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Neutrino mass hierarchy and neutrino oscillation parameters with one hundred thousand reactor events

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Abstract

High-statistics reactor neutrino experiments at medium baselines will probe mass-mixing parameters governing neutrino oscillations at long wavelength, driven by the $(\delta m^2, \theta_{12})$ and at short wavelength, driven by $(\Delta m^2, \theta_{13})$.The interference between these two oscillations will allow to probe the mass hierarchy. The determination of the neutrino mass spectrum hierarchy, however, will require an unprecedented level of detector performance and collected statistics, and the control of several systematics at (sub)percent level. In this work we perform accurate theoretical calculations of reactor event spectra and refined statistical analyses to show that with $O(10^5)$ reactor events, a typical sensitivity of $\sim 2\sigma$ could be achieved by an experiment such as JUNO. We also show the impact of the energy scale and spectrum shape systematics on the determination of the hierarchy.

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1. Introduction

In the last few years a relatively large value of θ_{13} has been measured, as suggested by previous global analyses [1]. Consequently, the possible determination of the hierarchy through future medium baseline (MBL) reactor experiments, as in the JUNO [2] and RENO-50 [3] projects, has been studied in a number of recent papers(see [4] for a complete list), suggesting that the hierarchy discrimination could reach a significance level of $\gtrsim 2\sigma$. In this work we discuss the requirements of this kind of projects, both from the theoretical and experimental point of view. On the theoretical side, accurate rate calculation and refined statistical analyses are required, while on the experimental side the detector performances, the control on the systematics and the collected statistics should achieve un unprecedented level.

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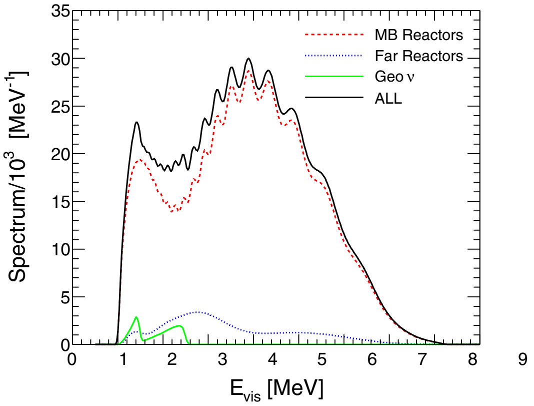

Figure 1. Energy spectrum of events expected in JUNO for NH.

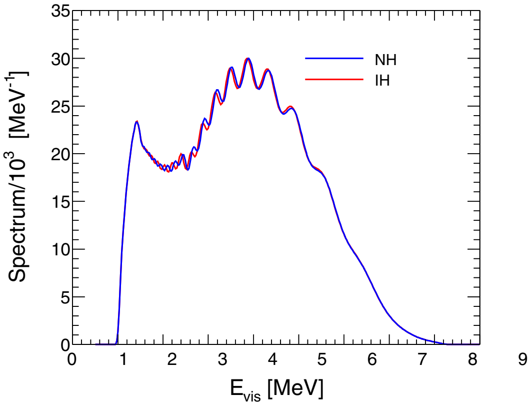

Figure 2. Comparison of spectra in NH and IH.

2. Theoretical rate calculation

The number of events per unit of the visible energy $S(E_{\rm vis})$ is obtained by integrating out the (unobservable) true energies of the incoming neutrino and of the outcoming positron of the inverse beta decay (IBD):

$$S(E_{\rm vis}) = \int_{m_e}^{\infty} dE_e \int_{E_T}^{\infty} dE \left(\sum_i \mathcal{N}_i \, \Phi_i(E) P_i(E) \right) \frac{d\sigma(E,\, E_e)}{dE_e} \, r(E_e + m_e,\, E_{\rm vis}) \, . \tag{1}$$

In equation (1) the main ingredients are the $\overline{\nu}_e$ flux $\Phi_i(E)$ and the $\overline{\nu}_e$ survival probability $P_i(E)$ (as explained in the following, we distinguish three sources of neutrinos, indicated by the index i) which are function of the $\overline{\nu}_e$ energy E, the IBD cross section $d\sigma(E,\, E_e)/dE_e$, that depends also on the positron energy E_e and the energy resolution function r which also depends on the true visible energy of the event, $E_e + m_e$. In the theoretical rate calculation we include the recoil effects, taking into account that the relation between the positron energy E_e and the neutrino energy E is not exactly $E - E_e = 1.293$ MeV, the so called recoilless approximation, but at a fixed E, E_e is typically displaced with respect to the recoilless approximation by a value of $O(E/m_p)$ and also acquires a spread of the same order. In the high-energy part of the spectrum ($E \simeq 6$–8 MeV), the effect of the recoil can reach the percent level and cannot be neglected, since it is of the same order of the required energy scale precision and energy resolution. The reactor neutrino survival probability appearing in (1) can be cast in a closed analytical form [4], including matter and multiple reactor effects. This fact is very important since it allows us to introduce a continuous parameter α that interpolates smoothly between normal hierarchy (NH, $\alpha = +1$) and inverted hierarchy (IH, $\alpha = -1$). The complete expression of the probability that we use is

