

Lessons from the first JUNO results

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ABSTRACT: First results from the JUNO reactor neutrino experiment already determine with world-leading precision the small neutrino squared-mass splitting Δm_{21}^2 and the mixing angle θ_{12} . In this article we perform an exploratory study beyond these, taking advantage of the first JUNO data release to discuss its sensitivity to the large squared-mass splitting, $\Delta m_{3\ell}^2$. When combined with constraints from global oscillation data, this may already contain some information on the neutrino mass ordering. Indeed, we find that the combination of the complementary $\Delta m_{3\ell}^2$ -determinations gives a slight preference for Normal Ordering, with a p -value for Inverted Ordering of 2%–2.6% (2.2σ – 2.3σ). We study the robustness of this

result with respect to potential systematic uncertainties and statistical fluctuations. Taken at face value, a full global analysis of oscillation data including the publicly available JUNO information and data leads to a preference for Normal Ordering with $\Delta\chi^2 = 4.6$ and 9.4 without and with Super-K and IceCube-24 atmospheric neutrino data, respectively.

KEYWORDS: Neutrino Mixing, Neutrino Interactions

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1 Introduction

In the realm of neutrino oscillation studies, the first results of the Jiangmen Underground Neutrino Observatory (JUNO) [1] represent a significant step forward. Just 59.1 days of exposure have been enough to reach world-leading precision on their dominant oscillation parameters, Δm_{21}^2 and θ_{12} . These first results constitute a milestone in the path to achieve JUNO's ultimate goals of precision measurements of Δm_{21}^2 , θ_{12} , and Δm_{31}^2 [2], and of determining the neutrino mass ordering (MO) with more than 3σ significance [3].

Determining the MO is an important open question in neutrino physics. Among others, it has significant implications for neutrinoless double beta decay searches, it can affect the neutrino mass scale relevant for cosmology, and it is key to break existing degeneracies, e.g., in leptonic CP violation [4]. While the intrinsic sensitivity of JUNO to the MO is based on a subtle interference effect between fast (Δm_{31}^2 -driven) and slow (Δm_{21}^2 -driven) oscillation modes [5, 6], a potentially much earlier identification of the MO could emerge from the combination of independent percent-level determinations of $|\Delta m_{31}^2|$ from JUNO and $\nu_\mu/\bar{\nu}_\mu$ disappearance data. This latter possibility was mentioned in refs. [6, 7] and demonstrated in detail in ref. [8], see also [9–12].

In this respect, it is important to remark that in ref. [1] the JUNO collaboration has not presented any results on $|\Delta m_{31}^2|$ and the MO with their first data, limiting the analysis (including the provided details on the systematic uncertainties) to the dominant oscillation mode due to Δm_{21}^2 and θ_{12} . Nevertheless, it can be an informative exercise to explore the possible sensitivity to $|\Delta m_{31}^2|$ and the MO of these first results within the publicly available information, as well as the dependence of these results on possible unknowns, especially in combination with the remaining global oscillation data.

With these goals in mind, in this paper we present our independent implementation of the analysis of the first JUNO data, which we describe in section 2. We perform a variety of analyses in order to reproduce the results of the collaboration on Δm_{21}^2 and θ_{12} , which have

been incorporated in our updated global analysis NuFIT-6.1 [4, 13] (section 3). With this well-tuned tool in hand, we make an exploratory study of the possible sensitivity to the large squared-mass splitting $\Delta m_{3\ell}^2$, discussing both its absolute value as well as the MO (section 4). We study its robustness against statistical fluctuations by running a Monte Carlo simulation of JUNO data in section 4.1, which allows us to perform a statistically consistent MO hypothesis test. We further investigate the potential impact of various systematic uncertainties in section 4.2. In the summary, section 5, we also comment on the MO discrimination of the global oscillation data including our attempted JUNO analysis.

In the following, we adopt the standard parametrization of the 3×3 unitary leptonic mixing matrix [14, 15], as discussed in ref. [4]. The $\bar{\nu}_e$ survival probability relevant for reactor experiments such as JUNO depends on the four parameters $\{\theta_{12}, \theta_{13}, \Delta m_{21}^2, \Delta m_{3\ell}^2\}$, with $\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$ and $m_{1,2,3}$ the masses of the three neutrino mass eigenstates. There are two non-equivalent orderings for the three neutrino masses: normal ordering (NO) with $m_1 < m_2 < m_3$, and inverted ordering (IO) with $m_3 < m_1 < m_2$. Thus one can parametrize the ordering in terms of the sign of $\Delta m_{3\ell}^2$ defined as

$$\Delta m_{3\ell}^2 \quad \text{with} \quad \begin{cases} \ell = 1 & \text{for } \Delta m_{3\ell}^2 > 0: \text{ normal ordering (NO),} \\ \ell = 2 & \text{for } \Delta m_{3\ell}^2 < 0: \text{ inverted ordering (IO).} \end{cases} \quad (1.1)$$

Recent global analyses within the three-flavour scenario can be found in refs. [4, 13, 16, 17].

2 JUNO analysis details

In this section, we describe our analysis of JUNO data that allows us to obtain the main quantitative results of this work. The neutrino detection reaction in JUNO is inverse beta decay (IBD), $\bar{\nu}_e + p \rightarrow e^+ + n$, and the energy deposited by the positron (so-called “prompt energy”, see below) allows to infer the neutrino energy. We fit the 66 data points in reconstructed prompt energy provided in figure 3 of ref. [1], 2379 events in total, corresponding to 59.1 days of data taking. The basic ingredients for the analysis are as follows.

Signal spectrum prediction. We compute the expected number of IBD signal events N_i^S in the reconstructed prompt energy bin i as a function of oscillation parameters $\vec{\omega}$:

$$N_i^S(\vec{\omega}) = C \sum_r \int dE_\nu \frac{\mathcal{P}_r}{4\pi L_r^2} \phi(E_\nu) \sigma_{\text{IBD}}(E_\nu) P_{ee}(E_\nu, L_r, \vec{\omega}) R_i(E_\nu), \quad (2.1)$$

where the sum in r extends over the nine reactors given in table 2 of [2] and L_r is the distance to each of them. This includes eight reactors at a distance of about 53 km and a single effective reactor from the Daya Bay complex at 215 km. The contribution of each reactor is weighted by its average power \mathcal{P}_r as given in the same table. In the absence of information on the relevant isotope composition contributing to the neutrino flux for the present JUNO data set, we adopt the same as for Daya Bay for all reactors. For the emitted flux per unit power, $\phi(E_\nu)$, we assume the un-oscillated flux extracted from data by the Daya Bay collaboration, including 25 pulls to parametrise the uncertainty, as described in appendix A. In eq. (2.1) C is a normalization constant accounting for the number of target

protons, lifetime and selection efficiencies; $\sigma_{\text{IBD}}(E_\nu)$ is the IBD cross section that we obtain from ref. [18] (we have checked that using the cross sections from refs. [19, 20] leads to very similar results); $R_i(E_\nu)$ is the energy response function for bin i , that we describe below; and $P_{ee}(E_\nu, \vec{\omega})$ is the neutrino flavor oscillation probability. For this last quantity, we use the analytic expression for 3-flavour oscillations

$$\begin{aligned}
 P_{ee} = & 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E_\nu} \\
 & - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu} \right),
 \end{aligned}
 \tag{2.2}$$

with $s_{ij} \equiv \sin \theta_{ij}$ and $c_{ij} \equiv \cos \theta_{ij}$. This expression holds for both mass orderings. We include matter effects by introducing effective mixing parameters in matter, expanding the dominant 12-term to linear order in the small parameter $A = 2E_\nu V / \Delta m_{21}^2$. We do not take into account subleading matter effects on the fast-oscillating terms in the second line of eq. (2.2) [21]. The resulting probability agrees within better than 0.4% with a full numerical calculation. We assume a constant matter density of 2.55 g/cm³ [1], see also refs. [22–24]. For all analyses below (except the global analysis results in section 5) we assume $\sin^2 \theta_{13} = 0.022 \pm 0.00056$ [4], taking into account the uncertainty by introducing a Gaussian pull (the results are very similar if θ_{13} is instead fixed).

