First K's

Now B's

Next ν's

CP Violation in the Lepton Sector:

Stephen Parke
Fermilab
Feb 28, 2005

- Intro
- $\nu_\mu \leftrightarrow \nu_e$
- Matter Effects
- Entanglement of CP and Mass Hierarchy
- Sensitivity to $\sin^2 2\theta_{13}$
- Summary and Conclusion

Leptonic CP and T Violation in Neutrino Oscillations

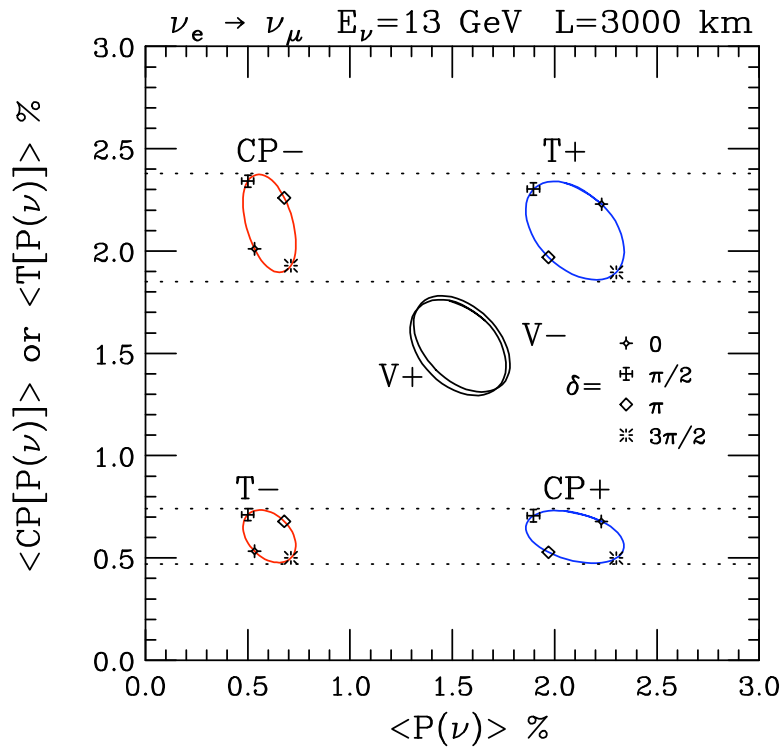
$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \leftrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e & \text{Super-Beams} \\ \text{T} & \Updownarrow & & \Updownarrow & \text{T} \\ & \nu_e \leftrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \leftrightarrow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

Leptogenesis

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

$$\nu_\mu \longleftrightarrow \nu_e$$

$$\bar\nu_e \longleftrightarrow \bar\nu_\mu$$



$$\nu_e \longleftrightarrow \nu_\mu$$

$$P_{mat}(\nu_e \to \nu_\mu, \delta m^2_{31}, \delta m^2_{21}, \delta)$$
$$\approx P_{mat}(\bar\nu_\mu \to \bar\nu_e, -\delta m^2_{31}, \delta m^2_{21}, \pi - \delta)$$

Minakata, Nunokawa + SP
hep-ph/0204171

Neutrino Mixing Matrix:

Like the Quark Sector:

The Neutrino Mass Eigenstates, $|\nu_i\rangle$, are a Mixture of Flavor States, $|\nu_\alpha\rangle$:

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle.$$

(using $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$)

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

Atmos. L/E $\mu \to \tau$ 500 km/GeV Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ 15,000 km/GeV

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

For Majorana Nu's

$$U \to U \begin{pmatrix} 1 & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

Phases α_2, α_3 are unobservable in oscillation phenomena, $(U_{\alpha i}U^*_{\beta i})$.

Important in neutrinoless double beta decay.

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.

Fukugita and Yanagida, Phys. Lett. B174, 45 (1986)
Frampton, Glashow and Yanagida – hep-ph/0208157
Endoh, Kaneko, Kang, Morozumi – hep-ph/0209098

Masses and Mixings:

(12) Parameters: SNO, KamLAND, SK

$$\delta m^2_{21} = +7.9 \pm 1.0 \times 10^{-5}\ eV^2$$

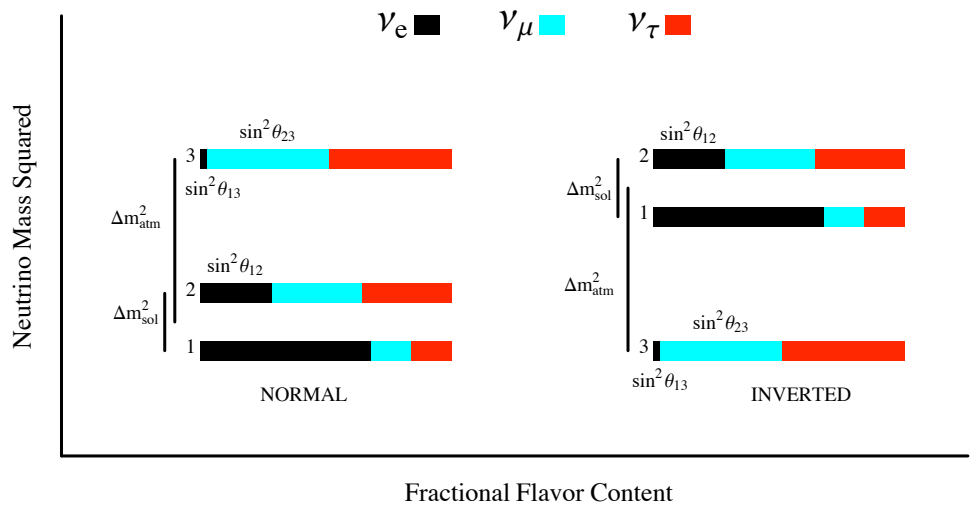
$$0.23 < \sin^2\theta_{12} < 0.35$$

$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

sign of δm^2_{21} determined at this C.L.

90% ^{8}B solar neutrinos exit the sun as ν_2.

Thus SNO's $\frac{CC}{NC} \approx \sin^2\theta_{12}$



(23) Parameters: SK, K2K

$$|\delta m^2_{32}| = 1.5 - 3.5 \times 10^{-3}\ eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known!

Sign of δm^2_{32} Unknown !!!

(13) Parameters: Chooz, SK, K2K

$$\sin^2\theta_{13} < 0.03 - 0.05$$

limit $|\delta m^2_{32}|$ dependent

$$0 \leq \delta_{CP} < 2\pi$$

Unknown!

