Probing charged-current non-standard interactions with neutrinos from a decay-at-rest source

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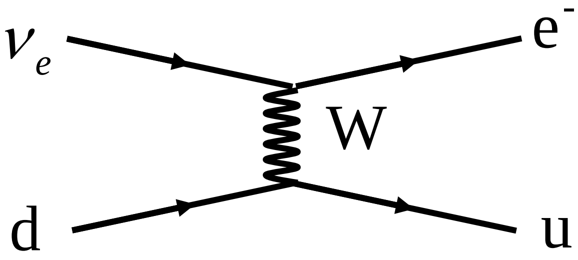
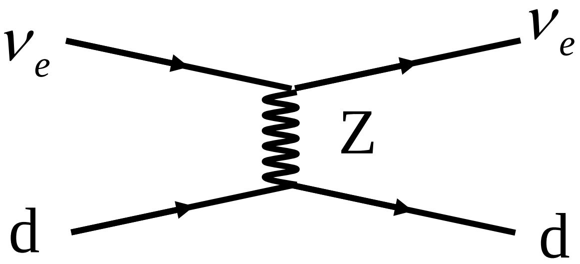
Non-standard interactions (NSI)

- In the Standard Model,

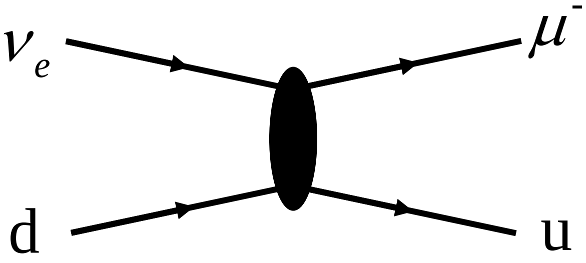


$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\alpha)(\overline{f}\gamma_\mu P_L f')$$

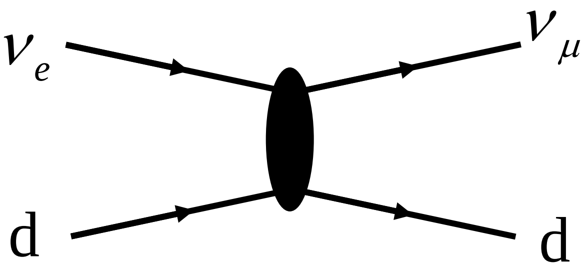


$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\alpha)(\overline{f}\gamma_\mu P_L f')$$

- With new physics, we can have non-standard interactions (NSI)



$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f')$$



$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f')$$

Effect of NSIs on neutrino oscillations

- CC NSIs affect the production and detection of neutrino flavours, introducing sub-leading interference terms between standard oscillation amplitudes

$$|\nu_\alpha^{\mathrm{s}}\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^{\mathrm{s}}_{\alpha\beta}|\nu_\beta\rangle = (1+\varepsilon^{\mathrm{s}})U|\nu_m\rangle\,,$$

$$\langle\nu_\beta^{\mathrm{d}}| = \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^{\mathrm{d}}_{\alpha\beta}\langle\nu_\alpha| = \langle\nu_m|U^\dagger[1+(\varepsilon^{\mathrm{d}})^\dagger]$$

- NC NSIs introduce extra energy-dependent terms in the propagation Hamiltonian and change the amplitudes and phases of oscillations

- Decay-at-rest sources produce low energy neutrinos, allowing us to disentangle high-energy NC NSI effects from CC NSI ones

Current bounds

- Bounds on CC NSIs from muon-decay, pion-decay, etc.

$$|\varepsilon^{ud}_{\alpha\beta}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \begin{array}{c} 1.8\cdot 10^{-6} \\ 0.026 \end{array} & 0.078 & 0.013 \\ \begin{array}{c} 0.087 \\ 0.12 \end{array} & \begin{array}{c} 0.013 \\ 0.018 \end{array} & 0.13 \end{pmatrix}$$

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\overline{u}\gamma_\mu P_{L,R} d)$$

$$|\varepsilon^{\mu e}_{\alpha\beta}| < \begin{pmatrix} 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \end{pmatrix}$$

$$\mathcal{L}_{CC} = (\overline{e}\gamma^\mu P_L \nu_\alpha)(\overline{\mu}\gamma_\mu P_{L,R} \nu_\beta)$$