Flux, cross section, and oscillation probability are calculated for a true neutrino energy E_ν . The observable in the detector is the energy deposited by the positron after annihilation, the so-called “prompt energy” $E_{\text{pr}} = E_e + m_e$ where E_e is the positron energy, that is related to E_ν by the kinematics of IBD — see, e.g., ref. [19]. This relationship, together with the energy resolution of the detector, is encapsulated in the function $R_i(E_\nu)$ in eq. (2.1).

In the limit of neglecting the momentum carried away by the recoiling neutron, there is a one-to-one relation between neutrino and prompt energies, $E_{\text{pr}} = E_\nu + m_e - \Delta$ with $\Delta = m_n - m_p$. In this limit, $R_i(E_\nu)$ is given by a convolution of a Dirac delta linking E_ν and E_{pr} and the Gaussian energy resolution of the detector. However, as discussed in ref. [21], for precision reactor experiments this is not a good approximation and neutron-recoil effects need to be taken into account. In our analysis, we include this by following the prescription described in ref. [21]. In detail, if $E_e^{\text{inf}}(E_\nu)$ and $E_e^{\text{sup}}(E_\nu)$ are the minimum and maximum kinematically allowed positron energies for a given neutrino energy E_ν (see, e.g., ref. [19] for explicit expressions), we obtain $R_i(E_\nu)$ by convolving a normalized top-hat function between $E_{\text{pr}}^{\text{inf}} = E_e^{\text{inf}} + m_e$ and $E_{\text{pr}}^{\text{sup}} = E_e^{\text{sup}} + m_e$ with the Gaussian energy resolution of the detector (see eqs. (35) and (36) in ref. [21] for explicit expressions).¹

Regarding the energy resolution of the detector, following eq. (8) in ref. [25], we adopt a Gaussian resolution of width

$$\sigma(E_{\text{pr}}) = E_{\text{pr}} \sqrt{a^2/E_{\text{pr}} + b^2},
 \tag{2.3}$$

with $a = 0.033$, $b = 0.01$ for E_{pr} in MeV. We also account for non-linearity in the detector energy response by modifying $E_{\text{pr}}^{\text{inf}}(E_\nu)$ and $E_{\text{pr}}^{\text{sup}}(E_\nu)$ as $E_{\text{pr}} \rightarrow E_{\text{pr}} F_{\text{n.l.}}(E_{\text{pr}})$, where $F_{\text{n.l.}}(E_{\text{pr}})$

¹Alternatively, we have checked that the main effect of the neutron recoil is a slight shift of E_e from $E_\nu - \Delta$, which can be approximately captured by setting $E_e(E_\nu) = (E_e^{\text{inf}} + E_e^{\text{sup}})/2$.

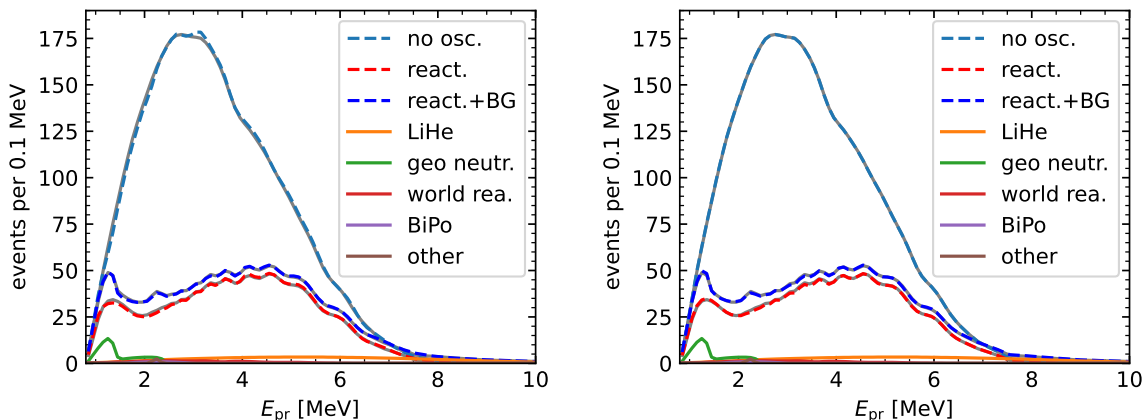


Figure 1. Predicted spectra (dashed) compared to the official JUNO ones [1] (grey). Left: based on our own predicted spectrum, normalized to match the normalization of their un-oscillated spectrum. Right: bin-per-bin rescaled to match the JUNO un-oscillated spectrum.

is the non-linearity function for positrons, that we extract from figure 6d in ref. [1] (see also ref. [25]).

Backgrounds. Following ref. [1], we separate the background into five components: ${}^9\text{Li}/{}^8\text{He}$ produced by cosmic muon spallation, that we denote as “LiHe”; geoneutrinos, that we denote as “Geo”; world reactors, that we denote as “world-react”; ${}^{214}\text{Bi}/{}^{214}\text{Po}$ from radon decay, that we denote as “BiPo”; and other sources of background, that we denote as “others”. The number of events of each of these backgrounds in bin i (N_i^{LiHe} , N_i^{Geo} , $N_i^{\text{world-react}}$, N_i^{BiPo} , and N_i^{others}) is read from figure 3 of ref. [1], with the exception of world reactors for which we take the un-oscillated reactor spectrum (since oscillations are averaged out for very far reactors, so the oscillated shape is proportional to the un-oscillated one). We normalize all background spectra to the total pre-fit rate for each background given in table 1 of ref. [1].

With all these elements, we obtain our predicted un-oscillated and best-fit oscillated spectra shown in dashed lines in the left panel of figure 1. In these predictions, the normalization constant C has been set to match the normalization of the JUNO un-oscillated spectrum. As seen in the figure, the predicted spectra agree very well with the official JUNO results (shown in grey). In the right panel, we scale our predictions bin-per-bin to match the JUNO un-oscillated spectrum, which gives a slightly better match to their oscillation parameter regions. Such minor tuning is inevitable given the lack of publicly available information on, e.g., the exact isotope composition and power of the relevant nuclear reactors.

Systematics. The following sources of systematic uncertainties j are included as pulls ξ_j in the statistical analysis described below, assuming Gaussian errors σ_j as follows:

- Normalization of the reactor neutrino event rate: $\sigma_{\text{norm}} = 1.8\%$, obtained by summing in quadrature all entries in table 2 of ref. [1].
- Normalization of each background component: $\sigma_{\text{bg},i} = 33\%$, 42% , 10% , 56% , 100% for $i = \text{LiHe}$, Geo , world-react , BiPo , other , respectively, as given in table 1 of ref. [1].

- Shape uncertainty for the LiHe background: set to 20% at 1 MeV and linearly proportional to energy [1].
- 25 pulls for the reactor flux uncertainty, as explained in appendix A.
- Energy scale uncertainties: we introduce two pulls ξ_{scl} and ξ_{bias} , which shift prompt energy as

$$E_{\text{pr}} \rightarrow \tilde{E}_{\text{pr}} \equiv E_{\text{pr}} [(1 + \xi_{\text{scl}}) F_{\text{n.l.}}(E_{\text{pr}}) + \xi_{\text{bias}}] \quad (2.4)$$

where ξ_{scl} and ξ_{bias} parametrize an uncertainty in the energy scale and an additive bias in the non-linearity correction $F_{\text{n.l.}}$, respectively. We find that the effect of both pulls is very similar when their uncertainty is kept at the nominal value $\sigma_{\text{scl}} = \sigma_{\text{bias}} = 0.5\%$ [1]. Therefore, in most of our analysis cases we only use one of them at a time, typically ξ_{scl} (we discuss this further in section 4.2).

- Energy resolution uncertainty: we introduce an uncertainty on the energy resolution by replacing $\sigma \rightarrow \tilde{\sigma} \equiv (1 + \xi_{\text{res}})\sigma$ in the response function $R_i(E_\nu)$, where σ is given in eq. (2.3). As we have not found publicly available information on the JUNO energy resolution uncertainty, we adopt a nominal uncertainty $\sigma_{\text{res}} = 5\%$. In section 4.2, we assess the impact of varying this uncertainty.

