Mass hierarchy and CP violation in T2K-II, NOνA-II and JUNO

Reference: S. Cao, A. Nath, T. V. Ngoc, Ng. K. Francis, N. T. Hong Van, **P. T. Quyen, PHYS. REV. D 103, 112010 (2021)**

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July 18, 2022

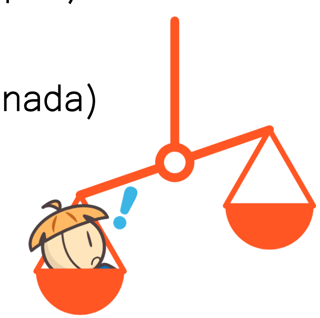
Neutrinos in the Standard Model

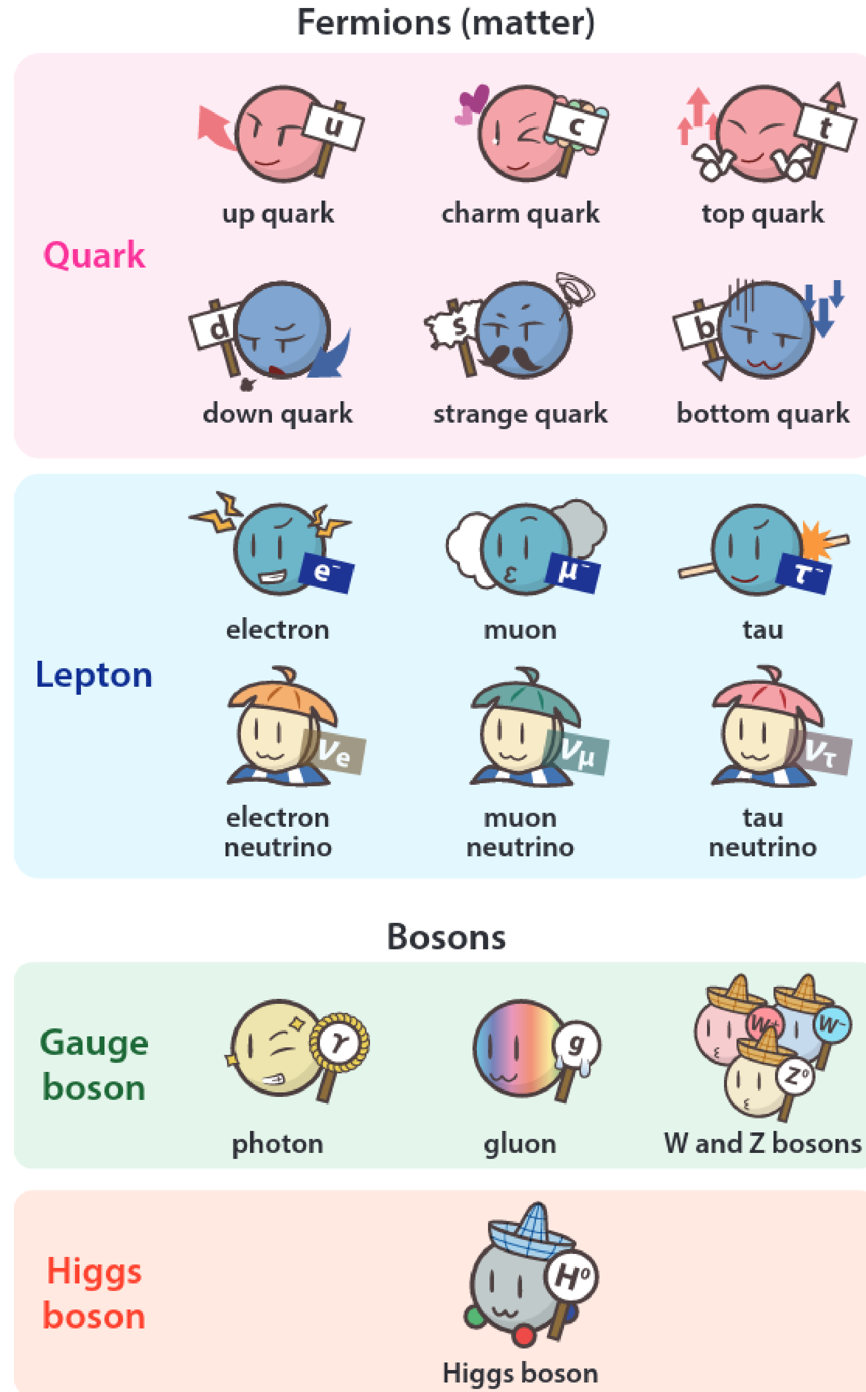
NEUTRINOS:

- very light (~10^{-6} electron mass)
- Spin = 1/2, electrically neutral leptons
- Most abundant fermions in the universe (~336 cosmic neutrinos/cc)
- Within the Standard model, neutrinos are massless.

