Measurement of Neutrino Flavor Oscillations with Hyper Kamiokande experiment

Presented by **Anna Antonova**

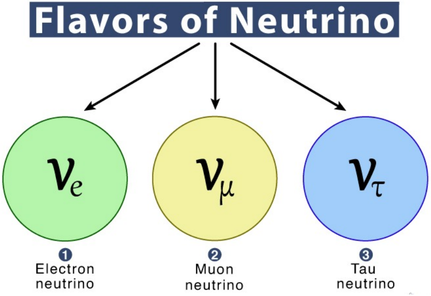
Internship supervisors **Boris Popov, Claire Dalmazzone**

Laboratoire de Physique Nucléaire et des Hautes Énergies (LPNHE)

Sorbonne Université

What are Neutrinos?

Three Flavors of Neutrinos



- Electrically neutral ($Q = 0$), spin-$\frac{1}{2}$ fermions
- Extremely small mass ($m << 1\,\text{eV}$)
- Interact only via weak force $\rightarrow$ "ghost particles"
- $\sim 10^{15}$ neutrinos pass through a detector every second, but only 10–20 interactions/day detected, even in large detectors

Neutrino Flavor Oscillation Phenomenon

A neutrino flavor state is a superposition of mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad \alpha = e,\ \mu,\ \tau \qquad |\nu_i\rangle = |\nu_1\rangle,\ |\nu_2\rangle,\ |\nu_3\rangle$$

Neutrino Mixing Matrix in PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Parametrization

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, and CP-violation phase δ_{CP}
Unknown: δ_{CP}

Neutrino Oscillations and CP Violation

Neutrino flavor state evolves as:

$$|\nu_\alpha(t,\vec{x})\rangle = \sum_j U^*_{\alpha j} e^{-i(E_j t - \vec{p}_j\cdot\vec{x})}|\nu_j\rangle, \qquad P(\nu_\alpha \to \nu_\beta) = \left|\sum_j U^*_{\alpha j} U_{\beta j} e^{-i(E_j t - \vec{p}_j\cdot\vec{x})}\right|^2$$

Oscillation phase: Neutrino oscillation arises from the interference of mass eigenstates, and the oscillation phase is the difference between their propagation phases:

$$\Delta\phi_{ij} = (E_i - E_j)t - (\vec{p}_i - \vec{p}_j)\cdot\vec{x} \approx \frac{\Delta m^2_{ij} L}{2E_\nu}$$

with: $\Delta m^2_{ij} = m_i^2 - m_j^2$: mass splitting, L: propagation length, E_ν: average neutrino energy.

Oscillation probability:

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right\} \sin^2\left(\frac{\Delta m^2_{ij} L}{4E_\nu}\right)$$

$$\pm\ 2\sum_{i>j} \Im\left\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right\} \sin\left(\frac{\Delta m^2_{ij} L}{2E_\nu}\right)$$

- $(+)$ for $\nu_\alpha \to \nu_\beta$, $(-)$ for $\bar{\nu}_\alpha \to \bar{\nu}_\beta$
- The imaginary term **represents** CP violation

CP Asymmetry in Vacuum

Electron (anti)neutrino appearence probabilities in vacuum

$$P(\nu_\mu \to \nu_e) = \cdots - 8\ \cos\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin\delta_{CP} \cdot \sin\Delta_{21}\ \sin\Delta_{31}\ \sin\Delta_{32} + \ldots$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \cdots + 8\ \cos\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin\delta_{CP} \cdot \sin\Delta_{21}\ \sin\Delta_{31}\ \sin\Delta_{32} + \ldots$$

The CP asymmetry between neutrino and antineutrino appearance is:

$$A_{CP}^{(\mu e)} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

$$= 16 \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cdot \boxed{\sin\delta_{CP}} \cdot \sin\Delta_{21} \cdot \sin\Delta_{31} \cdot \sin\Delta_{32}$$

In vacuum: the neutrino - antineutrino asymmetry arises **only from $\boldsymbol{\delta_{\mathrm{CP}}}$**

Matter Effects in Neutrino Oscillations

Neutrinos travel through matter (Earth's crust) $\Rightarrow$ interact via coherent forward scattering with electrons $\Rightarrow$ impact oscillation probabilities.

