Open Questions Strategy II

Stephen Parke
Fermilab

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

- 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 !!!

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

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

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

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

only CPV

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

only CPV

$$\mp 2\sqrt{P_{atm}}\sqrt{P_{sol}}\sin\Delta_{32}\sin\delta = \mp J\ \sin\Delta_{31}\ \sin\Delta_{32}\ \sin\Delta_{21}$$

$$J = \sin 2\theta_{23}\ \sin 2\theta_{12}\ \sin 2\theta_{13}\ \underbrace{\cos\theta_{13}}_{\approx 1}$$

$\nu_\mu \to \nu_e$

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 $\sin\Delta_{21}$

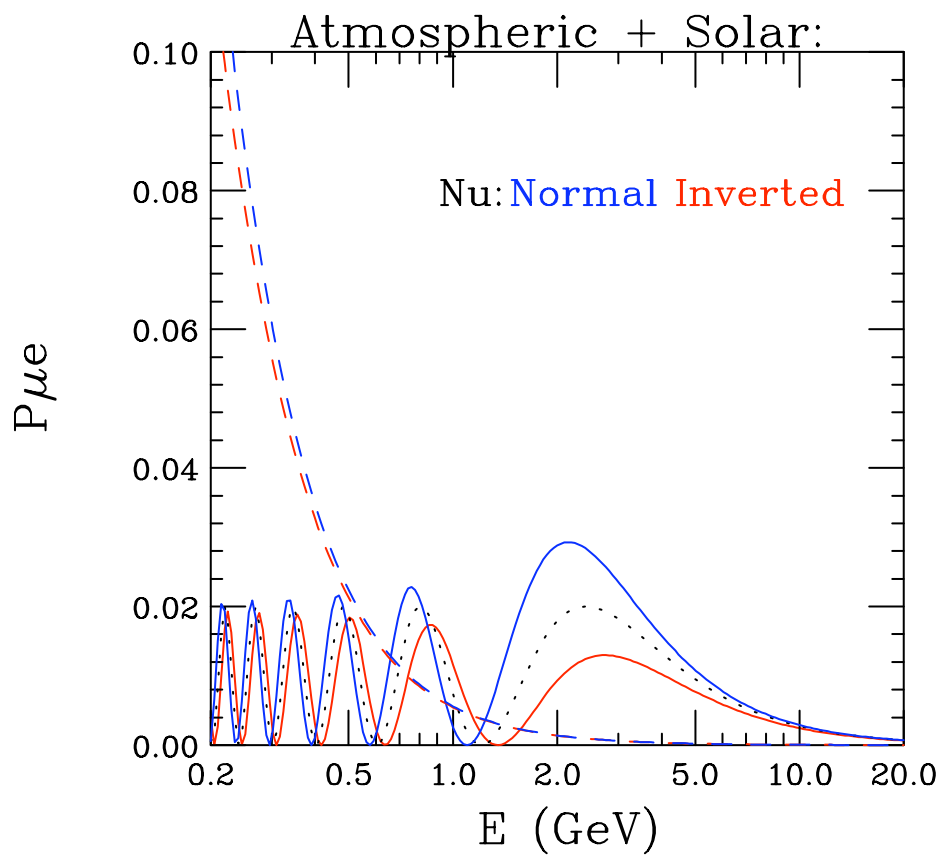
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

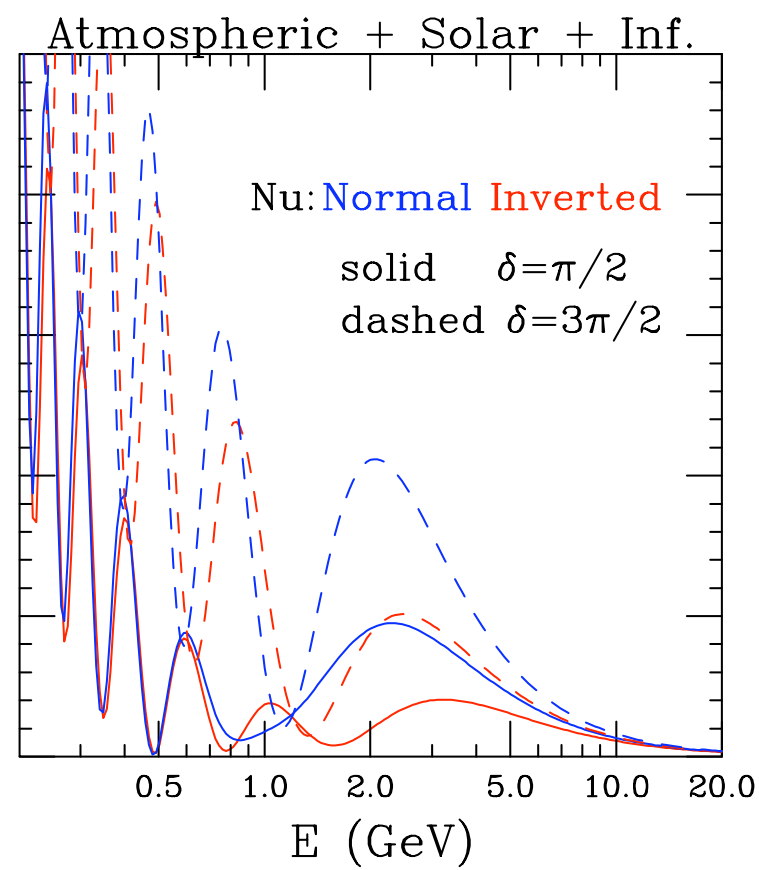
$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

In Matter:

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

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





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

$$P(\nu_\mu \to \nu_e)$$

$$\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}^2$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$+\cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left\{\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right\}\left\{\frac{\sin(aL)}{(aL)}\Delta_{21}\right\}$$

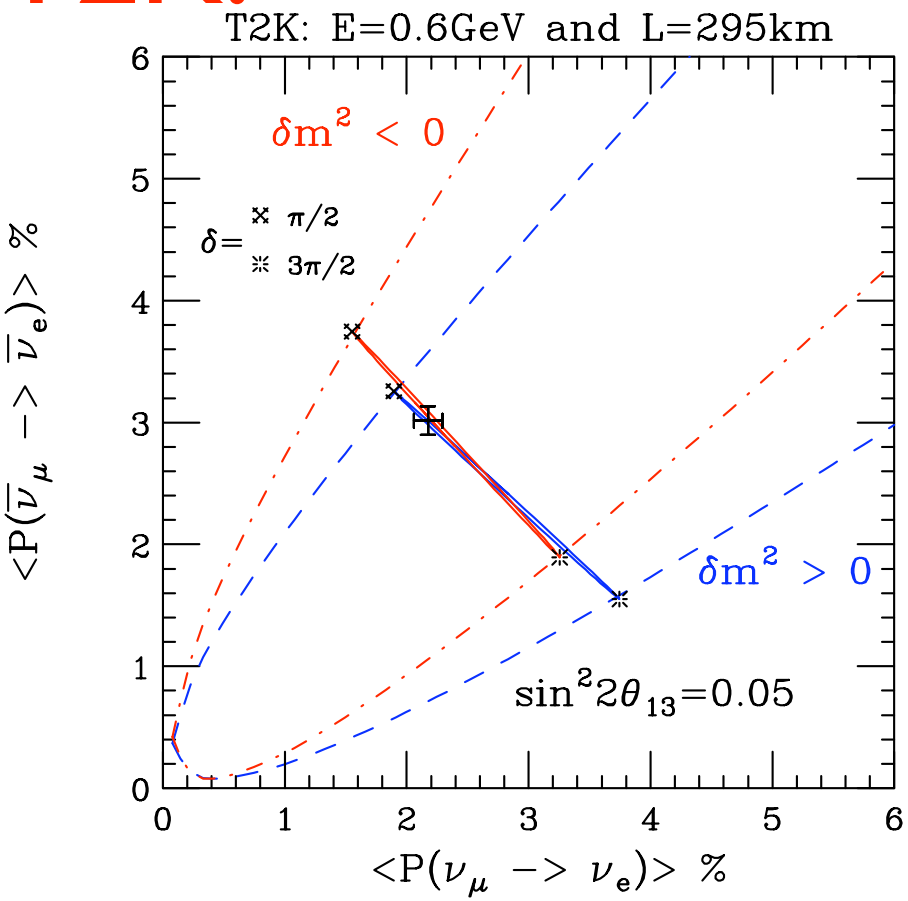
$$+\sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left\{\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right\}\left\{\frac{\sin(aL)}{(aL)}\Delta_{21}\right\}$$

for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ replace $\sin\delta \longrightarrow -\sin\delta$ and $a \longrightarrow -a$.

