Exploring 3-flavor effects with present and next generation long baseline superbeam neutrino experiments

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Neutrinos

- Neutrinos are the second most abundant particles in the universe.
- They are spin 1/2, electrically neutral leptons.
- They experience only the weak forces and the gravity.
- Thus, detecting them is a challenging task.
- Their weak interactions are successfully described by the standard model of particle physics.

Neutrino Oscillations

- Neutrinos are massless in the Standard Model(SM) of Particle Physics.
- However, neutrino experiments conclusively prove that neutrinos are massive and mixed. Very recent data from Planck satellite experiment: $\sum m_i \leq 0.23$ eV at 95% C.L. [Ade et. al. (Planck collaboration) 1303.5706]
- So, SM is an effective theory of the yet unknown theory beyond the SM
- We need to understand
  1. how neutrinos gain tiny masses?
  2. how they are mixed?
- This talk (and my work so far) is about (2)
- Clearly, neutrino is playing the role of a messenger of the new physics beyond the SM.
- The standard theory of neutrino oscillations in the plane-wave approximation was developed in 1975-76 by Eliezer and Swift, Fritzsch and Minkowsky, Bilenki and Pontecorvo.
- The formalism believes neutrinos to be ultra-relativistic.

Neutrino Oscillations

- Some early experiments provided a hint that there was deficit in the observed number of neutrino events compared to what the standard solar model predicted. This was called the solar neutrino problem.
- While initially, there were suspicion about the model itself and other possible sources of errors in the calculation, with time everyone started taking the solar neutrino problem seriously.
- The reason for this deficit was proposed to be possible oscillation of electron neutrino into other flavors.
- in 2001, the Super-Kamiokande collaboration and the Sudbury neutrino observatory conclusively proved the deficit and oscillations were established on strong footing.

Neutrino Oscillations

- The definition of neutrino flavor follows from the decay of W-boson. A W-boson can decay into a lepton and a neutrino. Neutrinos come in 3 flavors: ν_e, ν_μ and ν_τ. Reversing the argument, a ν_e can interact with a nuclei to give an electron only.
- Flavor eigenstates can be expressed as a linear combination of mass eigenstates. Since, we observe orthogonal neutrinos of 3 definite flavors, there must be at least 3 mass eigenstates.
- If the energies and momenta of the particles which participate in the neutrino production process are not measured with a degree of accuracy which would allow the determination of the massive neutrino which is emitted, then a superposition of massive neutrinos are generated. This is characteristic of neutrino oscillation experiments. Note that this feature hinges on the fact that neutrinos have very small mass differences.
- The oscillations are generated by the interference of different massive neutrinos, which are produced and detected coherently because of their very small mass differences.

Neutrino Oscillations: Two Flavor case

The flavor and mass eigenstates can be connected by the 2×2 unitary matrix parameterized by the mixing angle θ.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

According to the Schroedinger's equation, ν_1 and ν_2 have the simple time dependence $e^{-iEt/\hbar}$:

$$\nu_1(t) = \nu_1(0)e^{-iE_1t/\hbar};\ \nu_2(t) = \nu_2(0)e^{-iE_2t/\hbar}$$

After a time t,

$$\begin{bmatrix} \nu_e(t) \\ \nu_\mu(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1(t) \\ \nu_2(t) \end{bmatrix}$$

Neutrino Oscillation: Two Flavor case

$$\begin{bmatrix} \nu_e(t) \\ \nu_\mu(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{-iE_1 t/\hbar} & 0 \\ 0 & e^{-iE_2 t/\hbar} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

$$\begin{bmatrix} \nu_e(t) \\ \nu_\mu(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{-iE_1 t/\hbar} & 0 \\ 0 & e^{-iE_2 t/\hbar} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix}$$

$$\begin{bmatrix} \nu_e(t) \\ \nu_\mu(t) \end{bmatrix} = \begin{bmatrix} e^{-iE_1 t/\hbar}\cos^2\theta + e^{-iE_2 t/\hbar}\sin^2\theta & -e^{-iE_1 t/\hbar}\cos\theta\sin\theta + e^{-iE_2 t/\hbar}\cos\theta\sin\theta \\ -e^{-iE_1 t/\hbar}\cos\theta\sin\theta + e^{-iE_2 t/\hbar}\cos\theta\sin\theta & e^{-iE_1 t/\hbar}\sin^2\theta + e^{-iE_2 t/\hbar}\cos^2\theta \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix}$$

