FERMILAB-CONF-05-603-T

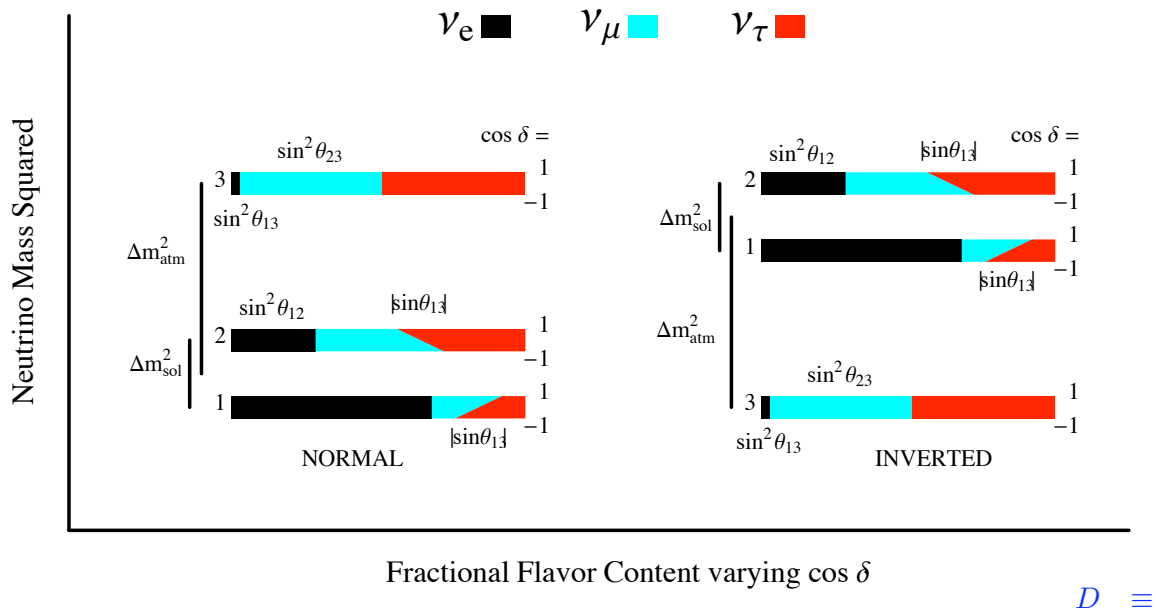
θ_{13}

Stephen Parke
Fermilab:

- ν_e fraction of ν_3: – $\sin^2\theta_{13}$
- mass hierarchy: – sign of δm^2_{31}
- CP violation: – $\sin\delta \neq 0$

observable

panic$^\nu$ October 30, 2005



independent of
$sign(\sin\delta_{CP})$,
Majorana phases α, β

Mena + SP
hep-ph/0312131

$$D \equiv \frac{1}{2} - \sin^2\theta_{23} = (|U_{\tau 3}|^2 - |U_{\mu 3}|^2)/2(1 - |U_{e3}|^2)$$

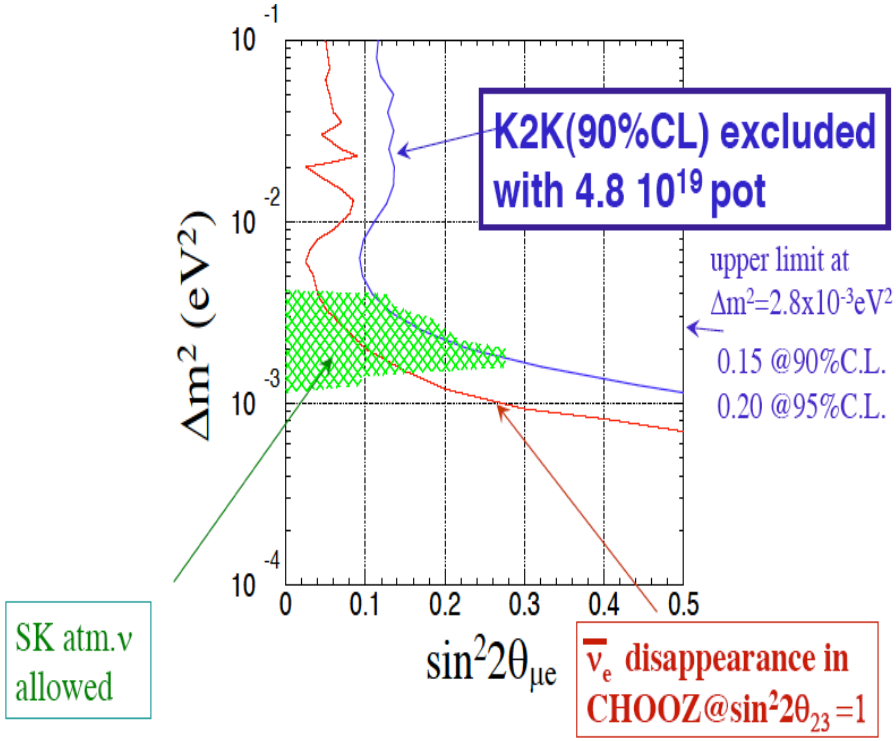
$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

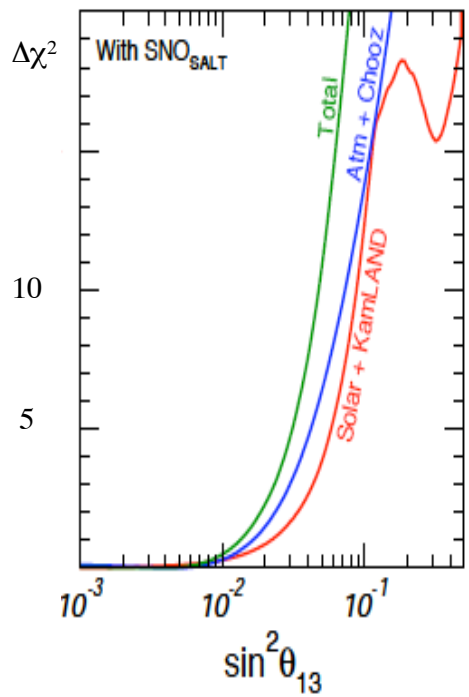
$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\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

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

No indication yet of nonzero θ_{13} from atmospheric, solar and terrestrial ν





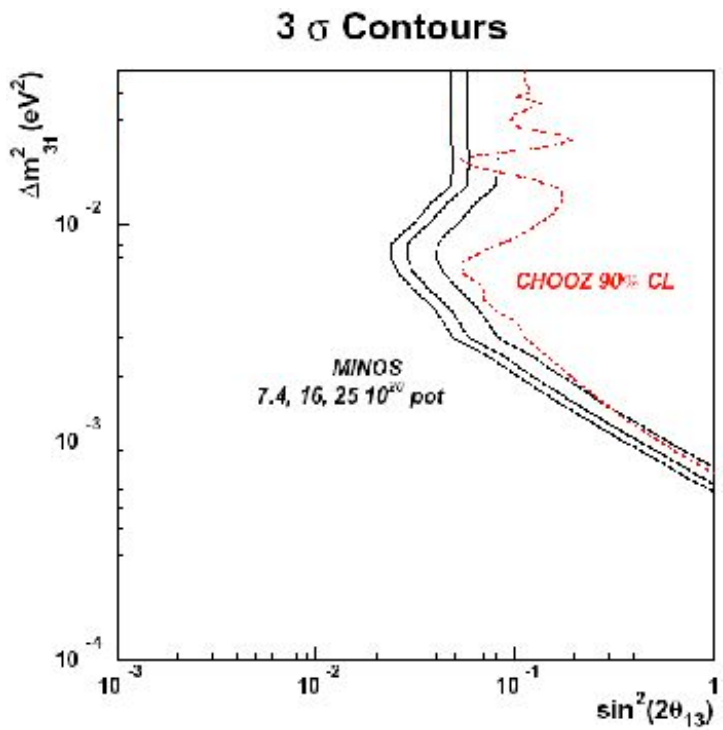
Maltoni et al.

