Physics Opportunities
at
Neutrino Factory:

Stephen Parke
Fermilab

NFMCC: Jan 25, 2009

"All the News That's Fit to Print"

The New York

VOL. CXLVII .... No. 51,179 FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the

Detecting Neutrinos

1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light,

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Bajram Curri, in nc

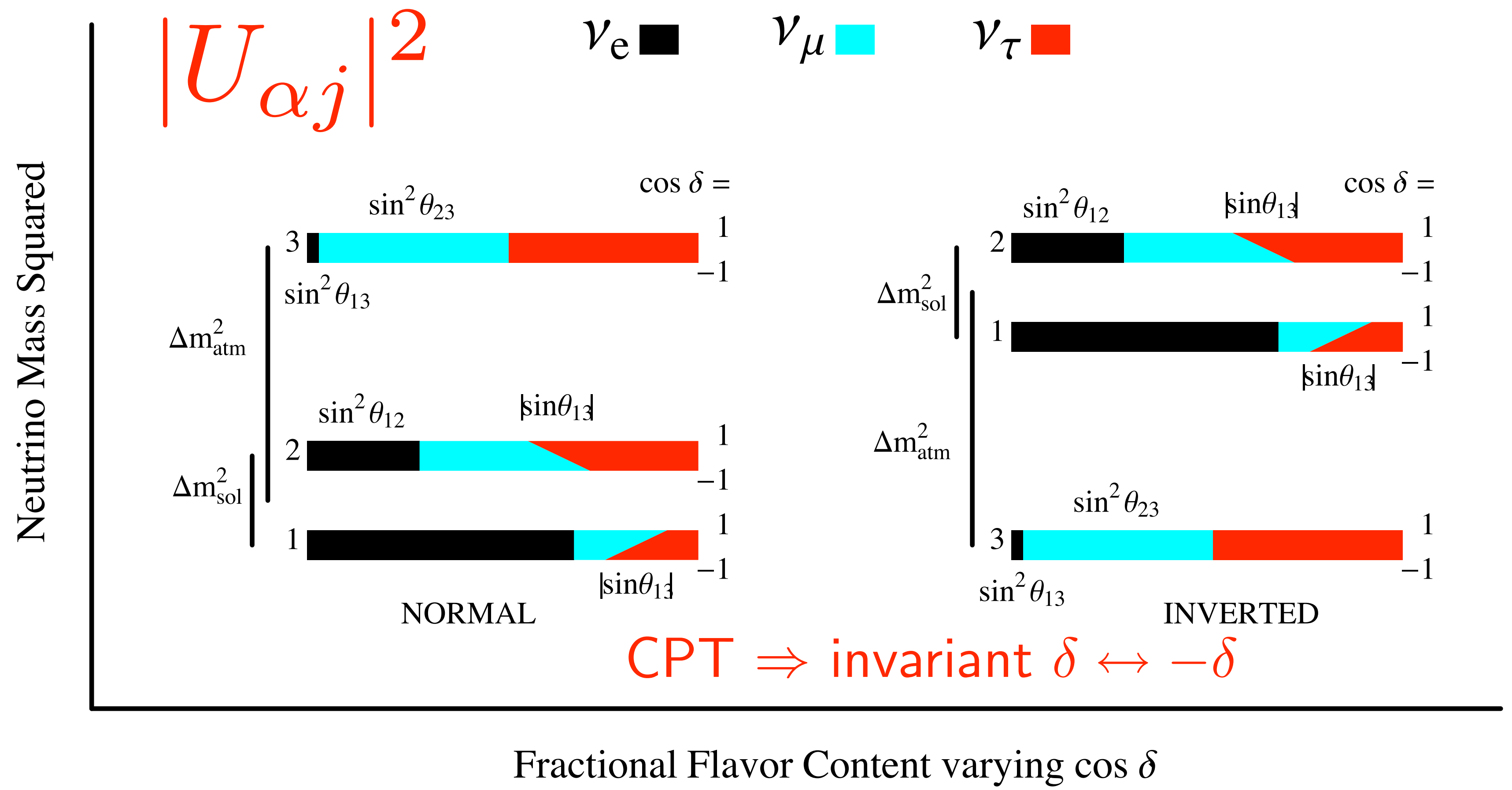
Mixing Matrix:

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

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

Atmos. L/E $\mu \to \tau$ — Atmos. L/E $\mu \leftrightarrow e$ — Solar L/E $e \to \mu, \tau$ — $0\nu\beta\beta$ decay

500km/GeV — 15km/MeV



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \qquad \sin^2\theta_{12} \sim 1/3$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \qquad \sin^2\theta_{23} \sim 1/2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03 \qquad \sin^2\theta_{13} < 3\%$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e \qquad 0 \leq \delta < 2\pi$$

One Global Fit:

Dominated by

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

arXiv:0808.2016

Neutrino

Mass Spectrum:

- Quasi-Degenerate ?
- Hierarchical ?
- Normal or Inverted ?

Mixings:

- Deviations from $U_{Tri-Bi-Max}$
  $\sin^2\theta_{13}$, $(\sin^2\theta_{23} - 1/2)$, $(\sin^2\theta_{12} - 1/3)$
- Relationship between these deviations and
  $V_{CKM} - 1$
  if any ?
- Magnitude and sign of CPV:
  $\propto \sin\theta_{13}\sin\delta$

eg: Sum rules

$$\theta_{13} \sim \theta_c/3\sqrt{2}\ .$$

$$\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,\mathrm{TBM}} - \frac{1}{2}\theta_c\cos\delta\ ,$$

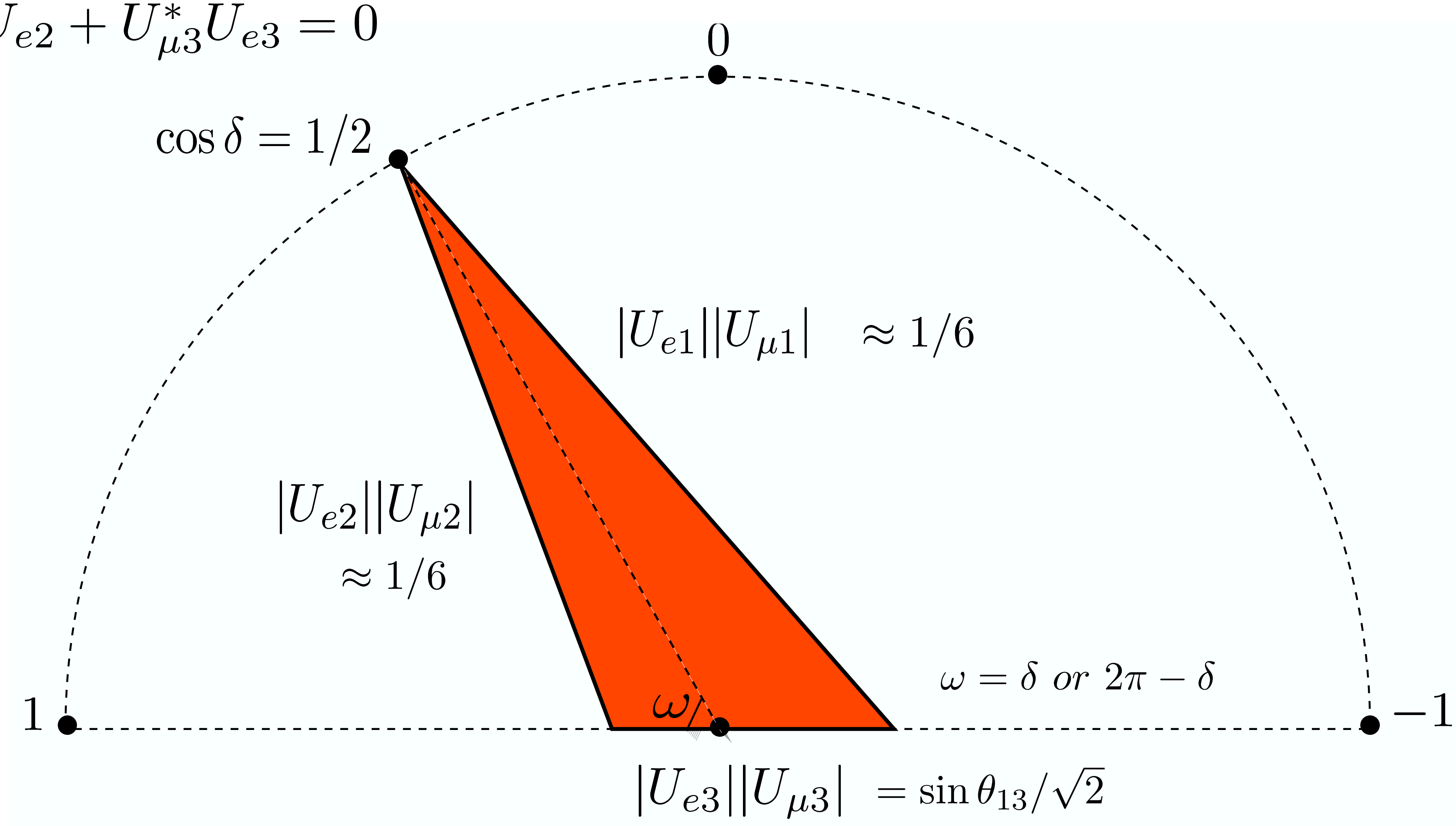
Chen and Mahanthappe - arXiv:0812:4981

Sine/Signs

- $|U_{e3}|^2$: $\sin^2\theta_{13}$
- Hierarchy: $sign(\delta m^2_{31}\ or\ \delta m^2_{32})$
- CPV: $\sin\delta$
- Maximal Mixing: $\sin^2\theta_{23} = \frac{1}{2}$
- Quadrant of δ: $\cos\delta = \pm\sqrt{1-\sin^2\delta}$
- Unitarity: lite sterile ν's
- New Interactions and Surprises

Unitarity Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$



$$|J| = 2 \times \mathcal{A}rea$$

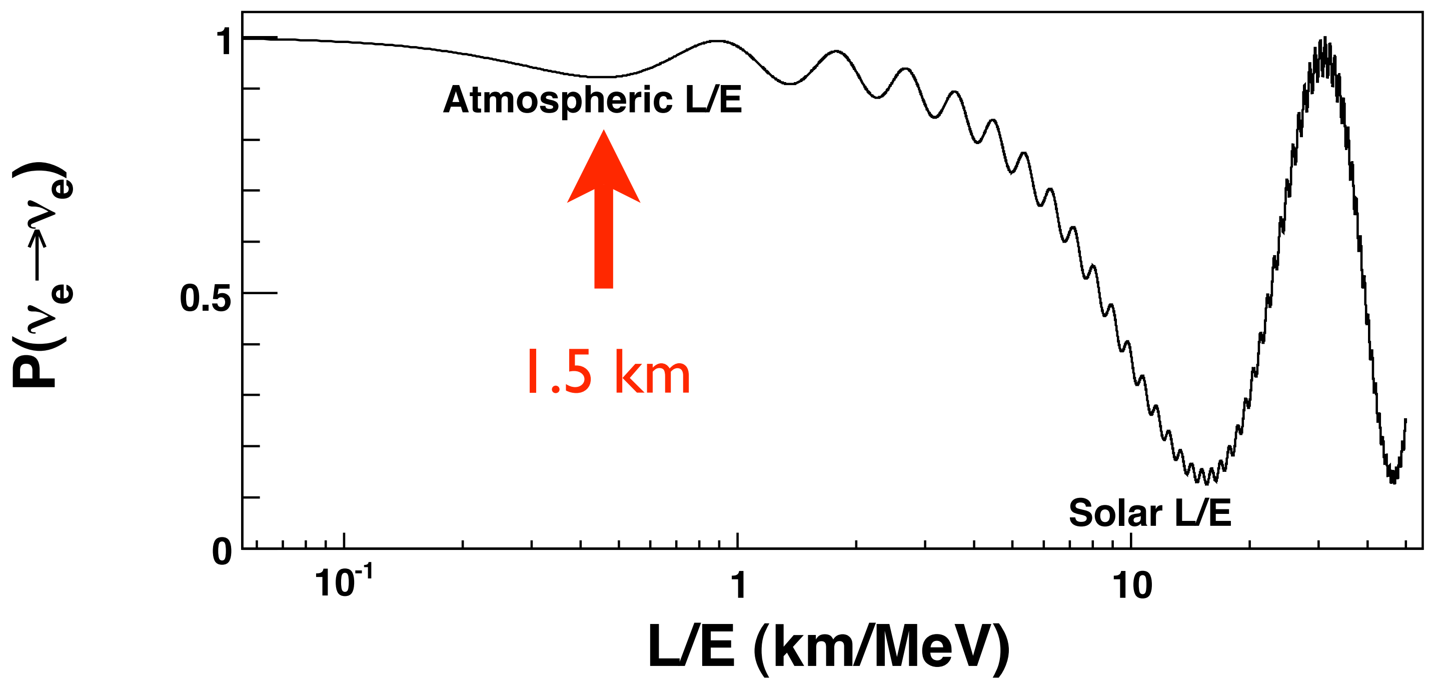
$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

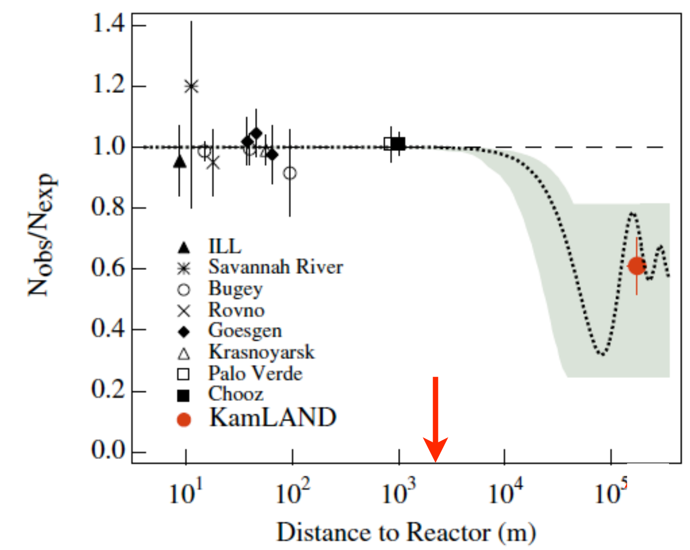
$\sin^2\theta_{13}$ from Reactor Neutrinos:

kinematic phase:

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

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





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

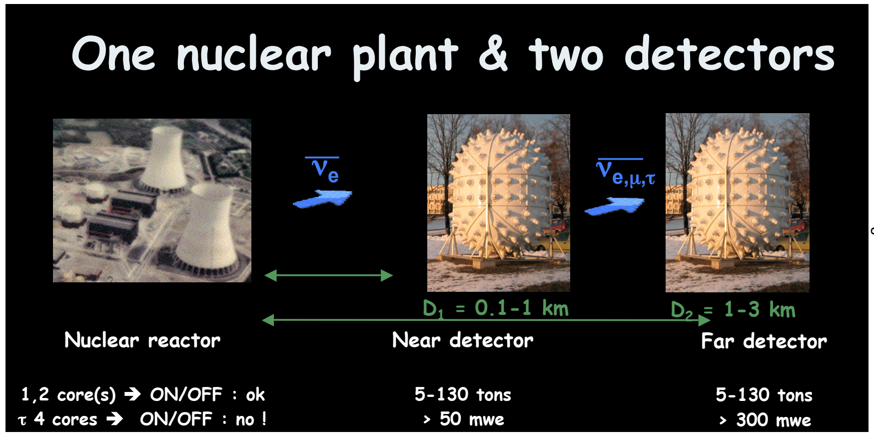
< 0.002

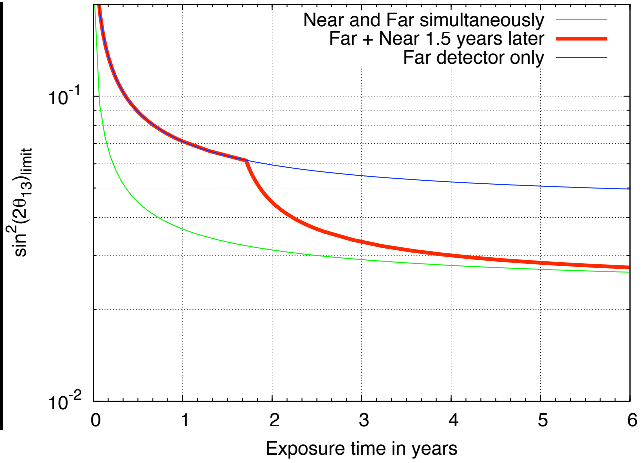
> 0.01

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

Double Chooz:

90% C.L. Sensitivities:

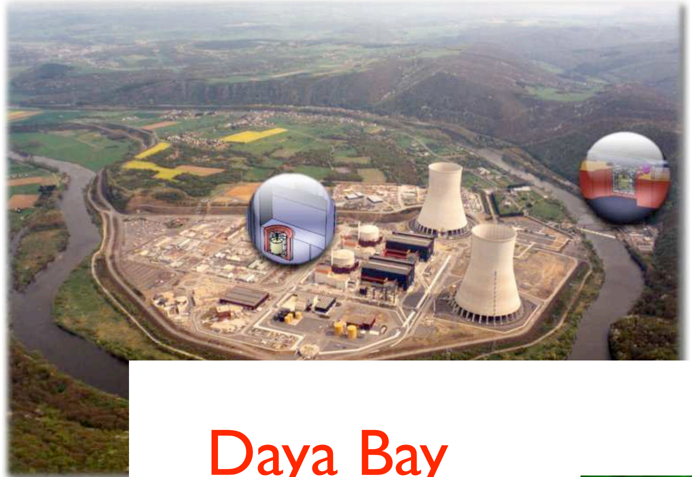




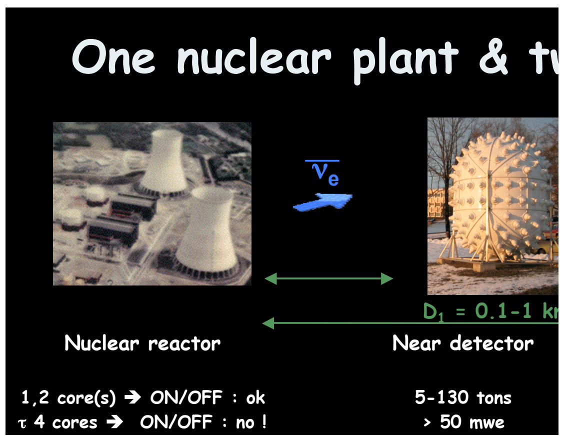
.03

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

Double Chooz:



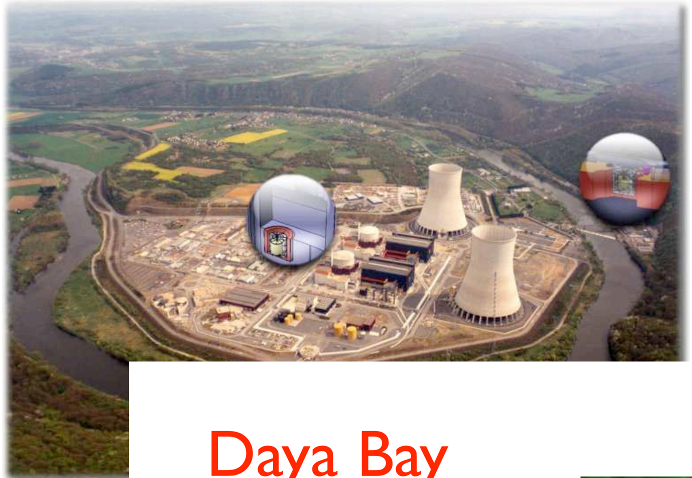
Daya Bay



90% C.L. Sensitivities:

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

Double Chooz:



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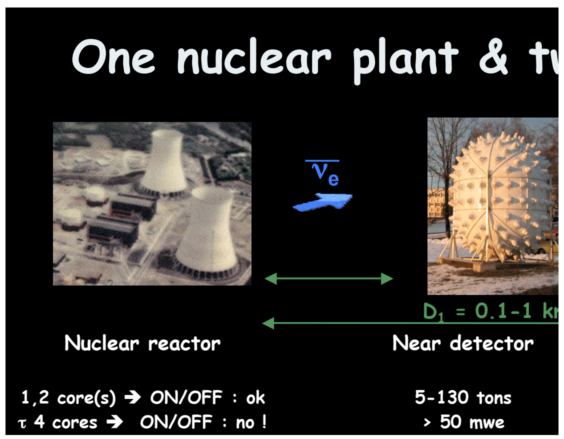
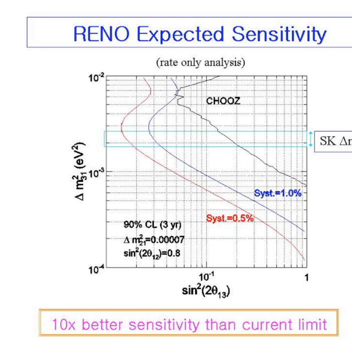


