Evidence for leptonic CP phase from NOνA, T2K and ICAL

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Introduction

- In neutrino oscillation one flavor evolves into another.
- This is because the flavor eigenstates and mass eigenstates are not same and related by

$$|\nu_\alpha\rangle = \sum_{i=1}^{N} U_{\alpha i}|\nu_i\rangle$$

Where U is the unitary PMNS matrix which diagonalize the neutrino mass matrix

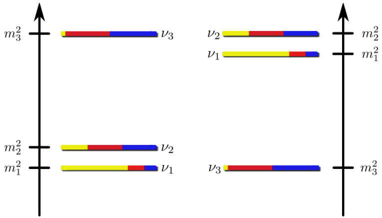
$$m_\nu = U m_\nu^{diag} U^T$$

where $m_\nu^{diag} = diag(m_1, m_2, m_3)$

- In standard three generation framework U can be parametrized by three mixing angles i.e θ_{12}, θ_{13}, θ_{23} and one phase δ_{CP}.

Continue...

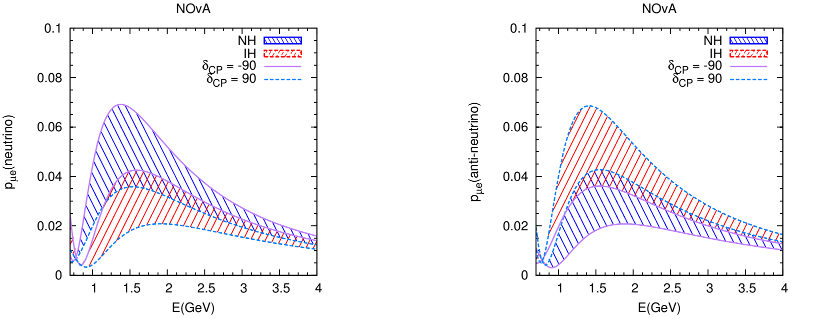
- Neutrino oscillation also involves two independent mass squared difference i.e the solar mass square difference $(m_2^2 - m_1^2 = \Delta_{21})$ and the atmospheric mass squared difference $(m_3^2 - m_1^2 = \Delta_{31})$.



- The undetermined sign of Δ_{31} give rise to two possible mass orderings i.e. Normal Hierarchy(NH i.e $m_3 > m_1$) and Inverted hierarchy(IH i.e $m_3 < m_1$)

- $P_{\mu e}$ can be expressed in terms $\alpha = \frac{\Delta_{21}}{\Delta_{31}}$, $\hat{A} = \frac{A}{\Delta_{31}}$, $\Delta = \frac{\Delta_{31} L}{4E}$

$$P_{\mu e} = 4 s_{13}^2 s_{23}^2 \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$



- degenerate region : (NH, 90) with (IH,-90)

Experimental Specification

- For NOνA(L=812 km), we have assumed a 14 kT totally active scintillator detector(TASD) for $5(\nu) + 5(\overline{\nu})$ years.
- T2K(L=295 km) is assumed to have a 22.5 kT Water Čerenkov detector, for $5(\nu) + 0(\overline{\nu})$ years.
- For atmospheric neutrinos we consider ICAL@INO, which can distinguish μ^+ and μ^- events, with a proposed mass of 50 kT.

Events for NOνA and T2K are simulated using GLoBES [1]

[1] P. Huber, J. Kopp, M. Lindner, M. Rolinec and W. Winter, Comput. Phys. Commun. **177**, 432 (2007)

The CP violation discovery χ^2

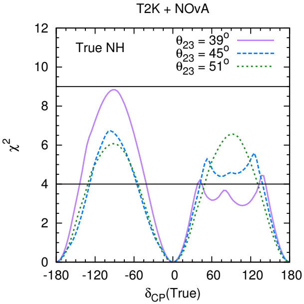
- The CPV discovery χ^2 is defined as

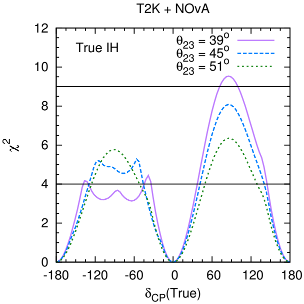
$$\chi^2 = \min \frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test} = 0, 180^o))^2}{N_{ex}(\delta_{CP}^{tr})}$$

- The discovery potential of the experiments is zero for true $\delta_{CP} = 0$ and 180°, while it is close to maximum at the maximally CP violating values $\delta_{CP} = \pm 90^\circ$

CPV discovery potential of NOνA and T2K

- The CPV χ^2 is plotted as a function of δ_{CP}(True)
- Hierarchy is marginalised in the test(Hierarchy unknown)





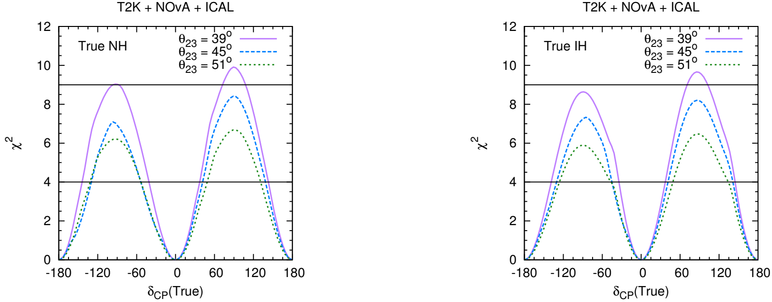
- There is a drop in χ^2 in degenerate region(recall:which is at (NH, 90) and (IH,-90)) i.e χ^2 minima comes in the wrong hierarchy.
- Hierarchy sensitivity increases with increasing θ_{23}.
- This results as removal of degeneracy at $\theta_{23} = 51^o$.