Chooz bound $\sin^2\theta_{13} < 0.04$

Quest for ν_e fraction in ν_3: $\sin^2\theta_{13}$

- Current LBL (MINOS)
- Atmospheric Neutrinos
- Low and High Energy Solar Neutrinos
- Supernova Neutrinos
- Short Baseline Reactor (Double Chooz, ...)
- Future Long Baseline (T2K, NuMI, BNL2?, ...)
- Neutrino Factories
- Beta Beams

MINOS:



Has some sensitivity to ν_e above backgrounds.

Primary goal is to measure $|\delta m^2_{32}|$ to 10%

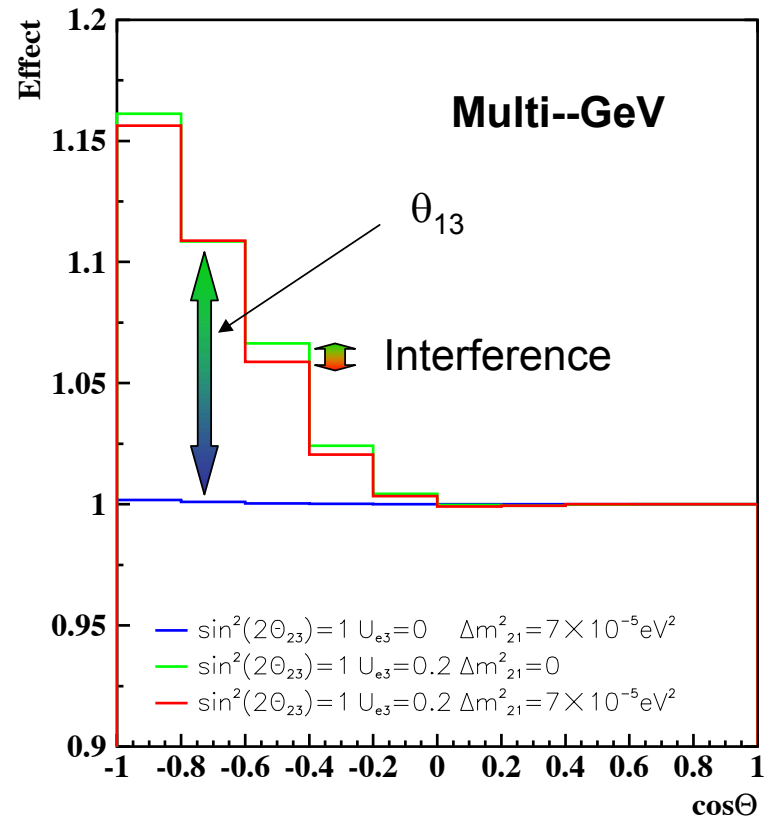
- Atmospheric Neutrinos

SK - Suzuki

— $|U_{e3}|=0.2$

— $\Delta m_{12}^2=7\times10^{-5}eV^2$

— Interference



• Low and High Energy Solar Neutrinos

Goswami + Smirnov
hep-ph/0411359

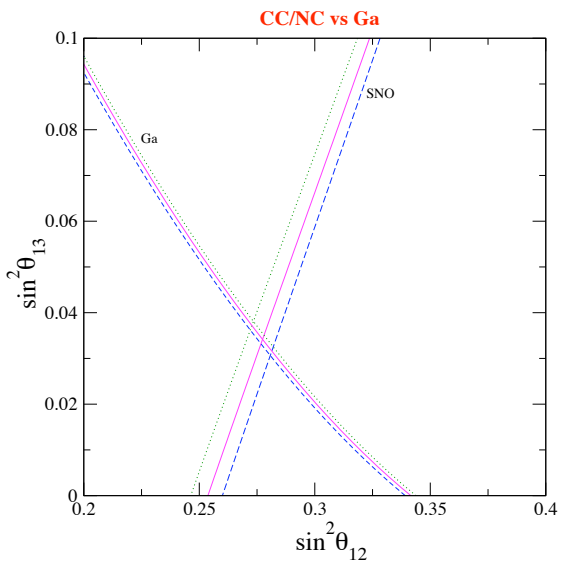


Figure 6: The iso-contours of CC/NC = 0.31 at SNO and $Q_{Ge} = 68.1$ SNU in Ga experiments in the $\sin^2\theta_{12} - \sin^2\theta_{13}$ plane for different values of Δm^2_{21} : $\Delta m^2_{21} = 9 \cdot 10^{-5}$ eV^2 - the dotted lines; $\Delta m^2_{21} = 8 \cdot 10^{-5}$ eV^2 - the solid lines; $\Delta m^2_{21} = 7 \cdot 10^{-5}$ eV^2 - the dashed lines.

$$\frac{CC}{NC} \sim \cos^2\theta_{13}\sin^2\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \uparrow$$

$$Ga \sim \cos^4\theta_{13}\cos^4\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \downarrow$$

$$\sin^2\theta_{\odot}^{^8B} \approx \sin^2\theta_{12} - 0.9\sin^2\theta_{13}$$

$$\sin^2\theta_{\odot}^{^8pp} \approx \sin^2\theta_{12} + 1.5\sin^2\theta_{13}$$

$$\sin^2\theta_{\odot}^{^8pp} - \sin^2\theta_{\odot}^{^8B} \approx 2.4\sin^2\theta_{13}$$

$$\sin^2\theta_{\odot}^{^8pep} \approx \sin^2\theta_{12} + (0.5???)\sin^2\theta_{13}$$

Nunokawa, Zukanovich + SP
hep-ph/0511nnn

Short Baseline $\bar{\nu}_e$ Disappearance: aka Reactor:

$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left[\sin^2 \Delta_{atm} + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right) \right] + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)^2$$

>1% 1 <3% <0.1%

kinematical phase $\Delta_{atm} = \frac{\delta m^2_{atm} L}{4E} = 1.27 \frac{\delta m^2_{atm} L}{E}$

The $\mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)$ VANISHES if

$$\begin{aligned} \delta m^2_{atm} &= \cos^2\theta_{12}\ \delta m^2_{31} + \sin^2\theta_{12}\ \delta m^2_{32} \\ &= m_3^2 - \underline{(\cos^2\theta_{12}\ m_1^2 + \sin^2\theta_{12}\ m_2^2)} \Rightarrow \delta m^2_{31} \quad when\ \theta_{12} \Rightarrow 0 \end{aligned}$$

Average ν_e mass in 1 and 2.

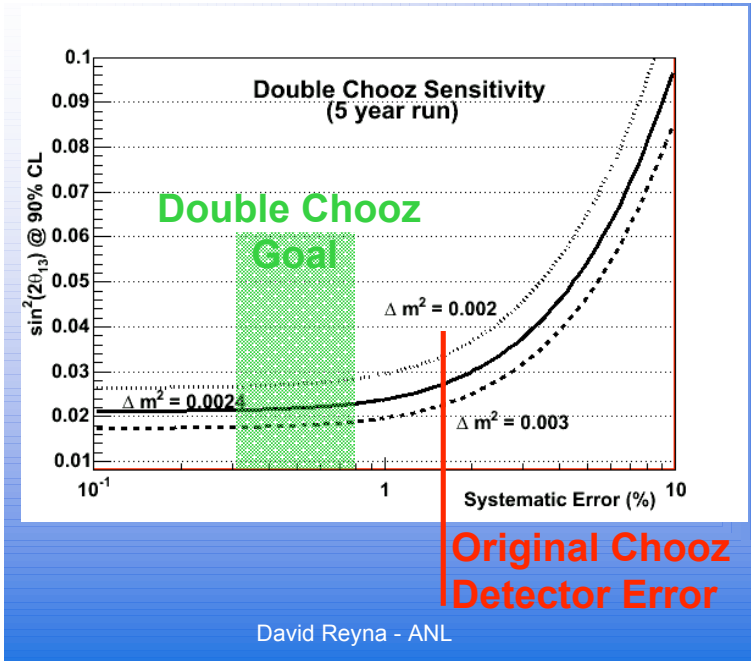
This is the $|\delta m^2_{atm}|_e$ that could be measured in such an experiment.

