Open Questions Strategy I

Stephen Parke
Fermilab

Reactor/Accelerator Sector: {13}

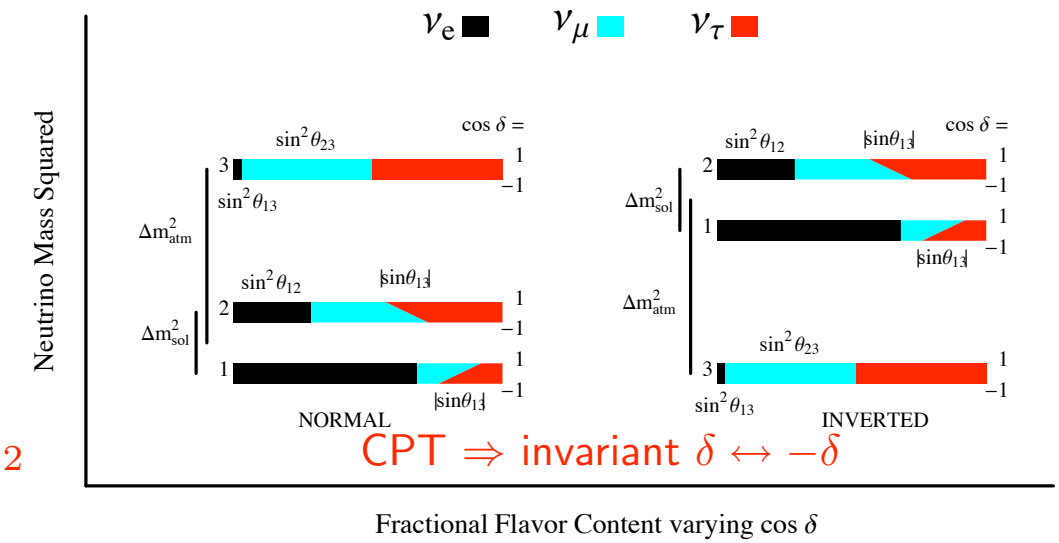
$|U_{\alpha j}|^2$

O. Mena + SP
hep-ph/0312131

$$\delta m^2_{21} = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$

$$\sin^2\theta_{12} = 0.31 \pm 0.03$$

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



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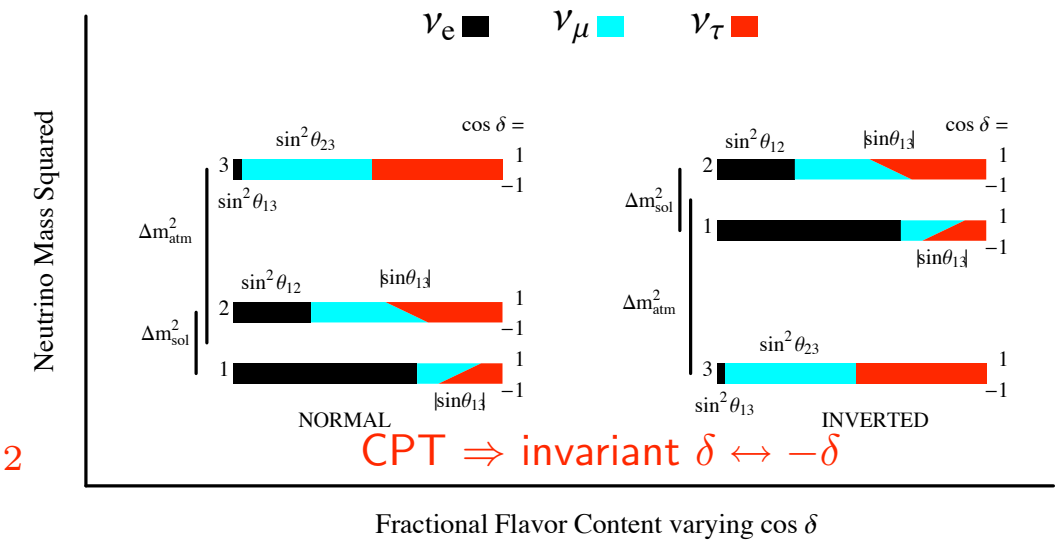

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2$$

$$\sin^2\theta_{23} = 0.50 \pm 0.14$$

Which δm^2_{atm} ?

Hierarchy?

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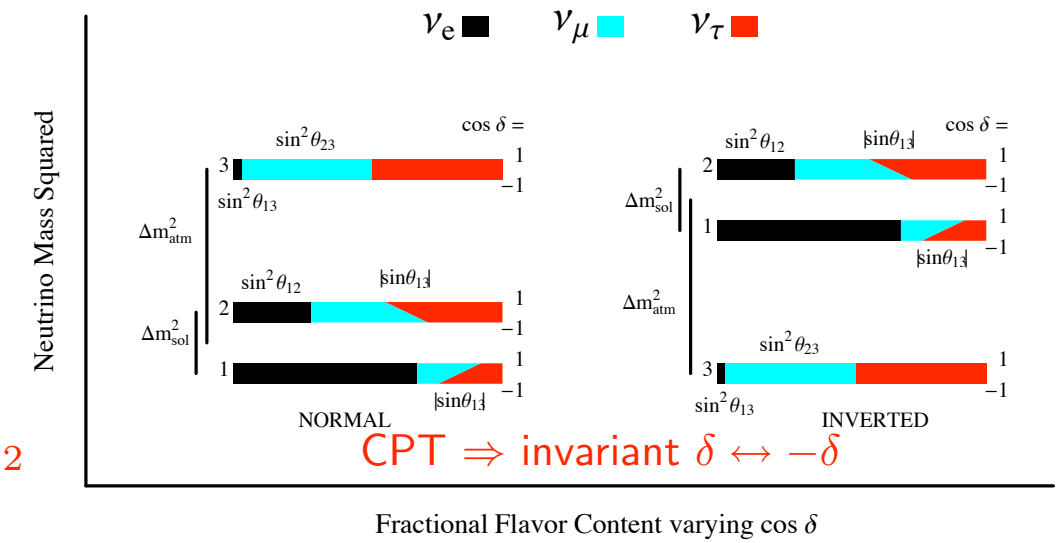

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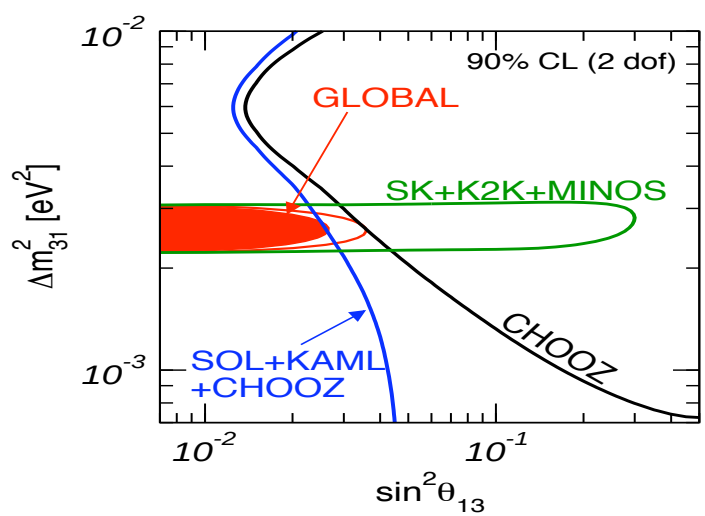
$$\sin^2\theta_{23} = 0.50 \pm 0.14$$

Which δm^2_{atm} ?

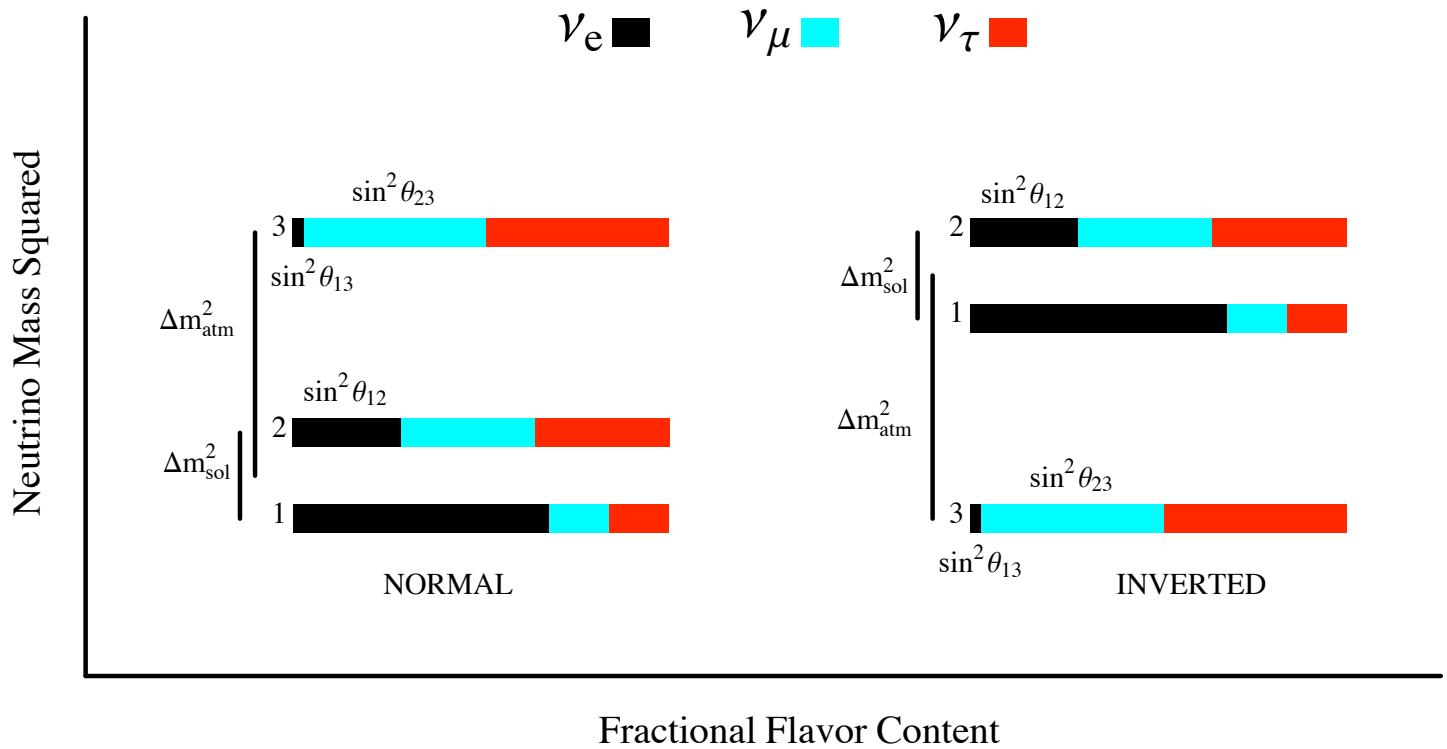
$$\sin^2\theta_{13} < 0.03$$

$$0 \leq \delta < 2\pi$$

Hierarchy?



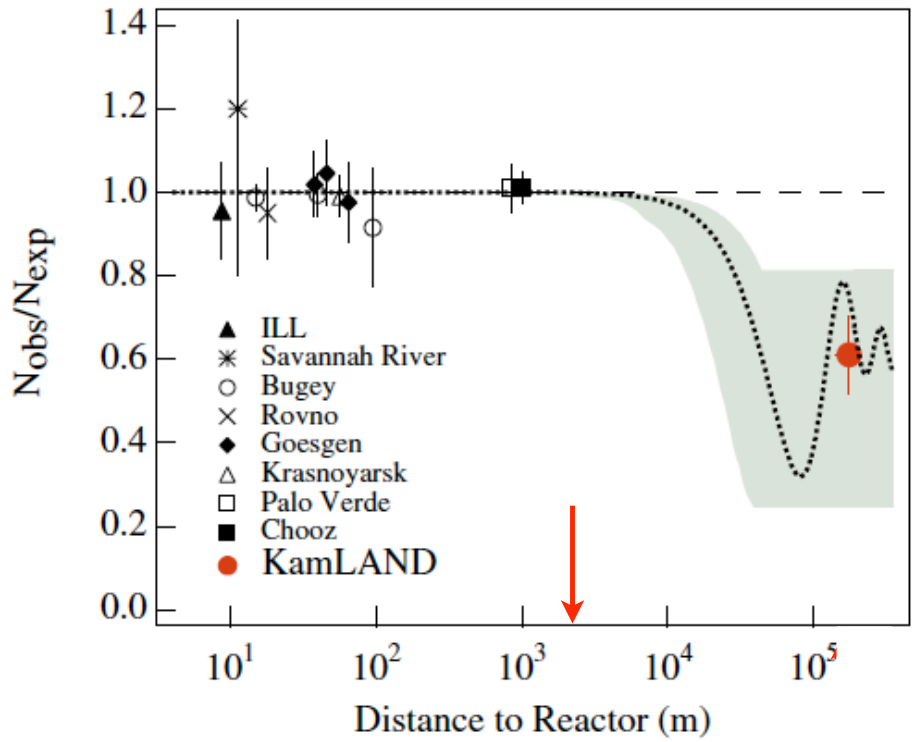
Maltoni etal
hep-ph/0405172v5



Implies Maximal Mixing in {23} Sector
and
Maximal CP Violation

θ_{13} from Reactor Disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$



kinematic phase:

