Study of the sensitivity to measure ν oscillation parameters with JUNO

TIPP

R. GUITTON, F. TOUCHTE-CODJO

University of Strasbourg, IPHC
Supervised by J. Pedro Athayde Marcondes de André

28/02/2024

Université de Strasbourg

Neutrino physics

There is much that we don't know about neutrino masses. But we do know that the masses are not zero.

Neutrino physics

History

1. Standard electroweak theory, first formulated by Weinberg in 1967
   - Neutrinos do not have mass: Occam's razor
2. One year later the solar neutrinos were observed by Davis *et al*
   - Deficit of their flux as compared with the prediction from the standard solar model, established by Bahcall *et al*
   - Anomaly attributed to the neutrino oscillation: *BSM*
   - No oscillation without neutrino masses and flavour mixing

Neutrino physics

In the standard three neutrino flavor scheme, neutrino oscillations imply that there exist three distinct neutrino mass eigenstates possessing definite neutrino masses, $m_i (i = 1, 2, 3)$, which are non-degenerate ($m_i \neq m_j$ for $i \neq j$).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e13} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 13} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 13} \end{pmatrix}}_{U_{MNPS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

with U_{MNPS} characterised by 3 mixing angles and 3 CP violation phases.

Neutrino physics

2 crucial parameters that remain poorly understood in neutrino physics:

1. CP violation phase
2. Neutrino Mass Ordering (NMO)

Mass ordering

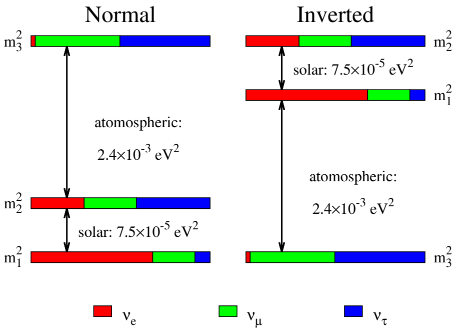


Figure 1: Illustration for the patterns of normal and inverted neutrino mass hierarchies.

The JUNO experiment

The JUNO experiment aims to precisely determine key neutrino properties, such as the CP violation phase and Neutrino Mass Ordering (NMO).

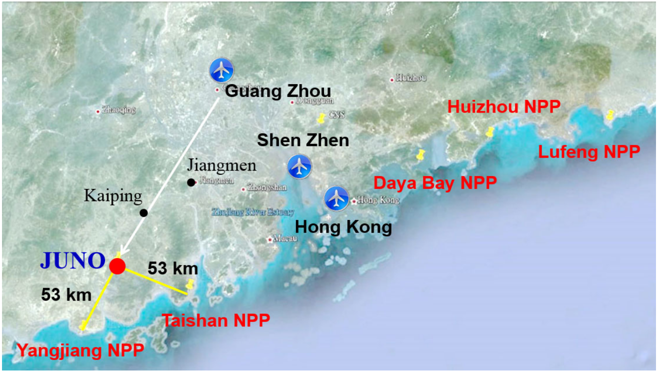


Figure 2: Location of the JUNO site

The JUNO experiment

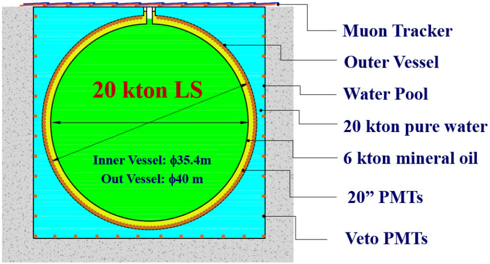


Figure 3: A schematic view of the JUNO detector

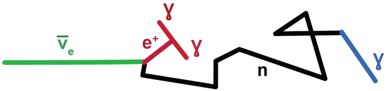


Figure 4: Inverse β decay process

Project steps

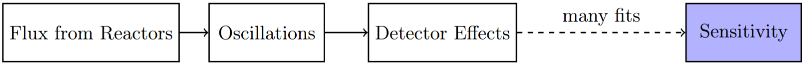


Figure 5: JUNO simulation

Reactor $\bar{\nu}_e$ flux

The reactor $\bar{\nu}$ spectrum car be represented by (P. Vogel, 1988) :

$$\frac{dN_{\bar{\nu}}}{dE_{\bar{\nu}}} = \text{Exp}(a_0 + a_1 E_{\bar{\nu}} + a_2 E_{\bar{\nu}}^2) \tag{2}$$