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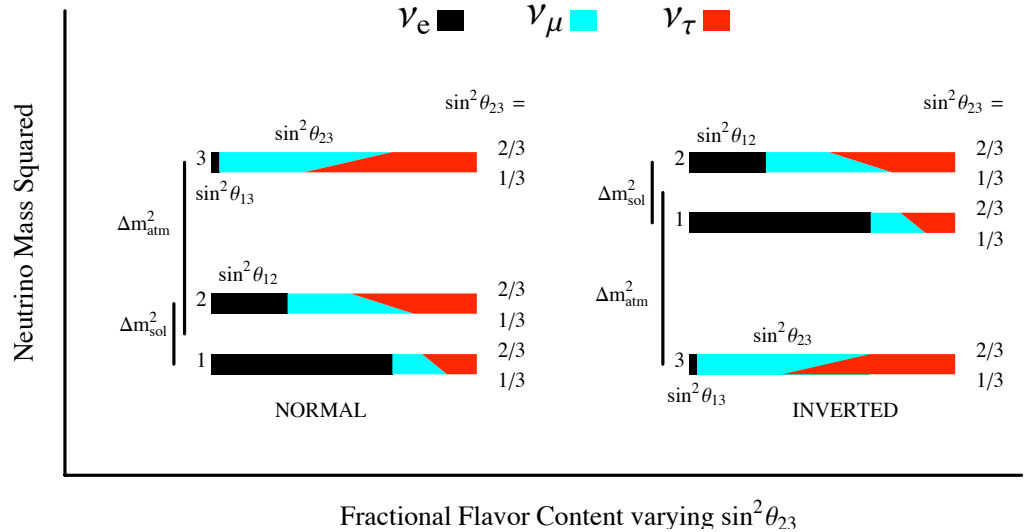

O. Mena + SP hep-ph/0312131

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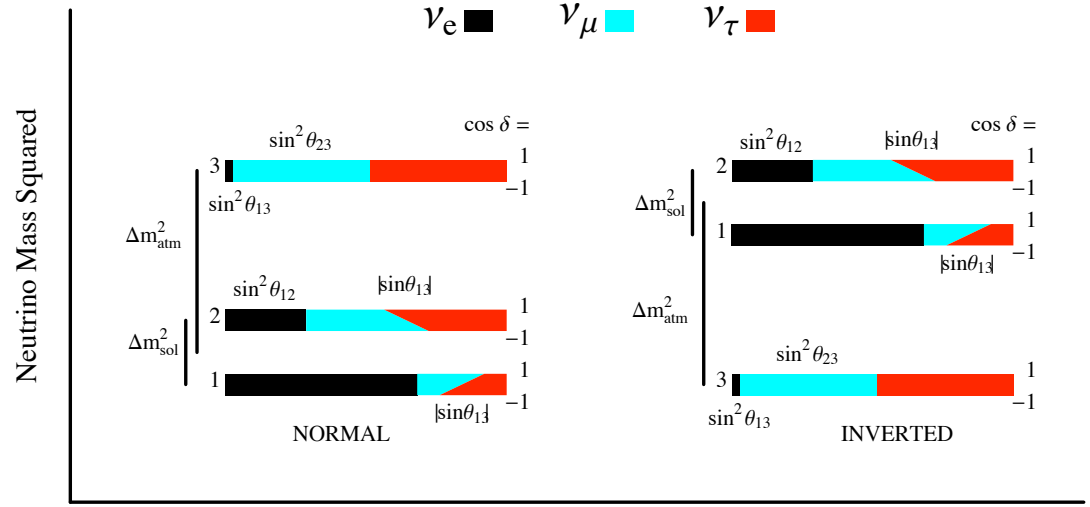

Fractional Flavor Content varying cos δ

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Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known!

Sign of δm^2_{32} Unknown !!!

(13) Parameters: Chooz, SK, K2K

$$\sin^2\theta_{13} < 0.03 - 0.05$$

limit $|\delta m^2_{32}|$ dependent

$$0 \leq \delta_{CP} < 2\pi$$

Unknown!

$\nu_\mu \leftrightarrow \nu_e$

$$-i\frac{d\nu_\alpha}{dt} = \left\{ U_{\alpha j}\,\frac{m_j^2}{2E}\,U^*_{\beta j} + \sqrt{2}G_F N_e\,\delta_{\alpha e}\delta_{\beta e} \right\}\nu_\beta$$

$re - diagonalize$

$$= \left\{ U(N)_{\alpha j}\,\frac{m_j^2(N)}{2E}\,U^*(N)_{\beta j} \right\}\nu_\beta$$

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle\nu_\beta|e^{-iH_0L}|\nu_\alpha\rangle\right|^2 = \sum_{i,j} U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}e^{-i\delta m^2_{ij}L/2E}$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j}\ Re\ (U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2(\frac{\delta m^2_{ij}L}{4E})$$

$$+\ 2\sum_{i>j}\ Im\ (U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin(\frac{\delta m^2_{ij}L}{2E})$$

$\nu_\mu \to \nu_e$

$$P_{\mu\to e} = \left| \sum_j U^*_{\mu j}\, U_{ej} e^{-i m_j^2 L/2E} \right|^2$$

Elimate $U^*_{\mu 1} U_{e1}$
using unitarity of U.
Use $\Delta_{ij} = \delta m^2_{ij} L/4E = 1.27 \delta m^2_{ij} L/E$

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

Square of Atmospheric+Solar amplitude:

$U^*_{\mu 3} U_{e3} = s_{23} s_{13} c_{13} e^{\mp i\delta}$ for ν and $\bar{\nu}$:

Approx. $U^*_{\mu 2} U_{e2} \approx c_{23} c_{13} s_{12} c_{12} + \mathcal{O}(s_{13})$:

$$P_{\mu\to e} \approx \left| 2 s_{23} s_{13} c_{13} \sin\Delta_{31} e^{-i(\Delta_{32} \pm \delta)} + 2 c_{23} c_{13} s_{12} c_{12} \sin\Delta_{21} \right|^2$$

Interference term different for ν and $\bar{\nu}$: CP violation !!!