In addition, in some of the analysis variants we introduce fixed “ad-hoc” rescaling factors r_i for some of the backgrounds, for $F_{\text{n.l.}}$, and for the energy resolution σ in eq. (2.3). Altogether, our predicted number of signal and background events in presence of the systematic pulls and rescaling factors is

$$\begin{aligned} N_i^S(\vec{\omega}, \vec{\xi}, \vec{r}) &= (1 + \xi_{\text{norm}}) \tilde{N}_i^S(\vec{\omega}, \xi_{\text{scl}}, \xi_{\text{bias}}, \xi_{\text{res}}, r_{\text{n.l.}}, r_{\text{res}}), \\ N_i^{\text{Geo}}(\vec{\xi}, \vec{r}) &= (1 + \xi_{\text{Geo}}) N_i^{\text{Geo}}, \\ N_i^{\text{LiHe}}(\vec{\xi}, \vec{r}) &= (1 + \xi_{\text{LiHe},1} + \xi_{\text{LiHe},2} E_i) r_{\text{BG}} N_i^{\text{LiHe}}, \\ N_i^{\text{BiPo}}(\vec{\xi}, \vec{r}) &= (1 + \xi_{\text{BiPo}}) r_{\text{BG}} N_i^{\text{BiPo}}, \\ N_i^{\text{world-reac}}(\vec{\xi}, \vec{r}) &= (1 + \xi_{\text{world-reac}}) r_{\text{BG}} N_i^{\text{world-reac}}, \\ N_i^{\text{other}}(\vec{\xi}, \vec{r}) &= (1 + \xi_{\text{other}}) r_{\text{BG}} N_i^{\text{other}} \end{aligned} \quad (2.5)$$

where \tilde{N}_i^S in the right hand side of the first line is obtained as in eq. (2.1) with modified reconstructed energy \tilde{E}_{pr} and energy resolution $\tilde{\sigma}$ as

$$\tilde{E}_{\text{pr}} = E_{\text{pr}} r_{\text{n.l.}} [(1 + \xi_{\text{scl}}) F_{\text{n.l.}}(E_{\text{pr}}) + \xi_{\text{bias}}], \quad (2.6)$$

$$\tilde{\sigma} = (1 + \xi_{\text{res}}) r_{\text{res}} \sigma. \quad (2.7)$$

Statistical analysis. With all these elements we build our χ^2 function for the oscillation parameters ($\vec{\omega}$), where we include the pull uncertainties as Gaussian penalties

$$\chi_{\text{JUNO}}^2(\vec{\omega}) = \min_{\vec{\xi}} \left[\chi_{\text{data}}^2(\vec{\omega}, \vec{\xi}) + \sum_j \frac{\xi_j^2}{\sigma_{\xi_j}^2} \right]. \quad (2.8)$$

	cnf 1	cnf 2	cnf 3	cnf 4	cnf 5	cnf 6
r_{BG}	1	1.15	1.15	1.15	1.	1.15
$r_{\text{n.l.}}$	1	1	1.024	1	1	1
$\sigma_{\text{bias}} (\%)$	0	0	0	5	0	0
r_{res}	1	1	1	1	1.3	1
$\sigma_{\text{res}} (\%)$	5	5	5	5	5	40
χ_{data}^2	CNP	Poisson	Poisson	Poisson	Poisson	Poisson
χ_{min}^2	49.4	49.2	48.9	49.2	50.1	49.1
$\Delta\chi_{\text{IO-NO}}^2$	3.18 (3.41)	3.05 (3.28)	0.30 (1.60)	2.89 (3.03)	2.08 (2.21)	2.06 (2.11)
T_0^{NO}	1.37 (1.72)	1.35 (1.69)	1.40 (1.70)	1.30 (1.65)	0.69 (0.84)	1.29 (1.58)
$-T_0^{\text{IO}}$	1.45 (1.69)	1.43 (1.66)	1.46 (1.65)	1.34 (1.56)	0.71 (0.82)	1.34 (1.53)

Table 1. Summary of different analysis configurations cnf 1–6, see section 2 for definitions. Our default configuration is cnf 2. For all configurations, $\sigma_{\text{norm}} = 1.8\%$ and $\sigma_{\text{scl}} = 0.5\%$. r_{BG} is a rescaling of all backgrounds except for geoneutrinos. χ_{min}^2 is given for JUNO only; the dof are 63 (66 bins minus 3 fitted parameters). $\Delta\chi_{\text{IO-NO}}^2$ and T_0 values are for JUNO combined with the $|\Delta m_{3\ell}^2|$ determination from NuFIT-6.1 without (with) SK-ATM. T_0 corresponds to $\Delta\chi_{\text{IO-NO}}^2$ for the Asimov data set assuming NuFIT-6.1 best-fit values for $\Delta m_{3\ell}^2$; see section 4.1 for a translation to p -values.

In ref. [1] the JUNO collaboration adopted the so-called CNP definition [26] for $\chi_{\text{data}}^2(\vec{\omega}, \xi_i)$, defined by $\chi_{\text{CNP}}^2 \equiv \sum_i (P_i - O_i)^2 / \sigma_i^2$ where O_i and P_i are the observed and predicted number of events in bin i , respectively, and

$$\sigma_i^2 = \frac{3}{\frac{1}{O_i} + \frac{2}{P_i}}. \quad (2.9)$$

The CNP χ^2 has been constructed in order to approximate the Poisson χ^2 , defined by $\chi_{\text{Poisson}}^2 \equiv 2 \sum_i [P_i - O_i + O_i \log(O_i/P_i)]$. We find that, while χ_{CNP}^2 gives results very similar to χ_{Poisson}^2 , they are not identical. Below, we show results for different analyses based on either of these two definitions.

3 Determination of Δm_{21}^2 and θ_{12}

Having specified the details of our JUNO data analysis, we first apply it to determining Δm_{21}^2 and θ_{12} , comparing our results with the official ones from the collaboration. We have performed several analysis variants with different configurations for some of the variables discussed above. In this paper, we present the representative results of six of them, denoted as cnf 1 to cnf 6. We list in table 1 the different assumptions about the parameters changed in the fit.

The first two variants, cnf 1 and cnf 2, illustrate our choices to reproduce the official Δm_{21}^2 and θ_{12} determination. We show the results for these configurations in figure 2. For each configuration, we compare with the official JUNO results for the determination of Δm_{21}^2 and $\sin^2 \theta_{12}$ as well as for the predicted spectra at the best-fit parameters quoted in ref. [1]. For the spectra shown in the right panels, we show the predicted reactor spectrum without pull shifts and the reactor+background spectrum including the pull shifts. In all cases, we have performed the analysis both by fixing $\Delta m_{3\ell}^2$ and by marginalizing over it, and we have