The reactor fuel of those power plant is composed by four main isotopes ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu. The total $\bar{\nu}$ from the reactor can be expressed as (L. Zhan,Y. Wang, J. Cao, L. Wen, 2008) :

$$\begin{aligned}\phi(E) = 0.58\,\text{Exp}(0.870 - 0.160E - 0.091E^2) \\ + 0.30\,\text{Exp}(0.896 - 0.239E - 0.0981E^2) \\ + 0.07\,\text{Exp}(0.976 - 0.162E - 0.0790E^2) \\ + 0.05\,\text{Exp}(0.793 - 0.080E - 0.1085E^2)\end{aligned} \tag{3}$$

Incoming flux

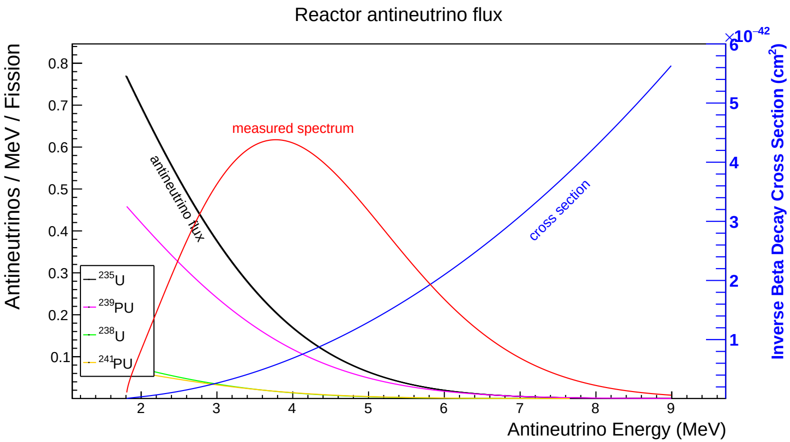


Figure 6: $\bar{\nu}$ reactor flux & cross section

Spectrum

The observed neutrino spectrum can be expressed as (JUNO Collaboration, 2022) :

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E) \quad (4)$$

where L is the distant between the reactor and detector, and $\sigma(E)$ is the inverse β decay ($\overline{\nu}_e + p \rightarrow e^+ + n$) cross section, which can be written using the positron energy

$$\sigma(E_e, p_e) = 0.095210^{-42} cm^2 (E_e p_e / 1MeV^2) \quad (5)$$

Spectrum

and $P_{ee}(E)$ is the survival probability of the $\overline{\nu}_e$:

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P21 &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P31 &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P32 &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned} \tag{6}$$

with $\Delta_{ij} = 1.27\Delta m_{ij}^2 L/E$ is the neutrinos mass-squared difference and θ_{ij} the mixing angle. The probability, and thus the spectrum depend of the mass hierarchy.

Mathematical expressions

Table 1: The best-fit values, together with the 1σ intervals, for the six three-flavor neutrino oscillation parameters from a global analysis of the experimental data JUNO Collaboration (2015).

Parameter	Best fit	1σ range
Normal neutrino mass ordering $(m_1 < m_2 < m_3)$		
$\Delta m^2_{21}/10^{-5}$ eV^2	7.54	7.32 — 7.80
$\Delta m^2_{31}/10^{-3}$ eV^2	2.47	2.41 — 2.53
$\sin^2\theta_{12}/10^{-1}$	3.08	2.91 — 3.25
$\sin^2\theta_{13}/10^{-2}$	2.34	2.15 — 2.54
$\sin^2\theta_{23}/10^{-1}$	4.37	4.14 — 4.70
$\delta/180^\circ$	1.39	1.12 — 1.77
Inverted neutrino mass ordering $(m_3 < m_1 < m_2)$		
$\Delta m^2_{21}/10^{-5}$ eV^2	7.54	7.32 — 7.80
$\Delta m^2_{13}/10^{-3}$ eV^2	2.42	2.36 — 2.48
$\sin^2\theta_{12}/10^{-1}$	3.08	2.91 — 3.25
$\sin^2\theta_{13}/10^{-2}$	2.40	2.18 — 2.59
$\sin^2\theta_{23}/10^{-1}$	4.55	4.24 — 5.94
$\delta/180^\circ$	1.31	0.98 — 1.60

