Effect of systematics in T2HKK and DUNE

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Based on: Ghosh, Yasuda (Ongoing)

Neutrino oscillation in 3 generation

Full three flavour vacuum probability formula:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}] sin^2\frac{\Delta_{ij}L}{4E} + 2\sum_{i<j} Im[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}] sin2\frac{\Delta_{ij}L}{4E}$$

$$\Delta_{ij} = m_i^2 - m_j^2$$

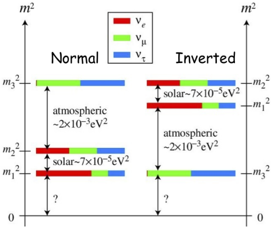
Parameters of neutrino oscillation:

- 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

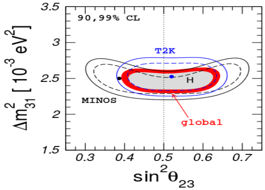
Comment

Neutrino oscillation can't probe absolute neutrino mass

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

Ongoing experiments to discover the unknowns
T2HK/T2HKK in Japan/Korea
DUNE in Fermilab

Advantage:

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

Problem: Affected by systematics

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

Specification

T2HK/T2HKK

- Detector type: water Cerenkov
- 187 kt in Kamioka and 187 kt in Korea for T2HKK and (187×2) kt in Kamioka for T2HK
- 1.3 MW beam, 27×10^{21} pot: 10 years of running
- 3 off-axis configuration of T2HKK: 2.5°, 2.0° and 1.5°
- $\nu : \bar{\nu} = 1 : 3$

DUNE

- 1.2 MW beam, 10×10^{21} pot: 10 years of running
- 35 kt Liquid Argon detector
- $\nu : \bar{\nu} = 1 : 1$

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

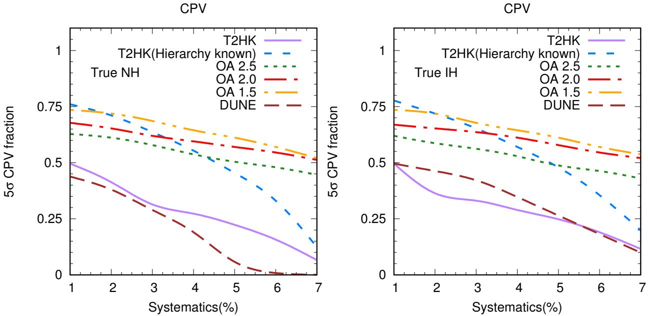
- both signal and background
- both appearance and disappearance channel
- both ν and $\bar{\nu}$