Why important?

- Affects mainly ν_e and $\bar{\nu}_e$ appearance channels.
- Enhances sensitivity to the mass ordering (sign of Δm^2_{31}).

Matter-corrected appearance probability:

$$P_{\text{matter}}(\nu_\mu \to \nu_e) = P_{\text{vacuum}}(\nu_\mu \to \nu_e) + 8\, c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \cdot \frac{aL}{4E} \cdot \cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cdot \sin\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Matter potential:

$$a = \pm 2\sqrt{2} G_F E n_e, \quad \begin{cases} + \text{ for neutrinos} \\ - \text{ for antineutrinos} \end{cases}$$

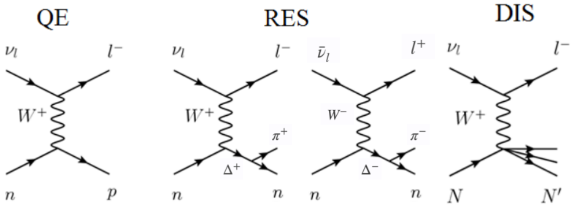
Mass ordering (MO) sensitivity:

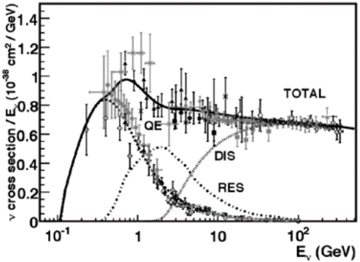
$$\text{Normal ordering (NO): } \Delta m^2_{31} > 0, \quad m_1 < m_2 < m_3$$

$$\text{Inverted ordering (IO): } \Delta m^2_{31} < 0, \quad m_3 < m_1 < m_2$$

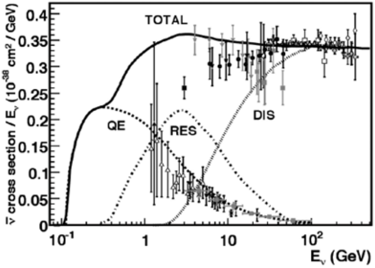
Charged-Current Neutrino Interactions in Water

Non elastic charged-current interaction





Neutrino Cross Section



Antineutrino Cross Section

Neutrino Energy Reconstruction in CC Interactions

Charged-Current Quasi-Elastic (CCQE) interactions are crucial for reconstructing neutrino energy and flavor, especially at energies below 1 GeV.

From the final state lepton kinematics:

$$E_\nu^{\text{CCQE}} = \frac{ME_\ell - m_\ell^2/2}{M - E_\ell + |\vec{p}_\ell| \cos\theta_\ell}$$

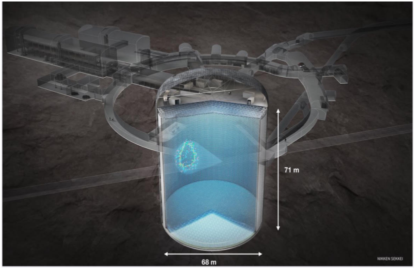
- M: mass of target nucleon (typically neutron)
- m_ℓ, $\vec{p}_\ell$, θ_ℓ: mass, momentum, production angle of the charged lepton

Resonant (RES) interactions can also allow neutrino energy reconstruction if the final-state lepton is observed:

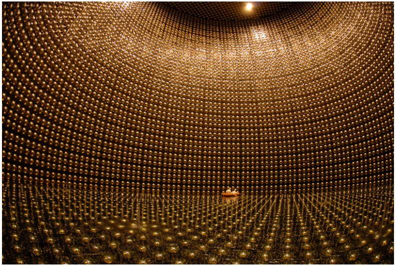
$$E_\nu^{\text{RES}} = \frac{M_\Delta^2 - M_p^2 + 2M_p E_\ell - m_\ell^2}{2(M_p - E_\ell + |\vec{p}_\ell| \cos\theta_\ell)}$$