We have, $\mathrm{P}_{\nu_e \to \nu_\mu} = \left[\sin 2\theta \ \sin(\frac{E_2 - E_1}{2\hbar} t)\right]^2 = \left[\sin 2\theta \ \sin(\frac{m_2^2 - m_1^2}{2\hbar} t)\right]^2$

- The off-diagonal terms are not zero any more.
- Oscillatory behavior in time.
- Note that for oscillation to occur, neutrinos have to have mass and they must also mix.

Neutrino Oscillation: Three Flavor case

The formalism for 3-flavors follows the same logic but is algebraically more challenging. Here, the unitary mixing matrix U which connects flavor eigenstates and the mass eigenstates is parameterized by 3 mixing angles and 1 CP-violating Dirac phase.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \mathrm{U}^*(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}) \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Between the three mass eigenvalues: m_1, m_2 and m_3, there are two independent mass-squared differences (to which the oscillations are sensitive). $\Delta_{31} = m_3^2 - m_1^2$ and $\Delta_{21} = m_2^2 - m_1^2$.
These form the 6 neutrino oscillation parameters.

Present status of the oscillation parameters

1. KamLAND and Solar neutrino data have fixed Δ_{21} and θ_{12}.
2. MINOS experiment has measured $|\Delta_{31}|$ and Atmospheric neutrino data have measured θ_{23}.
3. Contrary to the atmospheric neutrino results, MINOS hints at a deviation from $\theta_{23} = 45°$.
4. Very recently, Reactor neutrino data have measured θ_{13} precisely.

Global bestfits [Gonzalez-Garcia et. al. JHEP 1212 123 (2012)]:

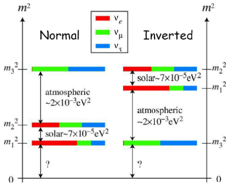
- $\theta_{12} = 34 \pm 2°$
- $\theta_{13} = 8°$
- $\theta_{23} = 45 \pm 8°$
- $\delta_{CP} = ??$
- $\Delta_{21} = 7.6 \times 10^{-5} (\text{eV})^2$
- $|\Delta_{31}| = 2.4 \times 10^{-3} (\text{eV})^2$

The unknowns in neutrino oscillations physics

Mass hierarchy

We do not know whether the hierarchy is

- Normal: $\boxed{m_1 < m_2 \ll m_3}$ or
- Inverted: $\boxed{m_3 \ll m_1 < m_2}$?



Octant of θ_{23}

Whether θ_{23} is lesser than or greater than $45°$?

Leptonic CP violation

Whether CP is violated in the leptonic sector?

i.e. $\boxed{\text{is } P(\alpha \to \beta) \neq P(\bar{\alpha} \to \bar{\beta}) \text{ ?}}$

Why do we need to know these unknowns?

To understand better the theory of neutrino masses and mixings!

- Mass hierarchy: Models which predict NH are very different from the ones which predict IH. Thus knowing, the hierarchy will help us in reducing the number of effective models.
- Octant of θ_{23}: We see the pattern of two large and one small mixing angle in the neutrino sector. A number of innovative ideas like $\mu \leftrightarrow \tau$ [Mohapatra and Nussinov, Phys.Rev. D60, 013002 (1999)] symmetry, A4 flavor symmetry [Babu et. al., Phys.Lett. B552, 207 (2003)] and quark-lepton complementarity [Minakata and Smirnov, Phys.Rev. D70, 073009 (2004)] have been invoked to explain this pattern.
- Leptonic CP violation: Can provide us crucial hints for baryogenesis and baryon asymmetry of the universe [Fukugita and Yanagida, Phys.Lett. B174, 45 (1986)].

- The experimental measurements made so far have used the disappearance channel: $P_{\mu\mu}$ (Atmospheric and MINOS) and P_{ee} (Solar and Reactors).
- These channels are characterised by large(~ 1) probabilities and the experiments looked for a deficit in the fluxes.
- Free and/or copious sources of neutrinos.
- Also, the analysis could be done in the 2-flavor approximation: 1-2 mixing for solar and 2-3 mixing for atmospheric.
- These measurements were easier to carry out and that is what we have till now.

