NEXT WEEK: Skip Tuesday

ROBERT PLUNKETT

DATES CHANGED TO

MARCH 9, 14 & 16

due to

http://www.fnal.gov/directorate/DirReviews/Neutrino_Wrkshp.html

θ_{13} & Beyond: Nu Worlds

CP

$\nu_\mu \leftrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ Super-Beams

T $\Updownarrow$ $\Updownarrow$ T

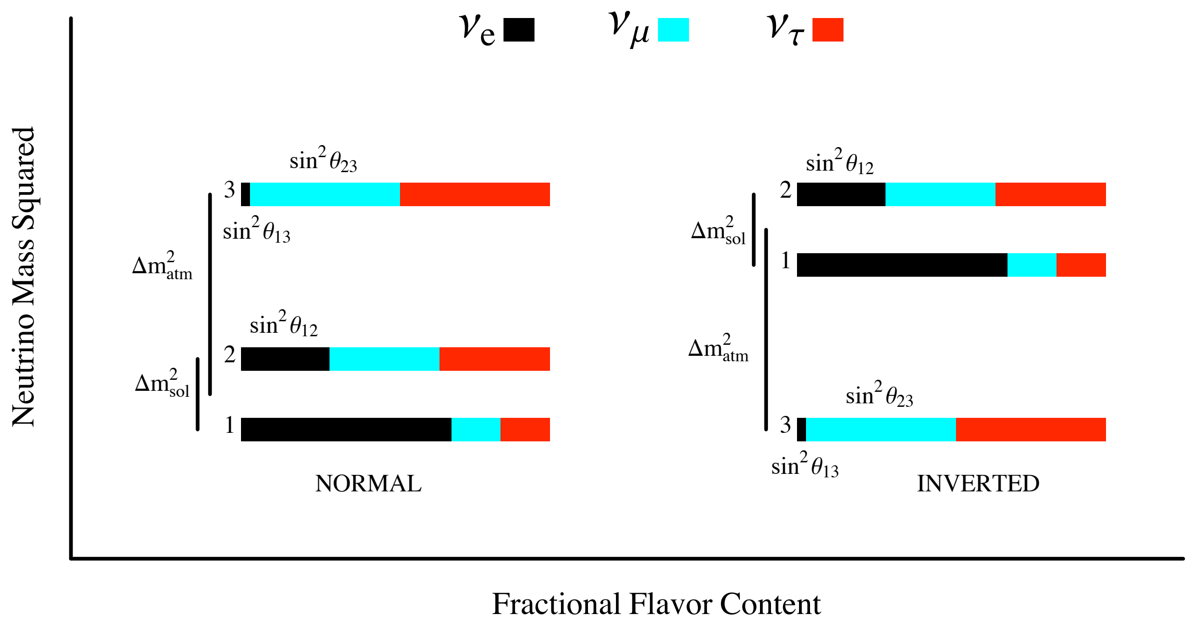
$\nu_e \leftrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ Nu-Factory

CP

Stephen Parke
Fermilab

Feb 23, 2006

http://theory.fnal.gov/people/parke/TALKS/2006/



- Fraction $\boldsymbol{\nu_e}$ in $\boldsymbol{\nu_3}$: $\mathbf{\sin^2\theta_{13}}$
- Mass Hierarchy: sign $\boldsymbol{\delta m^2_{31}}$
- CP Violation: $\mathbf{\sin\delta_{CP}}$

Vacuum: $\nu_\mu \rightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e) = |\, U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} \,|^2$$

$$= \ |2U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2$$

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

$e^{-iE_i t} \Rightarrow e^{-im_i^2 L/2E}$

CP violation !!! $\delta \rightarrow -\delta$ for $\bar{\nu}$

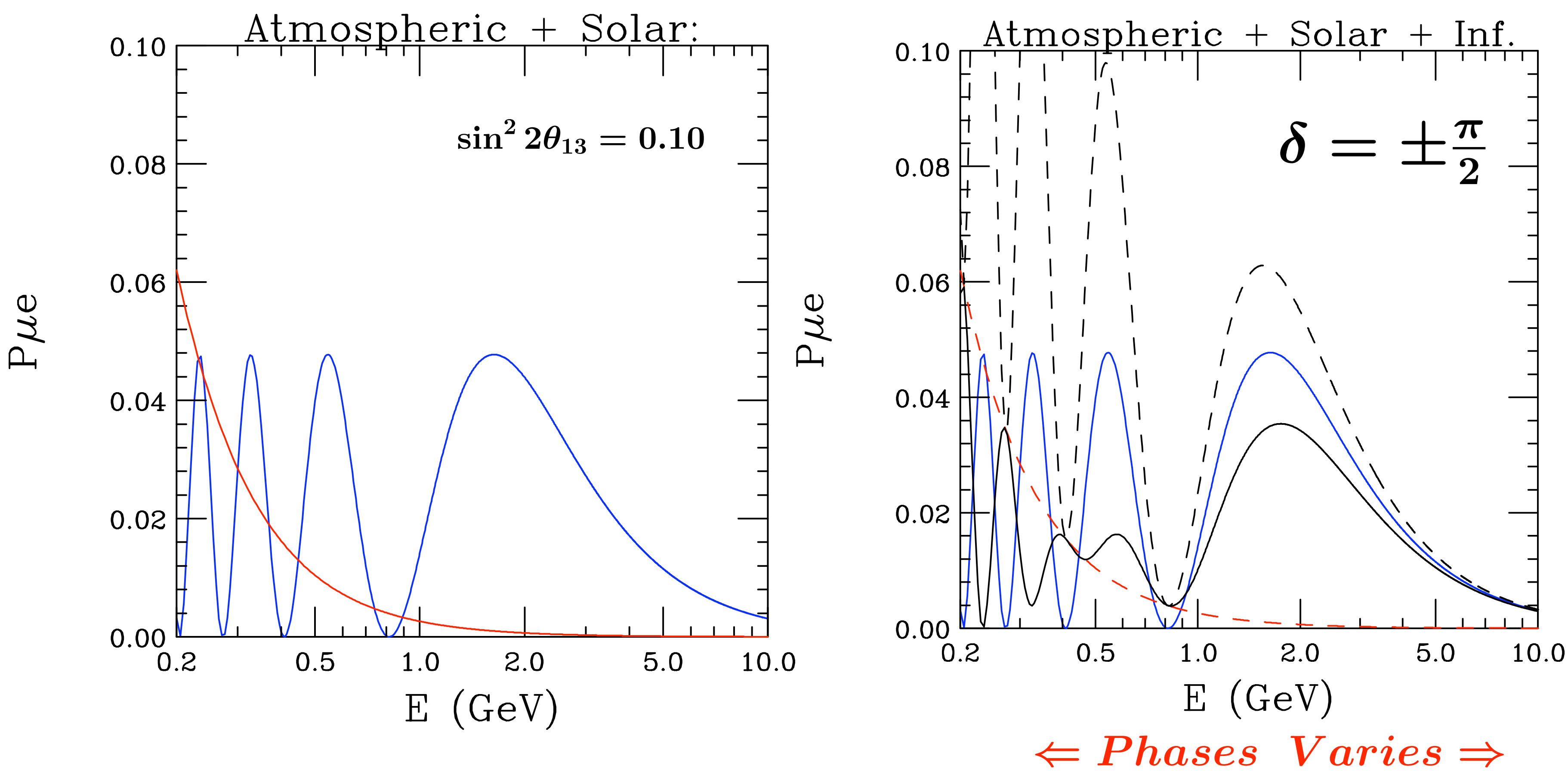
where $\sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$ and $\sqrt{P_{sol}} \approx \cos \theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$

$$P(\nu_\mu \rightarrow \nu_e) \ = \ P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} + \delta) + P_{sol}$$

