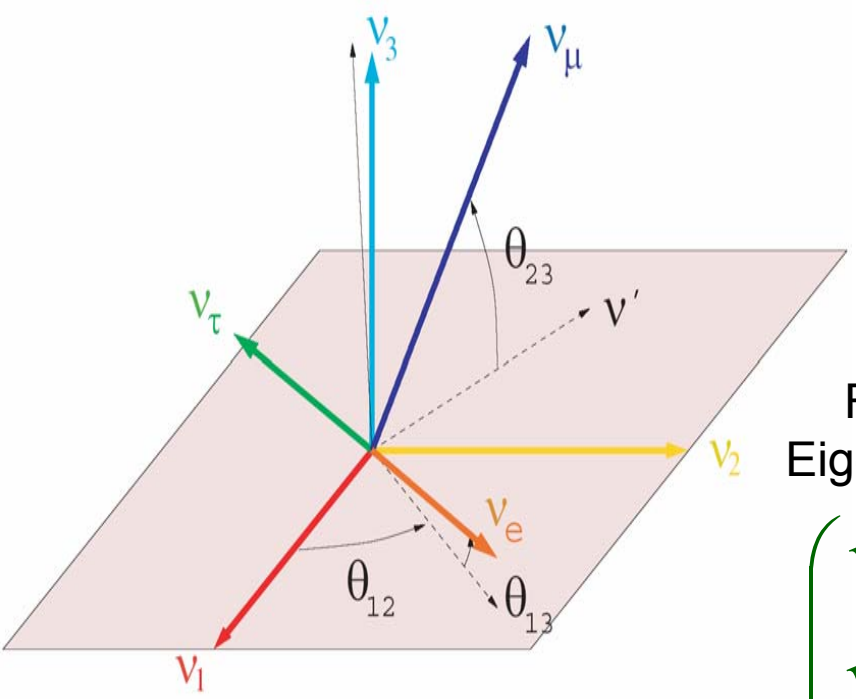
Off-Axis Physics Overview

H.Sobel
UCI
April 16, 2004
SAGENAP

- There has been a revolution in Neutrino Physics.
  - Observation of Atmospheric Neutrino oscillations (Super-K, Soudan, Macro).
  - Confirmation by K2K.
  - Observation of Solar Neutrino oscillations (Chlorine, Super-K, SAGE, Gallex, SNO)
  - Confirmation by KamLAND