*Super-Kamiokande[1] experiment (Japan)
led by Prof Takaki Kajita
*Sudbury Neutrino Observatory[2] (Canada)
led by Prof Arthur B McDonald

-- confirm neutrinos have mass by measuring **neutrino oscillations**.





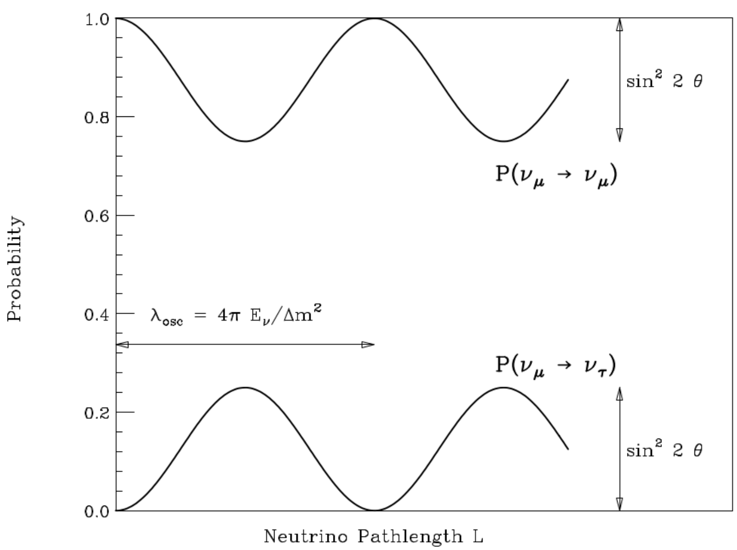
[1] Phys. Rev. Lett. 81, 1562 (1998)
[2] Phys. Rev. Lett. 89, 011301 (2002).

*Image courtesy: NEUTRINO MANGA

Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \textbf{where} \quad U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\text{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\text{CP}}} & c_{13}c_{23} \end{pmatrix}$$

Mass eigen states	Mass eigen values
ν_1	m_1
ν_2	m_2
ν_3	m_3



Neutrino Oscillation

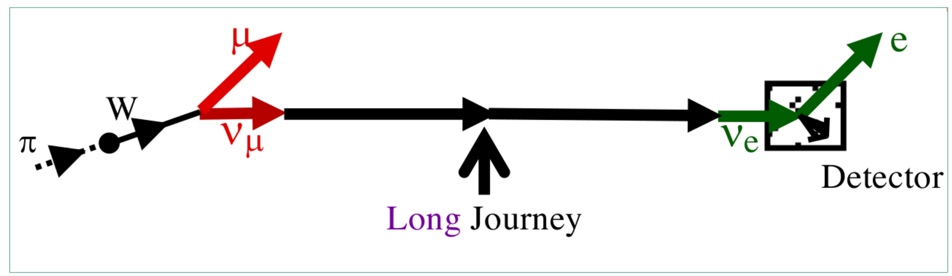


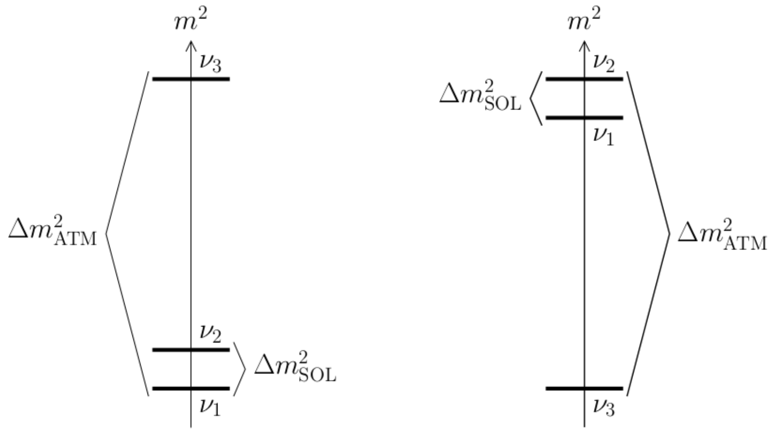
***Image: Boris Kayser's talk on neutrino phenomenology, VSoN 2018**

