$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV 15km/MeV

Physics Handles on the Neutrino Mass Hierarchy:

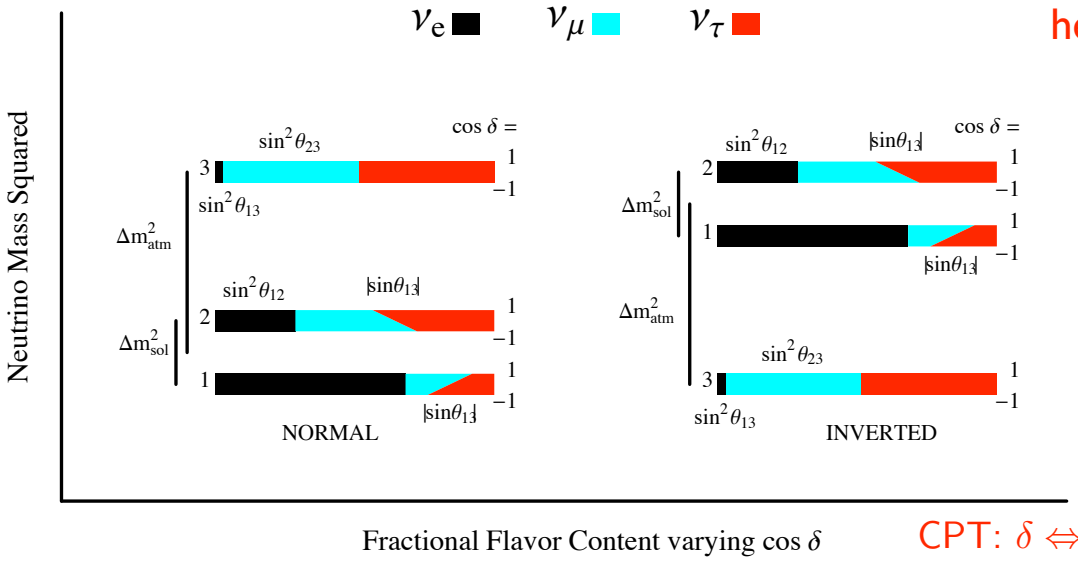
Stephen Parke, Fermilab

NO-VE 2006

- "Mass" Measurements
- Long Baseline $\nu_\mu \longrightarrow \nu_e$ or $\nu_e \longrightarrow \nu_\mu$
- Other Possibilities

Mixings:

$$|U_{\alpha i}|^2$$

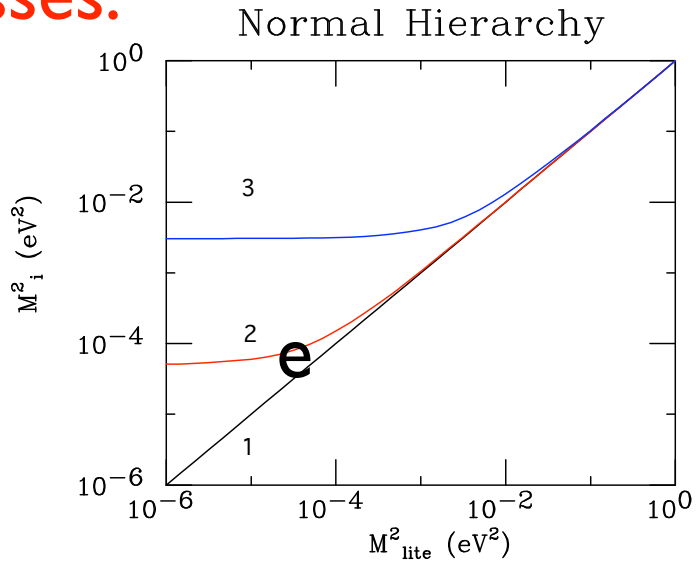


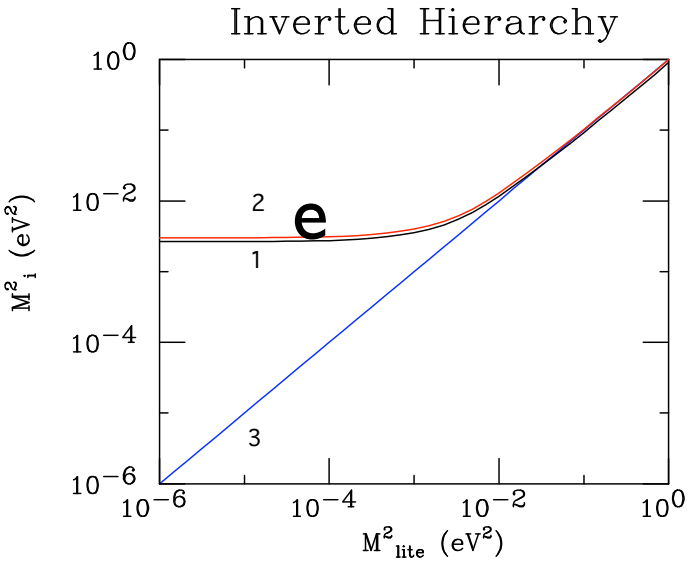
hep-ph/0312131

Less than 4% ν_e in the 3 state!

CPT: $\delta \Leftrightarrow -\delta$ Invariant!

Masses:





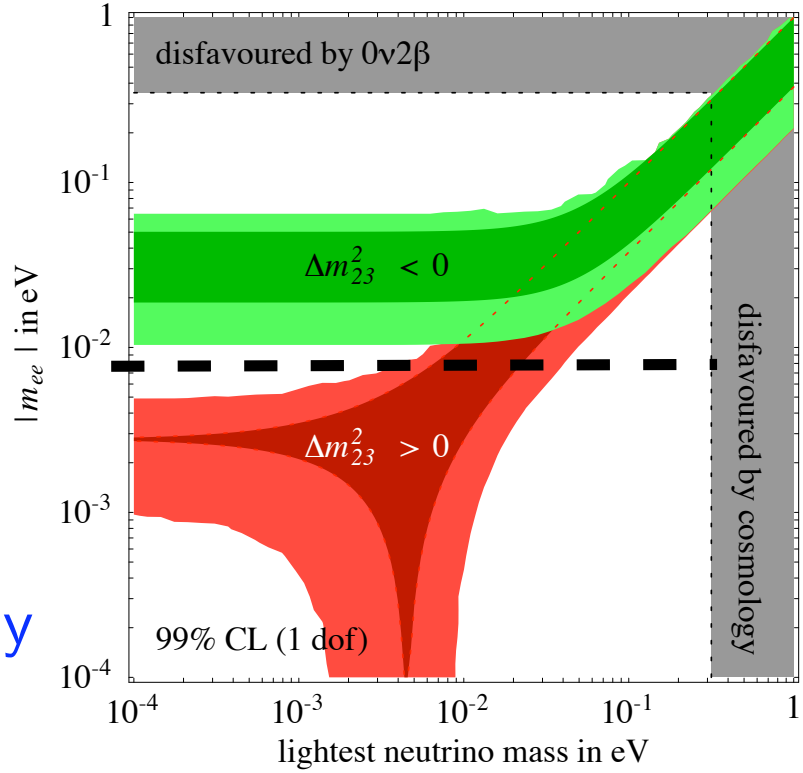
States 1 and 2 are ν_e rich.

Neutrinoless double beta decay

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

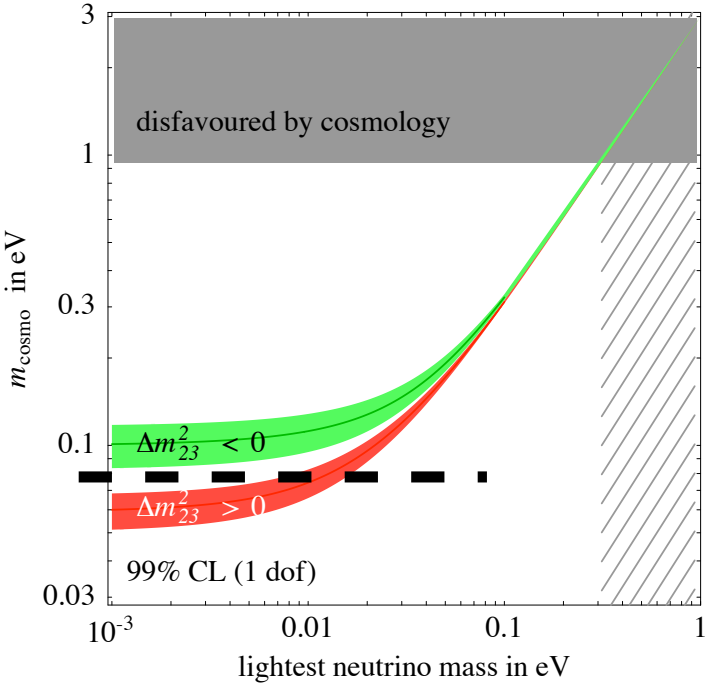
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

