Physics Potential of a 2540km Superbeam Experiment

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Overview

- Current aims of neutrino oscillation physics
- Problems encountered in achieving these aims
- Some current efforts
- Can we do better? The 2540 km baseline
- Results

Ancient history

- 1960s: Neutrino oscillation hypothesis and the PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad U_{\alpha i} = U_{\alpha i}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{cp})$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = P_{\alpha\beta} = P_{\alpha\beta}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{cp}, \Delta m^2_{21}, \Delta m^2_{31}; L, E)$$

- 1998: Super-Kamiokande confirms the neutrino oscillation hypothesis

Current status

- What we know:

  $\sin^2\theta_{12} = 0.304$, $\Delta m^2_{21} = 7.65 \times 10^{-5}$ eV^2 (solar, KamLAND)
  $\sin^2 2\theta_{23} = 1.0$ (-2%) , $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV^2 (±5%) (MINOS, T2K)
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- What we don't know:
  - Sign of $|\Delta m^2_{31}|$: Is it positive (Normal hierarchy, NH) or negative (Inverted hierarchy, IH)?
  - How small is θ_{13}? Is it non-zero?
  - What is the value of the CP-phase δ_{cp}?

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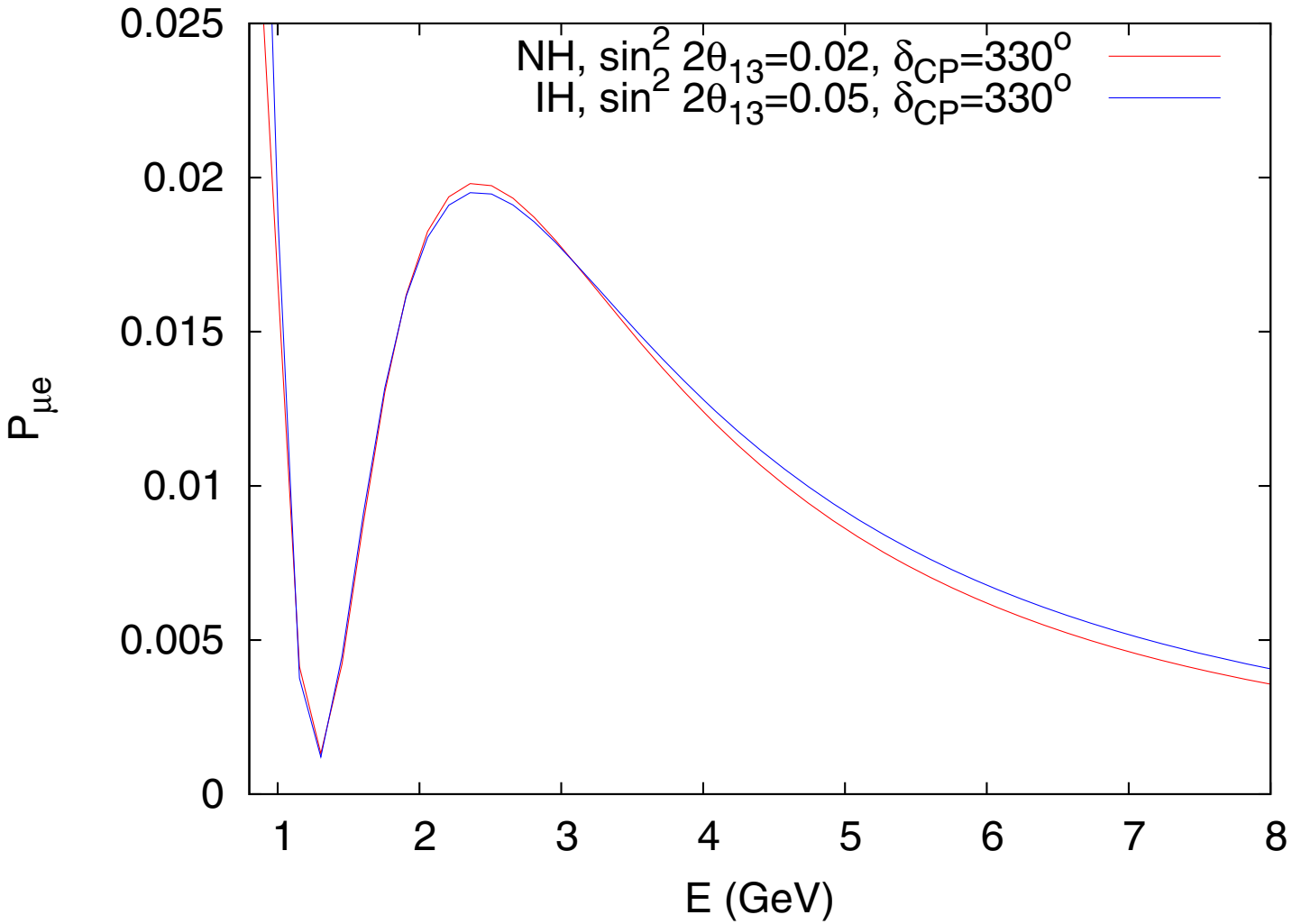
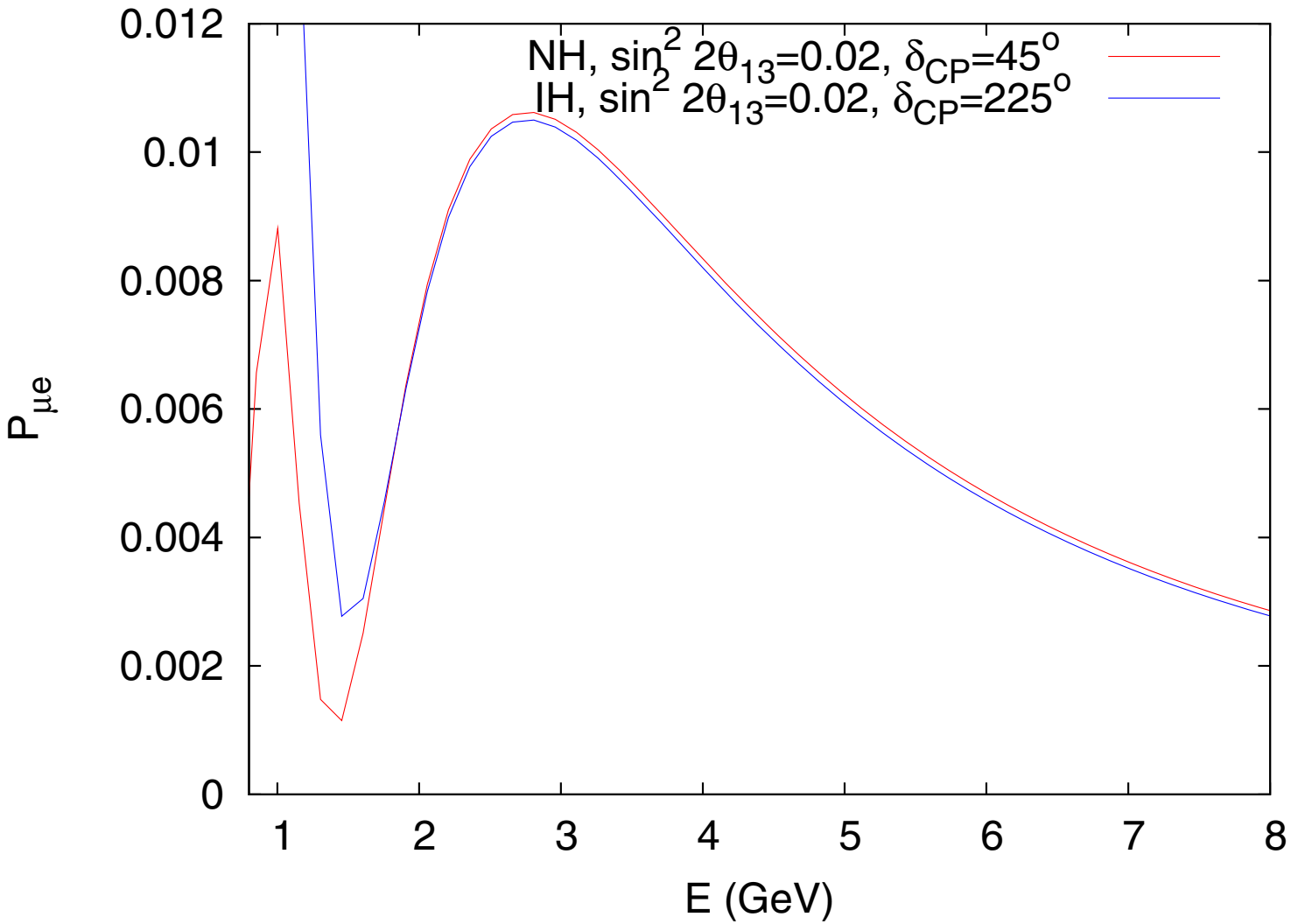
- Why don't we know these quantities?

