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JUNO sensitivity to mass ordering and oscillation parameters

Vanessa Cerrone[a,*] **, on behalf of the JUNO collaboration**

[a] *Dipartimento di Fisica e Astronomia dell'Università di Padova and INFN Sezione di Padova, Padova, Italy*

E-mail: vanessa.cerrone@pd.infn.it

The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment in South China, currently in the final stage of construction. It is located in an underground laboratory with approximately 650 m of rock overburden (1800 m.w.e.). The detector consists of a 20 kton liquid scintillator target, contained inside a 35.4-meter-diameter spherical acrylic vessel. The central detector (CD) is equipped with 17,612 20-inch and 25,600 3-inch Photomultipliers Tubes (PMTs), providing more than 75% total photocathode coverage.
JUNO's main goal is the determination of the neutrino mass ordering (NMO) with reactor antineutrinos, emitted from two adjacent nuclear power plants on a ~ 52.5 km baseline from the experimental site. JUNO's strategic location at a baseline corresponding to the first solar oscillation maximum, where the kinematic phase $\Delta_{21} \simeq \frac{\pi}{2}$, grants it the unique capability to simultaneously probe the effects of oscillations on both solar and atmospheric scales; moreover, it stands out as the first experiment to address the unresolved NMO question through vacuum-dominated oscillations and to simultaneously probe the effects of slow (Δm^2_{21}) and fast (Δm^2_{31}) oscillations.
Furthermore, the unparalleled size and energy resolution will enable to achieve a sub-percent precision on three parameters: Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$. JUNO will also have the capability to detect neutrinos generated by cosmic-ray showers interacting in the Earth's atmosphere. Atmospheric neutrinos offer a complementary sensitivity to the NMO, independent of reactor antineutrinos. This contribution will focus on JUNO's oscillation physics potential, with a particular emphasis on the reactor antineutrino analysis.

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1. Introduction

The standard three-neutrino paradigm describes neutrino oscillations with six (or eight) parameters: three mixing angles (θ_{12}, θ_{23}, θ_{13}), one Dirac CP phase ($\delta_{\rm CP}$), (two Majorana phases if neutrinos are of Majorana type, which are not relevant for oscillation), and two mass squared differences (Δm^2_{21}, Δm^2_{31} or Δm^2_{32}) [1, 2]. All parameters except $\delta_{\rm CP}$ are known to a few percent precision. However, many properties of neutrinos remain unknown, including their nature (Dirac or Majorana), the existence of CP violation in the leptonic sector, and the neutrino mass ordering (NMO). JUNO will be able to contribute to both the precision and discovery frontiers, significantly improving the precision on some parameters and investigating the NMO with reactor antineutrinos.

The Jiangmen Underground Neutrino Observatory (JUNO) [3] is a multi-purpose liquid scintillator (LS) experiment in South China, nearing completion. JUNO is primarily designed for the determination of the NMO with electron antineutrinos ($\overline{\nu}_e$), emitted from six 2.9 GW$_{\rm th}$ and two 4.6 GW$_{\rm th}$ reactor cores in the Yangjiang and Taishan nuclear power plants (NPPs), respectively. Figure 1 shows the locations of JUNO and its satellite experiment, the Taishan Antineutrino Observatory (TAO) [4], situated about 30 meters from one of the Taishan reactor cores. In order to achieve accurate results, JUNO relies on the precise knowledge of the oscillated reactor antineutrino spectrum shape, and this implies strict requirements on the design of the detector, whose schematic representation is reported in Figure 2. The driving features include energy resolution within 3% at 1 MeV, energy scale control with non-linearity effects below 1%, and high antineutrino statistics [3, 5, 6]. JUNO's dual photo-detection system, with 17,612 20-inch Large PMTs (LPMTs) and 25,600 3-inch Small PMTs (SPMTs), provides over 75% photocathode coverage. More details are available in [3].

