Issues in Standard Model Neutrino Physics

Stephen Parke
Fermilab

Project X Workshop
Nov 9 2009

Mixing Matrix:

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

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

Atmos. L/E $\mu \to \tau$ — 500km/GeV

Atmos. L/E $\mu \leftrightarrow e$

Solar L/E $e \to \mu, \tau$ — 15km/MeV

$0\nu\beta\beta$ decay

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

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solar/KamLAND

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Atmospheric Nus

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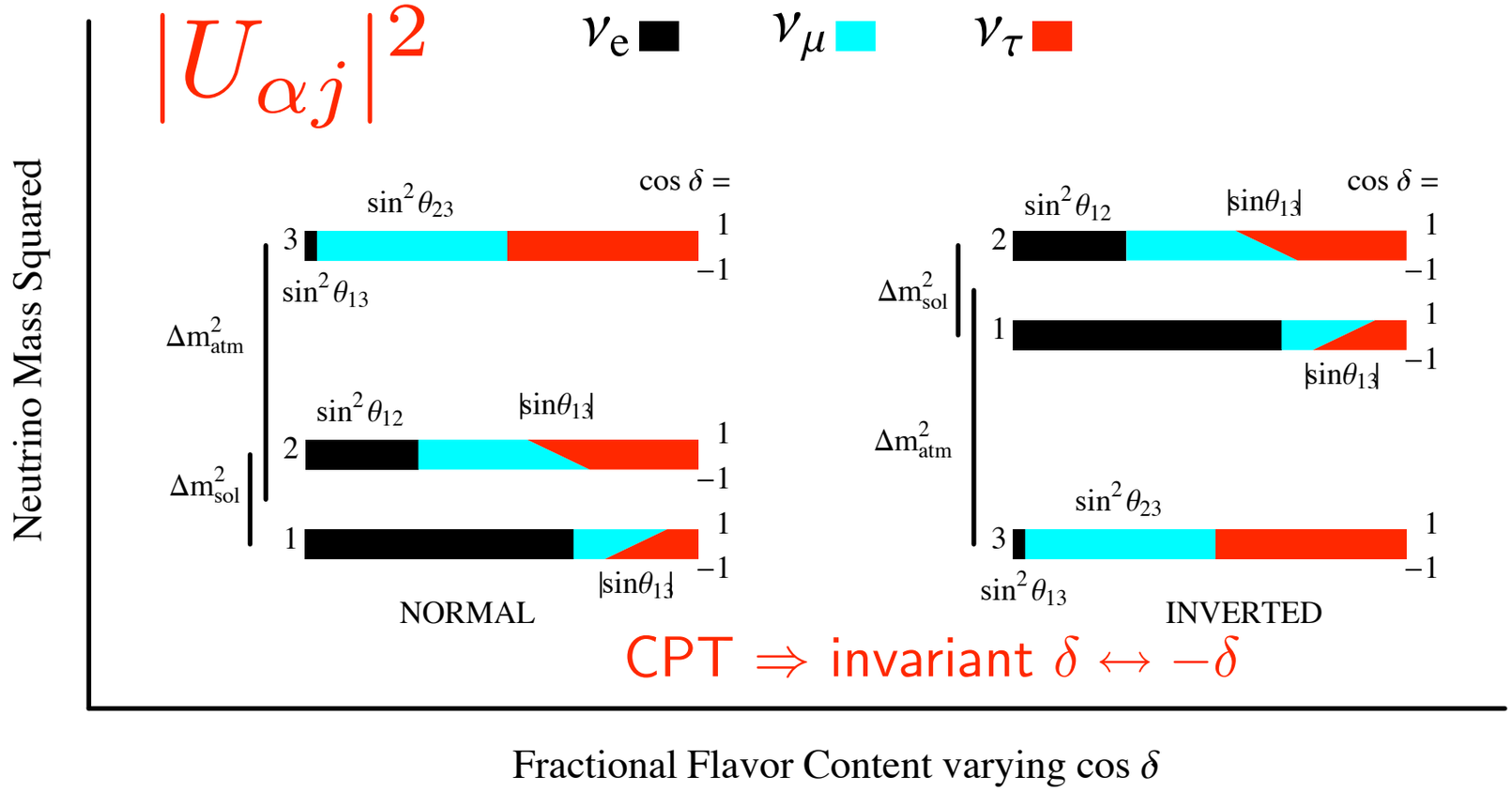
solar/KamLAND

Reactor/LBL

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

Atmospheric Nus



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

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

One Global Fit:

Dominated by

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND
MINOS
SNO
SuperK
Chooz

arXiv:0808.2016

At 2σ we have the following limits:

$$\begin{aligned} \sin^2\theta_{13} &< 0.04 \\ |\sin^2\theta_{12} - \frac{1}{3}| &< 0.04 \\ |\sin^2\theta_{23} - \frac{1}{2}| &< 0.12 \end{aligned}$$

Close to Tri-Bi-Maximal: accident or symmetry ?

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$$\begin{aligned} \sin^2\theta_{13} &< 0.04 \\ |\sin^2\theta_{12} - \frac{1}{3}| &< 0.04 \\ |\sin^2\theta_{23} - \frac{1}{2}| &< 0.12 \end{aligned}$$

Close to Tri-Bi-Maximal: accident or symmetry ?

In numerous models:

$$\sin^2\theta_{13},\ |\sin^2\theta_{12} - \tfrac{1}{3}|,\ |\sin^2\theta_{23} - \tfrac{1}{2}| \ \sim\ \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^n$$

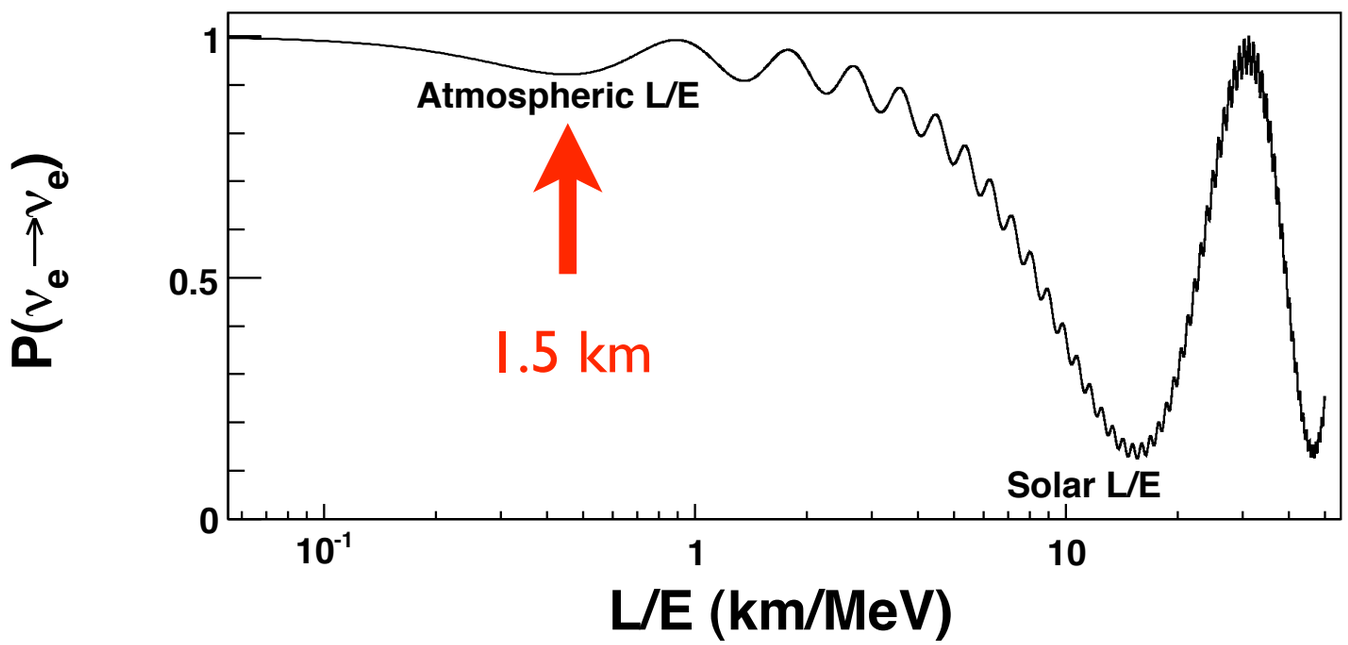
Experiment has probed down to n $\approx$ 1/2 to 1 !!!

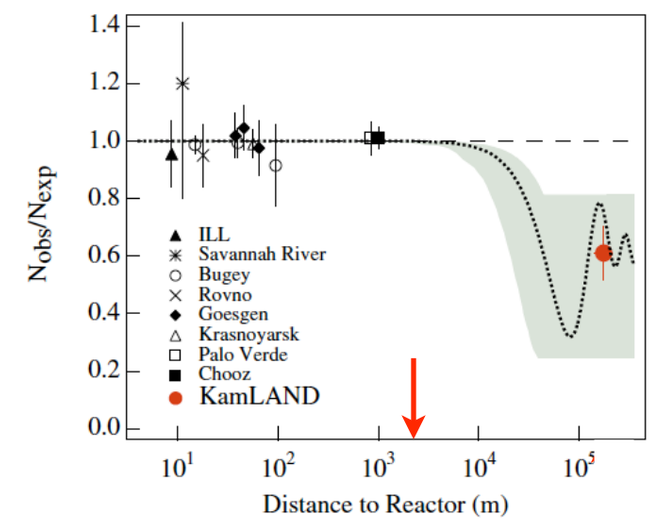
$\sin^2\theta_{13}$ from Reactor Neutrinos:

kinematic phase:

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

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





< 0.002

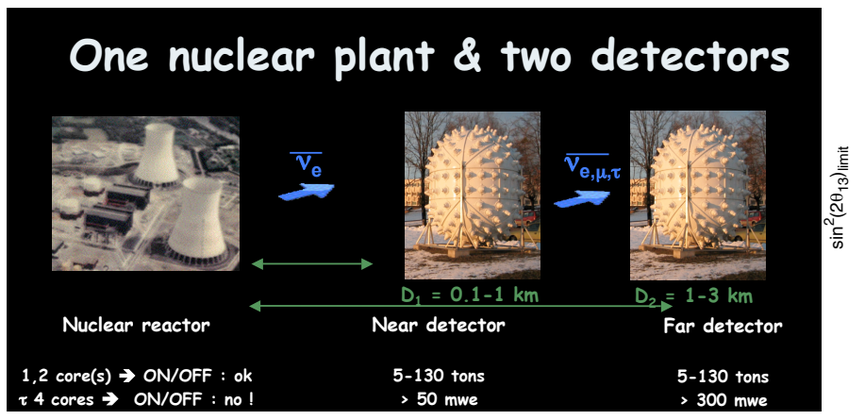
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

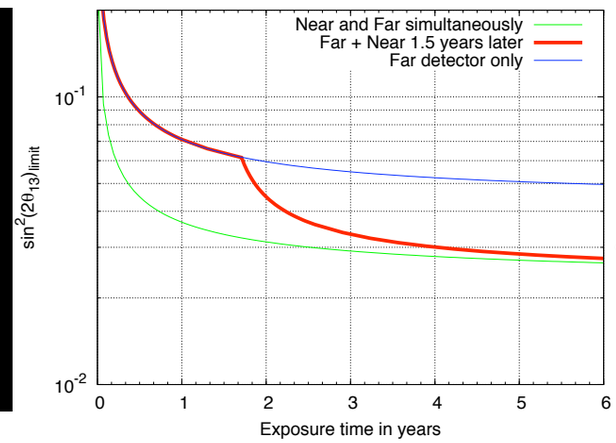
> 0.01

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

Double Chooz:

90% C.L. Sensitivities:



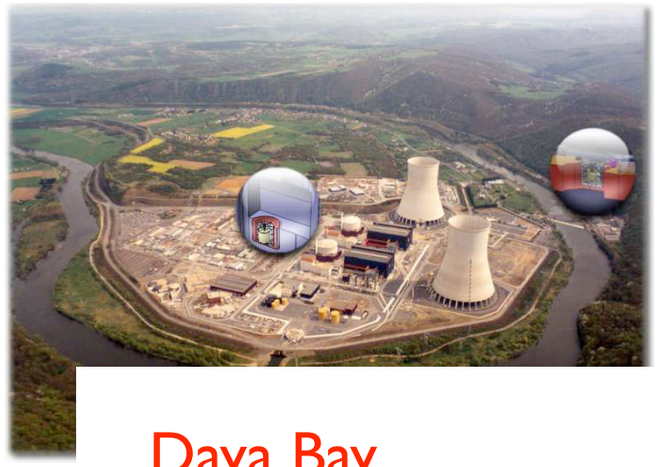


.03

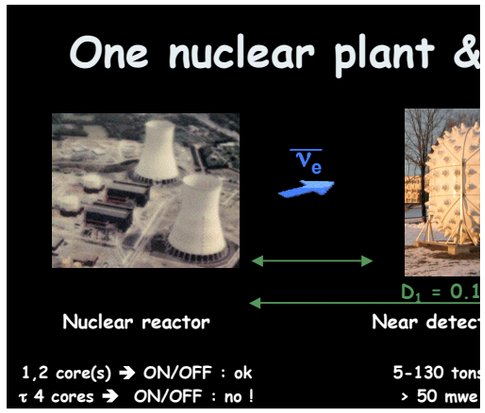
2014

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

Double Chooz:



Daya Bay

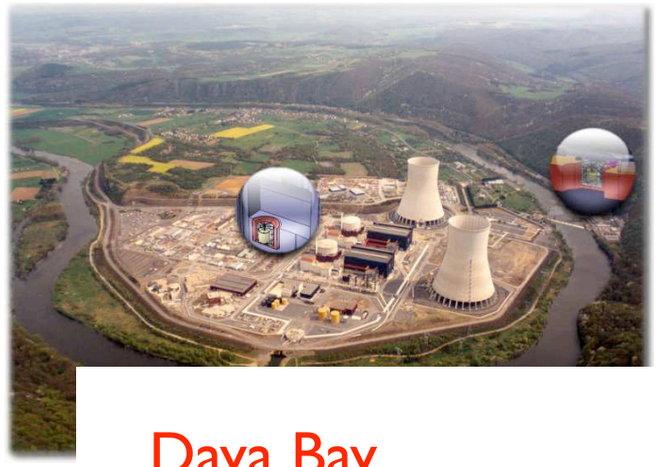


90% C.L.
Sensitivities:

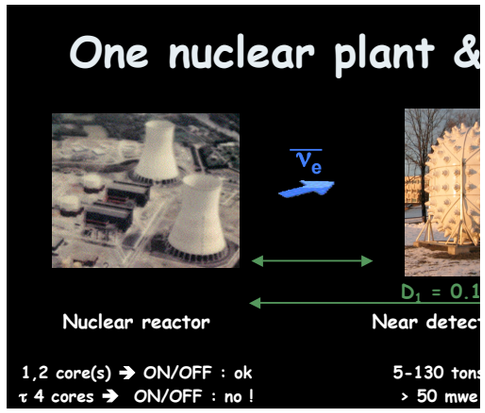
Near
+ Far
2011
then
3 yrs

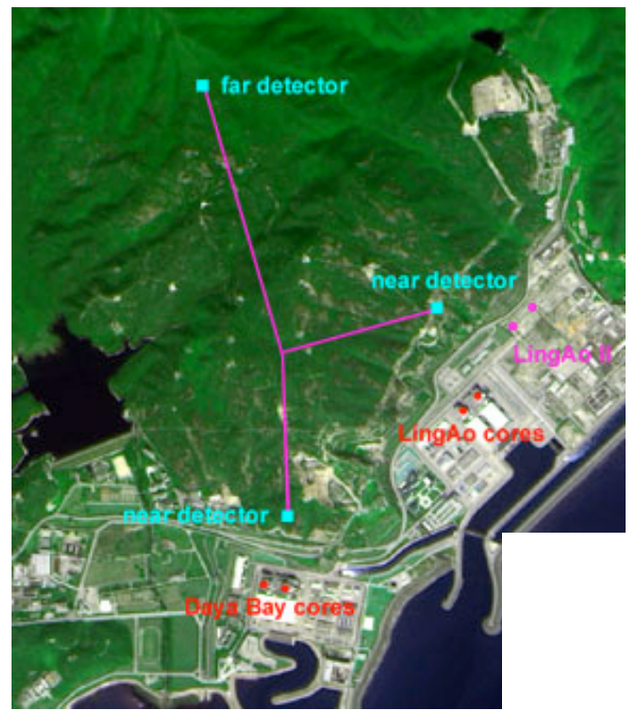
push the limit on
$\sin^2 2\theta_{13} < 0.01$

Double Chooz:



Daya Bay





90% C.L. Sensitivities:

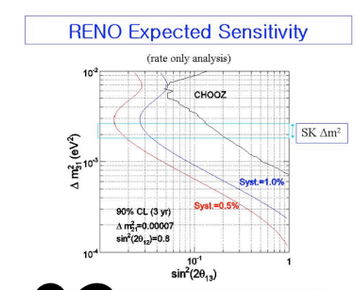
Near + Far 2011

RENO

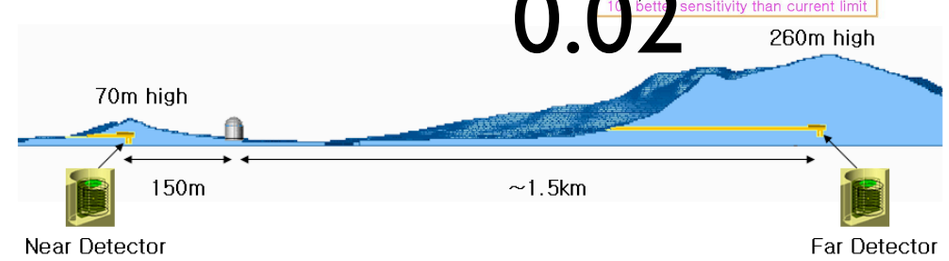
ν θ_{13}

(Reactor Experiment for Neutrino Oscillation)

push the limit $\sin^2 2\theta_{13} < 0.$



0.02



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

- 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 !!!

In Matter:

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

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

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

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

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

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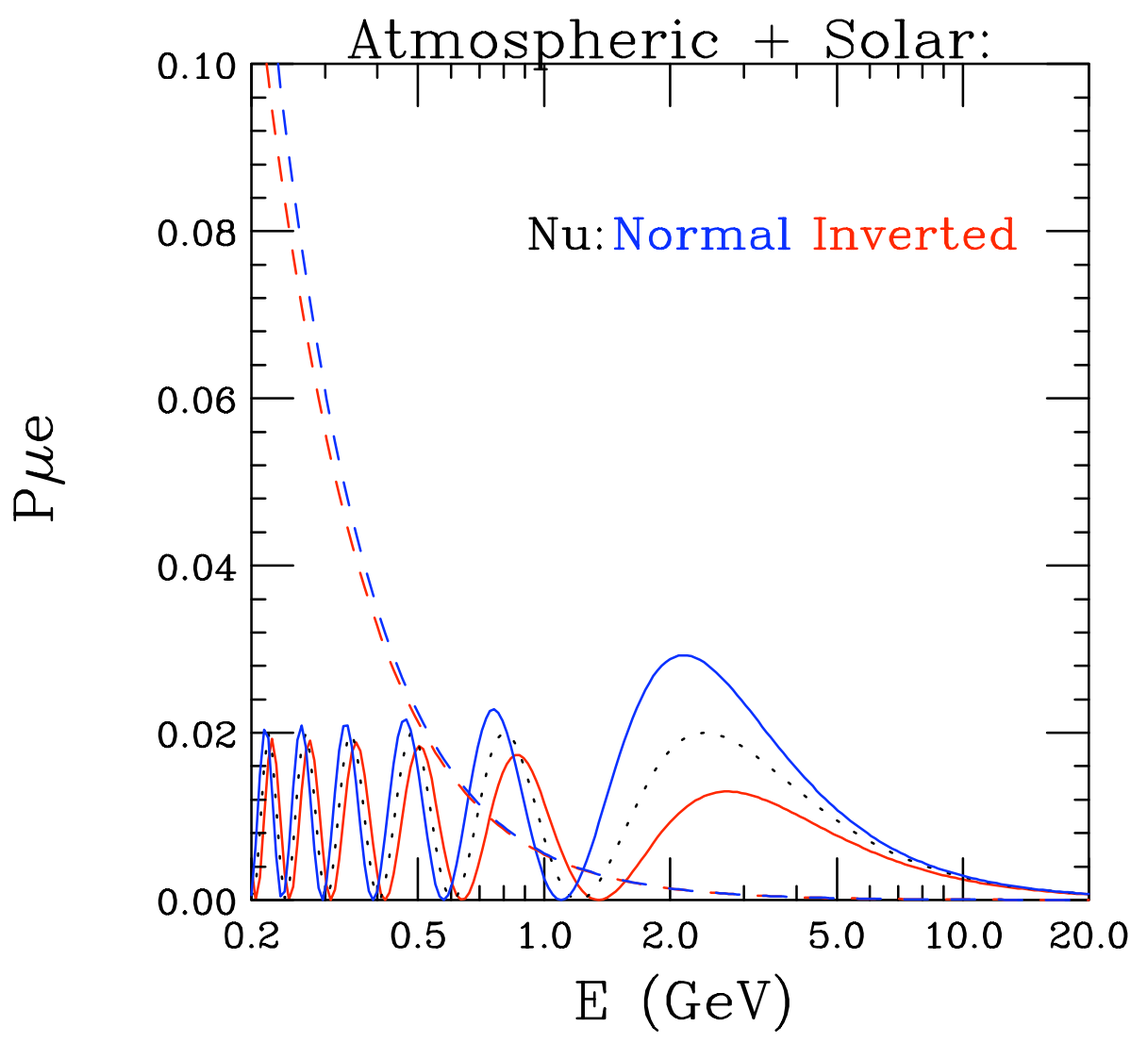

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and $\sin^2 2\theta_{13} = 0.04$

