Effect of systematics in T2HK, T2HKK, DUNE

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Based on

PRD 96 ('17) 013001, Monojit Ghosh & OY

PTEP 2018 ('18) 063C01, §7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)

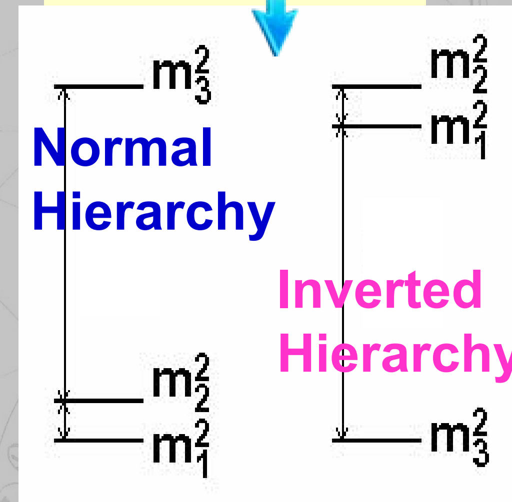
Outline of this talk

1. Introduction
2. Sensitivity of T2HK, DUNE, T2HKK for std case
3. Sensitivity of T2HK, DUNE, T2HKK for NSI
4. Conclusions

1. Introduction

Framework of 3 flavor ν oscillation

Both hierarchy patterns are allowed



Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

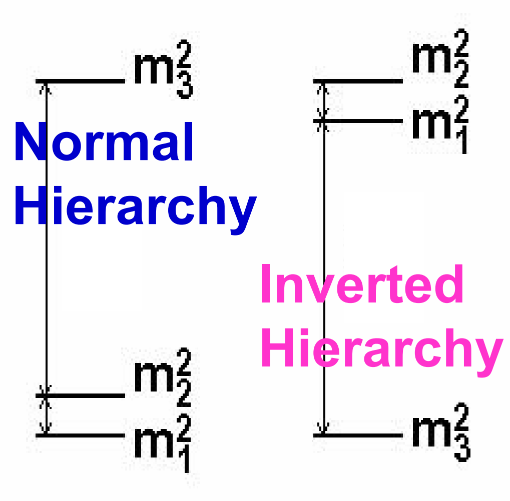
All 3 mixing angles have been measured (2012):

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5} eV^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3} eV^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS+Nova etc → $\theta_{13} \cong \pi / 20$

Next task is to measure sign(Δm^2_{31}) (Mass Hierarchy), $\pi/4-\theta_{23}$ (Octant) and δ (CP)



Proposed experiments

- T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV
- T2HHK(JP, JPARC-->Korea) L=1100km, E~1GeV
- DUNE (US, FNAL-->Homestake, SD) , L=1300km, E~2GeV

$$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$$

These experiments are expected to measure sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

In these long baseline experiments with intensive beams, systematic errors become important to sensitivity.

In this talk, we examine dependence of the sensitivity on the systematic errors.

2. Sensitivity of T2HK, DUNE, T2HKK for std case

2.1 Preliminary

The parameters assumed here:

T2HK
(L=295km, 187 kton fiducial volume) x2
ν:anti-ν = 1:3
Total exposure: 27 x 10^{21} POT

DUNE
L=1300km, 1.2MW, 40 kt LiAr detector,
ν:anti-ν = 1:1
Total exposure: 10 X 10^{21} POT

T2HKK

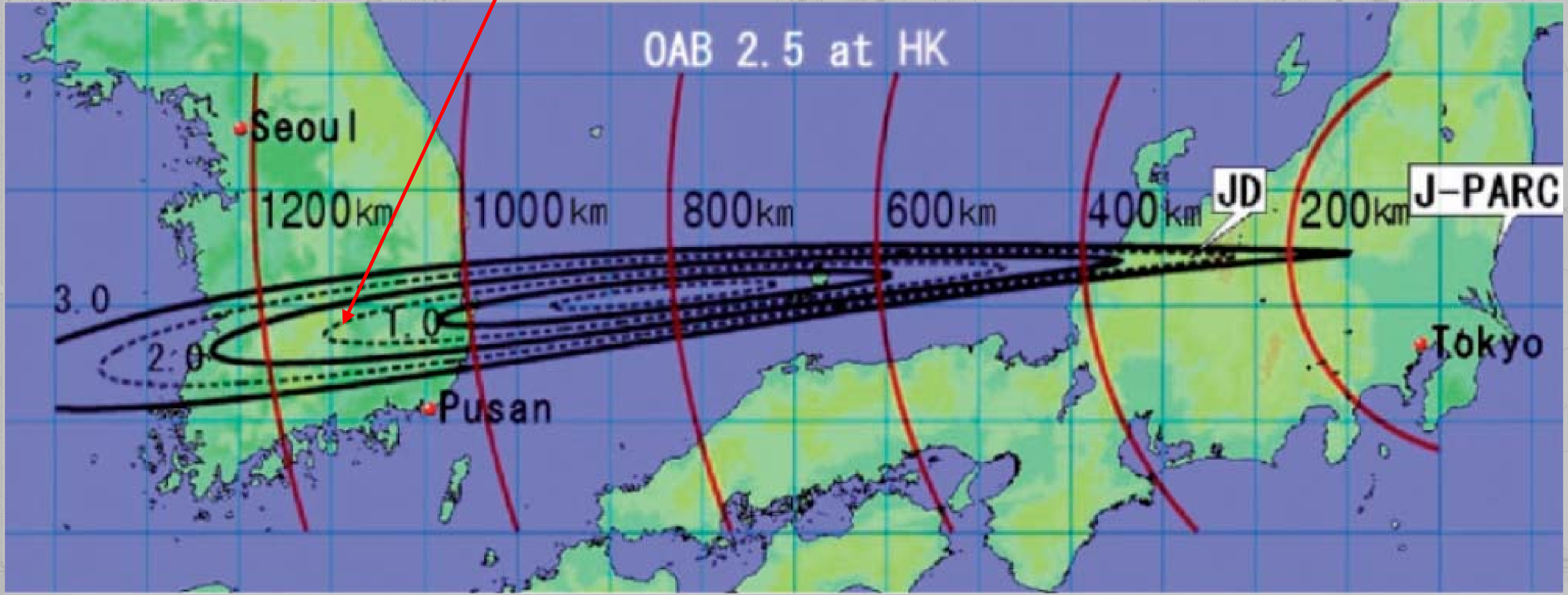
(L=295km, 187 kton fiducial volume)

+ (L=1100km, 187 kton fiducial volume)

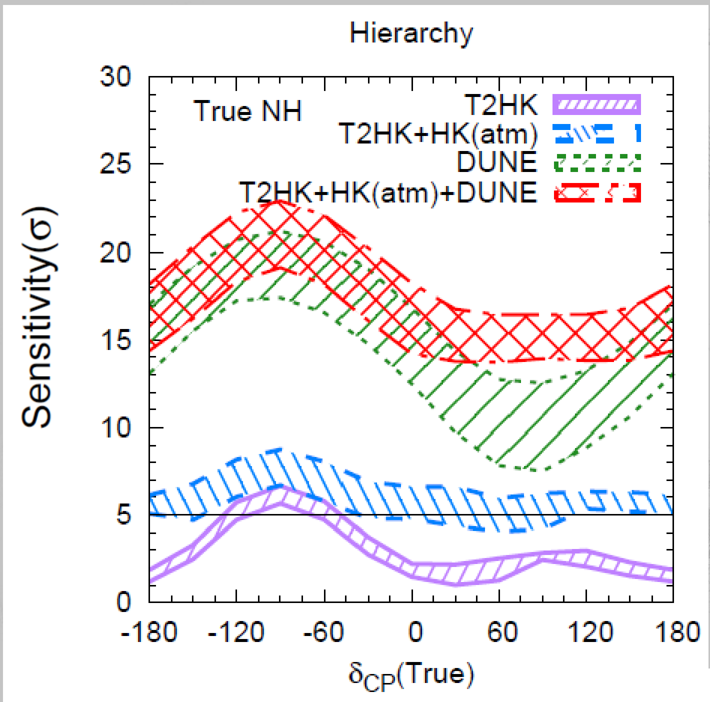
ν:anti-ν = 1:3

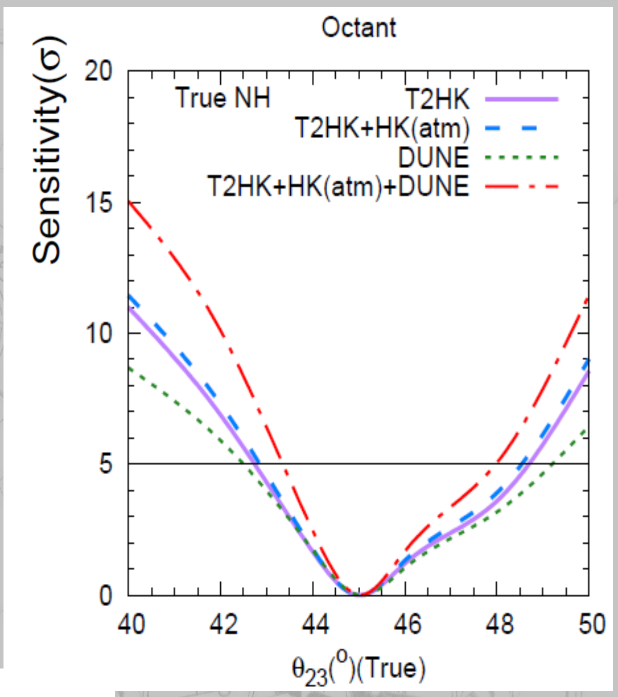
Total exposure: 27 x 10^{21} POT

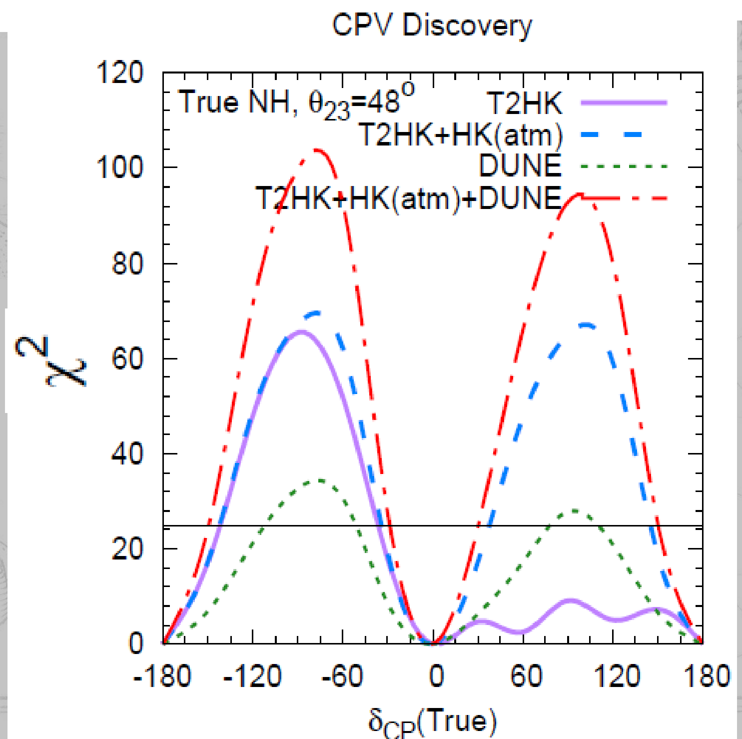
Off axis Angle = 1.5° is the best (w/ max #(events))



