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Probing mass hierarchy in reactor neutrino oscillations

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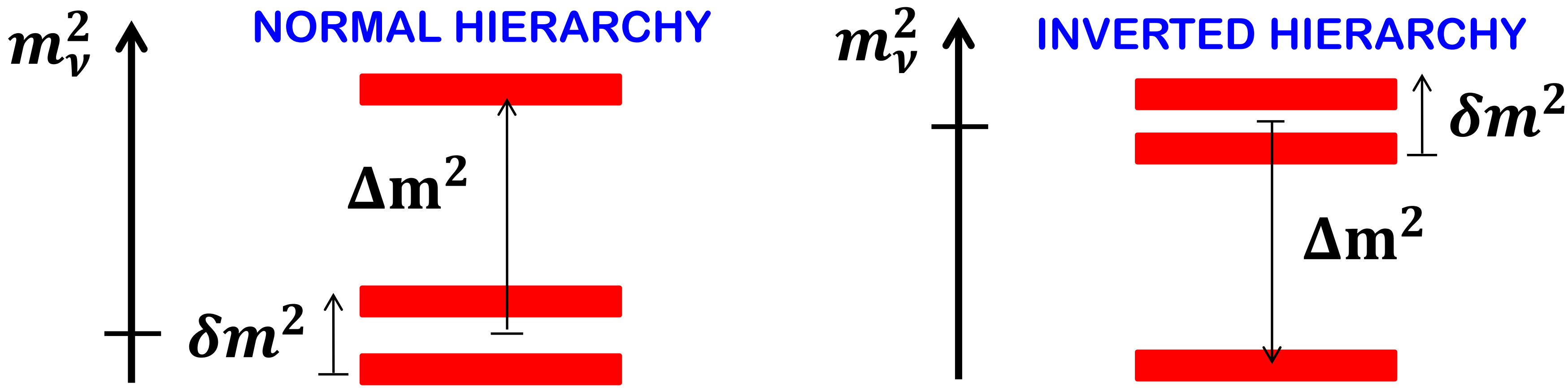
Medium baseline reactor ν oscillations

THE PROBLEM:

Assuming 3 neutrinos there are 2 mass differences: $\delta m^2 > 0, \Delta m^2 \lessgtr 0$



ONE POSSIBILE SOLUTION:

MBL reactors oscillations can probe the sign of Δm^2 (**MASS HIERARCHY**) through the tiny interference between δm^2-driven long wavelength and Δm^2-driven short wavelength oscillations at baseline $L \sim 50$ km.

REQUIREMENTS

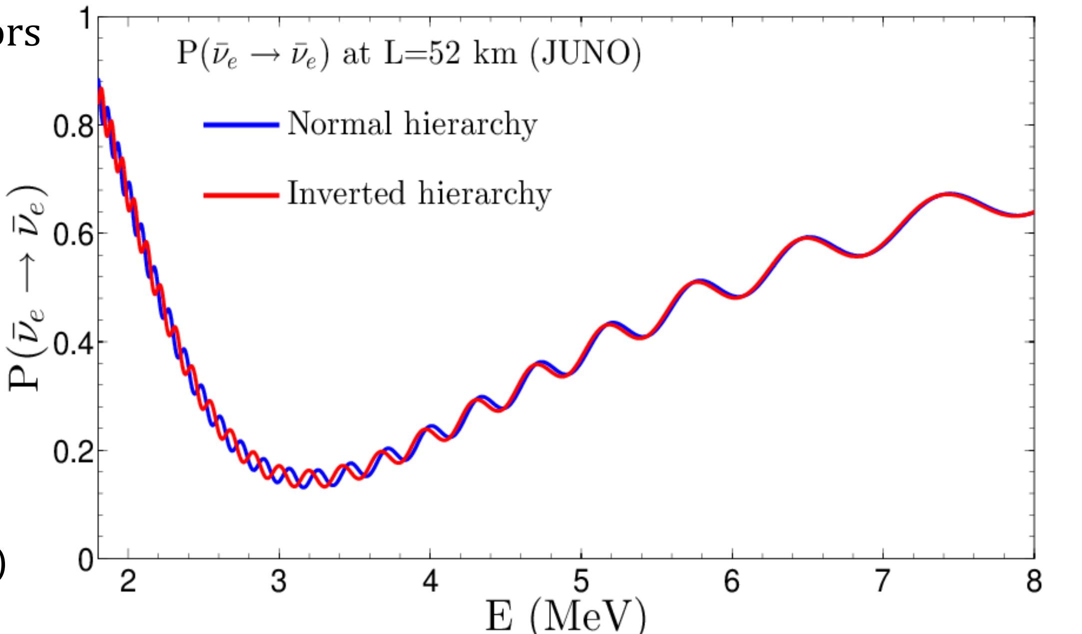
- EXPERIMENTAL: Huge statistics, high resolution
- THEORETICAL: Very accurate theoretical calculations
- PHENOMENOLOGICAL: Refined stat/syst analyses

