

# Nonstandard interactions at long-baseline neutrino experiments

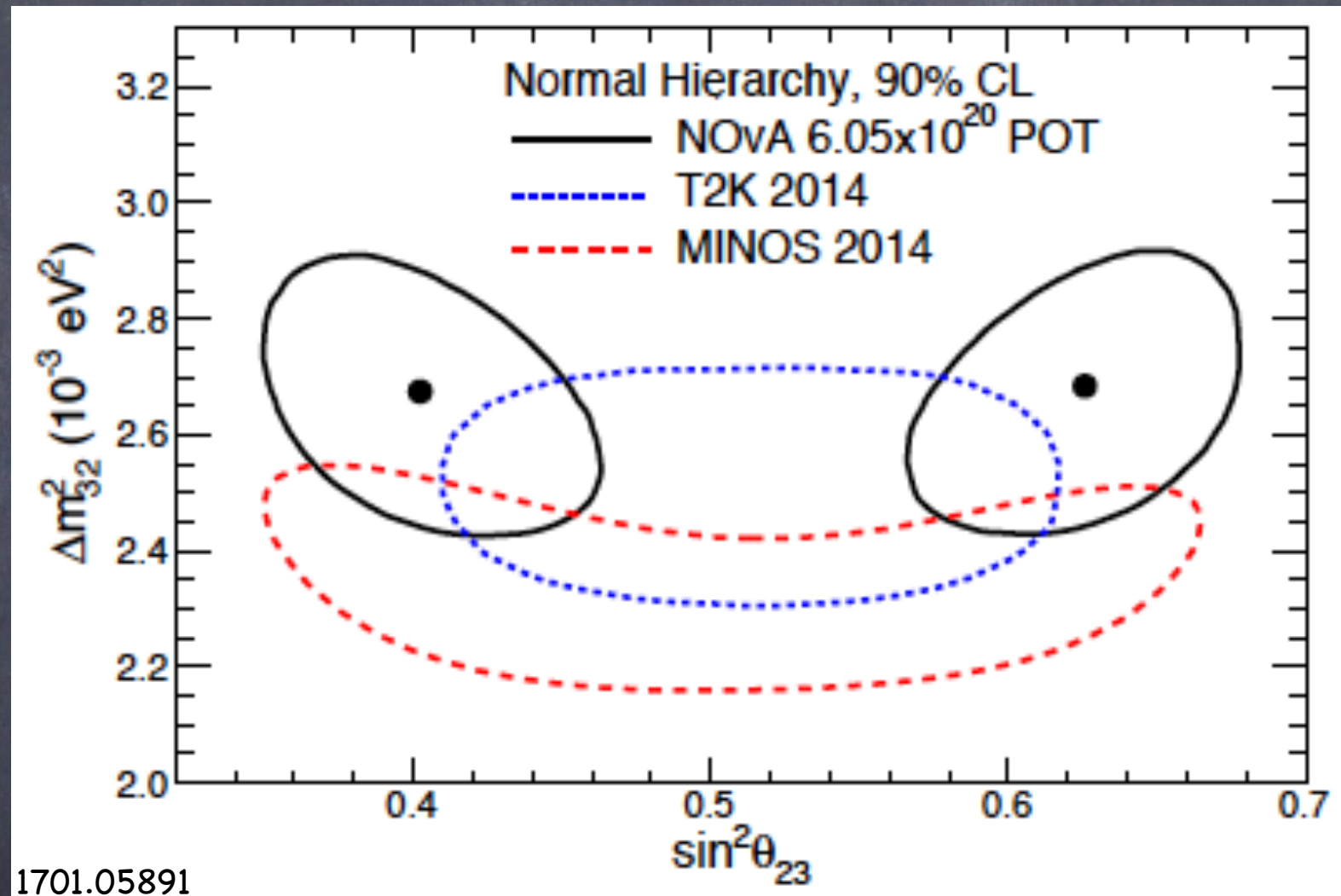
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with Liao and Whisnant

(1601.00927, 1609.01786, 1612.01443)



# Possible tension in standard oscillation picture



Maximal mixing ( $\theta_{23} = \pi/4$ ) excluded by NOvA at 2.6 sigma

# Nonstandard interactions in matter

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

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

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

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

On earth  $N_u = N_d = 3N_e$



# Resolving tension between NOvA and T2K

- Longer baseline at NOvA means larger matter effects and so larger NSI effects
- Muon neutrino survival probability dictated by