Sensitivity to Mass Hierarchy, Octant, CP has been studied in the past







Fukasawa, Ghosh, OY, NPB918 ('17) 337

Outline of our Analysis

Start with χ^2 with statistical errors:

$$\chi^2_{\rm stat} = \sum_i 2\left[N_i^{\rm test} - N_i^{\rm true} - N_i^{\rm true}\log\left(\frac{N_i^{\rm test}}{N_i^{\rm true}}\right)\right]$$

Sensitivity to Mass Hierarchy

$N_i^{true} = N_i^{true}(\Delta m_{\mu\mu}^2)$
$N_i^{test} = N_i^{test}(-\Delta m_{\mu\mu}^2)$

Sensitivity to Octant

$N_i^{true} = N_i^{true}(\theta_{23})$
$N_i^{test} = N_i^{test}(\pi/4-\theta_{23})$

Sensitivity to CP

$N_i^{true} = N_i^{true}(\delta)$
$N_i^{test} = N_i^{test}(\delta=0)$

+

$N_i^{true} = N_i^{true}(\delta)$
$N_i^{test} = N_i^{test}(\delta=\pi)$

Then introduce the systematic errors:

normalization error

$$N_i^{\text{test}} \to N_i^{\text{test}} \left(1 + \sum_k c_i^k \xi_k \right)$$

tilt error

$$N_i^{\text{test}} \to N_i^{\text{test}} \left(1 + \sum_k c_i^k \xi_k \frac{E_i - E_{\text{av}}}{E_{\text{max}} - E_{\text{min}}} \right)$$

Final χ^2 we work with:

$$\chi^2 = \min_{\{\text{osc. param.}, \xi_k\}} \left[\chi^2_{\text{stat}} + \sum_k \xi_k^2 \right]$$

Reference values of the systematic errors

HK arXiv:1412.4673

DUNE arXiv:1512.06148

	channel	HK	DUNE
ν	disappearance	3.3%	5%
	appearance	3.3%	2%
ν	disappearance	4.5%	5%
	appearance	6.2%	2%

c_1 = signal normalization error
c_2 = background normalization error
c_3 = signal tilt error
c_4 = background tilt error

For simplicity we assume $c_1 = c_2$ for all channels and vary only c_1 & c_2; $c_3 = c_4 = 10\%$ (2.5%) for T2HK(K) (DUNE)

2.2 Sensitivity to Mass Hierarchy

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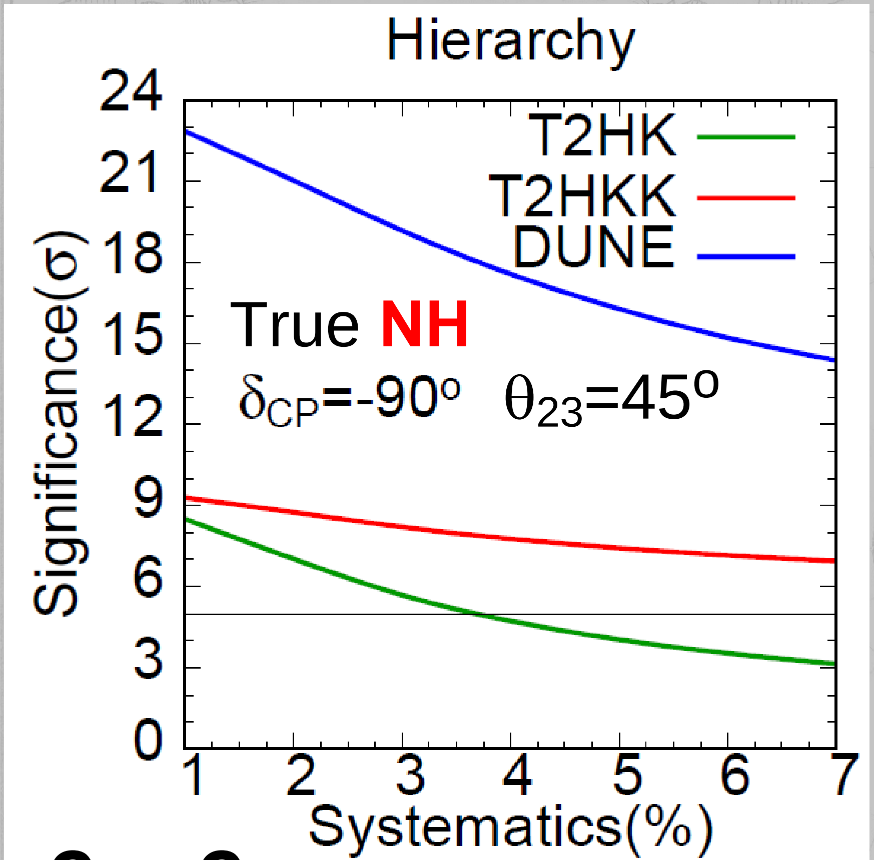
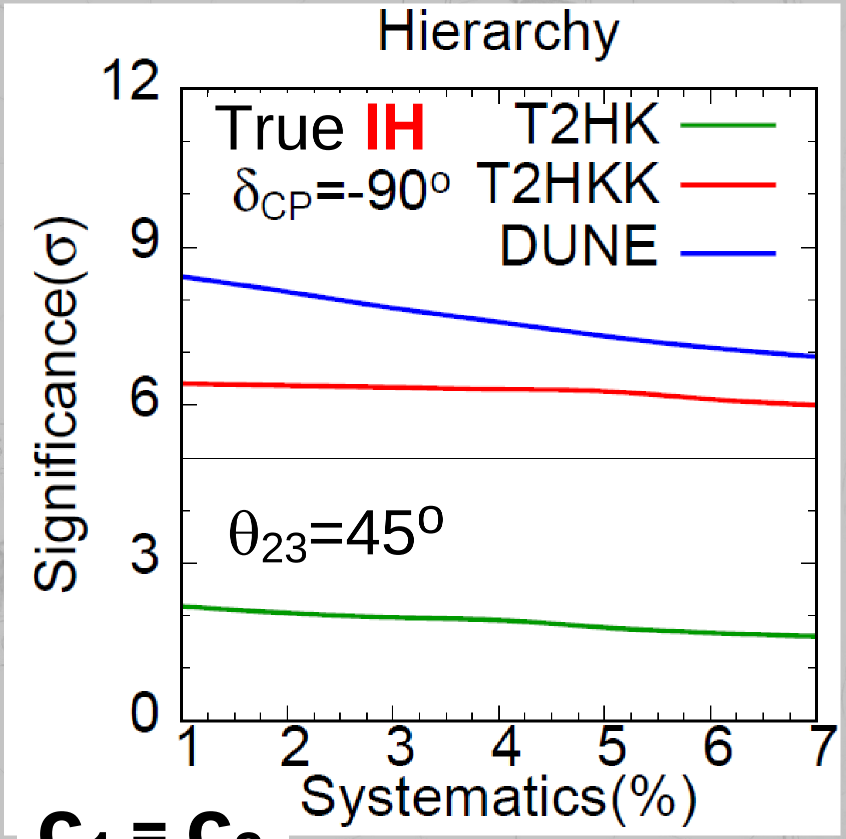


$c_1 = c_2$

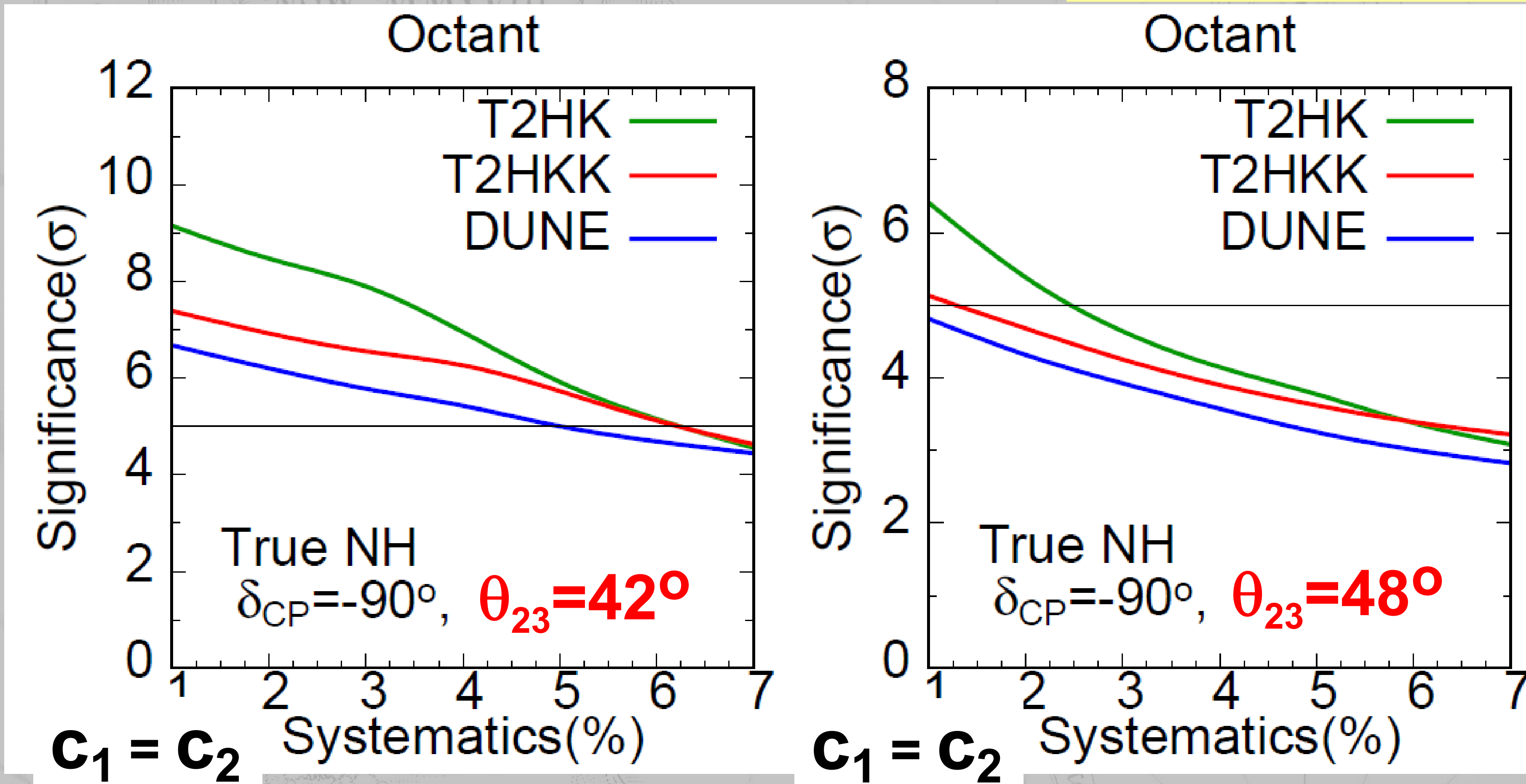


$c_1 = c_2$

- **Dependence of T2HK & DUNE stronger than that of T2HKK**
- **If true MH is NH & δ=-90^o & c_1 < 3.5% then T2HK is sufficient to determine MH at 5σ**