Oscillation Probability

Mass-squared differences

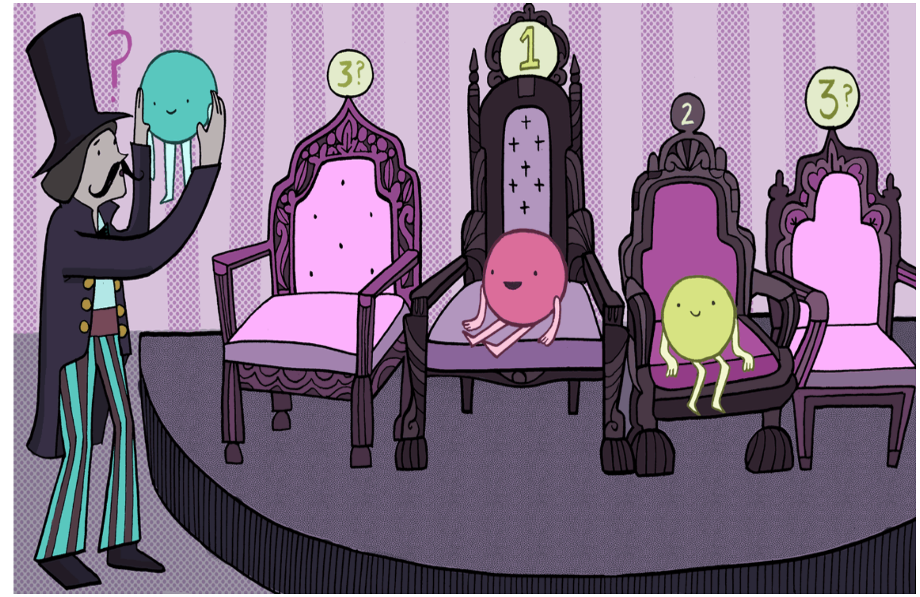
$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\ \exp\left(-i\frac{\boxed{\Delta m^2_{kj}}\,L}{2E}\right)$$

Mass Hierarchy (MH)



NORMAL HIERARCHY

INVERTED HIERARCHY



Is $m_1 < m_2 < m_3$ (normal) or $m_3 < m_1 < m_2$ (inverted) the truth?

i.e. What is the sign of **Δ**m^2_{31}?

Leptonic CP Violation

Are the oscillation probabilities $P_{\mu e} = \bar{P}_{\mu e}$?

We define CP Asymmetry in vacuum, as

$$A_{CP} = (P_{\mu e} - \bar{P}_{\mu e}) / (P_{\mu e} + \bar{P}_{\mu e})$$

$$A_{CP} = 16\, s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} s\,\delta\, s\,\Delta_{21}\, s\,\Delta_{31}\, s\,\Delta_{31}$$

Is $\boldsymbol{\delta}_{CP} \neq$ **nπ** where n=0,1,2?

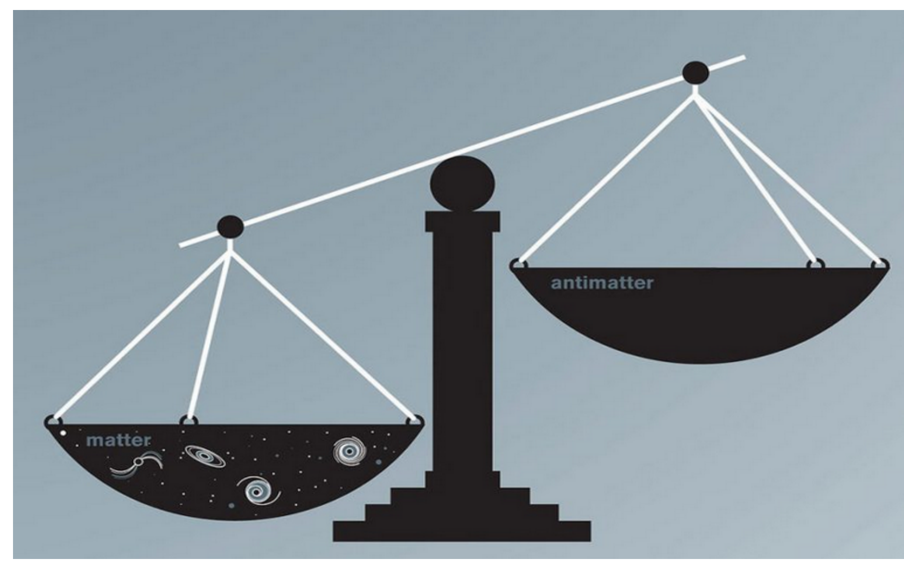


Image Courtesy: Symmetry Magazine

Oscillation probability at A-LBL

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \cdot \sin^2 \Delta_{21} \\
-8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2s_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

