Probing non-standard interactions with a muon decay-at-rest source

Sushant Raut

기초과학연구원
Institute for Basic Science

IBS - Center for Theoretical Physics of the Universe, Daejeon, South Korea

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CP violation

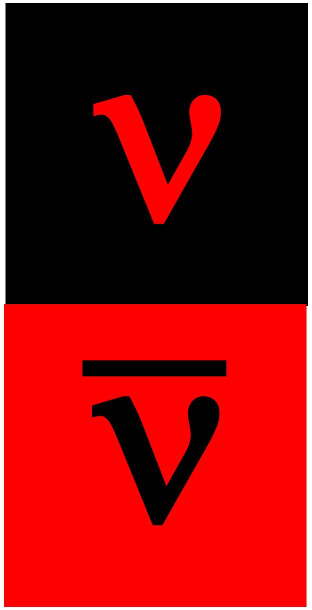
- Measuring CP violation in the lepton sector is one of the main aims of neutrino physics today
- Data from T2K already shows a weak preference for δ_{CP} in the lower half-plane, i.e. between -180º and 0º.
- A precision measurement of this parameter will play in important role in discriminating between new physics models: DUNE, T2HK, T2HKK, ESSνSB, etc.

$$P_{\mu e} = 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-A)\Delta)}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2(A\Delta)}{A^2}$$

$$+2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{CP})\frac{\sin((1-A)\Delta)}{(1-A)}\frac{\sin(A\Delta)}{A}$$

$$\text{where } \alpha = \Delta m^2{}_{21}/\Delta m^2{}_{31},\ \ \Delta = \Delta m^2{}_{31}L/4E,\ \ A = 2EV/\Delta m^2{}_{31}$$

Akhmedov et al, 2004



μDAR setup

- One of the proposed experiments for precisely measuring δ_{CP} is the muon decay-at-rest or μDAR setup

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \longrightarrow \bar{\nu}_e\, p \to n\, e^+$$

Conrad et al, 2009
Agarwalla et al, 2010
Alonso et al, 2010
Evslin et al, 2015

- Advantages:
  - Flux from three-body decay known exactly: Systematic uncertainty reduced
  - Inverse β-decay cross-section is large and well measured: Systematic uncertainty reduced
  - Delayed coincidence tag from neutron capture: Higher detection efficiency
  - No beam-on backgrounds: Fewer background events

- Hybrid setup: T2HK (ν) + μDAR (antiν) using the same SK/HK detectors

Experimental configuration

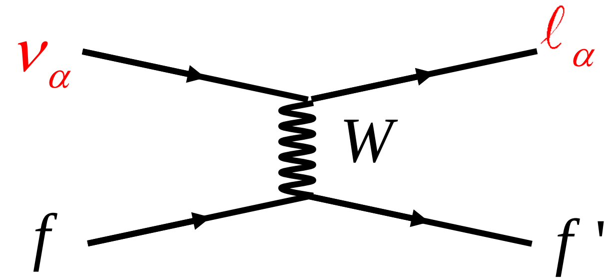
Experiment	Detector mass (kt)	Baseline (km)	Total pot	Systematic errors
Conventional T2HK	187×2	295	13.5×10^{21} (ν) + 13.5×10^{21} $(\bar{\nu})$	ν: 4.71% (4.13%) for app (disap), $\bar{\nu}$: 4.47% (4.16%) for app (disap). Errors are same for sg and bg.
T2HK with μ-DAR	187×2	295	27×10^{21} (ν), No $\bar{\nu}$	Same as above for ν.
μ-DAR **Evslin et al, 2015**	22.5(SK) + 187×2(HK)	15(SK) + 23(HK)	1.1×10^{25} $(\bar{\nu})$ (same for both SK and HK)	5% for both sg and bg (same for both SK and HK).

Improvement over conventional T2HK not only for CPV discovery but also for excluding the wrong mass hierarchy and octant of θ_{23}. **Agarwalla et al, 2017**

Can this setup probe CP violation in the presence of non-standard neutrino interactions (NSIs)?

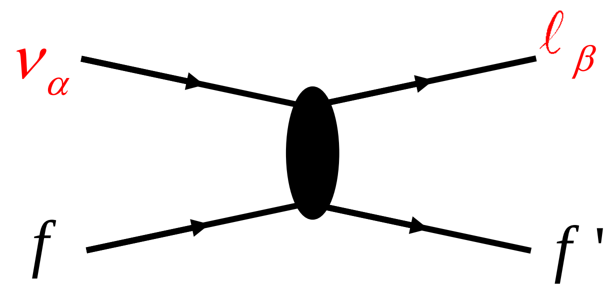
Non-standard interactions

- In the Standard Model, charged-current (CC) interactions of neutrinos are flavour-diagonal



$$\mathcal{L}_{CC} \sim G_F(\bar{\ell}_\alpha \gamma^\mu P_L \nu_\alpha)(\bar{f}' \gamma_\mu P_L f)$$

- With new physics, we can have a flavour violating NSI that modifies the neutrino production/ detection process



$$\mathcal{L}_{CC} \sim \varepsilon^{ff'}_{\alpha\beta} G_F(\bar{\ell}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}' \gamma_\mu P_X f)$$

- Neutral-current (NC) NSIs affect the propagation of neutrinos through matter and are energy dependent, hence neglected here

- NSI in neutrino production at DAR:

$$\mu^+ \to e^+ \nu_\alpha \bar{\nu}_\beta \qquad : \qquad \varepsilon_{\alpha\beta}^{\mu e}$$

- NSI in neutrino detection through IBD:

$$\bar{\nu}_\rho \, p \to n \, e^+ \qquad : \qquad \varepsilon_{\rho e}^{ud} \equiv \varepsilon_{\rho e}$$

- NSI in neutrino production at DAR:

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$$\bar{\nu}_\rho \, p \to n \, e^+ \quad : \quad \varepsilon^{ud}_{\rho e} \equiv \varepsilon_{\rho e}$$

Most of this talk

Agarwalla, Ghosh, SR

- NSI in neutrino production at DAR:

$$\mu^+ \to e^+ \nu_\alpha \bar{\nu}_\beta \qquad : \qquad \varepsilon^{\mu e}_{\alpha\beta}$$

Brief discussion

Ghosh, Mehta, Sinha, SR, Soumya

- NSI in neutrino detection through IBD:

$$\bar{\nu}_\rho \, p \to n e^+ \qquad : \qquad \varepsilon^{ud}_{\rho e} \equiv \varepsilon_{\rho e}$$