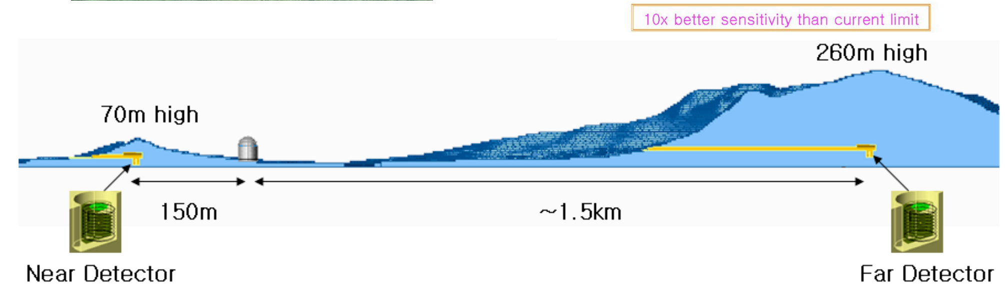
Daya Bay

push the limi

$$\sin^2 2\theta_{13} < 0$$

(Reactor Experiment for Neutrino Oscillation)





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

and related processes:

CP

$$\nu_\mu \to \nu_e \qquad \Longleftrightarrow \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

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

$$\nu_e \to \nu_\mu \qquad \Longleftrightarrow \qquad \bar{\nu}_e \to \bar{\nu}_\mu$$

CP

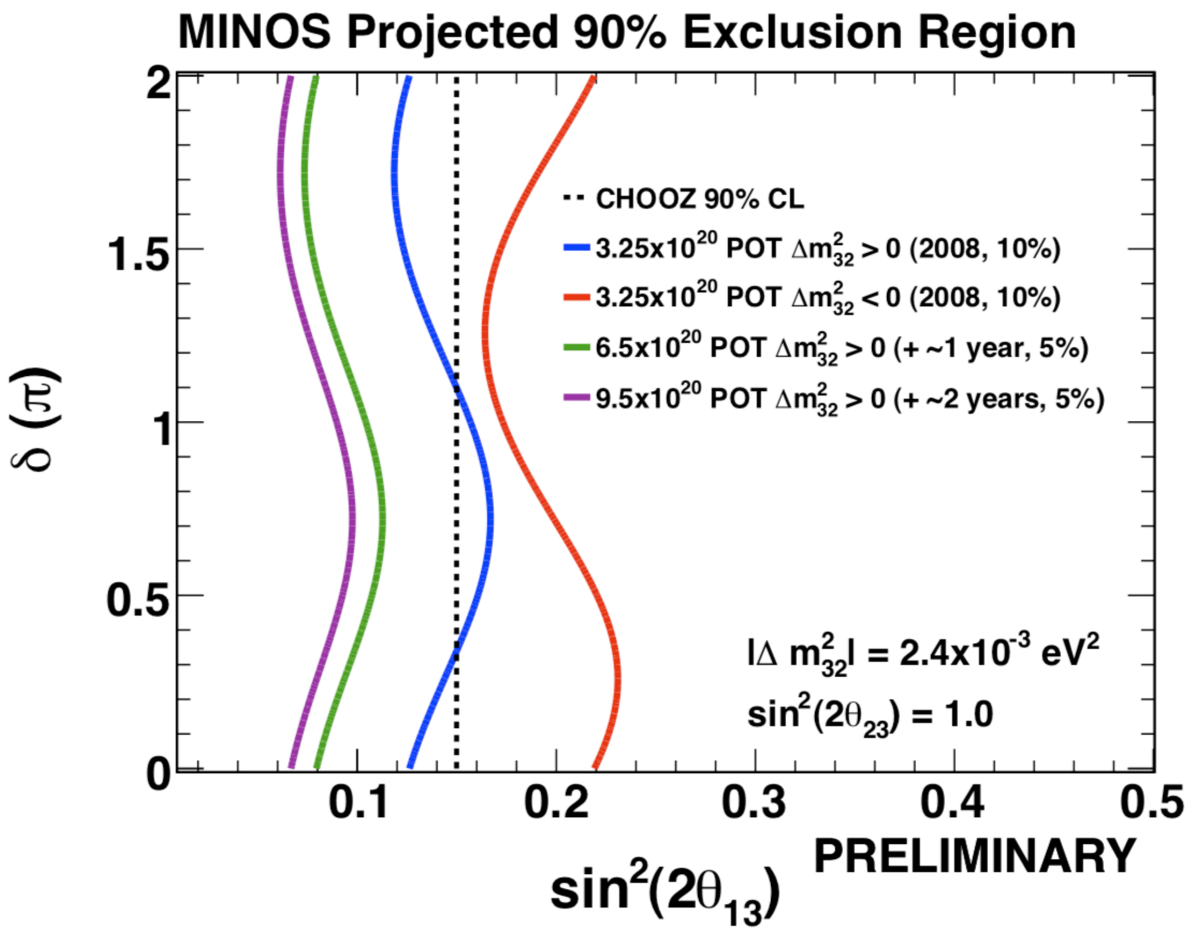
- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

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

MINOS:

ν_e Sensitivity

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008



At CHOOZ limit expect 12 ν_e signal events and 42 background events with 3.25×10^{20} protons.

Use sidebands to study predicted far detector backgrounds.

$\nu_\mu \longrightarrow \nu_e$

$$| \; U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} \; |^2$$

$\nu_\mu \longrightarrow \nu_e$

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

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

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

$\nu_\mu \to \nu_e$

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

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Atmospheric δm^2 — Solar δm^2

$\sqrt{P_{atm}}$ — $\sqrt{P_{sol}}$

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

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

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CP violation !!!

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

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

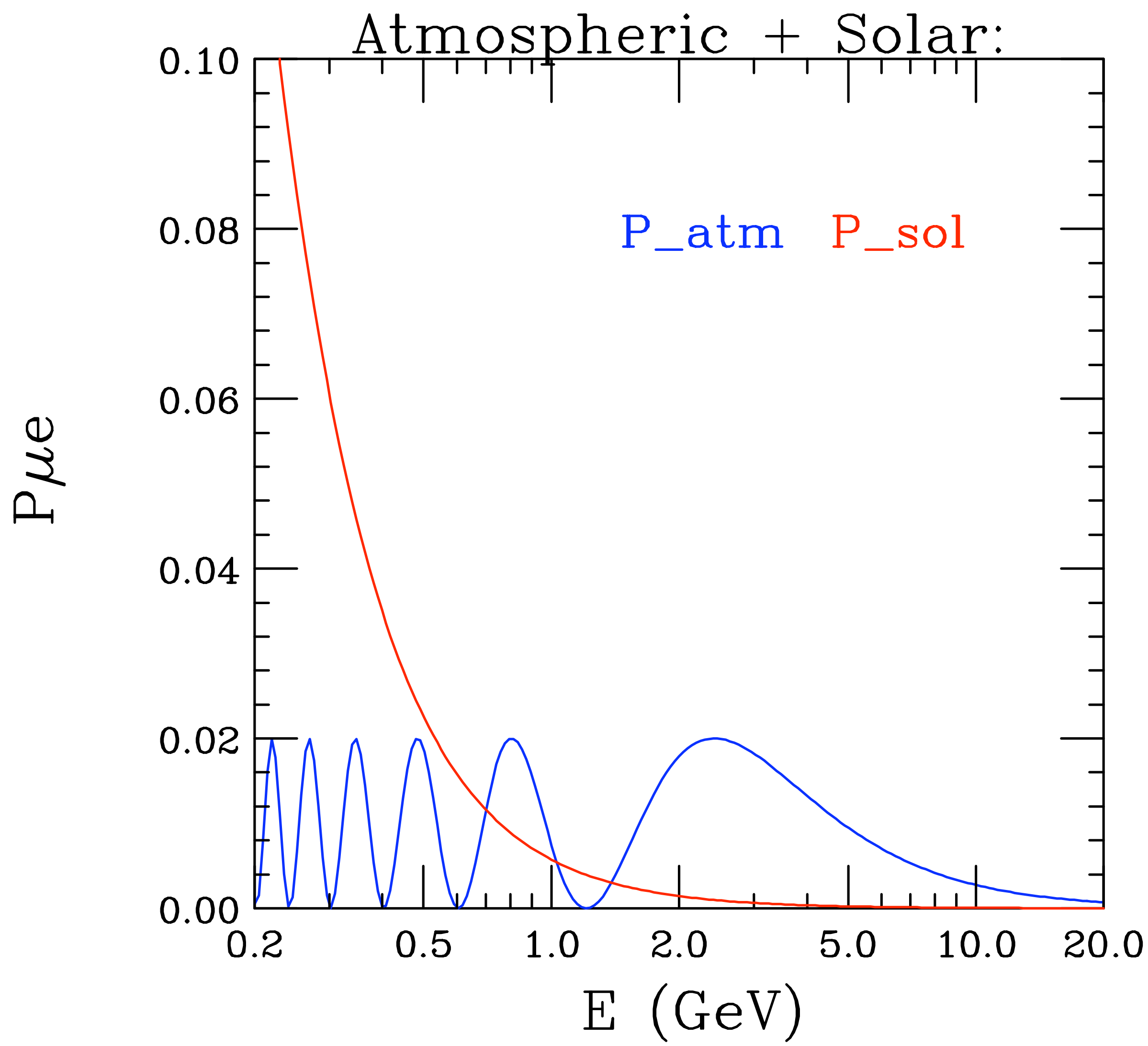
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}$$

only CPV

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

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

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



x 3

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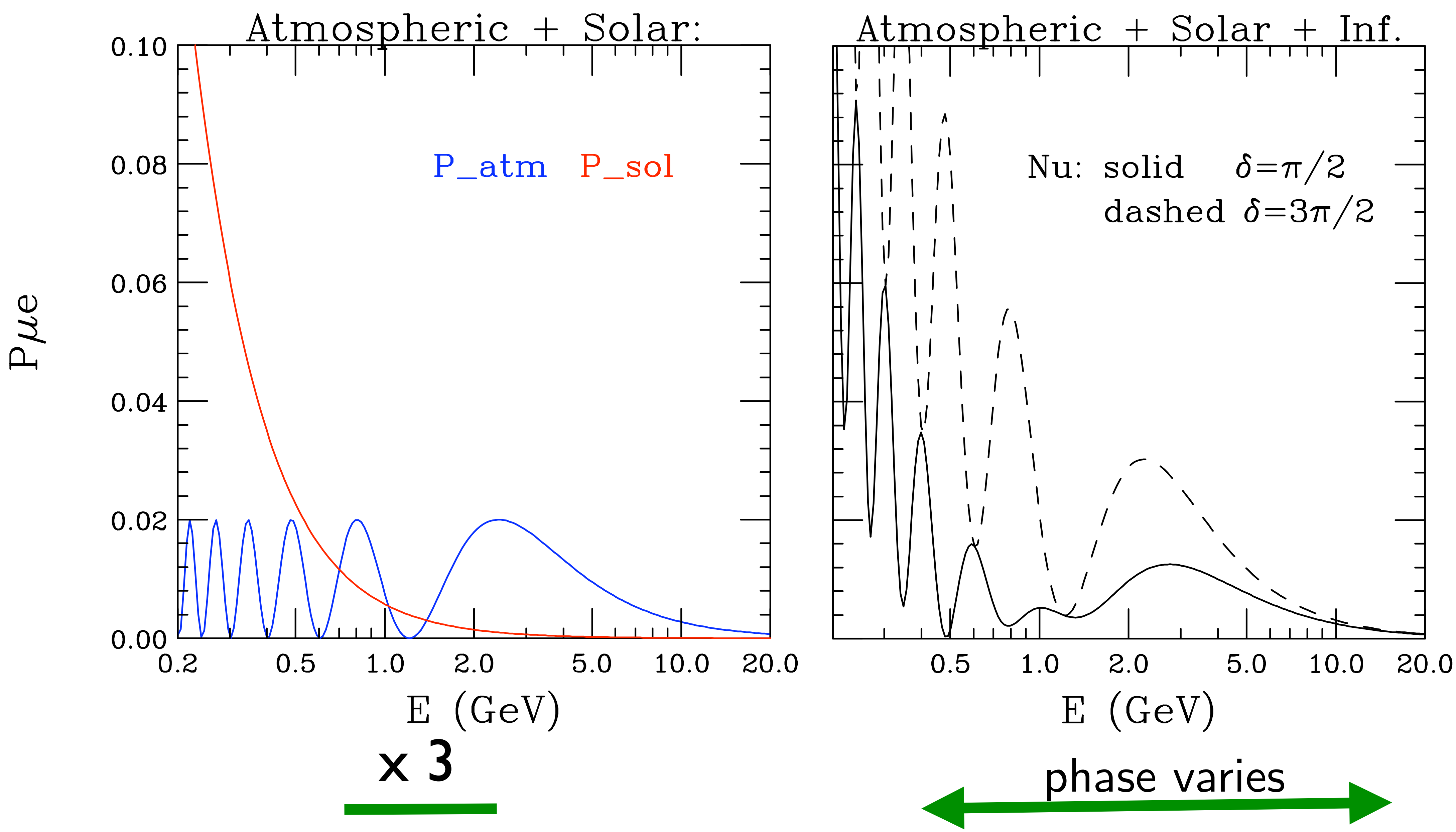
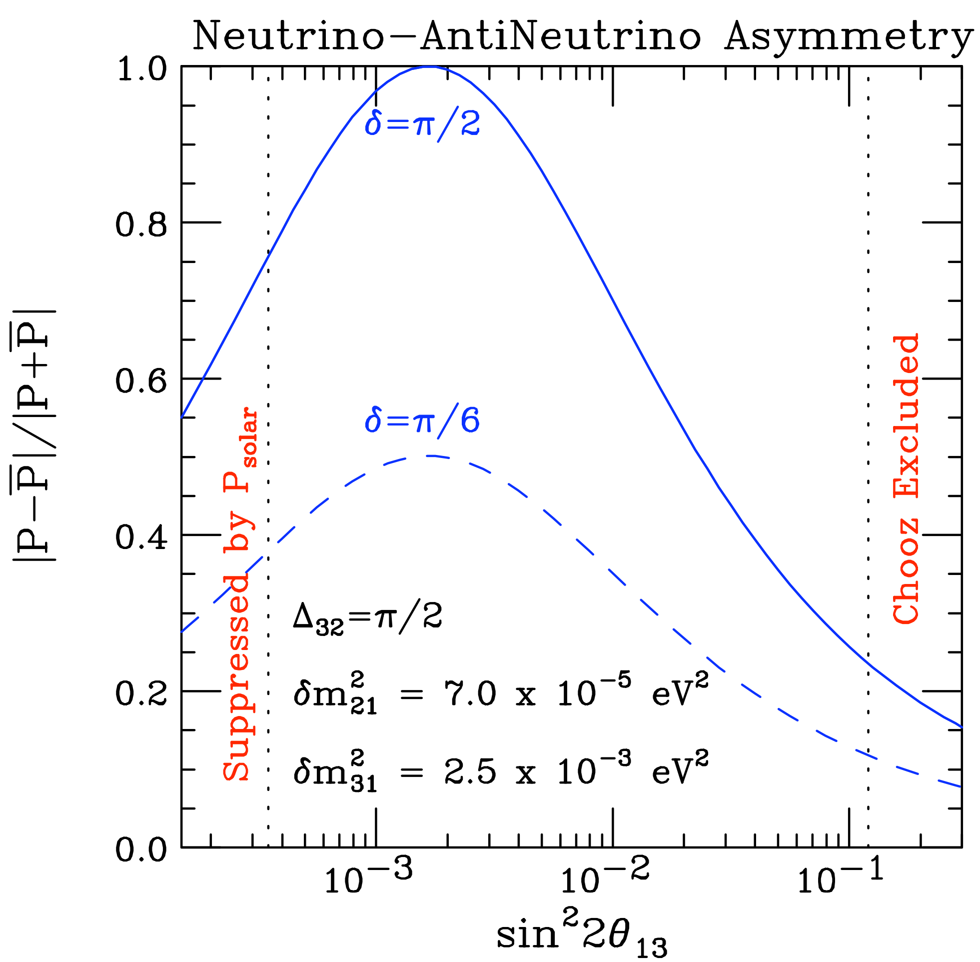


$$P_{\mu\to e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} |^2$$

Asymmetry Peaks:



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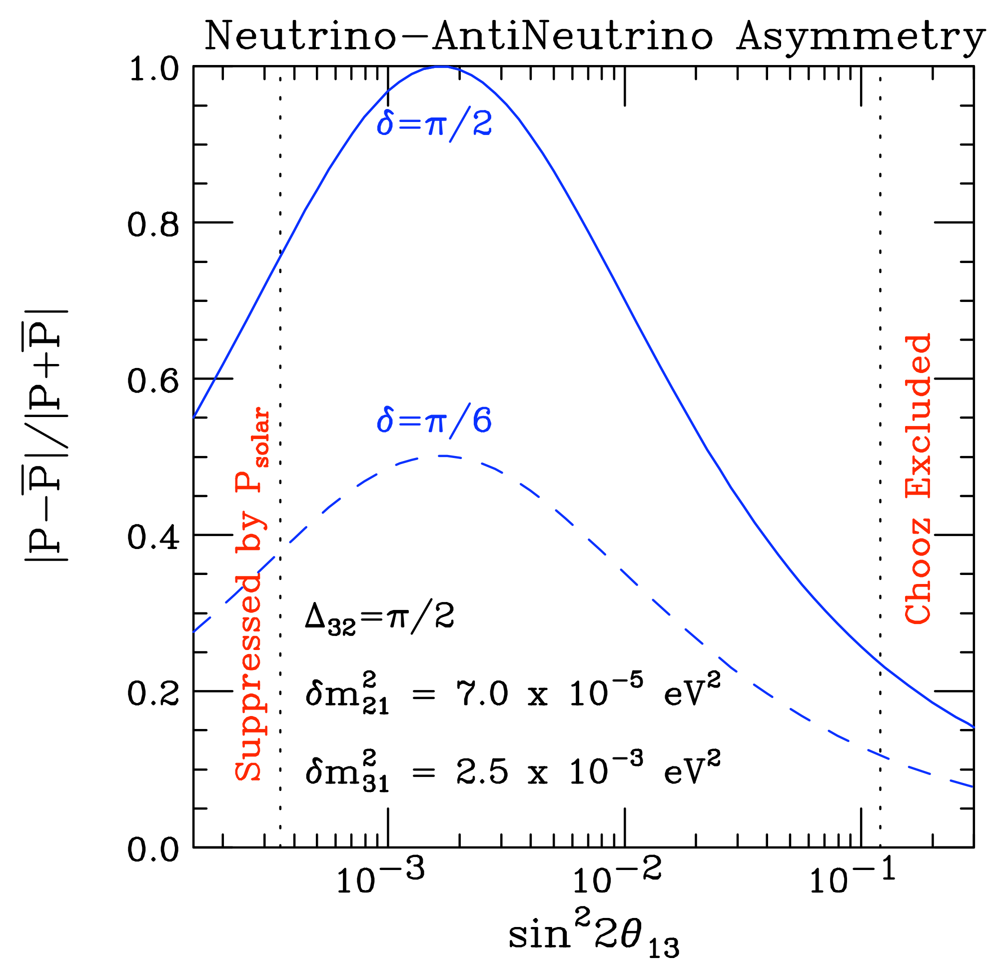

$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

In Matter:

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

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

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

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

In Matter:

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

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For $L = 1200\ km$
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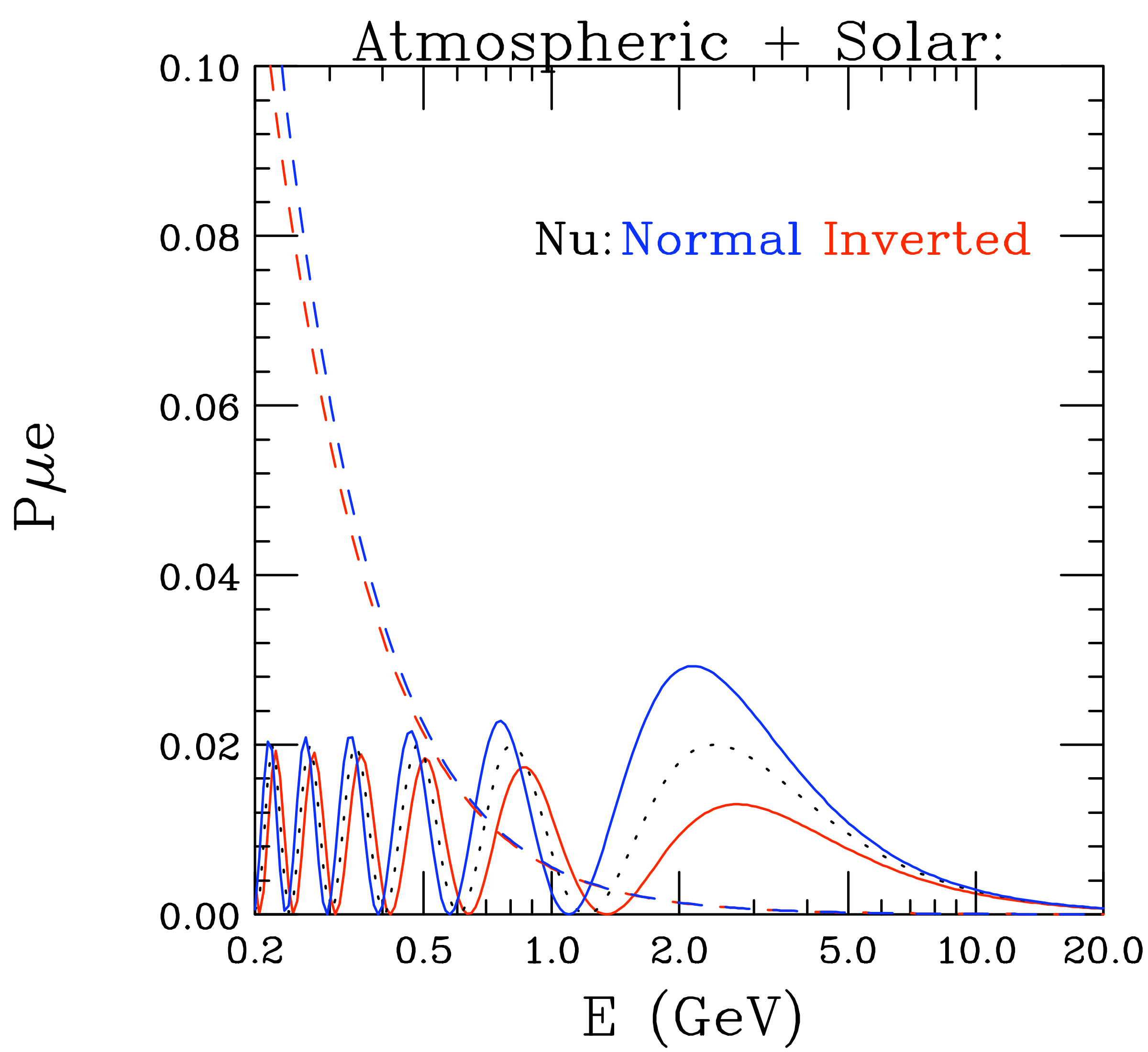

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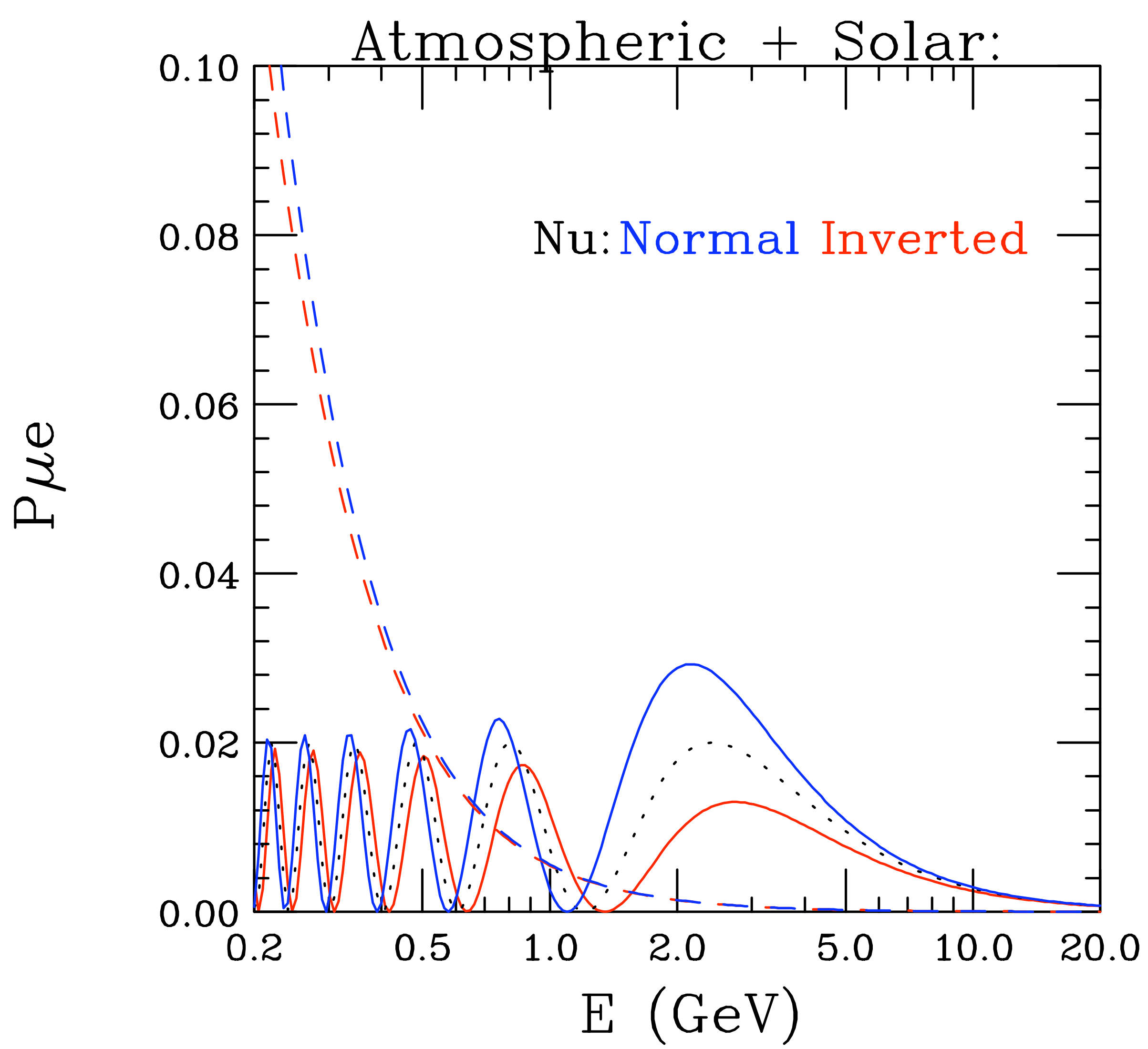
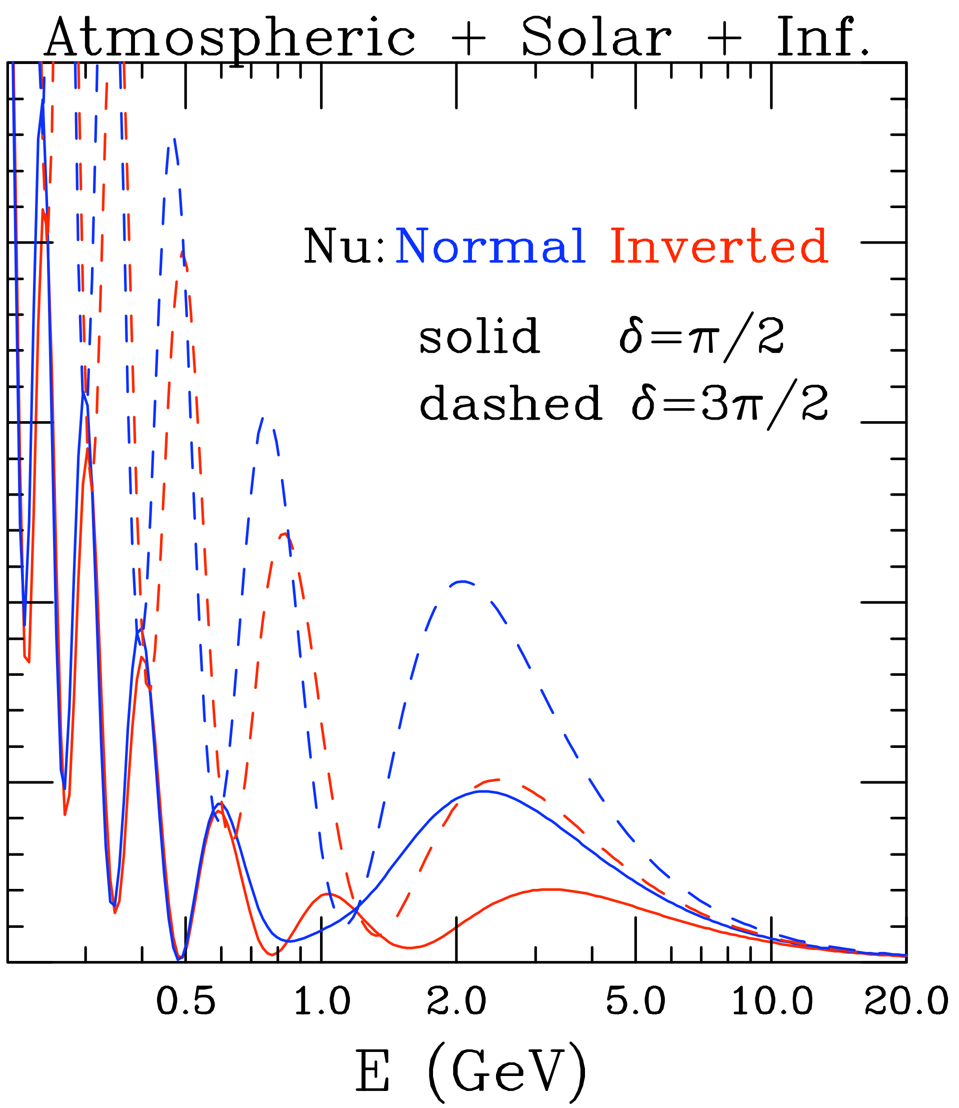
For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

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

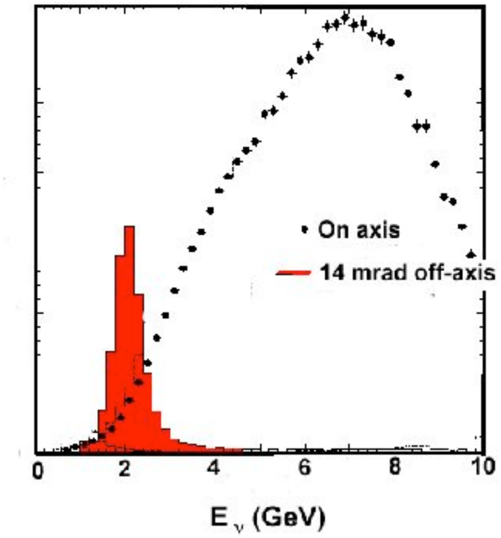
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





Off-Axis Beams

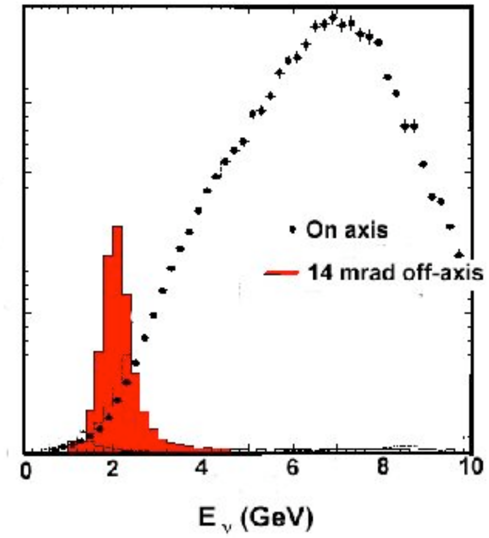
BNL 1994



π^0 suppression

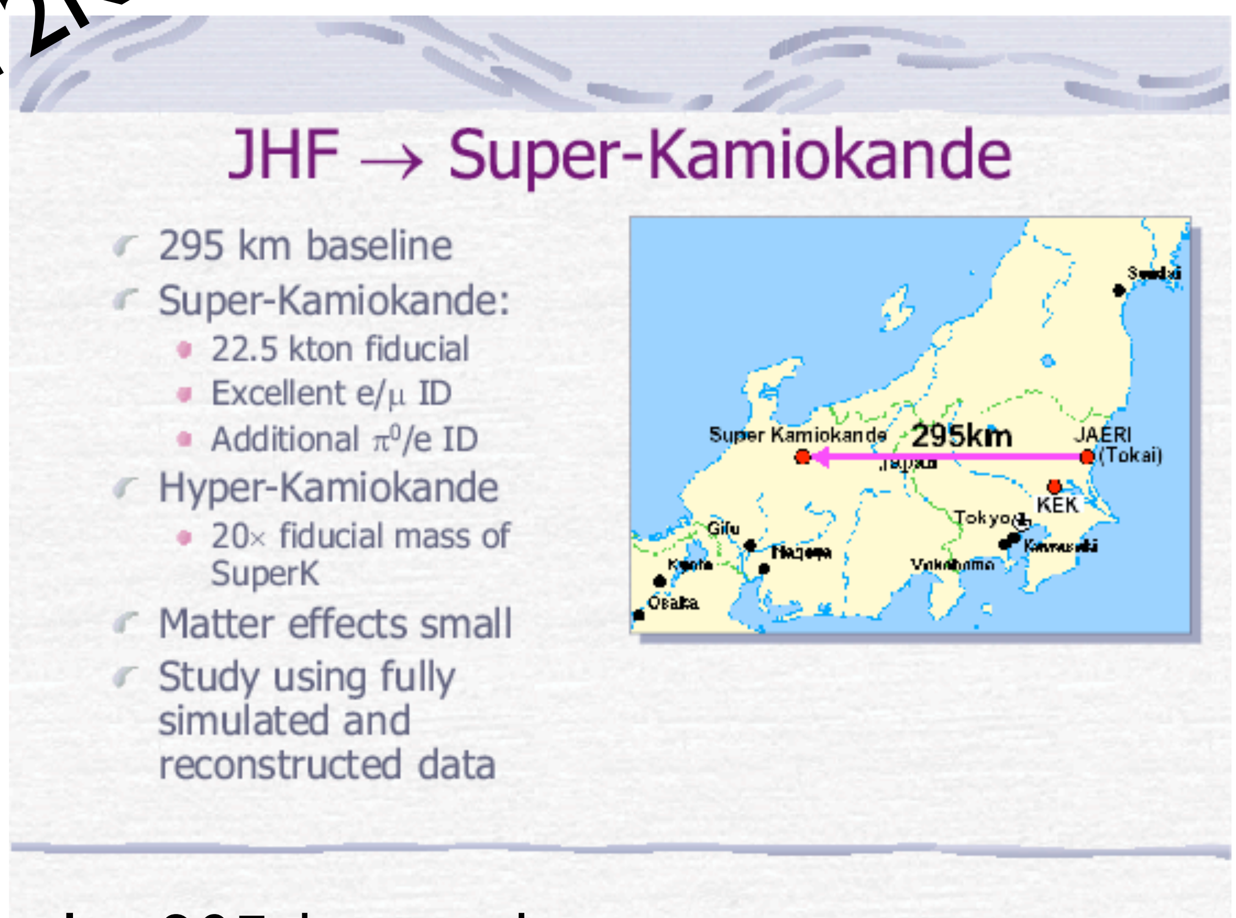
Off-Axis Beams

BNL 1994



π^0 suppression

T2K



L=295 km and

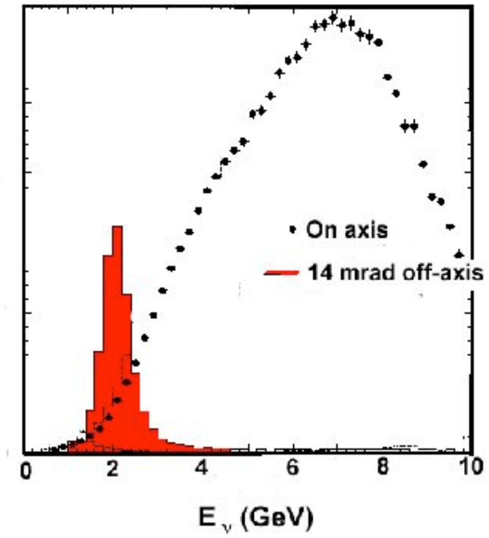
Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times 10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

