NEUTRINOS II

The Sequel

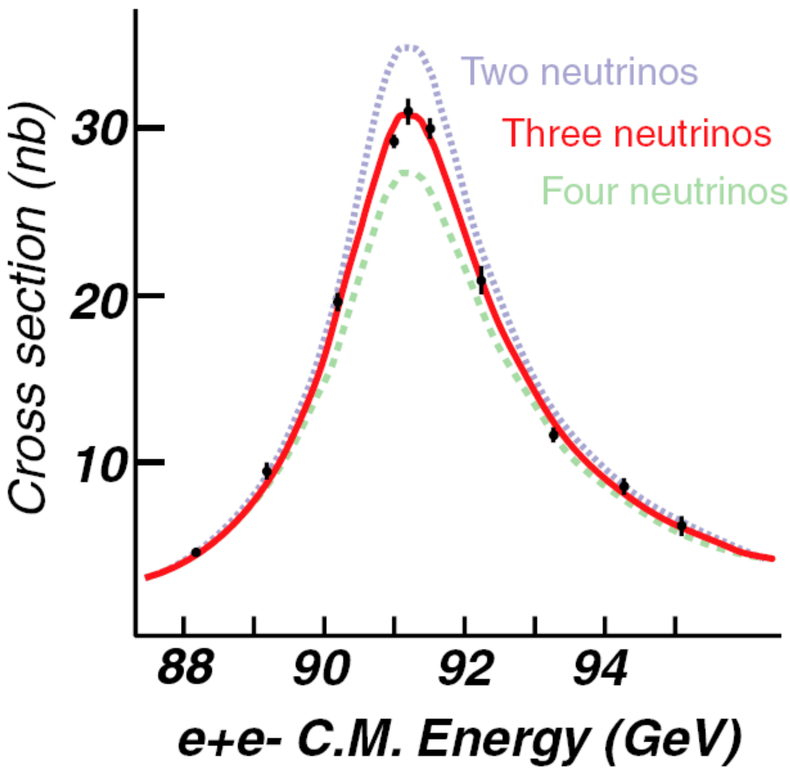
More About Neutrinos

Ed Kearns – Boston University

NEPPSR V - 2006

There is something unusual about this neutrino talk compared to many other neutrino talks you may have seen. Can you discern it?

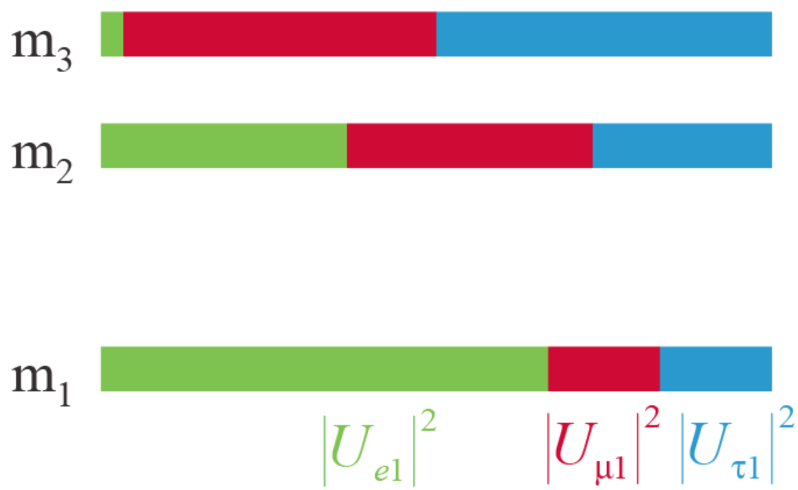
The Number of Neutrinos is Three

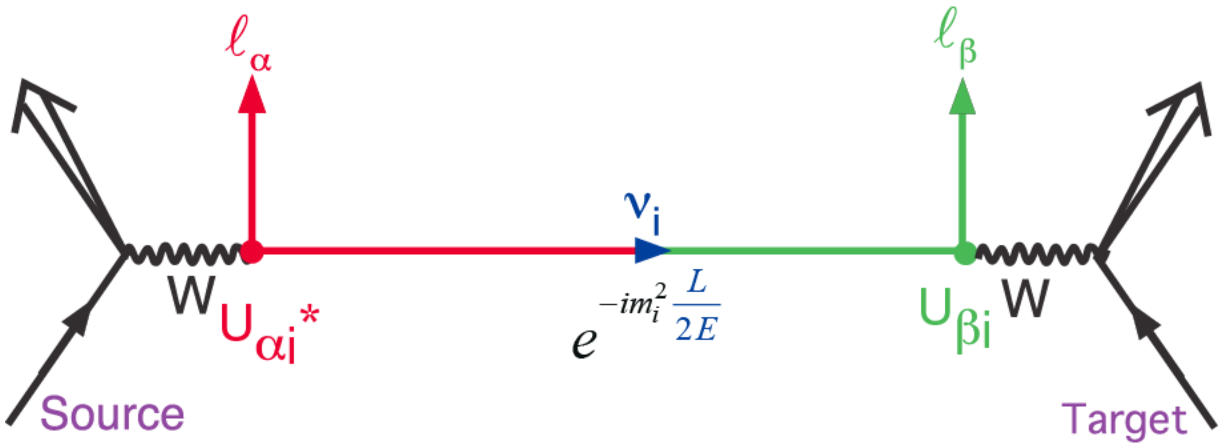


results from LEP experiments at CERN (1990's)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 1} & U_{\tau 1} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix (PMNS or MNS)





$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

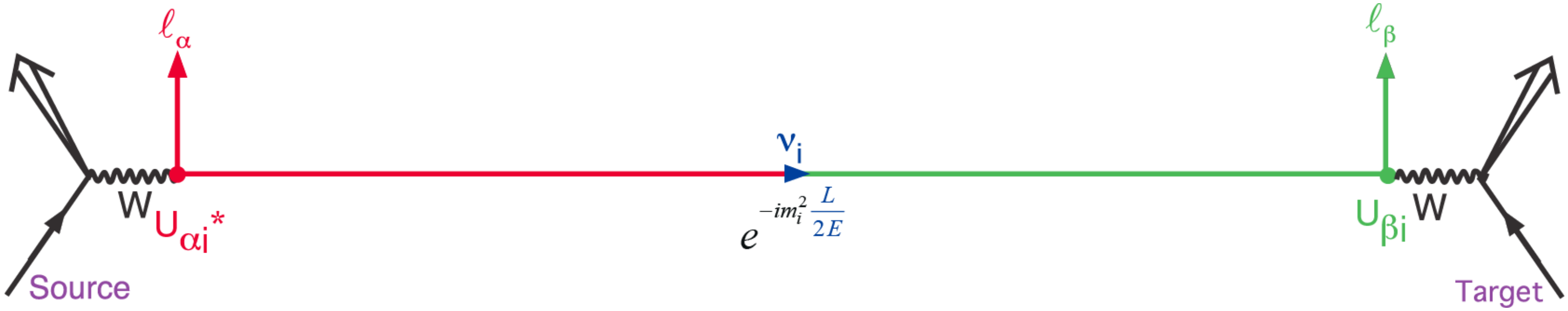
- sign for antineutrinos

$$\pm 2\sum_{i>j} \mathrm{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

often the case: one of the oscillatory terms remains zero under the experimental conditions (i.e. *L* too short, *E* too large etc.)

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right)$$

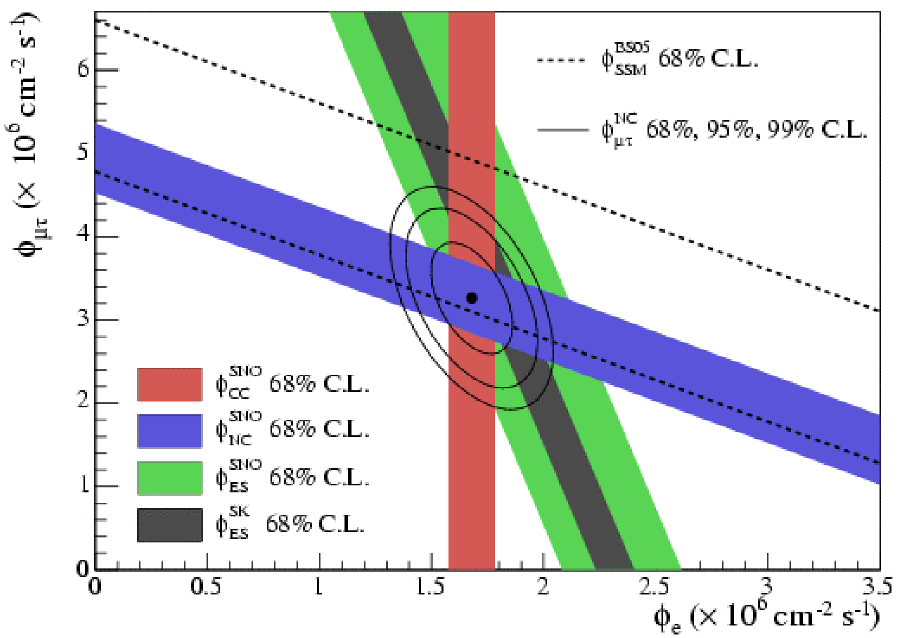
(L in km, E in GeV) or (L in m, E in MeV)



	Flavor Produced	Baseline	Energy	Flavor Detected	
The Sun	ν_e	10^{11} m	0.1-15 MeV	ν_e, NC	SNO, Super-K, others
Reactor	$\bar{\nu}_e$	1-200 km	0.3 GeV	$\bar{\nu}_e$	KamLAND, Chooz
	$\bar{\nu}_e$	0.3+2 km	0.3 GeV	$\bar{\nu}_e$	Double Chooz, Daya Bay
Cosmic rays	$(\nu_\mu+\bar{\nu}_\mu),(\nu_e+\bar{\nu}_e)$	10-10000 km	subGeV – TeV	$(\nu_\mu+\bar{\nu}_\mu),(\nu_e+\bar{\nu}_e)$	Super-K, others
Accelerator	ν_μ	250, 735 km	0.1-10 GeV	ν_μ,ν_e	K2K, MINOS
	ν_μ	295, 810 km	0.7, 2.2 GeV	ν_μ,ν_e	T2K, NOνA
	$\nu_\mu,\bar{\nu}_\mu$	540 m	500 MeV	$\nu_e,\bar{\nu}_e$	MiniBooNE
	$\nu_\mu,\bar{\nu}_\mu$	295+1000 km	0.5 GeV	$\nu_e,\bar{\nu}_e$	T2KK
Stopped π	$\bar{\nu}_\mu$	50 m	50 MeV	$\nu_e,\bar{\nu}_e$	LSND, KARMEN
Beta Beam	$\nu_e,\bar{\nu}_e$	??	0.2-10 GeV?	$\nu_e,\bar{\nu}_e,\nu_\mu,\bar{\nu}_\mu$	???
ν Factory	$(\nu_\mu+\bar{\nu}_e),(\nu_e+\bar{\nu}_\mu)$	??	20 GeV ?	$(\nu_e+\bar{\nu}_\mu),(\nu_\mu+\bar{\nu}_e)$	???

The first hints of neutrino mixing, and the first convincing results came from natural sources

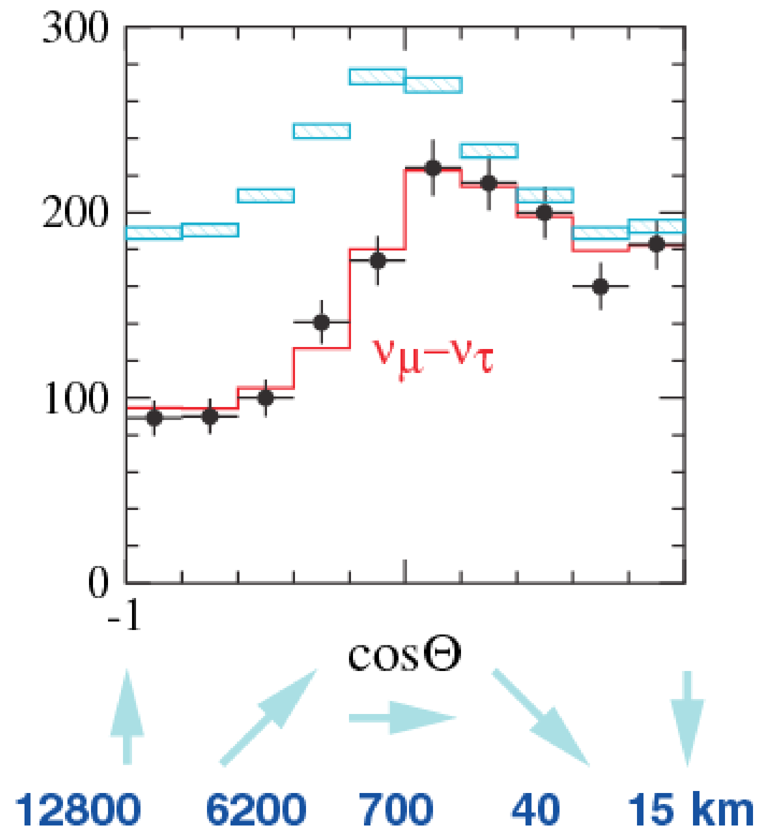
Solar Neutrinos



$$\Phi(\nu_e) < \Phi(\nu_e + \nu_\mu + \nu_\tau) \approx \Phi(\mathrm{SSM})$$

Also important: Super-K, Kamiokande, SAGE, Gallex/GNO, Homestake

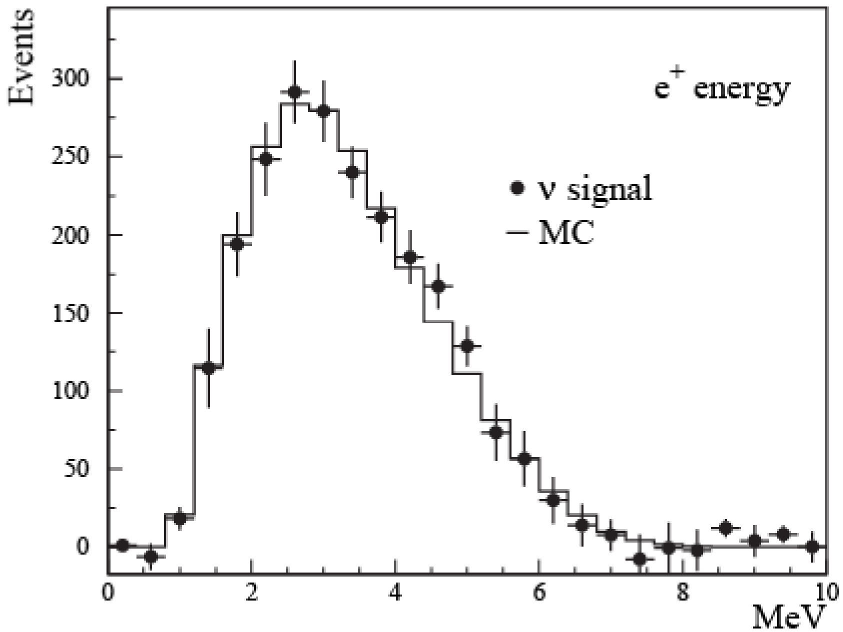
Atmospheric Neutrinos

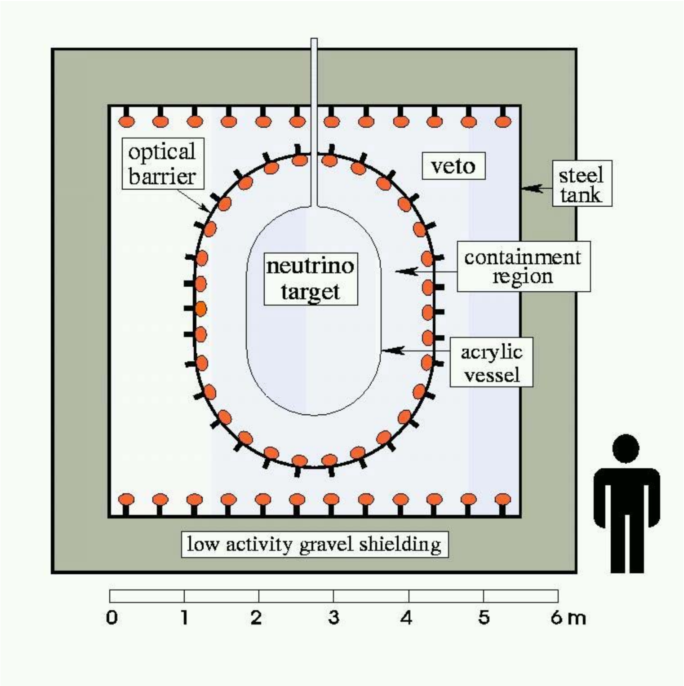


Confirmed by MACRO, Soudan 2

Started by Kamiokande and IMB

But we must keep in mind an important negative result – Chooz reactor experiment



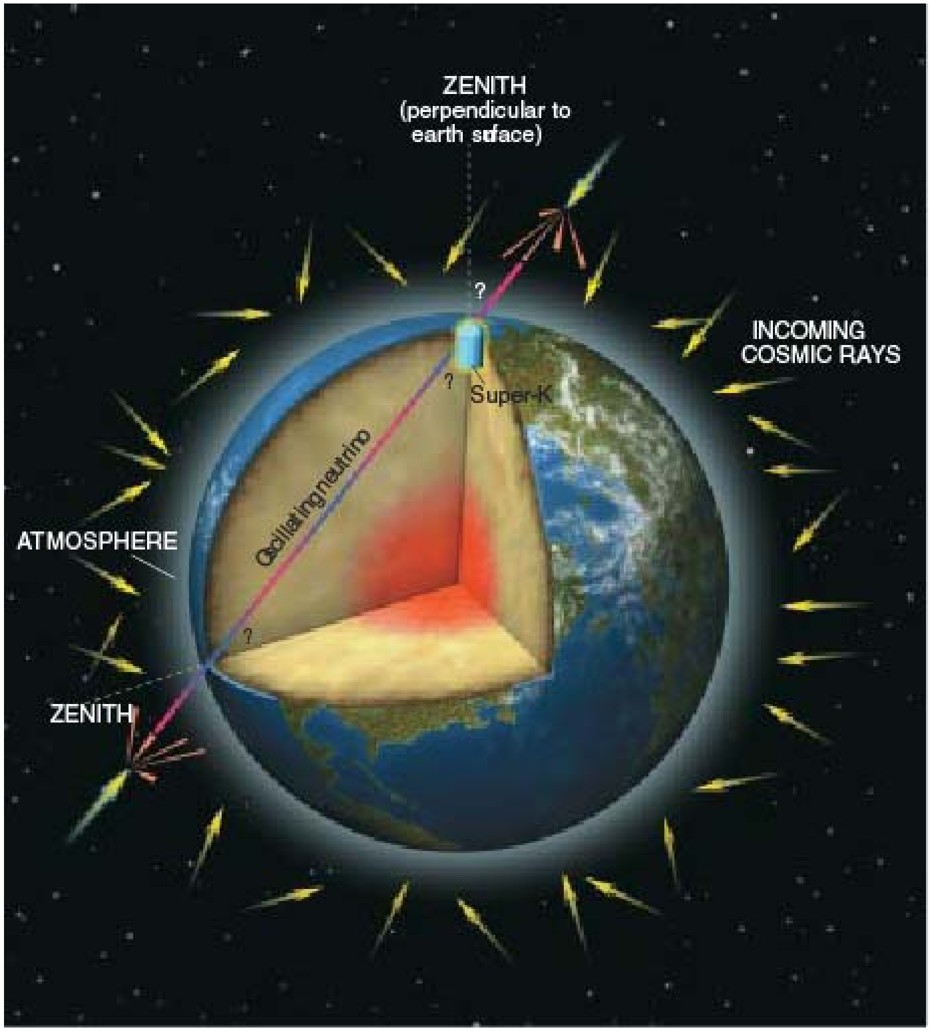


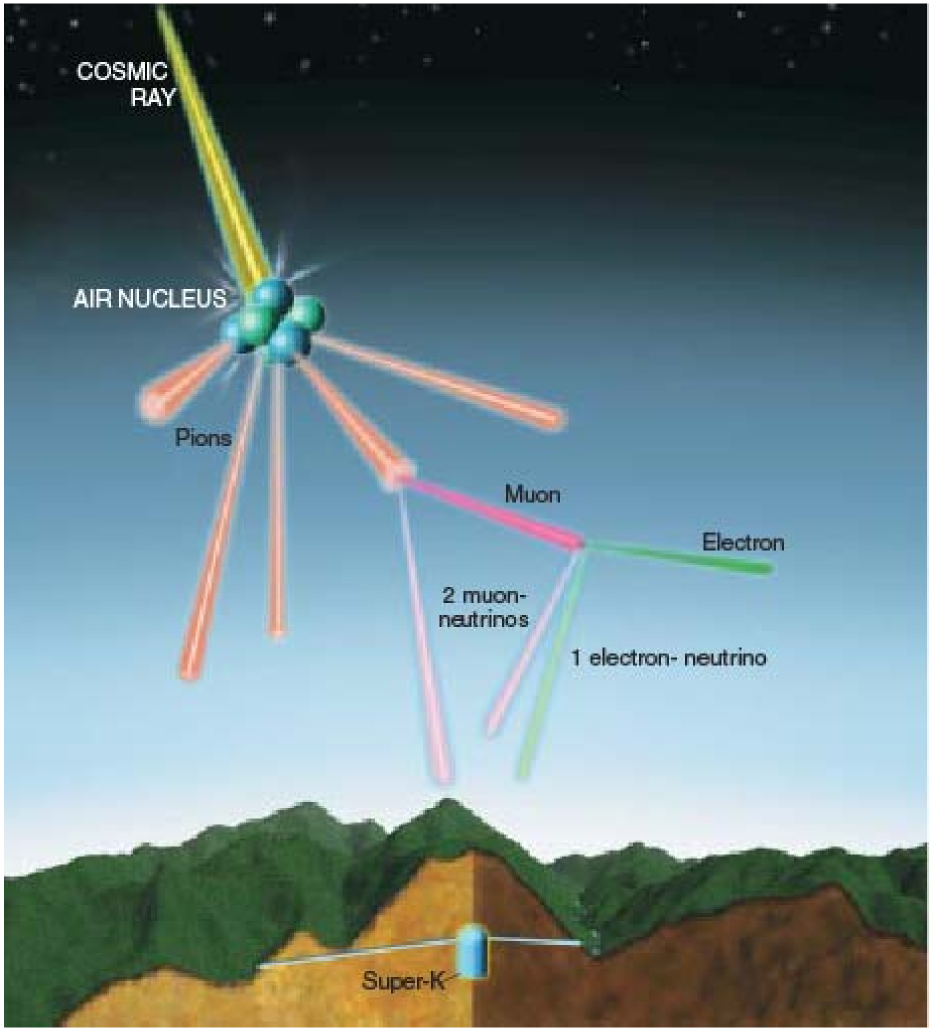
No evidence for electron neutrino disappearance over ~ 1 km

$$\sin^2 2\theta < 0.2 \ \ (\text{at } \Delta m^2 \sim 2\times10^{-3}\text{eV}^2)$$

