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Research Statement

The physics of neutrino oscillations is sensitive to 6 neutrino oscillation parameters: three mixing angle - θ_{12}, θ_{13} and θ_{23}, a CP violating phase - δ_{CP} and two independent mass-squared differences - $\Delta_{21}(m_2^2 - m_1^2)$ and $\Delta_{31}(m_3^2 - m_1^2)$ between the 3 mass eigenstates. Of these oscillation parameters, the remaining unknowns (after recent reactor neutrino data) are: the sign of Δ_{31}(known as the mass hierarchy problem), the value of the CP phase(δ_{CP}) and the octant of θ_{23} (whether θ_{23} is smaller or larger than 45°). My work focuses on studying the capabilities of various proposed experiments for determination of these unknowns.

M.Sc thesis: A study of matter effects in neutrino oscillations
For my master's degree thesis, I studied the basics of neutrino oscillation physics and how oscillation probabilities get affected by matter. I, then, derived the matter-modified PMNS mixing matrix and using it, the expression for the electron appearance probability($P_{\mu e}$) up to second order in Δ_{21}. Further, I explored an interesting phenomena in the electron appearance channel which is the following. For each baseline, there is a range of energy for which $P_{\mu e}$ is very small in case of inverted hierarchy and loses its δ_{CP} dependence. This happens because for these energies, there is no contribution from the 1st and 2nd order terms in $P_{\mu e}$. For a suitable baseline and energy range, this feature can be tapped to determine hierarchy with a high significance.

The software GLoBES(General Long Baseline Experiment Simulator)
The software GLoBES [1, 2] simulates neutrino oscillation long baseline and reactor experiments. In this software, it is possible to import experiment information at an abstract level and then process this information using a C-library to obtain oscillation probabilities, event numbers and $\Delta\chi^2$-values. I understand this software properly and have used it extensively for most of my work.

The Fermilab-Homestake 1300 km LBL experiment - DUSEL and Migration Matrices
As a first in understanding the software GLoBES and details of oscillation phenomenology, we tried to reproduce the results of [3]. This work was focused on studying the capabilities of a megaton water cerenkov detector at the Homestake mine which will search for electron events in a muon neutrino beam coming from Fermilab, 1300 km away. We succeeded in reproducing the relevant results at the events and $\Delta\chi^2$-level in this paper with a very good match. A distinct part of my work on this topic was generating the migration matrices needed for correct reproduction of the neutral current spectrum which acts as a background for electron appearance channel. The understanding for producing migration matrices was derived from [4]. Using the Monte Carlo events generator NUANCE and with purely kinematic considerations, I generated the migration matrices needed for this work. However, DUSEL, as it was envisaged, did not receive funding. Any publication did not come out from this work. But, I gained a lot from the tools and techniques developed during this work.

The "Bimagic" 2540 km long baseline superbeam experiment
In [5], the very interesting physics behind the 2540 km long baseline and neutrinos of energy around 3.3 GeV was first reported. This was later termed as the "bimagic" baseline in [6]. At this baseline and energy for neutrinos, the $P_{\mu e}$ oscillation probability is peaked for NH and shows substantial δ_{CP} dependence while for IH, it is suppressed and is independent of δ_{CP}. In [7, 8], we studied the physics potential of a neutrino superbeam experiment with a 2540 km baseline. We assumed a neutrino beam similar to the NuMI beam in medium energy configuration and a 100 kT totally active scintillator detector at a 7 mr off-axis location. We found that such a configuration has outstanding hierarchy discriminating capability. In conjunction with the data from the present reactor neutrino experiments, it can determine the neutrino mass hierarchy at 3σ level in less than 5 years, if $\sin^2(2\theta_{13}) > 0.01$, running in the neutrino mode alone. As a stand alone

experiment, with a 5 year neutrino run and a 5 year anti-neutrino run, it can determine non-zero θ_{13} at 3σ level if $\sin^2(2\theta_{13}) > 7\times10^{-3}$ and hierarchy at 3σ level if $\sin^2(2\theta_{13}) > 8\times10^{-3}$. This data can also distinguish $\delta_{CP} = \pi/2$ from the CP conserving values of 0 and π, for $\sin^2(2\theta_{13}) > 0.02$.

Mass hierarchy and δ_{CP} determination with present & upcoming LBL superbeam experiments
In June 2011, T2K reported its first results on θ_{13}. Since then, the reactor data has ruled out $\sin^2 2\theta_{13} = 0$ at a very high confidence level. The present global best-fit on $\sin^2 2\theta_{13}$ is close to 0.1. With such moderately large value of $\sin^2 2\theta_{13}$, the role of presently running and next generation long baseline superbeam experiments in finding the unknowns in neutrino physics has become important. In [9], we explored the combined physics potential of T2K and NOνA in light of the moderately large measured value of θ_{13}. For $\sin^2 2\theta_{13} = 0.1$, which is close to the best fit value, a 90% C.L. evidence for the hierarchy can be obtained only for the combinations (Normal hierarchy, $-170^\circ \le \delta_{CP} \le 0$) and (Inverted hierarchy, $0 \le \delta_{CP} \le 170^\circ$), with the currently planned runs of NOνA and T2K. However, the hierarchy can essentially be determined for any value of δ_{CP}, if the statistics of NOνA are increased by 50% and those of T2K are doubled. Such an increase will also give an allowed region of δ_{CP} around its true value, except for the CP conserving cases $\delta_{CP} = 0$ or 180°. We explored in detail the hierarchy-δ_{CP} degeneracy which is responsible for poorer sensitivities at relatively smaller baselines and showed that such a degeneracy can be lifted by combining data from two experiments at different baselines. We demonstrated that any measurement of δ_{CP} is not possible without first determining hierarchy and found that comparable data from a shorter baseline (L$\sim$130 km) experiment will not lead to any significant improvement.