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

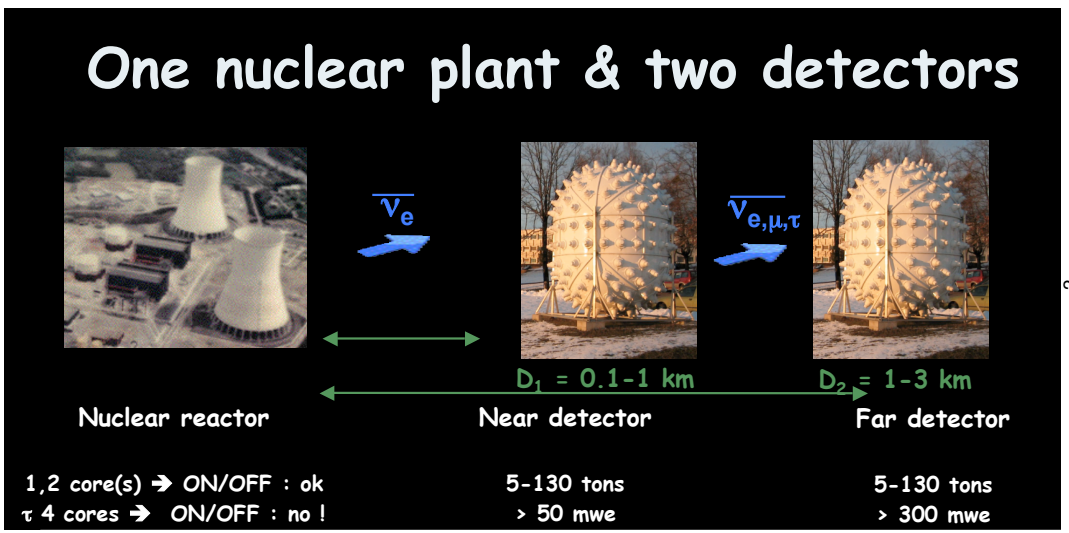
< 0.002

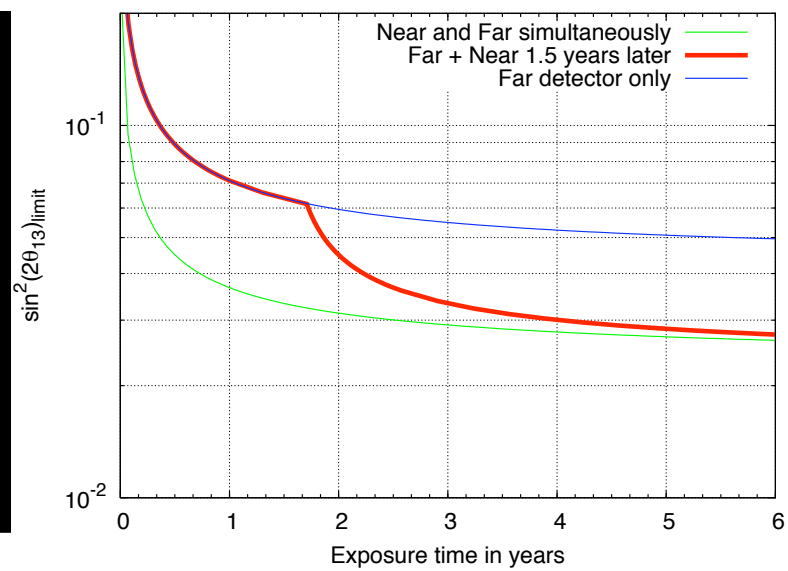
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

> 0.01

$$\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$$

Double Chooz:





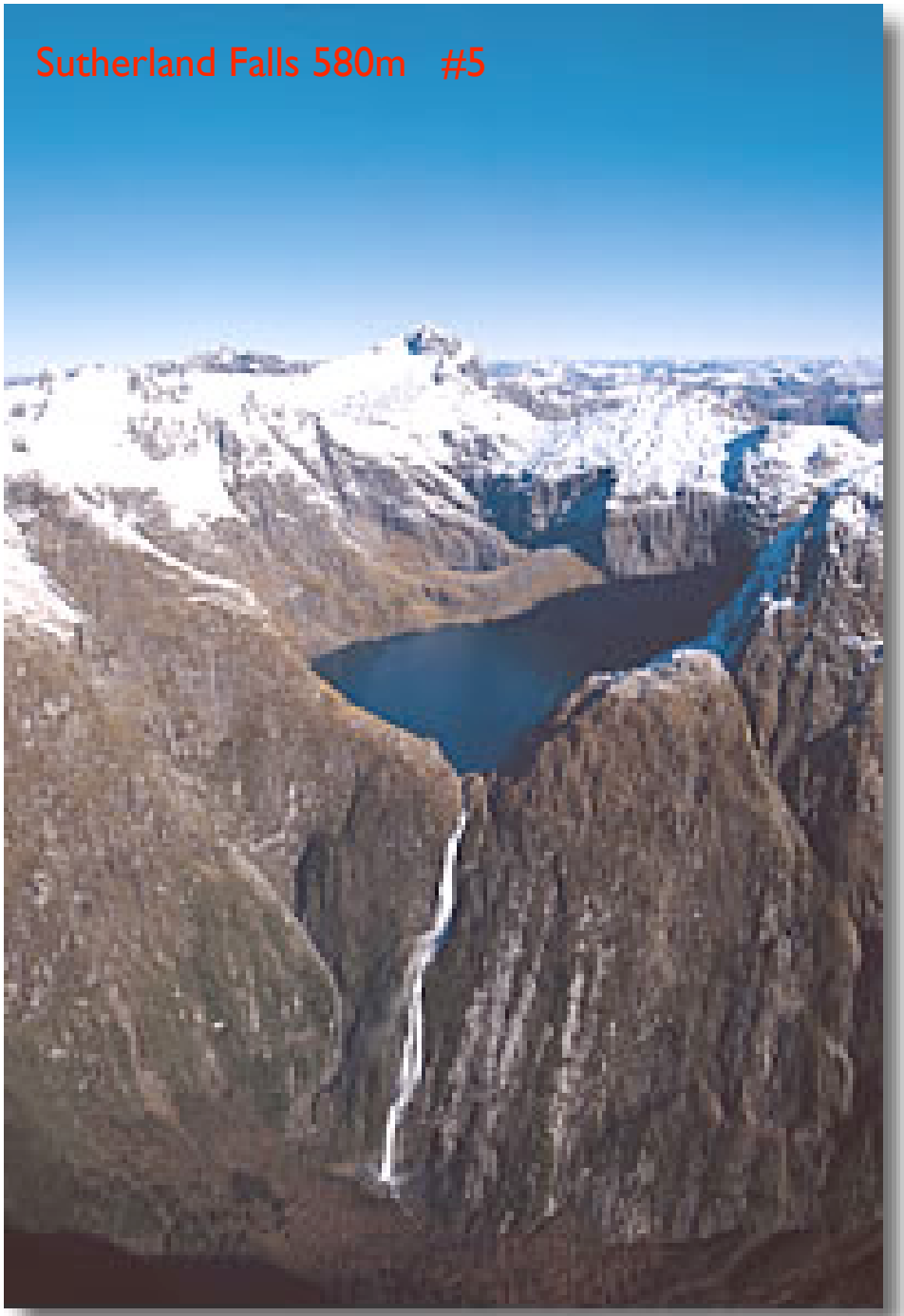
.03

Figure 18: $\sin^2(2\theta_{13})$ sensitivity limit for the detectors installation scheduled scenario

Daya Bay

push the limit on

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



$$\nu_\mu \longrightarrow \nu_e$$

and related processes:

$$
\begin{array}{ccccc}
 & & \text{CP} & & \\
 & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\
\text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\
 & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\
 & & \text{CP} & &
\end{array}
$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Even in matter, a vestige of CPT exists:
Instead of switch matter to anti-matter, switch neutrino hierarchy !!!

$\nu_\mu \longrightarrow \nu_e$

$$| \; U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \; |^2$$

use unitarity to eliminate $U^*_{\mu 1} U_{e1}$ term:

$\nu_\mu \longrightarrow \nu_e$

$$| \; U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \; |^2$$

use unitarity to eliminate $U^*_{\mu 1} U_{e1}$ term:

$$P(\nu_\mu \to \nu_e) \quad = \quad |2 U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2 U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2$$

$\nu_\mu \longrightarrow \nu_e$

$$| \; U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \; |^2$$

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Atmospheric δm^2

$$2 U^*_{\mu 3} U_{e3} = \sin\theta_{23} \sin 2\theta_{13} e^{-i\delta}$$

$\nu_\mu \longrightarrow \nu_e$

$$| \, U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \, |^2$$

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Atmospheric δm^2 Solar δm^2

$$2 U^*_{\mu 3} U_{e3} = \sin\theta_{23} \sin 2\theta_{13} e^{-i\delta}$$

$$2 U^*_{\mu 2} U_{e2} \approx \cos\theta_{23} \sin 2\theta_{12}$$

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

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

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

CP violation !!!

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

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

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

CP violation !!!

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

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

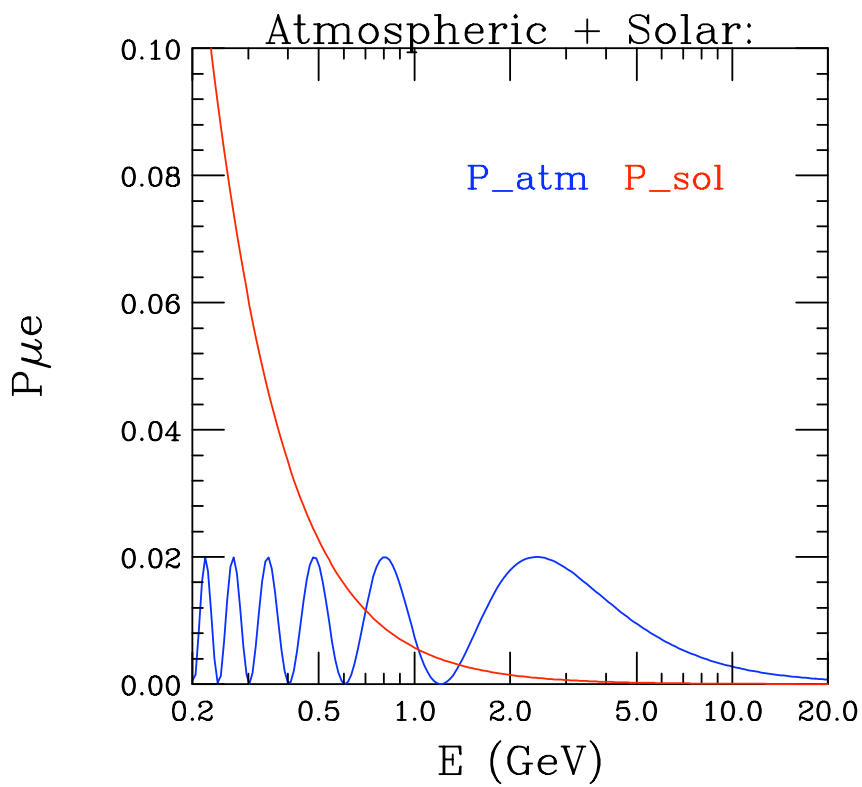
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}$$

