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Complementarity Between Hyperkamiokande and DUNE

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In this talk we present our results on the sensitivity to the neutrino mass hierarchy, the octant of the mixing angle and the CP phase in the future long baseline experiments T2HK and DUNE as well as in the atmospheric neutrino observation at Hyperkamiokande (HK).

1 Introduction

Thanks to the neutrino experiments in the last two decades, the values of the three mixing angles and the values of the mass squared differences are now determined in the three flavor mixing framework to some precision. The unknown quantities at present are: (i) the mass hierarchy or the sign of Δm^2_{31} (NH: normal hierarchy i.e., $\Delta m^2_{31} > 0$ or IH: inverted hierarchy i.e., $\Delta m^2_{31} > 0$), (ii) the octant of θ_{23} (LO: lower octant i.e., $\theta_{23} < 45^\circ$ or HO: higher octant i.e., $\theta_{23} > 45^\circ$) and (iii) the CP phase δ_{CP}. These unknown quantities are expected to be determined in the future experiments, such as T2HK[2], DUNE[3] and the atmospheric neutrino measurement at HK[4], etc. The T2HK experiment is an upgrade of the ongoing T2K experiment which will use a detector to have a volume almost 25 times larger than the existing T2K detector. HK is the atmospheric counterpart of the T2HK experiment. On the other hand DUNE is a high statistics beam based experiment to use high beam power, large detector volume and longer baseline. In this talk we study for the first time the joint sensitivity of the long-baseline experiments T2HK, DUNE and the atmospheric experiment HK in determining the remaining unknowns in neutrino oscillation sector.[b] In this work we study: (i) the sensitivity of the T2HK, HK and DUNE experiments, (ii) the synergy between the T2HK and HK experiments to resolve the parameter degeneracy in the neutrino oscillation, (iii) how far the sensitivities in determining hierarchy, octant and CP can be stretched when all these three powerful experiments are combined together and (iv) the precision measurements of θ_{23}, δ_{CP} and Δm^2_{31} of this setup.

2 Experimental Specification

For our analysis of T2HK, we took the specification from Ref. 2. We have considered a fiducial volume of 560 kt and a total exposure of 15.6×10^{21} protons on target (pot) running in equal neutrino-antineutrino mode. The systematics are taken as an overall normalization error of 2% (5%) for appearance channel and 0.1% (0.1%) for disappearance channel corresponding to signal (background). For DUNE we have taken the details of the configuration from Ref. 3. A flux corresponding to 1.2 MW beam power is considered in our analysis. We have considered 5 year runtime in neutrino mode and 5 year runtime in antineutrino mode. The detector volume

[a] Speaker

[b] This talk is based on Ref. 1.

