Study of the sensitivity to measure ν oscillation parameters with JUNO

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(Dated: February 22, 2025)

The Jiangmen Underground Neutrino Observatory (JUNO) is a next-generation liquid scintillator detector designed for precise neutrino oscillation measurement, located 52.2 km from several nuclear reactors in China. Our results confirm that JUNO should be able to determine the oscillation parameters $\sin(\theta_{12})$, $\Delta m^2{}_{12}$ and $\Delta m^2{}_{13}$ with world-leading precision under 0.5% as well as determining the neutrino mass hierarchy with 3 - 4σ significance after at least 6 years of data-taking.

INTRODUCTION

JUNO is a next-generation 20 kton multipurpose liquid scintillator detector designed to achieve sub-percent precision in measuring some key neutrino oscillation parameters and determine their mass hierarchy [1]. These properties govern the behavior of massive neutrinos and are essential for future leptonic CP violation or beyond Standard Model experiments. Our study focuses on analyzing JUNO's performance in order to improve current knowledge about neutrinos' fundamental properties.

REACTOR ANTINEUTRINO DETECTION

JUNO's 52.2 km baseline was optimized to benefit from the best sensitivity to the mass hierarchy: the detector will receive $\bar{\nu}_e$ coming from both the Taishan (2 cores each with a 4.6 GW thermal power) and the Yangjiang (6 cores, 2.9 GW each) nuclear reactors, as well as a contribution from Daya Bay (17.4 GW) sitting further [2]. Each reactor core emits $\bar{\nu}_e$ primarily through the β-decay of fission products from 4 dominant isotopes, U^{235} (58%), U^{238} (7%), Pu^{239} (30%) and Pu^{241} (5%), whose characteristic spectra were parametrized by [3], [4]. As the expected visible spectrum at JUNO results from the detection of inverse β-decay events (IBD), the reactor flux has to be convoluted with the IBD cross-section [5], the number of free protons in the detection target ($1.44{\cdot}10^{33}$), the $\bar{\nu}_e$ survival probability from the PMNS matrix [6], the detector efficiency (82.2%) and the detector energy response mapping $\bar{\nu}_e$ energies to visible detected energies. Proper control of systematic uncertainties is crucial to ensure accuracy; this includes IBD energy transfer, detector non-linearity [7] and energy resolution. We focused on the latter for our estimation of the visible flux. JUNO employs both large (LPMT) and small (SPMT) photomultiplier tubes for photon detection, each with finite energy resolution [8] causing a smearing effect between emitted $\bar{\nu}_e$ and visible energies. Fine structures in the spectrum become less distinct, affecting precision measurements of the oscillation parameters. We used equal-size bins for the incoming $\bar{\nu}_e$ energy between 1.8 MeV and 10 MeV and expect 49.6 events/day (1).

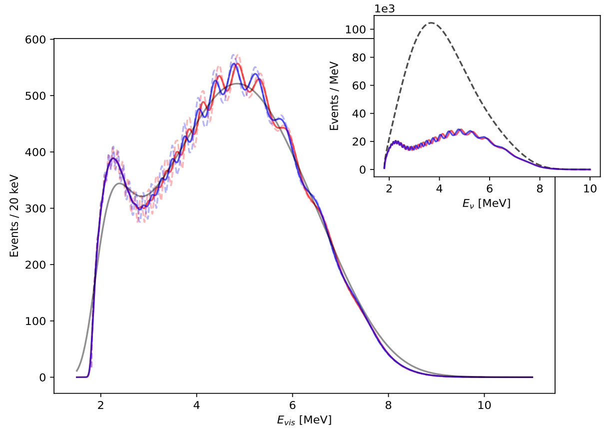

Figure 1: Visible energy spectrum for the NH (red) and IH (blue). LPMT and SPMT (gray) distort the original oscillation pattern (dashed). In the insert, the influence of oscillations on the reactors $\bar{\nu}_e$ flux (dashed) after 6 years are shown.

OSCILLATION PARAMETERS SENSITIVITY

Current measurements of $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, $\Delta m^2{}_{21}$ and $\Delta m^2{}_{31}$ [6] are to be improved by JUNO up to sub-percent accuracy. Assuming uncorrelated parameters first, we computed their predicted 1σ uncertainties at different data-taking times using a $\Delta\chi^2$ analysis between the current best-fit and parameter-shifted spectrum. Evaluating spectra for different shifted parameters and relating $\Delta\chi^2$ to confidence intervals derived from Wilks's theorem [9] provides a straightforward way to quantify relative precision. To explore both statistics- and systematics-dominated regimes, the study focuses on the 100 days, 6 and 20 years fluxes, showing a sub-0.5% precision is achieved for 3 parameters even before 6 years still with a limited ability to constrain $\sin^2\theta_{13}$ beyond current measurements (2). At this time, the uncertainties on $\sin^2\theta_{13}$ and $\Delta m^2{}_{31}$ remain statistics-dominated while those on $\sin^2\theta_{12}$ and $\Delta m^2{}_{21}$ begin to be affected by systematics with only small precision improvements extending data-taking. A relative shift from the results of [2] is attributed to neglected systematics.