Past vs. Future. The next step?

In three flavors:

- $\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$
- $U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$
- The 2-flavor and 3-flavor scenario are linked by the mixing angle θ_{13} and this angle directly controls the measurement of the 3-flavor parameters: hierarchy, octant and δ_{CP}.
- Till some time back, we only had an upper bound in θ_{13} and a value of 0 was allowed. This would have made it impossible to probe the 3-flavor effects. The reactor neutrino experiment Daya Bay, has recently measured θ_{13} to be $\sim 8^\circ$ with good precision.

Long baseline neutrino experiments

- Of baselines varying from 700km -7000km.
- An intense beam of neutrinos directed towards a detector.
- Most experiments plan to run in both ν as well as $\bar{\nu}$ mode.
- The beams primarily consists of the μ-type $\nu/\bar{\nu}$; contaminations are also present which lead to backgrounds.
- The beam is directed towards a detector which in general is located far-off and the beam travels through the earth which leads to matter effects.
- The distance that the beam travels i.e. the baseline, is important.
- The beam profile i.e. the E_ν at which the flux peaks, is also important.
- Finally, in the detector, one looks for electron appearance i.e. ν_μ which have oscillated to ν_e.

The $P_{\mu e}$ oscillation channel: matter effects

$\nu_\mu \to \nu_e$ oscillation probability, expanded perturbatively in $\alpha = \Delta_{21}/\Delta_{31}$:

$$
\begin{aligned}
P_{\mu e} \;=\; & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\
& + \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta} + \delta_{CP}) \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}} \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \frac{\sin^2 \hat{\Delta}\hat{A}}{\hat{A}^2}
\end{aligned}
$$

where

- $\hat{\Delta} = \Delta_{31} L/4E$
- $\hat{A} = A/\Delta_{31}$

Wolfenstein matter term: $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho(\mathrm{gm/cc}) E(\mathrm{GeV})$.

The $P_{\mu e}$ oscillation channel: degeneracies

The $P_{\mu e}$ channel

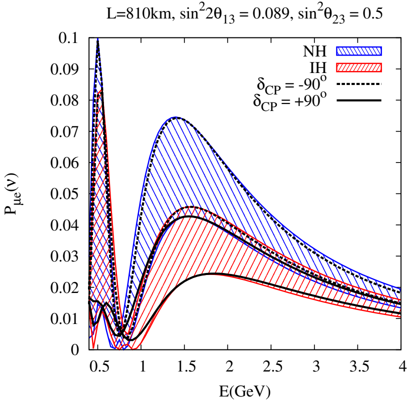
- Has sensitivity to all the neutrino parameters
- Pros: This feature, in principle, makes measurement of all neutrino parameters possible using superbeam
- Cons: This very feature handicaps it of various degeneracies

