PROCEEDINGS OF SCIENCE

Neutrino oscillation physics in JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino detector under construction in China. It is located 700 m underground, 53 km away from eight nuclear reactors. It will use 20 kt of liquid scintillator surrounded by 17,612 20" photomultipliers and 25,600 3" photomultipliers to detect neutrino interactions with a 3% energy resolution at 1 MeV. JUNO's main physics goals are the determination of the neutrino mass ordering and the high-precision measurement of Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}.

I will present how JUNO can measure the reactor antineutrino oscillations to reach a 3σ sensitivity to the neutrino mass ordering with 6 years of data. JUNO can also measure atmospheric neutrino oscillations to enhance this sensitivity. After 6 years, JUNO will improve the current precision on Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} by an order of magnitude, achieving precision well below the sub-percent level.

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1. The JUNO experiment

JUNO's main goals [1] are the precision measurement of neutrino oscillation parameters Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}, and the determination of the neutrino mass ordering. It will measure the oscillated energy spectrum of electron antineutrino produced 53 km away by eight nuclear reactor cores, as illustrated in Figure 1. The energy and chosen baseline mean JUNO will be the first experiment to measure both the solar and atmospheric neutrino oscillation parameters at the same time. The design [2] and picture of the detector as of Summer 2024 are shown in Figure 2. The 35.4 m-diameter acrylic vessel holding the liquid scintillator has mostly been assembled and more than half of the photomultipliers (PMTs) have been installed.

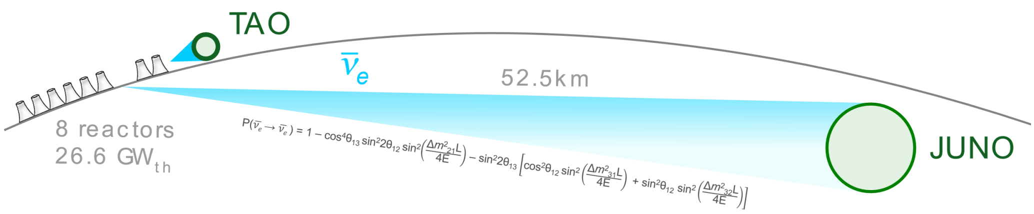

Figure 1: The oscillated electron antineutrino spectrum measured by JUNO 52.5 km away from eight nuclear reactor cores depends on both neutrino mass splittings, Δm^2_{21} and Δm^2_{31}, and two mixing angles, θ_{12} and θ_{13}.

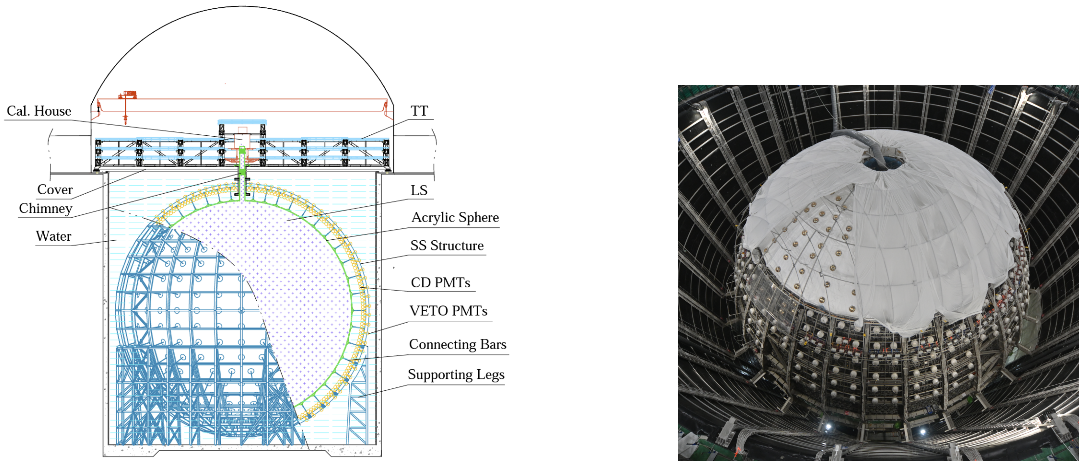

Figure 2: Design of the JUNO detector *(left)* and picture of the JUNO detector as of Summer 2024 *(right)*.

