NSI @ LBL

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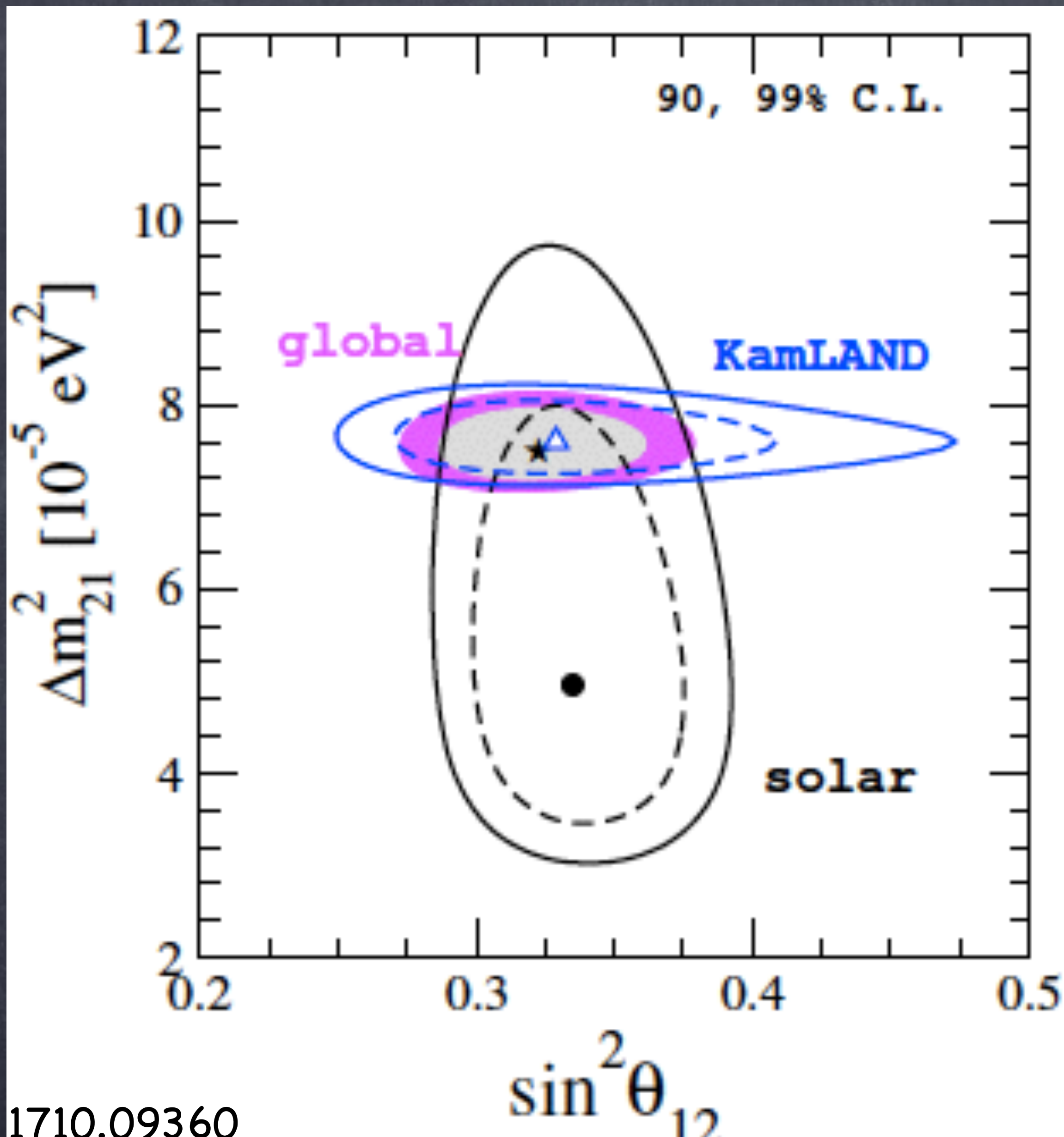
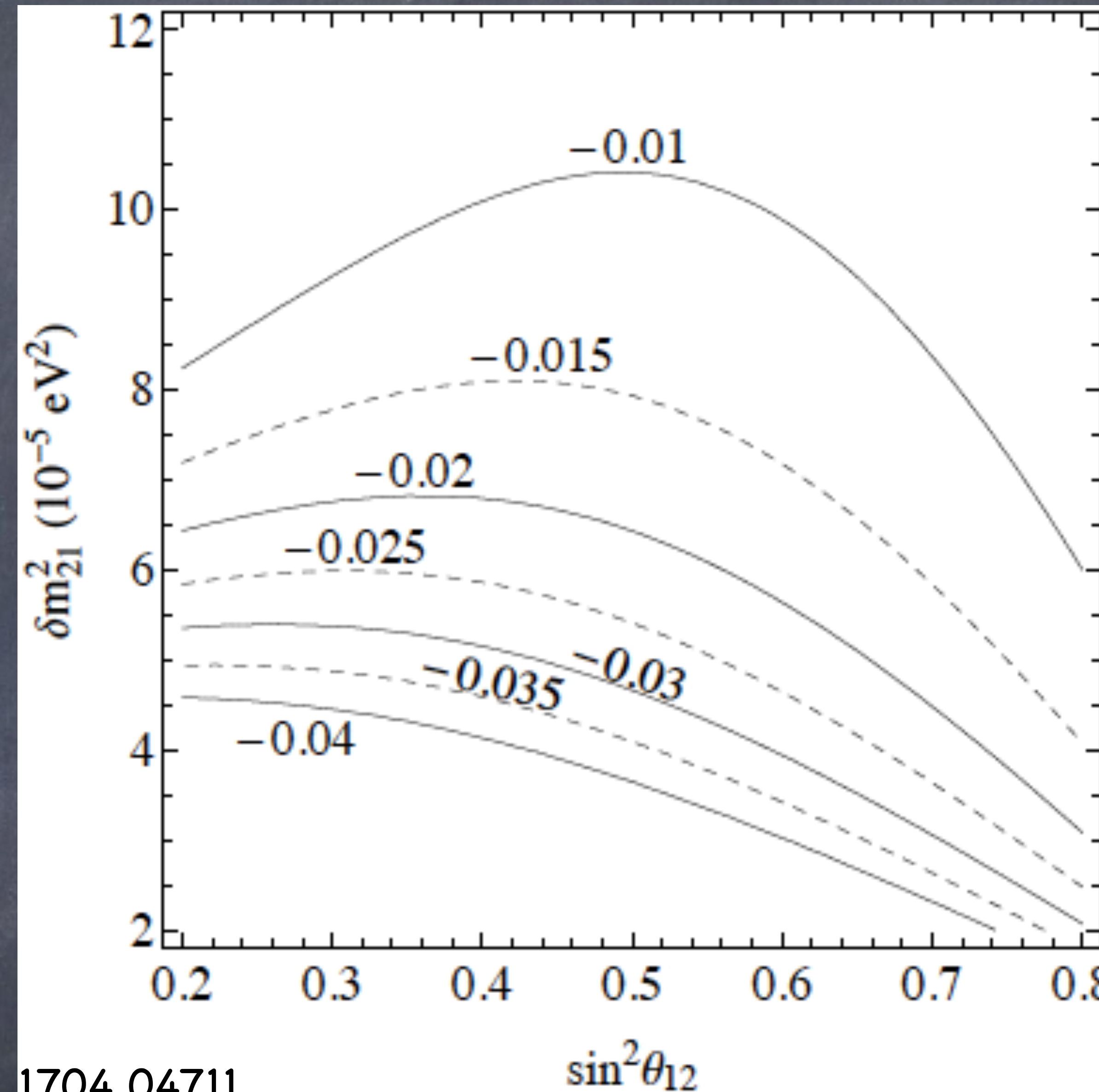
Possible tension in standard oscillation picture