only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta$$

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

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



x 3

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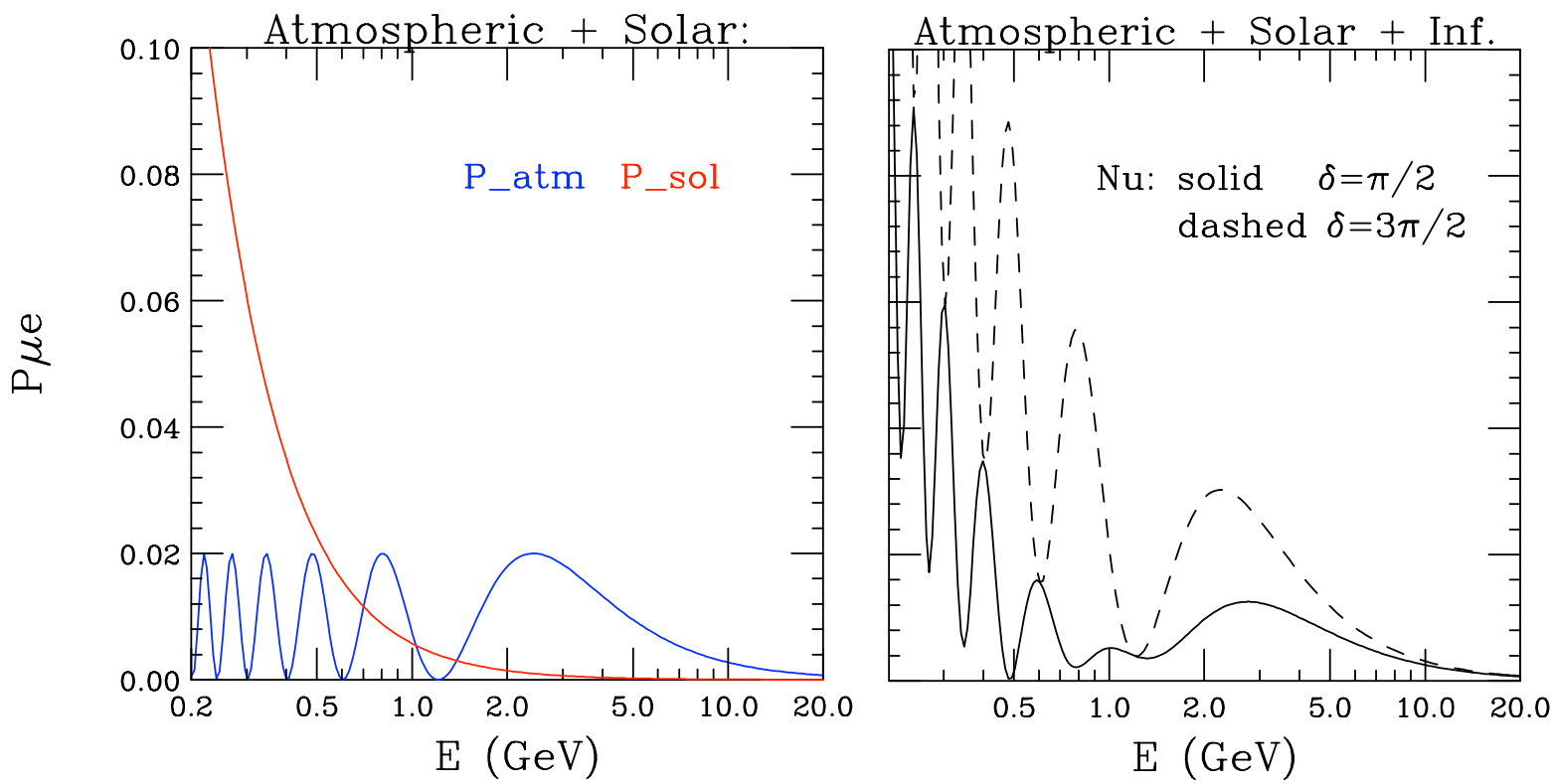
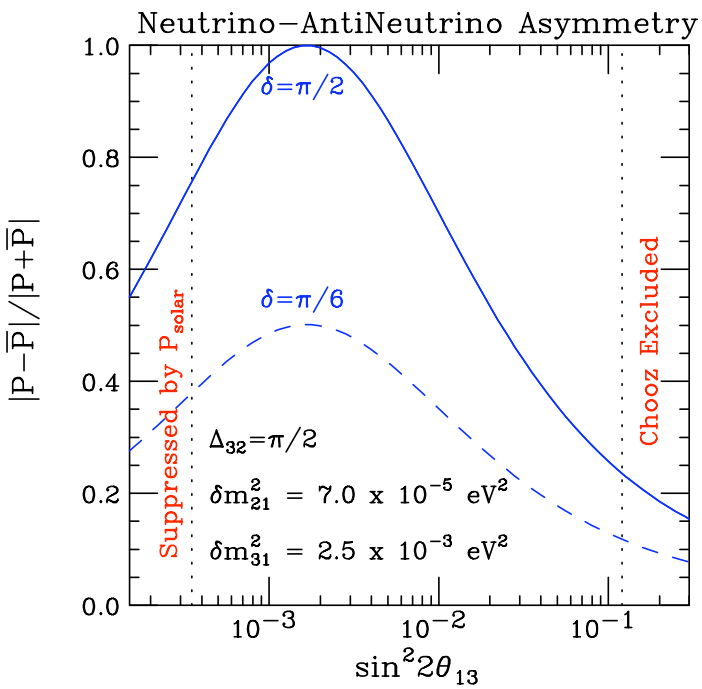


x 3

phase varies

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

Asymmetry Peaks:



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

=0.001

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

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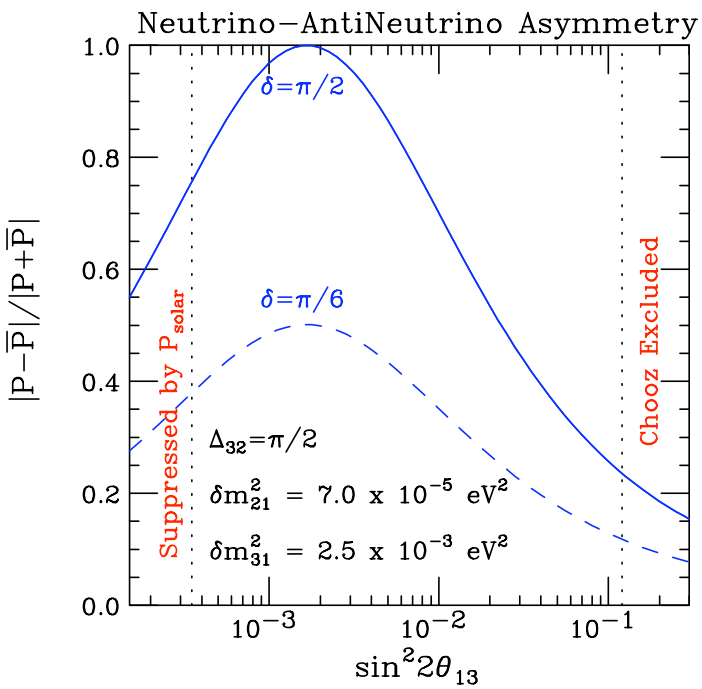
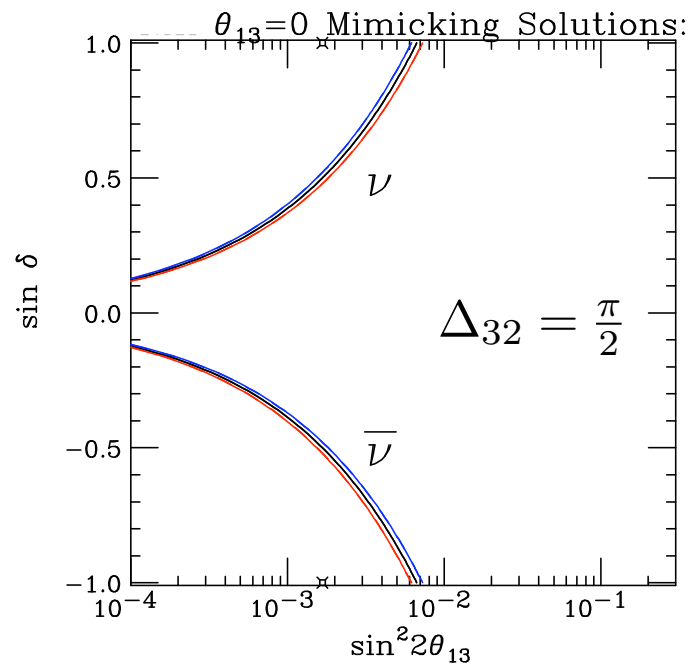


$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

Zero Mimicking Solutions:



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

$$P = P_{sol} \text{ =0.001}$$

Two Flavors: Vacuum and Uniform Matter

Vacuum: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \sin^2 \Delta_0$

Matter: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_N \sin^2 \Delta_N$

$\boxed{\text{BUT } \delta m_0^2 \sin 2\theta_0 = \delta m_N^2 \sin 2\theta_N}$ $\Rightarrow$ $\sin^2 2\theta_N = \left(\frac{\delta m_0^2}{\delta m_N^2}\right)^2 \sin^2 2\theta_0$

Therefore: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \left(\frac{\sin^2 \Delta_N}{\Delta_N^2}\right) \Delta_0^2$

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Therefore: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \left(\frac{\sin^2 \Delta_N}{\Delta_N^2}\right) \Delta_0^2$

$$\begin{aligned} \delta m_N^2 &= \sqrt{(\delta m_0^2 \cos 2\theta_0 - 2\sqrt{2} G_F N_e E)^2 + (\delta m_0^2 \sin 2\theta_0)^2} \\ &\approx \delta m_0^2 - 2\sqrt{2} G_F N_e E \qquad \text{for small } \theta_0. \end{aligned}$$

Two Flavors: Vacuum and Uniform Matter

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$$\Delta_N = \Delta - aL \text{ where } a = G_F N_e / \sqrt{2}$$

Therefore in Matter: $\boxed{P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \left(\frac{\sin \Delta_0 \mp aL}{\Delta_0 \mp aL}\right)^2 \Delta_0^2}$

$\nu_\mu \to \nu_e$

with MATTER

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

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

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

$\nu_\mu \to \nu_e$

with MATTER

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

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

in vac $\sin\Delta_{31}$

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

in vac $\sin\Delta_{21}$

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

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

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in vac $\sin\Delta_{31}$

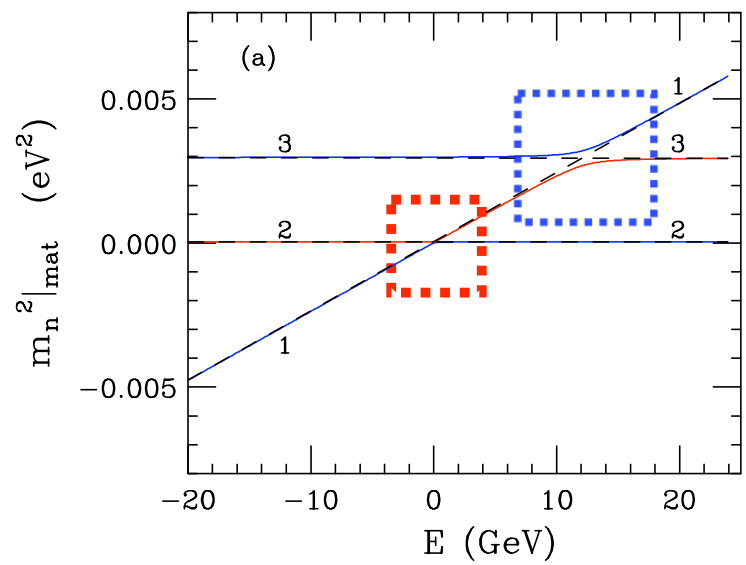
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

in vac $\sin\Delta_{21}$

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

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

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



In Matter:

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

Anti-Nu: Normal Inverted

dashes $\delta = \pi/2$

solid $\delta = 3\pi/2$

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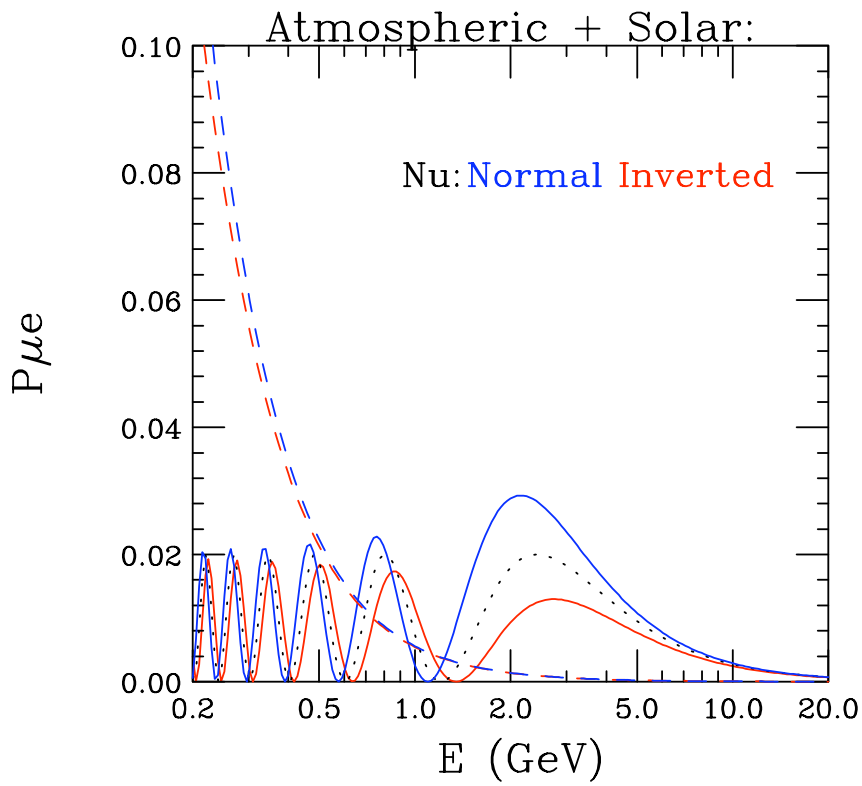