$\overline{\nu}_e$ Spectrum

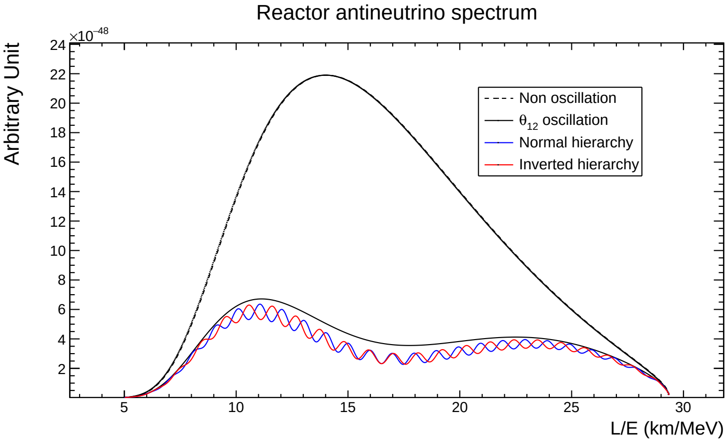


Figure 7: Antineutrinos spectrum as function of L/E (we took L=53km)

Spectrum

The expected visible energy spectrum observed at JUNO can be calculated as :

$$S(E_{vis}) = N_p \cdot \epsilon \cdot \int_{T_{DAQ}} dt \int_{1.8\ Mev}^{12\ MeV} dE_{\overline{\nu}_e} \cdot \phi(E_{\overline{\nu}_e}, t) \cdot \sigma(E_{\overline{\nu}_e}) \cdot R(E_{\overline{\nu}_e}, E_{vis}) \quad (7)$$

where

- $R(E_{\overline{\nu}_e}, E_{vis})$ is the detector energy response function that maps the antineutrino energy to the visible energy
- $\sigma(E_{\overline{\nu}_e})$ is the IBD cross-section
- $\phi(E_{\overline{\nu}_e}, t)$ is the oscillated reactor antineutrino flux in JUNO at time t
- T_{DAQ} is the total data taking time
- ϵ is the detection efficiency
- $N_p = 1,44 * 10^{33}$ is the number of free protons in the detector target

Detector response

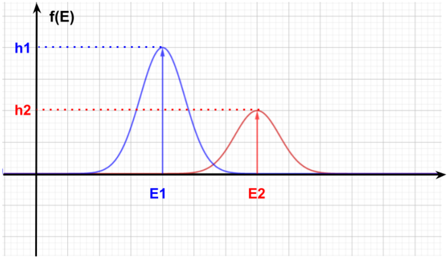
The visible energy and the $\overline{\nu}_e$ one are link by the relation : $E_{vis} = E_{\overline{\nu}_e} - 0.8$ MeV. Because the resolution of the detector energy is not perfect, the oscillations of the antineutrinos flux will be affected. Indeed, the visible energy resolution of the detector can be implemented by a Gaussian function with a standard deviation given by

$$\frac{\sigma_{E_{\text{vis}}}}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2} \tag{8}$$

where :

- a is related to the total number of detected photoelectrons
- b is related to the detector's spatial non-uniformity
- c is related to the PMT dark noise

$\overline{\nu}_e$ Spectrum

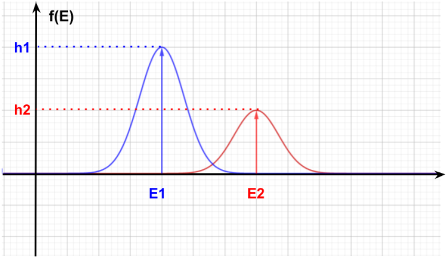


$$f(E) = h_1\delta(E - E_1) + h_2\delta(E - E_2)$$

$$f(E) \longrightarrow \tilde{f}(E) = h_1 g(E - E_1) + h_2 g(E - E_2)$$

$$g(E) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp(-\frac{E^2}{2\sigma^2})$$