Discrepancy in mass-squared difference driven by Super-K's day-night asymmetry measurement:

$$-3.3 \pm 1.0 \pm 0.5\%$$

Nonstandard interactions in matter

$$\mathcal{L}_{\rm NSI} = 2\sqrt{2} G_F \epsilon^{\mathfrak{f}C}_{\alpha\beta} \left[\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta\right] \left[\bar{\mathfrak{f}} \gamma_\rho P_C \mathfrak{f}\right] + \text{h.c.}$$

where $\alpha, \beta = e, \mu, \tau$, $C = L, R$, $\mathfrak{f} = u, d, e$

$$V = A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix} .$$

Here, $A \equiv 2\sqrt{2} G_F N_e E$ and $\epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f},C} \epsilon^{\mathfrak{f}C}_{\alpha\beta} \frac{N_{\mathfrak{f}}}{N_e}$

Vector interaction relevant for propagation:

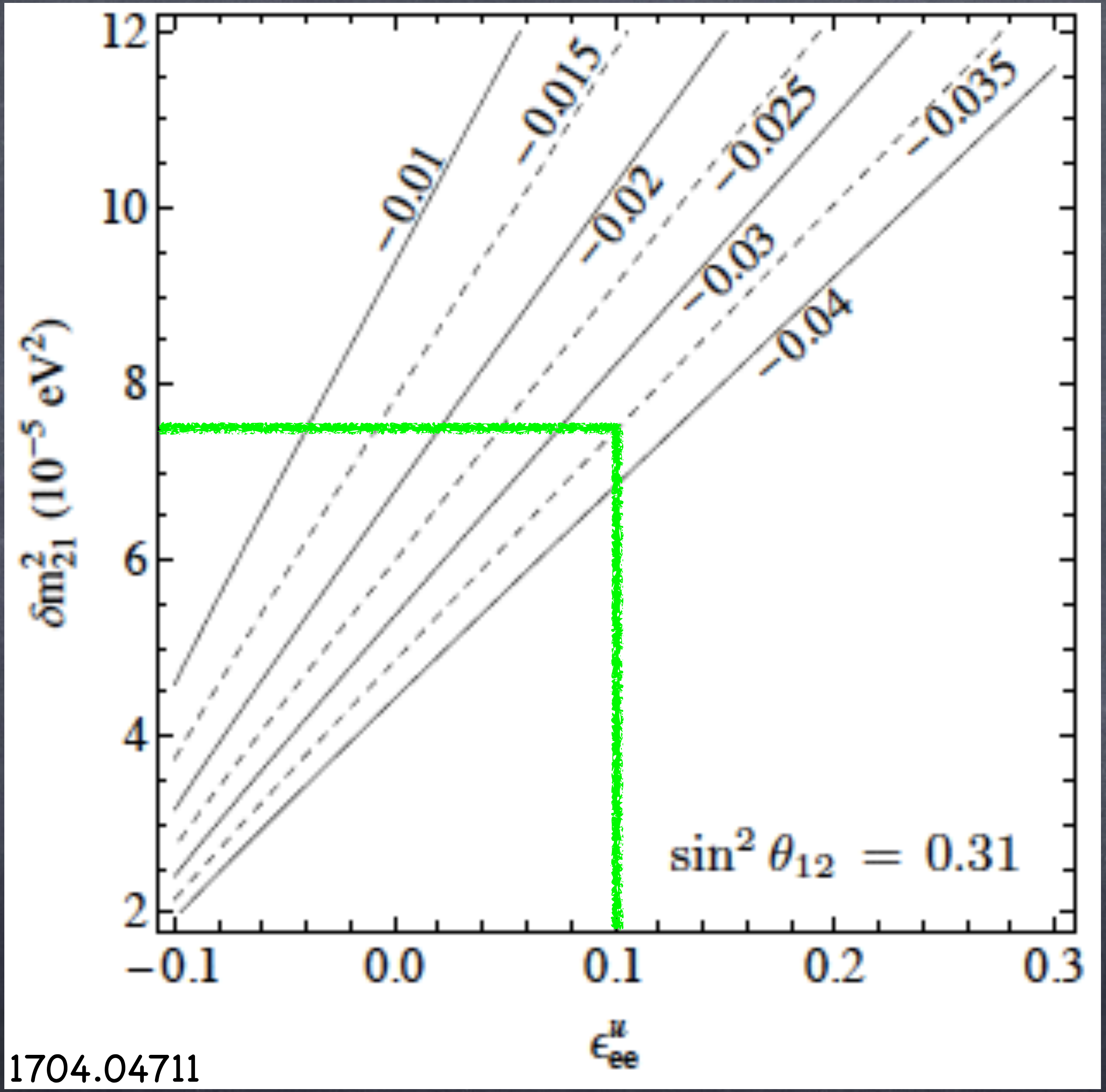
$$\epsilon^{\mathfrak{f}}_{\alpha\beta} \equiv \epsilon^{\mathfrak{f}L}_{\alpha\beta} + \epsilon^{\mathfrak{f}R}_{\alpha\beta} \quad \Longrightarrow \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f}} \epsilon^{\mathfrak{f}}_{\alpha\beta} \frac{N_{\mathfrak{f}}}{N_e}$$