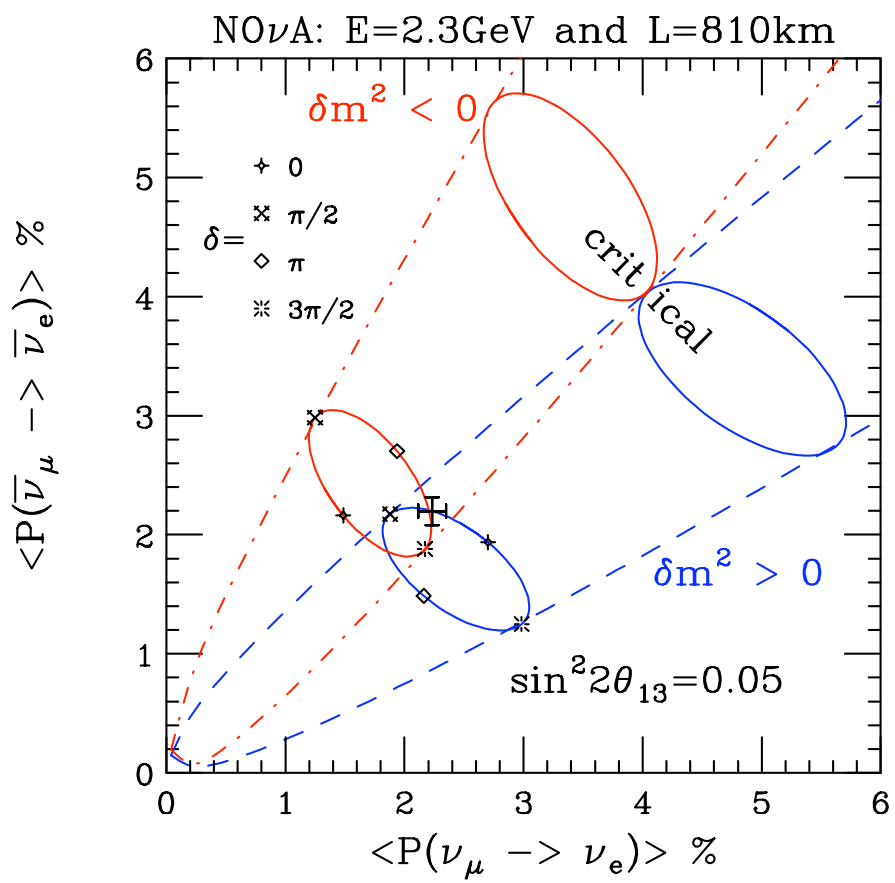
for $\nu_e \longrightarrow \nu_\mu$ replace $\sin\delta \longrightarrow -\sin\delta$.

for $\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$ replace $a \longrightarrow -a$.

T2K:

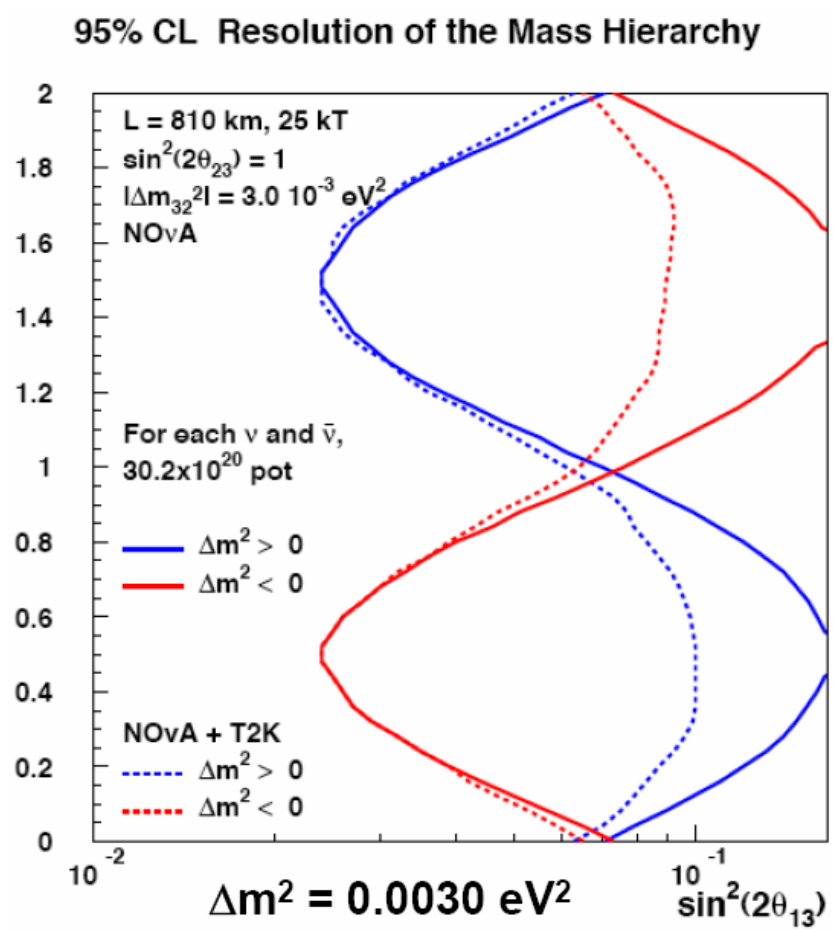

T2K: E=0.6GeV and L=295km
δm² < 0
δm² > 0
δ=
π/2
3π/2
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %

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)> %

NOvA + T2K(nu):