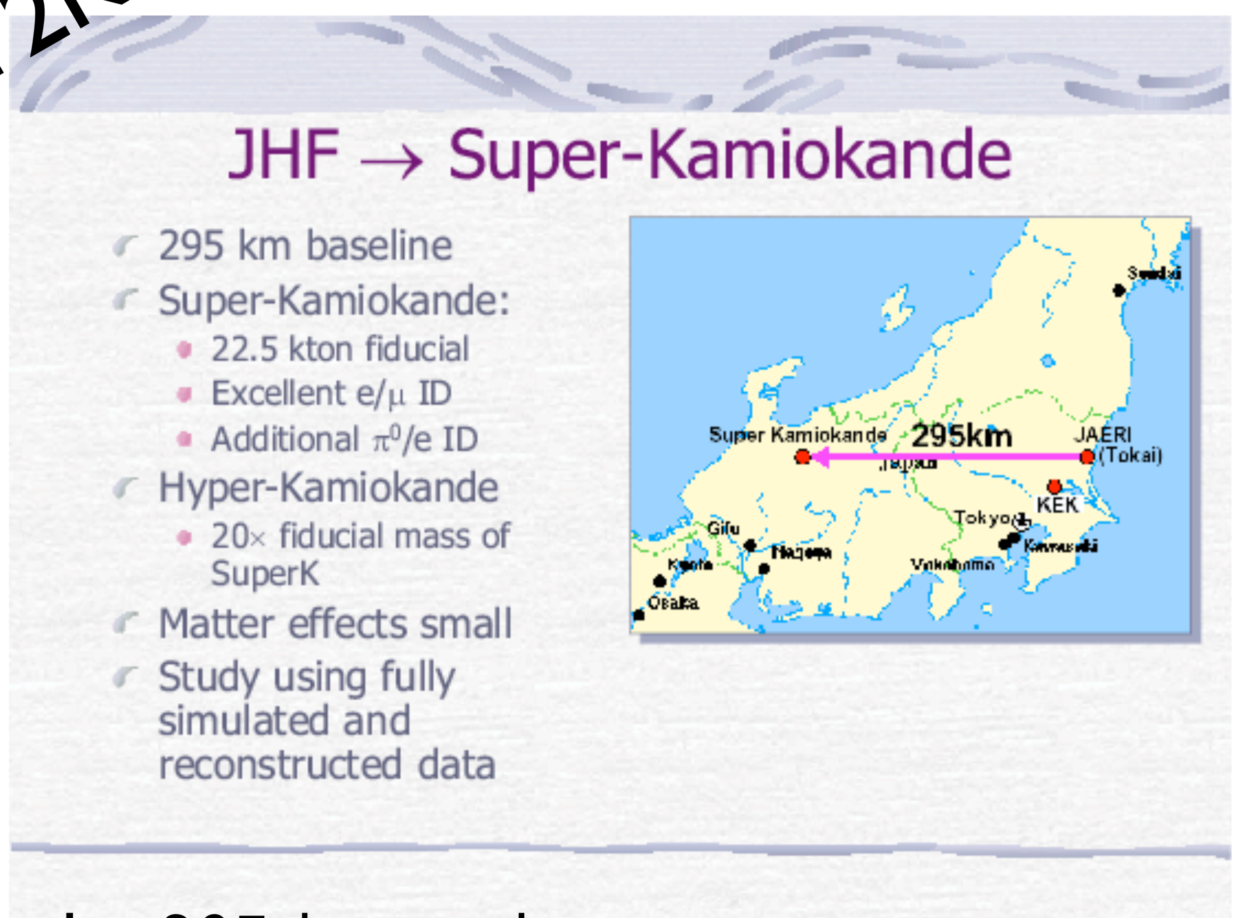
Off-Axis Beams

BNL 1994

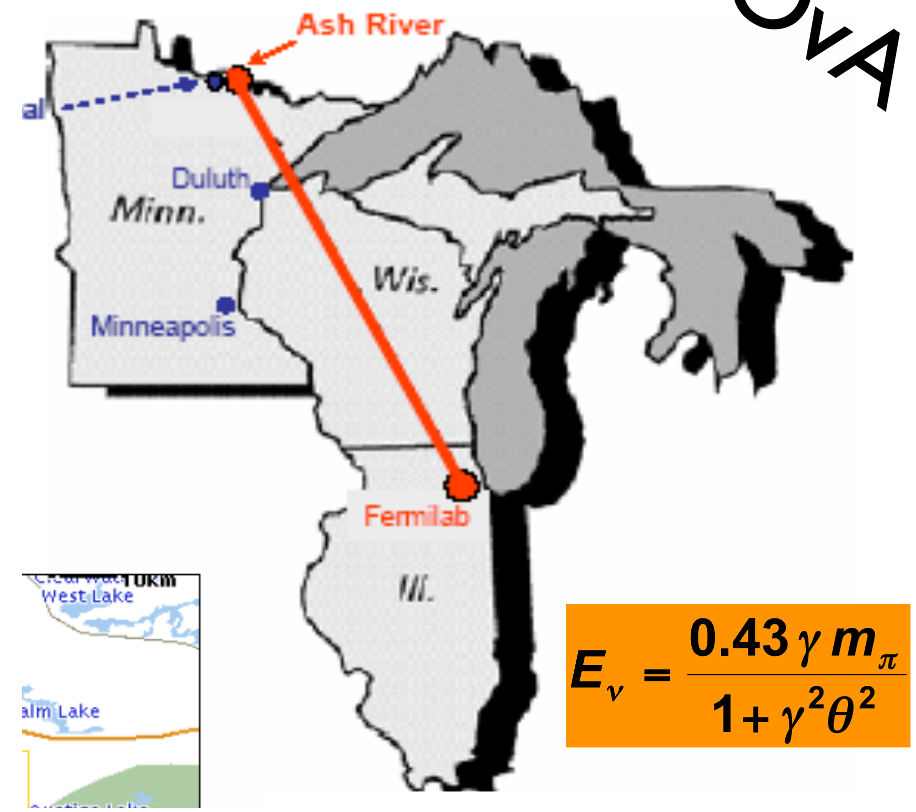


π^0 suppression

T2K



NOvA



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

L=700 - 1000 km and

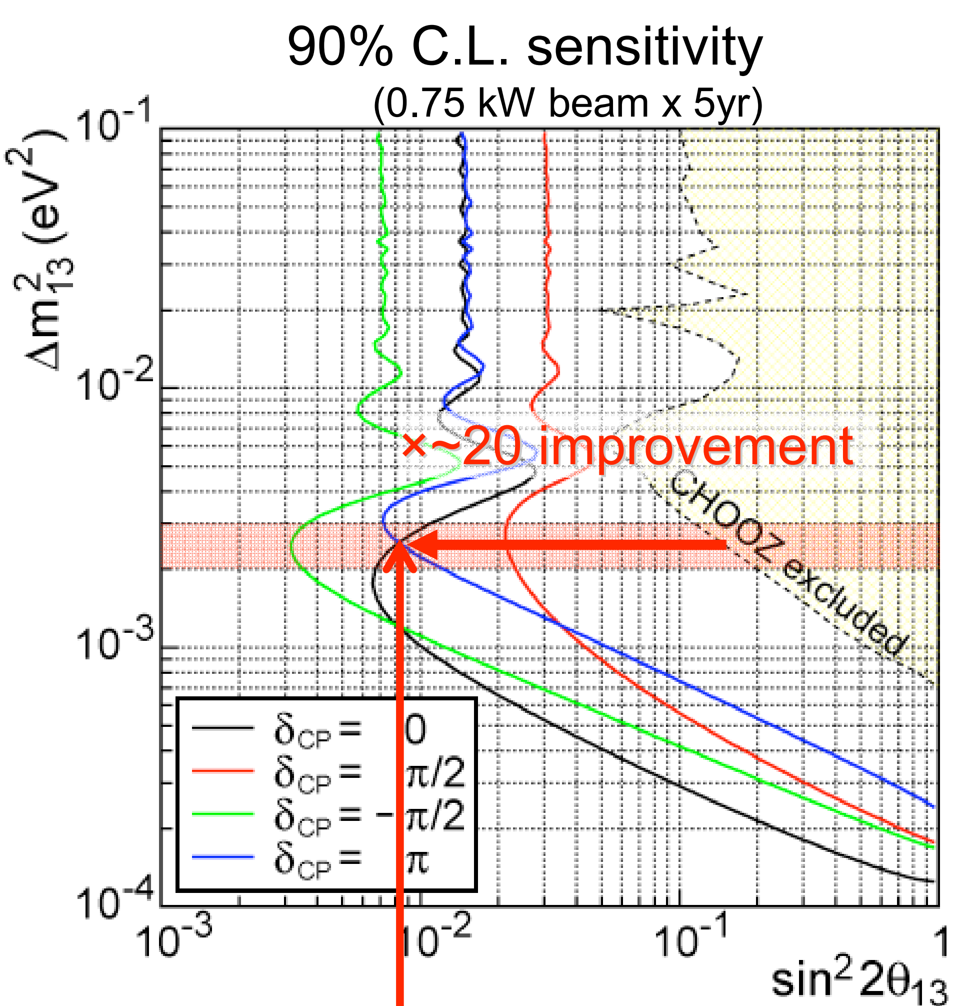
Energy near 2 GeV

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

0.4 upgrade to 2 MW

T2K

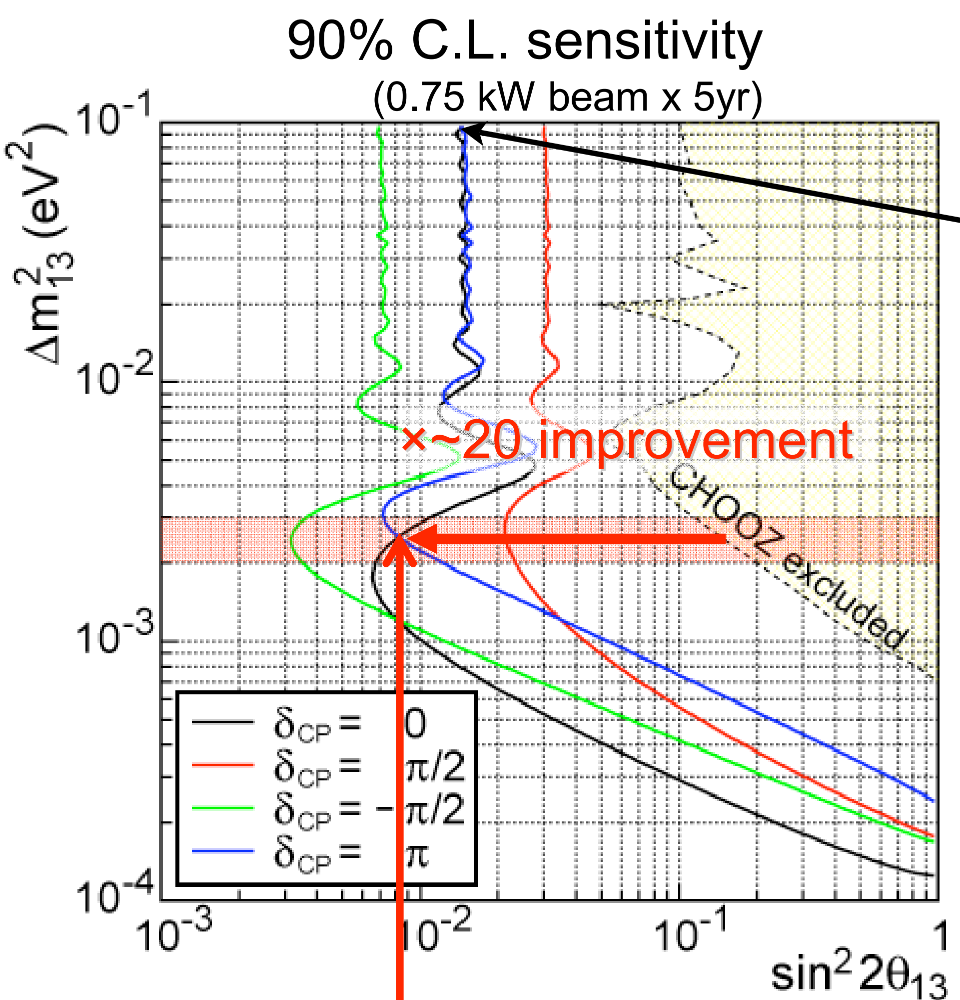
Search for ν_e appearance



$\sin^2 2\theta_{13}$ ~ 0.008 (δ_{CP} = 0,π)

T2K

Search for ν_e appearance



$\sin^2 2\theta_{13}$ ~ 0.008 (δ_{CP} = 0,π)

For LARGE δm^2_{31}

$$\langle P(\nu_\mu \to \nu_e)\rangle = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13} - \frac{1}{2}J.\Delta_{21} + \cos^2\theta_{23}\sin^2 2\theta_{12}\Delta^2_{12}$$

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

$$\Delta_{21} = \delta m^2_{21} L/4E$$

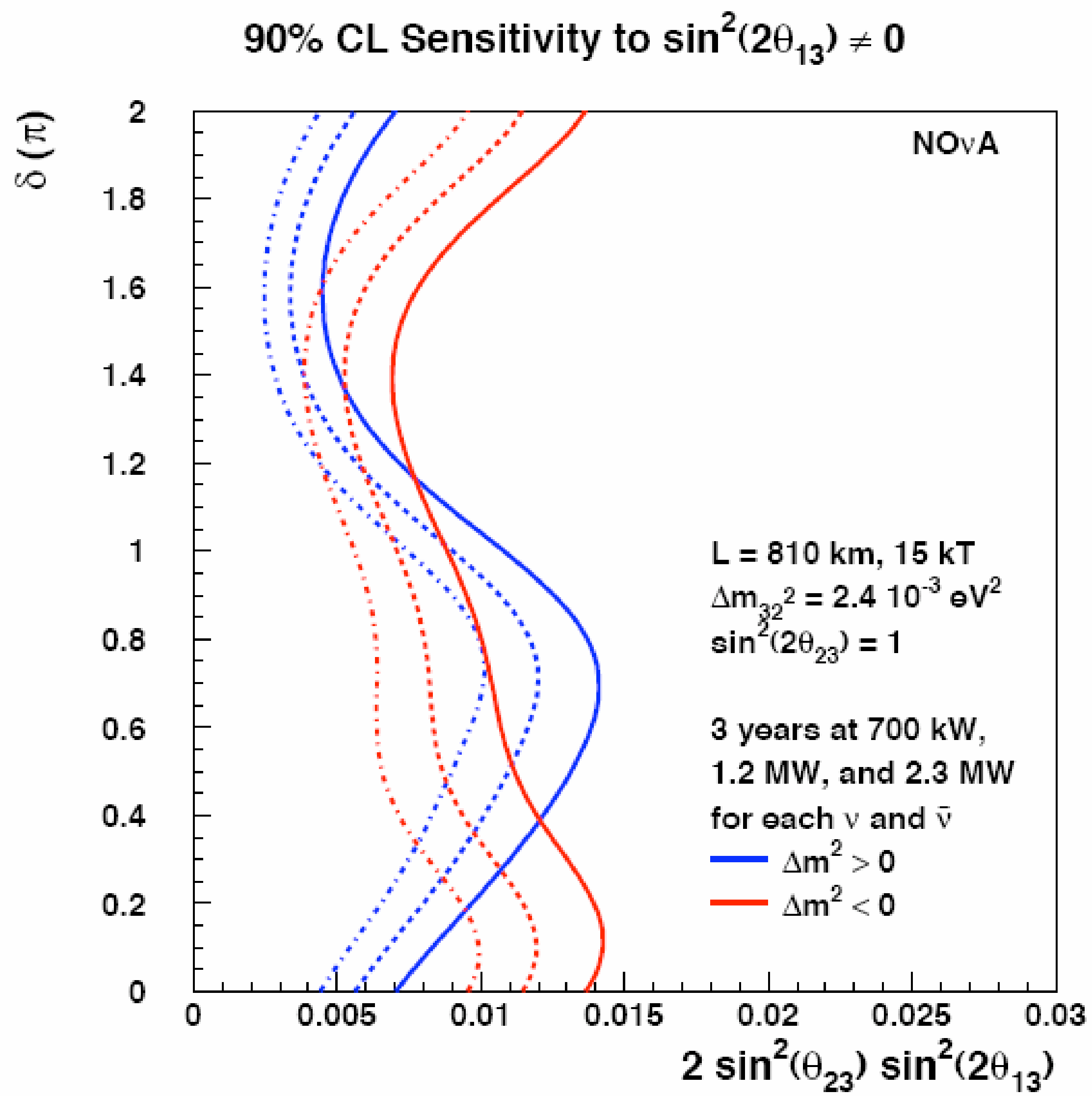
At $\delta = 0\ or\ \pi$

$$\langle P(\nu_\mu \to \nu_e)\rangle = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13} + \cos^2\theta_{23}\sin^2 2\theta_{12}\Delta^2_{12} \approx 0.5\%$$

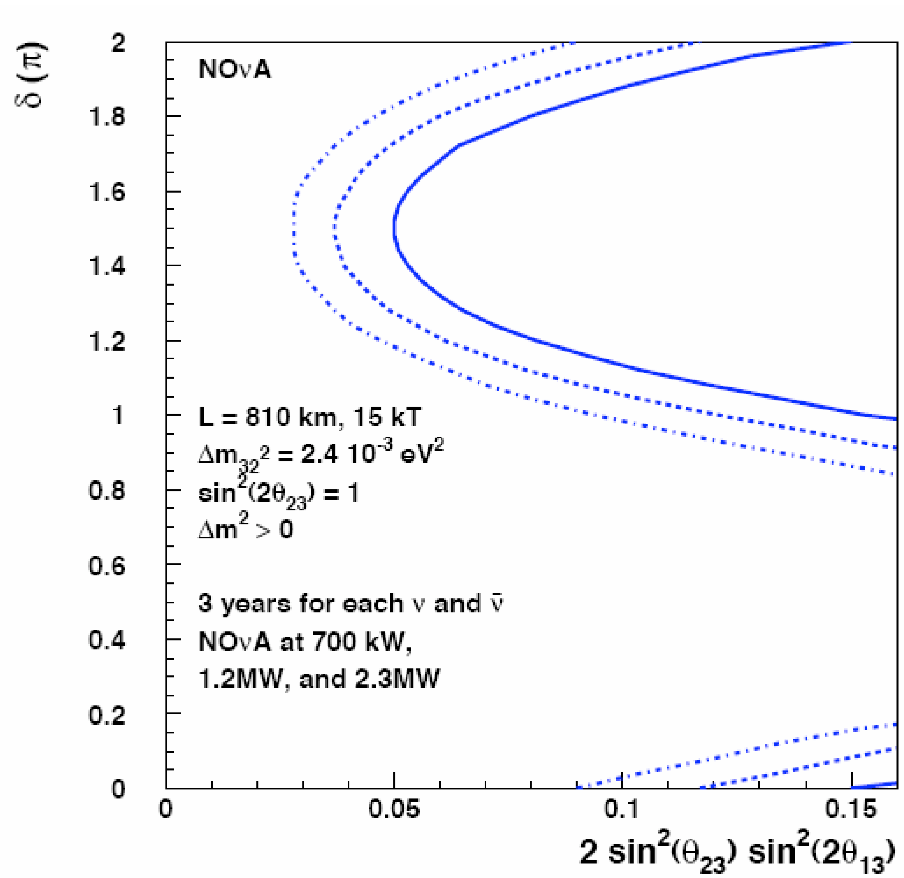
$$\langle P(\nu_\mu \to \nu_e)\rangle_{T2K} \approx 0.5\%$$

0.5% ν_e in beam

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

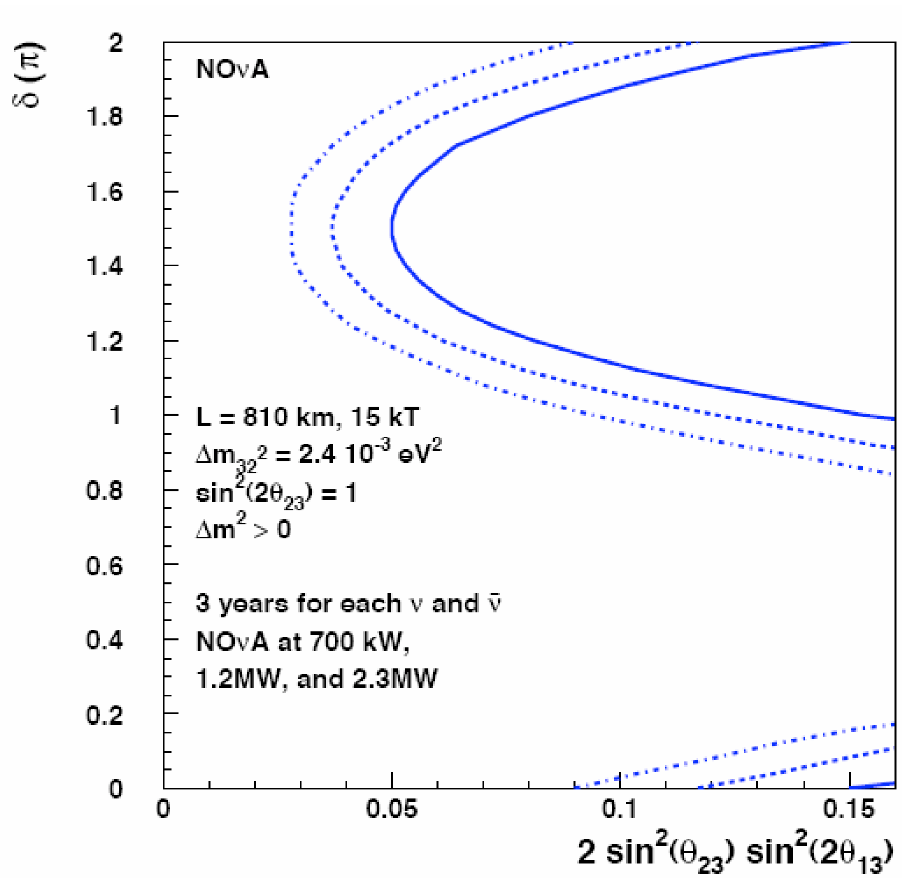


95% CL Resolution of the Mass Ordering
NOνA Alone



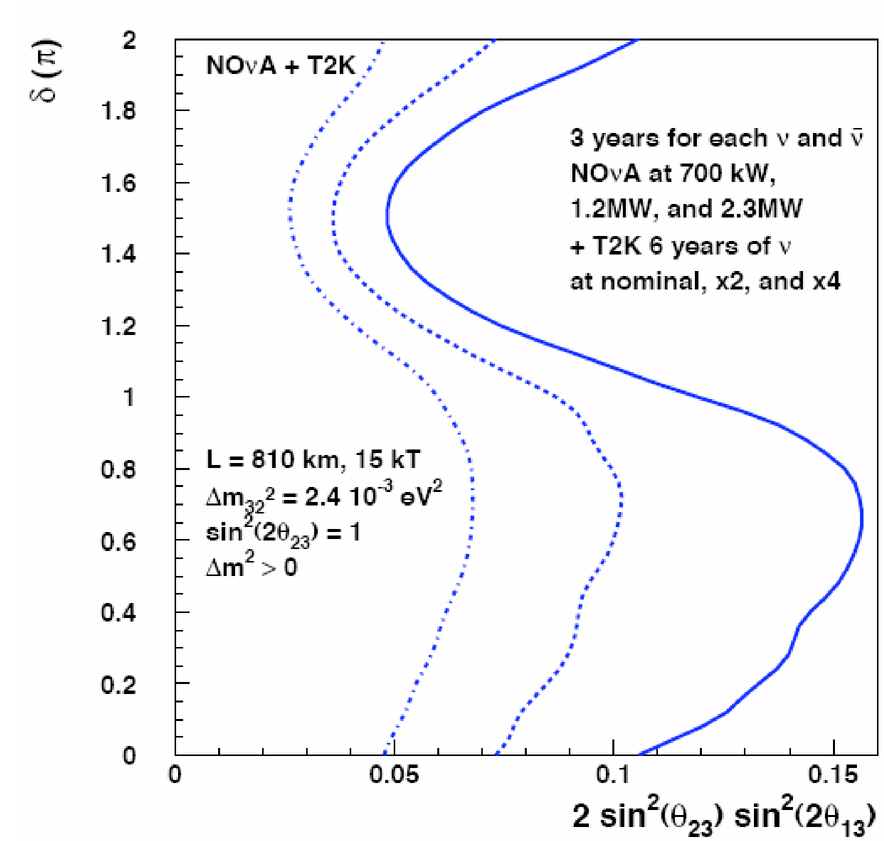
Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Alone