On earth $N_u = N_d = 3N_e$

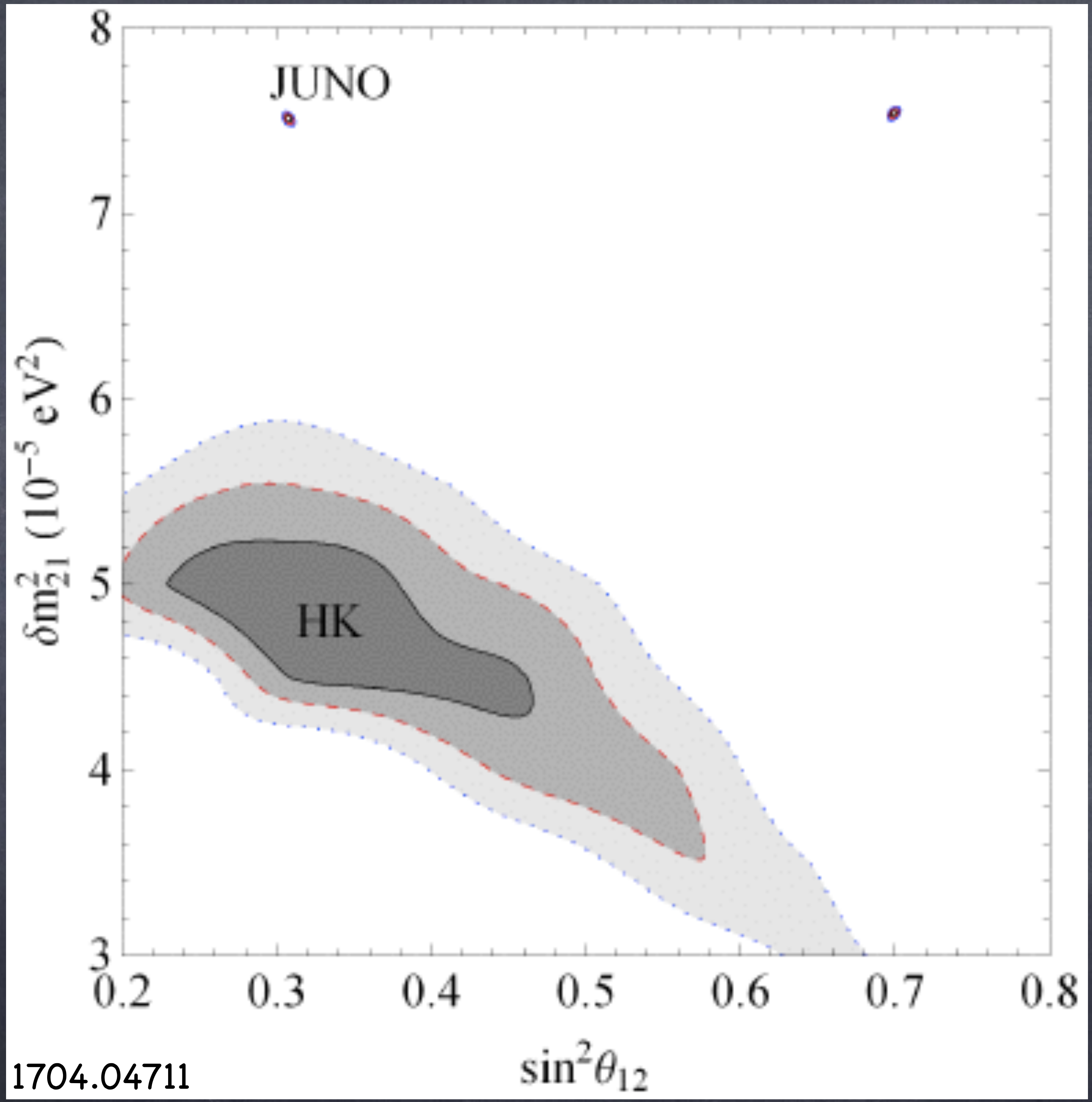
1805.04530

OSC		
	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.328, -1.958]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$

Iso-day-night asymmetry contours



$$\epsilon^u_{ee} = \epsilon^d_{ee} \sim 0.1$$



Hyper-K and JUNO can detect NSI

Future LBL experiments

Experiment	$\frac{L(\mathrm{km})}{E_{\mathrm{peak}}(\mathrm{GeV})}$	$\nu + \bar{\nu}$ Exposure (kt·MW·10^7s)	Signal norm. uncertainty	Background norm. uncertainty
DUNE (LAr)	$\frac{1300}{3.0}$	264 + 264 (80 GeV protons, 1.07 MW power, 1.47×10^{21} POT/yr, 40 kt fiducial mass, 3.5+3.5 yr)	app: 2.0% dis: 5.0%	app: 5-20% dis: 5-20%
T2HK (WC)	$\frac{295}{0.6}$	864.5 + 2593.5 (30 GeV protons, 1.3 MW power, 2.7×10^{21} POT/yr, 0.19 Mt each tank, 1.5+4.5 yr with 1 tank, 1+3 yr with 2 tanks)	app: 2.5% dis: 2.5%	app: 5% dis: 20%
T2HKK-1.5 (WC)	$\frac{295}{0.6} + \frac{1100}{0.8}$	1235 + 3705 (30 GeV protons, 1.3 MW power, 2.7×10^{21} POT/yr, 0.19 Mt each tank, 2.5+7.5 yr with 1 tank at KD and HK)	app: 2.5% dis: 2.5%	app: 5% dis: 20%
T2HKK-2.5 (WC)	$\frac{295}{0.6} + \frac{1100}{0.6}$			

For DUNE, 1 yr = 1.76×10^7s; for HyperK, 1 yr = 1.0×10^7s.

Appearance channels

NH

$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg\cos(\Delta+\delta) + y^2 g^2$$ ← Reduce to the SM when $\epsilon_{ee}=0$

$$+ \quad 4\hat{A}\epsilon_{e\mu}\left\{xf[s_{23}^2 f\cos(\phi_{e\mu}+\delta) + c_{23}^2 g\cos(\Delta+\delta+\phi_{e\mu})]\right.$$ ← 1st order due to $\epsilon_{e\mu}$

r suppressed → $$\left. +yg[c_{23}^2 g\cos\phi_{e\mu} + s_{23}^2 f\cos(\Delta-\phi_{e\mu})]\right\}$$

$$+ \quad 4\hat{A}\epsilon_{e\tau}s_{23}c_{23}\left\{xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})]\right.$$ ← 1st order due to $\epsilon_{e\tau}$

r suppressed → $$\left. -yg[g\cos\phi_{e\tau} - f\cos(\Delta-\phi_{e\tau})]\right\}$$

$$+ \quad 4\hat{A}^2\left(g^2c_{23}^2|c_{23}\epsilon_{e\mu} - s_{23}\epsilon_{e\tau}|^2 + f^2 s_{23}^2|s_{23}\epsilon_{e\mu}+c_{23}\epsilon_{e\tau}|^2\right)$$ ← 2nd order corrections

$$+ \quad 8\hat{A}^2 fgs_{23}c_{23}\left\{c_{23}\cos\Delta\left[s_{23}(\epsilon_{e\mu}^2-\epsilon_{e\tau}^2) + 2c_{23}\epsilon_{e\mu}\epsilon_{e\tau}\cos(\phi_{e\mu}-\phi_{e\tau})\right]\right.$$

$$\left. -\epsilon_{e\mu}\epsilon_{e\tau}\cos(\Delta-\phi_{e\mu}+\phi_{e\tau})\right\} + \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3)\,,$$

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

$$f,\bar{f} \equiv \frac{\sin[\Delta(1\mp\hat{A}(1+\epsilon_{ee}))]}{(1\mp\hat{A}(1+\epsilon_{ee}))}\,,\quad g \equiv \frac{\sin(\hat{A}(1+\epsilon_{ee})\Delta)}{\hat{A}(1+\epsilon_{ee})}\,,$$

$$\Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|\,,\quad \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|$$