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

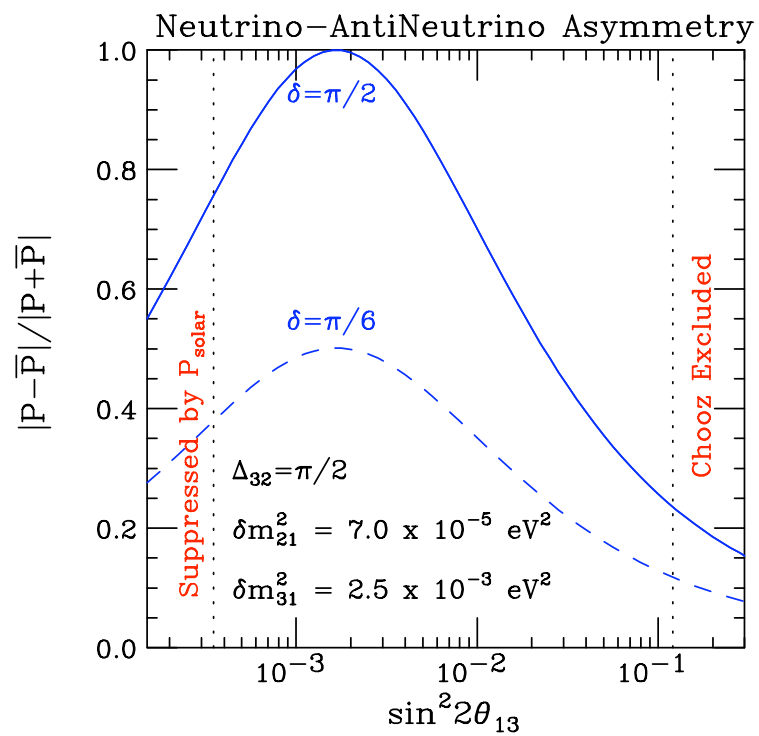
where $P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$

and $P_{sol} = \cos^2\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta_{21}$

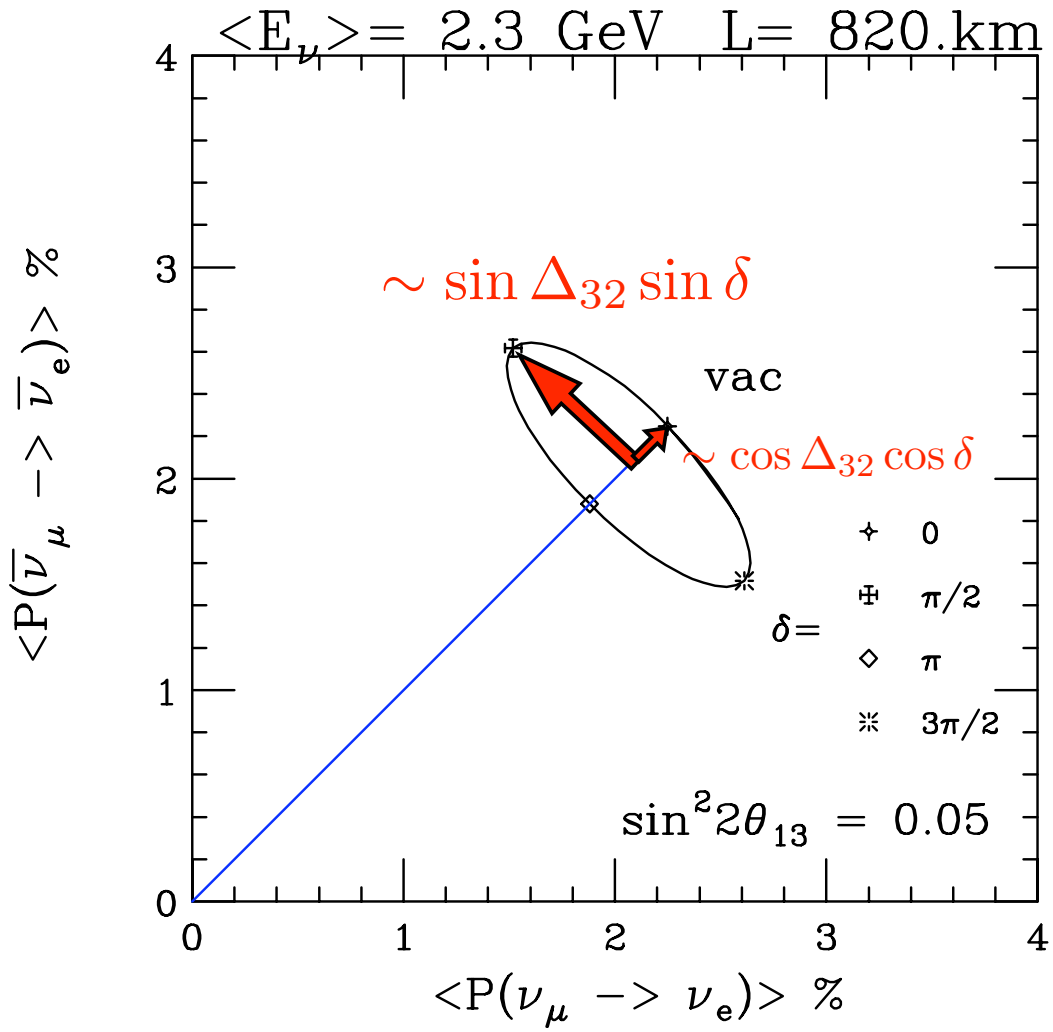
At the first atmospheric oscillation maximum, $\Delta_{32} = \frac{\pi}{2}$, the Neutrino-AntiNeutrino Asymmetry is maximum when

$$P_{atm} = P_{sol}$$

$$\sin^2 2\theta_{13} = \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left[\frac{\pi}{2}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\right]^2 \approx 0.002 \text{ !!!}$$

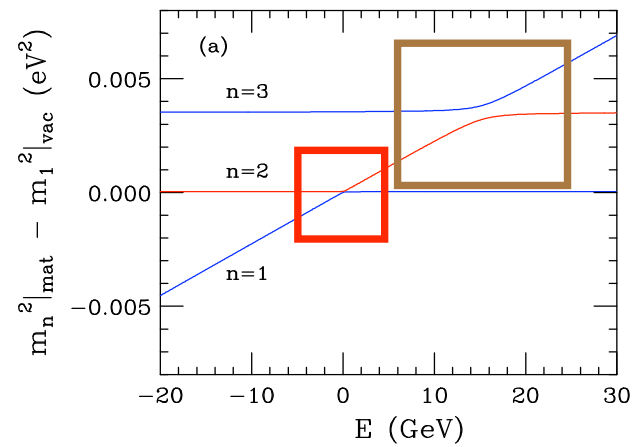


At the second oscillation maximum, $\Delta_{32} = \frac{3\pi}{2}$, the peak in the Asymmetry occurs when $\sin^2 2\theta_{13}$ is 9 times larger. BNL $\to$???.


