The JUNO LNF group

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in collaboration with

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1 The JUNO experiment

Despite the great progress accomplished in the last decades, a number of fundamental questions concerning the nature of neutrinos and their interactions remains. These elusive particles are among the least understood in the Standard Model. The fascinating and well-established phenomenon of neutrino oscillation has clearly shown that neutrinos do have masses but as it is sensitive only to the differences in the squared masses, the absolute mass has not yet been determined. Likewise it is not known how masses are ordered, i.e. if the mass of the neutrino mass eigenstate m_3 (the one with the least ν_e content) is heavier or lighter than the m_1, m_2 pair. The two possible options are known as normal or inverted mass hierarchy (MH). The neutrino MH is then among the most important issues in the future neutrino oscillation program, and it's also crucial for the neutrinoless double-beta experiments looking at Majorana neutrinos. The Jiangmen Underground Neutrino Observatory (JUNO) is an experiment designed to determine the neutrino mass hierarchy as a primary physics goal, by detecting reactor anti-neutrinos from two power plants at 53 km distance. The measurement of the anti-neutrino spectrum will also lead to the precise determination of three out of the six oscillation parameters to an accuracy of better than 1 %.

Mass hierarchy can be determined in JUNO exploiting an interference effect between the 3-flavour oscillations in the disappearance of electron anti-neutrino emitted from nuclear power reactors at the medium baseline. The interference manifests itself in a rapid oscillation pattern superimposed on the solar oscillation. The oscillation amplitude and the frequency of the pattern depend on the mass hierarchy, and are fully independent from the CP violation phase and the θ_{23} angle of the PMNS mixing matrix. The determination of the neutrino mass spectrum hierarchy, however, will require an unprecedented level of detector performance and collected statistics, as well as the control of several systematics at (sub)percent level.

The JUNO experiment will also be able to observe neutrinos from terrestrial (geo-neutrinos) and extra-terrestrial sources (solar, atmospheric and supernova neutrinos). JUNO can then be

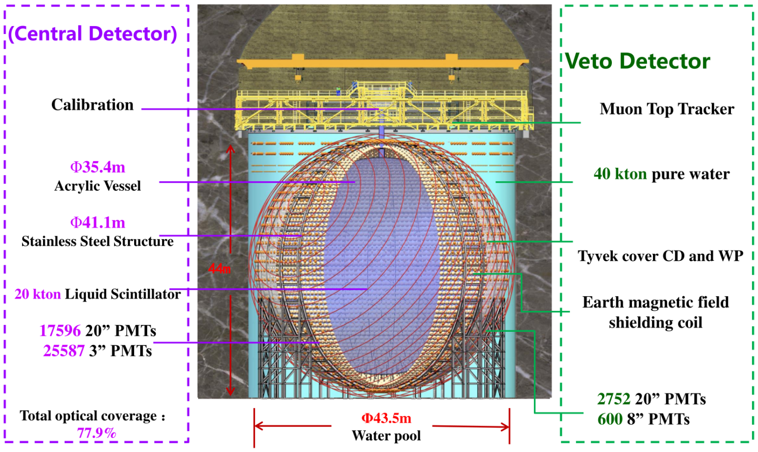

Figure 1: *JUNO detector description.*

defined as a multipurpose experiment able to explore the neutrino nature as well as to perform neutrino astronomy and astrophysics.