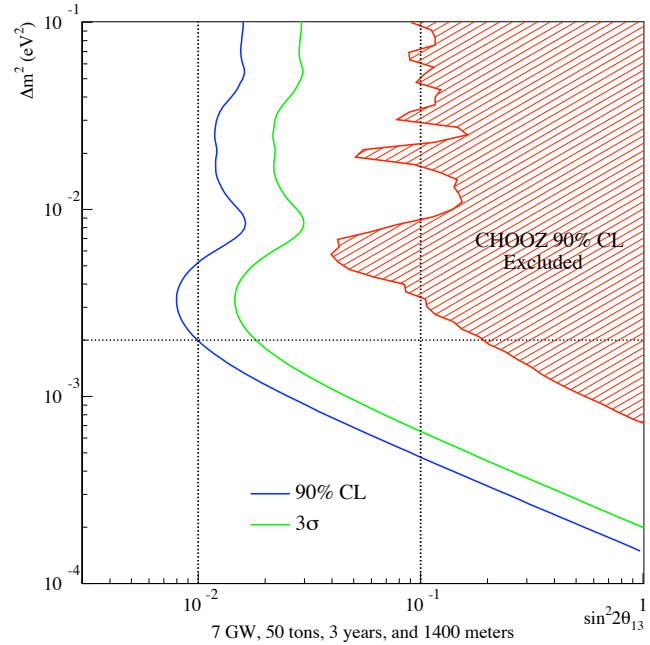
Nunokawa, Zukanovich + SP
hep-ph/0503283

- Normal Hierarchy: $|\delta m^2_{atm}|_e > |\delta m^2_{atm}|_\mu$
- Inverted Hierarchy: $|\delta m^2_{atm}|_e < |\delta m^2_{atm}|_\mu$
- Unfortunately difference is small 1 - 2 % !!!

where $|\delta m^2_{atm}|_\mu$ from ν_μ disappearance.

$|\delta m^2_{atm}|_\mu \Rightarrow \delta m^2_{32}$
when $\theta_{12} \Rightarrow 0$





J. Link, Columbia

- Pure measurement of $\sin^2\theta_{13}$
  — no contamination from
  $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy.

With Off-axis measurements of $\nu_\mu \to \nu_e$:

- of $\sin^2\theta_{23}\sin^2\theta_{13}$ can help resolve $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy for $\sin^2 2\theta_{23} \neq 1$.
- Help resolve hierarchy and $\sin\delta \neq 0$, maybe.

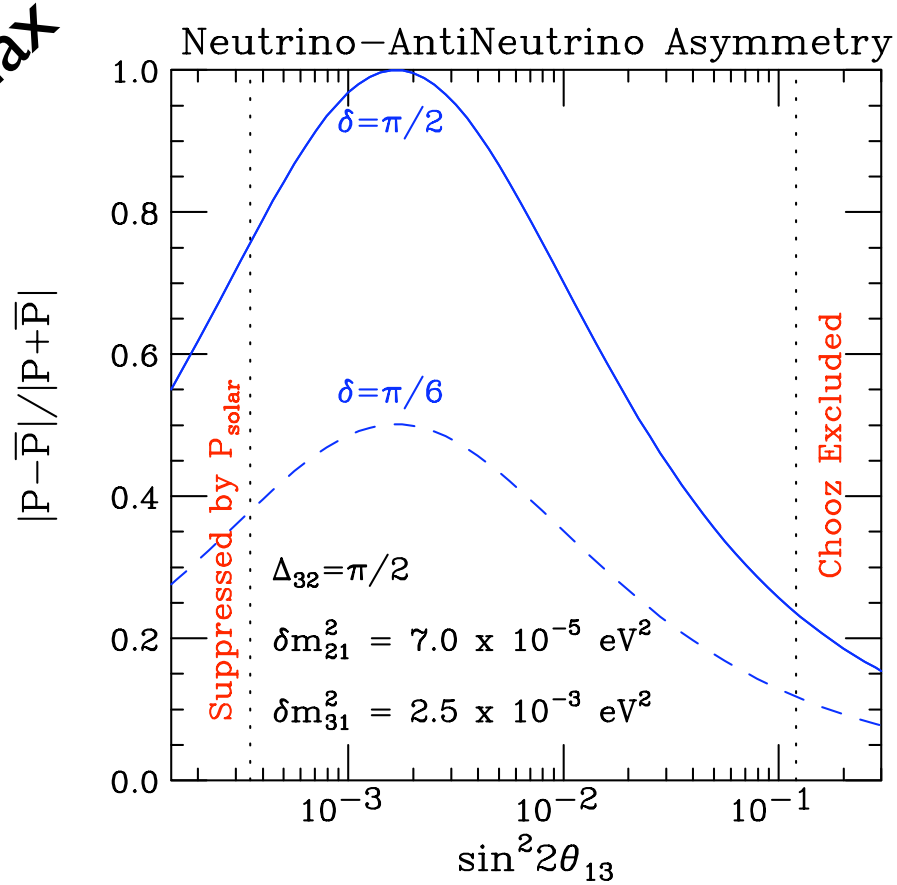
VAC LBL: $\nu_\mu \to \nu_e$

CP violation !!!

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

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

1st Vac Osc Max



$\nu_\mu \longrightarrow \nu_e$ with MATTER

CP violation !!!

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

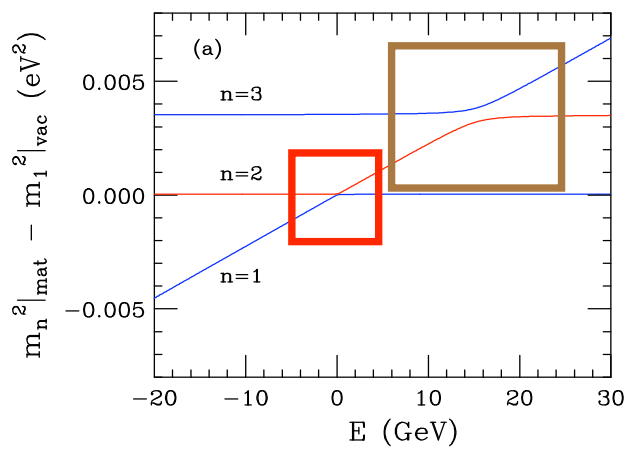
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$
$$\pm = sign(\delta m^2_{31})$$
$$\Delta_{ij} = |\delta m^2_{ij}|L/4E$$

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

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

$$\sin\Delta_{31} \Rightarrow \left(\frac{\Delta_{31}}{\Delta_{31}\mp aL}\right)\sin(\Delta_{31}\mp aL)$$
$$\sin\Delta_{21} \Rightarrow \left(\frac{\Delta_{21}}{\Delta_{21}\mp aL}\right)\sin(\Delta_{21}\mp aL)$$
$$\sin\Delta_{32} \Rightarrow \sin\Delta_{32}$$



Matter effects are IMPORTANT when $\sin(\Delta\mp aL) \neq (\Delta\mp aL)$.

Numerous Approaches to Studying $\nu_\mu \leftrightarrow \nu_e$ Transitions:

- Off Axis - Narrow Band Beams $\nu_\mu \rightarrow \nu_e$ (T2K and NOvA)
- On Axis - Broadband Beam $\nu_\mu \rightarrow \nu_e$ (BNL 2 HSK)
- Neutrino Factory $\nu_e \rightarrow \nu_\mu$
- Beta Beams $\nu_e \rightarrow \nu_\mu$

Off-Axis Neutrino Beams:

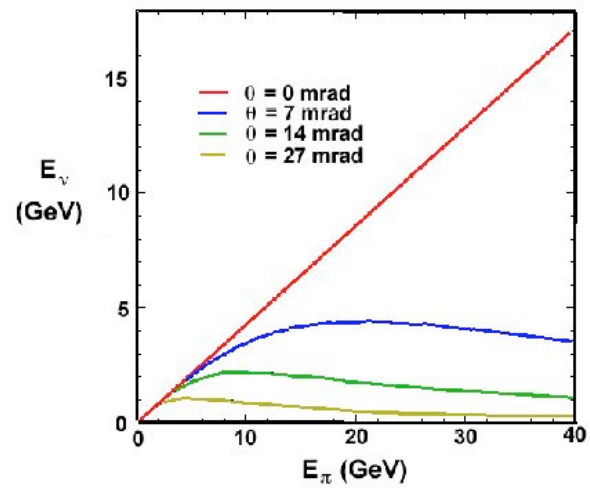
$$E_\nu = \frac{0.43 E_\pi}{(1+\theta^2\gamma_\pi^2)}$$

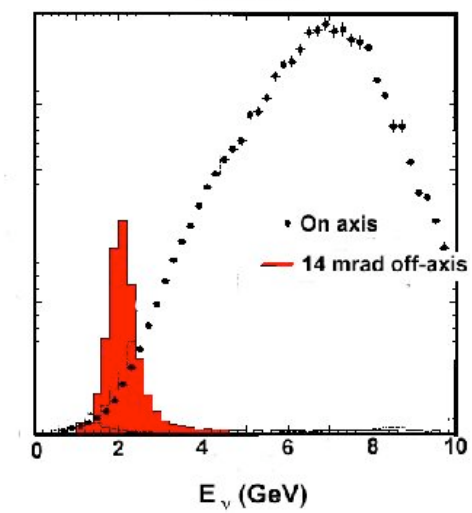
Off-Axis the beams are Narrow!
approx. gaussian with spread
20% $< E_\nu >$

GREAT !!!

