Capabilities of a 2540km Superbeam Experiment

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(to be submitted)

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Overview:

- The $P_{\mu e}$ oscillation channel, and parameter degeneracies
- Resolving the degeneracy
- Results: Hierarchy sensitivity at 2540km
- Results: Degeneracy resolution, θ_{13} exclusion and CPV exclusion at small θ_{13}.

Oscillation parameters

- Six observable parameters:
  θ_{12}, θ_{13}, θ_{23}, Δm^2_{21}, Δm^2_{31}, δ_{cp}
- Current status:
  $\sin^2\theta_{12} = 0.304$, $\Delta m^2_{21} = 7.65 \times 10^{-5}$ eV^2 (solar, KamLAND)
  $\sin^2\theta_{23} = 0.50$, $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV^2 (MINOS, T2K)
  $\sin^2 2\theta_{13} < 0.2$ (CHOOZ)
  [Huber, et al., 2009]
- Current problems:
  - Determination of the sign of Δm^2_{31}
  - Detection and measurement of θ_{13}
  - Detection and measurement of CP-violation

$P_{\mu e}$ and its degeneracies

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

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

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

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

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

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

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

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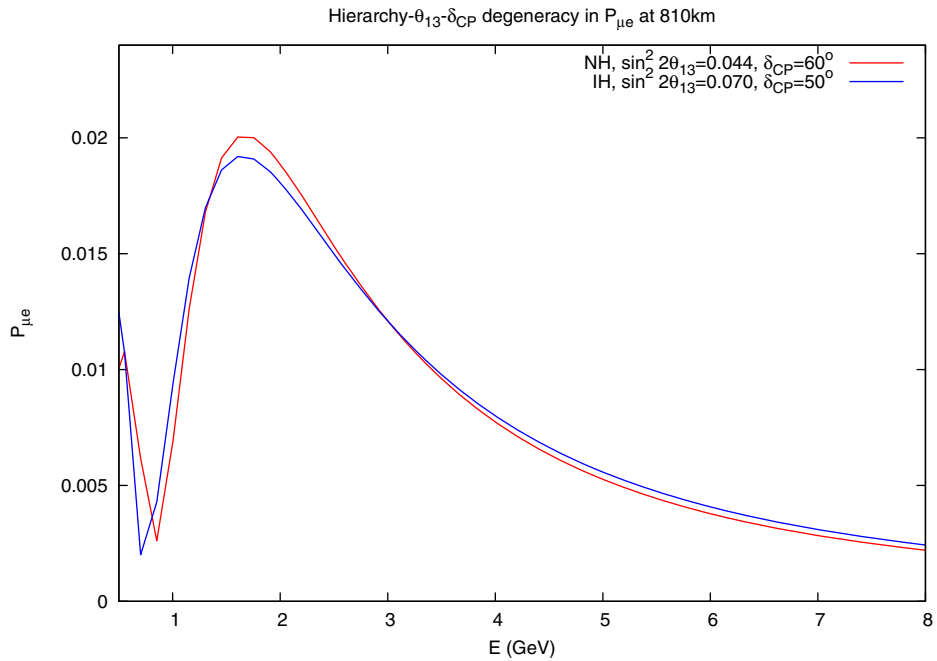

810km: $\mathbf{P_{NH}(\theta_{13}^1,\delta_{cp}^1) = P_{IH}(\theta_{13}^2,\delta_{cp}^2)}$

NH: $\sin^2 2\theta_{13} = 0.044$, $\delta_{cp} = 60^o$

IH: $\sin^2 2\theta_{13} = 0.070$, $\delta_{cp} = 50^o$

Resolving the degeneracy:
The magic baseline

- A possible solution: Set the δ_{cp} dependent term to zero by imposing sin(ÂΔ) = 0, which gives the magic baseline: L ≈ 7500 km (independent of the neutrino energy)

  [Barger et al., 2002; Huber et al., 2003]

  [Smirnov, 2006]

This leaves only θ_{13} effects in the oscillation probability, and the hierarchy can be determined cleanly.

- However, this baseline is quite long and a very intense beam of neutrinos is required for sufficient statistics, since the flux falls ~ $1/L^2$.
- Moreover, an experiment with this baseline cannot be used to determine or measure CP violation.

- But that is obvious! After all, the magic baseline was found by eliminating the δ_{cp} dependence.

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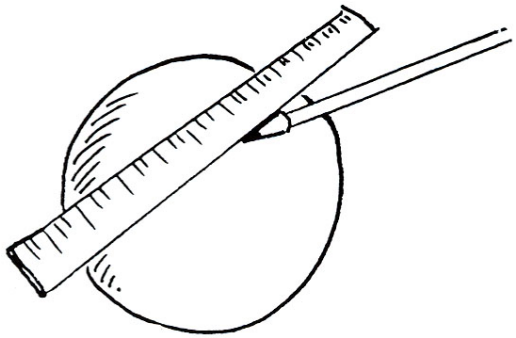

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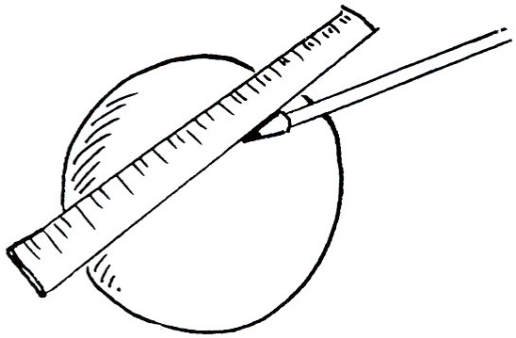

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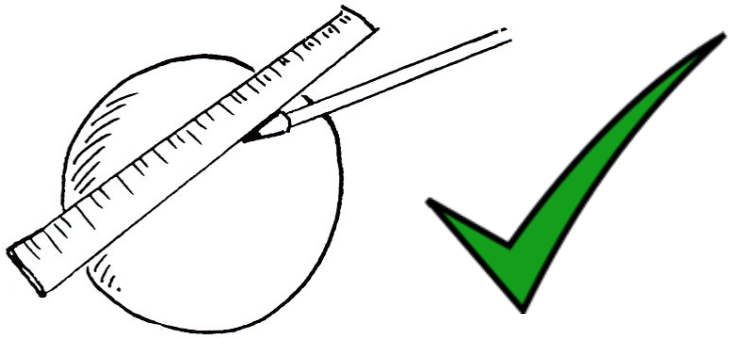

