Complementarity Between Hyper-K and DUNE

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International School of Nuclear Physics 39th Course
Erice-Sicily, Italy
September 16-24, 2017

Based on: (i) Fukasawa, MG, Yasuda, NPB **918**, 337 (2017)
(ii) MG, Yasuda, PRD **96**, 013001 (2017)

Neutrino Oscillation

- Neutrino oscillation: transition from one flavor to another
- Reason: Flavour and mass eigenstates are not same

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

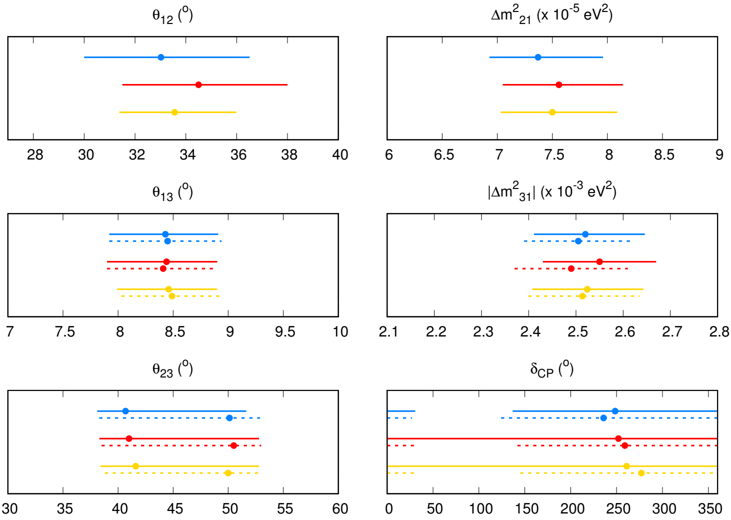
- The transition probability $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

Parameters of neutrino oscillation:

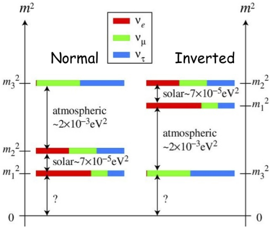
- Elements of U: Three mixing angles and one Dirac phase θ_{12}, θ_{23}, θ_{13}, δ_{CP}
- Two mass squared differences: Appears in $P_{\alpha\beta}$ $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$
- L and E

Current status of oscillation parameters

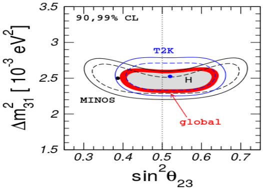


Bari, Valencia, Nufit

Unknowns



- The sign of Δm^2_{31} i.e.,
  $\Delta m^2_{31} > 0 \Rightarrow$ Normal Hierarchy (NH)
  or
  $\Delta m^2_{31} < 0 \Rightarrow$ Inverted Hierarchy (IH).



- The octant of θ_{23} i.e.,
  $\theta_{23} > 45^\circ \Rightarrow$ Higher Octant (HO) or
  $\theta_{23} < 45^\circ \Rightarrow$ Lower Octant (LO).

- δ_{CP} (violation and precision)

Present Experiments

Ongoing experiments to discover the unknowns

T2K in Japan

NOνA in Fermilab

Capability is limited due to:

- Less matter effect
- Low beam power
- Small detector volume

Future Experiments

Future experiments to discover the unknowns
T2HK/T2HKK, HK(atmospheric) in Japan/Korea
DUNE in Fermilab

- Large matter effect
- High beam power
- Huge detector volume

The Hyper-Kamiokande project

T2HK experiment

187×2 kt detector at Kamioka, $L = 295$ km, 2.5° off-axis beam

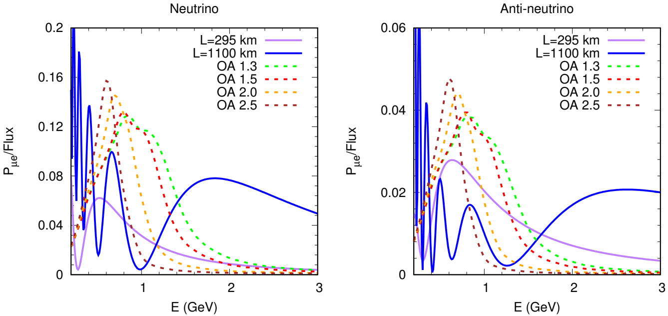
T2HKK experiment

187 kt detector in Korea, 187 kt detector in Kamioka with $L = 1100$ km, Various off-axis flux options from 1.3° to 2.5°