The detector, whose concept is shown in figure 1, will be placed in a 700 m deep underground laboratory located at Jiangmen (Guangdong province) in South China, 53 km away from the Taishan and Yangjiang reactor complexes. The central detector consists of a 20-kiloton of Linear Alkyl-Benzene (LAB) liquid scintillator contained inside a 12 cm thick and 35.4 m wide acrylic ball, supported by a Stainless-Steel Structure (SSS) of 40 m diameter, and instrumented by 17596 20-inch PMTs covering more than 75 % of the SSS area. In addition, 25587 3-inch PMTs will fill the gaps among the large PMTs in order to improve the energy and vertex resolutions. To achieve the primary goal of the MH determination, an unprecedented energy resolution of 3 % at 1 MeV is a critical parameter which requires a total photocathode coverage around 78% (including the small PMTs), a large PMT quantum efficiency (35%) and the LS attenuation length bigger than 20 m at 430 nm. An energy scale uncertainty lower than 1% is obtained by means of a dedicated calibration system and of the stereo-calorimetry with small PMTs. The central detector is immersed in a 44 m-high, 43.5-wide ultrapure water Cherenkov pool, instrumented by 2752 20-inch and 600 8-inch PMTs that will tag events coming from outside the neutrino target. It will also act as a passive shielding for gammas and neutrons induced by cosmic rays in the surrounding rock. A muon tracker, composed of three layers of plastic scintillator strips, will be installed on top of the detector in order to tag cosmic muons and validate the muon track reconstruction. A complete description of the experiment can be found in 1) and 2).

The installation of the central detector and of the Water Cerenkov veto has been completed in December 2024. In the first part of the 2025, the central detector and the water pool have been filled simultaneously with water. Subsequently from February to August the water inside the central detector has been replaced by the liquid scintillator. The detector is in data taking since August 30^{th} and after only two months the first results on neutrino oscillations were shown 3), with the most precise determination of Δm^2_{21} and θ_{12} (the so-called solar oscillation parameters) based

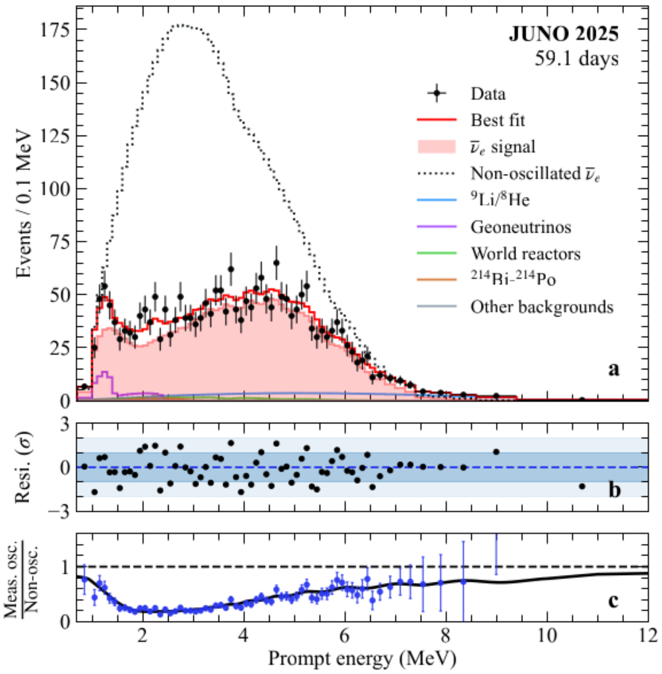

Figure 2: *Measured energy spectrum of inverse beta decay candidates. Black points show measured data with statistical error bars. Shaded red region represents expected neutrino signal. Black dotted line represents non-oscillated reactor neutrino expectation. Backgrounds are indicated by other solid lines.*

on the detection of 2379 inverse beta decays. In figure 2 the measured neutrino energy spectrum is shown. The solar parameters are obtained in a frequentist approach by the minimization of a binned χ^2, where the unoscillated neutrino spectrum is fixed by terms containing Daya Bay data, with an external constraint on $\sin^2\theta_{13}$ and Δm^2_{31} 5). The oscillation analysis yielded the results shown in figure 3 for the solar parameters for normal mass ordering scenario: $\Delta m^2_{21} = (7.50\pm0.12)\text{x}10^{-5}\text{eV}^2$ and $\sin^2\theta_{12} = 0.3092 \pm 0.0087$. The results obtained for the inverted mass hierarchy are fully compatible. In 4) the detector initial performances are also reported.