- Bounds on NC NSIs

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f')$$

μDAR setup

- Neutrino beam: T2HK (295 km) and antineutrino beam: μDAR (23 km) , both using Hyper-Kamiokande detector

- Flux spectrum is exactly known (standard three-body decay), detection cross-section (inverse-beta decay) is well measured. Therefore the systematic errors are much smaller than conventional beam experiments
- Short distance for antineutrinos allows for larger flux

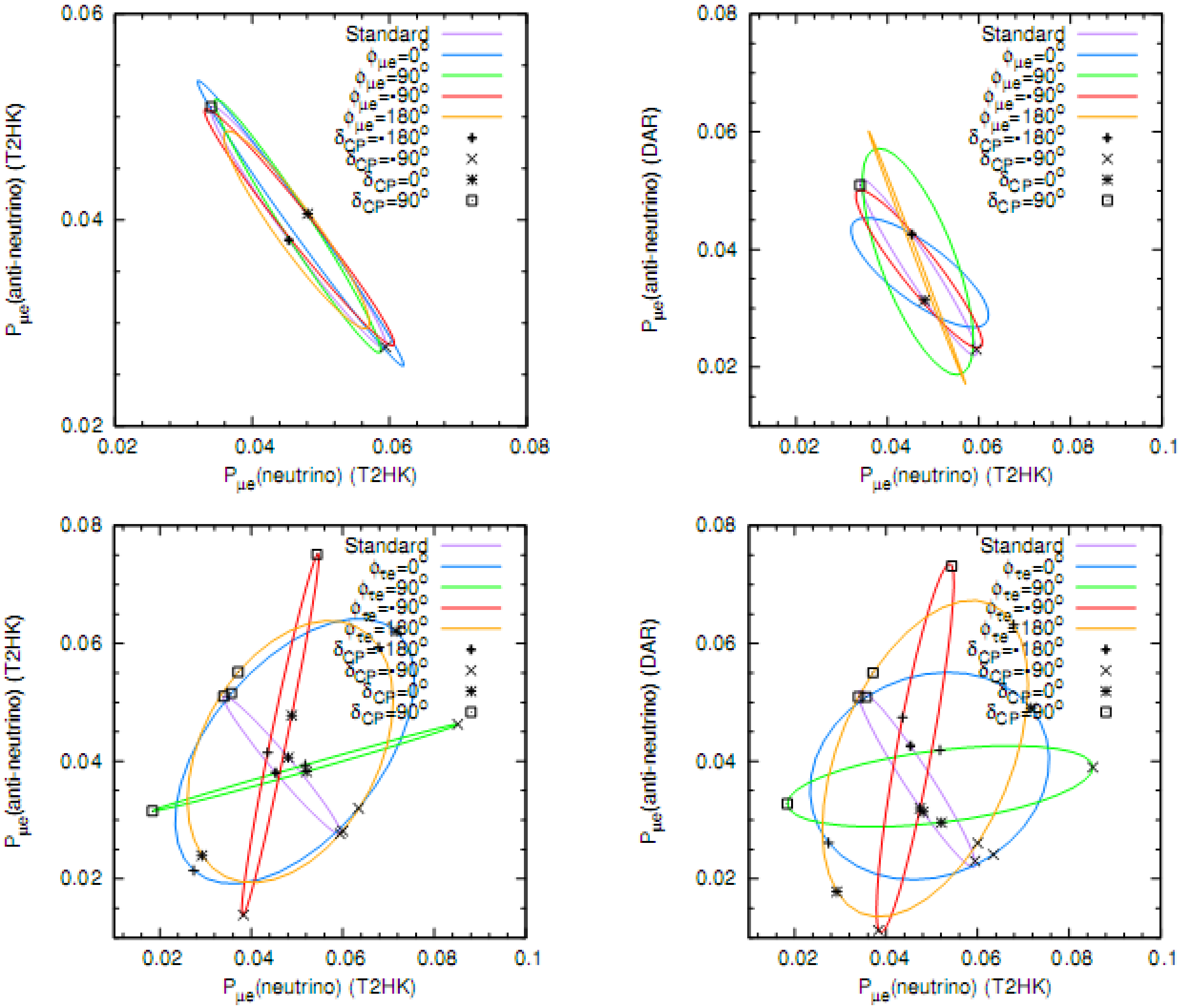
- The chosen distance is such that the energy peak is not at the oscillation maximum