CP violation !!!
$\delta \rightarrow -\delta$ for $\bar{\nu}$

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

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\sin\Delta_{31}$ and $\sqrt{P_{sol}} \approx \cos\theta_{23}\sin 2\theta_{12}\sin\Delta_{21}$



$$L = 810\ km$$

2 Flavor:

ν_e disappearance in Loooong Block of Lead:

$$\Delta_N = \frac{\delta m_N^2 L}{4E}$$

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta^N \sin^2 \Delta_N$$

same form as vacuum

BUT from $\delta m^2 \sin 2\theta$ invarance $\sin^2 2\theta^N = \left(\frac{\delta m^2}{\delta m_N^2}\right)^2 \sin^2 2\theta$

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \left(\frac{\delta m^2}{\delta m_N^2}\right)^2 \sin^2 \Delta_N = \sin^2 2\theta \left(\frac{\sin^2 \Delta_N}{\Delta_N^2}\right) \Delta^2$$

$$\Delta = \frac{\delta m^2 L}{4E}$$

enhancement or suppression depending on

$$\frac{\sin^2 \Delta_N}{\Delta_N^2} \lessgtr \frac{\sin^2 \Delta}{\Delta^2}$$

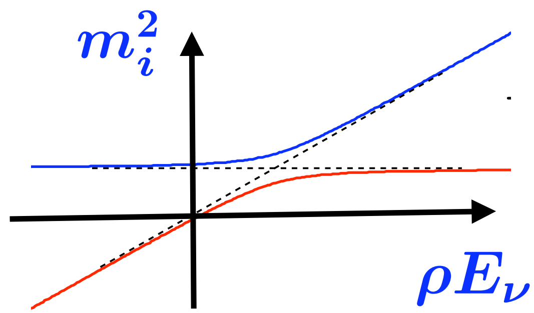
for small L this reduces to

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \; \Delta^2$$

same as vacuum small L.

$$\delta m_N^2 = \sqrt{(\delta m^2 \cos 2\theta - 2\sqrt{2} G_F N_e E_\nu)^2 + (\delta m^2 \sin 2\theta)^2}$$

$$\approx |\delta m^2 - 2\sqrt{2} G_F N_e E_\nu|$$



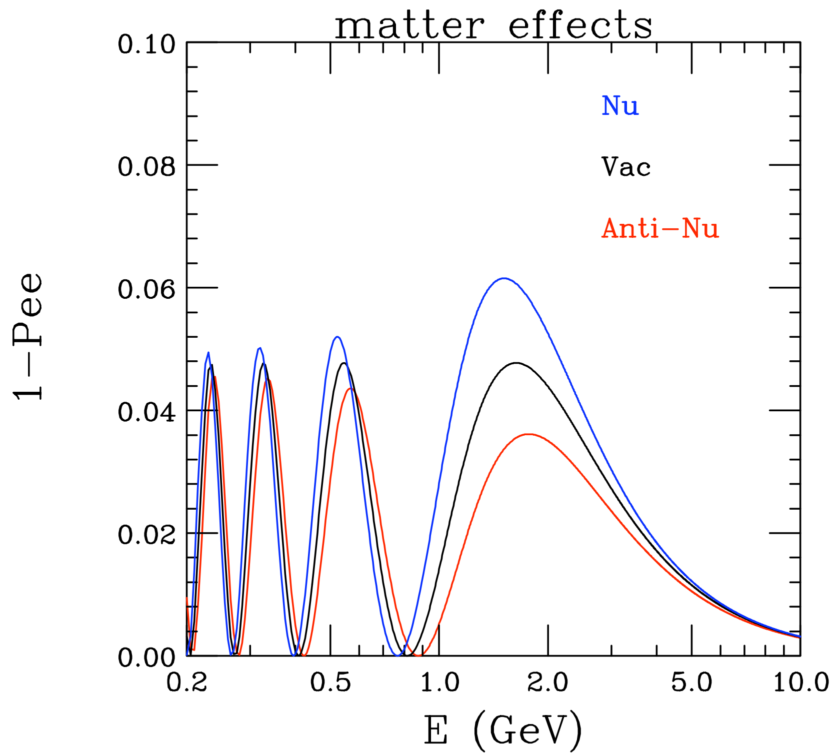
except near resonance:

$$\delta m^2 \cos 2\theta = 2\sqrt{2} G_F N_e E_\nu$$

$\Delta_N \approx |\Delta - aL|$ where $a = G_F N_e/\sqrt{2} \approx (4000 km)^{-1} \left(\frac{\rho}{3\ g.cm^{-3}}\right)$

$a \longrightarrow -a$ for anti-neutrinos:

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \, \frac{\sin^2(\Delta - aL)}{(\Delta - aL)^2} \, \Delta^2$$



$$L = 810\ km$$
$$\rho = 2.8\ g.cm^{-3}$$

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta\ \frac{\sin^2(\Delta - aL)}{(\Delta - aL)^2}\ \Delta^2$$

$\nu_\mu \rightarrow \nu_e$ with MATTER

$$P(\nu_\mu \rightarrow \nu_e) \approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