Most of this talk

Agarwalla, Ghosh, SR

Detector NSI parameters

- Redefine the neutrino states in terms of the SM fields:

$$|\nu_\alpha^d\rangle = \frac{1}{N_\alpha}\left(|\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\gamma\alpha}|\nu_\gamma\rangle\right) \quad ; \quad N_\alpha = \sqrt{\left[(1+\varepsilon)^\dagger(1+\varepsilon)\right]_{\alpha\alpha}}$$

Antusch et al, 2007

- In general there are 9 amplitudes + 9 phases = 18 new real parameters due to detector NSIs
- For DAR, energy < 50 MeV so only electrons can be produced in the final state. Therefore only $\varepsilon_{\gamma e}$ are relevant.
- Up to leading order, diagonal NSIs do not affect appearance channel probabilities. Only $\varepsilon_{\mu e}$ and $\varepsilon_{\tau e}$ are relevant.

$$|\varepsilon^L_{\mu e}| < 0.026,\ |\varepsilon^R_{\mu e}| < 0.037,\ |\varepsilon^L_{\tau e}| < 0.087,\ |\varepsilon^R_{\tau e}| < 0.12$$

NOMAD Collab, 2001,2003
Biggio et al, 2009

- Q1: Does the presence of NSIs affect the measurement of standard CPV at μDAR?
- Q2: Can μDAR measure CPV arising due to the NSI phase?

- We consider one NSI at a time (amplitude + phase)
- Assume the magnitude of the NSI to be a benchmark value of 0.05 (chosen to illustrate an impact on CP measurement, same order of magnitude as current bounds from NOMAD)

Probability level discussion

$$\Delta P_{\mu e}^{\rm vac}(\varepsilon_{\mu e}) \simeq -4|\varepsilon_{\mu e}| \sin\theta_{13}\cos 2\theta_{23}\sin\theta_{23}\cos(\phi_{\mu e}+\delta_{\rm CP})\sin^2\Delta$$
$$-2|\varepsilon_{\mu e}| \sin\theta_{13}\sin\theta_{23}\sin(\phi_{\mu e}+\delta_{\rm CP})\sin 2\Delta$$
$$+|\varepsilon_{\mu e}|\alpha\Delta\sin 2\theta_{12}\sin 2\theta_{23}\sin\theta_{23}\cos\phi_{\mu e}\sin 2\Delta$$
$$-2|\varepsilon_{\mu e}|\alpha\Delta\sin 2\theta_{12}\cos\theta_{23}\sin\phi_{\mu e}\left[1-2\sin^2\theta_{23}\sin^2 2\Delta\right] \ ,$$

$$\Delta P_{\mu e}^{\rm vac}(\varepsilon_{\tau e}) \simeq 4|\varepsilon_{\tau e}| \sin\theta_{13}\sin 2\theta_{23}\sin\theta_{23}\cos(\phi_{\tau e}+\delta_{\rm CP})\sin^2\Delta$$
$$+2|\varepsilon_{\tau e}|\alpha\Delta\sin 2\theta_{12}\sin 2\theta_{23}\cos\theta_{23}\sin\Delta\cos(\Delta-\phi_{\tau e}) \ .$$

Probability level discussion

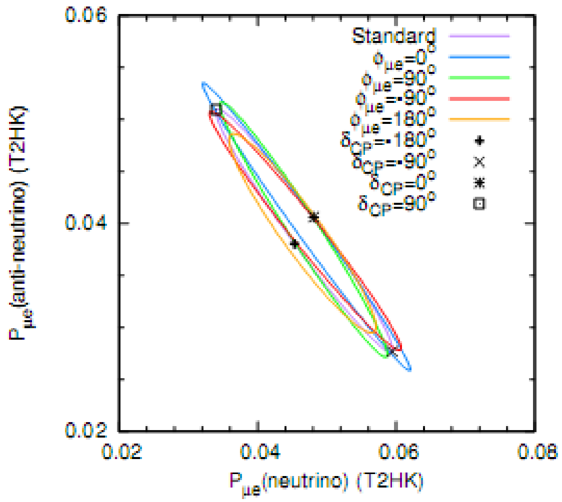
$$
\begin{aligned}
\Delta P^{\text{vac}}_{\mu e}(\varepsilon_{\mu e}) \simeq\ & -4|\varepsilon_{\mu e}| \sin\theta_{13} \cancel{\cos 2}\theta_{23} \sin\theta_{23} \cos(\phi_{\mu e} + \delta_{\text{CP}}) \sin^2\Delta \\
& -2|\varepsilon_{\mu e}| \sin\theta_{13} \sin\theta_{23} \sin(\phi_{\mu e} + \delta_{\text{CP}}) \cancel{\sin} 2\Delta \\
& +|\varepsilon_{\mu e}|\alpha\Delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\theta_{23} \cos\phi_{\mu e} \cancel{\sin} 2\Delta \\
& -2|\varepsilon_{\mu e}|\alpha\Delta \sin 2\theta_{12} \cos\theta_{23} \sin\phi_{\mu e} \left[1 - 2\sin^2\theta_{23} \cancel{\sin^2} 2\Delta\right] \ ,
\end{aligned}
$$

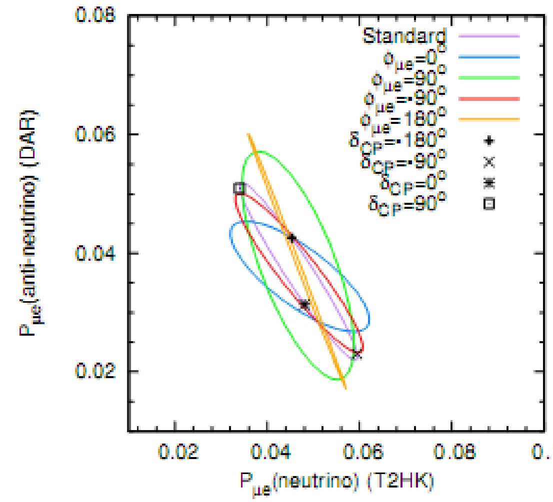
$$
\begin{aligned}
\Delta P^{\text{vac}}_{\mu e}(\varepsilon_{\tau e}) \simeq\ & 4|\varepsilon_{\tau e}| \sin\theta_{13} \sin 2\theta_{23} \sin\theta_{23} \cos(\phi_{\tau e} + \delta_{\text{CP}}) \sin^2\Delta \\
& +2|\varepsilon_{\tau e}|\alpha\Delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\theta_{23} \sin\Delta \cos(\Delta - \phi_{\tau e}) \ .
\end{aligned}
$$