2.3 Sensitivity to Octant

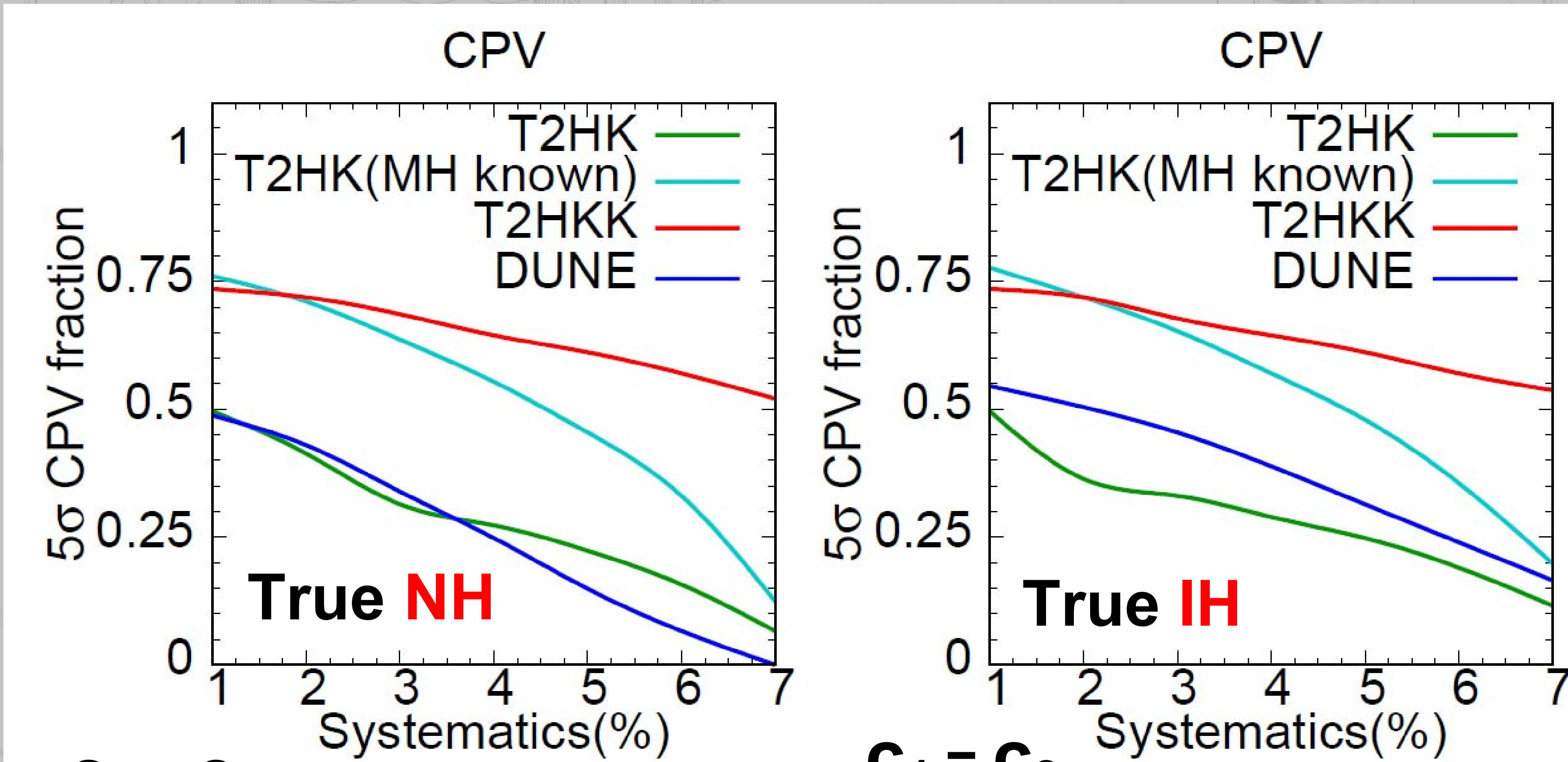
PRD 96 ('17) 013001, Monojit Ghosh & OY



- **Dependence of T2HK stronger than that of others**
- **Significance of Lower Octant (θ_{23}<45°) larger than that of Higher Octant (θ_{23}>45°)**

2.4 Sensitivity to CP

PRD 96 ('17) 013001,
Monojit Ghosh & OY

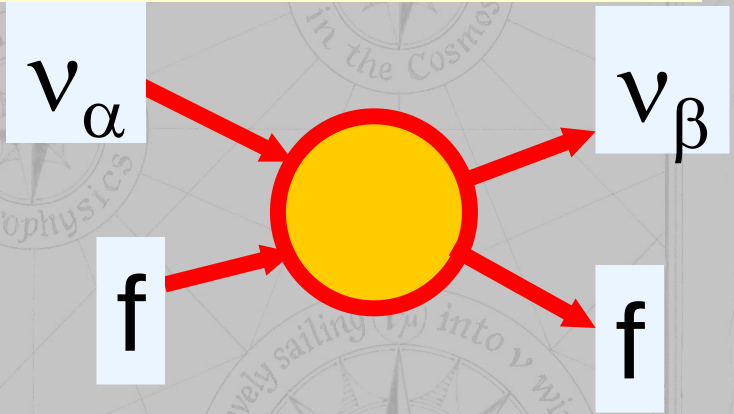


$c_1 = c_2$ $\qquad$ $c_1 = c_2$

- **Dependence of T2HK stronger than that of T2HKK**
- **If MH is known then T2HK w/ c_1<2% is better than T2HKK**

3. Sensitivity of T2HK, DUNE, T2HKK for NSI in ν propagation

3.1 Preliminary



Phenomenological New Physics considered in this talk: 4-fermi Non Standard Interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha\gamma^\mu\nu_\beta\,\bar{f}\gamma_\mu f'$$

neutral current non-standard interaction

Modification of matter effect

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

NP

$A \equiv \sqrt{2}G_F N_e$ $N_e \equiv$ electron density

● Constraints on $\varepsilon_{\alpha\beta}$

•Various non-oscillation ν experiments

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

Biggio et al., JHEP 0908, 090 (2009) w/o 1-loop arguments

μ-components are all small

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4\times 10^{0} & |\epsilon_{e\mu}| \lesssim 3\times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3\times 10^{0} \\ & |\epsilon_{\mu\mu}| \lesssim 7\times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2\times 10^{1} \end{pmatrix}$$

•High energy behavior of ν_{atm} data

$$\left|\, \varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee}) \right| \ll 1$$

Friedland-Lunardini, PRD72:053009,'05

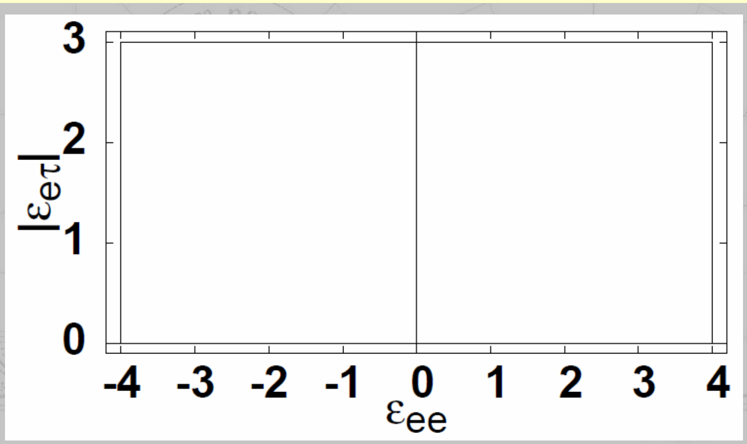
● Ansatz of our analysis on $\varepsilon_{\alpha\beta}$

To a good approximation, we are left with 3 independent variables ε_{ee}, | $\varepsilon_{e\tau}$ |, arg($\varepsilon_{e\tau}$)=ϕ_{31}:

$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \simeq A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

➡ **We perform analysis with 3 independent variables ε_{ee}, | $\varepsilon_{e\tau}$ |, ϕ_{31}=arg($\varepsilon_{e\tau}$) and give the allowed region in the (ε_{ee}, | $\varepsilon_{e\tau}$ |) plane by marginalizing w.r.t. ϕ_{31}=arg($\varepsilon_{e\tau}$)**

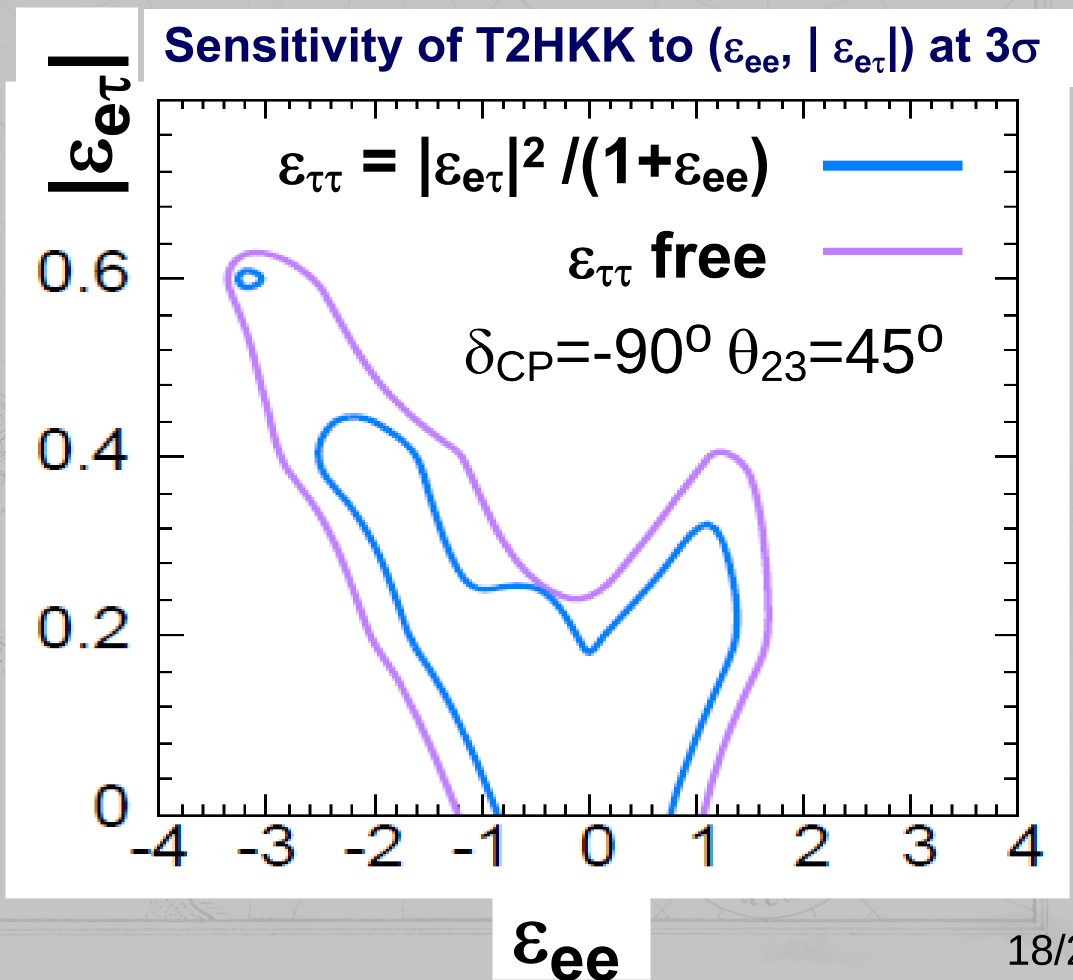
$$-4 \lesssim \epsilon_{ee} \lesssim 4,$$
$$|\epsilon_{e\tau}| \lesssim 3,$$
$$|\epsilon_{\tau\tau}| = \frac{|\epsilon_{e\tau}|^2}{|1+\epsilon_{ee}|}$$



Comment on the approximation $\varepsilon_{\tau\tau}=|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$

The sensitivity to (ε_{ee}, $|\varepsilon_{e\tau}|$) w/ or w/o this approximation is slightly different.