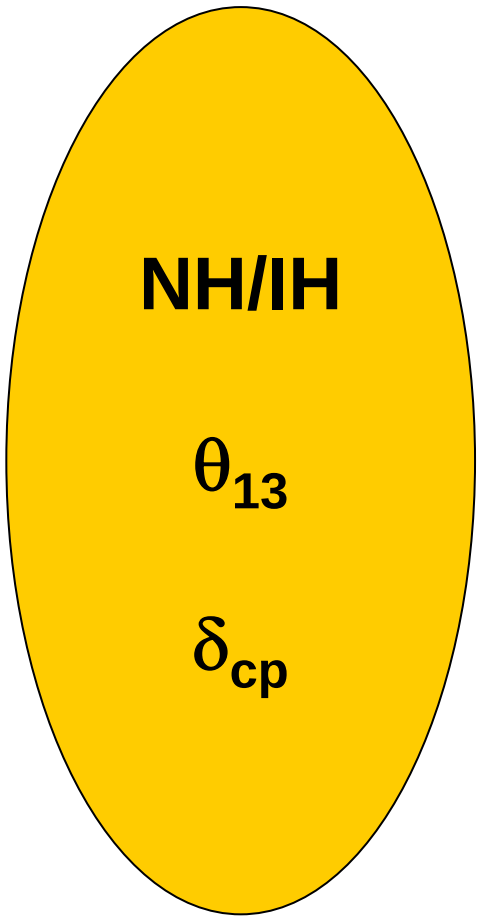
Hierarchy-θ_{13} degeneracy



Hierarchy-δ_{cp} degeneracy



Managing the unmanageable



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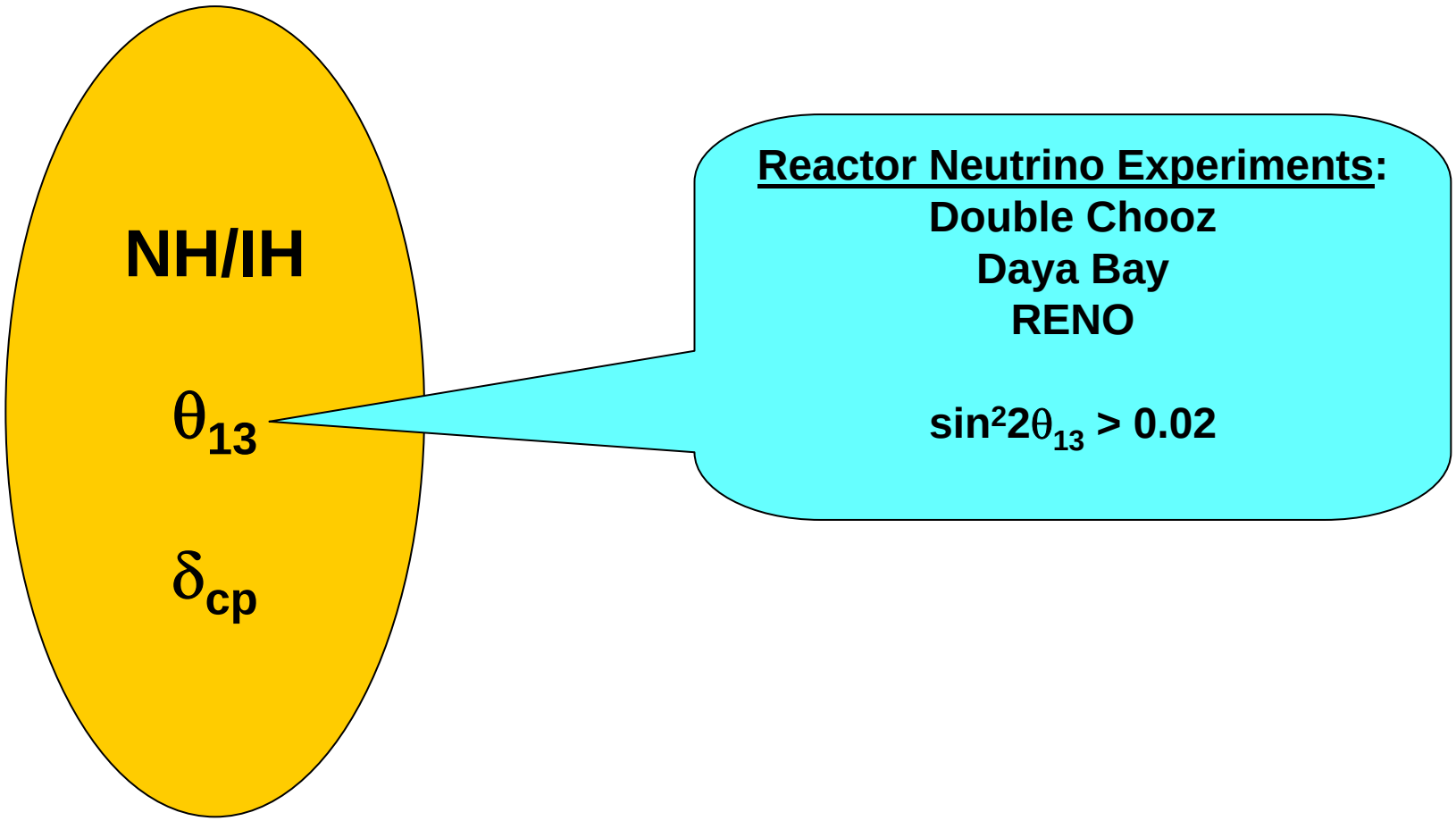