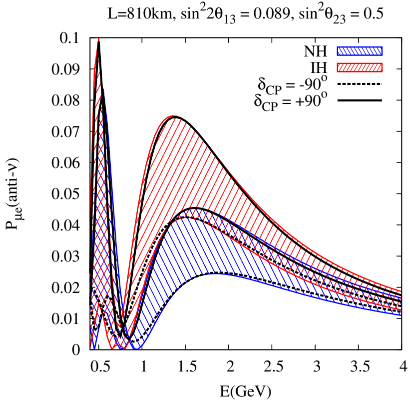
A measurement of $P_{\mu e}$ will have

- Hierarchy-δ_{CP} degeneracy
- Octant-δ_{CP} degeneracy

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy for 810 km

Left panel: Neutrinos & Right panel: Anti-neutrinos



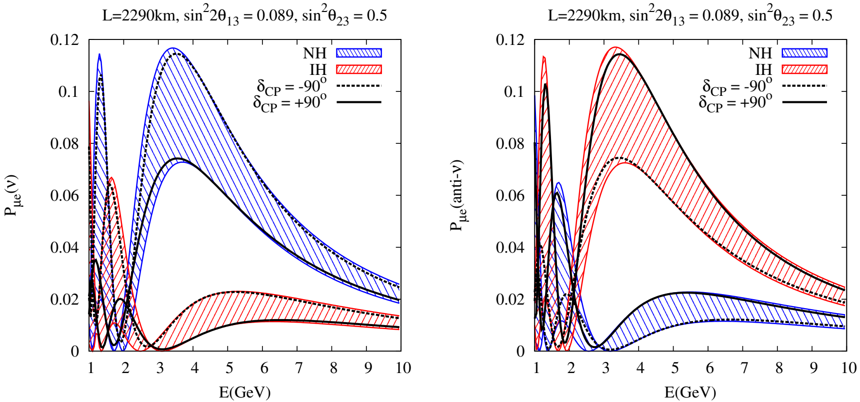


- Lower half plane ($-180^\circ \leq \delta_{CP} \leq 0$): favourable plane for NH
- Upper half plane ($0 \leq \delta_{CP} \leq 180^\circ$): favourable plane for IH

Resolving the degeneracy: The LBNO baseline

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy for 2290 km

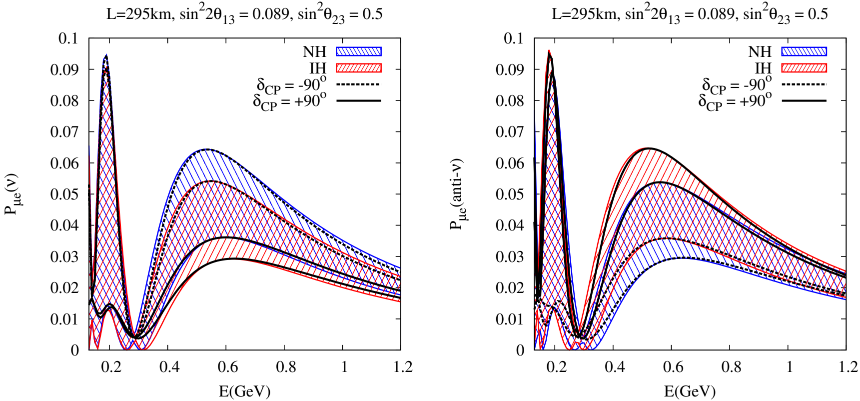
Left panel: Neutrinos & Right panel: Anti-neutrinos



- Clean separation between NH and IH around 1st Osc. maxima

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy for 295 km

Left panel: Neutrinos & Right panel: Anti-neutrinos

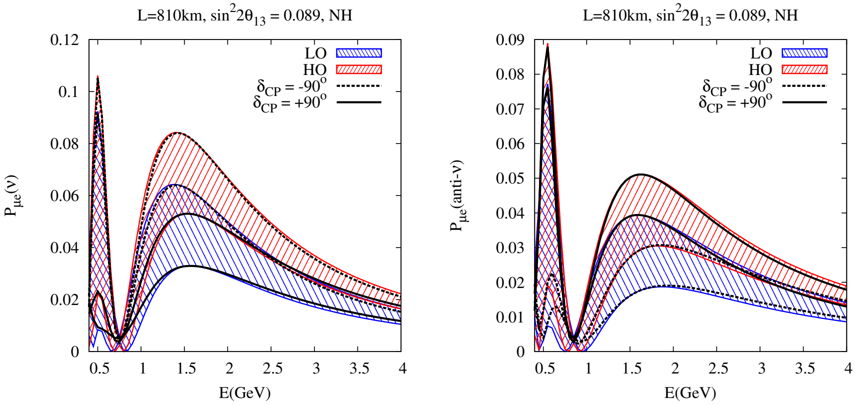


- The degeneracy pattern is different because of different matter effects.

Octant-δ_{CP} degeneracy

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy for 810 km

Left panel: Neutrinos & Right panel: Anti-neutrinos



- A balanced neutrino-anti-neutrino data will help.

Neutrino oscillation phenomenology

- The prime focus of neutrino physicists is the determination of the 3 unknowns mentioned over the previous slides.
- The weak interacting nature of neutrinos makes this task extremely challenging because to have significant results, one needs extremely high statistics. This means very intense neutrino beams and megaton sized detectors.
- There are various proposed experimental setups all over the world.
- But their cost runs into billions of dollars. Not all of them are going to come up.
- Phenomenology if of crucial importance as it tells us the capabilities of a particular setup.