Bi-probability plots: $\varepsilon_{\mu e}$

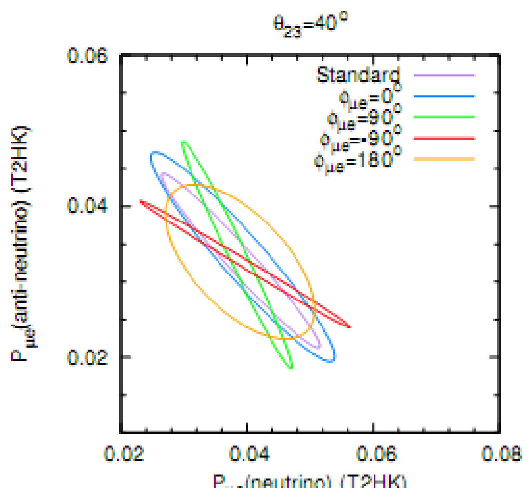
Only T2HK (0.6 GeV) | T2HK (0.6 GeV) + DAR (35 MeV)

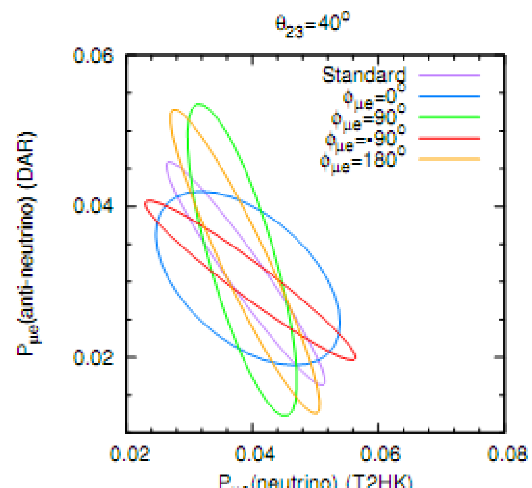
maximal θ_{23}





non-maximal θ_{23}





Bi-probability plots: $\varepsilon_{\tau e}$

Only T2HK (0.6 GeV)

T2HK (0.6 GeV) + DAR (35 MeV)

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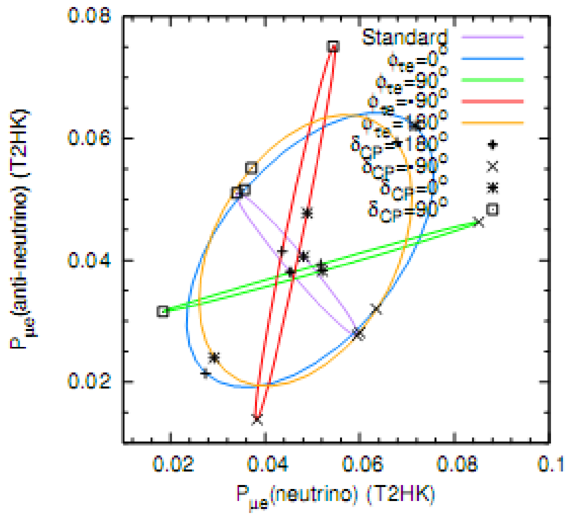

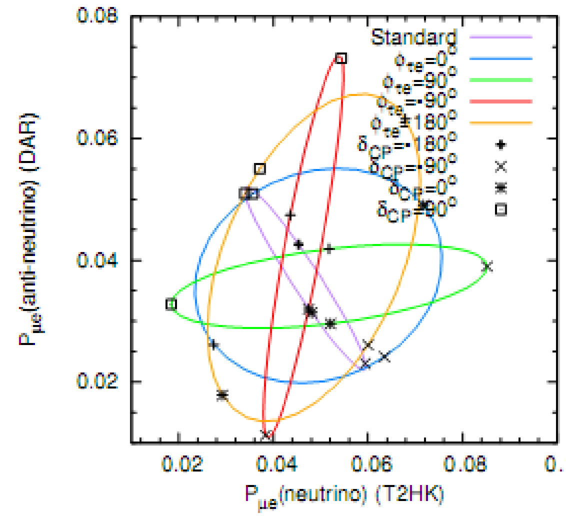

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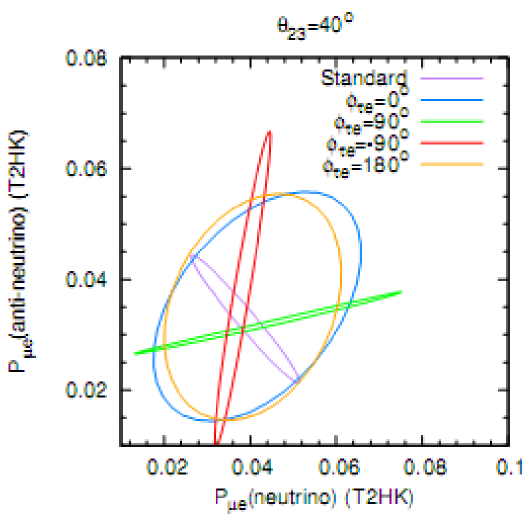
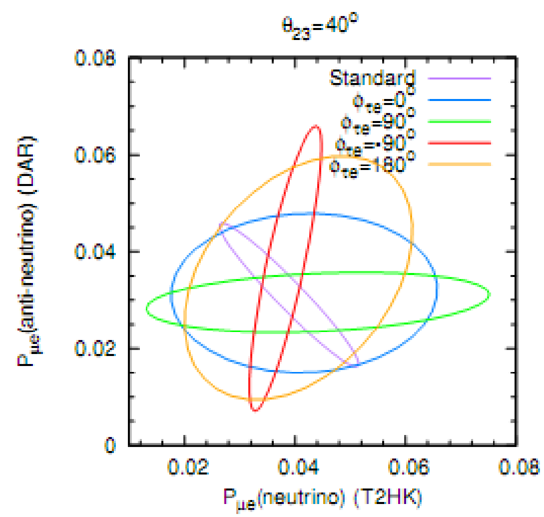