- M_Δ: mass of the resonance
- M_p: mass of the proton
- E_ℓ, $|\vec{p}_\ell|$, θ_ℓ: energy, momentum, production angle of the charged lepton

The Hyper-Kamiokande Detector



Hyper-Kamiokande detector



Interior of Cherenkov detector

- Hyper-Kamiokande (HK) is a next-generation water Cherenkov detector in Japan.
- Located 650m underground; total mass: 260kton; fiducial mass: 188kton.
- Inner detector: $\sim$20,000 50cm PMTs; Outer detector: $\sim$8,000 7.5cm PMTs.
- Sensitivity to atmospheric, solar, accelerator and supernova neutrinos.

Neutrino detection via Cherenkov radiation

Cherenkov condition:

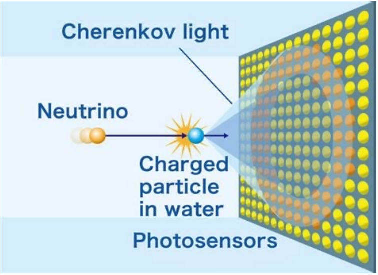
$$v > \frac{c}{n}, \quad n \approx 1.33$$

Cherenkov angle:

$$\cos \theta_C = \frac{1}{n\beta}, \quad \beta = \frac{v}{c}$$

Reconstruction principle:

- Light cone hits PMTs on the detector walls
- Time and position of hits reconstruct:
  - Interaction vertex
  - Lepton direction
  - Lepton energy

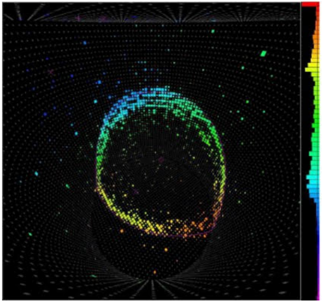


Cherenkov cone emitted and detected by PMTs

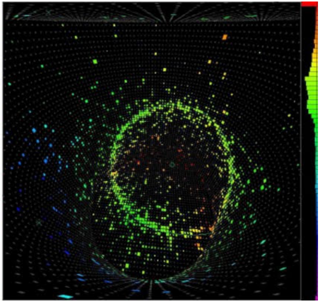
Identifying Lepton Type from Cherenkov Rings

In water Cherenkov detectors, the shape of the light ring reveals the type of charged lepton produced in a neutrino interaction.

- **Muons** travel in straight lines $\rightarrow$ produce **sharp, well-defined rings**
- **Electrons** scatter multiple times $\rightarrow$ produce **fuzzy, diffuse rings**

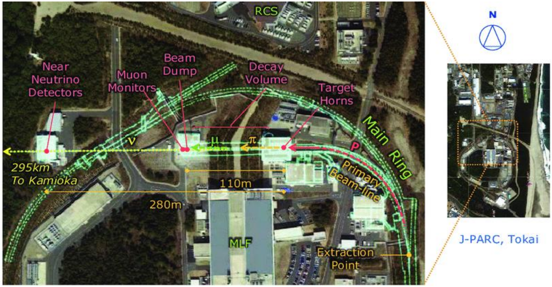


Muon-like ring



Electron-like ring

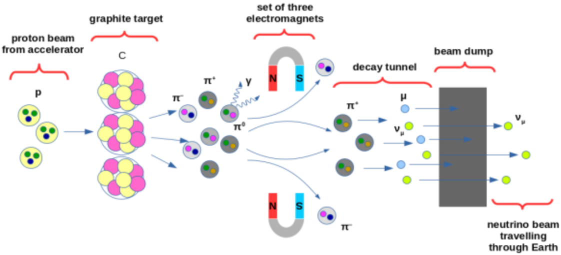
Long Baseline Experiment at **Hyper-Kamiokande**



J-PARC to HK beamline experimental facility

- 295 km baseline from J-PARC beamline to Hyper-Kamiokande
- Reuses near detecttors: ND280, INGRID
- Additional Intermediate Water Cherenkov detector (IWCD) at 850m
- Measures oscillations: $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}, \boldsymbol{\bar{\nu}_\mu} \rightarrow \boldsymbol{\bar{\nu}_e}$