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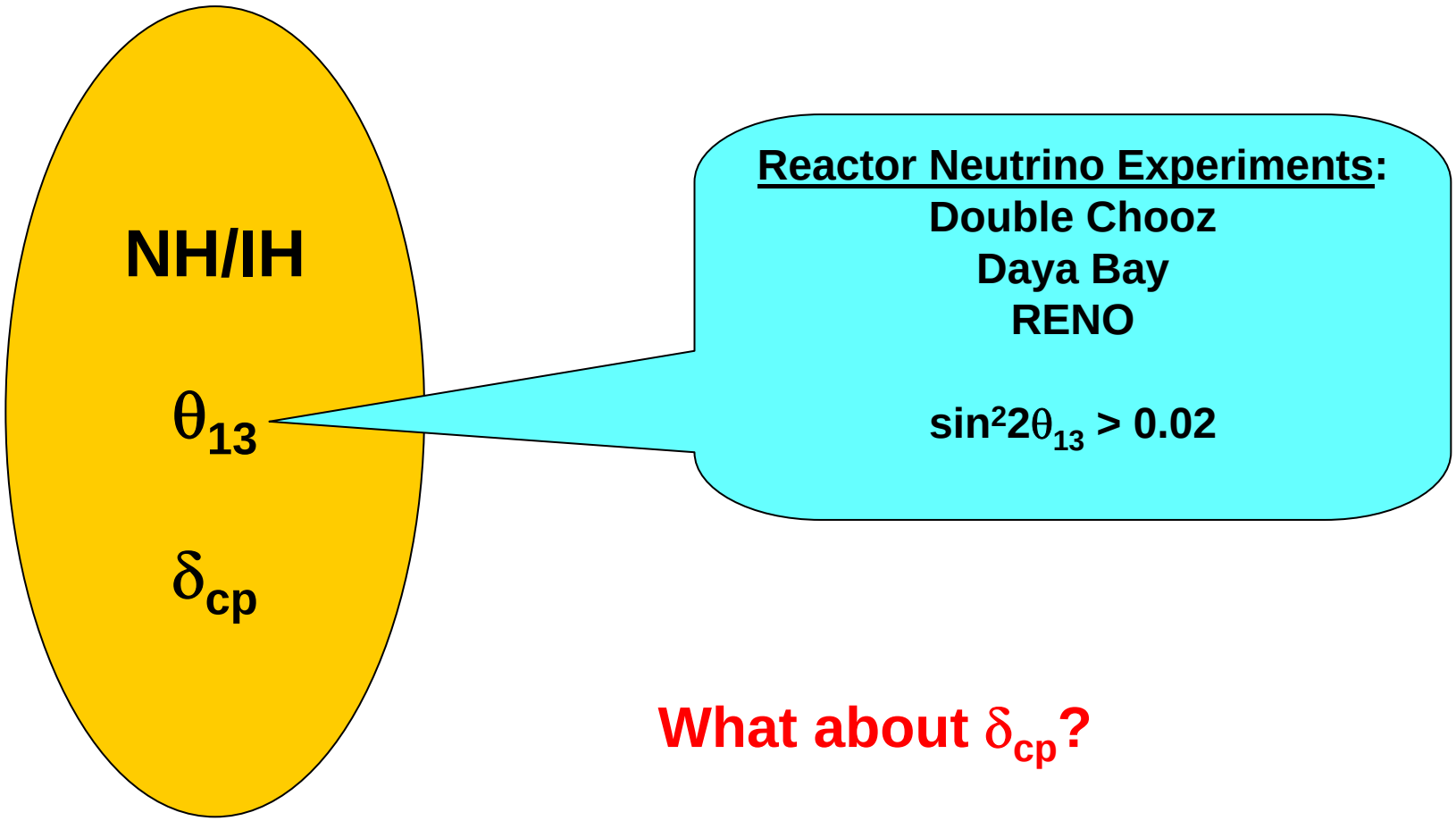
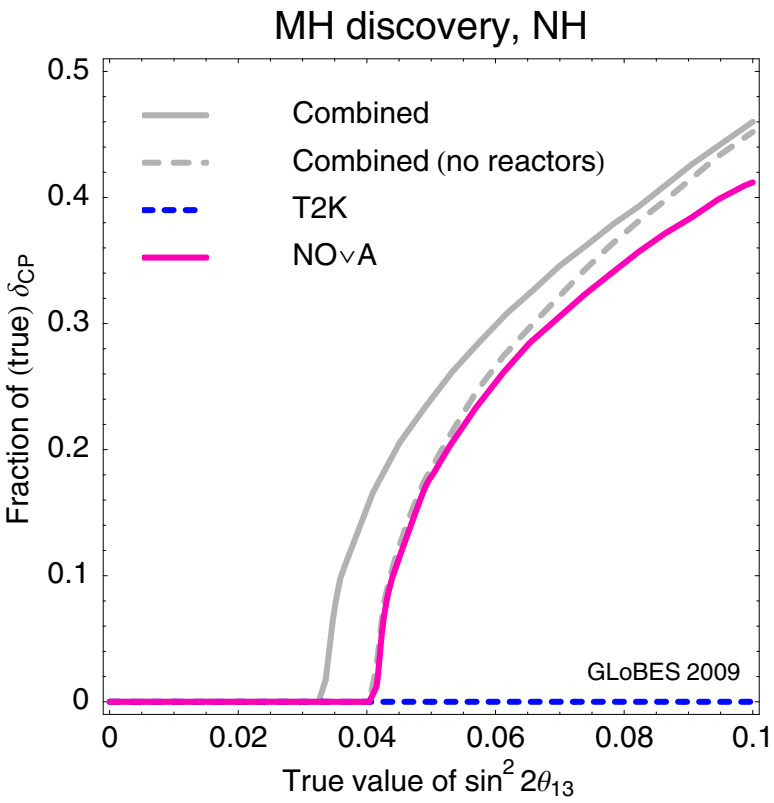
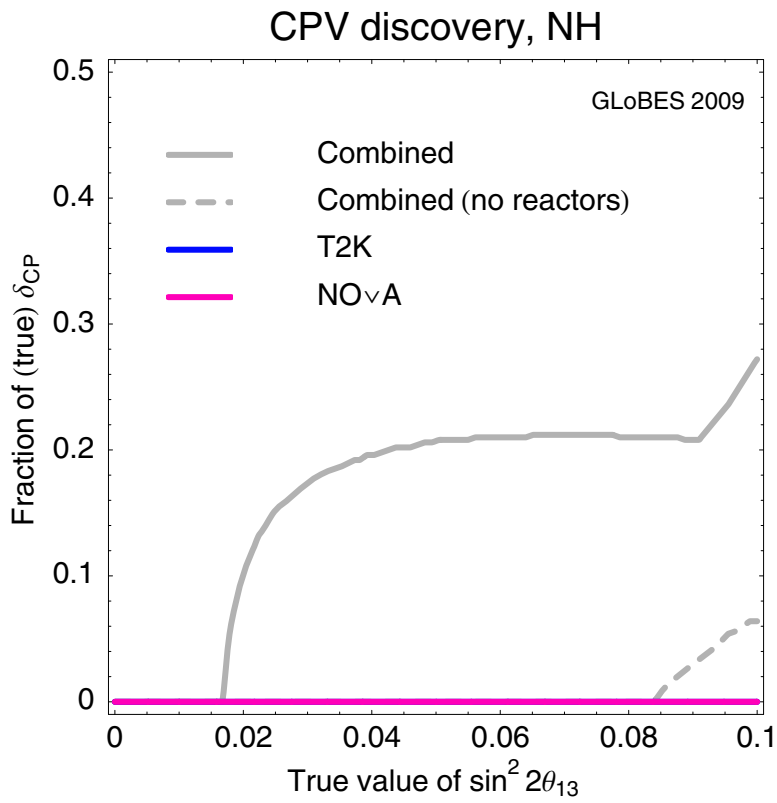