PTEP 2018 ('18) 063C01, §7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)

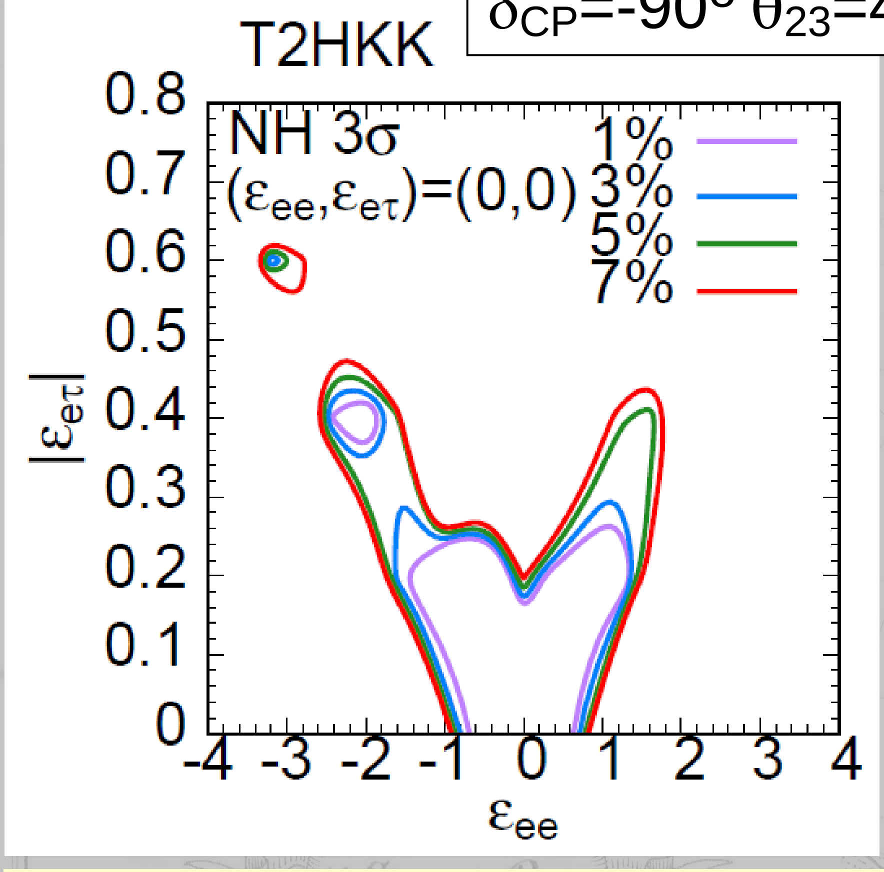


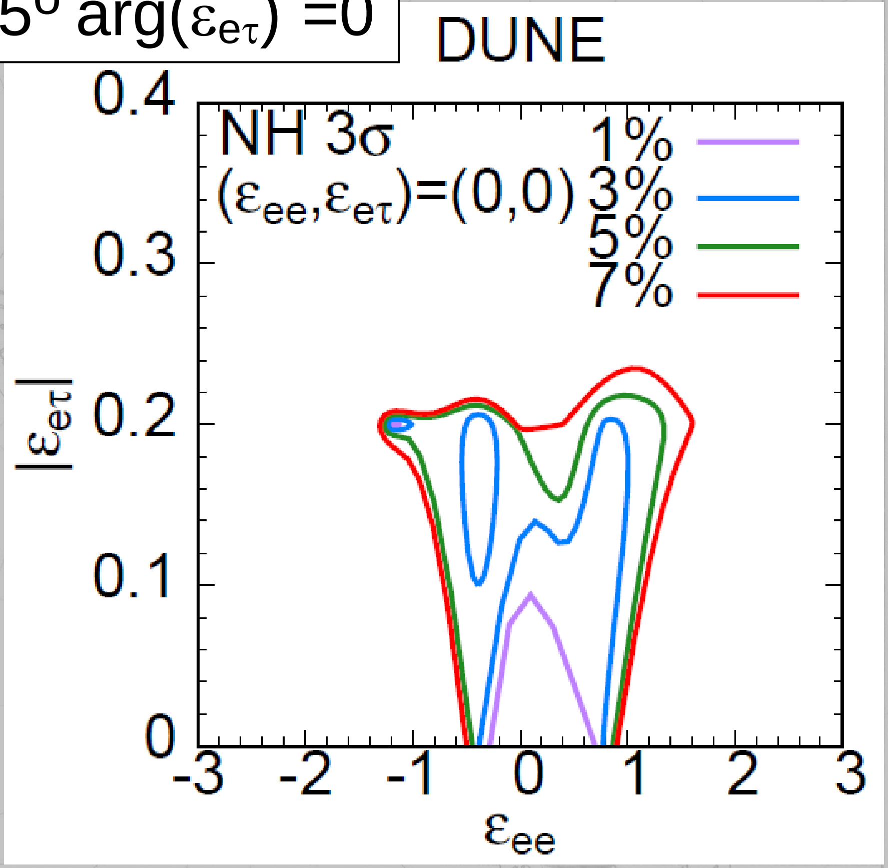
3.1 Sensitivity to (ε_{ee}, | $\varepsilon_{e\tau}$ |)

PRD 96 ('17) 013001, Monojit Ghosh & OY

T2HK (not plotted) has too short baseline length (L=295km)-> Sensitivity to NSI is much worse than others

δ_{CP}=-90° θ_{23}=45° arg($\varepsilon_{e\tau}$) =0

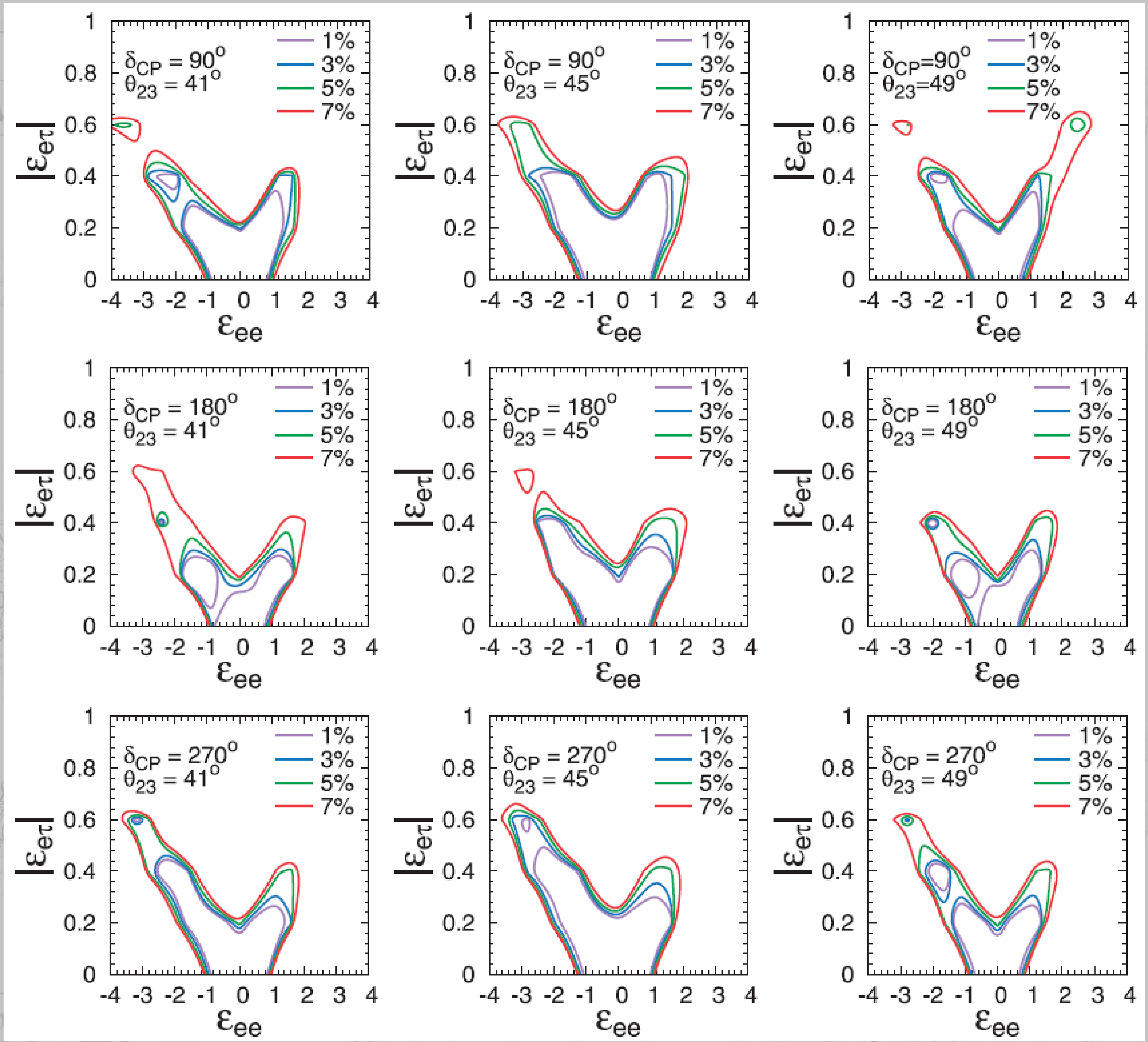




DUNE better than T2HKK; Reduction from 5% to 3% enhances sensitivity to NSI in both experiments

Sensitivity of T2HKK to (ε_{ee}, | $\varepsilon_{e\tau}$ |) for various values of θ_{23} and δ_{CP}

