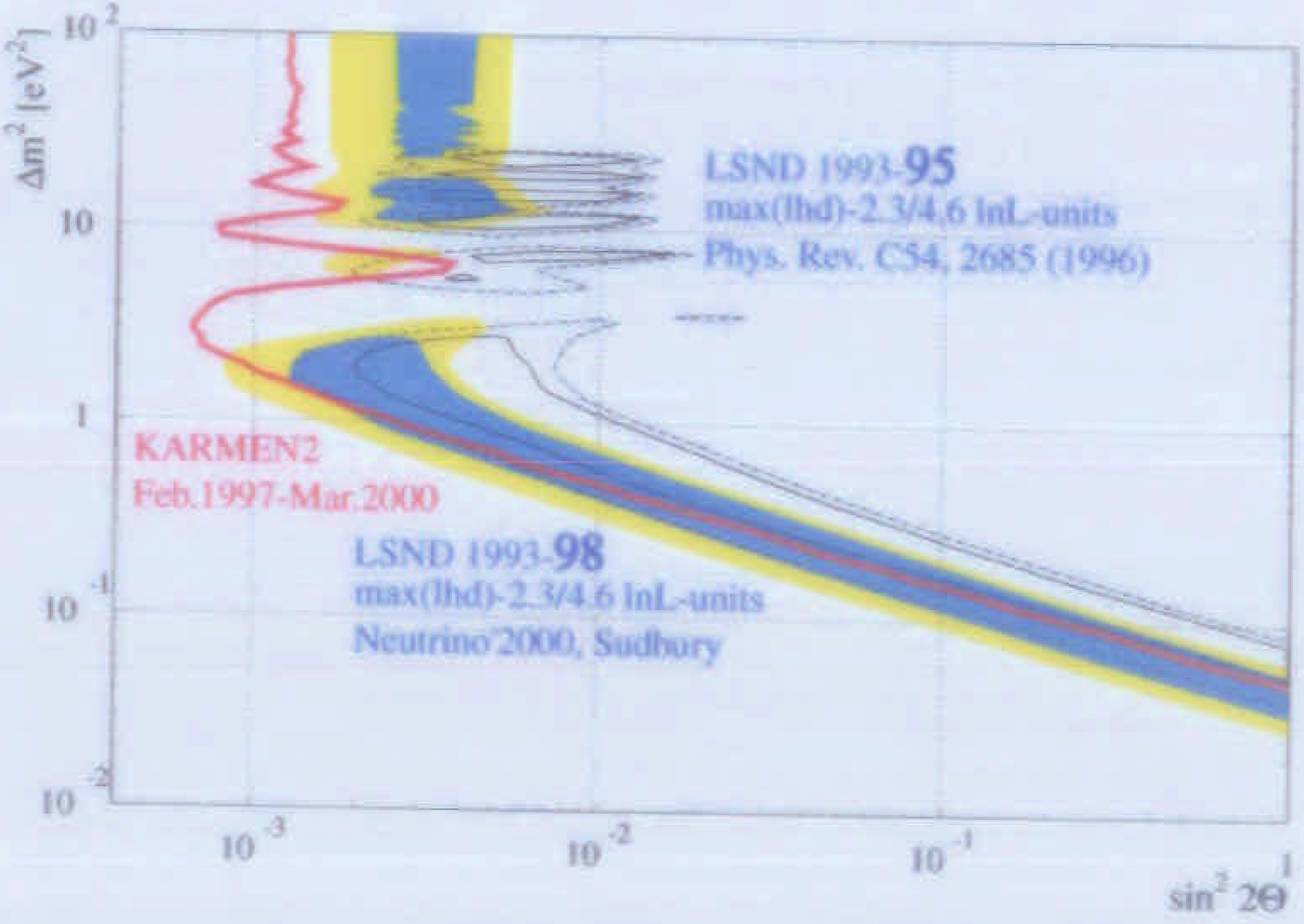




on	off	ν bkgd	Excess
83	33.7	16.6	32.7 ± 9.2

$P_{osci} = (0.25 \pm 0.06 \pm 0.04)\%$

LSND favored regions



Chooz hep-ex/9907037

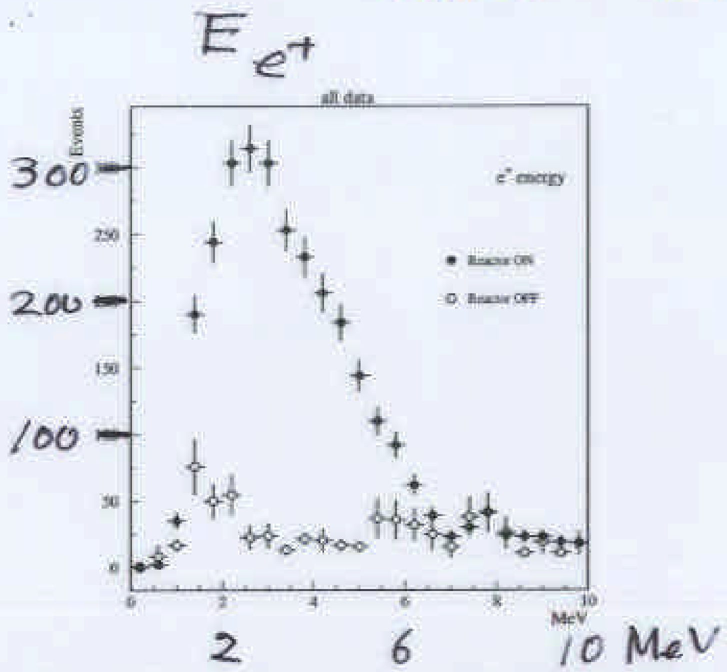


Figure 6: Positron energy spectra in reactor-ON and OFF periods.

L_k, this is given by:

$$S_k(E, L_k, \theta, \delta m^2) = \frac{1}{4\pi L_k^2} n_p \int h(L, L_k) \int \sigma(E_\nu) S(E_\nu) \times P(E_\nu, L, \theta, \delta m^2) r(E_{e^+}, E) \varepsilon(E_{e^+}) \, dE_{e^+} \, dL, \qquad (1)$$

where

E_ν, E_{e^+}	are related by $E_\nu = E_{e^+} + (M_n - M_p) + O(E_\nu/M_n)$,
n_p	is the total number of target protons,
$\sigma(E_\nu)$	is the neutrino cross section,
$S(E_\nu)$	is the antineutrino spectrum,
$h(L, L_k)$	is the spatial distribution function for the finite core and detector sizes,
$r(E_{e^+}, E)$	is the detector response function linking the visible energy E and the real positron energy E_{e^+},
$\varepsilon(E_{e^+})$	is the neutrino detection efficiency,
$P(E_\nu, L, \theta, \delta m^2)$	is the two-flavour survival probability.

The $\bar{\nu}_e$ spectrum was determined, for each fissile isotope, by using the $\bar{\nu}_e$ yields obtained by conversion of the β^--spectra measured at ILL [2]; these spectra were

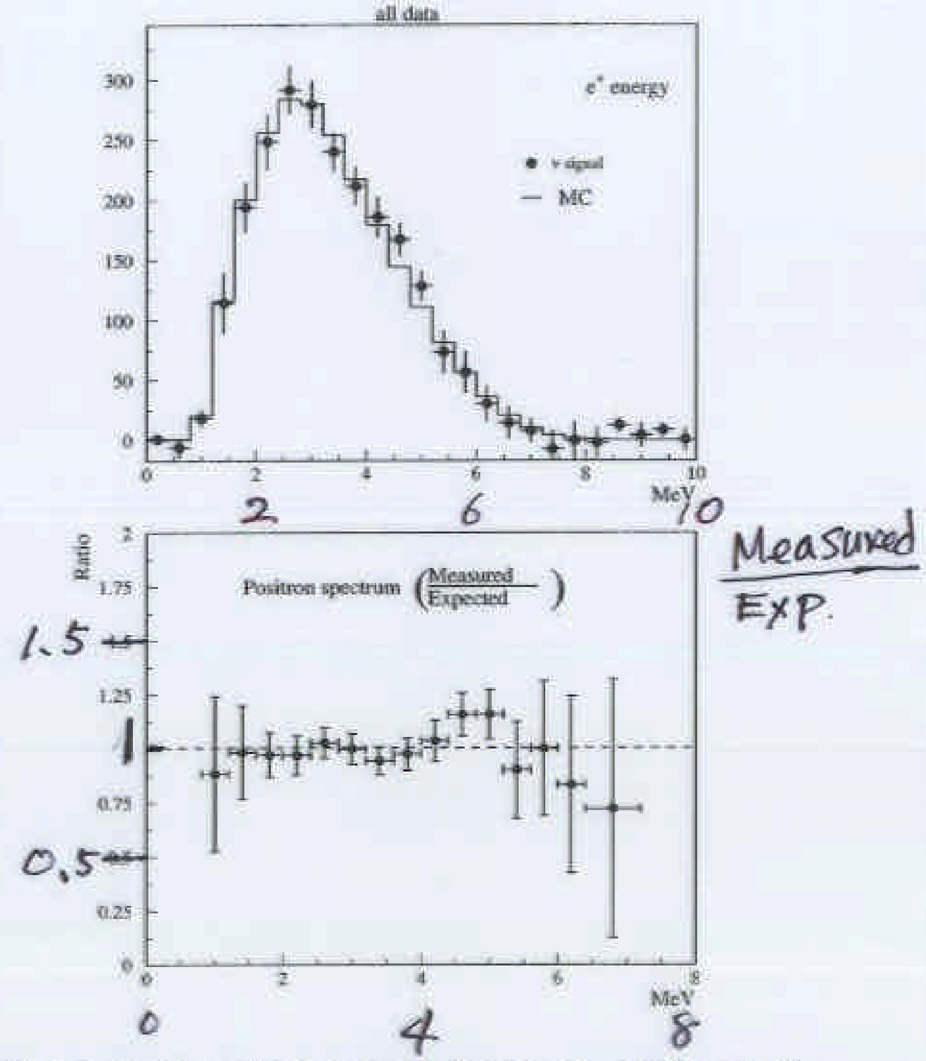


Figure 7: (above) Expected positron spectrum for the case of no oscillations, superimposed on the measured positron spectrum obtained from the subtraction of reactor-ON and reactor-OFF spectra; (below) measured vs. expected ratio. The errors shown are statistical.

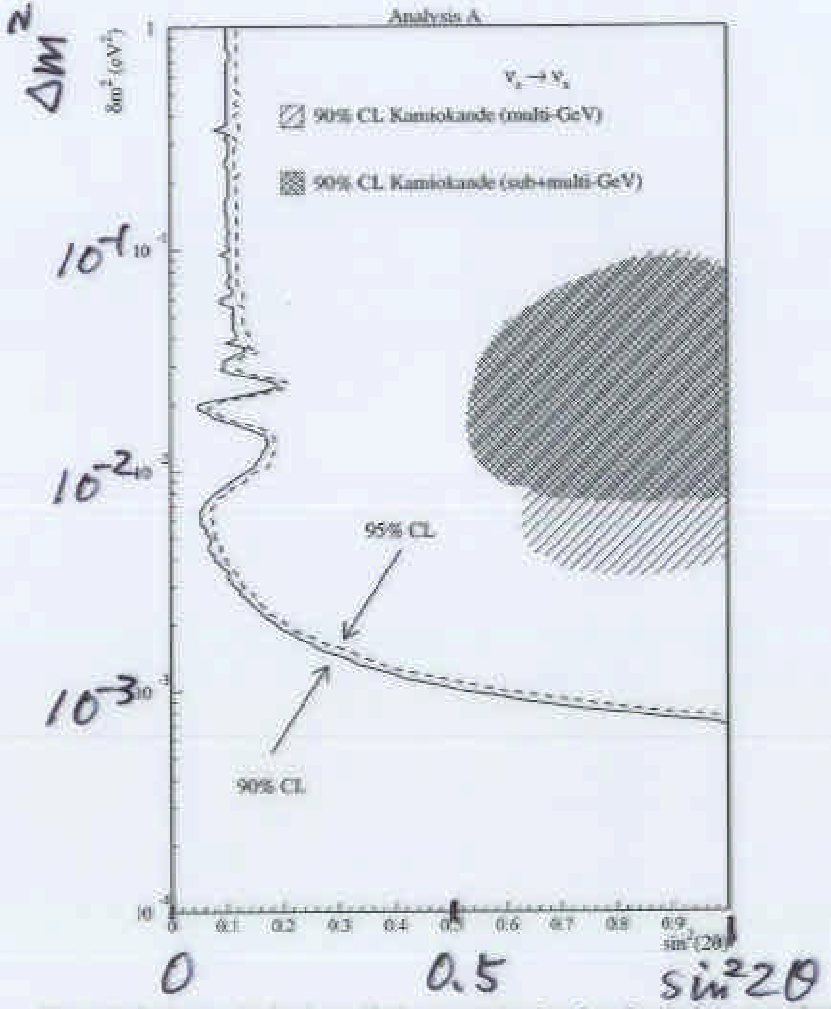


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

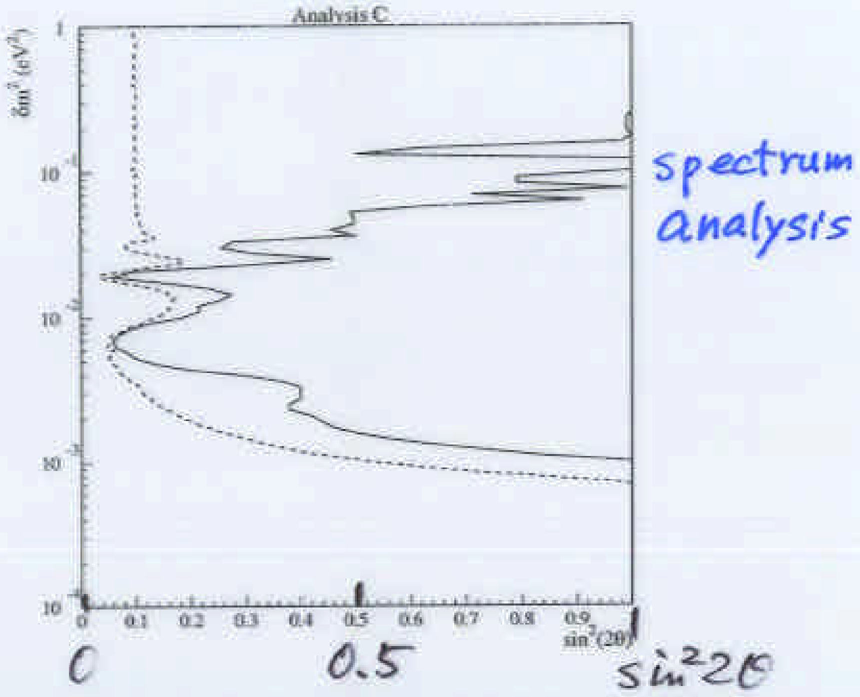


Figure 11: Exclusion plot at 90% C.L. obtained by the shape test (analysis C, solid line) compared to the integral test (analysis A, dashed line).