What about δ_{cp}?





Huber et al, 2009

Of course, one can do better with very intense beams and/or very large detectors, but those are futuristic by current standards!

Can we do better?

$$P_{\mu e} = C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$

$$+ \alpha C_1 \cos(\Delta + \delta_{cp}) \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}}$$

$$+ \alpha^2 C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

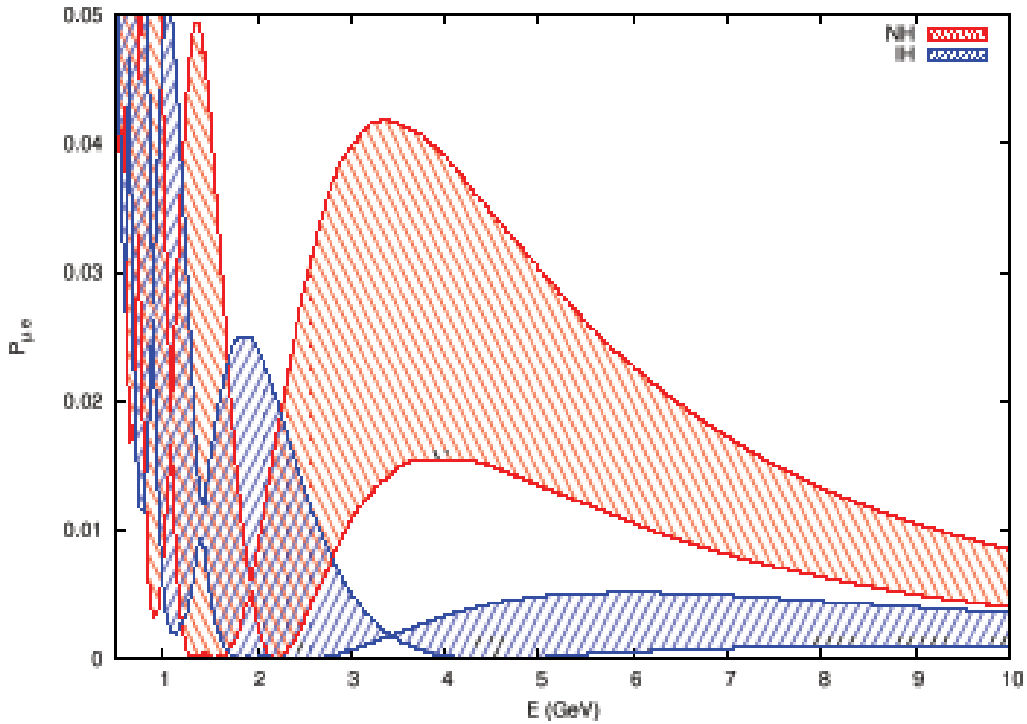
Can we do better?