Three Neutrino Picture



Flavor Eigenstates

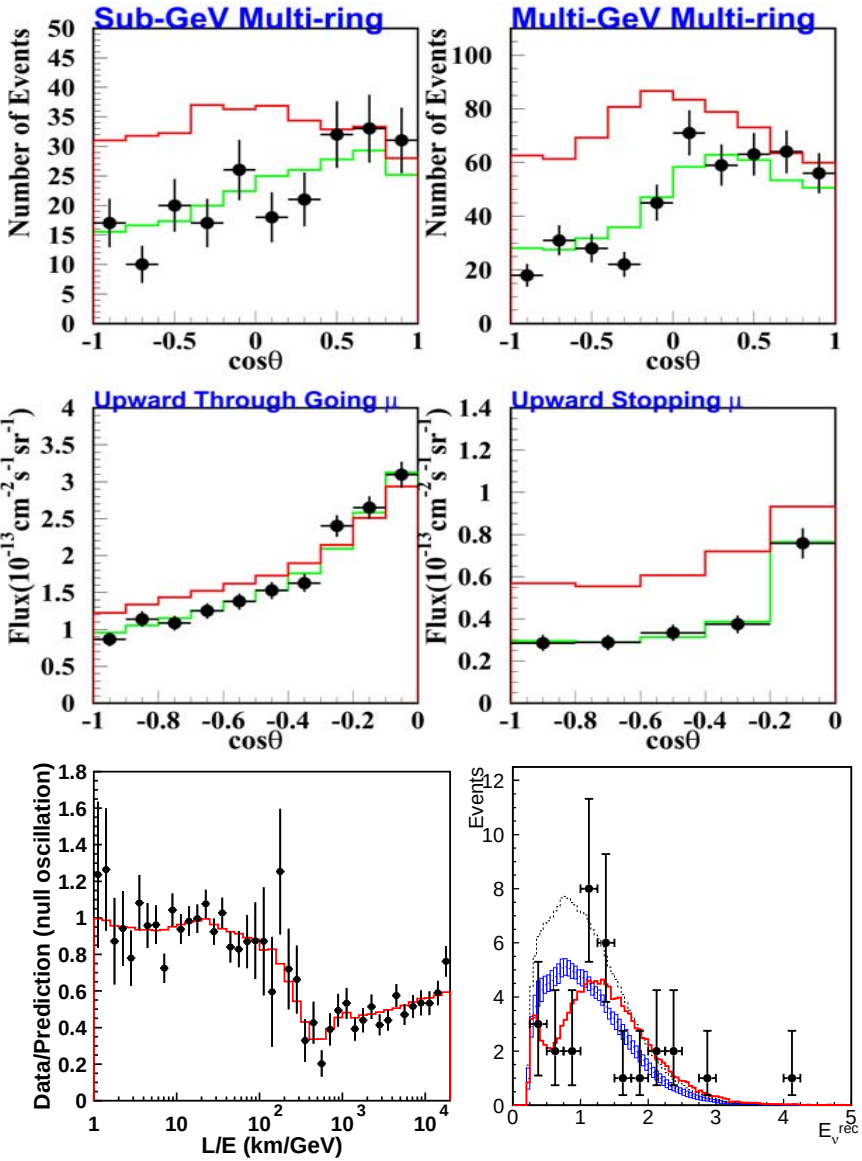
MNS
Maki-Nakagawa-Sakata
mixing matrix

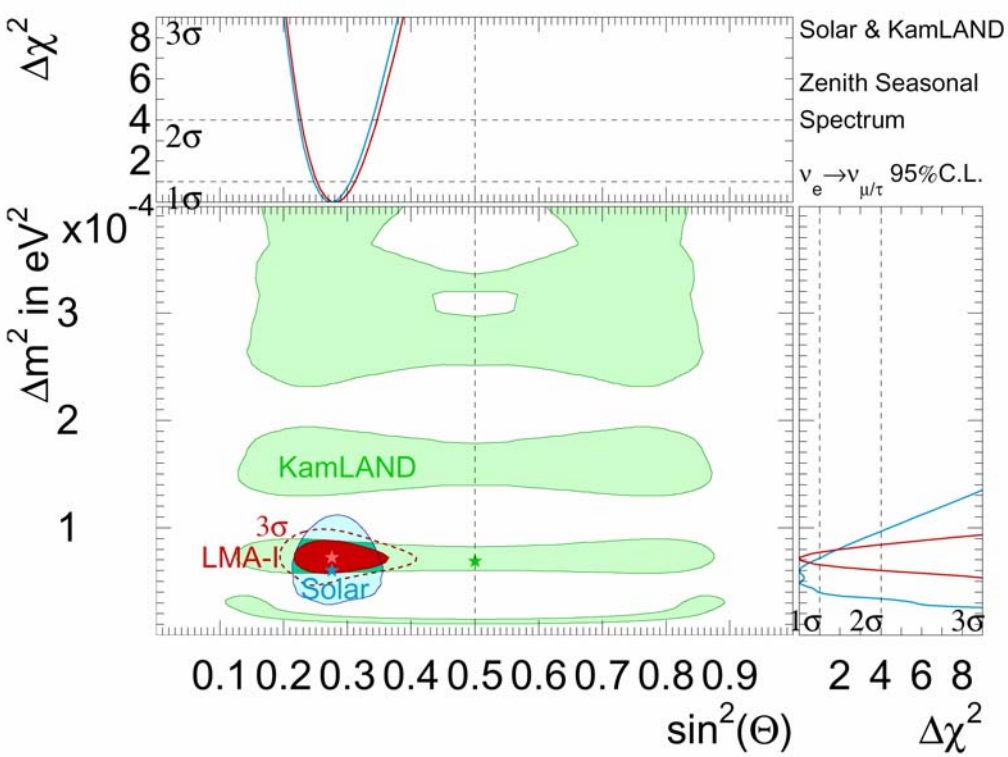
Mass eigenstates

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

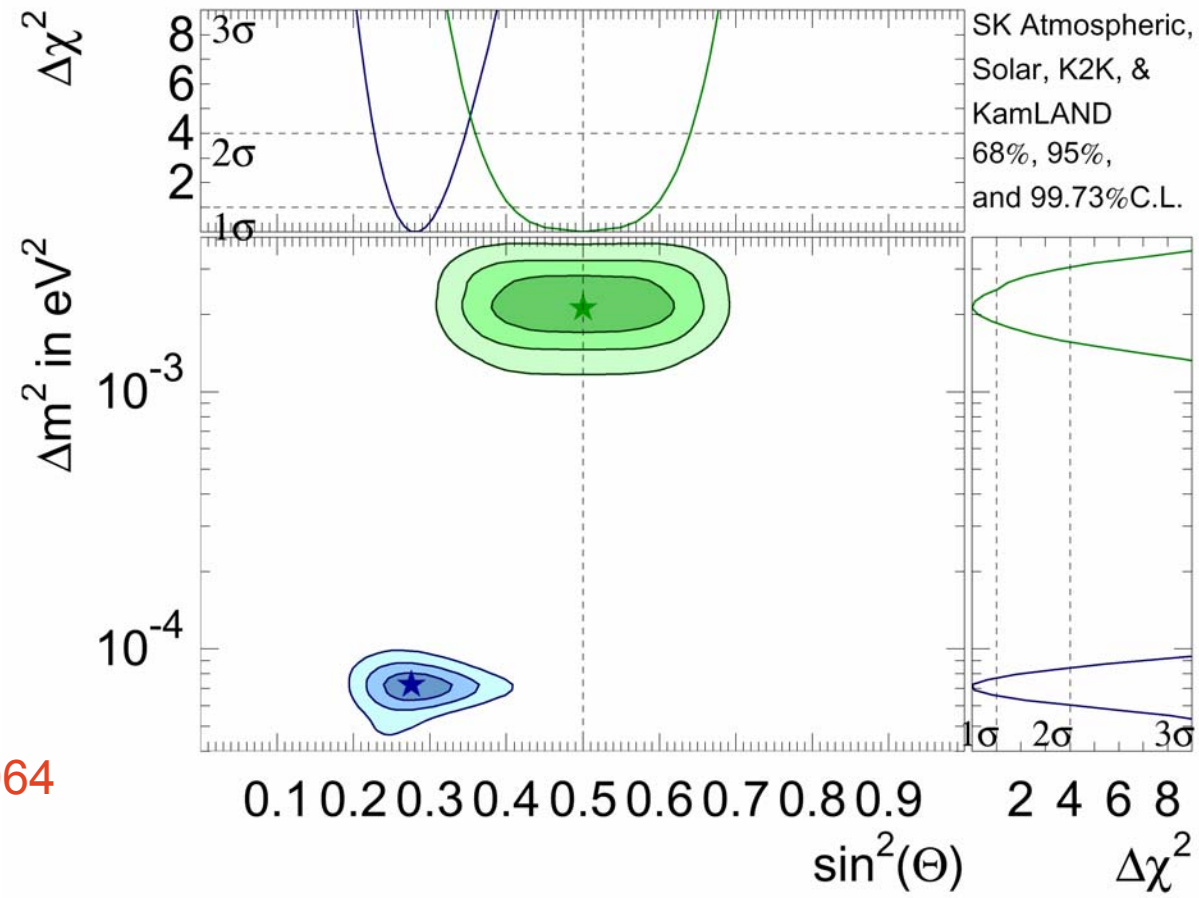
3 independent parameters
+ 1 complex phase
θ_{12}, θ_{23}, θ_{13}, δ

Current Results





Combined analysis



hep-ex/0310064

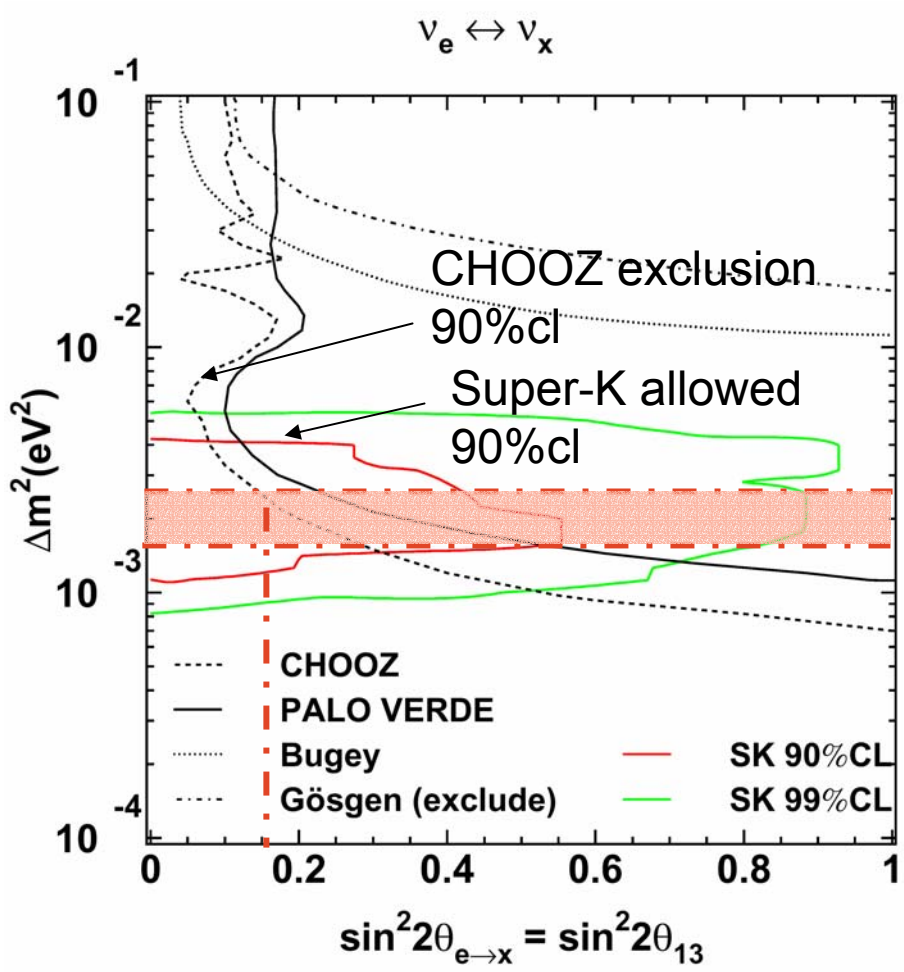
$1.6\times10^{-3}<\Delta m^2_{ATMOS}<2.6\times10^{-3}$ eV^2