NH 3σ

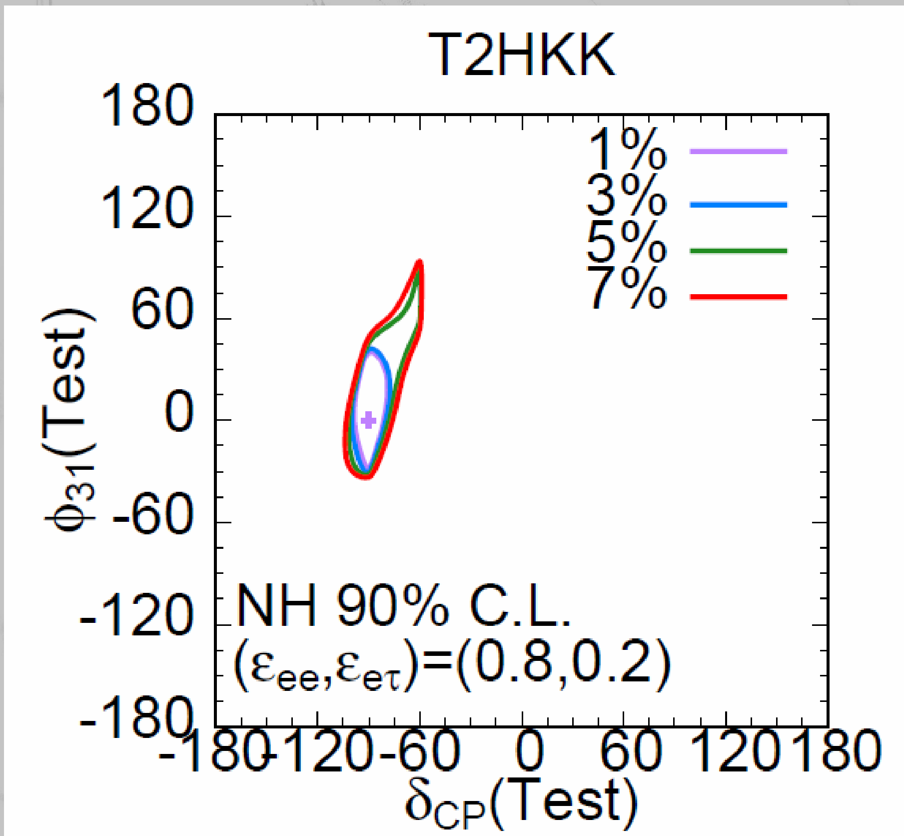


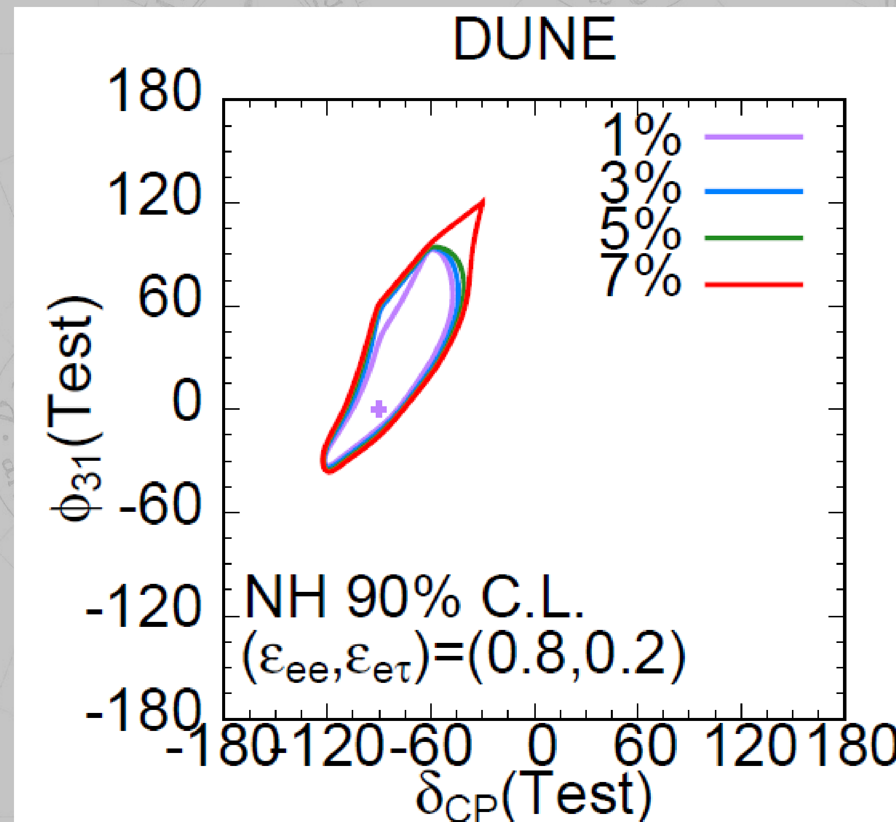
PTEP 2018 ('18) 063C01, § 7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)

The behaviors w.r.t. the systematic errors are similar.

3.2 Sensitivity to $\phi_{31} \equiv \arg(\varepsilon_{e\tau})$ & δ_{CP}

PRD 96 ('17) 013001, Monojit Ghosh & OY





T2HKK better than DUNE; Reduction from 5% to 3% in T2HKK enhances sensitivity to the phases

4. Conclusion

- **Measurements of the oscillation parameters at the future LBL experiments are sensitive to the systematic errors in the standard 3 flavor case as well as in the NSI case.**
- **[Standard case]**

If Mass Hierarchy is known & systematic error can be reduced to < 2%, then T2HK has the best sensitivity to CP.

- **[NSI case]**

T2HK has much poorer sensitivity to NSI than other two;

For $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$, DUNE w/ $c_1 < 5\%$ is the best;

For $(\delta_{CP}, \arg(\varepsilon_{e\tau}))$, T2HKK w/ $c_1 < 3\%$ is the best.

Backup slides

Hierarchy degeneracy in the three-flavor scenario

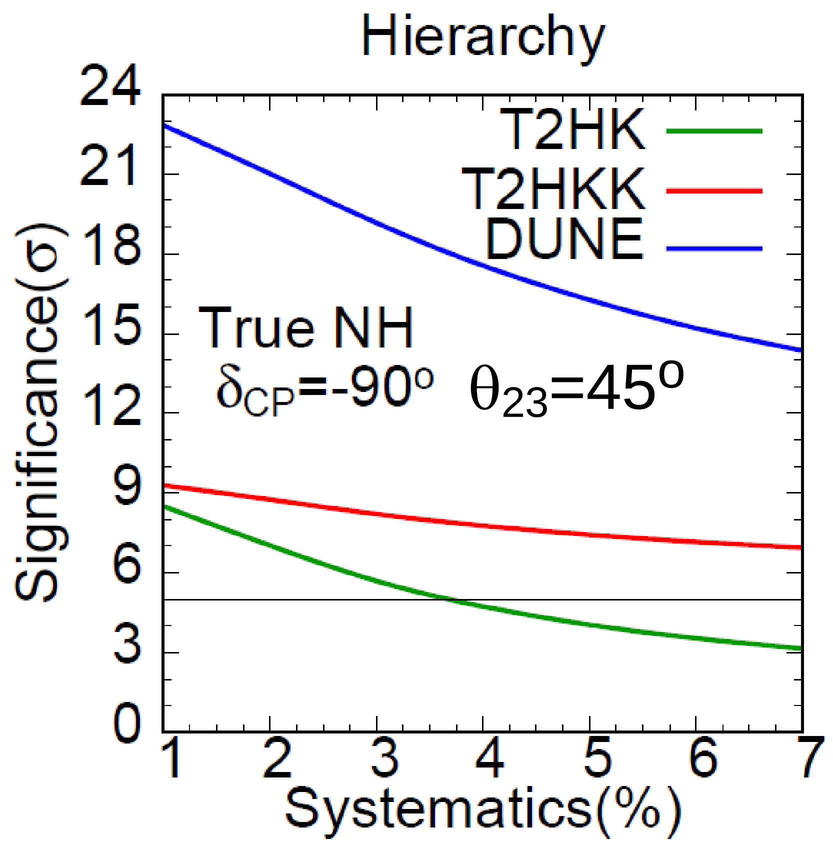
H. Nunokawa, S. J. Parke, R. Zukanovich Funchal, PRD 72, 013009 (2005)

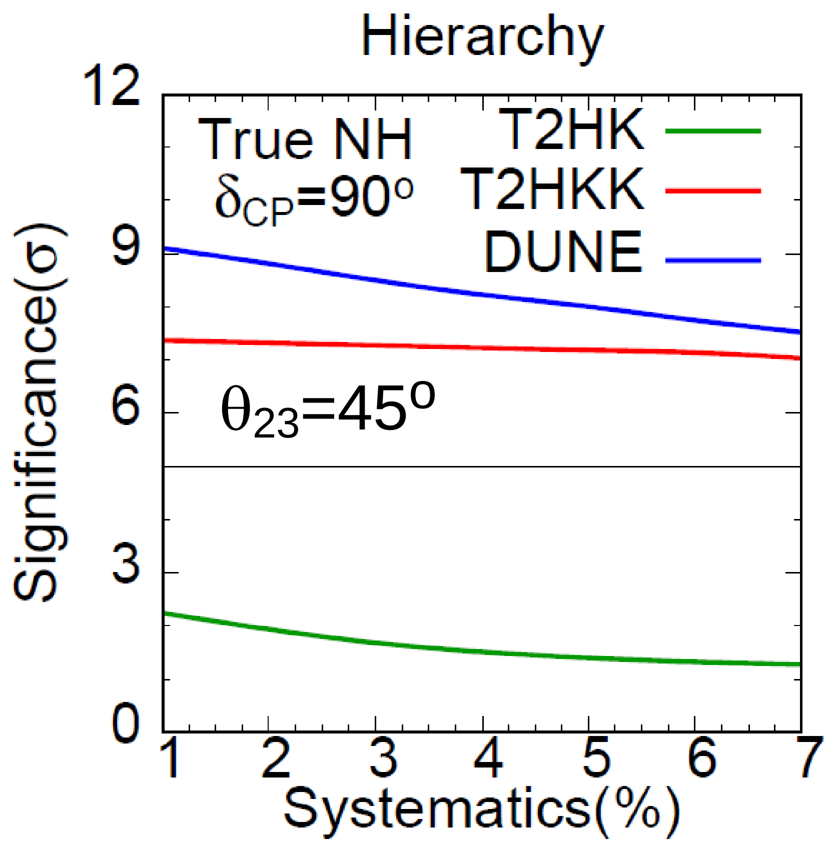
$$P_{\mu\mu}(\Delta m^2_{\mu\mu}) = P_{\mu\mu}(-\Delta m^2_{\mu\mu})$$

$$\Delta m^2_{31} = \Delta m^2_{\mu\mu} + (\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})\Delta m^2_{21}$$