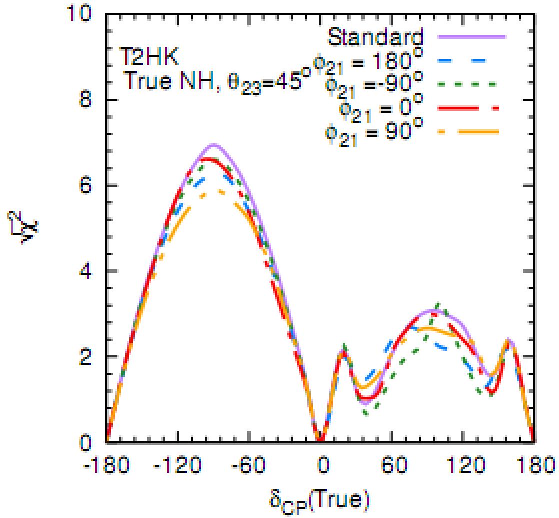
CPV discovery: $\varepsilon_{\mu e}$

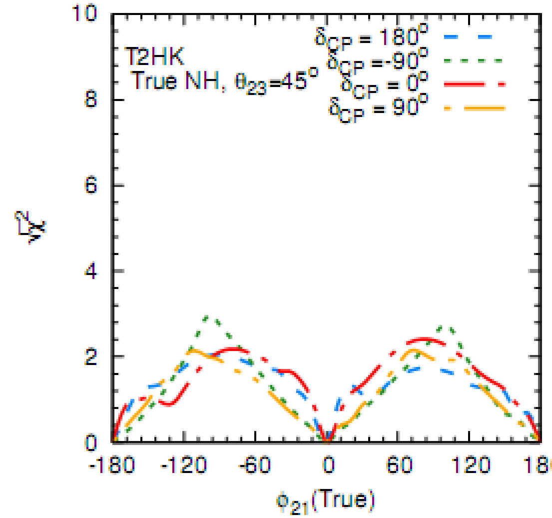
CPV due to δ_{CP}

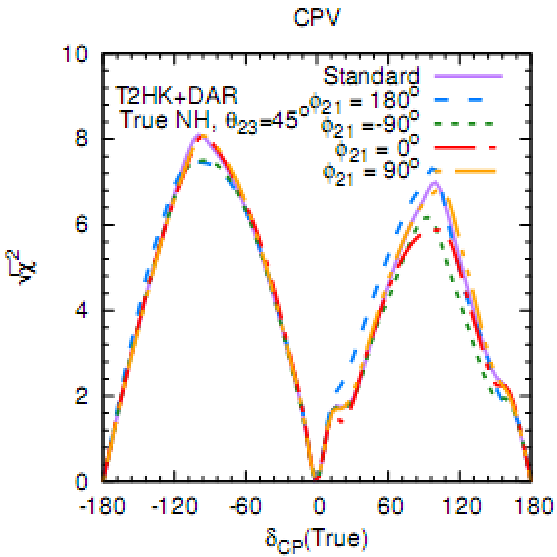
CPV due to ϕ

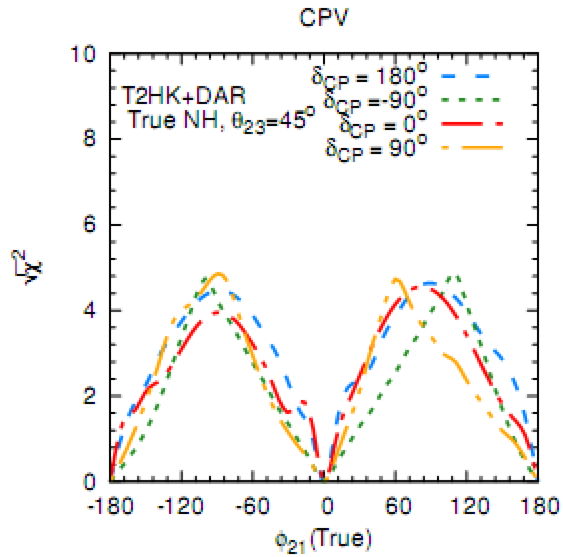
Only T2HK

T2HK + μDAR









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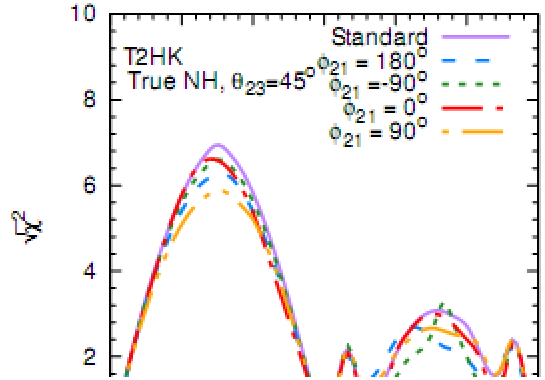
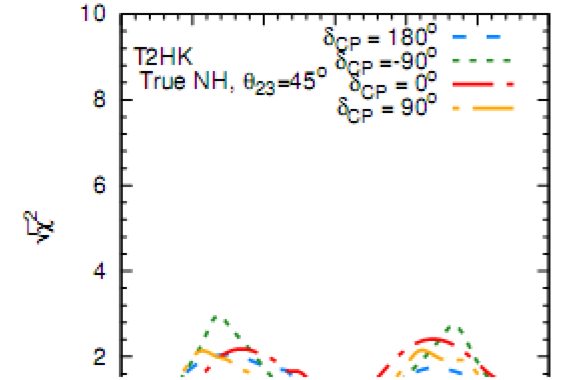
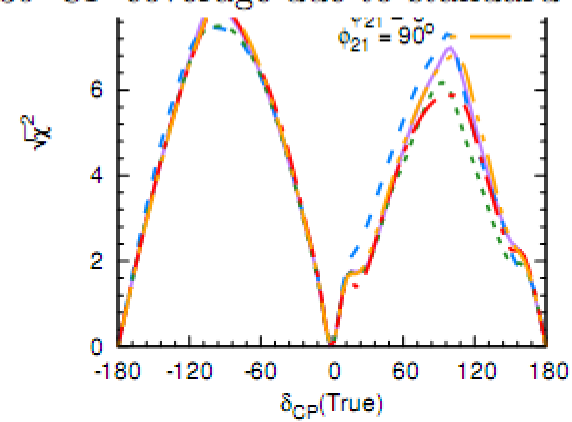


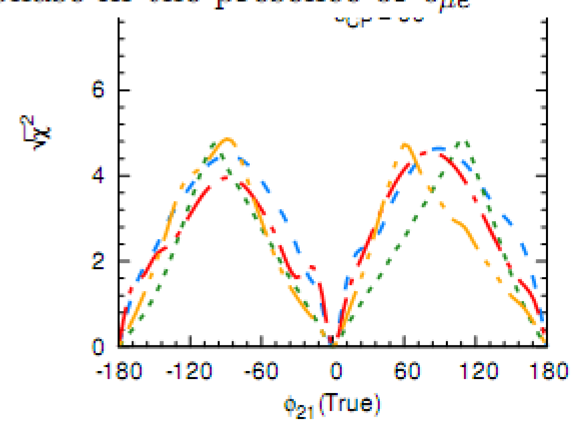


CPV Coverage for	Standard	$\phi_{\mu e} = 180^\circ$	$\phi_{\mu e} = -90^\circ$	$\phi_{\mu e} = 0^\circ$	$\phi_{\mu e} = +90^\circ$
T2HK	41	35	38	32	35
T2HK+DAR	62	65	59	62	62