- **30 GeV protons** hit graphite target → pions/kaons
- Mesons decay into $\boldsymbol{\mu^\pm}$ and $\boldsymbol{\nu_\mu / \bar{\nu}_\mu}$
- **FHC**: $\boldsymbol{\nu_\mu}$ beam , **RHC:** $\boldsymbol{\bar{\nu}_\mu}$ beam

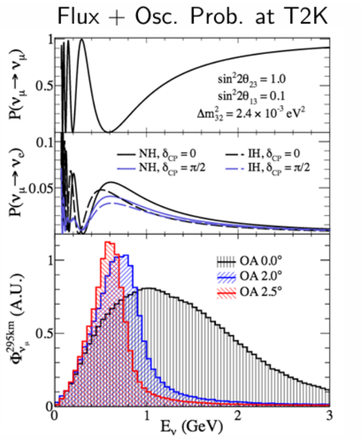


Neutrino beam production

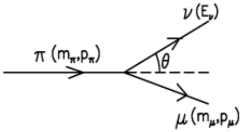
Off Axis configuration of HK Detector

- Detector positioned 2.5° off beam axis
- Produces narrow neutrino energy peak at $\sim 600\,\mathrm{MeV}$
- Matches oscillation maximum for $L = 295\,\mathrm{km}$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

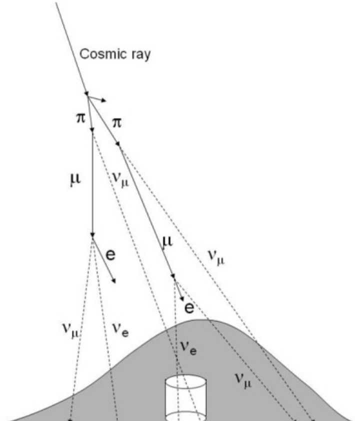


$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 \left(1.27\, \frac{\Delta m_{31}^2 L}{E_\nu}\right)$$



Atmospheric Neutrinos at HK

- Atmospheric neutrinos: appear from cosmic ray collisions
- Mostly ν_μ and ν_e from pion and muon decays
- Expected flavor ratio: $N_{\nu_\mu} : N_{\nu_e} \approx 2 : 1$
- Oscillations inferred from the asymmetry in up/down neutrino event rates



Neutrino event samples used in this work

Beam Neutrino Samples

Ring Type	Beam Mode
e-like	FHC (neutrino beam)
e-like	RHC (antineutrino beam)
μ-like	FHC (neutrino beam)
μ-like	RHC (antineutrino beam)

μ-like: events from $\nu_\mu, \bar{\nu}_\mu$
e-like: events from $\nu_e, \bar{\nu}_e$

Atmospheric Neutrino Samples

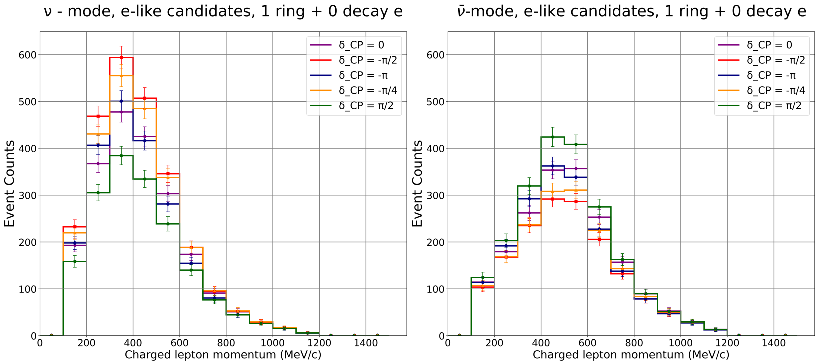
Sample	Decay Electron Signature
Sub-GeV e-like	0 decay e, ν_e and $\bar{\nu}_e$ indistinguishable
Multi-GeV μ-like	–
Multi-GeV e-like ν_e	$\geq$1 decay e
Multi-GeV e-like $\bar{\nu}_e$	0 decay e
Multi-ring e-like ν_e	$\geq$1 decay e
Multi-ring e-like $\bar{\nu}_e$	0 decay e

