Explore the sensitivity of neutrino mass ordering with the reactor-based medium-baseline JUNO experiment. How does it differ and compensate to the mesurement with the accelerator based long-baseline neutirno expperiments such as NOvA, T2K and future DUNE, Hyper-K.

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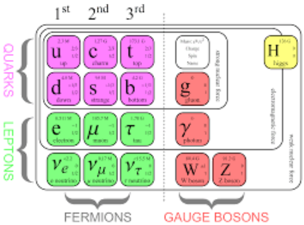
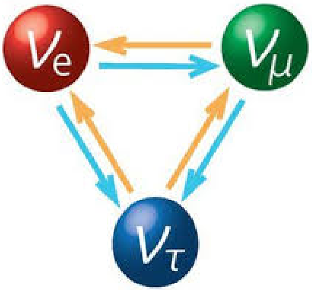
Introduction

- Neutrinos: Fundamental particles in the Standard Model.
- Neutrinos: Subatomic particles with very little mass, no electric charge. Three flavor: electron neutrino, muon neutrino, tau neutrino.
- Understanding neutrinos helps research more about the universe.



Neutrino Oscillation

- Neutrino oscillations are phenomena where a neutrino changes its flavor as it propagates.
- Three flavour neutrino oscillations depend on:
  Three mixing angles: θ_{12},θ_{13},θ_{23}.
  Two mass squared difference: Δm^2_{21}, Δm^2_{31}.
  One CP phase: δ_{cp}.
- Two Flavour neutrino oscillation formula:
  P$(\nu_i \to \nu_j) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



Current Picture of Standard Oscillation Parameters

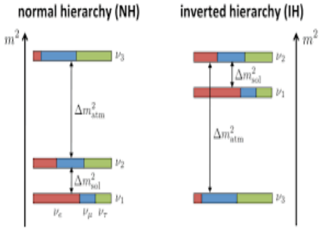
- Precisely known parameters:
  Mixing angles: θ_{12}, θ_{13}.
  Mass square term: Δm^2_{21}.
- The unknown parameters:
  θ_{23}: Octant is maximal$(= 45°)$ or non-maximal$(\neq 45°)$.
  Mass Hierarchy: Sign of atmospheric mass squared term Δm^2_{31}.
  Direc cp phase: δ_{cp}.
- We also don't know the absolute neutrino mass, CP, or if neutrino is its own anti-particle.

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/°$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$
	$\theta_{23}/°$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$
	$\theta_{13}/°$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$
	$\delta_{\rm CP}/°$	197^{+41}_{-25}	$108 \to 404$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$

What is Mass Hierarchy(MH) ?

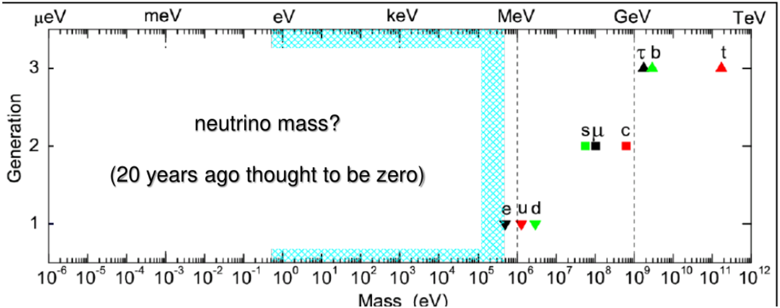
Neutrino Oscillation experiments are sensitive to the difference of mass square term ($\Delta m_{ij}^2 = m_i^2 - m_j^2$).

- Mass Hierarchy/Mass ordering:
  ordering of the masses of the three neutrino m1, m2, m3.
  Normal Ordering: $\Delta m_{31}^2 > 0$.
  Inverted Ordering: $\Delta m_{31}^2 < 0$.
- Challenges in determining mass hierarchy:
  Requires precise measurements of oscillation patterns.
  Sensitivity to small difference in the event spectra due to oscillation parameters.