Tilt error is fixed at 10% and never varied

Objective 1

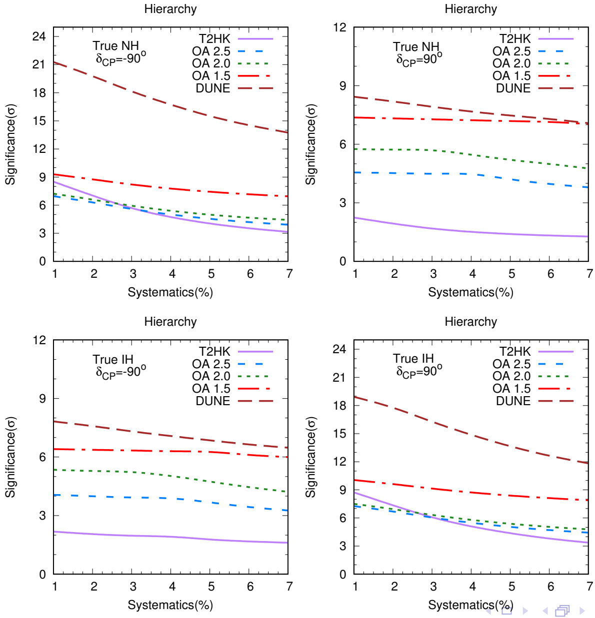
Sensitivity in standard 3 flavour case

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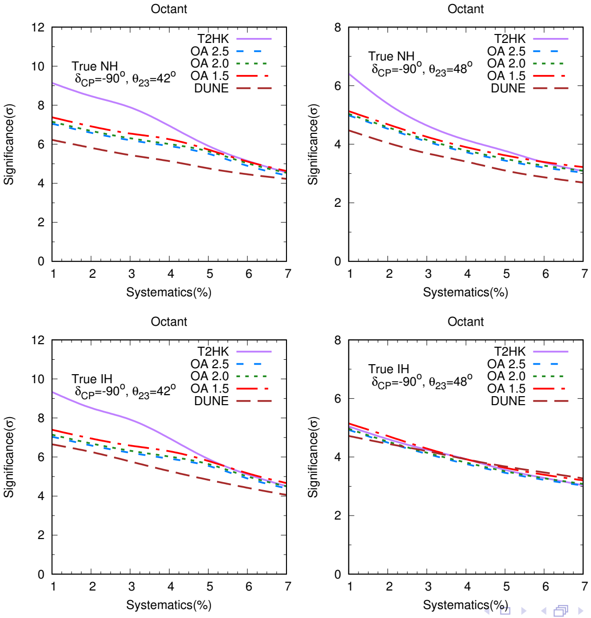
DUNE
Significance(σ)
Systematics(%)

Octant


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

Objective 2

Effect of systematics for Non-standard Interactions

What is non-standard interaction ?

Neutrino propagating in matter

- Standard NC interaction:

$$\nu_\alpha + f \to \nu_\alpha + f$$

- Non-standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

can arise from the following four-fermion interaction

$$\mathcal{L} = -G_F \epsilon^f_{\alpha\beta} \bar{\nu}_\alpha \gamma^\mu \nu_\beta \bar{f} \gamma_\mu f$$

with $\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{N_f}{N_e} \epsilon^f_{\alpha\beta}$

NSI in neutrino oscillation

- Evolution equation with standard oscillation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix} = \left[Udiag(E_1, E_2, E_3)U^{-1} + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix}$$

- Evolution equation with non-standard oscillation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix} = \left[Udiag(E_1, E_2, E_3)U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix}$$

with $A = \sqrt{2}G_F N_e$

Analysis

Bounds

$$|\epsilon_{ee}| < 4, \quad |\epsilon_{e\mu}| < 3 \times 10^{-1}, \quad |\epsilon_{e\tau}| < 3 \times 10^{0}\ , \quad |\epsilon_{\mu\mu}| < 7 \times 10^{-2}$$

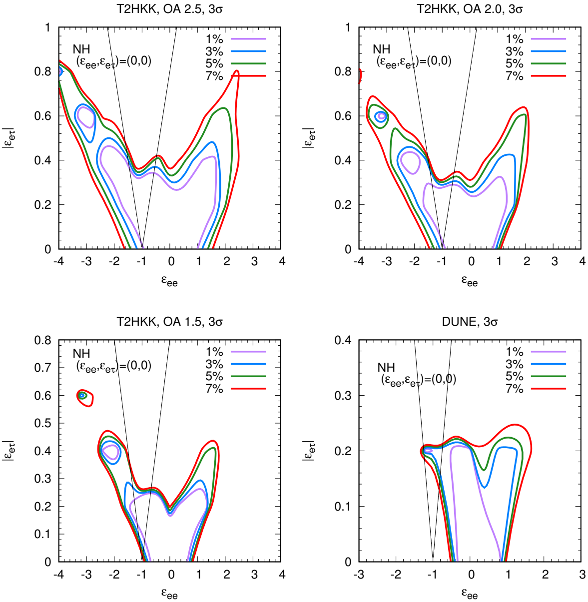
$$|\epsilon_{\mu\tau}| < 3 \times 10^{-1}, \quad |\epsilon_{\tau\tau}| < 2 \times 10^{1}\ , \epsilon_{\tau\tau} \simeq \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}\ .$$

Ansatz

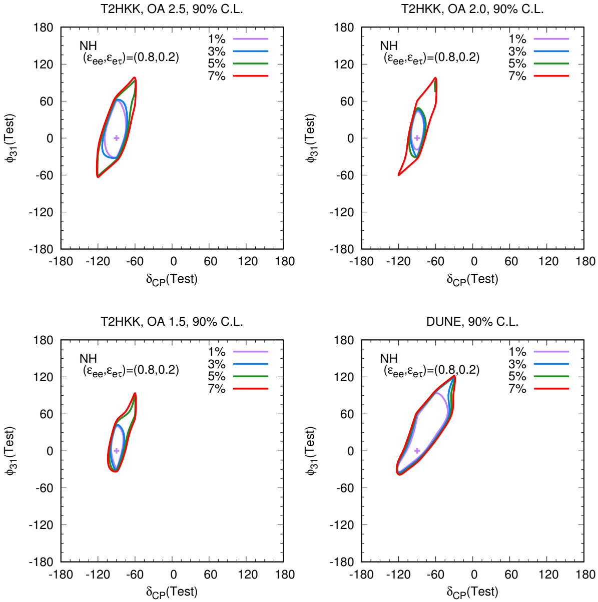
$$\mathcal{A} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon^*_{e\tau} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