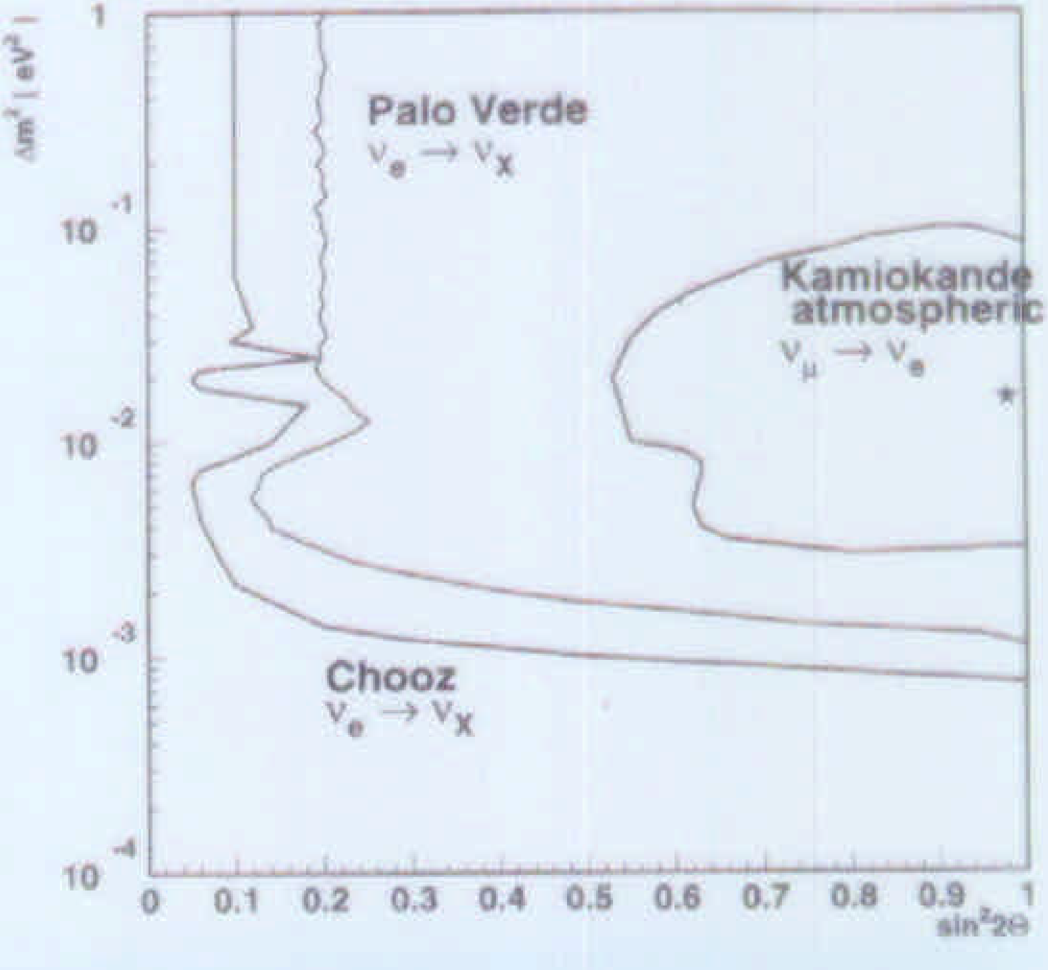
[1] M. Apollonio *et al.*, Phys. Lett. **B338** (1998) 383.

[2] K. Schreckenbach *et al.*, Phys. Lett. **B160** (1985) 325.

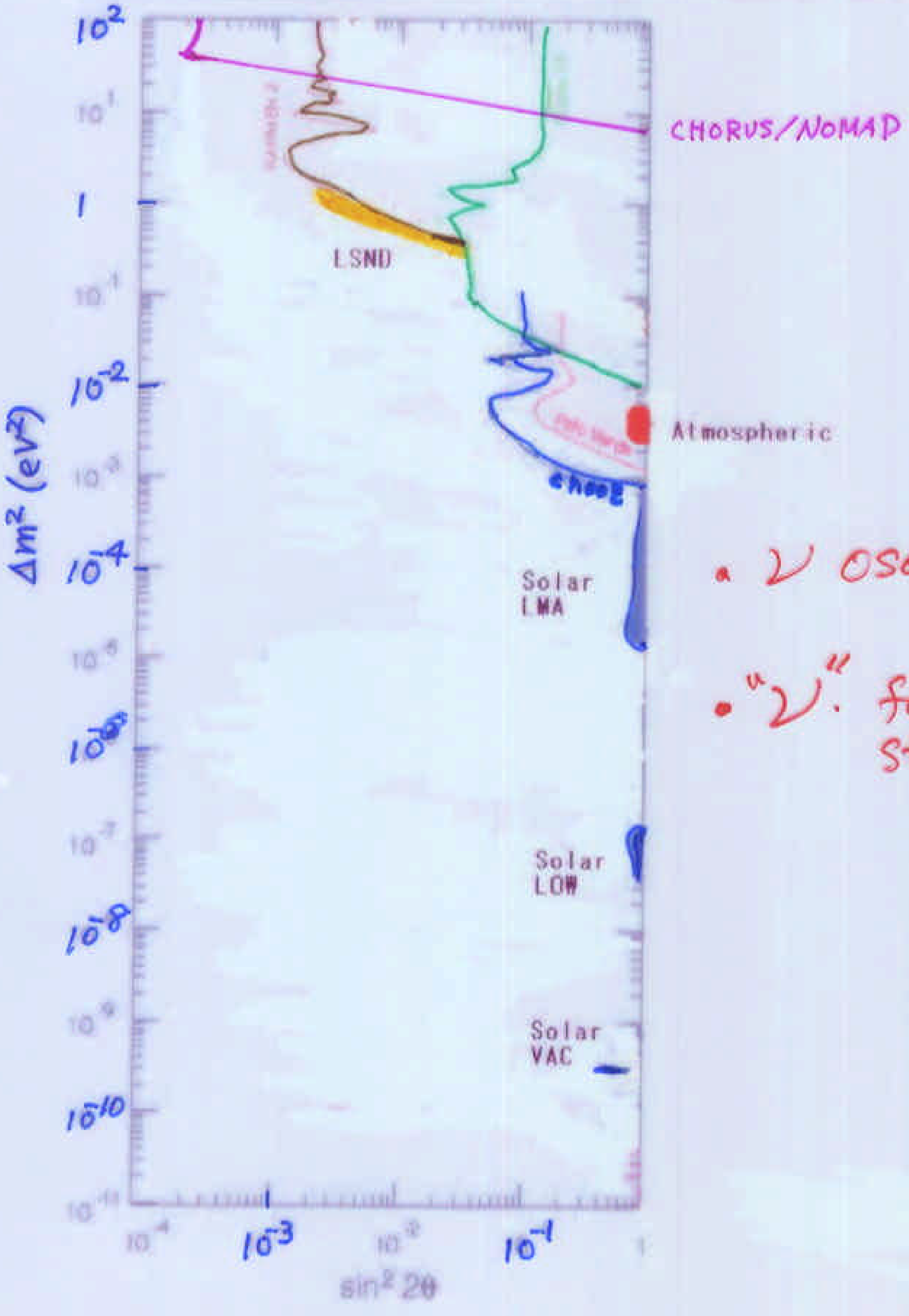
[3] Y. Declais *et al.*, Phys. Lett. **B338** (1994) 383.

[4] G. J. Feldman & R. D. Cousins, Phys. Rev. **D57** (1998) 3873.

[5] Y. Fukuda *et al.*, Phys. Lett. **B335** (1994) 237.


Palo Verde
$\nu_e \rightarrow \nu_X$
Kamiokande
atmospheric
$\nu_\mu \rightarrow \nu_e$
Chooz
$\nu_e \rightarrow \nu_X$
Δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\sin^2 2\Theta$

Oscillation Physics



- ν oscillation?
- "ν": forth? sterile?

3 generations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}\\ 0 & 1 & 0\\ -s_{13} & 0 & c_{13}\end{pmatrix}$$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{i\delta}\end{pmatrix}$$

$\Delta m^2_{solar} \ll \Delta m^2_{atm}$

$= m_2^2 - m_1^2 \qquad m_3^2 - m_1^2 \approx m_3^2 - m_2^2$

$$P(\nu_\mu \to \nu_\tau) = \cos^2\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2\left[\frac{\Delta m_{32}^2 L}{4E}\right]$$

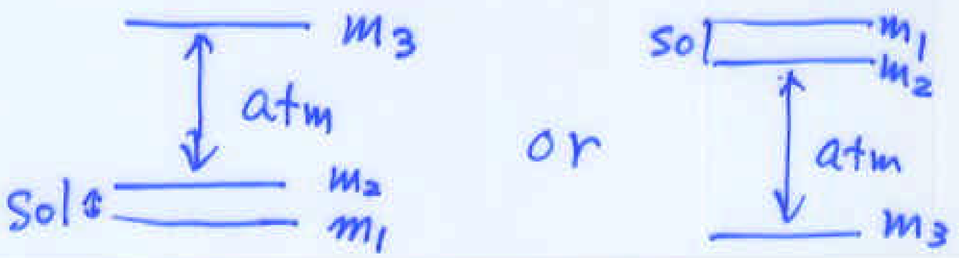
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left[\frac{\Delta m_{23}^2 L}{4E}\right]$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left[\frac{\Delta m_{23}^2 L}{4E}\right]$$

Appearance

Disappearance with $\quad P \propto \sin^2 \dfrac{1.27\cdot\Delta m^2\cdot L}{E}$

At fixed L $\quad P \propto \sin^2 \dfrac{\text{const}}{E_\nu}$



K2K (KEK 12 GeV PS to Super-K)

Final Goal

① Disappearance of ν_μ

$$\propto \sin^2\left(\frac{1.27 \times \Delta m^2 \times L\,(250\,\mathrm{km})}{E}\right)$$

② Search for ν_e appearance

Data taking 99 June → 00 June (~100 days)

Requirements and Accomplishments

① Direction ($\lesssim$ 3 mrad req. $E_\nu \sim 1$ GeV)
GPS (10^{-5}) Construction (10^{-4})
Beam Stability (10^{-3} rad)

② Near-far flux extrapolation
Confirmed $\pi^+(P, \theta)$ distribution
with Gas Cerenkov Monitor

③ Selection of KEK orig. ν ev.
GPS → Beam spill time ↕ ν TOF (~1 ms)
→ Event in SK

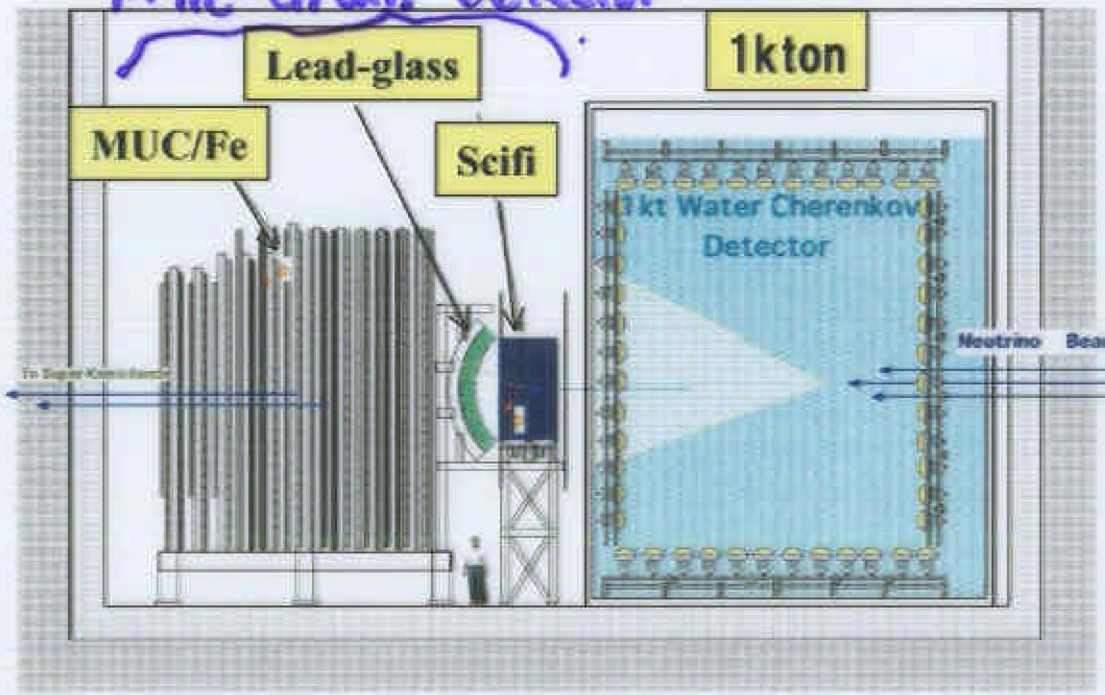
# of Events only this time.