Also Palo Verde Reactor experiment

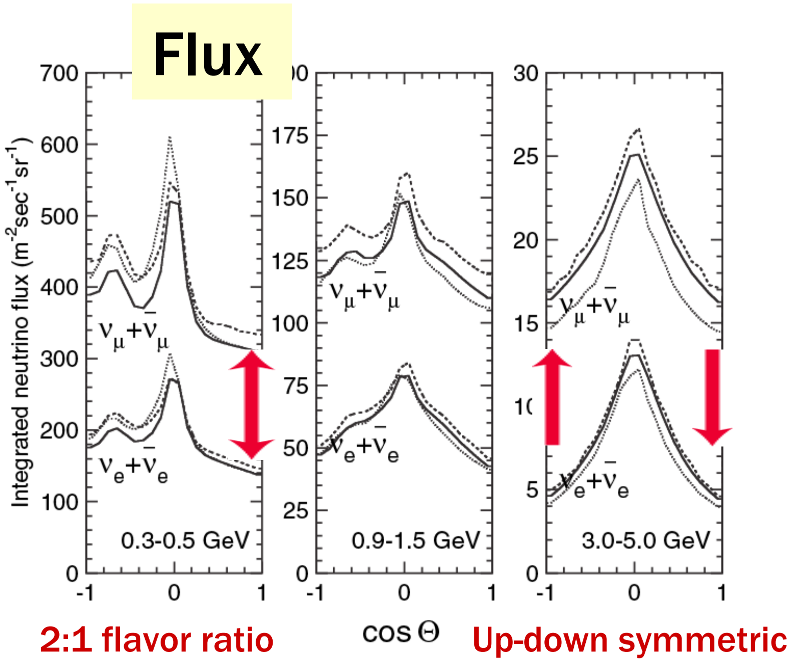
Atmospheric Neutrinos

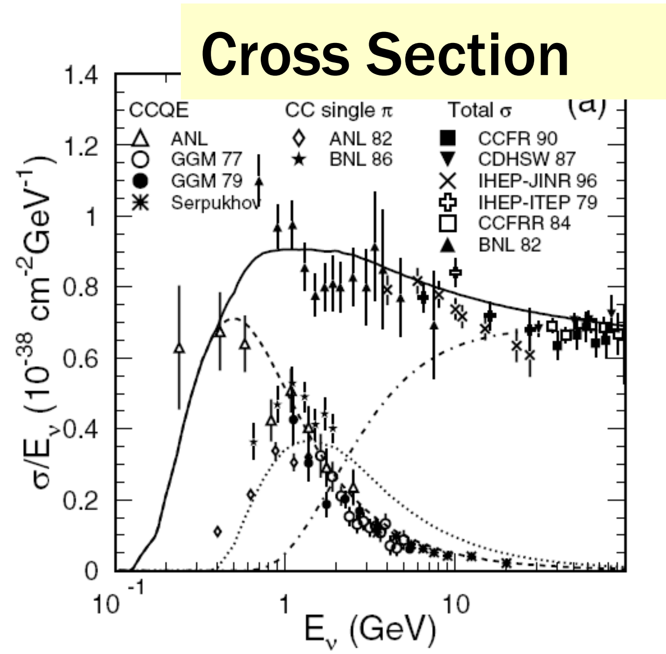


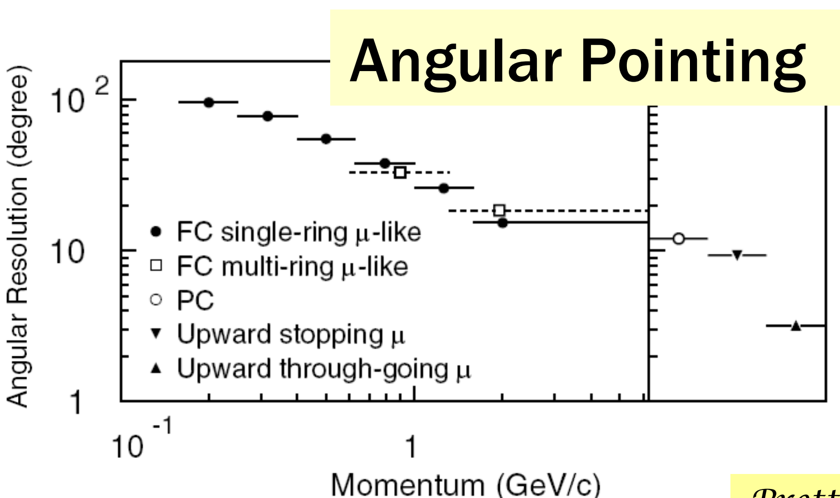


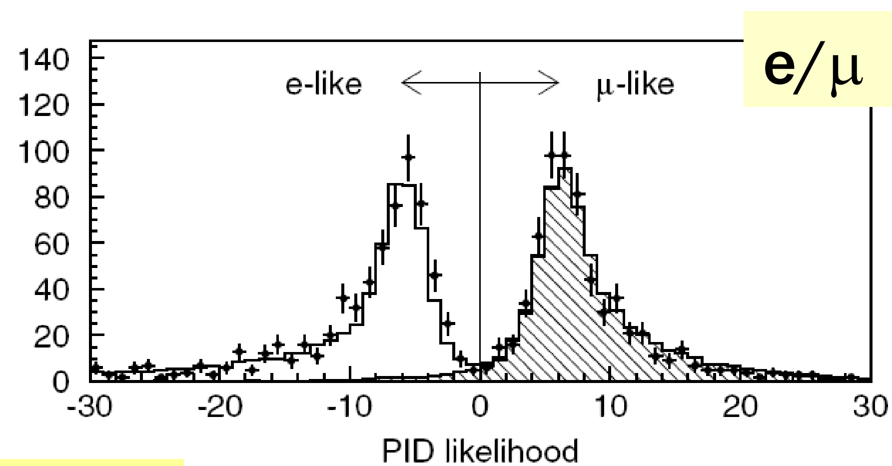
Pretty!

Atmospheric Neutrinos





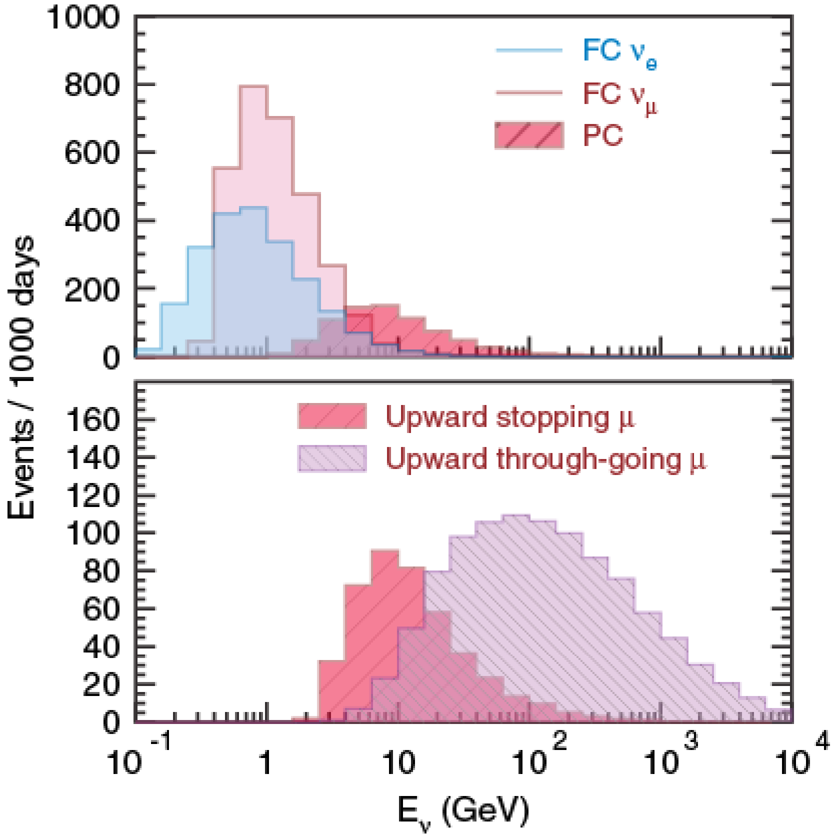




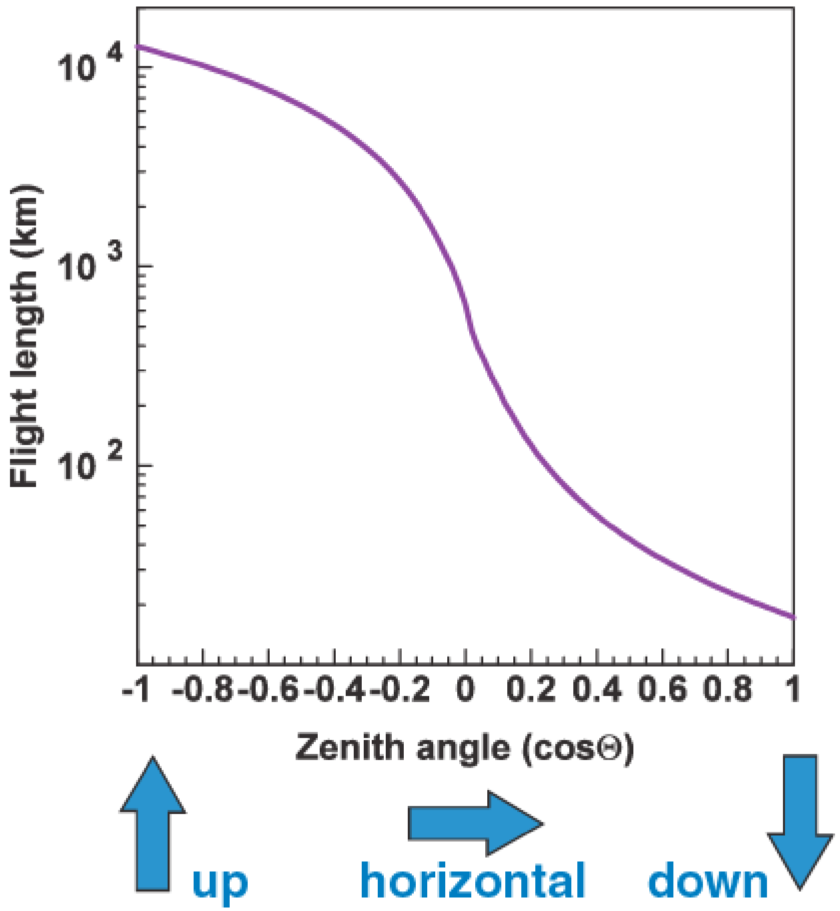
Pretty technical!