Problem: Motivation

- Why study Neutrino Mass Ordering?
- Mandatory steps to unravel the neutrino mass mechanism and the origin of neutrino masses.
- Mass ordering affects the behaviour of neutrinos in different environments including supernova and the early universe.



Experimental approaches for mass measurements

- Via Direct Mass measurement
  Cosmology
  Beta Decay: KATRIN
  Neutrinoless Double beta decay
- Via Neutrino Oscillation
  Accelerator Long baseline Experiments: NOvA, T2K, DUNE, Hyper-K
  Reactor Neutrino Experiments: JUNO
  Atmospheric Neutrino Experiments: IceCube, INO
  Cosmological Observations: Supernova Neutrinos : do not directly determine the mass hierarchy but set constraints on the total neutrino mass.

How to Measure MH in Reactor experiment

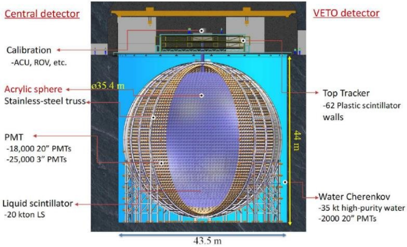
- Method:
  Analyzing the energy spectrum of reactor neutrinos.
  Observing oscillation patterns and their characteristics.
- Role of JUNO experiment:
  JUNO's high precision and energy resolution make it ideal for detecting subtle difference.
  Medium-baseline (53km) optimizes the sensitivity to mass-squared difference and mass ordering.

Juno Experiment: Overview

- JUNO detector catches neutrinos from two nuclear power plants.
- It observes the oscillations of anti-electron neutrino.
- Baseline is about 53 km. (relatively short)

Juno Experiment: Purpose

- Purpose : Determine the mass hierarchy and measure the value of $\Delta m^2_{21}, sin^2(2\theta_{12}), sin^2(2\theta_{13})$.
- Two ordering make different spectrums.
  Normal ordering
  Inverted ordering
- **In this project : We calculate the difference of spectrums and how well it chooses the mass ordering.**



Probability, Flux, Cross Section

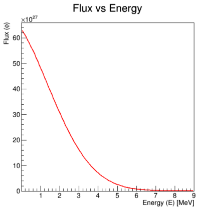
- The observed neutrino spectrum at a baseline L, $F(L/E)$, can be written as
- $$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$
  where E: electron antineutrino ($\overline{\nu}_e$) energy, $\phi(E)$: flux of $\overline{\nu}_e$ from the reactor,
  $\sigma(E)$: interaction cross section of $\overline{\nu}_e$ with matter,
  $P_{ee}(L/E)$ is the $\overline{\nu}_e$ survival probability.
- Fission: 3.125×10^{19} fission/s/GW.
- Target No: 4.4×10^{33}.

Probability, Flux, Cross Section

- The $\overline{\nu}_e$ flux $\phi(E)$ from the reactor can be parameterized as ,

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

  where four exponential terms are contributions from isotopes ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu in the reactor fuel, respectively.



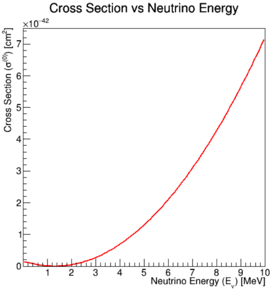
- Flux at the detector site: $\phi(E)_D = \frac{\phi(E)}{4\pi L^2}$

Probability, Flux, Cross Section

- Process: $\bar{\nu}_e + p \to e^+ + n$
- Cross section:

$$\sigma^{(0)} = 0.0952 \times 10^{-42}\mathrm{cm}^2 (E_e^{(0)} p_e^{(0)} / 1\mathrm{MeV}^2)$$

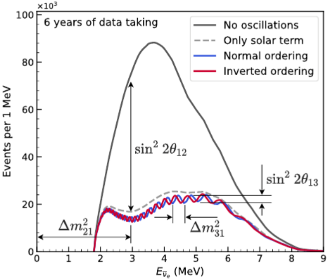
where $E_e^{(0)} = E_\nu - (M_n - M_p)$ is the positron energy when neutron recoil energy is neglected, and $p_e^{(0)}$ is the positron momentum.