$\sin^2 2\theta_{23}>0.91$

$6.1\times10^{-5}<\Delta m^2_{SOLAR}<8.5\times10^{-5}$ eV^2

$0.71<\sin^2 2\theta_{12}<0.91$

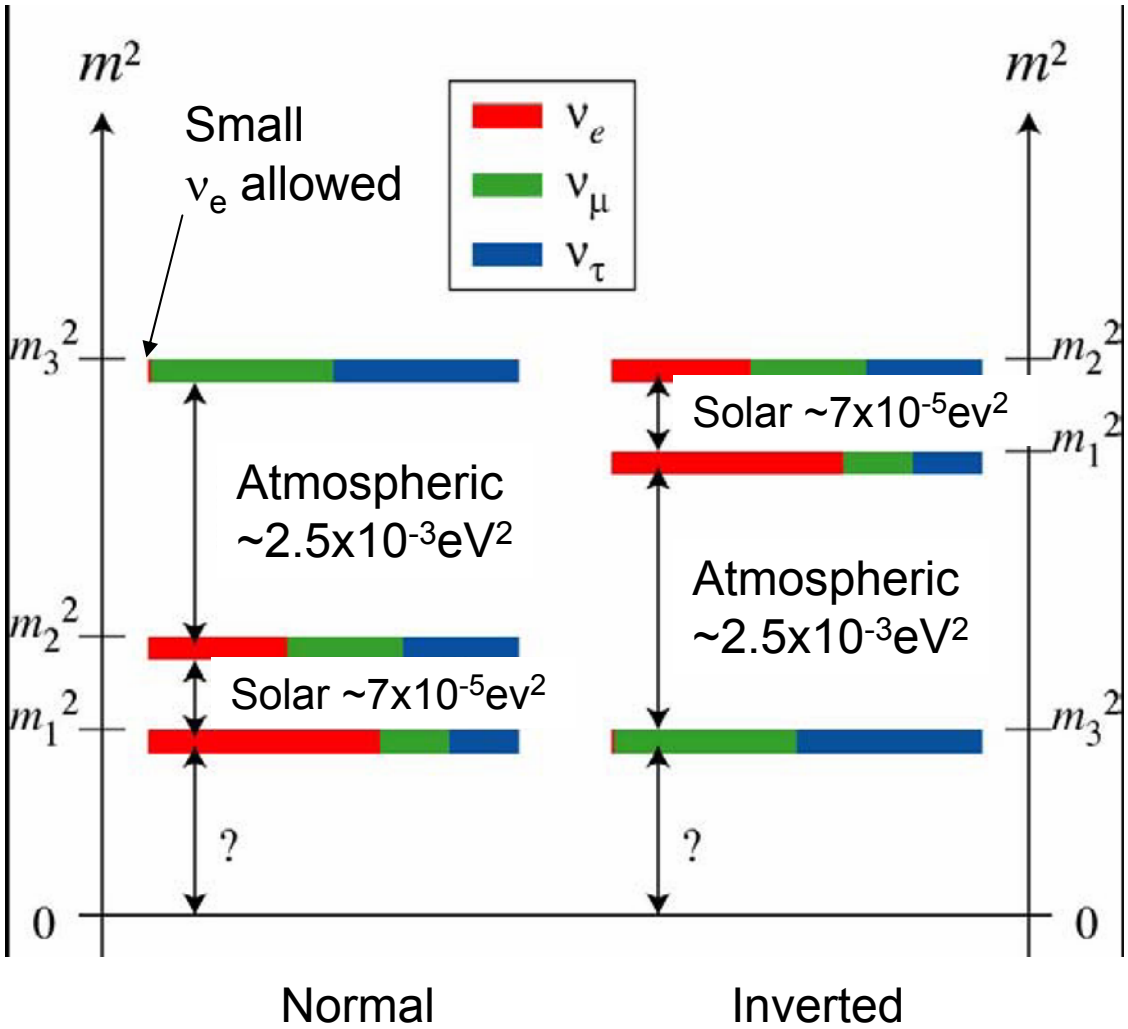
θ_{13} Limits



← δm^2_{23} allowed range

@δm^2=2.5x10^{-3} ev^2 $\sin^2 2\theta_{13}$<0.16 or θ < ~11.5^o

Mass Hierarchy



Remaining Questions

- Measurement of θ_{13}
  - Precision measurements of other quantities
- What is the value of Dirac CP phase δ?
- What is the mass hierarchy?
- What is the mass of the lightest neutrino?
- Are neutrinos Majorana particles?
  - If so what are Majorana phases?

Off-Axis Physics Program

Initial Goals

- Discover if θ_{13} is non-zero by observing ν_e appearance
- Attempt to resolve if θ_{23} is non-maximal.
- Precisely determine δm^2_{23} (~10^{-4} eV^2)

Combination of more than one distance and/or $\bar{\nu}_e$ running.

- Discovery of non-zero CP phase
- Determination of mass hierarchy

ν_e Appearance

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

Small, since chose L/E to match ATM

Where $J_r = c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}$ (Jarlskog factor)

So, $P_{vac}(\nu_\mu \longrightarrow \nu_e) \sim = \sin^2 2\theta_{13} s_{23}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)$

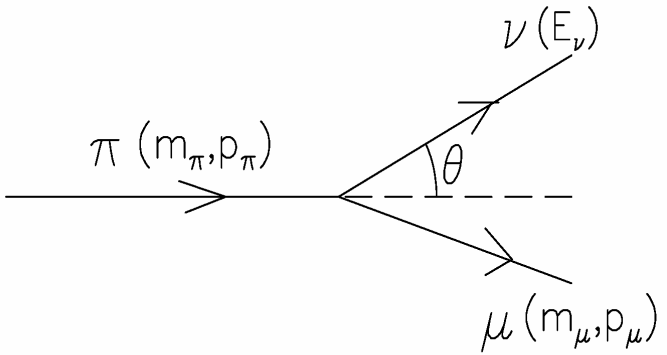
chose E to ~maximize $\sin^2\Delta_{ATM}$ at particular location:

- For NOνA: L=820 km E_ν=2.3 GeV
- For T2K: L=290 km E_ν=600 MeV

Off-axis Idea

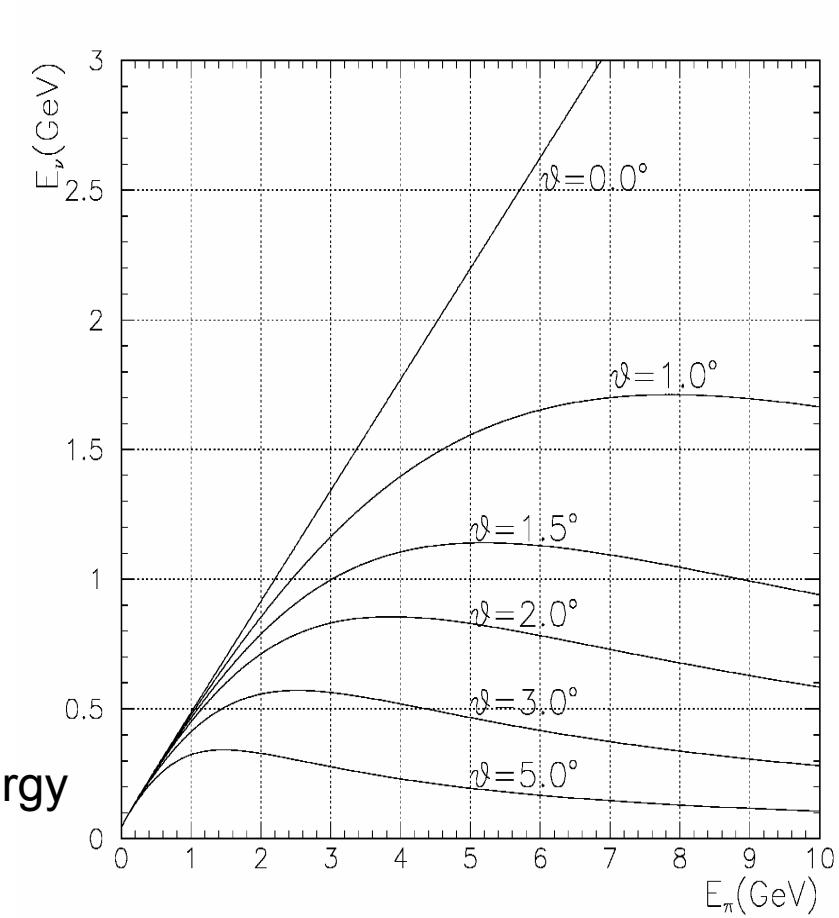
First pointed out in the Long Baseline Neutrino Oscillation Proposal for Experiment, E889, at Brookhaven.)