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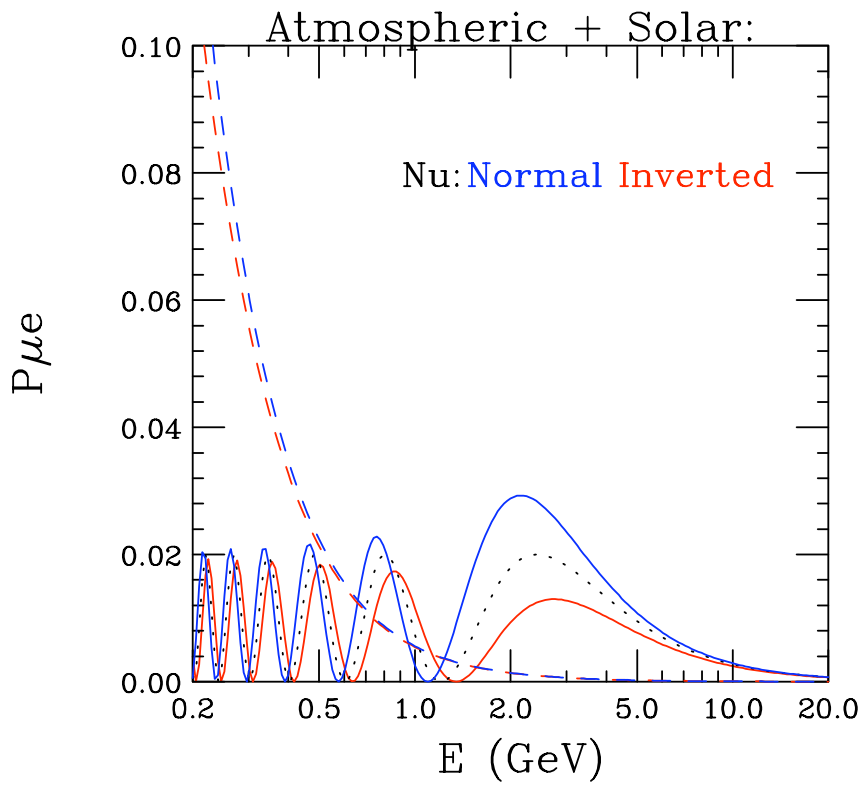
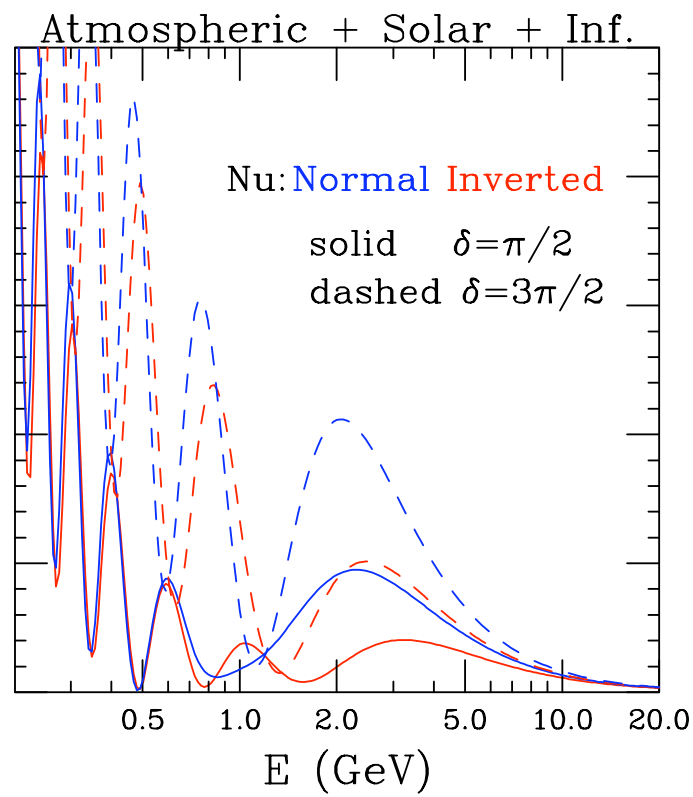


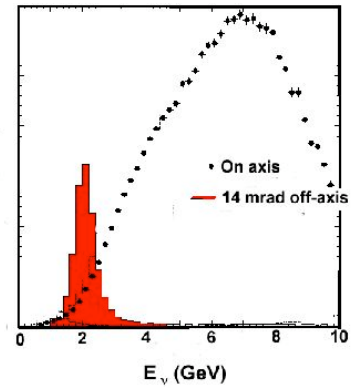


Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

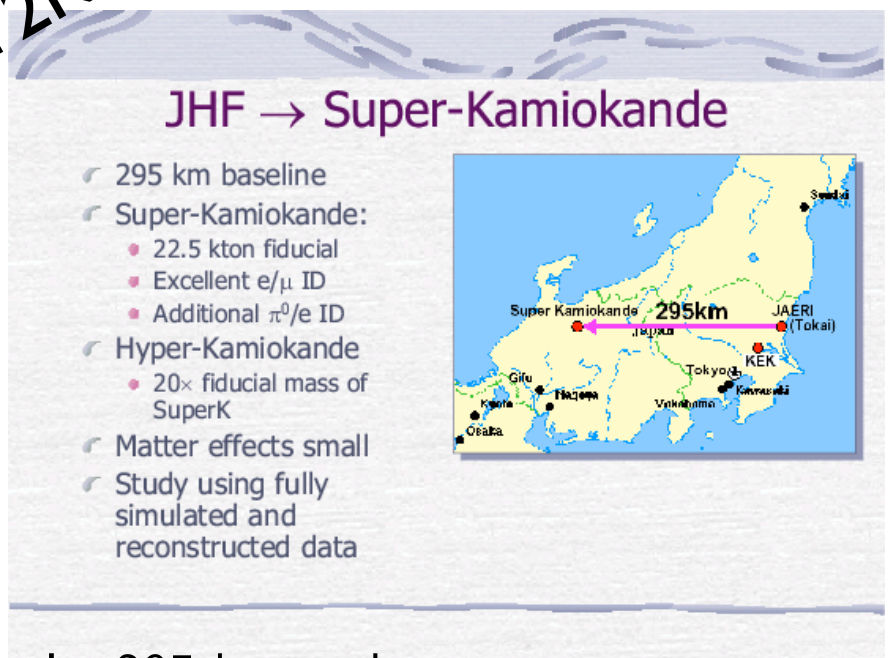
Counting Expts at First Osc. Max.

Off-Axis Beams

BNL 1994



T2K



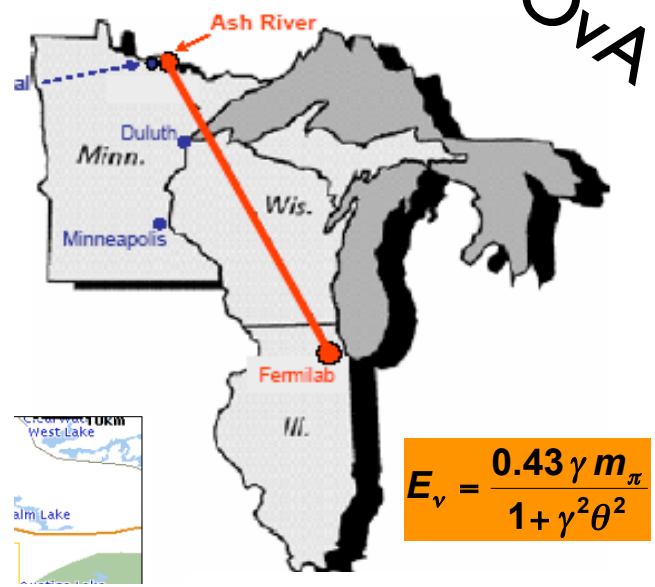
L=295 km and

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



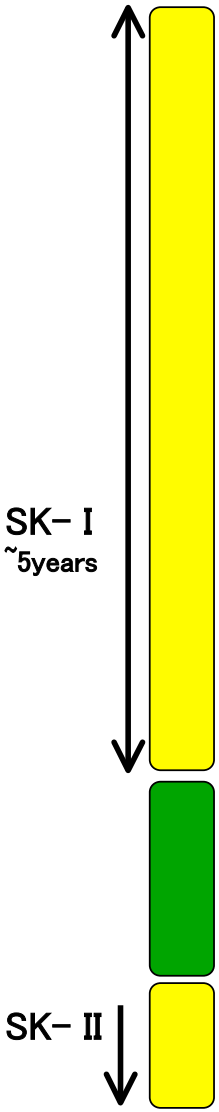
L=700 - 1000 km and

Energy near 2 GeV

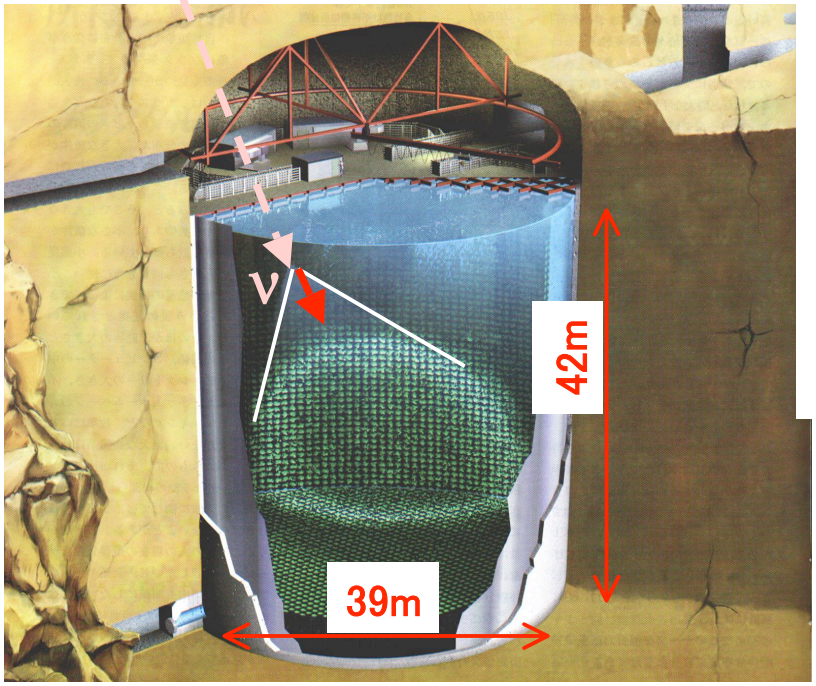
$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

Water Cherenkov detector



- 1996.4 Start data taking (SK- I)



- 2001.7 Stop data taking for detector upgrade
- 2001.11 Accident (6777 inner PMTs, 1100 outer PMTs were destroyed)
  partial reconstruction of the detector

- 2002.10 Resume data taking (SK- II) mostly for K2K (photocathode coverage of 20%, 7MeV

- 2005.10 Start full recovery work

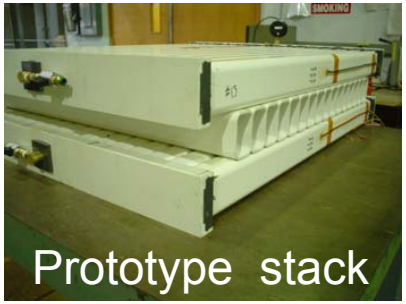
- 2700 w.e. overbuden
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- Photo cathode coverage: 40% of surface
- 1,885 anti-counter PMTs

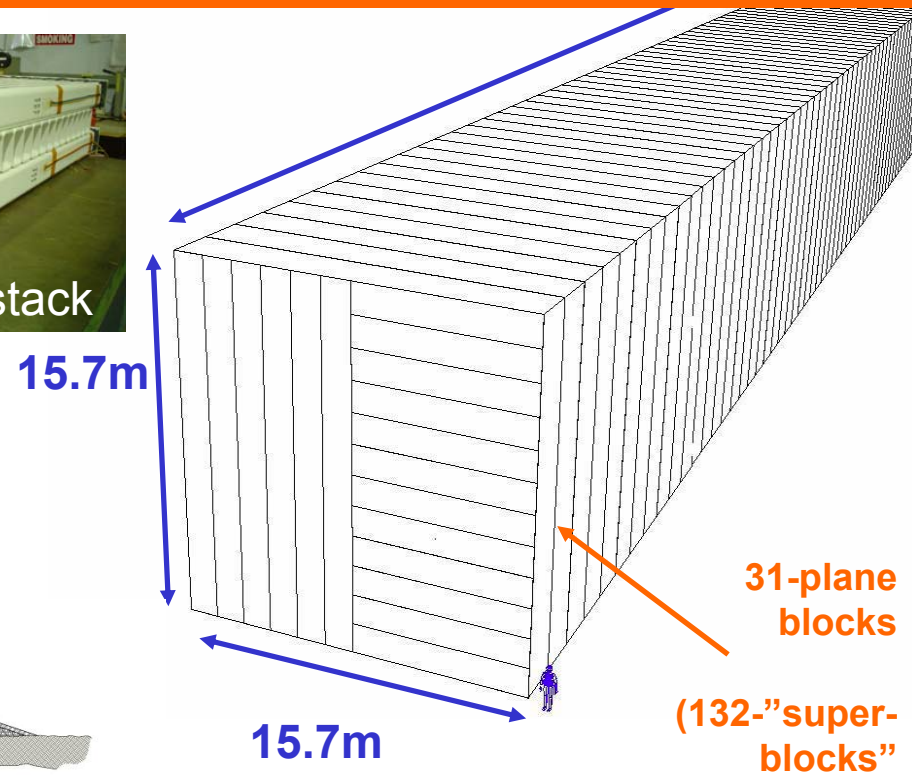
Acrylic + FRP vessel

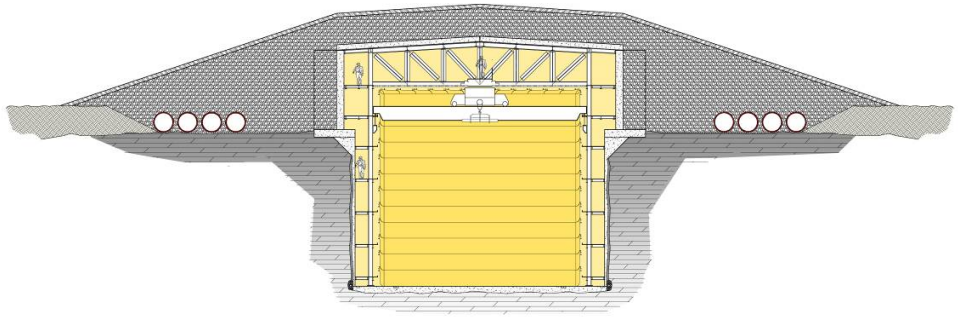
NOνA Far Detector we would like to build

