Atmospheric & Accelerator Neutrino Physics @ Jinping

Shao-Feng Ge

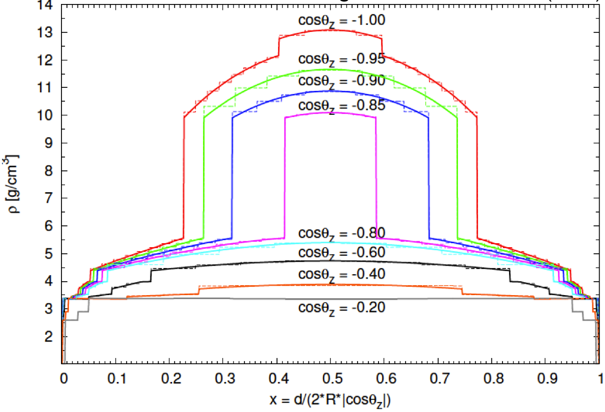
(gesf02@gmail.com)

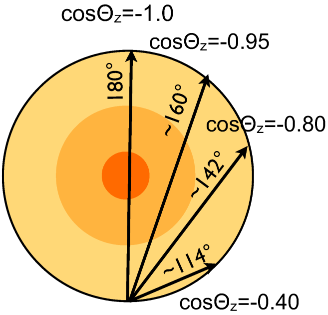
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

2014-6-5

PREM

Ge, Hagiwara, Okamura, Rott (2012)





- The PREM - Preliminary Reference Earth Model is based on a paper by Dziewonski and Anderson in 1981. It still still represents the standard framework for interpretation of seismological data

3.1. Propagation Basis

$$\mathcal{H} = \frac{1}{2E_\nu} \left[U \begin{pmatrix} 0 & & \\ & \delta m_s^2 & \\ & & \delta m_a^2 \end{pmatrix} U^\dagger + \begin{pmatrix} a(x) & & \\ & 0 & \\ & & 0 \end{pmatrix} \right], \tag{3.1}$$

where $a(x) \equiv 2E_\nu V(x) = 2\sqrt{2} E_\nu G_F N_e(x)$ characterizes the matter effect, $\delta m_s^2 \equiv \delta m_{12}^2$ & $\delta m_a^2 \equiv \delta m_{13}^2$,

$$U \equiv O_{23}(\theta_a) P_\delta O_{13}(\theta_r) P_\delta^\dagger O_{12}(\theta_s) = \begin{pmatrix} 1 & & \\ & c_a & s_a \\ & -s_a & c_a \end{pmatrix} \begin{pmatrix} 1 & & \\ & 1 & \\ & & e^{i\delta} \end{pmatrix} \begin{pmatrix} c_r & & s_r \\ & 1 & \\ -s_r & & c_r \end{pmatrix} \begin{pmatrix} 1 & & \\ & 1 & \\ & & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_s & s_s & \\ -s_s & c_s & \\ & & 1 \end{pmatrix},$$

where $c_\alpha \equiv \cos\theta_\alpha$ and $s_\alpha \equiv \sin\theta_\alpha$ with $(s, a, r) \equiv (12, 23, 13)$. Note that in this basis O_{23} and P_δ can be extracted out as overall matrices [42],

$$\mathcal{H} = \frac{1}{2E_\nu} (O_{23} P_\delta) \left[(O_{13} O_{12}) \begin{pmatrix} 0 & & \\ & \delta m_s^2 & \\ & & \delta m_a^2 \end{pmatrix} (O_{13} O_{12})^\dagger + \begin{pmatrix} a(x) & & \\ & 0 & \\ & & 0 \end{pmatrix} \right] (O_{23} P_\delta)^\dagger . \tag{3.2}$$

This is a huge simplification,

$$\mathcal{H}' = \frac{1}{2E_\nu} \left[(O_{13} O_{12}) \begin{pmatrix} 0 & & \\ & \delta m_s^2 & \\ & & \delta m_a^2 \end{pmatrix} (O_{13} O_{12})^\dagger + \begin{pmatrix} a(x) & & \\ & 0 & \\ & & 0 \end{pmatrix} \right] = (O_{23} P_\delta)^\dagger \mathcal{H} (O_{23} P_\delta) . \tag{3.3}$$