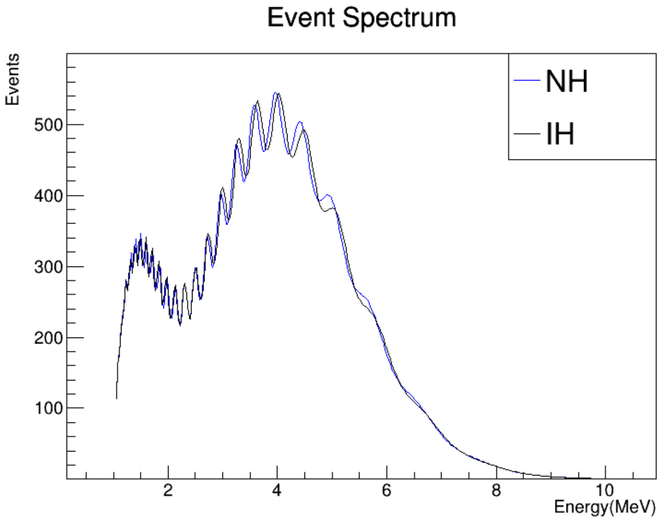
Probability, Flux, Cross Section

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$\mathrm{P}_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$\mathrm{P}_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$\mathrm{P}_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

- where $\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$, Δm^2_{ij} is the neutrino mass-squared difference $(m^2_i - m^2_j)$ in eV^2, θ_{ij} is the neutrino mixing angle, L is the baseline from reactor to $\overline{\nu}_e$ detector in meters, and E is the $\overline{\nu}_e$ energy in MeV.

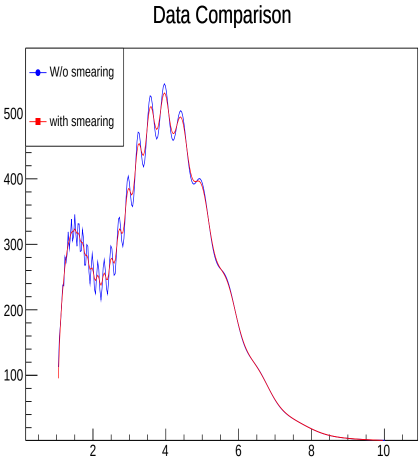


Event Energy Spectra: NH/MH



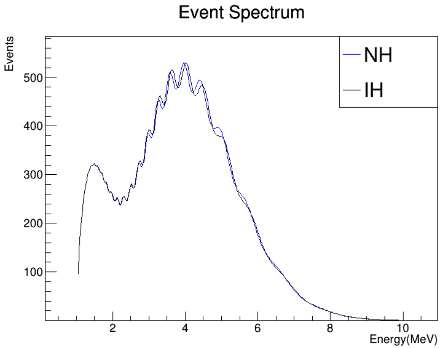
Correction for detector resolution

- The JUNO detector has nonzero resolution.
  The expectation for the spectrum we get thorough detector should consider this effect.
  The detector does not accurately detect energy, but conveys energy based on certain expected value distribution.
- Resolution:
  $$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}.$$