= CP-even terms = CP-odd term = due to matter effects

- In the leptonic mixing, CP symmetry is violated by the phase δ_{CP}.
- From the above expression, δ_{CP}=0 also produces CP asymmetry due to matter terms. It is because the matter effect produces a fake asymmetry *(as the Earth is composed of e^-, p^+ & n, not their anti-particle)*.
- It is, therefore, important to experimentally separate the effects of the Earth matter and natural CP-violation. This will allow to get information about the dirac CP violation phase in U_{PMNS}.

Phys.Rev.D 56 (1997) 3093-3099

Methodology

We simulate the statistical significance of --

- TWO accelerator-based Long Baseline (A-LBL) experiments,

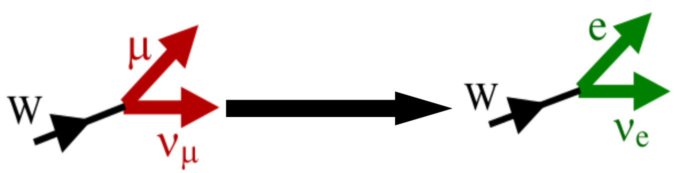
  1) T2K-II : the extended run of the ongoing Tokai-To-Kamioka experiment based in Japan.

  2) NOνA-II: the extended run of NuMI Off-Axis Neutrino Appearance Experiment, based in the USA.

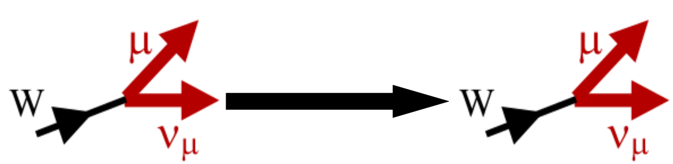
- ONE reactor-based Medium Baseline experiment (R-MBL),

  1) JUNO: Jiangmen Underground Neutrino Observatory, based in China.

Transition/Appearance Sample ($\nu_\mu \to \nu_e$):

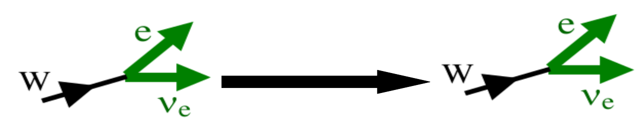


Survival/Disappearance Sample ($\nu_\mu \to \nu_\mu$):



T2K-II/NOνA-II

Survival/Disappearance Sample ($\bar{\nu}_e \to \bar{\nu}_e$):



JUNO

General Long Baseline Experiment Simulator (GLoBES)* is used for simulating the experiments, calculating the statistical significance.

* *10.1016/j.cpc.2007.05.004*

**See Talk by *Ngoc Tran, IFIRSE, Quy Nhon* for experiment specifications

Motivation

1) ν_μ ($\bar{\nu}_\mu$) disappearance provides a precise measurement of the atmospheric neutrino parameters, $\sin^2 2\theta_{23}$ and Δm^2_{31} ,

2) ν_e ($\bar{\nu}_e$) appearance rates are driven by $\sin^2 2\theta_{13}$ and are sensitive to δ_{CP} and the MH.

3) $\bar{\nu}_e$ disappearance is driven by both solar and atmospheric neutrino mass-squared splittings.

- The determination of MH and CPV in accelerator based long baseline neutrino experiments suffers due to the presence of degeneracies**[1]**.
  - CP degeneracy: (δ_{CP},θ_{13}) ambiguity
  - MH degeneracy: sgn(Δm^2_{31}) ambiguity
  - Octant degenracy: (θ_{23},$\pi/2$-θ_{23}) ambiguity
- This implies different sets of parameters giving equally good fit to the data.

Determination of MH and CPV depend on the ability to resolve the parameter degeneracies among δ_{CP}, the sign of Δm^2_{31}, θ_{13}, and θ_{23}.