1. S. K. Agarwalla, SP, S. K. Raut, S. U. Sankar, *Potential of optimized NOνA for large θ_{13} and combined performance with a LArTPC and T2K*, JHEP 1212, 075 (2012)
2. S. K. Agarwalla, SP, S. U. Sankar, *Resolving the octant of θ_{23} with T2K and NOνA*, arXiv:1301.2574
3. S. K. Agarwalla, SP, S. U. Sankar, *Exploring the three flavor effects with future superbeams using liquid argon detectors* , arXiv:1304.3251

Various LBL superbeam experiments

Present generation LBL superbeam experiments

- MINOS: 735 km
- T2K: 295 km
- NOνA: 810 km

Next generation LBL superbeam experiments

- CERN-Frejus: 130 km
- T2HK: 295 km
- CERN-Canfranc: 630 km
- CERN-Gran Sasso: 730 km
- Fermilab-Homestake: 1300 km
- CERN-Pyhasalmi: 2290 km

NOνA and T2K

Characteristic	NOνA	T2K
Baseline	810 km	295 km
Location	Fermilab-Ash River	J-PARC-Kamioka
Beam	NuMI beam 0.8° off - axis	JHF beam 2.5° off - axis
Beam power	0.7 MW	0.75 MW
Beam peaks at	2 GeV	0.6 GeV
$P_{\mu e}$ 1st Osc. Maximum	1.5 GeV	0.55 GeV
Detector	TASD, 14 kton	Water Čerenkov, 22.5 kton
Runtime	3 in ν+3 in $\bar{\nu}$	5 in ν

Reoptimization and upgrades in NOνA, post-large θ_{13}

- We study the physics reach of the reoptimized NOνA (in conjunction with T2K) to determine the mass hierarchy and CP violation
- There is considerable enthusiasm in the NOνA and LBNE collaborations for an additional small liquid argon detector at the Ash River site
- We consider the possiblility of such a module

Reoptimized NOνA

- Previous optimization: done under the assumption $\sin^2 2\theta_{13} = 0$ with objective to have least background
- New optimization: for moderately large θ_{13} with relaxed cuts for event selection criteria which allow more signal and background [talk by R. Patterson in NuFACT 12]

The main differences between the old criteria and new criteria are:

- The signal efficiencies for new NOνA are higher than that of old one by roughly a factor of 2 for neutrino events
- The background acceptance has also increased
- The NC spectrum shift to the measured energies is implemented through migration matrices. [LBNE Collaboration, T. Akiri et al. arXiv:1110.6249]
- We have taken care of the neutrino contamination in the anti-neutrino beam

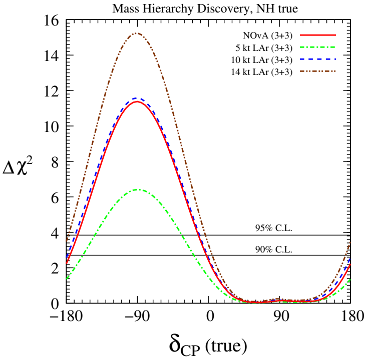
Liquid Argon TPC

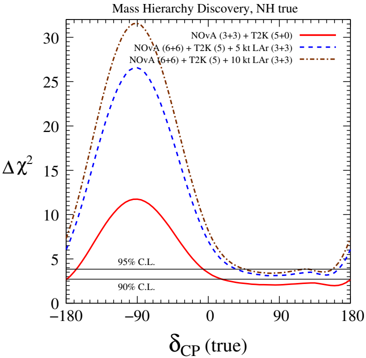
- A 10 kt liquid argon time projection chamber (LArTPC) constructed close to NOνA
- A signal efficiency of 80% for $e^{\pm}$ compared to 45% for TASD [LBNE Collaboration, T. Akiri et al. arXiv:1110.6249]
- The energy resolution and background rejection for the LArTPC and TASD are comparable
- Such a detector will come on line much later than NOνA
- In considering NOνA + LArTPC, we assume equal 6 years ν and $\bar{\nu}$ runs for NOνA and equal 3 years ν and $\bar{\nu}$ runs for LArTPC