Accurate analytical expression for the oscillation probability in matter

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq c_{13}^4 P_{\text{mat}}^{2\nu} + s_{13}^4 + 2 s_{13}^2 c_{13}^2 \sqrt{P_{\text{mat}}^{2\nu}}\, \text{w} \cos\left(\frac{\Delta m_{ee}^2 L}{2E} + \alpha\varphi\right)$$

where $c_{ij} = \cos\theta_{ij}$ $\quad s_{ij} = \sin\theta_{ij}$

- w = damping factor due to multiple reactors
- $P_{\text{mat}}^{2\nu} = P_{\text{mat}}^{2\nu}(\tilde{\theta}_{12}, \delta\tilde{m}^2)$, two neutrino oscillation probability in matter (analytical)
- $\alpha = \begin{cases} +1 \text{ (Normal hierarchy)} \\ -1 \text{ (Inverted hierarchy)} \\ 0 \text{ (undecidable hierarchy)} \end{cases}$
- $\varphi = \varphi(E, \theta_{12}, \delta m^2)$, non L/E phase embedding hierarchy information (analytical)

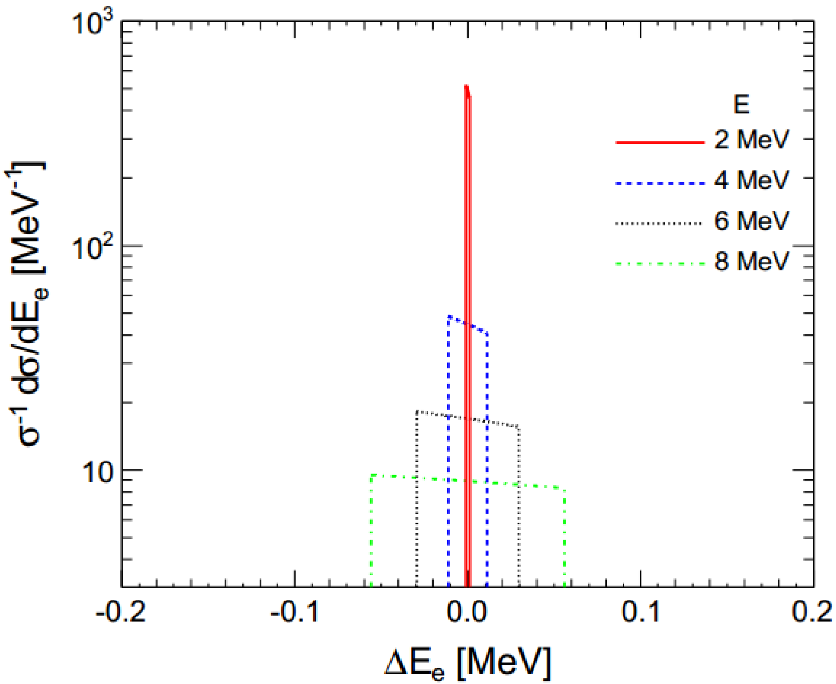


α = FREE PARAMETER

We «connect» continuously the two hypotheses: normal hierarchy ($\alpha = +1$) and inverted hierarchy ($\alpha = -1$)

Accurate description of nucleon recoil effects
(usually ignored)

INVERSE β DECAY: $\bar{\nu}_e + p \to e^+ + n$



In the high energy part of the spectrum there is a $O\left(E/m_p\right)$ correction to the relation $E - E_e \simeq m_n - m_p$ (recoiless approx). This correction is of the same order of energy resolution $\Delta E/E \sim O(1\%)$.