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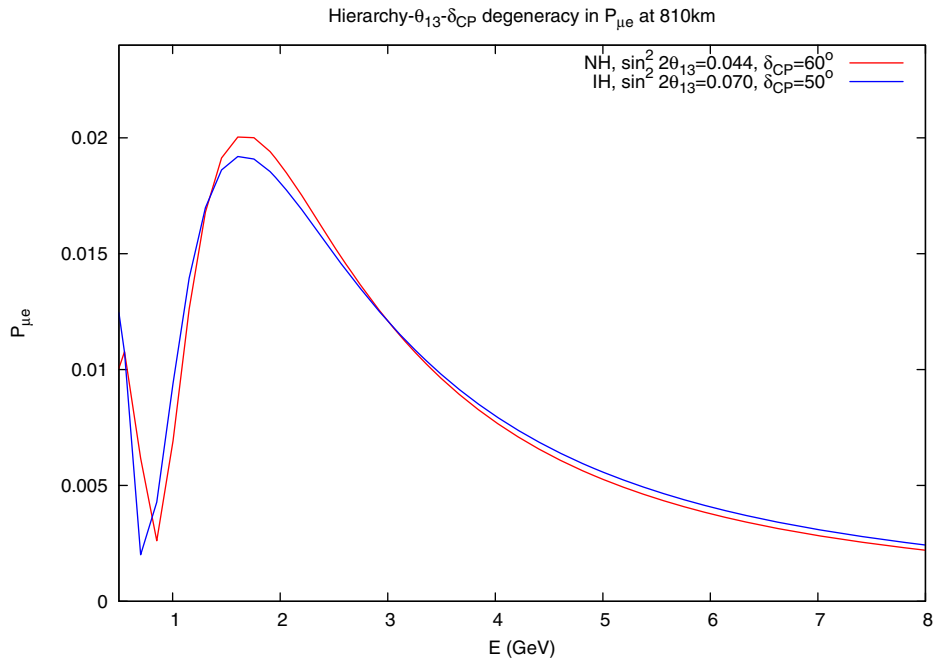

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Another 'magical' baseline

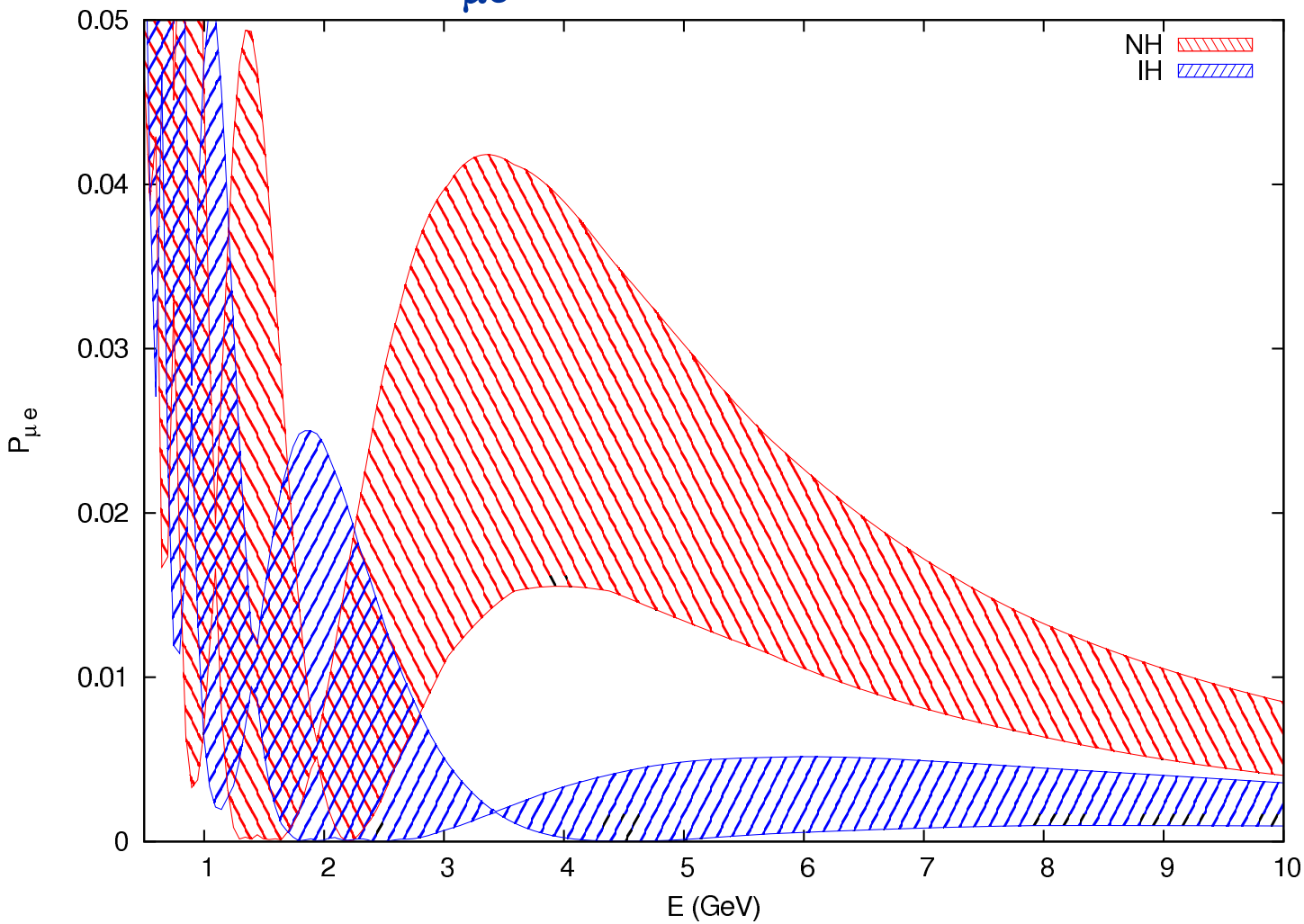
- Insist on δ_{cp} independence for inverted hierarchy (IH):
  $(1-\hat{A})\Delta = -\pi$
  (C_0 and C_1 terms disappear, probability becomes small)

  Demand that the probability for normal hierarchy (NH) be maximum: $(1-\hat{A})\Delta = \pi/2$