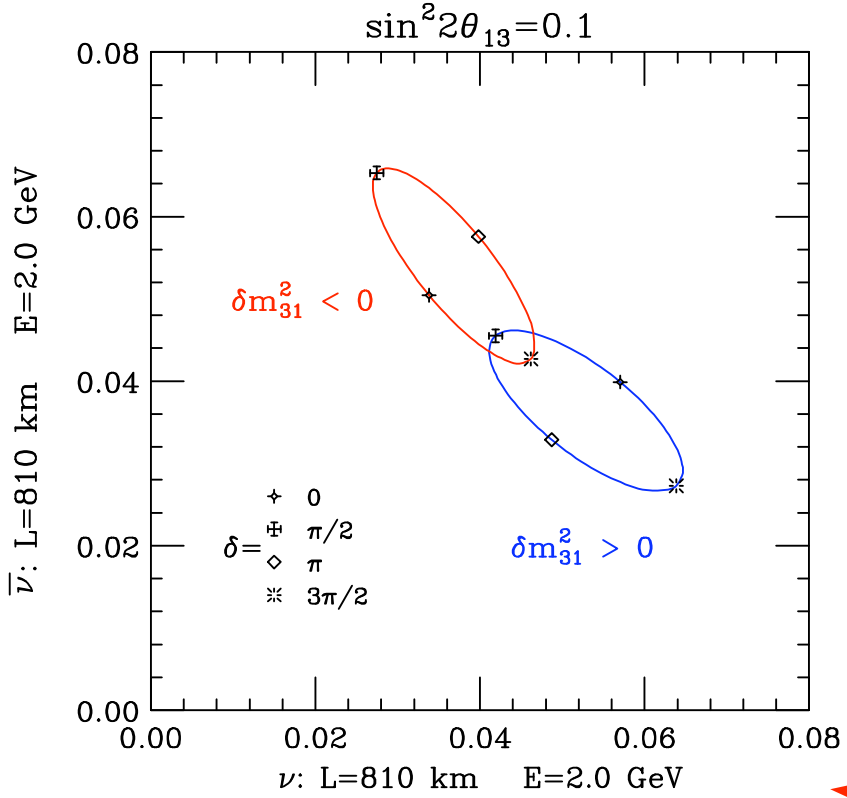
NOvA @ NO-VE 2007



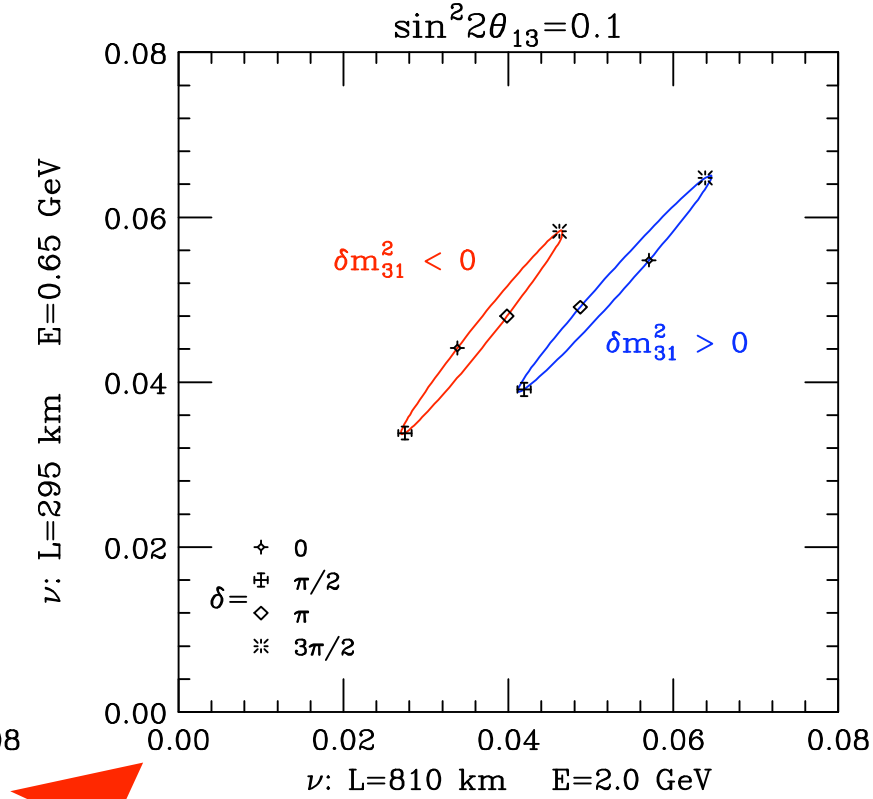
Half Neutrino Running + different <E>/L

Bi-Probability

nu-antinu v nu-nu



(a) Neutrino–Antineutrino



(b) Neutrino–Neutrino

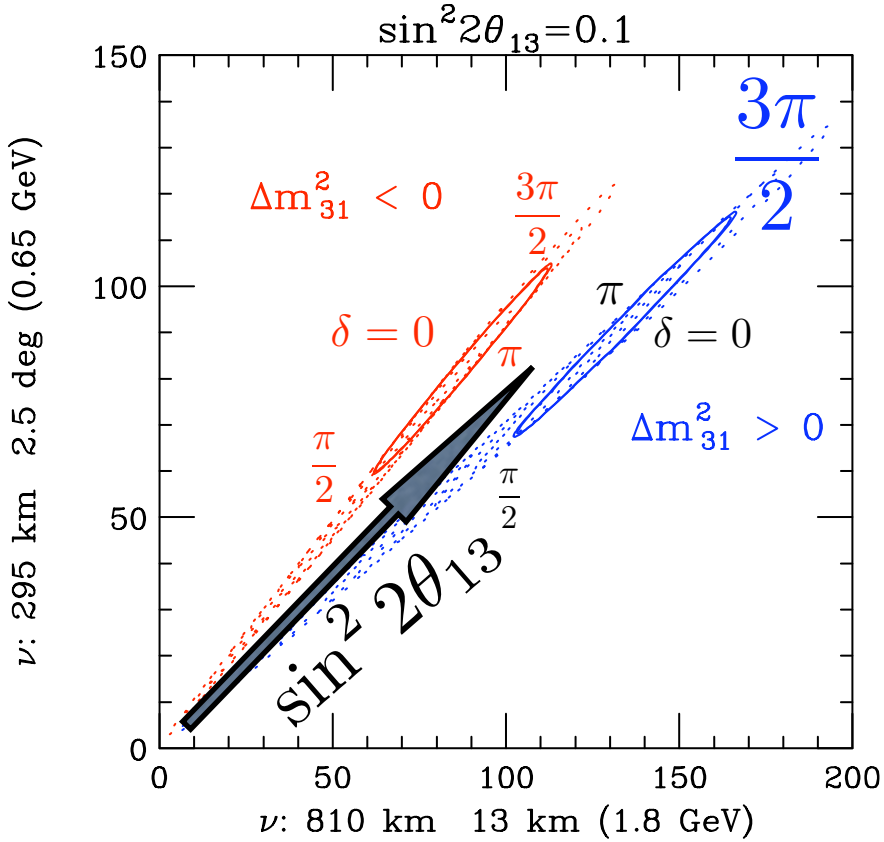
flat when

$$\Delta + \bar{\Delta} = \pi$$

$$P_N(\theta_{13}, \delta) = P_N(\theta_{13}, \delta') \quad \text{and} \quad P_F(\theta_{13}, \delta) = P_F(\theta_{13}, \delta')$$

flat when non-trivial solutions $\Delta_N = \Delta_F$,

same $\langle E \rangle / L$



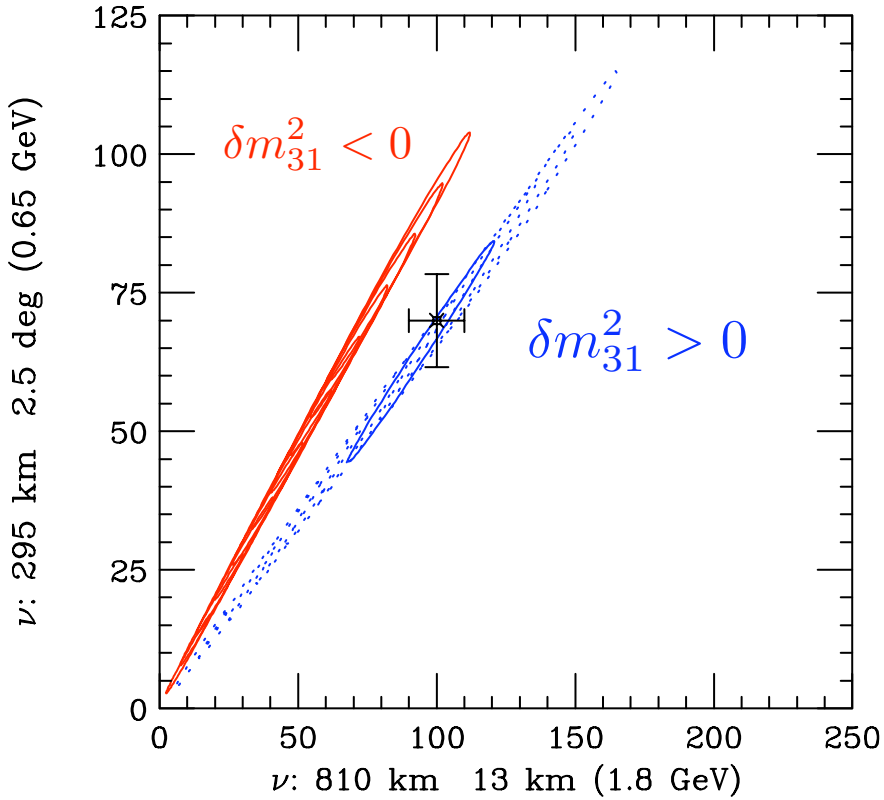
Chooz Bound : $\sin^2 2\theta_{13} = 0.12$

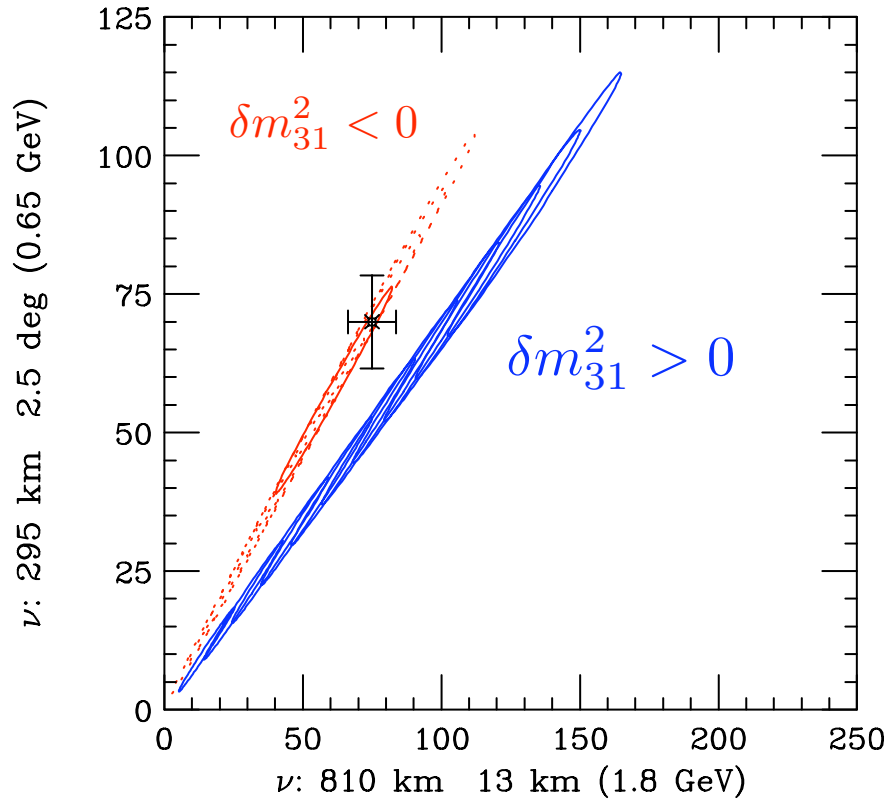
Horiz. separation matter effect for NOvA.

Vert. separation matter effect for T2K.

$$\sin^2 2\theta_{13} = 0.07$$

T2K





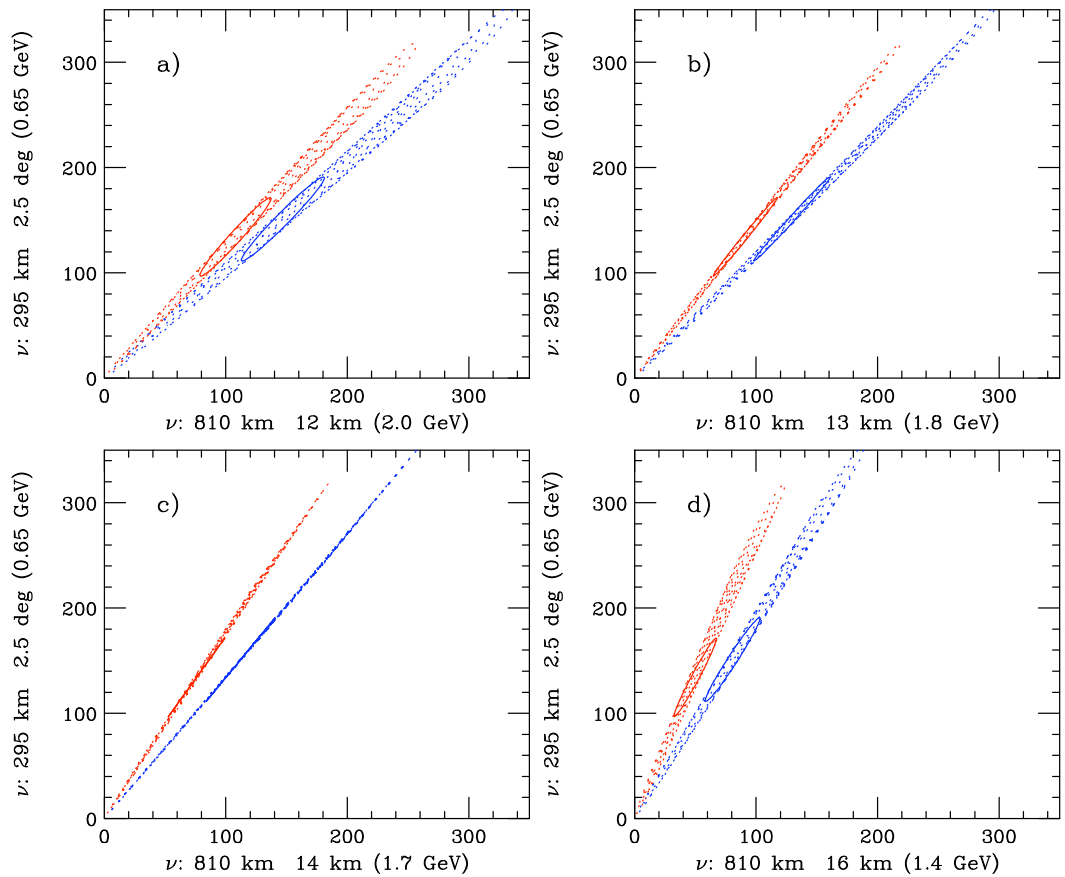
NOvA

NOvA + T2K Neutrinos Only:

Bi-Event Plots:

5 yrs

T2K:
750kW
22.5kton
eff=70%



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

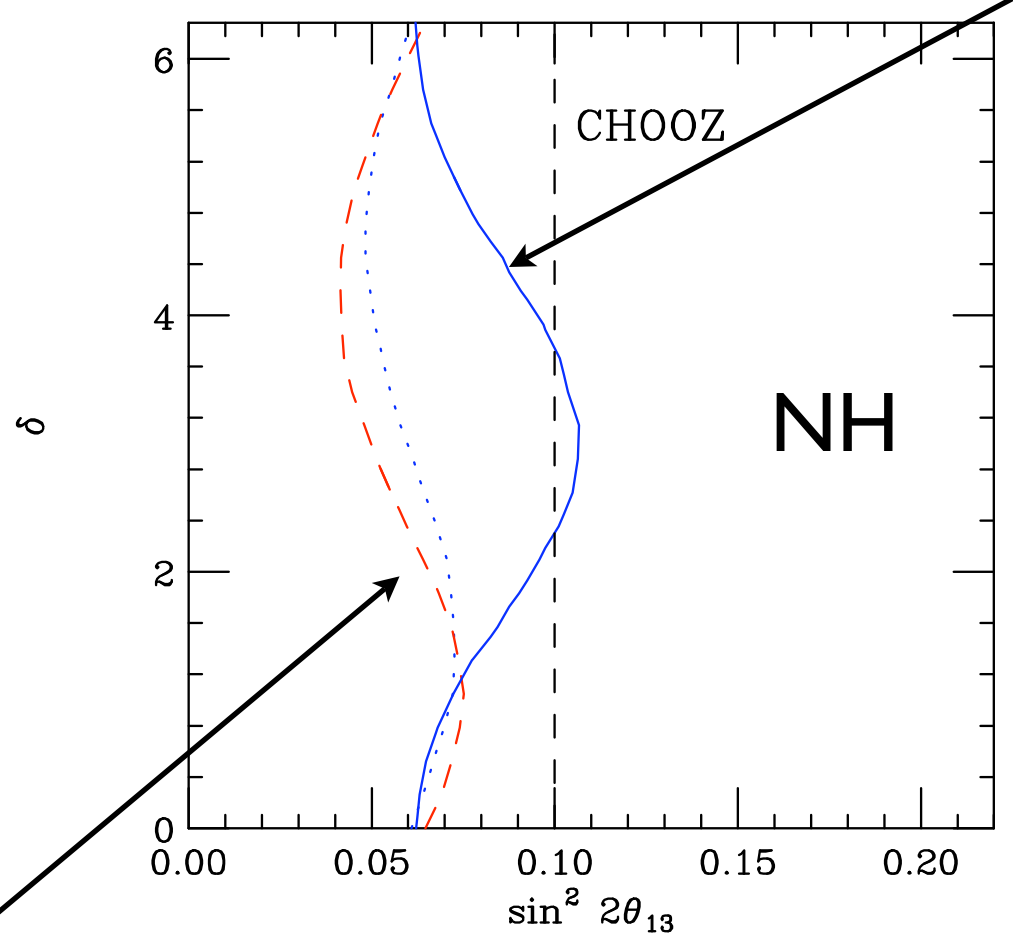
$\delta m^2_{31} < 0$

15% stat.
hit per step!

NOvA: 400kW
30kton eff=24%

Hierarchy Determination using 2 dof: 90% CL

2.5 deg & 12 km



(b) $\Delta m^2_{31} = +3.0 \times 10^{-3}$ eV^2

2.5 deg & 14 km

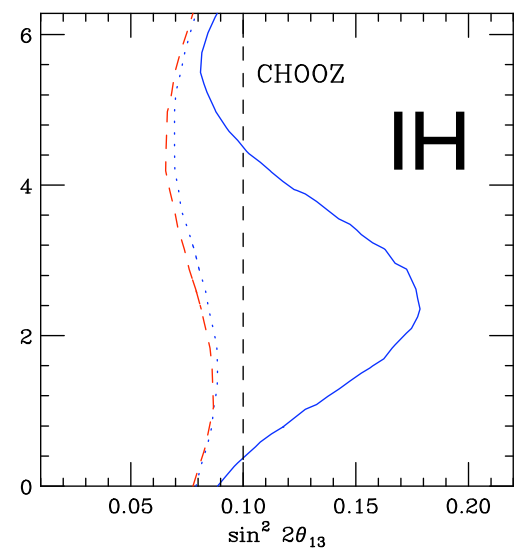
2.0 deg & 12 km

WHY 2 dof ????

90% at 2 dof

approx

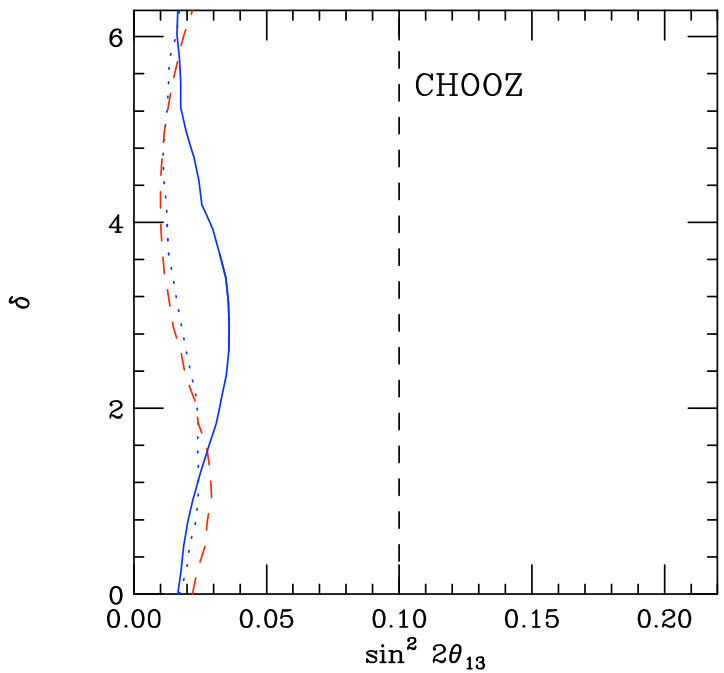
97% at 1 dof



(b) $\Delta m^2_{31} = -3.0 \times 10^{-3}$ eV^2

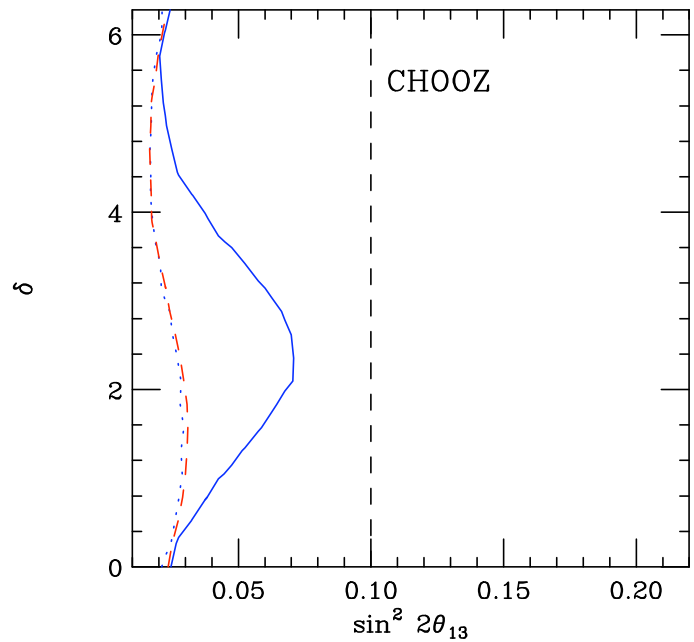
5 times Statistics !!!

NH



(b) $\Delta m^2_{31} = +3.0 \times 10^{-3}$ eV^2

IH

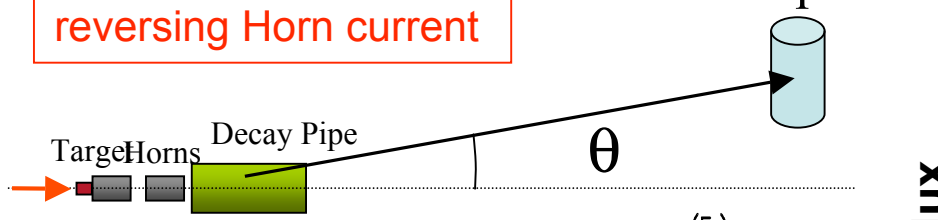


(b) $\Delta m^2_{31} = -3.0 \times 10^{-3}$ eV^2

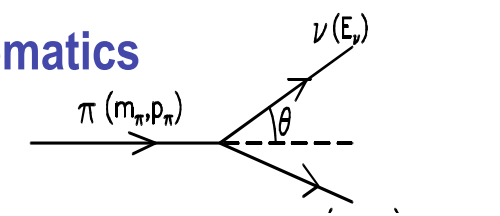
systematic errors ???