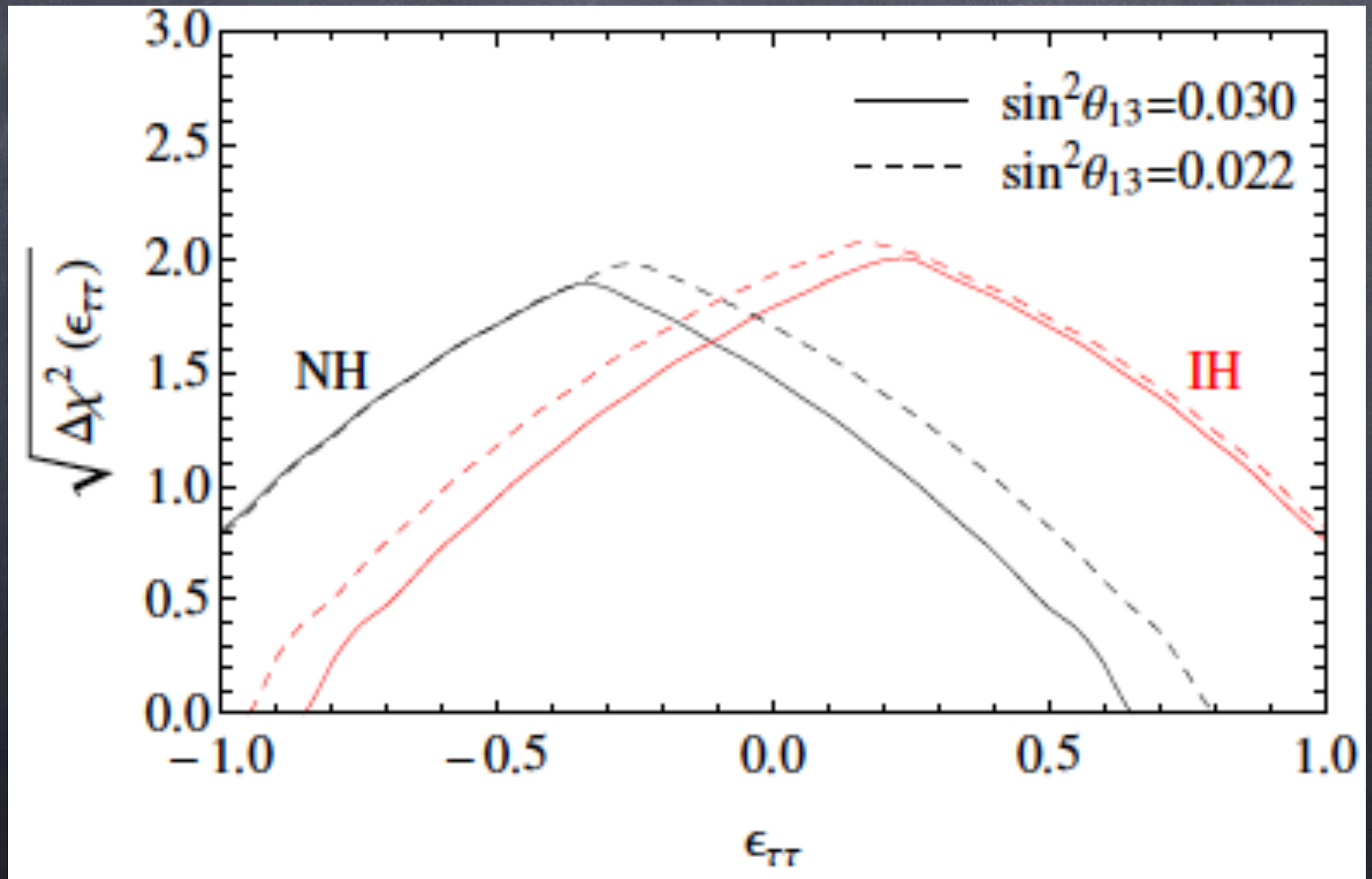
$$\frac{\Delta m^2}{\Delta m_{32}^2} = \sqrt{(\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2 + |\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}$$
$$\sin^2 2\theta = \left(1 + \frac{(\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2}{|\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}\right)^{-1} \quad . \quad \hat{A} = A/\Delta m_{32}^2$$