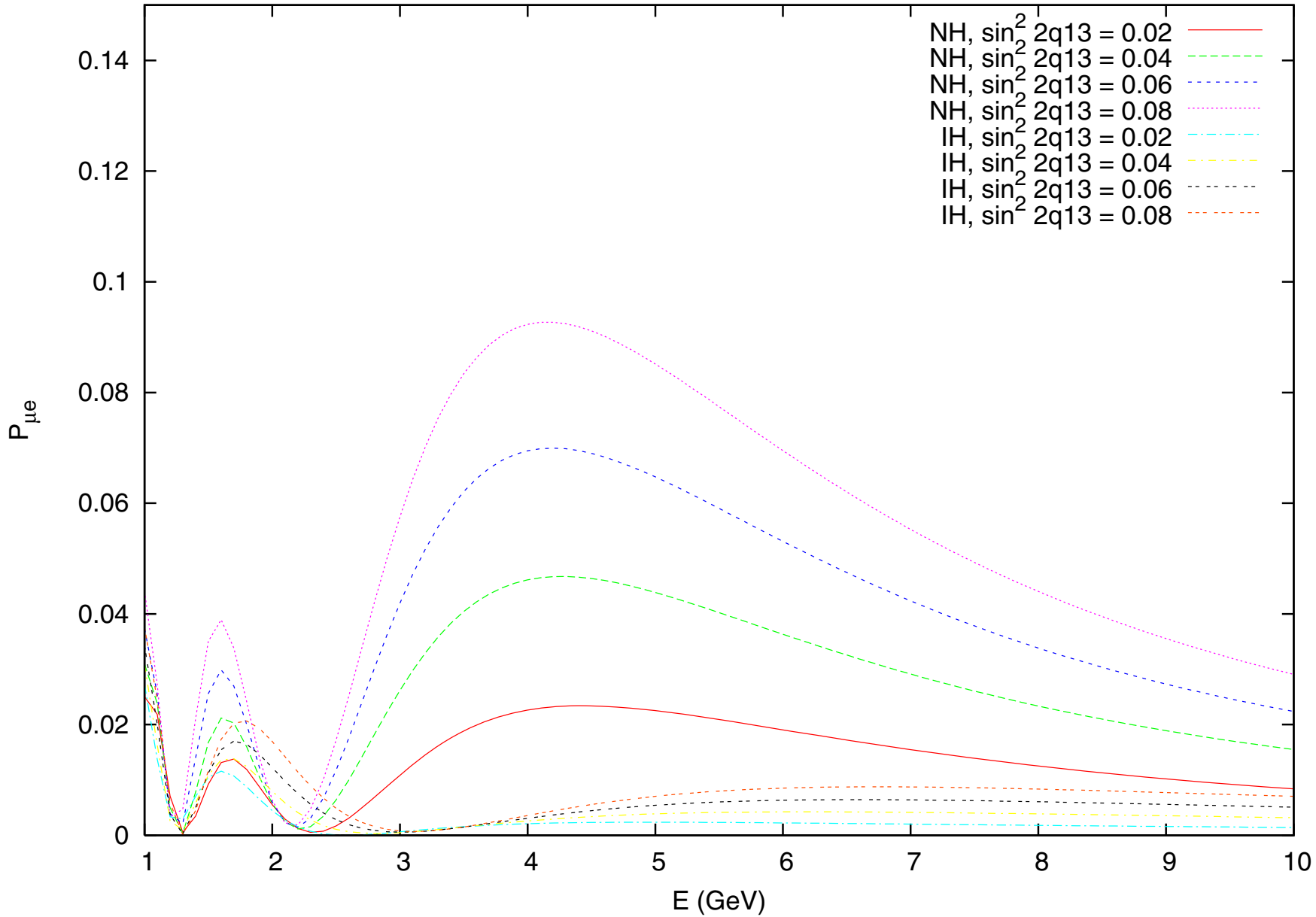
  This provides good discrimination between NH and IH

- Solving these simultaneously gives conditions on the baseline and energy:
  L = 2540 km , E = 3.3 GeV

$P_{\mu e}$ at 2540 km



$P_{\mu e}$ at 2540 km for $\sin^2 2\theta_{13} = 0.02$. The band represents variation due to δ_{cp}


NH, sin^2 2q13 = 0.02
NH, sin^2 2q13 = 0.04
NH, sin^2 2q13 = 0.06
NH, sin^2 2q13 = 0.08
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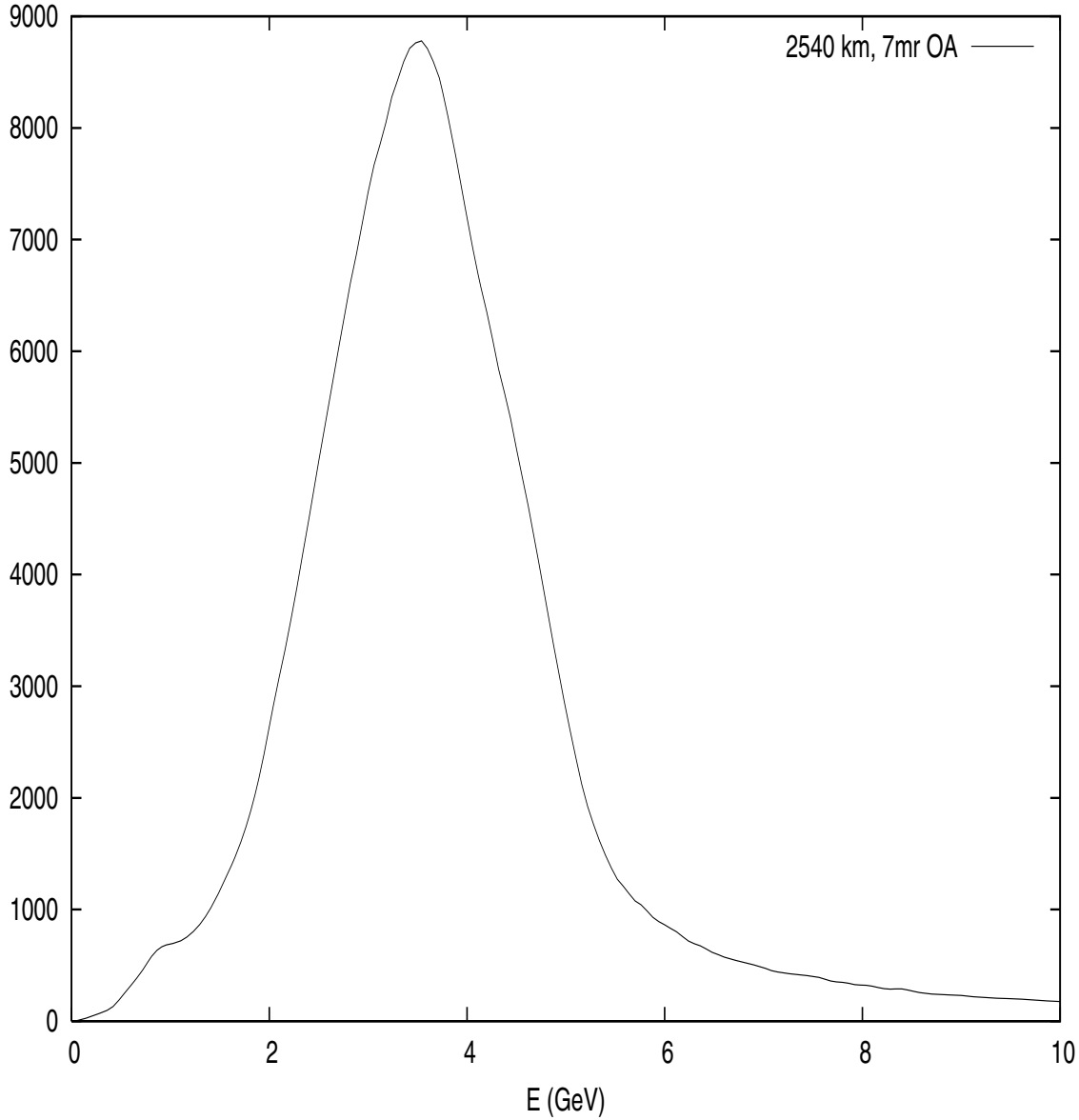
$P_{\mu e}$
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
1
2
3
4
5
6
7
8
9
10
E (GeV)

