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Neutrino mass ordering determination through combined analysis with JUNO and KM3NeT/ORCA

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Abstract

The determination of neutrino mass ordering (NMO) is one of the prime goals of several neutrino experiments. KM3NeT/ORCA and JUNO are two next-generation neutrino oscillation experiments both aiming at addressing this question. ORCA can determine the NMO by probing Earth matter effects on the oscillation of atmospheric neutrinos in the GeV energy range. JUNO, on the other hand, is sensitive to the NMO by investigating the interference effects of fast oscillations in the reactor electron antineutrino spectrum at medium baseline. This contribution presents the potential of determining the NMO through a combined analysis of JUNO and ORCA data. When measuring the Δm_{31}^2 with a wrong ordering assumption, the best-fit values are different between the two experiments. This tension, together with good constraints on the Δm_{31}^2 measurement by both experiments, enhances the combined NMO sensitivity beyond the simple sum of their sensitivities. The analysis shows that a 5σ significance is reachable in less than 2 years of data taking with both experiments for true normal neutrino mass ordering, assuming current global best-fit values of the oscillation parameters, while 6 years will be needed for any other parameter set.

1. Introduction

The discovery of neutrino oscillations [1, 2] at the turn of the last century unequivocally shows that neutrinos have mass. Since this discovery, significant progress has been made to determine several of the parameters needed to describe neutrino oscillations. There are nevertheless still some parameters that are yet to be measured, such as the presence and size of CP-violation in the lepton sector, the value and origin of the neutrino masses, and their ordering. Indeed, while neutrino oscillations imply that the neutrino flavor eigenstates (ν_e , ν_μ , ν_τ) are different from the neutrino mass eigenstates (ν_1 , ν_2 , ν_3) with masses (m_1 , m_2 , m_3 , respectively) and that these masses are different with $\Delta m_{jk}^2 = m_j^2 - m_k^2 \neq 0$, neutrino oscillations do not provide any way to measure each mass directly. Likewise, several experiments are mostly sensitive to the absolute value of Δm_{jk}^2 , which creates some uncertainty regarding the order of the neutrino masses. Currently, two different neutrino mass orderings (NMO) remain possible: the normal ordering (NO) with $m_1 < m_2 < m_3$ and the inverted ordering (IO) with $m_3 < m_1 < m_2$.

The determination of the NMO is one of the main goals of several experiments currently under construction, such as JUNO and KM3NeT/ORCA, on which the present study is based. An overview of these detectors, including how they perform the NMO determination, is provided in Secs. 2 and 3, respectively. Sec. 4 describes the procedure to combine the results of these experiments to obtain the combined sensitivity presented in Sec. 5. An extended description of this study and its results can be found in Ref. [4].

2. JUNO overview

The Jiangmen Underground Neutrino Observatory [5, 6] (JUNO) is a multipurpose experiment being build in the south east of China. The JUNO detector is located about 53 km from the Taishan and Yangjian Nuclear Power Plants (NPP), distance which was optimized to enhance the sensitivity to the NMO determination [5]. Electron antineutrinos from these NPPs will interact via the inverse beta decay interaction with liquid scintillator composing the JUNO neutrino target, with the outgoing positron carrying most of the initial neutrino's energy. In order to determine the NMO, JUNO needs to precisely reconstruct the energy spectrum of these antineutrinos by measuring the positron's visible energy with a resolution of about 3% at 1 MeV. The measured energy spectrum will be imprinted with the oscillation patterns from the oscillations induced by both Δm_{21}^2 and Δm_{31}^2 , and the interplay between these oscillation patterns makes it possible for JUNO to determine the NMO. Due to the requirement to observe precisely both oscillations, the energy resolution is a critical parameter for the success of JUNO.