Reasonable approximation: Top-hat function within kinematical recoil limits

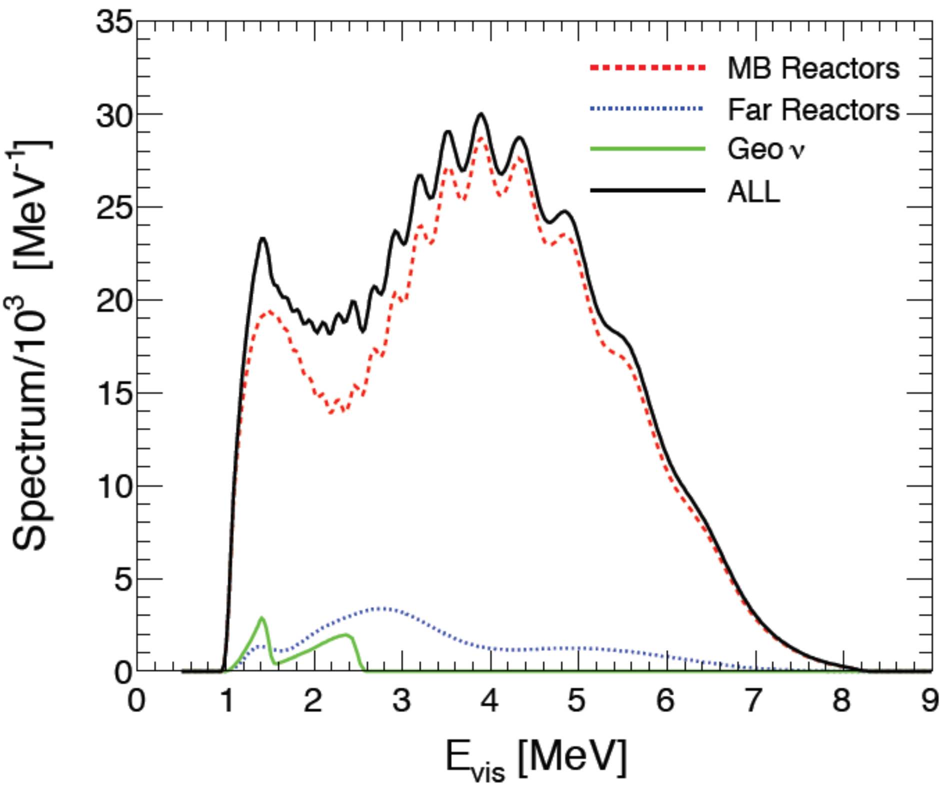
$$\frac{1}{\sigma(E)} \frac{d\sigma(E, E_e)}{dE_e} \simeq \frac{1}{E_2 - E_1}$$