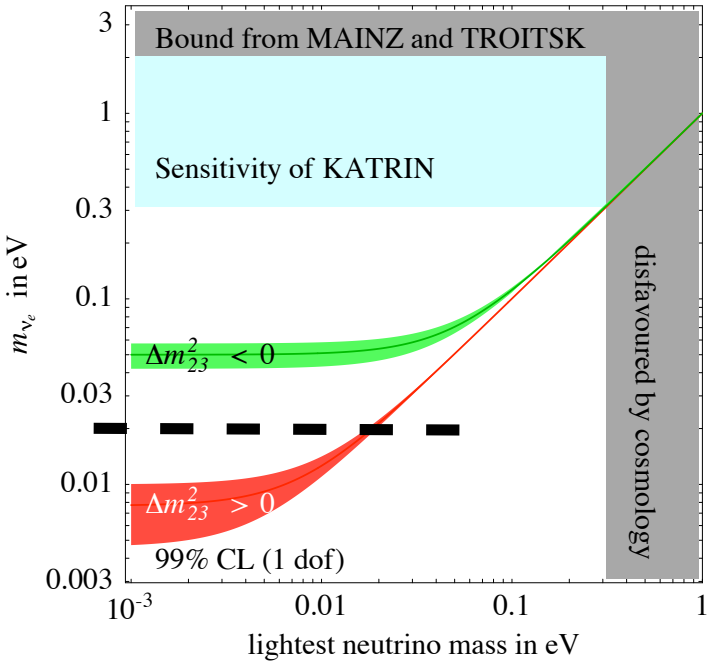
dividing point $m_{\beta\beta} \approx 10meV$ $\Rightarrow\Rightarrow$



Signal below $\sim$ 10 meV would imply Majorana and Normal Hierarchy!

: $\sum m_i$





Similarly, if Tritium decay exp. (Hyper-Katrin) could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, then Normal Hierarchy.

these 3 figs from Strummia and Vissani hep-ph/0503246

Long Baseline $\nu_\mu \longrightarrow \nu_e$ or $\nu_e \longrightarrow \nu_\mu$

- SUPERBEAMS: (0.4 to 4 MW)
  - Counting Expts (3 ways)
  - Spectrum Measurement
- NEW NEUTRINO BEAMS
  - Neutrino Factory (muon storage ring)
  - High Gamma Beta Beams

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} |^2$$

$\Updownarrow$

CP violation !!!

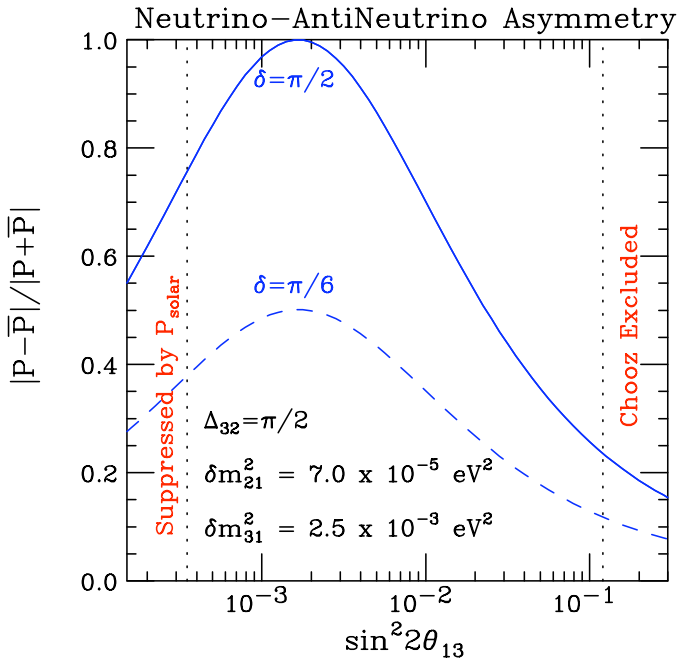
$$\Delta_{ij} = |\delta m^2_{ij}| L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} |^2$$

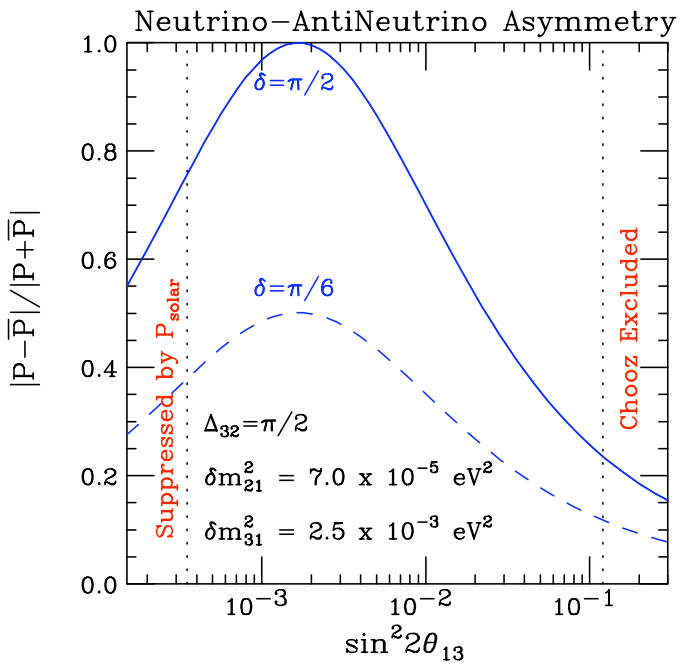
Asymmetry Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

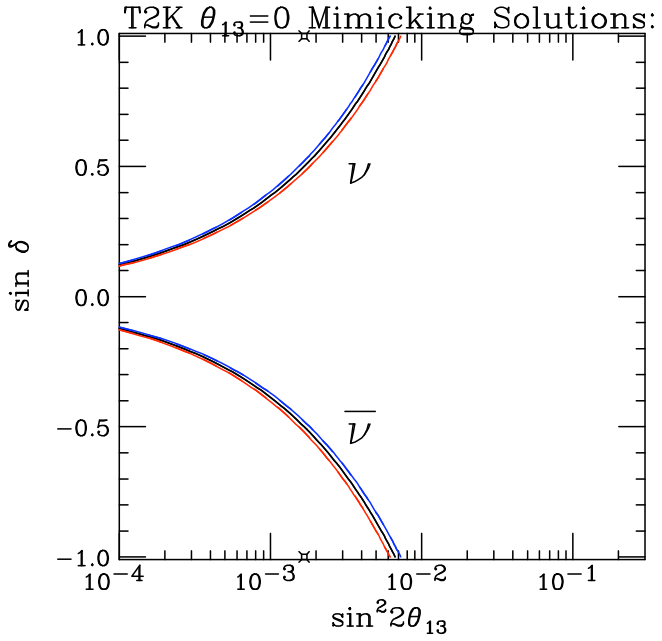
$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} |^2$$

Asymmetry Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

Zero Mimicking Solutions:



$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

$\nu_\mu \to \nu_e$ with MATTER

$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} |^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \dfrac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

in vac $\sin\Delta_{31}$

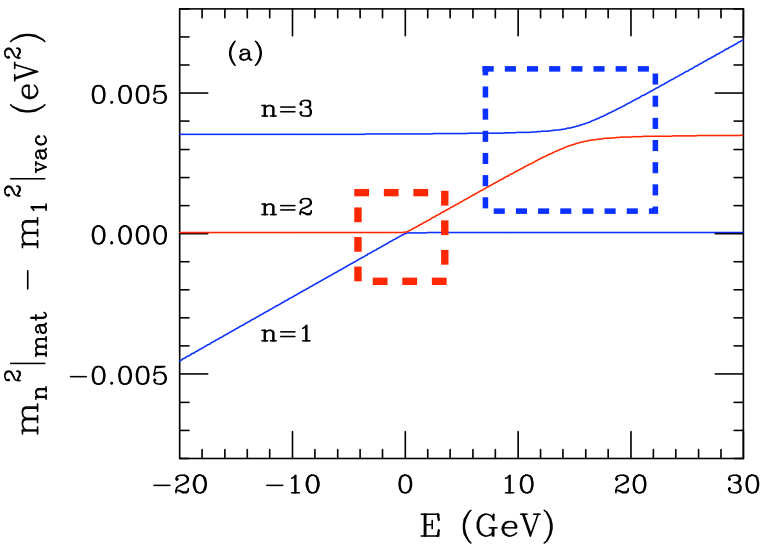
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \dfrac{\sin(aL)}{(aL)} \Delta_{21}$

in vac $\sin\Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

$$\pm = sign(\delta m^2_{31}) \quad \Delta_{ij} = |\delta m^2_{ij}| L/4E$$

$\{\delta m^2 \sin 2\theta\}$ is invariant



Counting Expts at First Osc. Max.