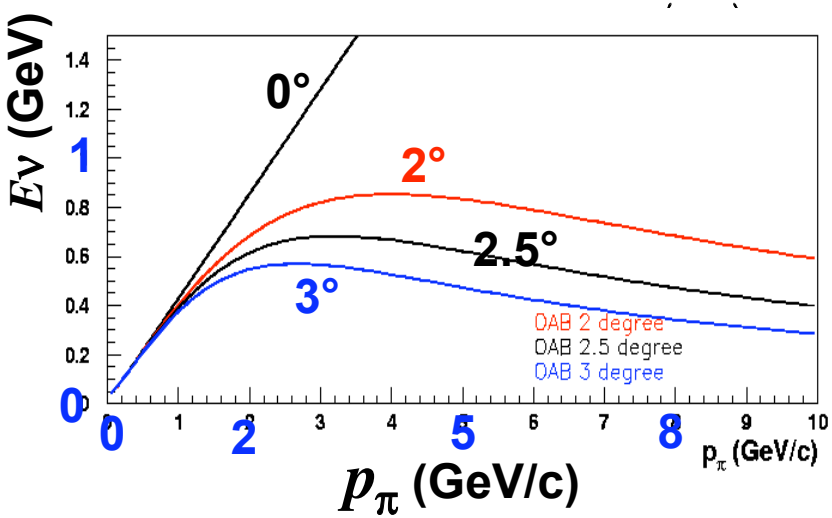
Narrow intense beam: Off-axis beam

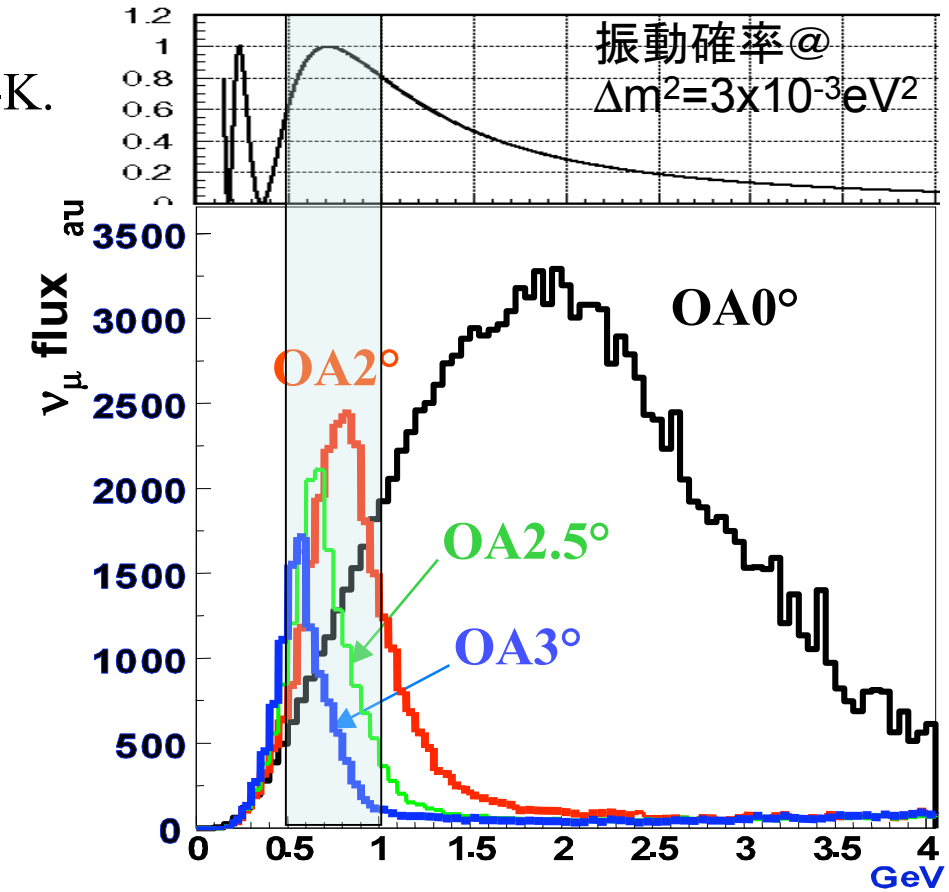
Anti-neutrinos by reversing Horn current



π decay Kinematics







- **Quasi Monochromatic Beam**
- **x 2~3 intense than NBB**
- **Tuned at oscillation maximum**

@SK (OAB 2.5 deg/1 yr, no-osci.)
~ 1030 ν_μ CC+NC single rings
~ 970 ν_μ CC single rings
ν_e ~0.4% at ν_μ peak

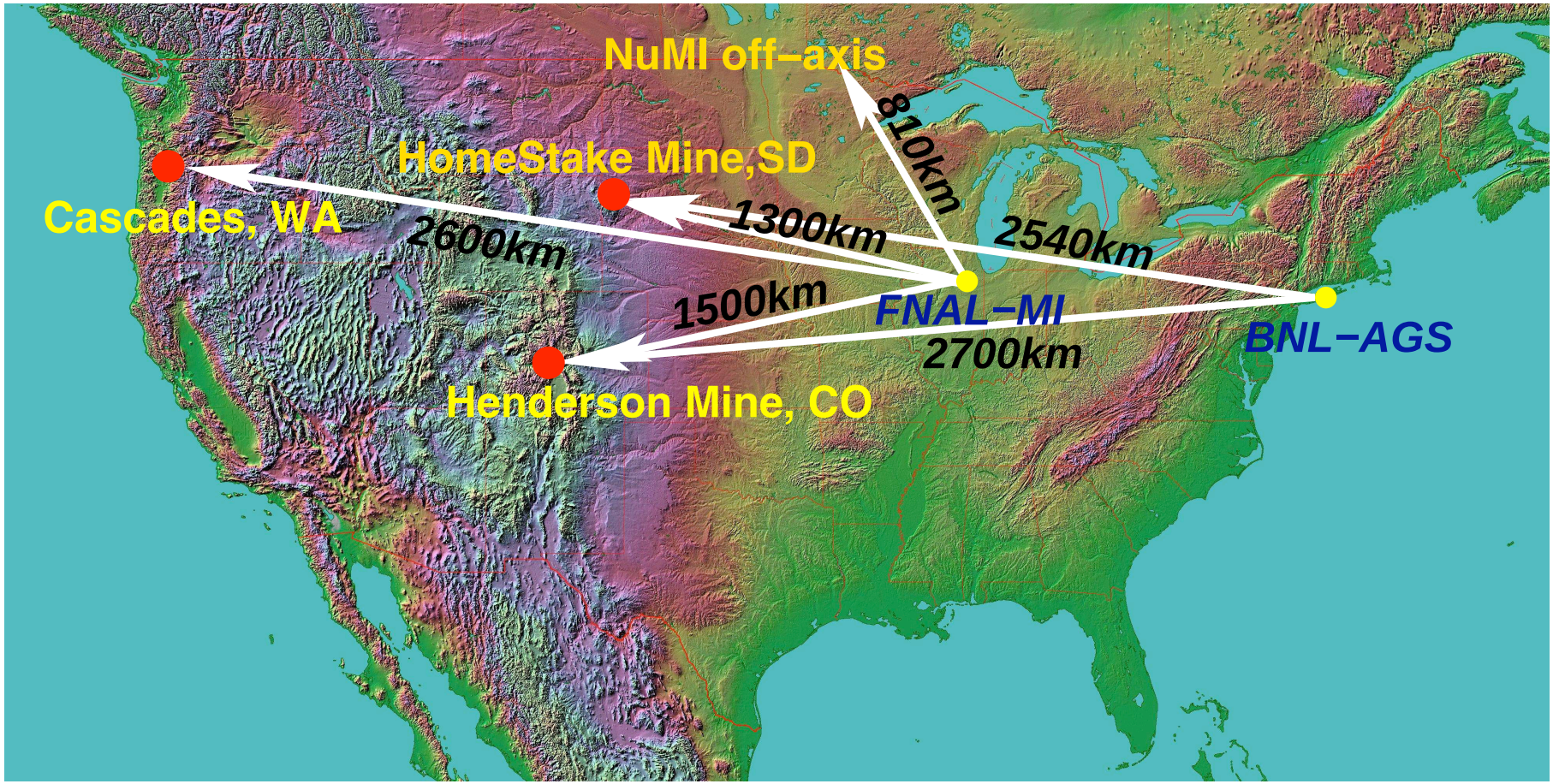
Suppose T2K ran @ 2.0 deg

<E> = 0.75 MeV

same <E>/L as NOvA 12km

- Increased Statistics:
- Improved sensitivity to $\sin^2\theta_{13}$???
  (flux, cross section and backgrounds)
- smaller matter effects:

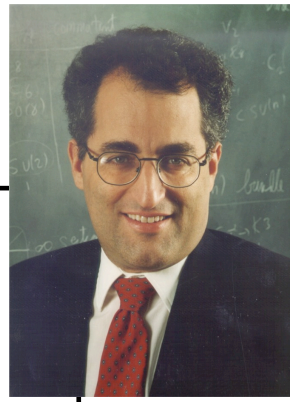
Beyond the First Oscillation Maximum:



Options

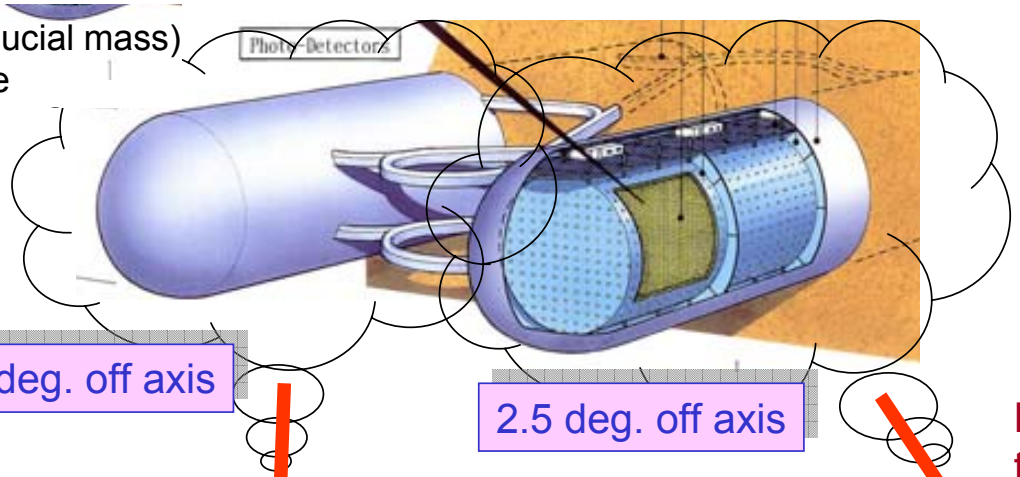
- Existing 120 GeV NuMI beam with an off-axis site.
- 28 GeV BNL-AGS Wide band beam over 2500 km.
- New on-axis 40-120 GeV FNAL-MI Wide Band Low Energy (WBLE) beam to DUSEL @ 1300-2700 km