$\overline{\nu}_e$ Spectrum



$$f(E) \longrightarrow \tilde{f}(E) = \sum_i f(E_i)g(E - E_i)$$

$$\tilde{f}(E) = \int_{E_{ref}} f(E_{ref})g(E - E_{ref})$$

$$\tilde{f} = f * g$$

$\overline{\nu}_e$ Spectrum

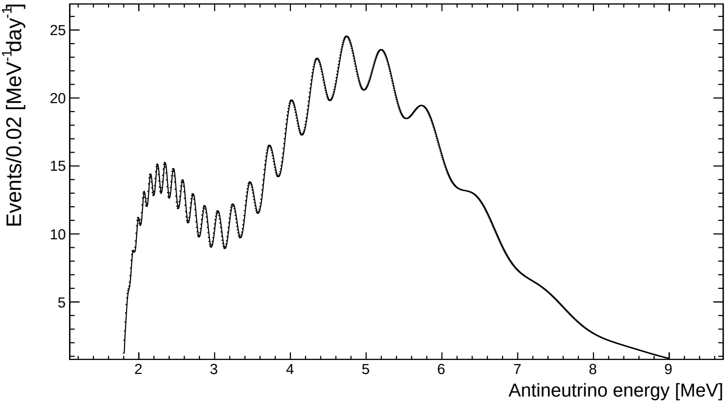


Figure 8: $\overline{\nu}_e$ spectrum per day before convolution (IH)

$\overline{\nu}_e$ Spectrum

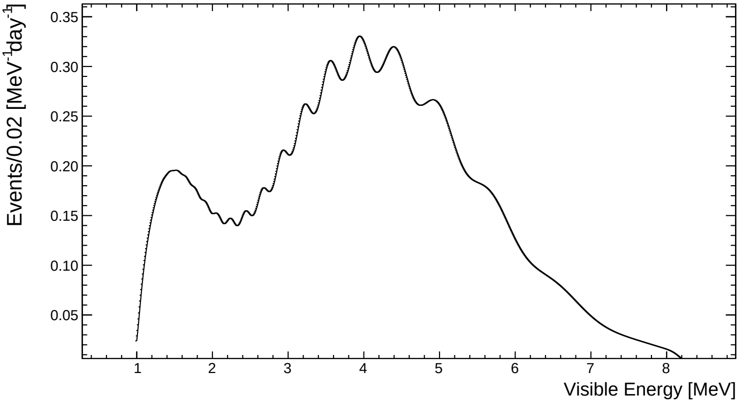


Figure 9: $\overline{\nu}_e$ spectrum per day after convolution (IH)

$\overline{\nu}_e$ Spectrum

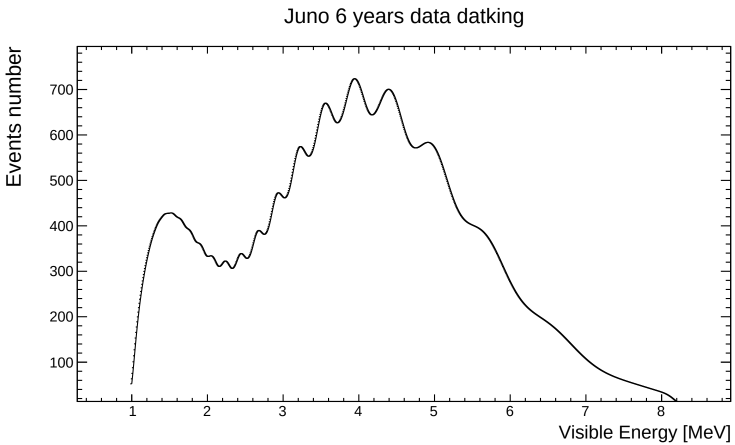


Figure 10: $\overline{\nu}_e$ spectrum for 6 years after convolution (IH)