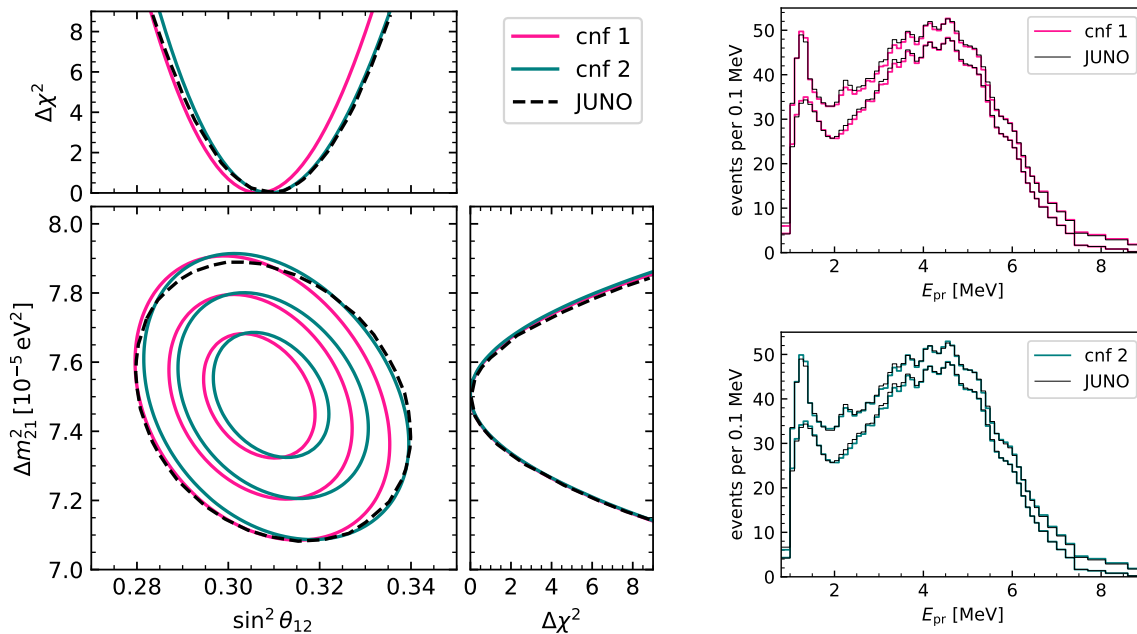


Figure 2. Left: determination of Δm_{21}^2 and $\sin^2\theta_{12}$ for the two configurations cnf 1 and cnf 2, compared to the JUNO results (black dashed line). Contours are for 1σ , 2σ , and 3σ (2 dof). Right: best-fit reactor neutrino spectra without pull shifts (lower histograms) and reactor neutrino+background spectra with pull shifts (higher histograms) for cnf 1 (upper) and cnf 2 (lower).

verified that the $(\Delta m_{21}^2, \sin^2\theta_{12})$ regions are unchanged within the precision of the plot, in agreement with ref. [1] (see also a corresponding discussion in ref. [27]).

The first configuration, cnf 1, corresponds to all pull uncertainties at their nominal values and no additional rescaling factors (after rescaling bin-by-bin the un-oscillated spectrum). Following the JUNO collaboration, we also adopt the CNP definition of χ^2 . From figure 2, we see that the allowed regions in $(\Delta m_{21}^2, \sin^2\theta_{12})$ are close to the ones of JUNO with a slightly smaller $\sin^2\theta_{12}$. In order to compensate for this, we have increased all backgrounds except for geoneutrinos by 15%. After additionally changing the χ^2 definition from CNP to Poisson, this corresponds to the configuration cnf 2. We see that, with this minor adjustment, cnf 2 provides an excellent reproduction of the official JUNO results. This background rescaling is well within their 1σ uncertainties, and it also leads to a slightly better reproduction of the best-fit JUNO spectrum shown in the right panels of figure 2, providing additional justification for increasing them. We adopt cnf 2 as our default configuration for further explorations. We notice in passing that all versions give a somewhat low χ^2 minimum (see table 1), yet compatible with statistical fluctuations. For example, $\chi^2 = 49.2$ for 63 dof corresponds to a goodness-of-fit of 89.8%.

We include these results in the global NuFIT 6.1 analysis [4, 13] by adding the corresponding $\chi_{\text{JUNO, cnf 2}}^2(\Delta m_{21}^2, \theta_{12}, \theta_{13})$ marginalized over $\Delta m_{3\ell}^2$. This way, no information on $\Delta m_{3\ell}^2$ is included in the combination, so that the global result is only based on information published by the JUNO collaboration (including the systematic uncertainties relevant for the analysis). We refer the reader to ref. [13] for the full set of figures and oscillation parameter

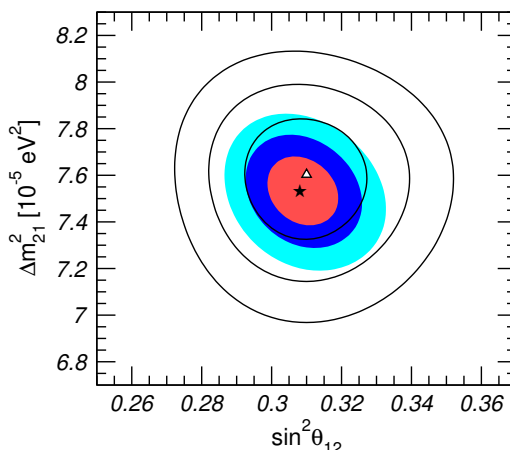


Figure 3. Impact of first JUNO data on the global determination of Δm_{21}^2 and $\sin^2 \theta_{12}$. We show the 1σ , 2σ , and 3σ allowed regions (2 dof) without (black) and with (colored) JUNO data.

values for this global analysis update, that also includes the latest results from SNO+ [28] and IceCube [29]. To highlight the impact of first JUNO results on Δm_{21}^2 and $\sin^2 \theta_{12}$, we show in figure 3 the allowed regions on these parameters without and with JUNO data. As the figure shows, JUNO already dominates the global analysis. Numerically, we find the following allowed parameter values within 1σ

$$\begin{aligned} \sin^2 \theta_{12} &= 0.3096^{+0.0057}_{-0.0073}, & \theta_{12} &= 33.81^{+0.35}_{-0.46}, \\ \Delta m_{21}^2 &= (7.530^{+0.096}_{-0.097}) \times 10^{-5} \text{ eV}^2, \end{aligned} \tag{3.1}$$

in good agreement with the global combination in ref. [27].

4 Sensitivity to $|\Delta m_{3\ell}^2|$ and the mass ordering

We now delve into the information on $\Delta m_{3\ell}^2$ from the JUNO analysis that we have so far marginalized over. We stress again that this goes beyond the analyses published by the JUNO collaboration, and has therefore an exploratory nature. The following results need to be corroborated by official analyses including relevant systematics and increased statistics.

The sensitivity to $\Delta m_{3\ell}^2$ emerges from “fast” oscillations with an amplitude controlled by $\sin^2 2\theta_{13}$, see the second line in eq. (2.2). These small oscillation features are clearly visible in the predicted spectra, for instance in figures 1 and 2. In the left panel of figure 4, we show the one-dimensional projection $\Delta\chi_{\text{JUNO}}^2(\Delta m_{3\ell}^2)$ after marginalizing over Δm_{21}^2 and θ_{12} for configurations cnf 1 and 2. We have verified that marginalizing over Δm_{21}^2 and θ_{12} or fixing them to their best-fit values gives identical results for the $\Delta m_{3\ell}^2$ determination. In other words, correlations between the ‘12’ parameters and $\Delta m_{3\ell}^2$ in the current JUNO analysis are negligible. As mentioned above, we impose the global determination of θ_{13} , $\sin^2 \theta_{13} = 0.022 \pm 0.00056$, as an external constraint on the fit. The profiles shown in figure 4 indicate several preferred values of $\Delta m_{3\ell}^2$, suggesting the presence of an oscillatory feature in the data with a χ^2 difference of $4 \lesssim \Delta\chi^2 \lesssim 8$ among different assumed phases for the oscillation.

For JUNO alone, the χ^2 difference between the best fits for NO and IO is negligibly small, $|\Delta\chi_{\text{IO-NO}}^2| < 10^{-3}$ for all configurations. We therefore conclude that the current

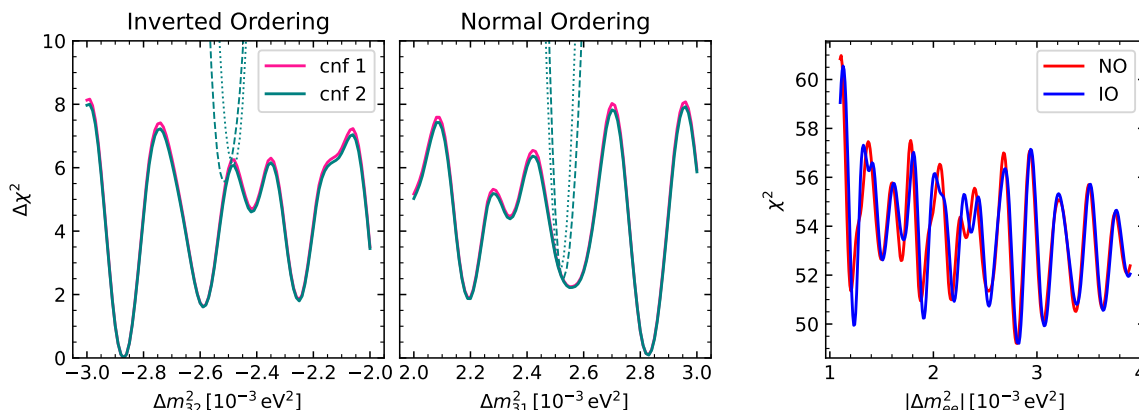


Figure 4. Dependence of χ_{JUNO}^2 on $\Delta m_{3\ell}^2$ for cnf 1 and 2 (two left panels) and on Δm_{ee}^2 with an extended range for cnf 2 (right panel). In the left panels, dashed and dotted curves correspond to $\Delta\chi_{\text{JUNO}}^2$ (cnf 2) combined with the determination of $|\Delta m_{3\ell}^2|$ from NuFIT-6.1 global data without and with SK-ATM, respectively.

