Magical properties of a 2540 km Superbeam expt

Determination of the ν mass hierarchy, and other possibilities…

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1. Introduction

$P_{\alpha\beta}$ (θ_{12}, θ_{13}, θ_{23}, Δm^2_{31}, Δm^2_{21}, δ_{CP})

Current unknowns:

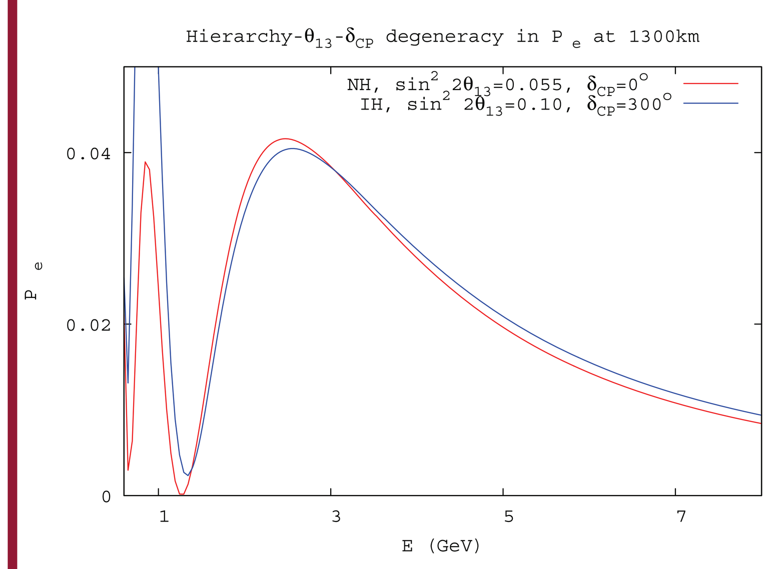
- $\mathrm{sgn}(\Delta m^2_{31})$: NH or IH
- $\sin^2 2\theta_{13}$
- δ_{cp}

$P_{\mu e}$ oscillation channel in the earth (expanded perturbatively alongside [1]) is sensitive to all of these, therefore a good candidate

$$P_{\mu e} = \sin^2 2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$
$$+ \alpha \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$
$$\cos(\Delta + \delta_{CP}) \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}}$$
$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

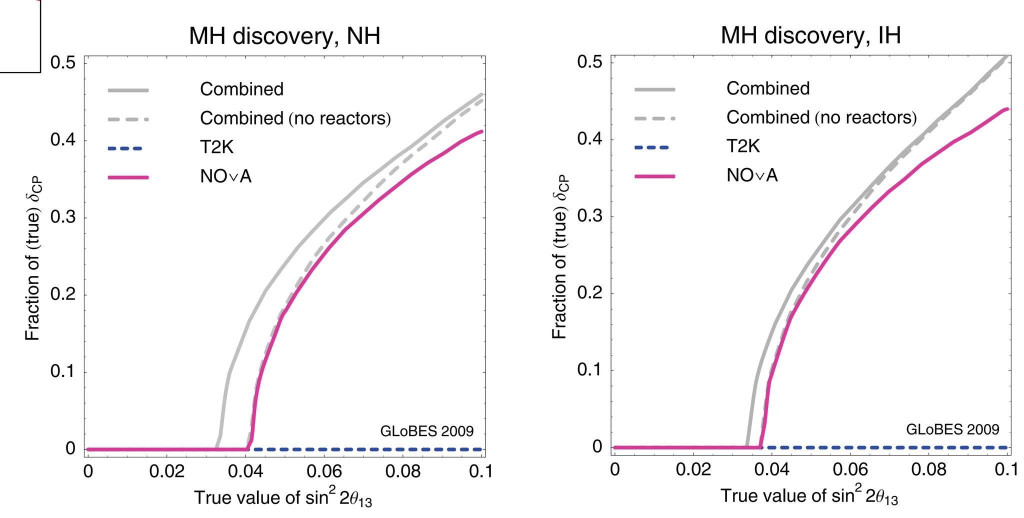
where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31} L/4E$, $\hat{A} = A/\Delta m^2_{31}$

The main problem in determining these unknowns: **Parameter degeneracy** [2], i.e. $P_{\mu e}$(NH, θ_{13}, δ_{CP}) = $P_{\mu e}$(IH, θ'_{13}, δ'_{CP})



In principle, one possible way to overcome the degeneracy problem is to combine results from more than one experiment

But, even the combined results of the currently planned experiments may not be able to determine the mass hierarchy! [3]



2. The magic baseline concept

Setting $\sin(\hat{A}\Delta)$=0 makes the δ_{CP} dependent term in $P_{\mu e}$ vanish, thus making the probability independent of δ_{CP} [4]. Solving this equation gives the required baseline, L = 7500 km. This condition is independent of the neutrino energy, E.