Sensitivity to Mass Hierarchy

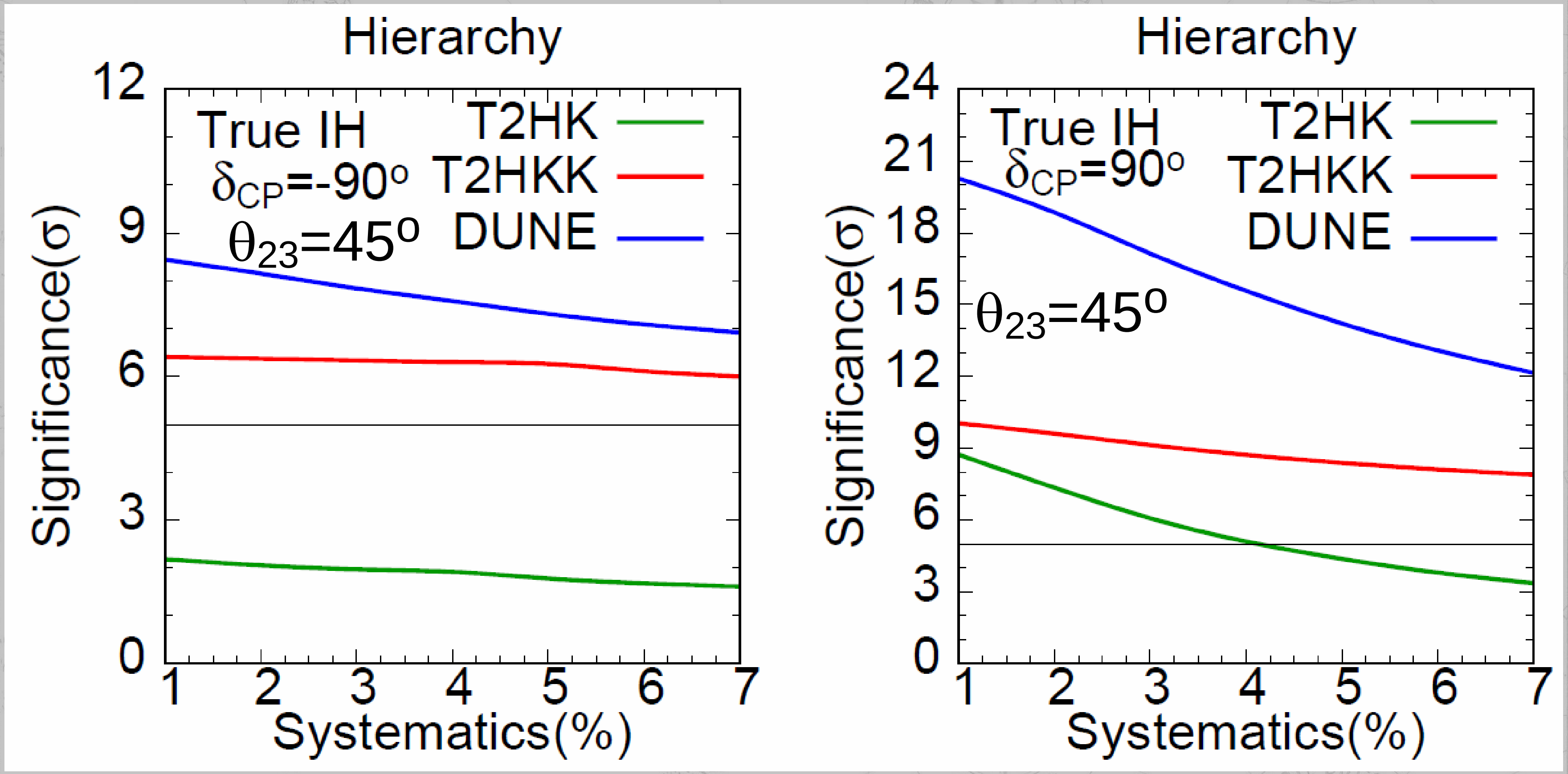
PRD 96 ('17) 013001, Monojit Ghosh & OY





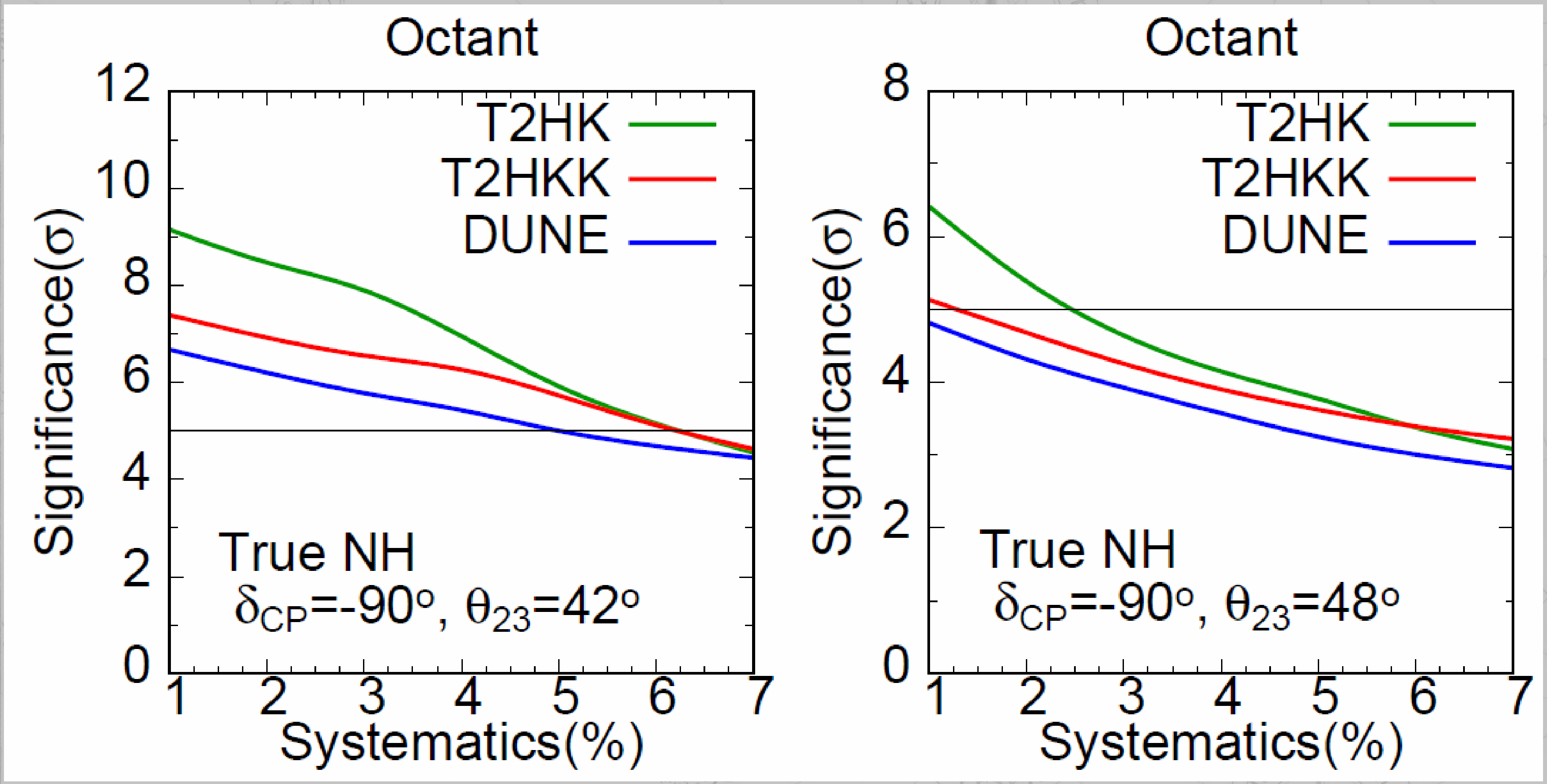
Sensitivity to Mass Hierarchy

PRD 96 ('17) 013001, Monojit Ghosh & OY



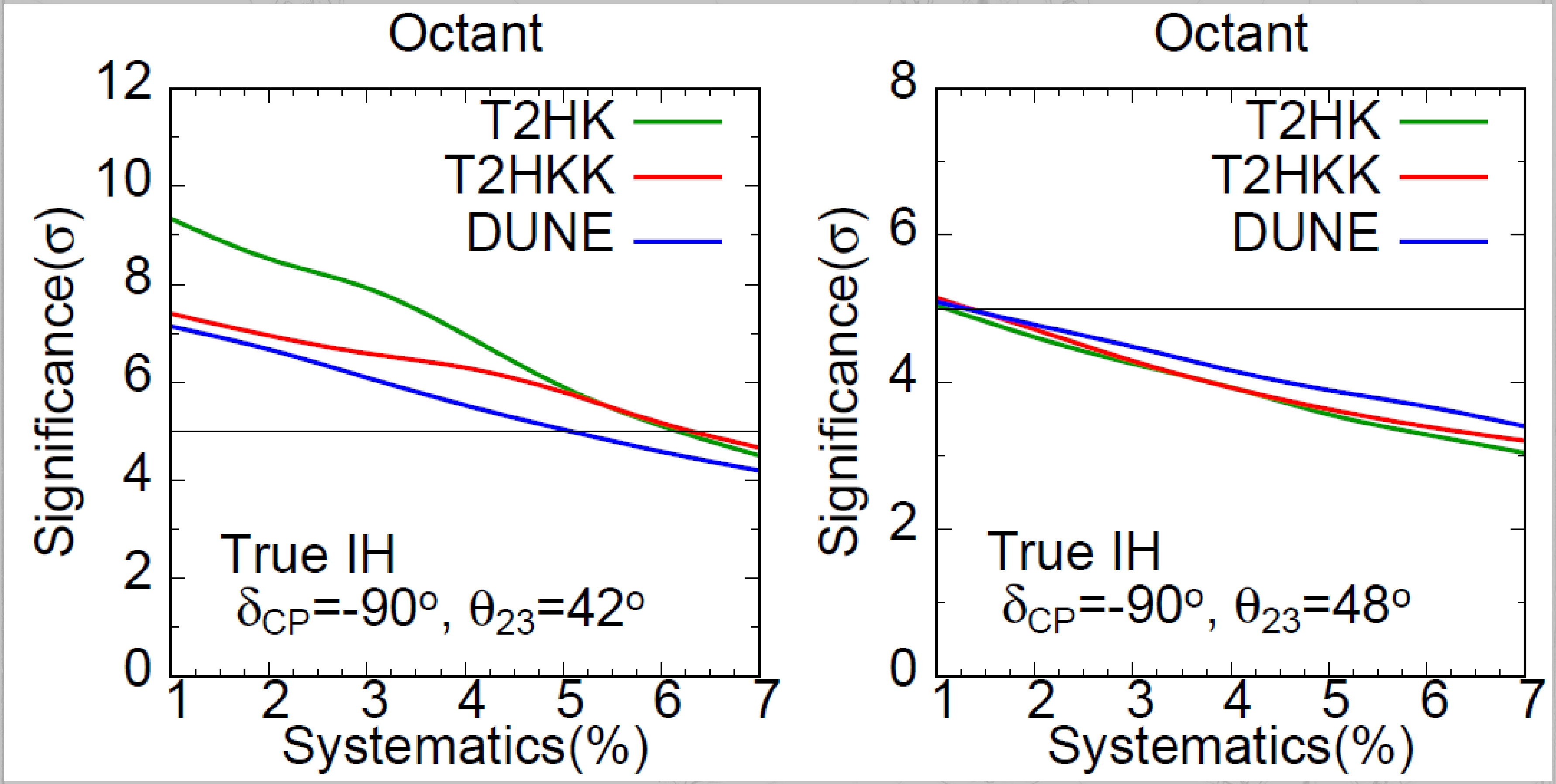
Sensitivity to Octant

PRD 96 ('17) 013001, Monojit Ghosh & OY