Free Parameters: ϵ_{ee}, $|\epsilon_{e\tau}|$, $\phi_{31} = arg(\epsilon_{e\tau})$

Bounds on NSI parameters



Constraining the phases



Summary

- Future generation high statistics experiments are extremely sensitive to the systematic errors
- Depending on the systematic errors sensitivity of one setup can be better/worse than other
- Planning of the T2HKK/T2HK will depend on how much systematics are improved

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Thank you

Backup slides

Backup

Applying systematics

$$M_i^{det(th)}(\vec{p}_{th}) = N_i^{det(th)}(\vec{p}_{th}) \left[1 + \sum_k \xi_k \pi^k + \sum_l \xi_l \pi^l \frac{E_i - E_{av}}{E_{max} - E_{min}} \right],$$

where the index $k(l)$ runs over the relevant normalization(tilt) systematic errors for a given experimental observable. All the pull variables $\{\xi_j\}$ take values in the range $(-3, 3)$, so that the errors can vary from -3σ to $+3\sigma$. Here, E_i is the mean energy of the i^{th} energy bin, E_{min} and E_{max} are the limits of the full energy range, and E_{av} is their average.

The Poissonian χ^2 is calculated for each detector as

$$\chi^{2\ det}(\vec{p}_{ex}, \vec{p}_{th}; \{\xi_j\}) = \sum_i 2 \left[M_i^{det(th)}(\vec{p}_{th}) - N_i^{det(ex)}(\vec{p}_{ex}) + N_i^{det(ex)}(\vec{p}_{ex}) \ln \left(\frac{N_i^{det(ex)}(\vec{p}_{ex})}{M_i^{det(th)}(\vec{p}_{th})} \right) \right].$$

The results from the two detector setups are then combined, along with a penalty for each source of systematic

T2HKK systematics

	Percent Error (%)				
Error Source	ν 1Rμ	$\bar{\nu}$ 1Rμ	ν 1Re	$\bar{\nu}$ 1Re	(ν 1Re)/($\bar{\nu}$ 1Re)
OAA=2.5°, $L = 1100$ km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	2.10	1.68	3.12
Energy Scale	0.02	0.02	0.01	0.01	0.01
Matter Density	0.04	0.08	0.43	0.09	0.53
NCπ^+ Bgnd.	1.28	1.25	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.32	1.41	1.88
CC non-QE Fraction	2.76	1.88	1.98	1.29	2.35
Extrapolation	2.70	2.60	2.44	3.06	1.95
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	4.69	4.16	4.54	4.47	4.86
OAA=2.0°, $L = 1100$ km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	2.01	1.67	3.07
Energy Scale	0.02	0.01	0.01	0.01	0.01
Matter Density	0.02	0.06	0.55	0.12	0.67
NCπ^+ Bgnd.	1.47	1.29	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.26	1.29	1.76
CC non-QE Fraction	0.87	0.82	1.24	0.76	1.51
Extrapolation	2.68	2.68	2.38	3.00	1.92
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	3.89	3.83	4.18	4.27	4.39
OAA=1.5°, $L = 1100$ km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	1.72	1.41	2.67
Energy Scale	0.01	0.01	0.01	0.01	0.01
Matter Density	0.01	0.06	0.24	0.28	0.53
NCπ^+ Bgnd.	1.61	1.30	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	1.42	1.37	1.93
CC non-QE Fraction	0.44	0.30	0.52	0.37	0.75
Extrapolation	2.67	2.60	2.23	2.88	1.84
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	3.83	3.81	3.84	4.11	3.91
OAA=2.5°, $L = 295$ km					
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.01	0.00	2.44	1.82	3.53
Energy Scale	0.04	0.03	0.42	0.63	0.21
Matter Density	–	–	–	–	–
NCπ^+ Bgnd.	2.33	1.79	0.00	0.00	0.00
ν_e & NCπ^0 Bgnd.	0.00	0.00	0.94	1.22	1.51
CC non-QE Fraction	1.68	1.72	2.07	1.00	2.25
Extrapolation	2.60	2.56	2.51	3.05	1.96
Far Detector Model	2.64	2.64	2.08	2.08	0.00
Total	4.13	4.15	4.71	4.47	4.90
OAA=2.5°, $L = 295$ km (Hyper-K Design Report)					
Total	3.6	3.6	3.2	3.9	–