dataset shows no sensitivity to the MO on its own. The JUNO-only best fits for the two orderings correspond to

$$\Delta m_{31}^2 = 2.83 \times 10^{-3} \text{ eV}^2, \quad \Delta m_{32}^2 = -2.87 \times 10^{-3} \text{ eV}^2. \quad (4.1)$$

In the right panel of figure 4, we show for cnf 2 an extended range in $|\Delta m_{3\ell}^2|$, plotted in terms of the effective squared-mass difference relevant for $\bar{\nu}_e$ disappearance in reactors, $\Delta m_{ee}^2 \equiv c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$ [8]. The best-fit points for both orderings correspond to the same value of $|\Delta m_{ee}^2| \approx 2.8 \times 10^{-3} \text{ eV}^2$ within good accuracy. However, as the figure shows, there are multiple minima with $\Delta\chi^2 \lesssim 2$, and therefore the particular location of the best-fit point is of no significance.

However, global oscillation data constrain $|\Delta m_{3\ell}^2|$ with percent-level precision. The NuFIT-6.1 results are (in units of 10^{-3} eV^2)

$$\begin{aligned} \Delta m_{31}^2 &= 2.521_{-0.018}^{+0.026}, & \Delta m_{32}^2 &= -2.510_{-0.023}^{+0.024} & (\text{NuFIT-6.1 w/o SK-ATM}), \\ \Delta m_{31}^2 &= 2.511_{-0.020}^{+0.021}, & \Delta m_{32}^2 &= -2.484 \pm 0.020 & (\text{NuFIT-6.1 with SK-ATM}), \end{aligned} \quad (4.2)$$

where we provide results for both mass orderings and for two variants of the global analysis, with and without the Super-Kamiokande and IceCube-24 atmospheric neutrino χ^2 tables added to the global analysis (here labeled “w/o SK-ATM” and “with SK-ATM” for simplicity), see refs. [4, 13] for details. We include this information into the JUNO analysis by adding an external prior to χ_{JUNO}^2 given by two-sided parabolas as a function of $\Delta m_{3\ell}^2$ with their minimum set to zero for both orderings. In this way, we isolate the MO discrimination power due to the combination of JUNO data and external information on $|\Delta m_{3\ell}^2|$.

The results are shown as dashed and dotted curves in the left panels of figure 4 for cnf 2 (for cnf 1, the results are very similar). We see that the agreement of JUNO with the remaining global data is somewhat better for NO, implying a preference for NO over IO. Assuming cnf 2, we find $\Delta\chi_{\text{IO-NO}}^2 = 3.05 (3.28)$ for NuFIT without (with) SK-ATM,

with similar results also for cnf 1 as seen in table 1. We quantify this result in terms of a hypothesis test and p -values in the next subsection.

The sensitivity of the dataset can be determined by the quantity T_0 [30], obtained from the Asimov datasets assuming the corresponding NuFIT-6.1 best fit values of $\Delta m_{3\ell}^2$ as “true values”. For both cnf 1 and 2 we find $|T_0| \approx 1.4$ (1.7) without (with) SK-ATM (see table 1 for detailed numbers). As discussed in ref. [30], $|T_0|$ and $\sqrt{|T_0|}$ roughly correspond to the expected value of $|\Delta\chi_{\text{IO-NO}}^2|$ and to the median MO sensitivity in units of standard deviations, respectively. This naively suggests that JUNO data might be slightly more sensitive than expected. We quantify this in the next subsection. For JUNO data alone (without the external constraint on $|\Delta m_{3\ell}^2|$) the Asimov sensitivity to the MO is negligible, $|T_0| \lesssim 10^{-3}$, hence current data on its own shows no sensitivity to the MO.

4.1 Monte Carlo simulation of MO result

From the above results on the T_0 values, we expect a relatively small — but non-negligible — sensitivity to the MO from this data combination. In this subsection, we investigate by Monte Carlo simulation the stability of the obtained preference for NO with respect to statistical fluctuations, and perform a MO hypothesis test to evaluate the p -value of IO. To this aim, we simulate a large set of randomly generated pseudo-data, and compare the result from true data to the expected distribution. For this study, we adopt configuration 2.

The procedure is as follows. First, we assume “true” oscillation parameters: $\sin^2 \theta_{12} = 0.31$, $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{13} = 0.022$, and one of the four cases for the $\Delta m_{3\ell}^2$ best fit points given in eq. (4.2). We calculate the reactor signal in JUNO for these parameters and add up the background prediction. Then, we generate random pseudo-data in each bin, Poisson-distributed around the total prediction. This pseudo-data set is analysed assuming both NO and IO. Since, as discussed above, correlations with $\sin^2 \theta_{12}$ and Δm_{21}^2 are negligible, we first minimize with respect to these parameters, then add the NuFIT-6.1 constraints on $|\Delta m_{3\ell}^2|$ as external prior as described above, and we finally minimize with respect to $|\Delta m_{3\ell}^2|$ to compute

$$\Delta\chi_{\text{IO-NO}}^2 \equiv \chi_{\min}^2(\text{IO}) - \chi_{\min}^2(\text{NO}). \tag{4.3}$$

This procedure is repeated 10^5 times and each $\Delta\chi_{\text{IO-NO}}^2$ value is stored in a histogram.

The corresponding distributions are shown in figure 5. The dashed curves in the figure show a Gaussian distribution with mean given by T_0 (see table 1) and standard deviation $2\sqrt{|T_0|}$, which is the expected distribution of $\Delta\chi_{\text{IO-NO}}^2$ [30, 31], indicating reasonable agreement. The p -value is obtained by comparing the observed value with the MC distribution, leading to p -values for IO — defined as the probability to obtain a value for $\Delta\chi_{\text{IO-NO}}^2$ equal to or larger than the observed one if IO were true — of 1.96% (2.57%) without (with) SK-ATM. When converted into Gaussian standard deviations, this corresponds to 2.3σ (2.2σ), somewhat higher than the naive $\sqrt{\Delta\chi_{\text{IO-NO}}^2} \approx 1.75\sigma$ (1.81σ) would suggest.