Relevant Neutrino Interactions:

- **QE:** $\nu_\ell + n \rightarrow \ell^- + p$
- **RES — Neutrino:** $\nu_\ell + n \rightarrow \ell^- + \Delta^+ \rightarrow \ell^- + n + \pi^+$
  $\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- **RES — Antineutrino:** $\bar{\nu}_\ell + n \rightarrow \ell^+ + \Delta^- \rightarrow \ell^+ + n + \pi^-$
  π^- is usually captured before it can decay

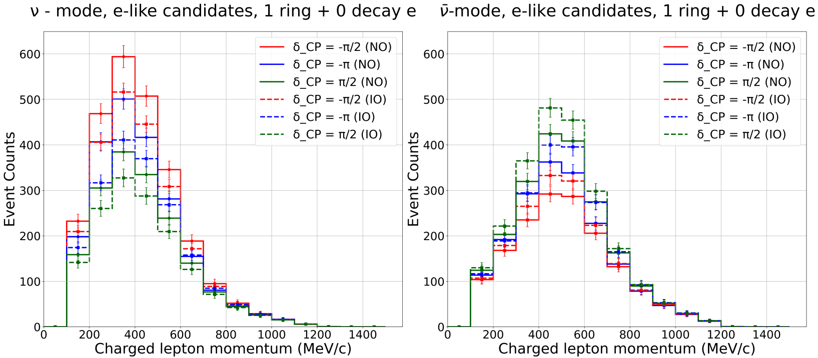
CP Violation Sensitivity in appearance events

- Simulated e-like 1-ring events at Hyper-K, 10-year exposure
- FHC mode ($\nu_\mu \to \nu_e$) vs. RHC mode ($\bar{\nu}_\mu \to \bar{\nu}_e$)



- Peak at 300–600 MeV/c: max $P(\nu_\mu \to \nu_e)$, largest sensitivity to δ_{CP}
- $\delta_{CP} = -\pi/2$: maximal ν_e appearance, minimal $\bar{\nu}_e$
- $\delta_{CP} = +\pi/2$: opposite effect — CP asymmetry visible

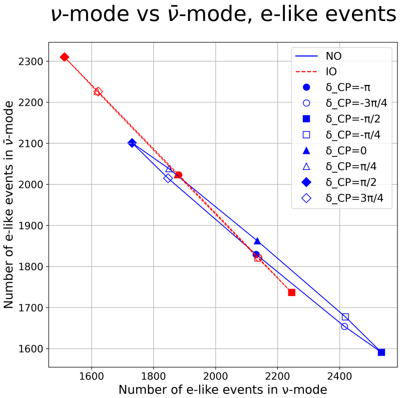
CP and Mass Ordering Degeneracy with Beam Neutrinos



Spectra of e-like 1-ring events for $\delta_{CP} = \pm\pi/2, -\pi$ for both NO and IO

- Degeneracy: $\delta_{CP} = -\pi$ (NO) $\delta_{CP} = -\pi/2$ (IO) in ν-mode
- Combining both modes improves separation but does not fully resolve degeneracy

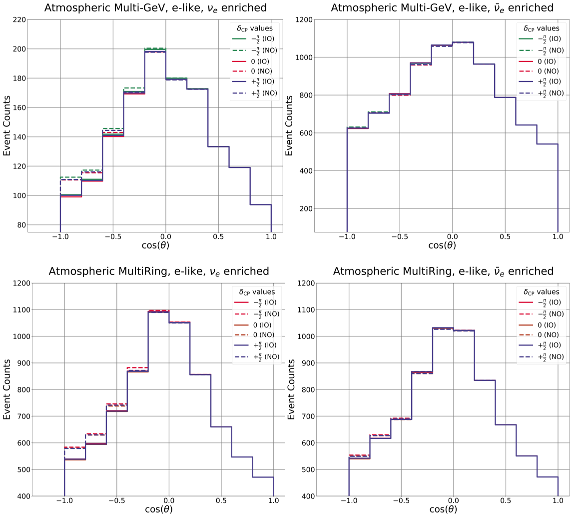
Correlation of appearance events in ν and $\bar{\nu}$ modes