- Neutrino v Anti-Neutrino One Expt.
- Neutrino v Anti-Neutrino Two Expts Different L's
- Neutrino v Neutrino Two Expts Different L's and EQUAL E/L's

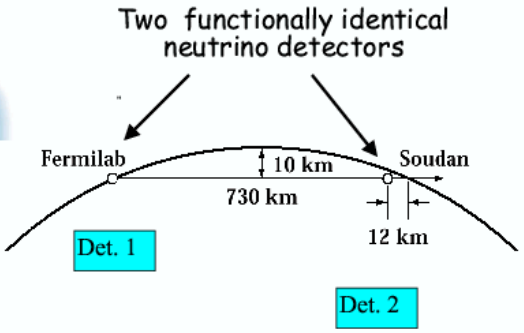
T2K

JHF → Super-Kamiokande

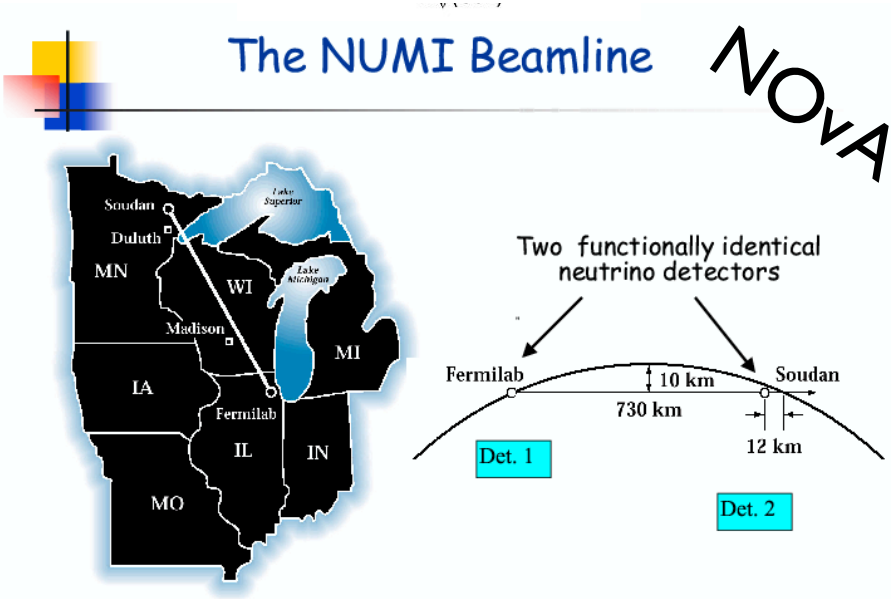
- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π^0/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

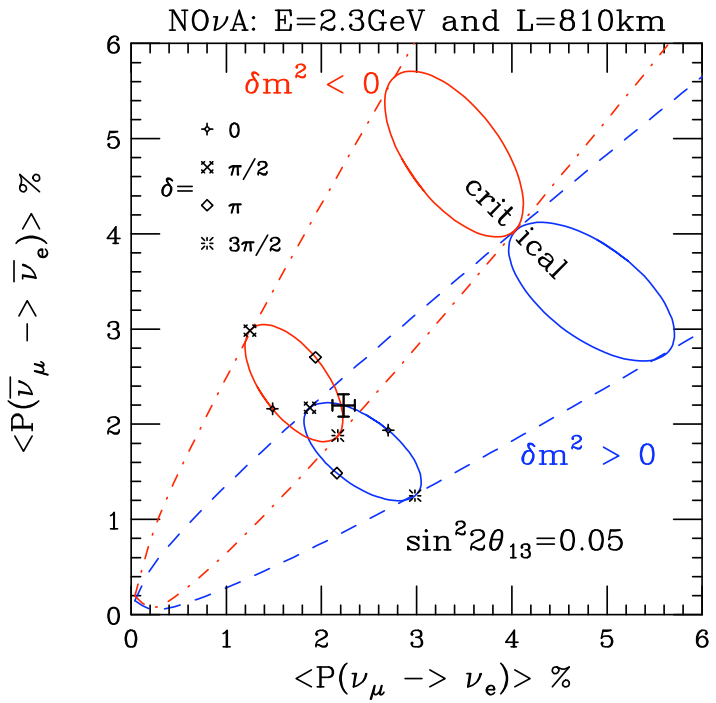
NOvA

The NUMI Beamline



Neutrino v Anti-Neutrino One Expt.





the overlap region

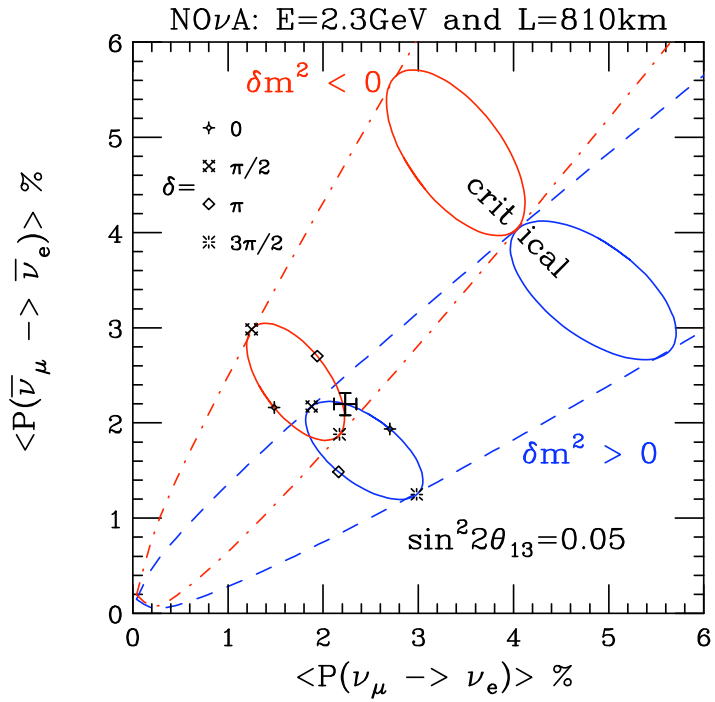
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

exact along diagonal --- approximately true throughout the overlap region!!!

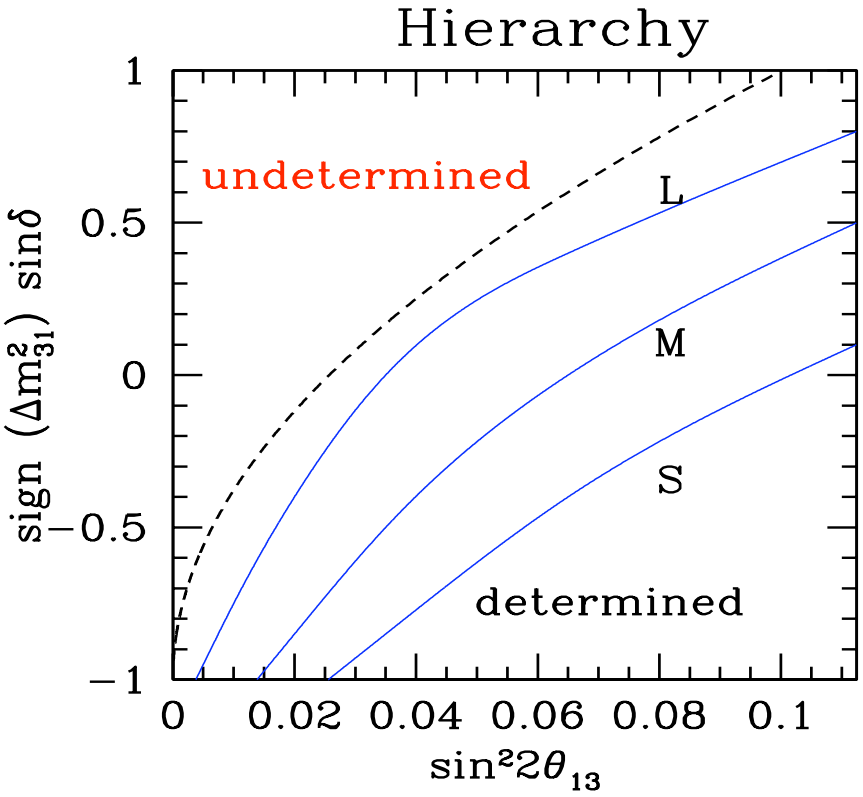
$$\theta_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}/(aL) \sim 1/6$$

i.e. $\sin^2 2\theta_{crit} = 0.10$

O. Mena + SP
hep-ph/0408070



NOvA:



S: 4 +4 yrs

M (=5*S):

Proton Driver

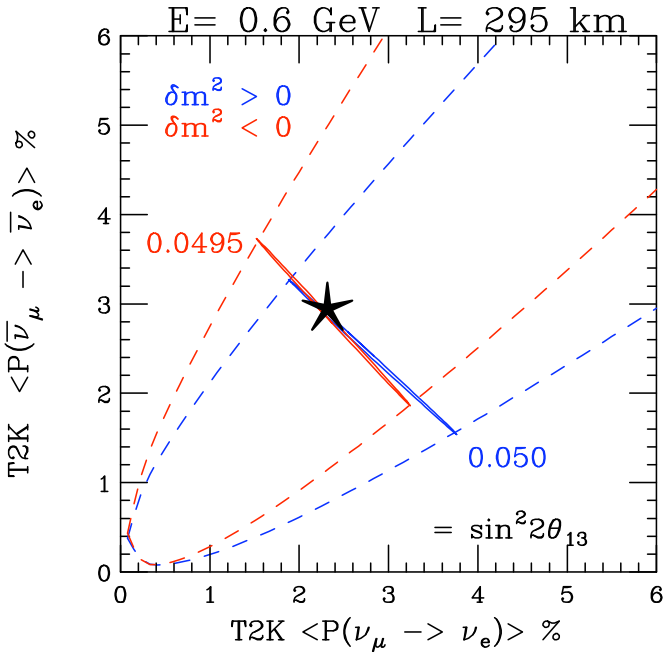
L (=5*M):