$$P^{3\nu}_{\rm mat} \simeq c^4_{13} P^{2\nu}_{\rm mat} + s^4_{13} + 2 s^2_{13} c^2_{13} \sqrt{P^{2\nu}_{\rm mat}} \, w \, \cos(2\Delta_{ee} + \alpha\varphi) \, , \tag{2}$$

where $P^{2\nu}_{\rm mat}$ is the $\overline{\nu}_e$ survival probability in two generations in matter and the factor w takes into to account the effect of multiple reactors (see [4] for the definition of all the relevant quantities in (2)). We have also found a very good analytical approximation to the phase φ:

$$\varphi \simeq 2 s^2_{12} \delta \left(1 - \frac{\sin\delta}{2\delta \sqrt{P^{2\nu}_{\rm vac}}} \right) . \tag{3}$$

3. Results ofAnalysis

We assume in our work the setup of the JUNO project [2]: the detector is placed at a distance $L = 52.474$ km from the reactors (there are two more reactors at a distance $\gtrsim 200$ km) and its mass is $M = 20$ kT. The power plants

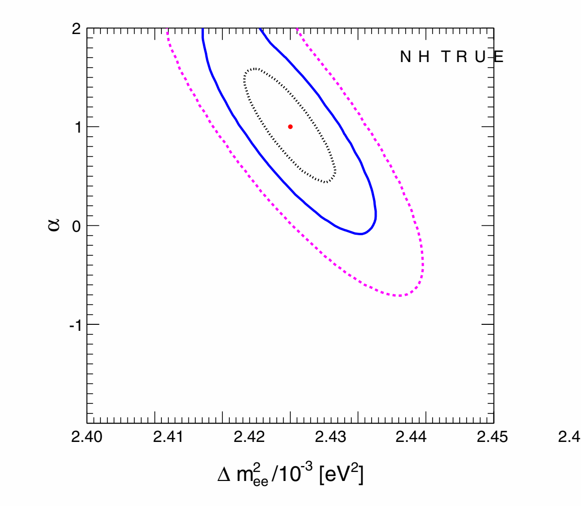

Figure 3. Constraints in the plane (Δm^2_{ee}, α) at 1, 2 and 3σ.

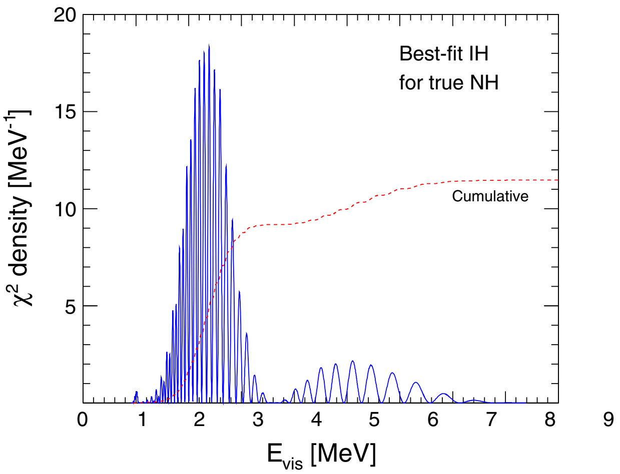

Figure 4. Density and cumulative distribution functions for χ^2_{stat} in the case of "wrong" inverted hierarchy, assuming "true" normal hierarchy.

deliver a power $P = 35.8$ GW. We also assume an exposure of 5 years, yielding a total of 3.4×10^5 events expected for no oscillations and $\sim 10^5$ events in presence of oscillations. The total number of events from the two far reactors are 6.5×10^3 and 10^4, with and without oscillations, respectively. The geoneutrino events, with and without oscillations, are $\sim 0.8 \times 10^3$ and $\sim 2.7 \times 10^3$. Figure 1 shows the total absolute spectrum of oscillated events and its three main components (medium-baseline reactors, far reactors, and geoneutrinos). The rate shown refers to the case of NH, with the oscillation parameters fixed at their best fits. Fig. 2 shows the comparison between NH and IH spectra for the same oscillation parameters as in Fig. 1. In the analysis, we compare the spectrum calculated for the central values of the oscillation parameters in one of the hierarchies (in the following we discuss the case of true NH ($\alpha = +1$)), with the spectra obtained by varying the continuous parameters (δm^2, Δm^2_{ee}, θ_{12}, θ_{13}, α). The χ^2 function that we evaluate contains statistical, parametric, and systematic components. We considered three systematic normalization factors, one for reactor spectra and two for geoneutrino spectra. Figure 3 shows the results of the fit in the plane (Δm^2_{ee}, α) for true NH ($\Delta\chi^2 = 1, 4, 9$). The wrong hierarchy case ($\alpha = -1$) is located at $\sim 3.4\sigma$ from the case $\alpha = +1$. However, in our formalism the determination of the hierarchy is compromised when the value $\alpha = 0$ cannot be excluded. In Fig. 3, the $\alpha = 0$ case is excluded at $\sim 1.7\sigma$, about 1/2 of the ~ 3.4 sigma, which formally separate the NH and IH cases. Thus, we independently recover the approximate "factor of two" reduction of the sensitivity with respect to naive expectations [5]. Similar results are found for the case of true IH. Therefore, the hierarchy can be discriminated, as the results in Fig 3 show, at a level slightly below $\sim 2\sigma$, in agreement with all recent estimates under similar assumptions. Assuming the case of true NH as in Fig. 3 the best fit for fixed $\alpha = -1$ (wrong hierarchy) is reached at $\chi^2 = 11.7$, and the larger contribution is statistical, as shown in Fig. 4, where its density is reported as function of the visible energy E_{vis}. The contribution to the χ^2 comes mostly from the fit in a small range at low energy, $E_{\mathrm{vis}} \in [1.5, 3.5]$ MeV.