Normal Ordering

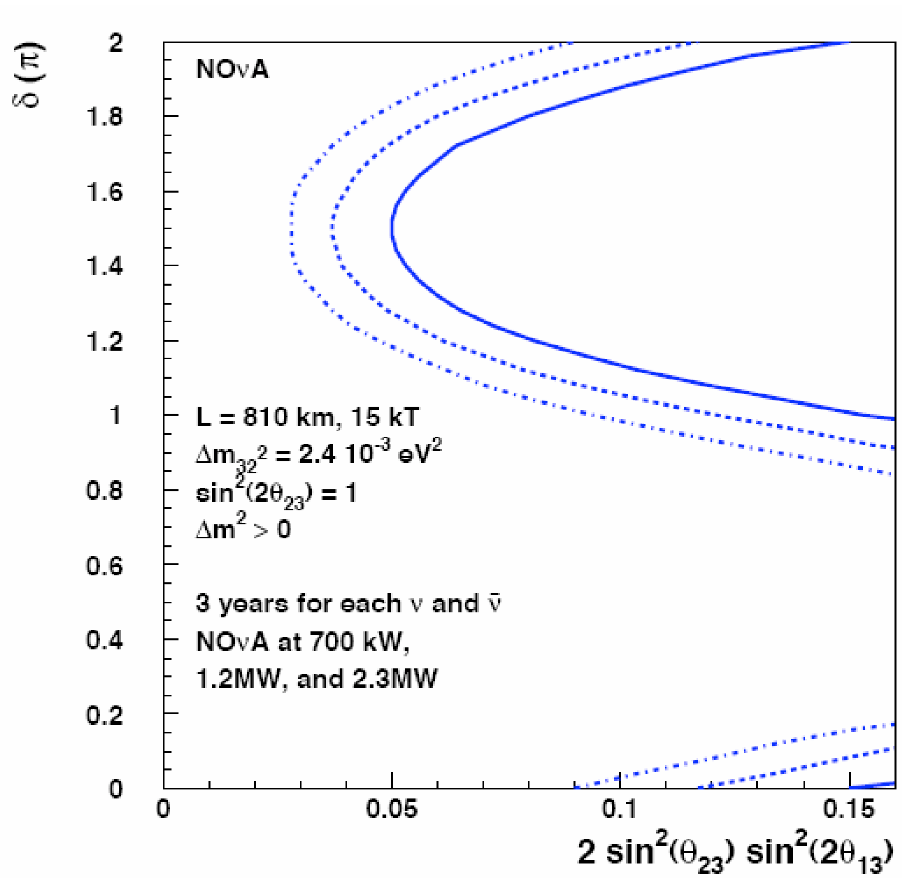
95% CL Resolution of the Mass Ordering
NOνA Plus T2K



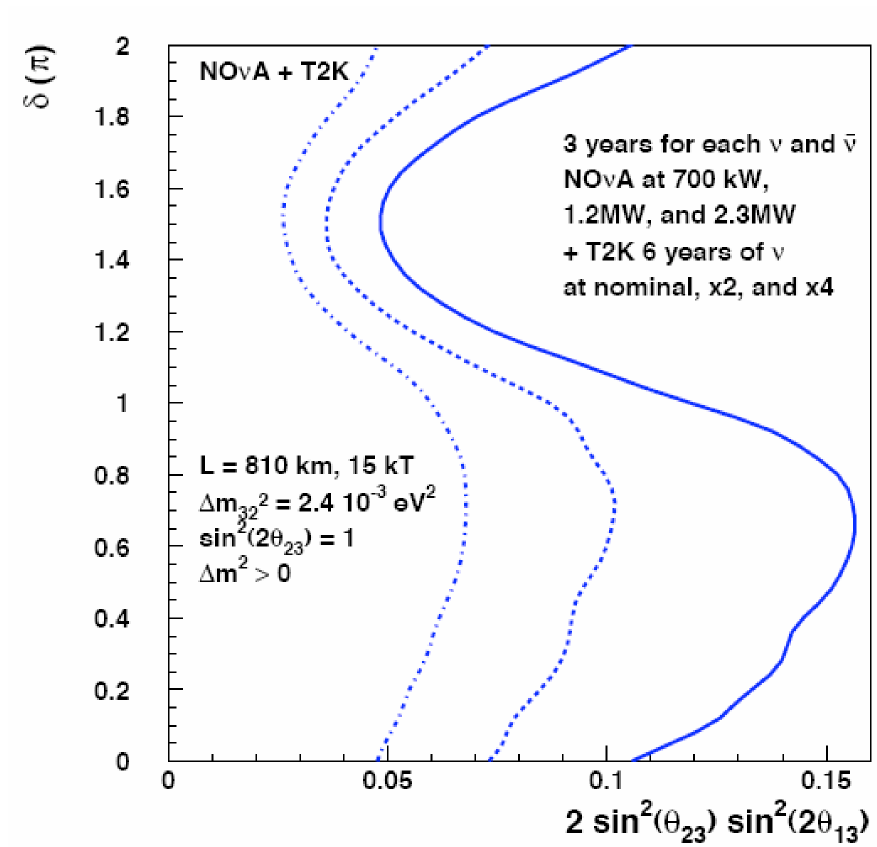
Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Alone

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



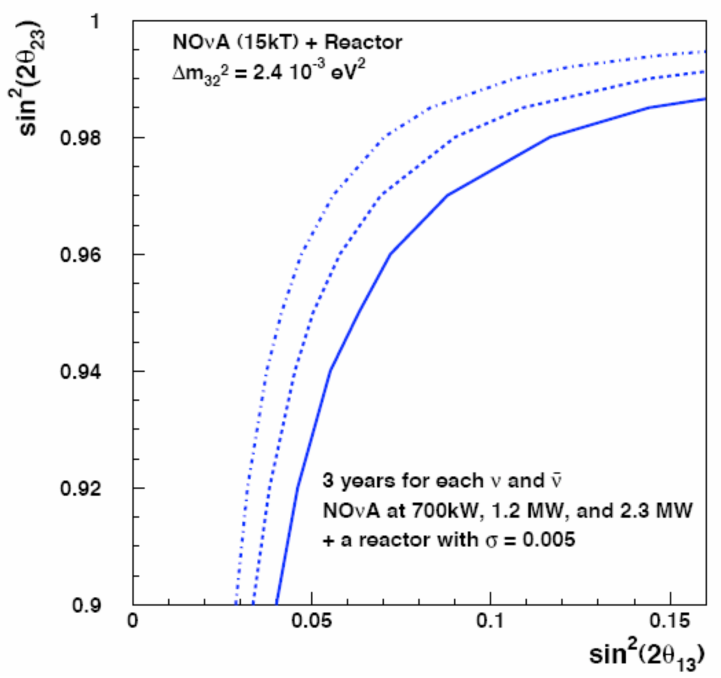
Normal Ordering



Normal Ordering

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

95% CL Resolution of the θ_{23} Ambiguity

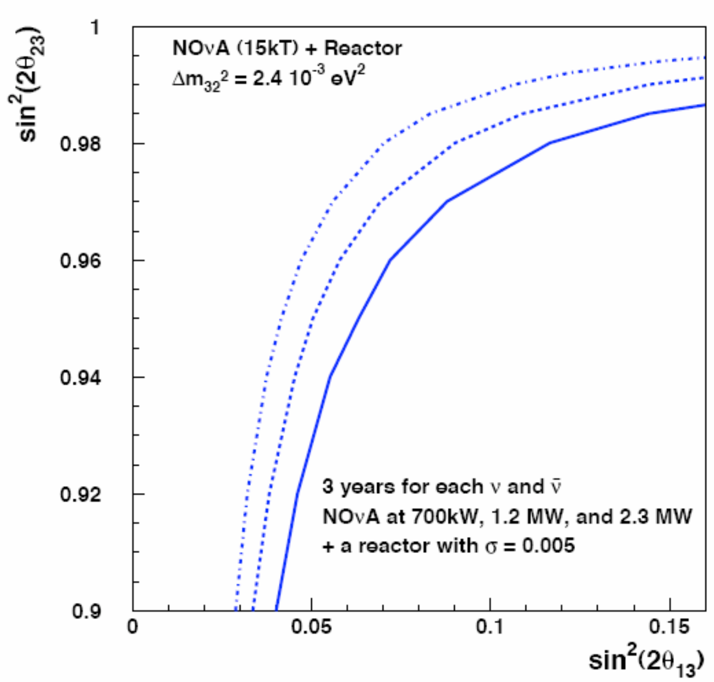


at Vac. Osc. Max.

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

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

95% CL Resolution of the θ_{23} Ambiguity

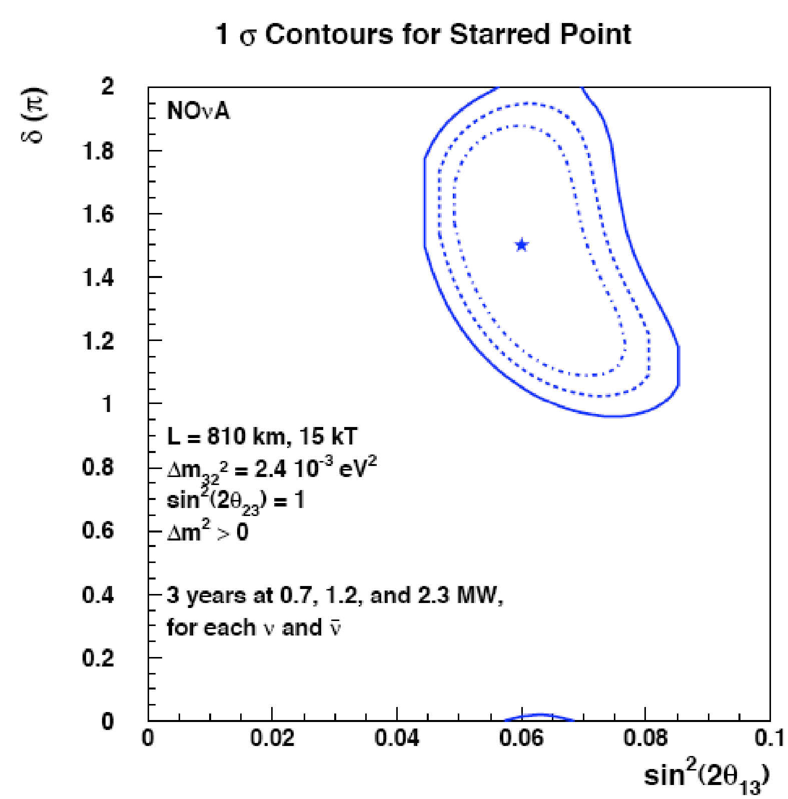


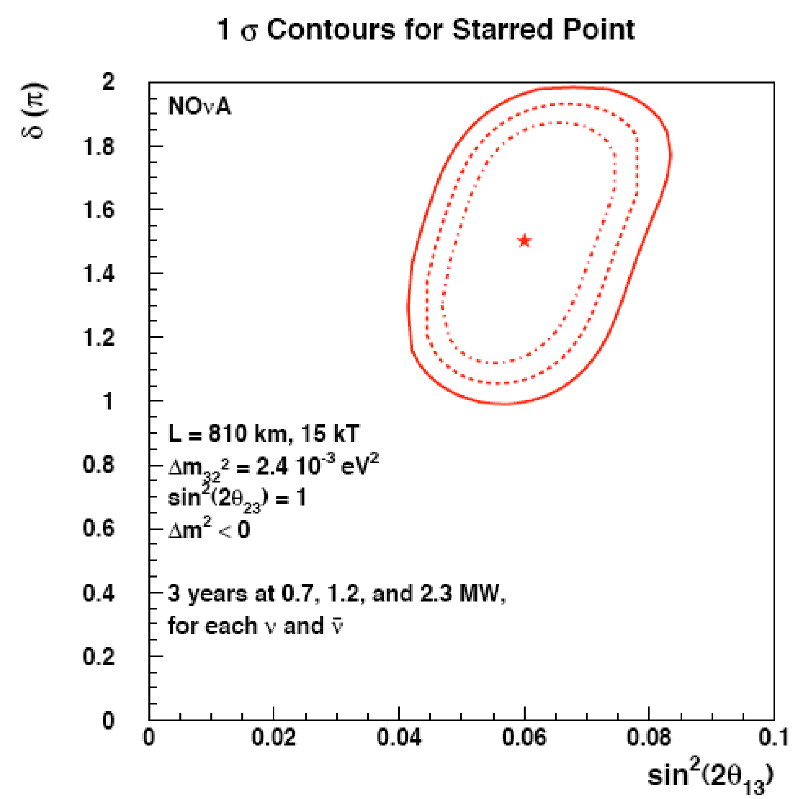
at Vac. Osc. Max.

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

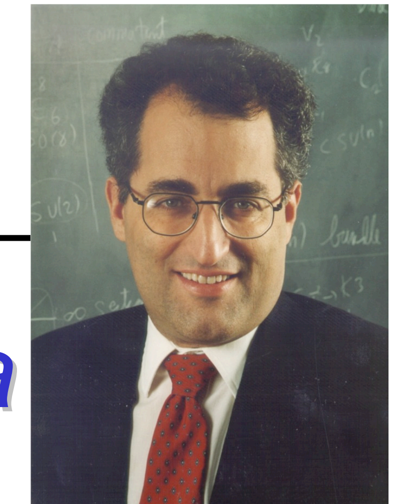
in $P + \bar{P}$ the matter effects approx. cancel
and CP effects approx. cancel.

CP Violation: δ vs. θ_{13} Contours



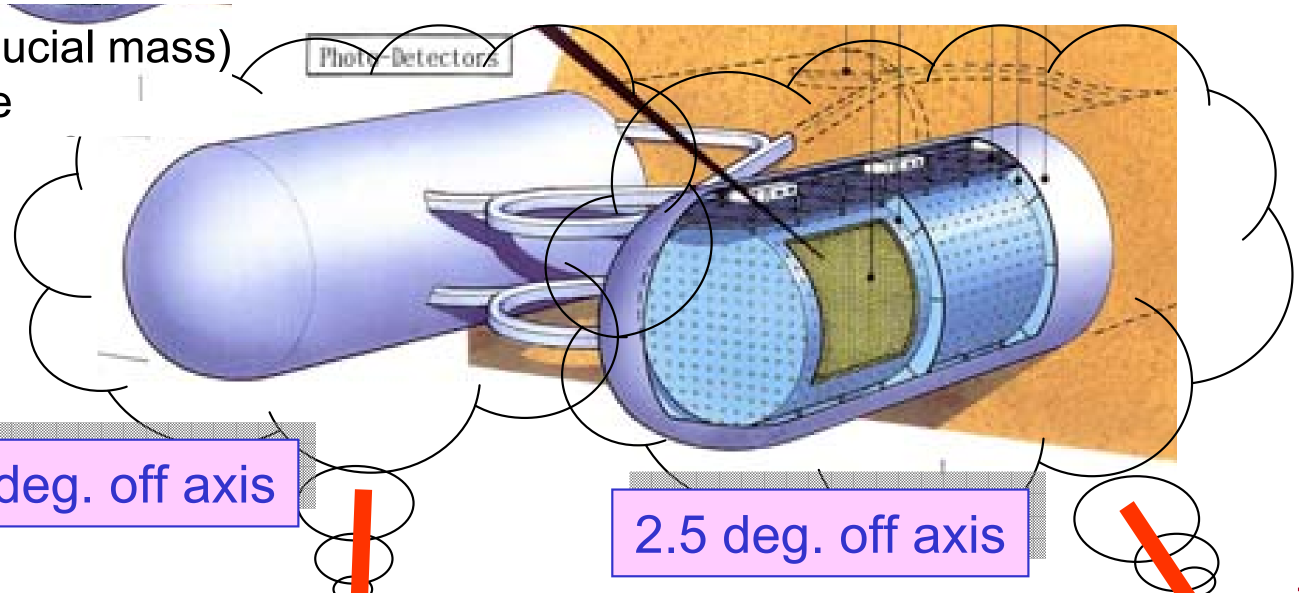


Off Axis:



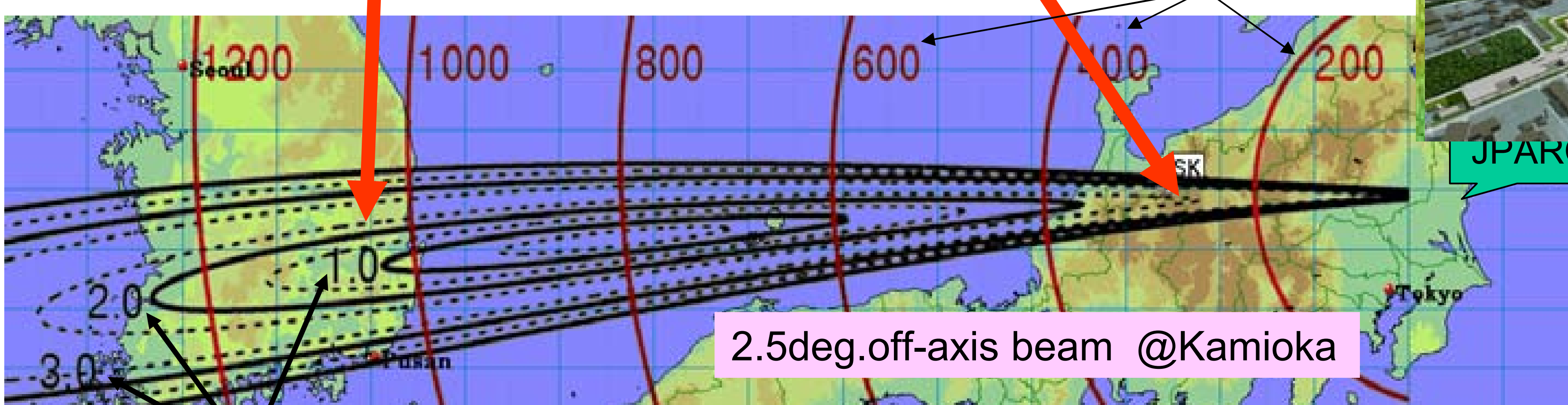
Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande



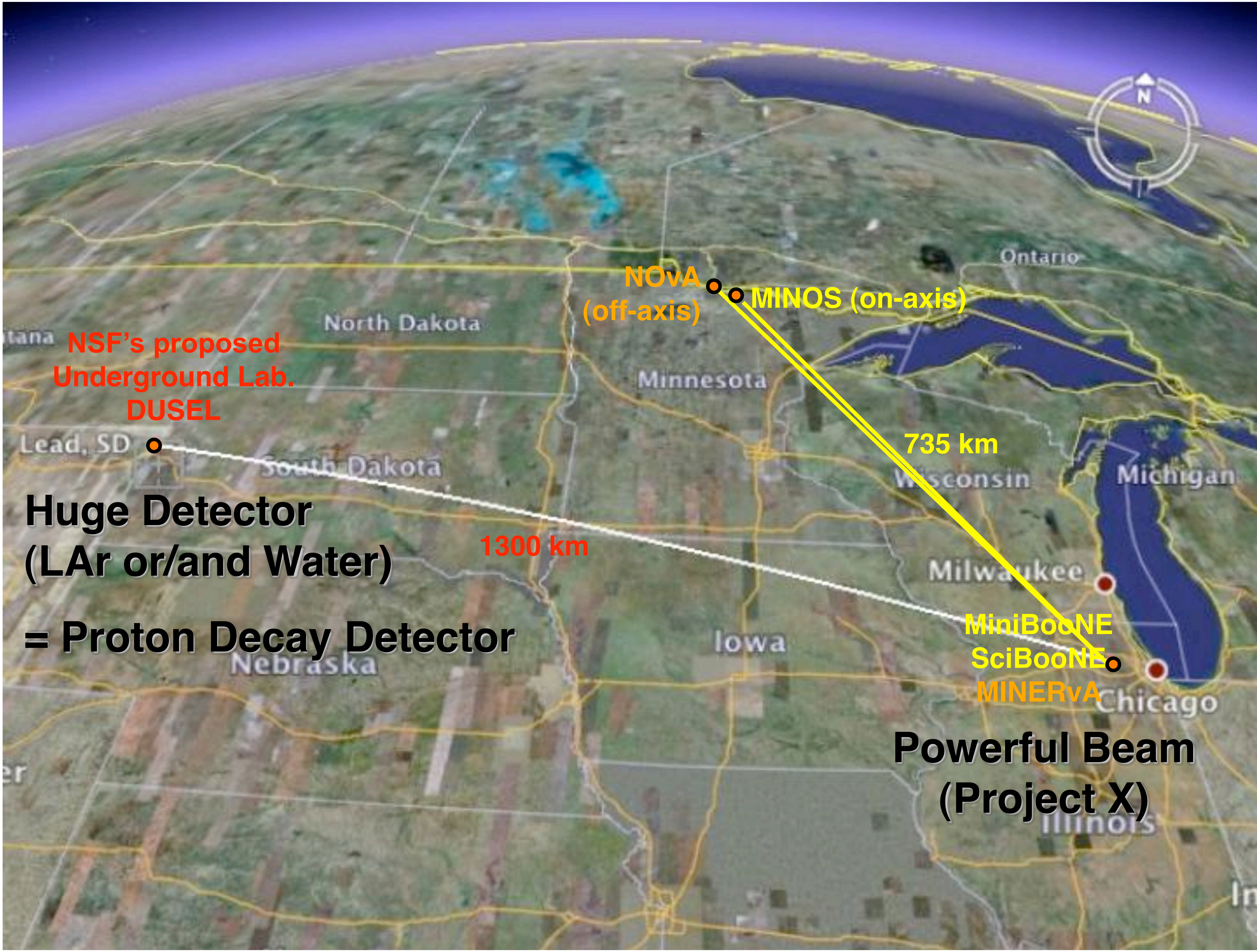
Total cost must be similar to the baseline design.