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

in vac $\sin\Delta_{31}$

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

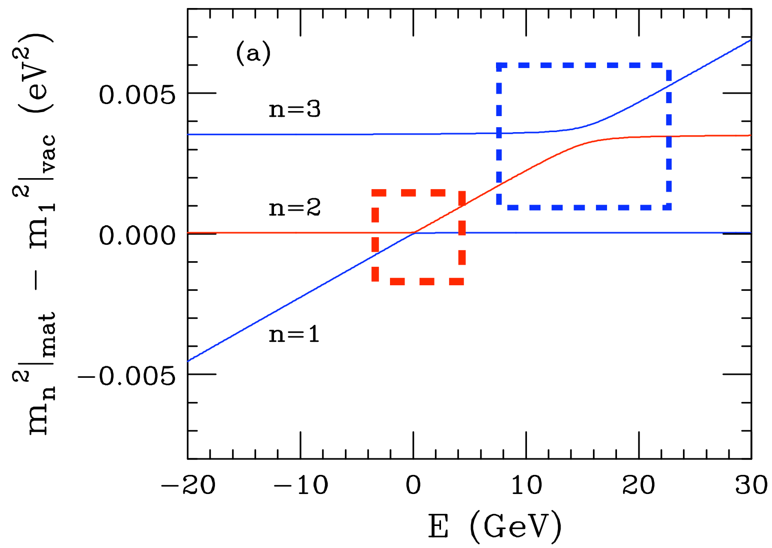
in vac $\sin\Delta_{21}$

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

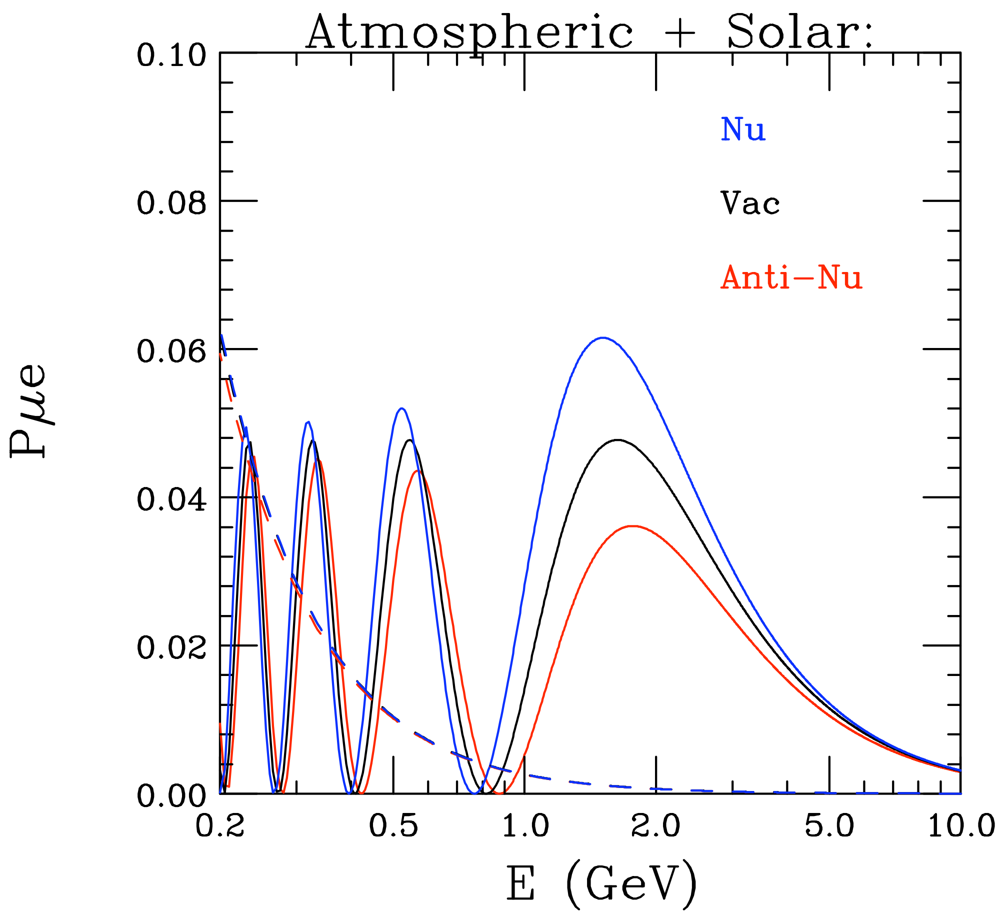
$\pm = sign(\delta m^2_{31})$ $\quad \Delta_{ij} = |\delta m^2_{ij}| L/4E$

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

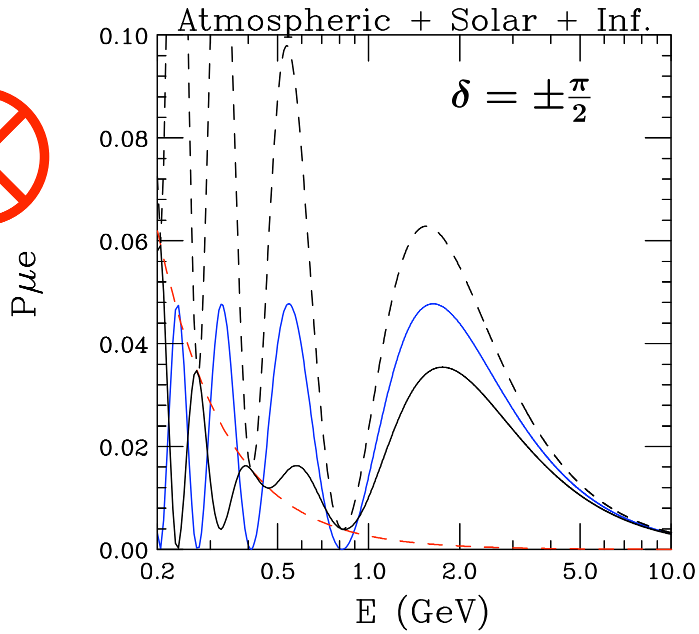
for anti-neutrinos: $a \rightarrow -a$ and $\delta \rightarrow -\delta$

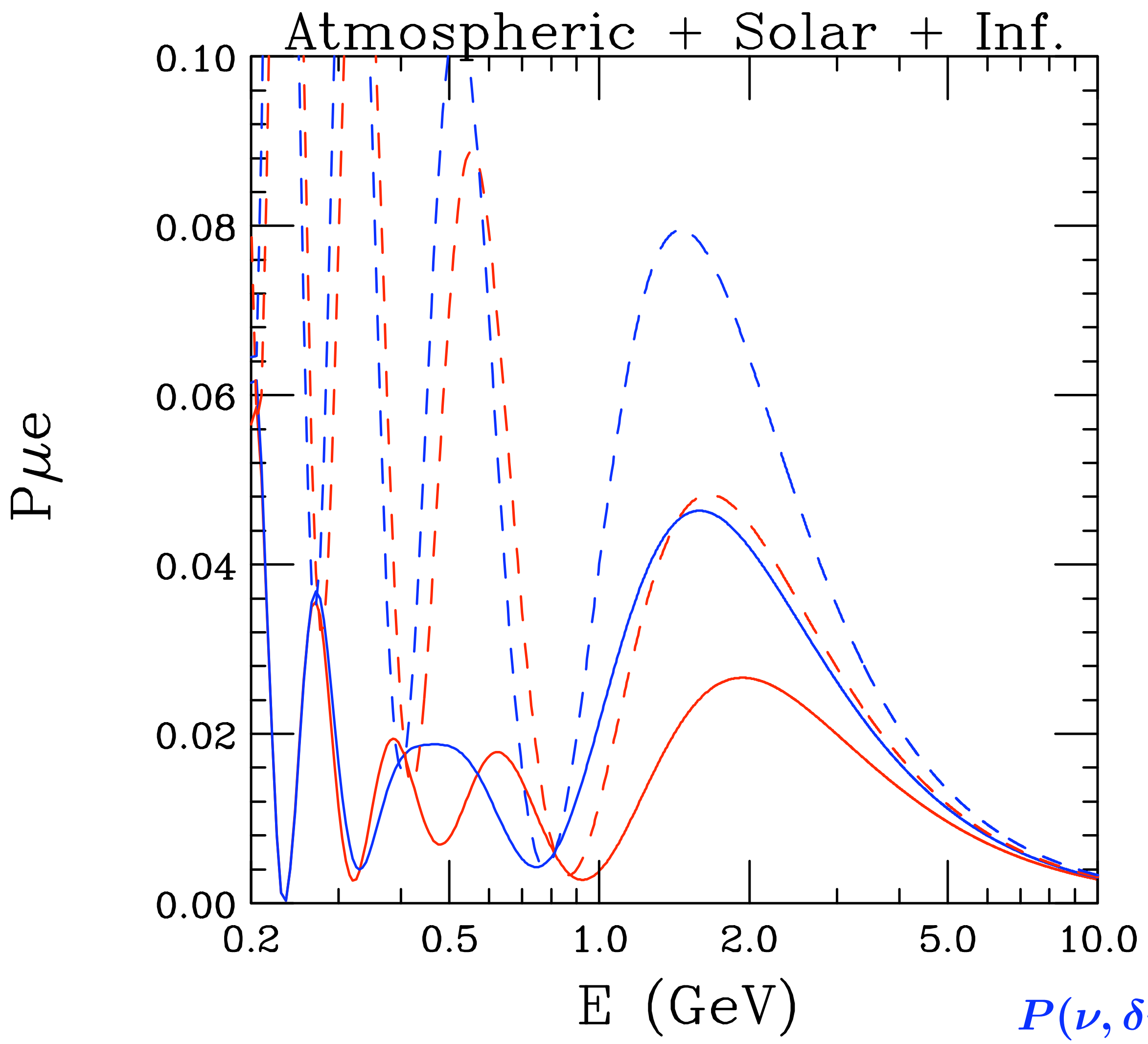


Matter



vacuum





4 combo's

ν:

dashes $\delta = \pi/2$

solid $\delta = -\pi/2$

normal

inverted

OR

$\bar{\nu}$:

dashes $\delta = -\pi/2$

solid $\delta = +\pi/2$

normal

inverted

$$P(\nu, \delta m^2_{31}, \delta) = P(\bar{\nu}, -\delta m^2_{31}, \delta + \pi)$$

OSCILLATION PATTERN HAS RICH STRUCTURE !!!