This magic baseline idea :

is good	has drawbacks
• because it eliminates the effect of δ_{CP}, and the mass hierarchy can be determined independent of it	• because the long baseline requires an intense beam from a (currently) futuristic source • because this experiment cannot make any statement regarding δ_{CP}

3. Our proposal

Instead of manipulating $\sin(\hat{A}\Delta)$, we manipulate **$\sin((1-\hat{A})\Delta)$**

Note that $\sin((1-\hat{A})\Delta)$ is a hierarchy dependent term, so using it amounts to imposing one condition for NH and another for IH

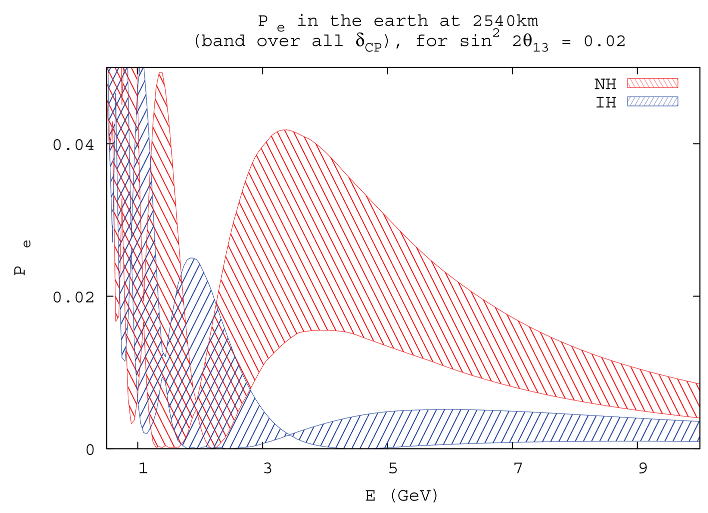
For IH: we impose $(1-\hat{A})\Delta = -\pi$, i.e. δ_{CP} independence for IH (and this also makes the probability very small)

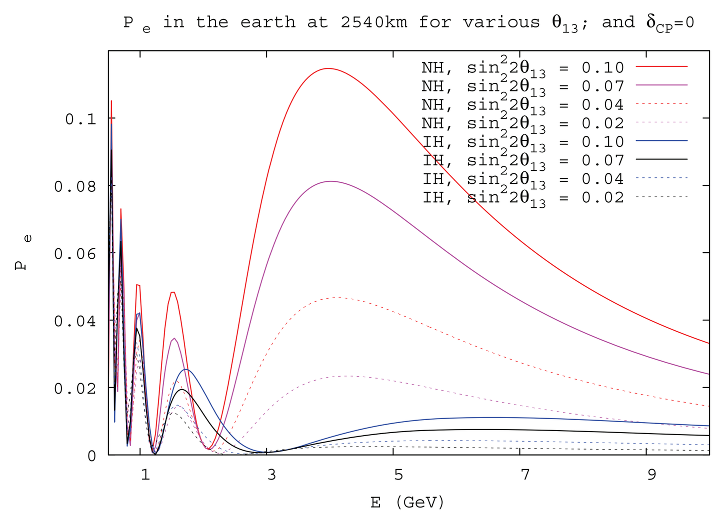
For NH: we impose $(1-\hat{A})\Delta = \pi/2$, i.e. NH maximized, for good distinction from IH

Thus, we have **1.27 ($|\Delta m^2_{31}|$+A)L/E** = π and **1.27 ($|\Delta m^2_{31}|$-A)L/E** = $\pi/2$

Solving these conditions simultaneously gives **L = 2540 km** and **E = 3.3 GeV**