- $P_{\mu e} \to \bar{P}_{\mu e}$

  $\hat{A} \to -\hat{A}\ (f \to \bar{f})$,

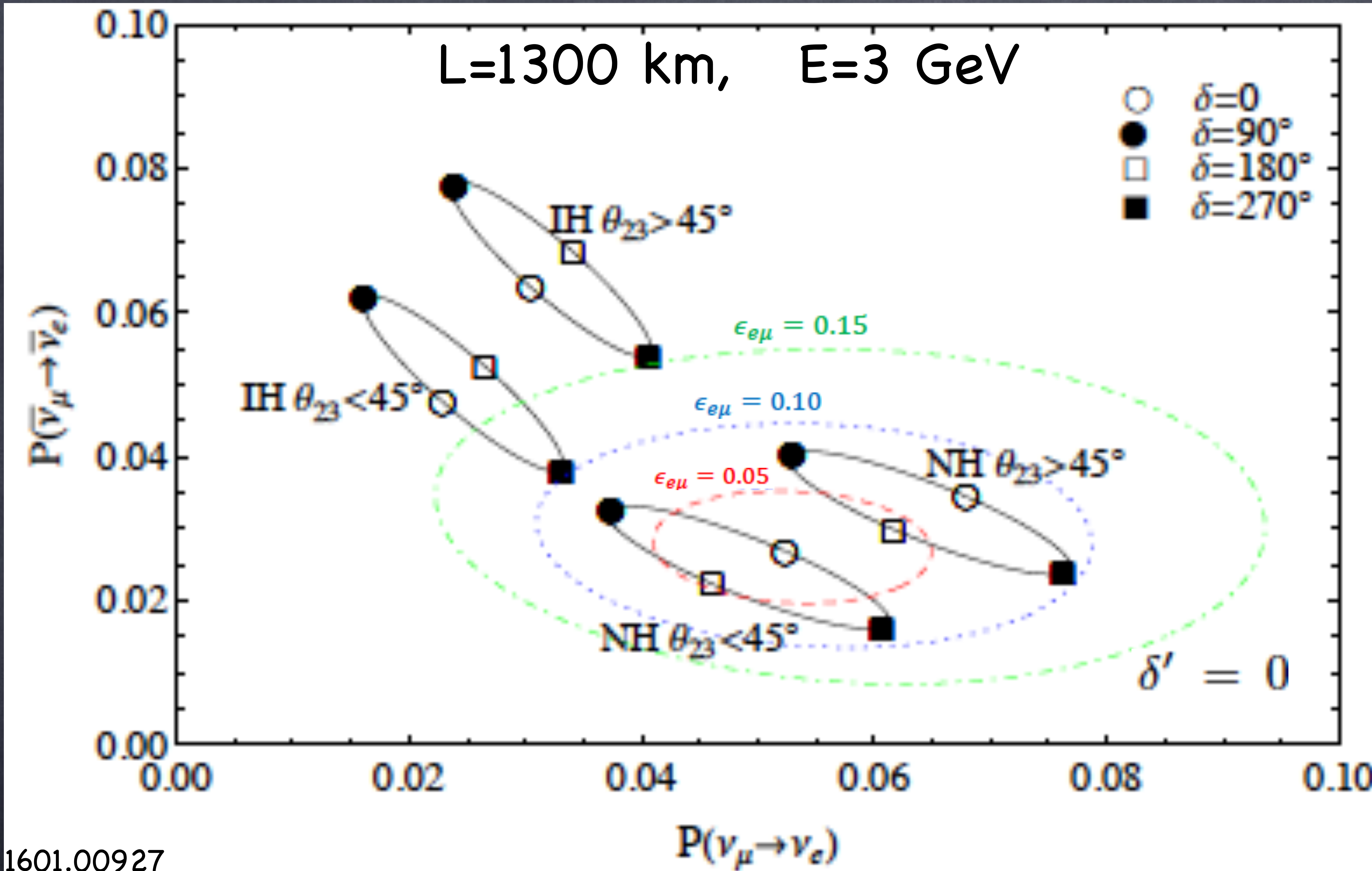
  $\delta \to -\delta$, $\phi_{\alpha\beta} \to -\phi_{\alpha\beta}$

- NH → IH

  $\Delta \to -\Delta$, $y \to -y$

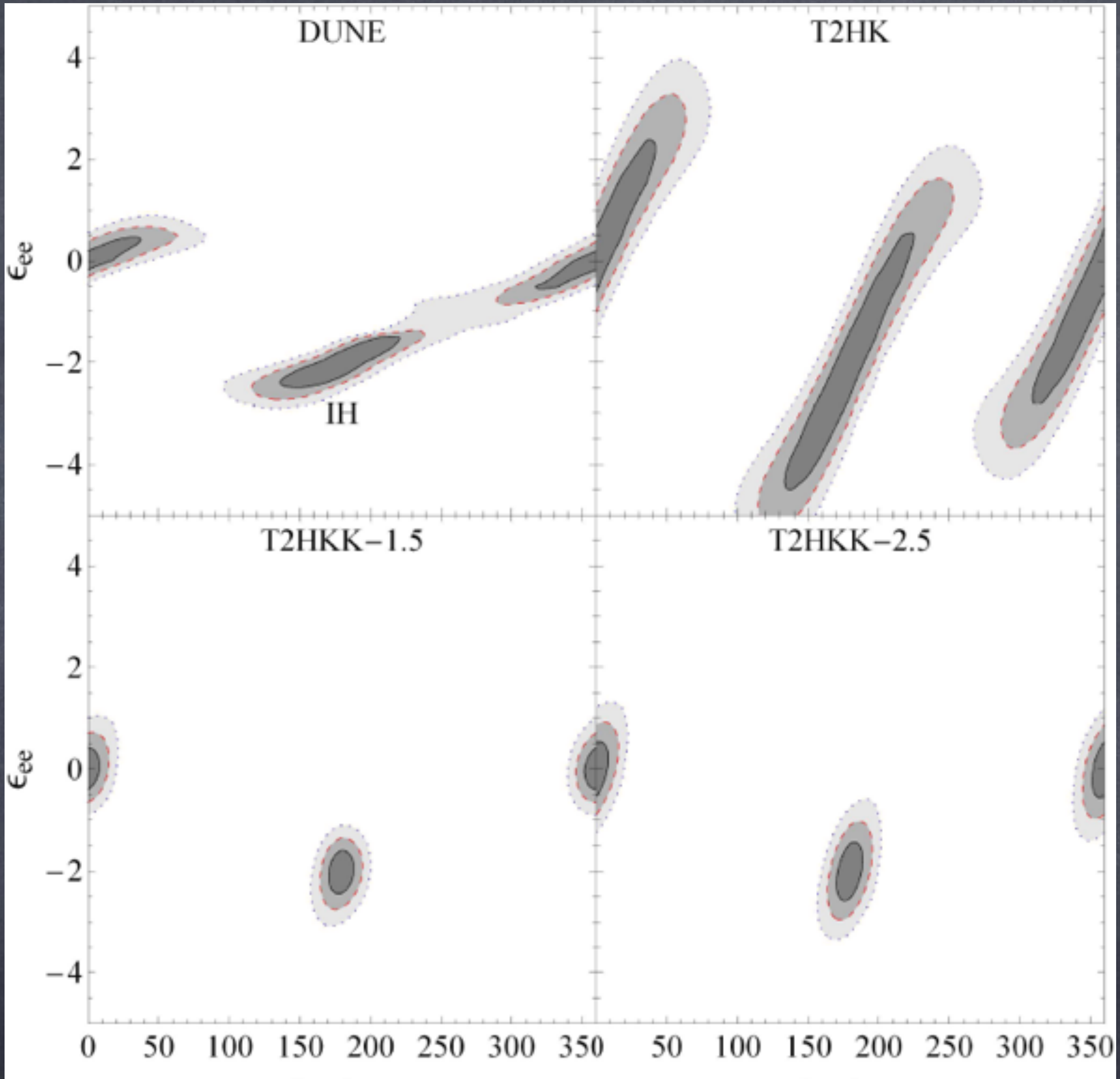
  $\hat{A} \to -\hat{A}\ (f \leftrightarrow -\bar{f}$, and $g \to -g)$