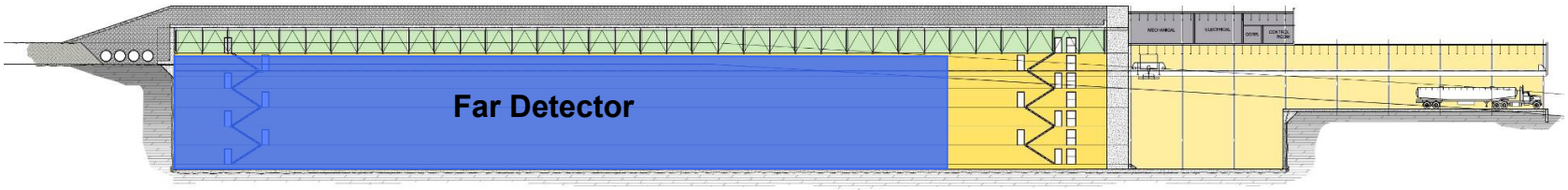
We will build as much of this as the funding will allow…

- TAD = Totally Active Detector
  - PVC = passive material
- mass N kT (N large)
  - ~80% scintillator
  - ~20% PVC extrusions
- Modular structure
  - 32 cells/extrusion
  - 12 extrusions/plane
  - 1984 planes
- Cell dimensions:
  - 3.9 cm x 6 cm x 15.7m
- U-shaped 0.7 mm WLS fiber into APD



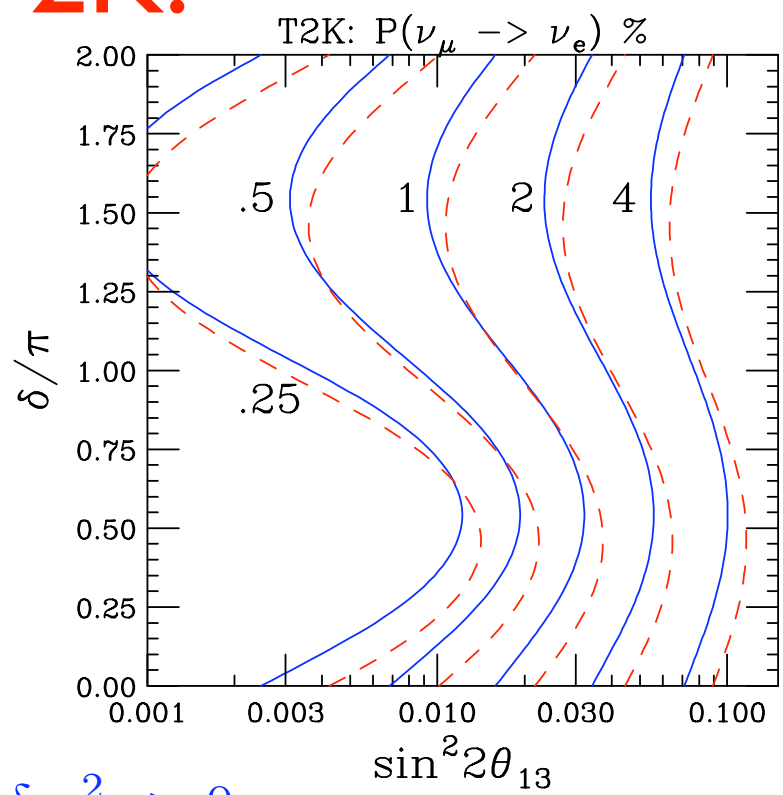






Sensitivity to $\sin^2 2\theta_{13}$

T2K:

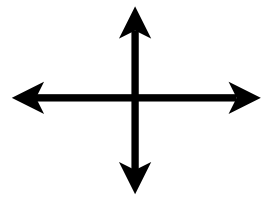


$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

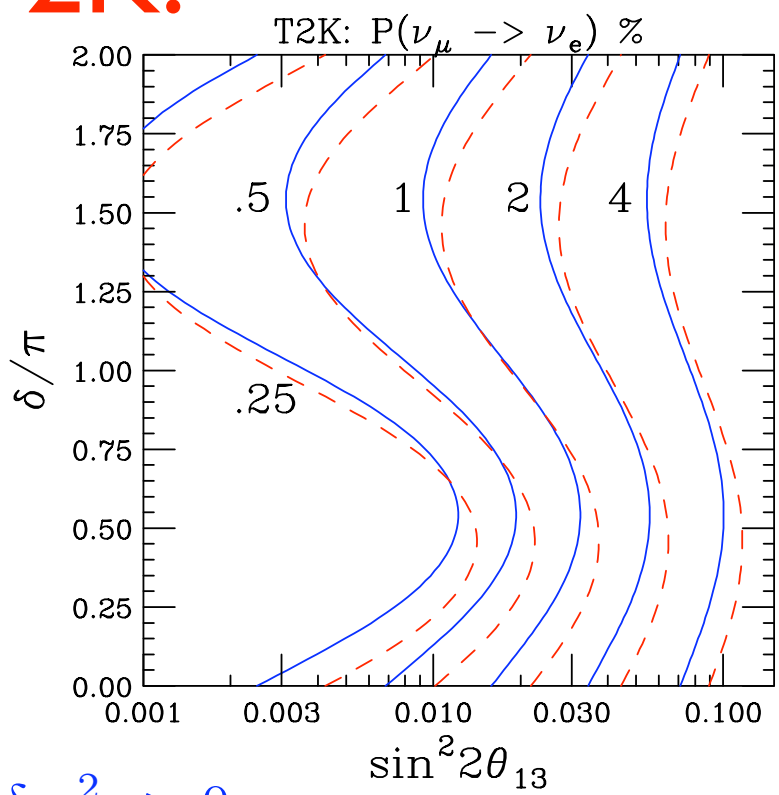
Beam 1%

VOM: $\Delta_{31} \neq \pi/2$



Matter Effect:

T2K:

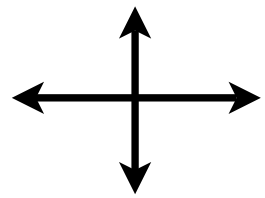


$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

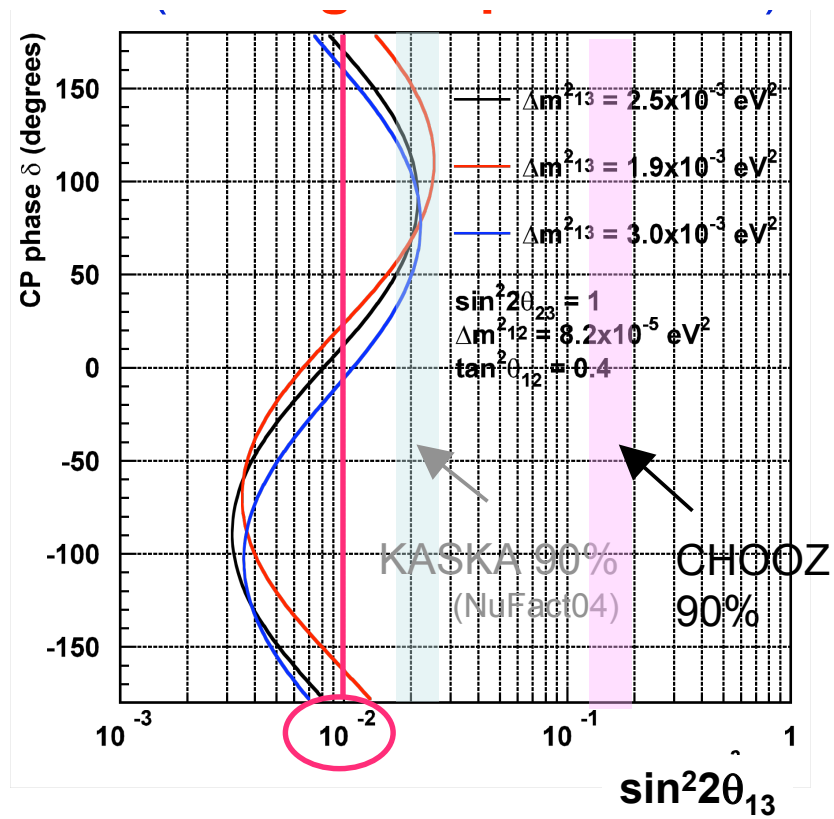
Beam 1%

VOM: $\Delta_{31} \neq \pi/2$



Matter Effect:

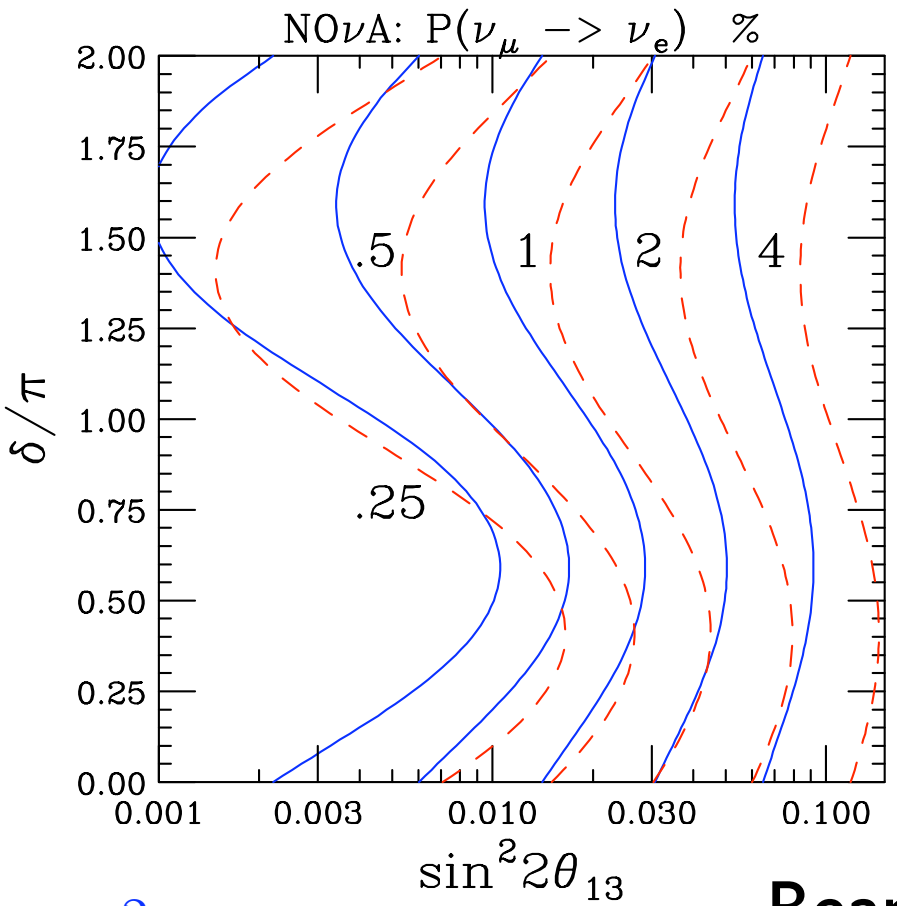
Aihara for T2K, P5 talk



Phase I

Sensitivity approx 0.5%

NOvA:

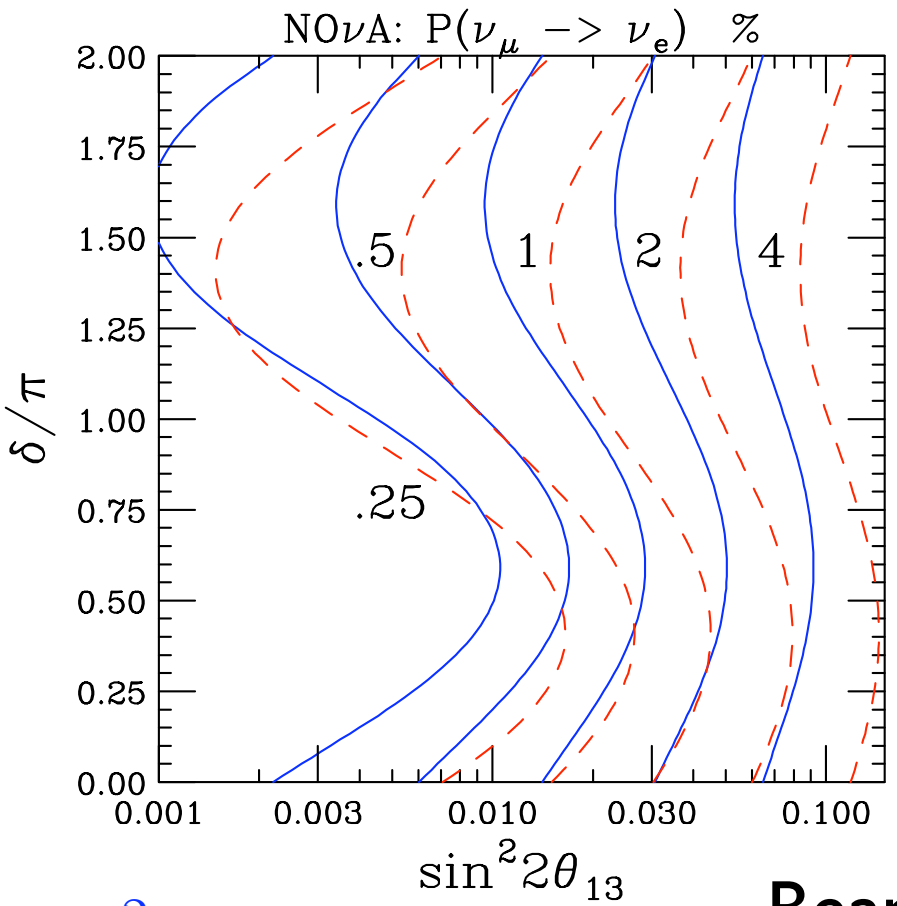


Beam 1%

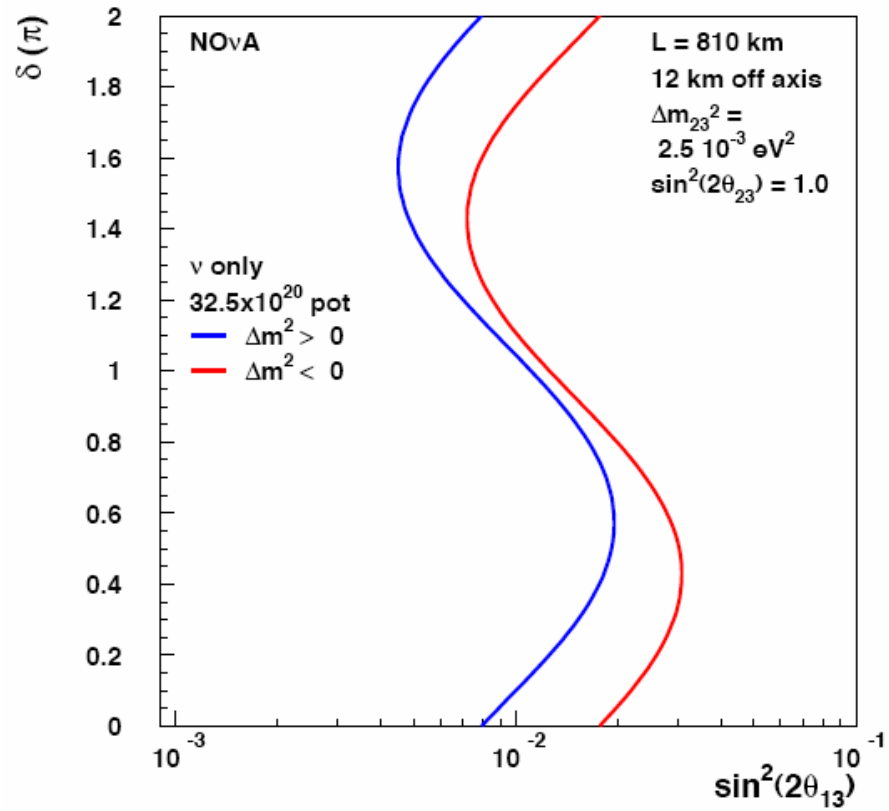
$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

NOvA:



NOvA @ NO-VE 2007



$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

Beam 1%

Phase I

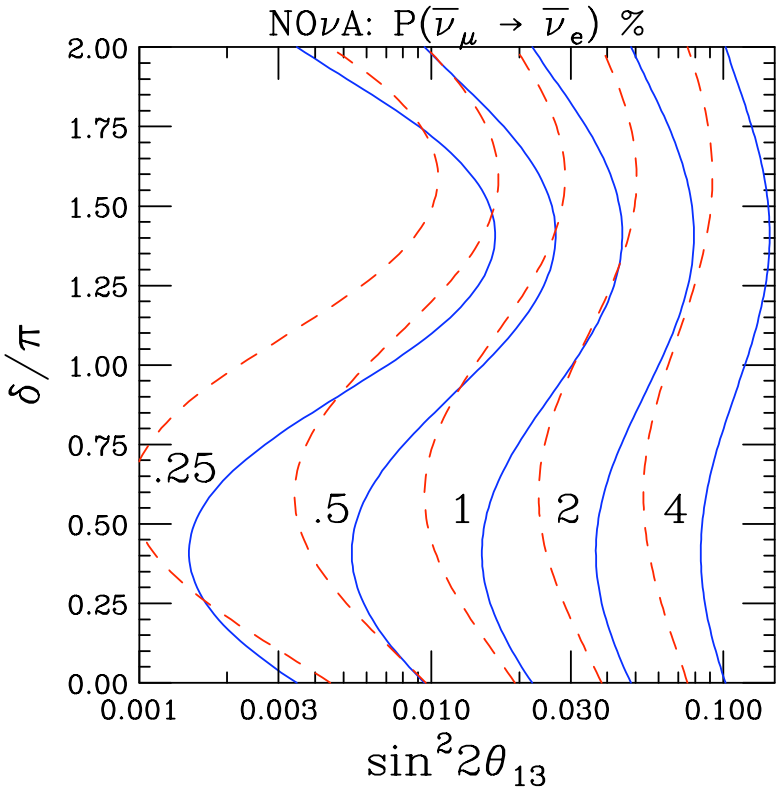
Sensitivity approx 0.5%

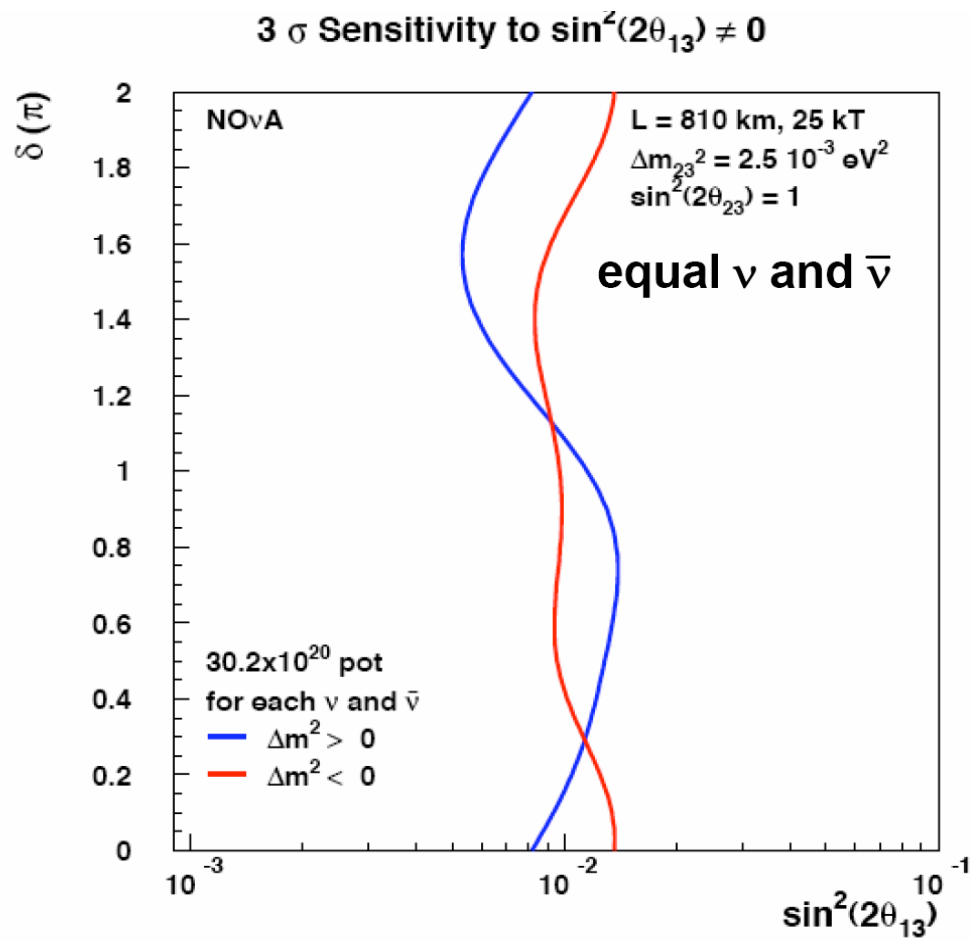
5 years with ν only run

NOvA:

$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

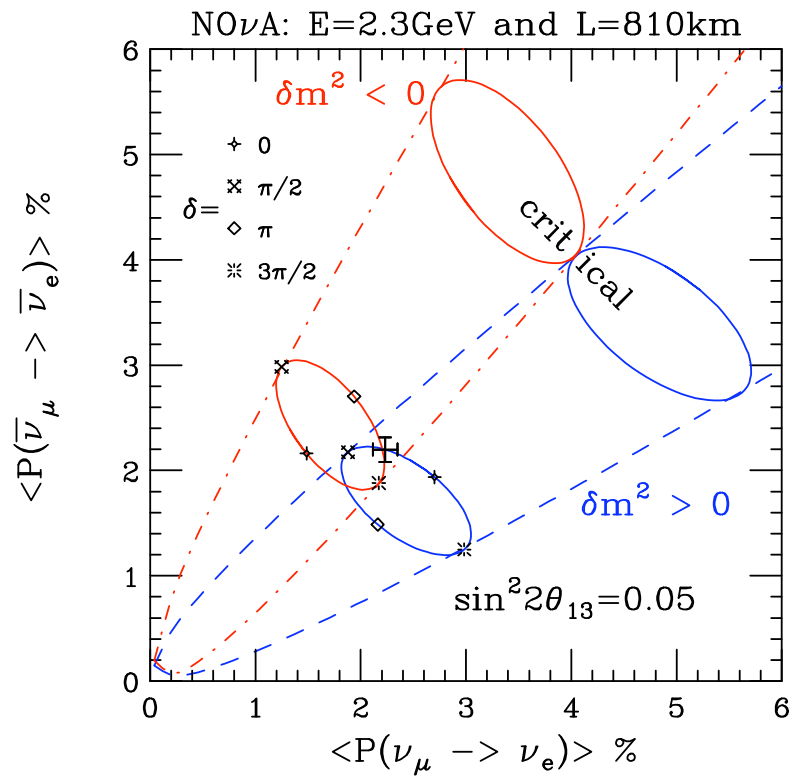




Beam >1%

Sensitivity to Hierarchy: $sign\ \delta m^2_{31}$

Neutrino v Anti-Neutrino One Expt.



in the overlap region

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

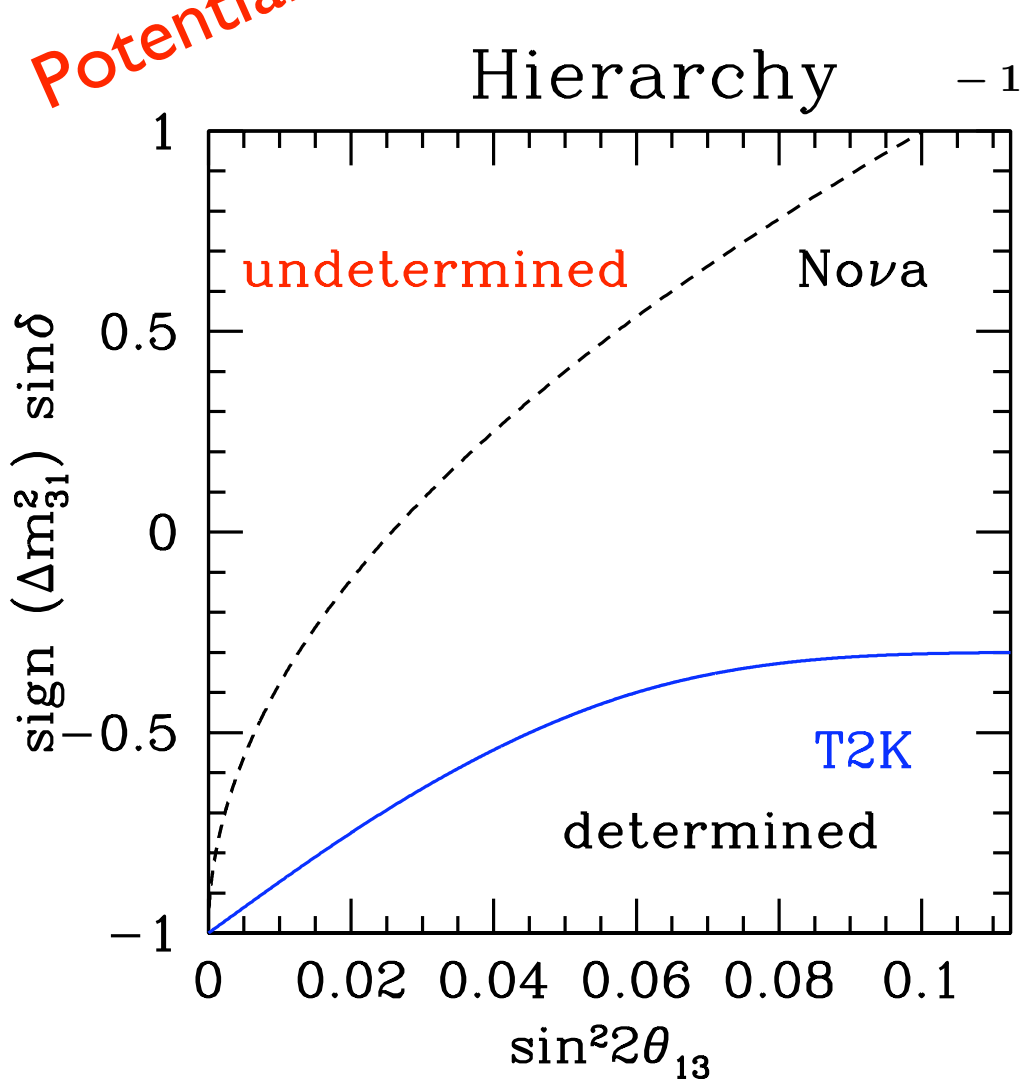
exact along diagonal --- approximately true throughout the overlap region!!!