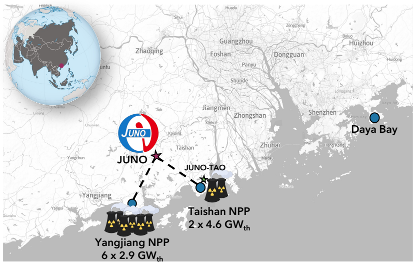

Figure 1: Location of the JUNO and TAO experiments in South China [3].

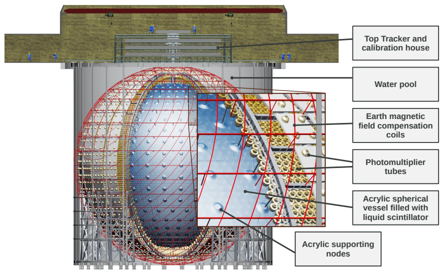

Figure 2: Schematic representation of the main JUNO detector [3].

2. Oscillation physics with reactor antineutrinos

The primary $\overline{\nu}_e$ signal is provided by the nearby NPPs, which operate commercial pressurized water reactors, where electron antineutrinos are produced by the β decay of fission products of four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The experiment is located at a baseline L of approximately 52.5 km, sitting in the first solar oscillation maximum, i.e., where the kinematic phase $\Delta_{21} \equiv \frac{\Delta m^2_{21} L}{4E} \simeq \frac{\pi}{2}$. This medium baseline configuration allows us to exploit three generation effects and measure four oscillation parameters with a single experiment. Indeed, JUNO stands out as the first experiment to simultaneously probe vacuum-dominated oscillations on both the solar and atmospheric scales [7]. JUNO is sensitive to the electron antineutrino survival probability, which has the following expression (in vacuum) [8]:

$$\begin{aligned} \mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) &= 1 - \sin^2 2\theta_{12}\, c^4_{13} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left(c^2_{12} \sin^2 \Delta_{31} + s^2_{12} \sin^2 \Delta_{32} \right) \\ &= 1 - \mathcal{P}_{21} - \mathcal{P}_{31} - \mathcal{P}_{32}, \end{aligned} \tag{1}$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $\Delta_{ij} = \Delta m^2_{ij} L/4E$, and $\mathcal{P}_{ij}$ represent the three terms associated with the respective Δ_{ij}-induced oscillations. Notably, there is no dependence on θ_{23} or $\delta_{\rm CP}$, but it is worth noting that the improvement in other parameters precision helps in constraining $\delta_{\rm CP}$ parameter space [9].

2.1 Antineutrino interaction and detector response

Reactor antineutrinos are detected in JUNO through the Inverse Beta Decay (IBD) reaction $\overline{\nu}_e + p \rightarrow e^+ + n$. The positron ($e^+$) rapidly deposits its energy and annihilates into two 0.511 MeV photons, thus producing a *prompt* signal. The neutron undergoes thermalization within the detector medium through multiple scatterings. After an average time of 220 µs it is captured predominantly on a free proton in the LS, thus emitting a 2.22 MeV γ-ray and giving rise to a *delayed* signal. The positron retains nearly all of the incoming antineutrino kinetic energy, making it a reliable proxy for the latter. As such, the energy spectrum generated by prompt signals provides a valuable means to investigate the $\overline{\nu}_e$ oscillation pattern. When positrons interact with the LS, they generate photons through scintillation and sub-dominant Cherenkov radiation. The relationship between the energy deposited by the positron (E_{dep}) and the number of scintillation photons detected by the PMTs is non-linear due to the quenching effect. The liquid scintillator non-linearity (LSNL) is characterized by the equation: $E_{\text{vis}} = f_{\text{LSNL}}(E_{\text{dep}}) \cdot E_{\text{dep}}$, where E_{vis} is the visible energy assuming perfect energy resolution, and $f_{\text{LSNL}}(E_{\text{dep}})$ is the LSNL function. The visible energy E_{vis} is further smeared due to the finite energy resolution of the detector [5, 6]. Figure 3 shows the expected prompt energy spectrum in JUNO with and without the effects of liquid scintillator non-linearity (NL) and energy resolution (Res).