Liao



$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$
$$\overline{P}^{SM}(\delta) = \overline{P}^{NSI}(\delta', \epsilon, \phi)$$

One NSI parameter



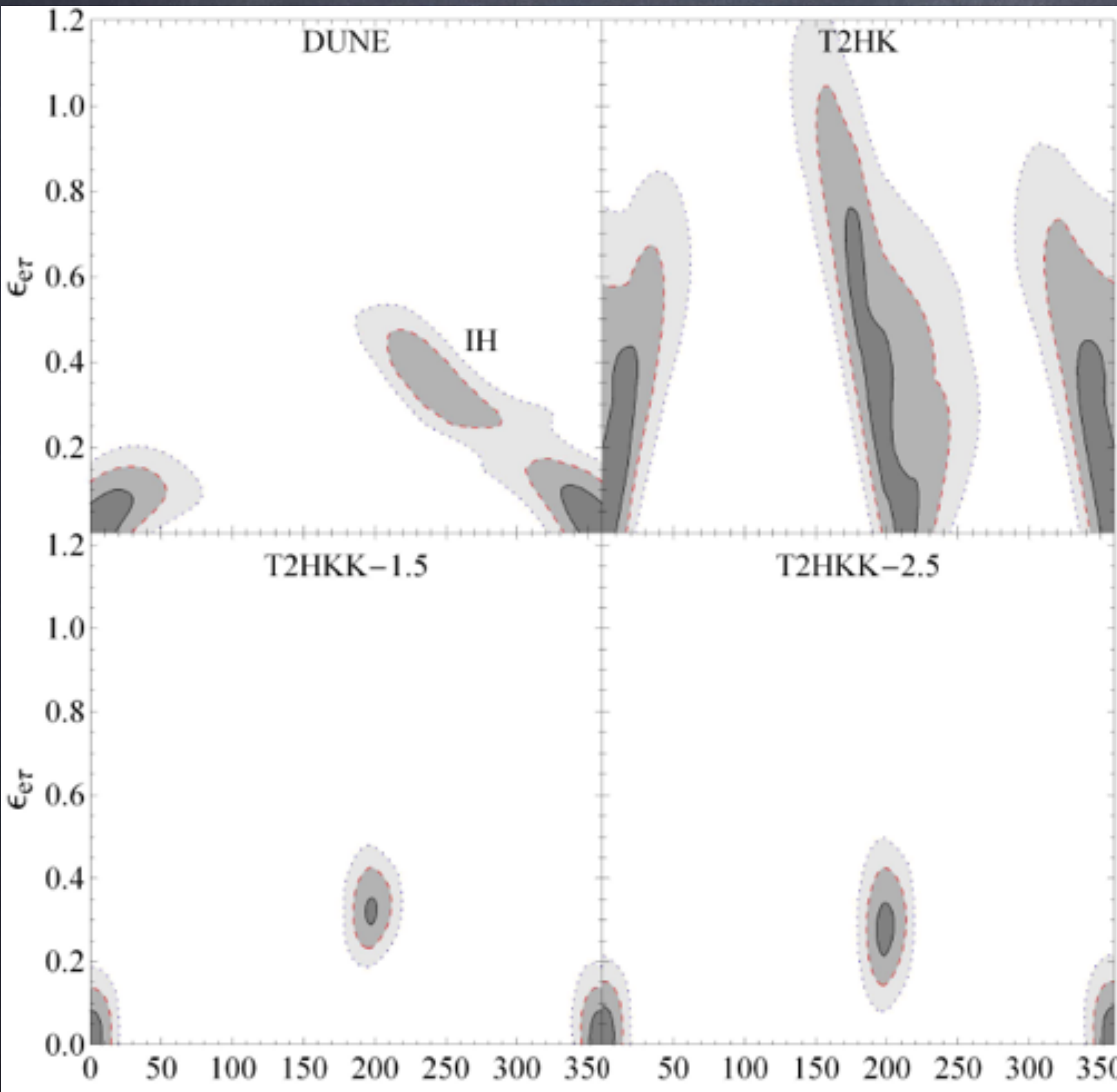
1612.01443

$$\delta m^2_{31} \to -\delta m^2_{32}, \quad \theta_{12} \to 90^\circ - \theta_{12}, \quad \delta \to 180^\circ - \delta$$

$$\epsilon_{ee} \to -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \to -\epsilon_{\alpha\beta} e^{-i\phi_{\alpha\beta}} (\alpha\beta \neq ee)$$