Selection

The best-fit values, together with the 1σ intervals, for the six three-flavor neutrino oscillation parameters from a global analysis of the experimental data

<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th></tr>
<tr><td>-</td><td>-</td><td>86</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>78</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">76</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>63</td></tr>
<tr><td>Combined</td><td>73%</td><td>63</td></tr>
</table>

χ^2 analysis

To determine the sensitivity of the detector a chi-squared analysis can be perform using the Pearson model given by JUNO Collaboration (2022) :

$$\chi^2_{REA} = \sum_{i=1}^{N_{bin}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\epsilon_k]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2} \tag{9}$$

with :

- M_i the mesured events
- T_i the predicted ones
- σ_k the systematic uncertainty
- ϵ_l the pull parameter
- α_{ik} the fraction of event contribution.

In this project the systematic uncertainty has been ignored.

χ^2 analysis

The 1σ limits of each parameter are obtained by marginalizing over all others, and finding the values for which χ^2 changes by a unit.

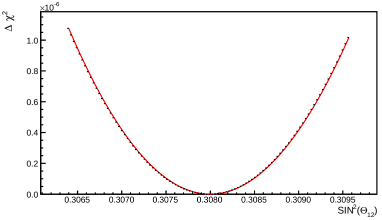


Figure 11: $\Delta\chi^2$ for $\sin^2(\theta_{12})$

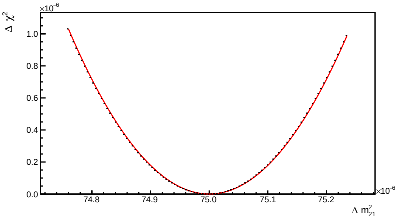


Figure 12: $\Delta\chi^2$ for Δm^2_{21})

Figure 13: $\Delta\chi^2$ for 6 years data taking

χ^2 analysis

	Central Value	PDG2020	6 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.0026 (12.1%)

Table 2: A summary of precision levels for the oscillation parameters. The current knowledge (PDG2020) is compared with the 6 years of JUNO data taking JUNO Collaboration (2015)

χ^2 analysis

We can assume inverted MH with the χ^2 method and take the difference of the minima as a measure of the MH sensitivity :

$$\Delta\chi^2_{MH} = |\chi^2_{min}(N) - \chi^2_{min}(I)| \tag{10}$$

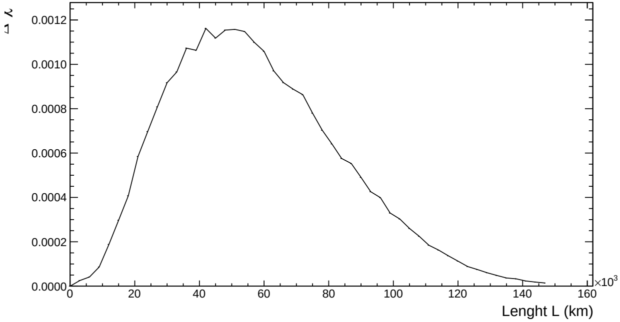


Figure 14: $\Delta\chi^2_{MH}$ a function of the distant L (reactor/detector) obtained for m_{31}

Conclusion

This project was a simple approach but represented a step by step modeling of the JUNO experiment.

- Reactor
- Propagation
- Detector
- Sensitivity

This project allowed us to become familiar with GitHub and Root. Others parameters than m_{31} can be tested to check the optimal distance.

References

JUNO Collaboration (18 Oct 2015). *Neutrino Physics with JUNO*. https://arxiv.org/abs/1507.05613v2.

JUNO Collaboration (28 Apr 2022). *Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO*. https://arxiv.org/abs/2204.13249.

L. Zhan,Y. Wang, J. Cao, L. Wen (26 Nov 2008). *Determination of the Neutrino Mass Hierarchy at an Intermediate Baseline*. https://arxiv.org/abs/0807.3203v2.

P. Vogel, J. E. (27 Dec 1988). *Neutrino electromagnetic form factor*. https://users.physics.unc.edu/~engelj/papers/ve.pdf.

Thanks!