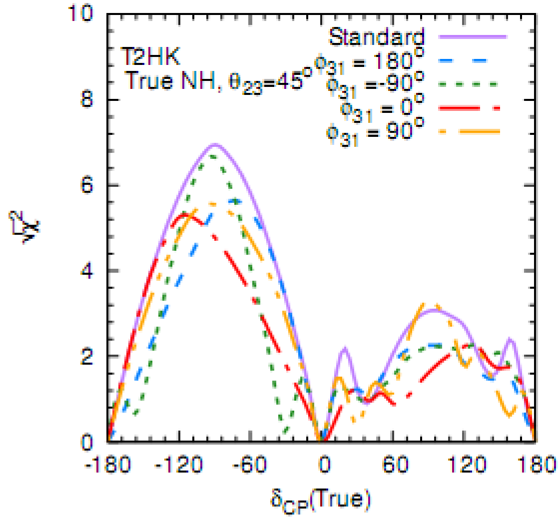
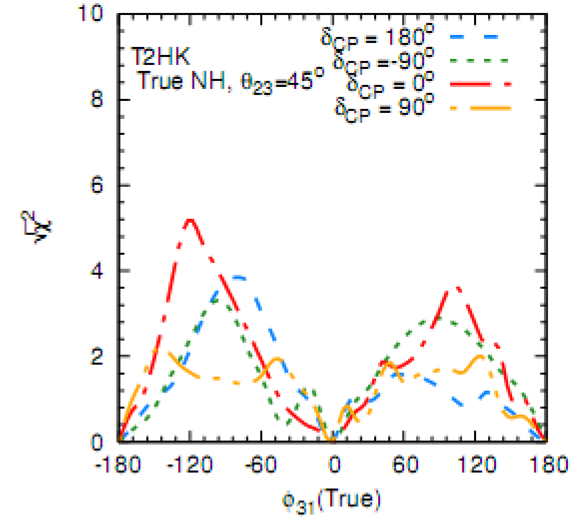
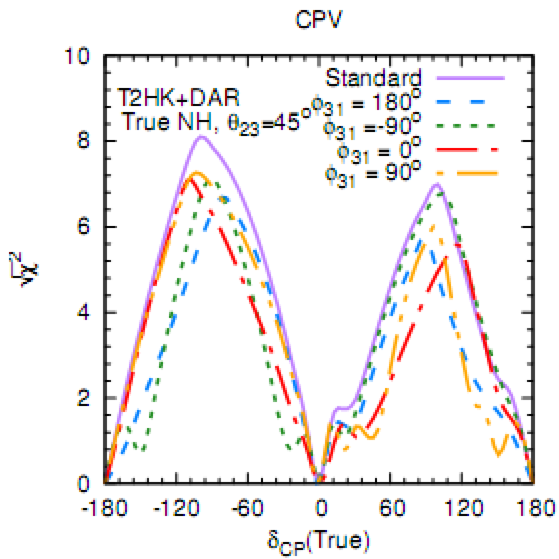
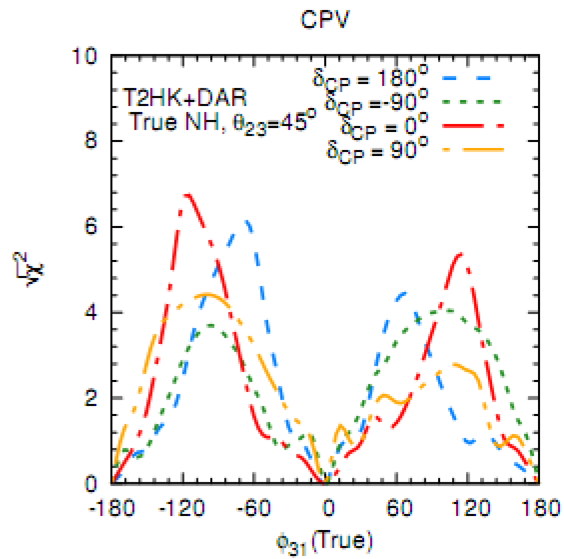
Table 2. 3σ CP coverage due to standard CP phase in the presence of $\epsilon_{\mu e}$

T2HK + μDAR





CPV discovery: $\varepsilon_{\tau e}$

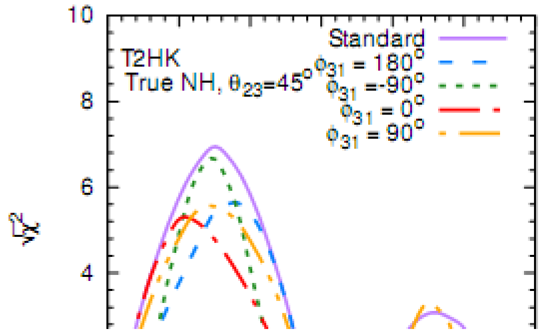
	CPV due to δ_{CP}	CPV due to ϕ
Only T2HK		
T2HK + μDAR		