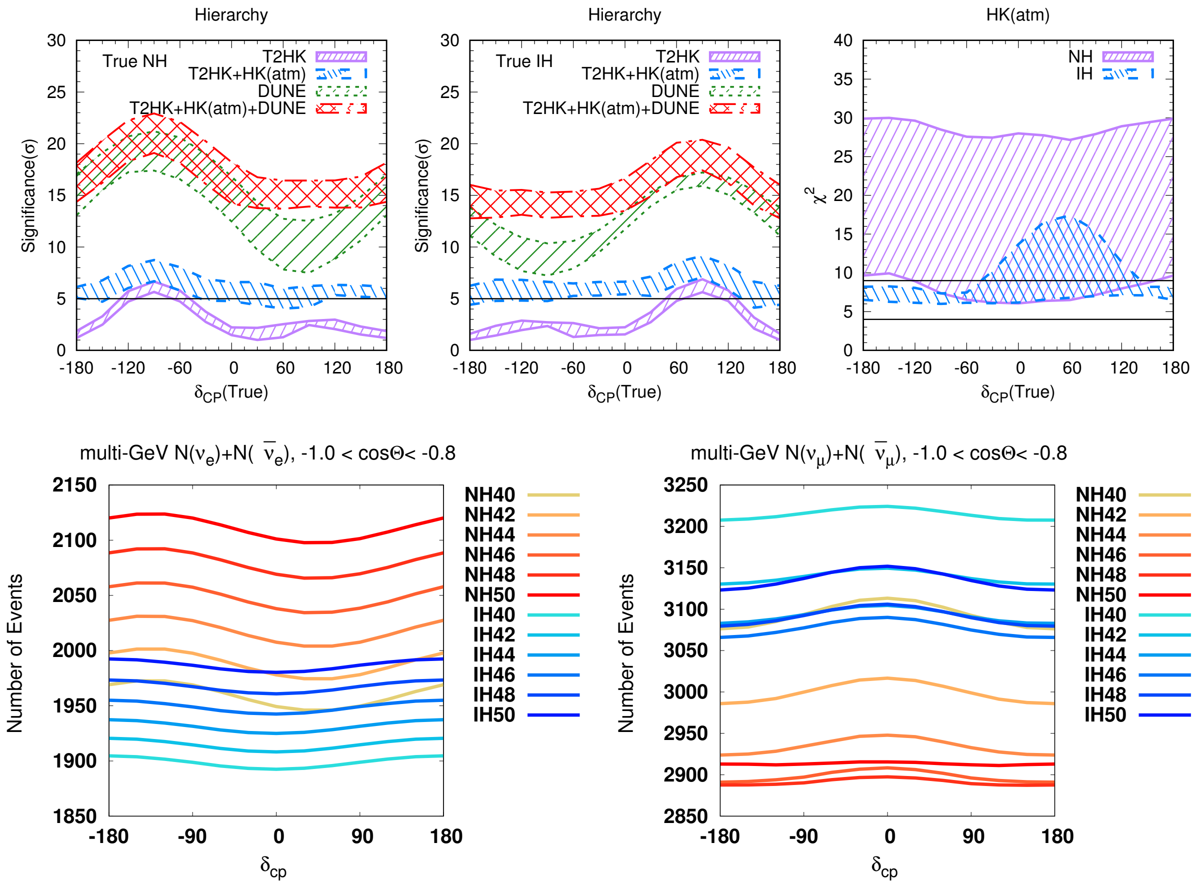

Figure 1 – Hierarchy sensitivity

is taken to be 35 kt. For systematics we have taken an overall normalization error of 2% (10%) for appearance channel and 5% (15%) for disappearance channel corresponding to signal (background). For HK we have taken the details from Ref. 4. A 560 kt water Cerenkov running for 10 year is considered. The systematics are same as used in Ref. 5.

3 Combined Sensitivity of T2HK, HK and DUNE for determining the unknown parameters

3.1 Hierarchy

We have calculated the hierarchy χ^2 by taking the true hierarchy in the simulated data and wrong hierarchy in theory. We have marginalized over θ_{23} from 38° - 52° and δ_{CP} from $-180°$ to $+180°$. We have given our results in Fig 1. From the left and middle panels of the upper row we see that for T2HK the hierarchy sensitivity is poor in the unfavorable parameter space i.e., $0° < \delta_{CP} < 180°$ for NH and $-180° < \delta_{CP} < 0°$ for IH. This is due to the presence of hierarchy-δ_{CP} degeneracy. In these plots the width of the bands is due to the variation of θ_{23} from 40° to 50°. If we add the HK data to T2HK then there is an improvement in the unfavorable regions and we obtain a 5σ hierarchy sensitivity for all the values of true δ_{CP}. However for the combination of T2HK+HK+DUNE, its possible to get a hierarchy sensitivity as high as 15σ for all the values of δ_{CP} for both the hierarchies. In the right panel of Fig. 1, we have shown the hierarchy sensitivity of HK alone. From that plot we understand that hierarchy sensitivity of HK is poor if the true hierarchy is IH. This feature can be explained from the bottom row of Fig. 1, where we have plotted the total electron (left panel) and the total muon (right panel) events as a function of δ_{CP} for different values of θ_{23}. From the plot we notice that in both the panels

NH-LO is degenerate with IH-HO. Thus because of this degeneracy the hierarchy sensitivity of HK for IH is poor as compared to NH.

3.2 Octant and CP

To calculate octant sensitivity χ^2 we have taken the true octant in the simulated data and the wrong octant in the theory. In this process we have marginalized over δ_{CP} and sign of Δm^2_{31} in theory. We have presented our results for octant sensitivity in the upper row of Fig. 2 as a function of true θ_{23}. From the figures we see that the octant sensitivity of T2HK, T2HK+HK and DUNE to exclude wrong octant solution at 5σ C.L is almost same. However, for the combined setup i.e., T2HK+HK+DUNE, there is a significant amount of improvement in the octant sensitivity. For the combined setup it is possible to have a 5σ octant sensitivity except $43.5^\circ < \theta_{23} < 48^\circ$ for both the hierarchies.