K2K Near Detector

Function

- Measure ν_μ flux, spectrum, profile
- Study ν_μ interactions at ~ 1 GeV

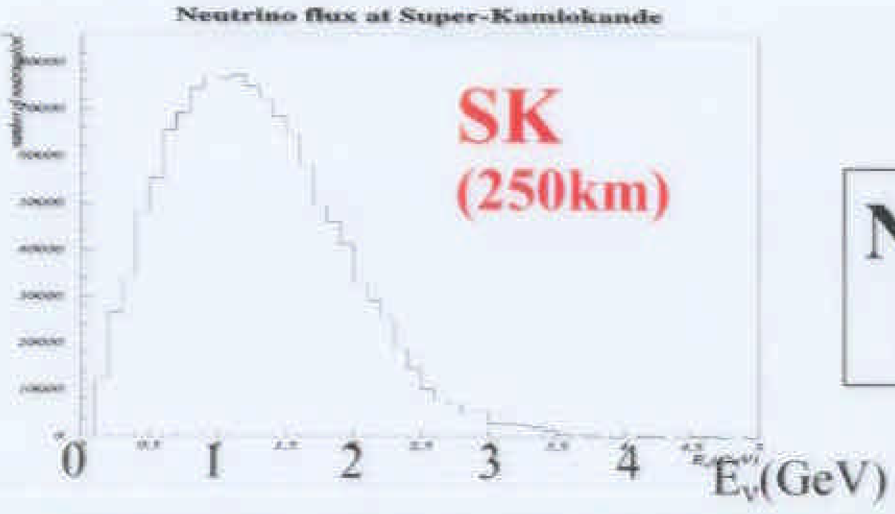
Fine-Grain Detector



- 1 kton water Cherenkov detector
  - Same type as SK
  - Common water target
- Scintillating-Fiber (SciFi) tracker
  - 2.4 m × 2.4 m × 20 (x,y) modules
  - 19 layers of 60-mm thick water target
  - σx = 1 mm
- Muon Range detector (MUC/Fe)
  - 12 layers of iron plates (total mass ~ 1kton) sandwiched by drift chambers
  - $\Delta E\mu$ =150 MeV.
- Lead-glass counter
  - $\Delta Ee / Ee$ = 10 %
- Scintillation Counters

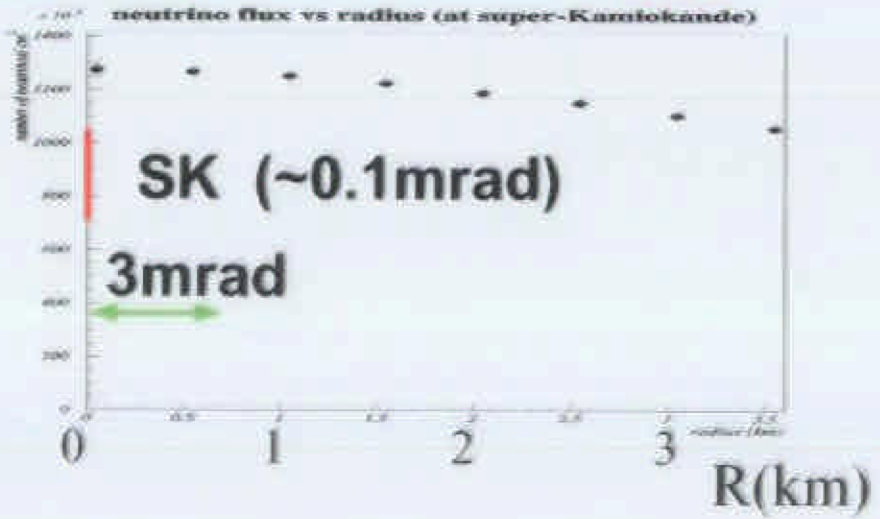
K2K

Neutrino Energy (Monte Carlo)

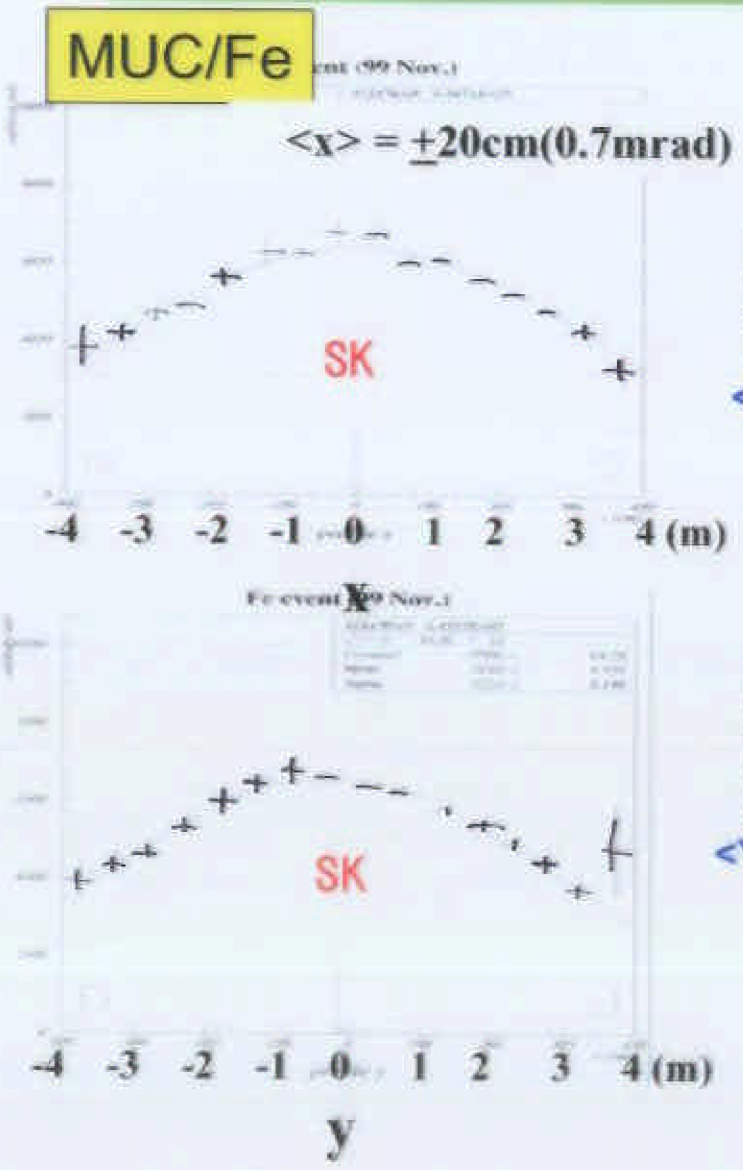


No change in flux and <E> (<3%) within 3 mrad.

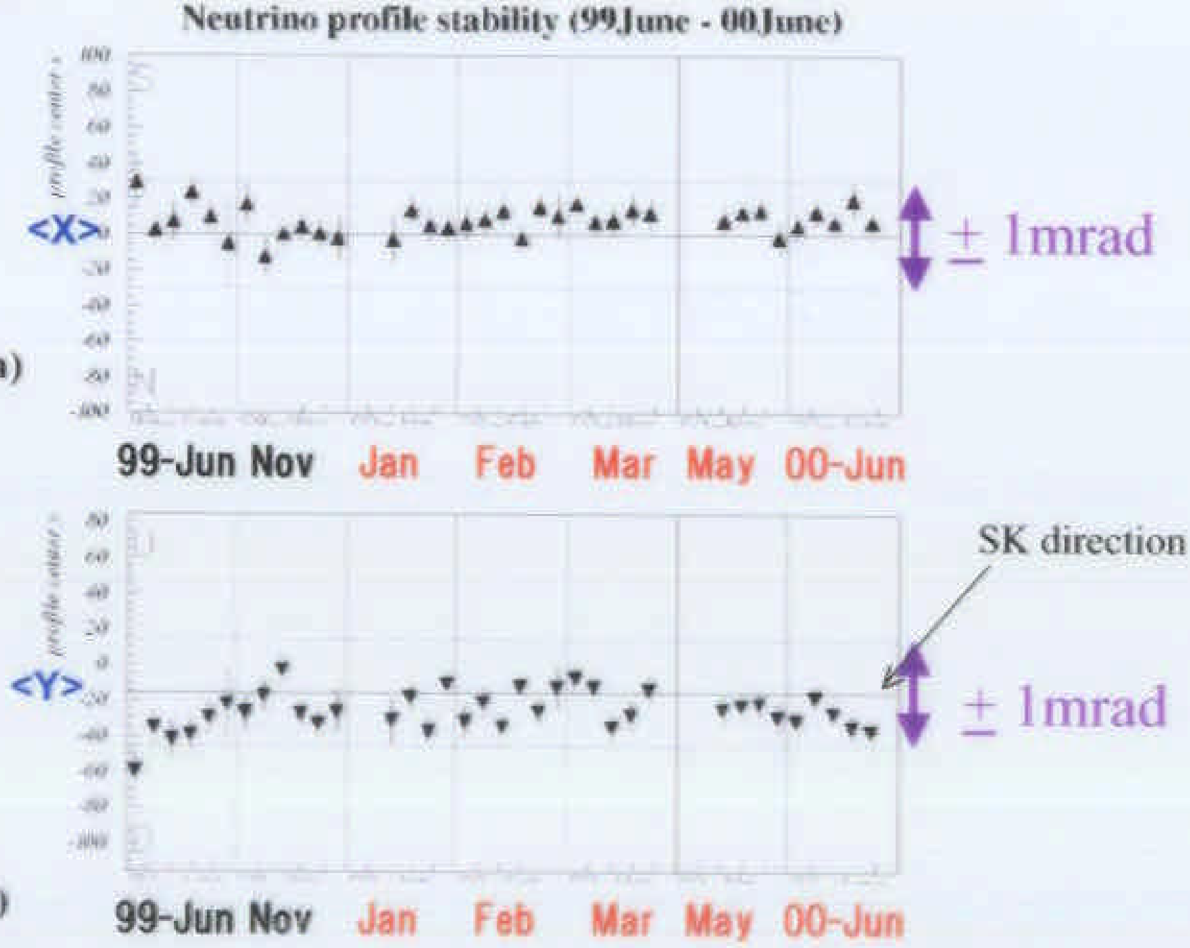
Neutrino Profile (Monte Carlo)



ν_μ Beam Profile & Its Time Stability

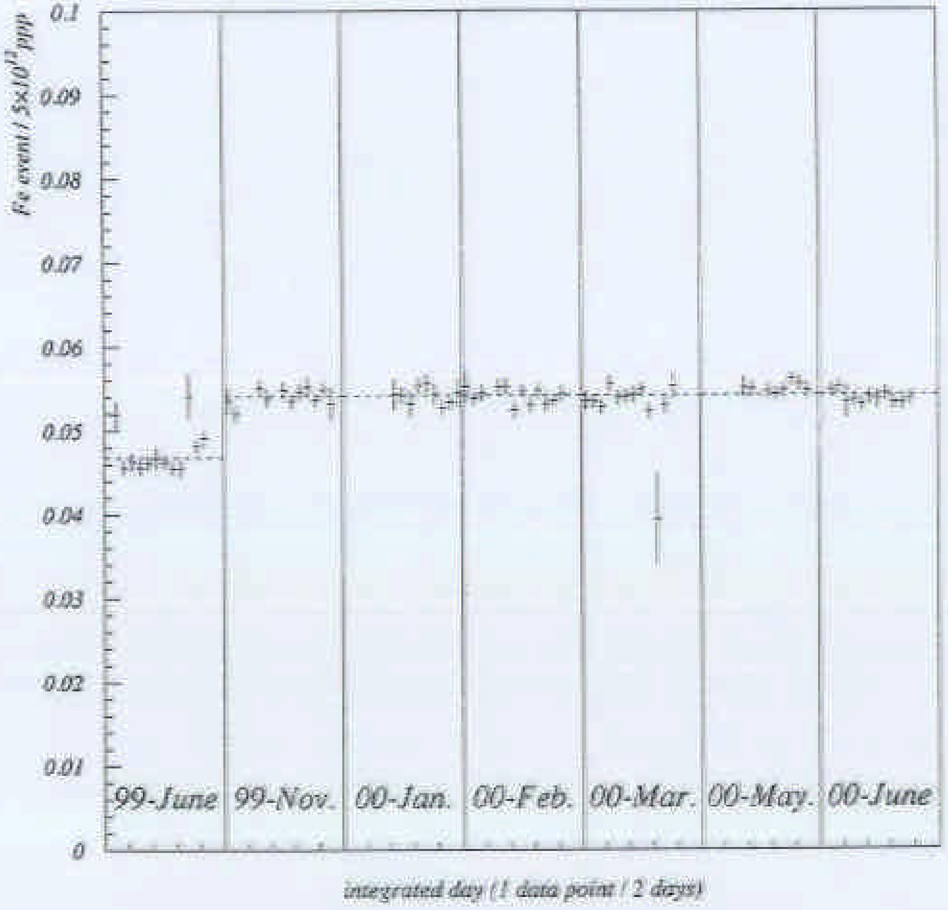


Beam direction to SK < 1mrad.