Off-axis Kinematics

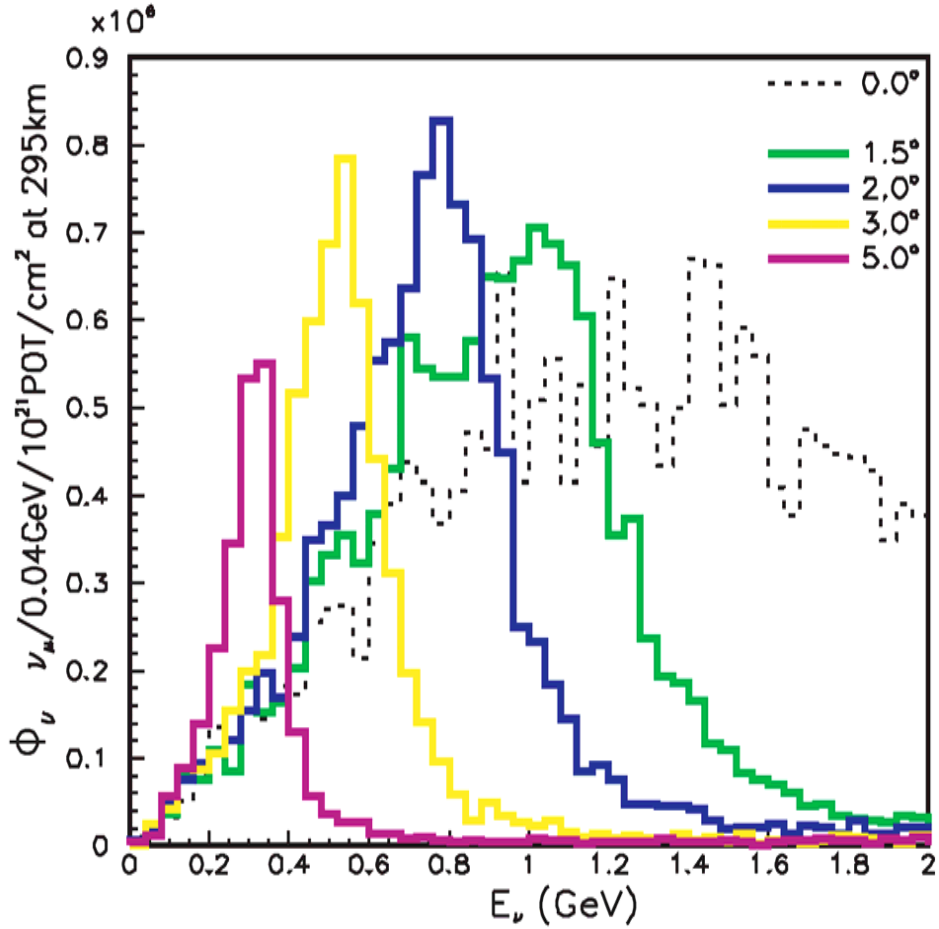


$$E_\nu = \frac{m_\pi^{\,2} - m_\mu^{\,2}}{2(E_\pi - p_\pi \cos\theta)}$$

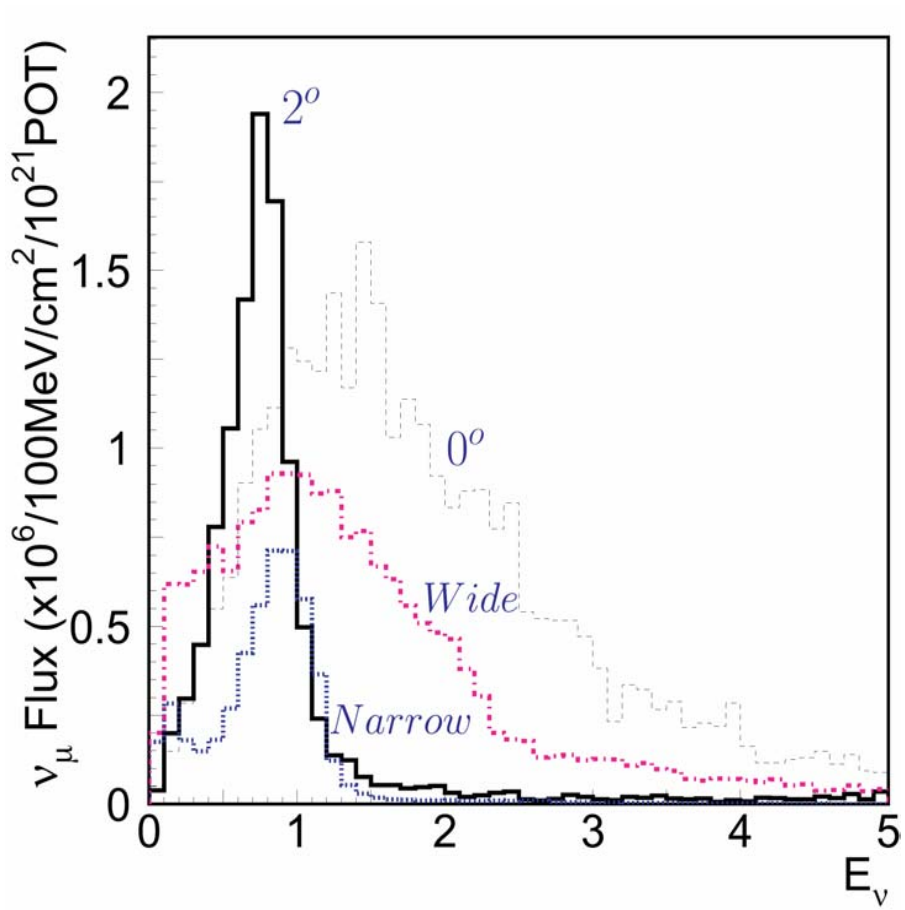
Energy of ν relatively independent of π energy



Pick an Angle ⇨ Pick an Energy



Energy varies linearly with angle



- Intensity of 2^o off-axis beam is higher than 0^o wide band.

High Intensity Proton Accelerators

	Power (MW)	Energy (GeV)	Intensity (10^{12} ppp)	Rep. rate (Hz)
KEK-PS	0.005	12	6	0.45
AGS	0.14	24	60	0.6
FNAL-MI	0.41	120	40	0.53
SPS	0.3	400	35	0.16
JHF-I	0.77	50	330	0.29
Super-AGS	1.3	28	120	2.5
FNAL-proton driver-I	1.2	16	30	15
SPL	4	2.2	230	50
JHF-II	4	50		

R&D

From Nakaya

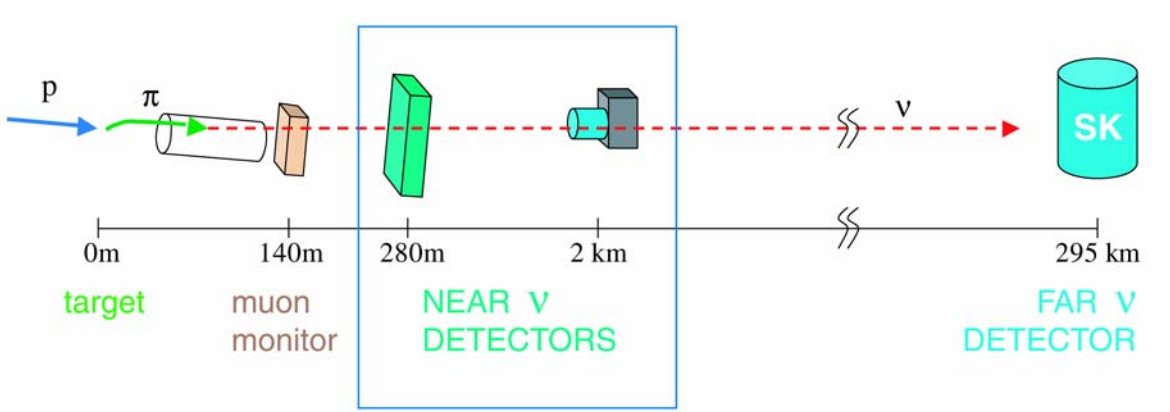
Neutrino Beams

	<Eν> (GeV)	L (km)	#CC ν/kt/yr
K2K	1.3	250	2
NuMi (High E)	15	730	3100
NuMi (Low E)	3.5	730	469
CNGS	17.7	732	2448
JHF-I	0.7	295	133
Numi off-axis	2.3	820	~80
Super AGS	1.5	2540	11
JHF-II	0.7	295	691
SPL	0.26	130	16.3
β beam**	0.58	130	84