HK(atm) experiment

187×2 kt detector, analyses the oscillations of atmospheric neutrinos

Probability and flux

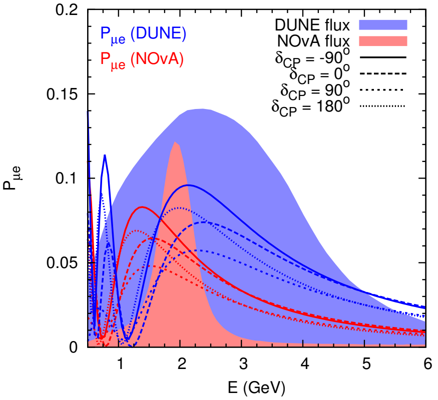


- Off-axis flux

The DUNE Experiment

- L=1300 km, E = 0.5 - 8 GeV
- Liquid Argon detector
- 1.2 MW beam $\implies$ 1.0×10^{21} Protons on Target (POT) per year
- On-axis flux

Flux and Prob



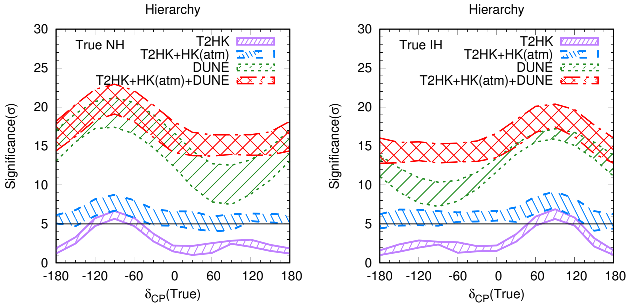
- Broad band flux
- Covers both the maxima

Objective

Mainly to study synergy between T2HK, HK(atm) and DUNE

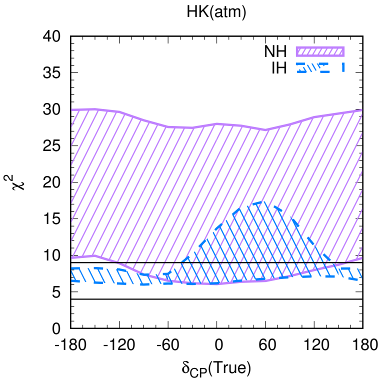
Will also briefly mention the synergy for T2HKK

Hierarchy



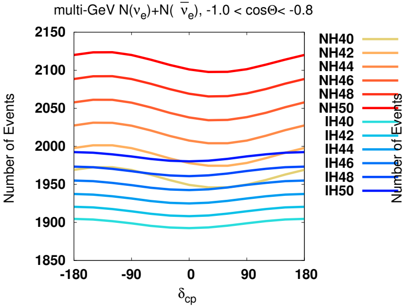
- Sensitivity of T2HK is poor in the degenerate region
- Inclusion of atm data improves sensitivity
- The full combination gives almost 15σ sensitivity

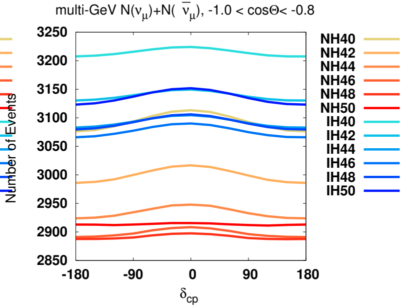
Hierarchy sensitivity of HK(atm)