Correlation of e-like 1-ring events in ν and $\bar{\nu}$ modes for different δ_{CP} and mass orderings (NO vs IO)

- Some degeneracies remain even after combining ν and $\bar{\nu}$-mode data
- Example: $\delta_{CP} = \pi/4$ (NO) $\delta_{CP} = -\pi$ (IO), or $\delta_{CP} = -\pi$ (NO) $\delta_{CP} = -3\pi/4$ (IO)

Sensitivity to MO with Atmospheric Neutrino samples



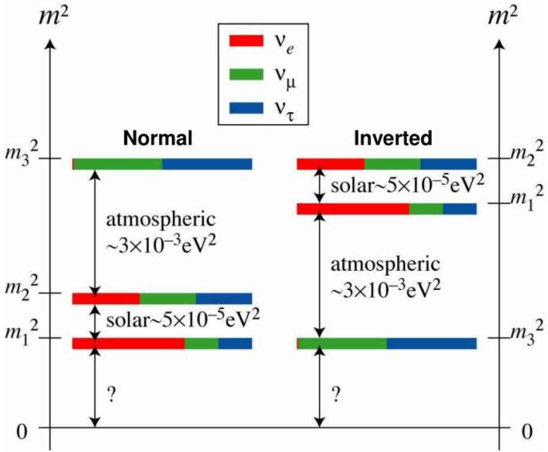
- ν_e-like rates in multi-GeV and multi-ring samples are sensitive to mass ordering (MO)
- Significant differences between NO and IO for upward-going events ($\cos\theta < 0$)

Conclusion

- Oscillation probability $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ depends on both δ_{CP} and mass ordering (MO)
- Hyper-Kamiokande aims to discover CP violation in the leptonic sector by measuring the phase δ_{CP}
- Beam neutrino samples provide strong sensitivity to δ_{CP}, but are not sensitive to MO, thus MO–δ_{CP} degeneracies are present
- Atmospheric neutrinos help resolve these degeneracies thanks to matter effects on upward-going events
- Combining both data sets lifts degeneracies and enhances precision on both parameters

Thank you for your attention!

Neutrino Masses and Hierarchy



Sample purity

Sample	ν_e purity	$\bar{\nu}_e$ purity
Multi-GeV e-like	80%	40%
Multi-ring e-like	60%	30%

Neutrino Mixing angles and experiments

Values of mixing angles and the experiments through which they were measured:

θ_{12}	$34^\circ \pm 1^\circ$	SNO, KamLAND
θ_{23}	$45^\circ \pm 8^\circ$	Super-Kamiokande, T2K, MINOS
θ_{13}	$8.7^\circ \pm 0.4^\circ$	RENO, Double Chooz, Daya Bay, T2K

Up/Down asymmetry for ν_e enriched samples

Multi-GeV Sample

Normal Ordering (NO)

δ_{CP}	A	σ_A	A/σ_A
$-\frac{\pi}{2}$	29.3	26.9	1.09
0	22.9	26.7	0.86
$+\frac{\pi}{2}$	25.2	26.8	0.94

Inverted Ordering (IO)

δ_{CP}	A	σ_A	A/σ_A
$-\frac{\pi}{2}$	7.2	26.4	0.27
0	3.1	26.4	0.12
$+\frac{\pi}{2}$	5.1	26.4	0.19

MultiRing Sample

Normal Ordering (NO)

δ_{CP}	A	σ_A	A/σ_A
$-\frac{\pi}{2}$	285.9	60.3	4.74
0	269.1	60.2	4.47
$+\frac{\pi}{2}$	272.1	60.2	4.52

Inverted Ordering (IO)