Propagation Basis

$$\nu_\alpha = [O_{23}(\theta_a) P_\delta]_{\alpha i} \nu_i' . \tag{3.4}$$

$$S = (O_{23} P_\delta) S' (O_{23} P_\delta)^\dagger \equiv (O_{23} P_\delta) \begin{pmatrix} S_{11}' & S_{12}' & S_{13}' \\ S_{21}' & S_{22}' & S_{23}' \\ S_{31}' & S_{32}' & S_{33}' \end{pmatrix} (O_{23} P_\delta)^\dagger , \tag{3.5}$$

with $S_{ij}' \equiv \langle \nu_j' | S' | \nu_i' \rangle$ and $S_{\beta\alpha} \equiv \langle \nu_\beta | S | \nu_\alpha \rangle$.

3.4. Expansion of Oscillation Probabilities with respect to $x_a = \cos 2\theta_a$ and δm_s^2

The deviation of θ_a from its maximal value $\theta \approx \frac{\pi}{4}$ can be explored analytically,

$$c_a^2 = \frac{1}{2}(1 + x_a)\,, \qquad s_a^2 = \frac{1}{2}(1 - x_a)\,, \qquad c_a^2 s_a^2 = \frac{1}{4}(1 - x_a^2) = \frac{1}{4} + \mathcal{O}(x_a^2)\,. \tag{3.23}$$

Then,

$$P_{\alpha\beta} \equiv P^{(0)}_{\alpha\beta} + P^{(1)}_{\alpha\beta} x_a + P^{(2)}_{\alpha\beta} \cos\delta + P^{(3)}_{\alpha\beta} \sin\delta + P^{(4)}_{\alpha\beta} x_a \cos\delta + P^{(5)}_{\alpha\beta} \cos^2\delta\,, \tag{3.24a}$$

$$\overline{P}_{\alpha\beta} \equiv \overline{P}^{(0)}_{\alpha\beta} + \overline{P}^{(1)}_{\alpha\beta} x_a + \overline{P}^{(2)}_{\alpha\beta} \cos\delta + \overline{P}^{(3)}_{\alpha\beta} \sin\delta + \overline{P}^{(4)}_{\alpha\beta} x_a \cos\delta + \overline{P}^{(5)}_{\alpha\beta} \cos^2\delta\,, \tag{3.24b}$$

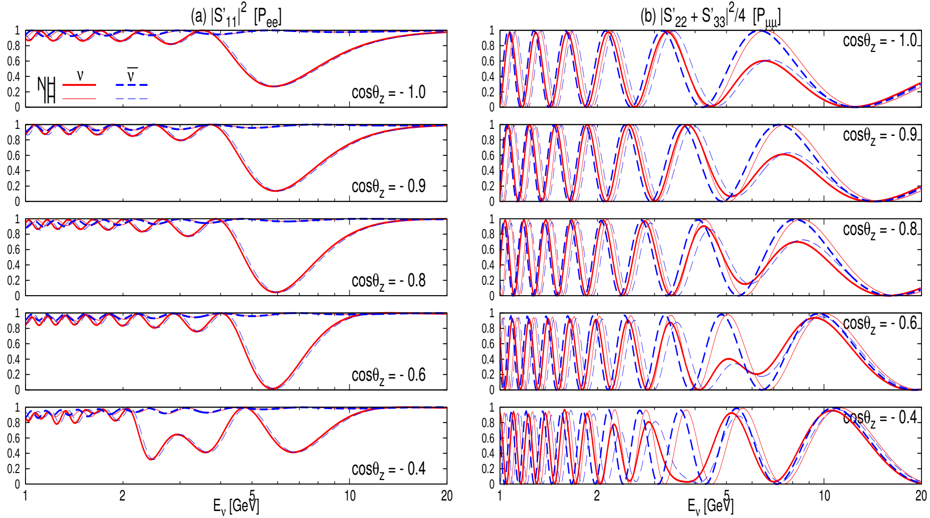
with,

	$P^{(k)}_{ee}$	$P^{(k)}_{e\mu}$	$P^{(k)}_{\mu e}$	$P^{(k)}_{\mu\mu}$
(0)	$\lvert S'_{11}\rvert$	$\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$\frac{1}{4}\lvert S'_{22}+S'_{33}\rvert^2$
(1)	0	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$
(2)	0	$\mathbb{R}(S'_{12}S'^*_{13})$	$\mathbb{R}(S'_{12}S'^*_{13})$	$-\mathbb{R}(S'_{12}S'^*_{13})$
(3)	0	$\mathbb{I}(S'_{12}S'^*_{13})$	$-\mathbb{I}(S'_{12}S'^*_{13})$	0
(4)	0	0	0	$\mathbb{R}[S'_{23}(S'_{22}-S'_{33})^*]$
(5)	0	0	0	0