PD + Liquid Argon

T2K

JHF → Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π^0/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data



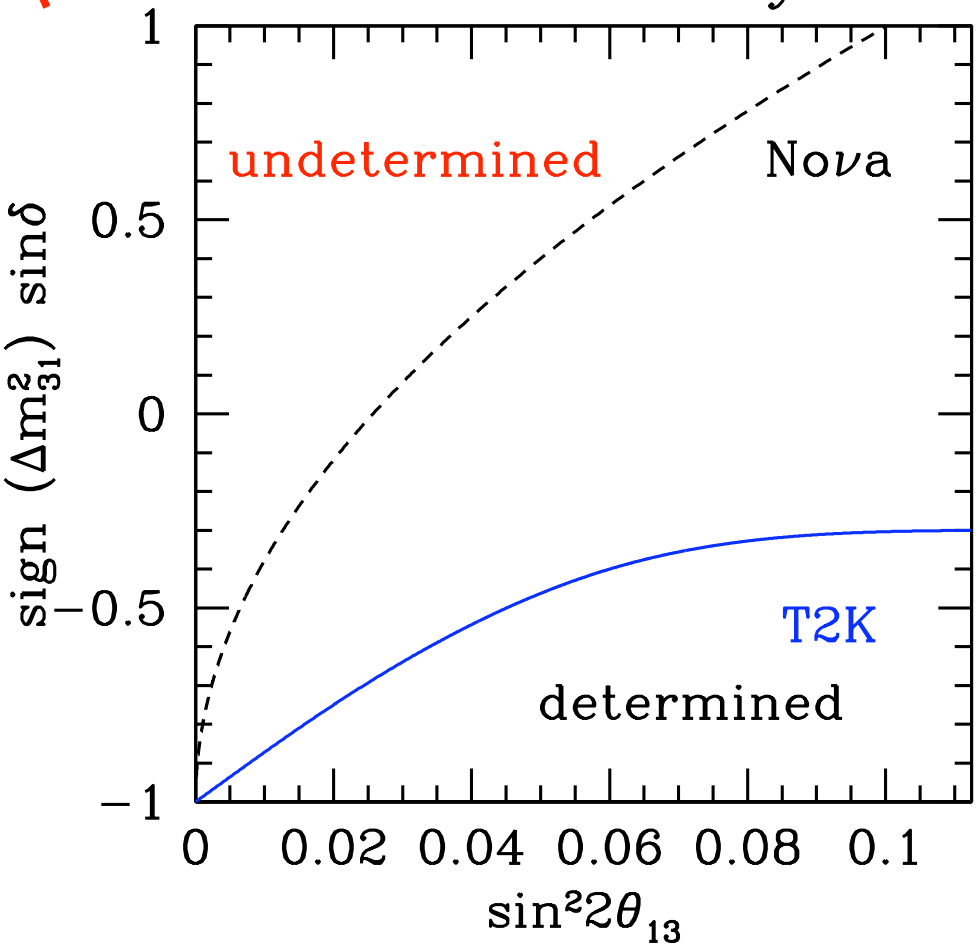
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

(ρL) for NOvA three times larger than (ρL) than T2K.

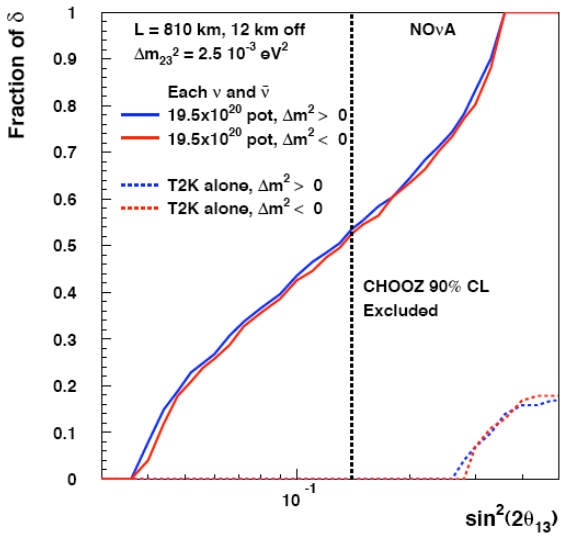
Potential

Hierarchy

$$-1 + 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

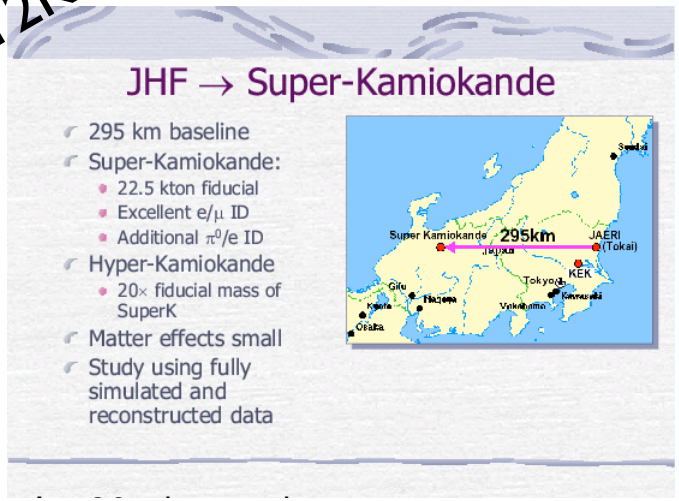


$$-1 + 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

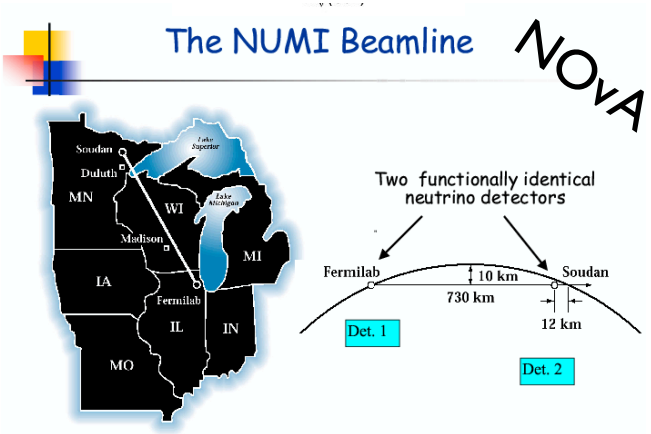


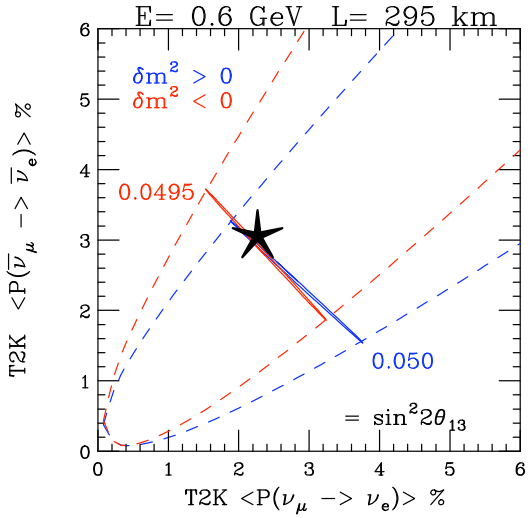
Neutrino v Anti-Neutrino
Two Expts. Different L's