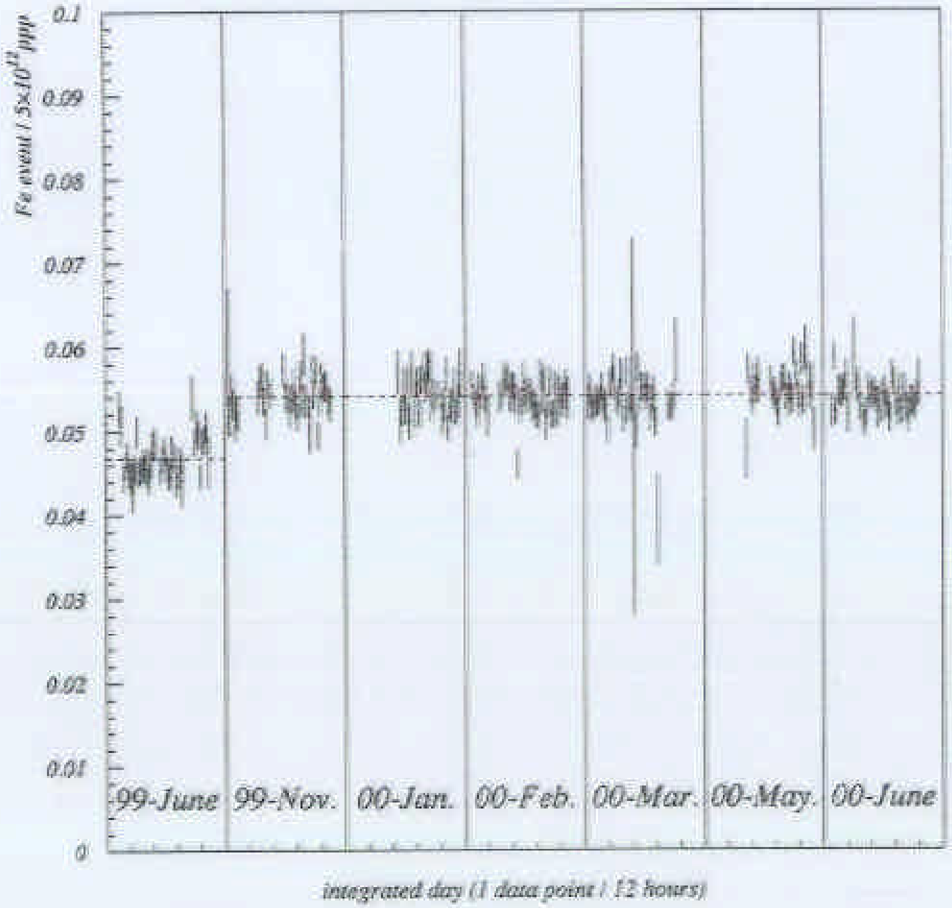


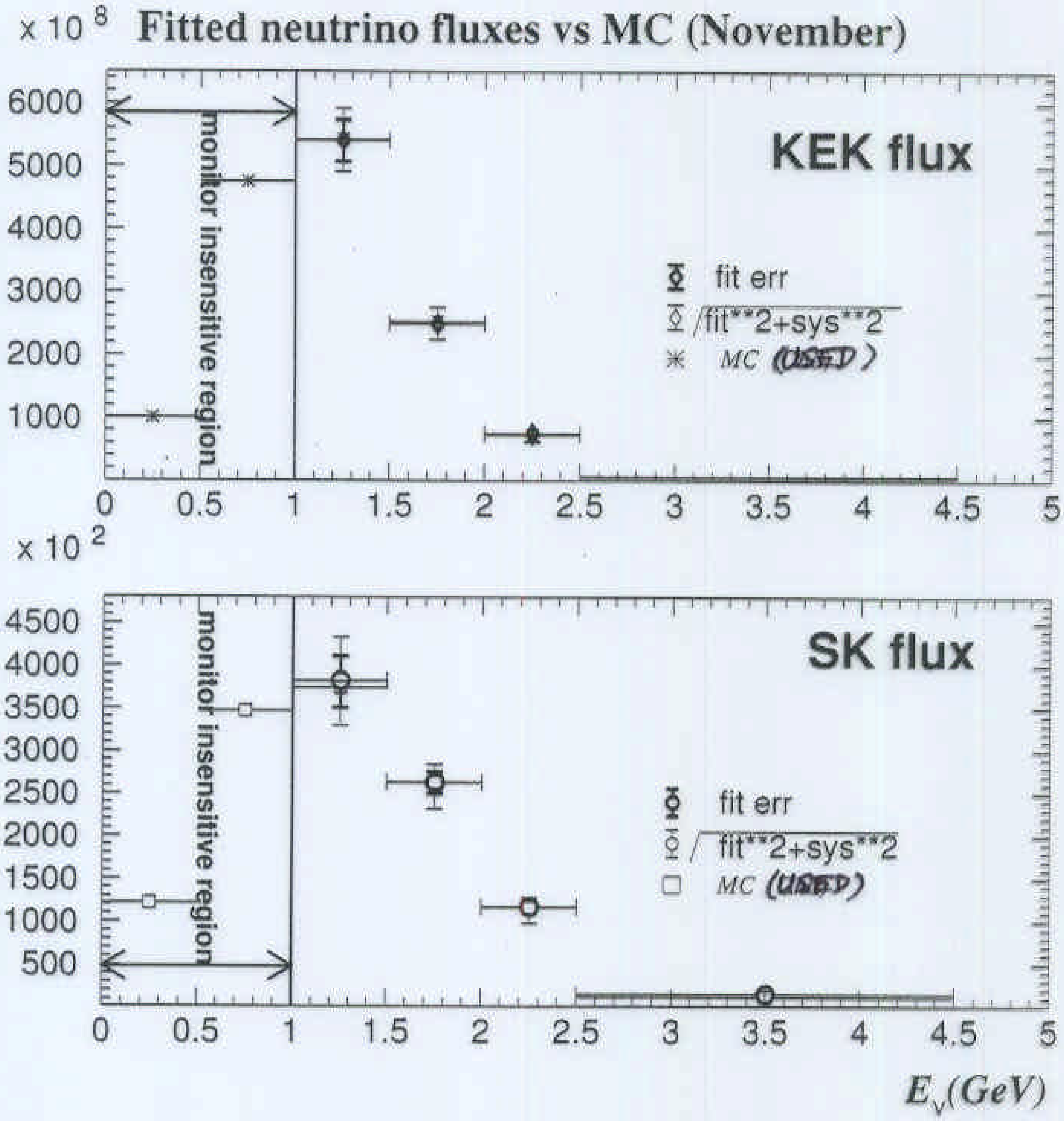
Event rate / 5×10^{12} p

Fe event rate stability (99June - 00June)



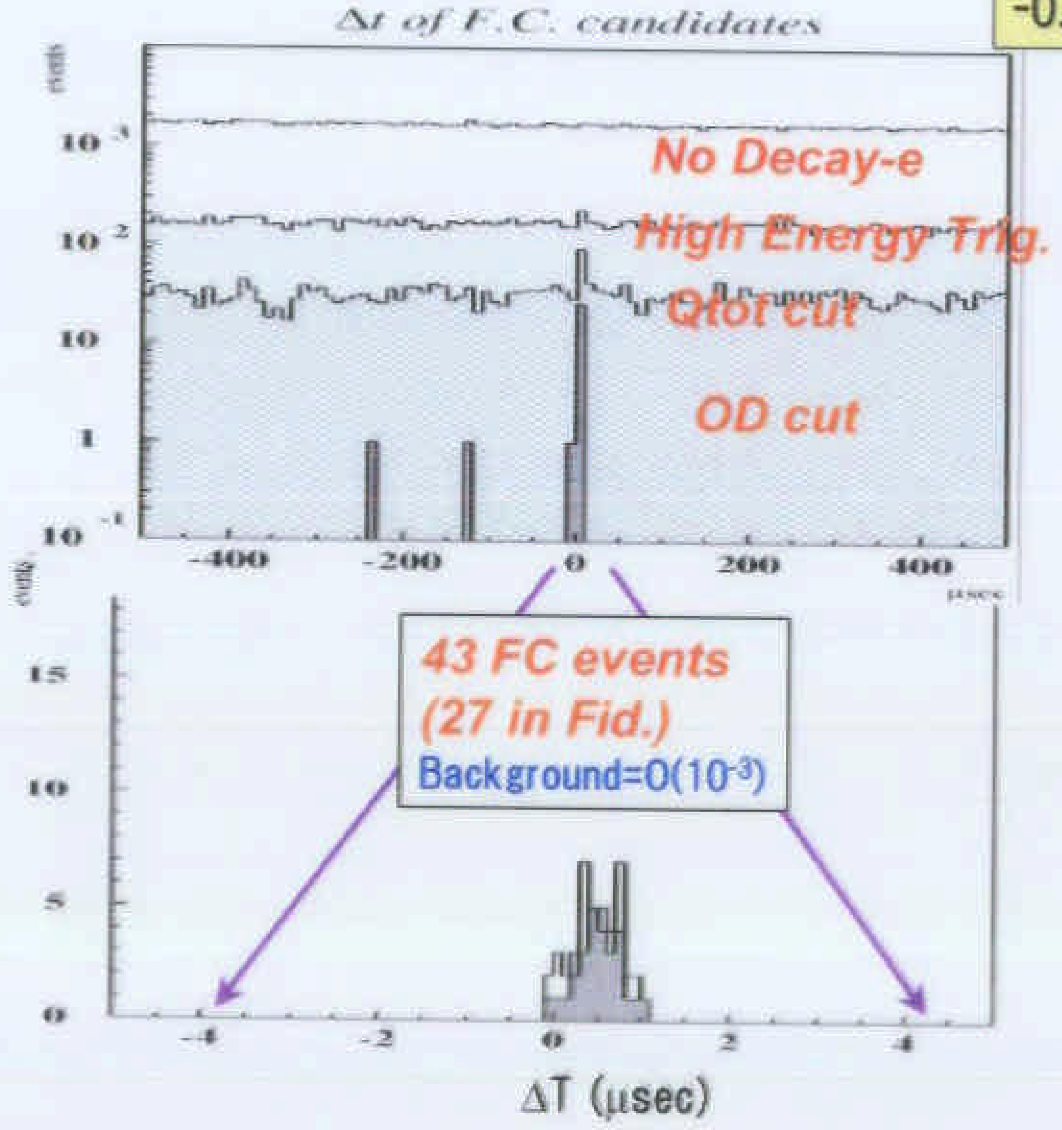
Fe event rate stability (99June - 00June)



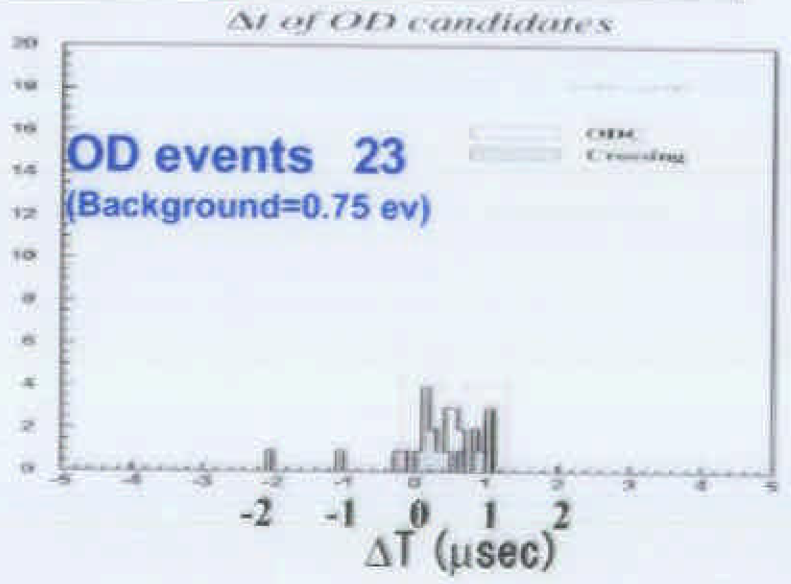

x 10 8
Fitted neutrino fluxes vs MC (November)
KEK flux
monitor insensitive region
fit err
√fit**2+sys**2
MC (USED)
6000
5000
4000
3000
2000
1000
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
x 10 2
SK flux
monitor insensitive region
fit err
√fit**2+sys**2
MC (USED)
4500
4000
3500
3000
2500
2000
1500
1000
500
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Eν(GeV)

Event Reduction for SK events

$-0.2 < \Delta T = T_{SK} - T_{KEK} - T_{TOF} < 1.3\ \mu sec$



KEK beam events(FC+OD) at the right time.