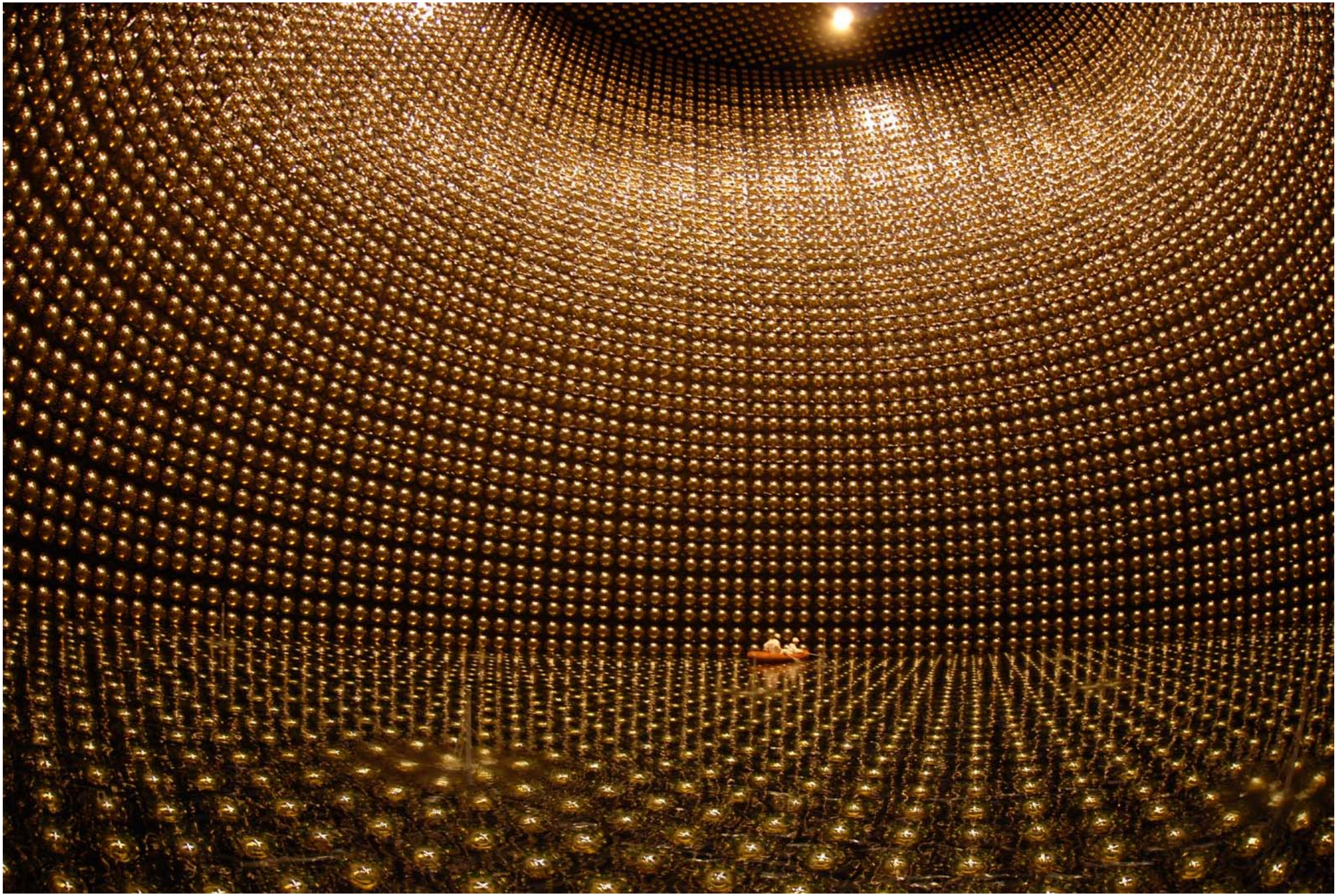
Atmospheric Neutrinos

5 decades of neutrino energy

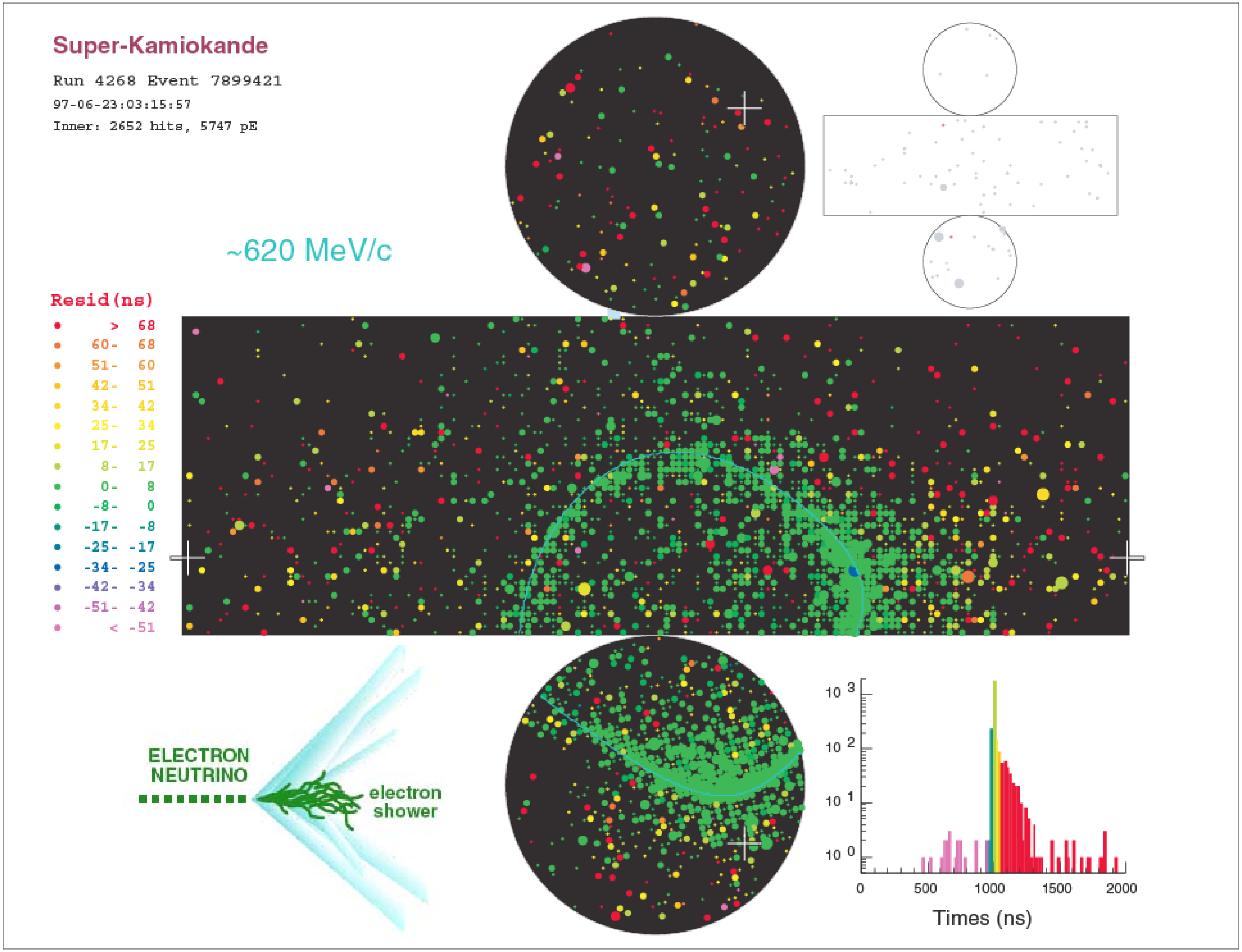


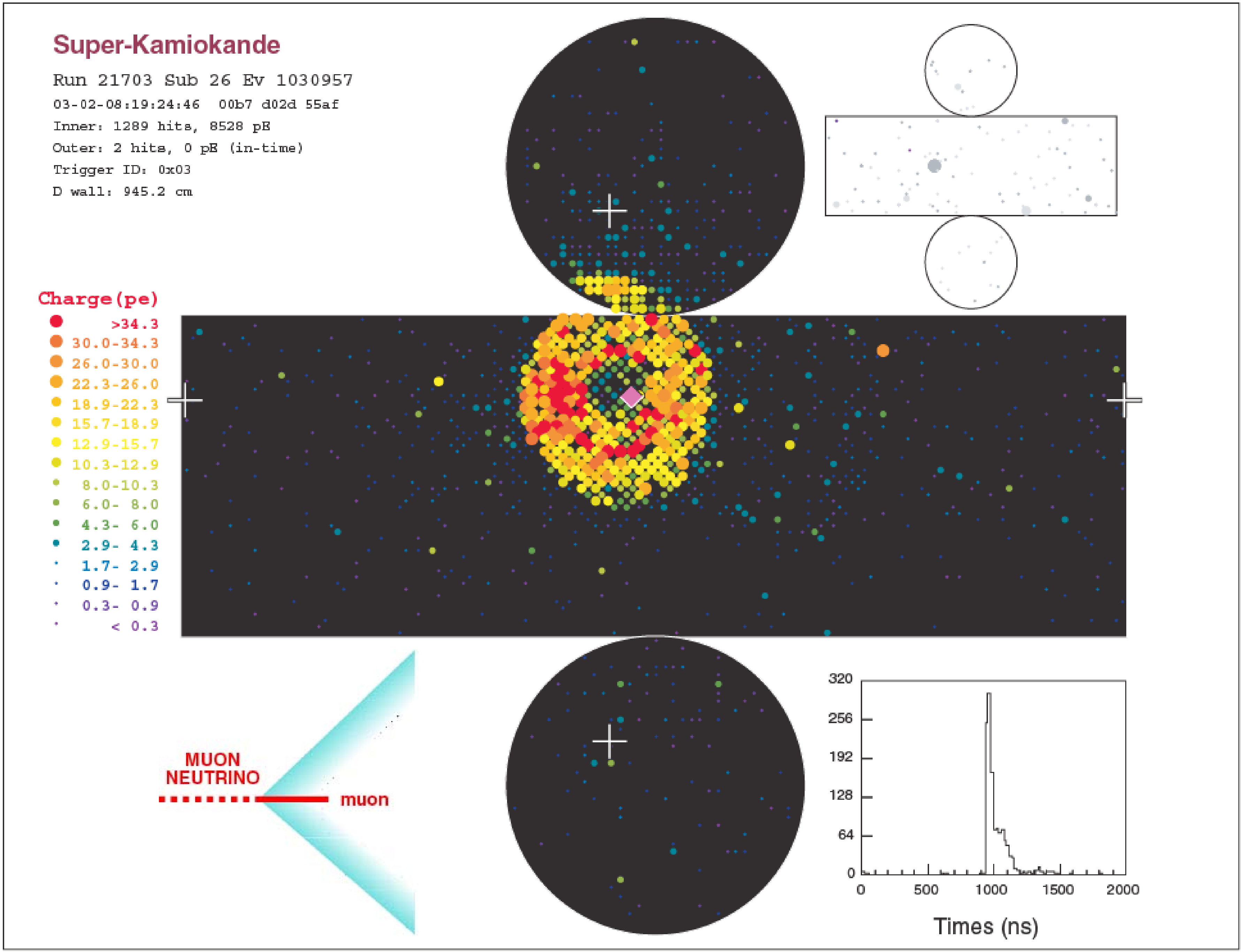
Three decades of pathlength



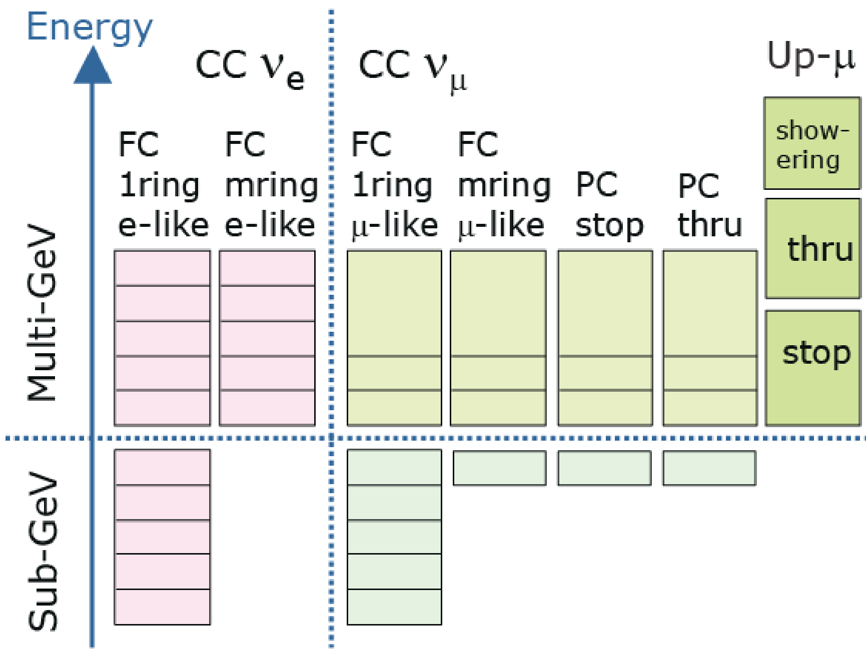


Super-Kamiokande III (newly rebuilt, filling in May 2006)


Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5747 pE
~620 MeV/c
Resid(ns)
> 68
60- 68
51- 60
42- 51
34- 42
25- 34
17- 25
8- 17
0- 8
-8- 0
-17- -8
-25- -17
-34- -25
-42- -34
-51- -42
< -51
ELECTRON NEUTRINO
electron shower
10 3
10 2
10 1
10 0
0
500
1000
1500
2000
Times (ns)


Super-Kamiokande
Run 21703 Sub 26 Ev 1030957
03-02-08:19:24:46 00b7 d02d 55af
Inner: 1289 hits, 8528 pE
Outer: 2 hits, 0 pE (in-time)
Trigger ID: 0x03
D wall: 945.2 cm
Charge(pe)
>34.3
30.0-34.3
26.0-30.0
22.3-26.0
18.9-22.3
15.7-18.9
12.9-15.7
10.3-12.9
8.0-10.3
6.0- 8.0
4.3- 6.0
2.9- 4.3
1.7- 2.9
0.9- 1.7
0.3- 0.9
< 0.3
MUON
NEUTRINO
muon
320
256
192
128
64
0
0
500
1000
1500
2000
Times (ns)

How we bin and fit the data at SK



380 bins × (SK-I+SK-II)
+ 70 systematic terms

number of p, Θ bins

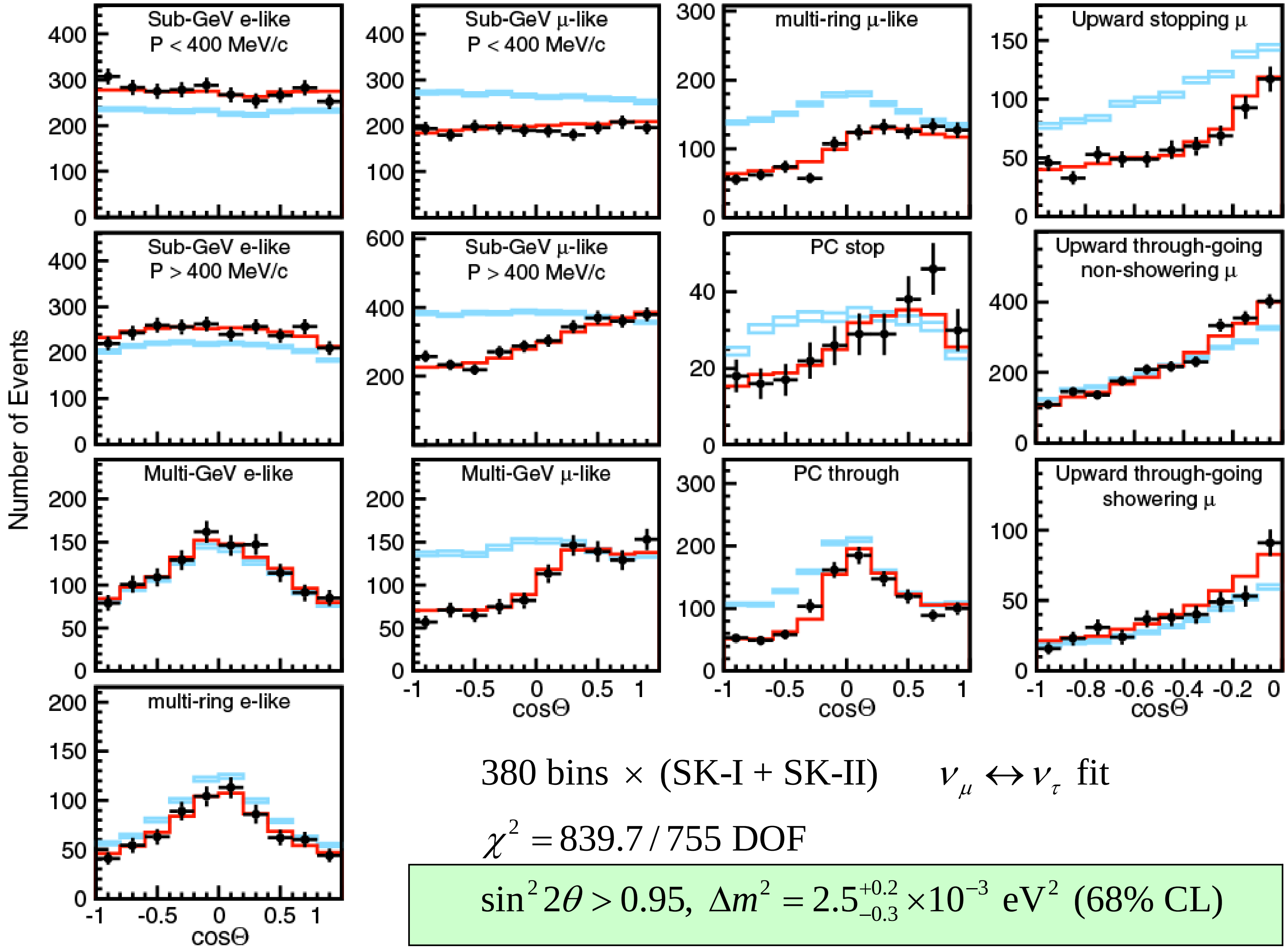
number of sys. effects (some norms. are free)

$$\chi^2 = \sum_{i=1}^{380} \frac{\left(N_i^{obs} - N_i^{\exp}(1 + \sum_{j=1}^{70} f_j^i \cdot \varepsilon_j)\right)^2}{\sigma_i^2} + \sum_{j=1}^{65} \left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

$$N_i^{\exp} = N_i^0 \cdot P(\nu_\alpha \to \nu_\beta) \cdot (1 + \sum_{j=1}^{39} f_j^i \cdot \varepsilon_j)$$

fractional change in predicted event rate due to variation in systematic parameter ε

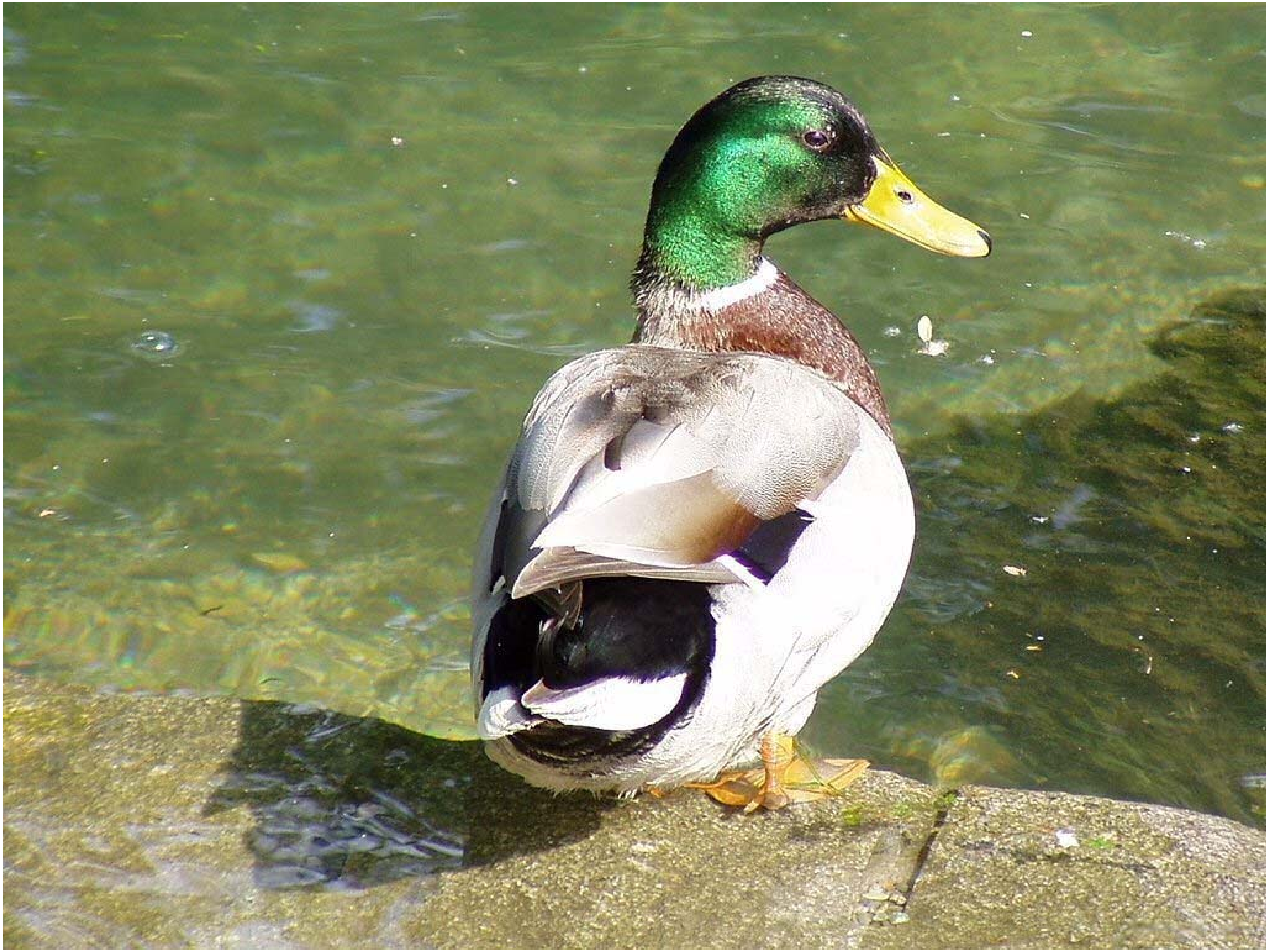
Muon Neutrino – Tau Neutrino Mixing



380 bins × (SK-I + SK-II) $\nu_\mu \leftrightarrow \nu_\tau$ fit

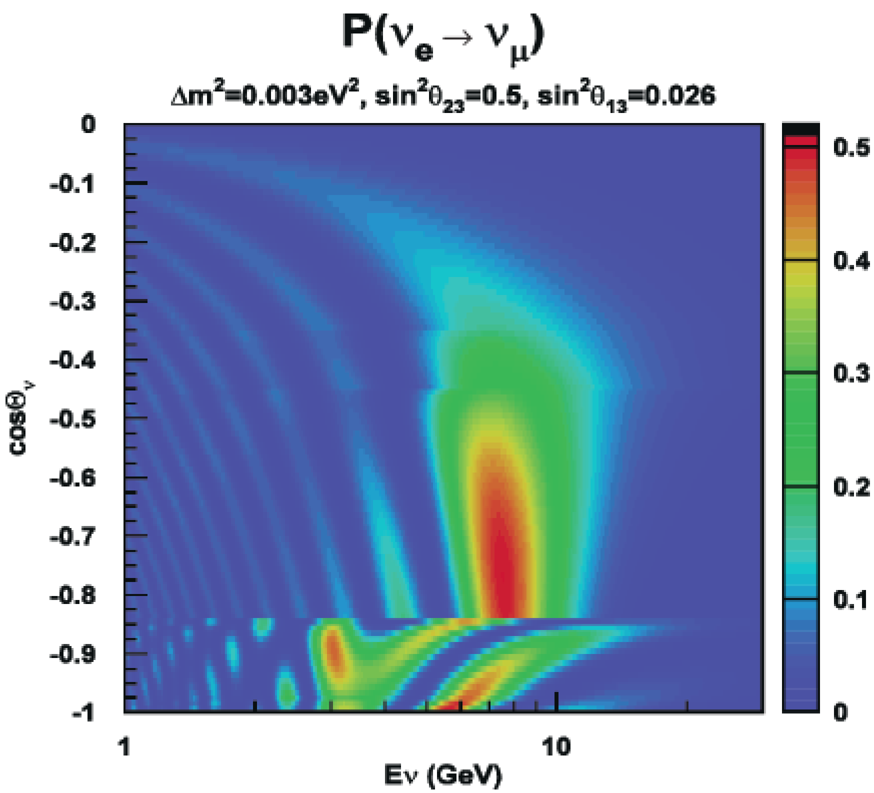
$\chi^2 = 839.7 / 755$ DOF

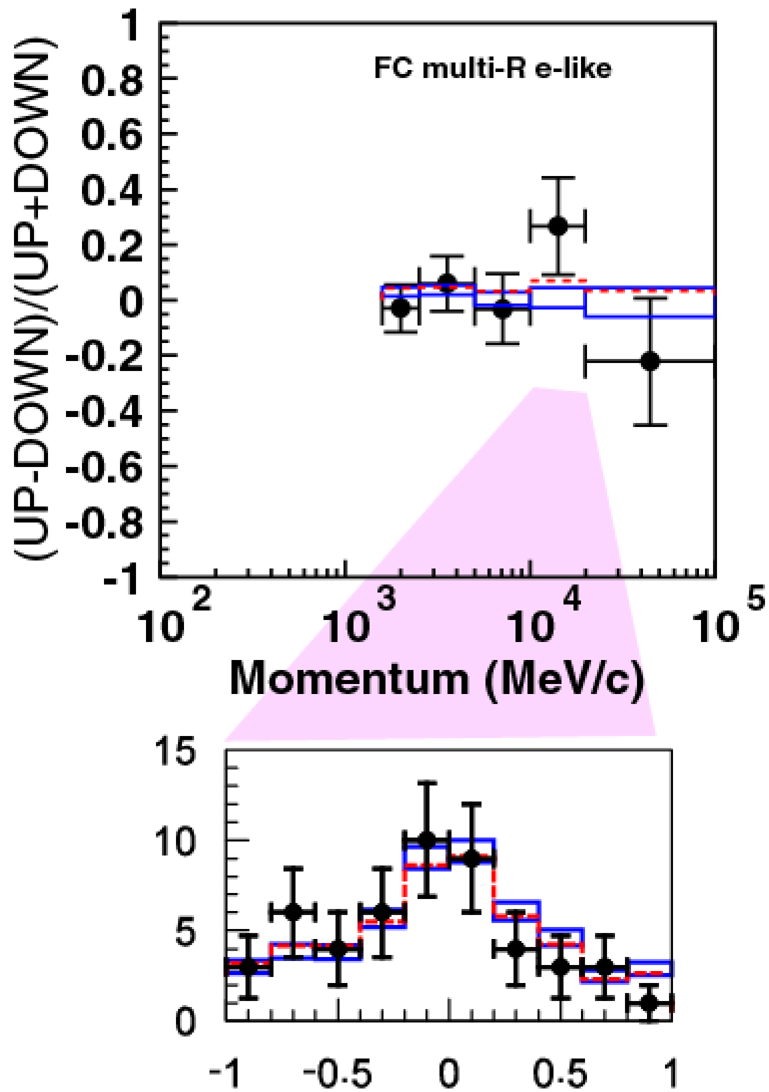
$\sin^2 2\theta > 0.95,\ \Delta m^2 = 2.5^{+0.2}_{-0.3} \times 10^{-3}$ eV^2 (68% CL)



What about electron neutrinos?