The 20 kt of highly-transparent, high-photon-yield liquid scintillator are surrounded by 17,612 20" photomultipliers [3] and 25,600 3" photomultipliers [4]. These high-efficiency PMTs (30%) provide a high photo-coverage, allowing an efficient collection of the light produced in the liquid scintillator, thus achieving an unprecedented 3% energy resolution at 1 MeV. This excellent energy resolution will help precision measurements but is also critical for the determination of the NMO. Indeed, the difference in the measured spectra under the two orderings is subtle and is illustrated in Figure 3. A precise knowledge of the reactor spectra is therefore also required. A dedicated satellite detector, TAO (Taishan Antineutrino Observatory) [5], has been designed to measure the reactor neutrino spectra with unprecedented accuracy and bring the spectra shape uncertainty below the

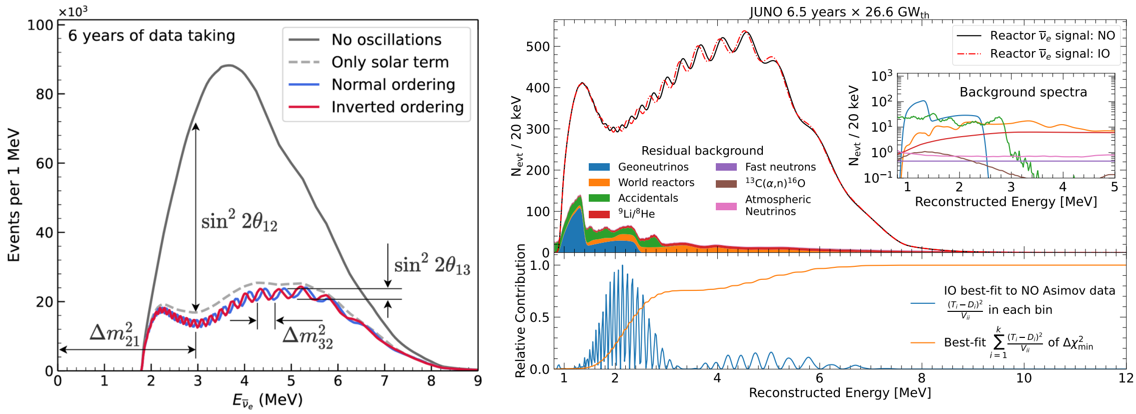

Figure 3: *(left)* Impact of the oscillation parameters on the oscillated neutrino spectrum measured by JUNO. *(right)* Expected signal and background spectra measured by JUNO after 6.5 years, and below, the relative contribution to the $\Delta\chi^2$ of a fit in the IO hypothesis to NO Asimov data, showing the most sensitive region to discriminate between the two mass orderings is 1.5-3MeV. Taken from [6].

percent level. To achieve this, the detector, holding 2.8 tons of Gadolinium-doped liquid scintillator, will be located 44 m from one of Taishan's power plant reactor cores, enabling the detection of a thousand neutrinos per day. Furthermore, the 4500 photoelectrons emitted per MeV deposited are read out by silicon photomultipliers covering 94 % of the detector walls[1], thereby offering an energy resolution better than 2% at 1 MeV.

Thanks to its large mass and powerful neutrino sources, JUNO will observe 47 signal events per day. JUNO's main detection channel comes from inverse beta decay events. The coincidence of a prompt light signal from the ionization and annihilation of the emitted positron and a delayed light signal following the capture of the emitted neutron provides us with a clear neutrino interaction signal and therefore helps us to reduce the background strongly. The detector is also located 700 m underground, which, combined with an efficient veto strategy (99.5%), means JUNO can reduce its background rate down to 7%. Indeed, the central detector is surrounded by 35 kton of ultrapure water, instrumented with 2400 20" PMTs, making up an outer Cherenkov detector acting as an active veto for the cosmic muons. In addition, an arrangement of plastic scintillators installed above the detector, the top tracker [7], allows the detection and reconstruction of the direction of downgoing muons. The ability to identify the cosmic tracks' path in the central detector means only a small fraction of the sensitive volume has to be vetoed to exclude potential cosmogenic backgrounds. The expected signal and different background spectra after 6.5 years are shown in Figure 3. The main backgrounds come from geoneutrinos and accidental coincidences mimicking an inverse beta decay event, mostly below 3 MeV.