2540 km is the distance from Brookhaven NL to Homestake [5], and the NuMI flux in medium energy tuning peaks around 3.5 GeV at locations 7 mr off-axis [6]





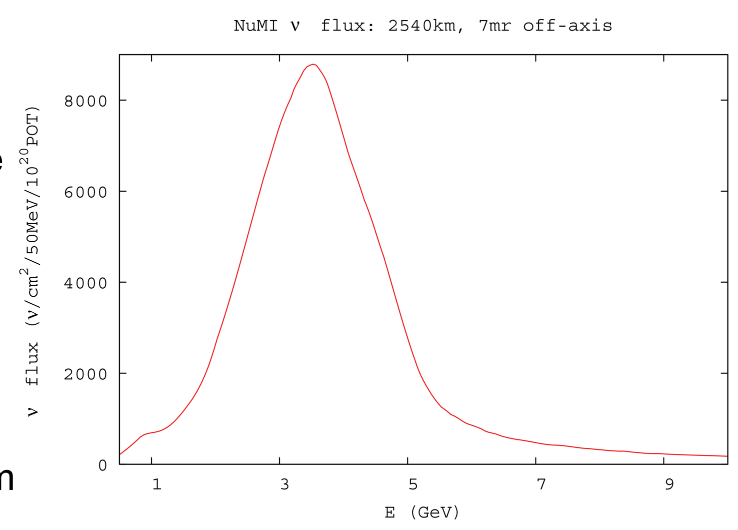
4. The experimental setup

• **The beam**

A NuMI-like beam : 7.3 x 10^{20} POT (120 GeV protons) in the medium energy option, located at Brookhaven [7]. This is perfectly feasible since the technology required for this beam is already available!

• **The detector**

A 300 kton liquid scintillator detector 2540 km away at Homestake mine. The beam is oriented such that the detector location is 7mr off the beam axis.



5. Numerical Analysis

- Energy range 0.8-10 GeV, divided into 0.4 GeV bins
- Energy smeared with a Gaussian distribution, using a (rather conservative) resolution of σ = 0.15 E
- Backgrounds due to beam ν_e and NC events assumed to be 1% of the unoscillated events [5]
- Systematics included using method of pulls [8]: 2% uncertainty in flux, 2% in detector systematics, 10% in cross section

- $\sin^2\theta_{12}$ = 0.31 , Δm^2_{21} = 8 x 10^{-5} eV^2 (fixed)
- $\sin^2\theta_{23}$ = 0.50 , $|\Delta m^2_{31}|$ = 2.5 x 10^{-3} eV^2 (marginalized over 3σ = 6% range)
- δ_{CP} allowed to vary over its entire allowed range in 45° steps
- True values of $\sin^2 2\theta_{13}$ considered in two ranges, from 0.05 to 0.10 (Double Chooz range) and from 0.02 to 0.05 (Daya Bay range)
- Both possibilities, NH and IH considered as the true hierarchy
- The experiment is run only in the neutrino mode

arXiv:0908.3741 [hep-ph]

5. Results and Conclusions

$\sin^2 2\theta_{13}$ true (D-Chooz range)	Exposure (NH) kt yr	Exposure (IH) kt yr
0.1	2.93	6.39
0.09	3.34	6.04
0.08	3.94	5.69
0.07	4.77	5.38
0.06	6.04	4.95
0.05	8.19	4.55

$\sin^2 2\theta_{13}$ true (Daya Bay range)	Exposure (NH) kt yr	Exposure (IH) kt yr
0.05	7.32	91.68
0.04	10.69	86.80
0.03	18.97	81.16
0.02	49.83	71.50

Exposures required to distinguish between the hierarchies at 3σ level

Thus, mass hierarchy determination is possible using a **single baseline** in **neutrino mode** only, using **current technology** for the beam and with **moderate exposure** in the detector, **irrespective of the value of δ_{CP}**

6. Future work

- A detailed analysis of the NC backgrounds involved is needed
- It may be possible to use this setup to probe δ_{CP}
- Combining this data with NOνA and Daya Bay will give better results
- Combined neutrino and antineutrino data will give better results
- A beta beam experiment at this baseline and energy will give a clean signal, since the $P_{e\mu}$ channel is almost free of backgrounds

References

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