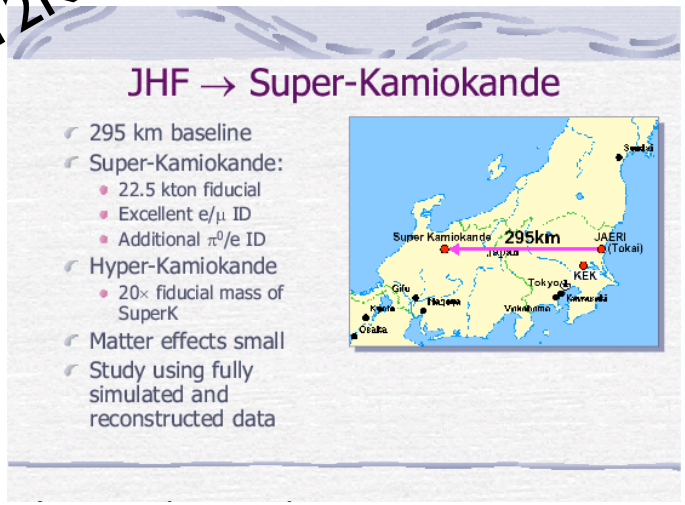
as the primary bckgrd to ν_e detection is π^0 coming from higher energy NC events. (ν_e contamination in beam is small 0.5% and apprx known.)

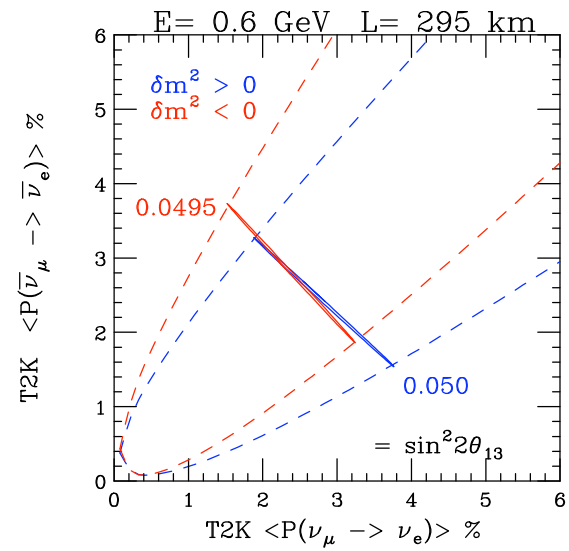
BNL-proposal '94

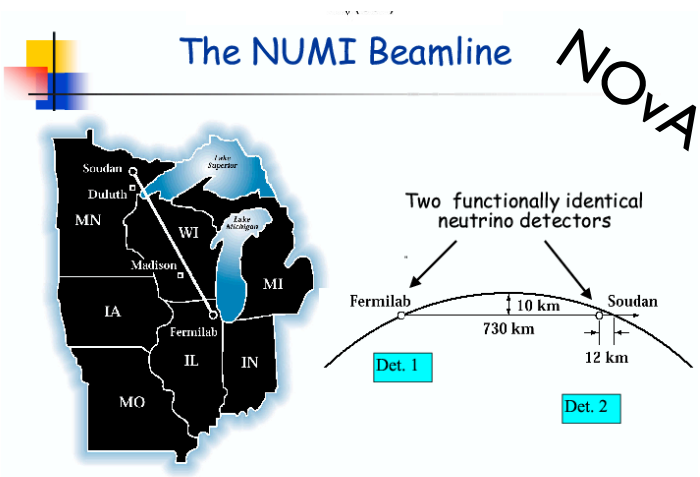




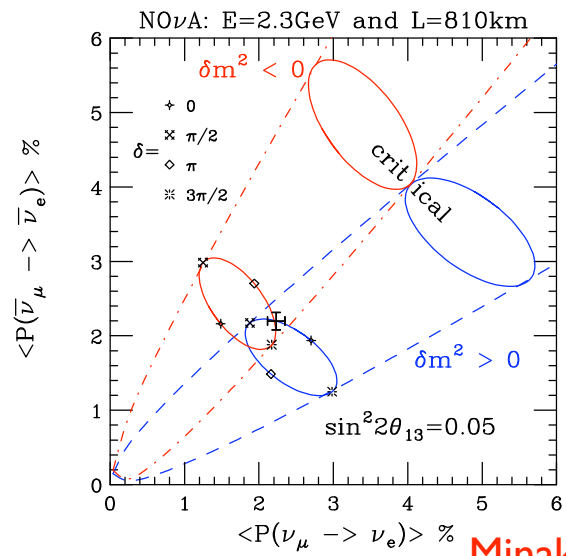
T2K







FLARE

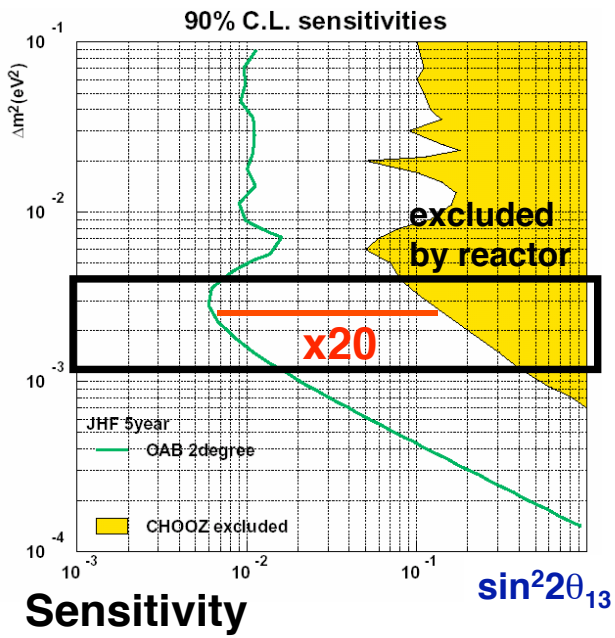


Minakata+Nunokawa
hep-ph/0108085

Sensitivity to θ_{13}

T2K:

Search for ν_e appearance



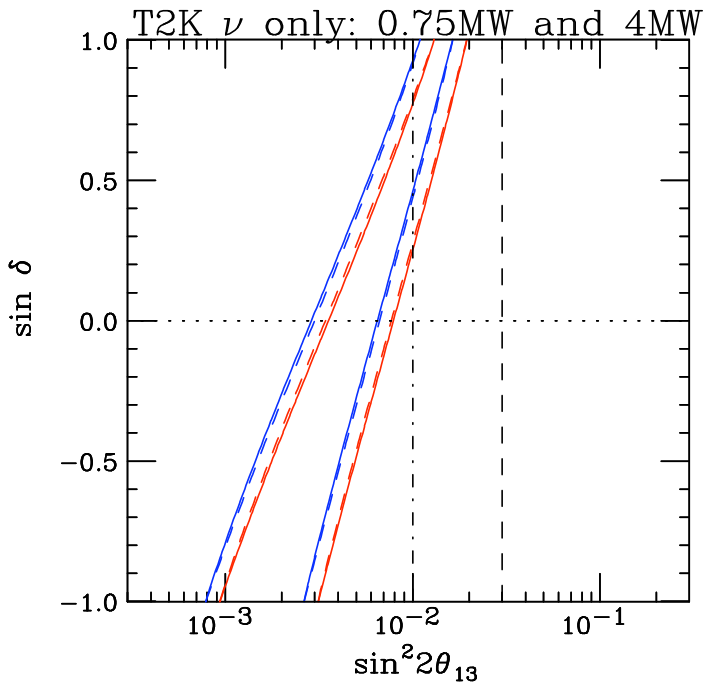
Sensitivity

$sin^22\theta_{13}$>0.006 (90%)