The collaboration also built, at a distance of about 30 from one of the cores, a reference detector, called TAO (Taishan Anti-neutrino Observatory) 6), in order to provide a a model-independent reference spectrum for JUNO and to investigate about anti-neutrino production models in reactors. The detector is composed by 2.8 t of liquid scintillator enclosed in an acrylic vessel, surrounded by a water Cherenkov veto and a top plastic scintillator (PS) tagger. For an improved energy reconstruction with respect to JUNO, the light read-out will be based on a full coverage of SiPM tiles (with PDE ∼ 50%). To cope with the thermal noise of semi-conductor devices, the liquid scintillator and the read-out electronics will be operated at -50 ^{o}C. TAO detector started data taking during February 2026 and it will be of fundamental importance in reducing systematic errors on anti-neutrino spectrum.

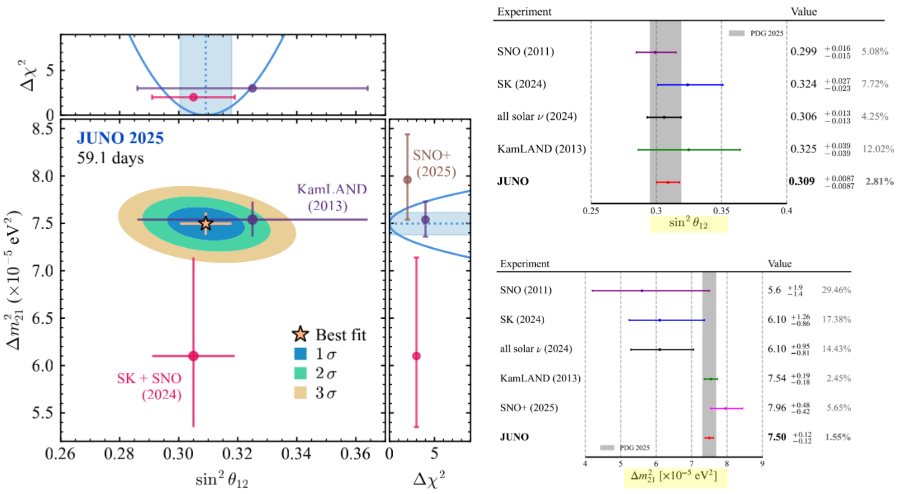

Figure 3: *JUNO results on solar oscillation parameters.*

2 Activities of the LNF group

The LNF group is responsible for the design, the realization and the installation of the Top Tracker electronics, in cooperation with the IPHC Strasbourg and the JINR Dubna groups. The JUNO Top Tracker 7) is used to select a golden sample of cosmic events in order to estimate the cosmogenic background for anti-neutrino detection and to monitor the performances of the central detector. The 62 walls constituting the OPERA Target Tracker 8) are used and disposed into three layers on top of JUNO experiment. Each wall is made by 4+4 crossed modules, each containing 64 scintillator strips, 2.6 cm wide and 6.7 m long; the light, collected by wavelength shifting fibers glued on the strips, is read-out on both fiber ends by 64 channel H7546 Multi-anode PhotoMulTipliers (MaPMT). Each wall contains therefore 16 MaPMTs. Due to the environment (rock) radioactivity, counting rates of up to 50 kHz/MaPMT are expected, therefore the electronics of the OPERA experiment needed to be replaced.

2.1 Top Tracker electronics description

A scheme of the acquisition is shown in figure 4. Like in OPERA, each MaPMT is served by two electronic boards, the Front-End (FE) board and the Read-Out (RO) board. The 16 RO boards are connected to the Concentrator board, located in the middle of the wall, to equalize the cable length.

The FE board contains a 64 channel MAROC3 chip 9), performing the discrimination of the 64 analog signals at 1/3 photo-electron (pe), the OR of the discriminated signals and the charge measurement by an internal Wilkinson ADC; a multiplexed analog output permits also to acquire the charge with an external ADC. The 64 digital outputs are multiplexed in an 8 channel output connection by an FPGA.