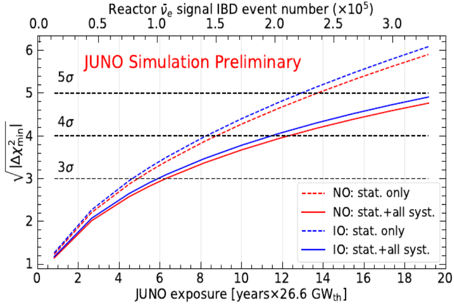


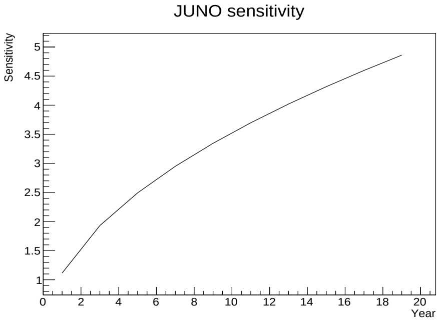
Chi Square Test and JUNO sensitivity for MH

- Now we have two spectrums, NH and IH. Chi square test is convenient for evaluating the certainty of difference of two spectrums.
- $\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$
  O_i is the observed frequency.
  E_i is the expected frequency.
  n is the number of data points.



JUNO sensitivity for MH





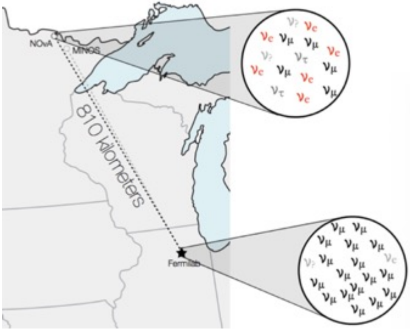
Final result : JUNO experiment will give the answer to the MH problem with the reliability of 3 (in 7 years), 5 (in 20 years).

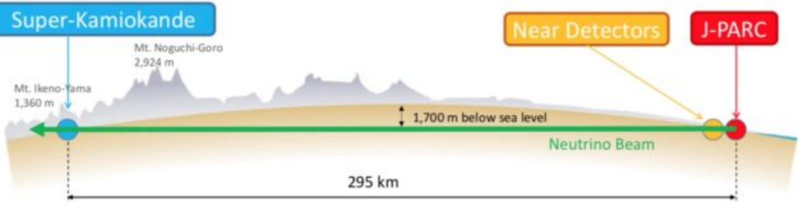
Experimental Comparison with LBL Experiments

- **What is the key Idea:**
- In accelerator experiments we can produce neutrino and antineutrino mode.
- Matter effect plays important role as neutrino/antineutrino travels a long distance.
- if there is Normal Hierarchy in the nature: It will enhance the neutrino oscillation and suppress antineutrino oscillation.
- if there is Inverted Hierarchy in the nature: It will enhance the anti-neutrino oscillation and suppress neutrino oscillation.
- Analyse the oscillated neutrino and antineutrino spectrum to distinguish the mass hierarchy.

Current Running LBL experiment

NOvA: Baseline 810 km.
(At Fermilab)
T2K: Baseline 295 km





SBL Vs LBL experiemnts

JUNO

- Medium baseline (50 KM)
- High precision
- Reactor antineutrino oscillation experiment
- Aim to determine mass ordering from $\bar{\nu}$ energy spectrum

T2K, NOνA

- T2K is a LBL(295 km)
- 1.97×10^{21} and 1.63×10^{21} protons on target in neutrino and antineutrino modes.
- NOνA is a LBL(810 km)
- 1.36×10^{21} and 1.25×10^{21} protons on target in neutrino and antineutrino modes.

Both experiments (T2K and NOνA) operate as a $\nu_\mu \to \nu_\mu/\overline{\nu}_\mu \to \overline{\nu}_\mu$ disappearance experiment as well as a $\nu_\mu \to \nu_e/\overline{\nu}_\mu \to \overline{\nu}_e$ appearance experiment.

Reference: FERMILAB-PUB-$24 - 0117$-T

Preference of different experiments on mass ordering

- T2K, NOνA $\rightarrow$ Normal ordering
- T2K+NOνA $\rightarrow$ Inverted ordering (Weak)
- Ice-cube $\rightarrow$ No preference
- Super kamiokande $\rightarrow$Normal ordering (92.3%CL)
- Global fit data $\rightarrow$ Normal ordering (very weak)

At the current time, we do not have 3 σ or more preference for one ordering over the other.