In the bottom row of Fig. 2, we have presented the CP violation (CPV) discovery χ^2 as a function of true δ_{CP}. The CPV discovery potential of an experiment is defined by its capability to distinguish a true value of δ_{CP} other than 0° and 180°. In calculating CPV χ^2 we have marginalized over θ_{23} and sign of Δm^2_{31} in theory. We have presented our results for $\theta_{23} = 48^\circ$ which is the current best-fit value of this mixing angle as obtained from the global analysis of the world data. From the plots we see that CP sensitivity of T2HK is poor in the unfavorable parameter space as mentioned earlier. But if we add HK data to T2HK, then there is an improvement in the unfavorable region. This is because the hierarchy sensitivity of HK resolves the hierarchy-δ_{CP} degeneracy. For the combined setup we find that a 10σ CP sensitivity is obtained for $\delta_{CP} = \pm 90^\circ$. In the lower panel of Fig. 2 we have plotted the fraction of δ_{CP} for which a 5σ CPV can be discovered as a function of θ_{23}. From these figures wee see that the sensitivity of T2HK and DUNE is similar for both the hierarchies. From the panels we also note that for the combined setup i.e., T2HK+HK+DUNE, CPV can be discovered at 5σ for at least 70% values of true δ_{CP} irrespective of the true value of θ_{23}.

4 Precision of δ_{CP}, θ_{23} and Δm^2_{31}

To gauge the precision of δ_{CP} in this setup, in the upper panels of Fig. 3 we have given 3σ C.L contours in the true δ_{CP} - test δ_{CP} plane. We have given our results for $\theta_{23} = 48^\circ$. From the plots we see that the precision of δ_{CP} is poor for T2HK. Apart from the true diagonal solution, there are also off diagonal fake solutions. As mentioned earlier, these wrong solutions appear due to the hierarchy-δ_{CP} degeneracy. But if we add HK data, then we see that these fake solutions disappears. This is again due to the hierarchy sensitivity of HK. We also notice from the figures that as we keep adding the data from different experiments, the precision of δ_{CP} gets improved. In the middle row we have given the 90% precision plots in the test δ_{CP} - test θ_{23} plane for different true values of δ_{CP} and θ_{23}. Here we have presented our results for normal hierarchy. From the plot we see that for true $\delta_{CP} = -180^\circ$, there are wrong CP solutions for T2HK around $\delta_{CP} = -30^\circ$. But when HK data is added to it we see that the wrong CP solutions get vanished. For the combined setup i.e., T2HK+HK+DUNE, we find that δ_{CP} can be measured within 20% precision for the true value of $\delta_{CP} = -90^\circ$ and $\theta_{23} = 46^\circ$. In the bottom row of Fig. 3, we have plotted the 1, 2 and 3 σ precision plots in θ_{23} - Δm^2_{31} plane. We show our results only for NH. The results for IH is similar as that of NH. From the plots we see that the sensitivity of the combined setup is always better the individual set up. For the combines setup of T2HK+HK+DUNE, it is possible to attain a 0.4% precision in Δm^2_{31} and a 1.3% precision for θ_{23}.