Detector NSI analysis

$$\begin{pmatrix} \varepsilon^d_{ee} & \varepsilon^d_{e\mu} & \varepsilon^d_{e\tau} \\ \boxed{\varepsilon^d_{\mu e}} & \varepsilon^d_{\mu\mu} & \varepsilon^d_{\mu\tau} \\ \boxed{\varepsilon^d_{\tau e}} & \varepsilon^d_{\tau\mu} & \varepsilon^d_{\tau\tau} \end{pmatrix}$$

$$\begin{aligned}
\Delta P^{\rm vac}_{\mu e}(\varepsilon^d_{\mu e}) \simeq & -4|\varepsilon^d_{\mu e}|\sin\theta_{13}\cos\cancel{2}\theta_{23}\sin\theta_{23}\cos(\phi^d_{\mu e}+\delta_{\rm CP})\sin^2\Delta \\
& -2|\varepsilon^d_{\mu e}|\sin\theta_{13}\sin\theta_{23}\sin(\phi^d_{\mu e}+\delta_{\rm CP})\sin\cancel{2}\Delta \\
& +|\varepsilon^d_{\mu e}|\alpha\Delta\sin 2\theta_{12}\sin 2\theta_{23}\sin\theta_{23}\cos\phi^d_{\mu e}\sin\cancel{2}\Delta \\
& -2|\varepsilon^d_{\mu e}|\alpha\Delta\sin 2\theta_{12}\cos\theta_{23}\sin\phi^d_{\mu e}\,\cancel{\left[1-2\sin^2\theta_{23}\sin^2 2\Delta\right]} \\
\Delta P^{\rm vac}_{\mu e}(\varepsilon^d_{\tau e}) \simeq & \; 4|\varepsilon^d_{\tau e}|\sin\theta_{13}\sin 2\theta_{23}\sin\theta_{23}\cos(\phi^d_{\tau e}+\delta_{\rm CP})\sin^2\Delta \\
& +2|\varepsilon^d_{\tau e}|\alpha\Delta\sin 2\theta_{12}\sin 2\theta_{23}\cos\theta_{23}\sin\Delta\cos(\Delta-\phi^d_{\tau e})\,.
\end{aligned}$$