5 yrs 0.75MW
with SK

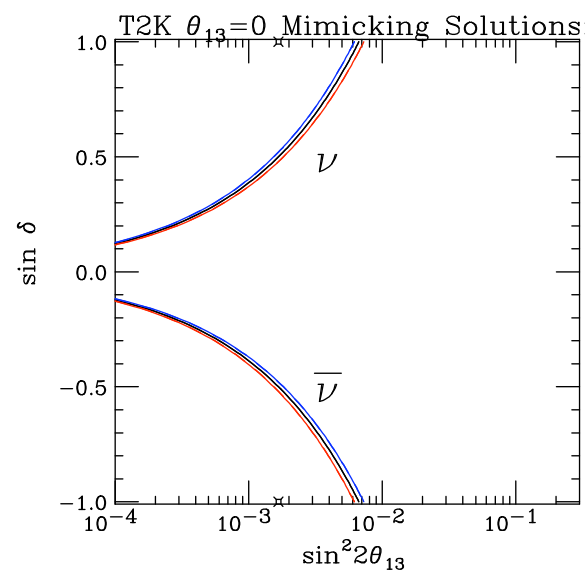
assumes $\delta = 0$

Question: What exposure is required to reach this sensitivity if $\delta = \pm\frac{\pi}{2}$?



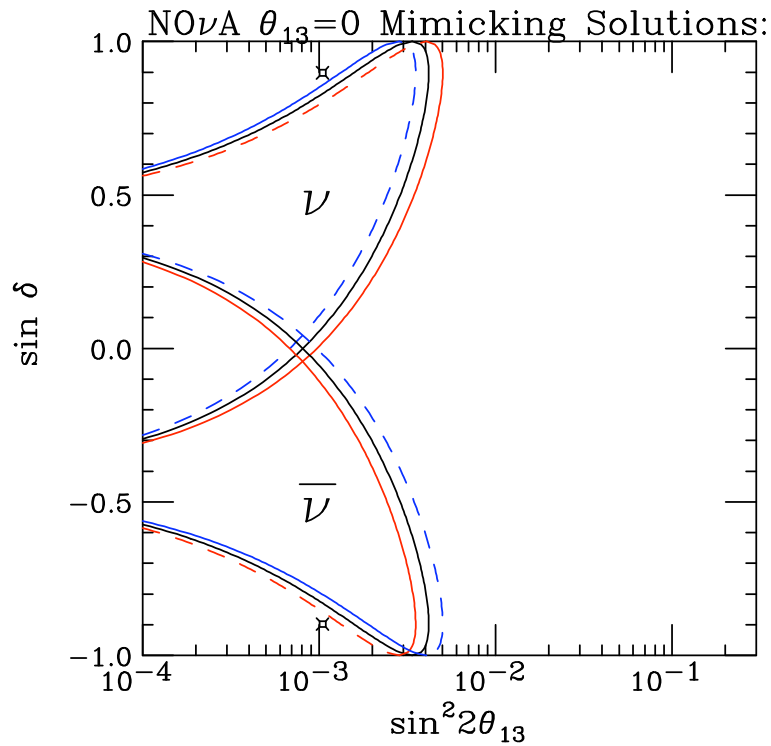
Zero Mimicking Soln:

$$\sqrt{P_{atm}} = \pm 2\sqrt{P_{sol}}\sin\delta$$



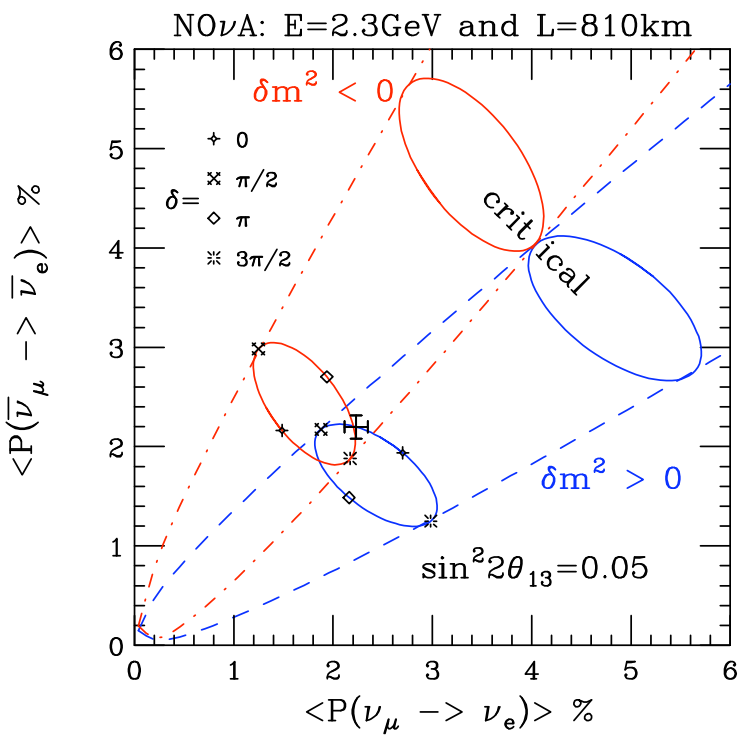
NuMI: NOvA, FLARE

Zero Mimicking Soln:

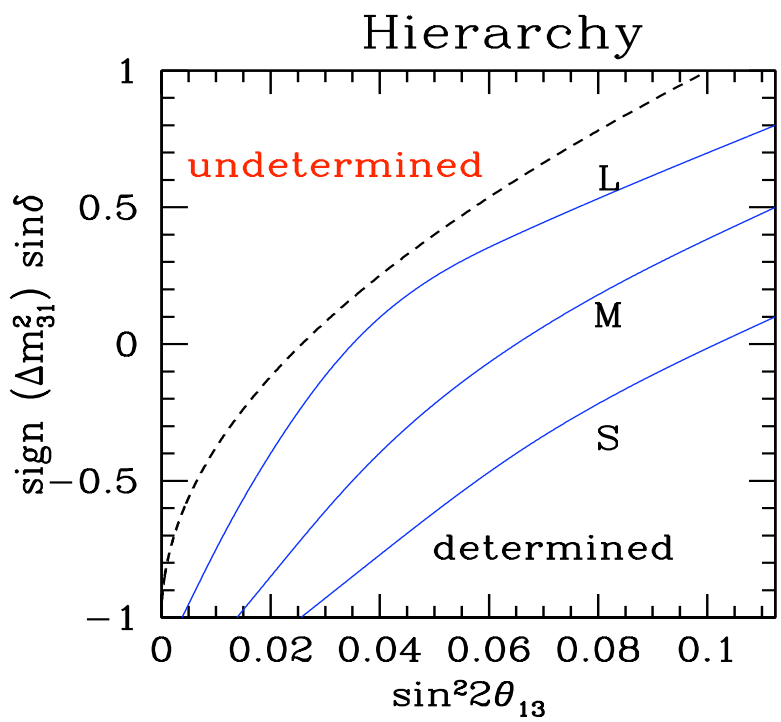


$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

NOvA, FLARE:



Mass x POT x Eff



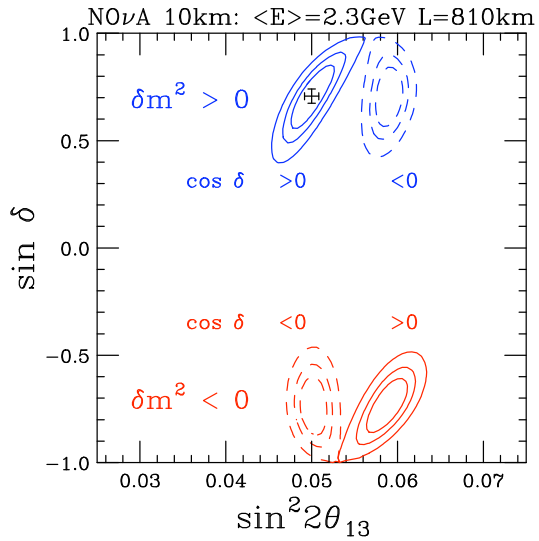
"S": 3e22 proton Ktons

=(3.5+3.5) yrs @ 6.5e20 pot/yr

x {30 ktons x 24%} or {9 ktons x 80%}

M: 5 x "S" L: 25 x "S"