- For maximal mixing, NSI can generate nonmaximal mixing with a much larger effect in NOvA than T2K

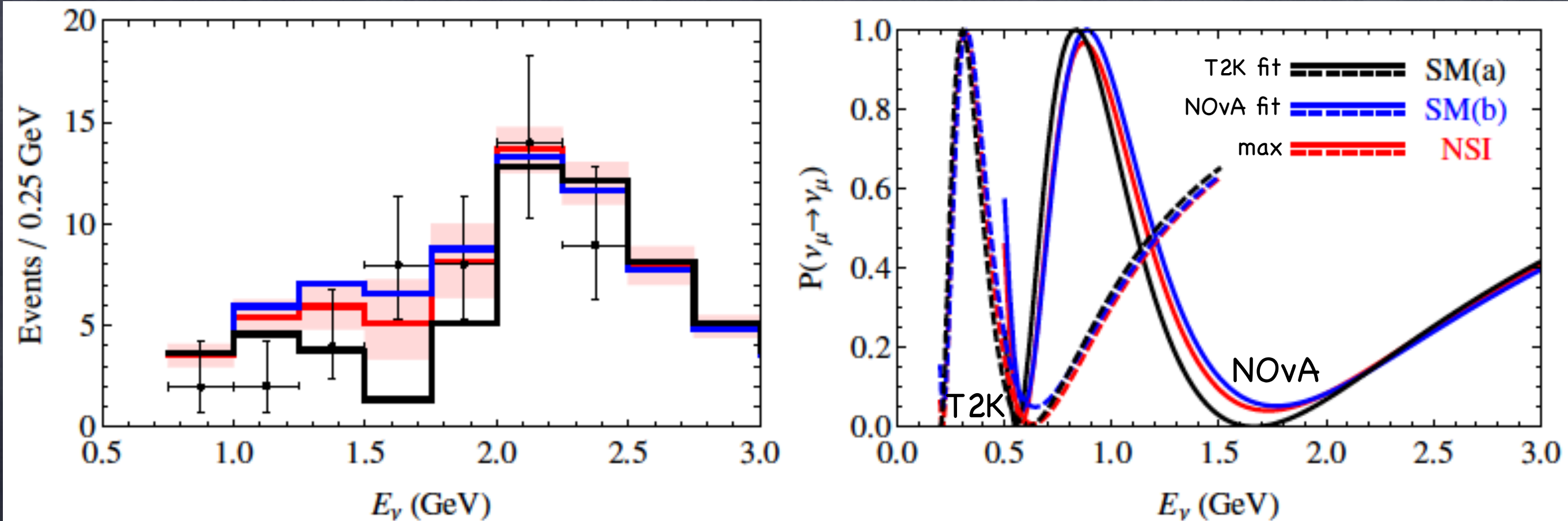
$$\hat{A}_{NOvA} \simeq 0.17 \quad \hat{A}_{T2K} \simeq 0.05$$

CL at which  $\theta_{23} = \pi/4$  is excluded:

$$\epsilon_{\mu\mu} = \epsilon_{\mu\tau} = 0, \quad |\epsilon_{e\tau}| < 1.2$$







To fit their data, NOvA required nonmaximal mixing and a larger mass-squared difference than T2K