On top of that, as it is clear from the figure, the observed value of $\Delta\chi_{\text{IO-NO}}^2$ is not very unusual if the true ordering is normal: the green shaded regions in figure 5 indicate approximately the $\pm 1\sigma$ expected interval for $\Delta\chi_{\text{IO-NO}}^2$ assuming NO, and the observed value

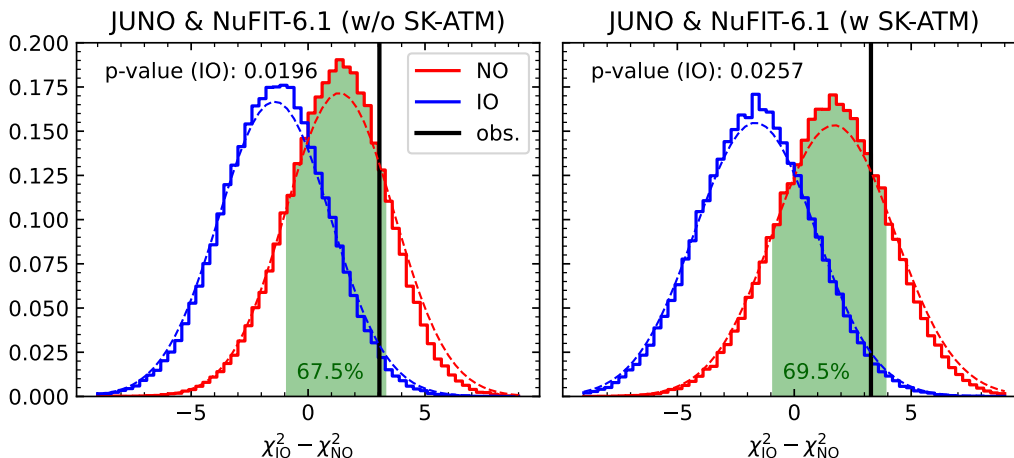


Figure 5. Monte Carlo simulation of the $\Delta\chi_{\text{IO-NO}}^2$ distribution for JUNO combined with the NuFIT-6.1 constraint on $|\Delta m_{3\ell}^2|$ without SK-ATM (left panel) and with SK-ATM (right panel). Black vertical lines indicate the values obtained by the observed data. The green shaded part in the left (right) panel contains 67.5% (69.5%) of the histogram for NO. Dashed curves show the Gaussian approximation based on the T_0 -value from the Asimov data set.

is inside it. Hence, although the observed value is larger than the mean (i.e., larger than T_0), such an upward fluctuation would not be very rare and is well within expectations.

We conclude this subsection with the following comment. Current JUNO data on its own — without external constraints on θ_{13} and $\Delta m_{3\ell}^2$ — cannot yet constrain these parameters with a precision comparable to the global oscillation data. However, once the external information is imposed, the percent-level precision from global data on these parameters (up to the MO ambiguity) leads to a very specific prediction for the oscillation pattern in JUNO, whose comparison with data provides already a non-negligible sensitivity to the MO. The Monte Carlo study presented here quantifies this, and shows how likely (or unlikely) it is that the better match for NO than for IO happens by pure chance.

4.2 Robustness of the mass ordering sensitivity

In order to study the robustness of the MO sensitivity that we find with our favoured configuration against possible unreported sources of systematic uncertainties, we have performed a series of fits in which some of the assumptions in cnf 2 are severely modified. While we do not necessarily suggest that these modifications are realistic, they serve as illustrative examples how the MO sensitivity could potentially be affected.

We summarize our findings with configurations cnf 3 to 6 listed in table 1. We focus on effects which are most likely to affect the determination of $\Delta m_{3\ell}^2$. In cnf 3 and 4 we study the impact of changes in the systematic uncertainties affecting the energy scale, while cnf 5 and 6 explore the impact of changes in the systematic uncertainties affecting the energy resolution. For each case, we verify how the changes modify the determination of the “12” parameters and the MO. The results are shown in figures 6 and 7.

The effect of a shift in the energy scale — which we have parametrized with the rescaling factor $r_{\text{n.l.}}$ — is illustrated with cnf 3, which is identical to cnf 2 except for an energy scale

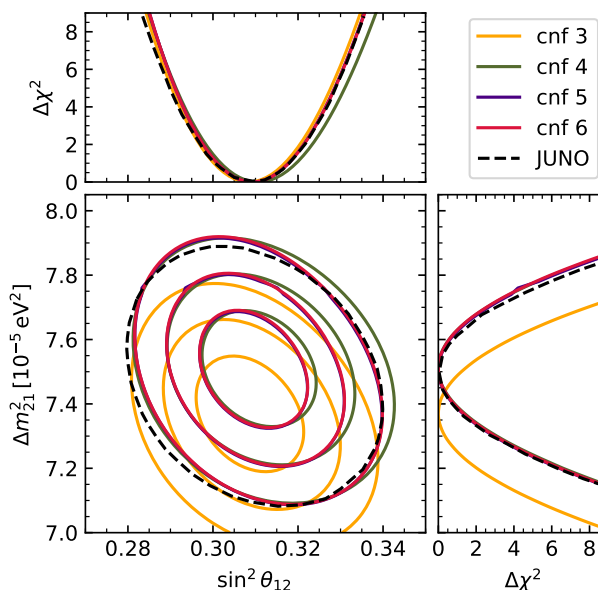


Figure 6. Determination of Δm_{21}^2 and $\sin^2 \theta_{12}$ for cnf 3–6 (see table 1) as labeled in the figure compared to the JUNO results (black dashed line). Regions are shown for 1σ , 2σ , 3σ (2 dof). Results for cnf 5 and cnf 6 are nearly identical and curves overlap.

shift by +2.4% (i.e., $r_{n.l.} = 1.024$). We see in the upper panels in figure 7 that this has a relatively strong impact on $\Delta\chi_{\text{IO-NO}}^2$ (see also table 1). Note that this modification does not affect the sensitivity to the $\Delta m_{3\ell}^2$ -induced oscillations itself (contrary to the modifications discussed in the following for cnf 4,5,6); its impact emerges from a relative shift of the JUNO and external constraints on $|\Delta m_{3\ell}^2|$, which may or may not lead to a reduced value of $\Delta\chi_{\text{IO-NO}}^2$. However, both squared-mass splittings Δm_{21}^2 and $\Delta m_{3\ell}^2$ are affected in the same way by such an energy rescaling, as can be seen in the corresponding regions in figure 6. Furthermore, the predicted spectrum no longer matches the official one provided by the JUNO collaboration, as seen in the upper right panel in figure 7. We conclude that this type of “systematic shift” has a potentially strong impact on the MO, but if we take the JUNO determination of Δm_{21}^2 as granted, such a shift is essentially eliminated. Quantitatively, the +2.4% shift chosen here for illustration leads roughly to a 1σ shift in Δm_{21}^2 . Hence, we would need a deviation of Δm_{21}^2 of order 1σ in order for this to have a sizeable impact.

To further illustrate this effect, in table 2 we show $\Delta\chi_{\text{IO-NO}}^2$ as a function of the energy-scale shift in steps of $\Delta r_{n.l.} = 0.5\%$. This step corresponds to one standard deviation of the energy scale uncertainty, i.e., cnf 3 is close to a $+5\sigma$ shift. We see that a 1σ shift of the energy scale has a relatively small impact, $\pm 2\sigma$ shifts can lead to a change in $\Delta\chi_{\text{IO-NO}}^2$ of around 1 unit (corresponding to a change of 30% in $\Delta\chi_{\text{IO-NO}}^2$), whereas shifts above 2σ may imply a more dramatic change. We note, however, that even in the $\pm 5\sigma$ range all $\Delta\chi_{\text{IO-NO}}^2$ remain positive (with one marginal exception), indicating that qualitatively the preference for NO is robust with respect to this type of systematic, especially taking into account that extensive calibration efforts of the JUNO collaboration strongly constrain the energy scale [25].