- Combining the data samples of the experiments T2K-II, NoνA-II and JUNO would enhance the CPV search and the MH determination since the JUNO sensitivity to the MH has no ambiguity to δ_{CP}.
- To further enhance the CPV search, one can break the δ_{CP}-θ_{13} degeneracy by using the constraint of θ_{13} from reactor-based short-baseline neutrino experiments.

[1] Phys. Rev. D 65, 073023 (2002)

Mass Hierarchy determination

To estimate quantitatively the sensitivity of the experiment(s) to the MH determination,

- we calculate the statistical significance $\sqrt{\Delta\chi^2}$ to exclude the inverted MH given the null hypothesis is a normal MH.

$$\sigma = \sqrt{\Delta\chi^2} = \sqrt{\chi^2_{NH} - \chi^2_{IH}}$$

- The sensitivity is calculated as a function of true δ_{CP} since for the accelerator LBL experiments, the capability to determine the MH depends on the values of the CP-violating phase δ_{CP}.

The oscillation parameters are based on NuFit 4.1:

$\sin^2\theta_{12}$	=	0.310,
Δm^2_{21}	=	7.39×10^{-5} eV^2,
$\sin^2\theta_{23}$	=	0.5, 0.43 and 0.6,
$\lvert\Delta m^2_{31}\rvert$	=	2.523×10^{-3} eV^{2,}
$\sin^2\theta_{13}$	=	0.02241

Results (MH)

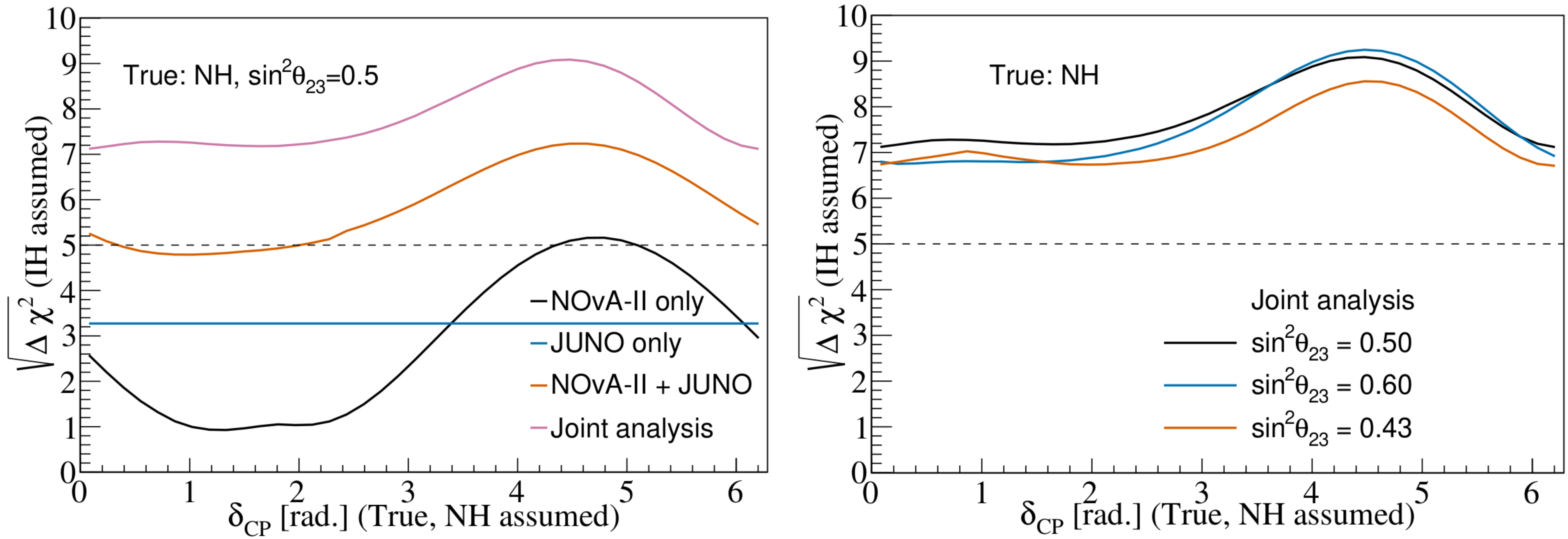


Figure 1: Mass hierarchy sensitivities as function of true $\boldsymbol{\delta}_{CP}$ for --

various experimental setups :

Left plot*

(i) JUNO only (at $\sin^2\theta_{23}$=0.5);

(ii) NOνA-II only (at $\sin^2\theta_{23}$=0.5);

(iii) a joint of JUNO and NOνA-II (at $\sin^2\theta_{23}$=0.5);

(iv) a joint of JUNO, NOνA-II, T2K-II and θ_{13} constraints from Reactor-Short Baseline (R-SBL) experiment (at $\sin^2\theta_{23}$=0.5);

Right plot*

A joint of JUNO, NOνA-II, T2K-II and θ_{13} constraints from R-SBL experiment (for different θ_{23}).