$\langle E_\nu \rangle = 2.3$ GeV L= 820.km
$\sim \sin\Delta_{32}\sin\delta$
vac
$\sim \cos\Delta_{32}\cos\delta$
$\delta =$
0
$\pi/2$
π
$3\pi/2$
$\sin^2 2\theta_{13} = 0.05$
$\langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle$ %
$\langle P(\nu_\mu \to \nu_e) \rangle$ %
0
1
2
3
4

Matter Effects:

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



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

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

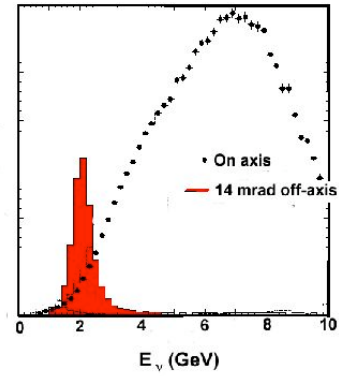
$$\sin \Delta_{32} \Rightarrow \sin \Delta_{32}$$

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

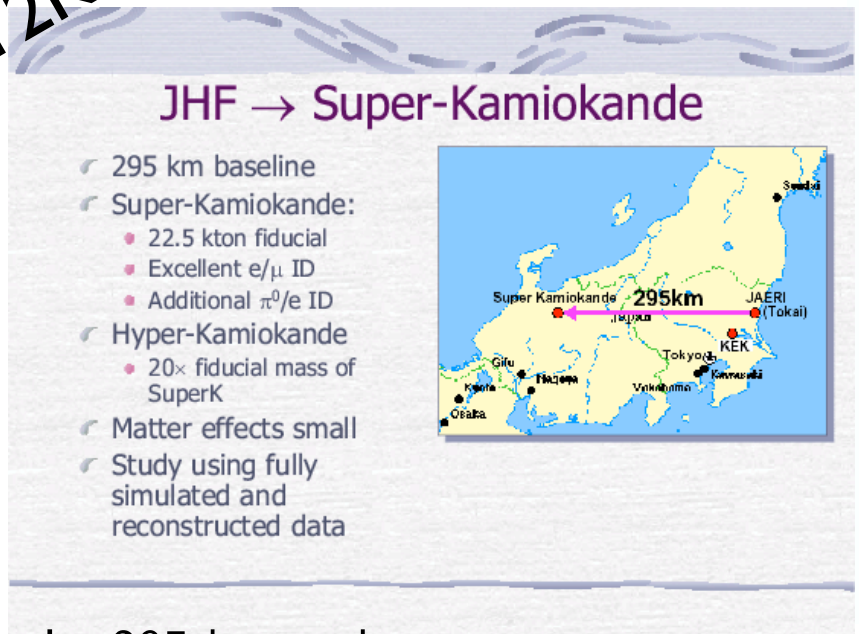
Matter effects are IMPORTANT when $\sin(\Delta \mp aL) \neq (\Delta \mp aL)$.

Off-Axis Beams:

BNL 1994



T2K



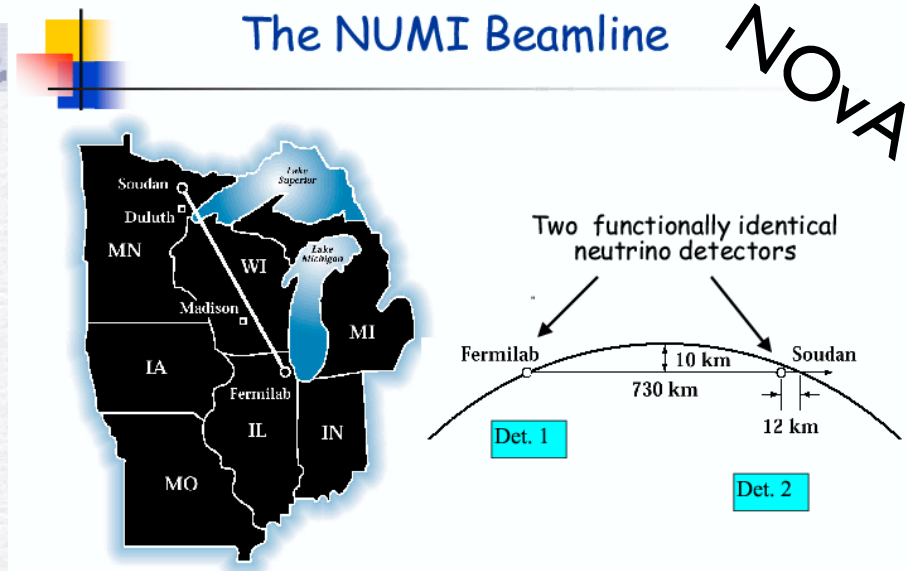
L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