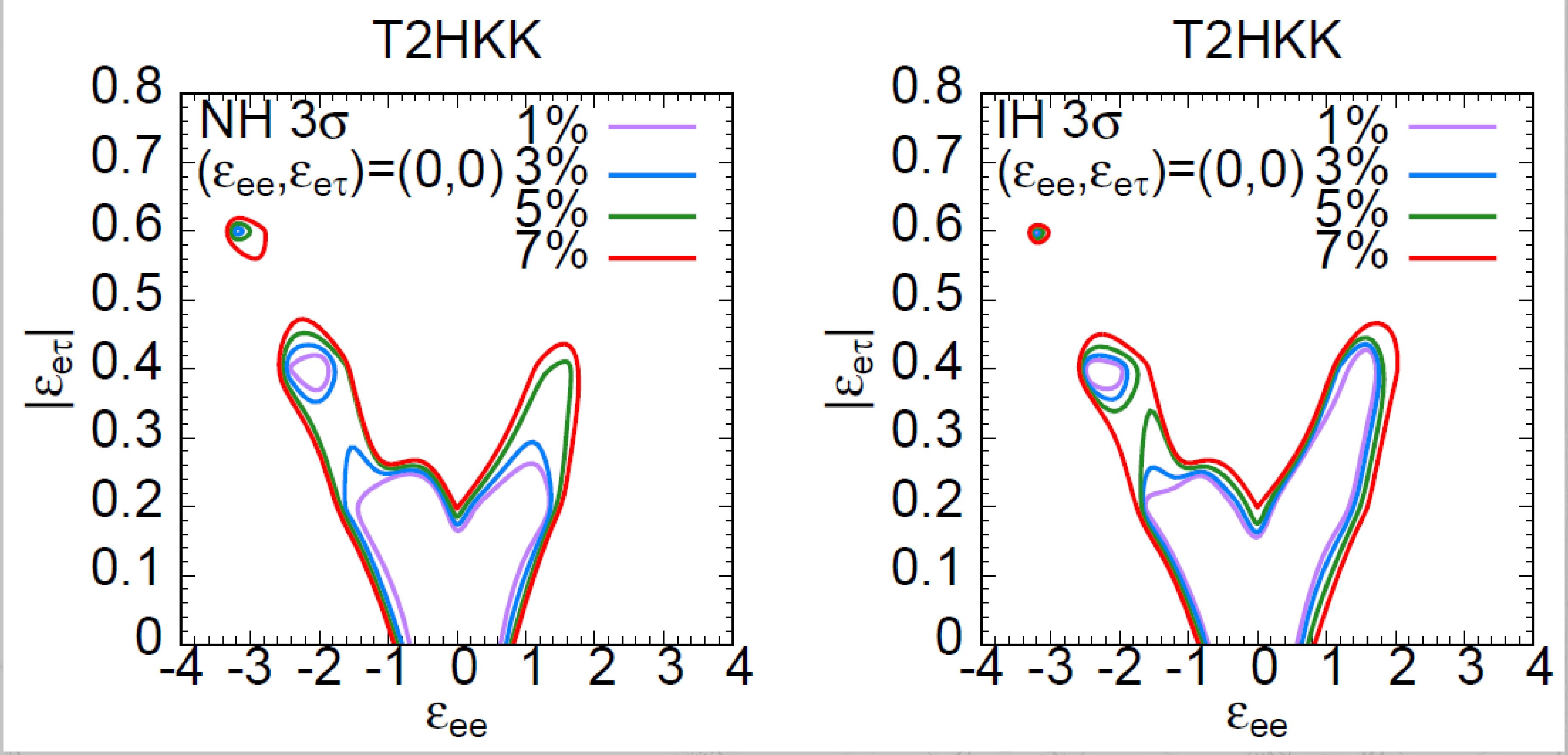
Sensitivity to Octant

PRD 96 ('17) 013001, Monojit Ghosh & OY



Sensitivity to (ε_{ee}, | $\varepsilon_{e\tau}$ |)

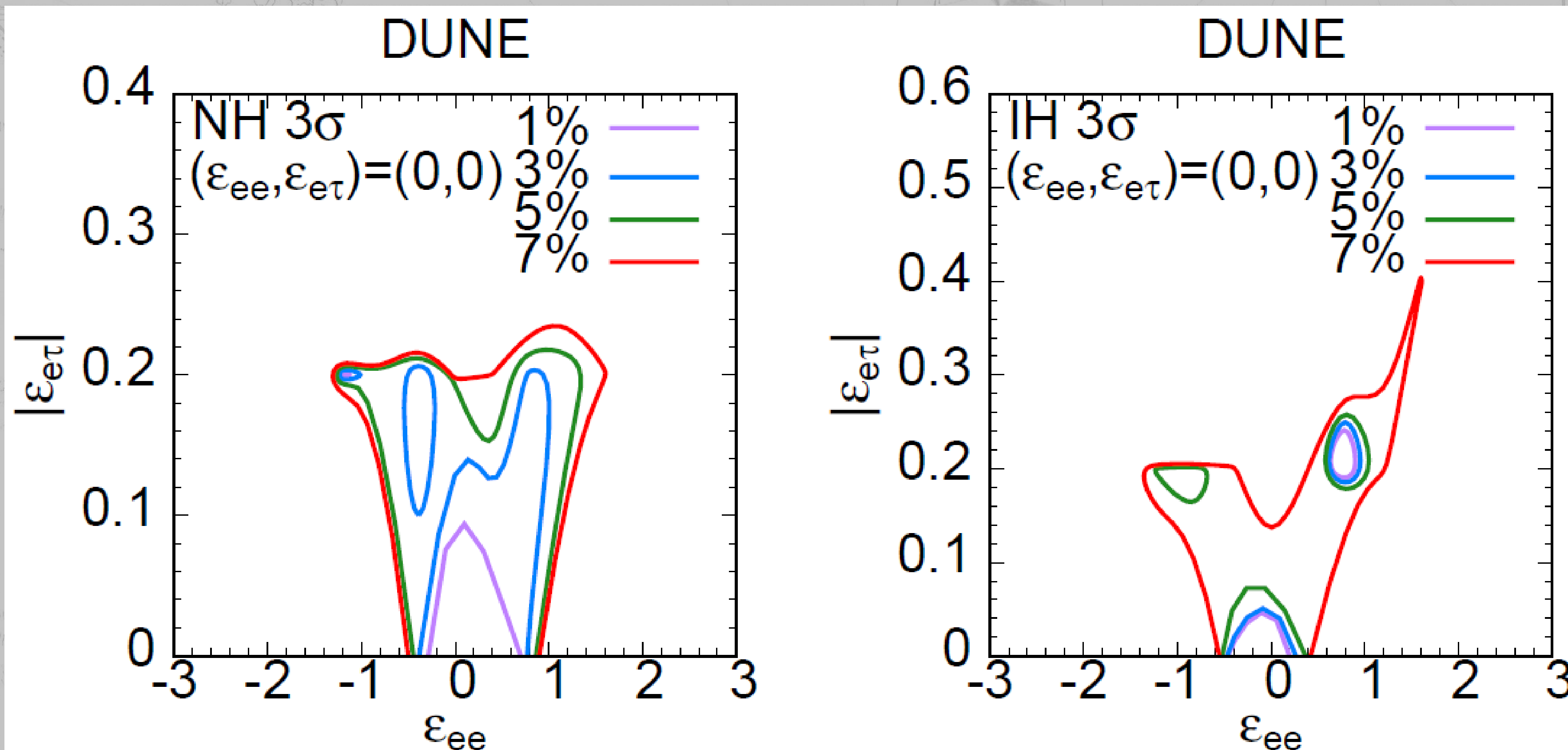
PRD 96 ('17) 013001, Monojit Ghosh & OY



True δ_{CP}=-90^o θ_{23}=45^o ϕ_{31}=0

Sensitivity to (ε_{ee}, | $\varepsilon_{e\tau}$ |)