Sensitivity of upgraded NOνA and T2K for mass hierarchy

Hierarchy discovery for various set-ups

Left panel: TASD vs. LArTPC for NH true & Right panel: Combined set-up for NH true

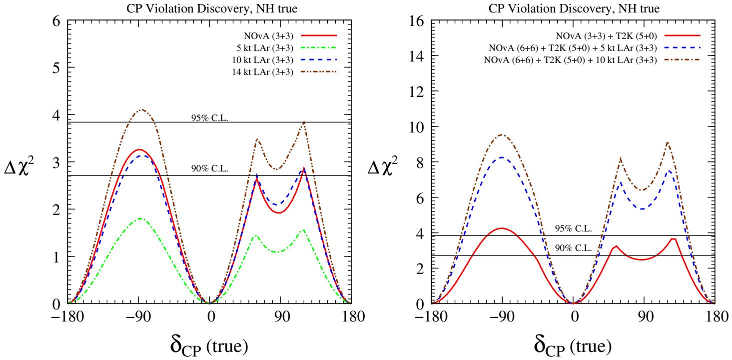




- Left panel: LArTPC of mass 10 kt can be as effective as 14 kton TASD
- Right panel: With the addition of a 10 kt LArTPC, close to 95% C.L. hierarchy discrimination becomes possible for all the values of δ_{CP}

Leptonic CP violation discovery for various set-ups

Left panel: TASD vs. LArTPC for NH true & Right panel: Combined set-up for NH true

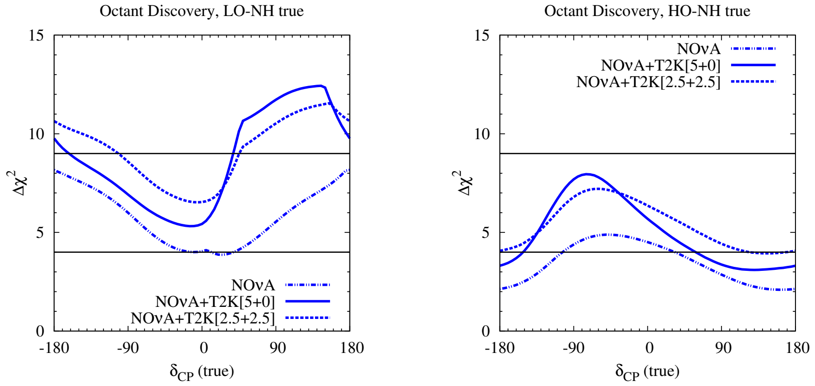


- Left panel: LArTPC of mass 10 kt can be as effective as 14 kton TASD
- Right panel: Addition of a 10 kt LArTPC significantly improves range of true δ_{CP} for which CP conservation can be ruled out at 95% C.L.

Sensitivity of upgraded NOνA and T2K for θ_{23} octant

θ_{23} octant discovery for various set-ups

Left panel: Lower Octant(LO) & Right panel: Higher Octant(HO)



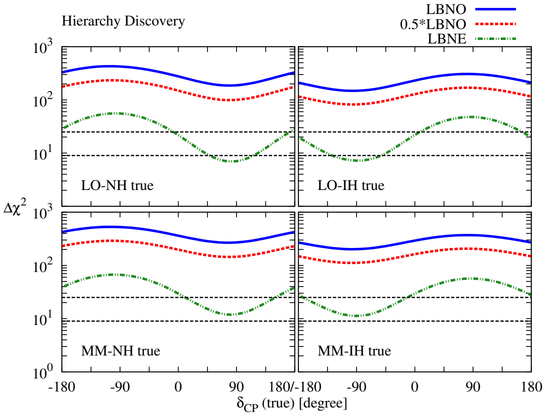
- A balanced neutrino-anti-neutrino data will help.