Detecting CP violation



$\varepsilon^d_{\mu e}$

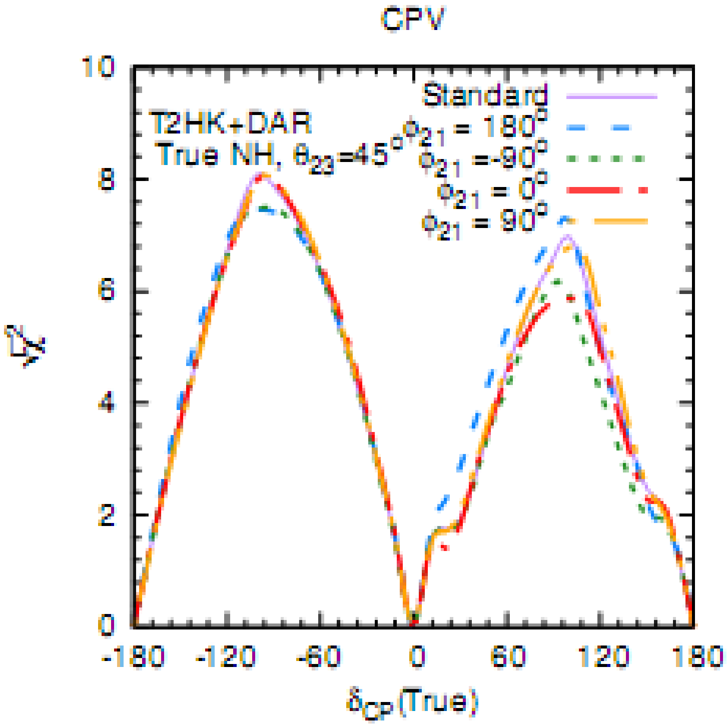
$\varepsilon^d_{\tau e}$

T2HK

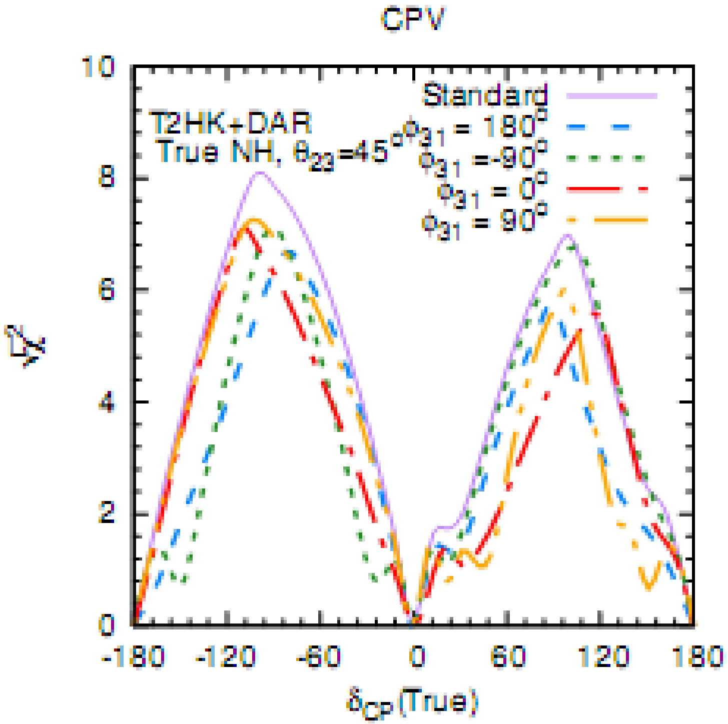
T2HK+μDAR

Effect on CP measurement

- Question: Does the presence of NSIs affect the ability to measure the standard CP phase δ_{CP}?