Off Axis: T2KK



Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

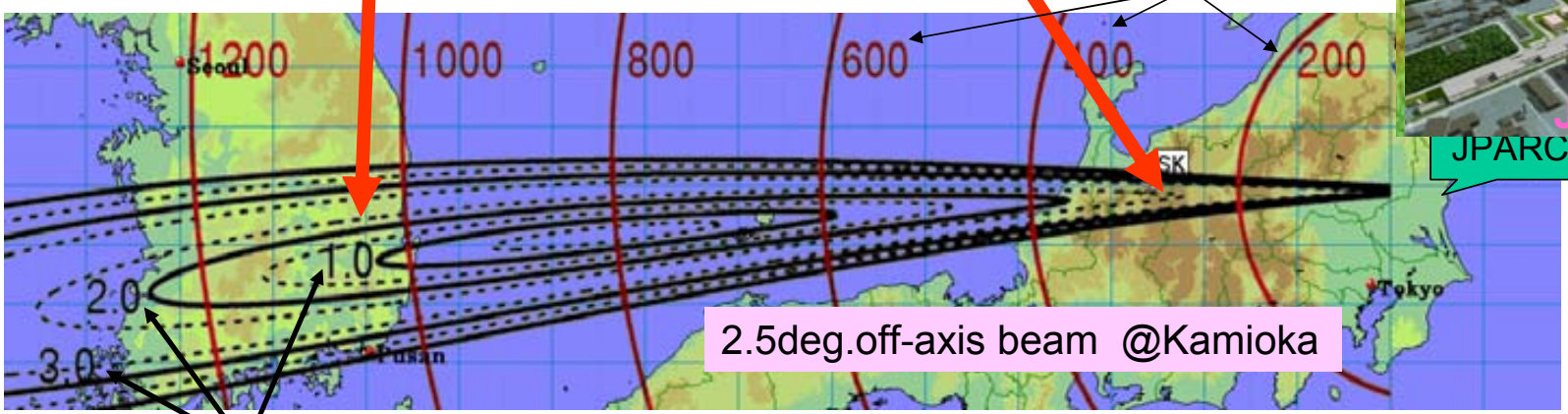


Total cost must be similar to the baseline design.

2.5 deg. off axis

2.5 deg. off axis

Distance from the target (km)



2.5deg.off-axis beam @Kamioka

Off-axis angle

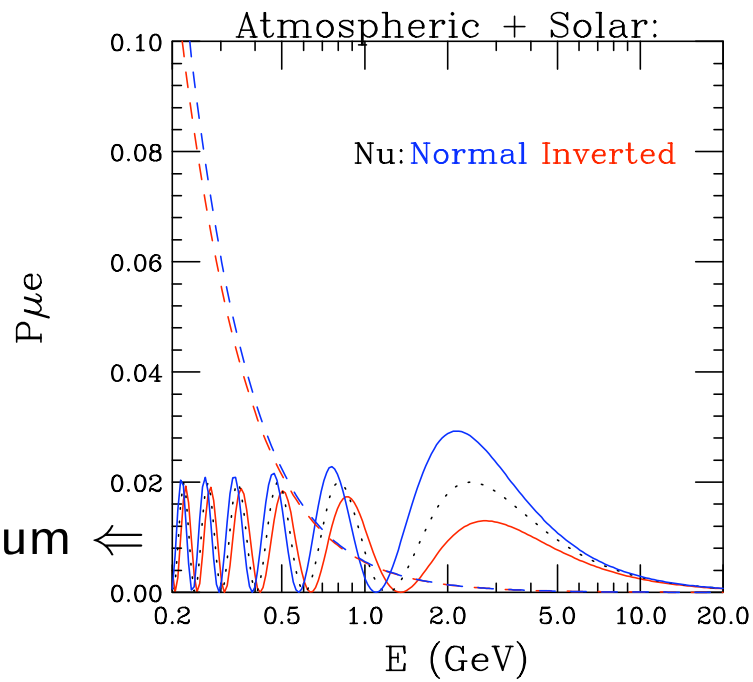
Broadband Beam: Same L, Lower E Fermilab to DUSEL

Narrow Band Beam: Same E, Longer L T2KK

In VACUUM the SAME but NOT in MATTER

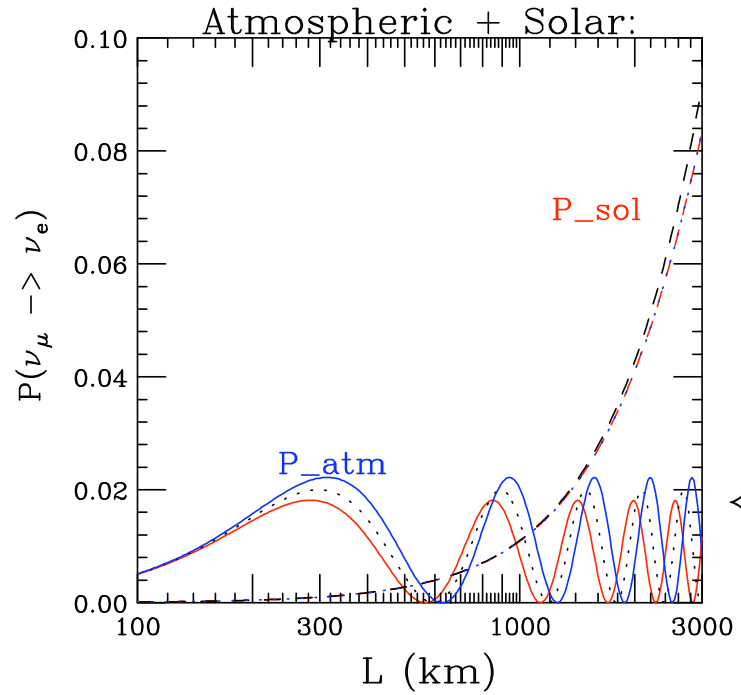
$$\sin^2 2\theta_{13} = 0.04$$

L=1200km



vacuum ⇐

E=0.6 GeV



⇐ same height

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

$\nu_\mu \to \nu_e$ 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 $\sin\Delta_{21}$

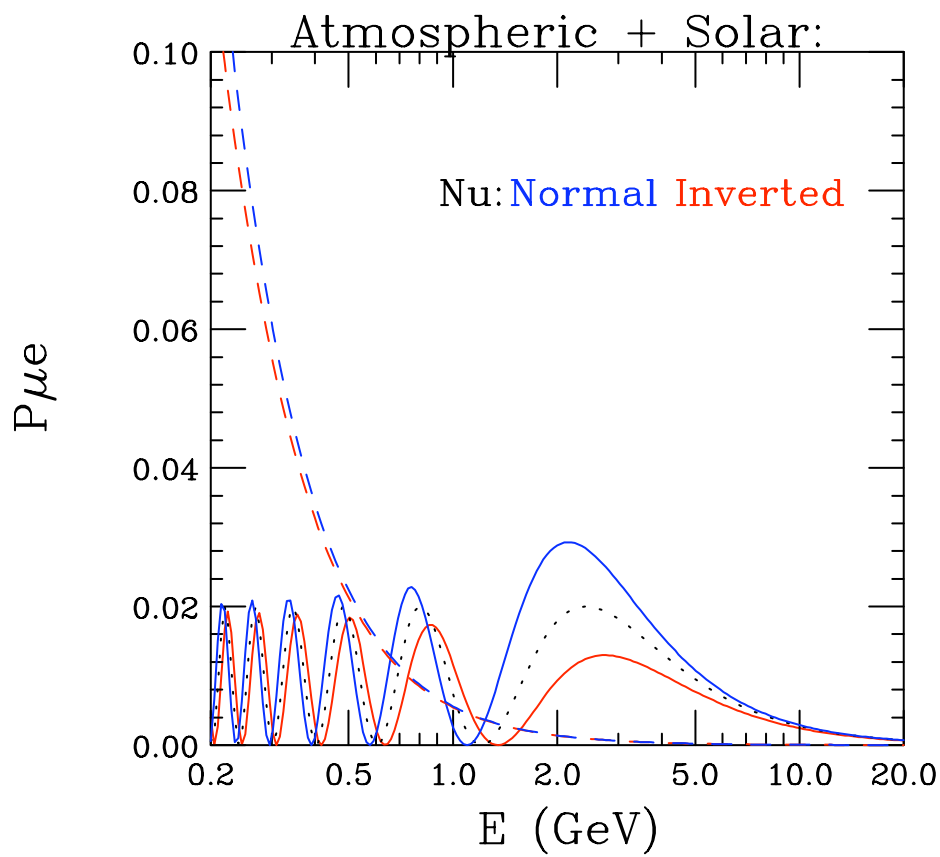
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