The RO board has been designed by CAEN; it contains a Cyclone5 GX FPGA. The board

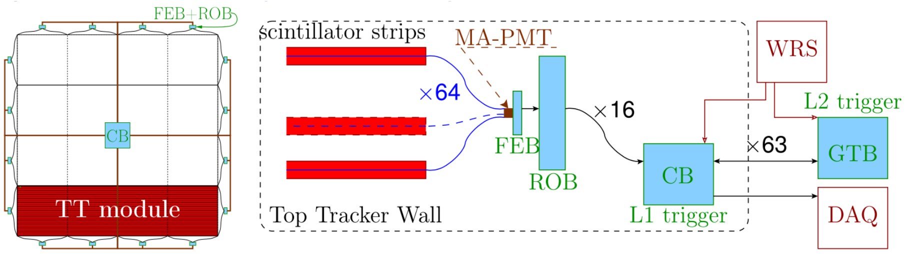

Figure 4: *Scheme of the acquisition system of one Top Tracker wall.*

configures the MAROC3 chip in the FE board and in presence of a signal in the MAROC, delivers the OR to the Concentrator board and starts the acquisition of the digital pattern and further of the charges of the fired strips through a track-and-hold technique. Two options are possible, to use the internal MAROC3 Wilkinson ADC or to multiplex in output analogic signals (OutQ) proportional to the charge and convert them using a 12 bit FADC located in the RO board. In absence of a coincidence between the x and y strips, performed in the Concentrator, a reset of the started MAROC3 acquisition is performed. The RO board also hosts an HV module (the MaPMT works at 800 V with currents up to 500 μA) and a test pulse unit for calibration purposes: the latter is recoverable from the OPERA experiments, while a special HV module has been designed by CAEN, A7511, matching JUNO Top Tracker specifications.

The Concentrator board performs the coincidence between the 16 MaPMT OR signals coming from x and y strips of the wall; a rate of about 50 kHz/wall is expected. A second level trigger board has been developed for data flow reduction.

The time synchronization throughout the entire apparatus is obtained, like in the other JUNO systems, by means of a White Rabbit system.

2.2 Top Tracker installation

The installation of the Top Tracker and of its electronics was performed during the first half of 2025, in parallel to the central detector filling with liquid scintillator, with the three layers (each composed by 20 walls) installed one after the other starting from the water pool cover. The distance between two layers is of about 1.5 m Three additional walls are placed on top of the calibration house above a movable platform, as shown in figure 5.

Top Tracker modules from OPERA, stacked in containers, have been brought underground directly inside the experimental hall above platforms running along the slope tunnel, which connects the underground laboratory to the surface assembly building. One container is shown in the center of figure 6. The modules have been extracted by means of proper tools and placed inside an adiacent rack, where the electronics has been replaced and tested, fixing also light leaks. The tested modules have been then assembled into one wall at the corner of the hall, as shown in figure 7. In parallel, at the entrance of the experimental hall, a new support structure was assembled in parallel. In this way an installation speed of about one wall/day has been achieved.

After the installation of each wall a positional survey has been performed using a teodolite.

Figure 5: *Picture of the Top Tracker system.*

Figure 6: *Picture of the experimental hall during the installation of the Top Tracker.*