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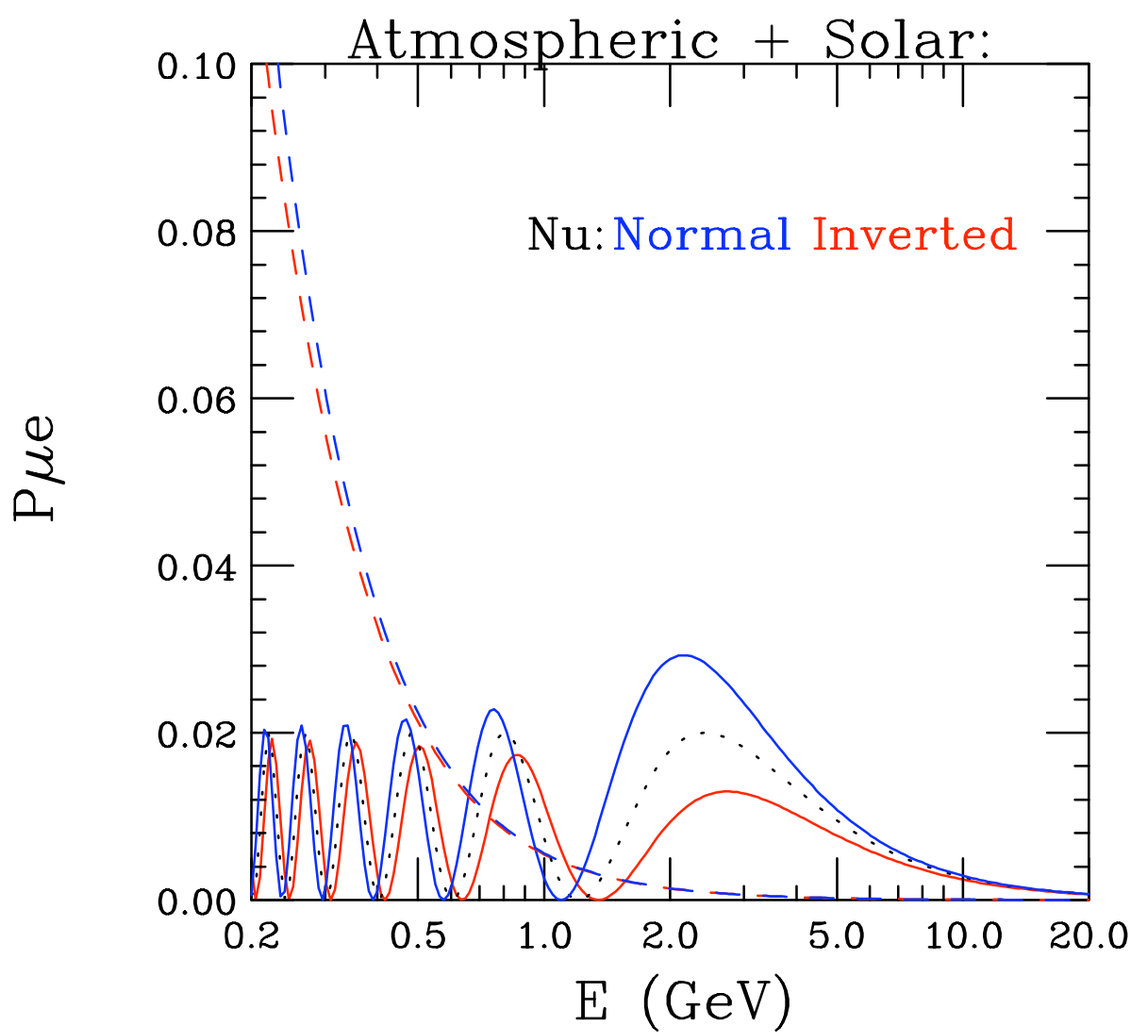
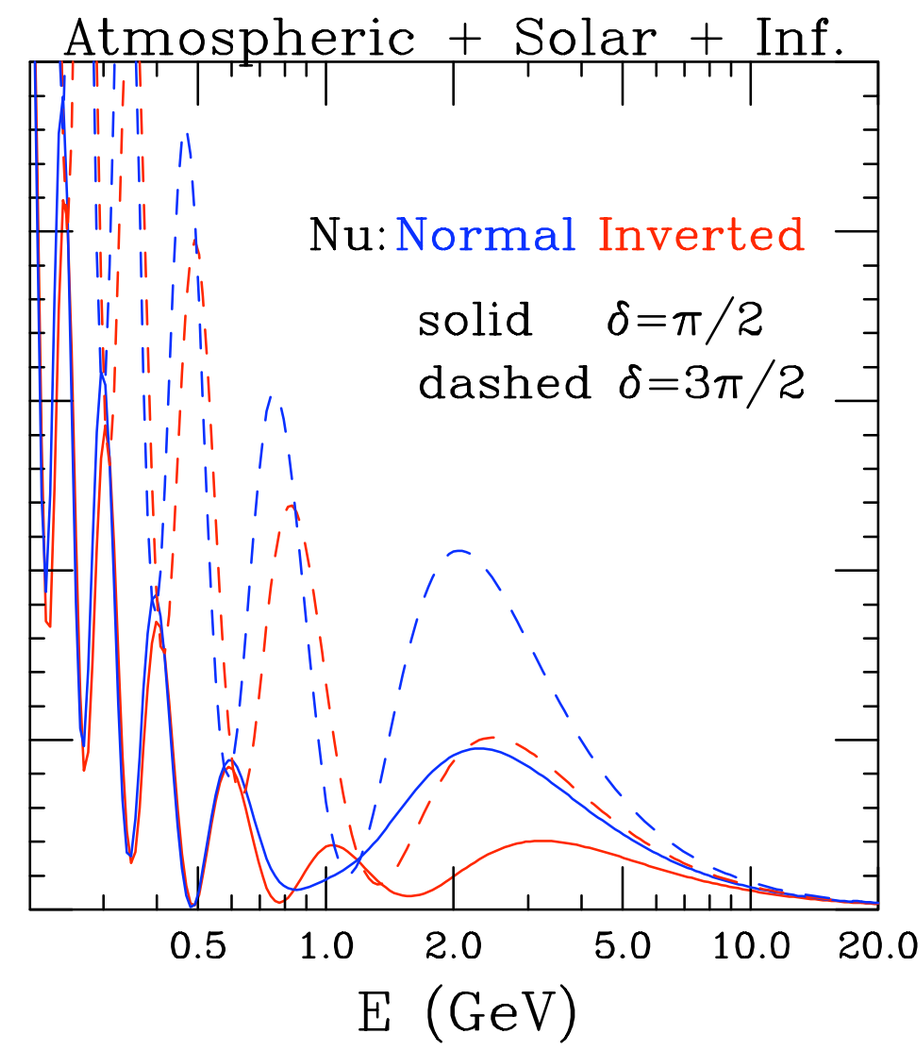
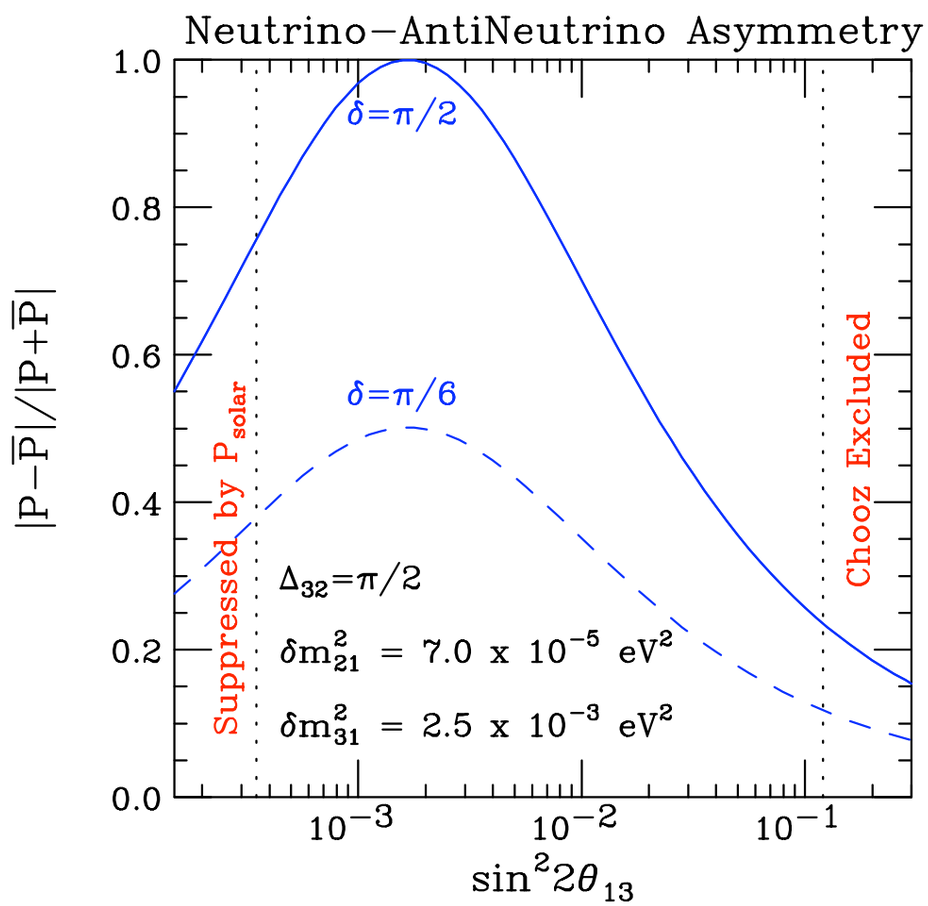
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





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

Asymmetry Peaks:



at the first peak

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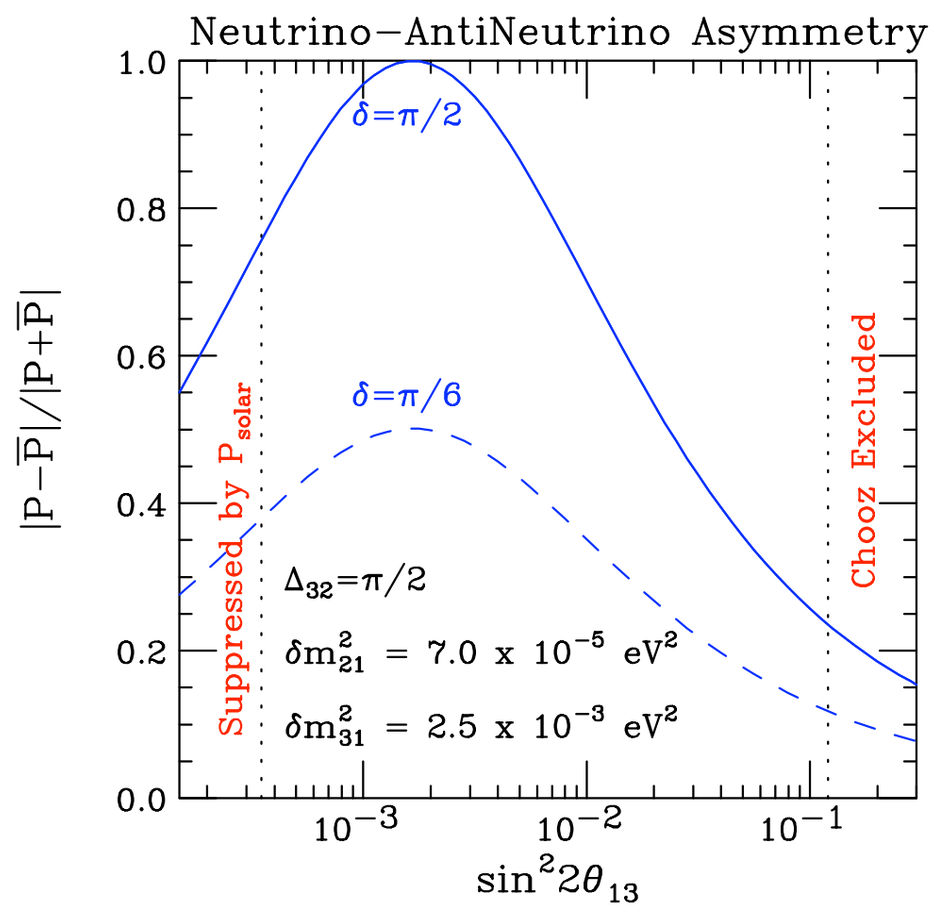

at the first peak

$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}} \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

$\nu_\mu \longrightarrow \nu_e$

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+2\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}$$

$$*\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

CPV

$$*(\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta)$$

CPC

$$+\cos^4\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$(\Delta_{31}-aL) = \Delta_{31}\left(1-\frac{aL}{\Delta_{31}}\right) = \Delta_{31}\left(1-\frac{2\sqrt{2}G_F N_e E}{\delta m_{31}^2}\right)$$

$$\Delta_{32} \approx \Delta_{31}$$

$$J = \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\sin\delta$$

at Vac. Osc. Max.

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} + 2P_\odot$$

in $P + \bar{P}$ the matter effects approx. cancel
and CP effects approx. cancel.

at Vac. Osc. Max.

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} + 2P_\odot$$

in $P + \bar{P}$ the matter effects approx. cancel
and CP effects approx. cancel.

directly comparable to reactor

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13}$$

at Vac. Osc. Max.