Mena+Parke
hep-ph/0505202

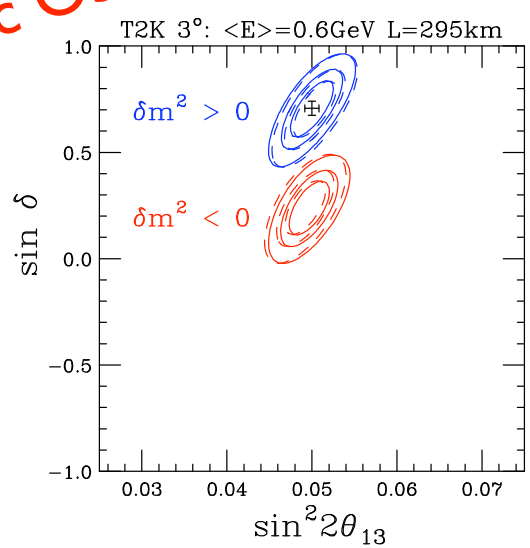


$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 1.41\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

factor of 3 !!!

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

Vac Osc Max



$$\left| \langle \sin\delta \rangle^{T2K}_{fake} - \langle \sin\delta \rangle^{NO\nu A}_{fake} \right| = 0.94\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}.$$

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

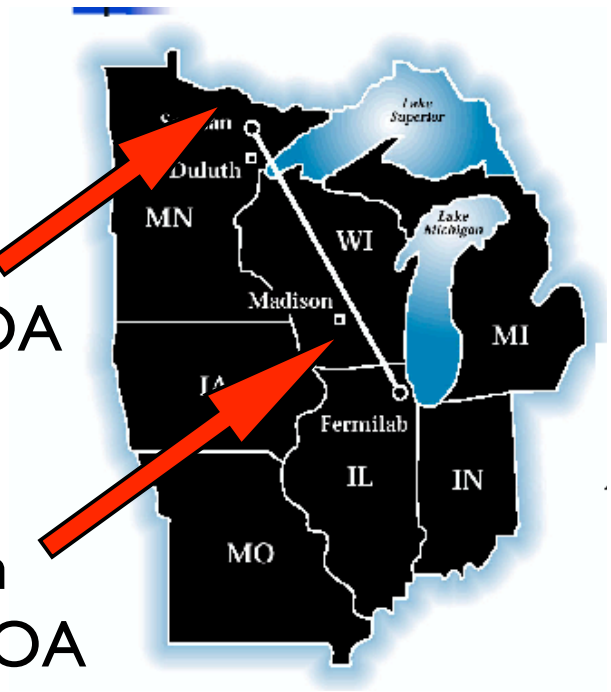
Mena + SP
hep-ph/0408070

NOvA plus "NEAR" DETECTOR

Mena, Palomares, Pascoli
hep-ph/0504015

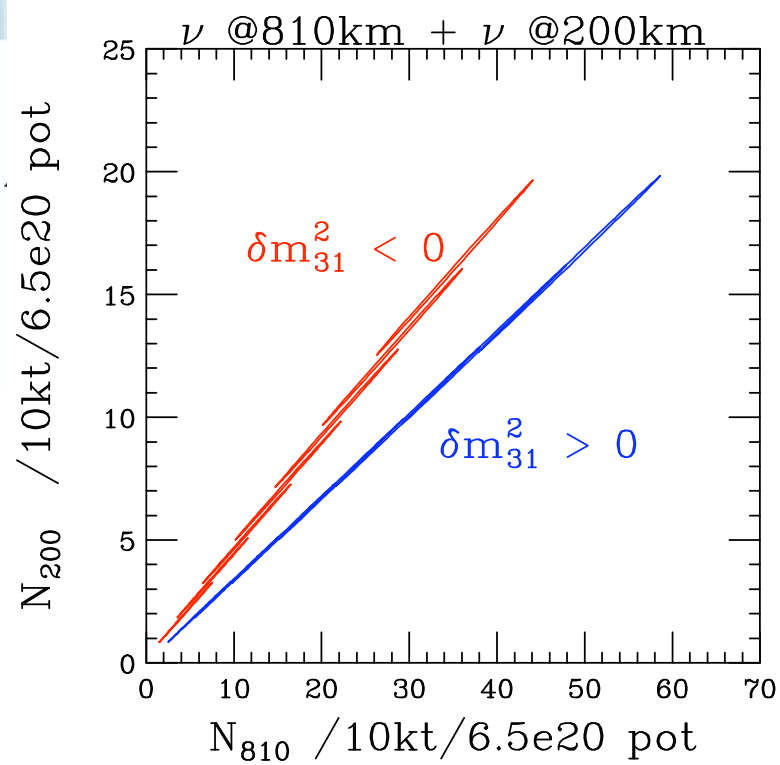
810km
@ 10 km OA
2.3 GeV

200km
@ 8 km OA
0.7 GeV



approx same
E/L

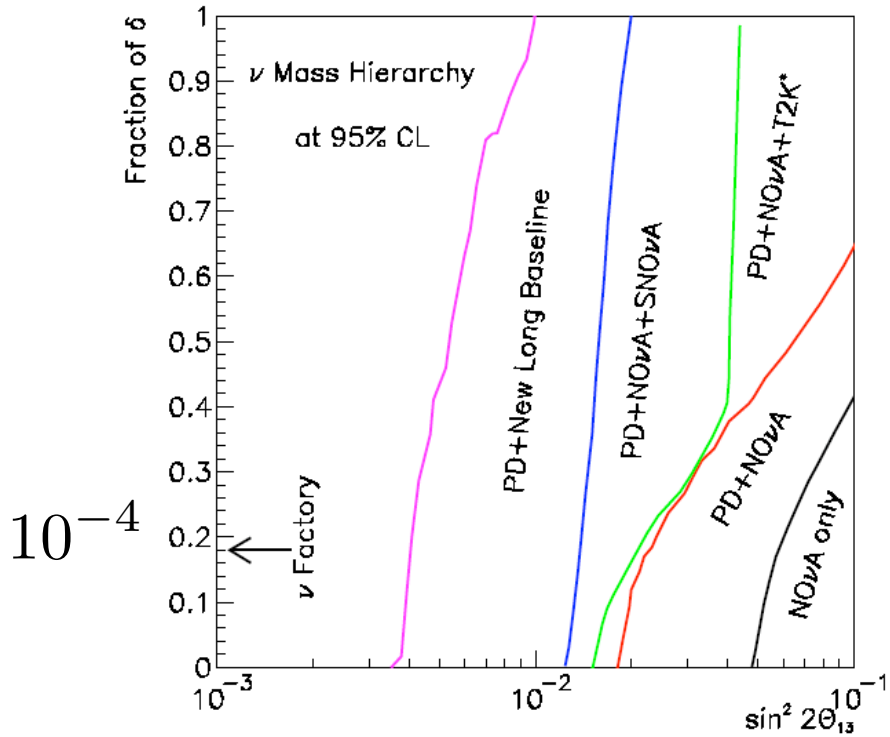
Neutrino - Neutrino



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

Mass Hierarchy

from Off Axis



Fermilab Proton Driver Report

Leptonic CP and T Violation in Neutrino Oscillations

$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \leftrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e & \text{Super-Beams} \\ \text{T} & \Updownarrow & & \Updownarrow & \text{T} \\ & \nu_e \leftrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu & \text{Nu-Factory} \\ & & \text{CP} & & \end{array}$$