$$\sin((1-\hat{A})\Delta) = 0 \qquad \text{IH}$$

$$\sin((1-\hat{A})\Delta) = 1 \qquad \text{NH}$$

L = 2540 km

E = 3.3 GeV



The proposed setup

- Since the difference in probabilities is maximum around 3.3 GeV, we choose a narrow band* neutrino beam whose flux peaks around 3-4 GeV, with moderate beam power(~ 1 MW)
- We choose a 100 kiloton Water Cerenkov detector placed 2540 km away from the source

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* Using a narrow band beam helps in cutting down the backgrounds: See poster by Suprabh Prakash

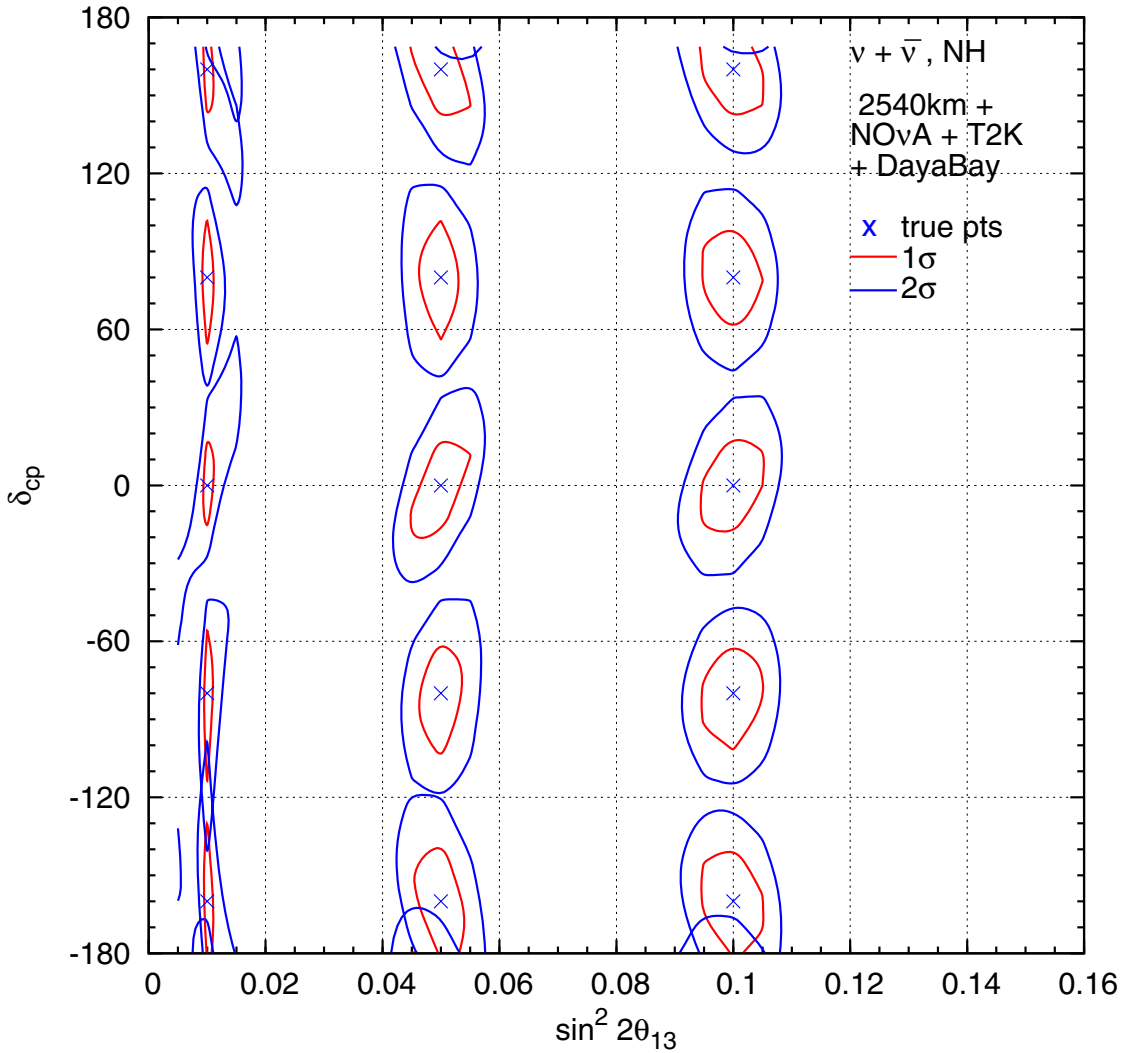
Hierarchy determination

$\sin^2 2\theta_{13}$	Run time (years), NH	Run time (years), IH
0.10	0.022	0.048
0.09	0.026	0.057
0.08	0.031	0.068
0.07	0.040	0.082
0.06	0.051	0.105
0.05	0.070	0.137
0.04	0.104	0.195
0.03	0.180	0.420
0.02	0.425	2.600
0.01	2.950	4.800

Runtime required for **3σ distinction** between the two hierarchies for the specified setup (in neutrino mode alone), combined with T2K, NOvA and the reactor expts.