Distance from the target (km)



Off-axis angle

see Kajita talk:



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

Narrow Band Beam: Same E, Longer L T2KK

Broadband Beam: Same L, Lower E Fermilab to DUSEL

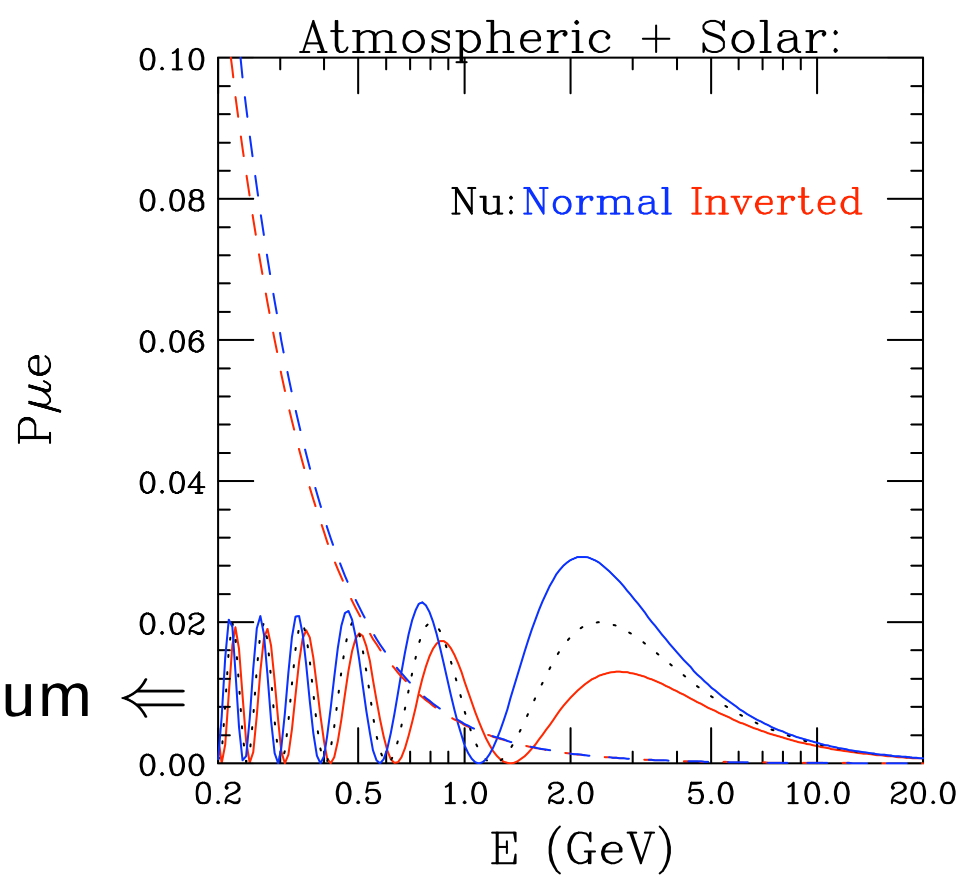
In VACUUM the SAME but NOT in MATTER

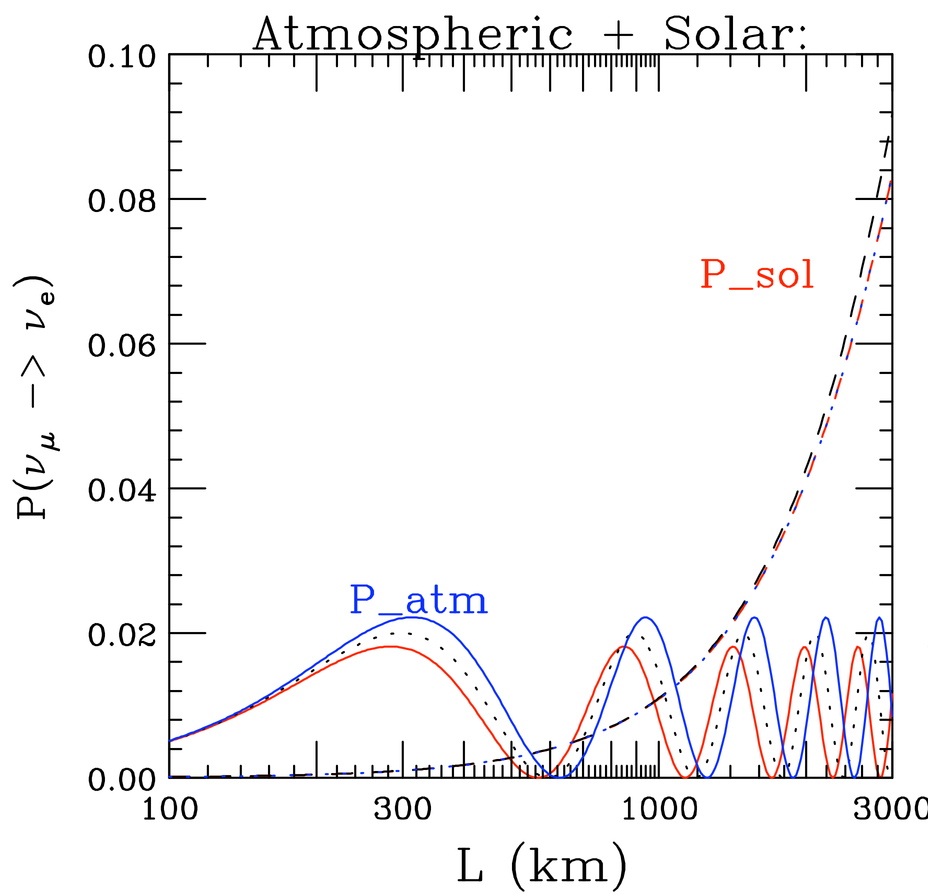
$\sin^2 2\theta_{13} = 0.04$

L=1200km

E=0.6 GeV

vacuum ⇐

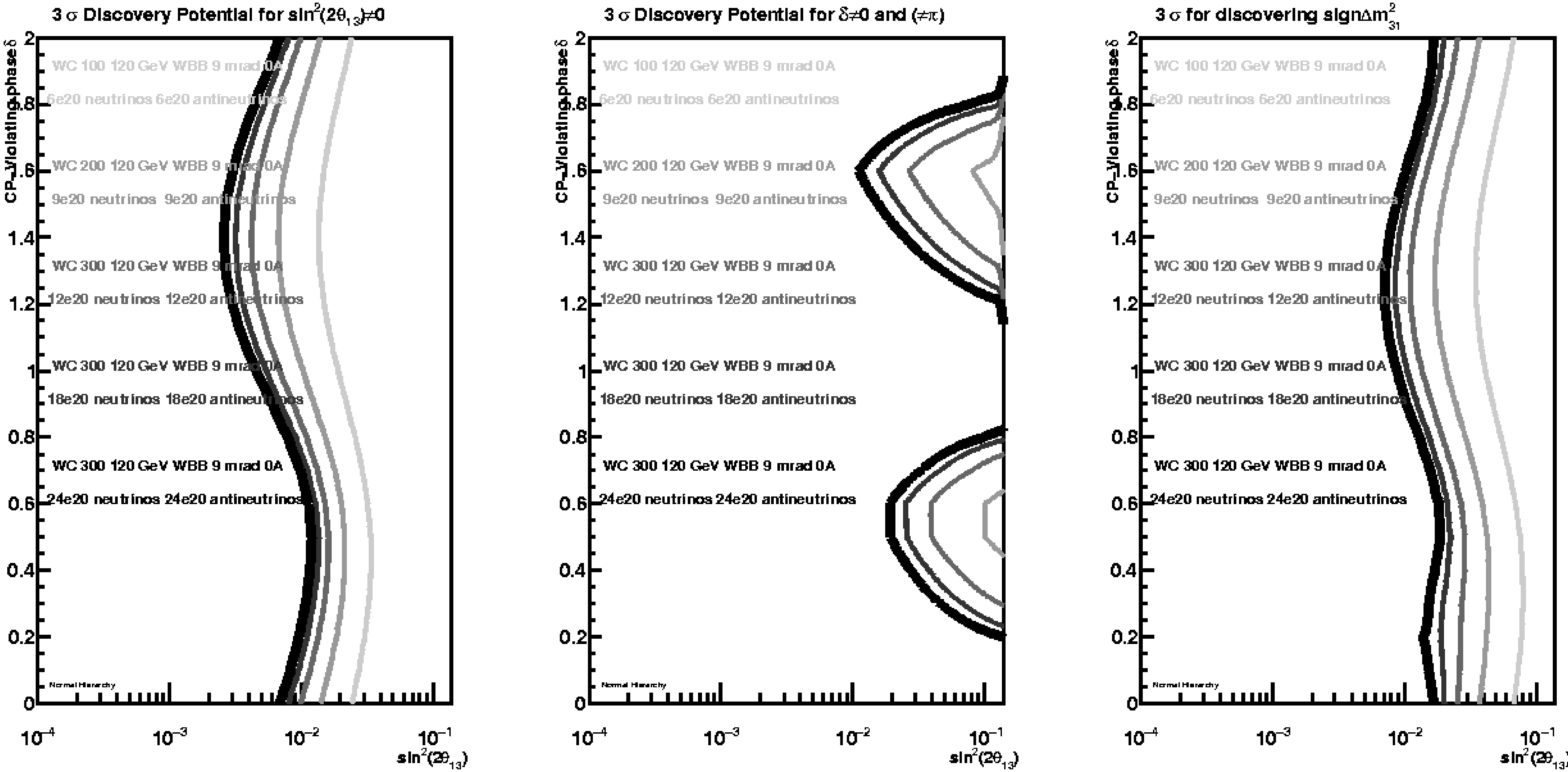




⇐ same height

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

Sensitivities for Water Cherenkov Detector :
Scenario 1 "Detector Module" = 100 KT

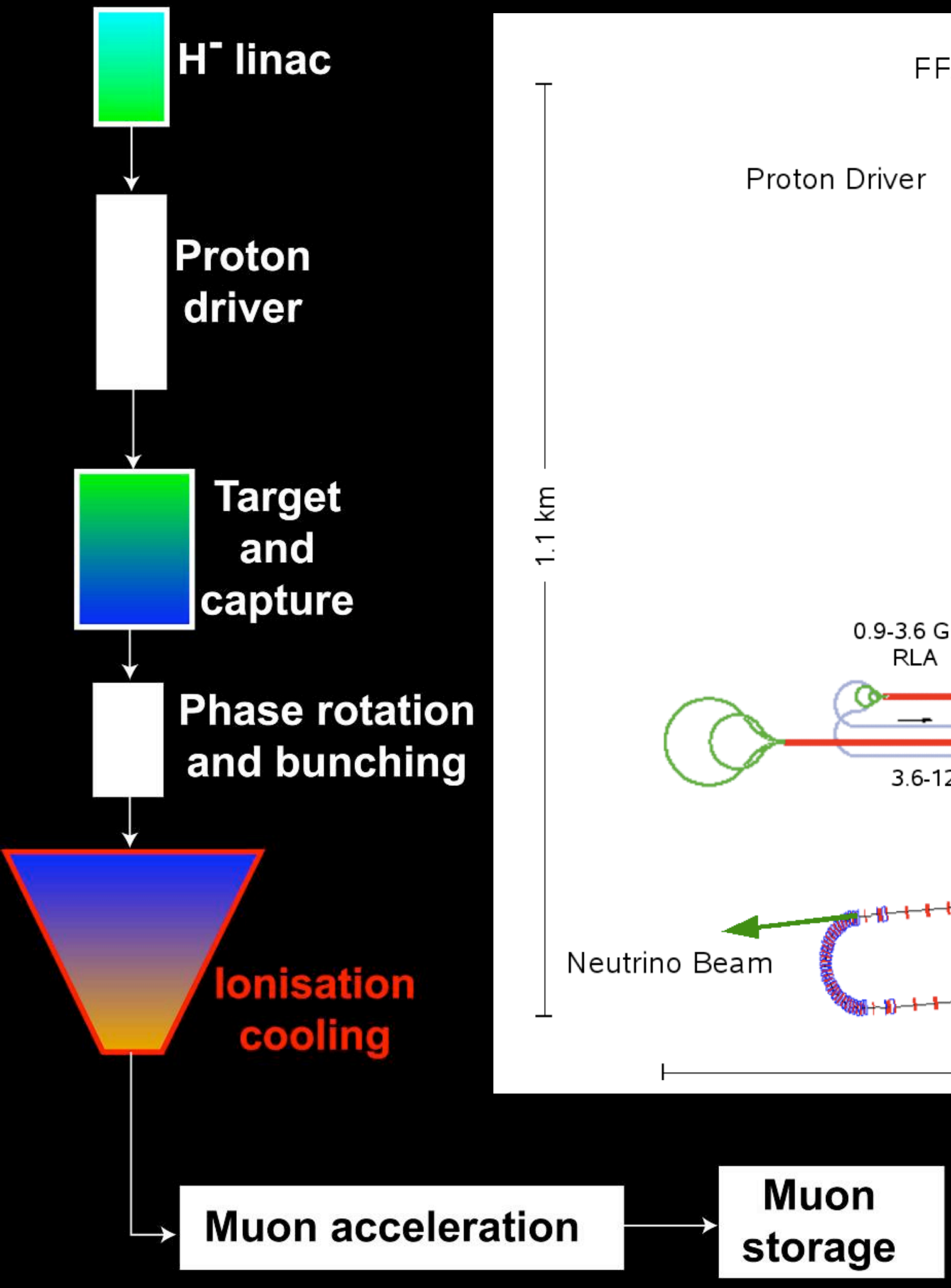


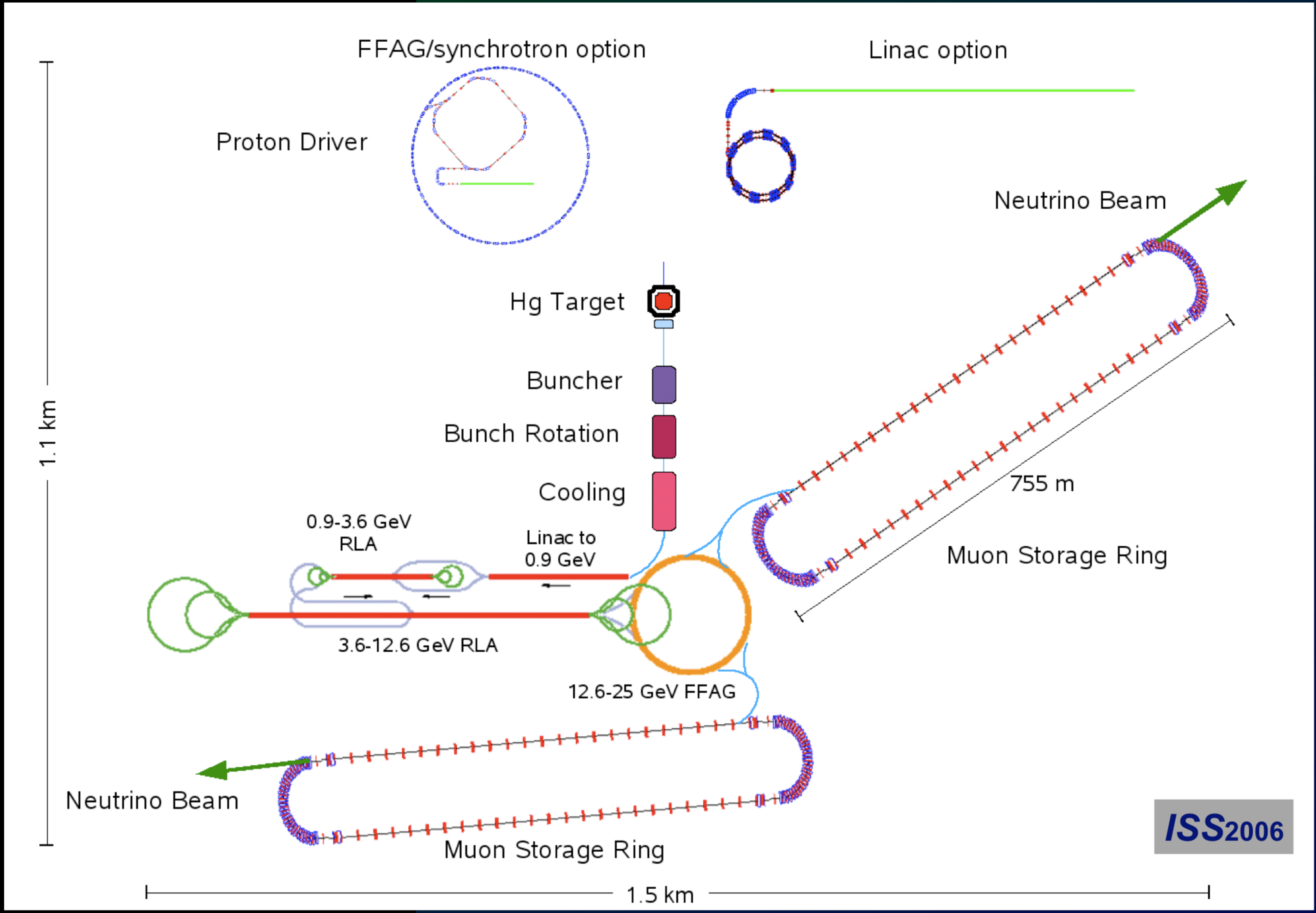
The 5 Curves correspond to the five 2 year intervals for the total 10 year period.

First curve is discovery potential after 2 years of running, second curve is discovery potential after 4 years of running etc.