Leptogenesis

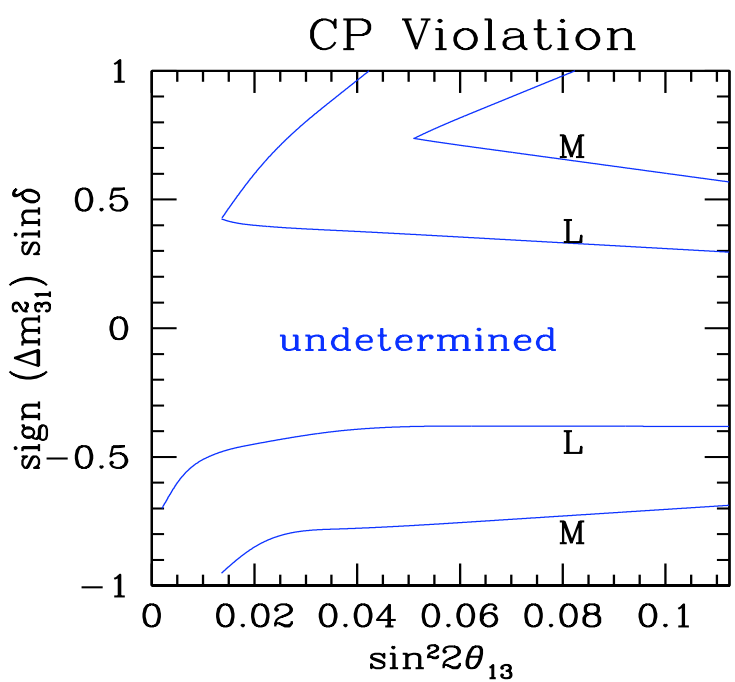
CP Violation and Leptogenesis

- For most Neutrino Mass Models there is a relationship between the Dirac CP phase δ and Majorana CP phases $\alpha_2,\ \alpha_3$.
- At a minimum they are all zero or all non-zero.
- $\alpha_2,\ \alpha_3$ are responsible for Leptogenesis in the early universe by allowing for different decay rates of Neutral Heavy Leptons:

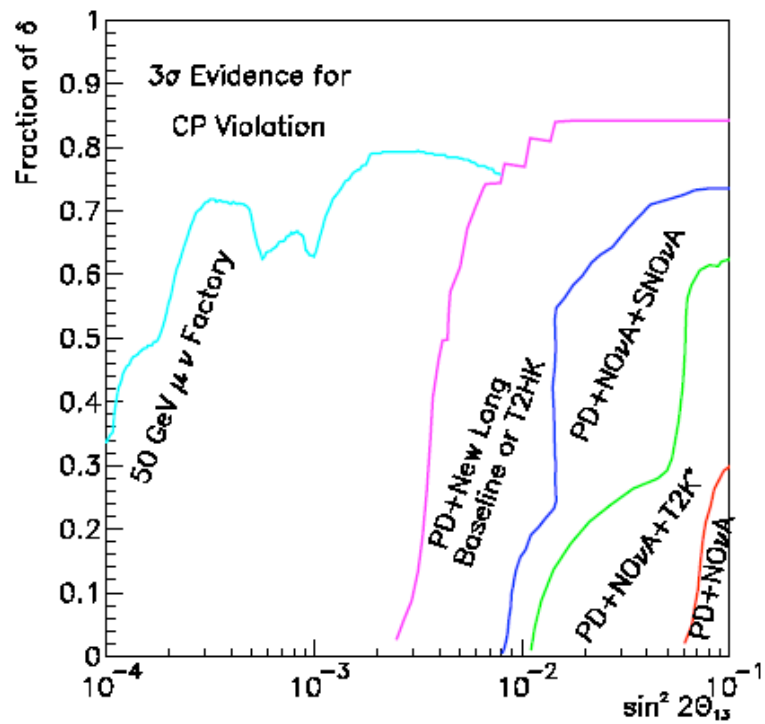
$$N \to l^+\phi^- \text{ and } N \to l^-\phi^+$$

- $B = \frac{1}{2}(B-L) + \frac{1}{2}(B+L)$, however $(B+L)$ violated.
- Hence the Dirac CP violating phase, δ, is a handle on Leptogenesis and hence Baryogenesis.

CP Violation: NOvA, FLARE



CP Violation



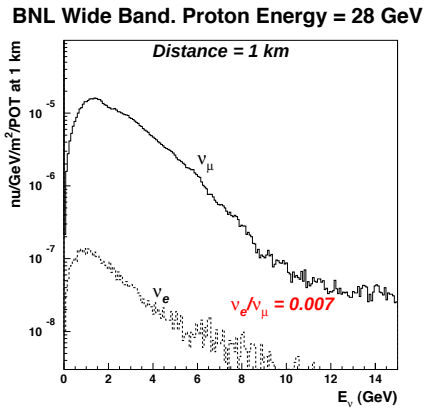
Solving Degeneracies:

Reactor + Off Axis:

Variable Measured	LBL $\nu_\mu \to \nu_\mu$	LBL $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	Reactor $\bar{\nu}_e \to \bar{\nu}_e$	Comments
$\lvert\Delta m^2_{32}\rvert$	Y	n	n	magnitude but not sign
$\sin^2 2\theta_{23}$	Y	n	n	$\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ ambiguous
$\sin^2 \theta_{13}$	n	n	Y	direct measurement
$\sin^2 \theta_{23} \sin^2 \theta_{13}$	n	Y	n	combination of θ_{23} and θ_{13}
sign(Δm^2_{32})	n	Y	n	via matter effects
$\cos \theta_{23} \sin \delta_{CP}$	n	Y	n	CP violation
$\cos \theta_{23} \cos \delta_{CP}$	n	?	n	extremely difficult

On Axis Beams:

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



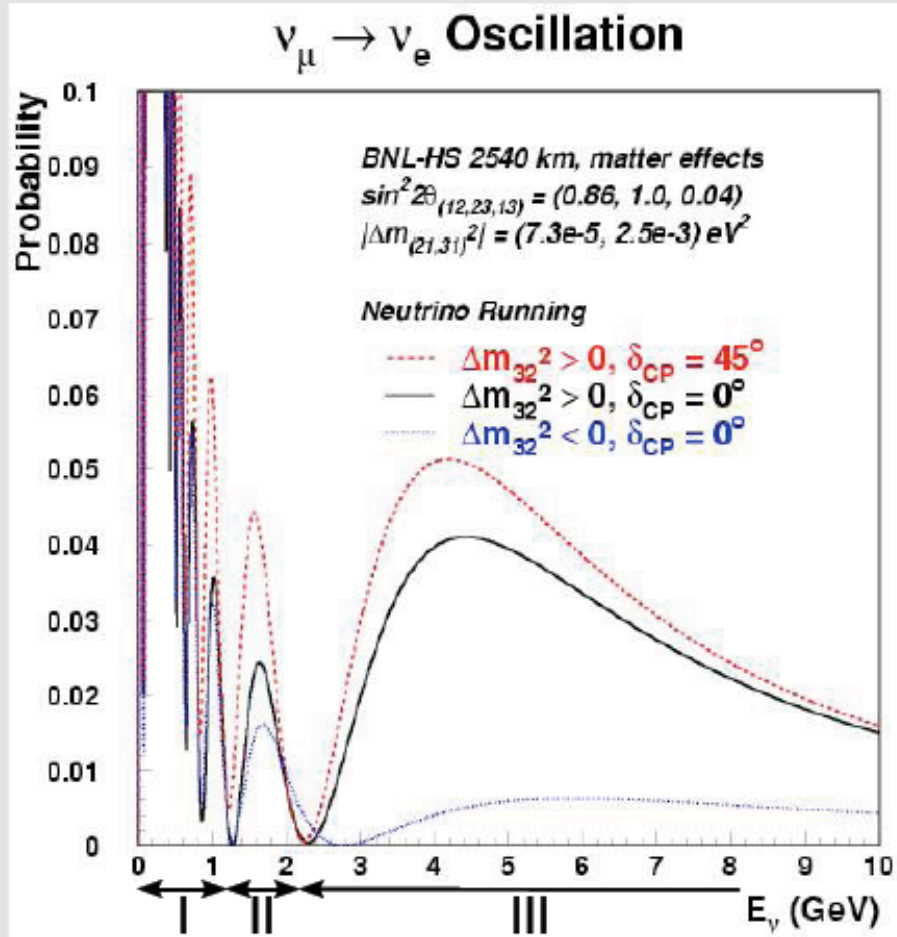
Why Broadband Beam?