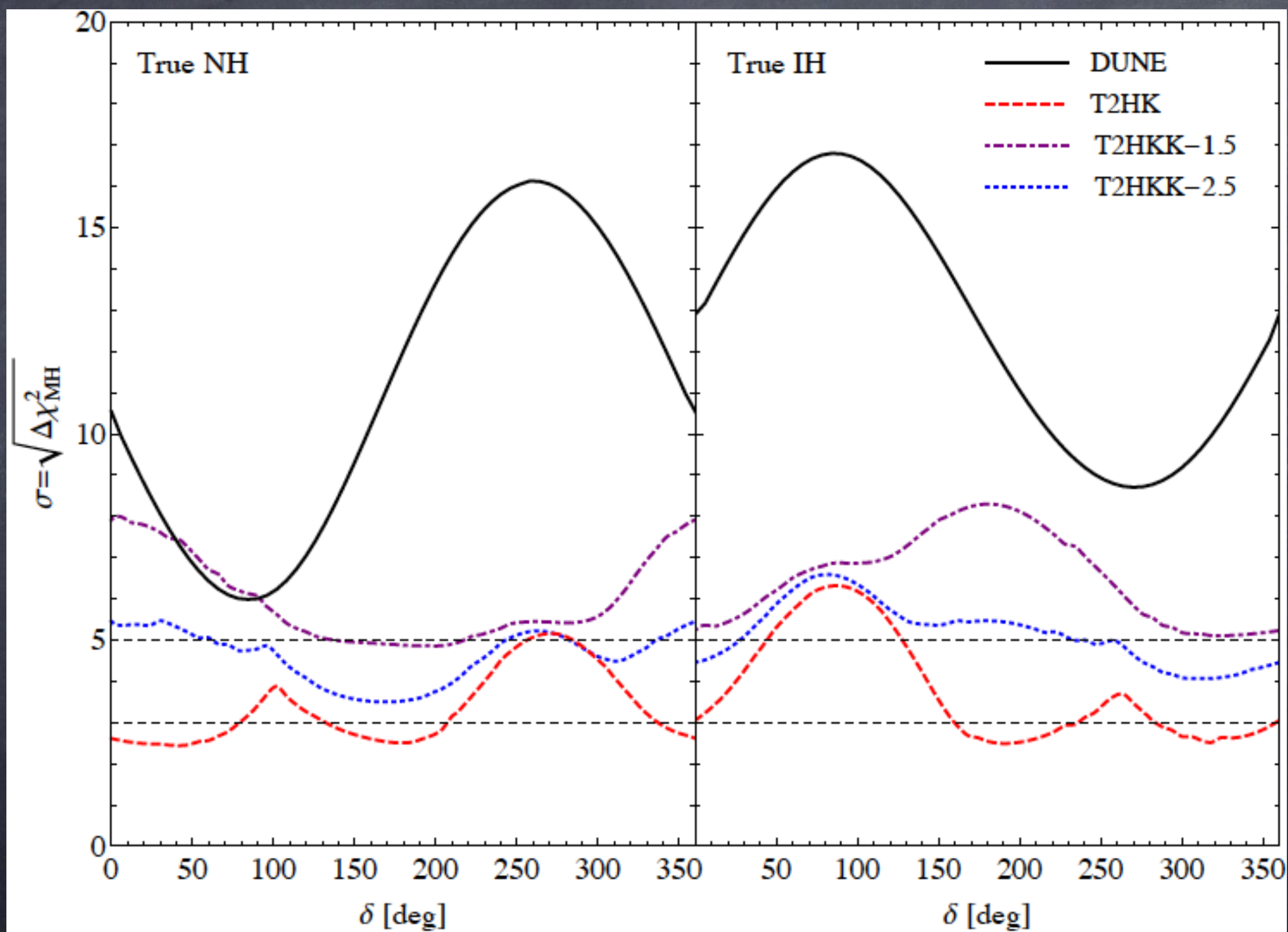
Could also fit with maximal mixing and NSI