Results (MH)

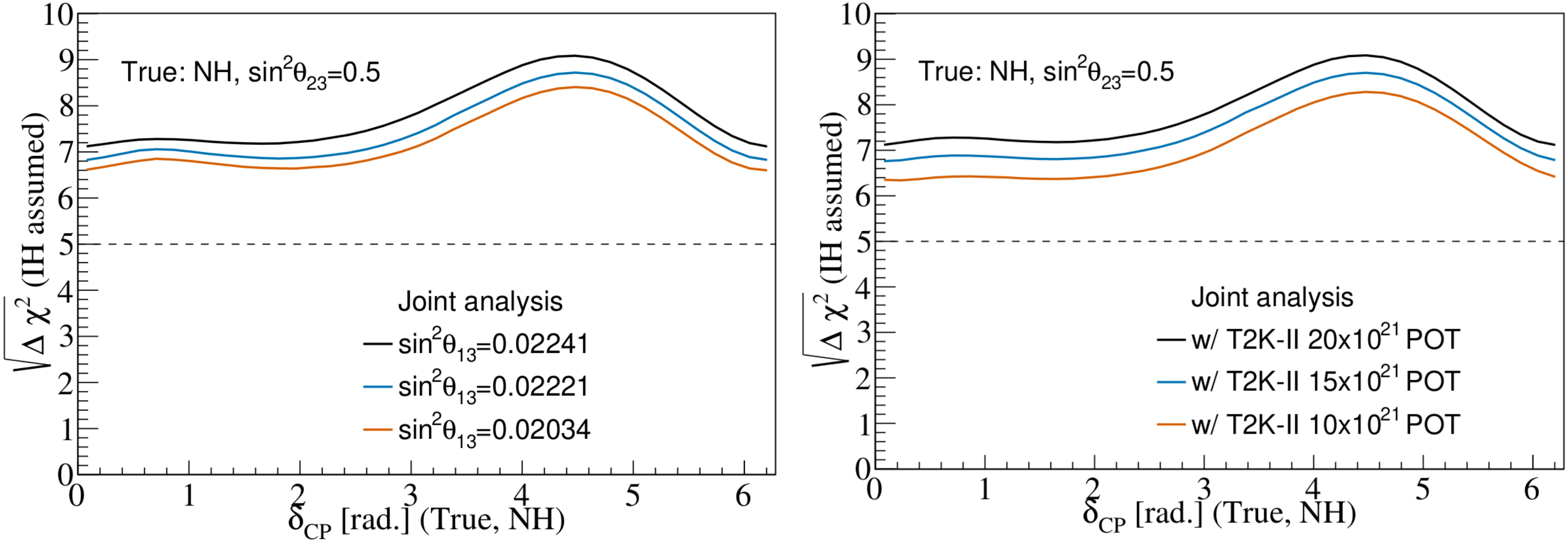


Figure 2. The effects of θ_{13} (left) and T2K-II runtime (right) on the sensitivity of neutrino mass hierarchy determination are studied. **$\sin^2\theta_{13}$= 0.02241** is the best fit obtained with NuFIT 4.1, $\sin^2\theta_{13}$= 0.02221 is with NuFIT 5.0. $\sin^2\theta_{13}$= 0.02034 is 3σ lower limit. The plots use a combined sensitivity of all considering experiments.

Discussion

MASS HIERARCHY:

1) A joint analysis of JUNO with the A-LBL experiments, NOνA-II and T2K-II, shows a great boost in the MH determination. This is expected since a joint analysis will break the parameter degeneracy between δ_{CP} and the sign of Δm^2_{31}.

2) The results conclude that the wrong mass hierarchy can be excluded at greater than 5σ C.L. for all the true values of δ_{CP} and for any value of θ_{23} in the range constrained by experiments.