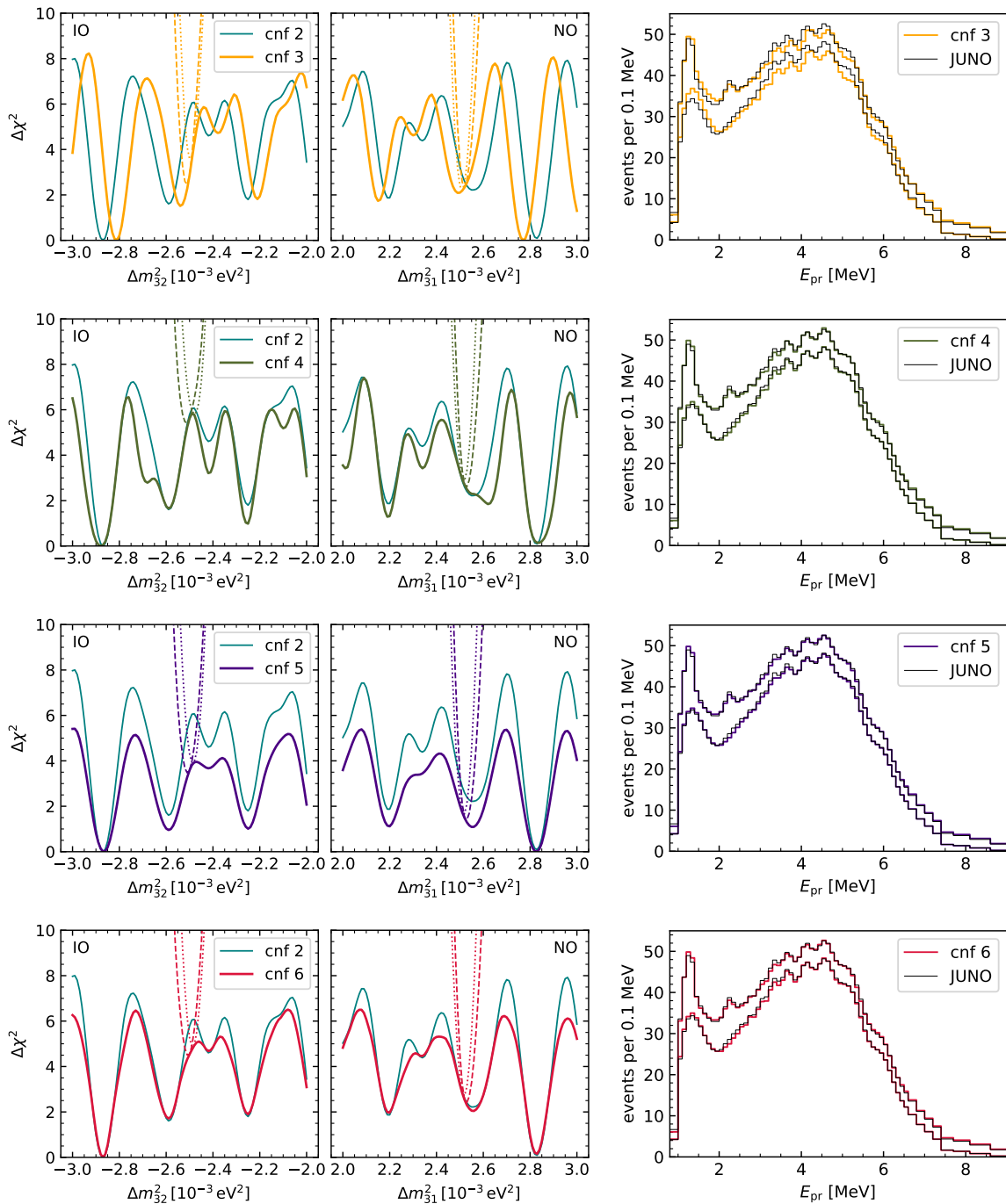


Figure 7. JUNO analysis variants cnf 3–6 (see table 1). Two left panels: dependence of $\Delta\chi^2_{\text{JUNO}}$ on $\Delta m^2_{3\ell}$ alone (solid) and in combination with NuFIT-6.1 (dashed w/o SK-ATM, dotted with SK-ATM). Right: best-fit reactor neutrino spectra without pull shifts (lower histograms) and reactor neutrino+background spectra with pull shifts (higher histograms), compared to the official spectra from the JUNO collaboration (black).

$r_{n.l.}$	0.975	0.980	0.985	0.990	0.995	1.000	1.005	1.010	1.015	1.020	1.025
$\#\sigma_{scl}$	-5σ	-4σ	-3σ	-2σ	-1σ	0	$+1\sigma$	$+2\sigma$	$+3\sigma$	$+4\sigma$	$+5\sigma$
$\Delta\chi^2$ (w/o SK-ATM)	1.01	1.79	2.49	3.03	3.20	3.05	2.61	2.05	1.47	0.83	0.26
$\Delta\chi^2$ (w SK-ATM)	-0.05	0.72	1.49	2.24	2.87	3.28	3.41	3.23	2.77	2.14	1.72

Table 2. $\Delta\chi_{\text{IO-NO}}^2$ as a function of the energy re-scaling factor $r_{n.l.}$ from combining the $|\Delta m_{3\ell}^2|$ information from JUNO with the one from NuFIT-6.1 without (third row) and with (fourth row) SK-ATM. The second row shows the size of the energy shift in units of the standard deviation of the energy scale uncertainty.

If, instead of a fixed energy-scale shift, we consider an increased energy-scale *uncertainty*, the corresponding pulls will affect the total spectrum (including the un-oscillated one). Therefore, its effects are limited by the measurement of the overall spectral shape. Configuration 4 corresponds to such a case, introducing a 10-times-increased energy scale uncertainty $\sigma_{\text{bias}} = 5\%$. Even with such a large energy scale uncertainty the solar parameters in figure 6 can be matched well. Although, as seen in the second row of figure 7, the $\Delta m_{3\ell}^2$ profile changes notably, the impact on the MO discrimination is small (see the three lower rows in table 1).

We next move to configurations 5 and 6, which both feature a worsened energy resolution. This partially washes out the fast oscillations and it therefore leads to a reduced significance of the oscillation pattern, as clearly visible in the χ^2 profiles in the two bottom rows of figure 7. Configuration 5 illustrates the effect of increasing the energy resolution by 30%, i.e., including a rescaling $r_{\text{res}} = 1.3$ in eq. (2.7). As seen in figure 6, the impact on the solar parameters and the spectra is minimal, but the sensitivity to $\Delta m_{3\ell}^2$ is clearly degraded as shown by the results in the third row in figure 7 and quantified in table 1. This is in accordance with the well-known result that energy resolution is crucial for this analysis.

Motivated by this, we finally investigate the impact of the *uncertainty* on the energy resolution, for which our default choice is $\sigma_{\text{res}} = 5\%$. We find that reducing this uncertainty by a factor of 10 has a very small impact, leading only to a negligible increase of $\Delta\chi_{\text{IO-NO}}^2$. Conversely, by increasing the uncertainty we find rather small impact as long as $\sigma_{\text{res}} \lesssim 20\%$. Configuration 6 corresponds to an extreme case where we have increased σ_{res} to 40%. As seen in figures 6 and 7, even in this case the impact on the “12” parameters and spectra is small, but $\Delta\chi_{\text{IO-NO}}^2$ is degraded.

We conclude from the results in this subsection that the systematics considered here may affect the MO discrimination. However, this is only the case if they are pushed to (potentially unrealistically) large values, which gives some confidence to the MO results. Nevertheless, we stress that our selection of possible systematics is certainly non-exhaustive. For instance, one may imagine a non-linear distortion of the energy scale affecting only part of spectrum. Another, even more critical issue could be the presence of unknown, percent-level bump-like features in the initial reactor anti-neutrino spectra [32]. This, however, will be addressed by dedicated future reactor flux measurements by JUNO-TAO [33], a near detector at ~ 30 m baseline where oscillations are negligible, which will provide a model-independent reference spectrum with sub-percent energy resolution.

5 Summary and implications for the global oscillation fit

In this paper, we have presented an exploratory study on the sensitivity of first data from the JUNO reactor experiment to the fast oscillations induced by the “atmospheric” squared-mass splitting $\Delta m_{3\ell}^2$. We have carefully tuned our re-analysis of JUNO spectral data to match as close as possible the published results, which focus on the leading “solar” parameters $\sin^2 \theta_{12}$ and Δm_{21}^2 . With this analysis at hand, we update the global determination of these parameters by adding JUNO to the remaining oscillation data, a combination released as NuFIT-6.1 [13]. This analysis relies only on results published by the JUNO collaboration and does not make use of any information on $\Delta m_{3\ell}^2$ from JUNO.

Departing from that simulation, in the present paper we however go beyond the results published by the JUNO collaboration, and study the possible sensitivity to $\Delta m_{3\ell}^2$. Our findings indicate the presence of fast oscillations, favouring certain values of $\Delta m_{3\ell}^2$ over others with a significance between 2σ and 3σ . While JUNO data on its own has negligible sensitivity to the neutrino MO, in combination with the independent determination of $|\Delta m_{3\ell}^2|$ from world oscillation data we find that the global value for NO is in somewhat better agreement with JUNO than for IO, with $\Delta\chi_{\text{IO-NO}}^2 \approx 3$.