(3.25)

$$S'_{12} \sim S'_{23} \sim \delta m_s^2 / \delta m_a^2 \sim 3\%$$

$$\mathcal{H}' = \frac{1}{2E_\nu}\left[(O_{13}O_{12})\begin{pmatrix}0 & & \\ & \delta m_s^2 & \\ & & \delta m_a^2\end{pmatrix}(O_{13}O_{12})^\dagger + \begin{pmatrix}a(x) & & \\ & 0 & \\ & & 0\end{pmatrix}\right] = (O_{23}P_\delta)^\dagger \mathcal{H}(O_{23}P_\delta)\,. \tag{3.4}$$



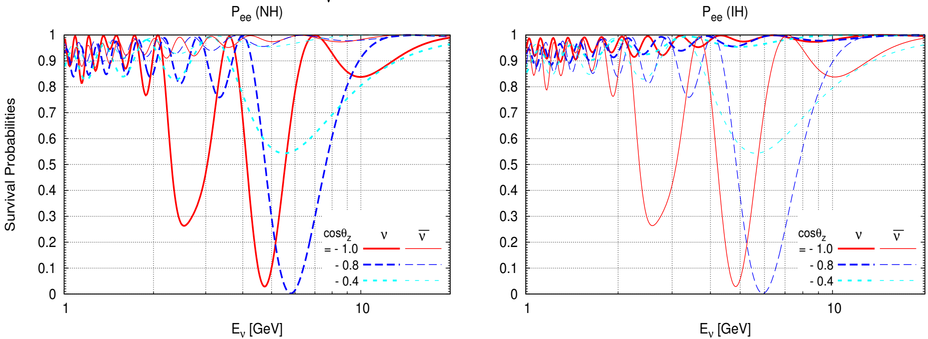
(Previous page)

	$P^{(k)}_{ee}$	$P^{(k)}_{e\mu}$	$P^{(k)}_{\mu e}$	$P^{(k)}_{\mu\mu}$
(0)	$\lvert S'_{11}\rvert$	$\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$\frac{1}{4}\lvert S'_{22}+S'_{33}\rvert^2$
(1)	0	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$	$-\frac{1}{2}(1-\lvert S'_{11}\rvert^2)$

(3.25)

MSW & Parametric Resonances

$$\sin 2\widetilde{\theta} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + (\cos 2\theta - 2E\mathbf{V}/\delta m^2)^2}}.$$

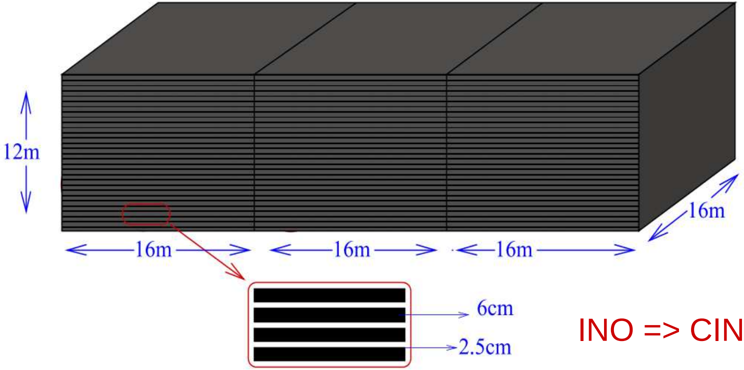


$$P_{\alpha\beta}|_{\alpha\neq\beta} \equiv |A_{\alpha\beta}|^2 = \sin^2 2\widetilde{\theta} \sin^2 \left(\delta\widetilde{m}^2 \frac{L}{4E} \right)$$

- **MSW** – resonance in **amplitude**
- **Parametric** – resonance in **oscillation phase**

Magnetized Iron Calorimeter

- **Iron** – **Target**
- **Gap** – **Active Detector**



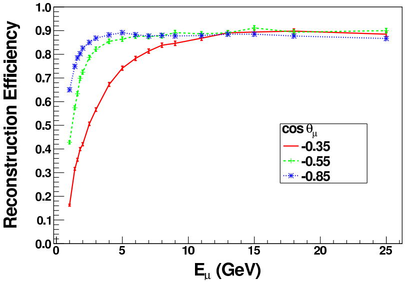
INO => CINO?