3) We find out that in Ref. *Scientific Reports (Nature) volume 12, Article number: 5393 (2022)*, the authors address a similar objective and come to a quite similar quantitative conclusion.

Leptonic CP Violation

- The statistical significance $\sqrt{\Delta\chi^2}$ for excluding the CP-conserving values (δ_{CP}= -π, 0, +π).

$$\Delta\chi^2(\delta_{true}) \sim Min\Big(\chi^2_{\text{total}}(\delta_{true}) - \chi^2_{\text{total}}(\delta_{test} = 0, \pm\pi,)\Big)$$

- For the minimization of χ^2 over the Mass Hierarchy (MH) options, we consider two cases:
  - ➔ MH is known and normal as the truth value,
  - ➔ MH is unknown.

Results (CPV)

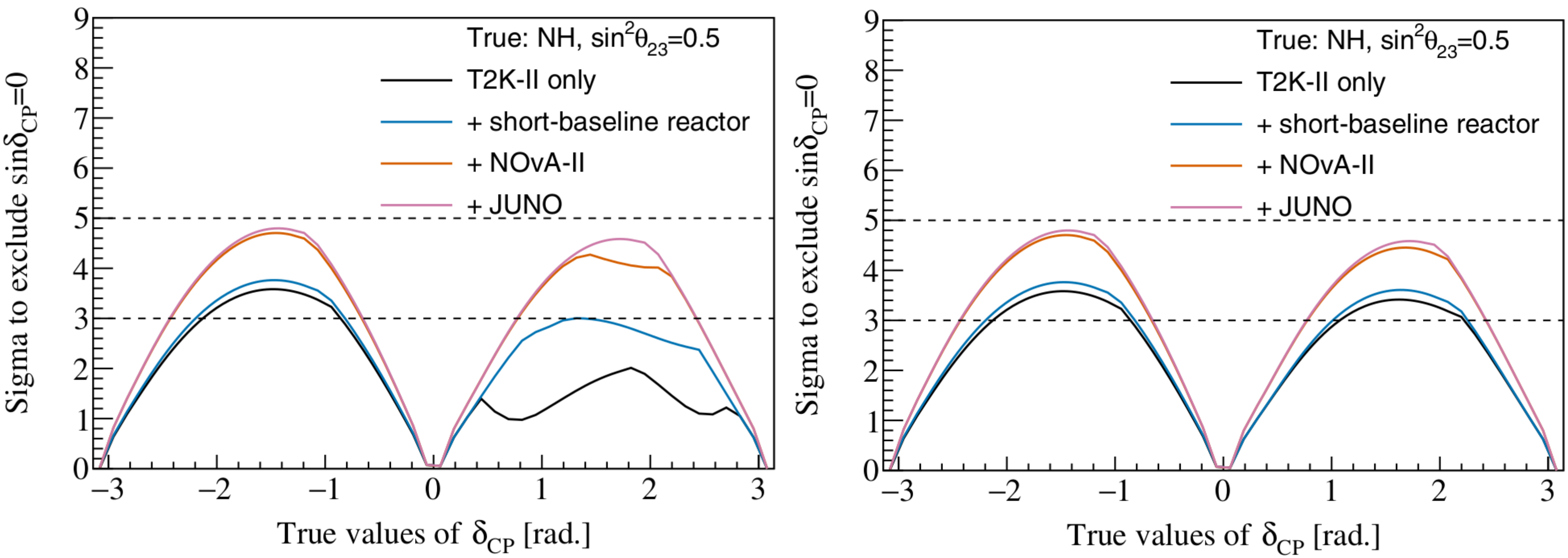


Figure 3: CP violation sensitivities as function of true $\boldsymbol{\delta}_{CP}$ for *various experimental setups* :

(i) T2K-II only (at $\sin^2\theta_{23}$=0.5);

(ii) a joint of T2K-II and NOνA-II (at $\sin^2\theta_{23}$=0.5);

(iii) a joint of JUNO, NOνA-II, T2K-II and θ_{13} constraints from Reactor-Short Baseline (R-SBL) experiment (at $\sin^2\theta_{23}$=0.5);

Left (Right) plot is with MH assumed to be unknown (known) in the analysis.

