Effects of NSI on neutrino oscillation parameters measurement

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Overview

1. Introduction
2. LMA-Dark solution
3. NSI and δ_{CP} degeneracies
4. NSI at solar neutrinos
5. NSI in Atmospheric neutrinos
6. Summary and Conclusion

- Neutrino oscillation provides a very strong evidence for physics BSM.
- In SM, neutrinos are introduced as truly massless fermions. On the contrary, neutrinos oscillate: after being produced, they change their flavours.
- Solar neutrino problem was the first evidence of neutrino oscillation.
- In 1978, Wolfenstein, proposed a possibility of flavor change of the massless neutrinos with non-diagonal neutral current non-standard interactions, during propagation in matter.
- Neutrino oscillation occurs since Flavor eigenstates (of weak interactions) and mass eigenstates (of free particle Hamiltonian) are not aligned for neutrinos.
- Flavor states and mass states are related by mixing matrix called PMNS matrix. (Pontecorvo-Maki-Nakagawa-Sakata matrix). This matrix can be parametrized by 4 parameters (3 angles and at least one phase).

Neutrino Oscillation

- There is a mixing between mass and flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle\,,\ \ \alpha = e, \mu, \tau, \quad i = 1, 2, 3 \tag{1}$$

- PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \tag{2}$$

- Mass eigenstates are total Hamiltonian eigestate while flavor eigenstates are not

$$H|\nu_k\rangle = E_k|\nu_k\rangle = i\frac{d}{dt}|\nu_k(t)\rangle \tag{3}$$

$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle \tag{4}$$

Neutrino Oscillation in Vacuum

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t} |\nu_k\rangle = \sum_\beta \sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k} |\nu_\beta\rangle \tag{5}$$

$$E_k \simeq E + \frac{m_k^2}{2E} \quad \& \quad E_k - E_j \simeq \frac{\Delta m^2_{kj}}{2E} \equiv \frac{m_k^2 - m_j^2}{2E} \tag{6}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{kj} L}{2E}} \tag{7}$$

- Neutrino oscillations are affected by matter interactions, which introduce a potential term in the Hamiltonian

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{8}$$

Neutrino Oscillation in Matter

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1,0,0) \tag{9}$$

$$\mathcal{H}_{vac} = U_{\mathrm{PMNS}} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger_{\mathrm{PMNS}} \tag{10}$$

- In the two-flavor approximation, the flavor evolution of neutrinos in matter is governed by the Schrödinger-like equation:

$$i\frac{d}{dx}\psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{11}$$

$$\mathcal{H}_F = \begin{bmatrix} -\Delta m^2 \cos 2\theta + A_{CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - A_{CC} \end{bmatrix} \tag{12}$$

- where θ is the mixing angle in vacuum and A_{CC} is the charged current potential in matter ($A_{CC} = 2\sqrt{2} G_F N_e E = 2 V_{CC} E$).

Neutrino Oscillation in Matter

- Hamiltonian Diagonalization

$$\mathcal{H}_M = U_M \mathcal{H}_F U_M \tag{13}$$

$$U_M = \begin{bmatrix} \cos 2\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos 2\theta_M \end{bmatrix} \tag{14}$$

$$\mathcal{H}_M = diag(-\Delta m_M^2, \Delta m_M^2) \tag{15}$$

- The effective parameters are given by:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{16}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{17}$$

- In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$

- Assuming neutral-current non-standard neutrino interaction

$$\mathcal{L}_{\mathrm{NSI}}^{NC} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fC} \left(\overline{\nu_\alpha} \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_C f\right) , \tag{18}$$

caused flavor change during neutrino propagation in matter

$$H_{mat}^{NSI} = \sqrt{2} G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \tag{19}$$

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{e} + (N_d/N_e)\epsilon_{\alpha\beta}^{d} + (N_u/N_e)\epsilon_{\alpha\beta}^{u} \tag{20}$$

- Using 2×2 effective Hamiltonian as following

$$H_{\text{vac}}^{\text{eff}} = \frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} , \tag{21}$$

$$H_{\text{mat}}^{\text{eff}} = \sqrt{2} G_F N_e(r) c_{13}^2 \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_f N_f(r) \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix} . \tag{22}$$