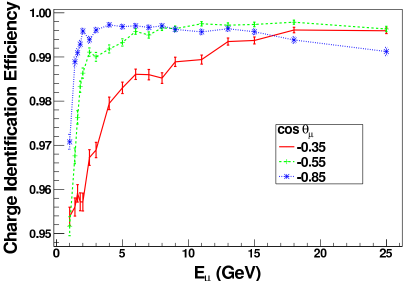
Figure 5.1: Schematic view of the 50 kton iron calorimeter detector consisting of 3 modules each having 140 layers of iron plates.

INO Project Report Vol.I

Muon Reconstruction

- Electron & hadrons are largely absorbed in the iron.
- **Only μ** can leave long enough track to measure its energy, momentum & charge.
  - Better measurement for vertical events!
  - **Reconstruction & Charge Identification Efficiencies**

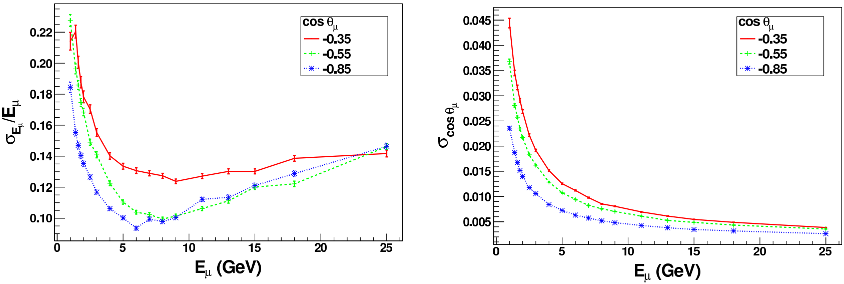




T. Thakore et. al. arXiv:1303.2534

Energy & Zenith Angle Resolutions

- Electron & hadrons are largely absorbed in the iron.
- **Only μ** can leave long enough track to measure its energy, momentum & charge.
  - **Better measurement for vertical events!**
  - Reconstruction & Charge Identification Efficiencies
  - **Energy & Zenith Angle Resolution**



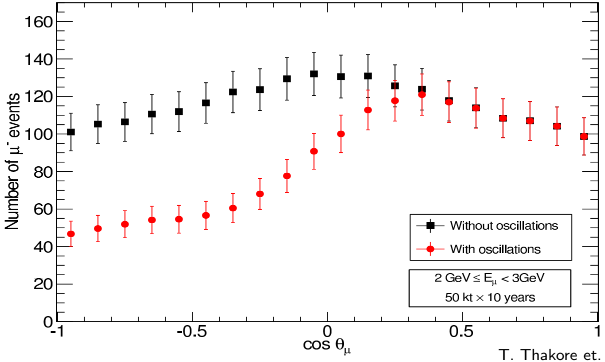
T. Thakore et. al. arXiv:1303.2534

MH – 3σ in 10 years

- Measured Event Rate:

$$\mathbf{N}_{\mu^\pm}(E_\mu,\cos\theta_\mu) = \epsilon^{\pm}_{CID}(E_\mu,|\cos\theta_\mu|)\epsilon^{\pm}_{R}(E_\mu,|\cos\theta_\mu|)\times\mathbf{N}^{\mathbf{true}}_{\mu^\pm}(E_\mu,\cos\theta_\mu) + [1-\epsilon^{\mp}_{CID}(E_\mu,|\cos\theta_\mu|)]\epsilon^{\mp}_{R}(E_\mu,|\cos\theta_\mu|)\times\mathbf{N}^{\mathbf{true}}_{\mu^\mp}(E_\mu,\cos\theta_\mu).$$