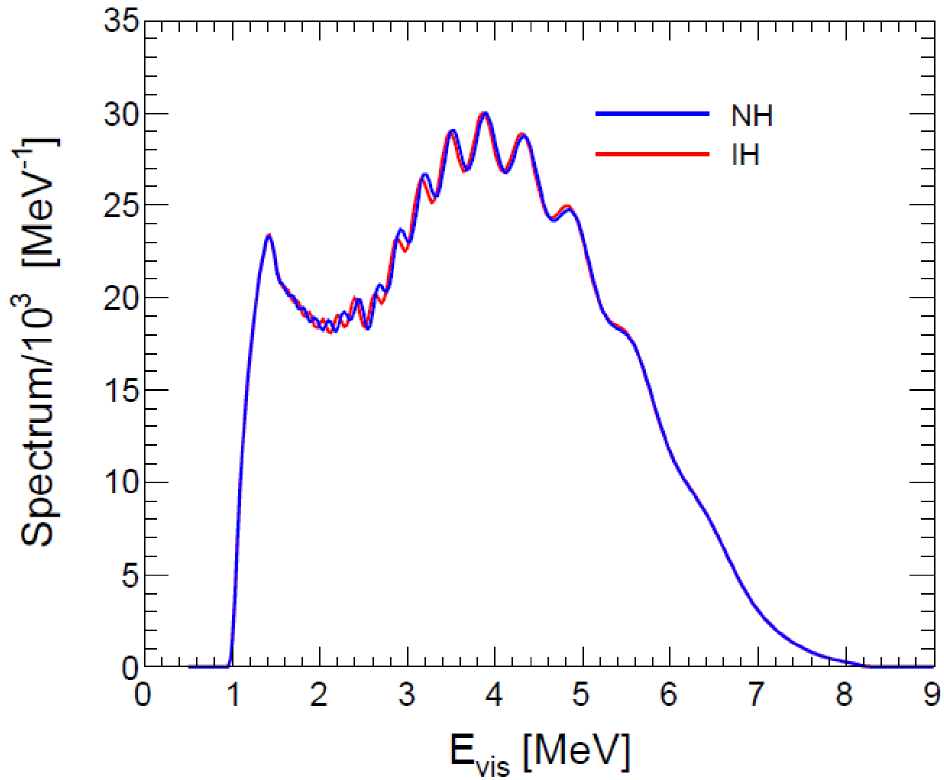
Correction to energy resolution function

Energy resolution function (gaussian) — Analytical integral

$$\int_{m_e}^{\infty} dE_e \frac{d\sigma(E, E_e)}{dE_e} \boxed{r(E_e + m_e, E_{vis})} \simeq \frac{\sigma(E)}{E_2 - E_1} \boxed{\int_{E_1}^{E_2} dE_e\, r(E_e + m_e, E_{vis})}$$

Example of spectrum for JUNO-like set-up





STATISTICS → $\sim 10^5$ events in 5 years

SYSTEMATICS →

$$\Phi_{reactor} \rightarrow \Phi_{reactor}(1 + f_R)$$
$$\Phi_{geo} \rightarrow \Phi_{geo}(1 + f_{Th})$$
$$\Phi_{geo} \rightarrow \Phi_{geo}(1 + f_U)$$

Statistical analysis

The true spectrum of events is calculated for global analysis best fit values of oscillation parameters and for a fixed hierarchy.

$$\chi^2 = \chi^2_{stat} + \chi^2_{par} + \chi^2_{sys}$$

$$\chi^2 = \chi^2\left(\delta m^2, \Delta m^2_{ee}, \theta_{12}, \theta_{13}, \alpha, f_{\mathrm{R}}, f_{\mathrm{U}}, f_{\mathrm{Th}}\right)$$

$$\chi^2_{\mathrm{par}} = \sum_{i=1}^{4} \left(\frac{p_i - \bar{p}_i}{\sigma_i}\right)^2$$