R&D

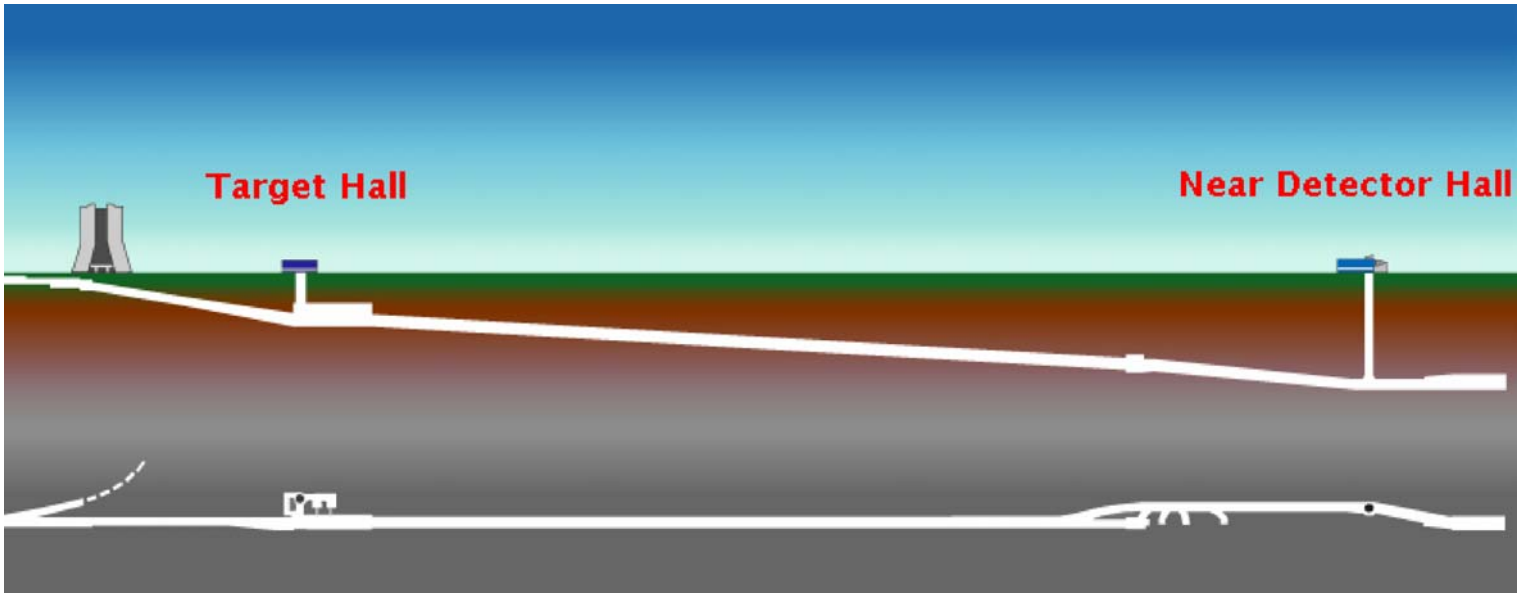
From Nakaya

T2K Experimental Layout



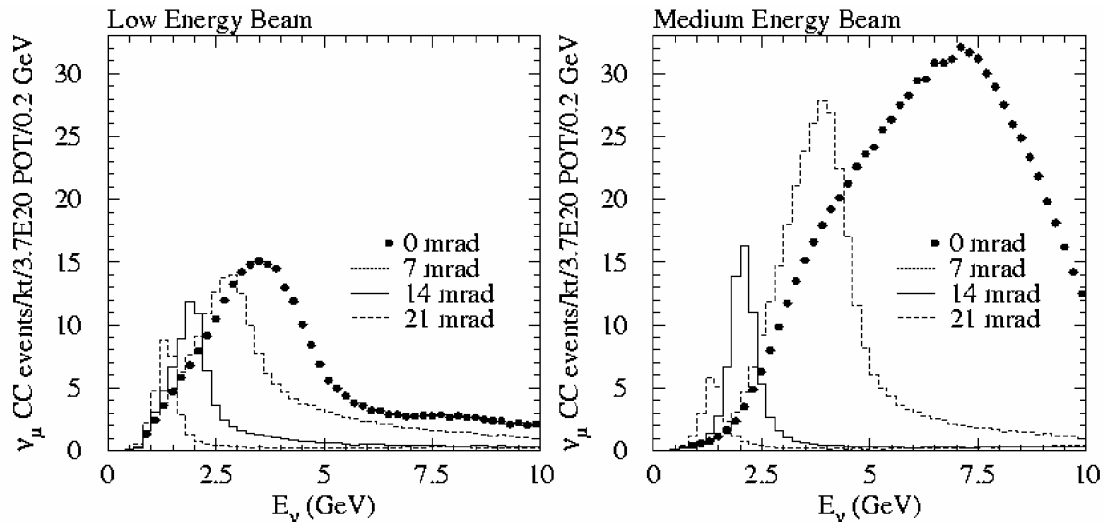
Neutrino energy will be tuned between 0.4 and 1.0 GeV corresponding to:
δm^2 from 1.6 to 4.0×10^{-3} eV^2
to cover δm^2_{ATM} range.

NuMI Beam



50 kt detector
In northern
Minnesota

820 km



Beam energy can
be varied.

Matter Effects

If we now include matter effects:

$$P_{matt\pm}[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] \Rightarrow \pm \cos 2\theta_{13} \sin^2 2\theta_{13} s^2_{23} \left(\frac{2Ea(x)}{\Delta m^2_{13}}\right) \sin^2 \left(\frac{\Delta m^2_{13} L}{4E}\right)$$

$$\mp \frac{a(x)L}{4} \sin^2 2\theta_{13} \cos 2\theta_{13} s^2_{23} \sin \left(\frac{\Delta m^2_{13} L}{2E}\right),$$

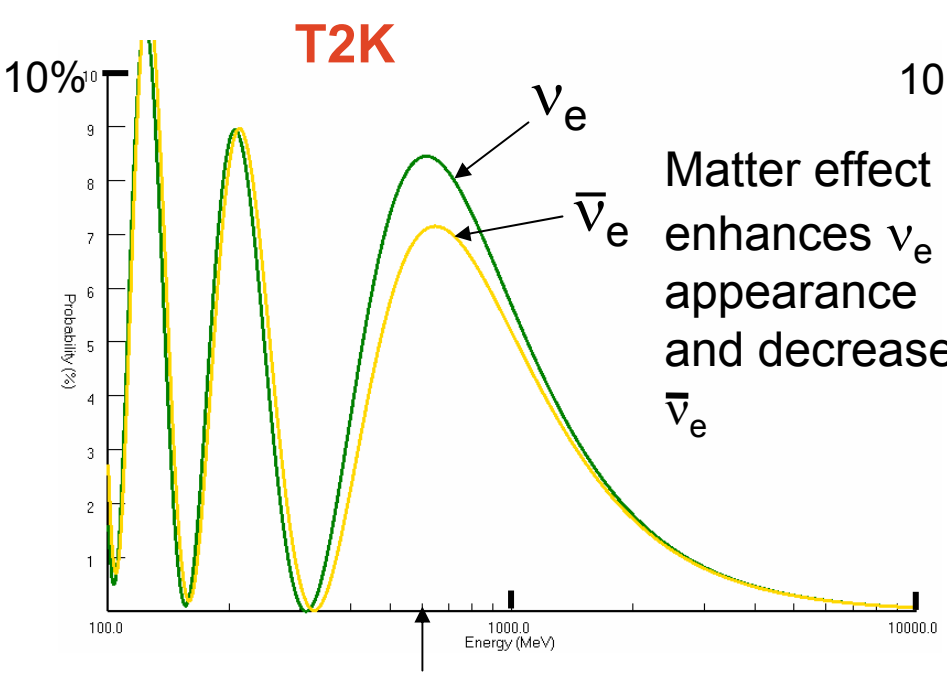
ν's

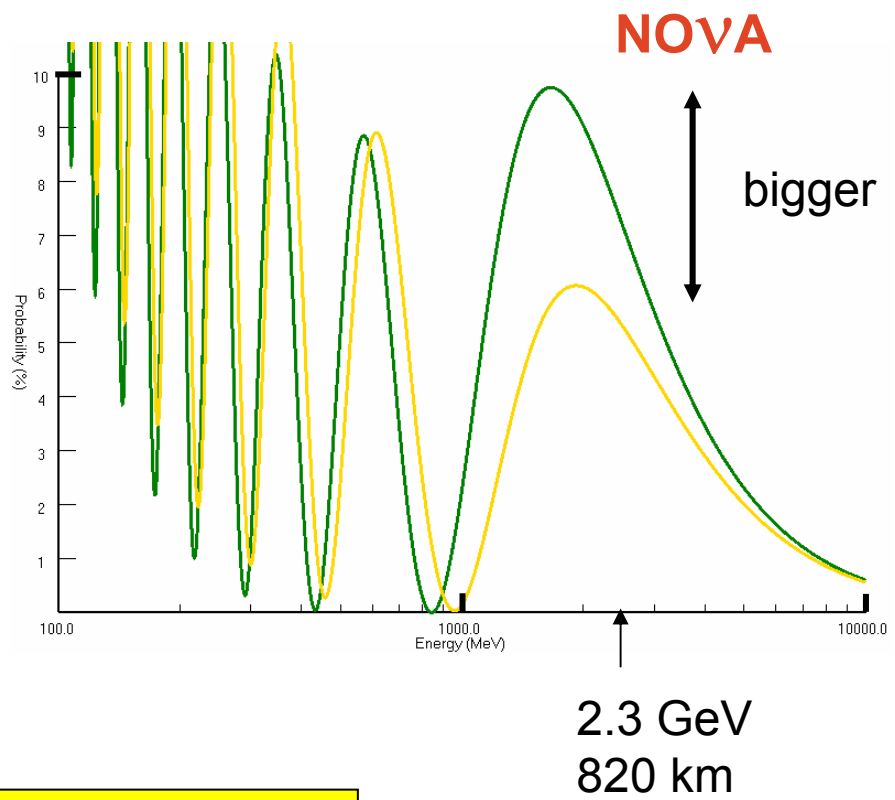
Where $a(x) = \sqrt{2} G_F N_e(x)$

Electron number density at x

- Matter induced effects are a function of E_ν and can be large for long path lengths.
  - T2K ~10%
  - Nova ~25% (higher energy and longer distance)
- Opposite sign
  - for ν and $\overline{\nu}$
  - for NH and IH