- The coefficients ϵ_D^f and ϵ_N^f are given

$$\epsilon_D^f = -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \tag{23}$$

$$+\mathrm{Re}\left[c_{13}s_{13}e^{i\delta}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right) - \left(1+s_{13}^2\right)c_{23}s_{23}\epsilon_{\mu\tau}^f\right]$$

$$\epsilon_N^f = c_{13}\left(c_{23}\,\epsilon_{e\mu}^f - s_{23}\,\epsilon_{e\tau}^f\right) \tag{24}$$

$$+s_{13}e^{-i\delta}\left[s_{23}^2\,\epsilon_{\mu\tau}^f - c_{23}^2\,\epsilon_{\mu\tau}^{f\,*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$

$$\tan 2\tilde{\theta}_{12} = \frac{|\sin 2\theta_{12} + 2\hat{A}_E\epsilon_N|}{\cos 2\theta_{12} - \hat{A}_E(c_{13}^2 - 2\epsilon_D)}\,, \tag{25}$$

- CC NSI

$$\mathcal{L}_{\mathrm{NSI}}^{CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'L}(\overline{l_\alpha}\gamma_\lambda P_L U_{\beta a}\nu_a)(\bar{f}\gamma^\lambda P_L f')^\dagger \tag{26}$$

- Evolution with H and $-H^*$ leads to the same oscillation probabilities

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12}, \;\; \delta \to \pi - \delta, \;\; \Delta_{31} \to -\Delta_{13} + \Delta_{21} \;\text{ and }\; V_{eff} \to -S \cdot V_{eff} \cdot S$$

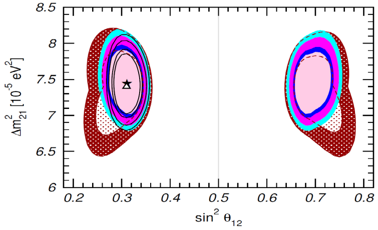
$$S = Diag(-1, 1, 1)$$

- P. B. and Y. Farzan, "Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50," JHEP **1407** (2014) 064 [arXiv:1403.0744 [hep-ph]].

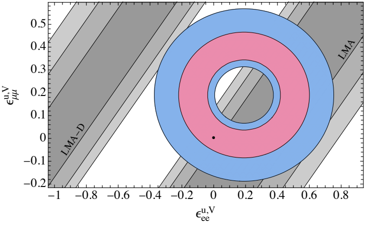
$$P_{\bar{e}\bar{e}} = 1 - \cos^4 2\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \frac{1}{2} \sin^2 2\theta_{13}$$
$$+ \sin^2 2\theta_{13} \left[\cos^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \right]$$

LMA-Dark solution

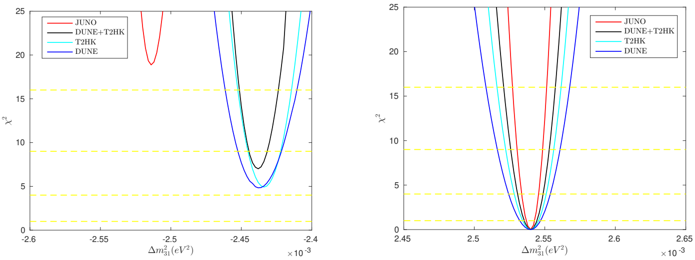
- M. C. Gonzalez-Garcia and M. Maltoni, "Determination of matter potential from global analysis of neutrino oscillation data," JHEP **1309** (2013) 152 [arXiv:1307.3092].



- P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, "A COHERENT enlightenment of the neutrino Dark Side," arXiv:1708.02899 [hep-ph].



NOνA



P. B and M. Rajaee, "Sensitivities of future reactor and long-baseline neutrino experiments to NSI," Phys. Rev. D **103** (2021) no.7, 075003 [arXiv:2010.12849 [hep-ph]].