The present study models JUNO based on the description of Ref. [5], with the exception that only the two already built reactor cores at the Taishan NPP are taken in consideration, as the construction of the two additional cores initially foreseen is currently uncertain [6]. The impact of this change is briefly discussed at the end of Sec. 5. It is worth noting that we do not consider any of the changes in detector performance that were presented recently in Ref. [7], where an improved performance of the detector compensates the reduction in sensitivity due to the loss of antineutrinos from two reactor cores at the Taishan

59 NPP.

60 3. KM3NeT/ORCA overview

61 The Oscillation Research with Cosmics in the Abyss
62 (ORCA) detector is part of the Cubic Kilometre Neutrino Tele-
63 scope [8] (KM3NeT) being deployed in the Mediterranean Sea.
64 KM3NeT is a water Cherenkov detector comprising two tridi-
65 mensional arrays of optical modules distributed to measure the
66 light produced by charged particles originating from neutrino
67 interactions in and around the detector, and traveling faster
68 than light in the surrounding medium. The distance between
69 neighbouring optical modules in the detector can be optimized,
70 to search for astrophysical neutrinos in the TeV–PeV range or
71 to study neutrino oscillations using atmospheric neutrinos with
72 energies above 1 GeV, which is the goal of ORCA. Using this
73 array, the NMO is determined by probing the imprint of matter
74 effects on the neutrino oscillation pattern measured as a func-
75 tion of the energy and direction of the neutrino. To perform this
76 measurement, the events detected in ORCA are distributed into
77 two separate classes based on their topology, in order to sep-
78 arate $\nu_\mu + \bar{\nu}_\mu$ CC interactions (classified mainly as track-like),
79 from $\nu_e + \bar{\nu}_e$ CC interactions (classified mostly as shower-like),
80 given that the impact of matter effects will be different for each
81 neutrino flavor being measured. An additional sample, contain-
82 ing the events that cannot be clearly classified as either track-
83 like or shower-like, is also created to maximise the purity of the
84 samples with a clear topological identification.

85 In this study, two scenarios for the treatment of systematic
86 errors for ORCA were considered. The baseline scenario uses
87 the same assumptions as in other recent ORCA analyses [9]
88 and is expected to better correspond to the systematic errors on
89 the ORCA detector. The optimistic scenario is based on the
90 treatment used in Ref. [10] that presents the expected sensitiv-
91 ity to the NMO from a combined study using JUNO and the
92 IceCube Upgrade and PINGU (proposed ice Cherenkov detec-
93 tors located in the South Pole). Note also that, for this study, all
94 sensitivity estimates are based on the performance of a fully-
95 deployed ORCA detector (with 115 detection lines).

96 4. Combined analysis

97 As mentioned in Secs. 2 and 3, the sources and energies of
98 the neutrinos used for the determination of the NMO in JUNO
99 and ORCA are very different. These two detectors also rely
100 on different detector media and methods used for the detection
101 of these neutrinos. Thanks to these significant differences, only
102 the neutrino oscillation parameters are shared between these ex-
103 periments while the other systematic errors are not correlated
104 between experiments. Furthermore, of the six parameters de-
105 scribing 3-flavor neutrino oscillations only two (Δm_{31}^2 and θ_{13})
106 impact both JUNO and ORCA and need to be considered jointly
107 in the combined analysis. The other four parameters either have
108 no impact on JUNO (δ_{CP} and θ_{23}) or have only a negligible im-
109 pact on ORCA (Δm_{21}^2 and θ_{12}), and so can be treated indepen-
110 dently in the analysis of either detector.

111 In order to perform the combined analysis, an Asimov dataset
112 of each experiment is used to compute the χ^2 for a given
113 ($\Delta m_{31}^2, \theta_{13}$) pair for each experiment separately, profiling for all
114 systematic errors and all other relevant oscillation parameters.
115 These computations are performed in a grid of ($\Delta m_{31}^2, \theta_{13}$) val-
ues to form a χ^2 map. The obtained χ^2 values are then added,
along with a prior term on θ_{13} , to produce the combined χ^2
value:

$$\chi^2(\Delta m_{31}^2, \theta_{13}) = \chi_{\text{JUNO}}^2(\Delta m_{31}^2, \theta_{13}) + \chi_{\text{ORCA}}^2(\Delta m_{31}^2, \theta_{13}) + \frac{(\sin^2 \theta_{13} - \sin^2 \theta_{13}^{\text{GF}})^2}{\sigma_{\sin^2 \theta_{13}}^{\text{GF}}}$$

where the prior term on θ_{13} is added to account for the fact that
current experiments have a better sensitivity to this oscillation
parameter than either JUNO or ORCA will have. The global
fit (GF) presented in Ref. [11] was used to obtain the θ_{13}^{GF} prior
value and uncertainty.