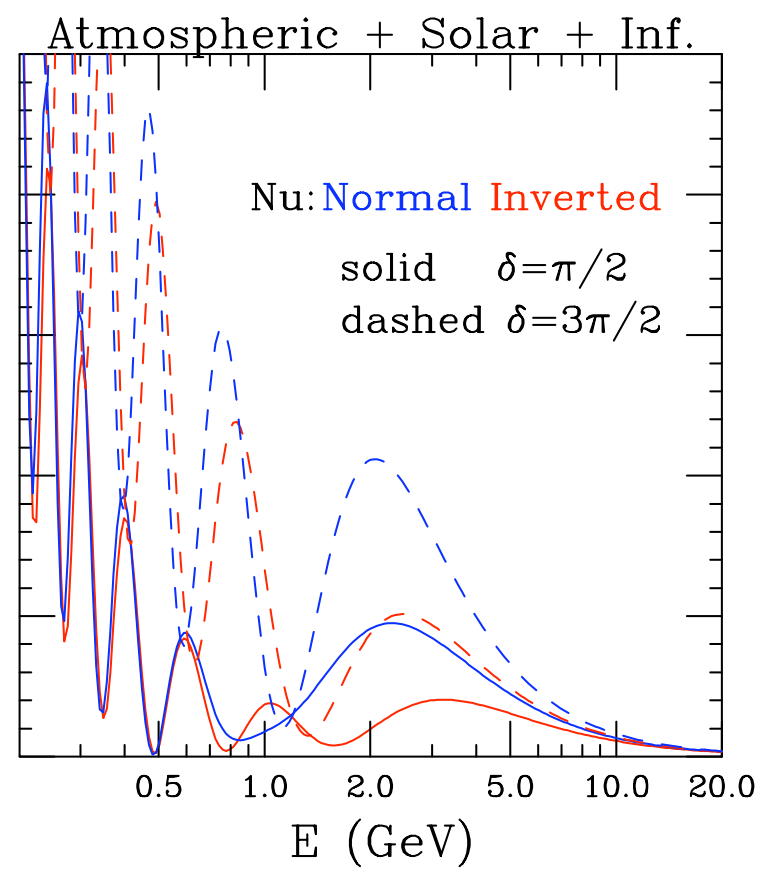
$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

In Matter:

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

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





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

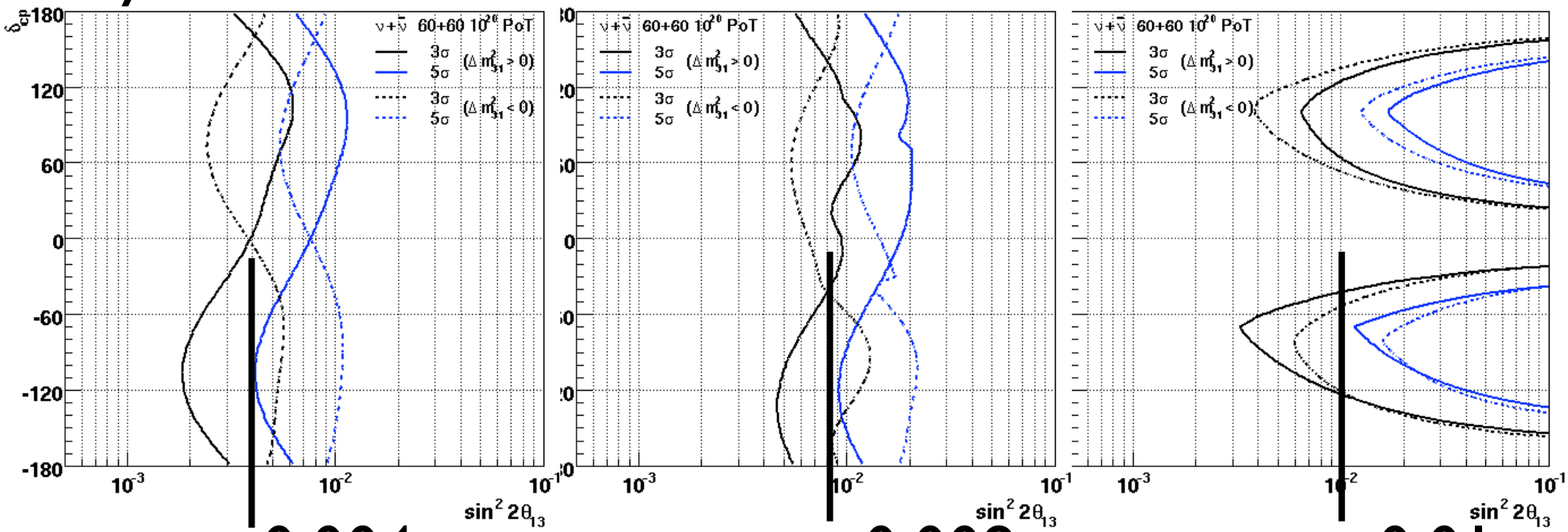
WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