# Future experiments

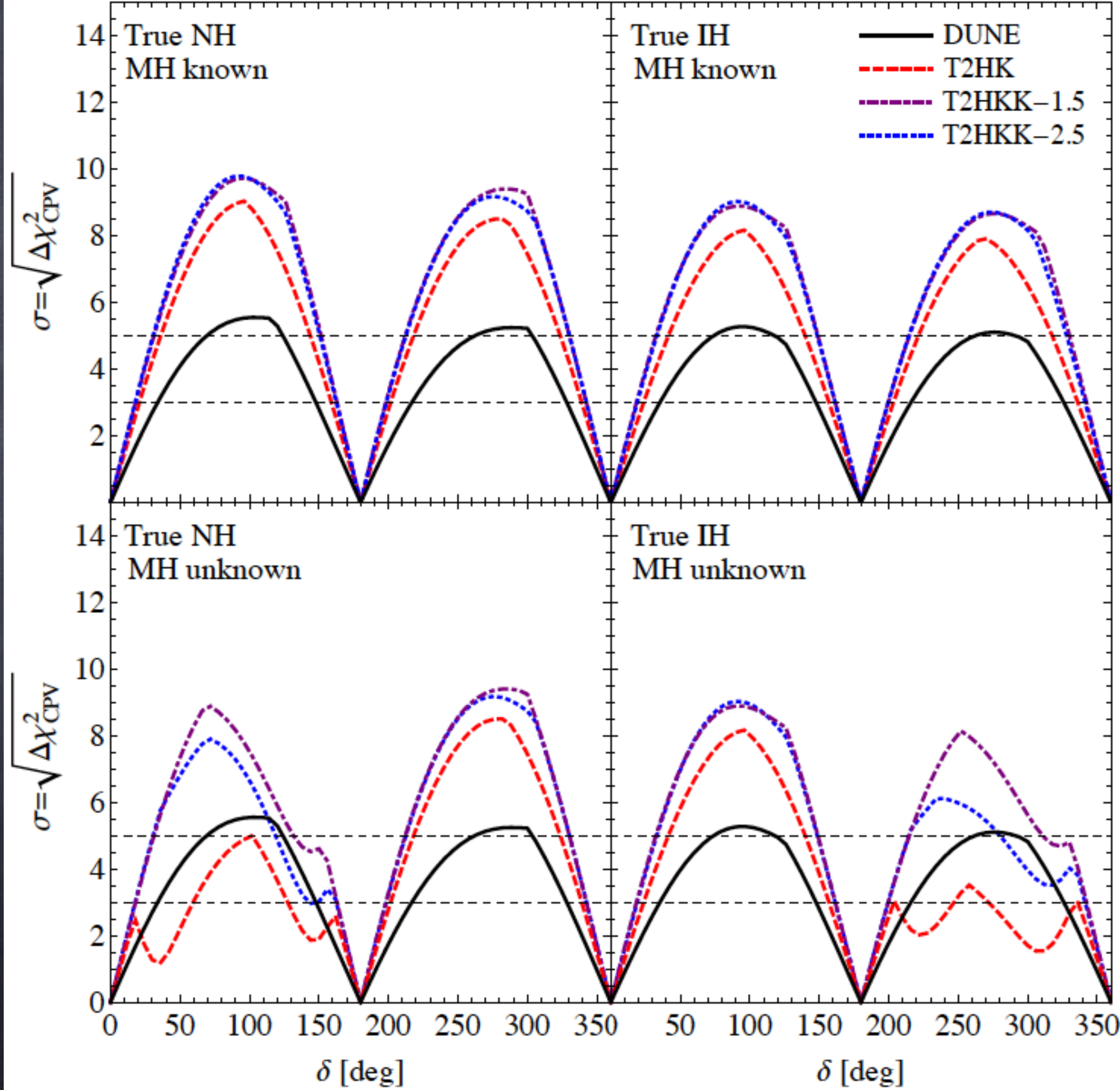
Experiment	$\frac{L(\text{km})}{E_{\text{peak}}(\text{GeV})}$	$\nu + \bar{\nu}$ Exposure (kt·MW·10 <sup>7</sup> s)	Signal norm. uncertainty	Background norm. uncertainty
DUNE (LAr)	$\frac{1300}{3.0}$	264 + 264 (80 GeV protons, 1.07 MW power, 1.47×10 <sup>21</sup> POT/yr, 40 kt fiducial mass, 3.5+3.5 yr)	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 <sup>21</sup> 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 <sup>21</sup> 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<sup>7</sup>s; for HyperK, 1 yr = 1.0 × 10<sup>7</sup>s.









# Appearance channels

NH

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

← Reduce to the SM  
when  $\epsilon_{ee} = 0$   
← 1<sup>st</sup> order due to  $\epsilon_{e\mu}$

$$+ 4\hat{A}\epsilon_{e\mu} \{xf[s_{23}^2 f \cos(\phi_{e\mu} + \delta) + c_{23}^2 g \cos(\Delta + \delta + \phi_{e\mu})]$$

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

$$+ 4\hat{A}\epsilon_{e\tau}s_{23}c_{23} \{xf[f \cos(\phi_{e\tau} + \delta) - g \cos(\Delta + \delta + \phi_{e\tau})]$$

← 1<sup>st</sup> order due to  $\epsilon_{e\tau}$

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

$$+ 4\hat{A}^2 (g^2 c_{23}^2 |c_{23}\epsilon_{e\mu} - s_{23}\epsilon_{e\tau}|^2 + f^2 s_{23}^2 |s_{23}\epsilon_{e\mu} + c_{23}\epsilon_{e\tau}|^2)$$