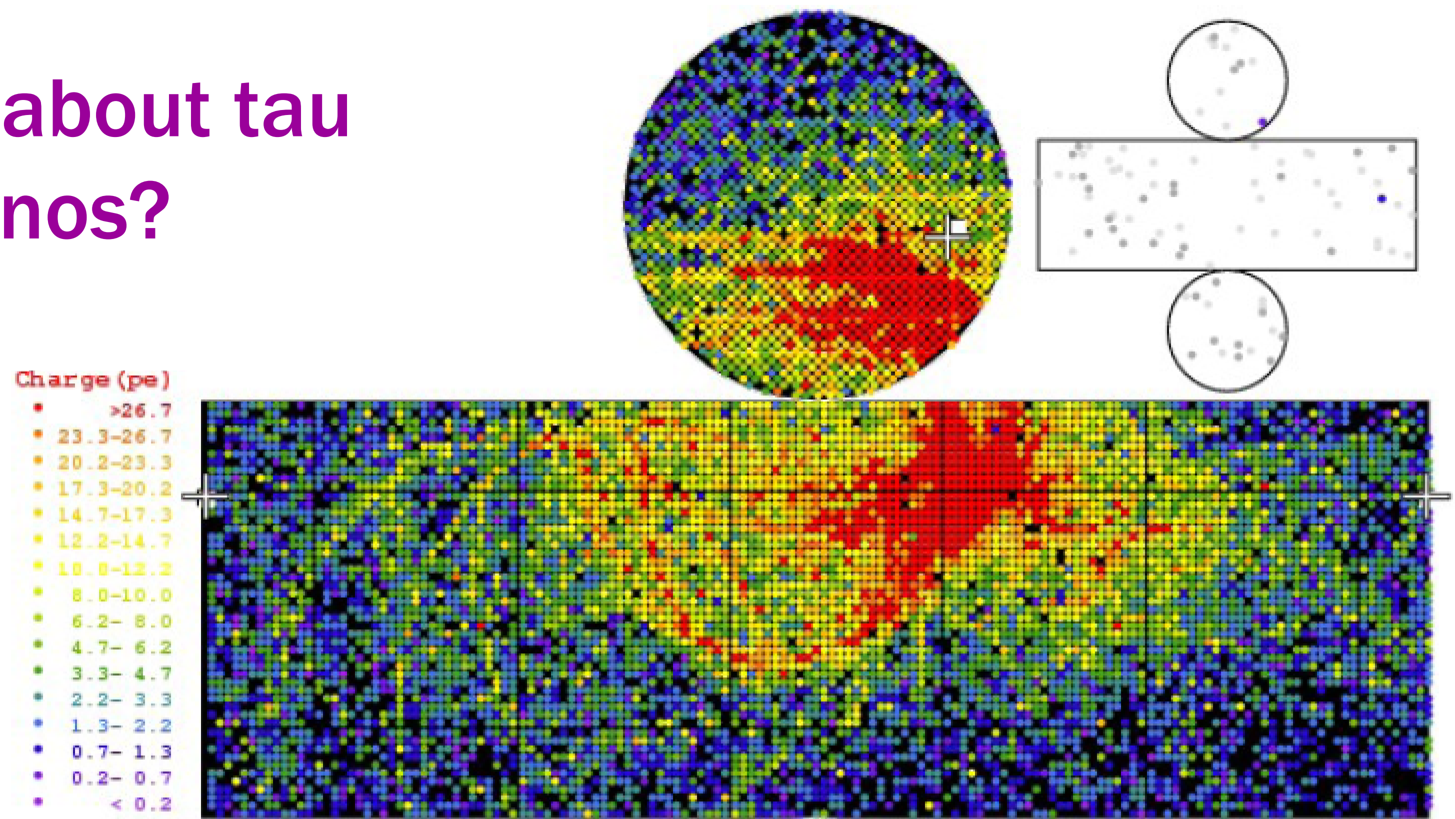
Strategy: bin data very finely and look for enhancement at certain energies and angles due to electron neutrino resonance in earth

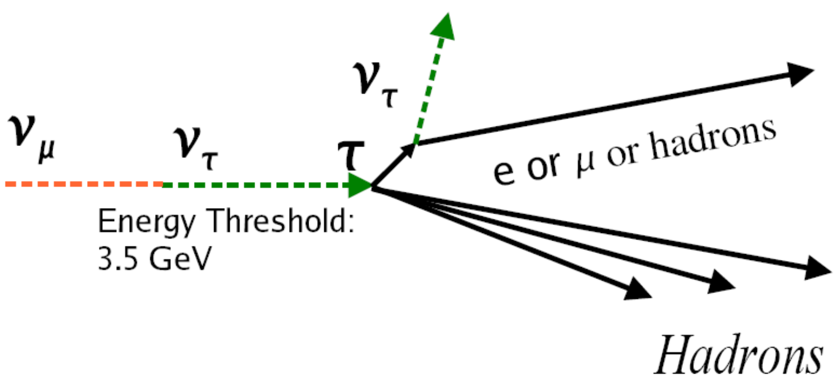


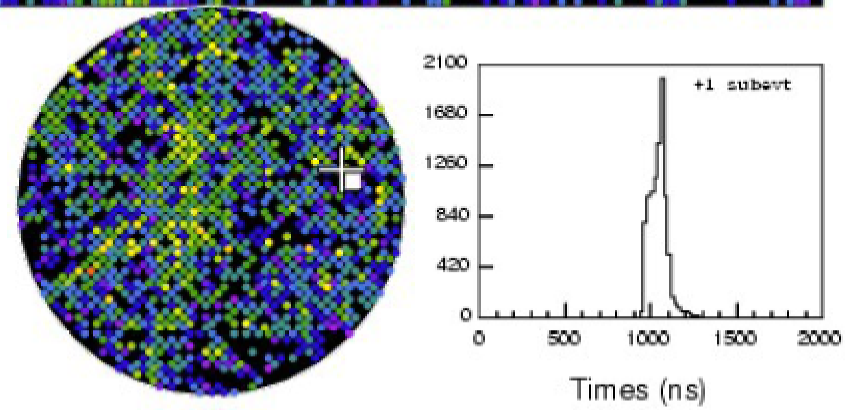


no signs of enhancement in this or other data sub-samples.

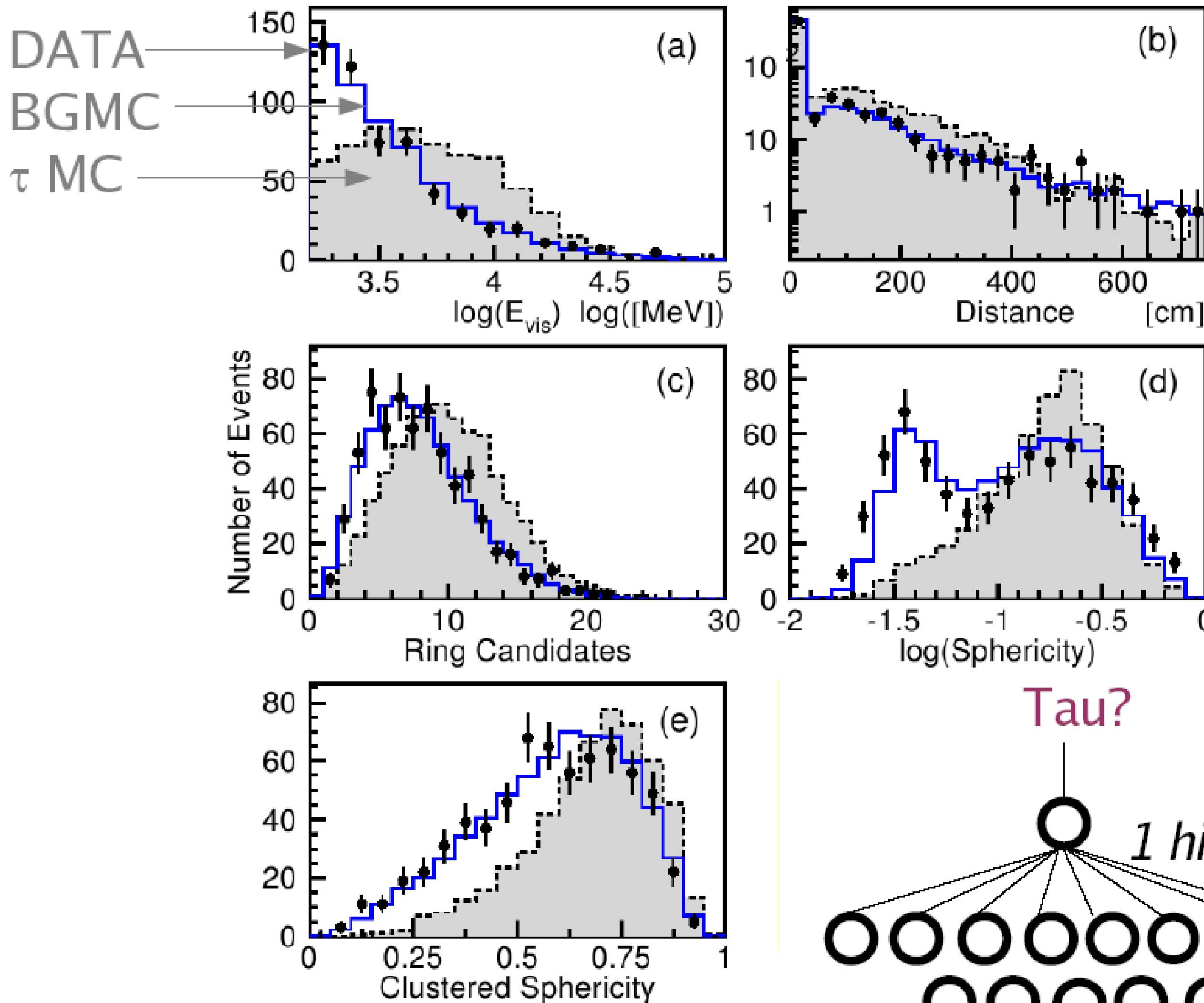
What about tau neutrinos?



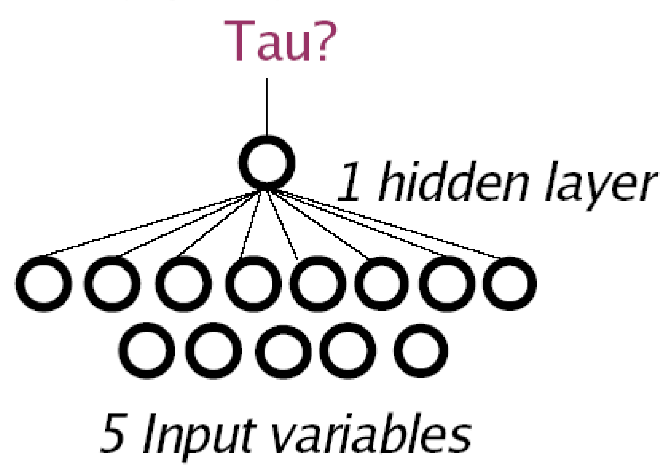




Neural Network Analysis of Tau Appearance



There should be no tau events in the down-going data.



Neural Network Analysis of Tau Appearance

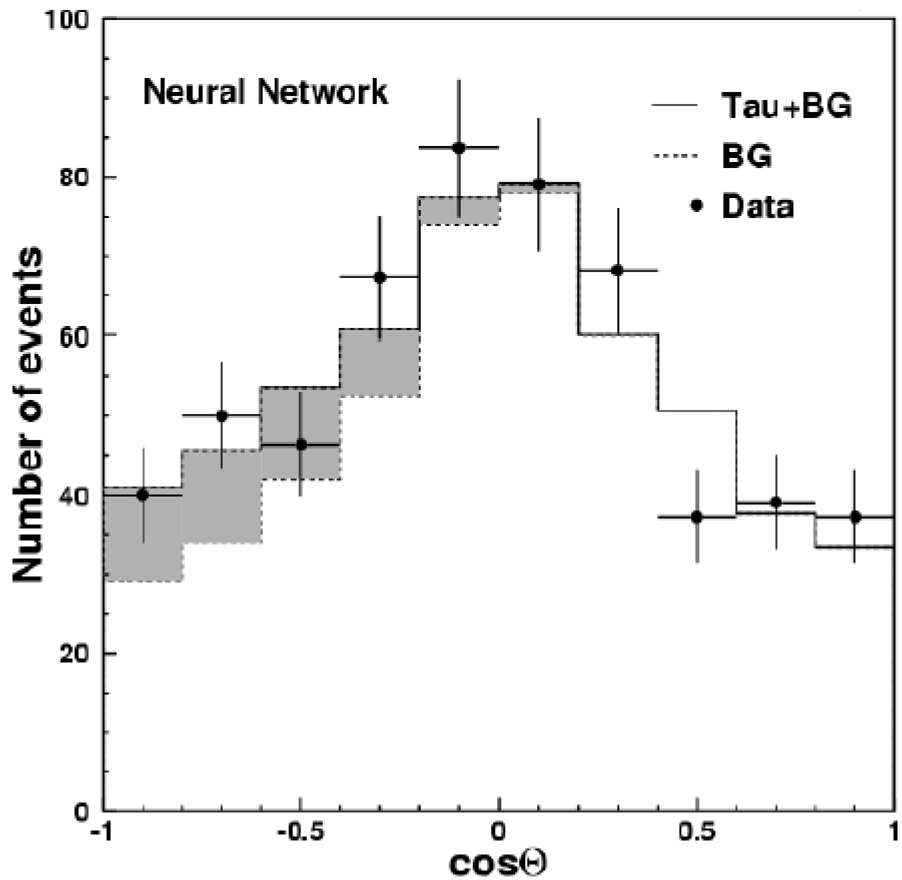
$$f(\cos(\theta)) = \alpha \times (Tau) + \beta \times (No\ Tau)$$

Tau Excess

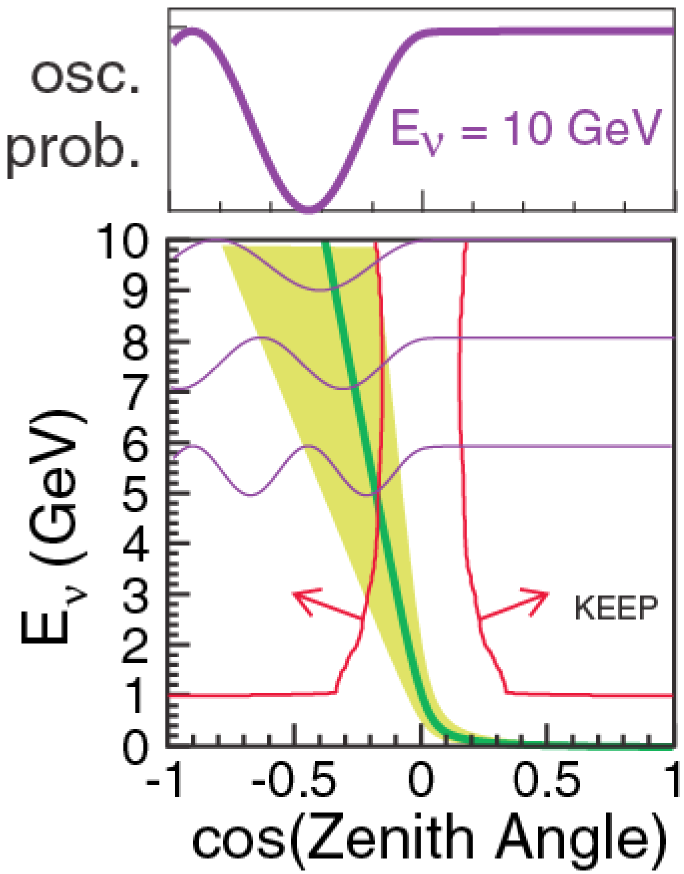
$134 \pm 48^{+16}_{-27}$ events in excess

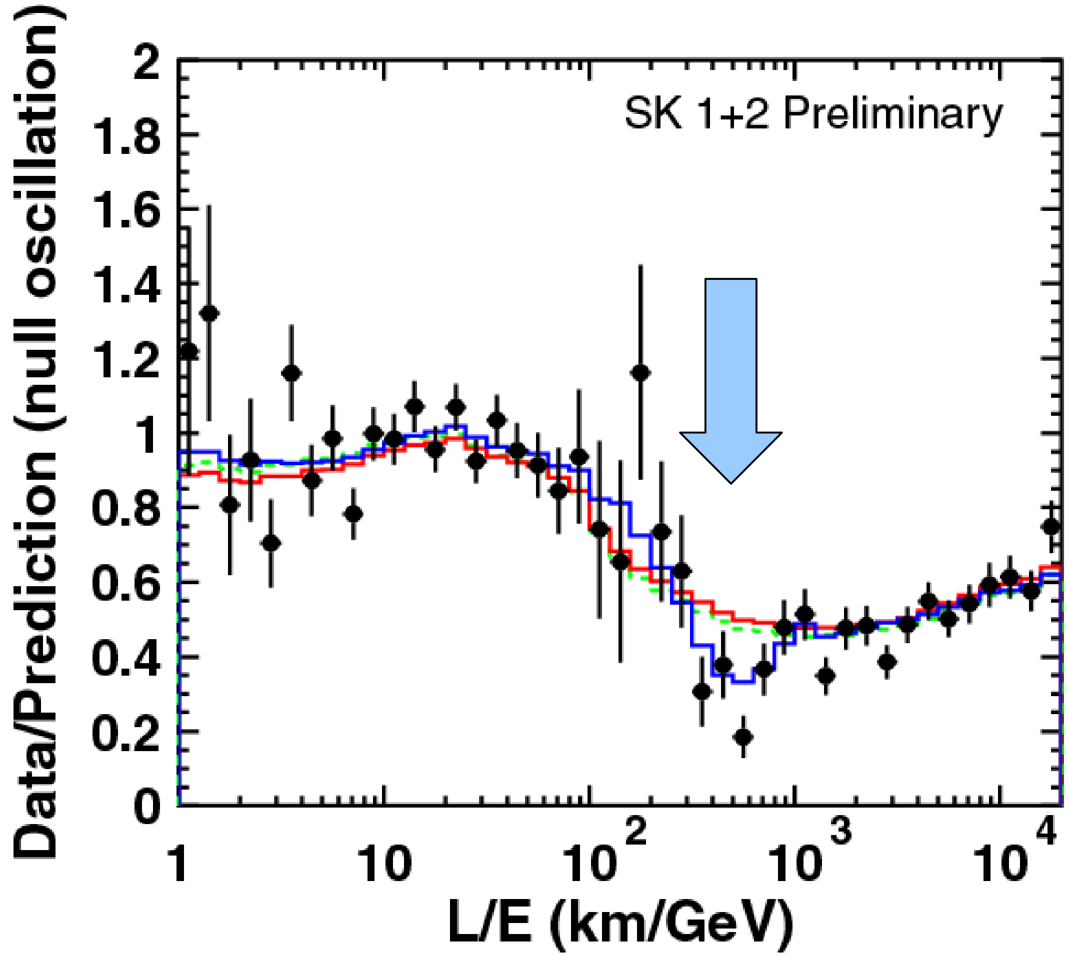
$cf.\ 78 \pm 27$ excess events expected

$\sim 2.4\sigma$ effect



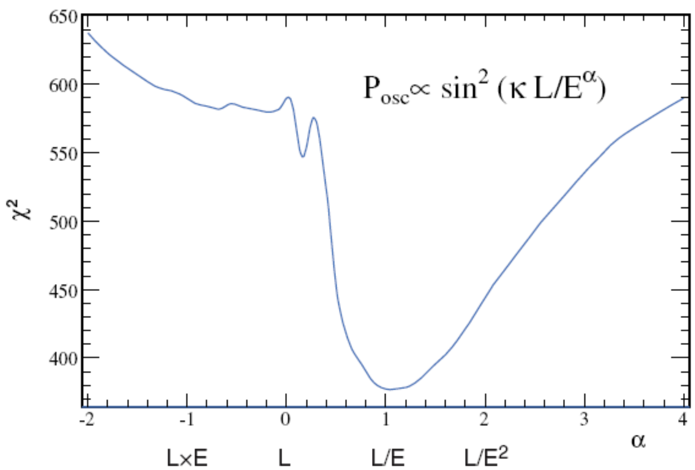
What about the oscillation pattern?





Expand Fiducial Volume
Keep events with good L/E resolution


the DoDo & Given
by G.EDWARDS
F.R.S. A.D. 1759.



Lorentz Invariance Violation?
Weak Equivalence Principle,
CPT Invariance Violation?

Best fit is at L/E^1.

$\Delta\chi^2 > 100$ disfavored by $> 10\sigma$

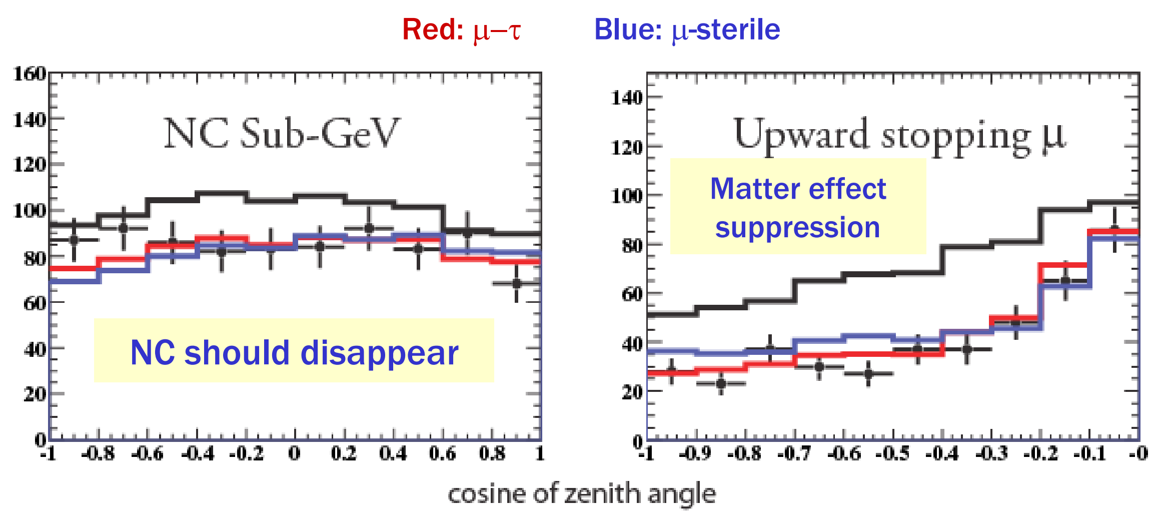
Sterile Neutrinos?