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

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

O. Mena + SP
hep-ph/0408070

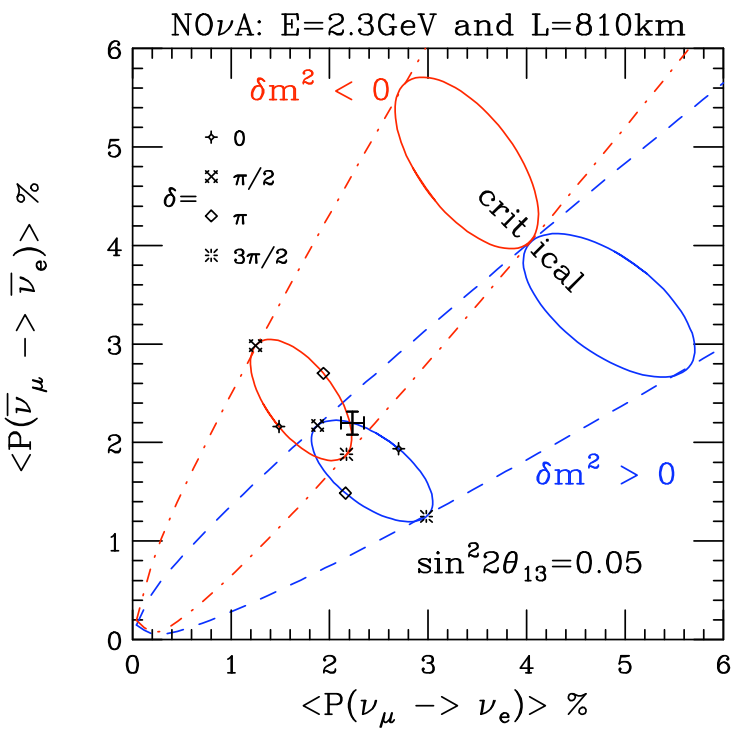
Potential



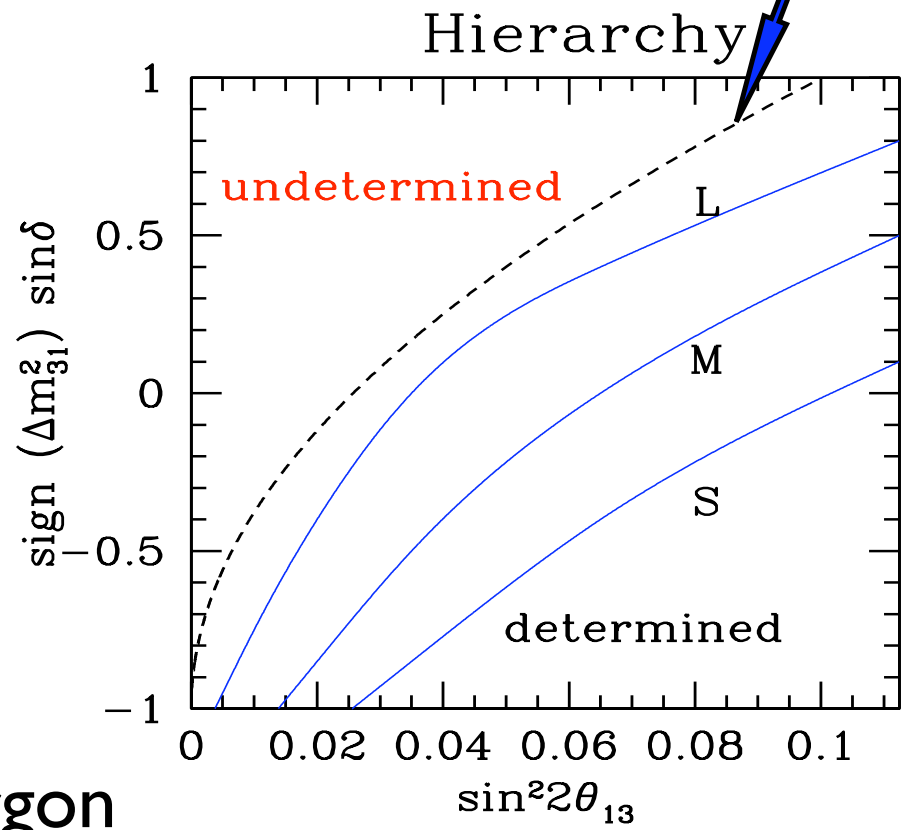
$$-1 + 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

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

NOvA:



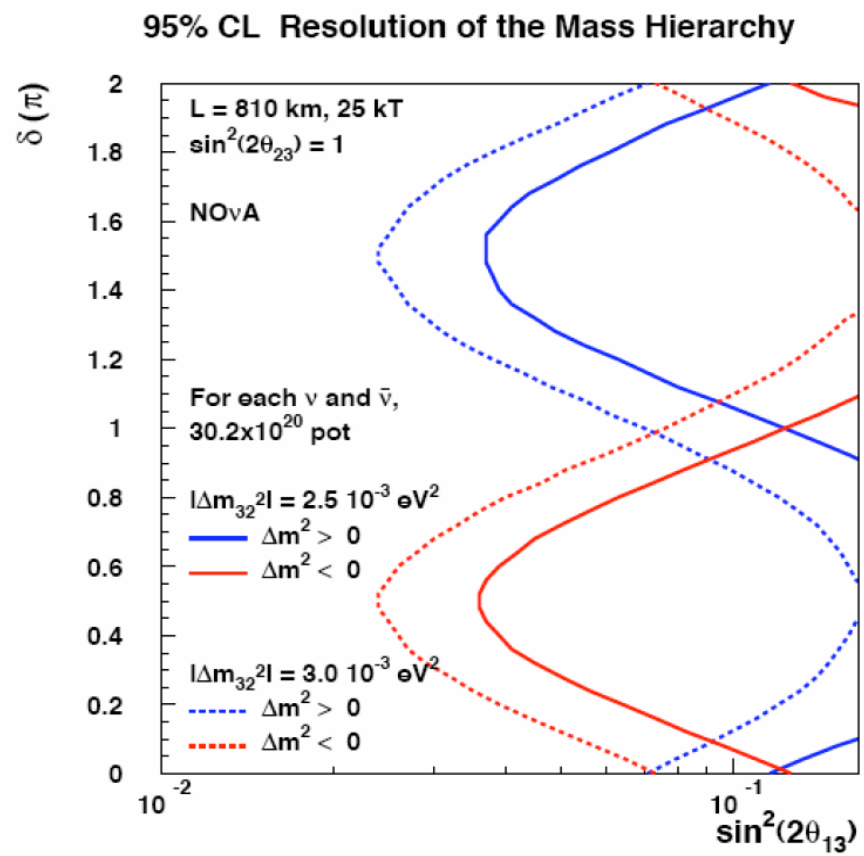
$$-1 + 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$



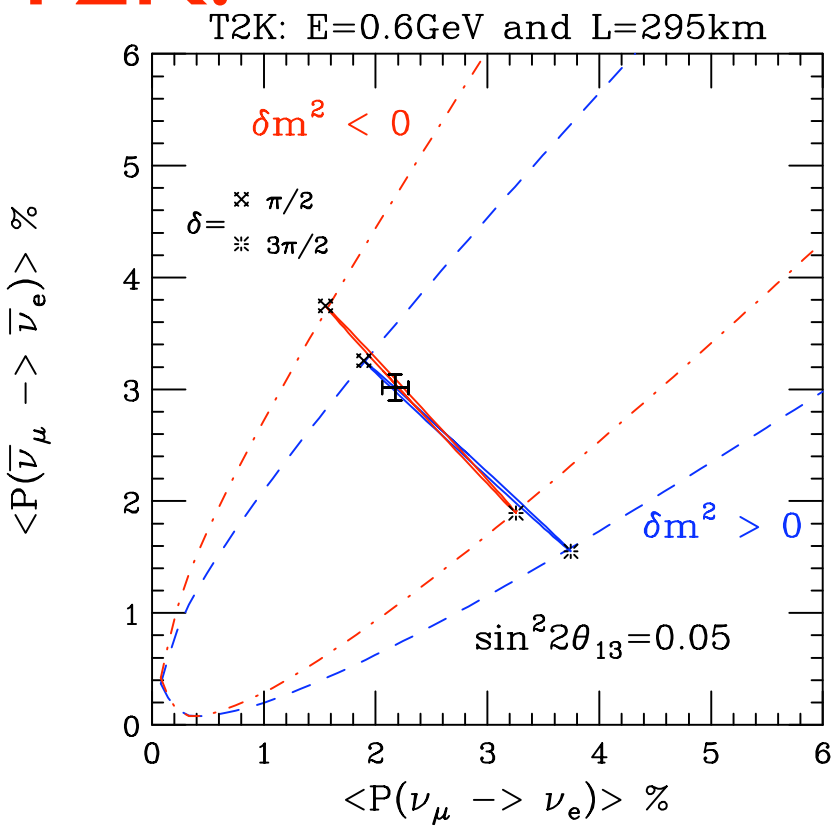
S: 4 +4 yrs

M (=5*S): Proton Driver

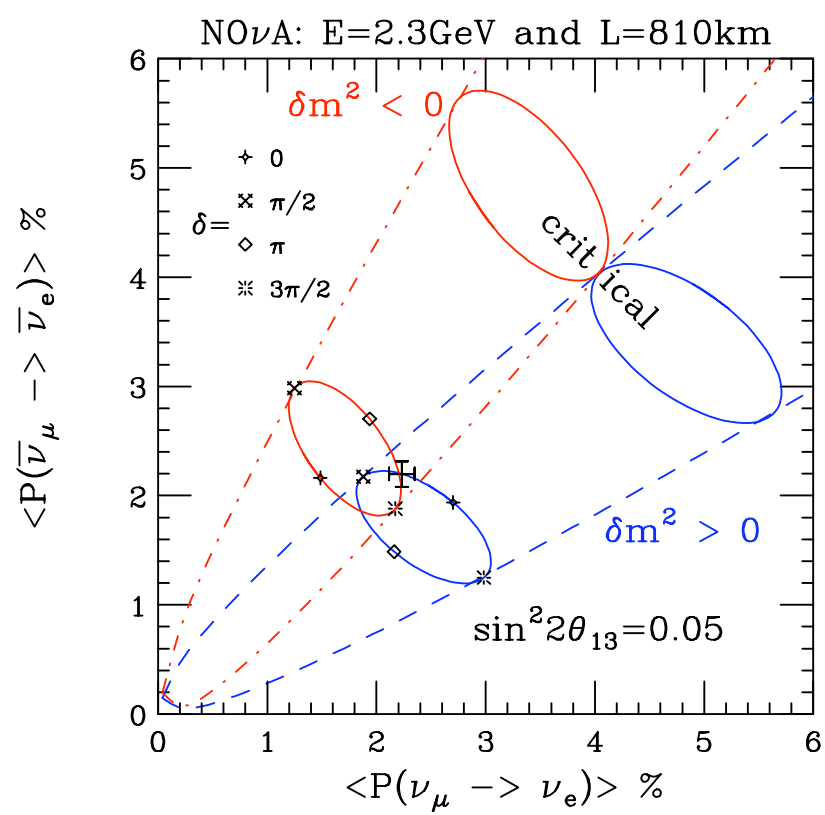
L (=5*M): PD + Liquid Argon

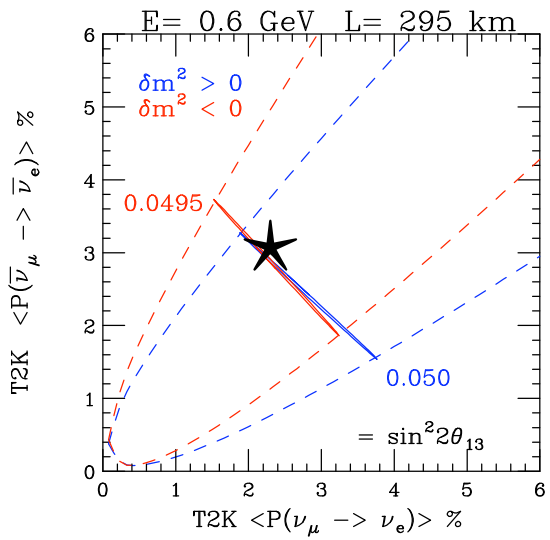

95% CL Resolution of the Mass Hierarchy
L = 810 km, 25 kT
sin²(2θ23) = 1
NOνA
For each ν and ν̄,
30.2x10²⁰ pot
|Δm32²| = 2.5 10⁻³ eV²
Δm² > 0
Δm² < 0
|Δm32²| = 3.0 10⁻³ eV²
Δm² > 0
Δm² < 0
δ (π)
sin²(2θ13)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10⁻²
10⁻¹

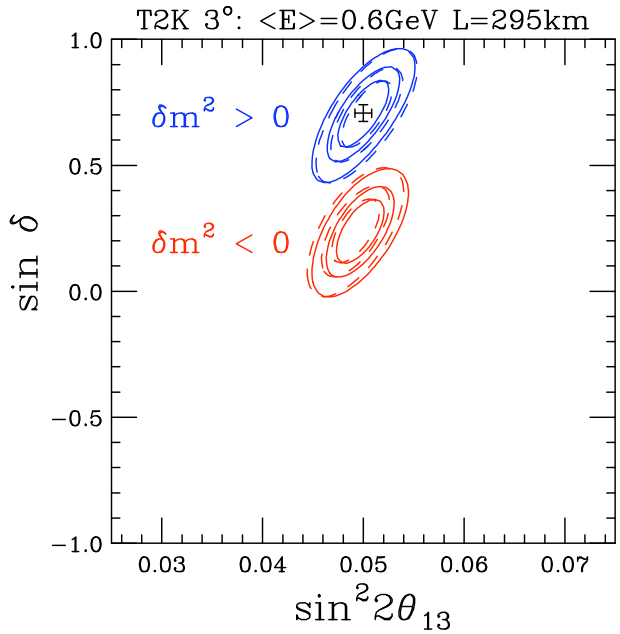
T2K:


T2K: E=0.6GeV and L=295km
δm² < 0
δm² > 0
δ=
π/2
3π/2
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %

NOvA:

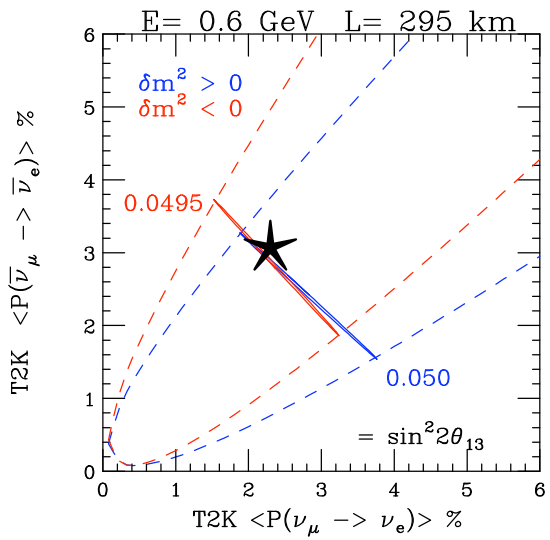

NOνA: E=2.3GeV and L=810km
δm² < 0
δm² > 0
δ=
0
π/2
π
3π/2
critical
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %

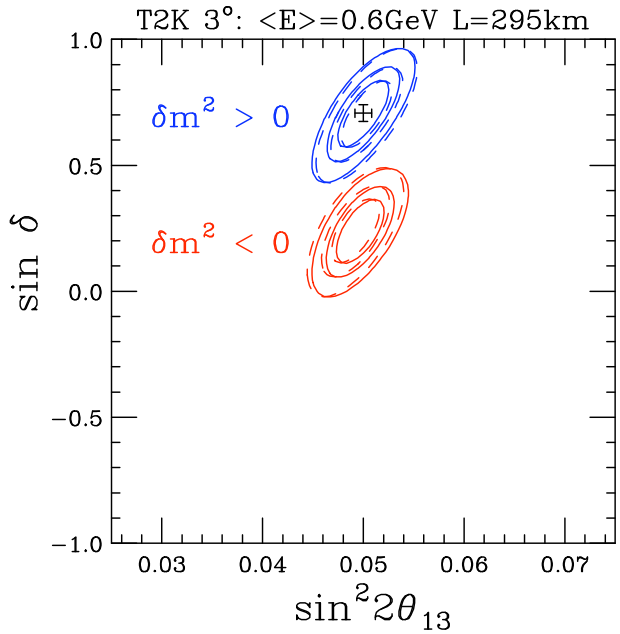




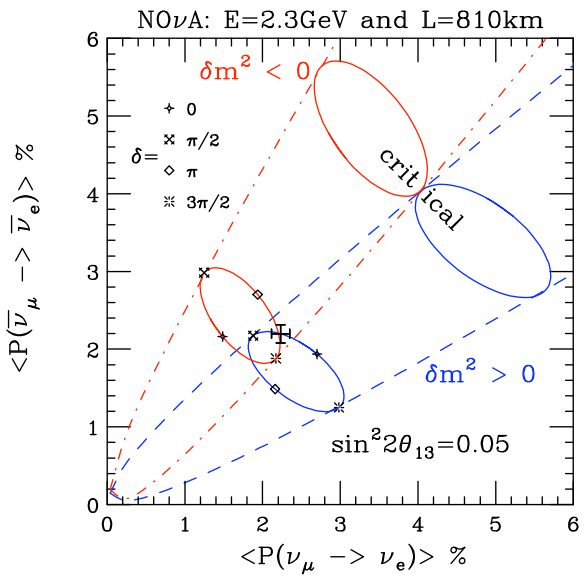
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

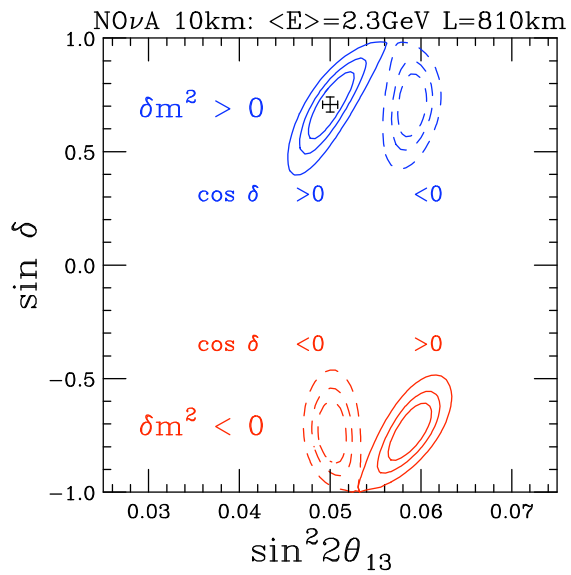
(ρL) for NOvA <u>three</u> times larger than (ρL) than T2K.





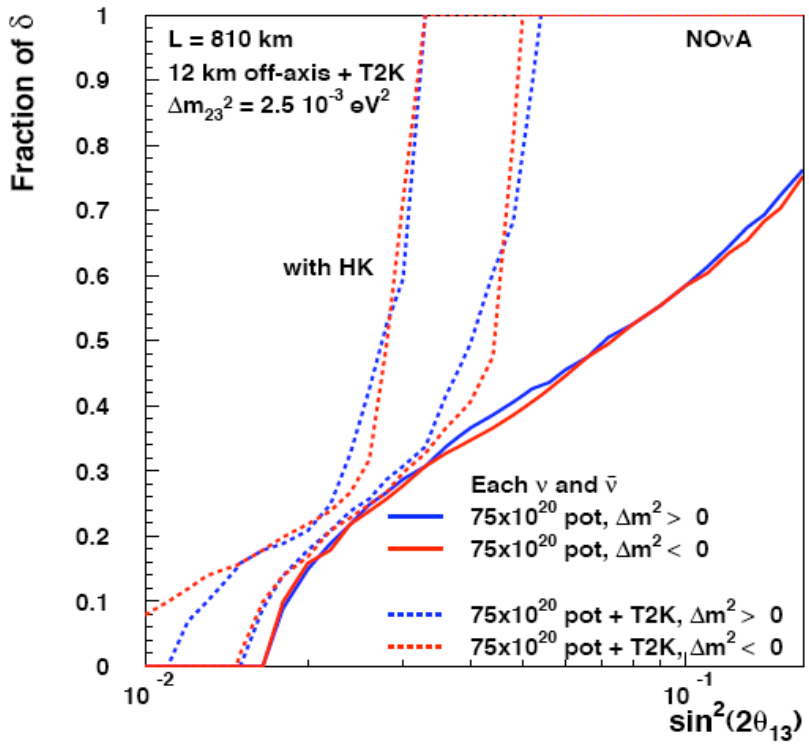
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$





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

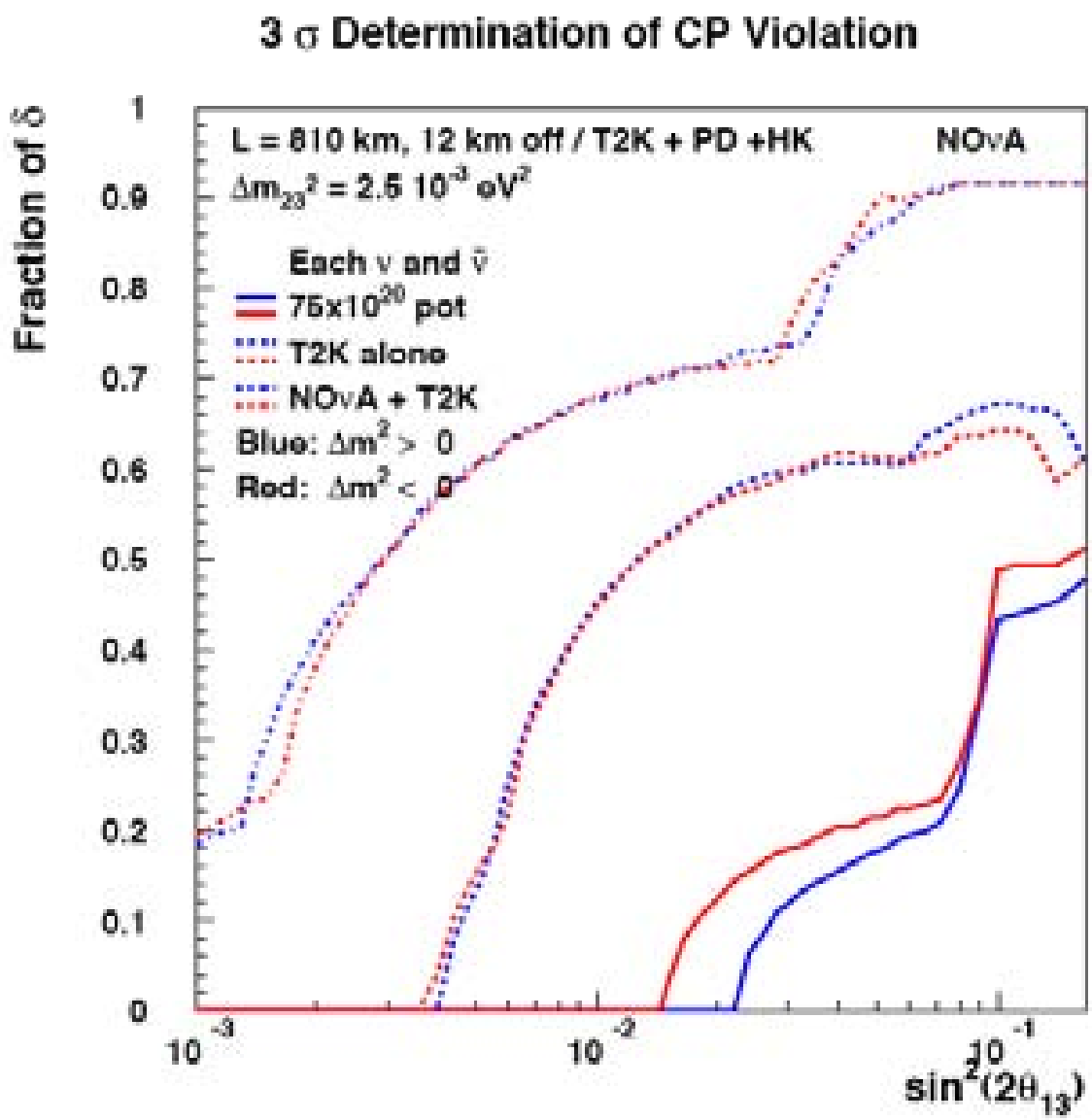
(ρL) for NOvA <u>three</u> times larger than (ρL) than T2K.



NOνA/PD with T2K Phase 2

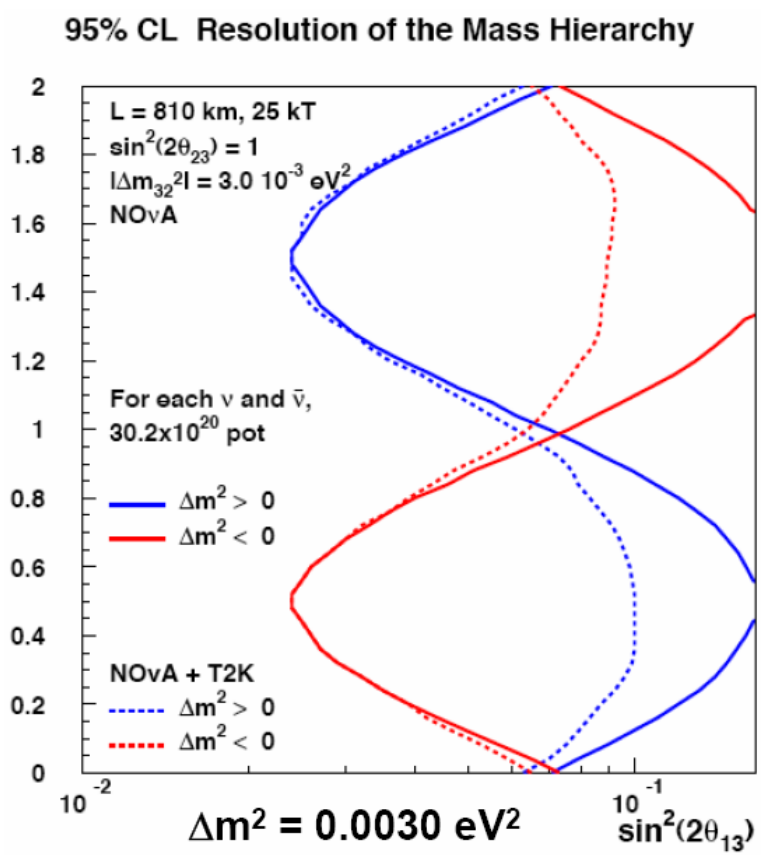
95% CL Resolution of the Mass Ordering

Sensitivity to CP violation: $\sin\delta$


3 σ Determination of CP Violation
L = 810 km, 12 km off / T2K + PD +HK
NOνA
Δm23² = 2.5 10⁻³ eV²
Each ν and ν̄
75x10²⁰ pot
T2K alone
NOνA + T2K
Blue: Δm² > 0
Red: Δm² < 0
Fraction of δ
sin²(2θ13)

NOvA + T2K(nu):

NOvA @ NO-VE 2007



Open Questions Strategy II

Stephen Parke
Fermilab