Atmospheric neutrinos have no CP sensitivity due to angular smearing

- The muon events in atmospheric neutrinos get contributions from both $P_{\mu\mu}$ and $P_{\mu e}$.
- In these probabilities, the δ_{CP}-dependent term always appears along with a factor of $\cos\Delta$ or $\sin\Delta$.
- If we consider even a 10% error range in the zenith angle and energy of the neutrino, this oscillating term varies over an entire cycle in this range.
- As a result, the δ_{CP}-sensitivity of the channel gets washed out because of smearing.

CPV discovery potential of NOνA+T2K+ICAL

- When ICAL data added the drop vanishes



- The hierarchy sensitivity of ICAL restores the minima at correct hierarchy
- Once minima comes in the right hierarchy, ICAL becomes useless
- This is why curves for $\theta_{23} = 51^o$ remains unaltered.

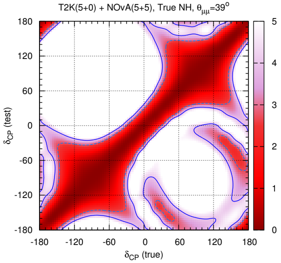
The CP precision χ^2

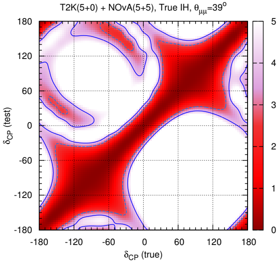
- The CP precision χ^2 is defined as

$$\chi^2 = \min \frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test}))^2}{N_{ex}(\delta_{CP}^{tr})}$$

- This shows the test δ_{CP} range allowed by the data for each true value of δ_{CP}, up to a specified confidence level

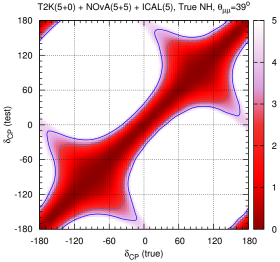
CP precision plots for NOνA and T2K

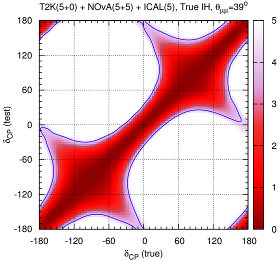




- The allowed values of δ_{CP} are represented by the shaded regions(at 90% and 95% C.L)
- Allowed region would be along the ${\delta_{CP}}^{tr} = {\delta_{CP}}^{test}$ diagonal
- Off diagonal allowed regions are the wrong hierarchy solutions(Again recall: (NH,90) and (IH,-90))

CP precision plots for NOνA+T2K+ICAL





- The wrong hierarchy solutions are excluded
- The allowed region along the diagonal remains unchanged

θ_{13} and θ_{23} dependence in CPV discovery χ^2

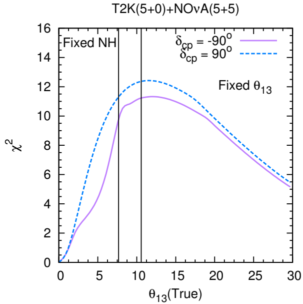
- The leading order term in $P_{\mu e}$ depends on $s^2_{13}s^2_{23}$ and subleading term on $\sin 2\theta_{13} \sin 2\theta_{23} f(\delta_{CP})$
- So θ_{13} and θ_{23} has similar dependence
- The χ^2 can be expressed as

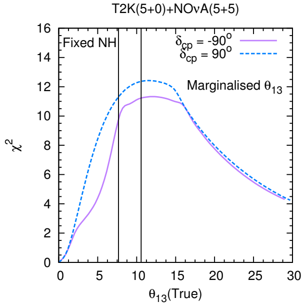
$$\chi^2 \sim \frac{P(\delta_{CP}) \sin^2 2\theta_{i3}}{Q \sin^2 \theta_{i3} + R(\delta_{CP}) \sin 2\theta_{i3}} \; ,$$

  where i=1,2

- for small values of θ_{i3}, $\chi^2 \sim \theta_{i3}$ which is an increasing function
- when θ_{i3} is close to 90°, $\chi^2 \sim (90^\circ - \theta_{i3})^2$ which decreases with θ_{i3}.
- Therefore, CP sensitivity initially increases with θ_{i3} , peaks at an optimal value, and then decreases with θ_{i3}