We have evaluated the statistical significance of this result by means of a Monte Carlo simulation, finding that the p -value for IO is around 2% to 2.5%, depending on the used external data. Hence, we obtain a $\sim 2\sigma$ preference of NO over IO. While the obtained result corresponds to a slight upward fluctuation compared to the median sensitivity, the obtained value for $\Delta\chi_{\text{IO-NO}}^2$ is within the 68% expected interval for NO and hence well within the statistically expected range.

These results emerge purely from combining the information on $|\Delta m_{3\ell}^2|$ from JUNO with the remaining oscillation data, and do not take into account the information on the MO already available in the global data without the JUNO contribution, which are $\Delta\chi_{\text{IO-NO}}^2 = 1.49$ (5.91) without (with) SK-ATM [13]. If we include this information now in the combined analysis of JUNO and remaining world oscillation data, we find an overall preference for NO with

$$\begin{aligned} \Delta\chi_{\text{IO-NO}}^2 &= 4.62 && \text{(JUNO \& NuFIT-6.1 w/o SK-ATM),} \\ \Delta\chi_{\text{IO-NO}}^2 &= 9.41 && \text{(JUNO \& NuFIT-6.1 with SK-ATM),} \end{aligned} \tag{5.1}$$

where the two values correspond to either including or not including the external χ^2 tables from Super-Kamiokande and IceCube-24 atmospheric neutrino data.

Apart from this effect on the MO and the dramatic impact of JUNO data on the “12” parameters discussed in section 3, the impact on all other oscillation parameters is very small. In particular, for $\Delta m_{3\ell}^2$ we find the following changes of the global fit results when including the information from JUNO on this parameter (in units of 10^{-3} eV^2):

$$\begin{aligned} 2.521_{-0.018}^{+0.026} &\rightarrow 2.529_{-0.021}^{+0.021}, & -2.500_{-0.023}^{+0.024} &\rightarrow -2.515_{-0.025}^{+0.031} && \text{(w/o SK-ATM),} \\ 2.511_{-0.020}^{+0.021} &\rightarrow 2.519_{-0.020}^{+0.017}, & -2.483_{-0.020}^{+0.020} &\rightarrow -2.484_{-0.026}^{+0.026} && \text{(with SK-ATM).} \end{aligned} \tag{5.2}$$

We emphasize that the JUNO results concerning the MO need to be considered preliminary. They will have to be confirmed by dedicated studies within the collaboration, including precise assessment and publication of the relevant systematic uncertainties. Because of this,

we have discussed a number of possible systematic uncertainties and quantified their potential impact on the $|\Delta m_{3\ell}^2|$ determination.

In conclusion, the results shown here demonstrate the power of the JUNO experimental setup, providing some intriguing sensitivity already with its first 59.1 days of data. These results make us look forward to future data releases from this experiment.

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A Implementation of reactor neutrino fluxes

In this appendix we give a detailed description of our implementation of the reactor neutrino fluxes, based on the reconstructed spectra provided by the Daya Bay collaboration. We base our implementation on the information available in the supplemental material of ref. [34], which updates and supersedes the results presented in ref. [35] while following the same approach and conventions. The explicit construction of the reactor fluxes can be divided into three steps.

First of all, in principle one should adapt the Daya-Bay flux measurements — which were collected with average fission fractions $\bar{F}(^{235}\text{U}) : \bar{F}(^{238}\text{U}) : \bar{F}(^{239}\text{Pu}) : \bar{F}(^{241}\text{Pu}) = 0.564 : 0.076 : 0.304 : 0.056$ — to the specific isotopic composition of the JUNO run. However, lacking the detailed information on such composition, we simply assume it to be the same as the Daya-Bay average, so that no isotope correction is required and we can just extract the flux information from the «total» part of the ancillary files of ref. [34]. Concretely, the total $\bar{\nu}_e$ energy spectra weighted by IBD cross section Φ_i^0 (with $i = 1 \dots 25$) is provided in the form of 25 energy-averaged bins (24 uniformly spaced between 1.8 and 7.8 MeV, plus a larger one from 7.8 to 9.5 MeV) together with the corresponding 25×25 covariance matrix C_{ij} (which we extract from the complete 75×75 one given in the supplemental material, by discarding the 50 lines and columns relative to the individual ^{235}U and ^{239}Pu isotopes). Thus Φ_i^0 and C_{ij} encode our knowledge of the reactor flux and its uncertainties.

The second step consists in recasting the covariance matrix to the pull formalism, so that it can be smoothly implemented into our codes on the same footing as all the other systematic uncertainties. To this aim, we recall that C_{ij} is a real symmetric positive-definite matrix, hence it can be decomposed as $C_{ij} = \sum_k O_{ik} O_{jk} D_k^2$ where D_k^2 are its positive eigenvalues and

O_{ik} is a real orthogonal matrix. Defining $\Psi_{ik} \equiv O_{ik} D_k$ we can introduce the pull-dependent $\bar{\nu}_e$ energy spectra $\Phi_i(\vec{\xi}_{\text{flux}}) = \Phi_i^0 + \sum_k \Psi_{ik} \xi_{\text{flux}}^k$, where ξ_{flux}^k (for $k = 1 \dots 25$) are univariate zero-centered uncorrelated pulls. Obviously $\Phi_i(0) = \Phi_i^0$, while the induced covariance matrix is precisely $C_{ij} = \sum_k \Psi_{ik} \Psi_{jk}$ as required.

The final step involves converting the bin-averaged IBD-weighted $\bar{\nu}_e$ spectra $\Phi_i(\vec{\xi}_{\text{flux}})$ into a continuous flux shape $\phi(E_\nu, \vec{\xi}_{\text{flux}}) = \phi^0(E_\nu) + \sum_k \psi_k(E_\nu) \xi_{\text{flux}}^k$ which can be inserted into eq. (2.1) and properly integrated. To achieve this, we resort to cubic interpolation. Concretely, we begin by writing:

$$\phi^0(E_\nu) \equiv \phi_{\text{huber}}(E_\nu) \sum_n y_n^0 \delta_n(E_\nu), \quad \psi_k(E_\nu) \equiv \phi_{\text{huber}}(E_\nu) \sum_n y_{nk} \delta_n(E_\nu) \quad (\text{A.1})$$

where $\delta_n(E_\nu)$ (for $n = 1 \dots 25$) are piecewise cubic polynomials used in the interpolation procedure, and $\phi_{\text{huber}}(E_\nu)$ denotes the total reactor neutrino flux as predicted in ref. [36] (calculated assuming the Daya-Bay fission fractions quoted above). Here $\phi_{\text{huber}}(E_\nu)$ is introduced solely for the purpose of normalization, to ensure that all the y_n^0 and y_{nk} coefficient (to be determined later) are of order 1. Let us now recall the definition of Φ_i^0 (and, by extension, that of Ψ_{ik}):

$$\Phi_i^0 = \langle \phi^0 \sigma_{\text{IBD}} \rangle_i, \quad \Psi_{ik} = \langle \psi_k \sigma_{\text{IBD}} \rangle_i, \quad \langle f \rangle_i \equiv \frac{1}{E_{i+1} - E_i} \int_{E_i}^{E_{i+1}} f(E_\nu) dE_\nu \quad (\text{A.2})$$

where $\sigma_{\text{IBD}}(E_\nu)$ is the IBD cross-section. Substituting eq. (A.1) into these formulas, we obtain:

$$\Phi_i^0 = \sum_n M_{in} y_n^0, \quad \Psi_{ik} = \sum_n M_{in} y_{nk}, \quad M_{in} \equiv \langle \phi_{\text{huber}} \sigma_{\text{IBD}} \delta_n \rangle_i \quad (\text{A.3})$$

which can be immediately inverted, yielding:

$$y_n^0 \equiv \sum_i M_{ni}^{-1} \Phi_i^0, \quad y_{nk} \equiv \sum_i M_{ni}^{-1} \Psi_{ik}. \quad (\text{A.4})$$

Substituting these expressions into eq. (A.1) provides the required interpolation.

Data Availability Statement. This article has no associated data or the data will not be deposited.

Code Availability Statement. This article has no associated code or the code will not be deposited.

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