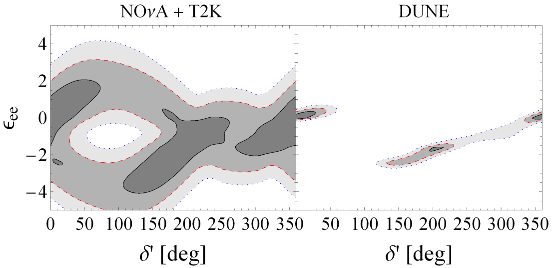
δ_{CP} degeneracies

Considering only non-zero ϵ_{ee}

$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg\cos(\Delta + \delta) + y^2 g^2 + \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3)\,, \quad (27)$$

$$x \equiv 2s_{13}s_{23}\,, \quad y \equiv 2rs_{12}c_{12}c_{23}\,, \quad r = |\delta m_{21}^2/\delta m_{31}^2|\,,$$

$$\mathrm{f} \equiv \frac{\sin[\Delta(1-\hat{A}(1+\epsilon_{ee}))]}{(1-\hat{A}(1+\epsilon_{ee}))}\,,\ g \equiv \frac{\sin(\hat{A}(1+\epsilon_{ee})\Delta)}{\hat{A}(1+\epsilon_{ee})}\,, \Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|,\ \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|\,.$$



J. Liao, D. Marfatia and K. Whisnant, Phys. Rev. D **93** (2016) no.9, 093016 [arXiv:1601.00927 [hep-ph]].

δ_{CP} degeneracies

Considering only non-zero $\epsilon_{e\mu}$

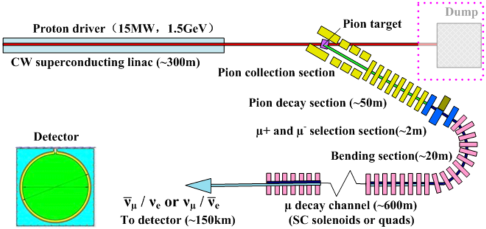
$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg \cos(\Delta + \delta) + y^2 g^2$$

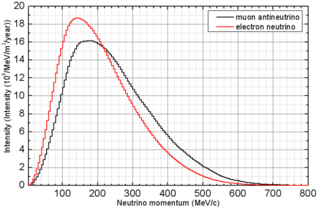
$$\begin{aligned}
&+ 4\ \epsilon_{e\mu} \left\{ xf [s_{23}^2 f \cos(\phi_{e\mu} + \delta) + c_{23}^2 g \cos(\Delta + \delta + \phi_{e\mu})] \right. \\
&\qquad\qquad \left. + yg [c_{23}^2 g \cos\phi_{e\mu} + s_{23}^2 f \cos(\Delta - \phi_{e\mu})] \right\} \\
&+ 4\ ^2 g^2 c_{23}^2 |c_{23}\epsilon_{e\mu}|^2 + 4\hat{A}^2 f^2 s_{23}^2 |s_{23}\epsilon_{e\mu}|^2 + 8\hat{A}^2 fg s_{23}^2 c_{23}^2 \epsilon_{e\mu}^2 \cos\Delta \\
&+ \mathrm{O}(\mathrm{s}_{13}^2 \epsilon, s_{13}\epsilon^2, \epsilon^3)\,,
\end{aligned}$$

$$x \equiv 2 s_{13} s_{23}\,, \quad y \equiv 2 r s_{12} c_{12} c_{23}\,, \quad r = |\delta m_{21}^2 / \delta m_{31}^2|\,,$$

$$\mathrm{f} \equiv \frac{\sin[\Delta(1-\hat{A})]}{(1-\hat{A})}\,,\ g \equiv \frac{\sin(\hat{A}\Delta)}{\hat{A}}\ \Delta \equiv \left| \frac{\delta m_{31}^2 L}{4E} \right|,\ \hat{A} \equiv \left| \frac{A}{\delta m_{31}^2} \right|.$$

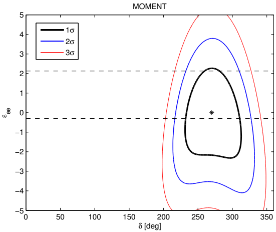
MOMENT



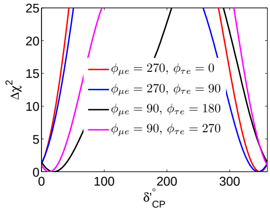


https://indico.cern.ch/event/351600/contributions/1754021/

- P. B. and Y. Farzan, "CP-Violation and NSI at the MOMENT," JHEP **1607** (2016) 109 [arXiv:1602.07099 [hep-ph]].