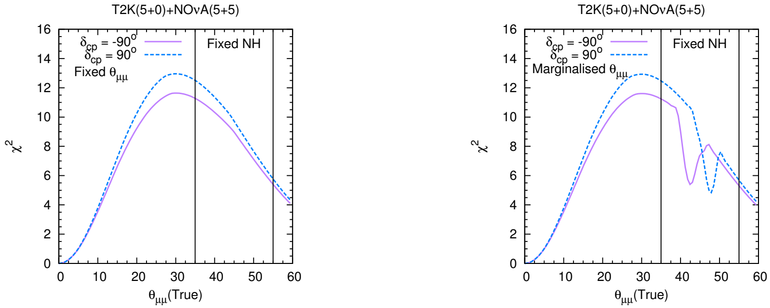
CPV discovery χ^2 vs θ_{13}





- The vertical lines denote the current θ_{13} range ($\sin^2 2\theta_{13} = 0.07 - 0.13$)
- It lies in a region where the sensitivity to CP violation is maximum

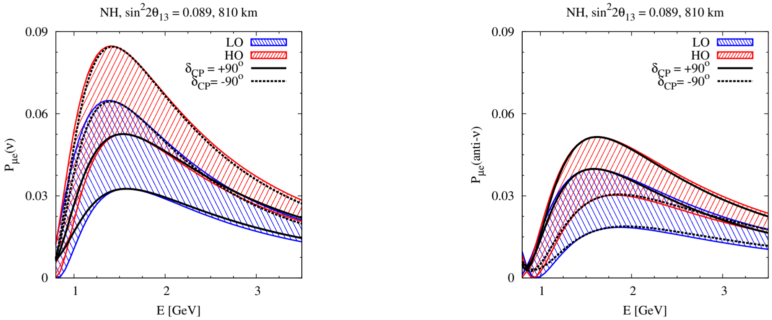
CPV discovery χ^2 vs θ_{23}



- CP sensitivity falls in the allowed 3σ range
- we see a wiggle in the discovery χ^2 in $40 < \theta_{23} < 49$ when θ_{23} is marginalized
- This signals the presence of δ_{CP}-octant degeneracy

The δ_{CP}-octant degeneracy in NOνA

- LO: Lower Octant i.e $35^o < \theta_{23} < 45^o$
  HO: Higher Octant i.e $45^o < \theta_{23} < 55^o$

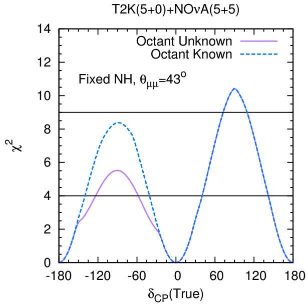


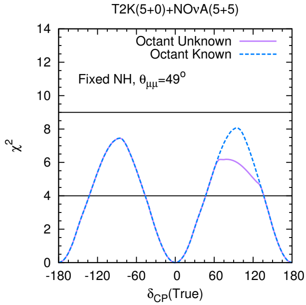
- For neutrino mode the degeneracy is in the region (-90, LO) and (90, HO),which is resolved by anti-neutrino mode
- For the anti-neutrino mode the degeneracy is in the region (-90, HO) and (90, LO) which is resolved by neutrino mode [2]

[2] S. K. Agarwalla, S. Prakash and S. U. Sankar, JHEP **1307**, 131 (2013)

The octant sensitivity of NOνA and T2K

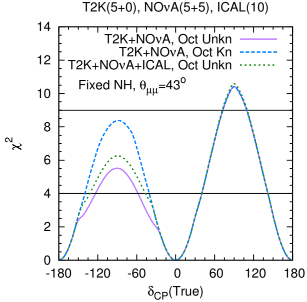
- The CPV χ^2 is plotted as a function of δ_{CP}(True)
- Hierarchy is kept fixed at NH(i.e Hierarchy known)

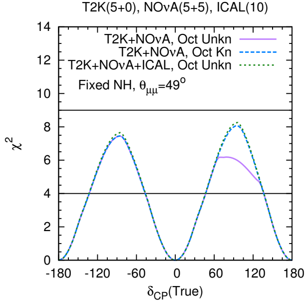




- There is a drop in the (-90,LO) and (90,HO) when octant is unknown.
- The degeneracy in the (90,LO) and (-90,HO) is resolved by dominant neutrino run

The octant sensitivity of NOνA+T2K+ICAL





- The δ_{CP}-octant degeneracy is restricted to $41 < \theta_{23} < 48$ when ICAL data is added
- This results in resolving the degeneracy at 49 but not at 42

Conclusion

- we see that there is a drop in CP sensitivity for NOνA and T2K in the degenerate region due to hierarchy-δ_{CP} degeneracy
- Inclusion of ICAL exclude the wrong hierarchy solutions
- Present value of θ_{13} lies in the range where CP sensitivity is maximum
- There is also a drop in CP χ^2 in the region of $40 < \theta_{23} < 49$ due to δ_{CP}-octant degeneracy in NOνA and T2K
- Addition of ICAL restricts it to $41 < \theta_{23} < 48$

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Thank You