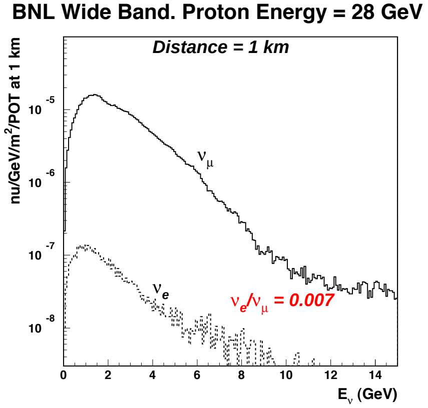
WOW!!!

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

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

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?

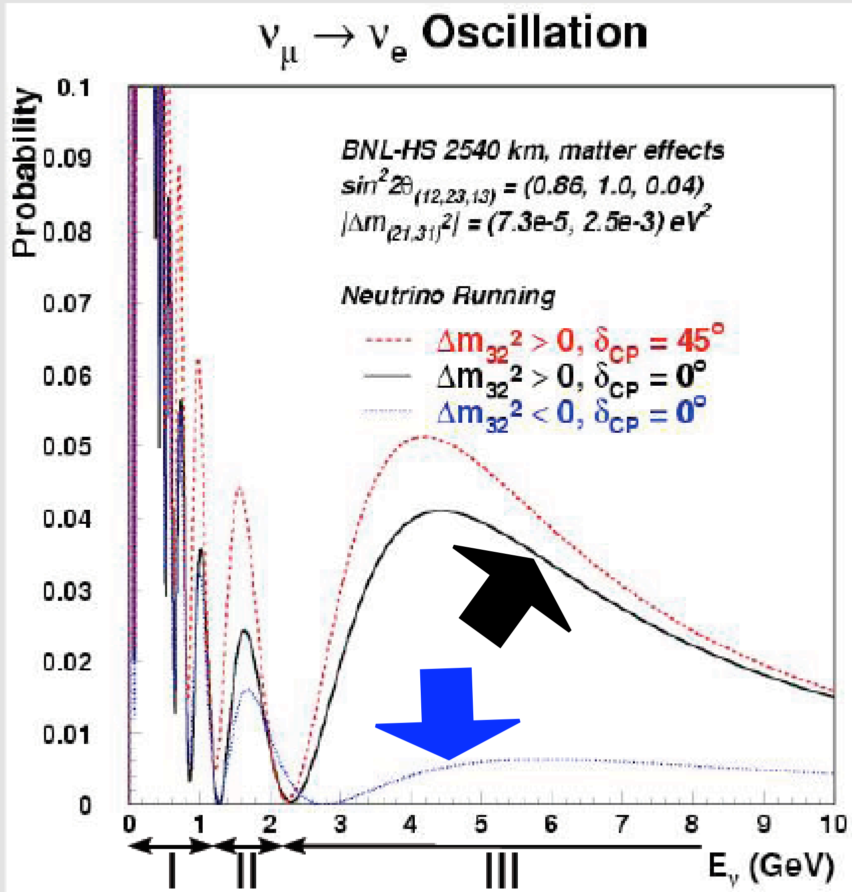
observe multiple nodes
extraction of oscillating signal from background.

larger energies

larger cross sections
less running time for anti-neutrinos

Sensitive to different parameters in different energy regions:

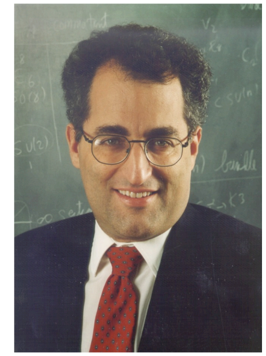
	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\mathrm{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+

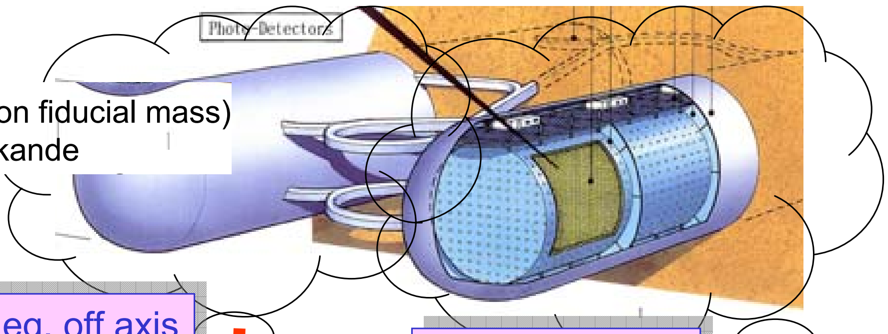


2450 km, 500 kt, 1MW, 5+5 yrs, 95 % CL

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

Some recent progress: detector in Korea





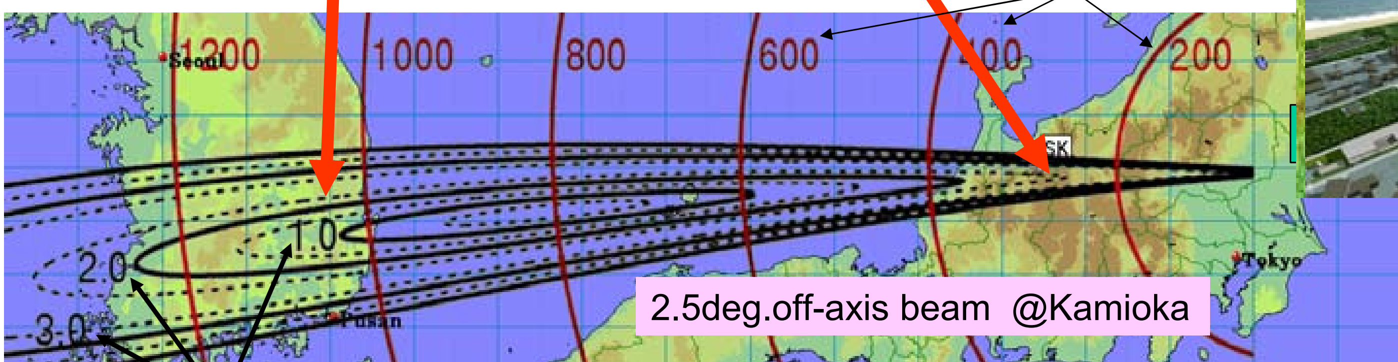
1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

Total cost must be similar to the baseline design.