- Since the difference between NH and IH is maximum in the energy range from 3-4 GeV, we require a neutrino beam with a flux that peaks in this region. We use the NuMI beam in the medium energy option with 10×10^{20} pot/year.

- We consider a 100 kT liquid scintillator detector located 2540 km away from the source, at a location 7 mr off the beam axis.

  Thus, the total exposure used is 1000×10^{20} pot kT/year.
  (Note: $15 \times 7.3 \times 10^{20}$ pot kT/yr expected for NOvA)

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



Advantages of this setup

- This setup makes use of a beam which can be easily attained using current technology.
- Using this setup, it is possible to determine the neutrino mass hierarchy with moderate exposure and in neutrino mode only.
- This is true irrespective of the value of δ_{cp} and for values of θ_{13} in the range detectable by Double Chooz, Daya Bay and RENO.

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

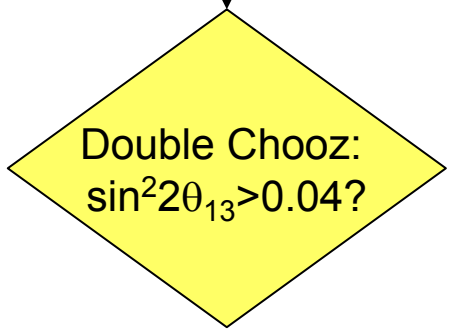
- Systematics: 5% normalization error, 2.5% tilt error on both signal and background. 5% error in matter density

$\sin^2 2\theta_{13}$	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 in years for **3σ hierarchy distinction**, for the specified setup, combined with T2K, NOvA and the reactor expts.

An algorithm

Run the proposed 2540km experiment in **neutrino mode for a few months**.



An algorithm

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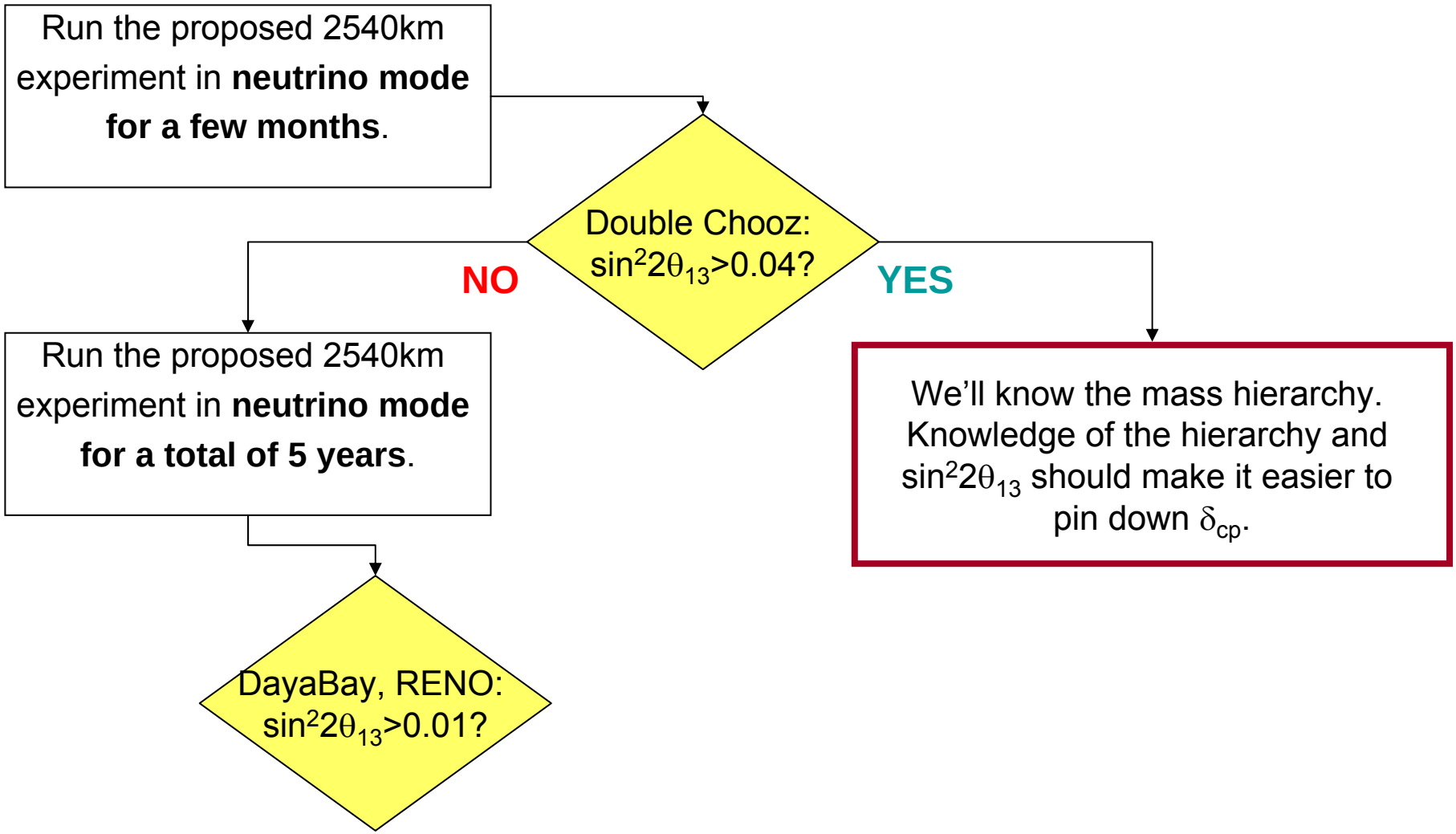
Double Chooz: $\sin^2 2\theta_{13} > 0.04$?