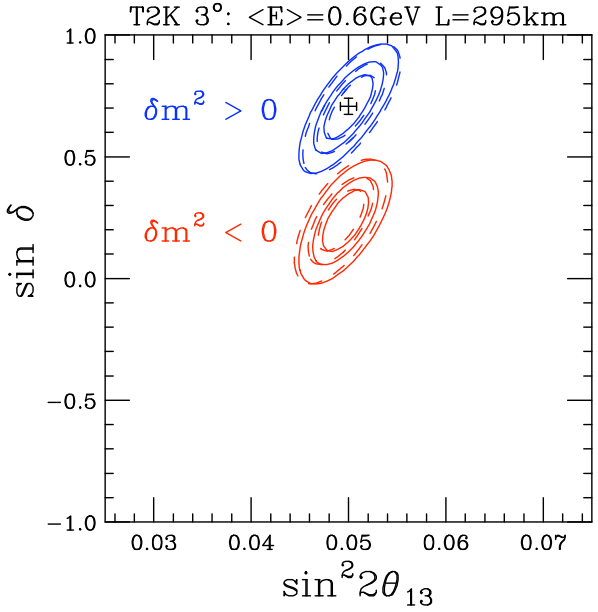
T2K



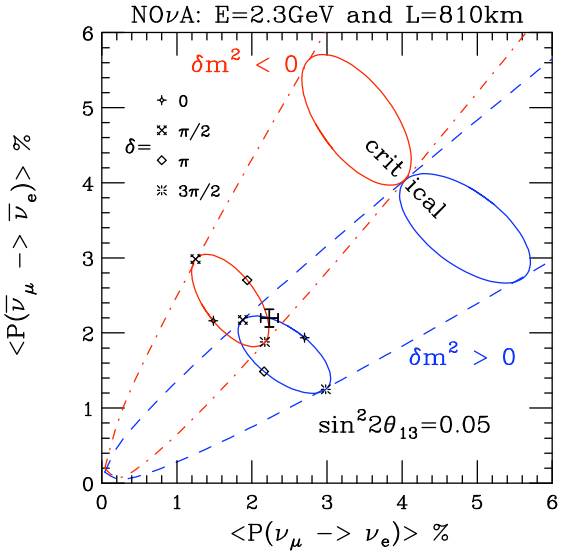
NOvA

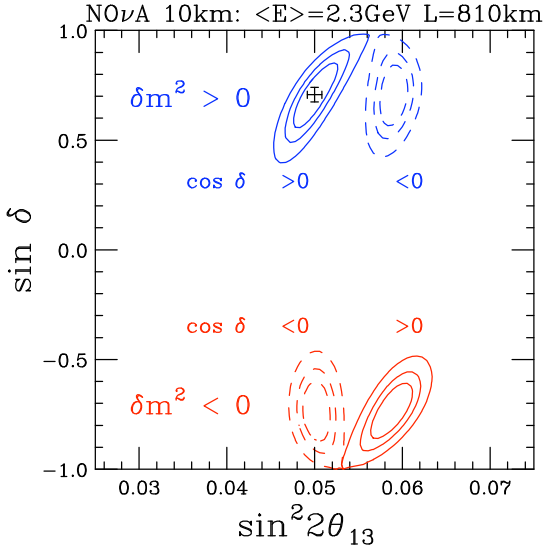






$$\langle \sin\delta \rangle_+ \;-\; \langle \sin\delta \rangle_- \;\approx\; 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$





$$\langle \sin\delta \rangle_+ \;-\; \langle \sin\delta \rangle_- \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$|\langle \sin\delta \rangle^{T2K}_{true} - \langle \sin\delta \rangle^{NO\nu A}_{true}| \approx 0$$

$$|\langle \sin\delta \rangle^{T2K}_{fake} - \langle \sin\delta \rangle^{NO\nu A}_{fake}| \approx 0.93 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

if the measurement uncertainty on $\sin\delta$

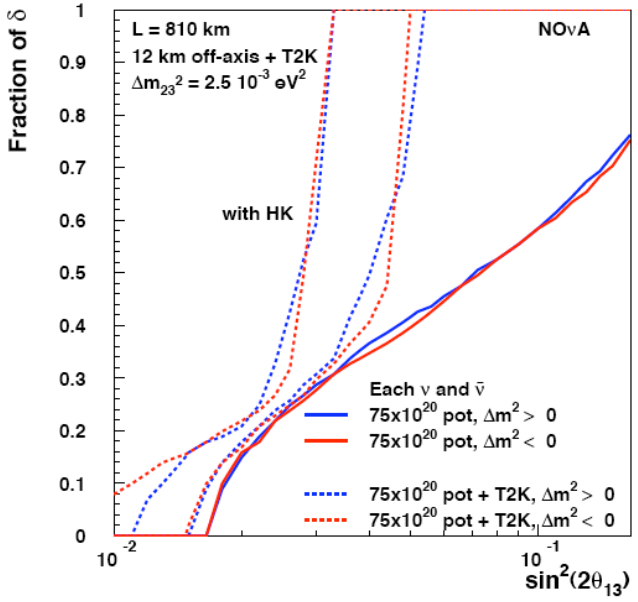
$$\approx \pm 0.2$$

then the two fake solutions are well separated down to

$$\sin^2 2\theta_{13} \approx 0.01$$

Hierarchy is Determined

95% CL

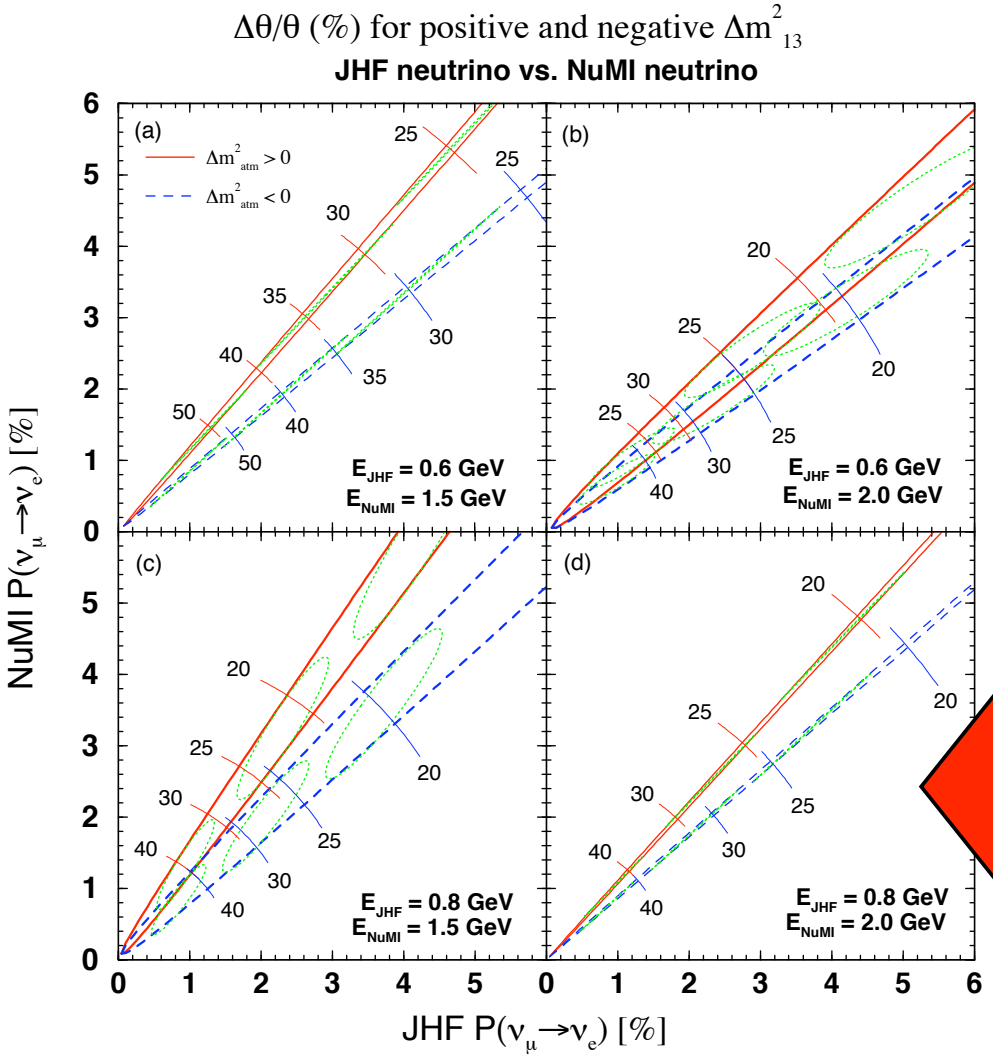


NOνA/PD with T2K Phase 2

Neutrino v Neutrino

Two Expts. Different L's

Same E/L !



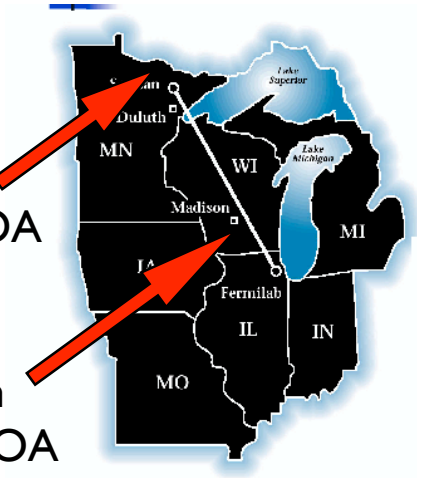
"Fans" narrow as the (E/L)'s become equal.