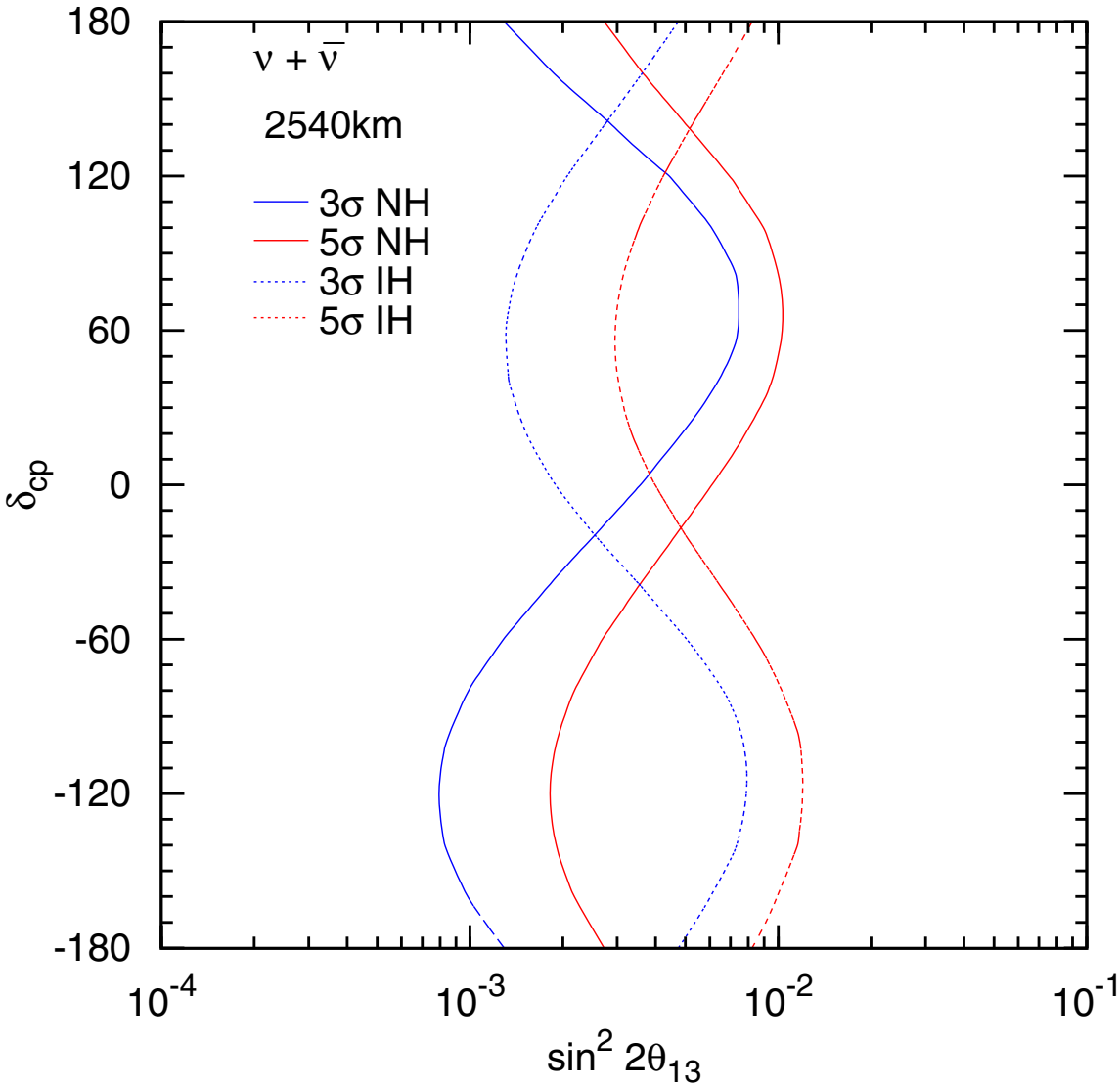
These results are **irrespective of the value of δ_{cp} .**

Sensitivity contours



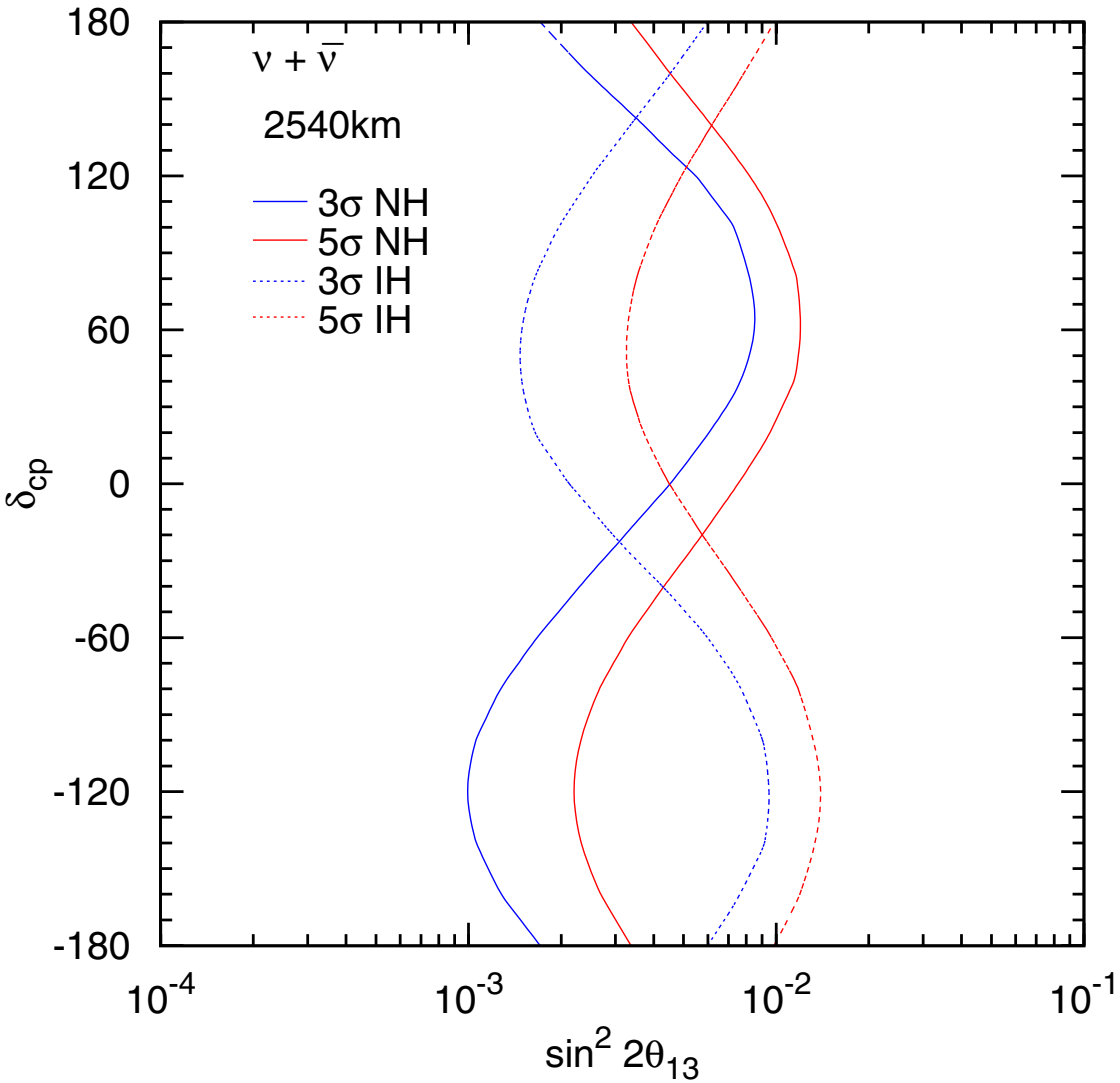
Sensitivity in the $\sin^2 2\theta_{13}$- δ_{cp} plane for the 2540km setup + T2K + NOvA + reactor expts (5yr neutrino and 5yr antineutrino running).