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} + 2P_\odot$$

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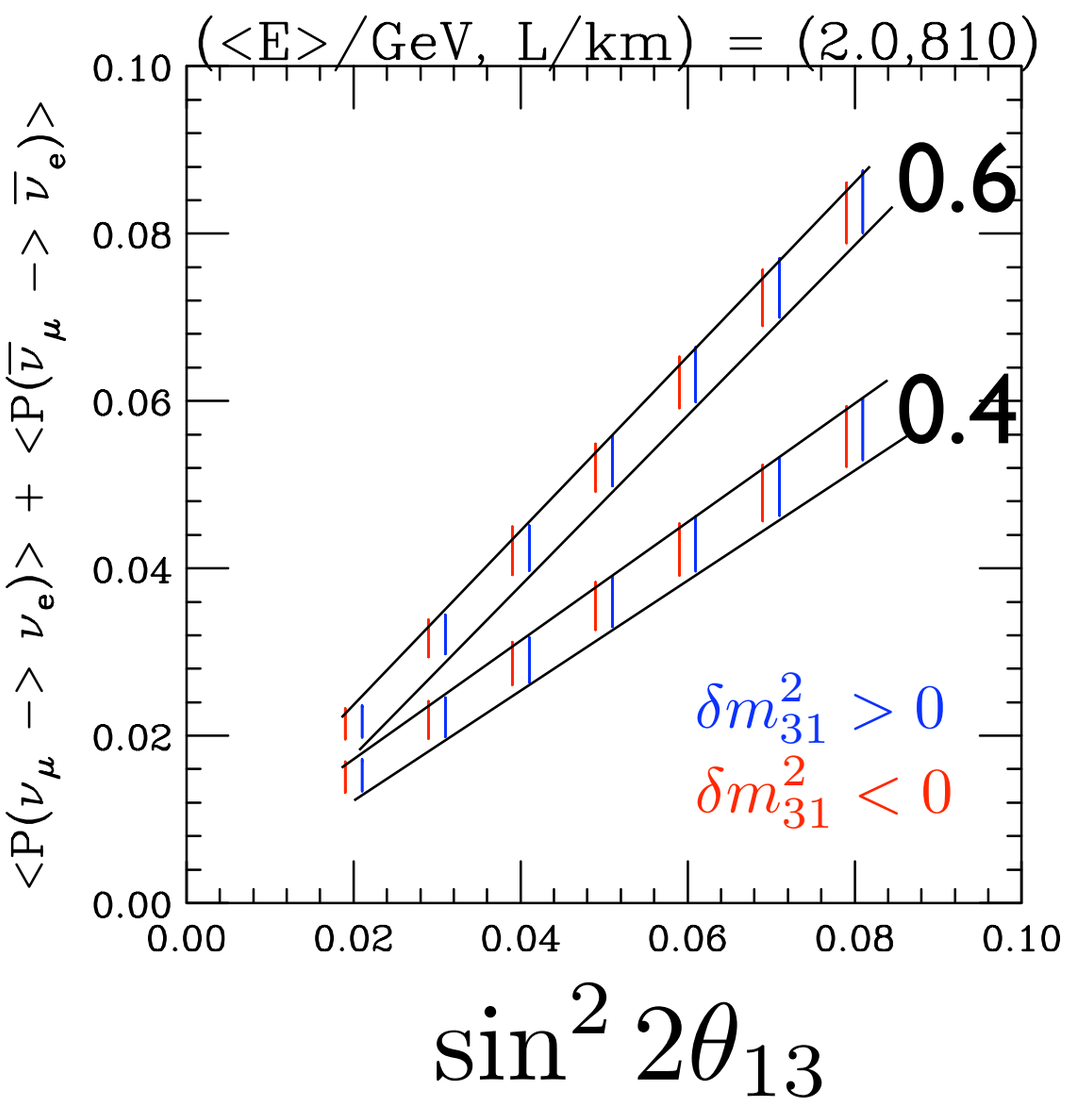
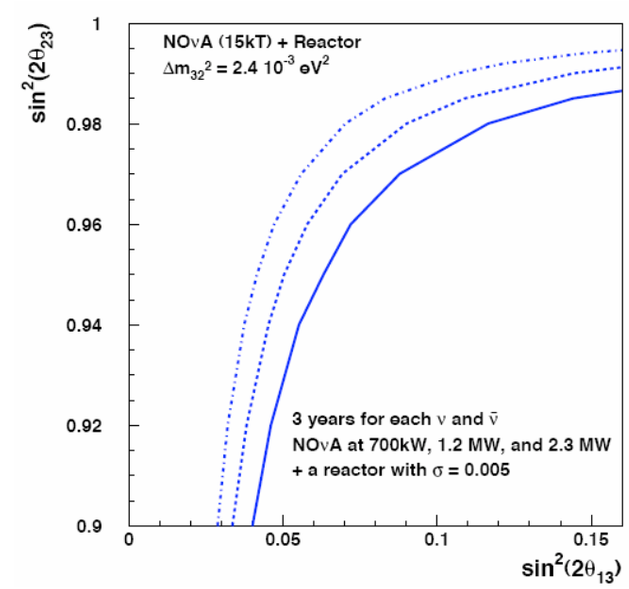
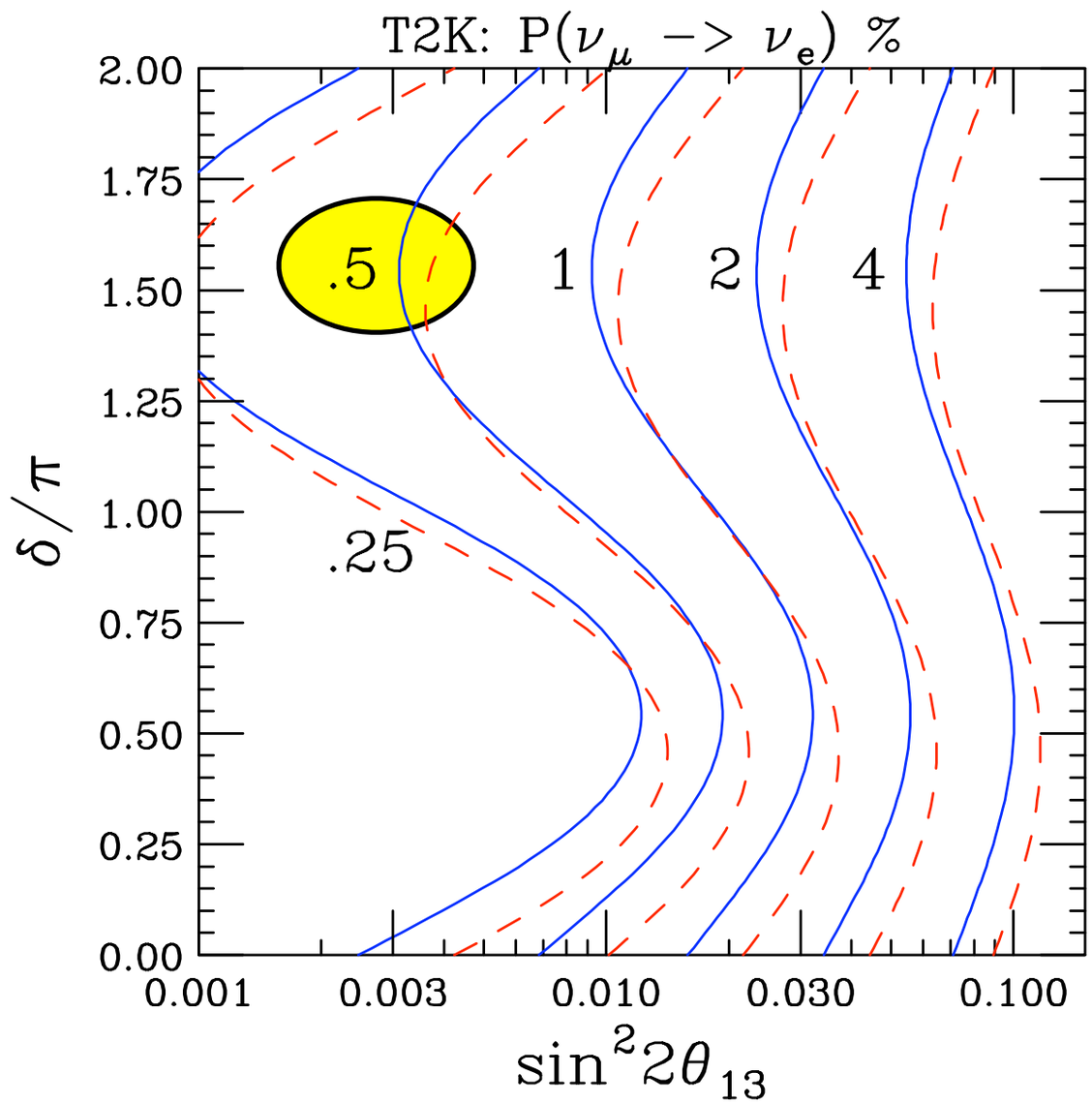


95% CL Resolution of the θ_{23} Ambiguity



For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6
(4*0.4*0.6=0.96)

T2K:

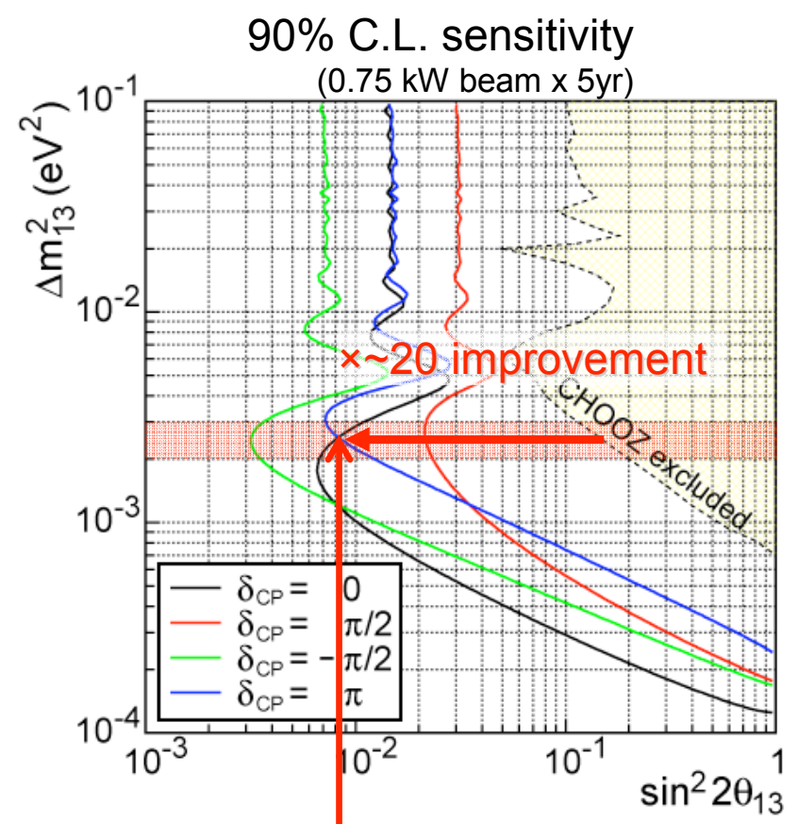


$\delta m^2_{31} > 0$

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

Beam 0.5%

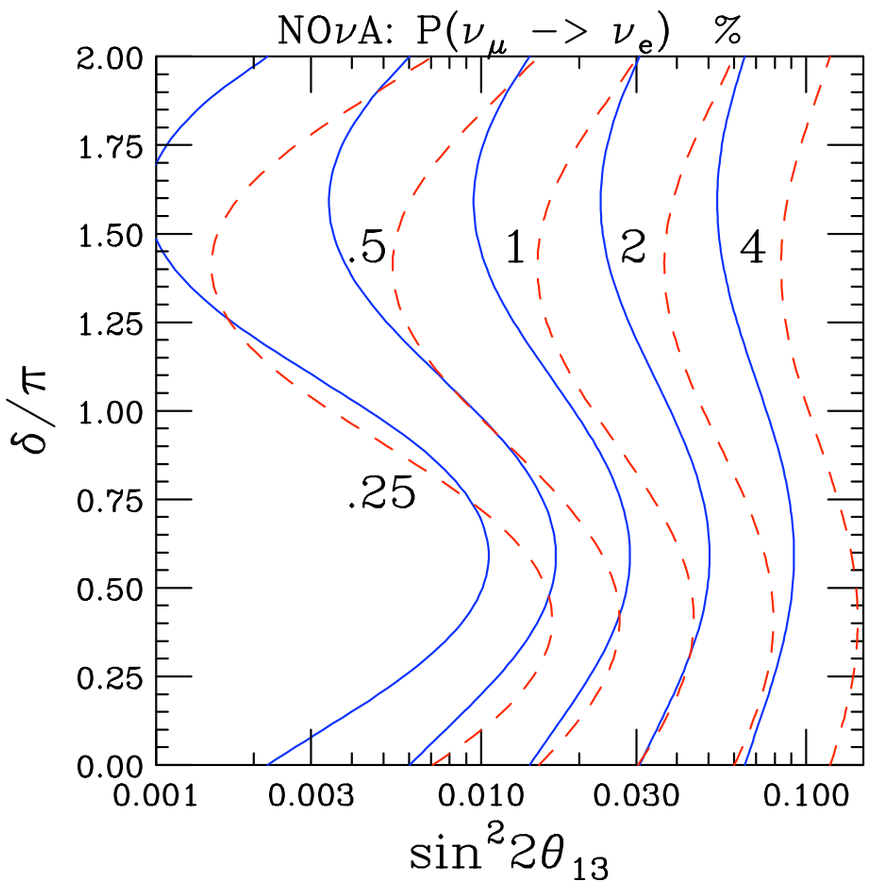
Search for ν_e appearance



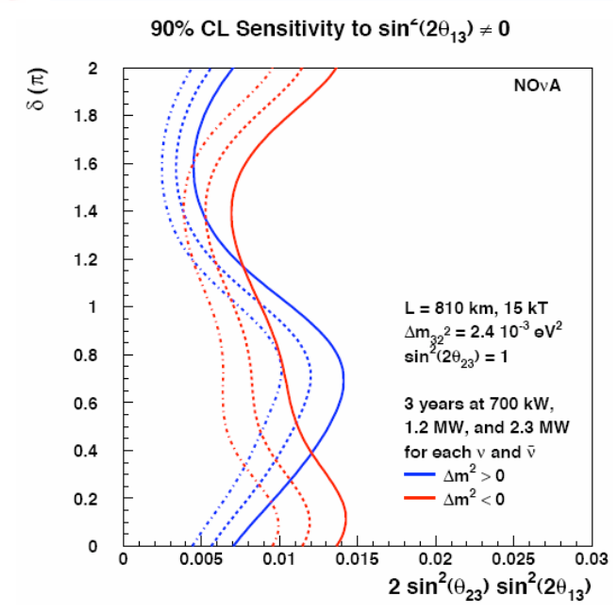
$\sin^2 2\theta_{13} \sim 0.008$ ($\delta_{CP} = 0,\pi$)