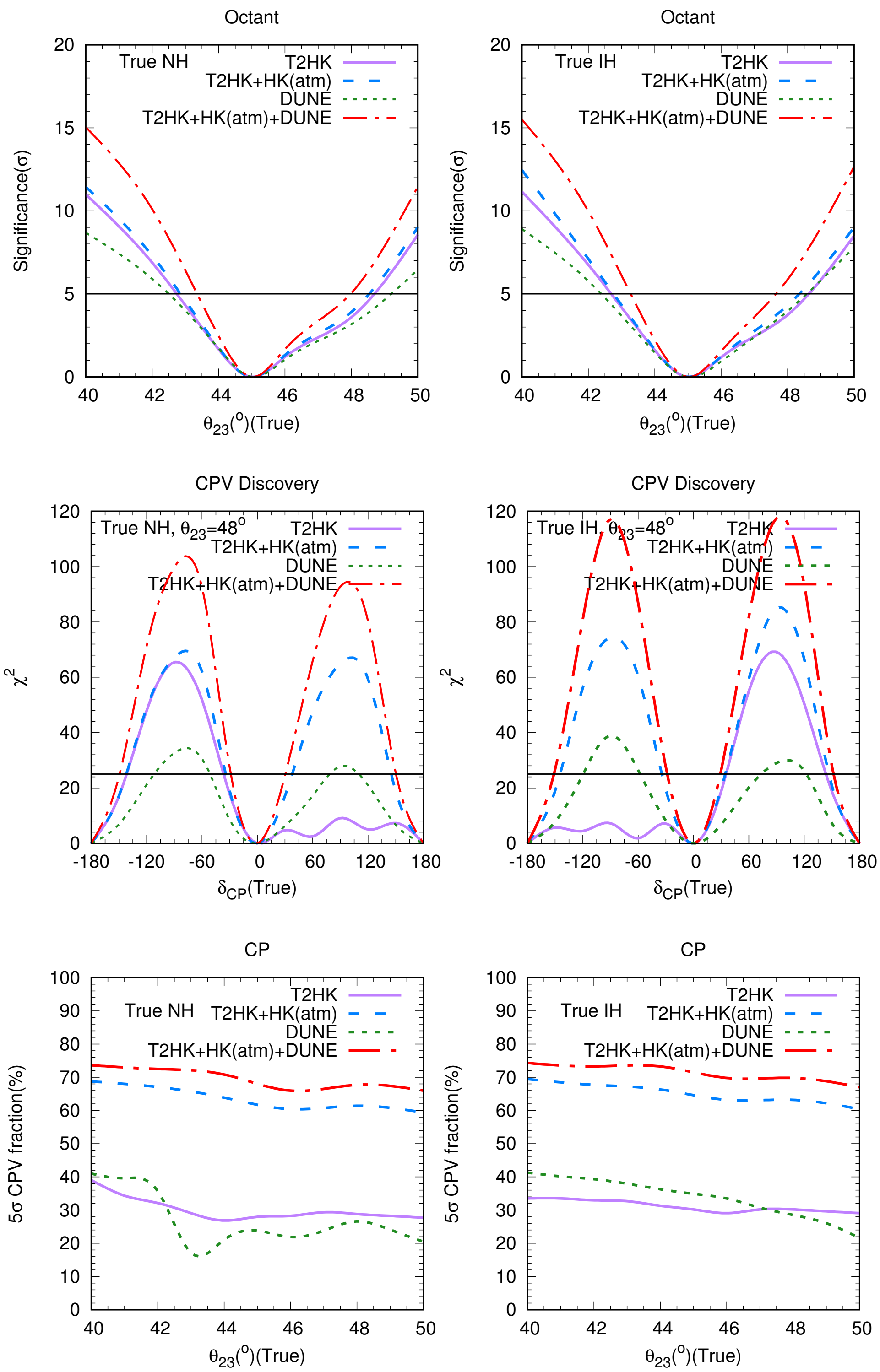

Figure 2 – Octant and CP sensitivity

5 Conclusion

In this talk we have presented the sensitivity of T2HK, HK and DUNE to mass hierarchy, octant of the mixing angle θ_{23} and δ_{CP}. Although it is difficult for T2HK to resolve the sign degeneracy for unfavorable region of the CP phase, when we combine it with the atmospheric neutrino measurement at Hyperkamiokande, we can determine the mass hierarchy at $5\,\sigma$ C.L. for any