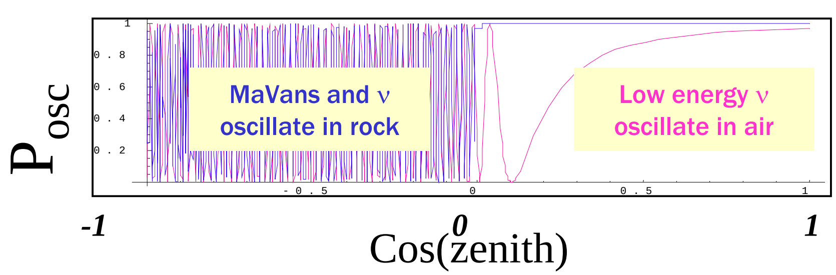
$\nu_\mu \leftrightarrow \nu_{sterile}$ $\chi^2 = 513.5/438$ DOF

$\nu_\mu \leftrightarrow \nu_\tau$ $\chi^2 = 481.5/438$ DOF

$\Delta\chi^2 = 31$

$\sqrt{\Delta\chi^2} = 5.6\sigma$



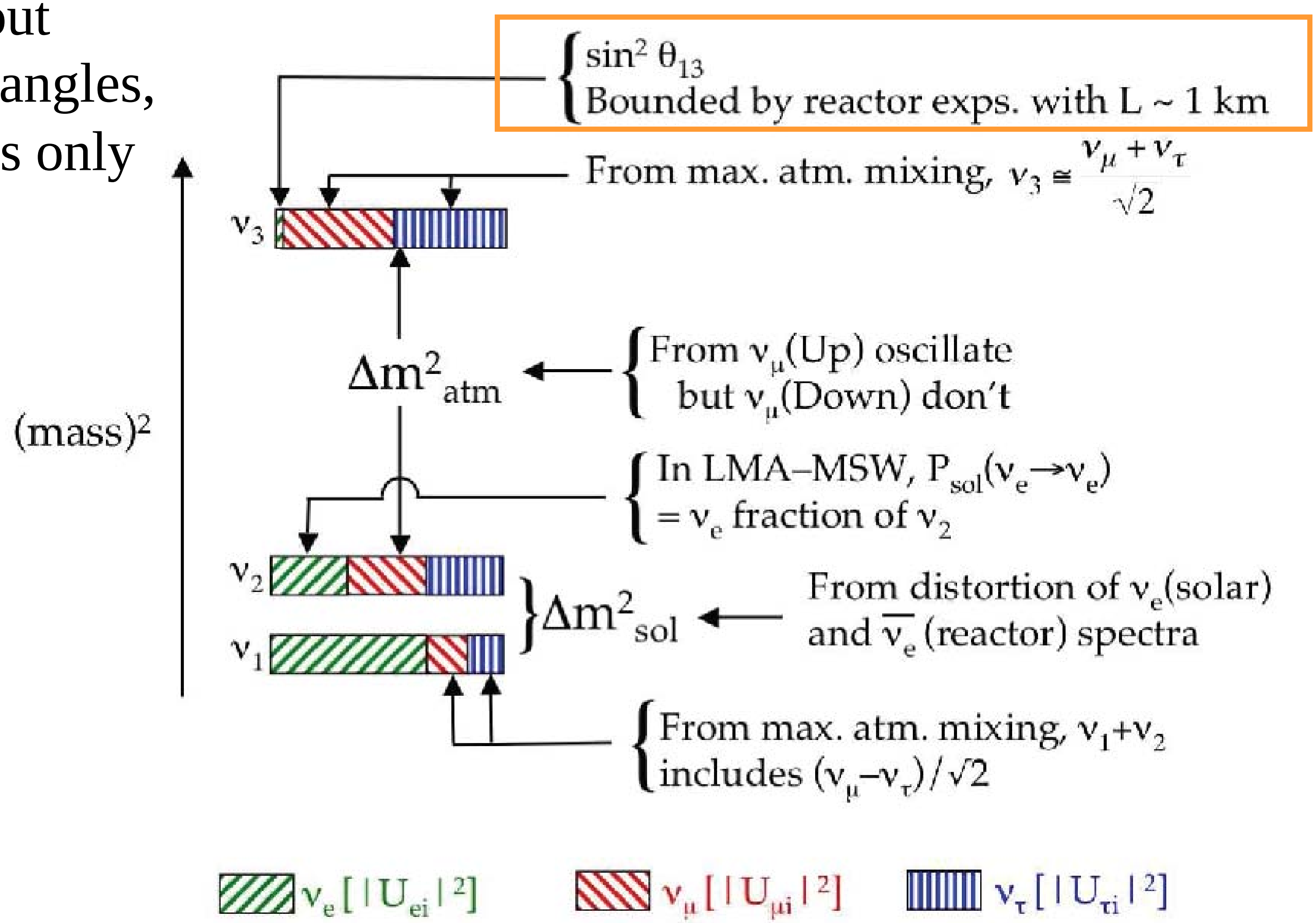


$\Delta\chi^2 = 19.5$ 4.4σ

MaVaNs?

hep-ph/0401099 – Dark energy related scalar field causes ρ dependent Δm^2

We know a certain amount about the mixing angles, except θ_{13} is only bounded.



By B. Kayser

Neutrino Mixing Matrix Parameterization

times Majorana Phases (not shown)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

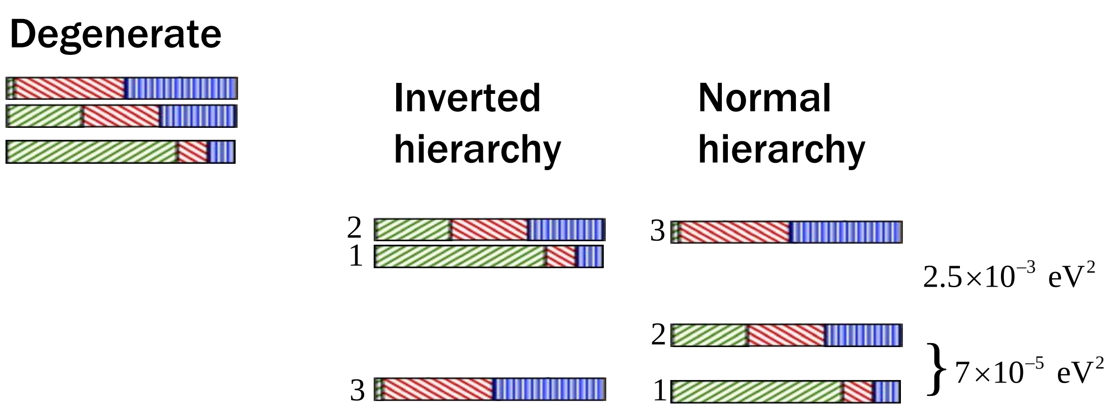
$\theta_{23} \sim \theta_{atm.} \approx 45^\circ$ $\theta_{13} < 12^\circ$ $\theta_{12} \sim \theta_{solar} \approx 32^\circ$

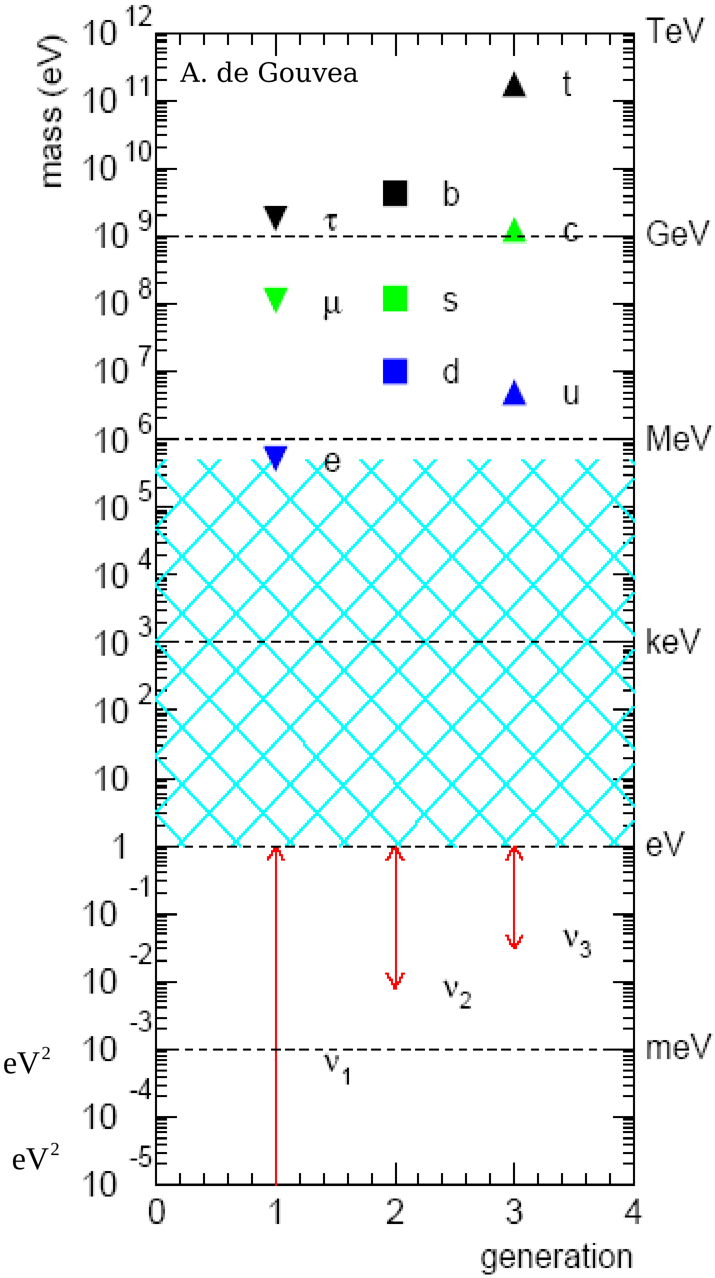
δ is totally unknown

WHY??

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

We know the neutrino is much lighter than the quarks and leptons, and we have measured the mass splittings pretty well. The most massive must have m > 0.05 eV ($\sqrt{\Delta m^2_{atm}}$). We know the heirarchy between 1 and 2. But we don't know:





Three Active Neutrinos

$$LSND: \quad \Delta m^2 \sim eV^2$$

$$Atmospheric: \quad \Delta m^2 \sim 2.5\times10^{-3} eV^2$$

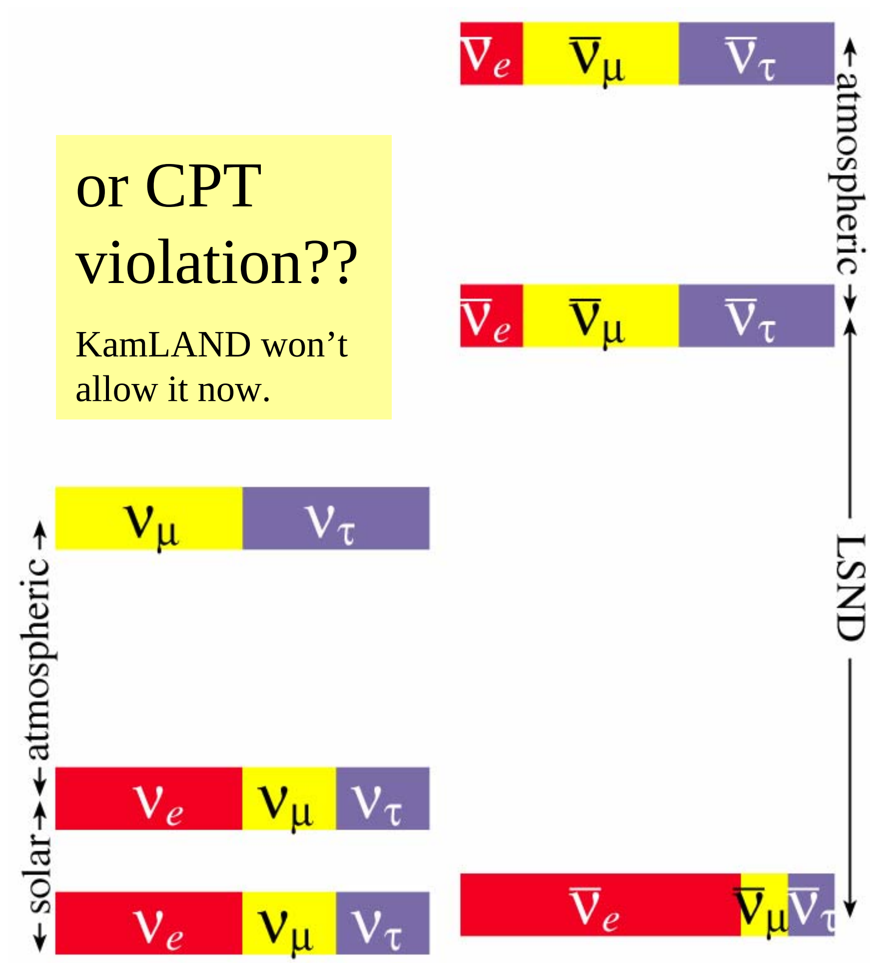
$$Solar: \quad \Delta m^2 \sim 8\times10^{-5} eV^2$$

Pick any two!

or a sterile neutrino??

or CPT violation??

KamLAND won't allow it now.



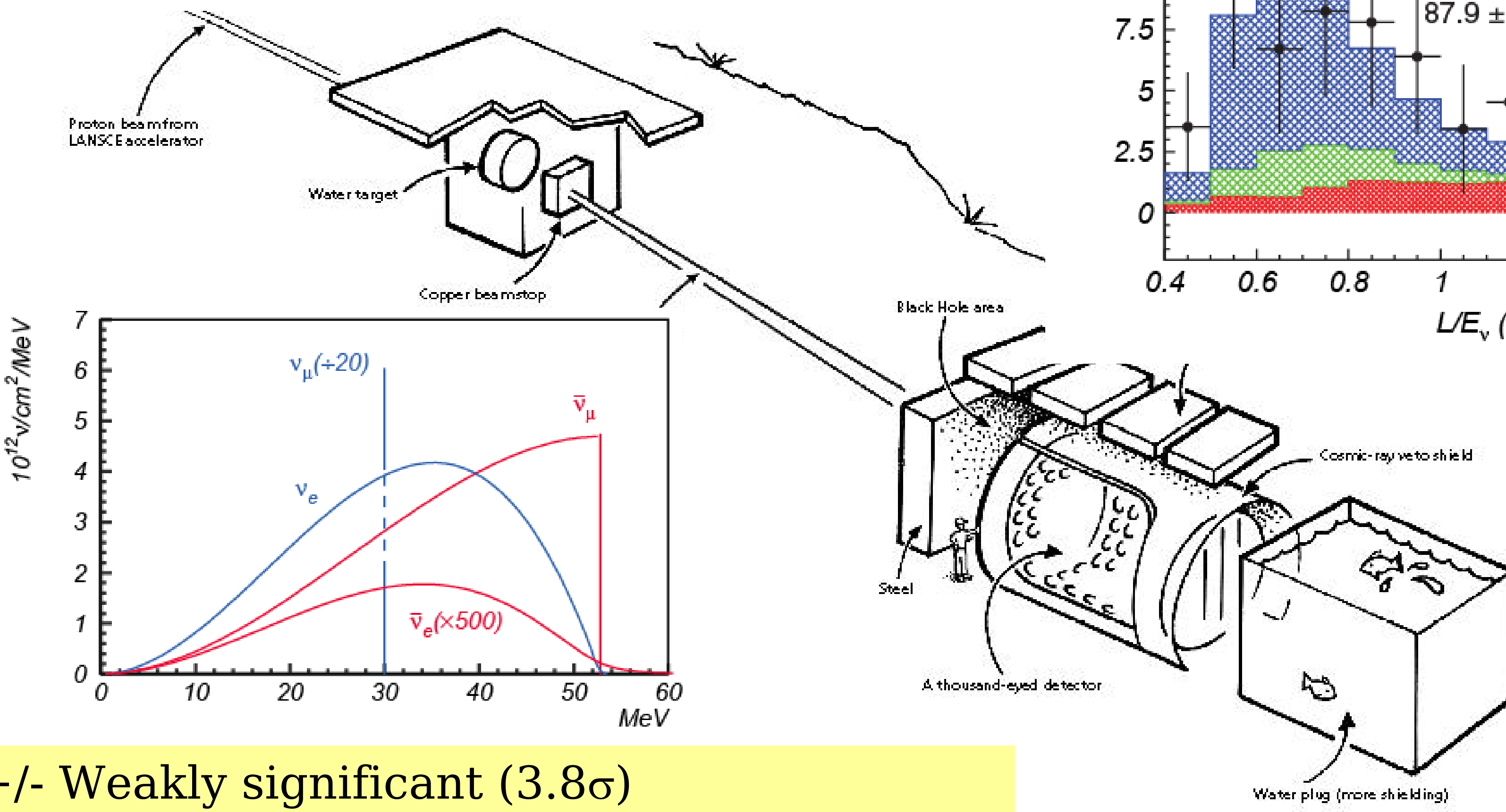
H. Murayama

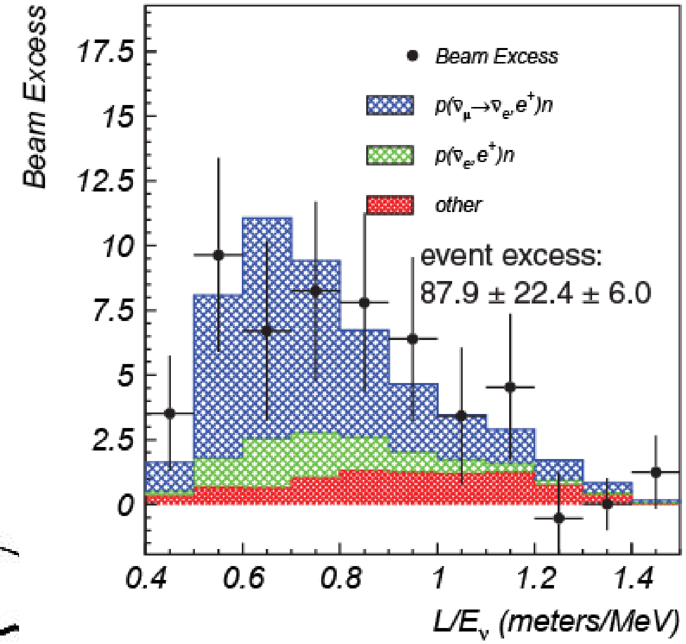
stopped pion beam ⇒
decay-at-rest spectra:

LSND

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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





+/- Weakly significant (3.8σ)
+ No known defect
- Complementary experiment, KARMEN, sees no effect (+ but with less sensitivity)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

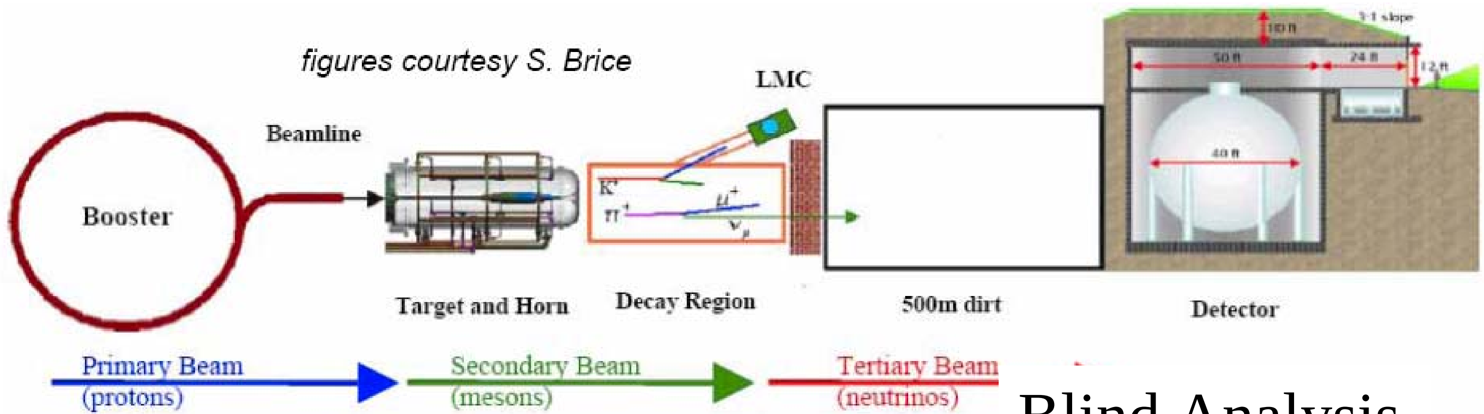
$$n + p \rightarrow d + \gamma\,(2.2\ \text{MeV})$$

MiniBooNE

$L = 540$ m ($10\times$ LSND)

$E = 500$ MeV ($10\times$ LSND)