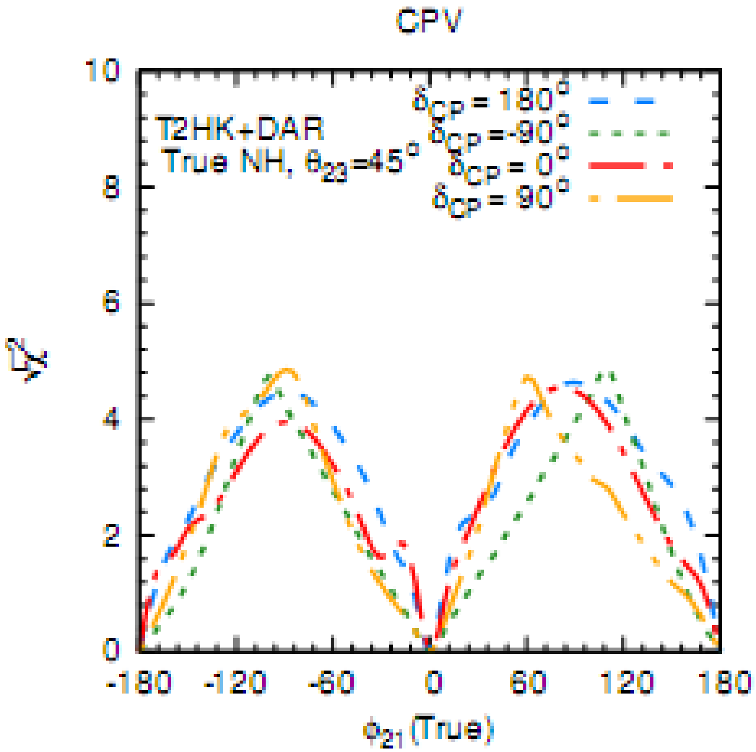
$\varepsilon^d_{\mu e}$



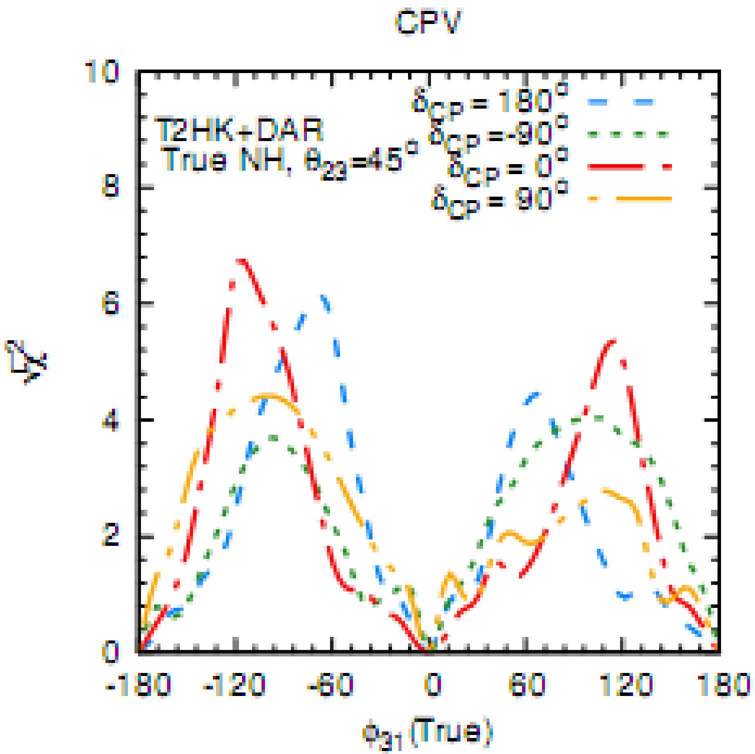
$\varepsilon^d_{\tau e}$

Probing NSI CP violation

- Question: Can we measure CP violation due to the extra non-standard phase?

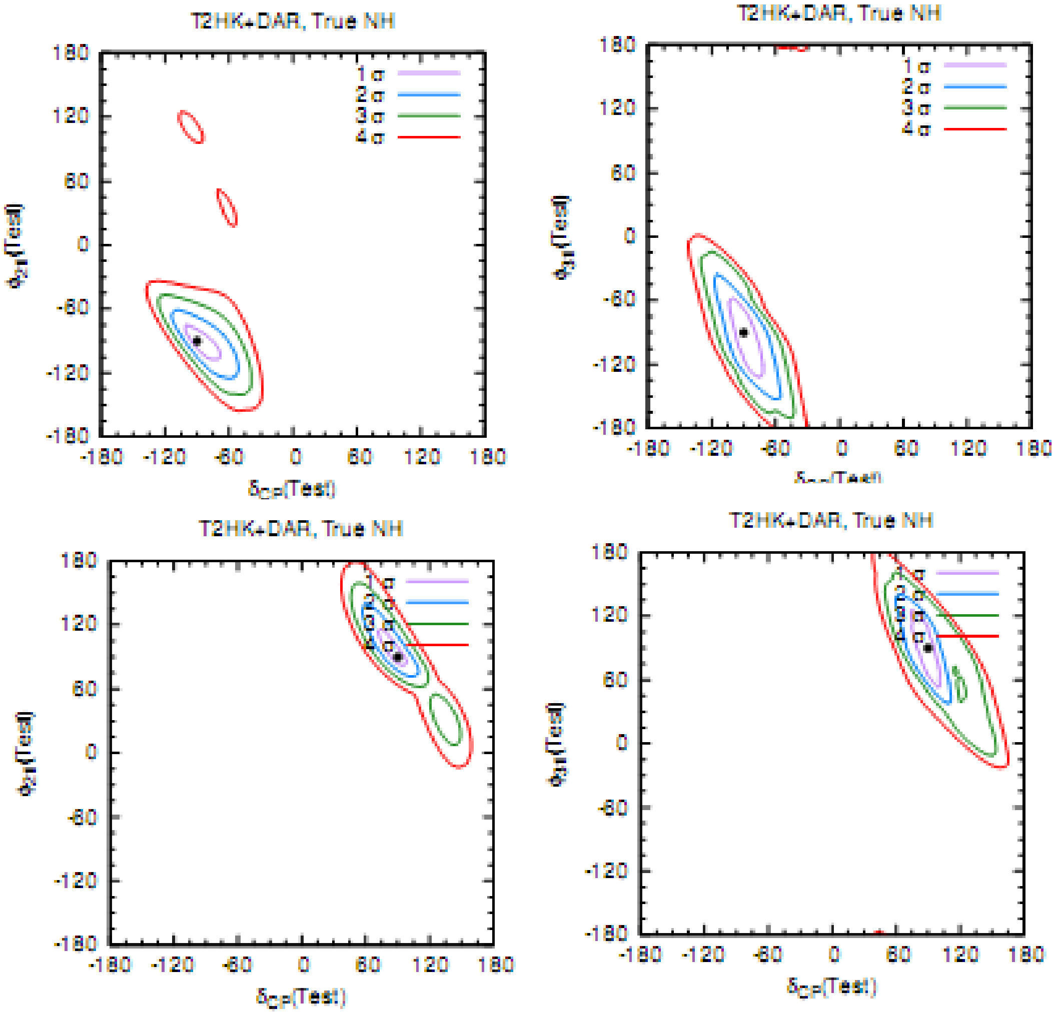


$\varepsilon^{d}_{\mu e}$



$\varepsilon^{d}_{\tau e}$

Correlations between the phases



$\varepsilon^{d}_{\mu e}$ $\varepsilon^{d}_{\tau e}$

- Combination of the two phases is the relevant CP violating quantity (can be seen from reparametrizing the probability formula)
- Can be important for leptogenesis