NOvA



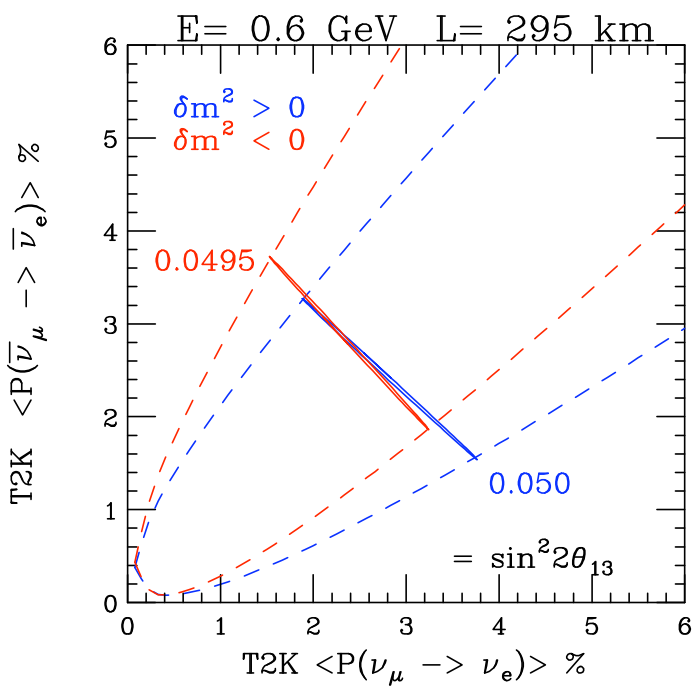
L=700 - 1000 km and

Energy near 2 GeV

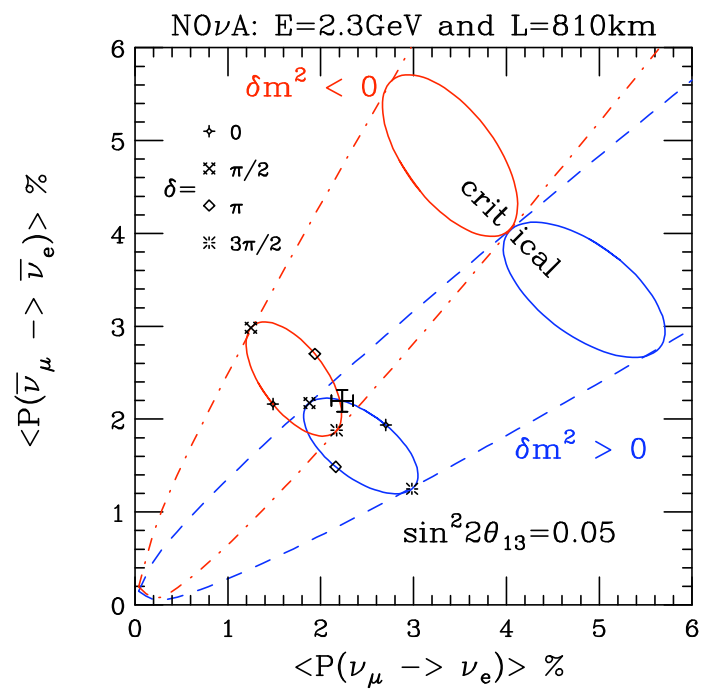
$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

T2K:



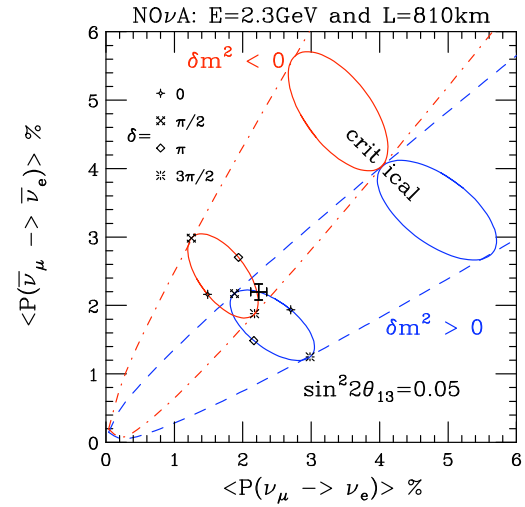
NOvA:



Matter Effects 3 times more important for NOvA than T2K.

Along the Diagonal:

O. Mena + SP
hep-ph/0408070



along $$P = \overline{P}$$

ansatz $$\theta = \theta_c(\sin\delta_P - \beta\cos\delta_P)$$

where

$$\sin\delta_P = \sqrt{\frac{(P - P_{sol})/(P_c - P_{sol}) + \beta^2}{1+\beta^2}} \qquad \cos\delta_P = \pm\sqrt{1-\sin^2\delta_P}$$

$$\text{with} \quad \beta \propto (aL)\cos\Delta_{32} << 1$$

$$\boxed{\langle\sin\delta\rangle_+ - \langle\sin\delta\rangle_- = 2\langle\theta\rangle/\theta_c}$$

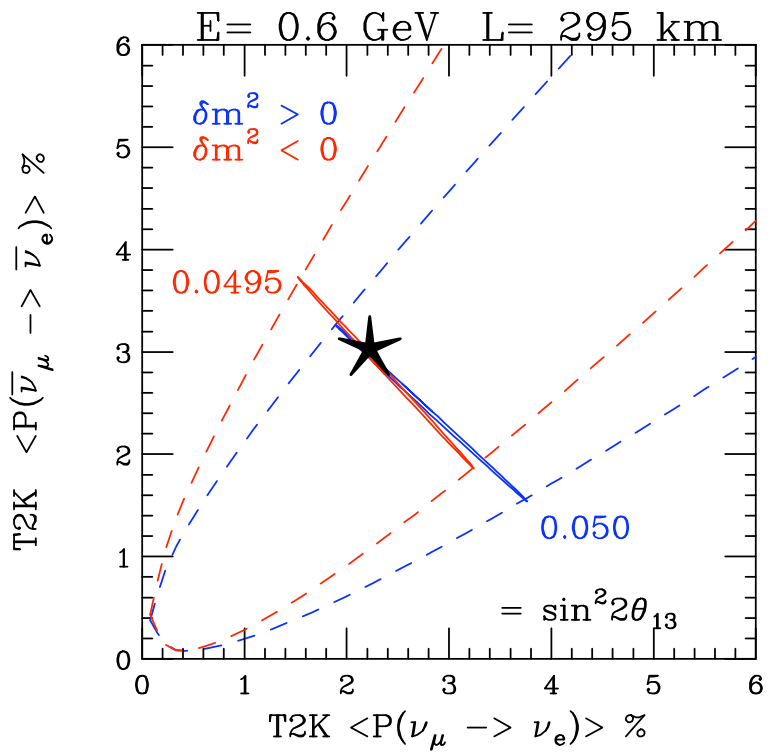
exact along diagonal --- approximately true throughout the overlap region!!!

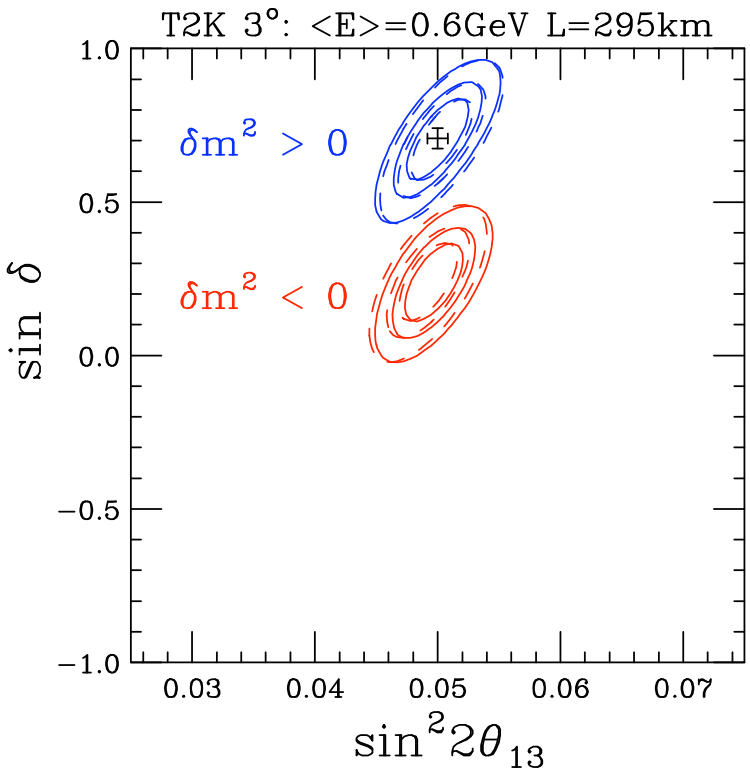
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}$$