1403.0744, 1604.05772

Mass hierarchy resolved at DUNE and T2HKK



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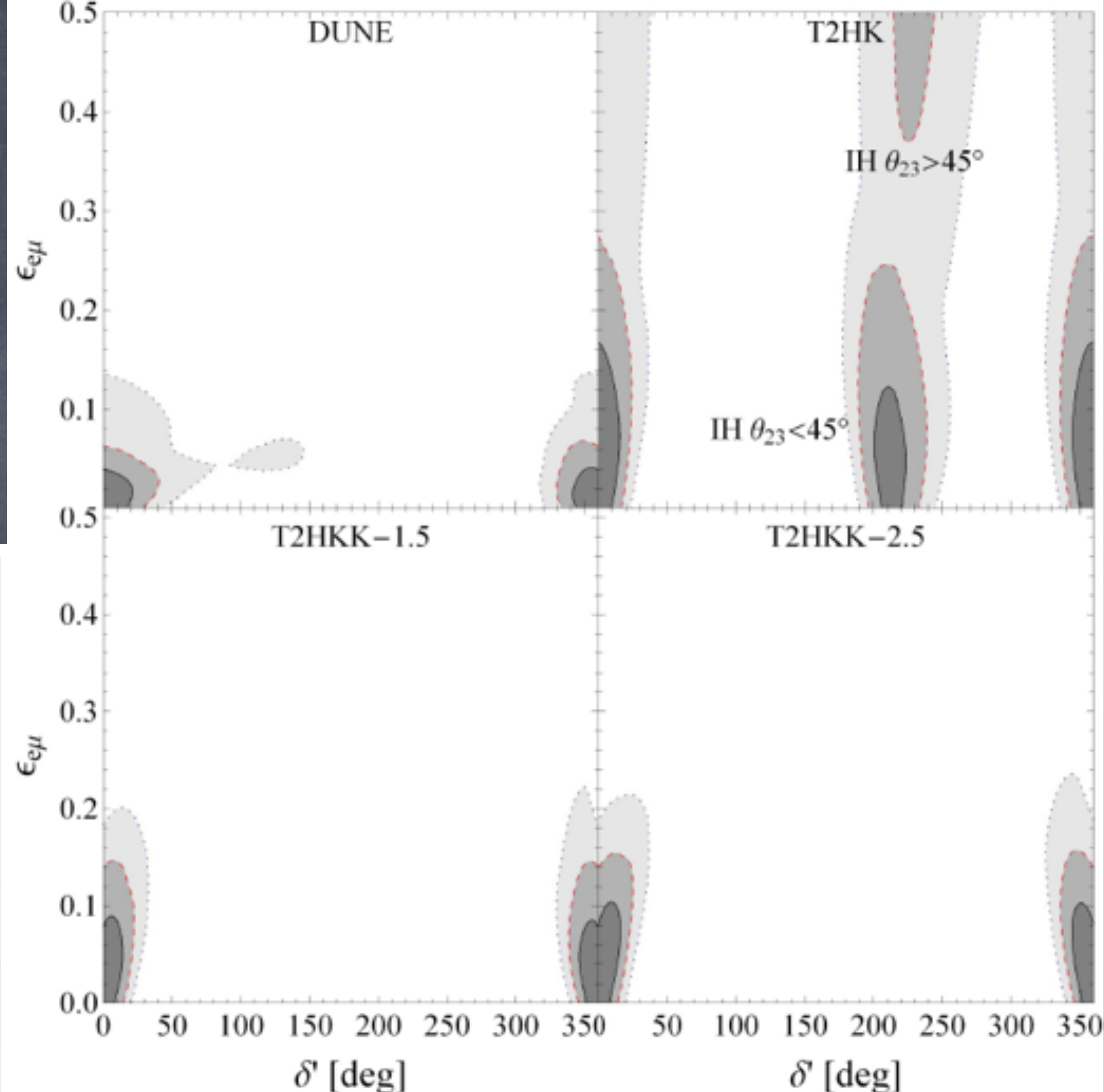
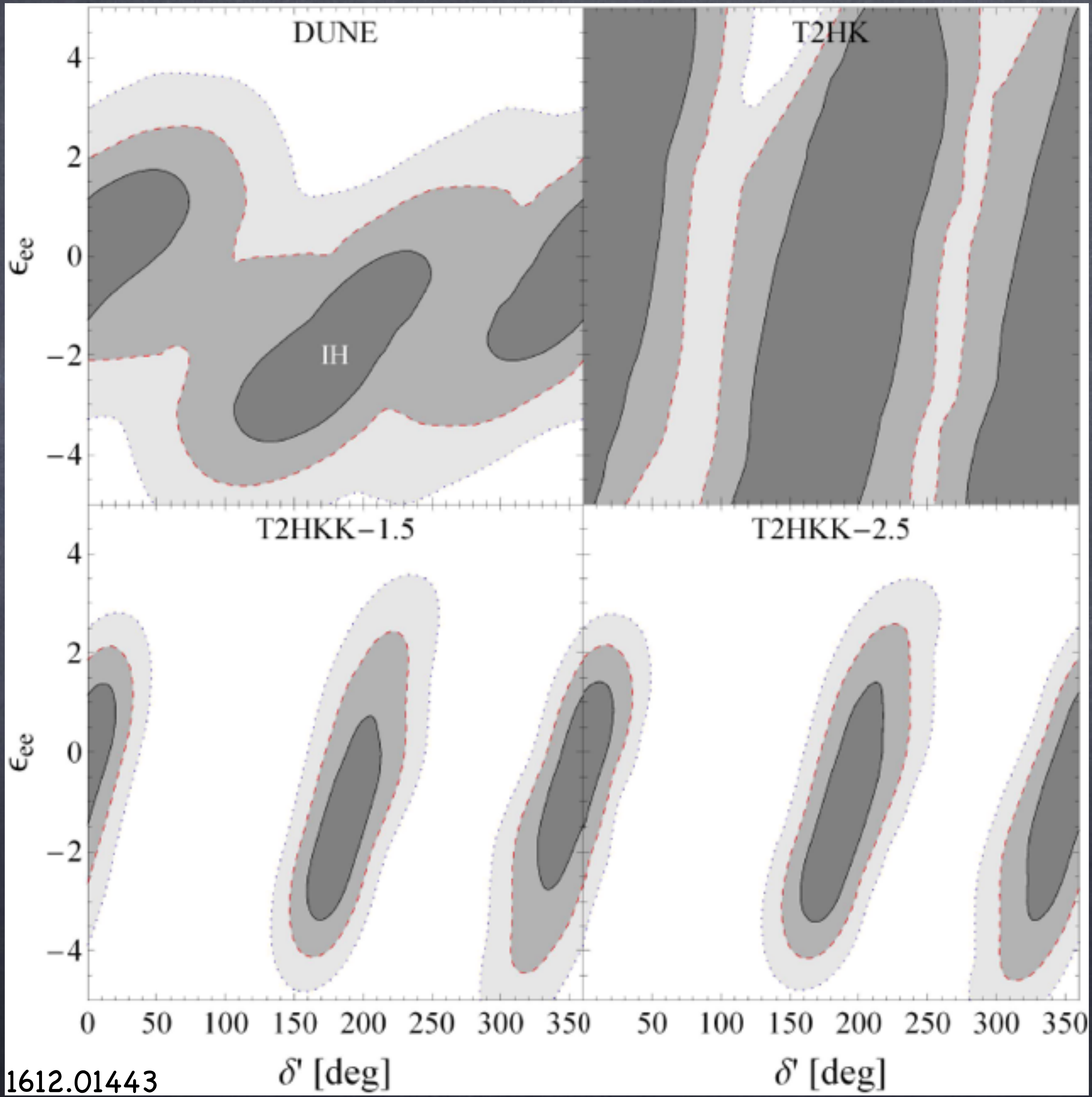