- Sensitivity is poor for IH
- To understand let us look at the events

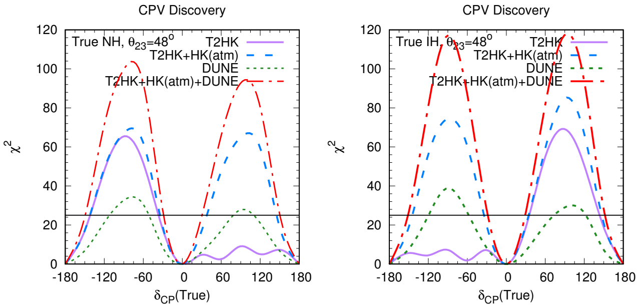
Hierarchy





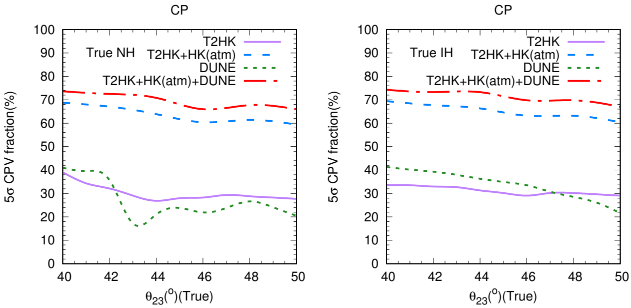
- NH40 is degenerate with IH50
- This is because the lack of charge id

CPV



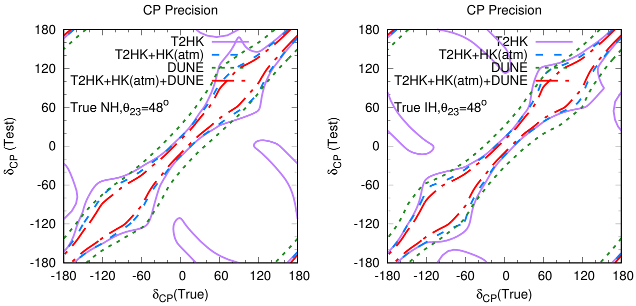
- Sensitivity of T2HK is poor in the degenerate region
- In the non-degenerate region, T2HK is better than DUNE due to more number of events

CPV Coverage



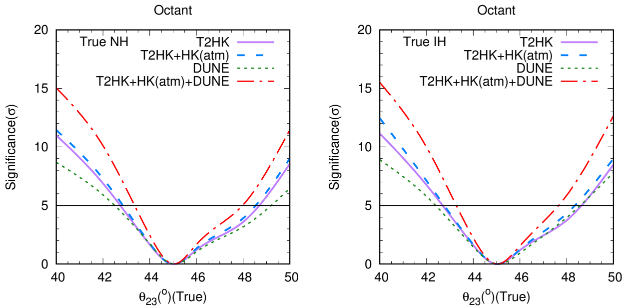
- Sensitivity is same for T2HK and DUNE
- The full combination gives almost 75% CPV coverage

CP Precision



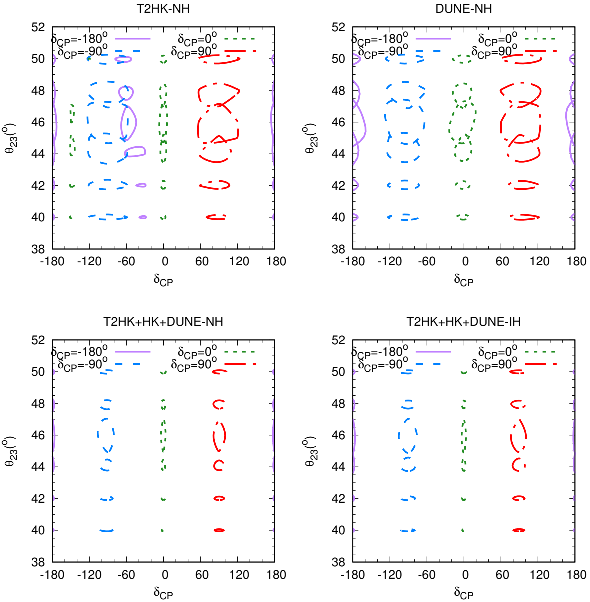
- Sensitivity of T2HK is poor due to degeneracy
- Inclusion of atmospheric data improves the sensitivity