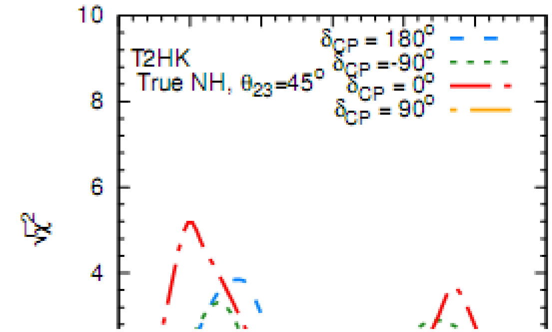
CPV discovery: $\varepsilon_{\tau e}$

CPV due to δ_{CP}

CPV due to ϕ

Only T2HK

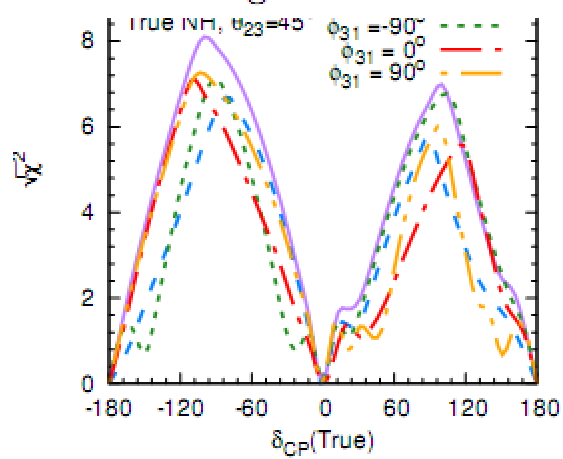


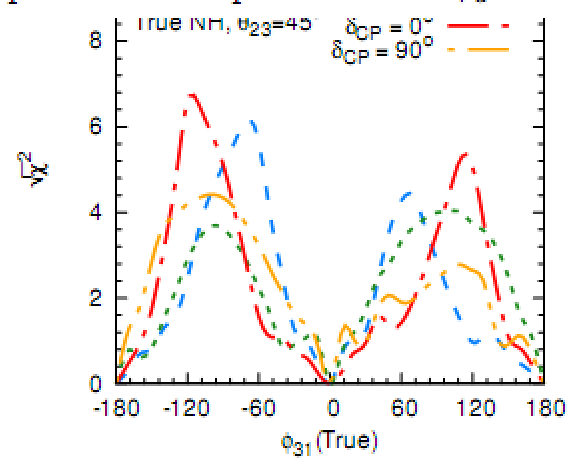


CPV Coverage for	Standard	$\phi_{\tau e} = 180^\circ$	$\phi_{\tau e} = -90^\circ$	$\phi_{\tau e} = 0^\circ$	$\phi_{\tau e} = +90^\circ$
T2HK	41	30	22	27	35
T2HK+DAR	62	51	51	54	51

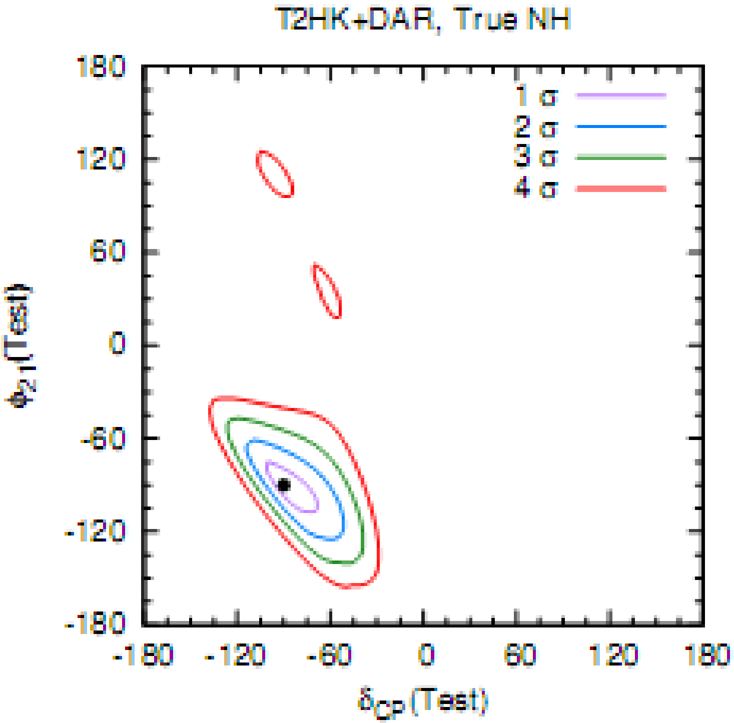
Table 3. 3σ CP coverage due to standard CP phase in the presence of $\epsilon_{\tau e}$

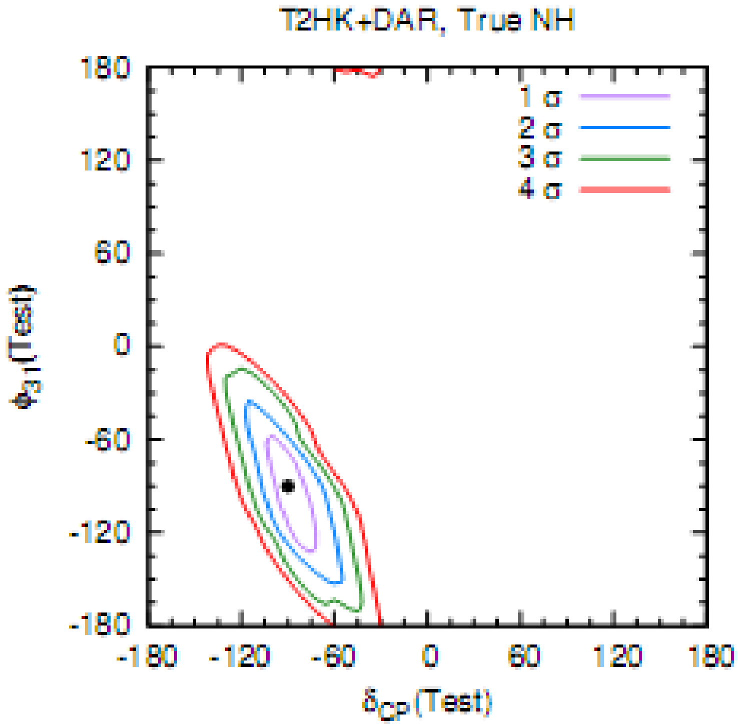
T2HK + μDAR





Correlations between phases



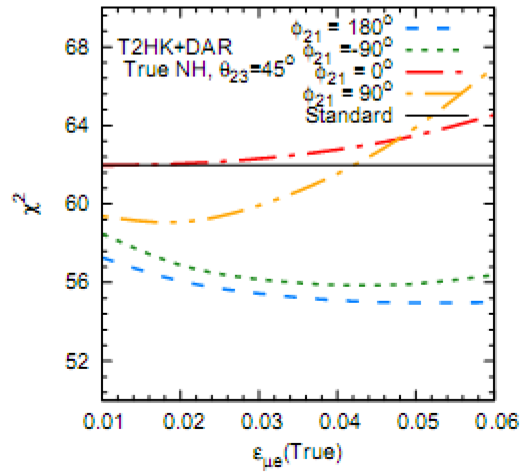


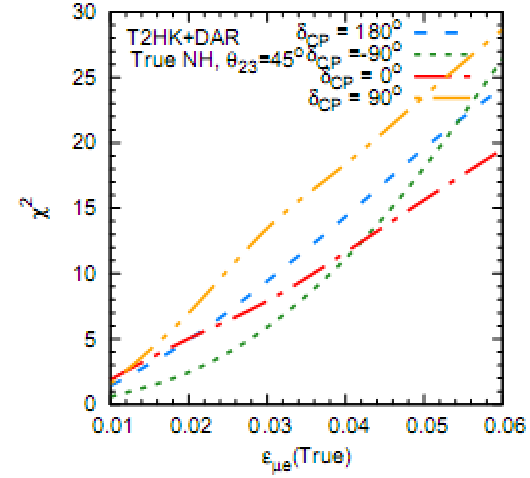
$$\Delta P_{\mu e}^{\rm vac}(\varepsilon_{\tau e}) \simeq 4|\varepsilon_{\tau e}| \sin\theta_{13} \sin 2\theta_{23} \sin\theta_{23} \cos(\phi_{\tau e} + \delta_{\rm CP}) \sin^2\Delta$$
$$+2|\varepsilon_{\tau e}|\alpha\Delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\theta_{23} \sin\Delta \cos(\Delta - \phi_{\tau e}) \ .$$