This χ^2 is then used to evaluate the $\overline{\Delta\chi^2} = \chi_{\text{WO}}^2 - \chi_{\text{TO}}^2$, where
 χ_{WO}^2 (χ_{TO}^2) is the minimum value of the χ^2 for the wrong (true)
ordering in the χ^2 map. An example distribution of each in-
dependent experiment χ^2 profile along with the combined χ^2
profile is shown in Fig. 1 as a function of Δm_{31}^2 .

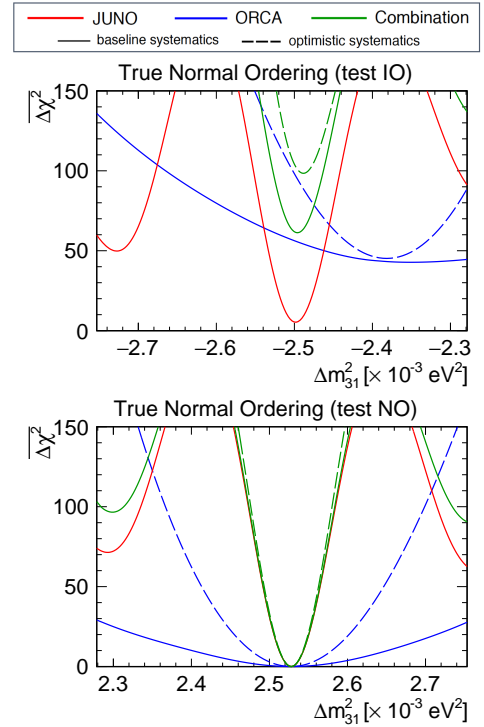


Figure 1: $\overline{\Delta\chi^2}$ profile for 6 years of data taking.

When the ordering tested is the true ordering, one can see that
both experiments obtain their minimum χ^2 value for the same
 Δm_{31}^2 . However, when the ordering tested is the wrong order-
ing, each experiment will obtain their minimum χ^2 at a different
 Δm_{31}^2 , which creates a tension between these measurements and
boosts the sensitivity of the combined analysis beyond just the
one obtained from adding the sensitivities to the NMO from
each experiment separately.

5. Results and Conclusion

Fig. 2 shows the NMO sensitivity as a function of time for each experiment independently, as well as for the combined analysis performed in this study. If the true ordering is normal, and for the current best-fit θ_{23} value from Ref. [11], a 5σ determination of the NMO is expected with 3 years of data from ORCA alone. In this case, the combined analysis would reduce the time required to reach such sensitivity by 1–2 years, depending on the systematic error scenario used. However, if the true ordering is inverted, it would take more than 10 years of data to achieve a 5σ determination of the NMO using ORCA alone, while the combined analysis of JUNO and ORCA would reach such a sensitivity after 6 years. It is also worth noting that the ORCA sensitivity to the NMO strongly depends on the true value of θ_{23} , with the NO and IO scenarios presented above corresponding roughly to the best and worst sensitivities obtained for various values of θ_{23} and for either ordering. Further discussion on the impact of θ_{23} is provided in Ref. [4].

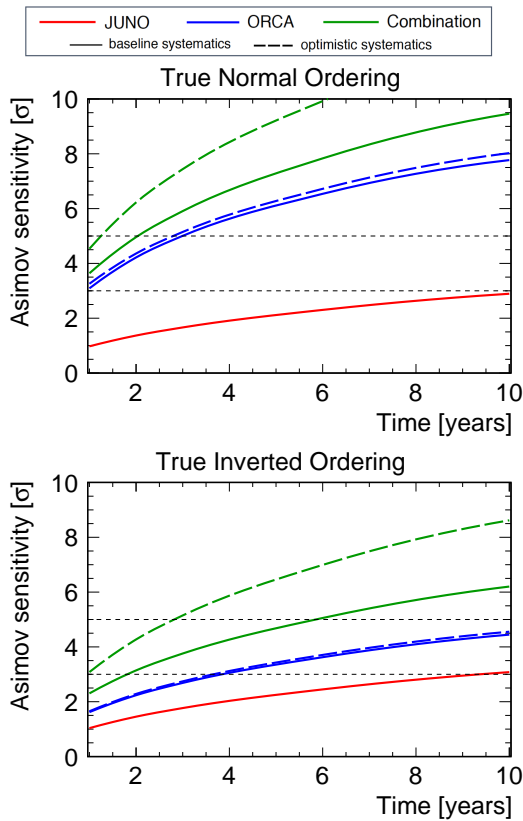


Figure 2: NMO sensitivity as a function of time.