2.5 deg. off axis

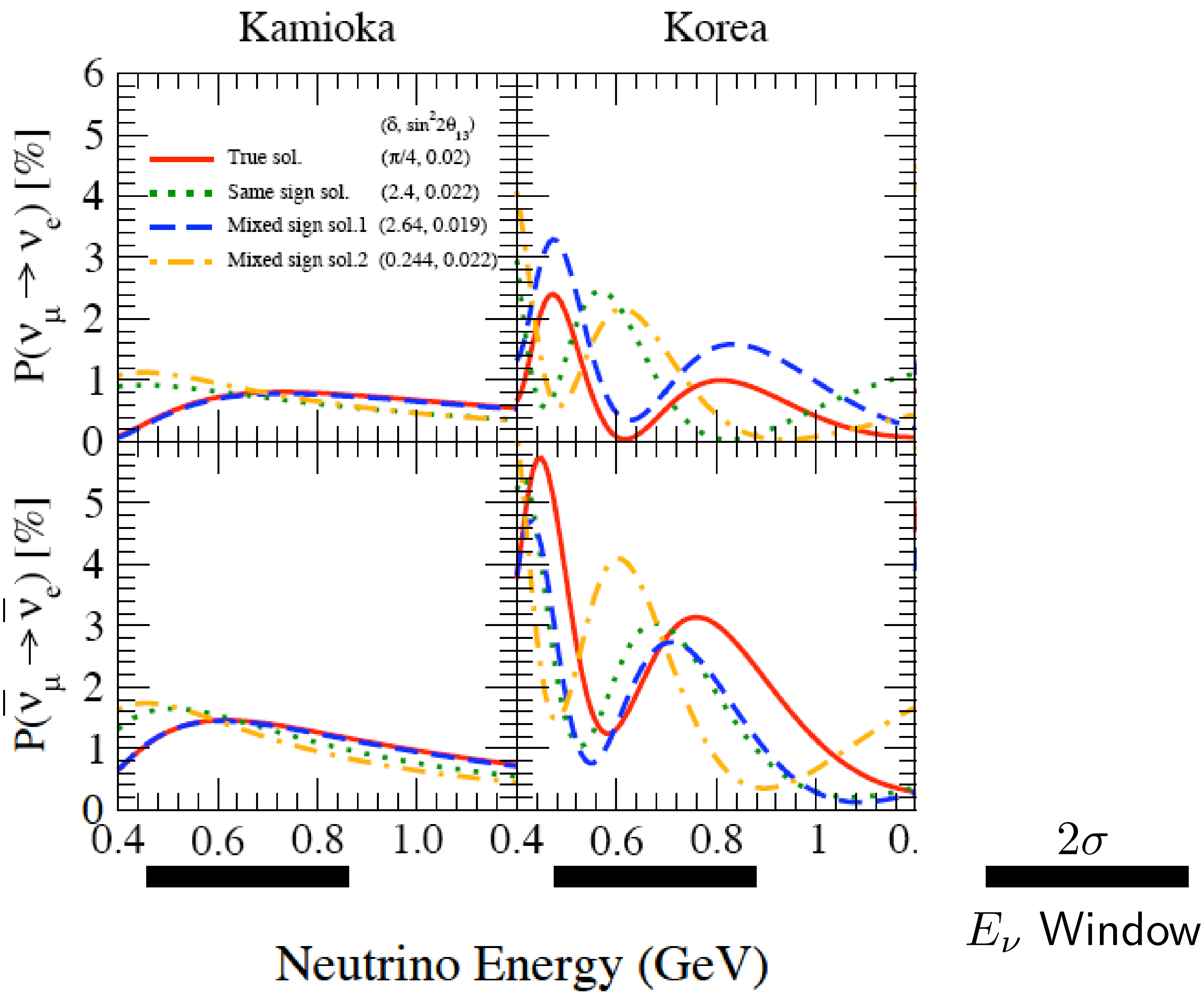
2.5 deg. off axis

Distance from the target (km)



2.5deg.off-axis beam @Kamioka

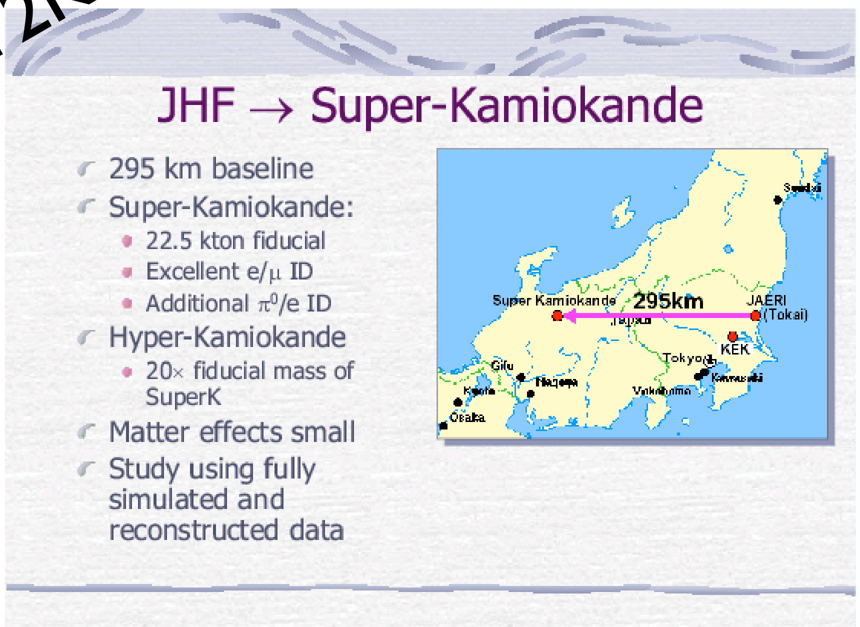
Off-axis angle



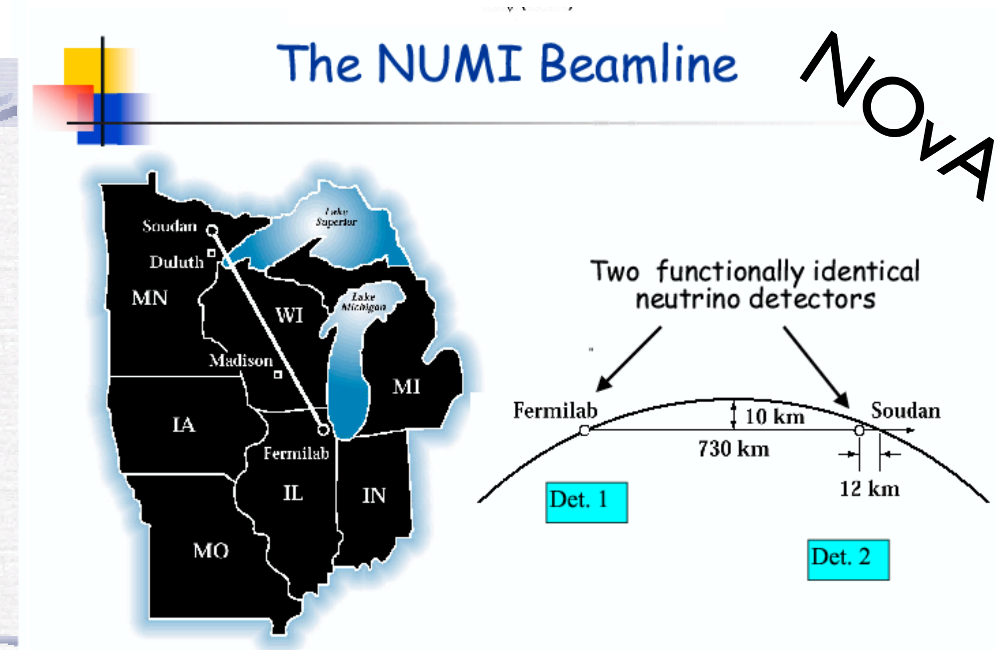
Ishitsuka, Kajita, Minakata and Nunokawa hep-ph/0504026

Counting Experiments:

T2K



NOvA



L=295 km

2.5 degree Off Axis

<E> = 0.65 GeV

20% spread

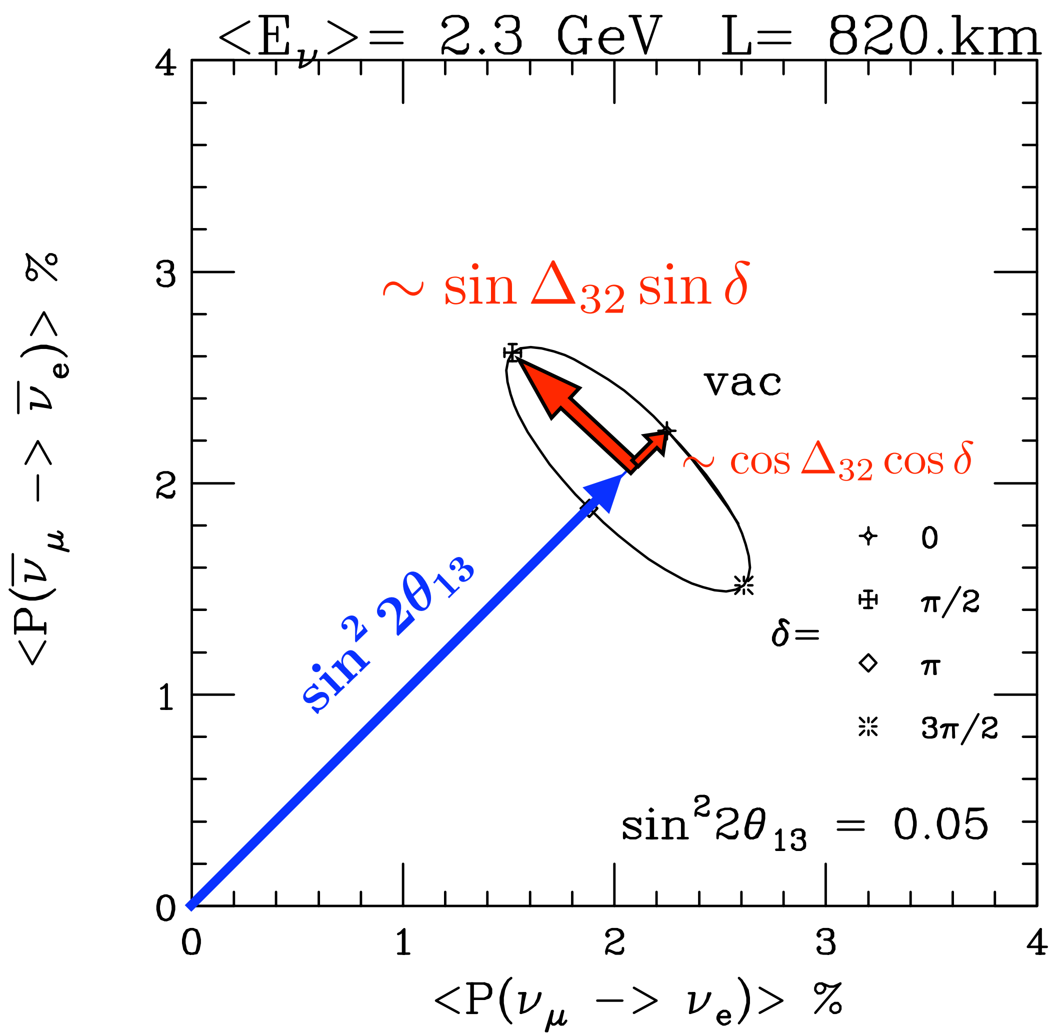
L=810 km

12 km Off Axis

<E> = 2.0 GeV

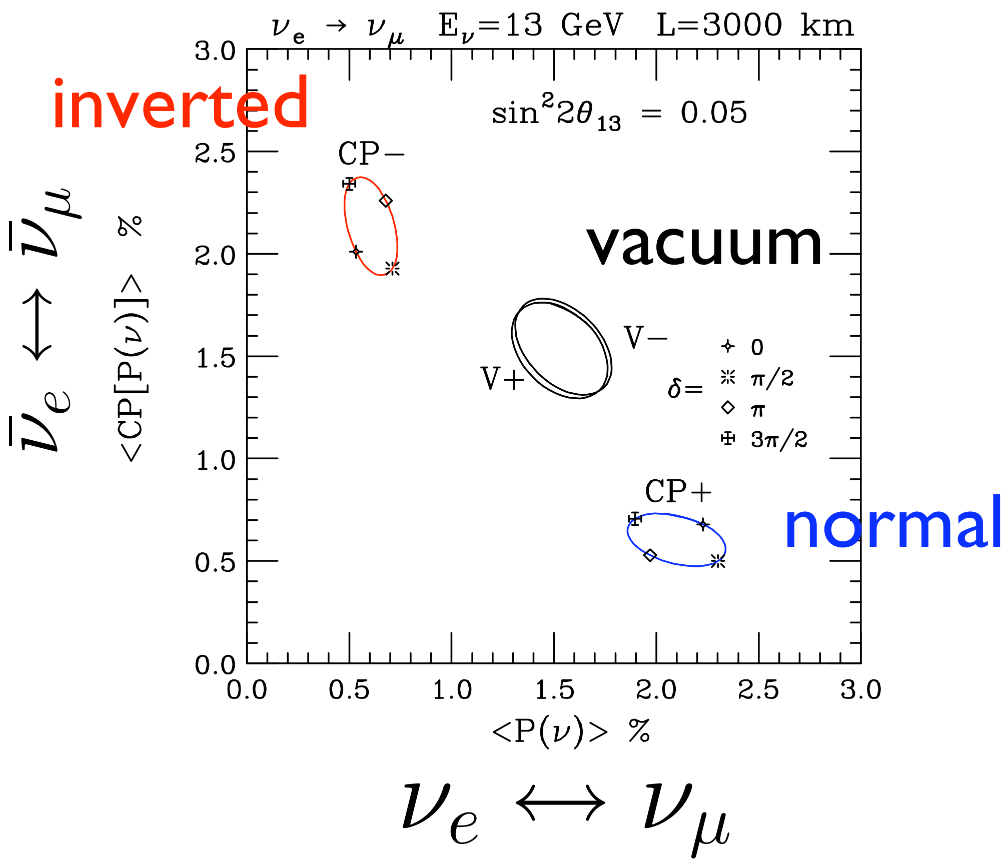
15% spread

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

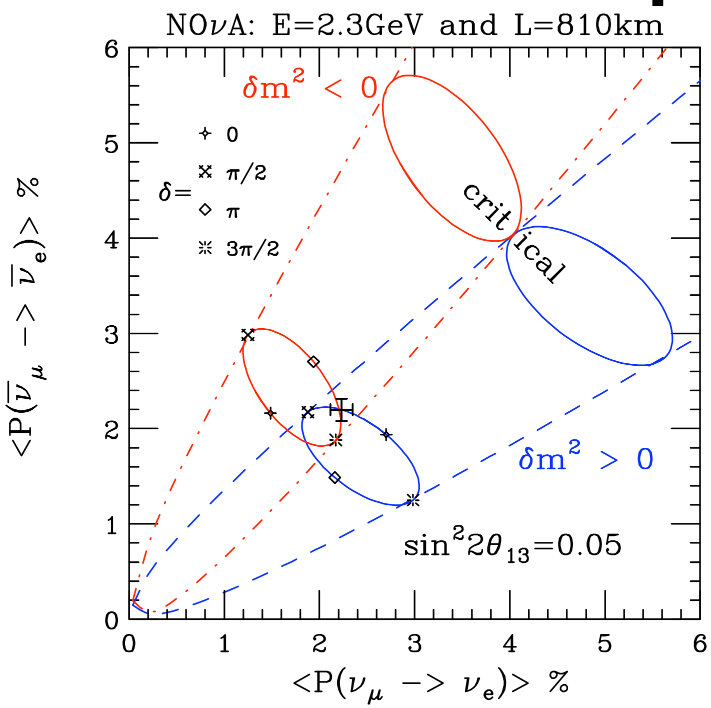


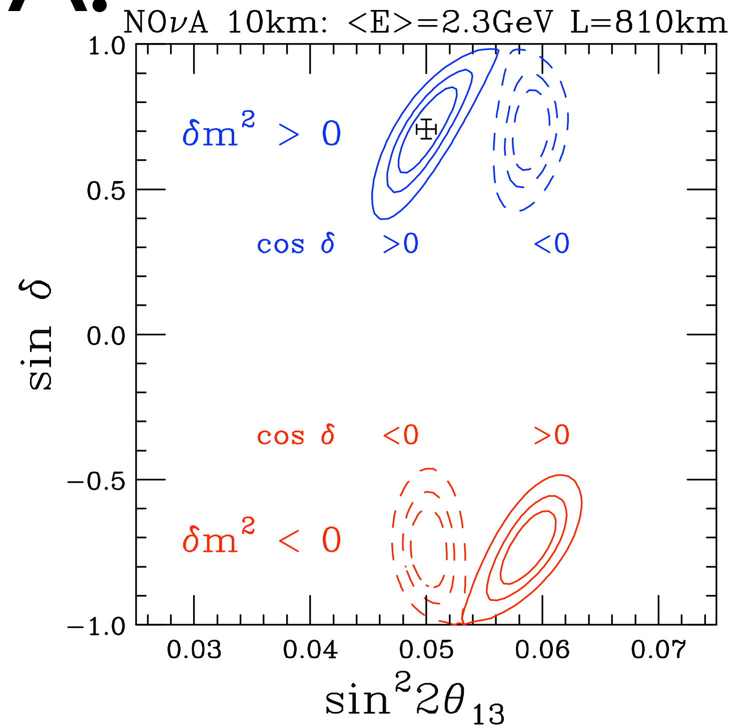
Mass Hierarchy: – sign of δm^2_{31}

Matter Effects



NOvA:

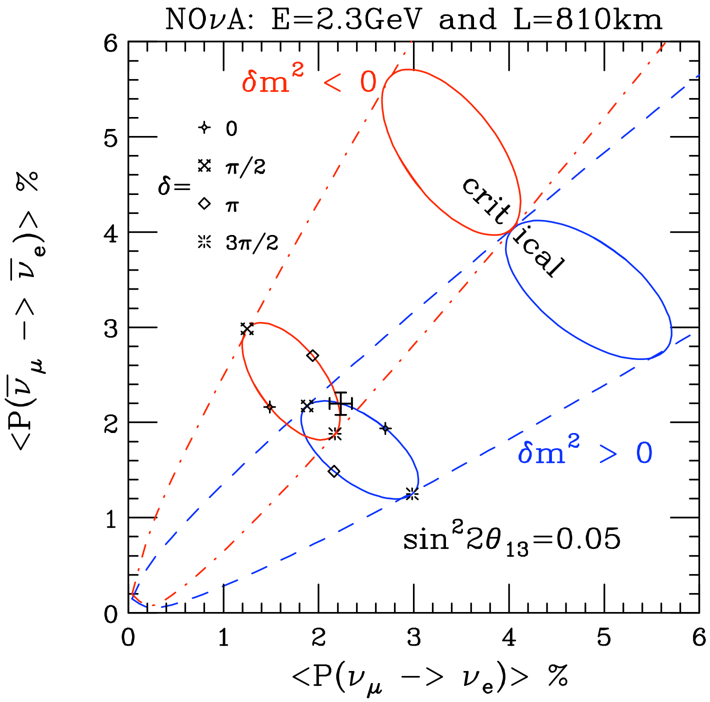


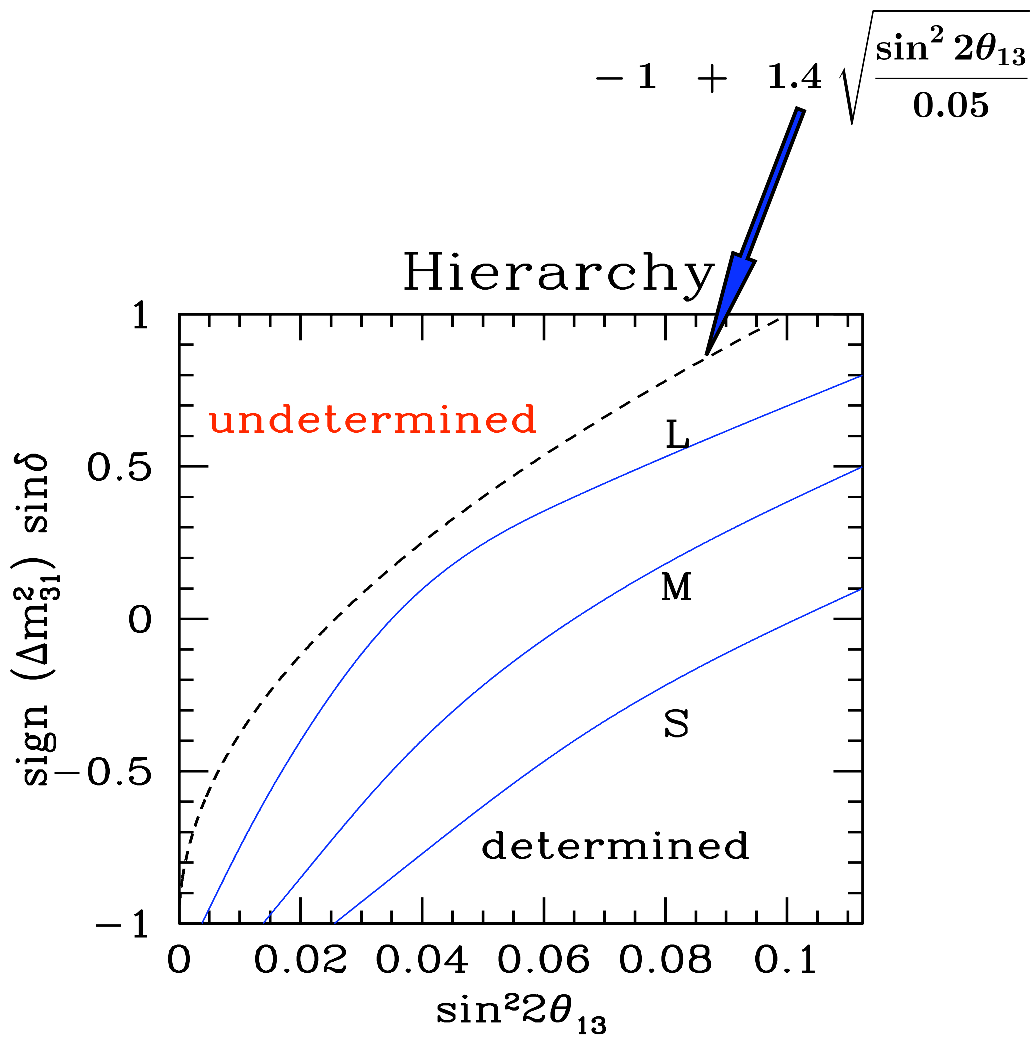


$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$\theta_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\left(\frac{4\Delta^2/\pi^2}{1-\Delta\cot\Delta}\right)/(aL) \sim 1/6$$

NOvA:





S: 4 +4 yrs

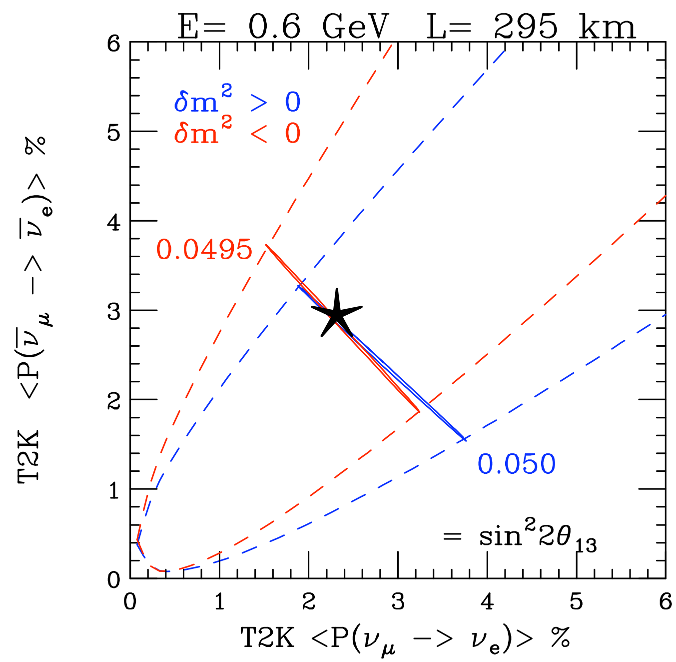
M (=5*S):