Summary of FC events (Jun99-Jun00)

	N_{SK}^{obs}	$N_{SK}^{expected}$ ($\sin^2 2\theta = 1$)			
		null oscillation	$\Delta m^2 = 3 \times 10^{-3}$	5×10^{-3}	7×10^{-3} (eV^2)
FC (22.5 kt)	27	$40.3^{+4.7}_{-4.6}$	$26.6^{+3.4}_{-3.3}$	$17.8^{+2.3}_{-2.2}$	$14.9^{+1.9}_{-1.9}$
1-ring	15	24.3 ± 3.6	14.4 ± 2.3	9.4 ± 1.5	8.6 ± 1.4
μ-like	14	21.9 ± 3.5	12.4 ± 2.1	7.5 ± 1.3	6.8 ± 1.2
e-like	1	2.4 ± 0.5	2.1 ± 0.4	1.9 ± 0.4	1.8 ± 0.4
multi ring	12	16.0 ± 2.7	12.2 ± 2.1	8.4 ± 1.5	6.3 ± 1.1

- 2σ away from null oscillation
- Long Base-line Experimental methods

Near Future

Oscillation Pattern K2K

Solar LMA Test by reactor-ν
Kamland 2001

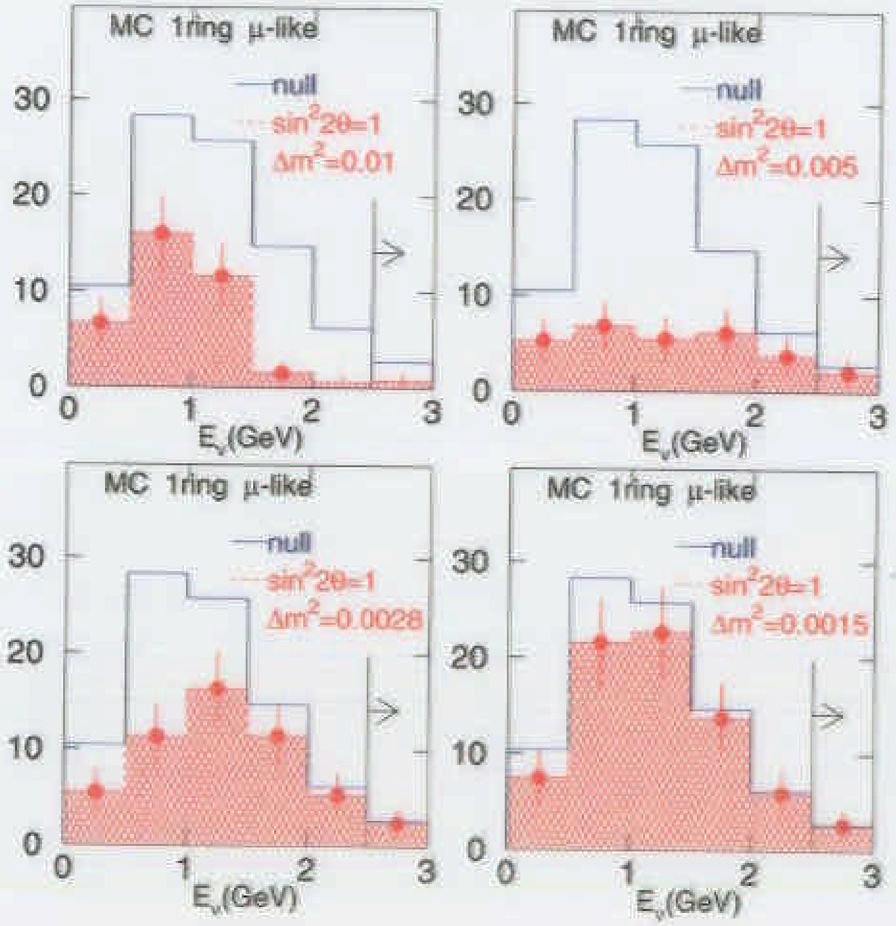
$\nu_{sterile}$ (LSND effect) Mini BooNE 2001

Osci. Pattern, $(\Delta m^2, \sin^2 2\theta)$ MINOS 2003
NC/CC, e appearance

τ appearance, e-appearance CNGS 2005
ICARUS/OPERA

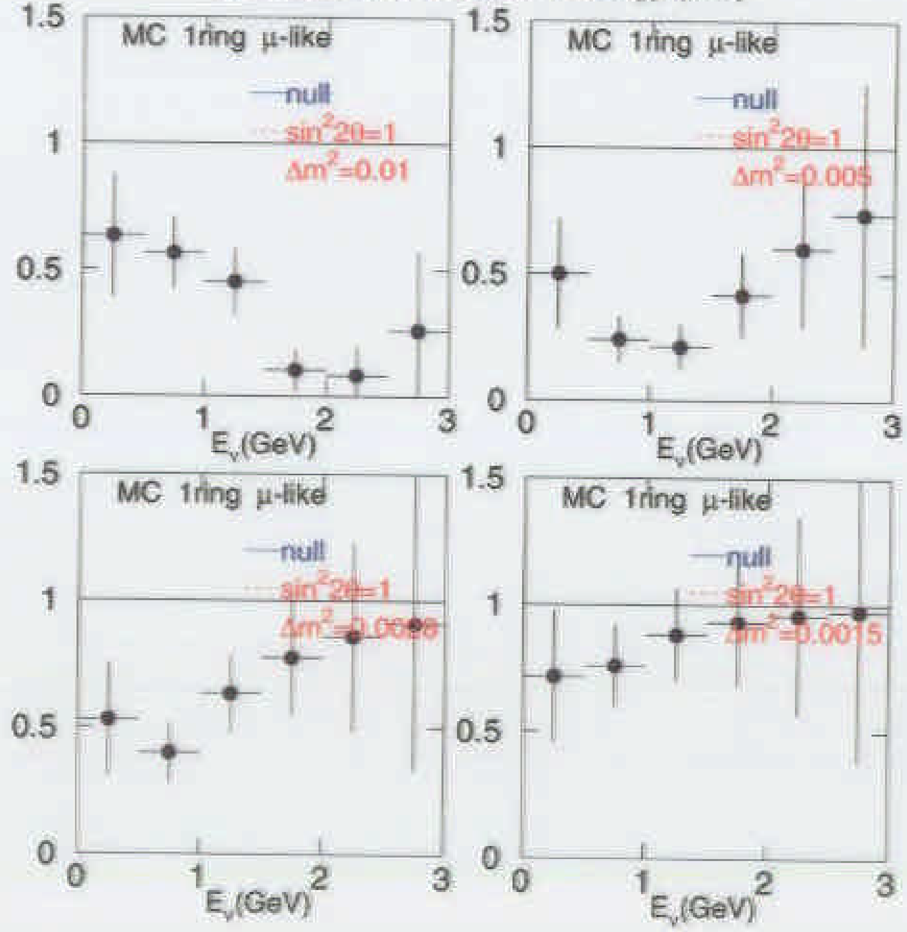
$\delta(\Delta m^2, \sin^2 2\theta)$, e-appearance
JHF-ν 2006?

Reconstructed Neutrino Energy (MC)



200~300 more days

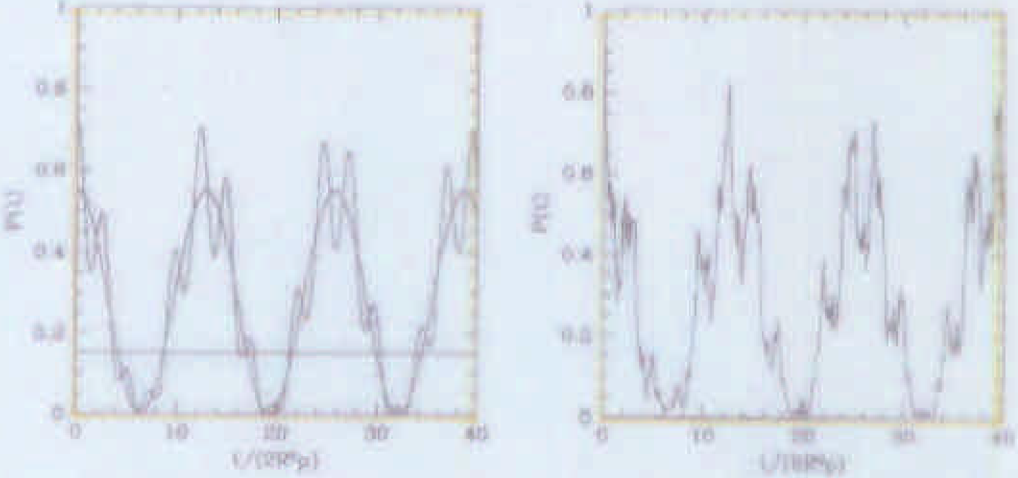
Reconstructed Neutrino Energy (MC)



But what about neutrino oscillations?

$$P_{\nu_L \to \nu_L}(t) = \left| \sum_k |U_{\nu k}|^2 \exp\left(\frac{i\lambda_k^2 t}{2p}\right) \right|^2 .$$

Note: $\mathcal{M}$-matrix non-diagonal $\Longrightarrow$ U-matrix non-diagonal.
Thus, still have oscillations!

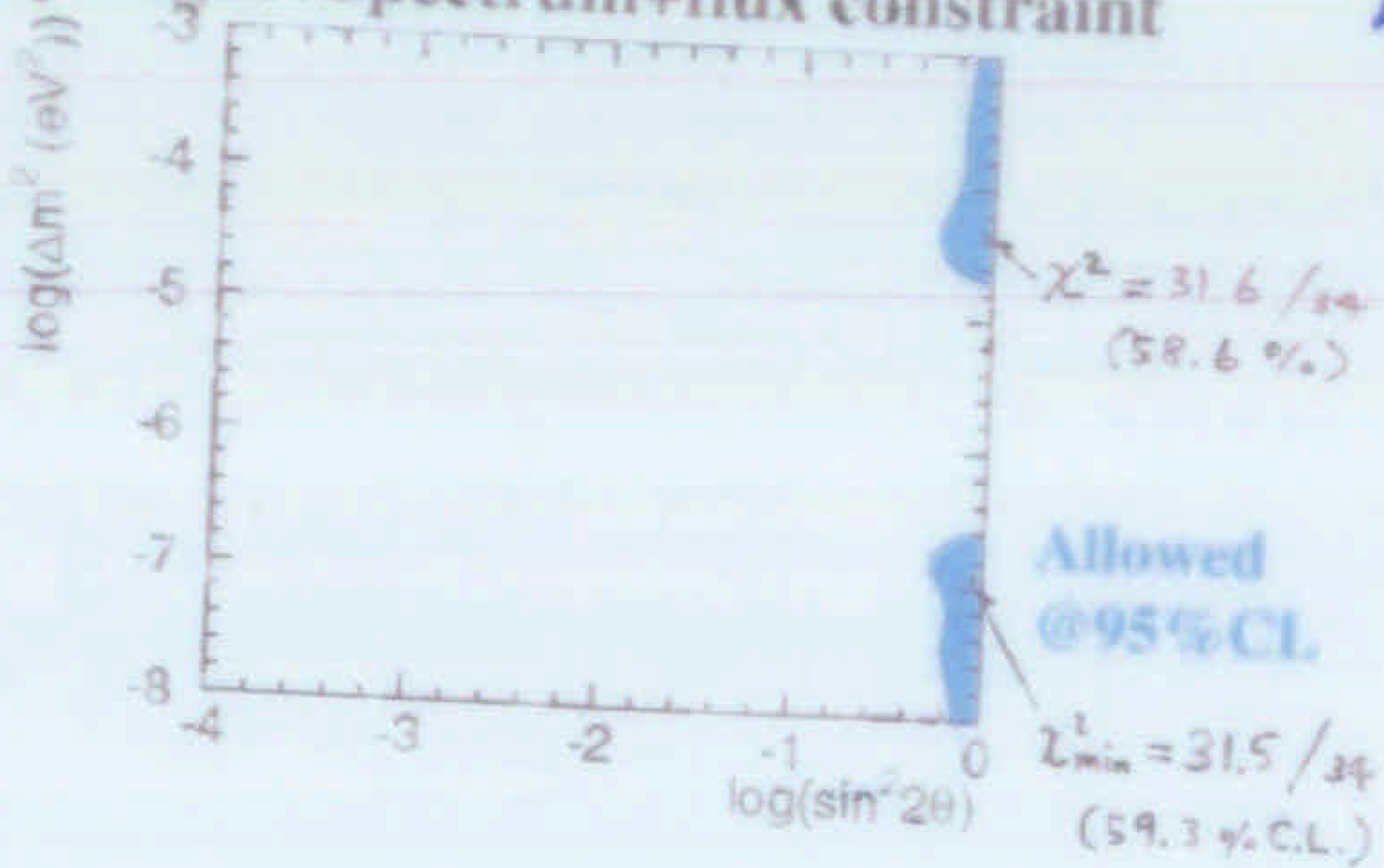


- Neutrino oscillations without neutrino masses in $D \geq 5$!
- Oscillations still effectively periodic.
- Regenerations never total, but deficits total.
- Oscillation length set by first eigenvalue interval $\approx R^{-1}$.
- Easy to generalize to flavor oscillations, even with $(\nu_e, \nu_\mu, \nu_\tau)$ massless! Oscillations *indirect* via KK states...

Thus, in such scenarios, neutrino oscillations are evidence not for neutrino masses, but for extra spacetime dimensions!