300 kT WCh

60 10^20 POT for each nu and anu

th13 mass ordering CP violation

Stat+syst

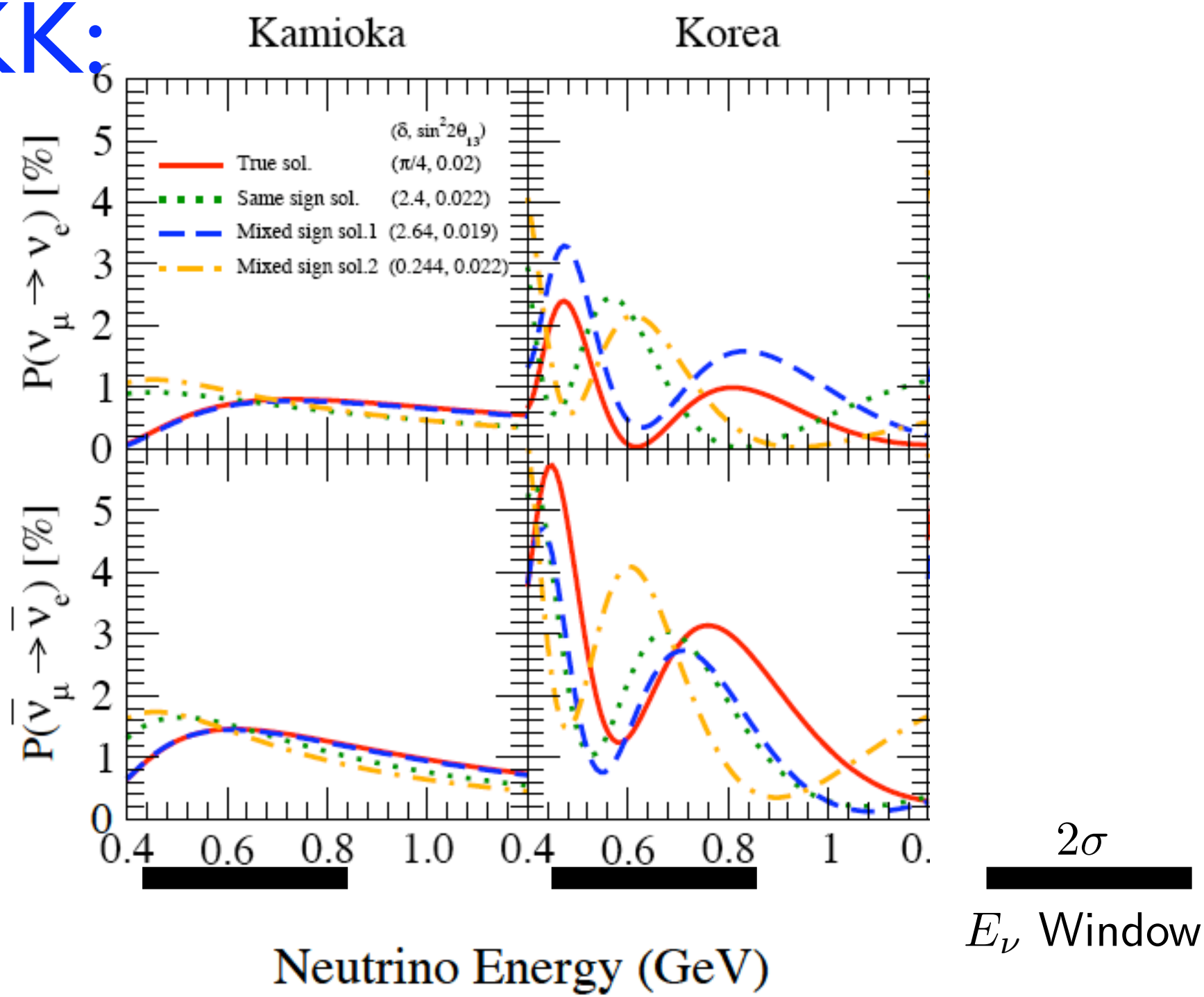


0.004 0.008 0.01

CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

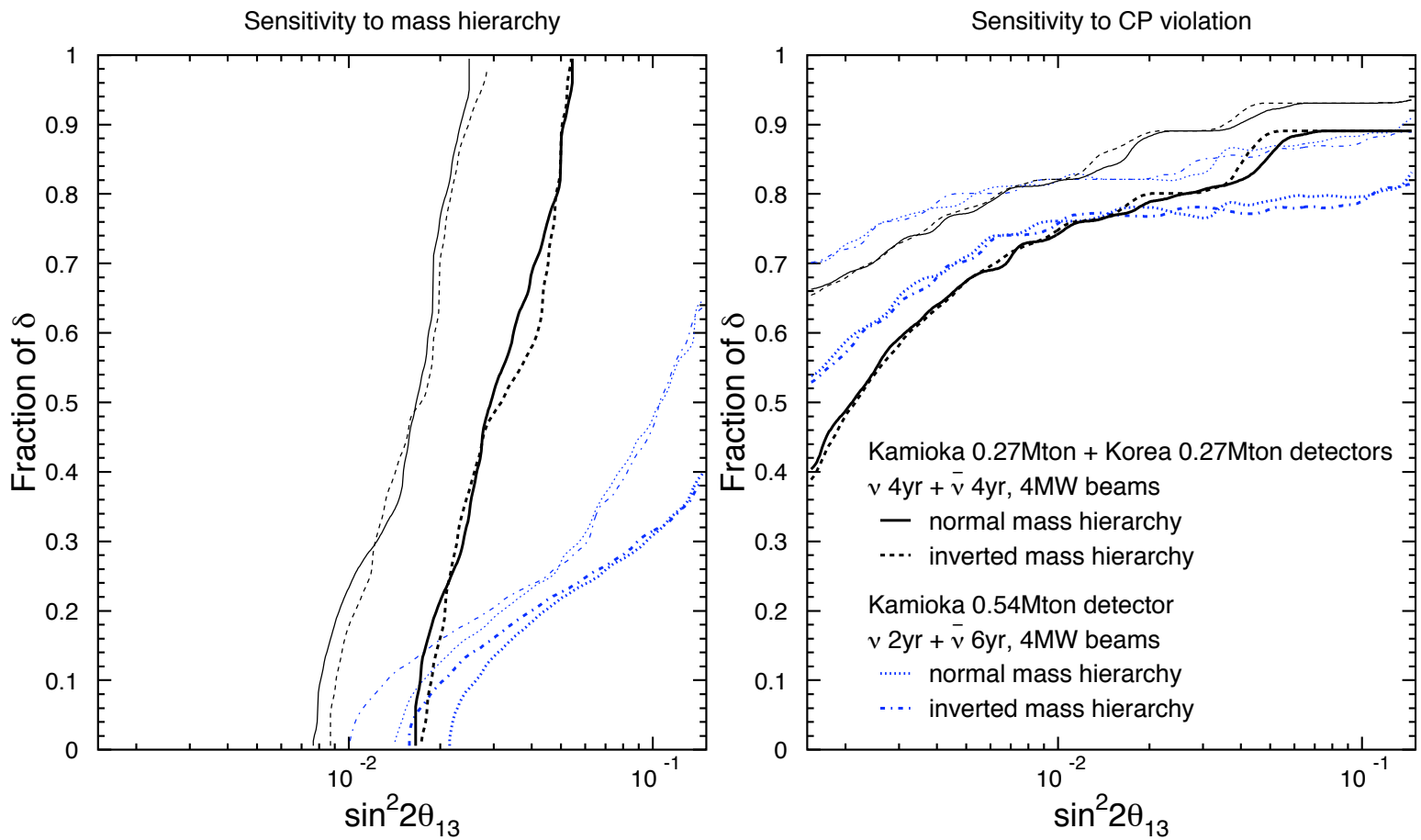
Report the value of th13 at the 50% CP fraction.

T2KK:



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

T2KK:


Sensitivity to mass hierarchy
Sensitivity to CP violation
Fraction of δ
sin²2θ13
Kamioka 0.27Mton + Korea 0.27Mton detectors
ν 4yr + ν̄ 4yr, 4MW beams
normal mass hierarchy
inverted mass hierarchy
Kamioka 0.54Mton detector
ν 2yr + ν̄ 6yr, 4MW beams
normal mass hierarchy
inverted mass hierarchy

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

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

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

depends on θ_{13}
amplification or suppression
by matter (E)

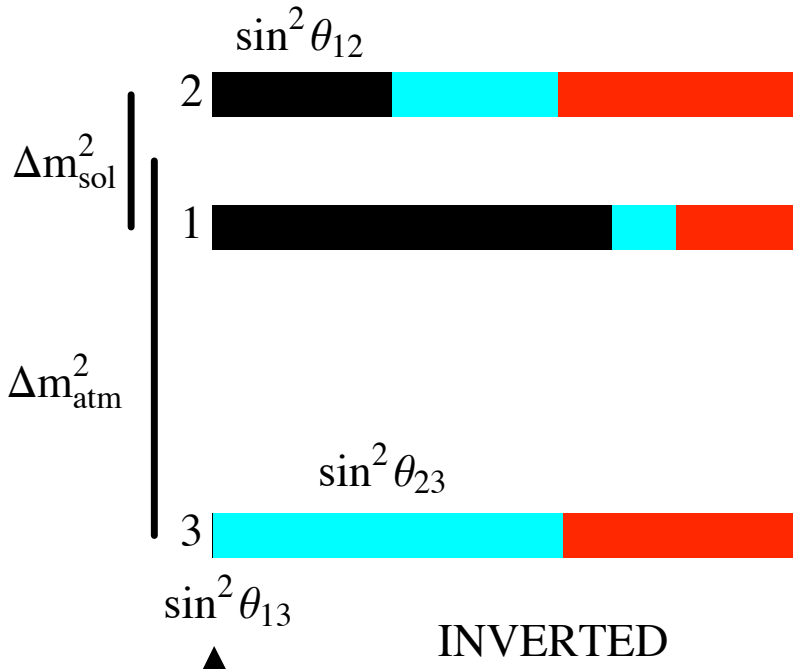
Suppression $\geq$ Enhancement

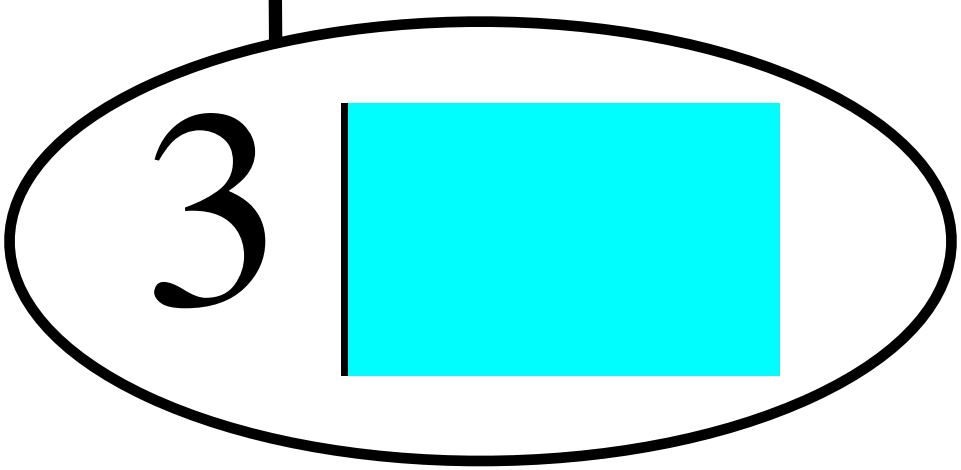
independent of θ_{13}
$\approx$ independent of
matter effect

L/E $\geq$ significant fraction of 500 km/GeV

Event rate: $E(E/L)^2$

pdg 2026:





$$\sin^2\theta_{12} \approx 0.31$$

$$\sin^2\theta_{13} \approx 0.007$$

$$\sin^2\theta_{23} \approx 0.60$$

$$\delta \approx 3\pi/4$$

Summary:

CP

$\nu_\mu \longrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

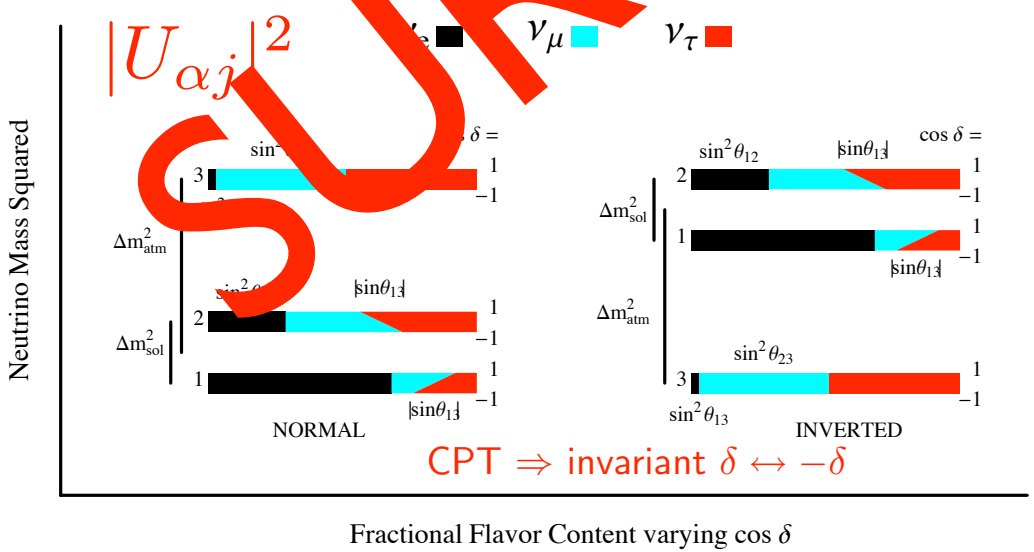
T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$\nu_e \longrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \longrightarrow \bar{\nu}_\mu$

CP

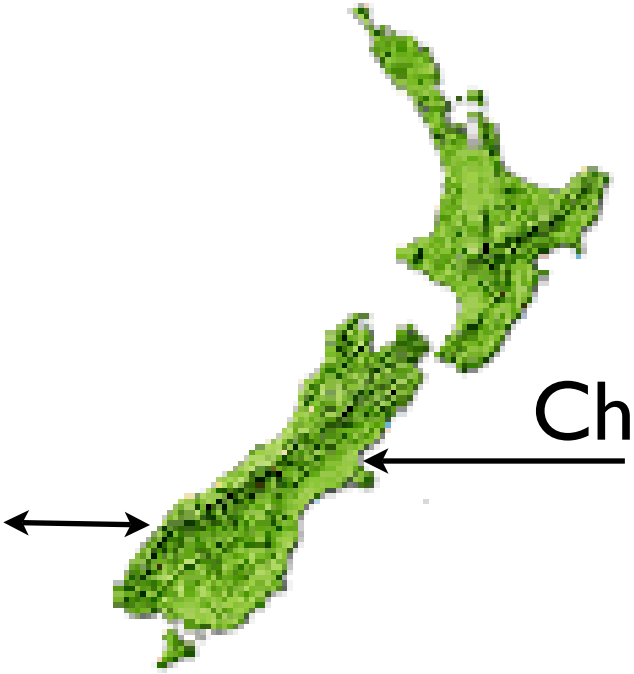
SURPRISES!!!

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



- Size of $|U_{e3}|^2$
- Hierarchy ?
- CPV ?
- Maximal {23} Mixing ?
- .....
- New Interactions and Surprises !!!

Neutrino 2008
May 26-31



www.neutrino2008.co.nz