θ_{13}= 0 exclusion



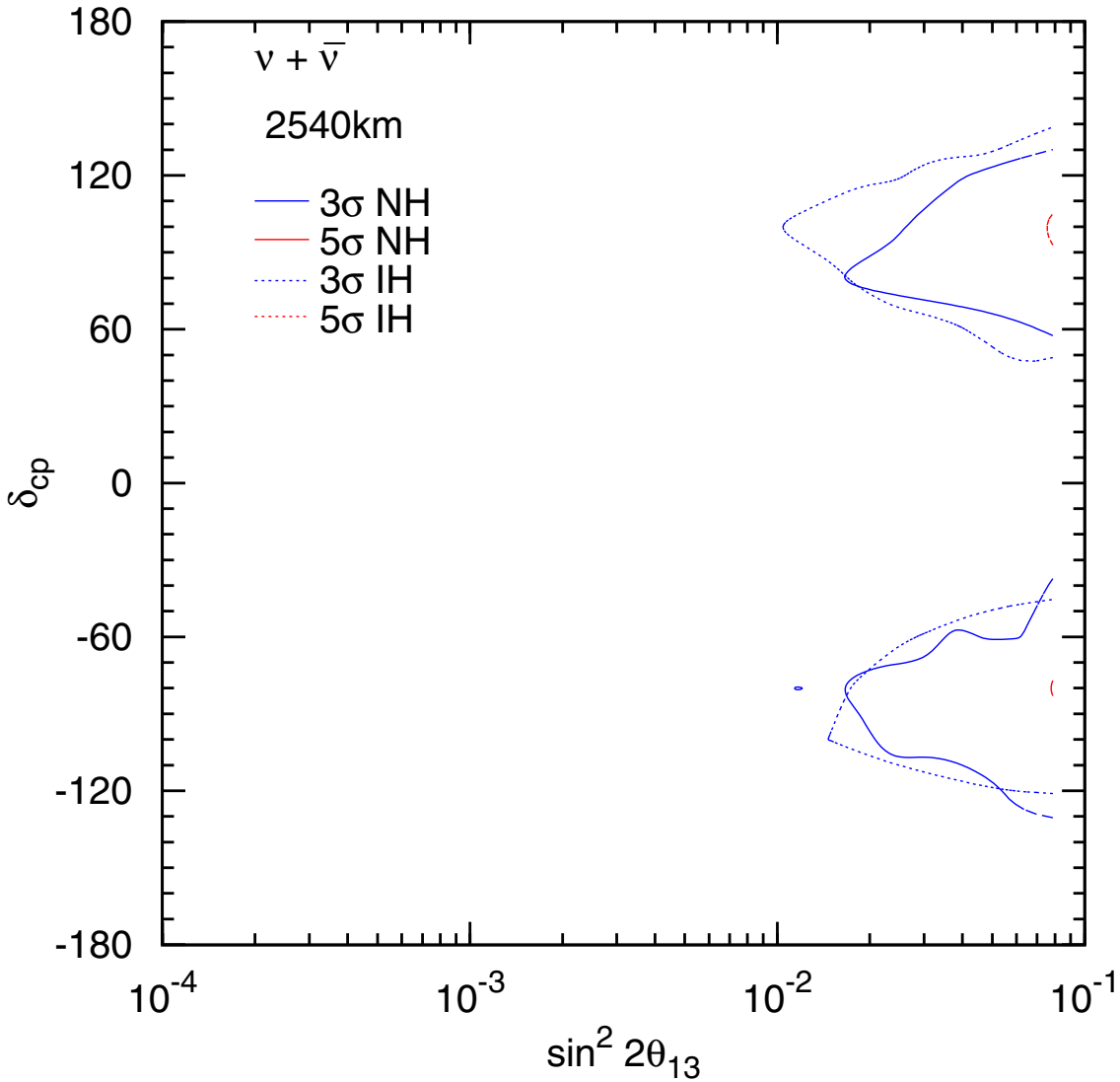
Exclusion of $\sin^2 2\theta_{13} = 0$ for the 2540km setup (5yr neutrino and 5yr antineutrino running).

Hierarchy exclusion



Exclusion of the wrong hierarchy for the 2540km setup (5yr neutrino and 5yr antineutrino running).

CP Violation discovery



Discovery of CP violation for the 2540km setup (5yr neutrino and 5yr antineutrino running).

Conclusions

- A 2540 km baseline along with a beam with flux peaking around 3-4 GeV is capable of a δ_{cp}-independent measurement of the mass hierarchy for $\sin^2 2\theta_{13}$ at least as small as 0.01 using only the neutrino run. The required exposure is moderate.

- For these values of $\sin^2 2\theta_{13}$ sensitivity in the $\sin^2 2\theta_{13}$- δ_{cp} plane is good, on combining with the current experiments.