4. Possible impact of energy scale errors and spectral shape uncertainties

Particular changes in energy scale ($E \to E'$) at percent level [6] can flip the sign of the hierarchy-dependent phase φ in Eq. (2) (namely, $\alpha = \pm 1 \to \alpha = \mp 1$). It has been shown that these transformations can compromise the hierarchy determination [6], even if they do not lead to a complete degeneracy between the observable spectra in NH and IH. One example is shown in Fig. 5. As a consequence of the energy scale transformation in Fig. 5, the parameter α is shifted from the true value $\alpha = +1$ to a wrong fitted value $\alpha \simeq -1$, as shown in Figure 6, in the plane (Δm^2_{ee}, α).

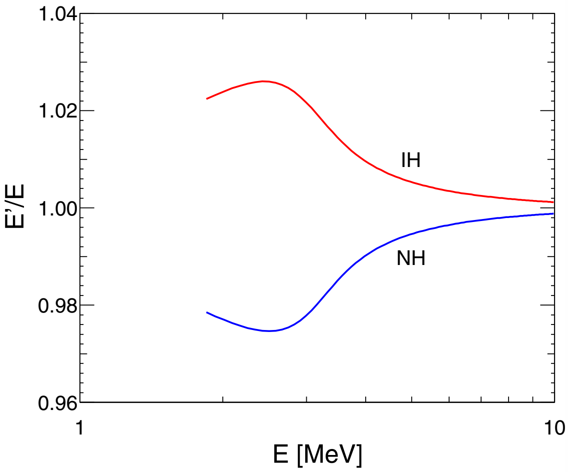

Figure 5. Ratio E'/E which flips the sign of the phase φ.

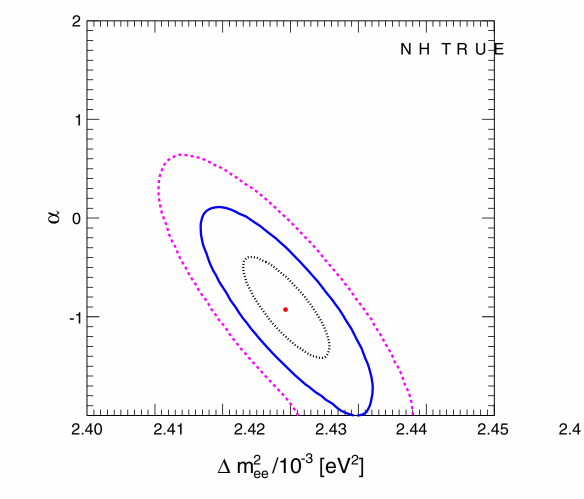

Figure 6. Constraints in the plane (Δm^2_{ee}, α) for true NH, with energy scale variations a in Fig. 5.

However, at the best fit in Fig. 6, the fit is very poor, since $\chi^2 \simeq 360$. An energy scale transformation as in Fig. 5 is able to swap the hierarchy in the fit (Fig. 6), but it induces a mismatch in the spectral features around threshold and thus a very high χ^2 value at best fit.

5. Summary and conclusions

Medium-baseline reactor neutrino experiments, as the JUNO and RENO-50 projects, can probe the oscillation parameters $(\theta_{12}, \theta_{13}, \delta m^2, \Delta m^2)$ and the hierarchy. We studied some issues related to the precision calculations and refined statistical analyses of reactor event spectra. We have analytically included IBD recoil effects in the theoretical rate calculation. We have also analytically included matter propagation and multiple reactor damping effects in the oscillation probability and introduced a continuous parameter α to discriminate the hierarchy. We have found a typical sensitivity to the hierarchy slightly below 2σ in JUNO. Further systematic uncertainties, associated to energy scale and spectrum shape distortions, may seriously compromise the hierarchy sensitivity.

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