Super-Kamiokande
Day/Night+Spectrum+flux constraint

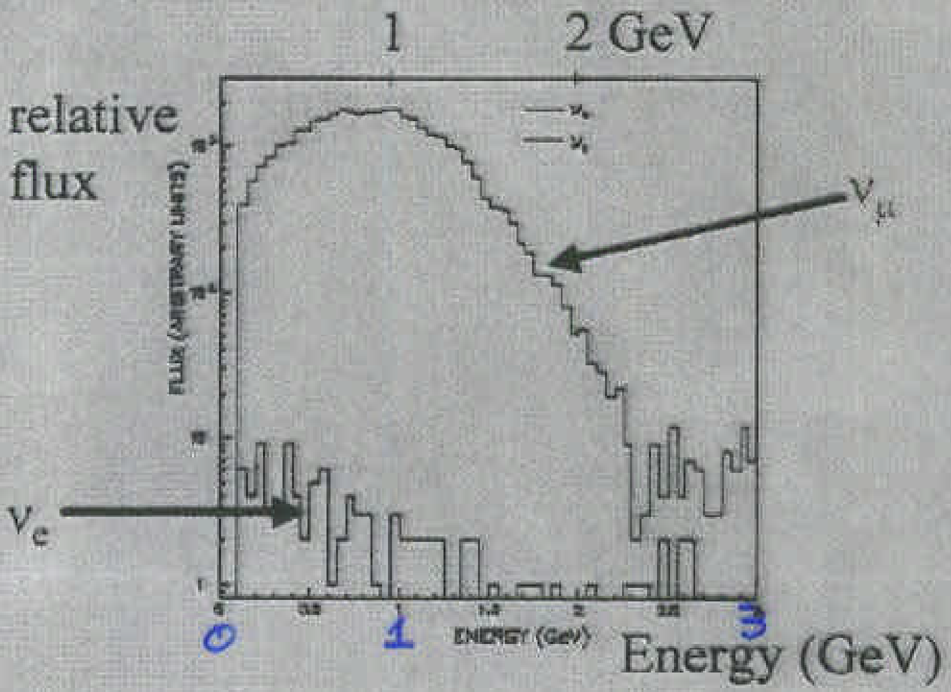
Y. Suzuki
ν2000



Kam land reactor

Mini BooNE

Neutrino Beam

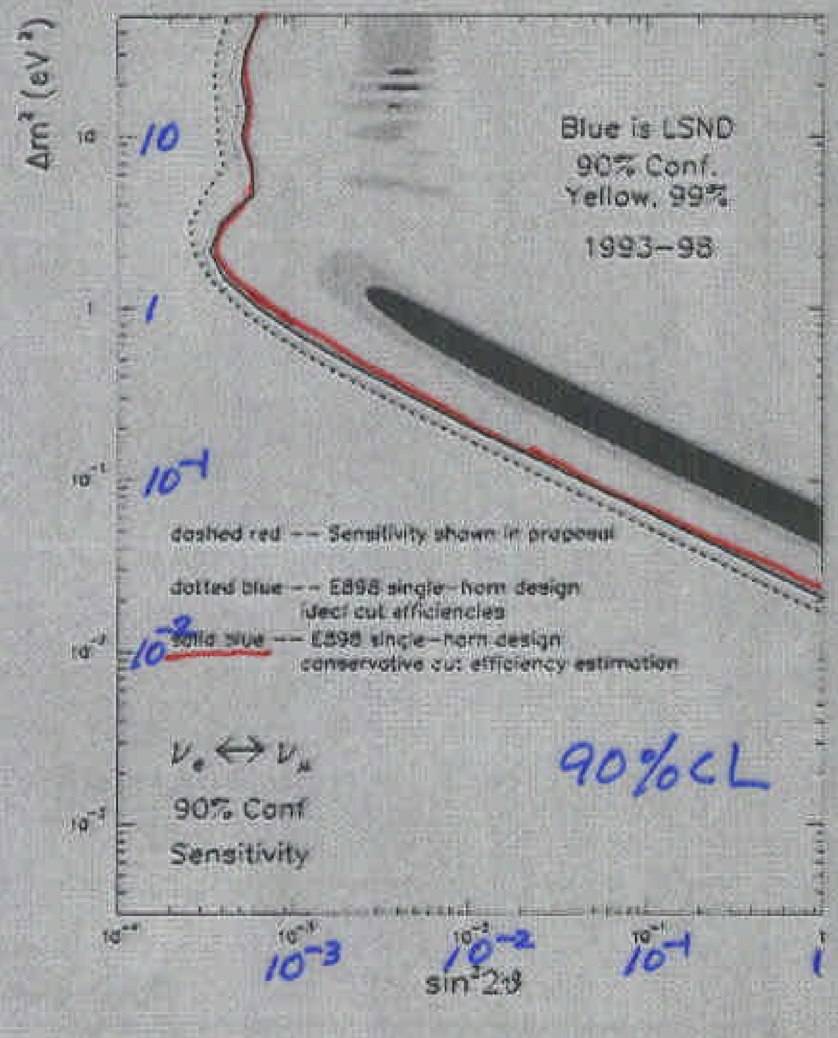


50 m decay length
flux in detector located at 500 m

8 GeV Booster
5×10^{12} PPP X 5 Hz
Start 2001

Bazarko - 18

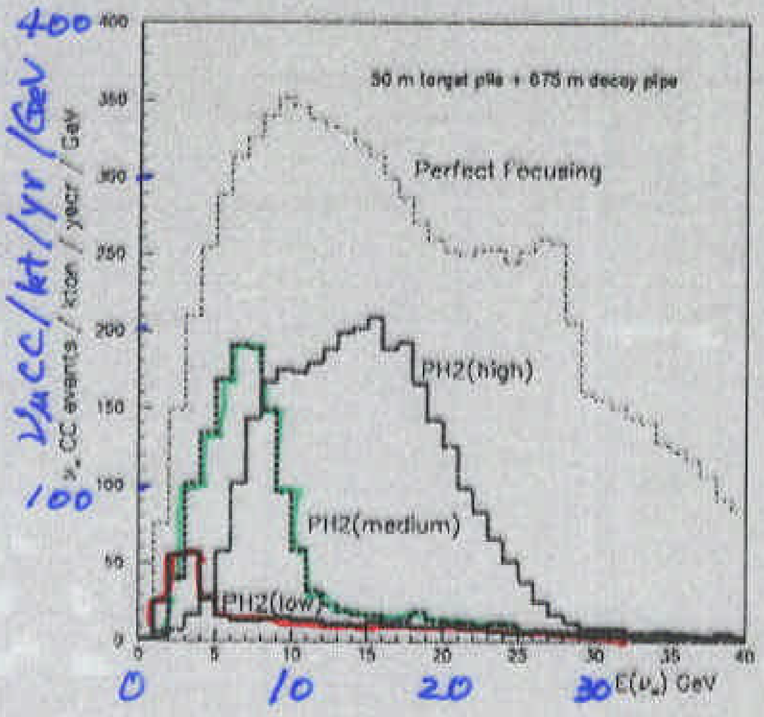
MiniBooNE expected sensitivity



Final horn design, most conservative mis-id estimate,
one calendar year of running

$\mu \to \nu_e$ component known to 5%
$K \to \nu_e$ 10%
μ mis-ID 5%
π^0 mis-ID 5%

NuMI: Flexible Neutrino Beam

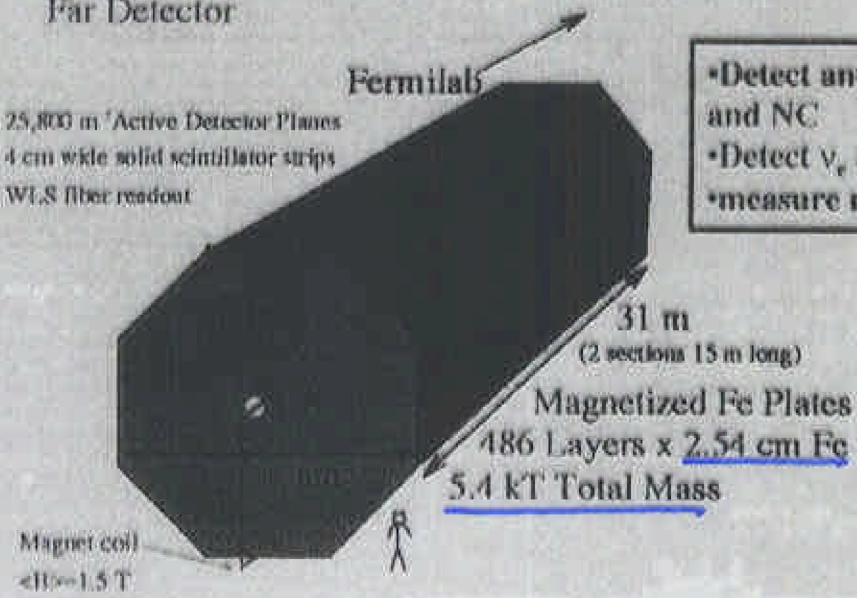


- CC Events Rates in Minos 5kt detector:
  - High 16,000/yr
  - Medium 7,000/yr
  - Low 2,500/yr

MINOS Far Detector

Far Detector

25,800 m² Active Detector Planes
4 cm wide solid scintillator strips
WLS fiber readout

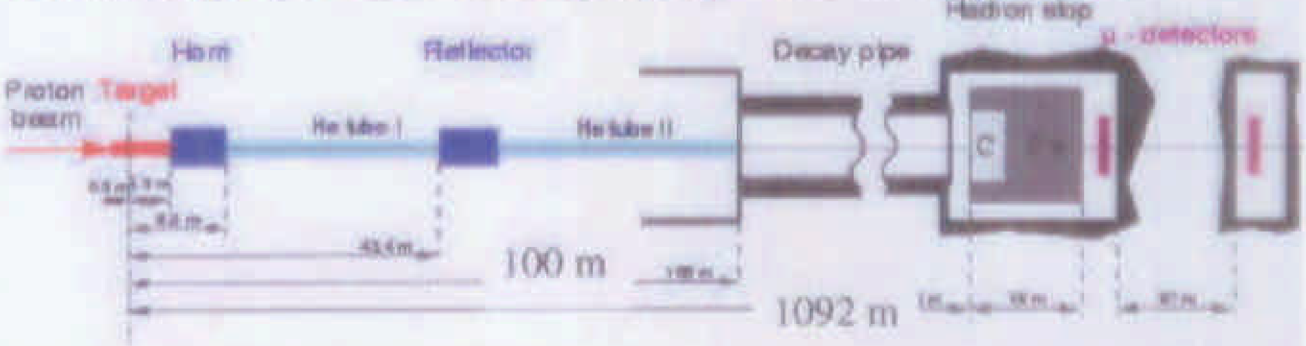


- Detect and identify ν_μ CC and NC
- Detect ν_e and ν_τ NC/CC
- measure neutrino energy

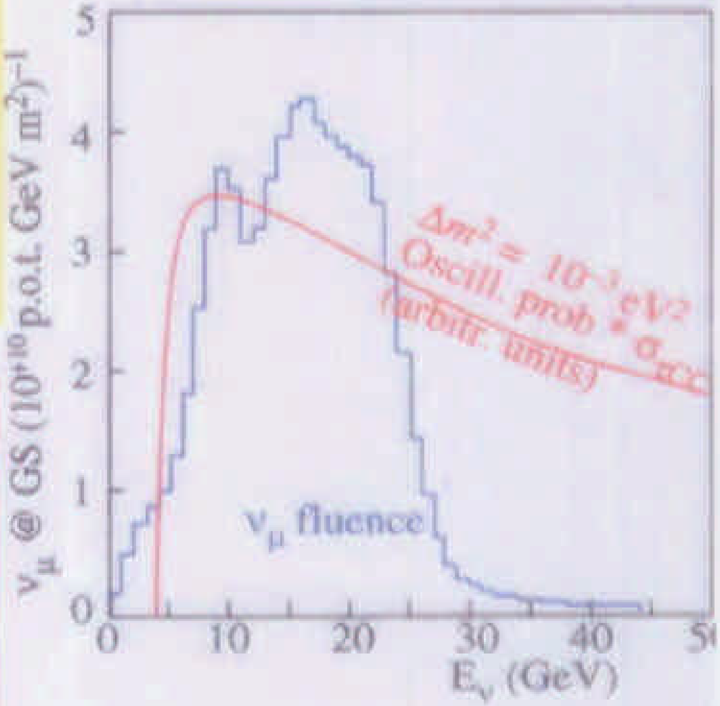
4 cm wide sci.
WLS fiber readout

CNGS

Beam design by a CERN-INFN group optimised for τ appearance



p beam energy 400 GeV
pot/y (shared) 4.5×10^{19}
(dedicated) 7.6×10^{19}
2500 CC ν_μ interactions/kt*yr
ν_τ interactions = 25 / (kt*yr)
for $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2
full mixing



τ detection channels

CC interactions $\nu_\tau + N \rightarrow \tau^- + X$

$\tau^- \rightarrow$

$\mu^- \nu_\tau \nu_\tau$	18%
$h^- \nu_\tau n\pi^0$	50%
$e^- \nu_\tau \nu_e$	18%
$\pi^+ \pi^- \pi^+ \nu_\tau n\pi^0$	14%