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

and $\sqrt{P_{sol}} = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}} \qquad \text{for T2K}$$

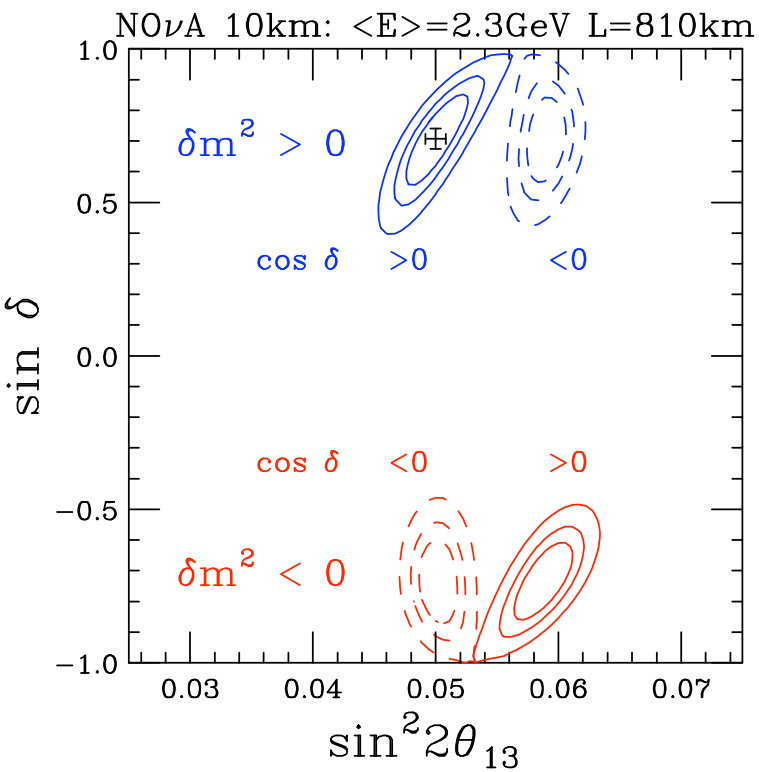


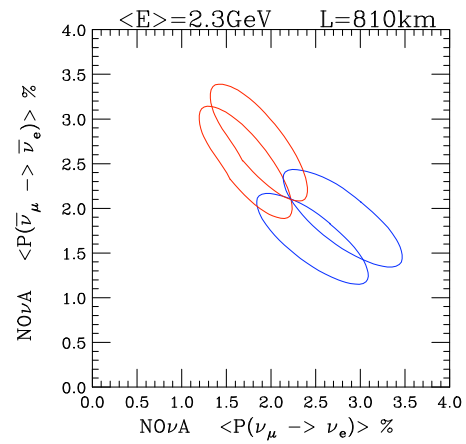


5yr + 5yr: 0.75 MW: HyperK

no info on sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$

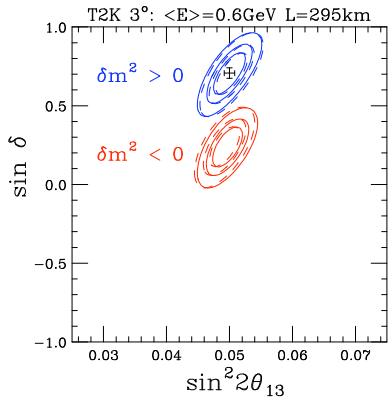
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 1.41\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}} \qquad \text{for NO}\nu\text{A.}$$

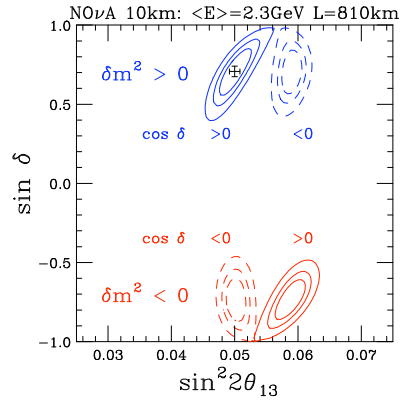




5yr+5yr: 2 MW: 50kton hi-eff.

sensitive to sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$





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

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

if the measurement uncertainty on

$$\sin\delta \approx \pm 0.2$$

then the 2 fake solutions are well separated down to

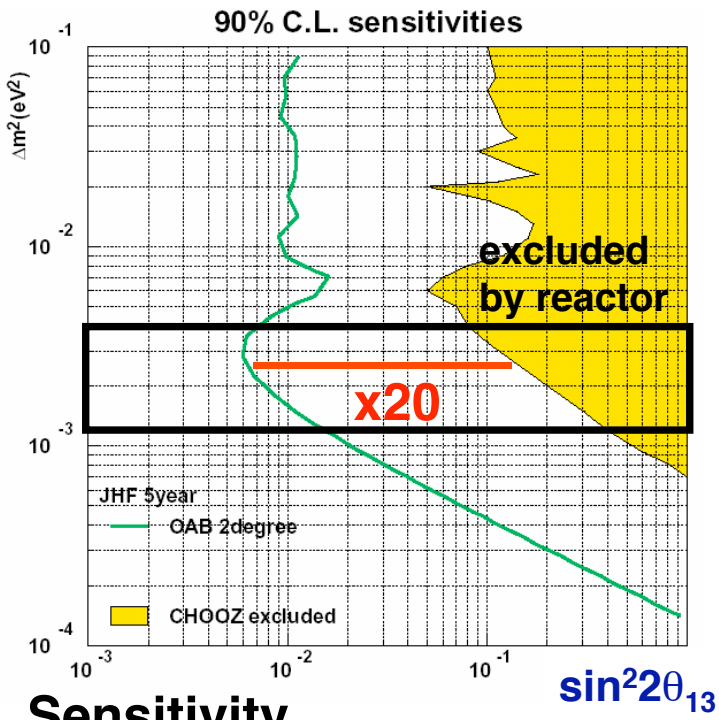
$$\sin^2 2\theta_{13} \approx 0.01$$

hence the Hierarchy is Determined -- CP Violation???