$\nu_e(\bar{\nu}_e)$ Prob. vs. Energy at CHOOZ Limit



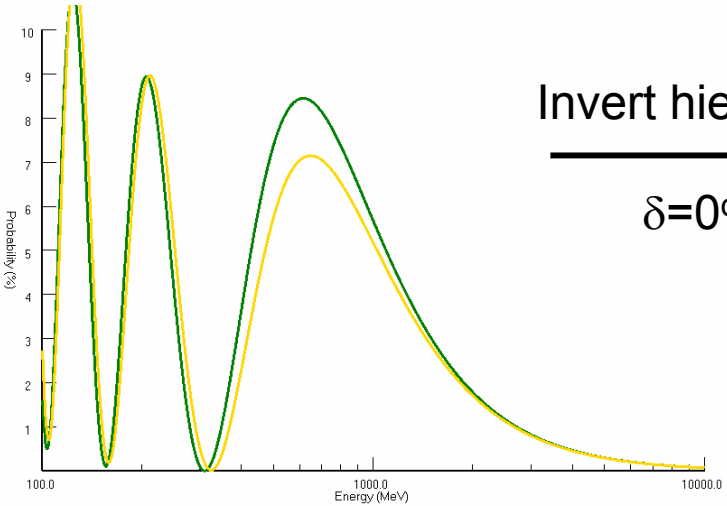


$\delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\sin^2 2\theta_{23}=1.0$