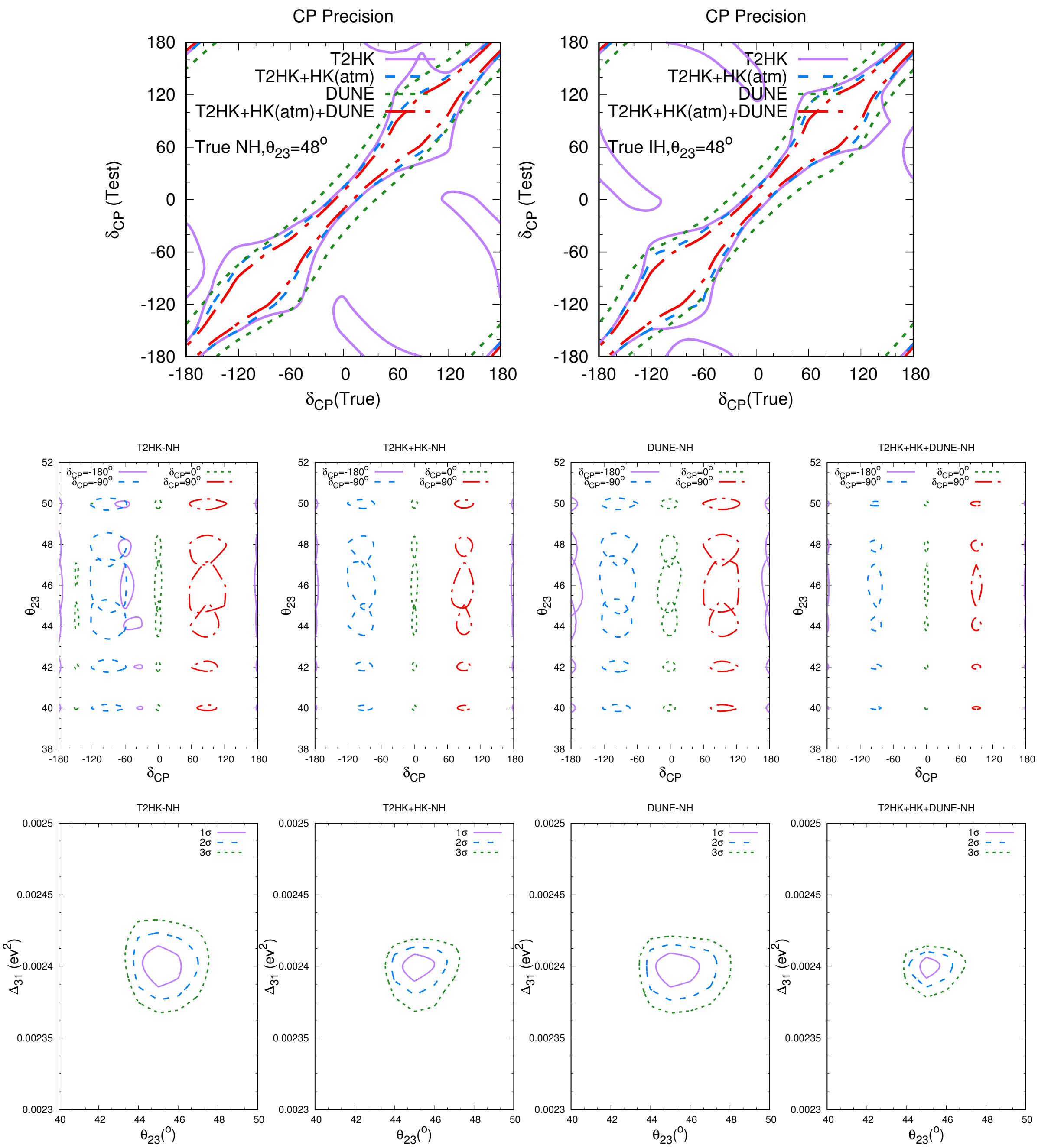

Figure 3 – Precision of δ_{CP}, θ_{23} and Δm^2_{31}

value of δ_{CP}. On the other hand, DUNE can determine the mass hierarchy at least at $8\,\sigma$ C.L. by itself. Furthermore, if we combine all of them, then the significance to mass hierarchy is at least $15\,\sigma$ C.L. In our analysis we found out that the octant sensitivity of T2HK, T2HK+HK and DUNE are quite similar in ruling out the wrong octant at 5σ C.L. But for T2HK+HK+DUNE the increase in the octant sensitivity is significant. For CP violation discovery we find that the combination T2HK+HK can measure CP violation at $8\,\sigma$ C.L. for $\delta_{CP} = \pm 90^\circ$ and for T2HK+HK+DUNE the significance for CP violation is around $10\,\sigma$ C.L. for $\delta_{CP} = \pm 90^\circ$. It is also quite impressive that with the combination of all the three experiment CP violation can be established at 5σ C.L for at least 70% true values of δ_{CP}. In the combination of all these experiments above, the precision in Δm^2_{31} and θ_{23} is 0.4% and 1.3%, which is an improvement by one order of magnitude in precision with respect to the current data. On the other hand, the precision in δ_{CP} is 20%. We will be in the era of precision measurements of neutrino oscillation parameters, and combination of Hyperkamiokande and DUNE will play an important role in determination of δ_{CP} as well as θ_{23}.

Acknowledgements

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