Minakata, Nunokawa and SP hep-ph/0301210

T2K: 2 degrees

NOvA: 12 km

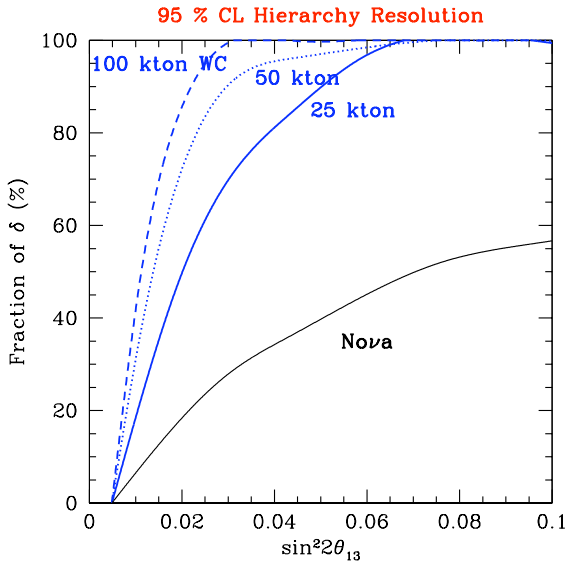
NOvA plus "NEAR" DETECTOR



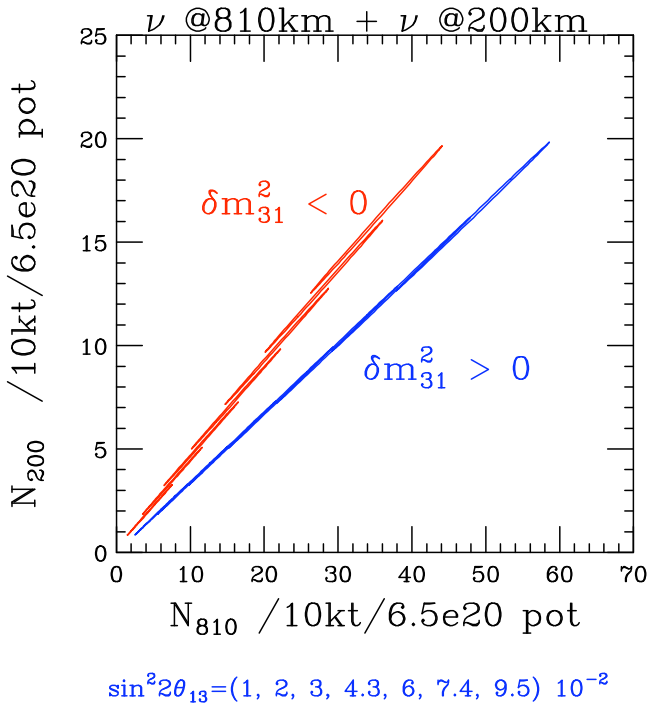
810km
@ 10 km OA
2.3 GeV

200km
@ 8 km OA
0.7 GeV

approx same
E/L



Neutrino - Neutrino



$\sin^2 2\theta_{13}$=(1, 2, 3, 4.3, 6, 7.4, 9.5) 10^{-2}

Mena, Palomares, Pascoli
hep-ph/0504015

with Proton Driver

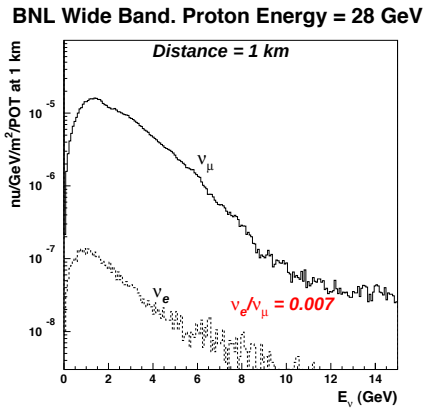
Spectrum Measurements:

- On Axis
- Off Axis - 2nd Peak

On Axis Beams:

- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake

Brookhaven Proposal



Why Broadband Beam?

observe multiple nodes extraction of oscillating signal from background.

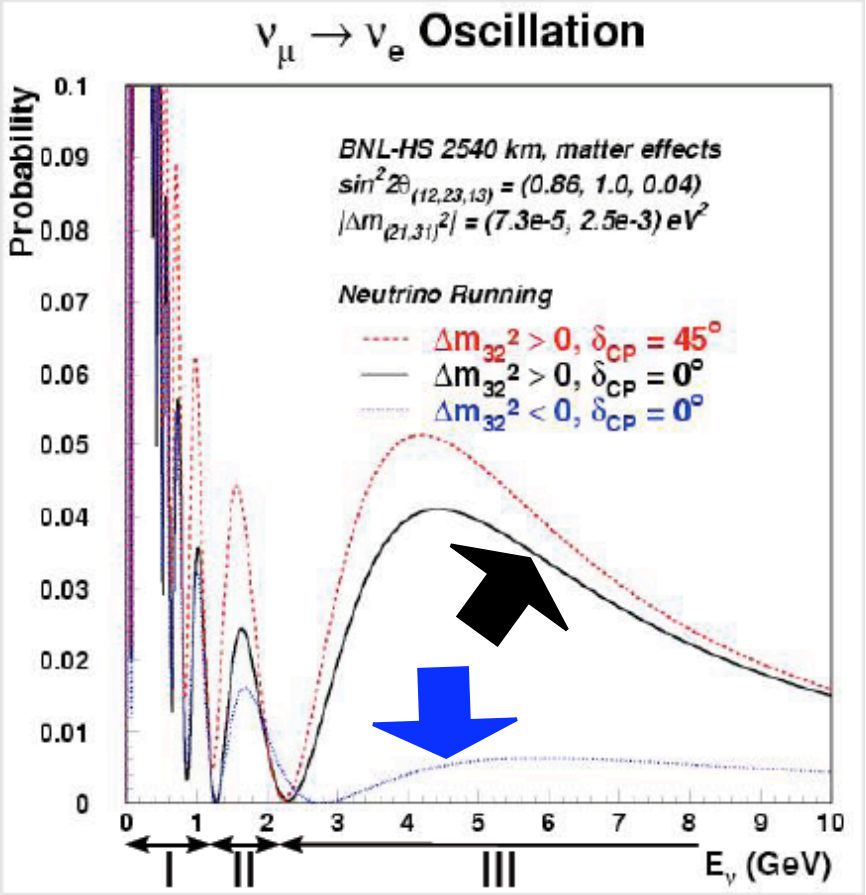
larger energies

larger cross sections

less running time for anti-neutrinos

Sensitive to different parameters in different energy regions:

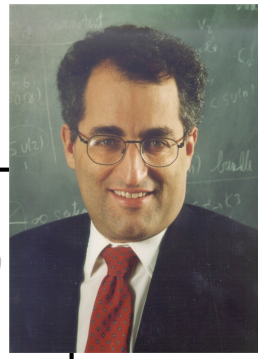
	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
sign(Δm^2_{32})	0	0	++
δ_{CP}	+	++	+
solar	++	+	+



2450 km, 500 kt, 1MW, 5+5 yrs, 95 % CL

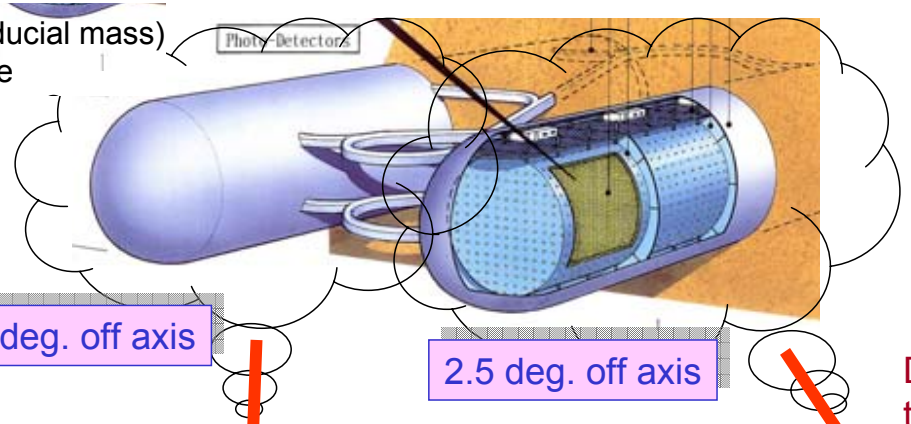
Hierarchy resolved for $\sin^2 2\theta_{13} > 0.008$ for all δ.

Off Axis:



Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

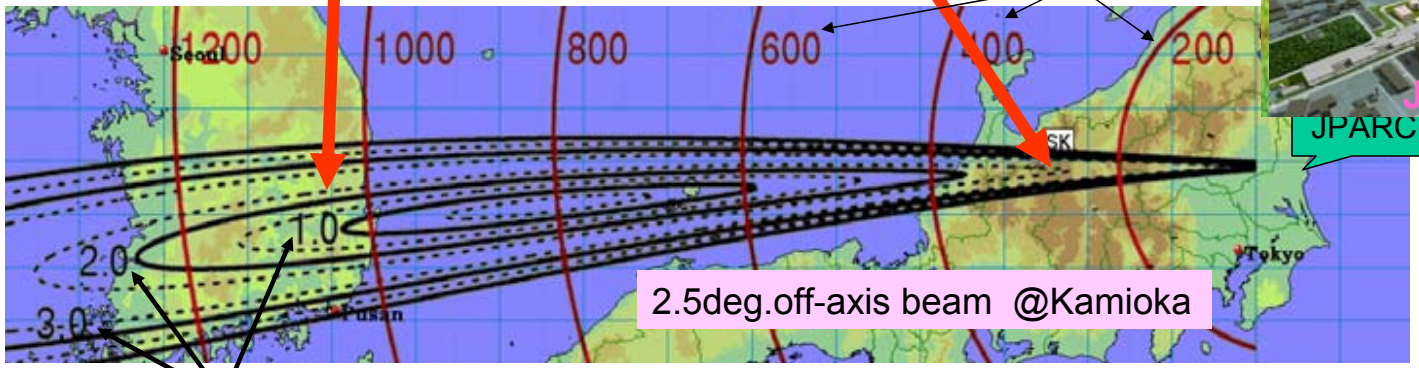


2.5 deg. off axis

2.5 deg. off axis

Total cost must be similar to the baseline design.