Sensitivity to θ_{13}

T2K:

Search for ν_e appearance



Sensitivity

$\sin^2 2\theta_{13} > 0.006$ (90%)

5 yrs 0.75MW
with SK

assumes $\delta = 0$

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

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

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

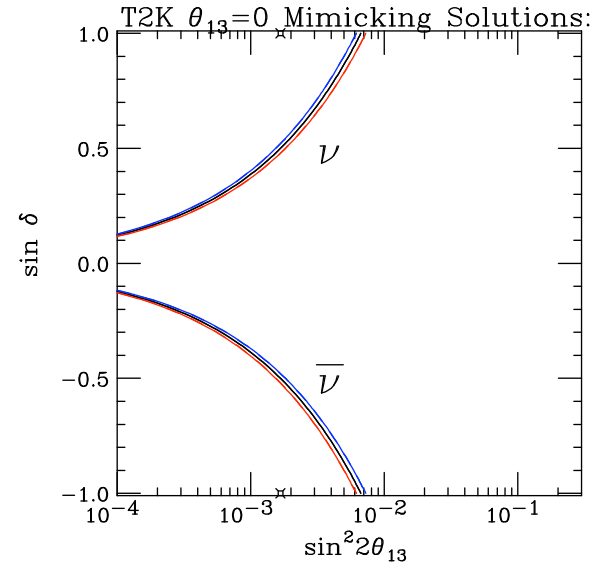
$P(\delta = -\frac{\pi}{2}) = 9P_{sol}$ half exposure required.

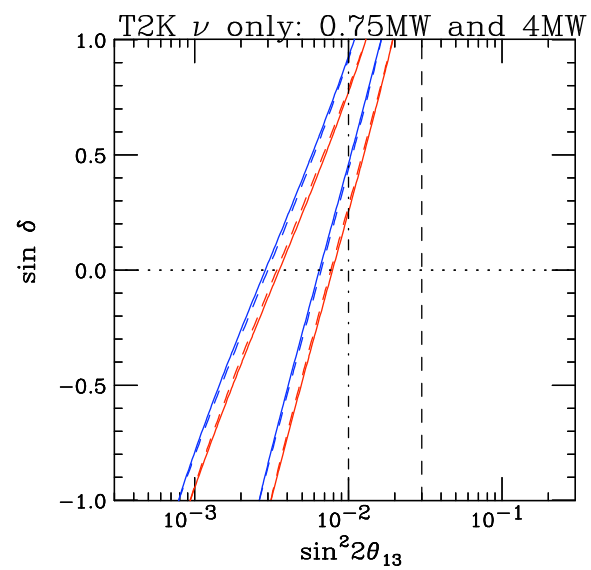
$P(\delta = \frac{\pi}{2}) = P_{sol}$ NO contribution from θ_{13} !!!!

Also

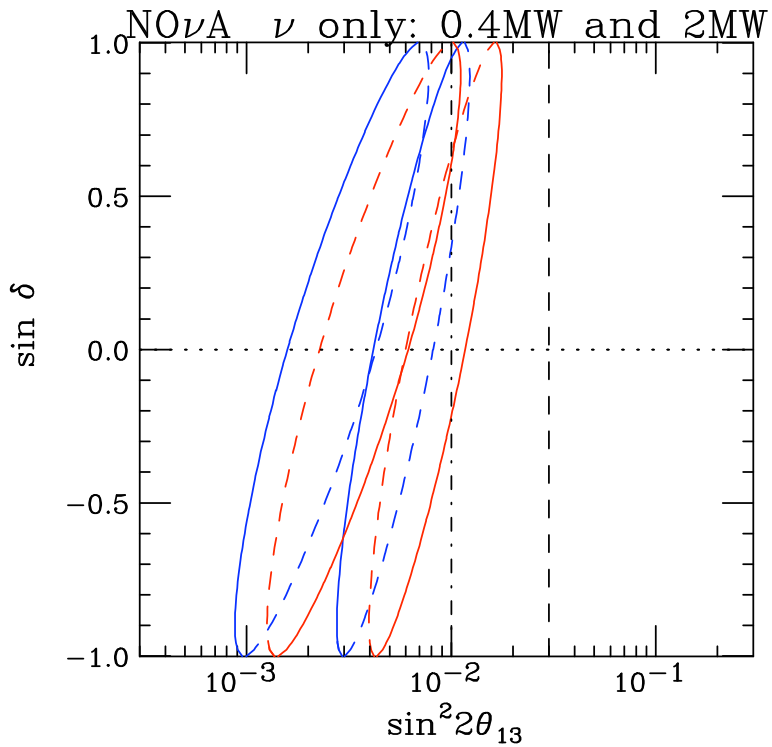
$P(\delta = -\frac{\pi}{2}) = 5P_{sol}$ when $\sin^2 2\theta_{13} = 0.003$

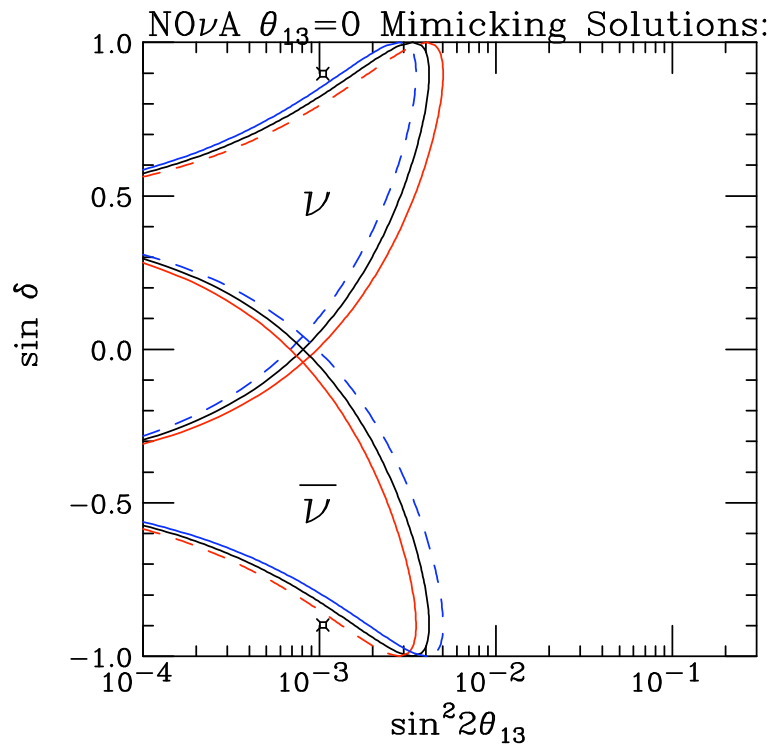
$P(\delta = \frac{\pi}{2}) = 5P_{sol}$ when $\sin^2 2\theta_{13} = 0.02$