NOvA:

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



Sensitivity to $\sin^2(2\theta_{13}) \neq 0$



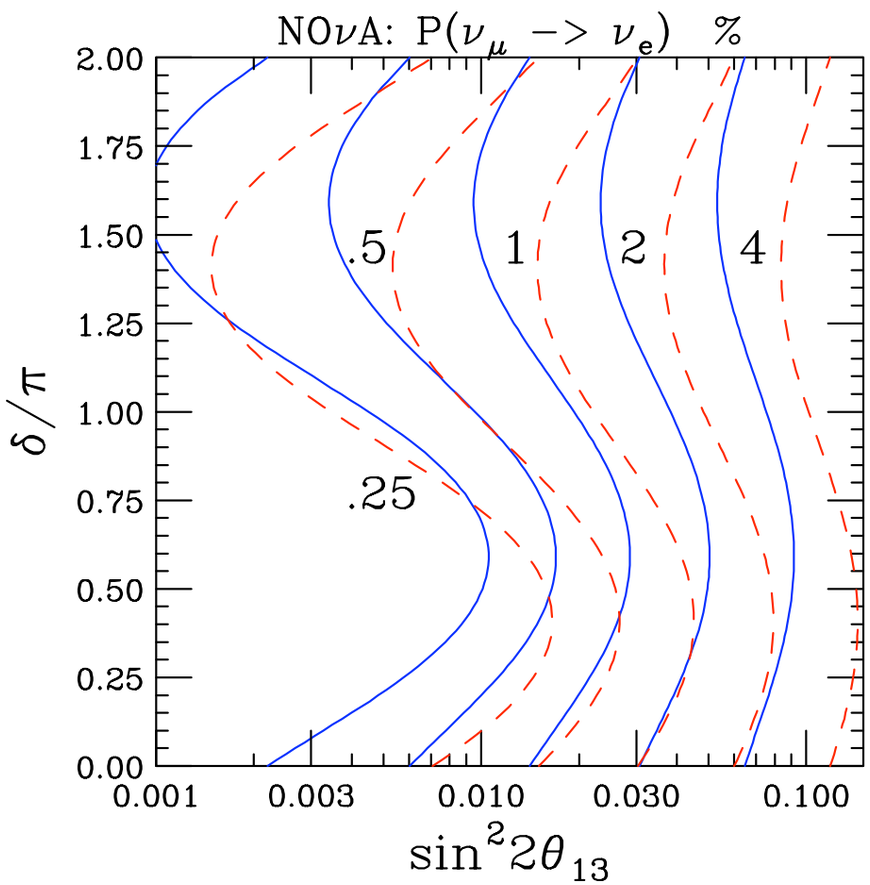
Beam 0.5-1%

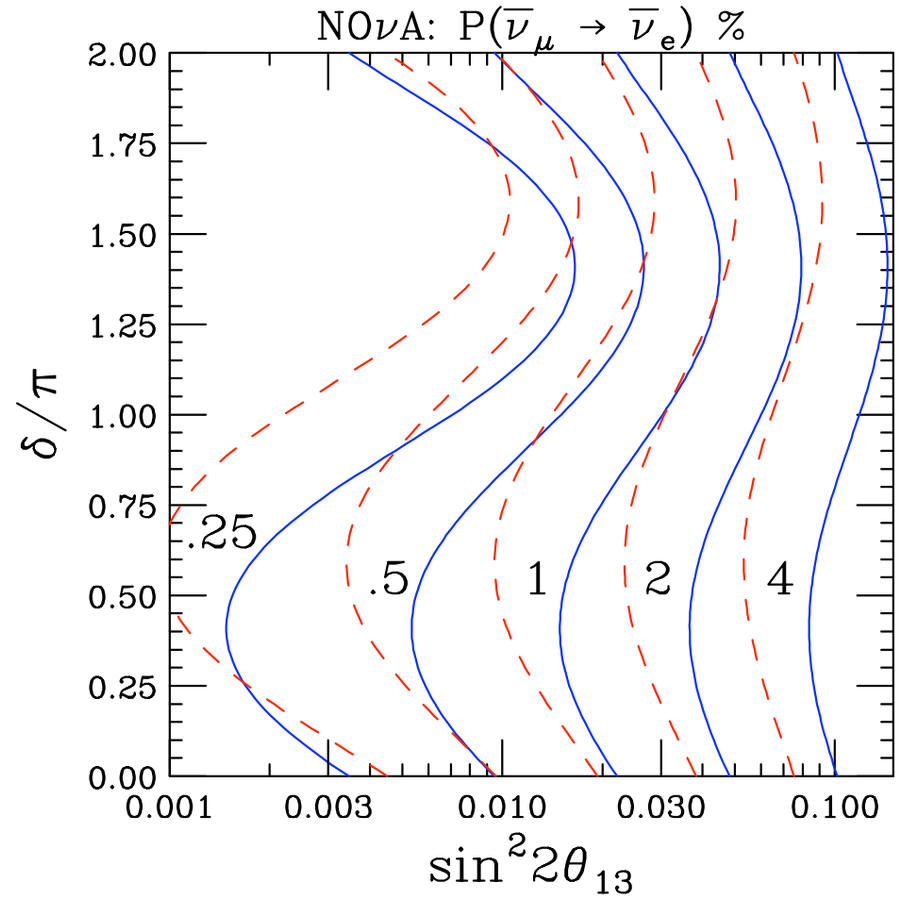
Phase I

Sensitivity approx 0.5-1%

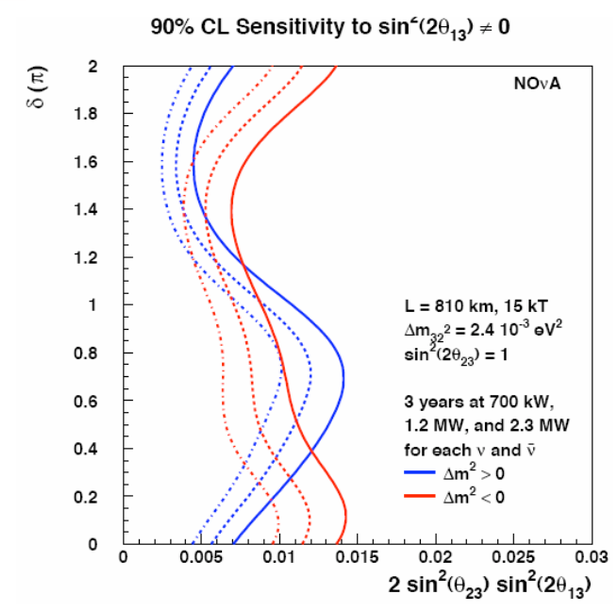
NOvA:

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





Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

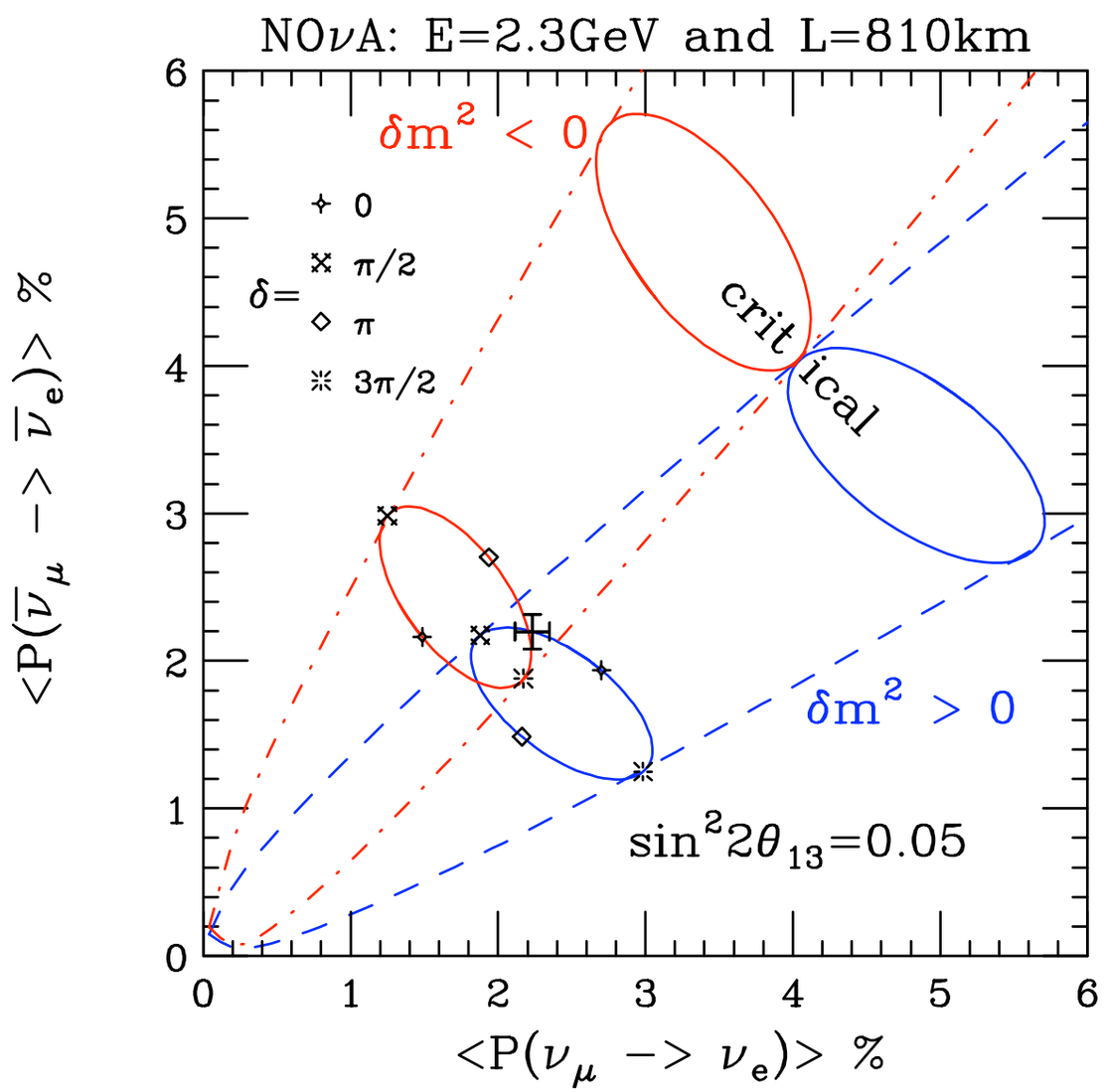


Beam 0.5-1%

Phase I

Sensitivity approx 0.5-1%

NOvA:



in the overlap region

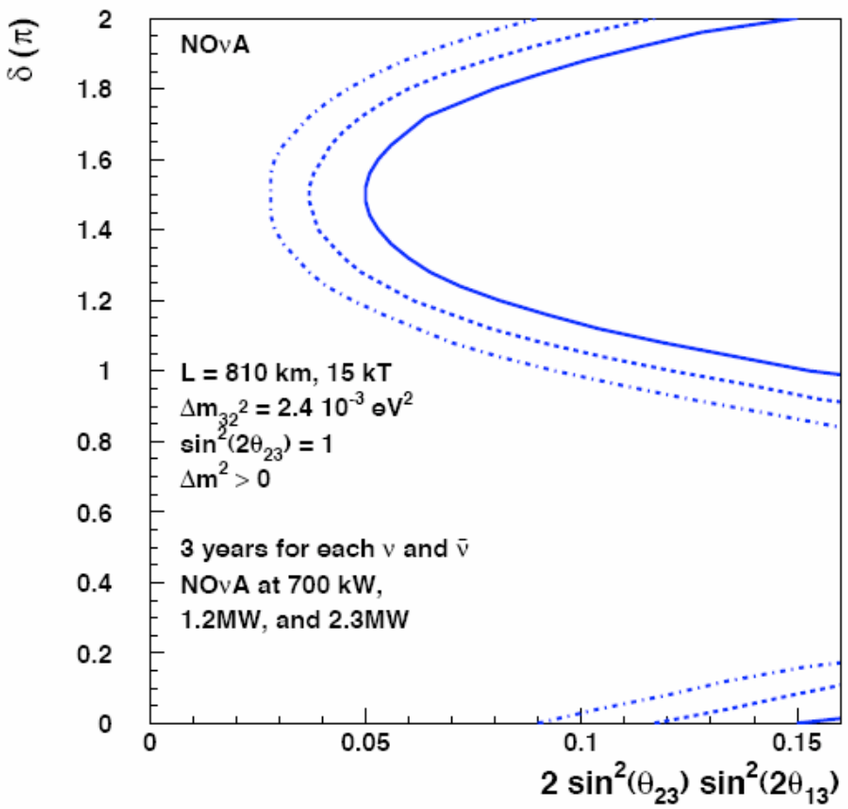
$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \quad = \quad 2\langle\theta\rangle/\theta_{crit} \quad \approx \quad 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