Background rejection tools

direct observation of decay (CHORUS, DONUT, OPERA)
- **$\gamma c\tau$ = O (1 mm)**
- high spatial granularity
  - only possibility: emulsions, 1 μm granularity

kinematics (NOMAD, ICARUS + spectrometer& tail catcher)
- good particle identification
- good resolution in momentum unbalance (unseen neutrinos)

35

ICARUS. Discovery capability

τ appearance. Electron channel

- Look fo excess at low electron energies
- Exploit superior e/π^0 separation capability

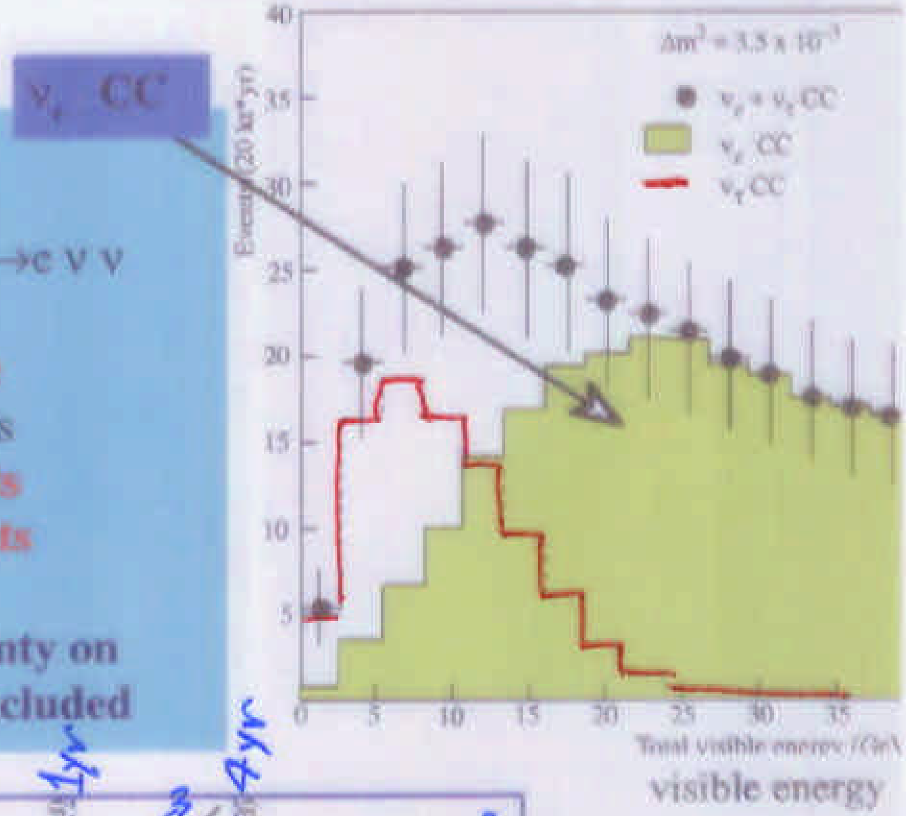
Backgrounds

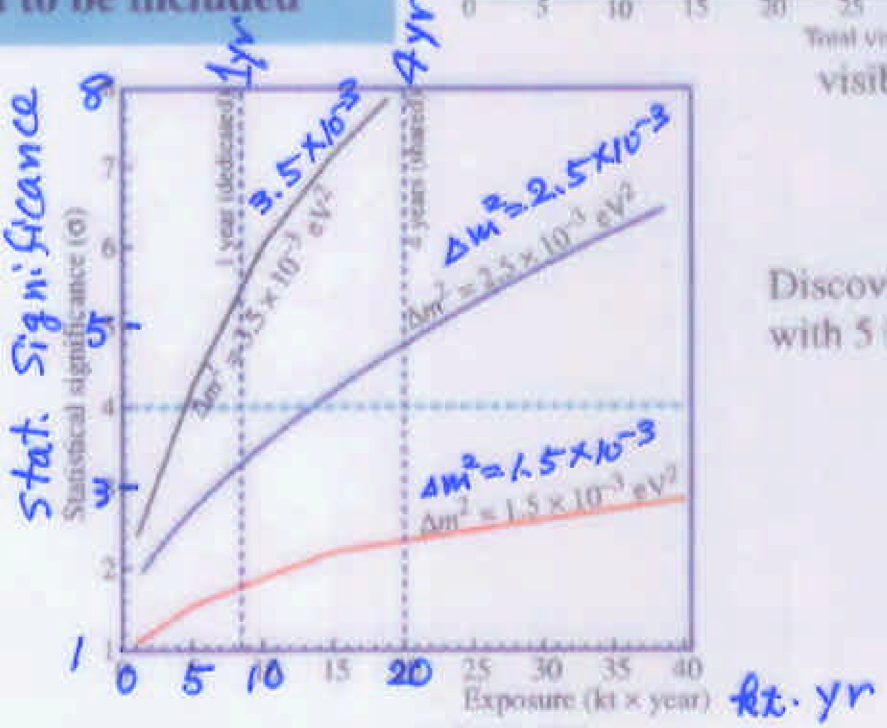
- ν_e CC events
  - exploit small ν_e contamination in the beam
- non prompt electrons from NC and CC evts

$\Delta m^2 = 3.5 \times 10^{-3} eV^2$
470 ν_τ CC
110 ν_τ CC with $\tau \to e \nu \nu$

20 kt*year exposure
After kinematical cuts
τ events = 35 events
Bkgnd ≈ 5.1 events

Systematic uncertainty on background to be included





Discovery potenti
with 5 kt fid. mas

Signal and background

5 years exposure (2.25 x 10^20 p.o.t). Full mixing. Different Δm^2

τ decay mode	Signal (1.5x10-3 eV2) 1.5×10^{-3} eV	Signal (3.2x10-3 eV2) 3.2×10^{-3}	Signal (5.0x10-3 eV2) 5×10^{-3}	BG
electr. (long) $\tau\to e\nu\nu$	1.3	5.9	14.2	0.16
muon (long) $\tau\to\mu\nu\nu$	1.3	5.7	13.8	0.13
hadron (short) $\tau\to h\nu$	1.1	4.9	11.8	0.25
electr. (short)	0.4	1.8	4.3	0.03
Total	4.1 4.1	18.3 18.3	44.1 44.1	0.57 0.57

long (kink)

short (impact par.)

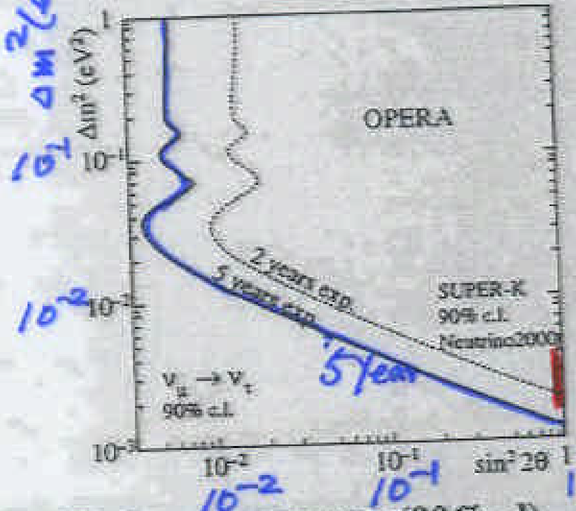
Total τ detection efficiency = 8.7%

Discovery limits & measurement of parameters

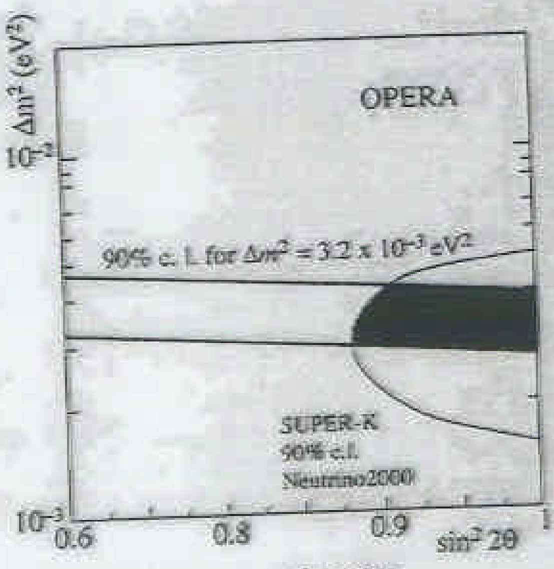
Numbers of detected τ
2.25 x 10^20 pot
(5 years)
full mixing

4 ev. @ 1.5×10^{-3} eV²
18 ev. @ 3.2×10^{-3} eV²
44 ev. @ 5×10^{-3} eV²

background 0.6 ev



Determination of oscillation parameters (90% cl)



MINOS Physics Measurements

- Obtain firm evidence for oscillations:
  (Near/Far comparison reduces systematic uncertainties)
  - CC interaction rate and energy distribution
  - NC/CC rate ratio and energy distribution

- Measurement of oscillation parameters, Δm^2, $\sin^2 2\theta$
  - CC energy distribution

  $\delta \sin^2 2\theta \sim 0.05$
  $\delta \Delta m^2 \sim 0.0002$
  @ ($\Delta m^2 = 0.003$, $\sin^2 2\theta = 0.8$)

- Determination of the oscillation mode(s)
  - NC/CC rate measurements: a tool to discriminate against $\nu_{sterile}$ — 4σ $\nu_\mu \to \nu_{sterile}$
  - Identification of ν_e by topological criteria — $\nu_\mu \to \nu_e$ $\sim 3\%$
  - Identification of ν_τ by its exclusive decay modes (works best if Δm^2 is relatively high) — $\nu_\mu \to \nu_\tau$

JHF-ν experiment

A second generation long baseline neutrino oscillation experiment in Japan

Super-K: 50 kton Water Cherenkov

JAERI (Tokaimura)

0.75 MW 50 GeV PS

(ideal for ν experiment)

- Precision measurement of ν oscillation parameters ($\sin^2 2\theta_{23}$, Δm_{23}^2).
- Discovery of $\nu_\mu \rightarrow \nu_e$ ($\sin^2 2\theta_{13}$)

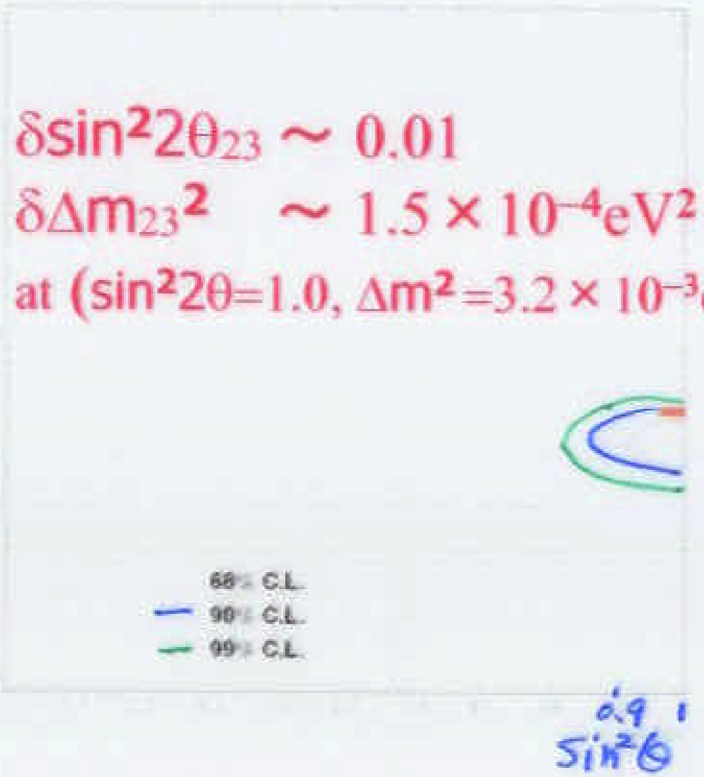
Precision and Sensitivity (5years)

ν_μ disappearance

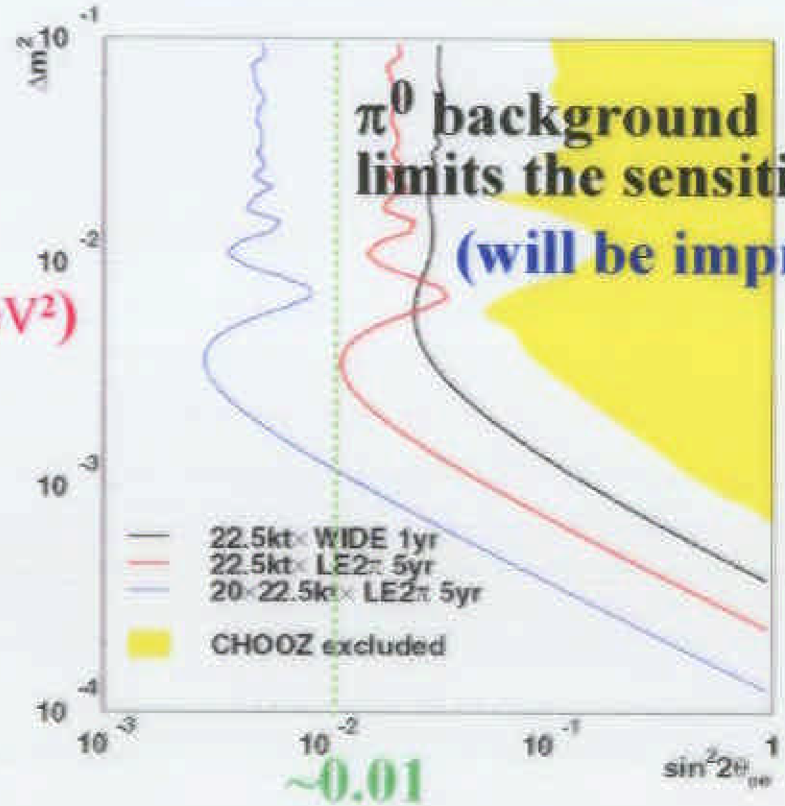
$\delta \sin^2 2\theta_{23} \sim 0.01$

$\delta \Delta m_{23}^2 \sim 1.5 \times 10^{-4} eV^2$

at ($\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.2 \times 10^{-3} eV^2$)