Variation of the NSI amplitude

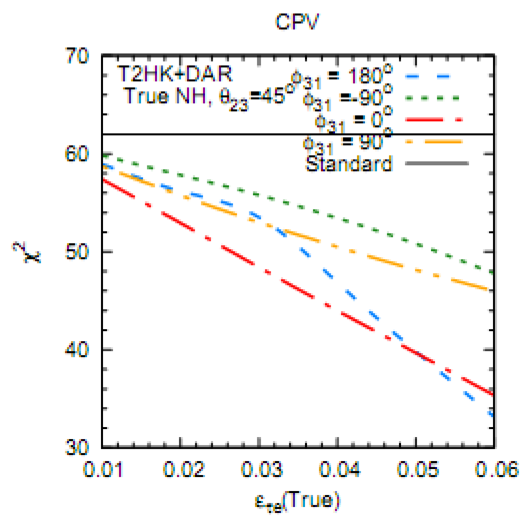
CPV due to δ_{CP} | CPV due to ϕ

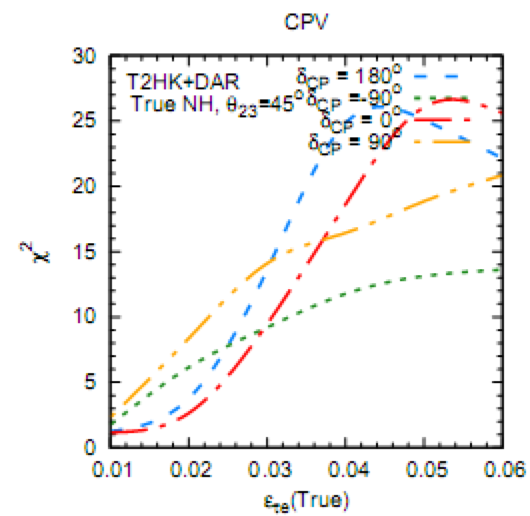
$\varepsilon_{\mu e}$





$\varepsilon_{\tau e}$





Source NSI parameters

$$\mu^+ \to e^+ \nu_\alpha \bar{\nu}_\beta \quad : \quad \varepsilon^{\mu e}_{\alpha\beta}$$

$$|\bar{\nu}^s_\mu \nu^s_e\rangle = \frac{1}{N}\left(|\bar{\nu}_\mu\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon^{\mu e *}_{\mu\gamma} |\bar{\nu}_\gamma\rangle\right)\left(|\nu_e\rangle + \sum_{\sigma=e,\mu,\tau} \varepsilon^{\mu e}_{e\sigma} |\nu_\sigma\rangle\right) \quad ;$$

$$N = \sqrt{\left[(1+\varepsilon)^\dagger (1+\varepsilon)\right]_{ee}} \sqrt{\left[(1+\varepsilon)^\dagger (1+\varepsilon)\right]_{\mu\mu}}$$

$$P(\bar{\nu}^s_\mu \to \bar{\nu}_e) = \sum_X P(\bar{\nu}^s_\mu \nu^s_e \to \bar{\nu}_e \nu_X)$$

- The only relevant NSI parameters are $\varepsilon^{\mu e}_{\mu e}$, $\varepsilon^{\mu e}_{\mu\mu}$ and $\varepsilon^{\mu e}_{\mu\tau}$.

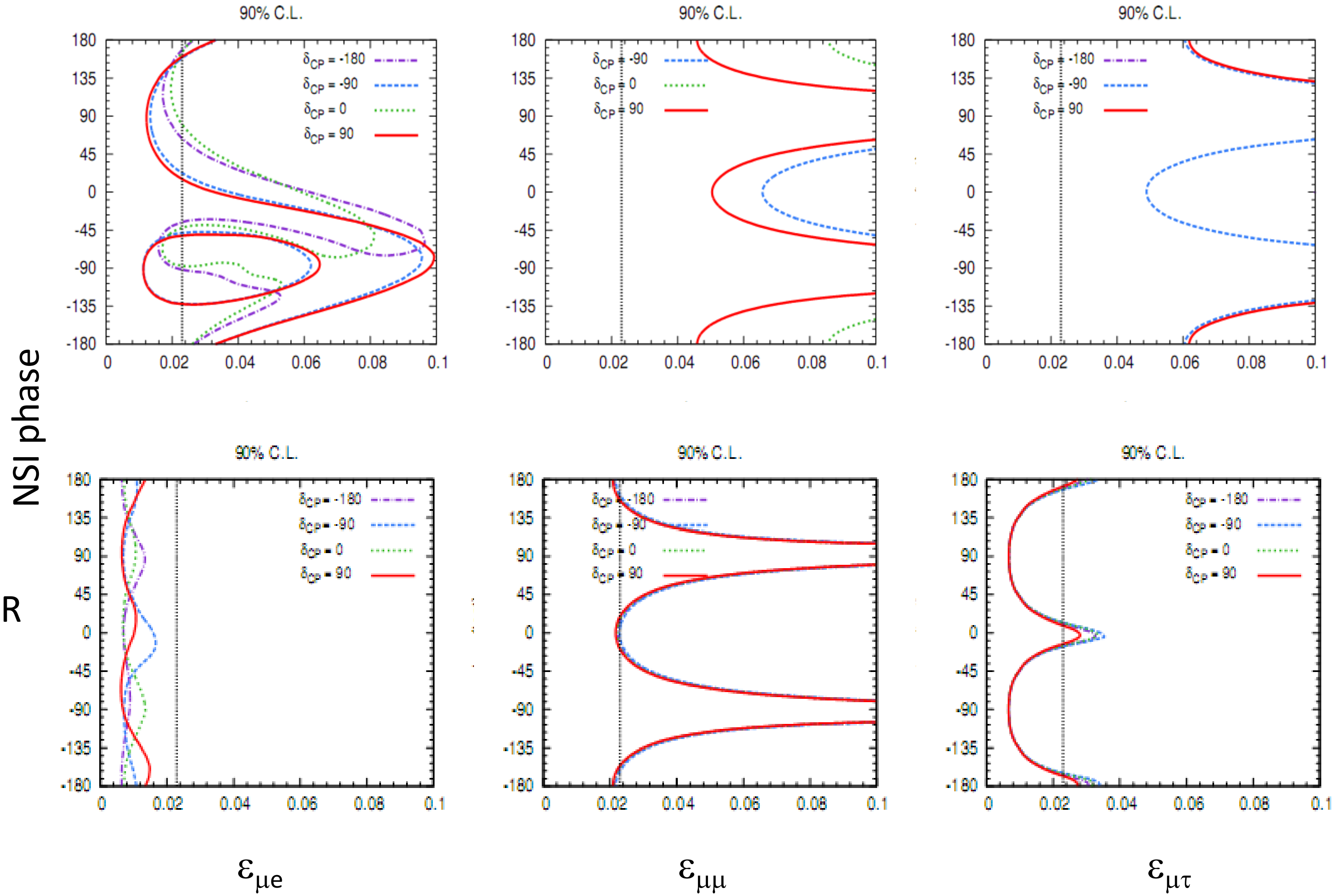
$$\begin{aligned} P(\nu^s_\mu \to \nu_e) &= 4\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta \\ &+ 2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{\rm CP})\Delta\sin\Delta \\ &- 4|\varepsilon^{\mu e}_{\mu e}|\sin\theta_{13}\sin\theta_{23}\sin(\Delta+\delta_{\rm CP}+\phi^{\mu e}_{\mu e})\sin\Delta \\ &- 2|\varepsilon^{\mu e}_{\mu e}|\alpha\sin 2\theta_{12}\cos\theta_{23}\sin\phi^{\mu e}_{\mu e}\Delta\,, \end{aligned}$$