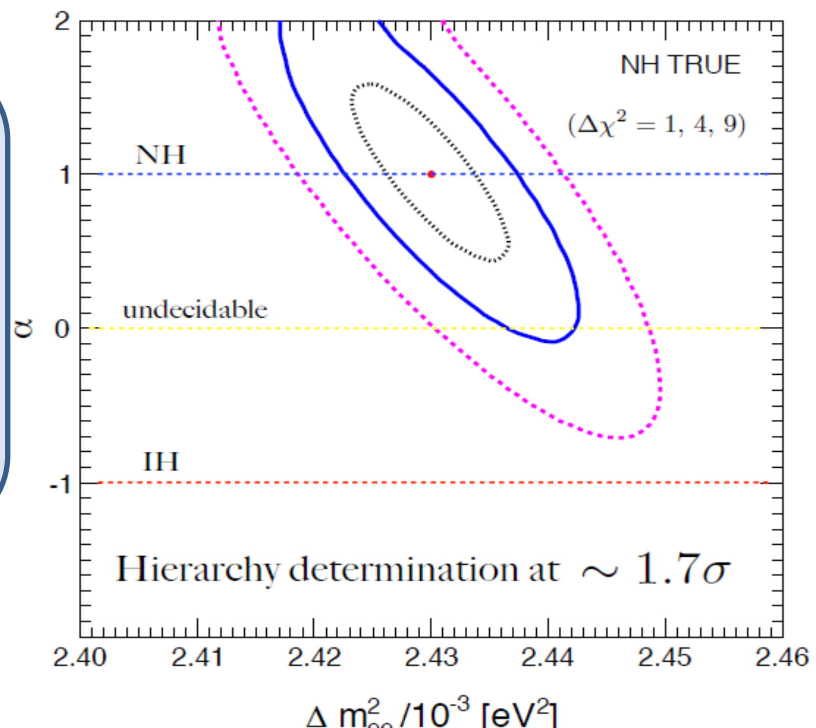
all parameters floating

$$\chi^2_{\mathrm{sys}} = \sum_i \left(\frac{f_i - 1}{s_i}\right)^2$$

RESULTS FOR «TRUE NH»:

- Distance of wrong hierarchy from true one $\sim 3.4\sigma$
- Distance of undecidable hierarchy from true one $\sim 1.7\sigma$

Similar results for TRUE IH

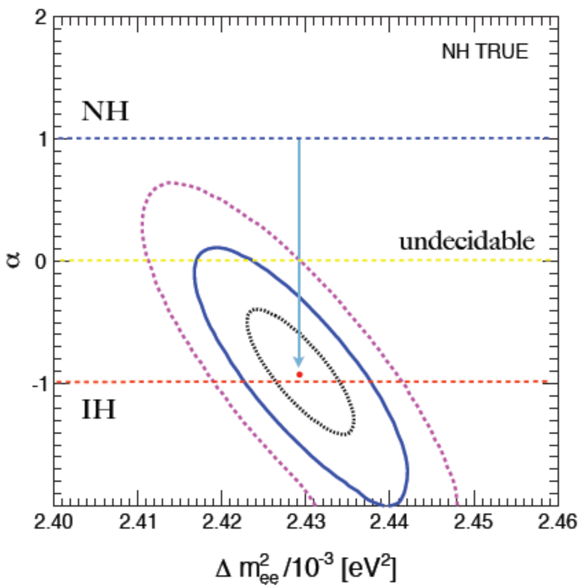


Non linear energy scale uncertainties $E \to E'$

Non linear $E \to E'$ transformations can mimic the wrong hierarchy at a slightly different Δm^2:

$$\frac{\Delta m_{ee}^2 L}{2E} \pm \varphi(E) = \frac{\Delta m_{ee}^{2\,\prime} L}{2E'} \mp \varphi(E')$$

There is an infinite class of such transformations. One example of effects:



Now the best fit is at $\alpha = -1$, despite having assumed normal hierarchy. However, the χ^2 is large O(100), because there is a mismatch of reactor and geoneutrino spectra at low energy

If spectral errors $\delta(\Phi\sigma)$ are of the same order of the deviations $\Phi(E)\sigma(E) \to \Phi(E')\sigma(E')$ then the NH-IH degeneracy is almost complete with $\chi^2 \sim O(10)$

Conclusions

Medium baseline reactor experiments can probe the neutrino mass hierarchy.
In this context we have shown:

How to include analitically the recoil effects of the nucleon

An analytical approximation of the oscillation probabilities
including effects of matter and of multiple reactors.

Non linear $E \to E'$ transformations, togheter with spectral
uncertainties, may mimic wrong hierarchy.
However, this issue deserves further studies.

It is possible to condense hierarchy information in a continuous parameter α
(+1=NH, -1 = IH). The distance between $\alpha = +1$ and $\alpha = -1$
is $\sim 3\sigma$ in JUNO-like experiments.