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

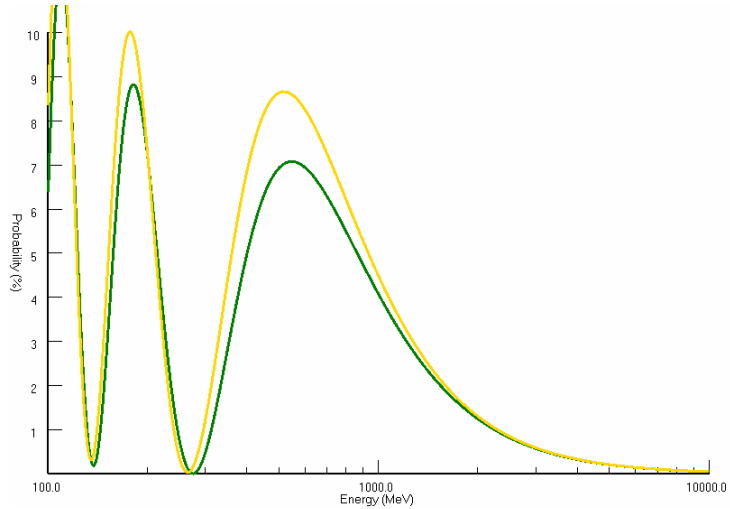
$\sin^2 2\theta_{13}=0.16$

Hierarchy/CP Degeneracy



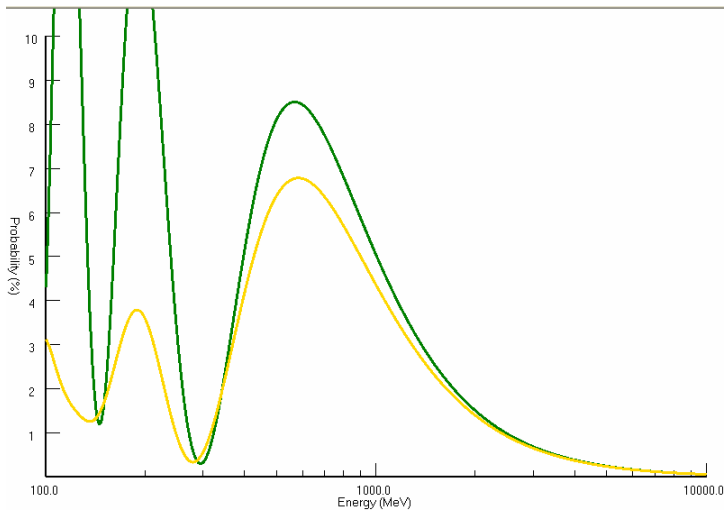
Invert hierarchy

$\delta=0^o$



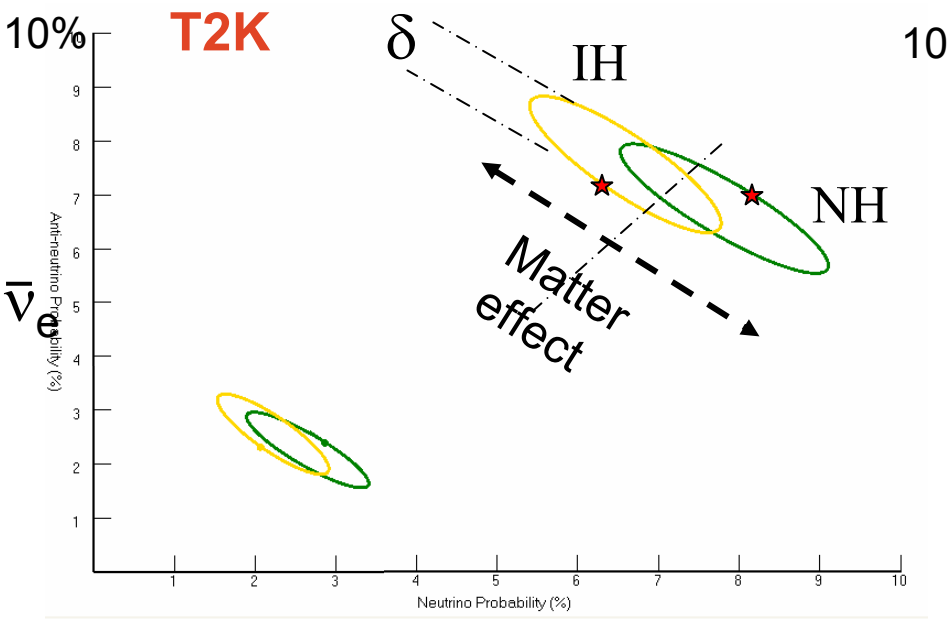
Invert hierarchy

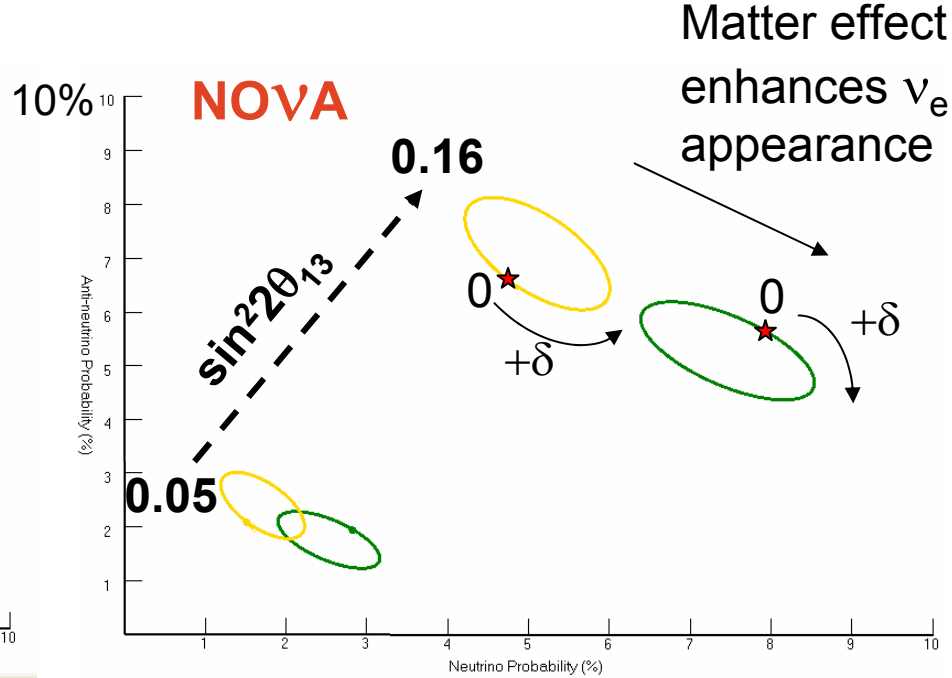
$\delta=-90^o$



$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

Minakata & Nunokawa hep-ph/0108085

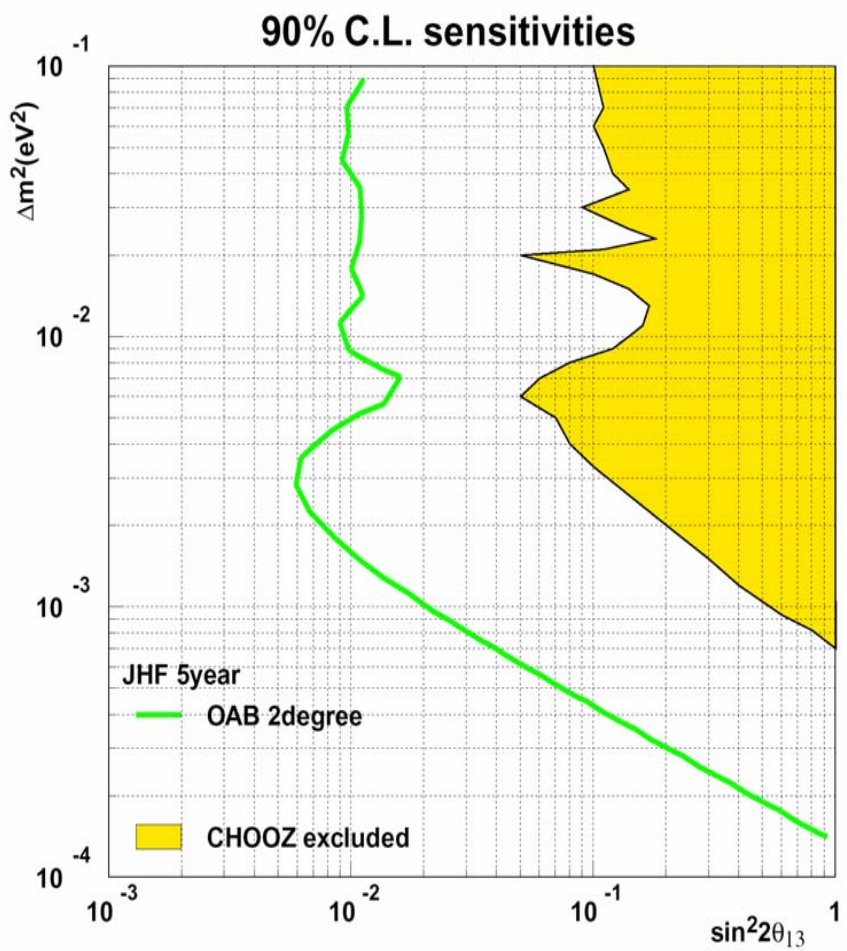


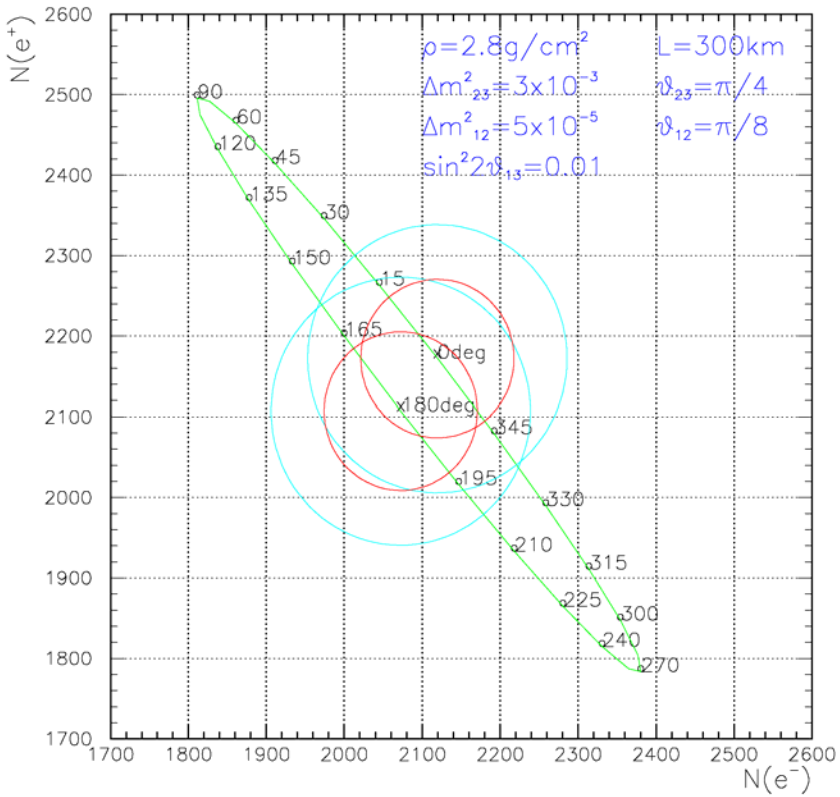


$\delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\sin^2 2\theta_{23}=1.0$