Kopp et al, 2007

Bounds on NSI parameters

Only μDAR

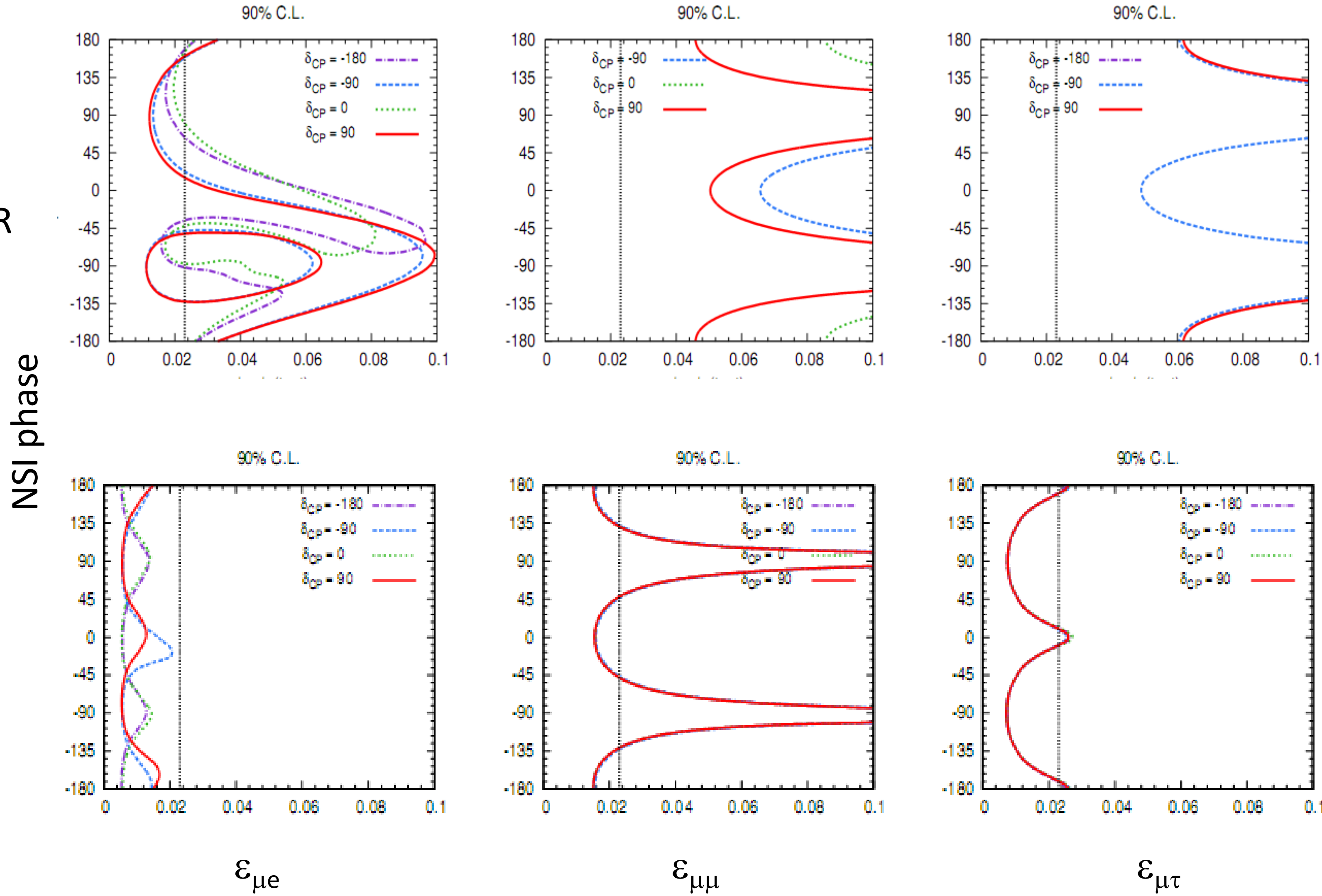
T2HK + μDAR



Bounds on NSI parameters

Only μDAR

T2HK(1:3)
+ μDAR



Summary

- μDAR which has been shown to have good sensitivity to standard oscillation physics can also be used to probe CC NSIs.
- No interference with NC NSIs due to the low energy involved.
- Spectral information will be important to measure the detector NSI $\varepsilon_{\mu e}$.
- The standard CP sensitivity is not compromised due to the existence of new physics. CPV due to the new phases can also be discovered at this setup.
- Correlations between the standard and non-standard phases can be probed
- Bounds on the source NSI parameters can be improved beyond the existing ones.

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- Bounds on the source NSI parameters can be improved beyond the existing ones.

Thank you.

maximal θ_{23}

non-maximal θ_{23}