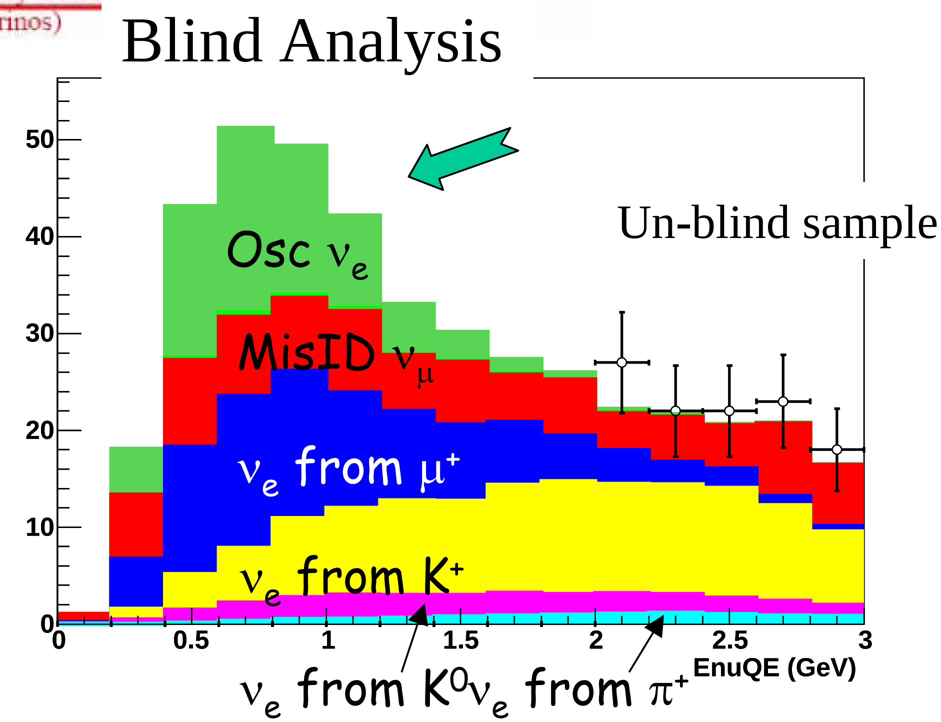
ν_μ not $\bar{\nu}_\mu$



950 kl of pure mineral oil
Cherenkov+scintillation
1280 PMTs

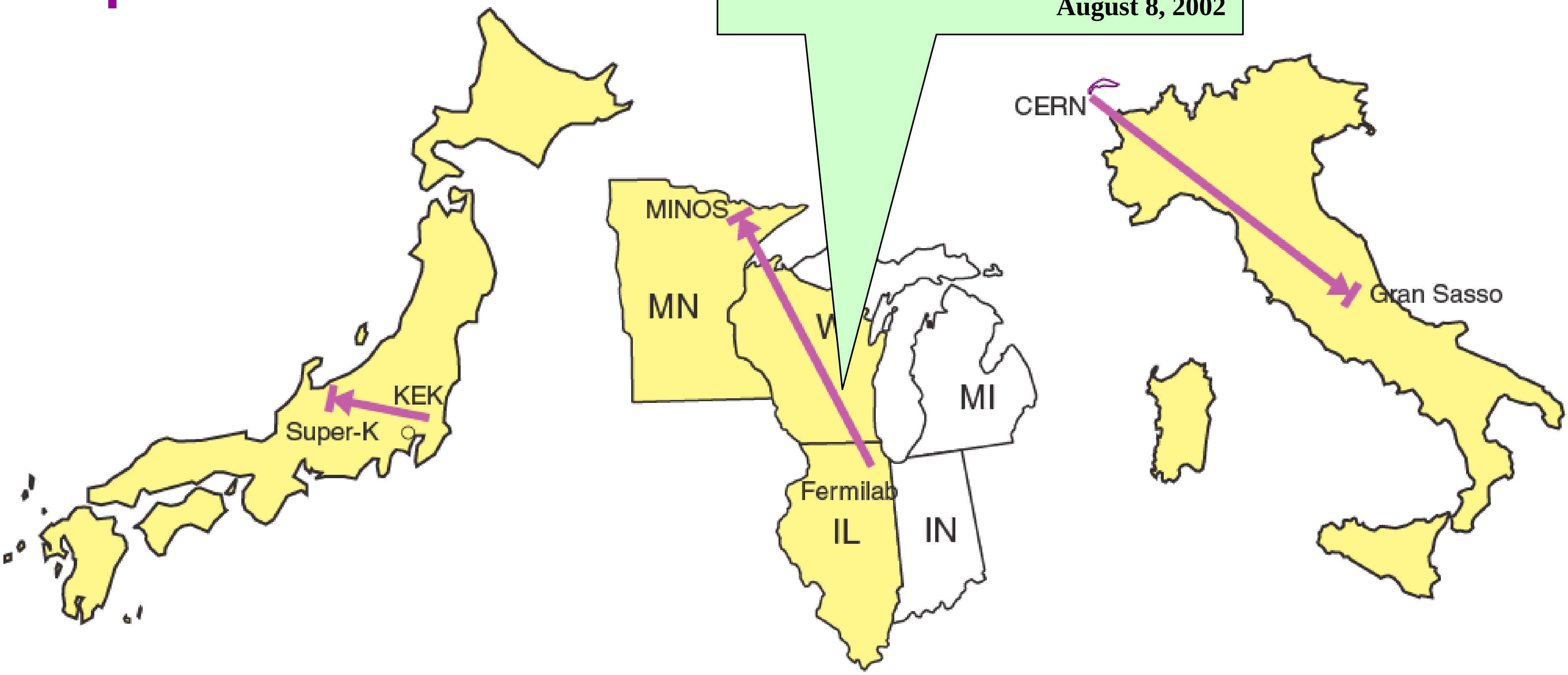
STATUS:

- 7.2×10^{20} pot
- anti-ν since Jan. 2006
- Expect result "real soon now"
- Important to be unambiguous and correct!



Long Baseline Experiments

ILLINOIS LAB WILL BOMBARD WISCONSIN WITH NEUTRINOS
Wisconsin State Journal
August 8, 2002



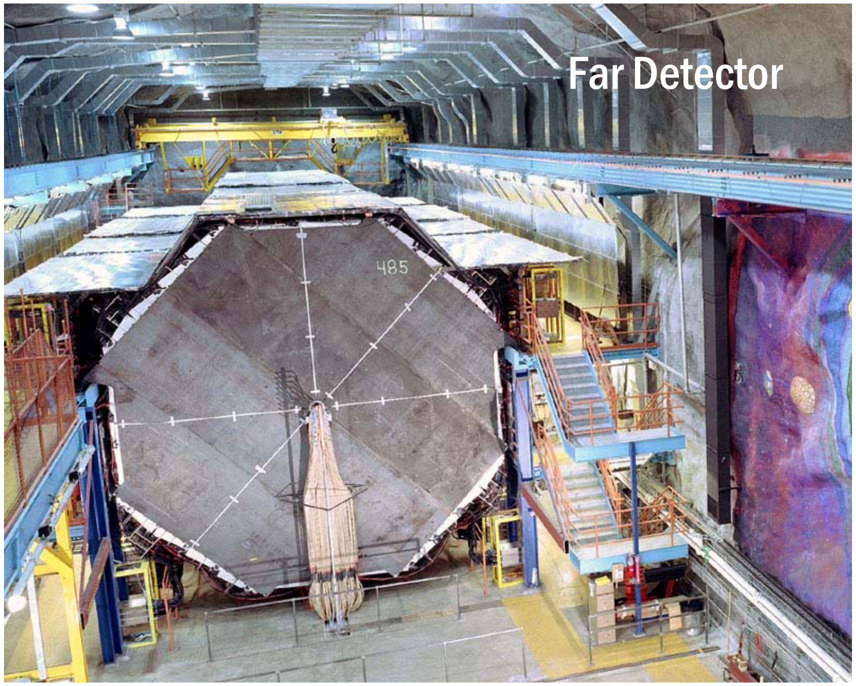
KEK - Kamioka (K2K)
~1 GeV neutrinos
L=250 km
1999-2004

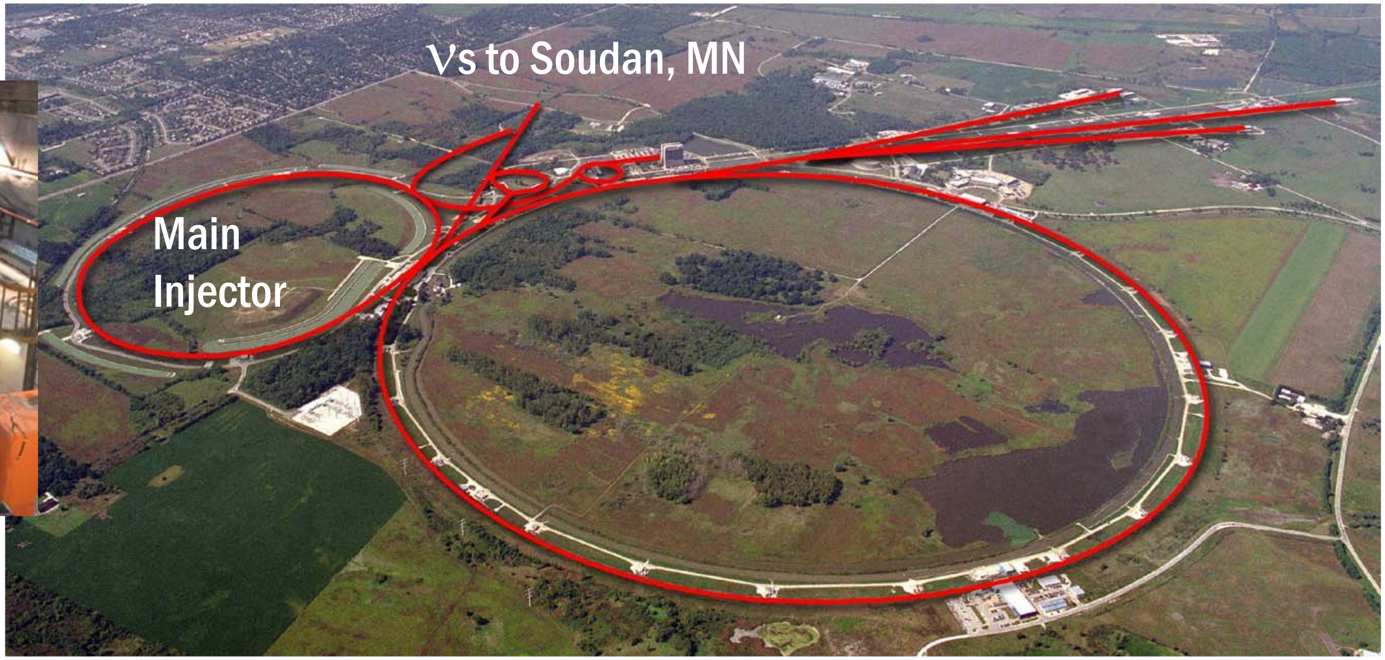
Fermilab – Soudan (MINOS)
~3 GeV neutrinos
L=735 km
Started 2005

CERN – Gran Sasso (Opera/ICARUS)
~17 GeV neutrinos (broadband)
L=732 km
Starts in 2006

MINOS

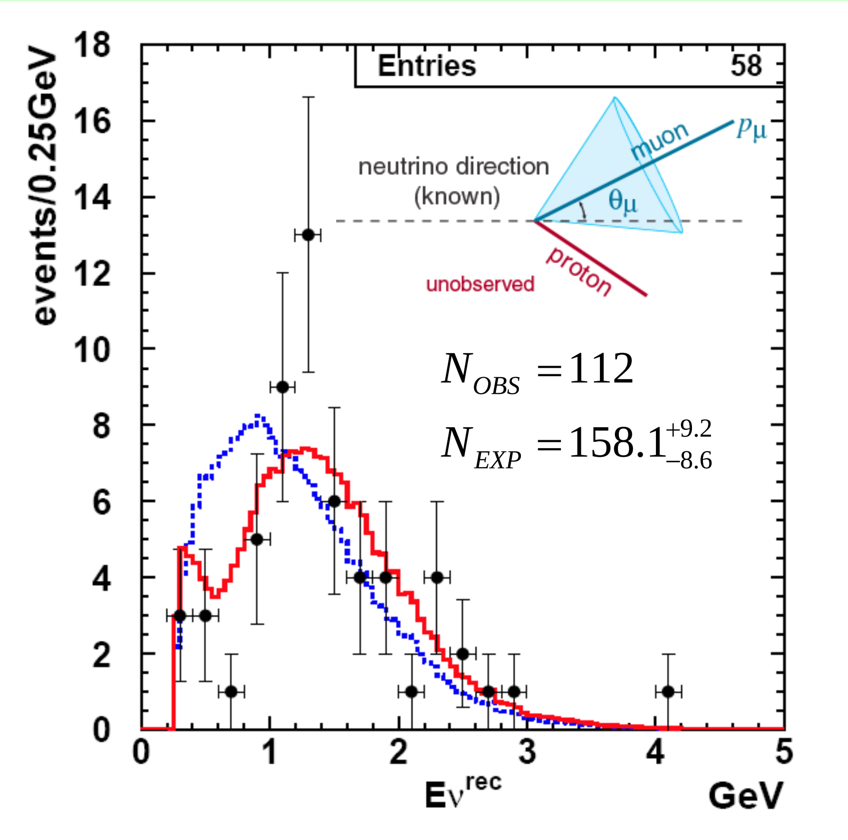
120 GeV protons, 4x10^{13} ppp, 1.87 s cycle
0.4 MW beam power
1 kton near detector
5.4 kton far detector
484 steel/scintillator planes
1.2 T solenoidal magnetic field
750 km baseline, peak energy ~ 3 GeV
92% ν_μ, 1.5% ν_e/ν_e-bar

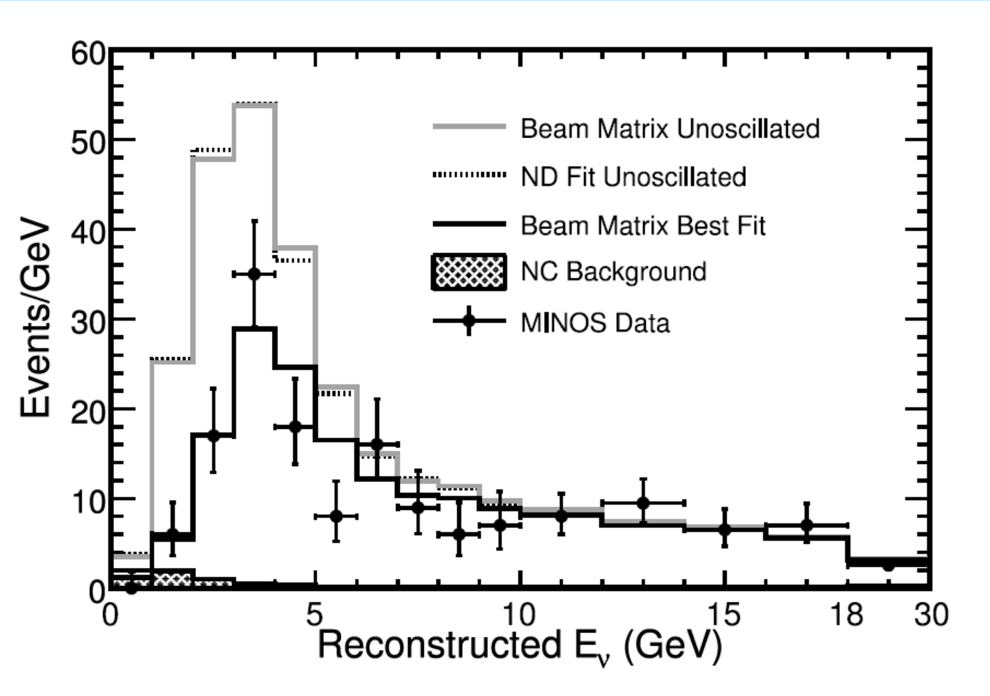




Final results from K2K

First results from MINOS





> 4σ confirmation of atmospheric neutrino mixing

$$\Delta m^2_{32} = 2.74^{+0.44}_{-0.26} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} > 0.87\ \ (68\%\ \mathrm{CL})$$

θ_{13} – Gateway Parameter

$$P_{vac\pm}[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)] = \sin^2 2\theta_{13} s_{23}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)$$
$$- \frac{1}{2} s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 \left(\frac{\Delta m_{12}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right)$$
$$+ 2J_r \cos\delta \left(\frac{\Delta m_{12}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right)$$
$$\mp 4J_r \sin\delta \left(\frac{\Delta m_{12}^2 L}{2E}\right) \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right),$$

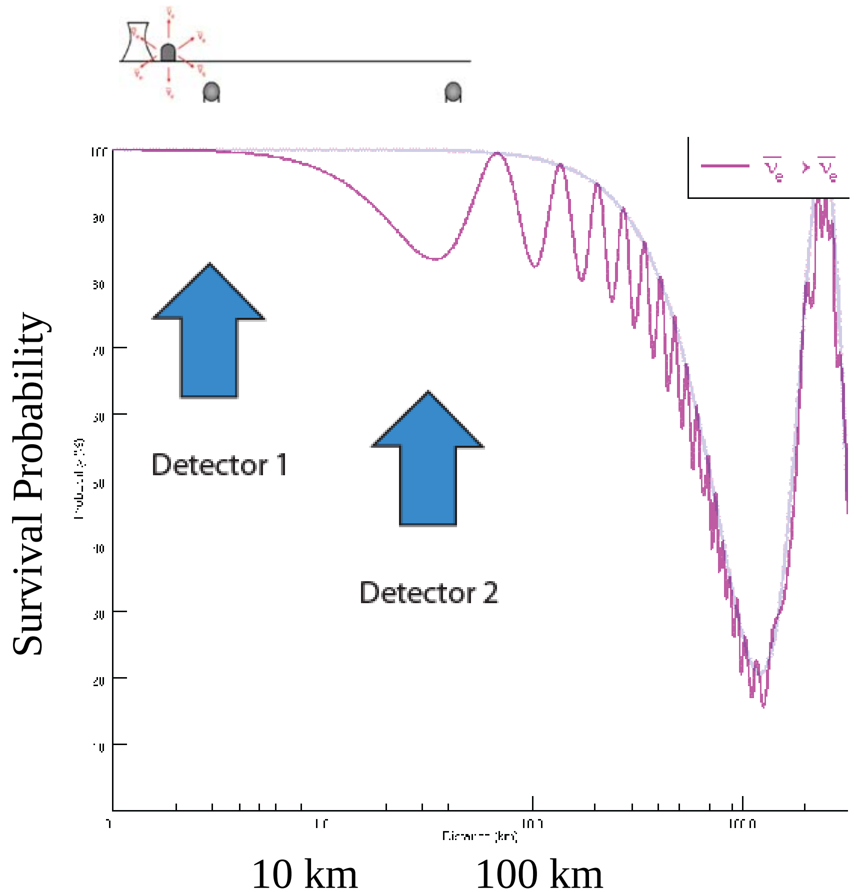
$$J_r = c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}$$

\+ terms in matter effect

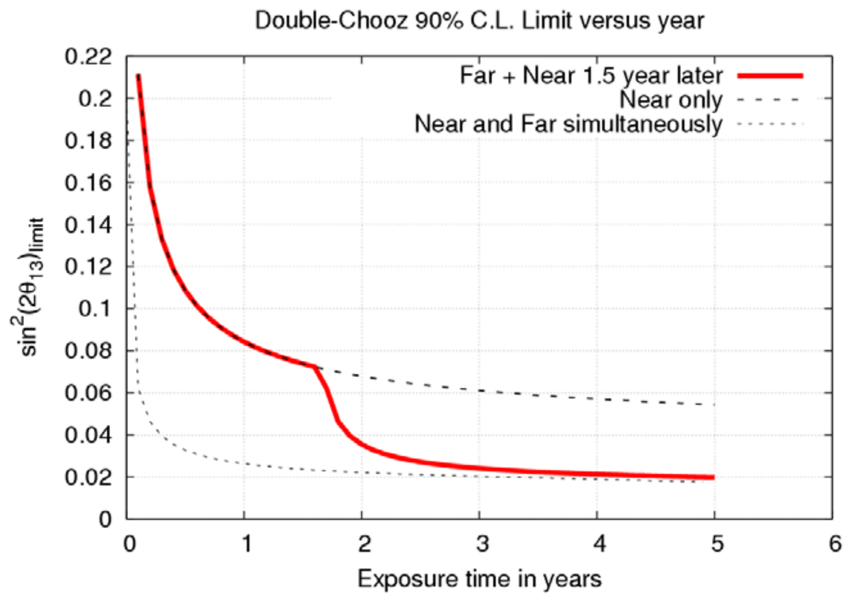
CP violating phase

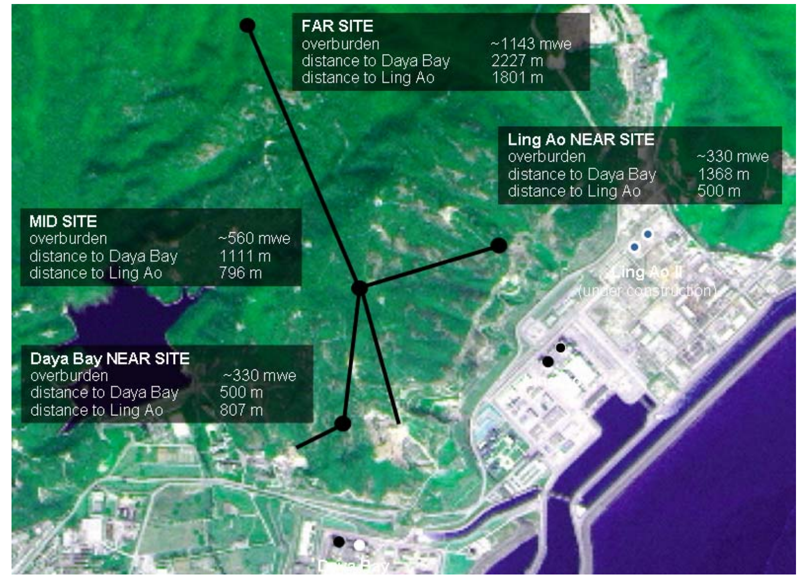
Precision Reactor Experiments

$$P_{ee} \to 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \right)$$



- only depends on θ_{13}, not δ or hierarchy
- Requires careful control of systematics > 1%
- Require multiple detectors
- Require overburden to reduce background
- Can reach $\sin^2 2\theta \sim 0.01$