Hierarchy not resolved
Wrong determination of the CP phase possible

3 NSI parameters



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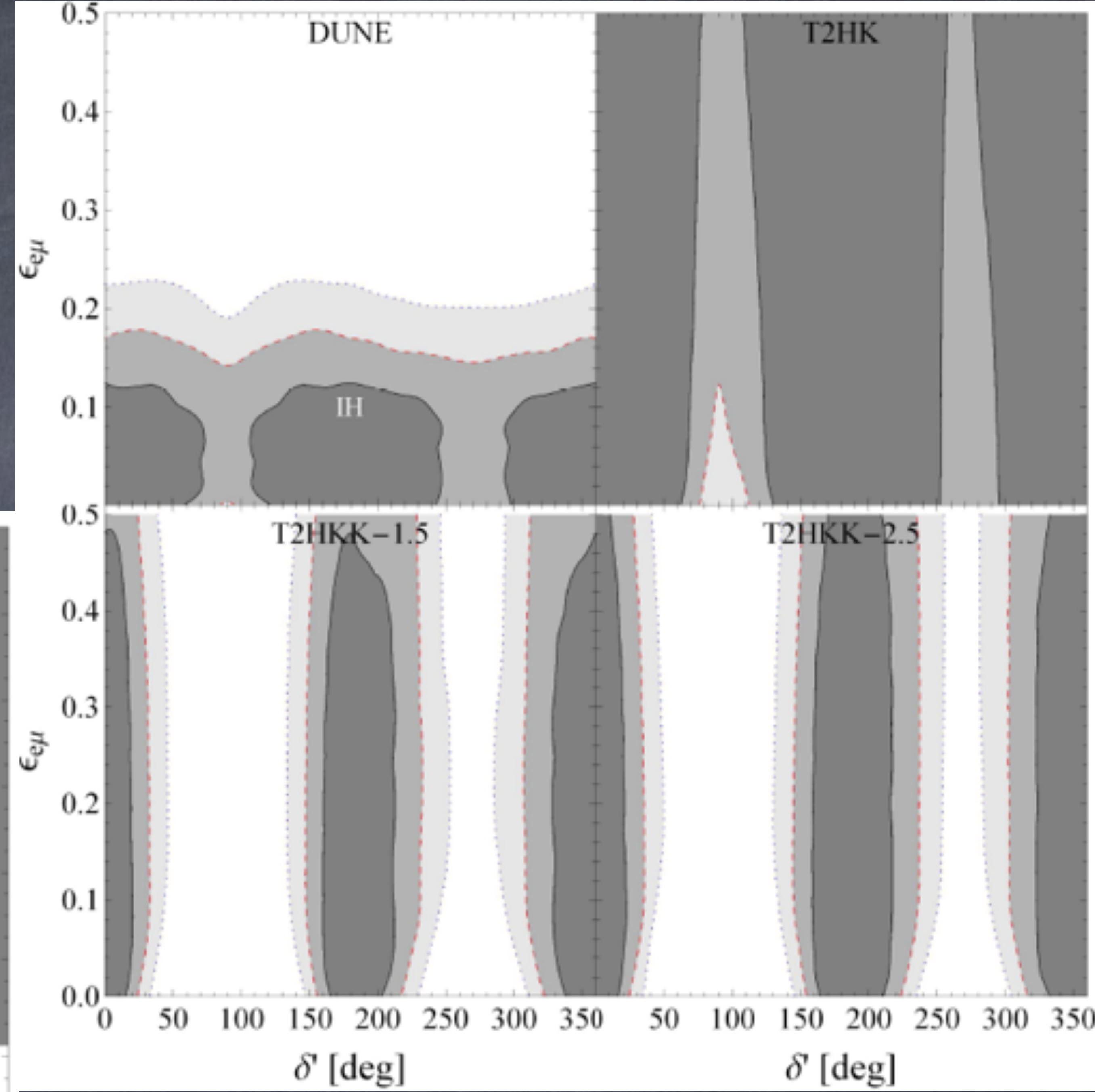
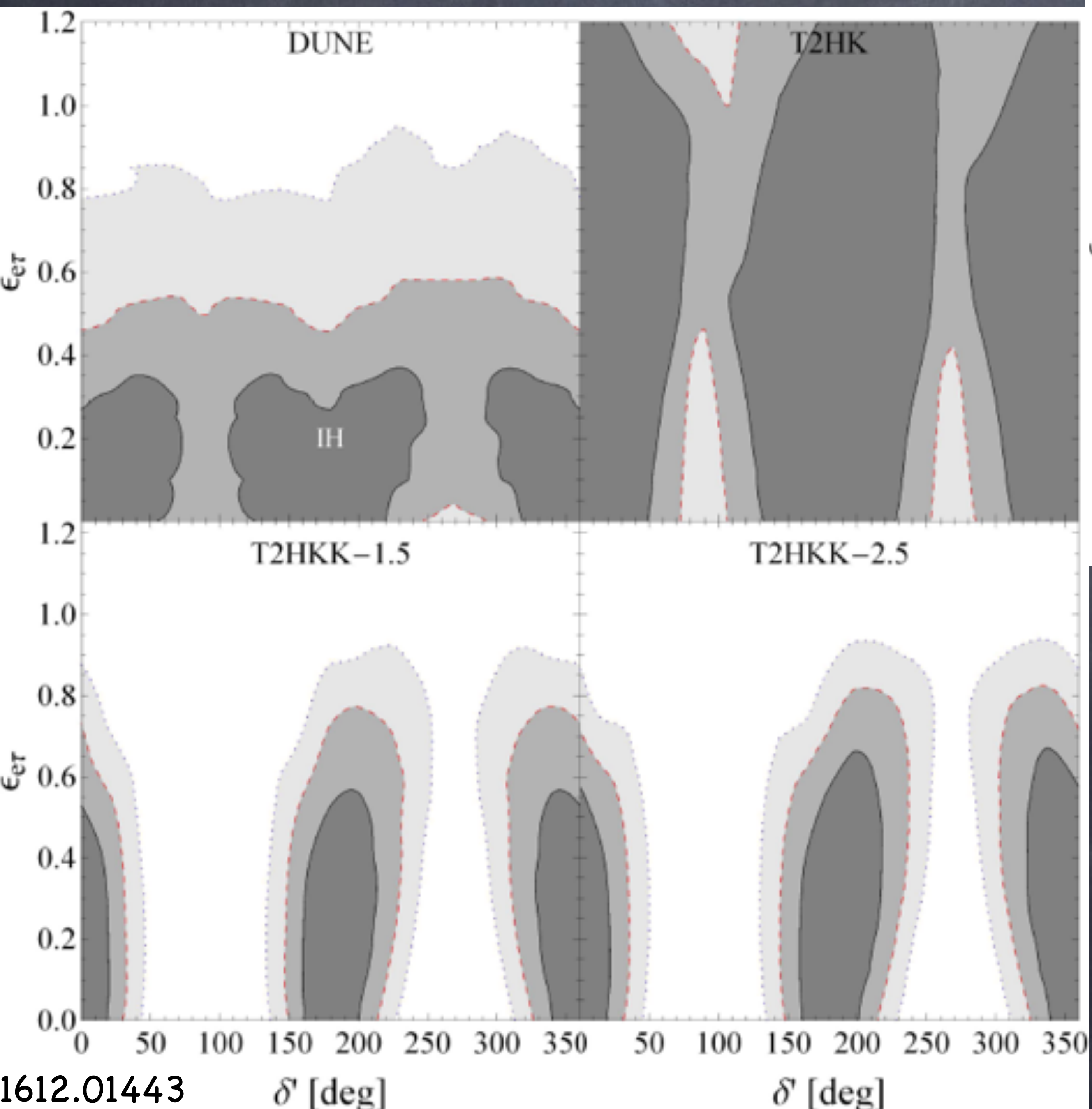
Constraint on $\epsilon_{e\mu}$ much weaker at T2HK and T2HKK





$$\epsilon_{e\mu} = \tan\theta_{23}\epsilon_{e\tau}$$

Degeneracy between NSI parameters unbroken at T2HK and T2HKK because of the lower energy J-PARC beam