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	++	+	+

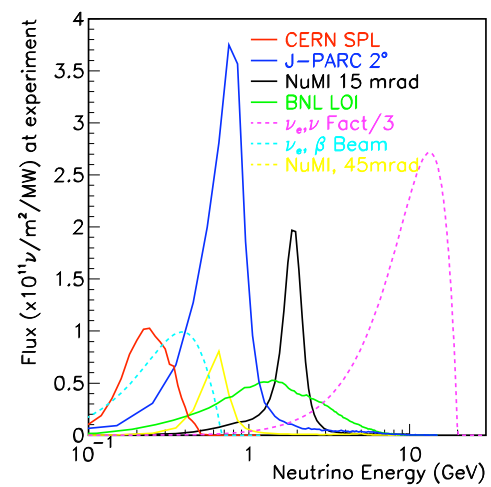


- Many Off Axis experiments in one!

Why is $\nu_e \to \nu_\mu$ at a ν Factory Easy?

- Neutrinos/MW proton power *cf* conventional beams $\propto (E_\mu/15)^3$
- No Intrinsic ν_μ in the beam, only $\bar{\nu}_\mu$'s
- Charge of Muon easier to measure than e/π^0 separation
- Detector Technology straightforward (see MINOS)
- Backgrounds at $\leq 10^{-4}$ level, not few $\times 10^{-3}$

Comparison of Fluxes per MegaWatt at each experiment:



Note ν Factory flux divided by 3 to fit on graph!

- Higher E means larger cross section, more events.
- Higher E allows larger L for same E/L, bigger matter effects (amplifies P_{atm}).

Conclusions:

the θ_{13} window

is a

WONDERFUL OPPORTUNITY:

- $\sin^2\theta_{13} \neq 0$ Reactor and LBL needed.
- For Mass Hierarchy we need more than one Off-Axis Exp. T2K + "NuMI exp." OR an On-Axis Exp.
- CP violation: Need many events: this implies Big detectors, Powerful Source, High Eff. (also $$$)

new technology needed

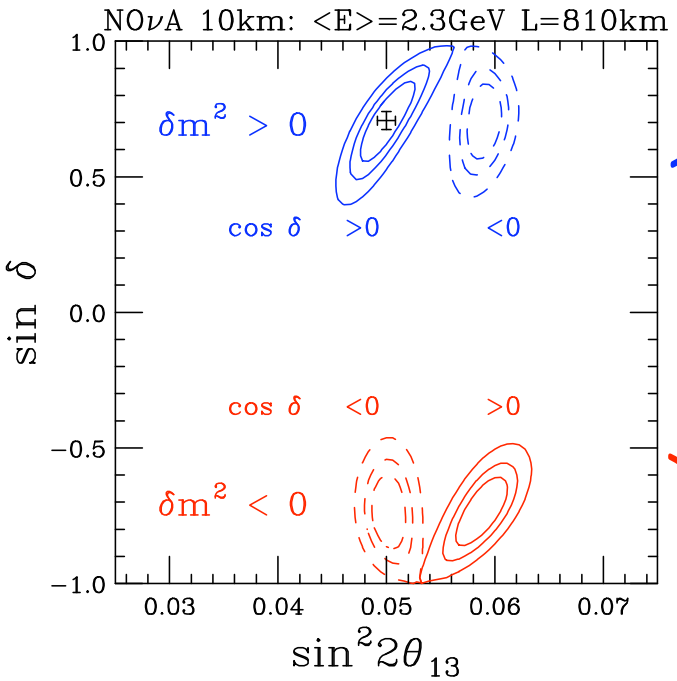
Star Trek: The Next Generation

Geordi La Forge: in "The Enemy"

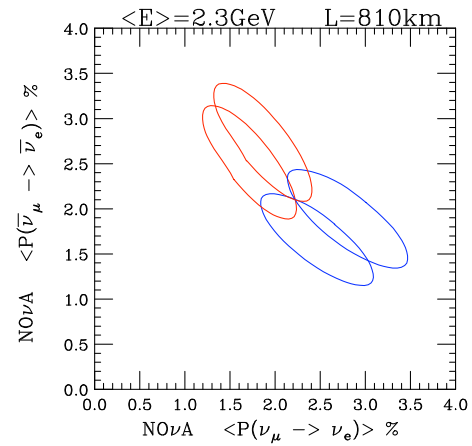
The visor "sees" Neutrinos!!!

... but this requires special New Physics !!!

Parameter Degeneracies:



4 ellipses:



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

$$= \left(\frac{4}{3\pi}\right)^2 \left(\frac{\tan\theta_{23}}{\sin 2\theta_{12}}\right) \left(\frac{\delta m^2_{31}}{\delta m^2_{21}}\right) (a_E L) \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$(a_E L)_{NOvA} = 3\ (a_E L)_{T2K}$$

$$a \approx \frac{1}{4000\ km}$$

Burget-Castell etal
hep-ph/0103258

$$\Leftrightarrow$$

$$\sim \Delta_{31} \cot \Delta_{31}$$

0 when $\boldsymbol{\Delta_{31} = \pi/2}$

Mena + SP
hep-ph/0408070

T2K:

$$\sqrt{P_{atm}} = \pm 2\sqrt{P_{sol}}\sin\delta$$

T2K will operate at Vacuum Oscillation Maximum

$$P(\mu \to e) = P_{atm} - 2\sqrt{P_{atm}P_{sol}}\sin\delta + P_{sol}$$

at $\sin^2 2\theta_{13} = 0.006$ $\qquad P_{atm} = 4P_{sol}$

$$(\ P_{sol} = 0.1\%)$$

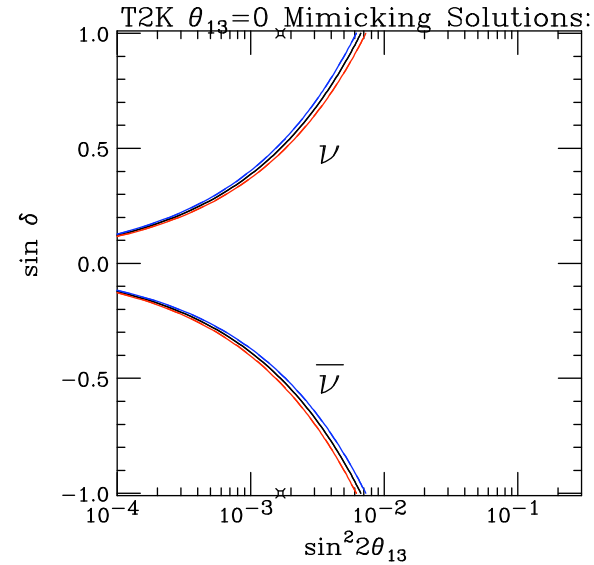
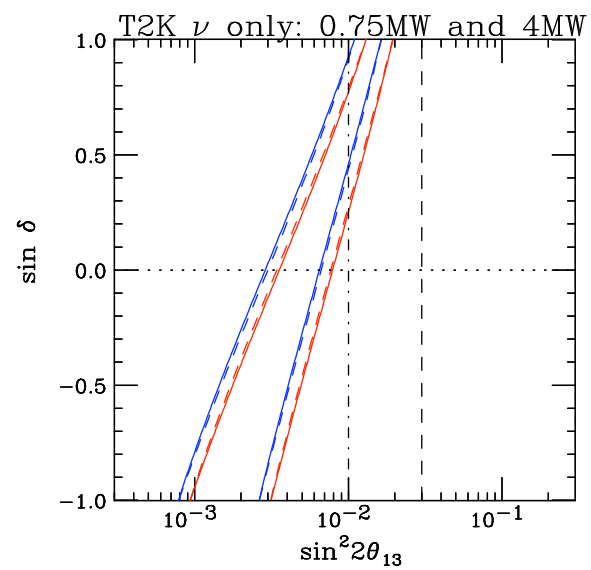
Therefore

$P(\delta = 0) = 5P_{sol}$

$P(\delta = -\frac{\pi}{2}) = 9P_{sol}$ half exposure required.

$P(\delta = \frac{\pi}{2}) = P_{sol}$ NO contribution from θ_{13} !!!!

Also

$P(\delta = -\frac{\pi}{2}) = 5P_{sol}$ when $\sin^2 2\theta_{13} = 0.003$

$P(\delta = \frac{\pi}{2}) = 5P_{sol}$ when $\sin^2 2\theta_{13} = 0.02$