δ_{CP}	A	σ_A	A/σ_A
$-\frac{\pi}{2}$	179.1	59.5	3.01
0	170.0	59.4	2.86
$+\frac{\pi}{2}$	175.3	59.4	2.95

Sensitivity to δ_{CP} from total event rates (NO)

ν_e SAMPLE (hnue1R_X;1)

δ_1	δ_2	ΔN	$\sigma_{\Delta N}$	Significance
$-\frac{\pi}{2}$	0	400.3	68.3	5.86σ
$+\frac{\pi}{2}$	0	-404.1	62.2	-6.50σ
$+\frac{\pi}{2}$	$-\frac{\pi}{2}$	-804.4	65.3	-12.32σ
$-\frac{\pi}{4}$	0	283.8	67.5	4.21σ

$\bar{\nu}_e$ SAMPLE (hnuebar1R_X;1)

δ_1	δ_2	ΔN	$\sigma_{\Delta N}$	Significance
$-\frac{\pi}{2}$	0	-271.7	58.8	-4.62σ
$+\frac{\pi}{2}$	0	238.7	63.0	3.79σ
$+\frac{\pi}{2}$	$-\frac{\pi}{2}$	510.4	60.8	8.40σ
$-\frac{\pi}{4}$	0	-185.3	59.5	-3.11σ

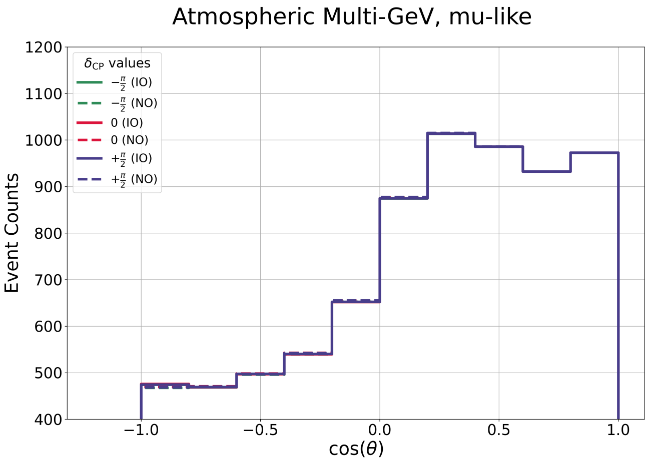
Up/Down Asymmetry and Mass Ordering Sensitivity

Multi-GeV Samples

Sample	δ_{CP}	A_{NO}	A_{IO}	ΔA	$\sigma_{\Delta A}$	Significance
ν_e enriched	$-\frac{\pi}{2}$	29.3	7.2	22.2	37.7	0.59
	0	22.9	3.1	19.9	37.6	0.53
	$+\frac{\pi}{2}$	25.2	5.1	20.1	37.6	0.53
$\bar{\nu}_e$ enriched	$-\frac{\pi}{2}$	177.1	165.9	11.2	90.7	0.12
	0	159.8	164.8	−4.9	90.6	−0.05
	$+\frac{\pi}{2}$	165.1	164.0	1.0	90.6	0.01

MultiRing Samples

Sample	δ_{CP}	A_{NO}	A_{IO}	ΔA	$\sigma_{\Delta A}$	Significance
ν_e enriched	$-\frac{\pi}{2}$	285.9	179.1	106.8	84.7	1.26
	0	269.1	170.0	99.1	84.6	1.17
	$+\frac{\pi}{2}$	272.1	175.3	96.8	84.6	1.14
$\bar{\nu}_e$ enriched	$-\frac{\pi}{2}$	186.0	155.6	30.4	84.3	0.36
	0	173.7	154.2	19.5	84.2	0.23
	$+\frac{\pi}{2}$	175.6	155.9	19.7	84.2	0.23



Atmospheric Multi-GeV, mu-like
δCP values
−π/2 (IO)
−π/2 (NO)
0 (IO)
0 (NO)
+π/2 (IO)
+π/2 (NO)
Event Counts
cos(θ)
1200
1100
1000
900
800
700
600
500
400
−1.0
−0.5
0.0
0.5
1.0