Neutrino Factory:

IDS-NF baseline: accelerator





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

when $\sin(aL)/(aL) \approx 1$

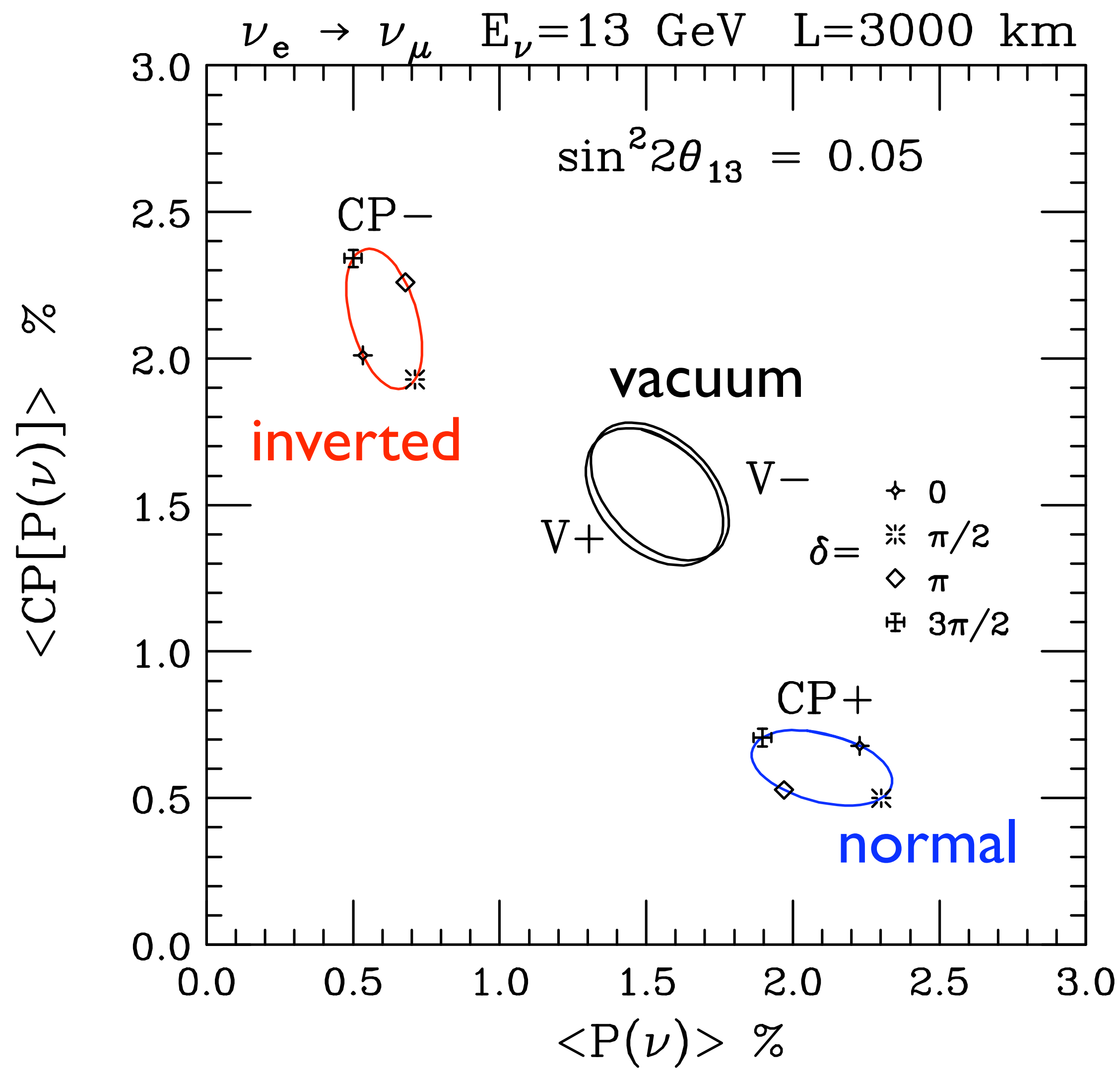
L/E $\geq$ significant fraction of 500 km/GeV

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

Mass Hierarchy: – sign of δm^2_{31}

Matter Effects

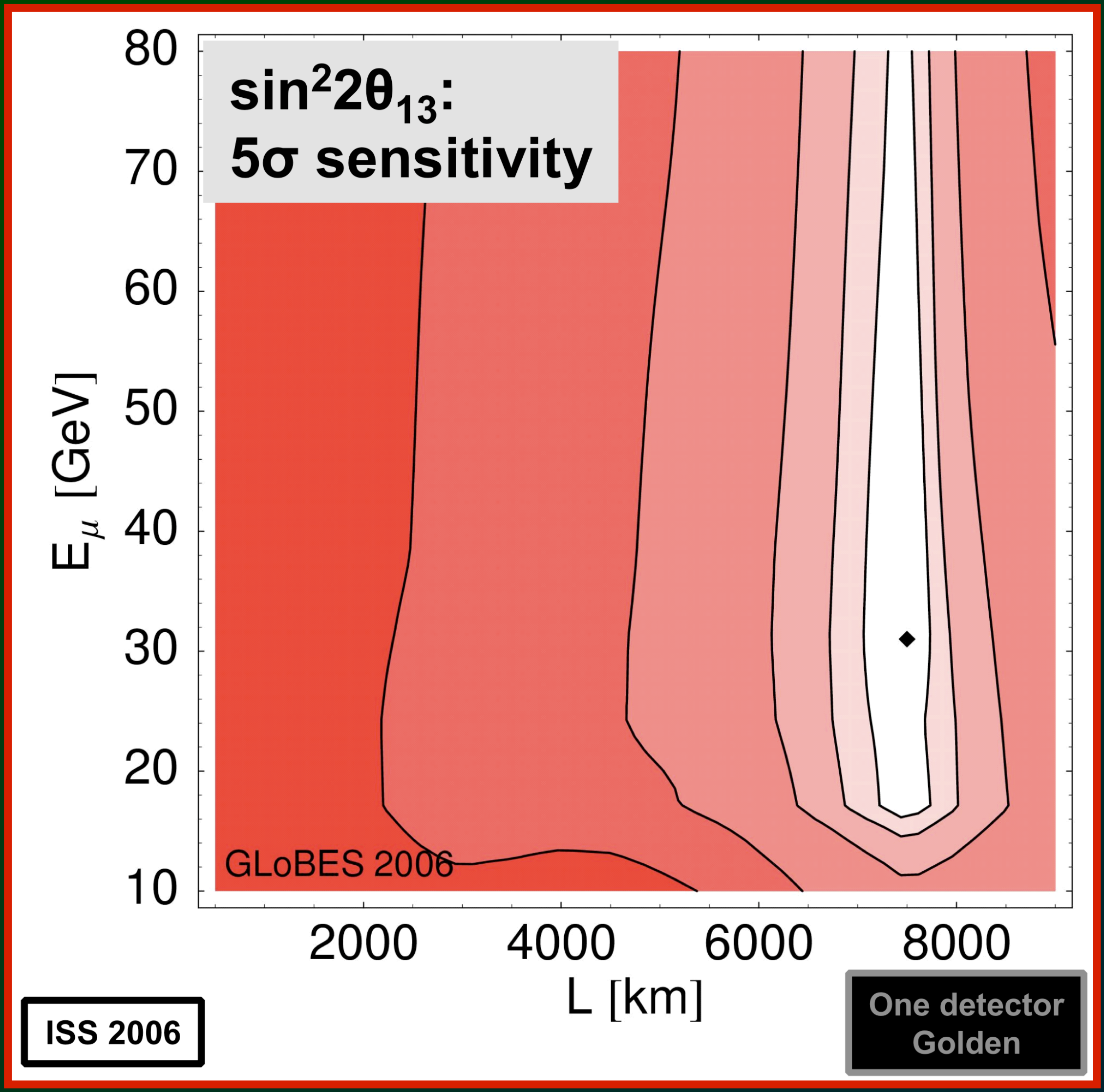
$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$

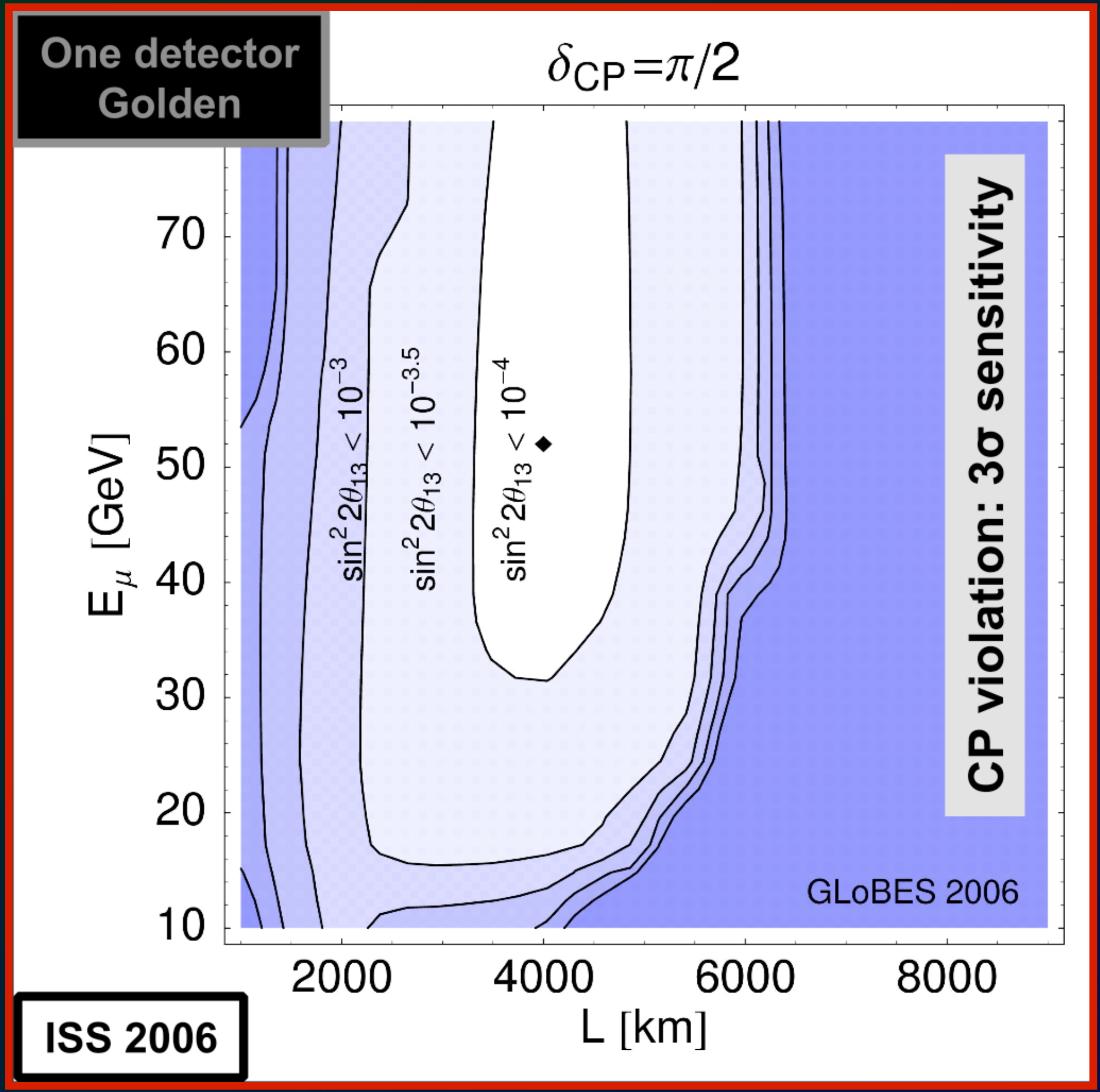


$\nu_e \leftrightarrow \nu_\mu$

Suppression $\geq$ Enhancement

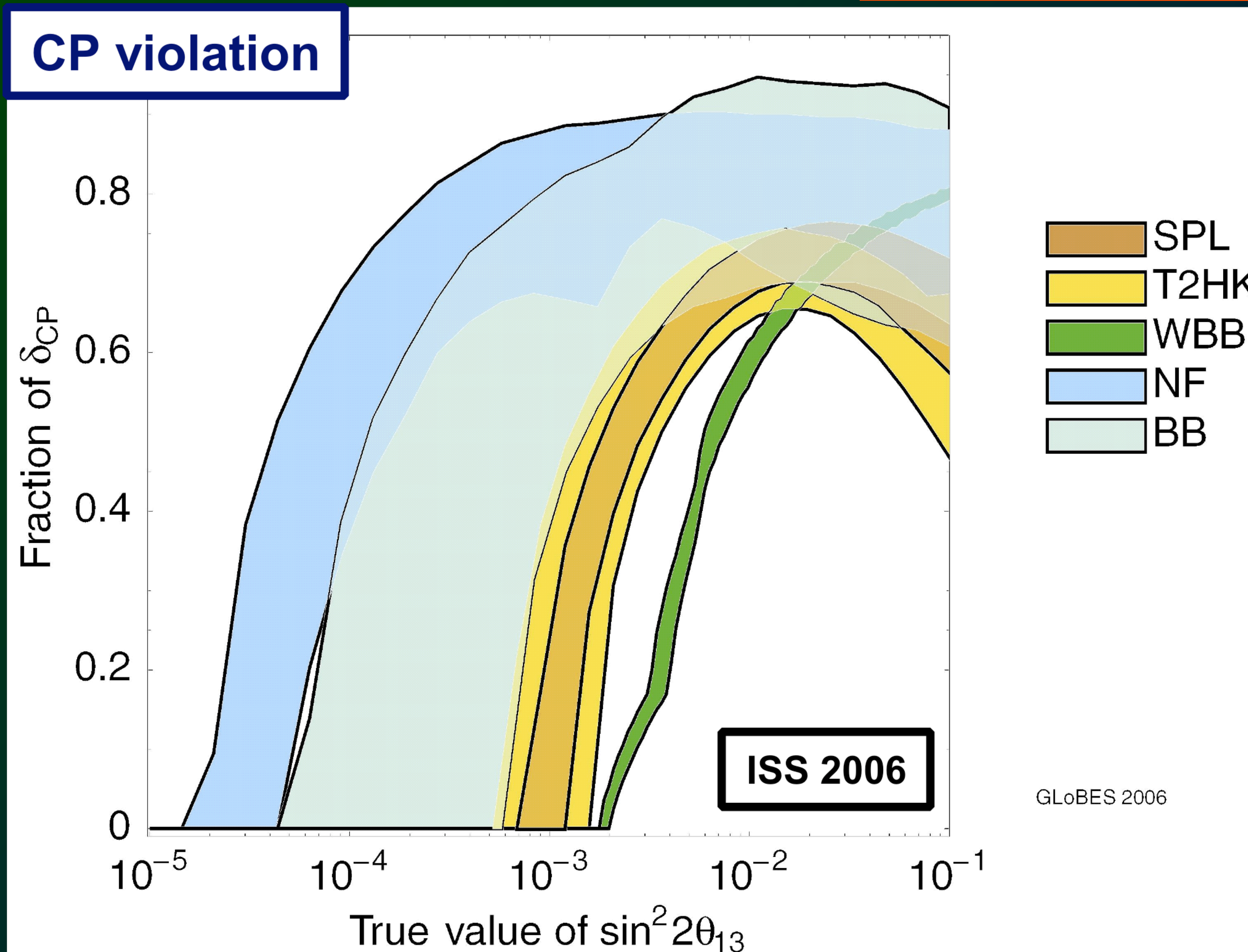
NF: $\nu_e \rightarrow \nu_\mu$ (golden channel) optimisation





- Magic baseline (7500 km) good degeneracy solver
- Best sensitivity to CP requires baseline ~4000 km
- Stored muon energy: 25 GeV

Comparison:



Neutrino Factory
Golden, 4000, E_μ = 50 GeV
Golden* (4000 km), Golden* (7500 km) E_μ = 20 GeV

Beta beam
γ = 100 500 kT H_2O Ç (130 km)
γ = 350 500 kT H_2O Ç (730 km)

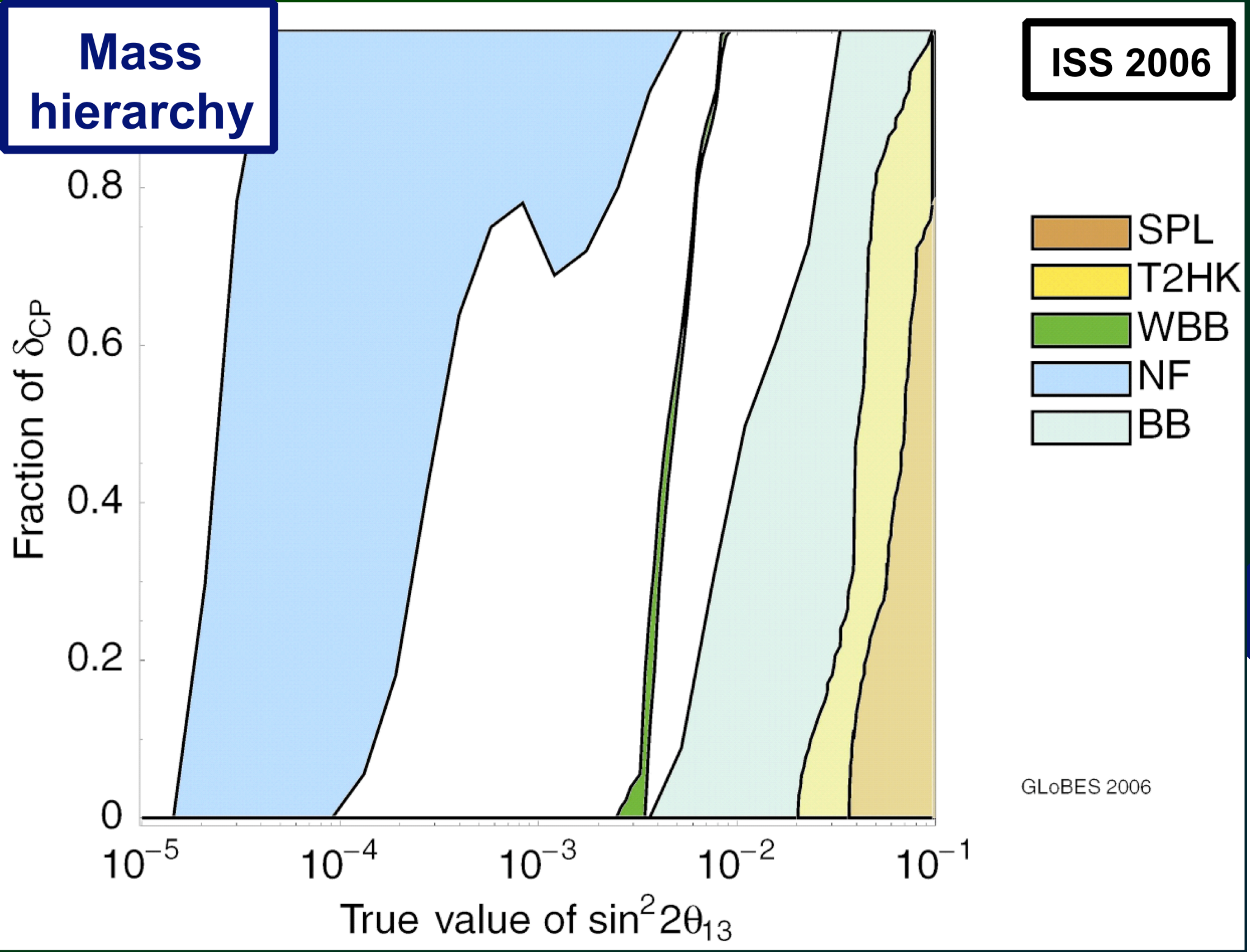
WBB
Systematics from proposal

T2HK
Systematics: 2% – 5%

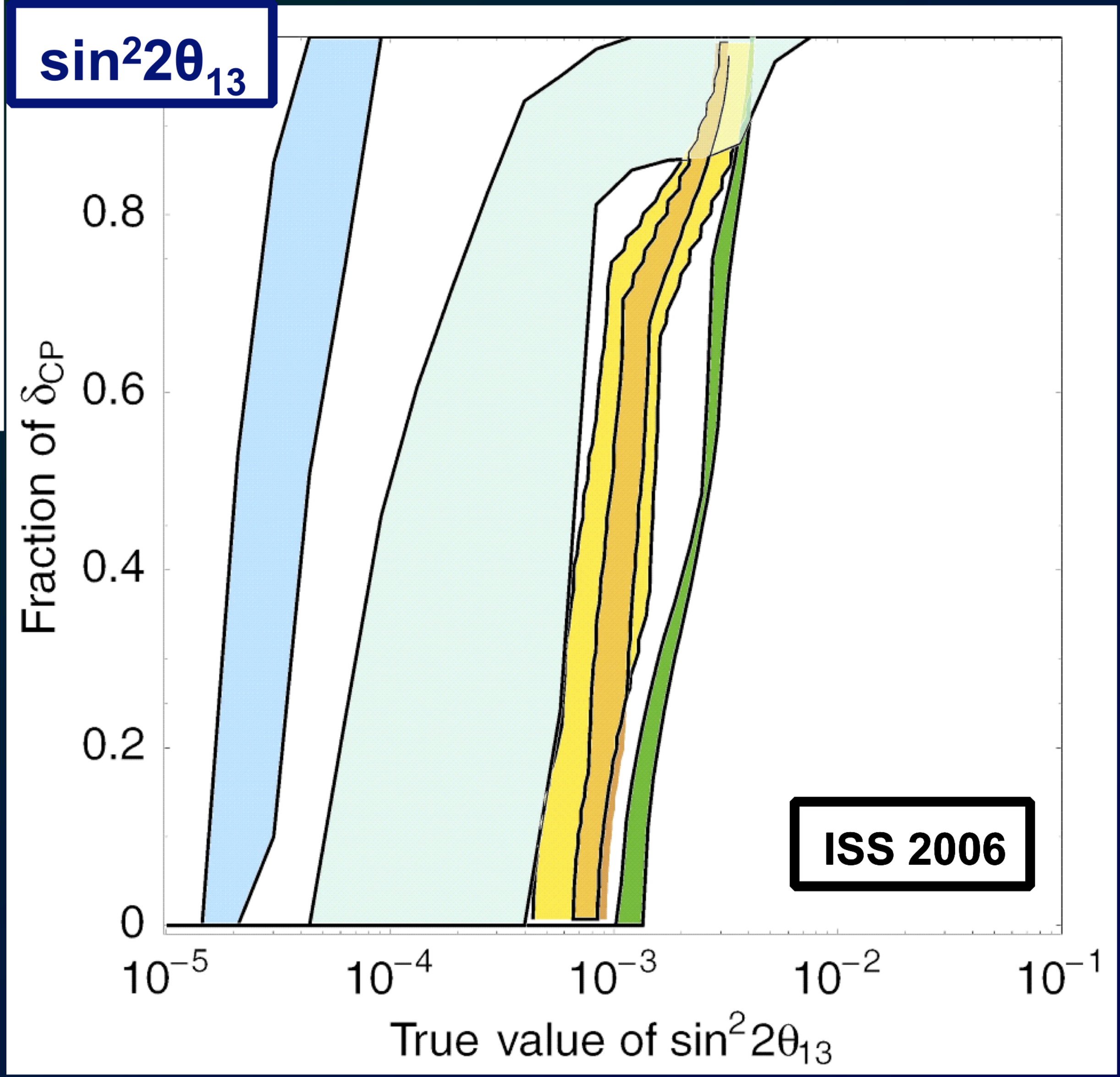
SPL
Systematics: 2% – 5%

Comparison:

Mass hierarchy



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



Neutrino Factory
Golden, 4000, E_μ = 50 GeV
Golden* (4000 km), Golden* (7500 km) E_μ = 20 GeV

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WBB
Systematics from proposal

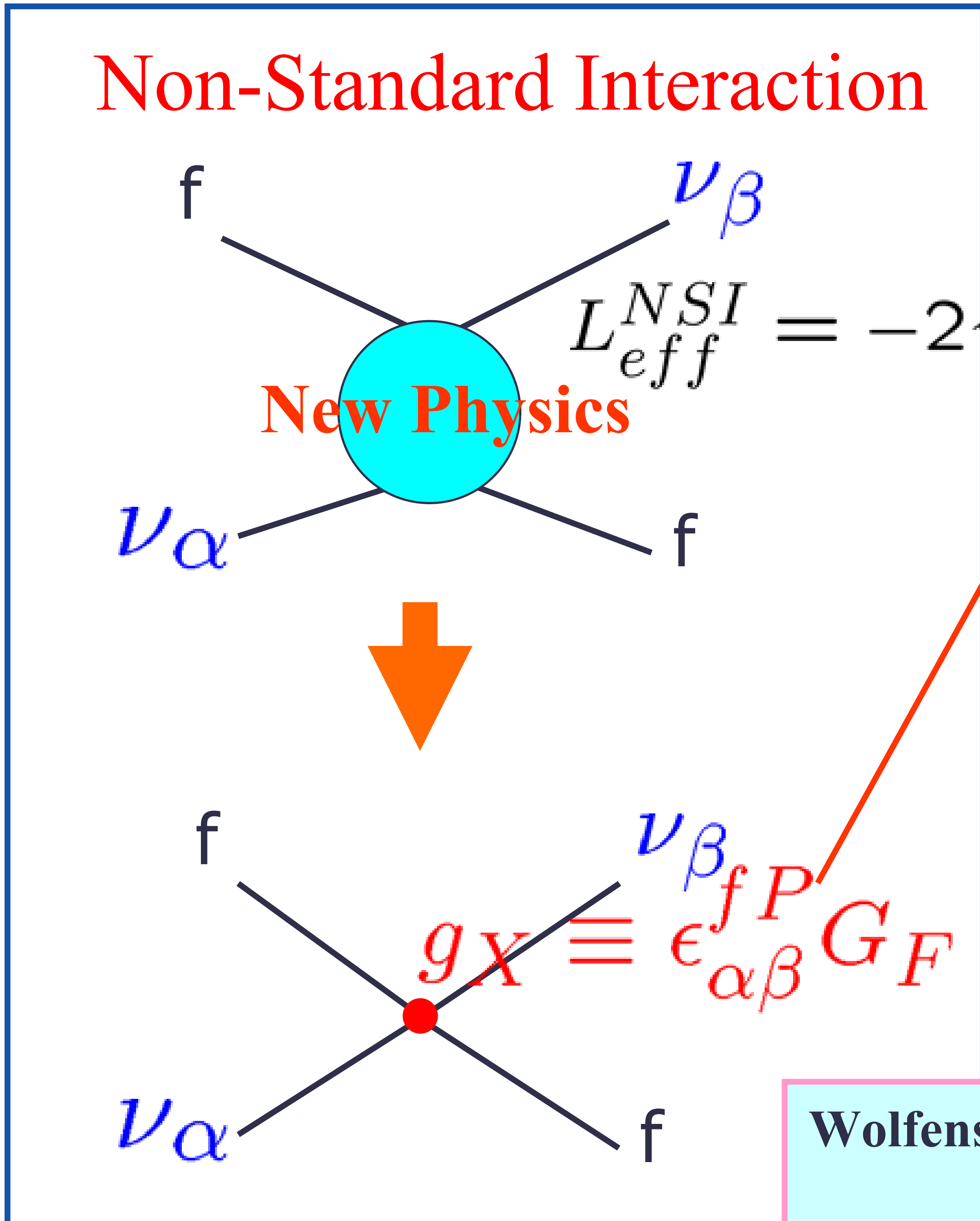
T2HK
Systematics: 2% – 5%

SPL
Systematics: 2% – 5%

Neutrino Factory & Non-Standard Interactions: (NSI)

eg Z' at LHC

Non-Standard neutrino Interaction



Shoichi Uchinami

Nei Cipriano Ribeiro*1, Hisakazu Minakata*2, Hiroshi Nunokawa,*1 and Renata Zukanovich Funchal*3

$$L^{NSI}_{eff} = -2\sqrt{2}\epsilon^{fP}_{\alpha\beta} G_F (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f}\gamma^\mu P f)$$

$$P_L \equiv \frac{1}{2}(1-\gamma_5),\ P_R \equiv \frac{1}{2}(1+\gamma_5)$$

Naive Estimation $\epsilon_{\alpha\beta} \propto \frac{m_W^2}{m_X^2}$

If new physics scale ~ 1(10) TeV

$$\epsilon_{\alpha\beta} \sim 0.01(0.0001)$$

Wolfenstein '78, Grossman '95, Berezhiani-Rossi '02 and many people…

We concentrated on effects of NSI in ν propagation in matter

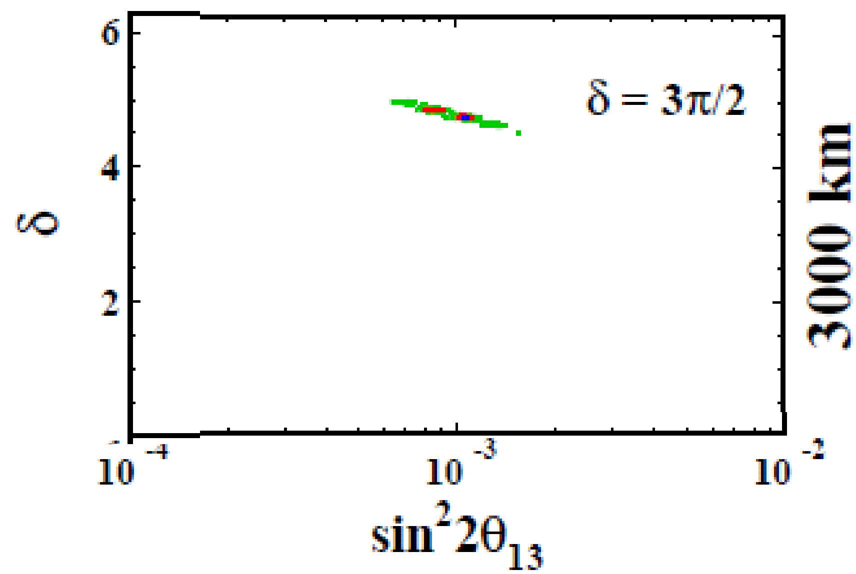
$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^{-1} + \begin{pmatrix} 2\sqrt{2}G_F n_e E & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0\end{pmatrix}\right]$$

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^{-1} + 2Ea\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

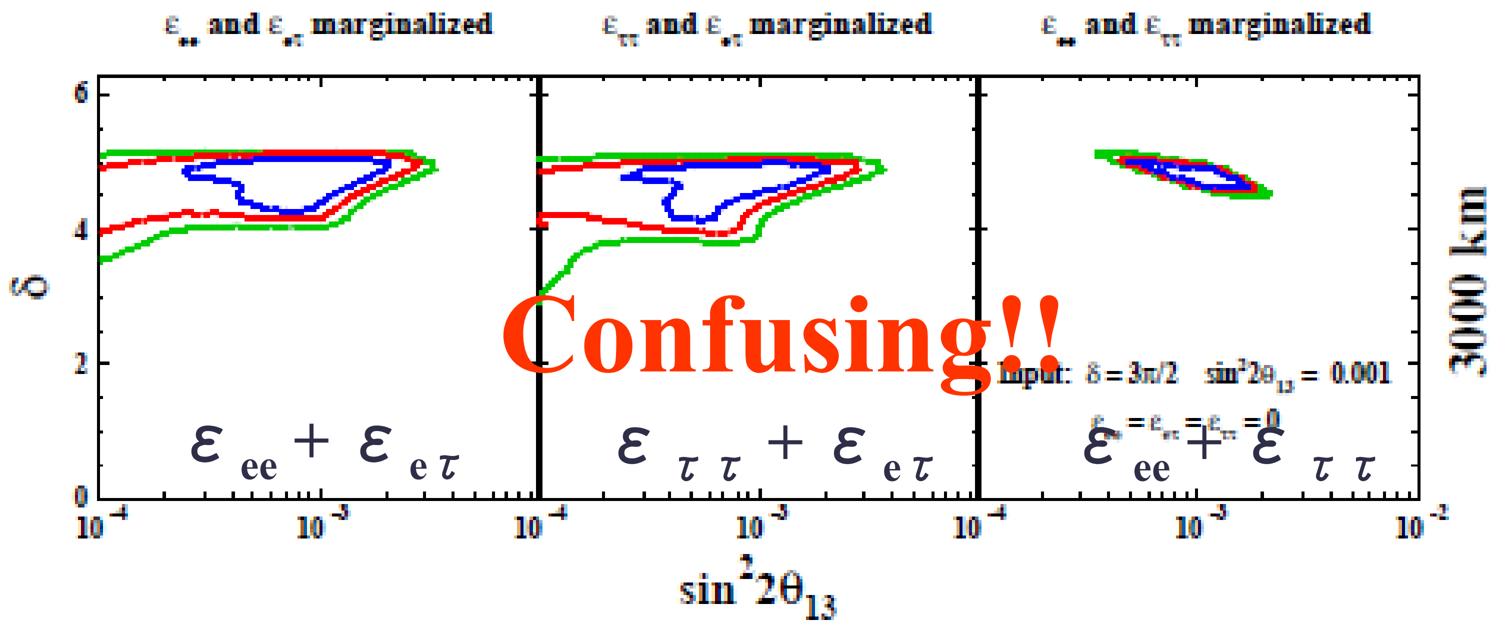
$$a \equiv \sqrt{2}G_F n_e$$

Valle, Gago-Guzzo-Nunokawa-Teves-Zukanovich Funchal

standard case



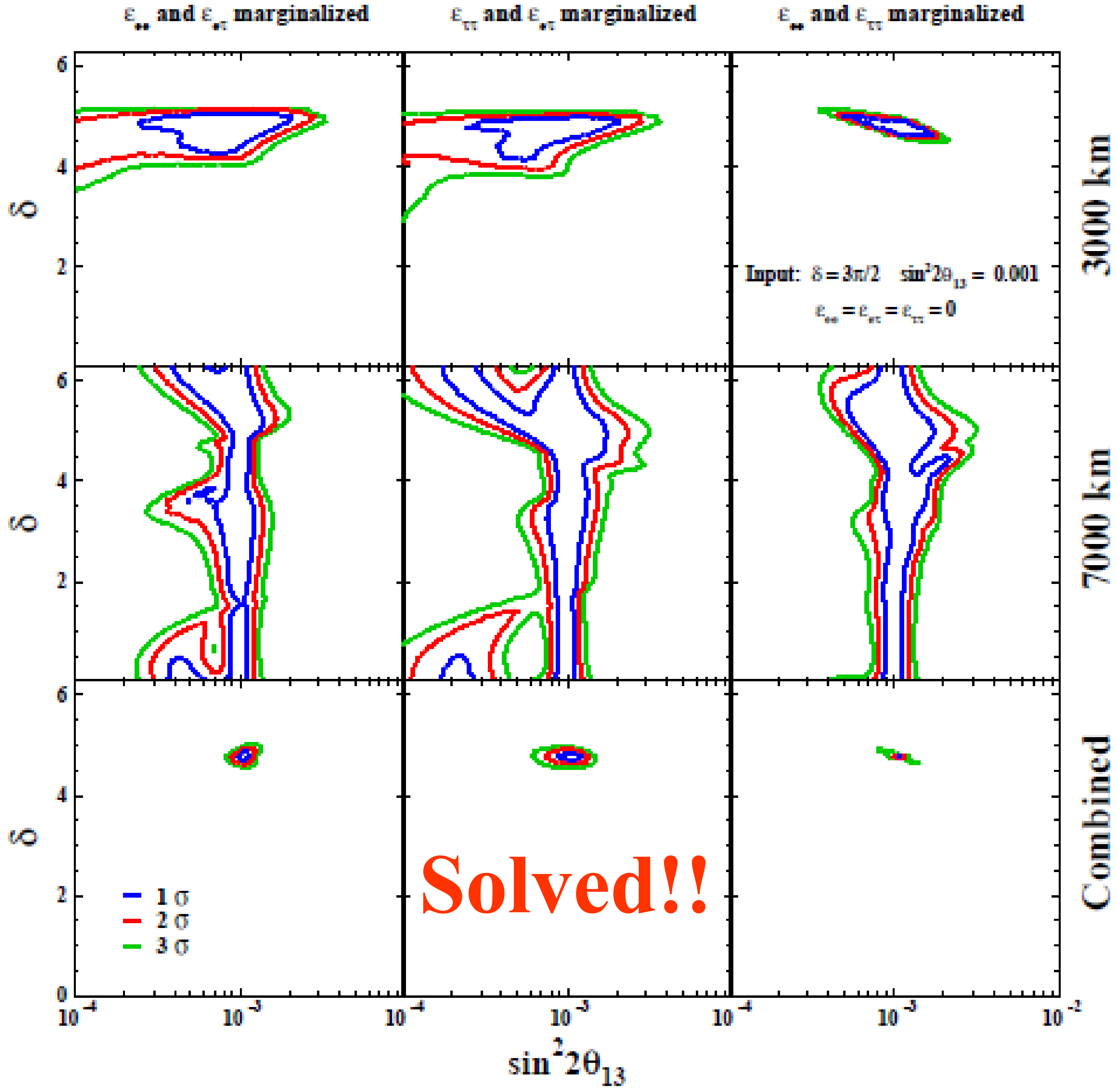
If we take account of the possible existence of NSI

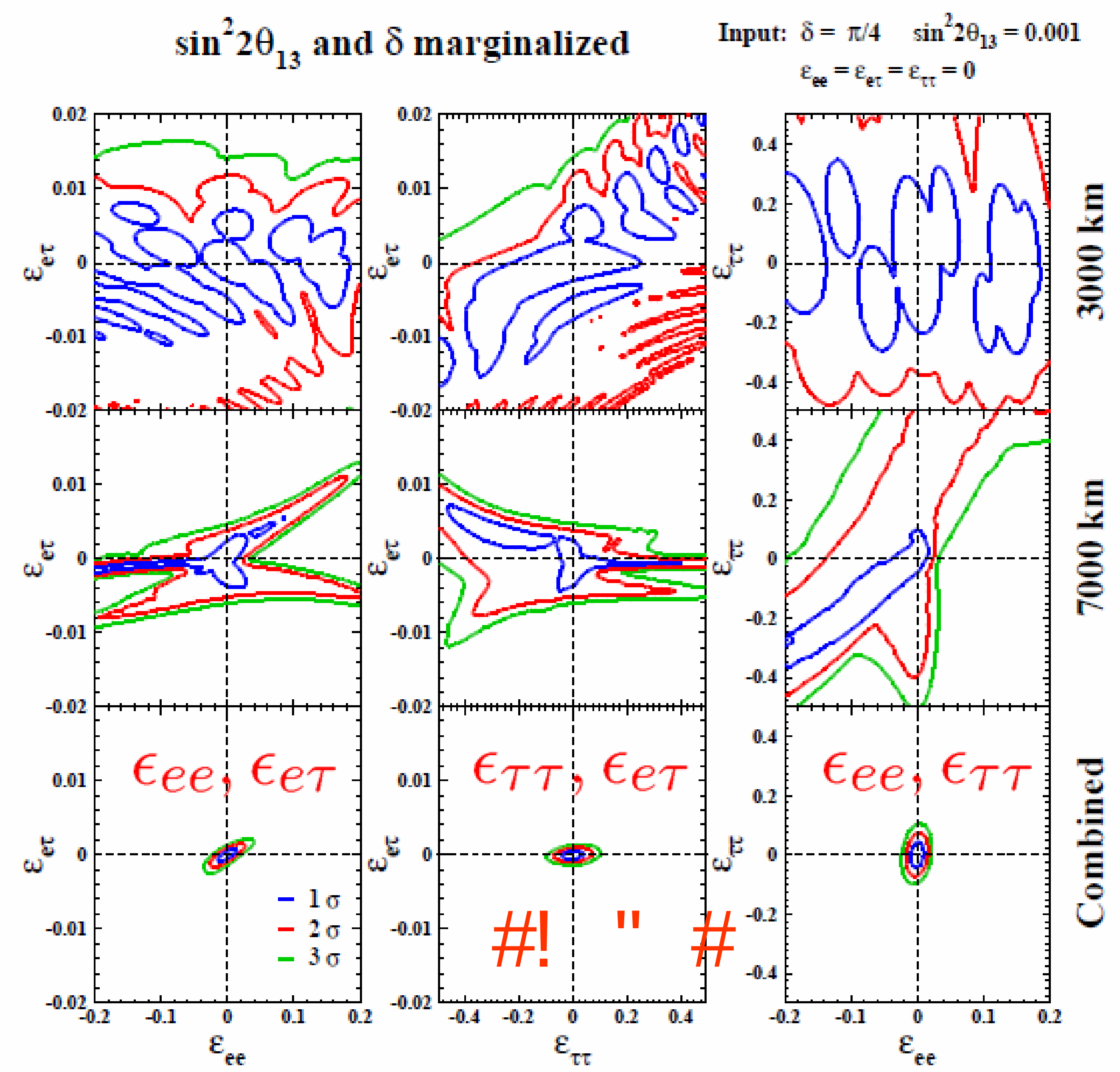


all $\varepsilon = 0$

our setting

2 detector setting





sin²2θ13 and δ marginalized
Input: δ = π/4 sin²2θ13 = 0.001
εee = εeτ = εττ = 0
3000 km
7000 km
Combined
εee, εeτ
εττ, εeτ
εee, εττ
1σ
2σ
3σ
εee
εττ
εeτ

Neutrino factory with two detectors at L=3000km and 7000km

1. solves the problem that the presence of NSI confuses the precision measurement of θ_{13} and δ

2. is powerful enough to probe into extremely small values of the NSI parameters.

$$\varepsilon_{e\tau} \sim O(10^{-3})$$
$$\varepsilon_{e\mu} \sim O(10^{-4})$$

(2 σ)

Conclusions:

- Neutrino Physics desperately needs to go beyond Megawatt traditional neutrino beams and Megaton water Cerenkov detectors: Neutrino Factory is an excellent possibility.
- For large $\sin^2 2\theta_{13}$ $(\geq 0.003\text{-}0.01 \text{ say})$ the low energy option could provide precision measurements of the mixings to give meaningful tests to various sum rules coming from models and also explore the possibility of new physics as sub-leading effects.
- For smaller values of $\sin^2 2\theta_{13}$ the higher energy option provides unprecedented sensitivity to small values $\sin^2 2\theta_{13}$ and has the capability to untangle neutrino mixings from other new physics. (eg NSI Z').