2. Neutrino oscillation physics

JUNO's great detector capabilities make it a multipurpose experiment [8] which can study solar neutrinos, geoneutrinos, and neutrinos from core-collapse supernovae and the diffuse supernova

[1]The liquid scintillator is operated at -50°C.

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neutrino background, but its main purpose remains the study of neutrino oscillations.

2.1 High-precision measurements of Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}

The precision that JUNO can reach on Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} has been estimated and reported in a dedicated paper [9]. The evolution of the relative precision on these parameters as a function of time is shown in Figure 4. Within the first 100 days of running, JUNO will improve upon our current knowledge of these three parameters. After 6 years, all parameters will be measured with better than a 0.5% precision, even reaching close to the per mille precision for Δm^2_{31}. Such precise measurements will remain the best for many years and even decades to come.

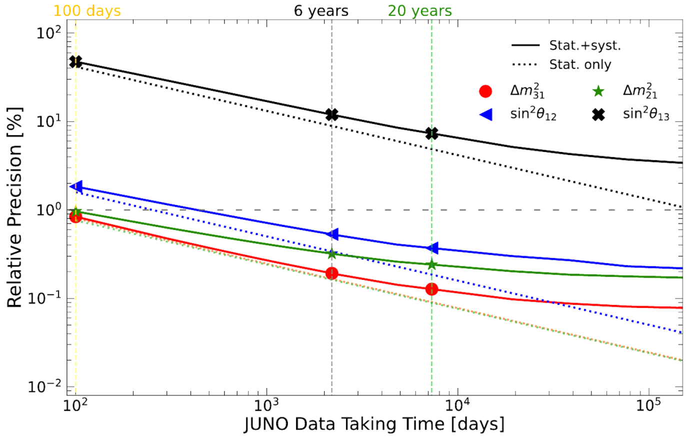

Figure 4: Relative precision on the oscillation parameters as a function of the JUNO exposure. JUNO will measure Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ with a precision well below the percent and even reach close to the per mille precision. Taken from [9].

2.2 Determination of the neutrino mass ordering

JUNO's sensitivity to the neutrino mass ordering has been updated and released in a recent paper [6]. The new analysis takes into account the latest estimated signal and background rates, uses an improved estimation of the energy resolution (2.95% at 1 MeV) [10], and performs a joint JUNO and TAO analysis. The sensitivity reached by JUNO as a function of time is reported in Figure 5. Depending on the mass ordering, JUNO can reach a 3σ median sensitivity after 6.5-7.1 years. Figure 5 also shows that this sensitivity is relatively independent of the other oscillation parameters. Indeed, only large changes to the other oscillation parameters would noticeably impact JUNO's NMO sensitivity which illustrates one of the powers of JUNO's approach. Furthermore, this measurement is performed with vacuum-dominated oscillations, which will allow for interesting comparisons with measurements relying on matter-dominated oscillations.

2.3 Atmospheric neutrino oscillations

JUNO can also detect atmospheric neutrinos after they have oscillated through the Earth. The ability to accurately reconstruct the directions [11] of the neutrino-induced tracks, in addition to their energies, is here critical since it relates to the amount of matter they went through. Not only

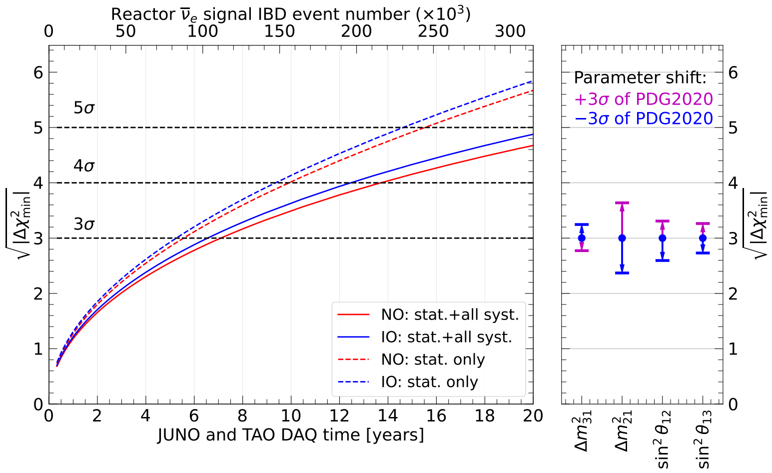

Figure 5: Significance of determining the neutrino mass ordering as a function of JUNO's exposure [6]. A 3σ determination can be obtained after 7.1 years of data taking. The impact of a $\pm 3\sigma$ shift of the oscillation parameters with respect to the PDG2020 values on the NMO significance is shown on the right.