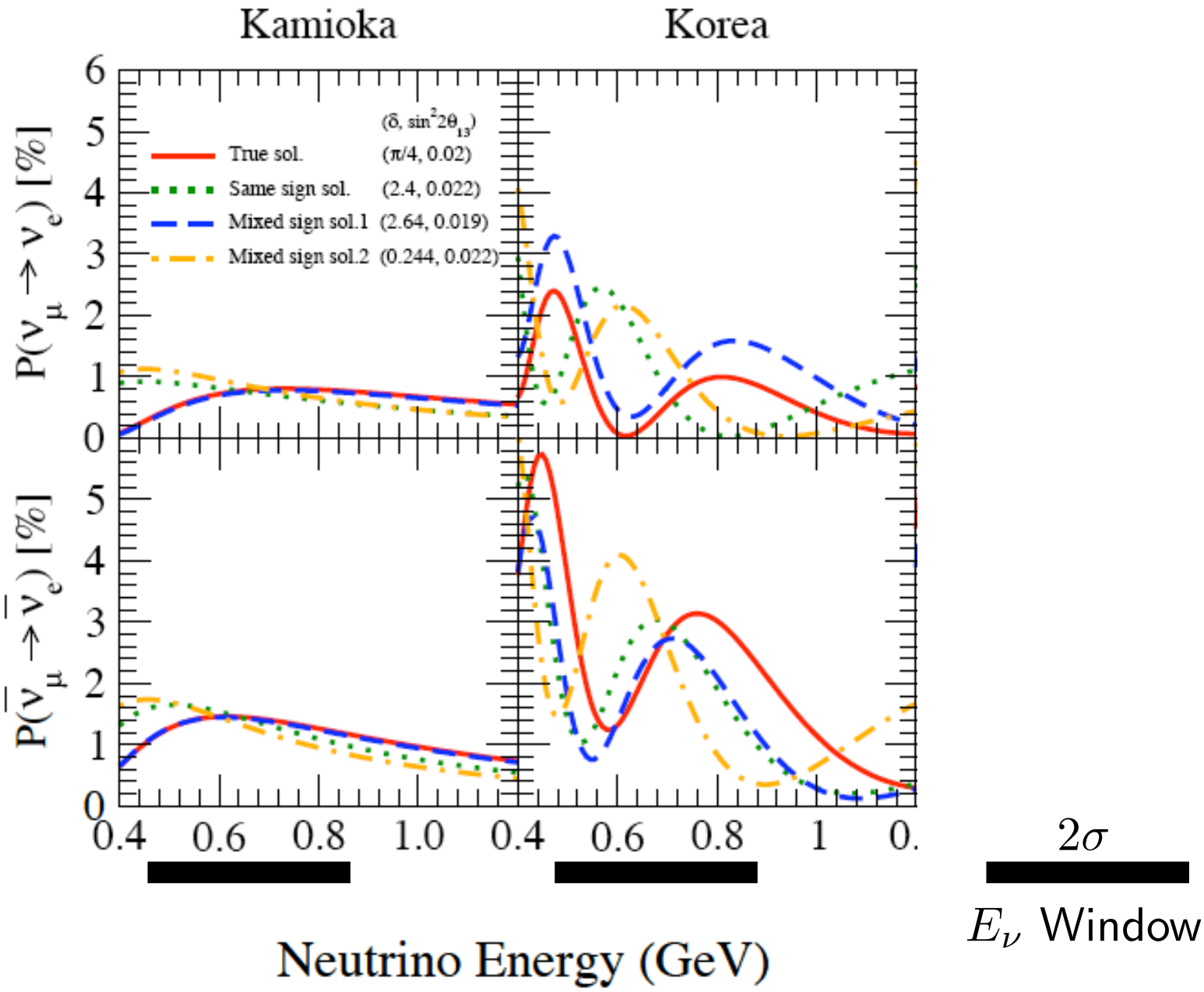
Distance from the target (km)



2.5deg.off-axis beam @Kamioka

Off-axis angle

see Kajita talk:

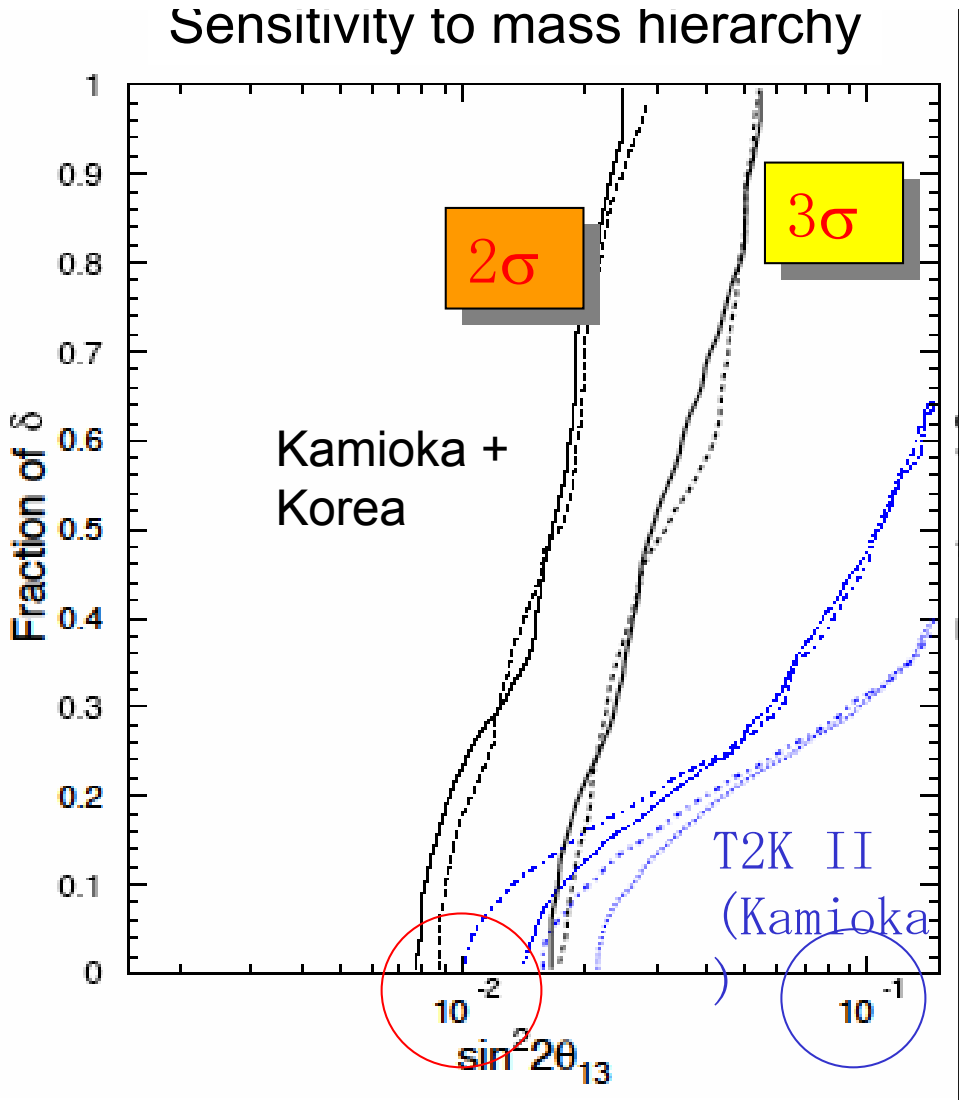


Ishitsuka, Kajita, Minakata and Nunokawa hep-ph/0504026

Tokai to Kamioka-Korea

Expected sensitivity

Neutrino + anti-neutrino runs = 8 years



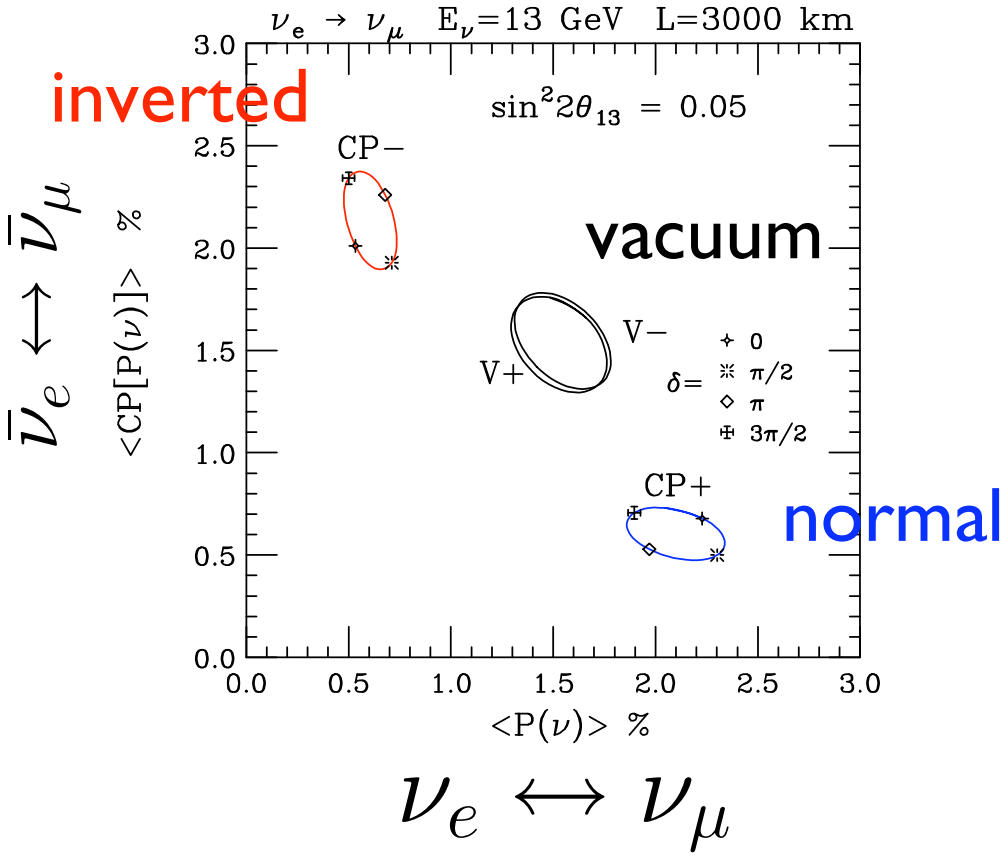
- NEW NEUTRINO BEAMS
  - Neutrino Factory (muon storage ring)
  - High Gamma Beta Beams

see Winter talk:

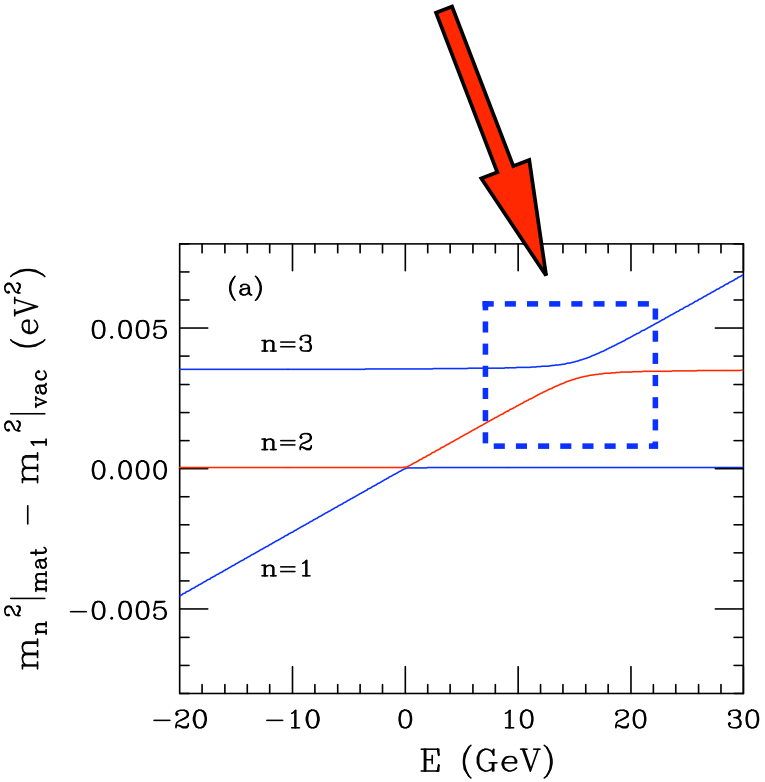
Neutrino Factory:

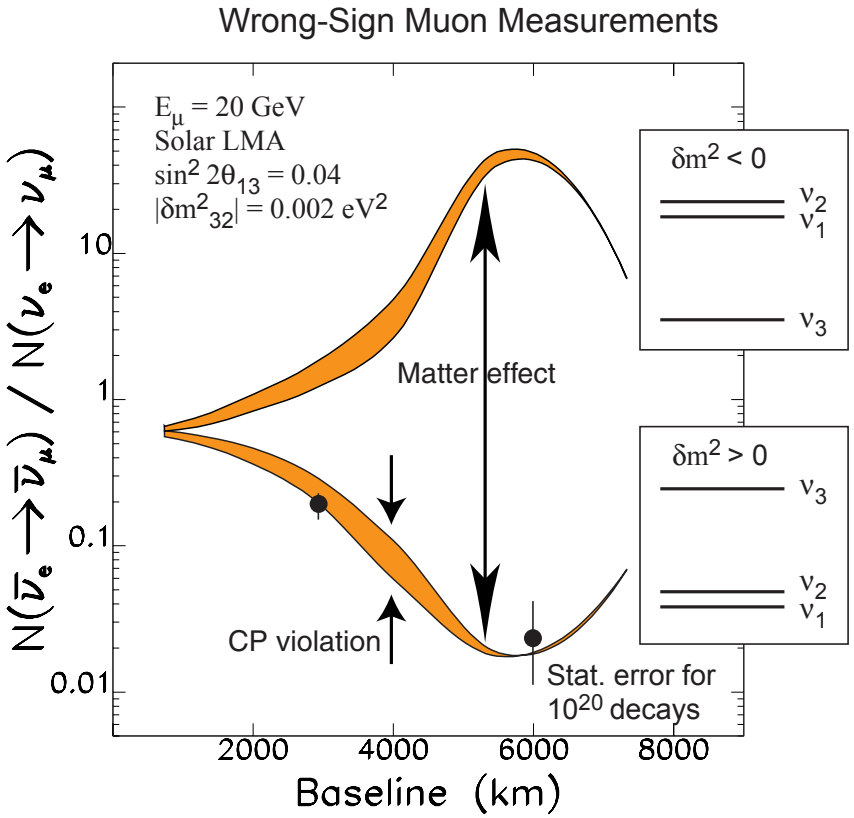
Mass Hierarchy: – sign of δm^2_{31}

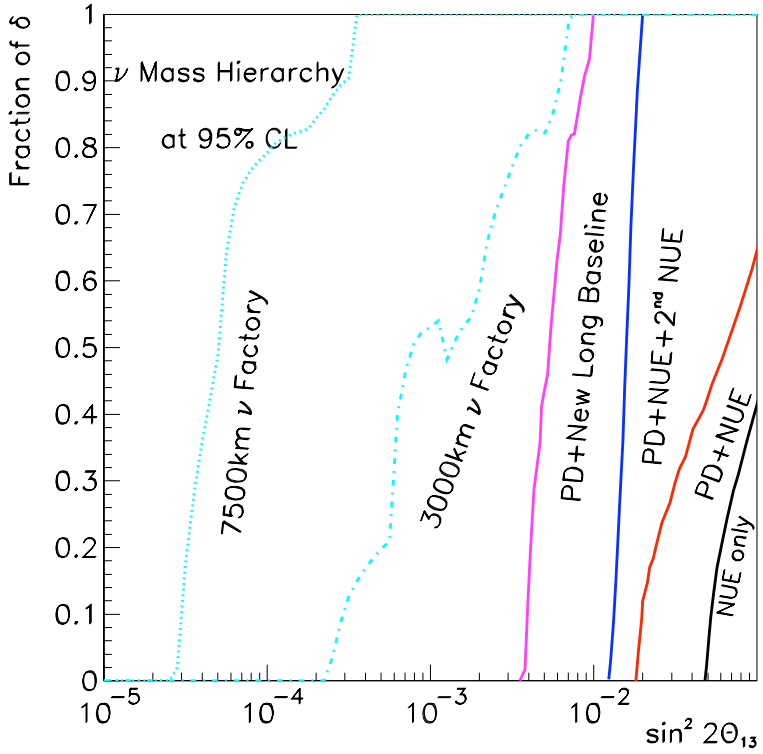
Matter Effects



"Amplification" near Resonance !







Neutrino Factory:

Only way to get to very small values of $\sin^2 2\theta_{13}$

Other Possibilities

- Supernova (Raffelt)
- Atmospheric
- Precision Disappearance Measurements
- High Energy Cosmic Neutrinos (Quigg)
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Conclusions for Hierarchy Determination:

- Near Term: NOvA + T2K a powerful combination for $\sin^2 2\theta_{13}$ > 0.02 - 0.03
- For smaller $\sin^2 2\theta_{13}$ spectrum measurements are needed
- Very small values: Neutrino Factory
- Other