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

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

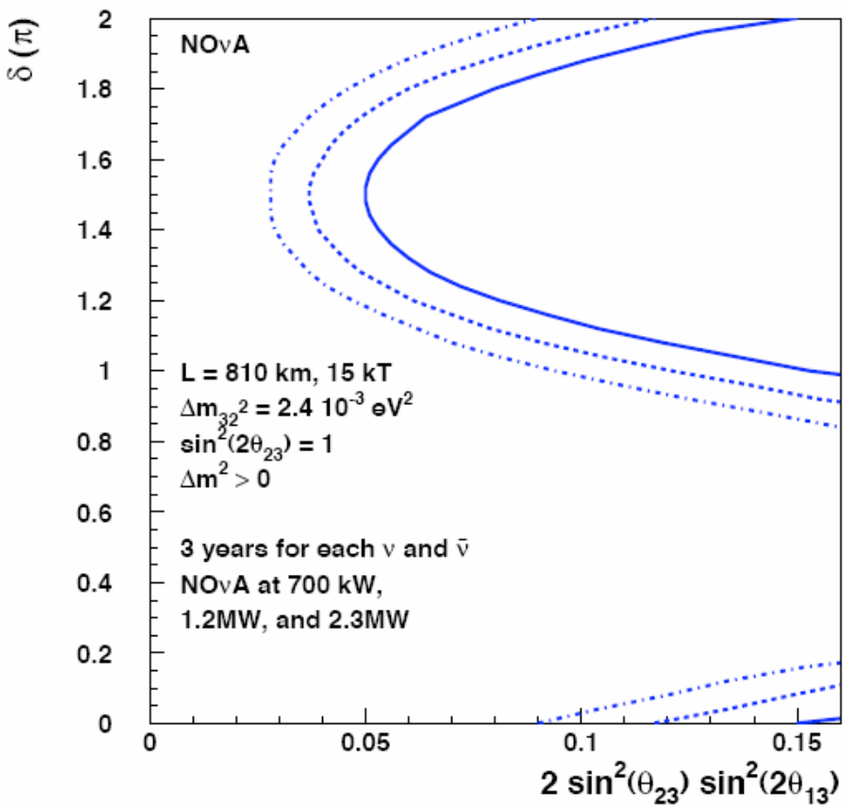
i.e. $\sin^2 2\theta_{crit} = 0.10$

95% CL Resolution of the Mass Ordering
NOνA Alone



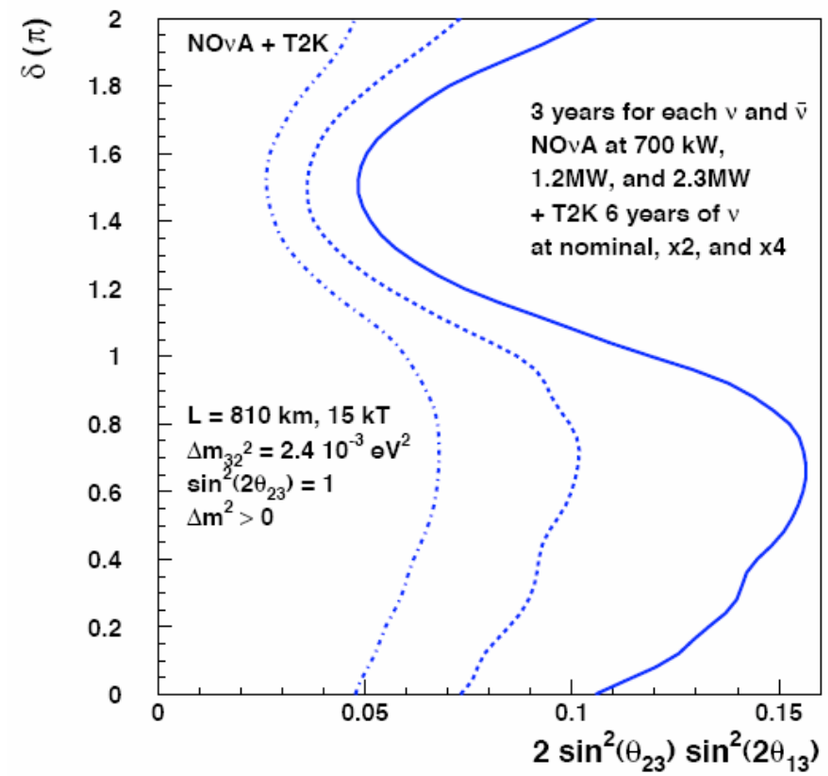
Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Alone



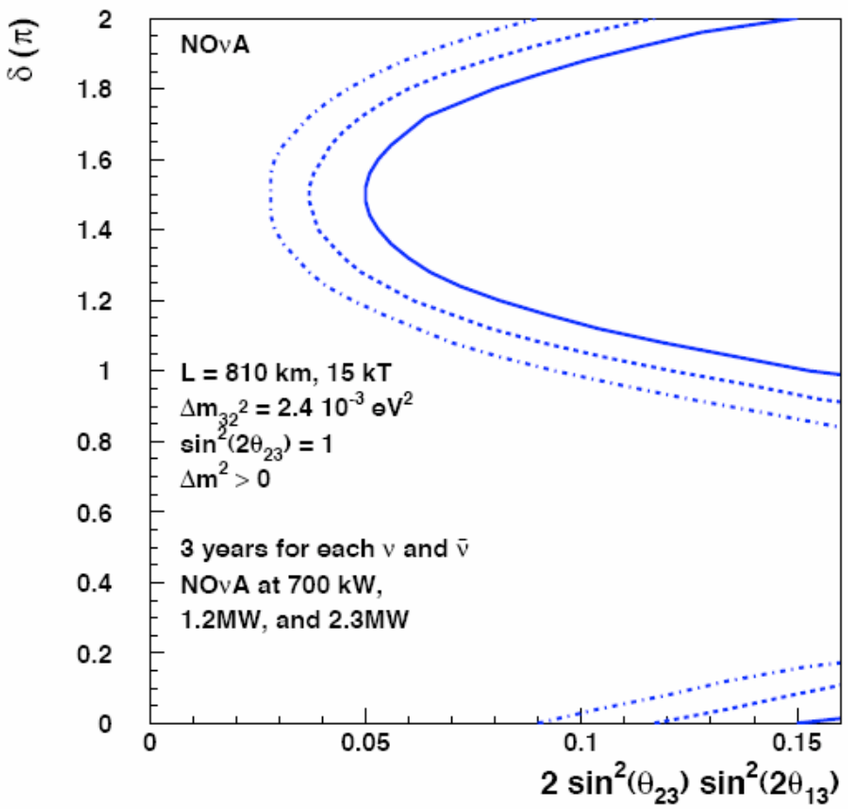
Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



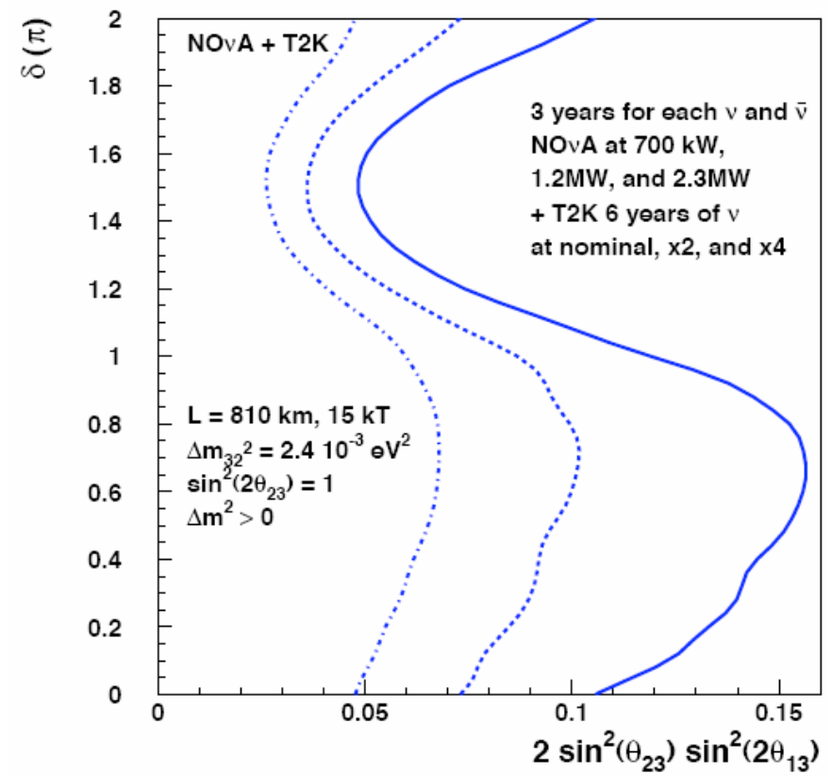
Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Alone



Normal Ordering

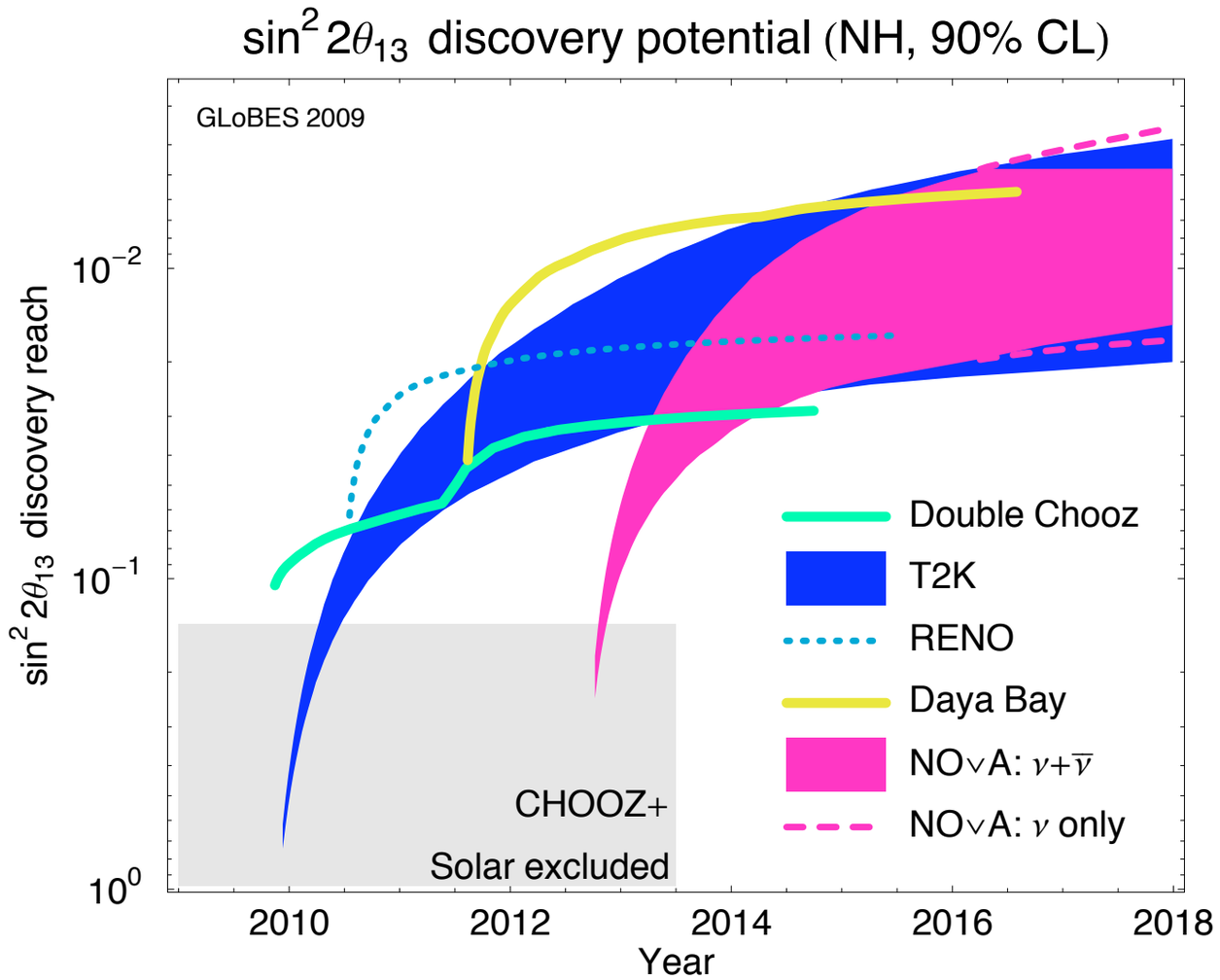
95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

for Inverted Hierarchy $\delta \rightarrow \pi - \delta$

Huber, Lindner, Schwetz, Winter
arXiv:0907.189



(if IH similar)