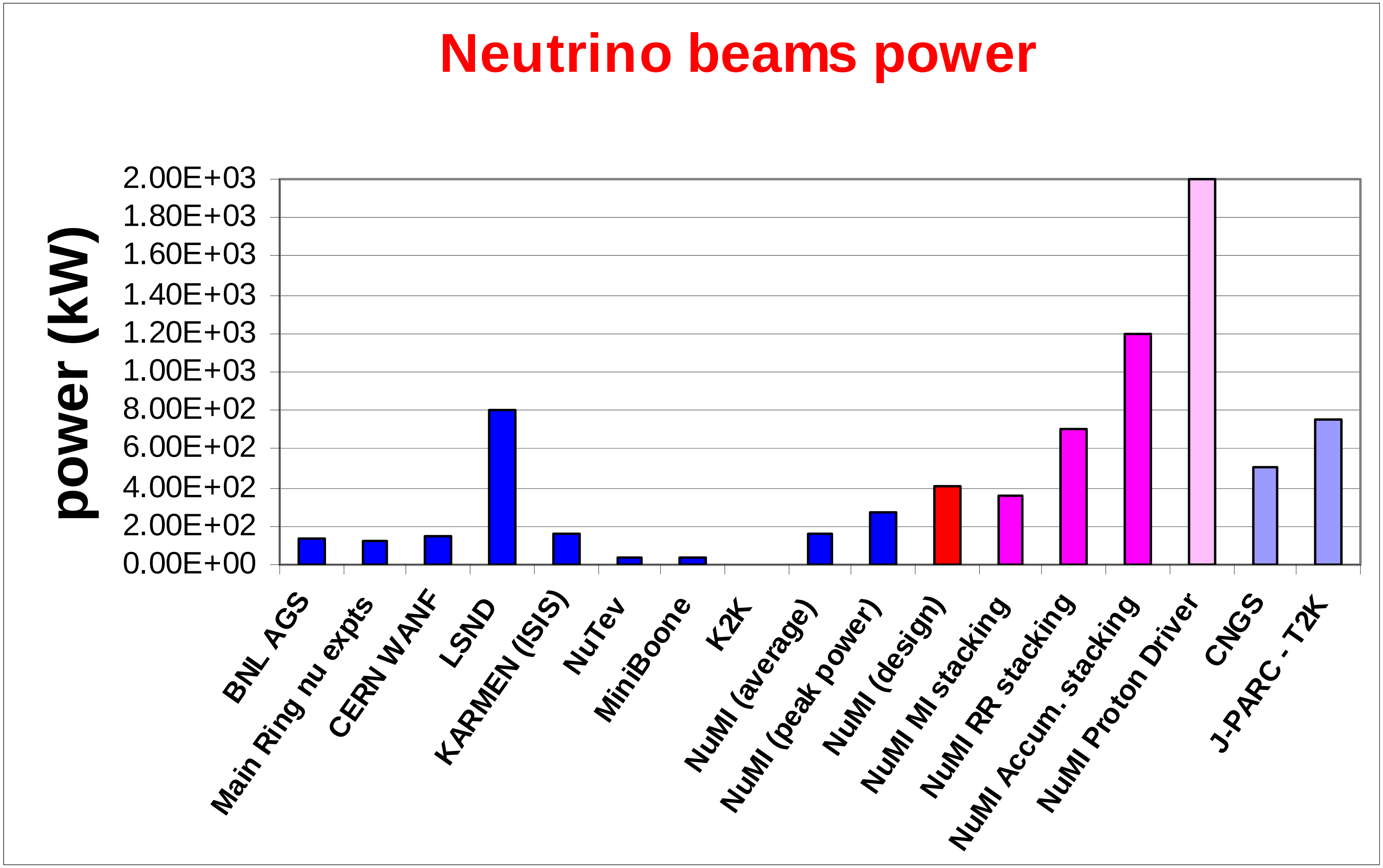
Double Chooz (France):

- 2 x 4 GW reactor cores
- 50-300 mwe overburden
- 0.3/1 km baseline
- Existing infrastructure – early start? (above)
- 2x10 ton modules – fixed
- Goal of 0.6% systematics
- Reach $\sin^2 2\theta \sim 0.03$

Daya Bay (Hong Kong):

- 6 reactor cores, 17 GW total
- 200-1000 mwe overburden
- 0.3/1.8-2.2 km baseline
- Construct tunnels and labs (above)
- 8x20 ton modules – moveable
- Goal of 0.36% systematics
- Reach $\sin^2 2\theta \sim 0.01$

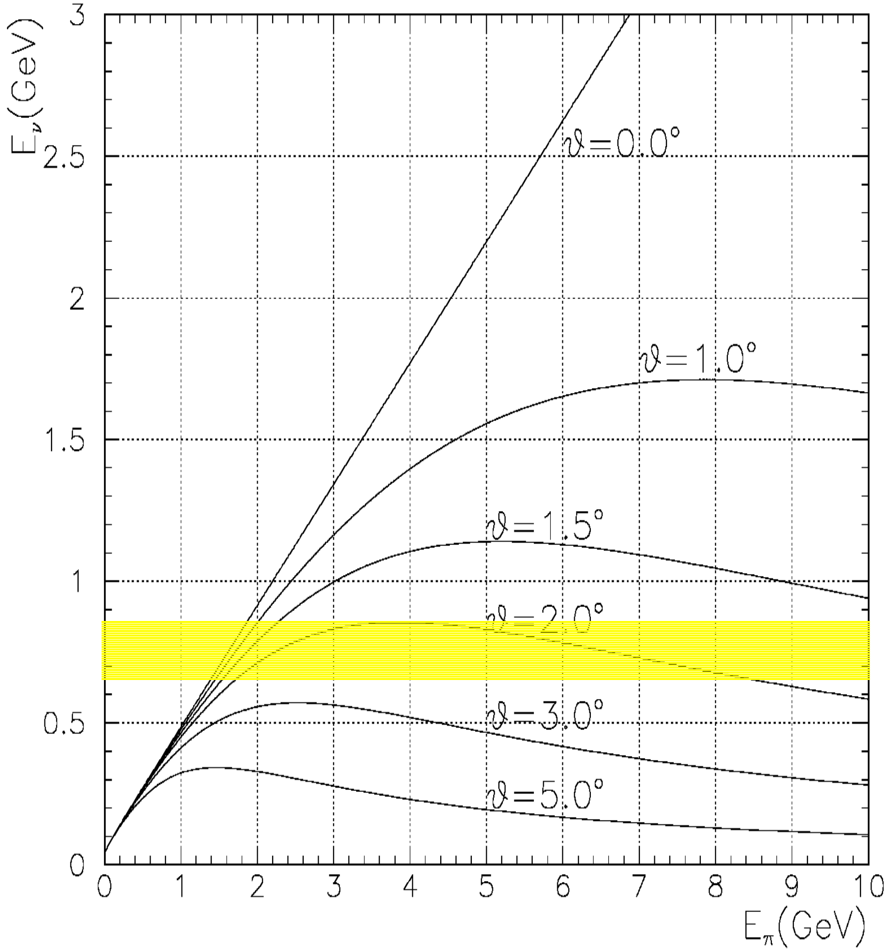
Neutrino flux is roughly proportional to proton beam power.

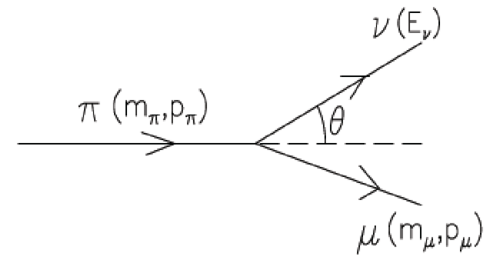


Power[W]=(protons/pulse)×(energy[eV])×(repetition rate[Hz])×(1.6×10^{-19}[C/proton])

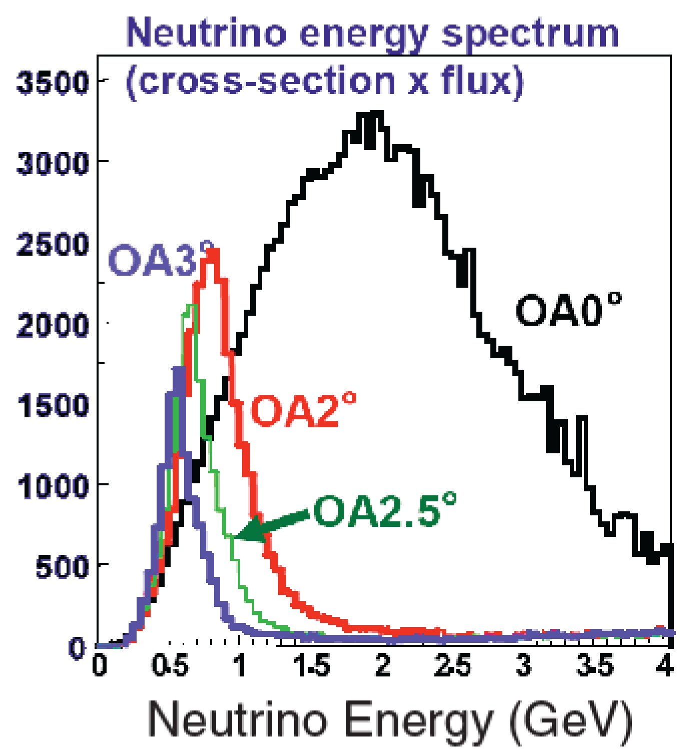
or if available: Power[W]=(beam current[A])×(beam energy[eV])

Off-Axis Technique



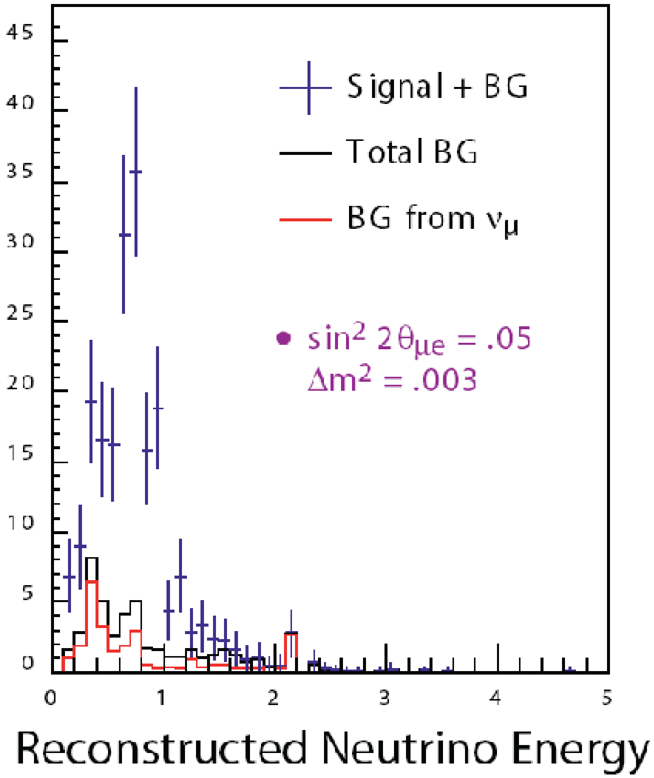


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

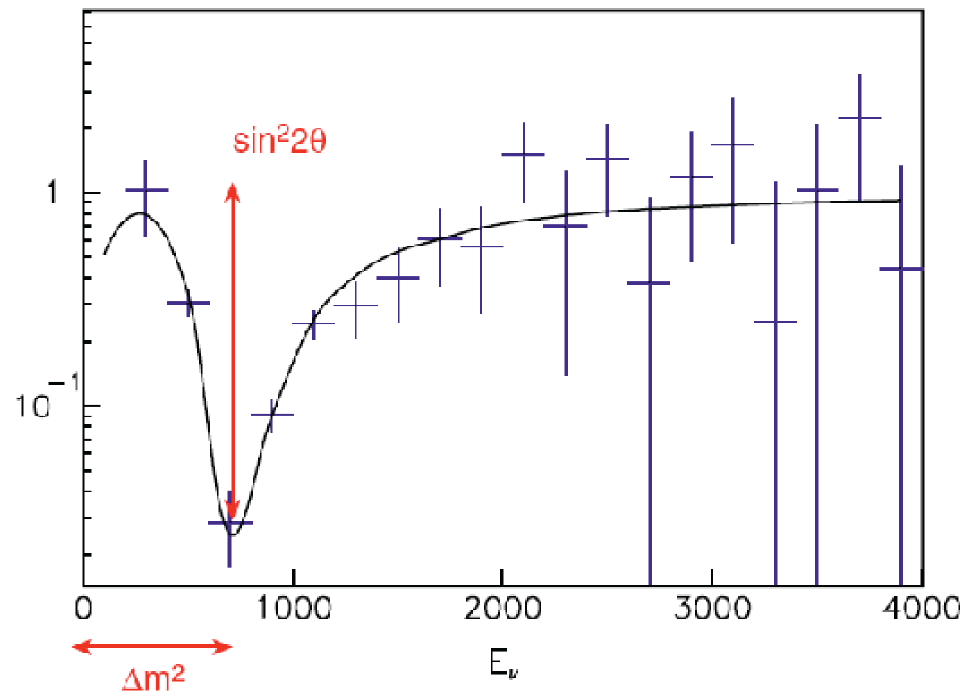


Physics Goals

Discover ν_e appearance (first such result barring LSND/MiniBooNE), measuring non-zero θ_{13}

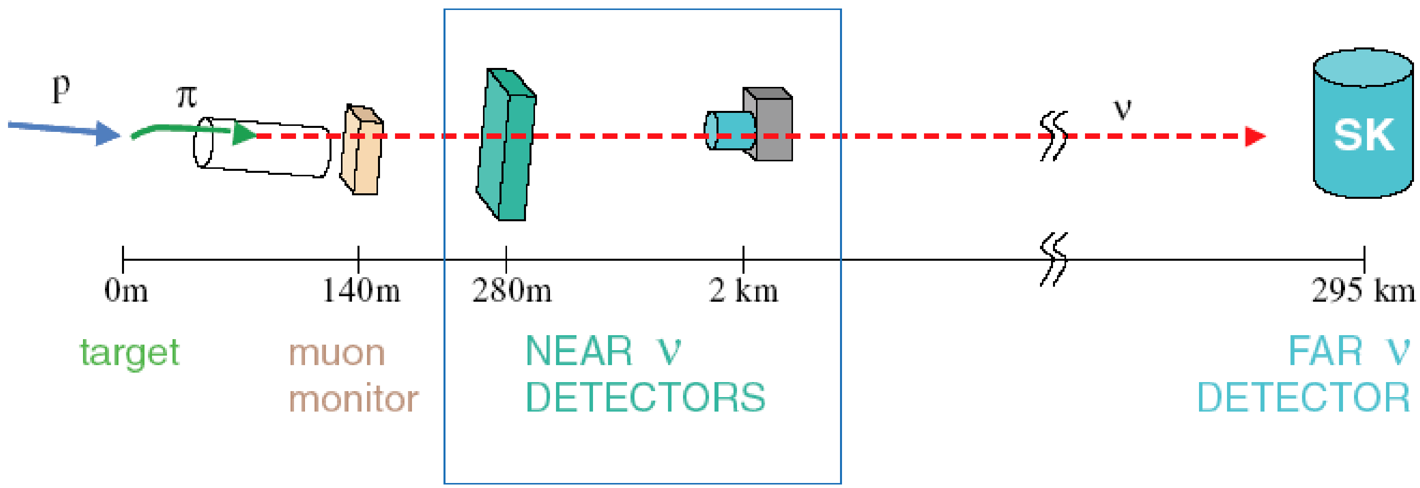


Resolve if θ_{23} is non-maximal
More precisely measure Δm_{23}



50 GeV protons
330 x 10^{12} ppp
0.275 Hz
~0.75 MW

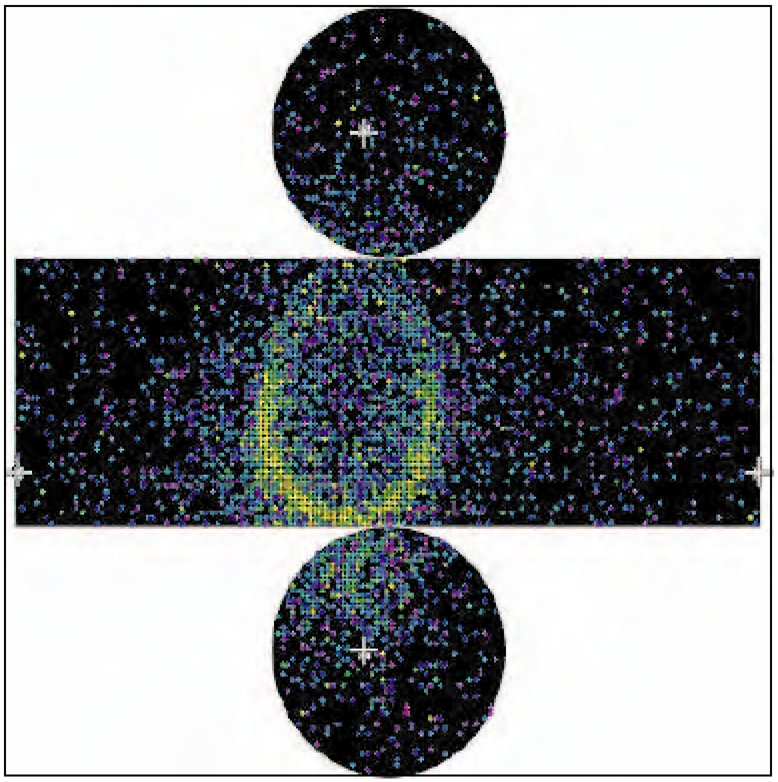
Phase I: 0.75 MW and Super-Kamiokande

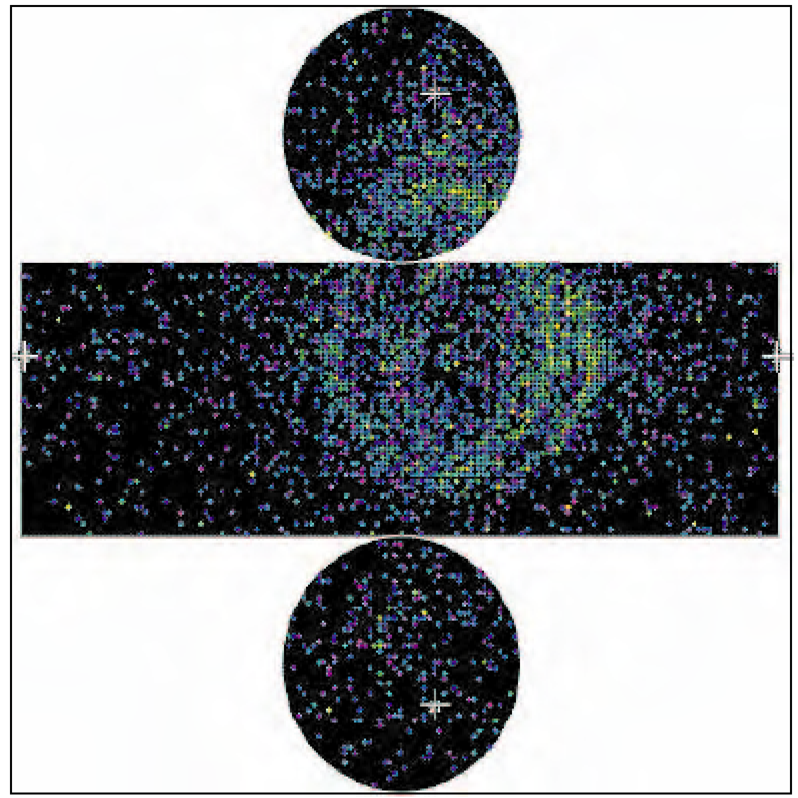


One is signal, one is background

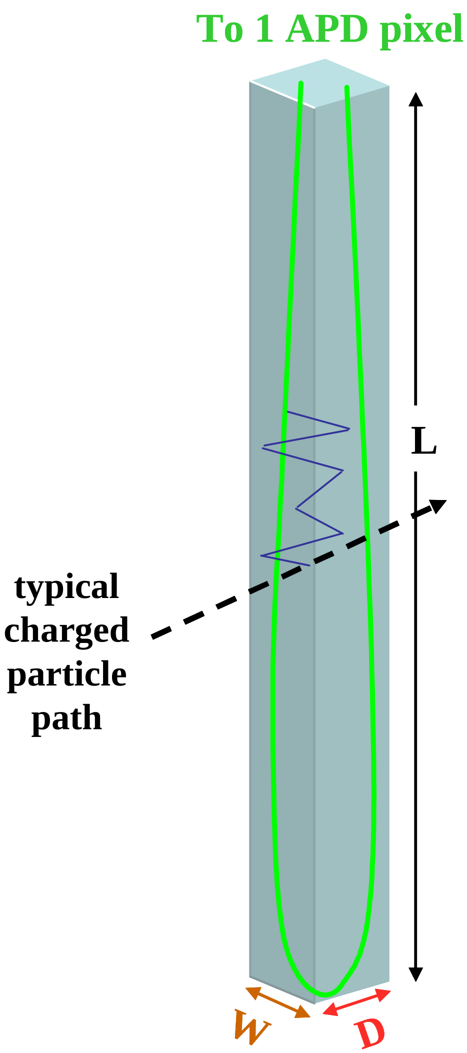
$\nu_e + n \rightarrow e^- + p$

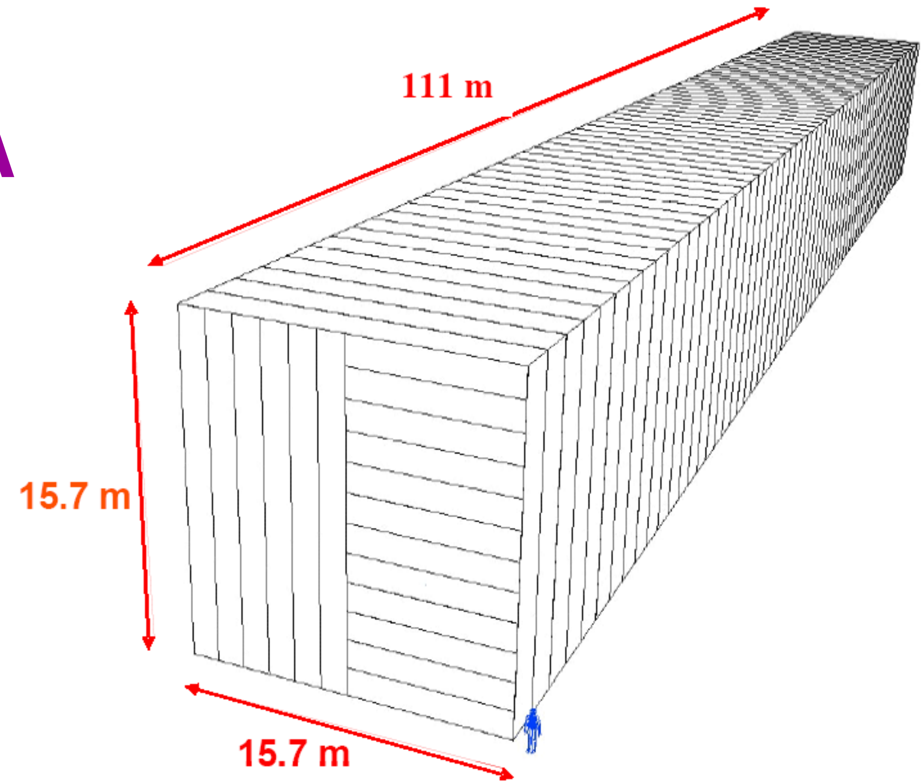
$\nu_\mu + p \rightarrow \nu_\mu + p + \pi^0$