NOvA:

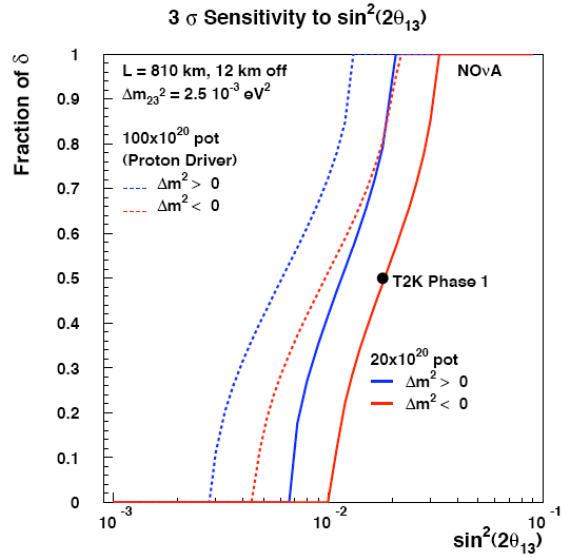




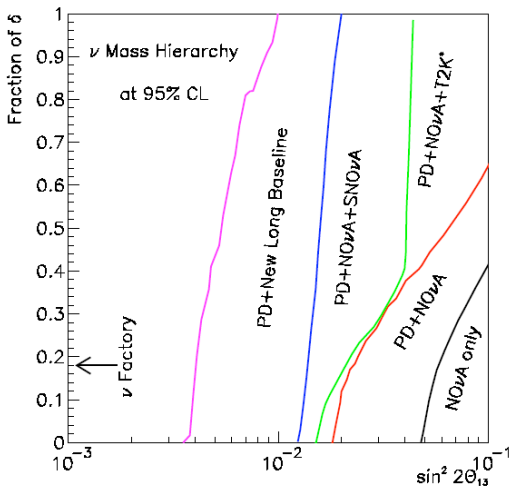
$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

NOvA + ...

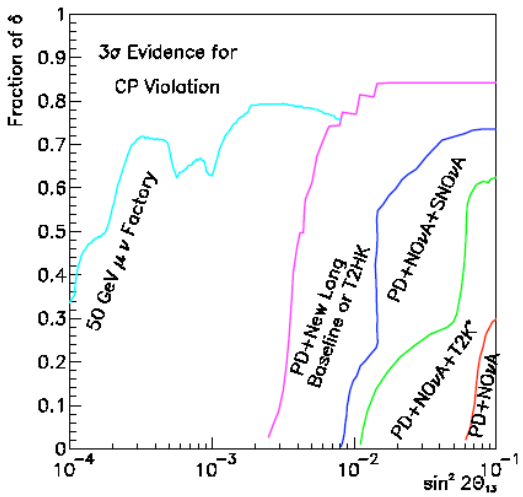
Sensitivity



Mass Hierarchy



CP Violation



Summary

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

CONCLUSION

$P(\nu_\mu \to \nu_e)$ at the Atmospheric δm^2 scale

is THE key to the physics that will resolve the mass hierarchy and tell us whether or not CP is violated in the ν-sector. $\sin^2 2\theta_{13}$ is the controlling parameter for $\nu_\mu \to \nu_e$.

Mass Hierarchy

Is the spectrum of Neutrinos NORMAL or INVERTED? (sign of δm^2_{31})
NuMI/NOνA is in a unique position to address this question.
Without the hierarchy being determined, it is unlikely that T2K can ever claim to see CP violation.

CP Violation in Neutrino Oscillations ($\sin\delta \neq 0$)

CP-violation in the ν-sector maybe our only window into leptogenesis at very high energies. The Superheavy seesaw partners of the Neutrinos are responsible for leptogenesis and hence baryogenesis.

Majorana v Dirac? Steriles? Mass ν_{lite}?

Extras:

Super-Chooz:

interest in Japan, Europe, Russia, USA (CA and IL), China ....

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

>1% 1 <3% <0.1%

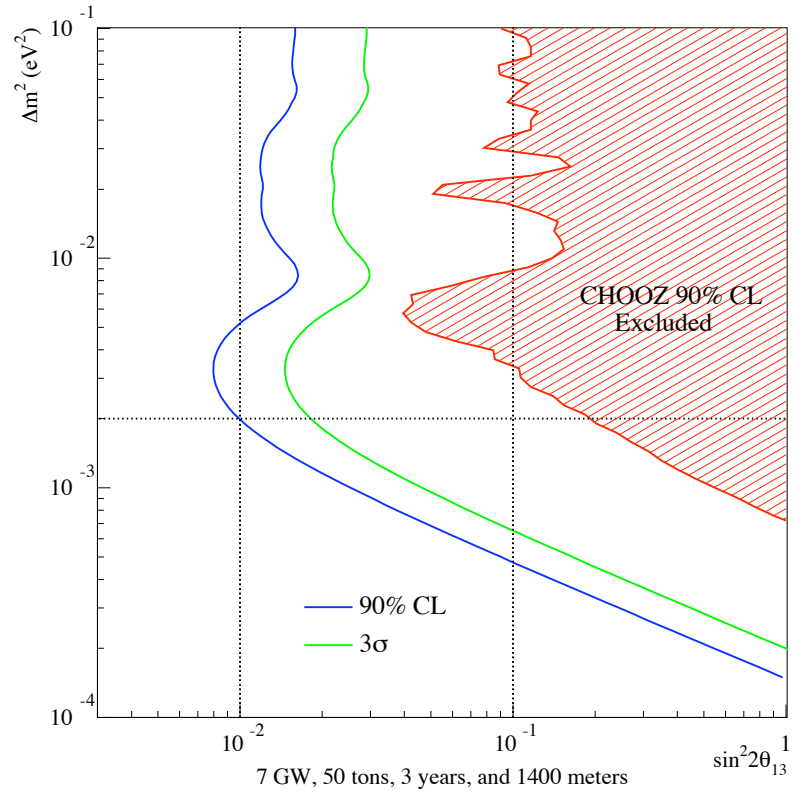
kinematical phase $\Delta_{atm} = \frac{\delta m^2_{atm} L}{4E} = 1.27 \frac{\delta m^2_{atm} L}{E}$

Clean measurement of

$\sin^2 2\theta_{13}$ down to 0.01

Systematics limit experiment:

Could be "quick" and "cheap" but ...



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