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

T2K Sensitivity

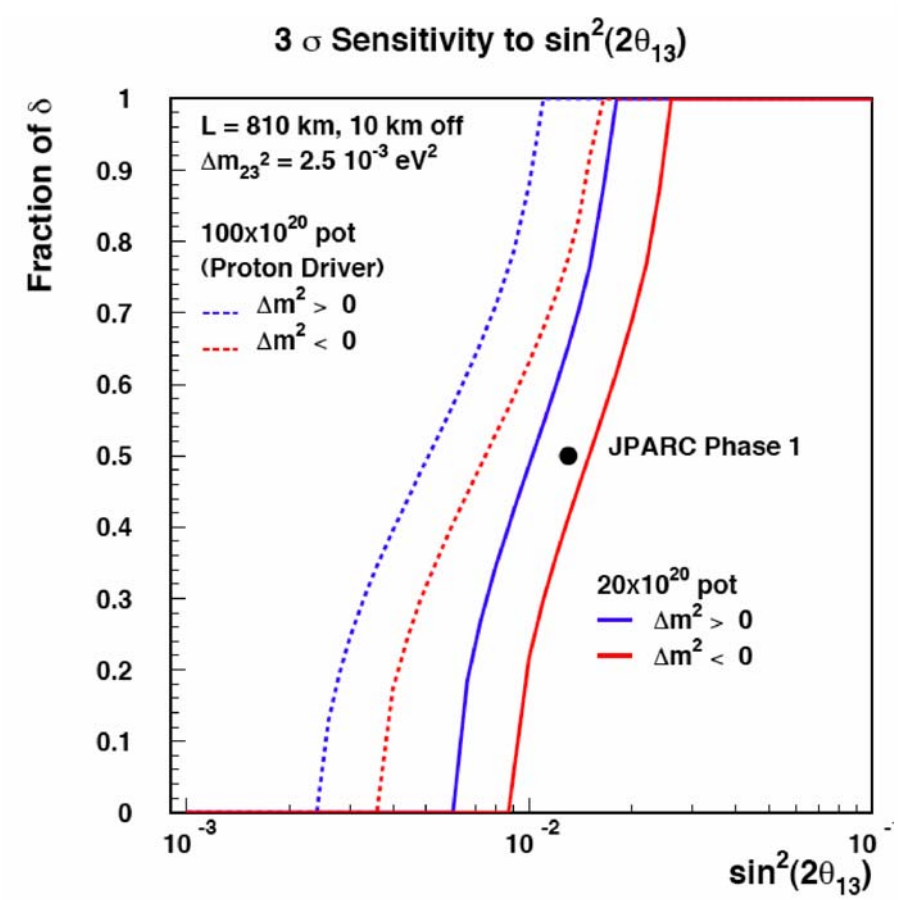


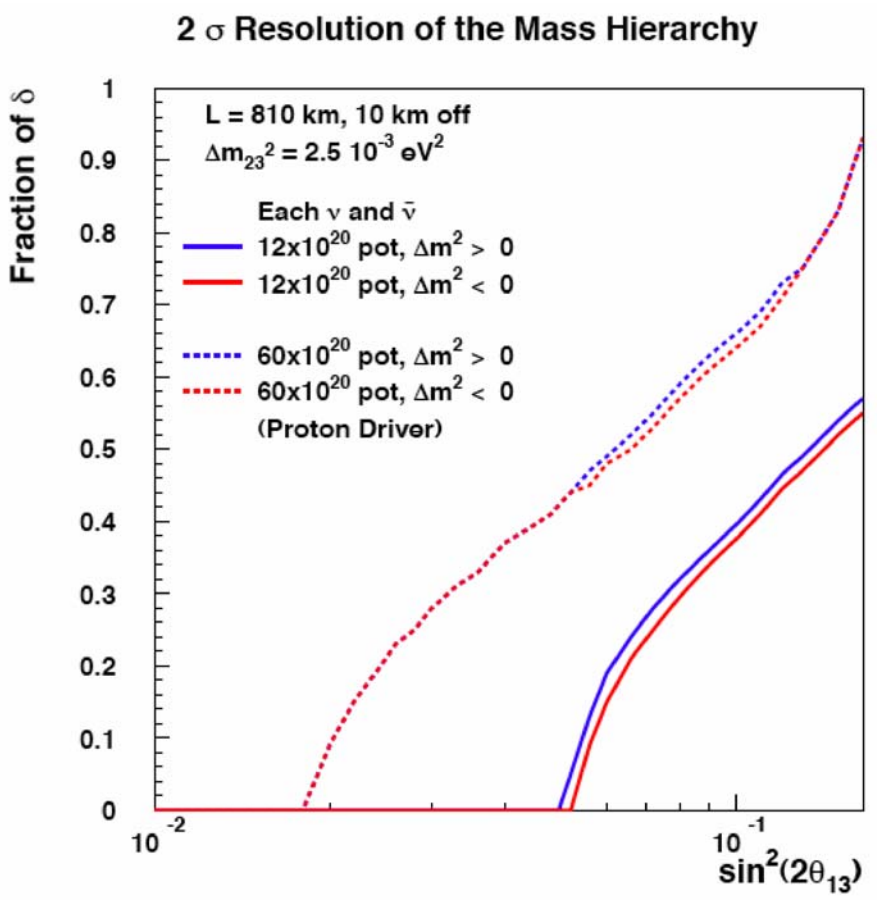


2 years ν_μ, 6 years $\overline{\nu}_\mu$

3σ discovery possible if $|\delta| > 20^o$

NOνA Sensitivity



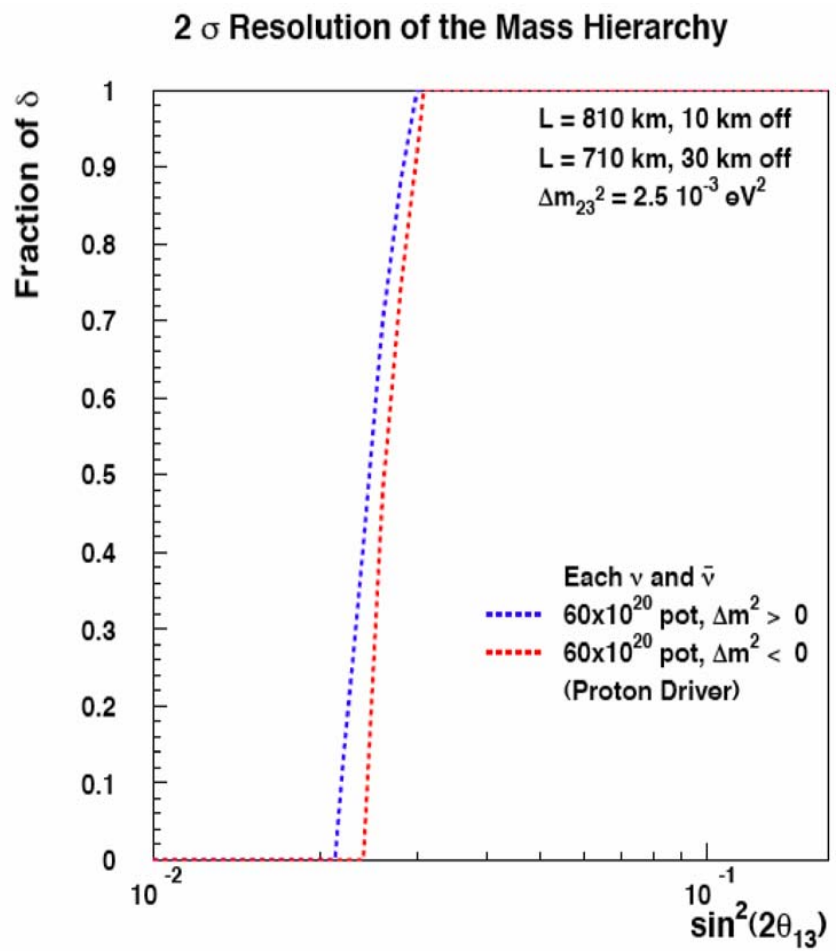


Do Better On Hierarchy Resolution

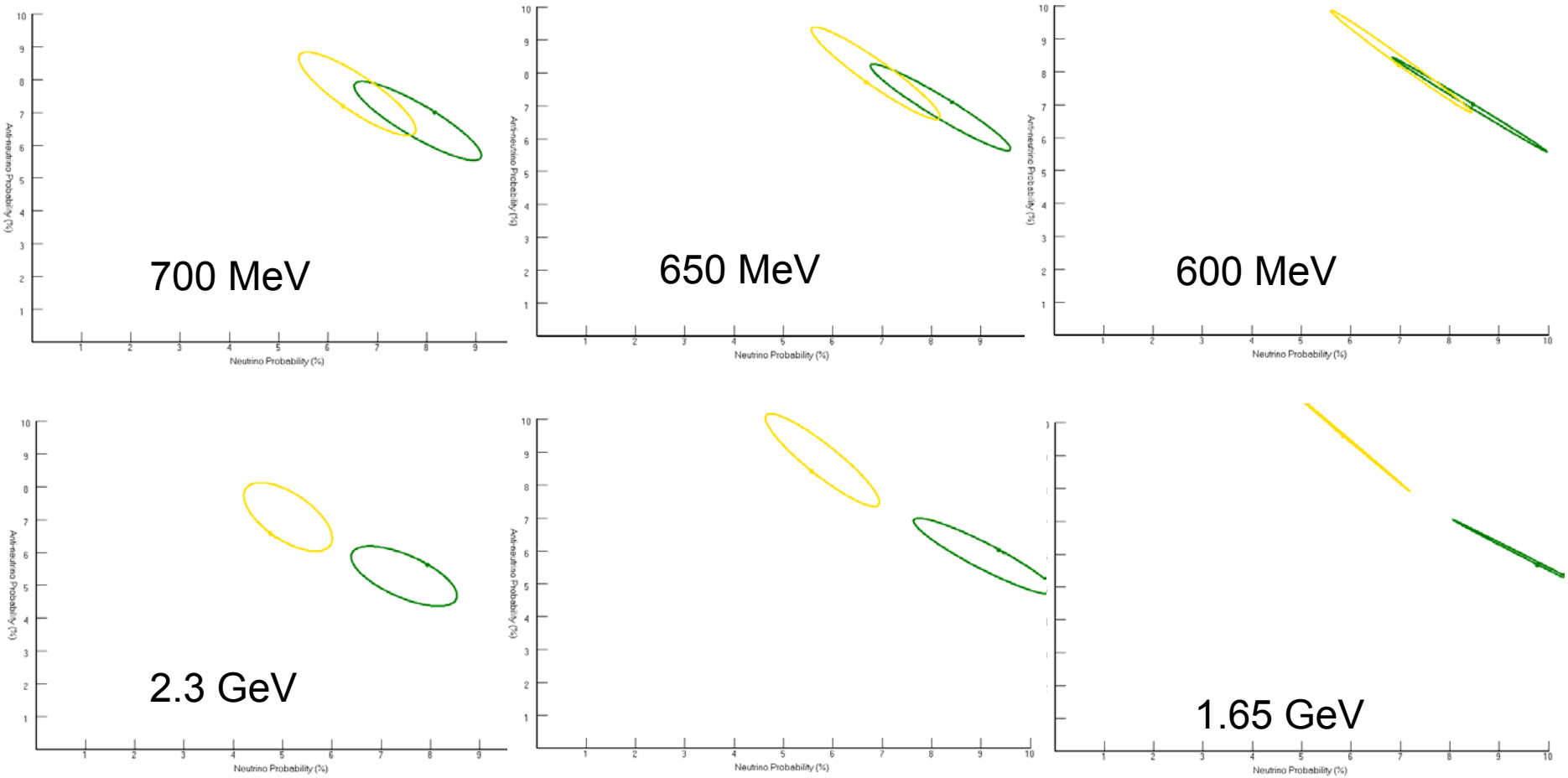
NOνA study:

Two Far Detectors Different Energies

Optimization under study



Eliminate δ Uncertainty



Tune to oscillation maximum and measure with ν and $\bar{\nu}$

Hep-ph/0112345

Summary

The off-axis technique is a very promising method to:

- discover if θ_{13} is non-zero by observing ν_e appearance
- enable high precision measurements of

θ_{23} and δm^2_{23}

- More studies are needed to optimize the procedure for establishing the mass hierarchy and for searching for non-zero CP phase.
- Most likely several complimentary techniques will have to be used.
  - Different distances
  - Neutrino and anti-neutrino beams
  - Reactor measurements of θ_{13}