Octant

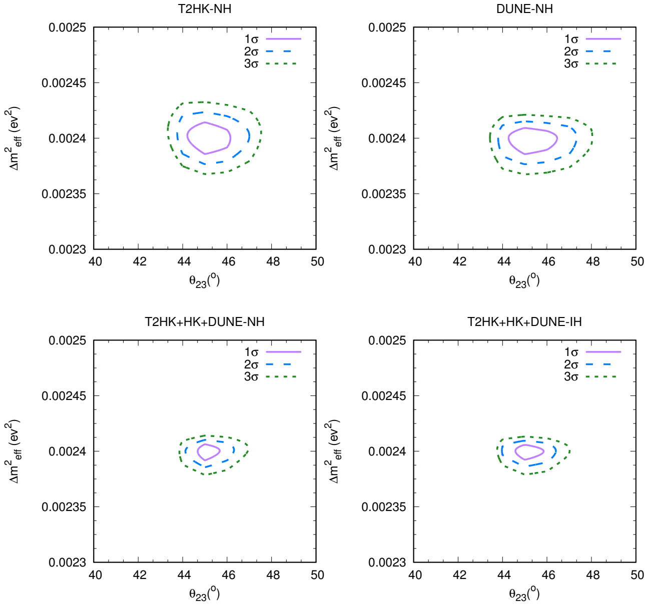


- Sensitivity of T2HK is better than DUNE
- Inclusion of atmospheric data does not improve the sensitivity much

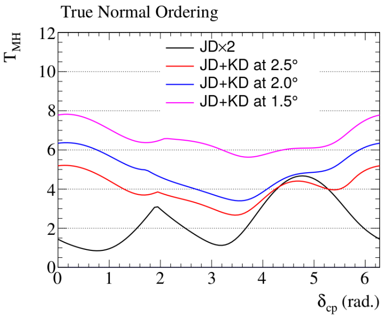
θ_{23} - δ_{CP} precision (90% C.L)

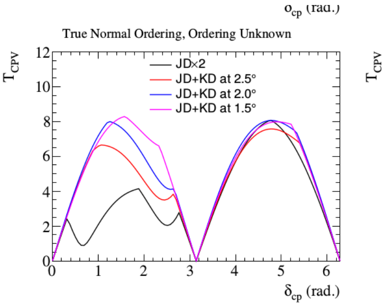


θ_{23} - Δm^2_{31} precision (90% C.L)



Results for T2HKK

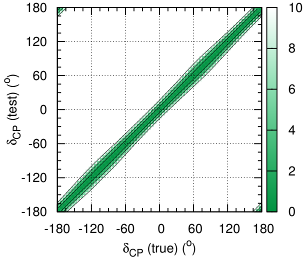


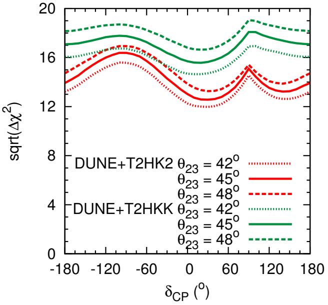


- One detector at Kamioka and another at Korea
- JD $\times 2$: T2HK, JD $+$ KD : T2HKK