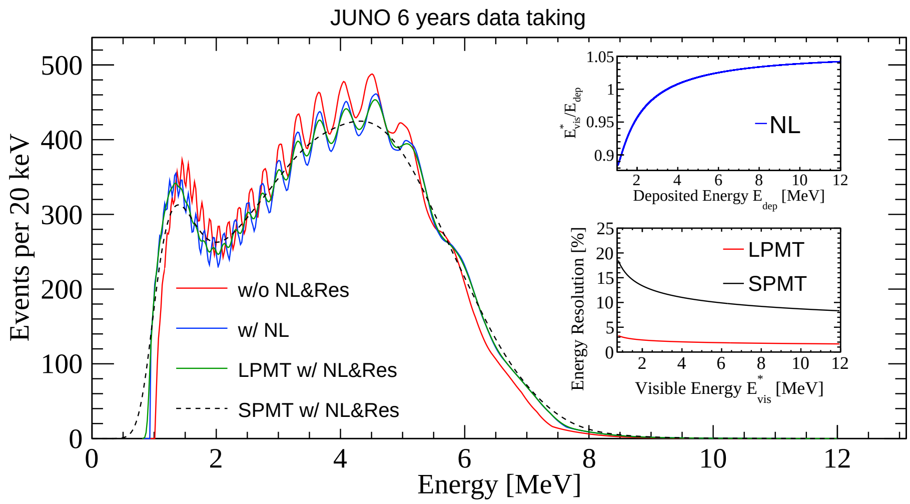

Figure 3: Expected prompt energy spectrum with and without the different detector response effects [10].

2.2 Event selection and backgrounds

The IBD reaction provides a distinctive double signature to achieve effective signal/background discrimination. Among the major backgrounds, it is possible to identify, for example, geoneutrinos, the long-lived cosmogenic isotopes ^{9}Li and ^{8}He, and accidental coincidences mainly due to radioactive contamination. Several selection criteria are devised to efficiently perform event selection [10–12]. The reconstructed energy spectrum, i.e., after all detector effects, in both the Normal Ordering (NO) and Inverted Ordering (IO) hypotheses is reported in Figure 4: the reactor antineutrino signal and all residual backgrounds are shown. In-depth information about backgrounds and selection criteria can be found in Refs. [10, 11].

3. Sensitivity to mass ordering and oscillation parameters

To extract the neutrino oscillation parameters and assess the NMO sensitivity, the analysis involves simultaneously fitting JUNO and TAO nominal spectra, against a hypothesis model based on the standard three-flavor framework. TAO simulated data is used to constrain the reactor antineutrino energy spectrum, while the

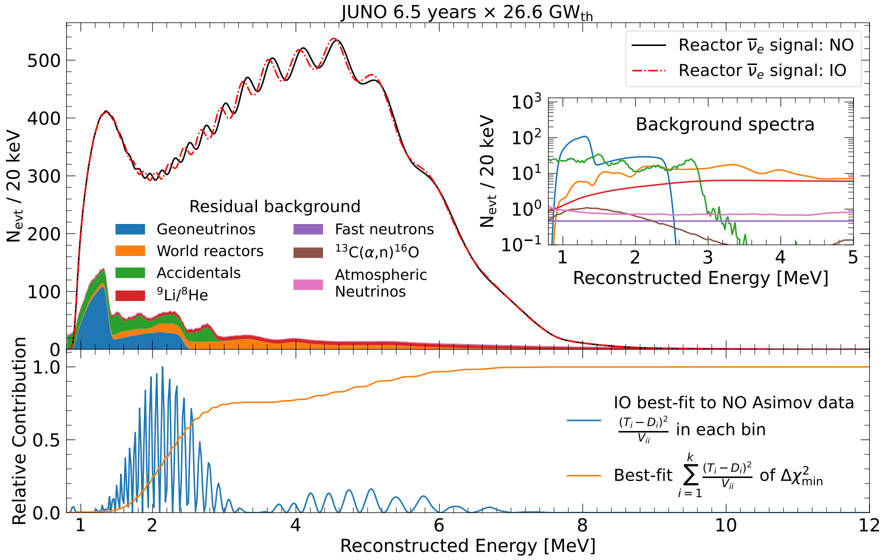

Figure 4: Top: Reconstructed energy spectra of JUNO in both the NO and IO scenarios without any statistical or systematic fluctuations [11]. Bottom: Relative contribution to the $\Delta\chi^2$ and cumulative $\Delta\chi^2$ obtained when fitting the IO spectrum with the NO hypothesis.