Reference: FERMILAB-PUB-$24-0117$-T

Realization of mass ordering

The exact $\bar{\nu}_e$ survival probability in vacuum is given by:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) \quad (2)$$

Here, $\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$
$\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32} \approx \sin^2\Delta_{ee}$

$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$

Reference: PHYSICAL REVIEW D $93, 053008(2016)$

Realization of mass ordering

The effective atmospheric Δm^2 (Δm^2_{atm}) for ν_e and $\bar{\nu}_e$ disappearance at a baseline divided by neutrino energy of 0.5 km/GeV, in vacuum, is given by

$$\Delta m^2_{ee} = \Delta m^2_{31} \cos^2\theta_{12} + \Delta m^2_{32} \sin^2\theta_{12} \tag{3}$$

Similarly, for ν_μ (and $\bar{\nu}_\mu$) disappearance, in vacuum, $\Delta m^2_{\mu\mu}$ is given by

$$\Delta m^2_{\mu\mu} \approx \Delta m^2_{31} \sin^2\theta_{12} + \Delta m^2_{32} \cos^2\theta_{12} + \sin\theta_{13} \cos\delta \Delta m^2_{21} \tag{4}$$

For NO $\Delta m^2_{31} > \Delta m^2_{32}$

$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ for NO whereas $|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$ for IO

Reference: FERMILAB-PUB-$24-0117$-T

Result comparison

JUNO

$$\Delta m^2_{ee}\Big|^{\text{JU}}_{\text{IO}} = \Delta m^2_{ee}\Big|^{\text{JU}}_{\text{NO}} + 1.8\times10^{-5}\,\text{eV}^2 \quad (5)$$

The JUNO (JU) detector will give a $\left|\Delta m^2_{ee}\right|$ for IO which is 0.7% larger than $\left|\Delta m^2_{ee}\right|$ fit for NO..

T2K, NOνA

The T2K results are:

$$\left|\Delta m^2_{32}\right|_{\text{NO}} = (2.49 \pm 0.05)\times 10^{-3}\,\text{eV}^2 \quad (6)$$

$$\left|\Delta m^2_{31}\right|_{\text{IO}} = (2.46 \pm 0.05)\times 10^{-3}\,\text{eV}^2 \quad (7)$$

NOνA's results are given by:

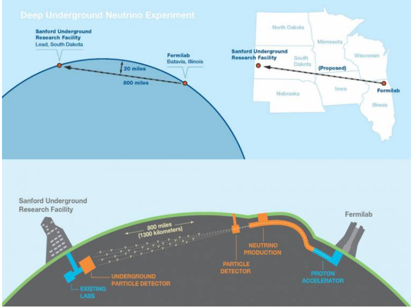
$$\left|\Delta m^2_{32}\right|_{\text{NO}} = (2.39 \pm 0.06)\times 10^{-3}\,\text{eV}^2 \quad (8)$$

$$\left|\Delta m^2_{32}\right|_{\text{IO}} = (2.44 \pm 0.06)\times 10^{-3}\,\text{eV}^2 \quad (9)$$

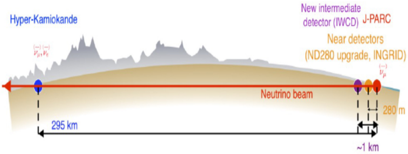
Reference: FERMILAB-PUB-$24-0117$-T

DUNE & Hyper-K

DUNE: Baseline 1395 km.



Hyper-K: Same baseline as T2K.
But detector mass is very high.



Conclusion

- Mass Hierarchy is important to study.
- Currently there is tension with available data.
- JUNO can hint for the possible mass hierarchy.
- Sensitivity of JUNO is less the 5σ for the 20 year of run period.
- Future LBL experiments are hope for the discovery (sensitivity greater than 5σ) of mass hierarchy.

Thank You!