LBNE and LBNO

Characteristic	Long baseline neutrino experiment (LBNE)	Long baseline neutrino oscillation experiment(LBNO)
Baseline	1300 km	2290 km
Location	Fermilab - Homestake	CERN-Pyhasalmi
Beam	On-axis	Wide band beam
Beam power	0.7 MW	0.75 MW
Beam peaks at	$\sim$ 2.5 GeV	$\sim$ 3.5 GeV
$P_{\mu e}$ 1st Osc. Maximum	2.5 GeV	3.5 GeV
Detector	LArTPC 10kt	LArTPC 20kt
Runtime	5 in ν+5 in $\bar{\nu}$	5 in ν+5 in $\bar{\nu}$

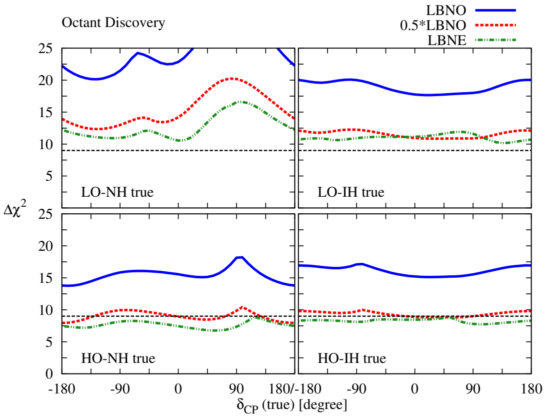
Sensitivity of LBNE and LBNO for mass hierarchy

Mass hierarchy discovery for various set-ups



- LBNO has a $\sim 10\sigma$ hierarchy discovery potential for all octant-hierarchy combinations and for any δ_{CP} value
- LBNE will not provide a 5σ result for about 50% of the δ_{CP} range.

θ_{23} - octant discovery for various set-ups



- Both the set-ups have reasonable sensitivities; about 4σ for LBNO and 3σ for LBNE.


THANK
you !

Appearance channel and matter effects

- The appearance channel (in which a ν_μ oscillates to and is detected as ν_e) is the best bet to find the unknowns of neutrino physics as it is sensitive to all those parameters.
- It was mentioned in the previous slide that in LBL experiments, the beam is made to travel through the earth. This serves a very special purpose.
- Earth affects the propagation of the 3 different neutrino eigenstates differently because, in general, it has more electron/positrons compared to other charged leptons.
- Because of matter effects, the neutrino probabilities are affected differently for the two hierarchies. Matter amplifies $P_{\mu e}$ for neutrinos and NH while suppresses it for IH. The behavior is reverse for anti-neutrinos.
- So, depending on the predicted number of events in the detector and the observed data, these experiments are, in principle, capable of discerning the hierarchy.

Reactor neutrino experiments

- Fission in nuclear reactors is a copious source of electron anti-neutrinos.
- The reactor neutrino experiments detect electron anti-neutrinos through the inverse neutron decay process: $\nu_e + p \rightarrow n + e^+$.
- The baselines for these experiments vary from 100m to 1km.
- The experiments generally have a near detector and a far detector. The purpose of the near detector is to measure the anti-neutrino flux accurately. Then the far detector measures the flux again.
- This re-measurement looks for a depletion in the anti-neutrino flux. Thus, what one measures here is the disappearance of $\bar{\nu_e}$.
- $P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2(\frac{1.27\ L\ \Delta_{31}}{4E})$
- Thus the depletion in the number of events, in the far detector, from expected, can give an estimate of the mixing angle θ_{13}.

Reactor neutrinos and θ_{13}

- Sometime back, the reactor experiments Daya Bay (in China), Double Chooz (in France) and RENO (in Korea) provided us with a measurement of $\sin^2 2\theta_{13}$ with a high confidence.
- The value of θ_{13} measured is moderately large $\sim 8^\circ$.
- This is a very welcome news for the neutrino physics community as θ_{13} directly controls the performance of long baseline experiments.
- The appearance probability and hence the number of events observed in the detector in LBL experiments is directly proportional to $\sin^2 2\theta_{13}$ and hence with a large θ_{13}, one can hope to have some results even with moderate statistics which would have been impossible if $\theta_{13} \sim 0$

Summary

- Neutrino oscillations are on very strong footing. While, there may be interesting new physics addendum, the neutrino physics community does not doubt the phenomena.
- Neutrino oscillation experiments are of crucial importance as they will provide us with inputs for selection/ rejection for various beyond standard model theories.
- Neutrino experiments are a very challenging task and require arduous engineering and manpower.