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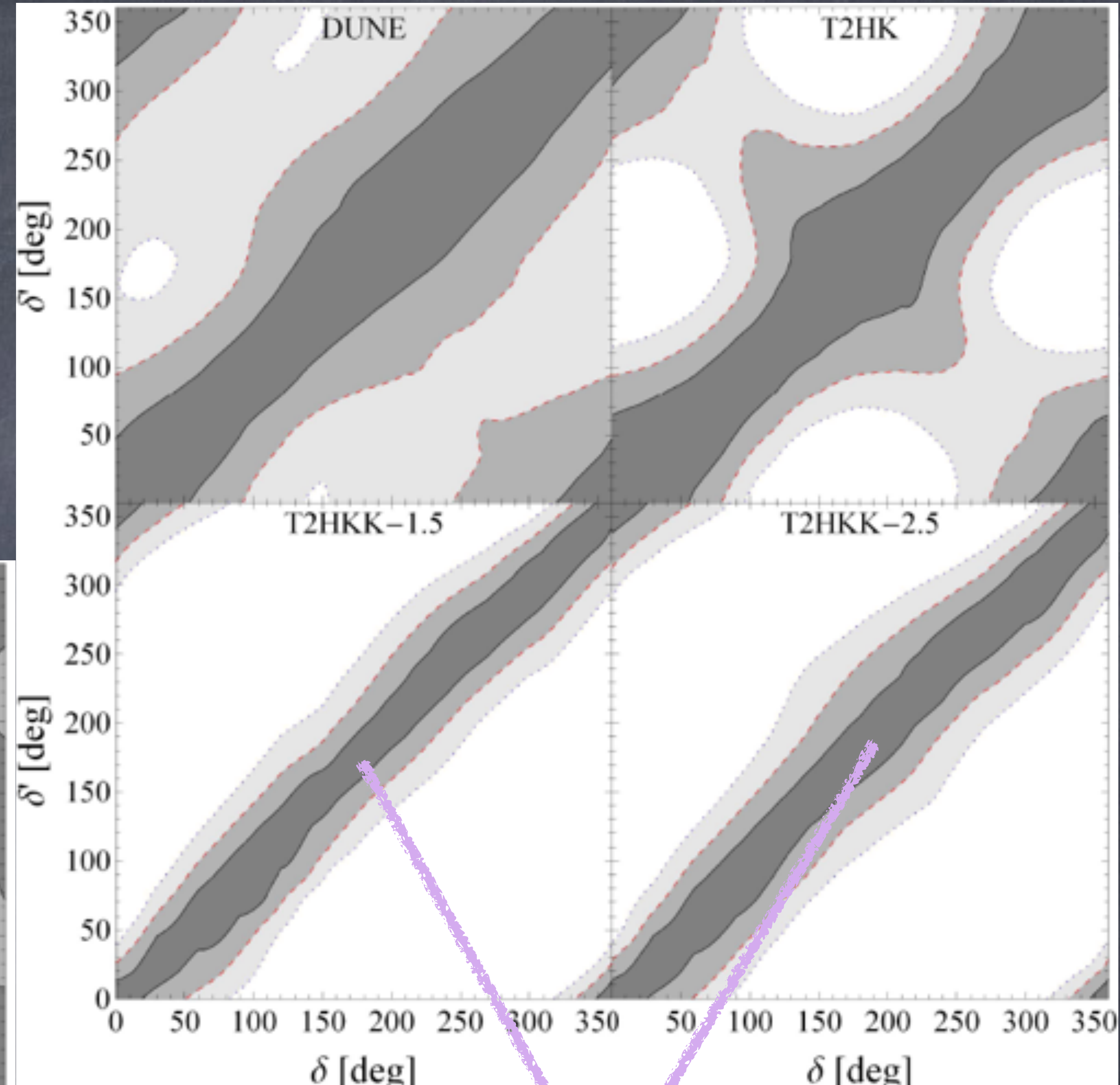
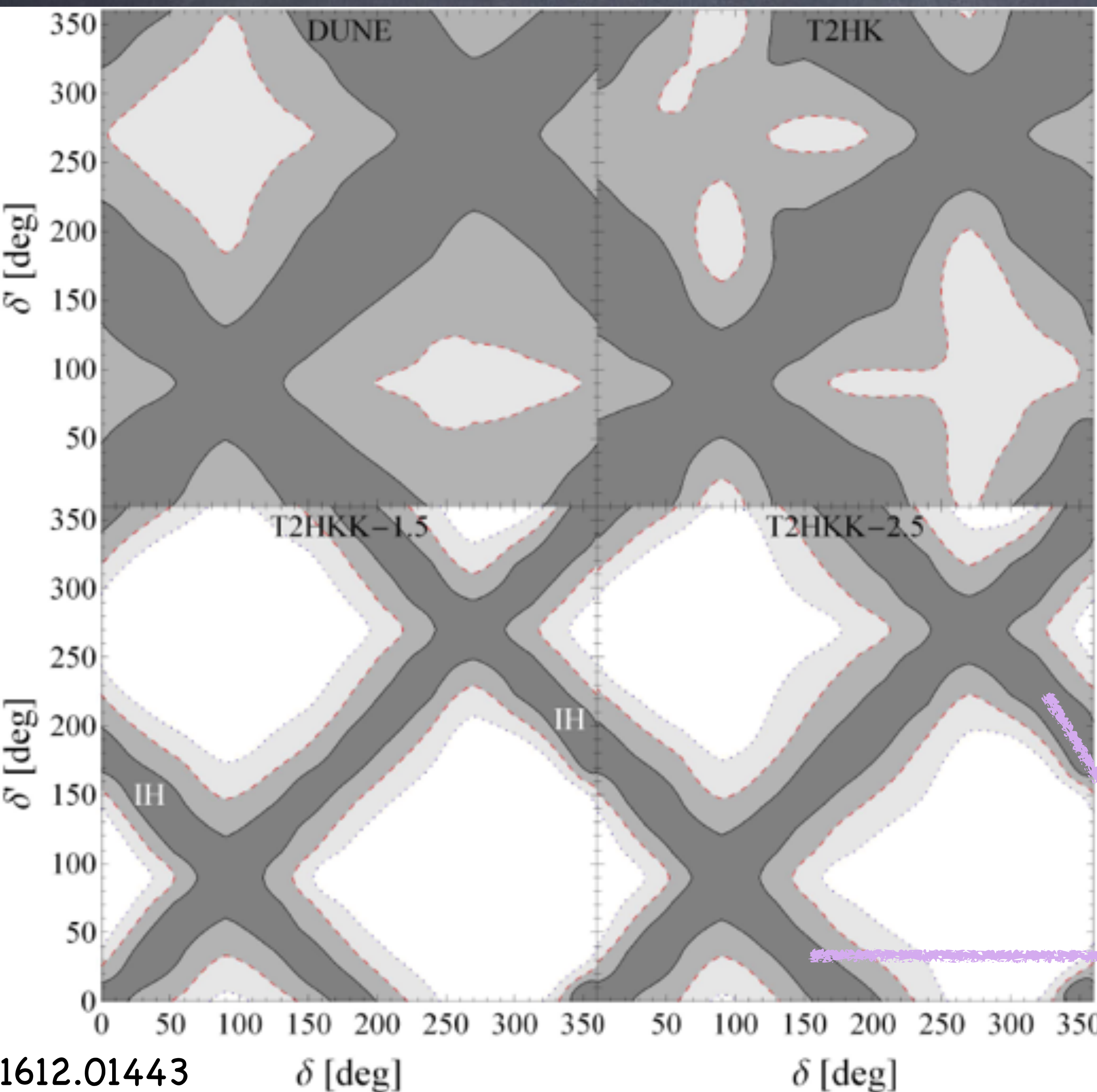
CP sensitivity

MH known

T2HKK better than DUNE for CP; is the only expt. that can measure the CP phase if MH is unknown



MH unknown



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$\delta' = \delta$ holds when $\epsilon = 0$

IH and $\delta' = 180 - \delta$

Summary

- At LBL expts, degeneracies between SM and NSI parameters, and between NSI parameters strongly affect sensitivities
- If $\epsilon_{ee} - \epsilon_{\mu\mu}$ is O(1), impossible to determine hierarchy at oscillation experiments
- DUNE has best sensitivity to NSI
- T2HKK has best sensitivity to CP phase (even) in the presence of NSI