are the energies and baseline at play here different from reactor neutrinos, but the matter-dominated oscillations offer JUNO another window to study neutrino oscillations, which complements that of its main analysis. Preliminary studies also show that JUNO will be able to discriminate between electron and muon tracks, and between neutrino- and antineutrino-induced events. The spare PMTs will be installed on top of the aforementioned water pool to further improve both the track direction reconstruction and the particle identification capabilities. This means atmospheric neutrinos can be used to independently constrain the neutrino mass ordering. This sensitivity is shown in Figure 6. It also opens the possibility of combining both JUNO's reactor and atmospheric neutrino oscillation analysis to improve JUNO's overall sensitivity to the neutrino mass ordering.

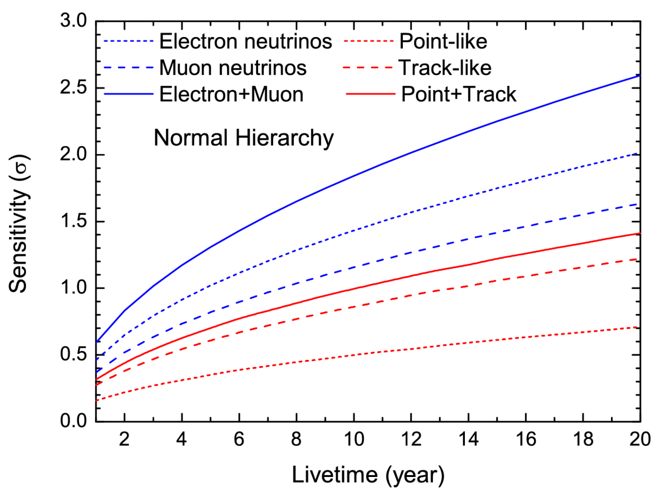

Figure 6: Significance of determining the neutrino mass ordering using different atmospheric neutrino channels as a function of JUNO's exposure. Taken from [1].

3. Conclusions

The completion of the detector construction is anticipated by the end of 2024, and the first data is expected in 2025. JUNO is paving the way towards the precision era in neutrino physics. For the first time, a single experiment will measure more than half of the neutrino oscillation parameters. JUNO will provide world-leading measurements of Δm^2_{21}, θ_{12}, and Δm^2_{31}, well below the percent precision, and reach a 3-σ sensitivity to the neutrino mass ordering after 7.1 years. These measurements can be further complimented by JUNO's own atmospheric neutrino oscillation measurement, but also other atmospheric and long-baseline neutrino oscillation experiments.

References

[1] F. An et al., *Neutrino physics with JUNO*, J. Phys. G: Nucl. Part. Phys. 43 030401

[2] JUNO collaboration, *The Design and Technology Development of the JUNO Central Detector*, arXiv:2311.17314

[3] A. Abusleme et al., *Mass testing and characterization of 20-inch PMTs for JUNO*, Eur. Phys. J. C (2022) 82: 1168

[4] C. Cao et al., *Mass production and characterization of 3-inch PMTs for the JUNO experiment*, NIM A 1005 (2021) 165347

[5] JUNO collaboration, *TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution*, arXiv:2005.08745

[6] JUNO collaboration, *Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO*, Chin. Phys. C (2024)

[7] JUNO collaboration, *The JUNO experiment Top Tracker*, NIM A 1057 (2023) 168680

[8] JUNO collaboration, *JUNO physics and detector*, PPNP 123 (2022) 103927

[9] JUNO collaboration, *Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO*, Chin. Phys. C 46 (2022) 12

[10] JUNO collaboration, *Prediction of Energy Resolution in the JUNO Experiment*, arXiv:2405.17860

[11] Z. Yang et al., *First attempt of directionality reconstruction for atmospheric neutrinos in a large homogeneous liquid scintillator detector*, Phys. Rev. D 109 (2024), 052005