$\nu_\mu \rightarrow \nu_e$ appearance



π^0 background limits the sensitivity **(will be improved)**

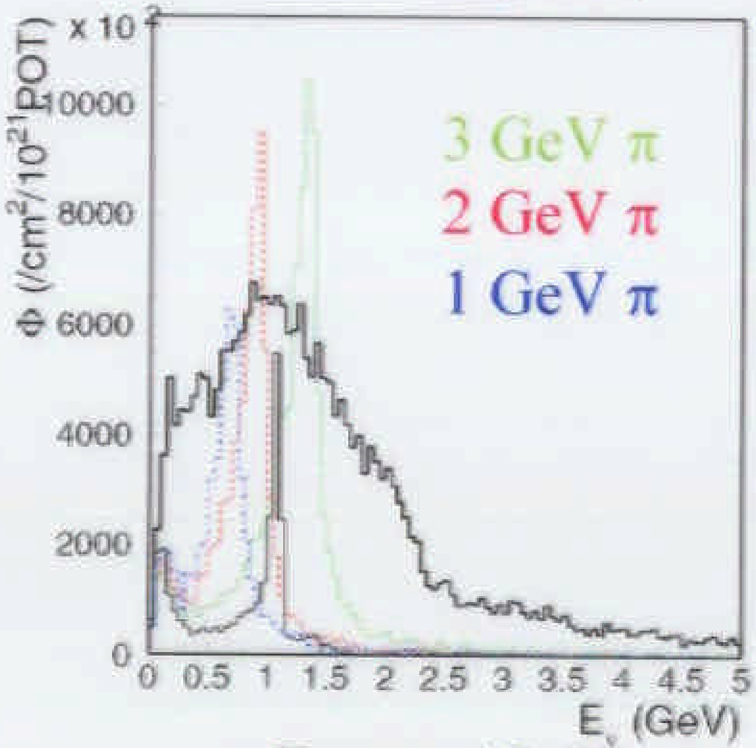
➢ Possible Upgrade

JHF-II(~4MW) × more massive detector

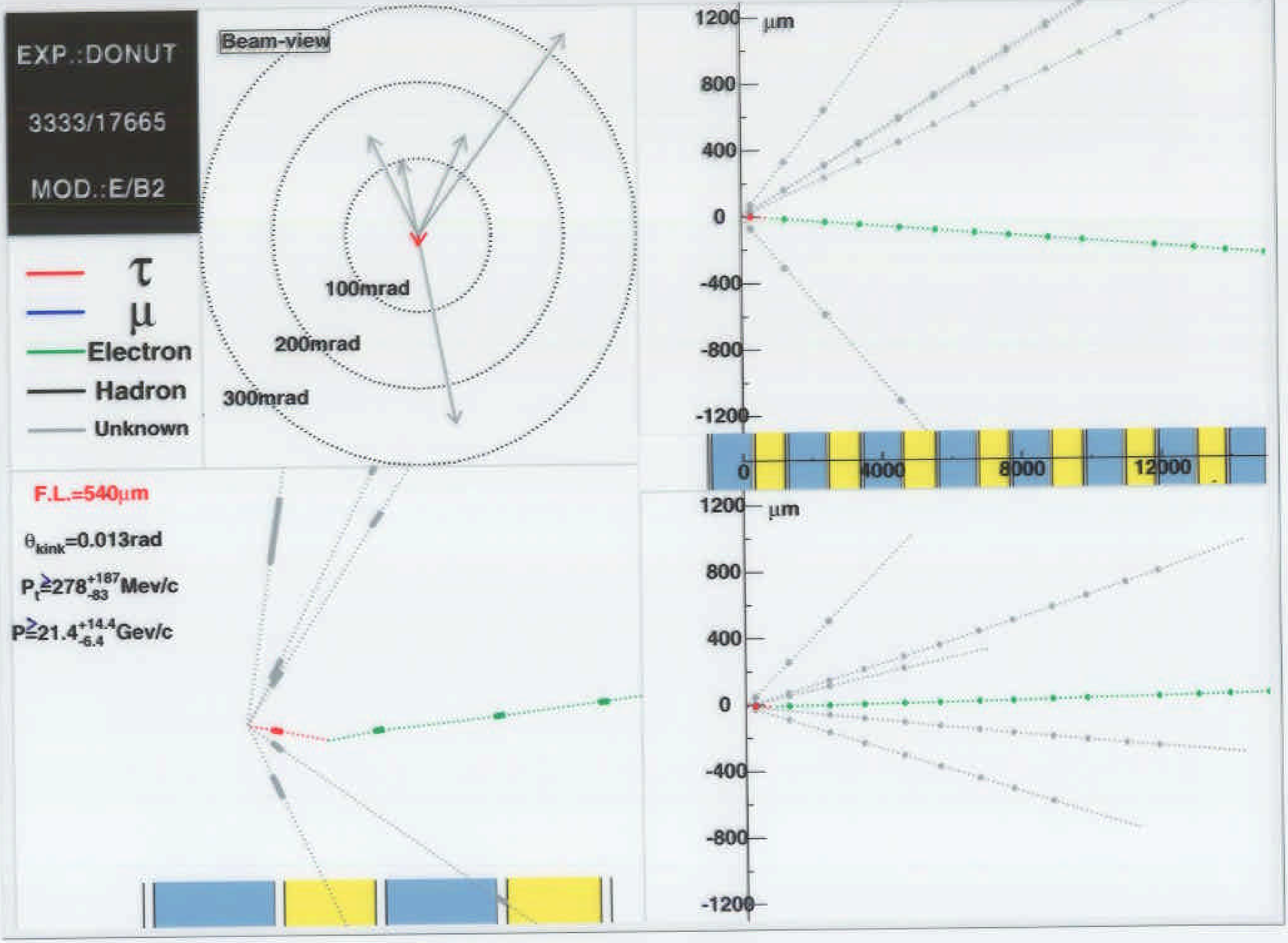
TWO ν beams (Conventional technique)

- **Wide Band Beam** (~10,000 ν **interactions at SK 50k tons/year)**
- **Narrow Band Beam** (well-understood ν beam from monochromatic π)

ν flux at Super-K (/cm²/10²¹POT)
one year (=100 days)



ν Energy (GeV)


EXP.:DONUT
3333/17665
MOD.:E/B2
τ
μ
Electron
Hadron
Unknown
Beam-view
100mrad
200mrad
300mrad
F.L.=540μm
θkink=0.013rad
Pt≧278+187-83 Mev/c
P≧21.4+14.4-6.4 Gev/c
1200 μm
800
400
0
-400
-800
-1200
0
4000
8000
12000

Statistics in DONUT

Reconstructed ν_{int} Candidate in fidutial Volume — 699 ev

||

rejection of small multiplicity Event ($n_s \leq 2$)

rejection of Super High μ-BG region

⇐ High Density BG μ-on $3-10 \times 10^4/cm^2$

~ $10^5/cm^2$ side band (low energy μ

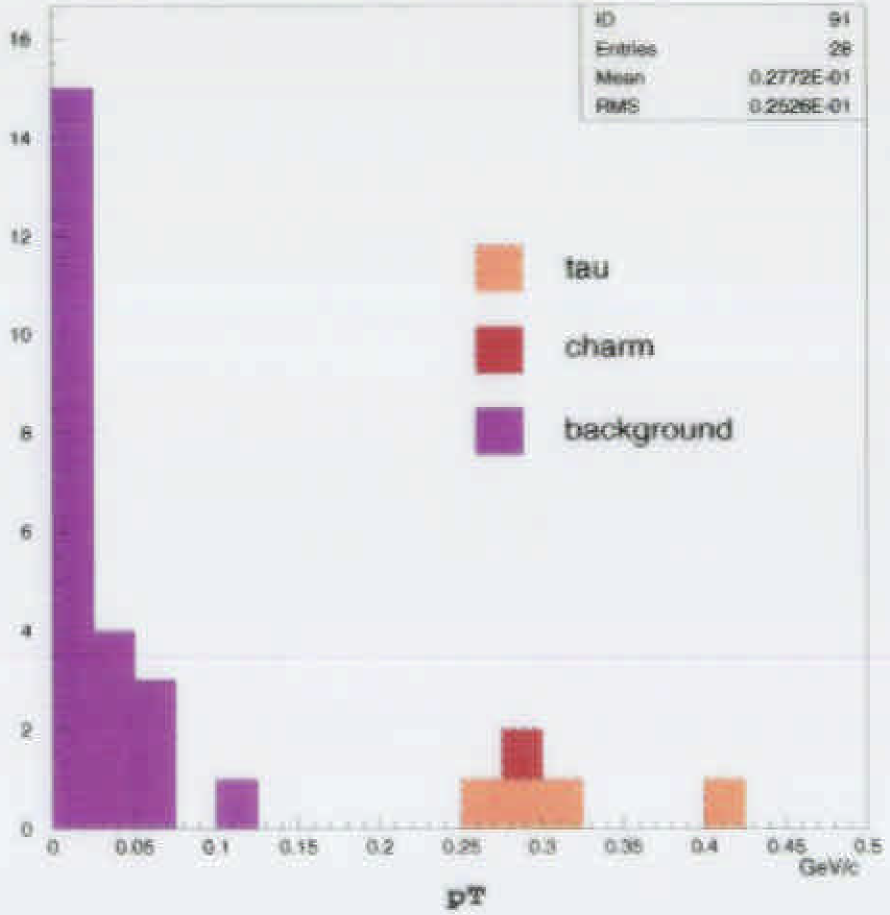
⇓

Vertex Location tried	451	⇐ NETScan
Vertex Located (Feb. 2000)	262	
Systematic Decay Search was applied	203	

ν_τ^{cc} events — 5 (4 long decay, 1 short decay)

expected BG (0.44 for long, 0.13 for short)

Background+Signal: Interactions Distribution of Kinks



Same plot as previous slide, but *color enhanced* !

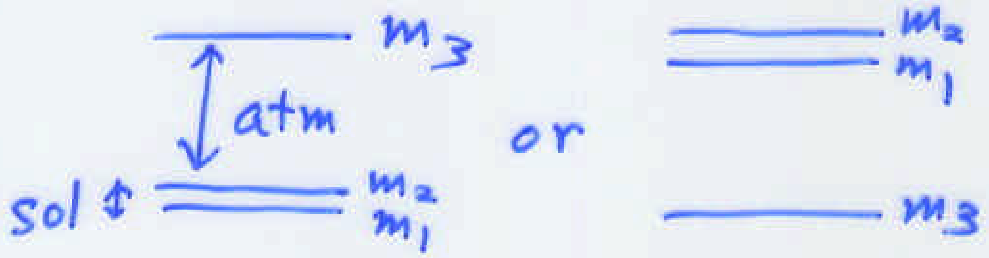
$$\nu_3 \sim \frac{1}{\sqrt{2}}(\nu_\mu + \nu_\tau)$$

$$\nu_2 \sim \frac{1}{2}\nu_e + \frac{1}{\sqrt{2}}(\nu_\mu - \nu_\tau)$$

$$\nu_1 \sim \frac{1}{2}\nu_e - \frac{1}{\sqrt{2}}(\nu_\mu - \nu_\tau)$$

generation — Mass ?

Is $m_3 > m_1, m_2$ or $m_3 < m_1, m_2$



- Matter effect (MSW)

ν_e Extra potential $\nu_e - e$ c.c.

$$\sin^2 2\theta = \frac{\sin^2 2\theta_{13}}{\left(\frac{2EV}{m_3^2 - m_2^2} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}$$

if $m_3 > m_2$ resonance

Optimal

$$E_\nu = 15\,\text{GeV} \left(\frac{\Delta m^2}{3.5 \times 10^{-3}\,\text{eV}^2}\right)\left(\frac{2.8\,\text{g/cm}^3}{\rho}\right)$$

(Lindner)

CP̸ : Appear only in appearance

$$A_{CP} = \frac{(\nu_\mu \to \nu_e) - (\bar{\nu}_\mu \to \bar{\nu}_e)}{(\nu_\mu \to \nu_e) + (\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\sim \frac{4 \sin 2\theta_{12} \sin\delta}{\sin\theta_{13}} \cdot \sin \frac{2\Delta m_{12}^2}{4E} L$$

solar $\nu \Rightarrow (\theta_{12}, \Delta m_{12}^2)$

Atm region $\nu_\mu \to \nu_e \to \theta_{13}$

Low energy conventional beam

$$A_{CP} \propto \frac{L}{E}$$

But limited by ν_e appearance ID capability (π^0 bkg) (ν_e contam.)

Nu-factory

$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$\bar{\nu}_e$ — osci — $\bar{\nu}_\mu$ } wrong sign μ

$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$\nu_e \longrightarrow \nu_\mu$ }

Future heavily depends on the results in coming decade