YES

We'll know the mass hierarchy. Knowledge of the hierarchy and $\sin^2 2\theta_{13}$ should make it easier to pin down δ_{cp}.

An algorithm



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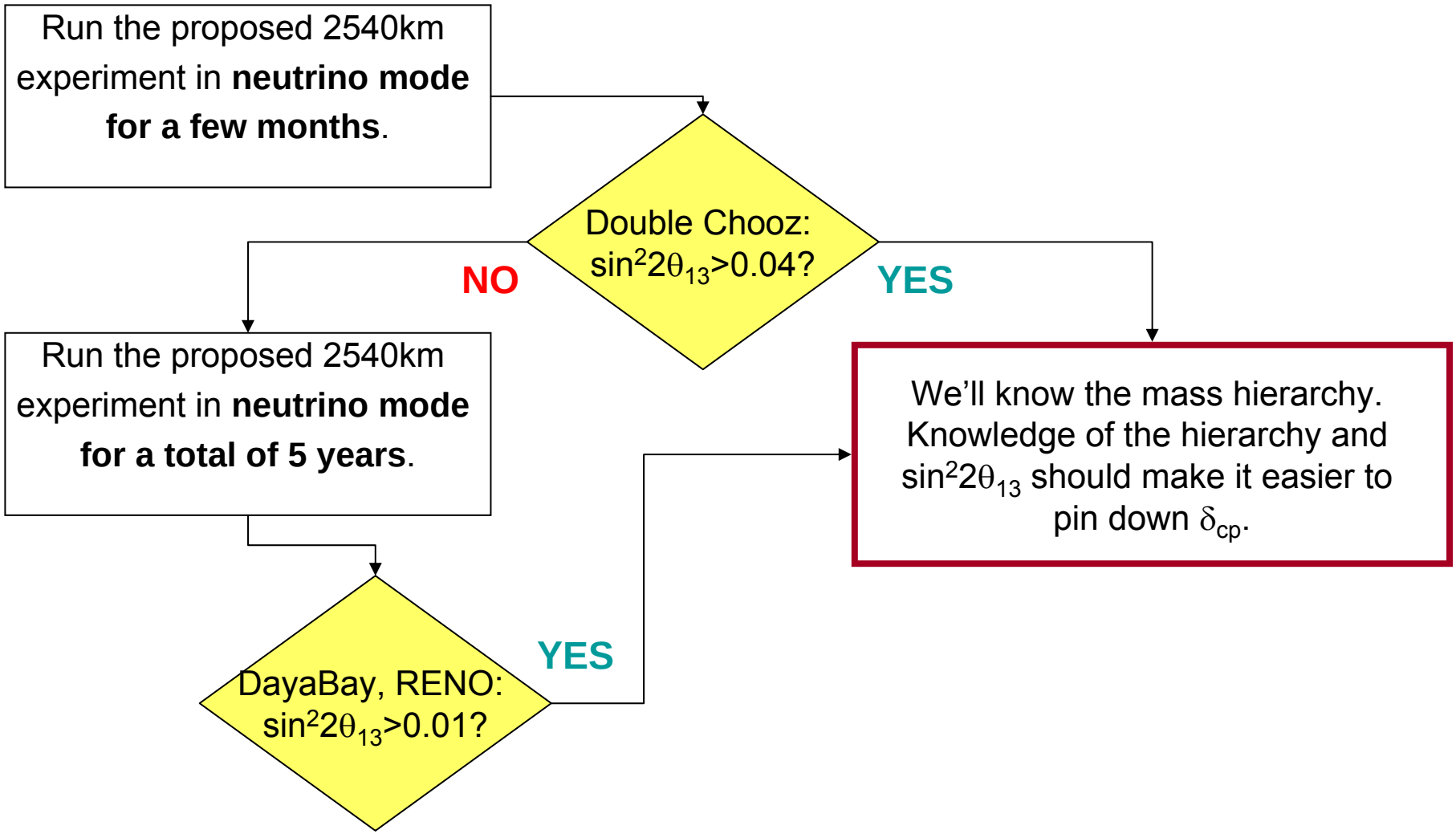