- Even for smaller $\sin^2 2\theta_{13}$, the reach of the setup with the full neutrino + antineutrino run is competitive with current proposals in spite of the modest specifications.

Also check out the capabilities of a Neutrino Factory at 2540 km – Dighe, Goswami, Ray (2010); Beta Beam at 2300 km – Peltoniemi (2009)

THANK YOU

Backup Slides

The $P_{\mu e}$ oscillation channel

$$P_{\mu e} = C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha C_1 \cos(\Delta + \delta_{cp}) \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}} + \alpha^2 C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

[Cervera et al., 2001; Akhmedov et al., 2004]

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}$$

$$\Delta = \frac{1.27 \Delta m^2_{31} L}{E}$$

$$\hat{A} = A / \Delta m^2_{31}$$

	NH	IH
neutrino	$\Delta>0$ A>0 $\delta_{cp}>0$	$\Delta<0$ A>0 $\delta_{cp}>0$
anti-neutrino	$\Delta>0$ A<0 $\delta_{cp}<0$	$\Delta<0$ A<0 $\delta_{cp}<0$

The Magic Baseline: 7500 km

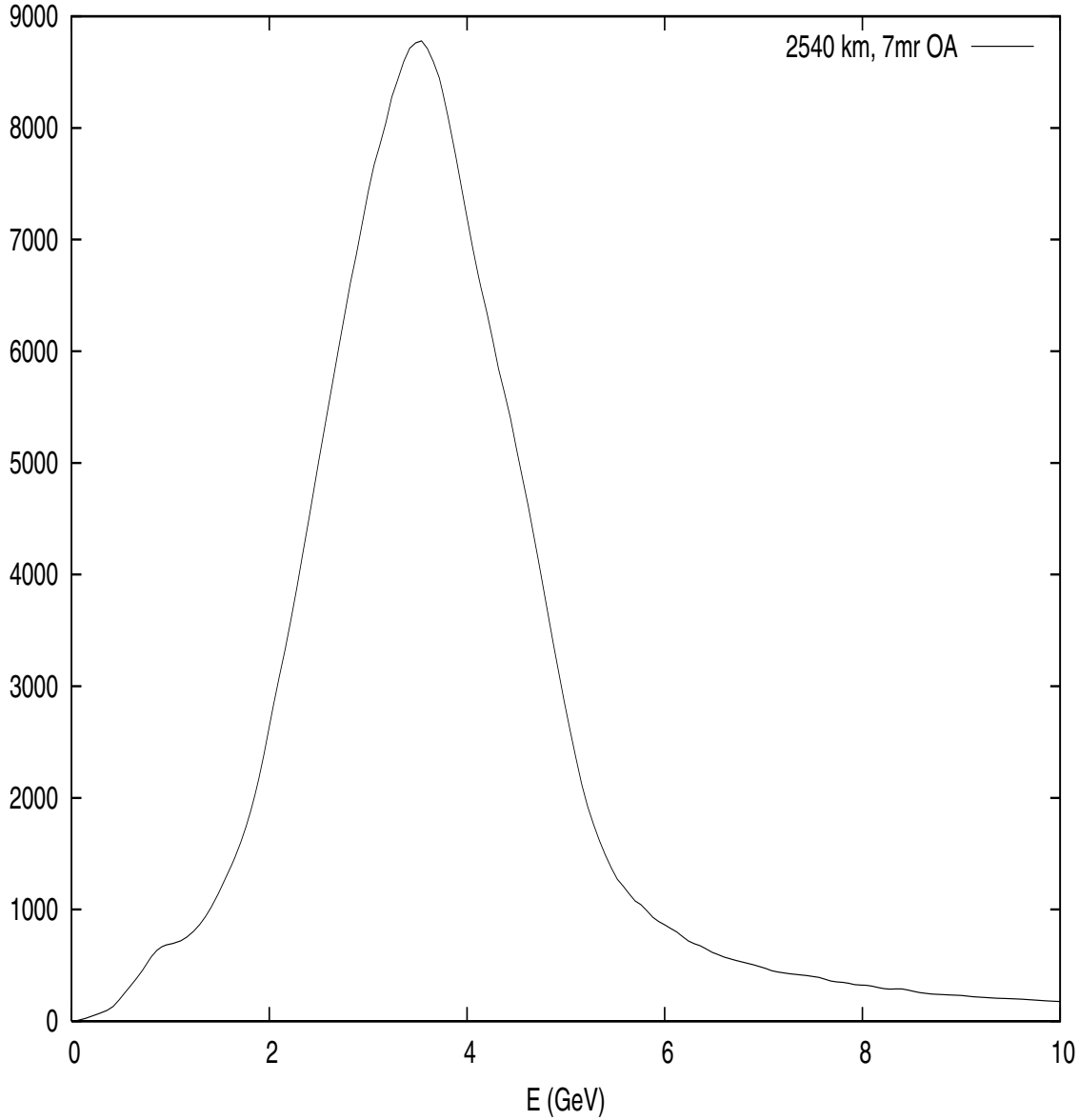
$$\sin(\hat{A}\Delta) = 0 \quad \Rightarrow L = 7500 km$$

Probability (for both hierarchies and all energies) becomes independent of δ_{cp}

- We don't have to worry about this degeneracy
- Good separation between the two hierarchies

- The baseline is too long – need a very intense source
- No information about δ_{cp}

No-oscillation event rate for ν_μ from the NuMI beam, at a 7mr off-axis location



Numerical Analysis

- All simulations were carried out using GLoBES (version 3.0.15)

- Parameter values considered:

  $\sin^2\theta_{12} = 0.304$, $\Delta m^2_{21} = 7.65 \times 10^{-5}$ eV^2 (fixed)

  $\sin^2\theta_{23} = 0.50 \pm 2\%$, $|\Delta m^2_{31}| = (2.4 \pm 5\%) \times 10^{-3}$ eV^2

  δ_{cp} allowed to vary over $[0,2\pi)$

  True values of $\sin^2 2\theta_{13}$ from 0.01 to 0.10 considered

  (current reactor experiment range)

- Background reducing cuts similar to NOvA

- Systematics: 5% normalization error, 2.5% tilt error on both signal and background. 5% error in matter density

An algorithm