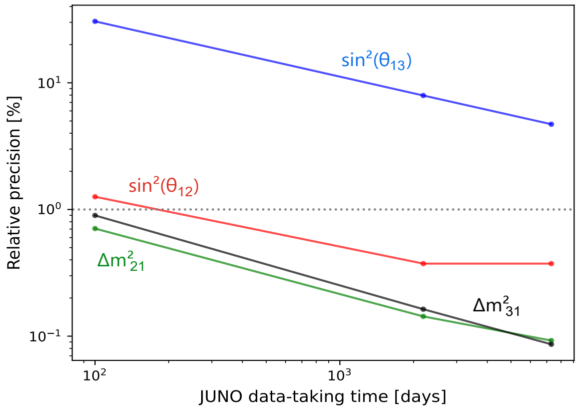

Figure 2: Time evolution of the NH oscillation parameters precision. Only LPMT are considered [10] (SPMT increase the detected light yield by only 3%)

An improved analysis was performed with a better handling of systematics and correlations [11] requiring a modified $\Delta\chi^2$ method with the construction of a covariance matrix. It incorporates both statistical and systematic uncertainties, including those related to flux, detection, and background [2]. Parameters now vary by pairs while the other two are fixed to their best-known values; minimizing the χ^2 function over these 2D projections of the parameter space allows to compute both the Hessian matrix [12] and correlation factors [13] between parameter pairs. We see that most parameters are weakly correlated (I), which enables independent constraints on each parameter and enhances sensitivity. As $\sin^2\theta_{13}$ and $\Delta m^2{}_{31}$ govern the amplitude and frequency of oscillations, neglecting JUNO's energy non-linearities in our study causes its response to energy shifts to become more uniform and results in an overestimated coupling between these parameters. JUNO's ability to independently disentangle the effects of the parameters is directly related to the proper description of its systematics.

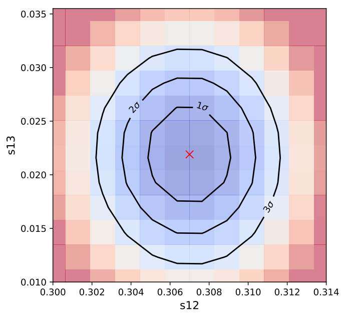

Figure 3: Example of $\Delta\chi^2$ contour map

Table I: Estimated correlation coefficients for pairs of oscillation parameters (6 years data-taking)

$\|\rho\|$	$\Delta m^2{}_{31}$	$\Delta m^2{}_{21}$	$\sin^2(\theta_{12})$
$\sin^2(\theta_{13})$	< 0.38852	< 0.03777	< 0.01337
$\sin^2(\theta_{12})$	< 0.02456	< 0.01252	1
$\Delta m^2{}_{21}$	< 0.00964	1	< 0.01252

HIERARCHY SENSITIVITY

Determining whether the mass ordering follows the normal or inverted hierarchy with JUNO would help constrain theoretical models and explore the properties of neutrinos ($0\nu2\beta$ decay, absolute mass, etc). [14], [15] This ability results from subtle differences in the oscillation patterns and has to be estimated at several times. Our analysis quantified the difference between predicted flux spectra for both hierarchies using a χ^2 procedure, assuming one spectrum is true and the other is affected by Gaussian noise to simulate experimental uncertainties. This difference is then related to a significance level through the inverse survival function [16], the outcome is the time evolution of the hierarchy distinction significance. After at least 6 years of data-taking, JUNO is expected to be able to distinguish between the NH and IH with a 3σ significance (4). We have assumed the NH to be true but the same procedure can be performed assuming IH without changing the general conclusion.

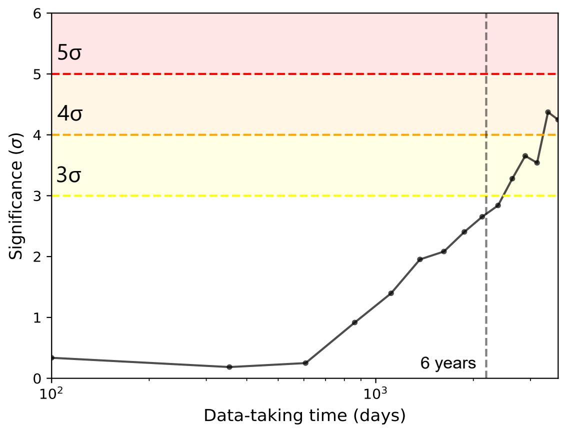

Figure 4: Example of time evolution of the significance level associated to JUNO's ability to distinguish hierarchies (at least 6 years are required)

CONCLUSION

Our study confirms that JUNO should achieve world-leading precision below 0.5% measuring $\sin^2\theta_{12}$, $\Delta m^2{}_{21}$ and $\Delta m^2{}_{31}$ as well as determine the mass hierarchy after at least 6 years of data-taking, which will improve both theoretical and experimental knowledge. However, our results ought to be put in perspective with a better description of the detector geometry and effects as well as the latest data from other experiments. JUNO will impact particle physics more broadly, one example being refining searches for $0\nu2\beta$ decay, which could provide insight into the fundamental nature of neutrinos [17], [18].

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