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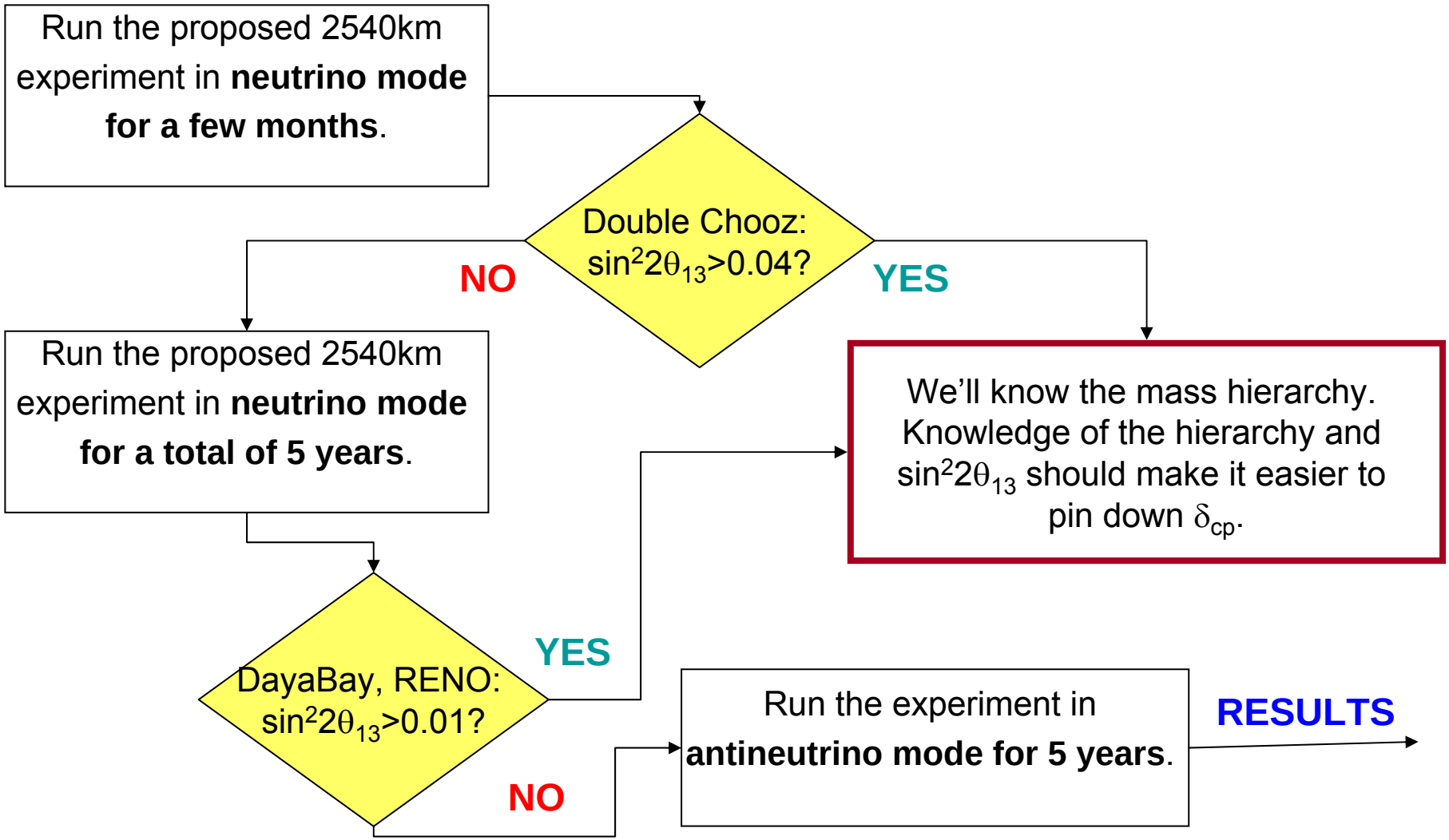
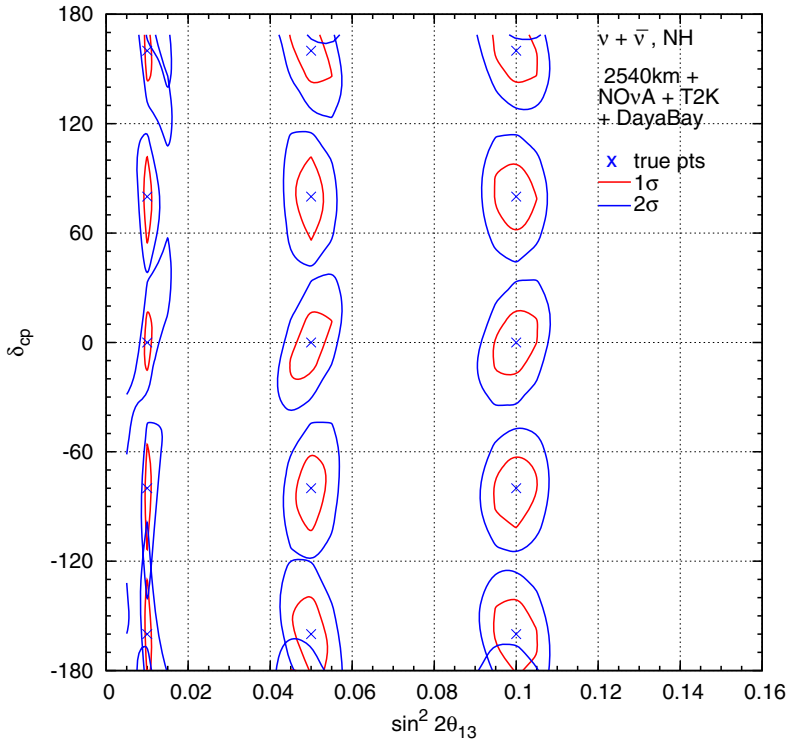