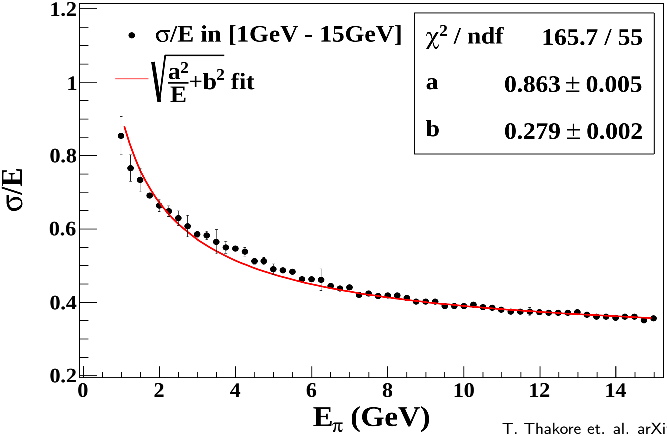
with $\epsilon_{\mathbf{R}} = \epsilon^{\pm}_{\mathbf{R}}$ & $\epsilon_{\mathbf{CID}} = \epsilon^{\pm}_{\mathbf{CID}}$.



T. Thakore et. al. arXiv:1303.2534

Possible Enhancements

- **Hadron Information**

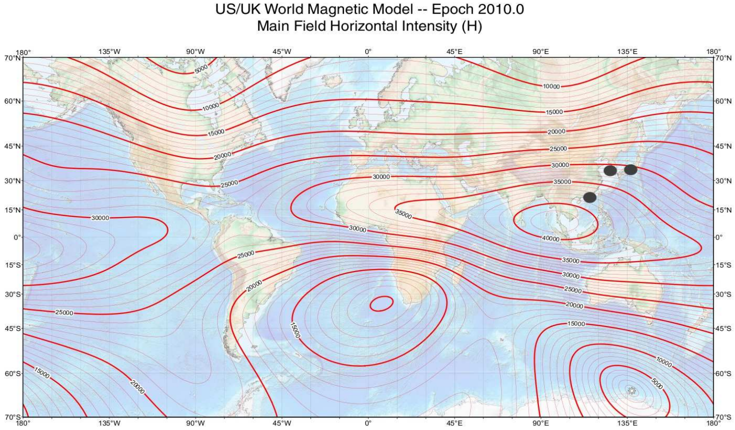


T. Thakore et. al. arXiv:1303.2534

- **Octant of the Atmospheric Angle θ_{23}**

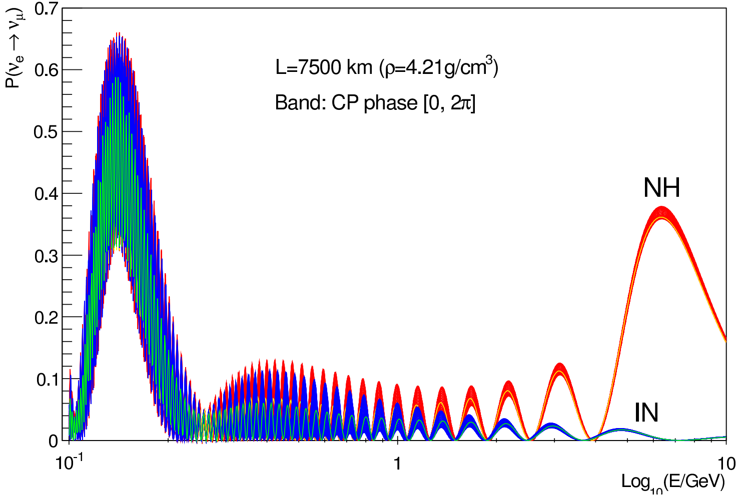
Advantages

- **Larger Flux by $\sim 20\%$**



- **Endless of Power**
- **Tunnel done, lab can be ready soon**

CP Phase with Sub-GeV Atmospheric ν



- The CP dependence is more significant @ low energy!