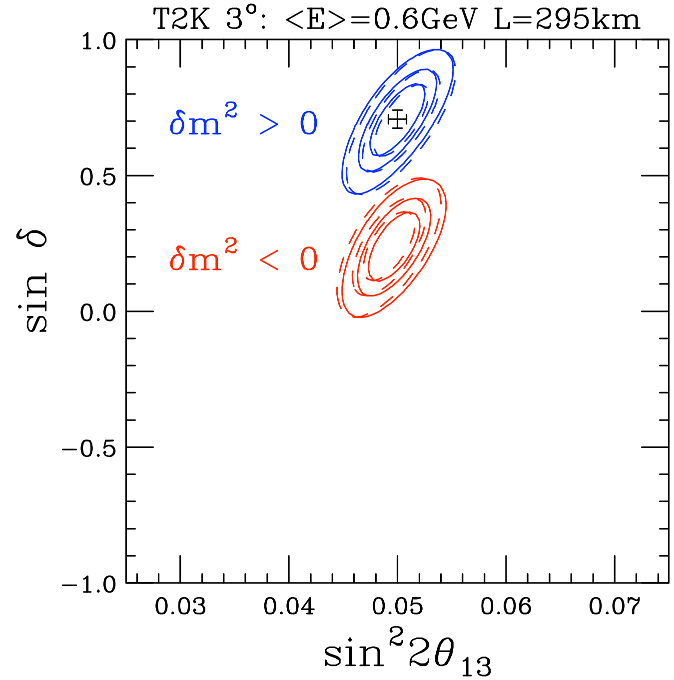
Proton Driver

L (=5*M):

PD + Liquid Argon

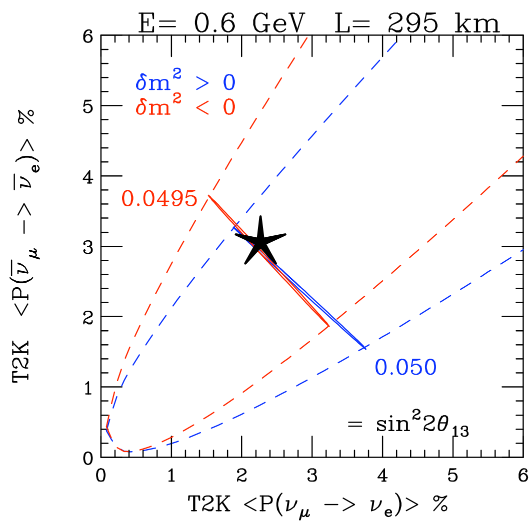
T2K:

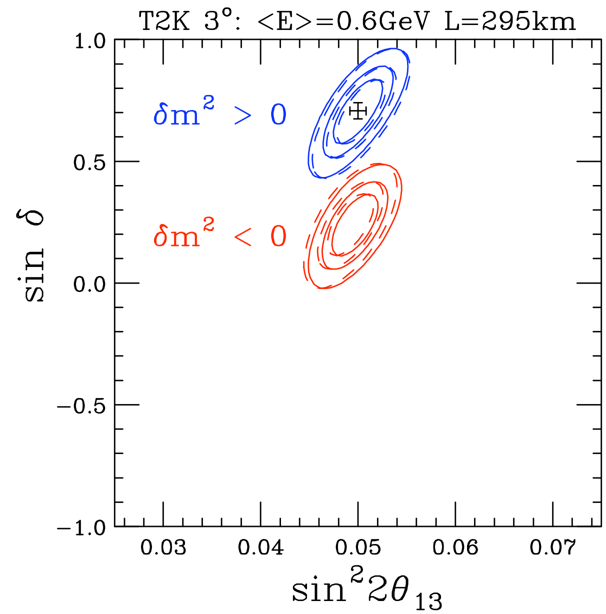




$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

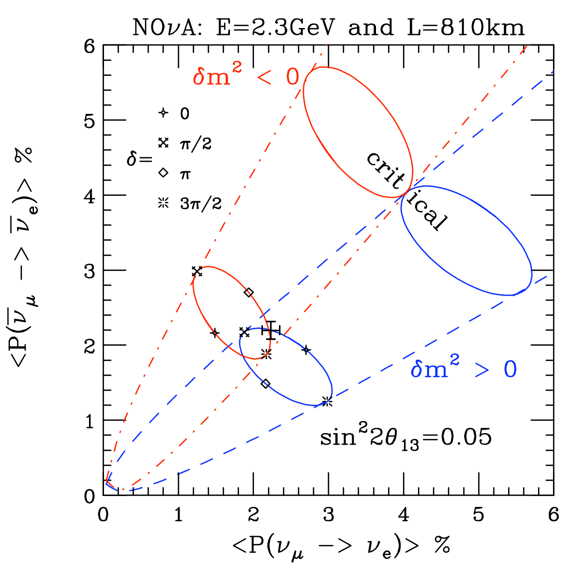
(ρL) for NOvA <u>three</u> times larger than (ρL) than T2K.

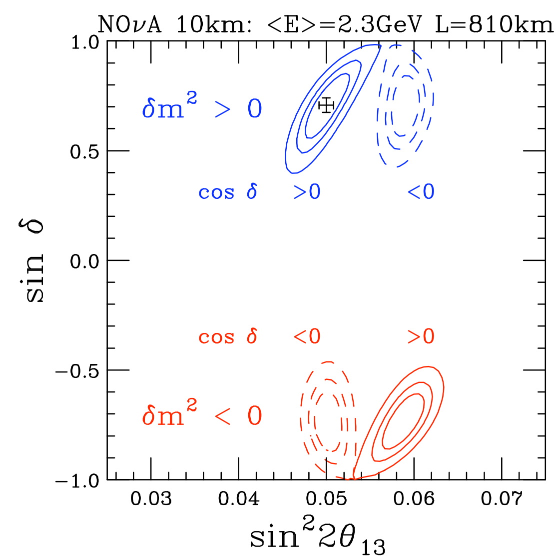




$$\langle \sin\delta\rangle_+ \; - \; \langle \sin\delta\rangle_-$$

$$\approx \; 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$





$$\langle \sin\delta\rangle_+ \; - \; \langle \sin\delta\rangle_-$$

$$\approx \; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

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

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

if the measurement uncertainty on $\sin\delta$

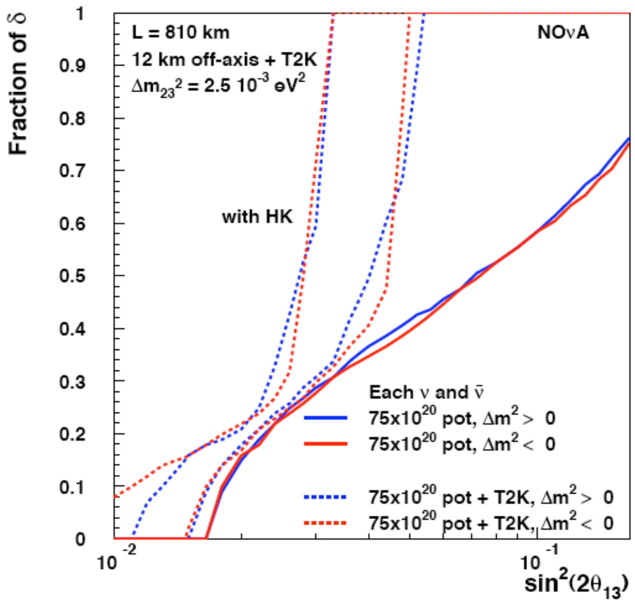
$$\approx \pm 0.2$$

then the two fake solutions are well separated down to

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

Hierarchy is Determined

95% CL



NOvA/PD with T2K Phase 2

Summary: $\nu_\mu \longrightarrow \nu_e$

- Fabulous Laboratory for Neutrino Oscillations
- Sensitive to
  - Fraction ν_e in ν_3: $\sin^2\theta_{13}$
  - Mass Hierarchy: sign δm^2_{31}
  - CP Violation: $\sin\delta_{CP}$

  - Atmospheric: $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$
  - CPC: $\cos\delta_{CP}$
  - Solar: $\delta m^2_{21} \sin^2 2\theta_{12}$
- Potential for Surprises!