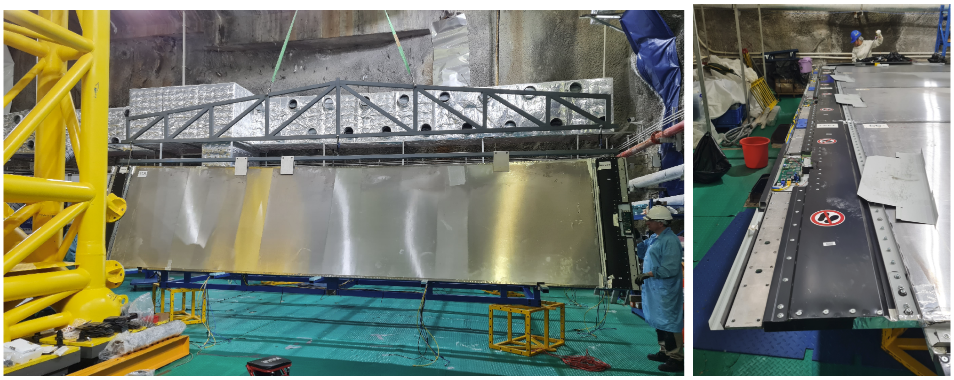

Figure 7: *Picture of the assembly of one wall (left): one module is placed above the blue support structure. The detail of the read-out electronics is also shown (right).*

The Top Tracker system is in acquisition since September 2025 maintenance campaign. Following the first tests on the installed electronics, a revision of the firmware of the different boards, in collaboration with CAEN, is ongoing to fix the last bugs.

3 Publications in year 2025

1. The JUNO collaboration, "JUNO sensitivity to invisible decay modes of neutrons", Eur. Phys. J. C85 (2025) 1,5.
2. The JUNO collaboration, "Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO", Chinese Phys. C 49 (2025) 033104.
3. A. Gavrikov et al., "Interpretable machine learning approach for electron antineutrino selection in a large liquid scintillator detector", Phys. Lett. B 860 (2025) 139141.
4. The JUNO collaboration, "Prediction of Energy Resolution in the JUNO Experiment" Chinese Phys. C 49 (2025) 013003.
5. M. Beretta et al., "Fluorescence emission of the JUNO liquid scintillator", JINST 20 (2025) P05009.
6. The JUNO collaboration, "Simulation of the background from ^{13}C(α, n)^{16}O reaction in the JUNO scintillator", Arxiv:2503.00968, Eur. Phys. C 85 (2025) 1080.
7. A. Gavrikov et al., "Simulation-based inference for Precision Neutrino Physics through Neural Monte Carlo tuning", ArXiv:2507.23297.
8. The JUNO collaboration, "Design, waterproofing, and mass production of the 3-inch PMT frontend system of JUNO", ArXiv:2510.06616.
9. The JUNO collaboration, "Prospects for geoneutrino detection with JUNO", ArXiv:2511.07227

10. The JUNO collaboration, “First measurement of reactor neutrino oscillations at JUNO”, ArXiv:2511.14593.
11. The JUNO collaboration, “Initial performance results of the JUNO detector”, ArXiv:2511.14590.
12. A. Barresi et al., “Ultra-trace analysis of U and Th in organic liquid scintillators with high sensitivity”, ArXiv:2512.08988.

References

1. The JUNO Collaboration, Conceptual Design Report, ArXiv:1508.07166 (2015).
2. The JUNO collaboration, “JUNO physics and detector”, ArXiv:2104.02565, Progr. Part. Nucl. Phys. 123 (2022) 103927, DOI: 10.1016/j.ppnp.2021.103927.
3. The JUNO collaboration, “First measurement of reactor neutrino oscillations at JUNO”, ArXiv:2511.14593.
4. The JUNO collaboration, “Initial performance results of the JUNO detector”, ArXiv:2511.14590.
5. The Daya Bay collaboration, “Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay”, Phys. Rev. Lett. 130, 161802 (2023).
6. The JUNO Collaboration, ”TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution”, arXiv:2005.08745 (2020).
7. The JUNO collaboration, “The JUNO experiment Top Tracker”, ArXiv:2303.05172, NIMA 1057 (2023) 168680.
8. T. Adam *et al.*, Nucl. Instrum. Meth. A577 (2007) 523.
9. http://omega.in2p3.fr/index.php/products/maroc-front-end-chip.html.