NOνA

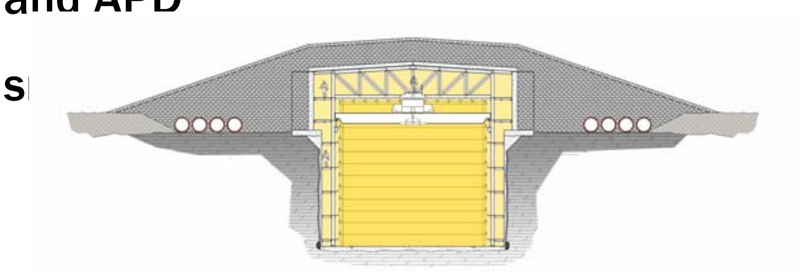




30 (25) kton totally active detector

Planes of liquid scintillator (mineral oil) read by WLS fiber and APD

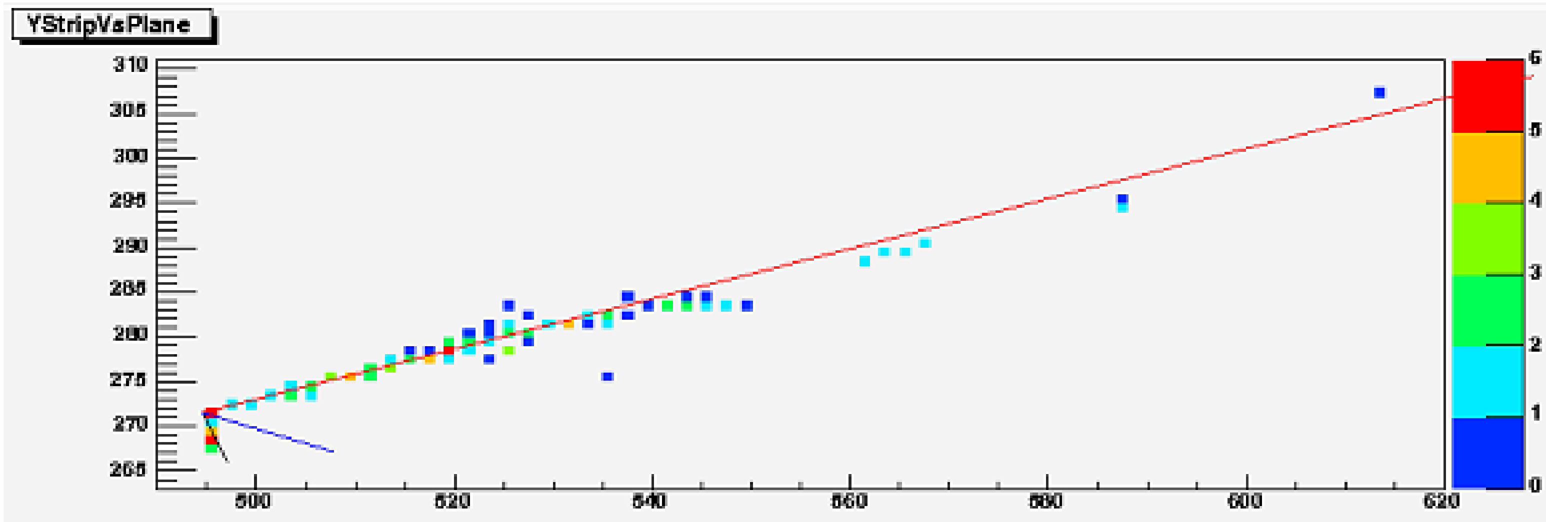
Surface detector with s
overburden (right)

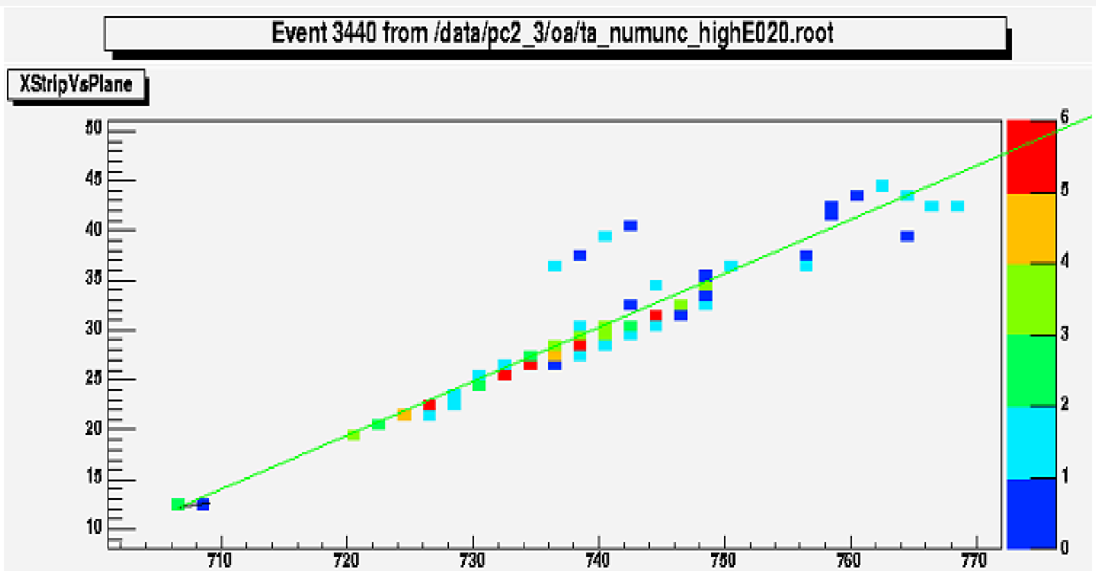


One is signal, one is background

$\nu_e + p \rightarrow e^- + p + \pi^+$

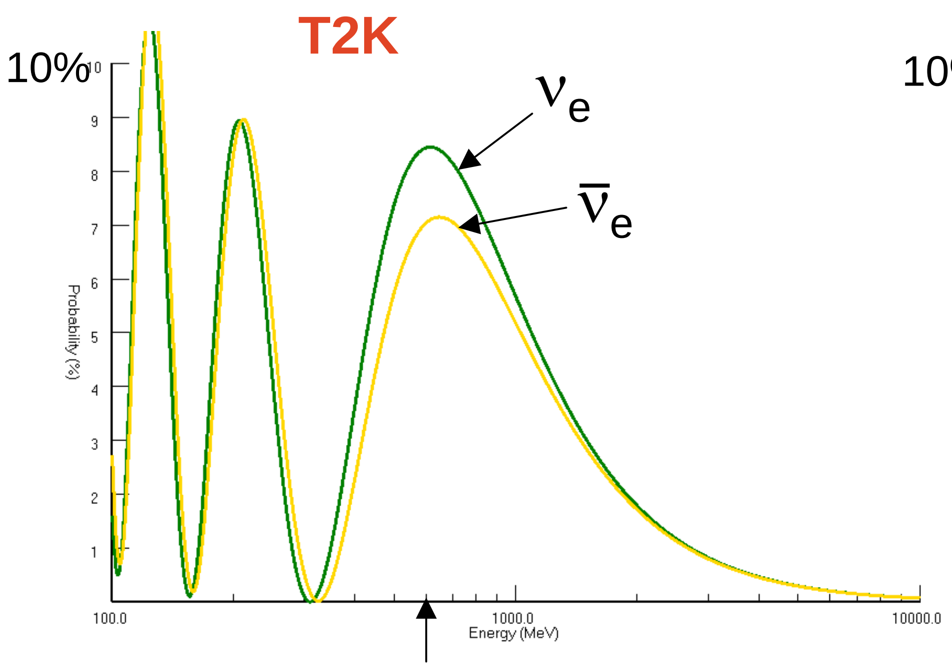
$\nu_\mu + N \rightarrow \nu_\mu + p + \pi^0$



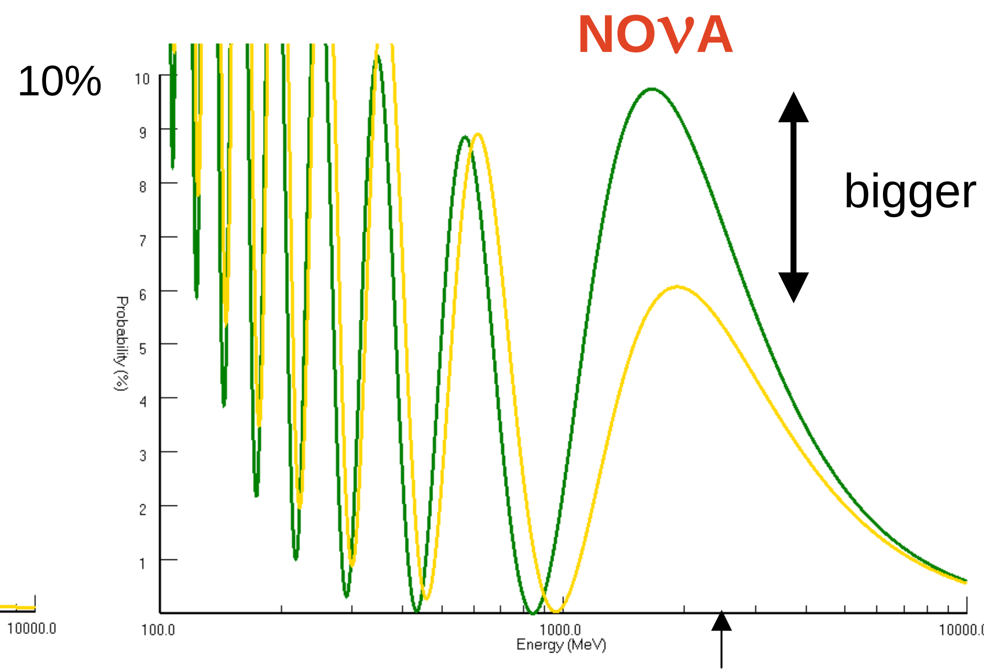


Resolving the Mass Hierarchy

Matter effect enhances ν_e appearance for normal hierarchy
Effect is reversed (enhanced anti-ν_e) for inverted hierarchy



600 MeV
290 km



2.3 GeV
820 km

$\delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\sin^2 2\theta_{23}=1.0$

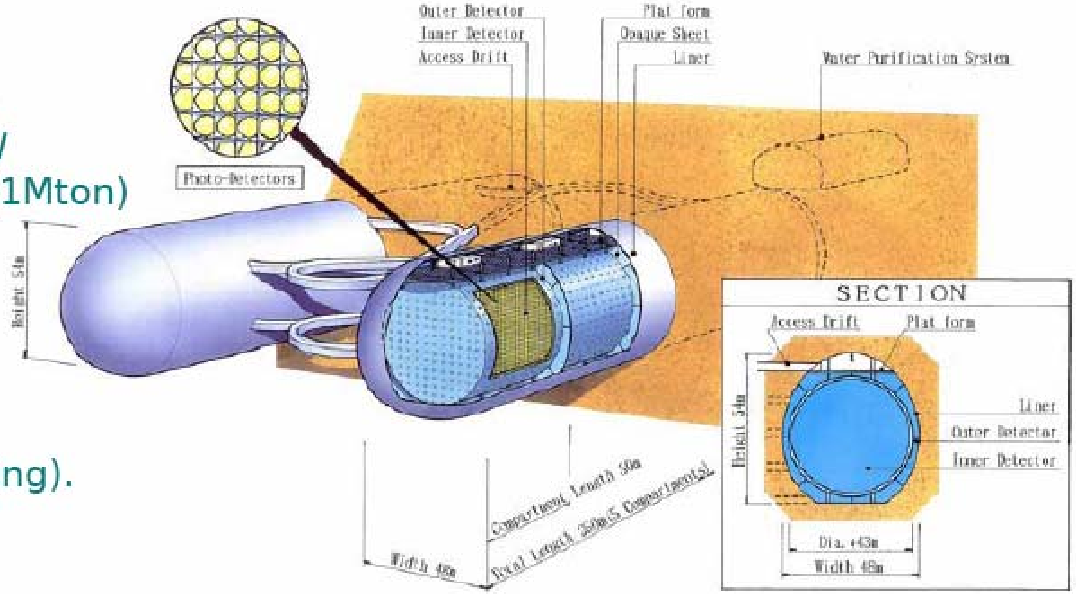
$\delta m^2_{12}=7.1\times10^{-5}$ eV^2 $\sin^2 2\theta_{12}=0.81$

$\sin^2 2\theta_{13}=0.16$

Beyond T2K and NOνA

T2K PHASE-II

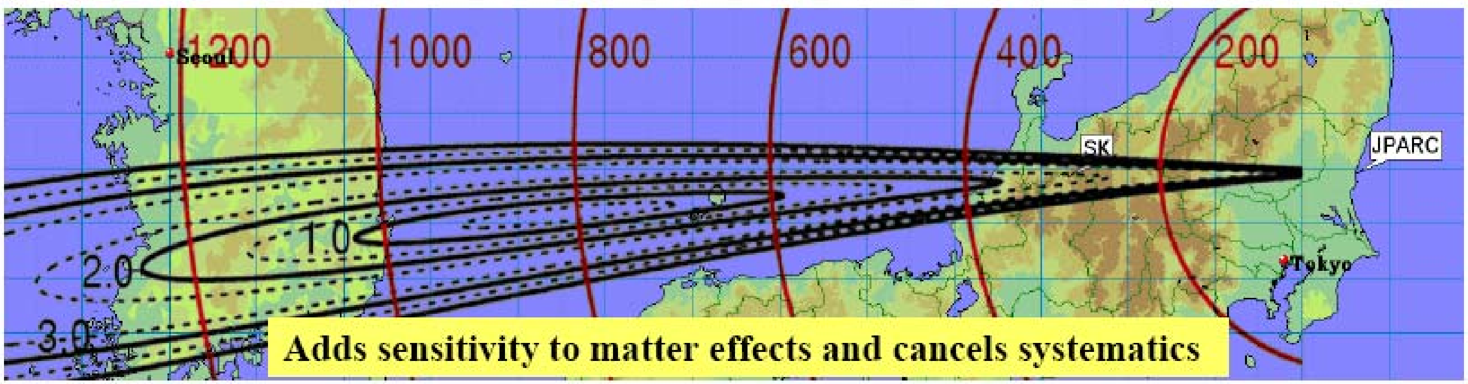
JPARC .77 MW -> 4MW
SK (50kT) -> Hyper-K(1Mton)



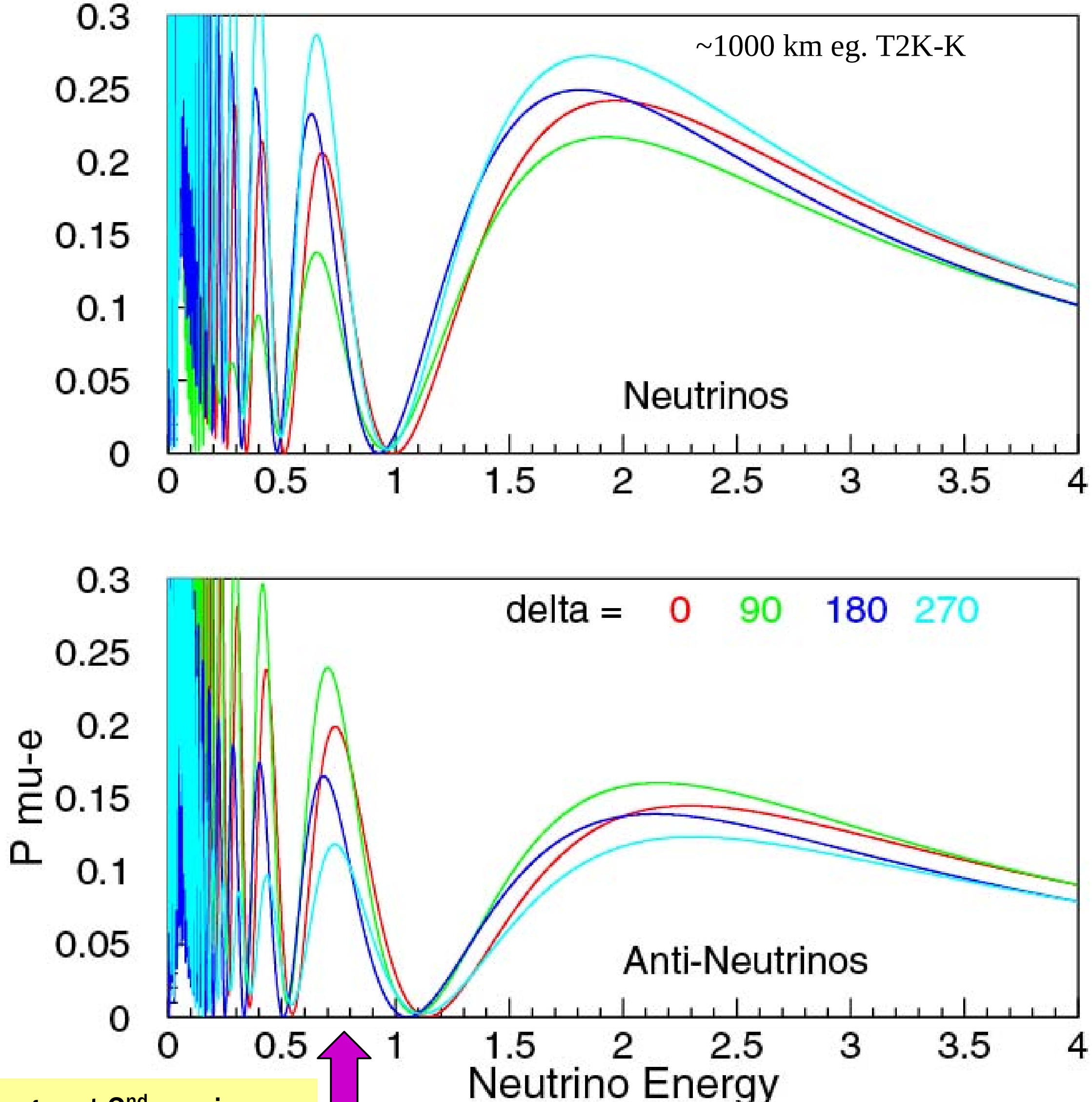
GOAL:

Measure CP Violation
(use ν and anti-ν running).

Idea under study:Put ½ of Hyper-K in Korea.



$$P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$



A.K.A. CP Violation

CP Asymmetry stronger at 2^{nd} maximum

To do list:

- Are there only three neutrino states? (LSND)
  - mini-BooNE Real soon- 2006?!
- Can we really make an appearance experiment?
  - CNGS, SK? (τ); T2K, NOνA (e)
- What is the absolute mass scale?
  - KATRIN, $0\nu\beta\beta$, precision cosmology?
- Are neutrinos their own antiparticle? (Majorana)
  - Numerous $0\nu\beta\beta$ experiments being proposed
- What is the sign of the large Δm^2? (heirarchy or)
  - NOνA + T2K
- What is the value of θ_{23}? Is it truly maximal?
  - NOνA, T2K
- What is the value of θ_{13}? Is it really zero?
  - NOνA, T2K, new reactor experiment
- What is the value of δ?
  - upgraded off-axis experiments (eg. Hyper-K+4MW beam)

There was something unusual about this neutrino talk compared to many other neutrino talks you may have seen. Did you discern it?

No contours!

This is not because contours (confidence intervals) are bad. They are generally a very appropriate way to present a final result, and a very good way of comparing results (i.e by overlaying them). But contours are fully digested final answers… there is no way to evaluate the character or quality of the **data**. As was mentioned: when reading a paper or proposal, try to find the important plot that characterizes the result, not simply states it. I recently seem to see many talks that seem to show only the contours. It's like seeing a talk that reports only the final numbers (with ±errors), and no other details. I imagine 90% of all neutrino physicists can sketch the Chooz contour for $\sin^2\theta_{23}$, but many fewer can sketch the data and fit that produced it.

So as an exercise for myself, I made this lecture without contours.

Caveat: one set snuck in- can you find it?