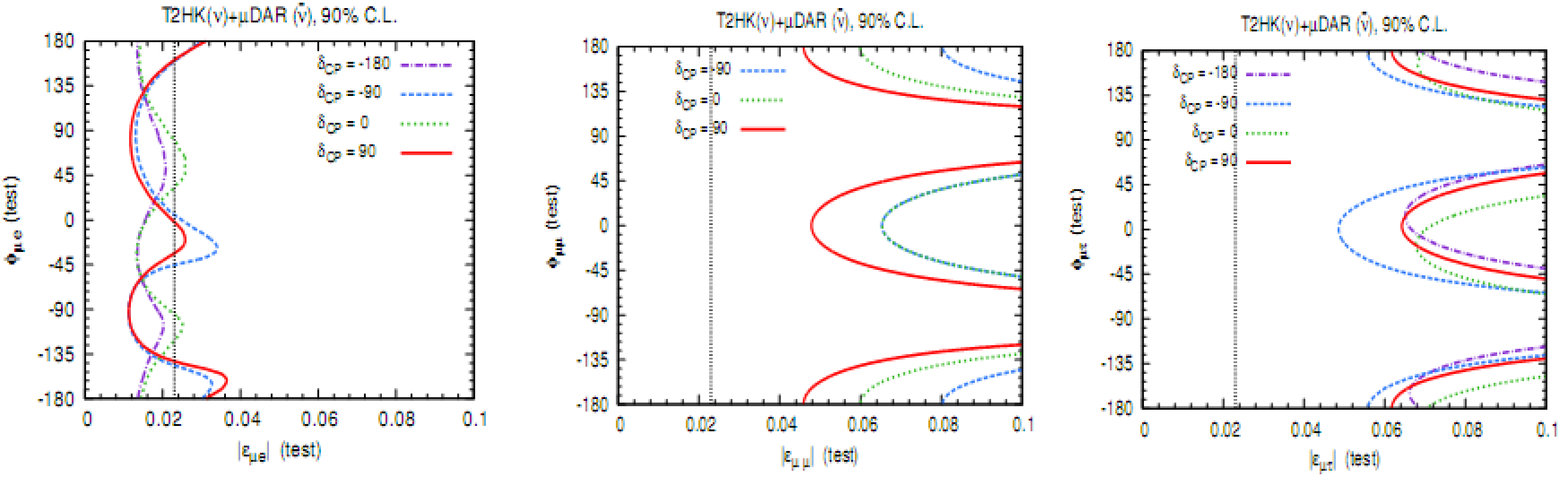
Source NSI

$$\mu^+ \to e^+ \, \overline{\nu_\beta} \, \nu_\alpha$$

$$\begin{bmatrix} \varepsilon^{\mu e}_{ee} & 1+\varepsilon^{\mu e}_{e\mu} & \varepsilon^{\mu e}_{e\tau} \\ \varepsilon^{\mu e}_{\mu e} & \varepsilon^{\mu e}_{\mu\mu} & \varepsilon^{\mu e}_{\mu\tau} \\ \varepsilon^{\mu e}_{\tau e} & \varepsilon^{\mu e}_{\tau\mu} & \varepsilon^{\mu e}_{\tau\tau} \end{bmatrix}$$

- Only the column-wise sum of parameters are relevant, i.e. we have effectively only three complex parameters

Constraints on the NSIs



- Synergy with T2HK in constraining standard oscillation parameters

- Question: Is there an experiment that can disentangle the three parameters that are summed over in each column?

Summary

- Muon decay-at-rest experiments allow us to measure CC NSIs without interference from NC NSIs
- Low systematics helps to increase the sensitivity of this experiment

- Only two relevant detector NSIs, whose phases induce measurable CP violation
- Measurement of standard CP violation is not affected by the presence of these NSIs
- Correlations can be discovered between the two phases

- Source NSIs are fundamentally different from detector NSIs
- Constraints can be placed on them with the help of synergy from conventional experiments like T2HK