Fig. 3 shows the NMO sensitivity as a function of time for the current (8 cores) and initially planned (10 cores) number of cores running at the NPPs providing the $\bar{\nu}_e$ for JUNO. This figure shows that, while the number of cores available to JUNO will strongly affect its individual sensitivity to the NMO, with a 3σ determination varying from 10 years to 6 years, it has only a small impact on the sensitivity of the combined analysis. This happens because, in both scenarios, JUNO will be able to precisely measure Δm_{31}^2 , which will create a similar tension

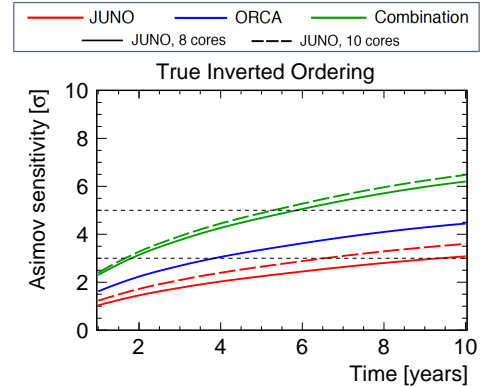


Figure 3: NMO sensitivity as a function of time with different number of NPP at 53 km from JUNO.

to boost the combined NMO sensitivity. It is worth noting, in any case, that the JUNO-only NMO sensitivity is expected to be closer to the 10 cores scenario presented here, even though only 8 cores are expected to be available, thanks to several other improvements in the analysis and modeling of the detector [7].

In summary, the NMO is expected to be determined at 5σ in at most ~ 6 years when doing a combined JUNO and ORCA analysis. This is a significantly shorter time than required by either experiment separately. Even for favorable oscillation parameters where the time required to determine the NMO would be shorter, a combined analysis will still reduce the time required to make this determination by at least a year.

For further discussions and results, please refer to the full paper describing this analysis provided in Ref. [4].

References

- [1] Y. Fukuda et al. (Super-Kamiokande Collaboration). Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.* 81:1562–1567, 1998, [hep-ex/9807003].
- [2] Q. R. Ahmad et al. (SNO Collaboration). Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.* 89:011301, 2002, [nucl-ex/0204008].
- [3] P. A. Zyla et al. (Particle Data Group Collaboration). Review of Particle Physics. *PTEP* 2020(8):083C01, 2020. And references therein.
- [4] S. Aiello et al. (JUNO Collaboration members and KM3NeT Collaboration). Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering. *JHEP* 03:055, 2022, [2108.06293].
- [5] F. An et al. (JUNO Collaboration). Neutrino Physics with JUNO. *J. Phys. G* 43(3):030401, 2016, [1507.05613].
- [6] A. Abusleme et al. (JUNO Collaboration). JUNO physics and detector. *Prog. Part. Nucl. Phys.* 123:103927, 2022, [2104.02565].
- [7] J. Zhang et al. (JUNO Collaboration). JUNO Neutrino Mass Ordering Sensitivity. DOI:10.5281/zenodo.6775075. Presented at Neutrino 2022.
- [8] S. Adrian-Martinez et al. (KM3Net Collaboration). Letter of intent for KM3NeT 2.0. *J. Phys. G* 43(8):084001, 2016, [1601.07459].
- [9] S. Aiello et al. (KM3NeT Collaboration). Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA. *Eur. Phys. J. C* 82(1):26, 2022, [2103.09885].
- [10] M. G. Aartsen et al. (IceCube-Gen2 Collaboration). Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU. *Phys. Rev. D* 101(3):032006, 2020, [1911.06745].
- [11] I. Esteban et al. Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of θ_{23} , δ_{CP} , and the mass ordering. *JHEP* 01:106, 2019, [1811.05487].