Results (CPV)

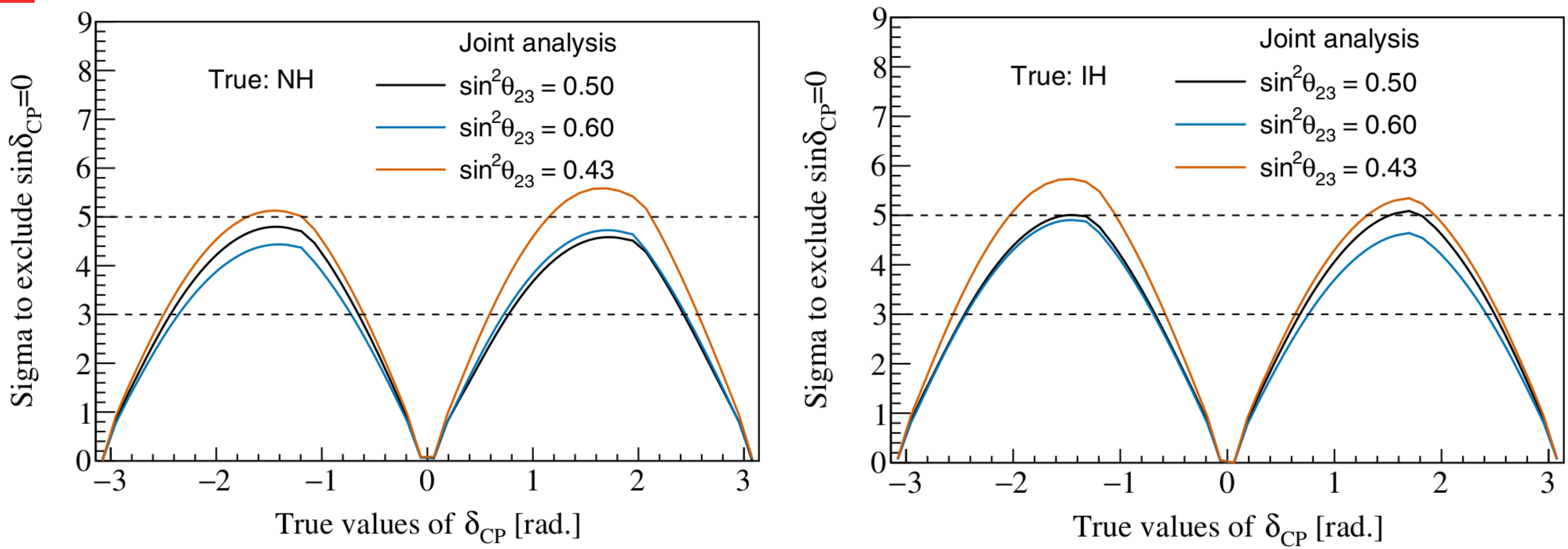


Figure 4: CPV sensitivity as a function of the true value of δ_{CP} obtained with a joint analysis of all considered experiments at different true $\sin^2\theta_{23}$ values (0.43, 0.5, 0.6). The left (right) plot is with the normal (inverted) MH as the truth value, respectively.

Table. Fractional region of δ_{CP}, depending on $\sin^2\theta_{23}$, can be explored with 3σ or higher significance.

Value of $\sin^2\theta_{23}$	**0.43**	**0.50**	**0.60**
Fraction of true δ_{CP} values (%), NH	61.6	54.6	53.3
Fraction of true δ_{CP} values (%), IH	61.7	57.2	54.2

Discussion

LEPTONIC CP VIOLATION:

1) The CPV sensitivity is shown as a function of the true value of δ_{CP} for both MH options obtained by different analyses:
   (i) T2K-II only;
   (ii) a joint T2K-II and R-SBL experiments;
   (iii) a joint of T2K-II, NOνA-II and R-SBL experiments; and
   (iv) a joint of T2K-II, NOνA-II, JUNO and reactor short-baseline (R-SBL) experiments.

The result shows that whether the MH is known or unknown affects on the first three analyses, but not the fourth. This is because the MH can be determined conclusively with a joint analysis of all considered experiments.

2) It can be seen that the sensitivity to CP violation is driven by T2K-II and NoνA-II. Contribution of the R-SBL neutrino experiment is significant only at the region where δ_{CP} is between 0 and π and when the MH is not determined conclusively.
3) At δ_{CP} close to +π/2 and -π/2, which is indicated by recent T2K data, the sensitivity of the joint analysis with all considered experiments can reach approximately the 5σ C.L..
4) Particularly, CP-conserving values of δ_{CP} can be excluded with at least a 3σ C.L. for 50% of all the possible true values of δ_{CP}.

Thank you for your attention.