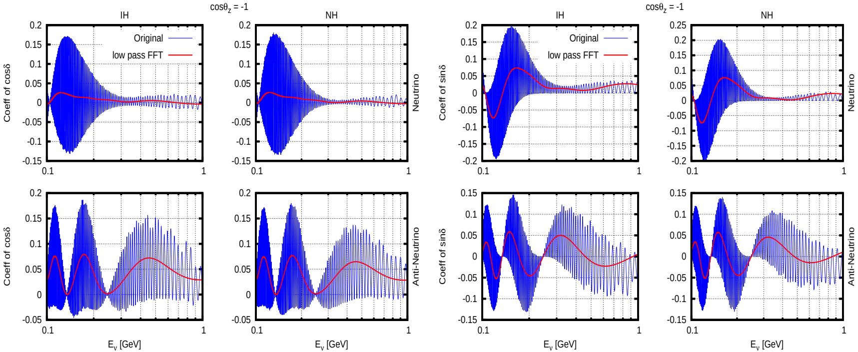
CP Dependence

Dependence on θ_{23} and δ_D is analytic:

$$P_{\alpha\beta} \equiv P^{(0)}_{\alpha\beta} + P^{(1)}_{\alpha\beta} x_a + \boldsymbol{P^{(2)}_{\alpha\beta}} \cos \boldsymbol{\delta'_D} + \boldsymbol{P^{(3)}_{\alpha\beta}} \sin \boldsymbol{\delta'_D} + P^{(4)}_{\alpha\beta} x_a \cos \delta'_D + P^{(5)}_{\alpha\beta} x_a^2 + P^{(6)}_{\alpha\beta} \cos^2 \delta'_D \,,$$

$$\overline{P}_{\alpha\beta} \equiv \overline{P}^{(0)}_{\alpha\beta} + \overline{P}^{(1)}_{\alpha\beta} x_a + \boldsymbol{\overline{P}^{(2)}_{\alpha\beta}} \cos \boldsymbol{\delta'_D} + \boldsymbol{\overline{P}^{(3)}_{\alpha\beta}} \sin \boldsymbol{\delta'_D} + \overline{P}^{(4)}_{\alpha\beta} x_a \cos \delta'_D + \overline{P}^{(5)}_{\alpha\beta} x_a^2 + \overline{P}^{(6)}_{\alpha\beta} \cos^2 \delta'_D \,,$$

with $x_a \equiv \cos 2\theta_{23}$ & $\cos \boldsymbol{\delta'_D} \equiv \sqrt{1 - x_a^2} \cos \delta$, $\sin \boldsymbol{\delta'_D} \equiv \sqrt{1 - x_a^2} \sin \delta$.



Flavor Decomposition

Number of signal [1/(kt·year)]=Flux(E, zenith, v-flavor) [1/(GeV·sr·s·m^2)]

×2π·$d$cos(zenith) [sr]×dE [GeV]

×Oscillation-Probability(zenith, v-flavor, δ_{CP}, MH)

×Exposure [60·60·24·365 s/year]

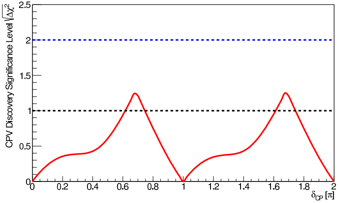
×Σ{σ(nucleus, E, v-flavor) [m^2]·N(nuclei) [/kt]}.

initial \ final	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e	ν_μ
$\bar{\nu}_e$	×	25%	–	–
$\bar{\nu}_\mu$	10%	-3%	–	–
ν_e	–	–	×	-11.5%
ν_μ	–	–	-2.6%	2.4%

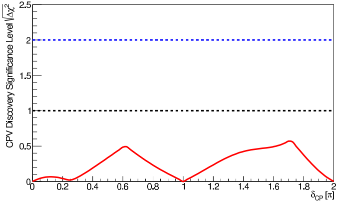
Table: Summary of the discrepancies between 0 & 0.7π.