T2HKK report, 1611.06118

Synergy between T2HKK and DUNE





- Left: CP, Right: Hierarchy
- 15° CP precision at 1σ

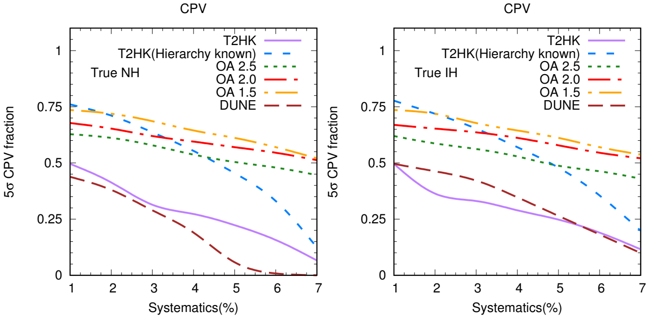
S. K. Raut, 1703.07136

Effect of Systematics

Problem: DUNE and Hyper-K are affected by systematics

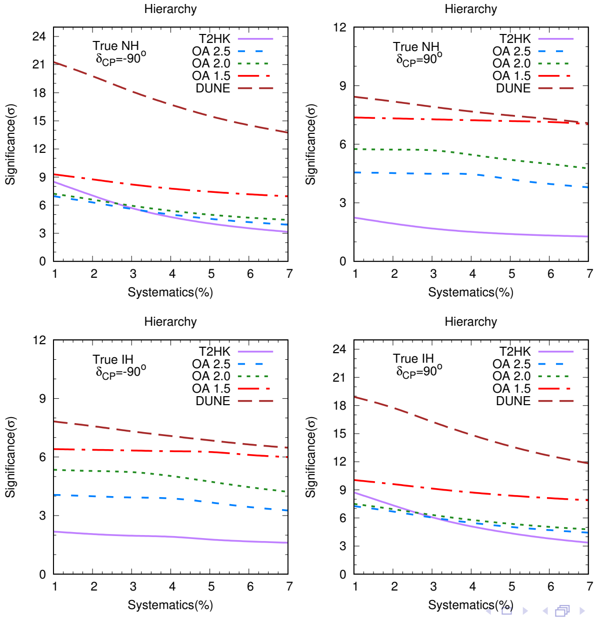
- High statistics experiments
- Sensitive to systematic uncertainties
- A small change in the systematics $\rightarrow$ large change in sensitivity

CPV

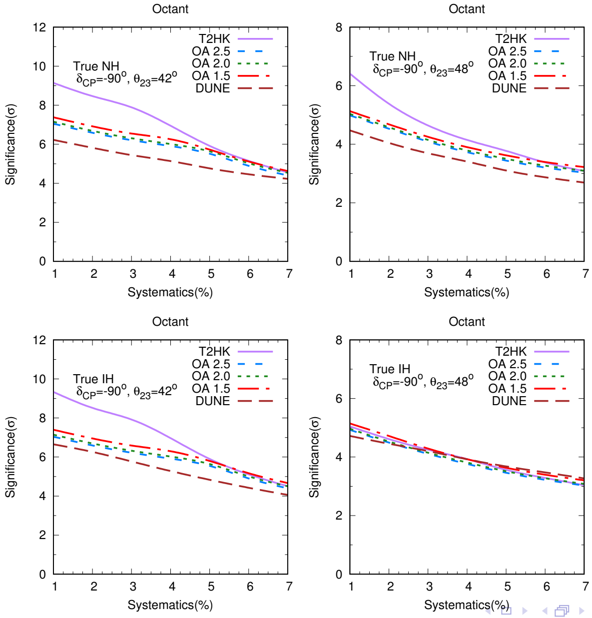


- Curves of T2HK is steeper than T2HKK because of greater number of event sample at T2HK
- If hierarchy is known then sensitivity of T2HK is better than any of T2HKK if systematics is 1%

Hierarchy


Hierarchy
True NH
δ_{CP}=-90°
T2HK
OA 2.5
OA 2.0
OA 1.5
DUNE
Significance(σ)
Systematics(%)
Hierarchy
True NH
δ_{CP}=90°
T2HK
OA 2.5
OA 2.0
OA 1.5
DUNE
Significance(σ)
Systematics(%)
Hierarchy
True IH
δ_{CP}=-90°
T2HK
OA 2.5
OA 2.0
OA 1.5
DUNE
Significance(σ)
Systematics(%)
Hierarchy
True IH
δ_{CP}=90°
T2HK
OA 2.5
OA 2.0
OA 1.5
DUNE
Significance(σ)
Systematics(%)

Octant


Octant
Significance(σ)
Systematics(%)
True NH
δ_{CP}=-90^o, θ_{23}=42^o
T2HK
OA 2.5
OA 2.0
OA 1.5
DUNE
Octant
True NH
δ_{CP}=-90^o, θ_{23}=48^o
Octant
True IH
δ_{CP}=-90^o, θ_{23}=42^o
Octant
True IH
δ_{CP}=-90^o, θ_{23}=48^o

Summary

- Hyper-K and DUNE are the most powerful projects to determine the unknown oscillation parameters
- DUNE has the highest hierarchy sensitivity due to larger baseline
- Hyper-K has the best CP sensitivity due to large number of events
- Combination of Hyper-K and DUNE is best for determination of both hierarchy and CP
- Systematic errors are important

Summary

- Hyper-K and DUNE are the most powerful projects to determine the unknown oscillation parameters
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- Systematic errors are important

Thank you

Treatment of Systematics

4 pull variables

- signal normalization (affect the scaling of the events)
- background normalization
- signal tilt (affect the energy dependence of the events)
- background tilt

a systematic error of $x\%$ implies: a normalization error of $x\%$ for

- both signal and background
- both appearance and disappearance channel
- both ν and $\bar{\nu}$

Tilt error is fixed at 10% and never varied