Assumes $\sin^2\theta_{23} = \frac{1}{2}$

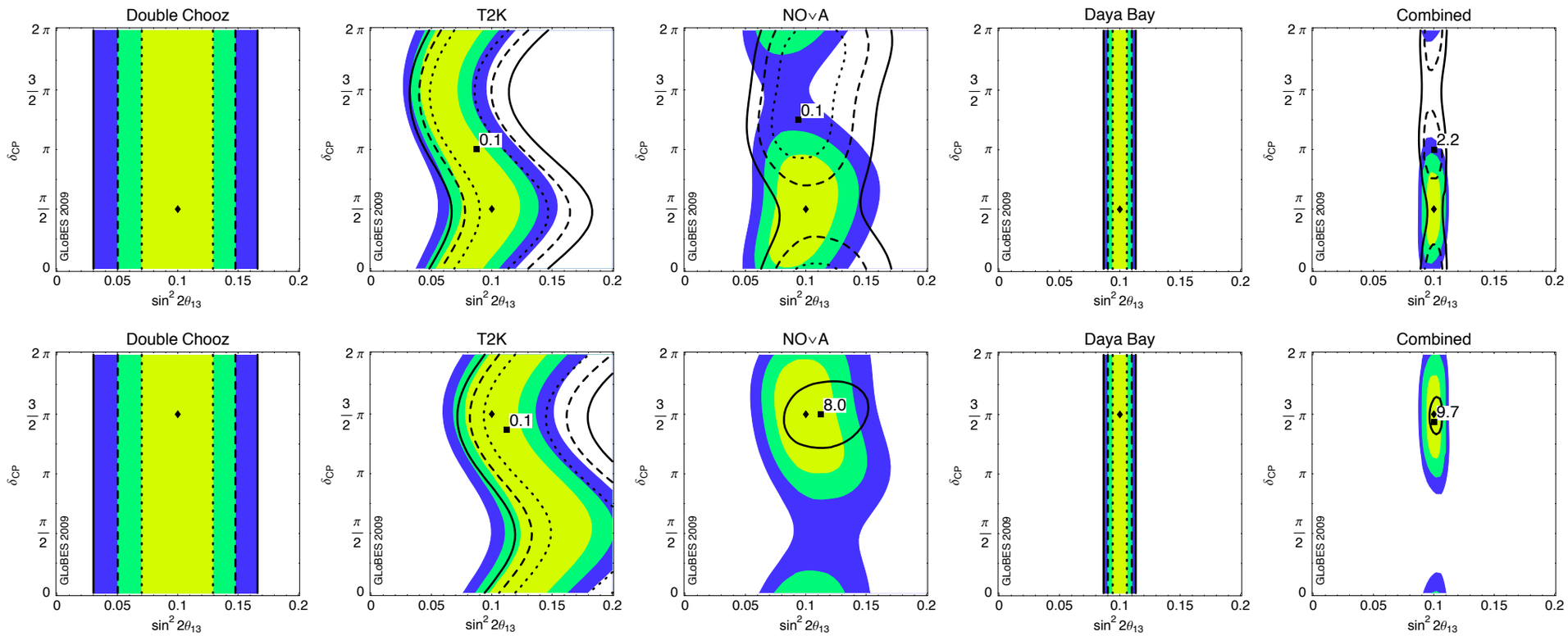
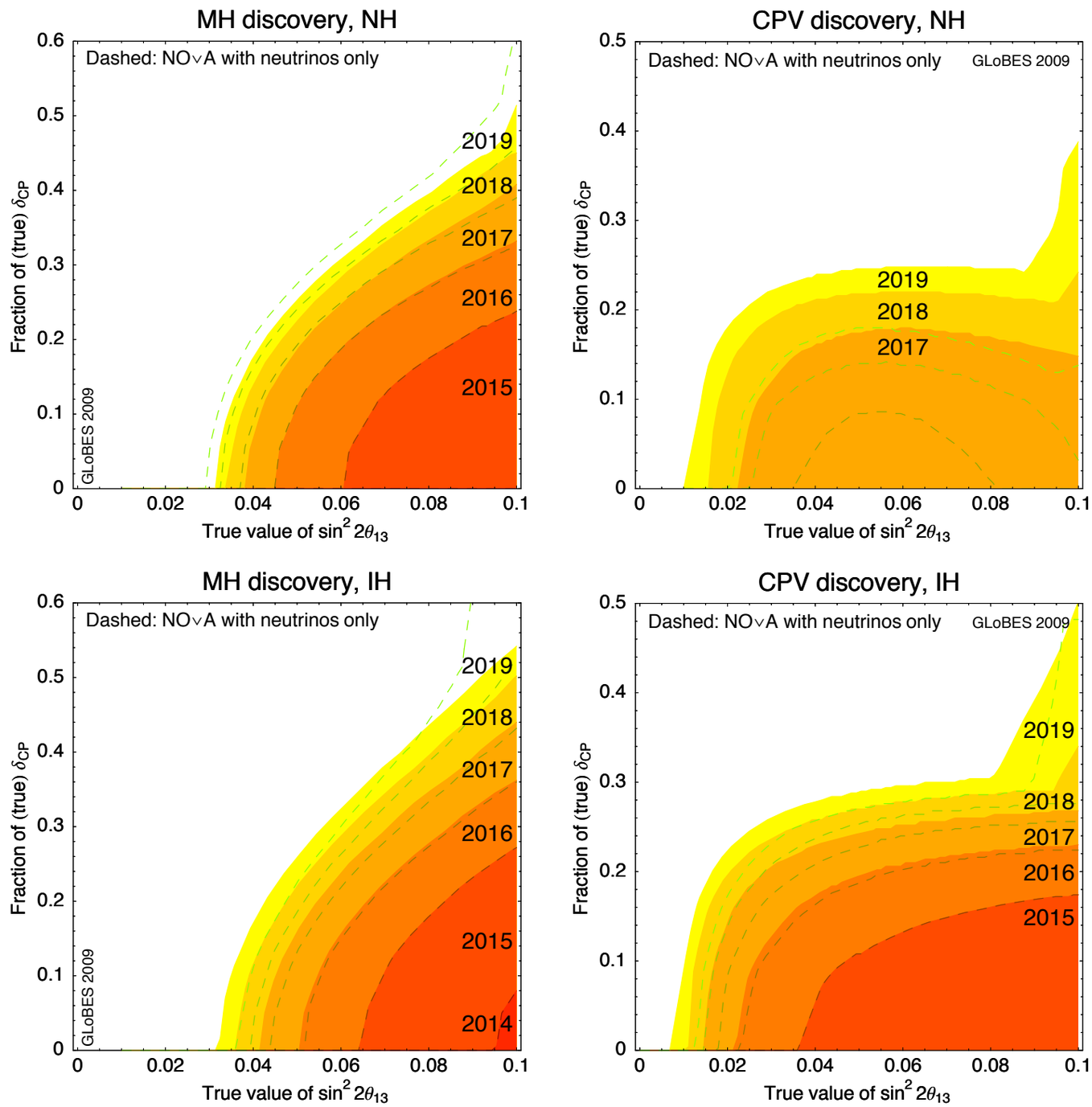
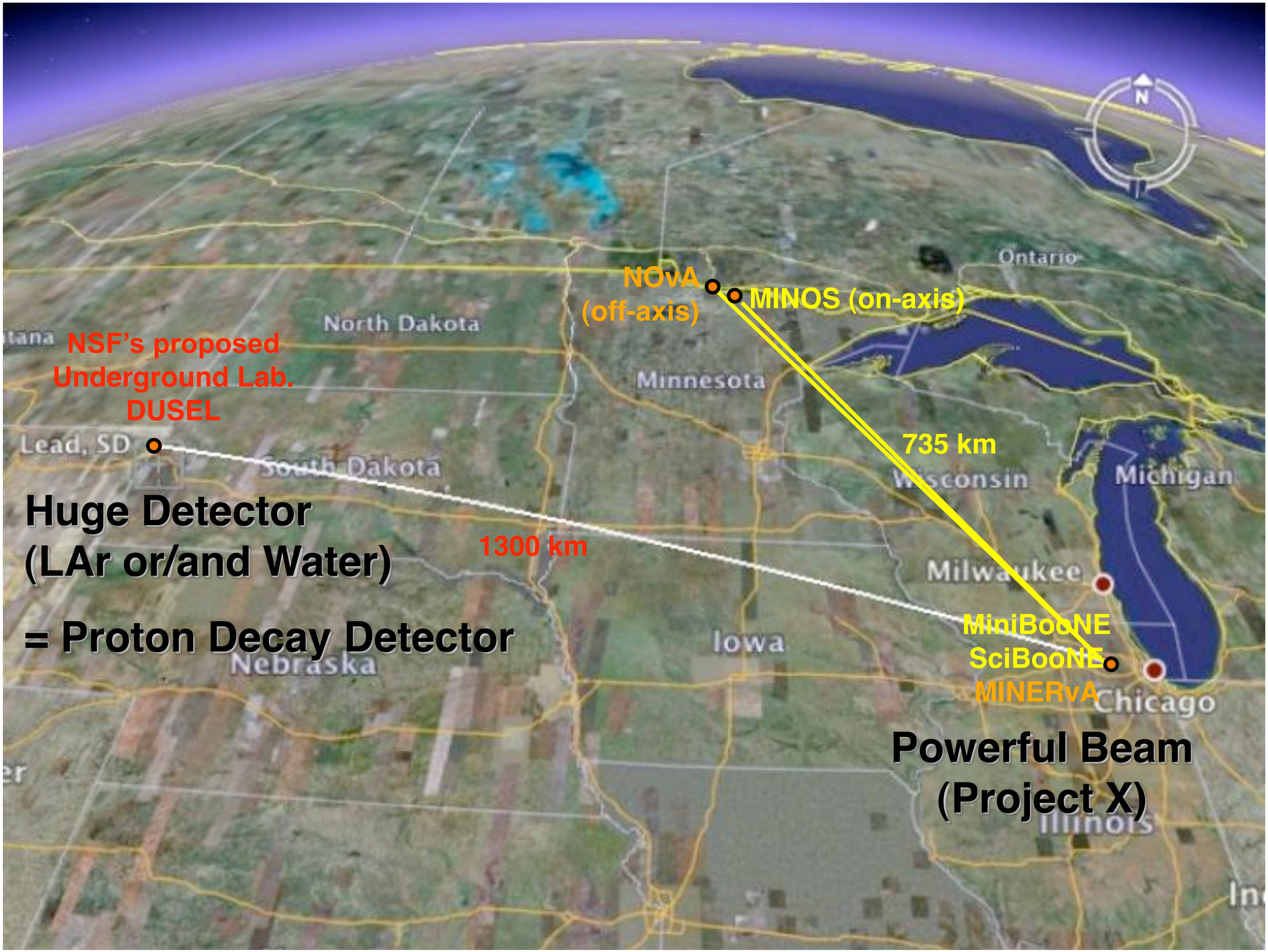


Figure 2: Fits in the θ_{13}-$\delta_{\rm CP}$ plane for $\sin^2 2\theta_{13} = 0.1$ and $\delta_{\rm CP} = \pi/2$ (upper row) and $\delta_{\rm CP} = 3\pi/2$ (lower row). A normal simulated hierarchy is assumed. The contours refer to 1σ, 2σ, and 3σ (2 d.o.f.). The fit contours for the right fit hierarchy are shaded (colored), the ones for the wrong fit hierarchy fit are shown as curves. The best-fit values are marked by diamonds and boxes for the right and wrong hierarchy, respectively, where the minimum χ^2 for the wrong hierarchy is explicitely shown.