Inducing fake CP phase by CC NSI and Constraints on CC NSI by near and far detectors of DUNE

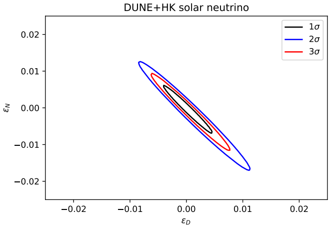


- P. B. , A. N. Khan and W. Wang, "Sensitivities to charged-current nonstandard neutrino interactions at DUNE," J. Phys. G **44** (2017) no.12, 125001.

$\lvert\epsilon_{\alpha\beta}\rvert$	FD	ND	Current C.
$\lvert\epsilon^s_{\mu e}\rvert$	0.016	0.013	0.026
$\lvert\epsilon^s_{\mu\mu}\rvert$	0.028	0.007	0.078
$\lvert\epsilon^s_{\mu\tau}\rvert$	0.074	-	0.013
$\lvert\epsilon^d_{ee}\rvert$	0.057	0.005	0.041
$\lvert\epsilon^d_{e\mu}\rvert$	0.049	-	0.026
$\lvert\epsilon^d_{\mu e}\rvert$	0.019	0.013	0.025
$\lvert\epsilon^d_{\mu\mu}\rvert$	0.032	0.007	0.078
$\lvert\epsilon^d_{\tau e}\rvert$	0.113	-	0.041
$\lvert\epsilon^d_{\tau\mu}\rvert$	0.076	-	0.013

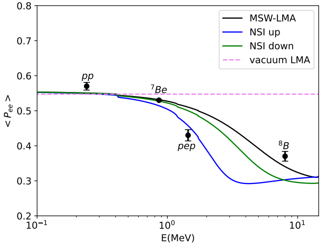
C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0908** (2009) 090 [arXiv:0907.0097 [hep-ph]].

NSI at solar neutrinos



- P. B and M. Rajaee, "Sensitivities of future solar neutrino observatories to nonstandard neutrino interactions," Phys. Rev. D **102** (2020) no.3, 035024 [arXiv:2003.12984 [hep-ph]].

- LSC. at Yemilab



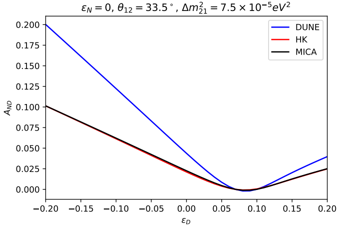
S. H. Seo *et al.* "Physics Potential of a Few Kiloton Scale Neutrino Detector at a Deep Underground Lab in Korea," [arXiv:2309.13435 [hep-ex]].

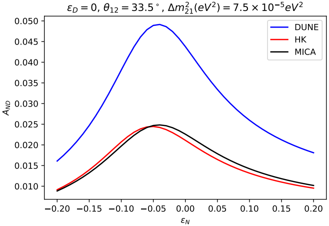
Day-Night asymmetry and NSI

- The differences of survival probability during night and day is given by

$$\Delta P(E,\eta) = P_N - P_D = \kappa(E)\left[\int_0^L dx\ V(x)\sin\phi^m(L-x,E) + I_2\right] \quad (28)$$

$$\kappa(E) \equiv -\frac{1}{2}c_{13}^4\cos 2\tilde{\theta}_{12}^s \sin 2\theta_{12}(\sin 2\theta_{12}(c_{13}^2 - 2\epsilon_D^E) + 2\cos 2\theta_{12}\epsilon_N^E) \quad (29)$$





NC NSI and Neutrino Electon Scattering

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1)^2 + (g_2)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2}\right] \quad (30)$$

where within the standard model

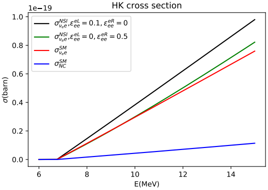
$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \frac{1}{2} + \sin^2\theta_W = 0.73$$