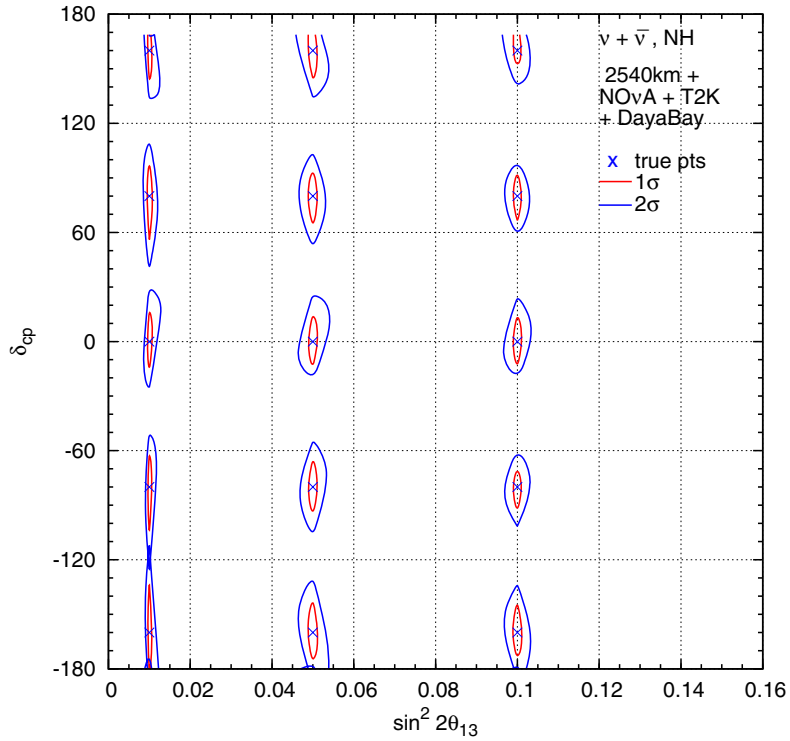
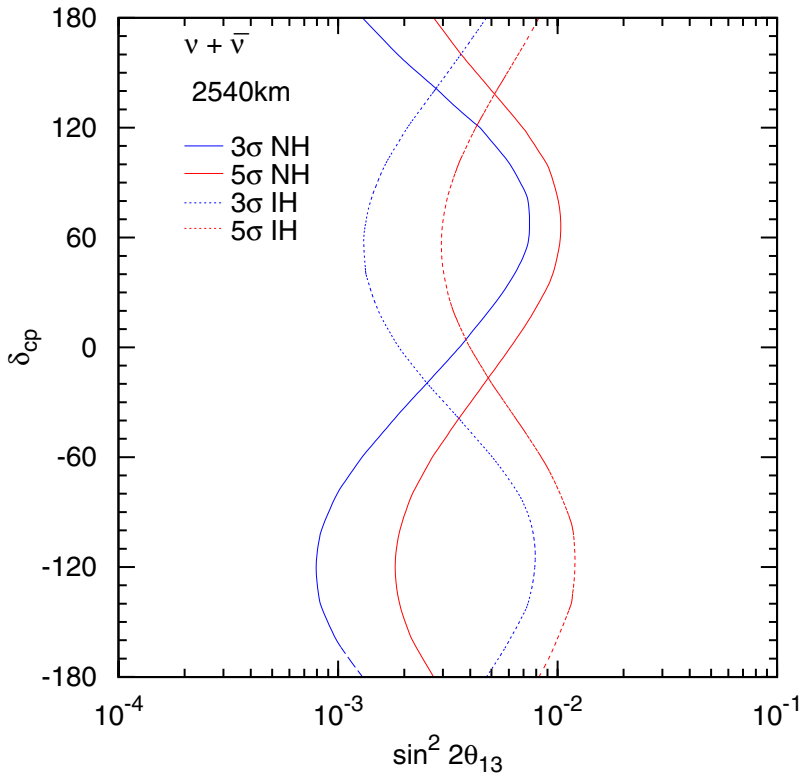
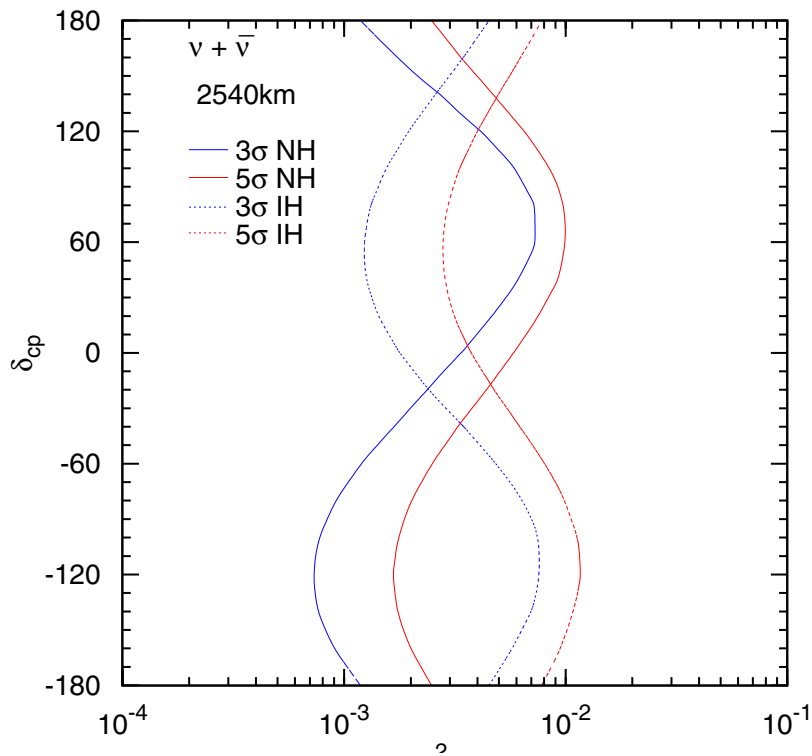