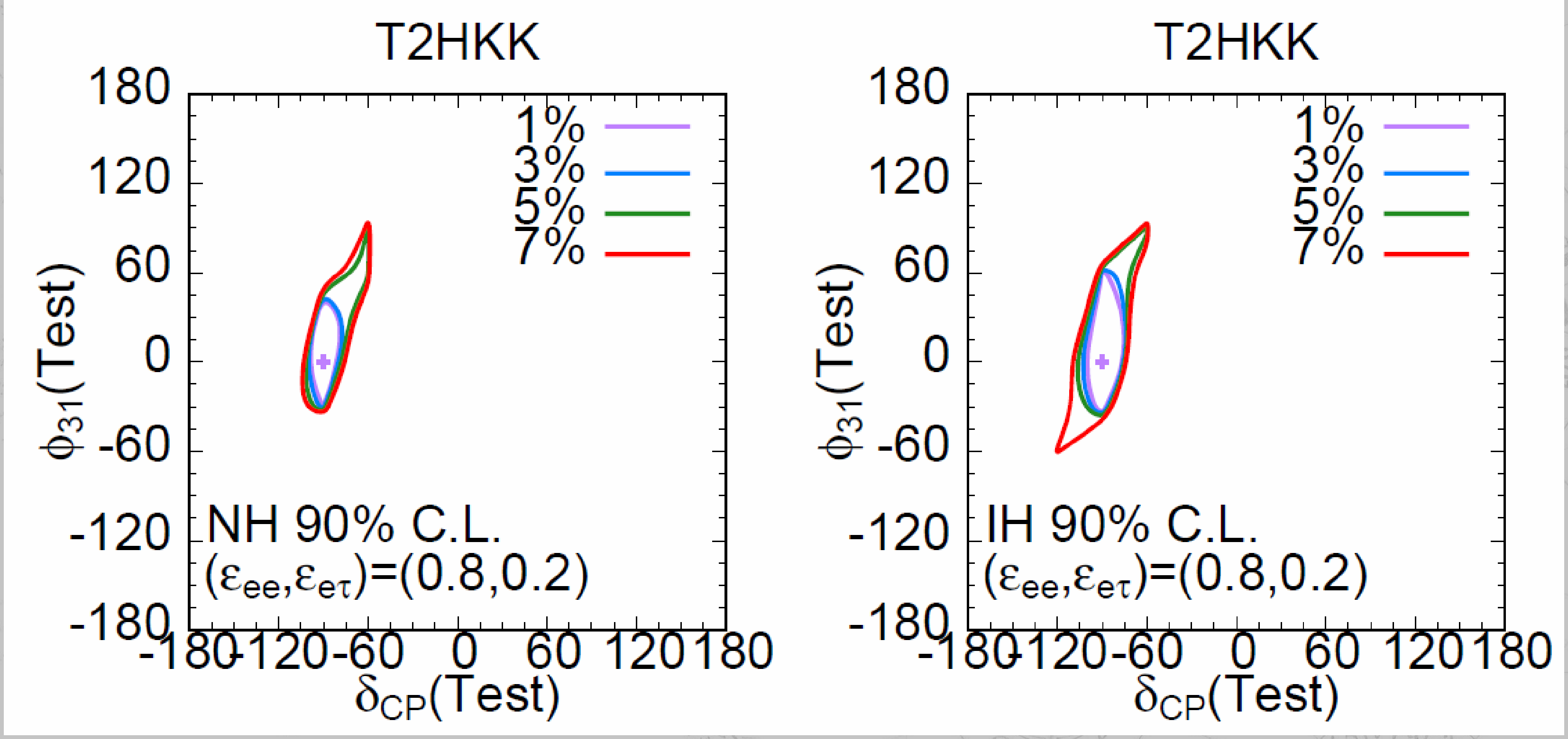
PRD 96 ('17) 013001, Monojit Ghosh & OY



True δ_{CP}=-90^{o} θ_{23}=45^{o} ϕ_{31}=0

Sensitivity to $\phi_{31} \equiv \arg(\varepsilon_{e\tau})$ & δ_{CP}

PRD 96 ('17) 013001, Monojit Ghosh & OY



True δ_{CP}=-90^o θ_{23}=45^o ϕ_{31}=0

Sensitivity to $\phi_{31} \equiv \arg(\varepsilon_{e\tau})$ & δ_{CP}

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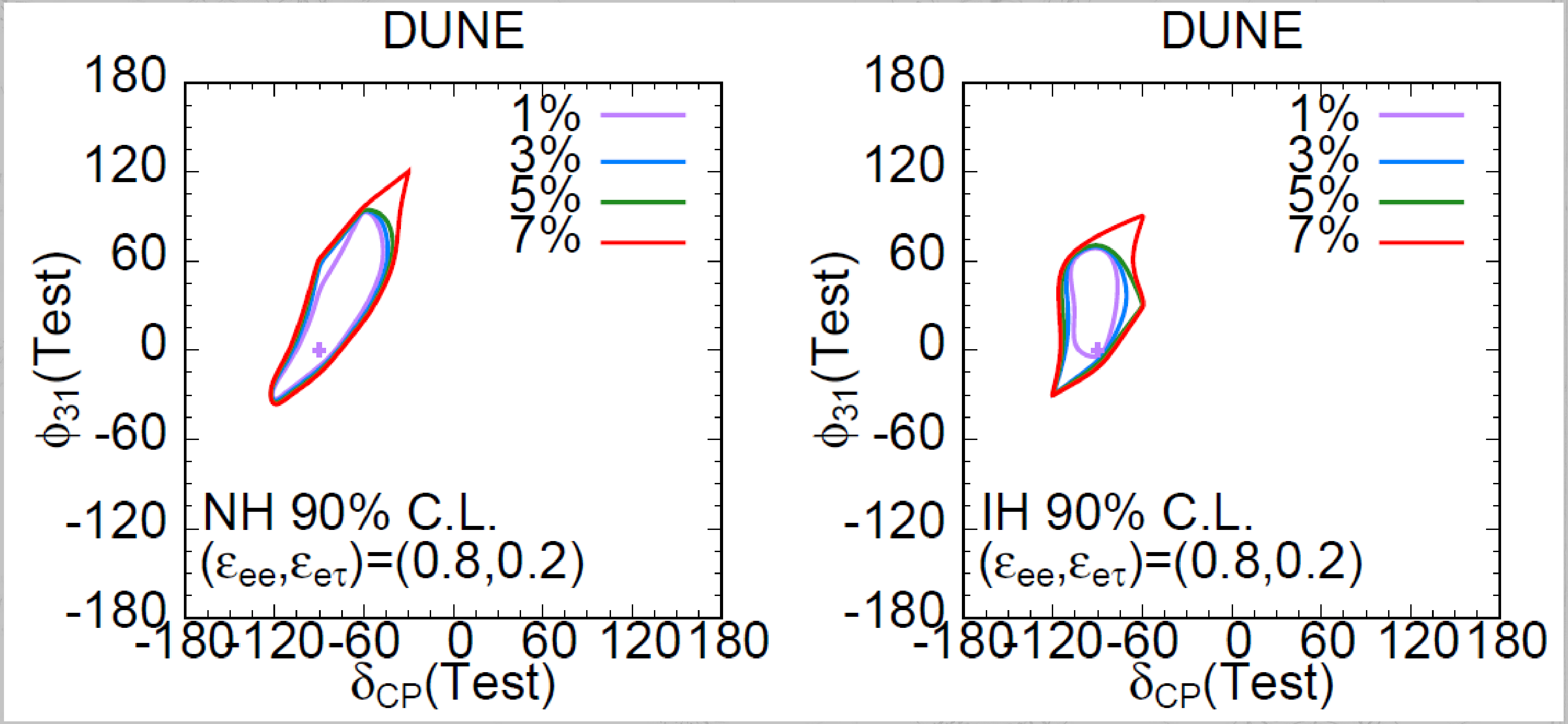
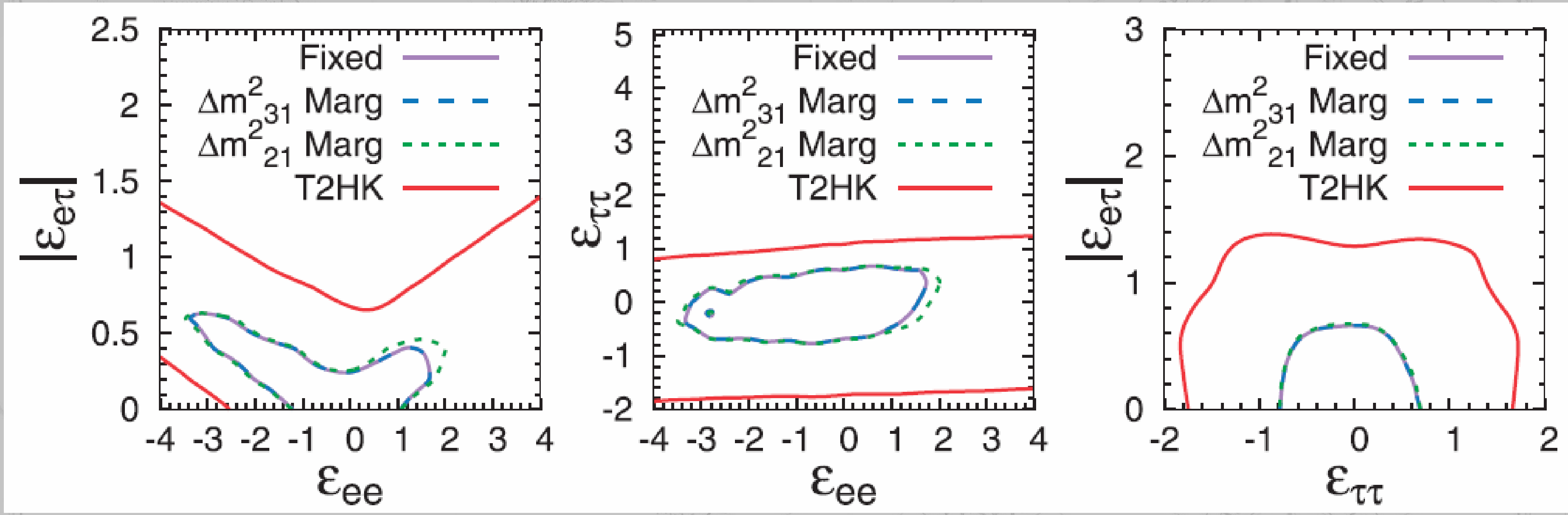


True $\delta_{CP}=-90^o$ $\theta_{23}=45^o$ $\phi_{31}=0$

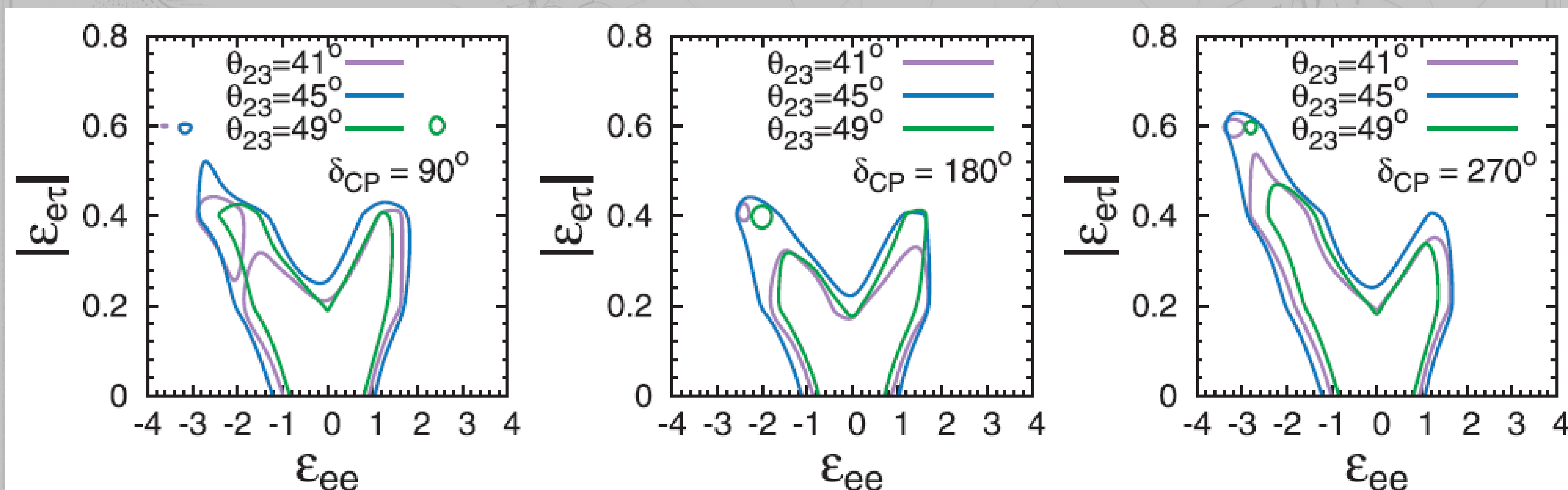
Sensitivity of T2HKK to (ε_{ee}, | $\varepsilon_{e\tau}$ |) w/ or w/o marginalization w.r.t. each Δm^2_{jk}

PTEP 2018 ('18) 063C01, §7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)



Sensitivity of T2HKK to (ε_{ee}, | $\varepsilon_{e\tau}$ |) for various values of θ_{23} and δ_{CP}

PTEP 2018 ('18) 063C01, §7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)



Sensitivity of T2HKK to (ε_{ee}, $|\varepsilon_{e\tau}|$) for various values of θ_{23} w/o the condition $\varepsilon_{\tau\tau}=|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$

PTEP 2018 ('18) 063C01, §7.1, Monojit Ghosh & OY et al. (Hyper-Kamiokande Proto-Collaboration)