Sensitivity – 1σ for 20kt×10yr

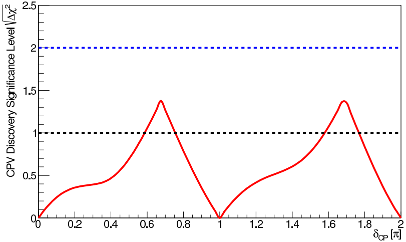
$$\Delta\chi^2 \equiv \min\{\chi^2(0), \chi^2(\pi)\}$$



(a) ν_e plus $\bar{\nu}_e$



(b) ν_μ plus $\bar{\nu}_\mu$

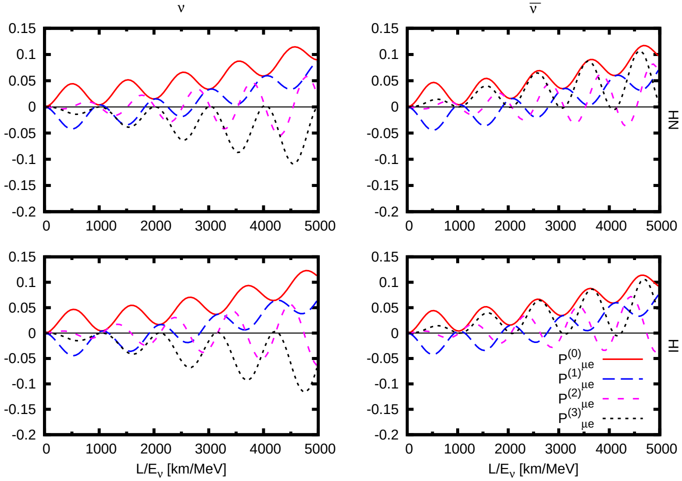


(c) All channels, combine (a) and (b)

Accelerator Neutrino

Lanzhou ⇒ Jinping

- $L \simeq 500$km
- $100\text{MeV} \lesssim E_\nu \lesssim 200\text{MeV}$



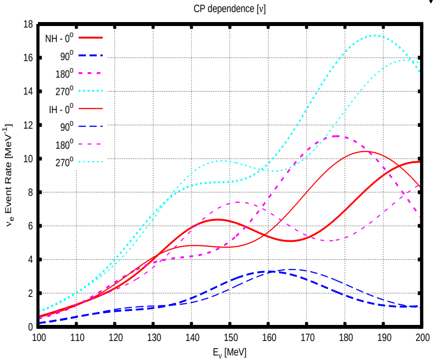
Accelerator Neutrino

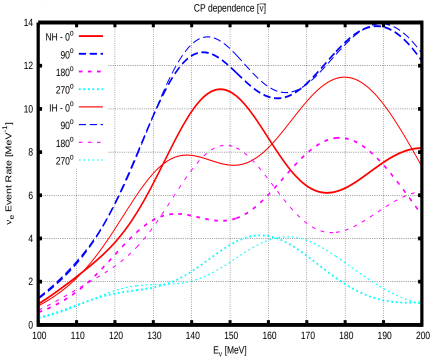
- Shifted JHF flux:

$$\phi(E_\nu) = 40\phi^{JHF}(4E_\nu)$$

- Energy resolution:

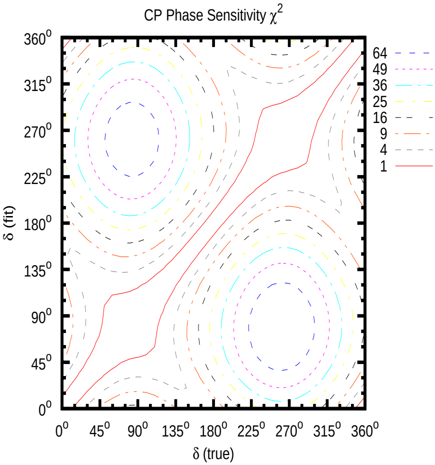
$$\frac{\delta E_\nu}{E_\nu} \approx \frac{1}{\sqrt{E_\nu/\mathrm{MeV}}}$$

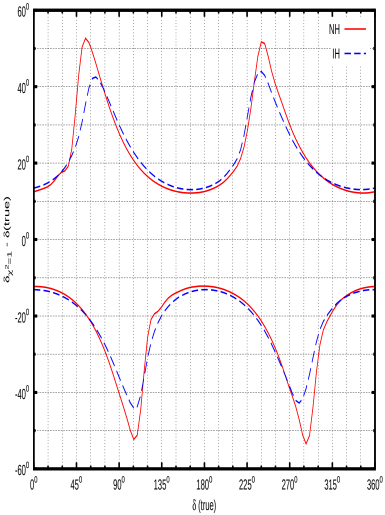




CP Sensitivity

- Detector $\sim$ 20kt
- 4yr for ν & 8yr for $\bar{\nu}$





Thank You!