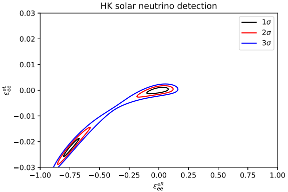
$$g_2^{\nu_e} = g_1^{\bar{\nu}_e} = g_2^{\nu_\mu} = g_1^{\bar{\nu}_\mu} = \sin^2\theta_W = 0.23$$

$$g_1^{\nu_\mu} = g_2^{\bar{\nu}_\mu} = -\frac{1}{2} + \sin^2\theta_W = -0.27.$$

- Considering the NC NSI

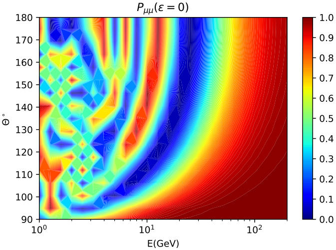
$$g_1^{e\ NSI} = g_1^e + \epsilon_{ee}^{eL}, \quad g_2^{e\ NSI} = g_2^e + \epsilon_{ee}^{eR} \quad (31)$$

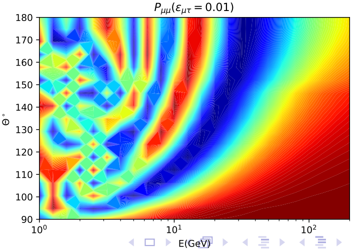




NSI in Atmospheric neutrino experiments

- P. B, M. Rajaee and S. Shin, "Nonstandard interaction of atmospheric neutrino in future experiments," Phys. Rev. D **106** (2022) no.11, 115029 [arXiv:2206.02594 [hep-ph]].
- For energies $E > 10$ GeV, energies much above the θ_{13} resonance, oscillation probabilities obtained for 2 system is a good approximation.
- For energies more than 10 GeV, the only relevant NSI parameters are $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$
- Oscillograms for theprobability $P_{\mu\mu}$ assuming $\delta_{CP} = 0°$.





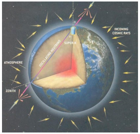
Constraints on NSI using atmospheric neutrinos

- In the energy range of 1 -10 GeV, the effect of δ_{CP} becomes more significant because of the θ_{13} resonance effect

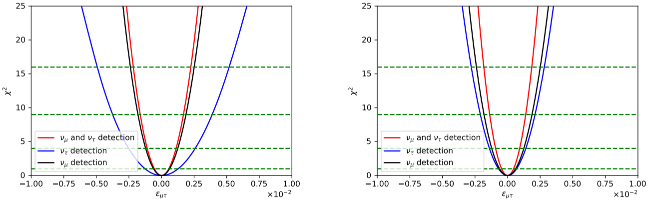
$$H_{mat} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

higher energies (More than 10 GeV)

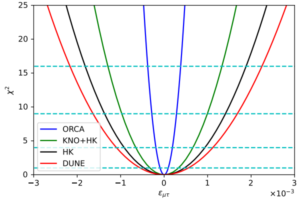
lower Energies (less than 10 GeV)

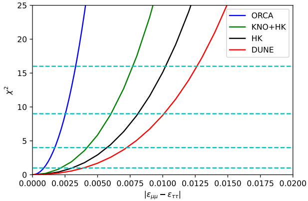


- Include ν_τ detection channel improve the sensitivity to NSI parameters

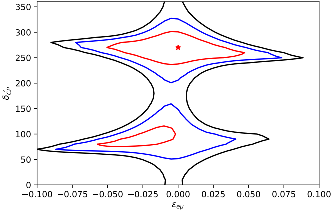


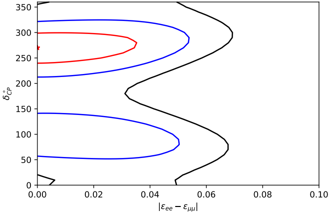
- Constraints of $\epsilon_{e\mu}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$





- Atmospheric neutrinos at HK





Summary

- NSI parameters uncertainaty affect the oscillation parameters measurements
- Short-baseline neutrino exeperiments can study both CC NSI and NC NSI and test LMA-Dark solution
- Effect of NC NSI can be studied by combining a low energy and a high energy neutrino experiment

Thank you for your attention.