oscillation pattern is inferred from the JUNO spectrum. An Asimov pseudo-dataset is built under both the NO and IO hypotheses. Then, the median sensitivity discriminator is defined as: $\Delta\chi^2 \equiv |\chi^2_{\rm min}(\rm NO) - \chi^2_{\rm min}(\rm IO)|$. The resulting $\Delta\chi^2$ is reported in Figure 5 as a function of JUNO data taking time for both NO (red) and IO (blue) hypotheses: with $\sim$ 6.5 years of data taking at full 26.6 GW$_{\rm th}$ reactor power, JUNO can reach a median sensitivity of $\sim 3\sigma$ [11]. Furthermore, ongoing studies are exploring the possibility of incorporating additional information from the detection of atmospheric neutrinos [3, 11] in JUNO. The obtained relative precision on the oscillation parameters [10] is reported in Figure 6. It is estimated that with 6 years of data, JUNO can determine the parameters Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ with a precision of $\sim$ 0.2%, $\sim$ 0.3%, and $\sim$ 0.5%, respectively. Moreover, JUNO is foreseen to already exceed global precision on these parameters within the first months of data acquisition. It is also worth noting that thanks to this highly improved precision, especially on Δm^2_{31}, a substantial enhancement in NMO sensitivity can be potentially achieved through combined analyses involving JUNO, long-baseline accelerator experiments [13–15] and/or atmospheric experiments [16, 17].

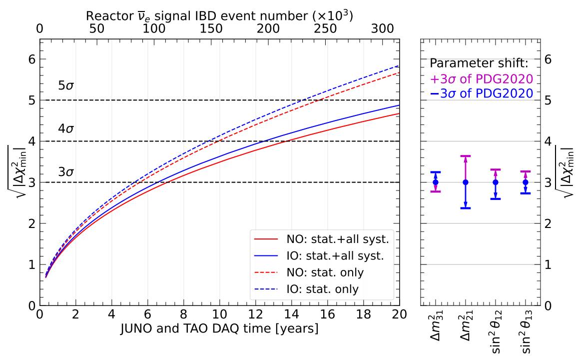

Figure 5: NMO median sensitivity as a function of JUNO exposure [11].

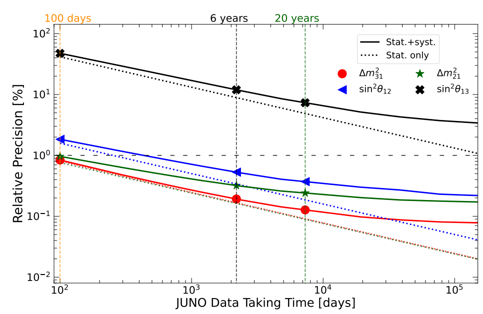

Figure 6: Relative precision on oscillation parameters as a function of JUNO exposure [10].

4. Conclusions

JUNO is a next-generation liquid scintillator neutrino observatory under construction in South China. With its unprecedented size and energy resolution, JUNO will precisely measure the oscillated $\overline{\nu}_e$ spectrum and determine Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{13}$, and $\sin^2\theta_{12}$. The experiment aims to achieve sub-percent precision [10] for Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$, representing a significant milestone in the oscillation physics field. Additionally, JUNO is uniquely capable of resolving the mass ordering through vacuum-dominated oscillations of reactor antineutrinos. It is expected to reach a 3σ sensitivity level within approximately 6.5 years of operation at 26.6 $\mathrm{GW_{th}}$ reactor power.

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