Assumes $\sin^2\theta_{23} = \frac{1}{2}$


MH discovery, NH
Dashed: NOνA with neutrinos only
GLoBES 2009
2019
2018
2017
2016
2015
Fraction of (true) δ_{CP}
True value of $\sin^2 2\theta_{13}$
CPV discovery, NH
Dashed: NOνA with neutrinos only
GLoBES 2009
2019
2018
2017
Fraction of (true) δ_{CP}
True value of $\sin^2 2\theta_{13}$
MH discovery, IH
Dashed: NOνA with neutrinos only
GLoBES 2009
2019
2018
2017
2016
2015
2014
Fraction of (true) δ_{CP}
True value of $\sin^2 2\theta_{13}$
CPV discovery, IH
Dashed: NOνA with neutrinos only
GLoBES 2009
2019
2018
2017
2016
2015
Fraction of (true) δ_{CP}
True value of $\sin^2 2\theta_{13}$


NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
735 km
South Dakota
Wisconsin
Michigan
Huge Detector
(LAr or/and Water)
1300 km
Milwaukee
= Proton Decay Detector
MiniBooNE
SciBooNE
MINERvA
Iowa
Nebraska
Chicago
Powerful Beam
(Project X)
Illinois

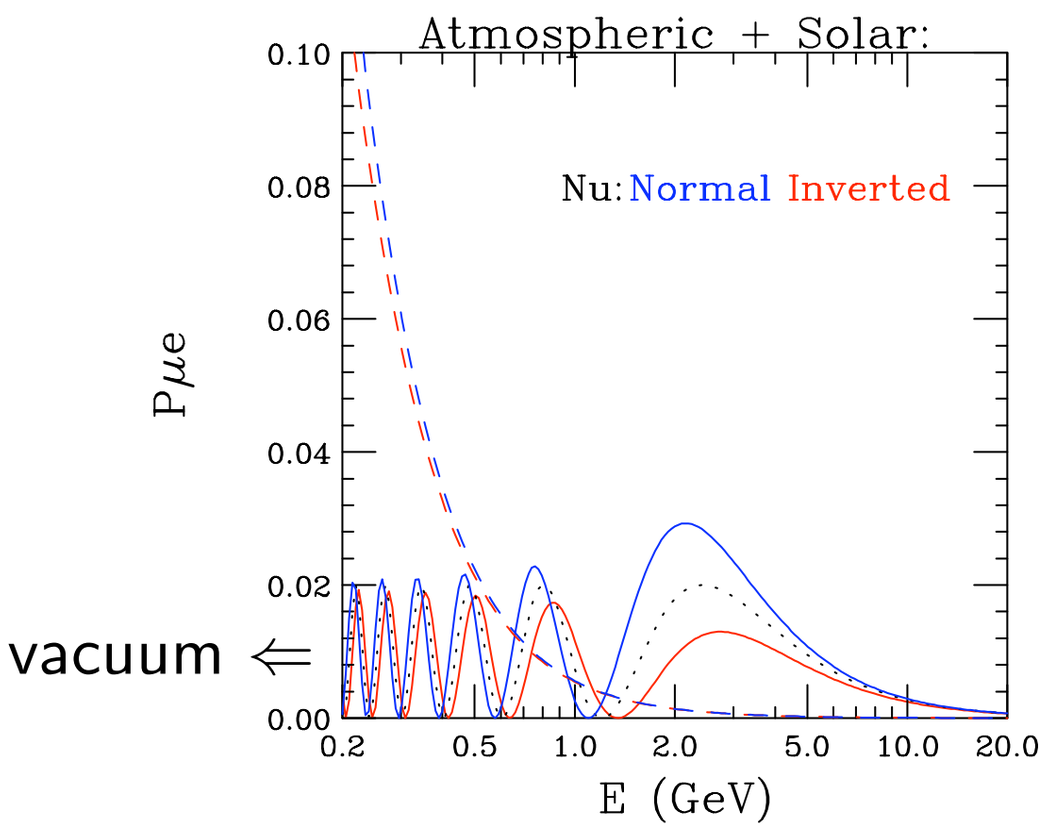
Narrow Band Beam: Same E, Longer L T2KK

Broadband Beam: Same L, Lower E Fermilab to DUSEL

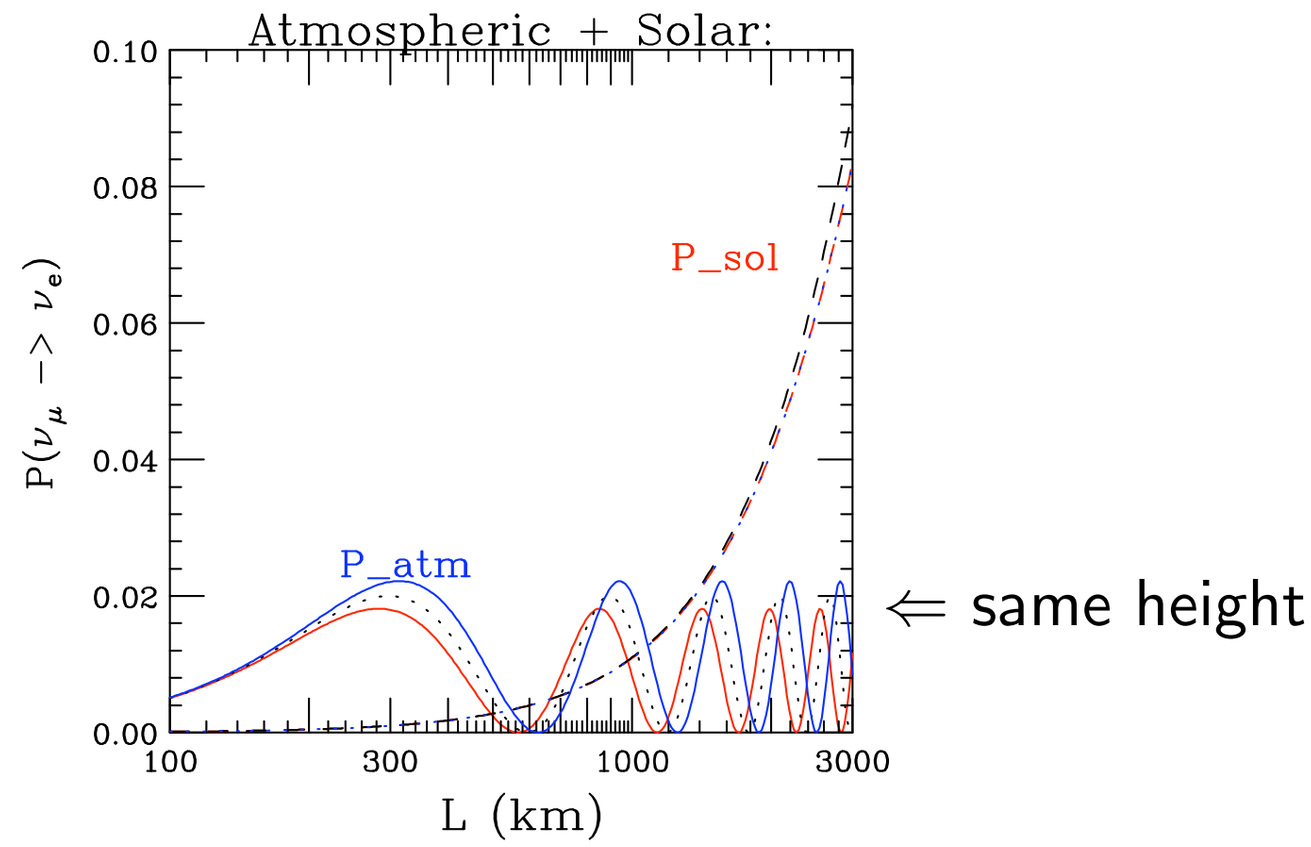
In VACUUM the SAME but NOT in MATTER

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

L=1200km



E=0.6 GeV



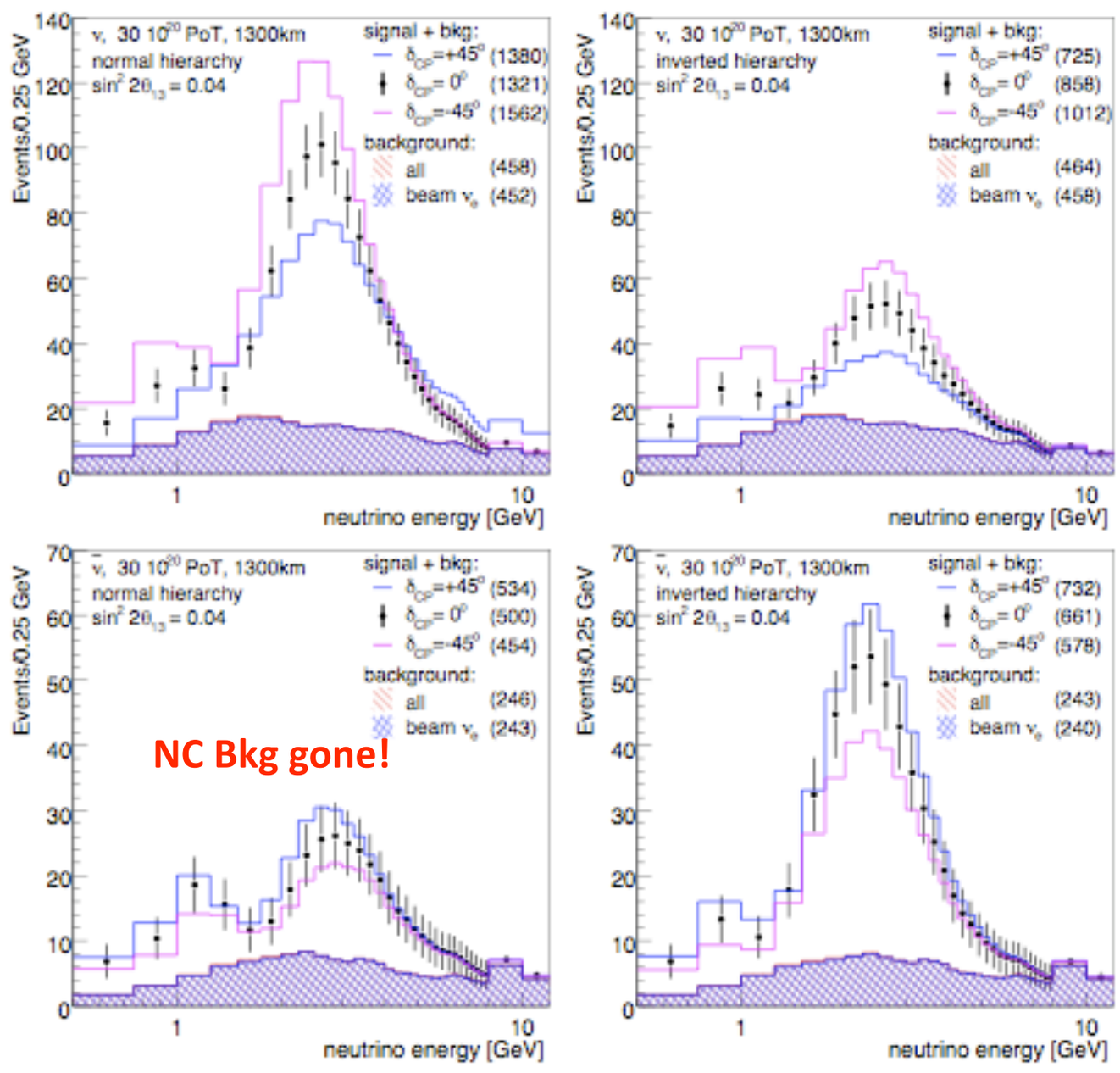
$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

LIQUID ARGON: 100KT

Normal Inverted

ν

$\bar{\nu}$



Studies suggest 100 kt LAR = 300kt WC

Summary & Conclusions

- Constraint on $|\sin^2\theta_{23} - \frac{1}{2}|$ could be improved early in T2K/NOvA running.

- if $\sin^2 2\theta_{23} \neq 1$ then need to break the $\sin^2\theta_{23} < \text{or} > \frac{1}{2}$ degeneracy! Makes comparison of reactor and long baseline limits more complicated.

- REASONABLE GOAL:

$$\sin^2\theta_{13},\ |\sin^2\theta_{12} - \tfrac{1}{3}|,\ |\sin^2\theta_{23} - \tfrac{1}{2}| \ \sim\ \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 10^{-3}$$

- Wide Band Beams:
  - precision info coming from first (highest energy) peak:
  - degeneracies broken by info at second peak