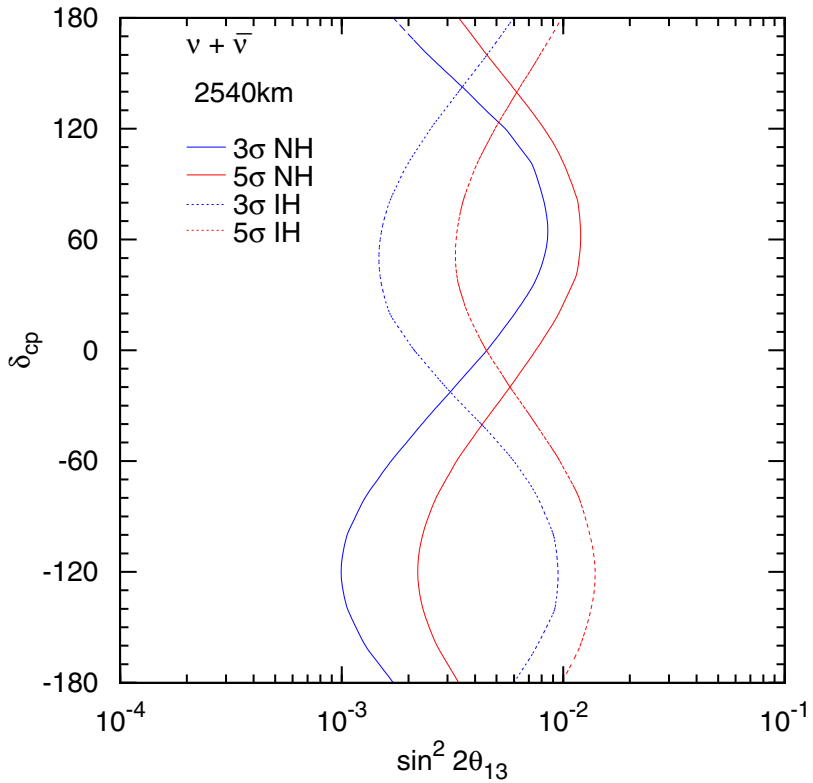


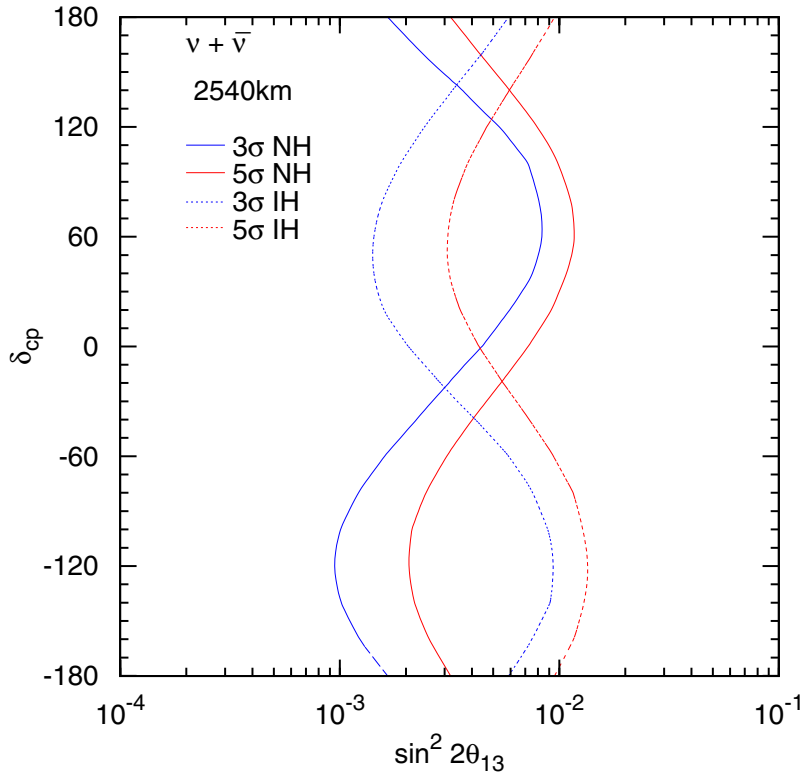
Sensitivity in the $\sin^2 2\theta_{13}$- δ_{cp} plane for the 2540km setup + T2K + NOvA + reactor expts (5yr neutrino and 5yr antineutrino running). The plot on the right is only from the statistical information, while the plot on the left includes systematics.



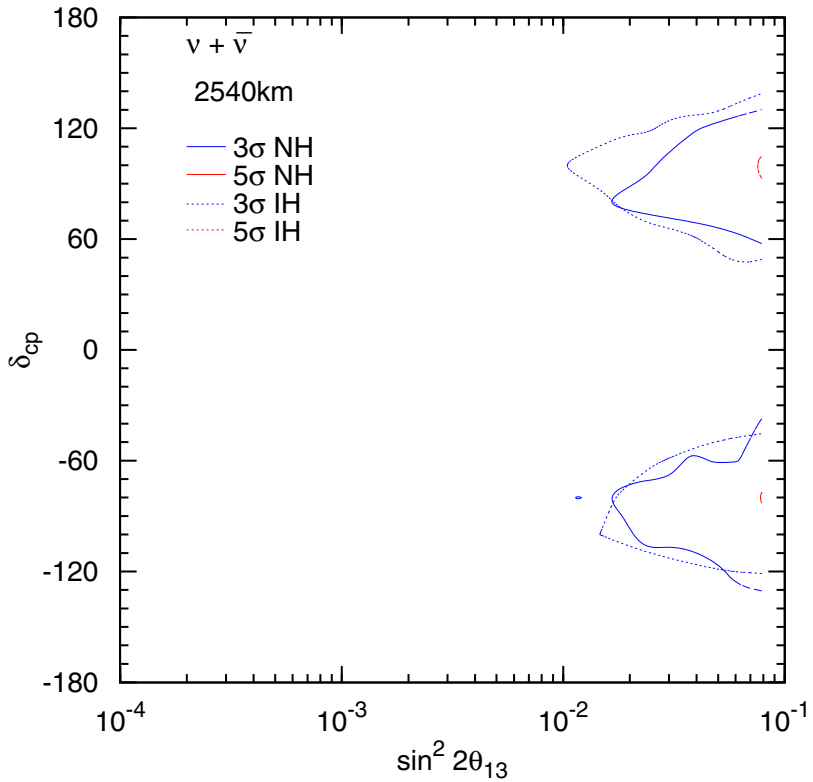


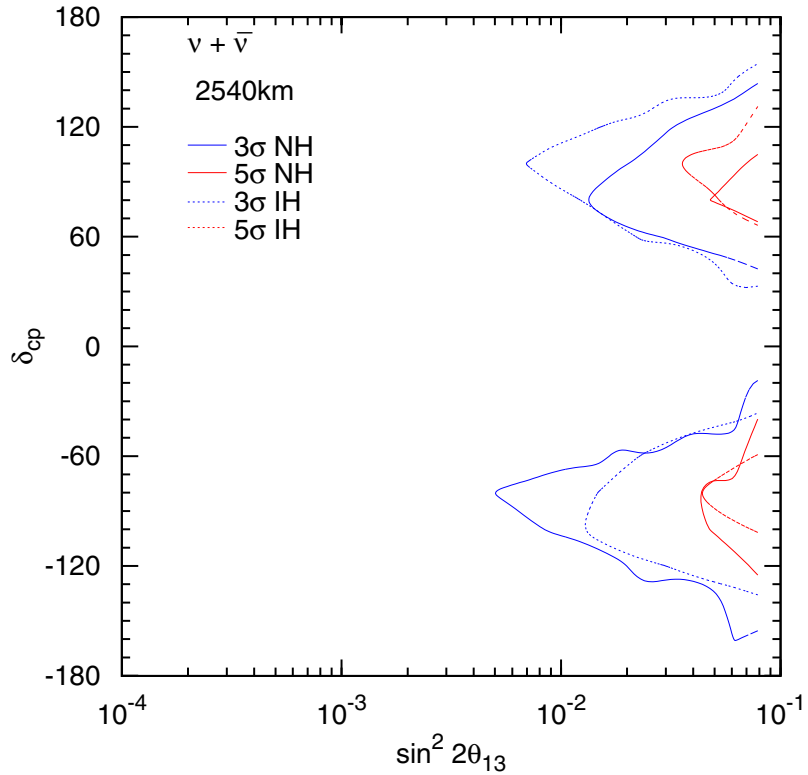
Exclusion of $\sin^2 2\theta_{13} = 0$ for the 2540km setup (5yr neutrino and 5yr antineutrino running). The plot on the right is only from the statistical information, while the plot on the left includes systematics.





Exclusion of the wrong hierarchy for the 2540km setup (5yr neutrino and 5yr antineutrino running). The plot on the right is only from the statistical information, while the plot on the left includes systematics.





Exclusion of CP conservation for the 2540km setup (5yr neutrino and 5yr antineutrino running). The plot on the right is only from the statistical information, while the plot on the left includes systematics.

Conclusions

- A 2450 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 beam power used is attainable by current standards, and 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 in spite of the modest specifications.

THANK YOU