Mass hierarchy & Octant determination with Atmospheric neutrinos
In [10], we explored the capabilities of a 50 kT magnetized liquid argon neutrino detector for mass hierarchy and octant determination. While participating in this work, I fully understood the mechanism of atmospheric neutrino analysis and I am presently working to develop an effective atmospheric neutrino analysis code of my own. Atmospheric neutrino detectors may not match the precision to pin down the energy and direction of an event characteristic of long baseline experiments. Nonetheless, they have some strong compensating advantages. Atmospheric neutrinos offer a broad range in baselines ($L \sim$ 20 km to 12500 km) and energy E (100 MeV to 10 TeV). They are either insensitive to, or, help in resolving the degeneracies that plague the long baseline superbeam experiments. Large-mass liquid argon time projection chambers (LArTPCs) offer one of the most promising technologies for charged particle detection. They have unprecedented capabilities for the detection of neutrino interactions because of their precise and sensitive spatial and calorimetric resolution. In this work, we have shown that a 50 kT magnetized liquid argon neutrino detector can ascertain the mass hierarchy with a significance larger than 4σ with moderate exposure times, and the octant at the level of 2σ to 3σ with greater exposure.

Reoptimized NOνA, in the large θ_{13} scenario, along with a 10 kton liquid argon detector
In light of the recently measured moderately large value of θ_{13}, NOνA experiment has reoptimized its event selection criteria. The previous optimization was done under the most pessimistic assumption of $\sin^2 2\theta_{13} = 0$. The cuts were effected so as to have the maximum signal to background ratio. But now, with $\sin^2 2\theta_{13}$ being large, one can afford to have looser cuts so as to allow more signal as well as background. In [11], we studied the improvement in the sensitivity to the neutrino mass hierarchy and to leptonic CP violation due to these new features. The information about reoptimization done by the collaboration was derived from [12, 13]. We found that for favorable values of δ_{CP}, NOνA's sensitivity to mass hierarchy and leptonic CP violation is increased by 20%. Addition of 5 years of neutrino data from T2K to NOνA more than doubles the range of δ_{CP} for which the leptonic CP violation can be discovered, compared to stand alone NOνA. But for unfavorable values of δ_{CP}, the combination of NOνA and T2K are not enough to provide even a 90% C.L. hint of hierarchy discovery. Therefore, we further explored the improvement in the hierarchy and CP violation sensitivities due to the addition of a 10 kt liquid argon detector placed close to NOνA site. The capabilities of such a detector are equivalent to those of NOνA in all respects. We find that combined data from 10 kt liquid argon detector (3 years of ν + 3 years of $\bar{\nu}$ run), NOνA (6 years of ν + 6 years of $\bar{\nu}$ run) and T2K (5 years of ν run) can give a close to 2σ hint of hierarchy discovery for all values of δ_{CP}. With this combined data, we can achieve CP violation discovery at 95% C.L. for roughly 60% values

of δ_{CP}.

Resolving the octant of θ_{23} with present and upcoming long baseline superbeam experiments
Preliminary results of MINOS experiment [14] indicate that θ_{23} is not maximal. Global fits [15, 16, 17] to world neutrino data suggest two nearly degenerate solutions for θ_{23}: one in the lower octant (LO: $\theta_{23} < \pi/4$) and the other in the higher octant (HO: $\theta_{23} > \pi/4$). $\nu_\mu \to \nu_e$ oscillations in superbeam experiments are sensitive to the octant and are capable of resolving this degeneracy. In [18], we study the prospects of this resolution by the current T2K and upcoming NOνA experiments. Because of the hierarchy-δ_{CP} degeneracy and the octant-δ_{CP} degeneracy, the impact of hierarchy on octant resolution has to be taken into account. As in the case of hierarchy determination, there exist favorable (unfavorable) values of δ_{CP} for which octant resolution is easy (challenging). However, for octant resolution the unfavorable δ_{CP} values of the neutrino data are favorable for the anti-neutrino data and vice-verse. This is in contrast to the case of hierarchy determination. In this paper, we compute the combined sensitivity of T2K and NOνA to resolve the octant ambiguity. If LO is the true octant, then NOνA can rule out HO at 2σ C.L., irrespective of the hierarchy and δ_{CP}. Addition of T2K data improves the octant sensitivity. If HO and normal hierarchy are the true choices, then the combined data from NOνA and T2K with its designed five years run in neutrino mode, is incapable of a 2σ resolution of the octant for all δ_{CP}. A 2σ resolution of the octant, for all combinations of neutrino parameters, becomes possible if T2K has balanced neutrino and anti-neutrino runs of 2.5 years each.

Work in progress
I plan to finish two more projects for my Ph.D thesis. A very brief description of those work is as follows.

- Studying the physics potential of MINOS+.
- On a different theme, a work on a possible Higgs decay mode.

Future research interests
The experience and expertise that I have gained in neutrino oscillation phenomenology will help me in continuing to work on this topic alongside some other exciting topics in high energy physics as the primary work. I am keen to work on some of the following topics.

- Flavor physics
- Dark matter and dark energy
- Sterile neutrinos
- Neutrino masses and mixing models
- Electroweak phenomenology
- B-physics

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