← 2<sup>nd</sup> order  
corrections

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

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

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

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

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

•  $P_{\mu e} \rightarrow \bar{P}_{\mu e}$

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

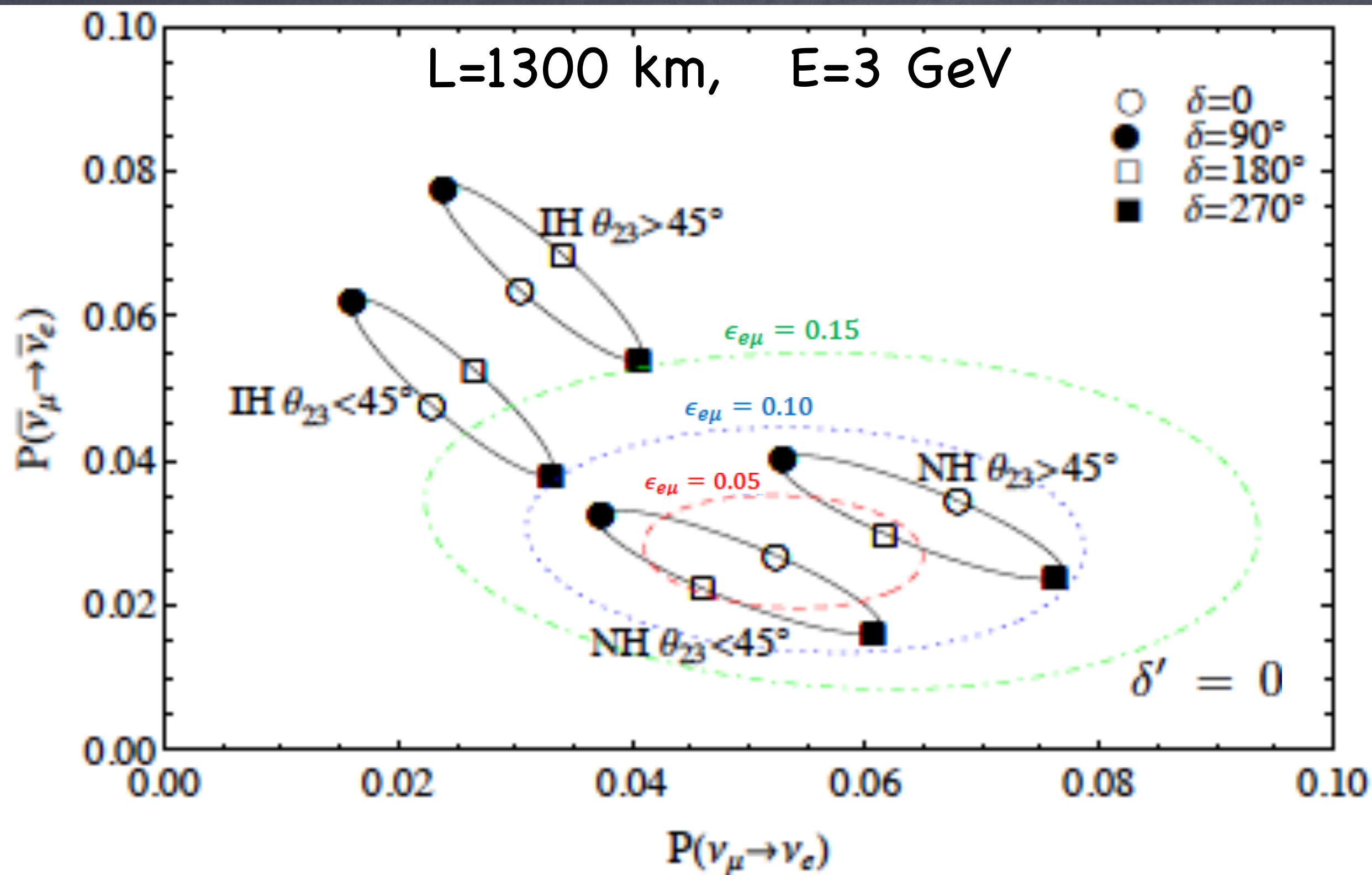
$$\delta \rightarrow -\delta, \quad \phi_{\alpha\beta} \rightarrow -\phi_{\alpha\beta}$$

• NH → IH

$$\Delta \rightarrow -\Delta, \quad y \rightarrow -y$$

$$\hat{A} \rightarrow -\hat{A} \quad (f \leftrightarrow -\bar{f}, \text{ and } g \rightarrow -g)$$

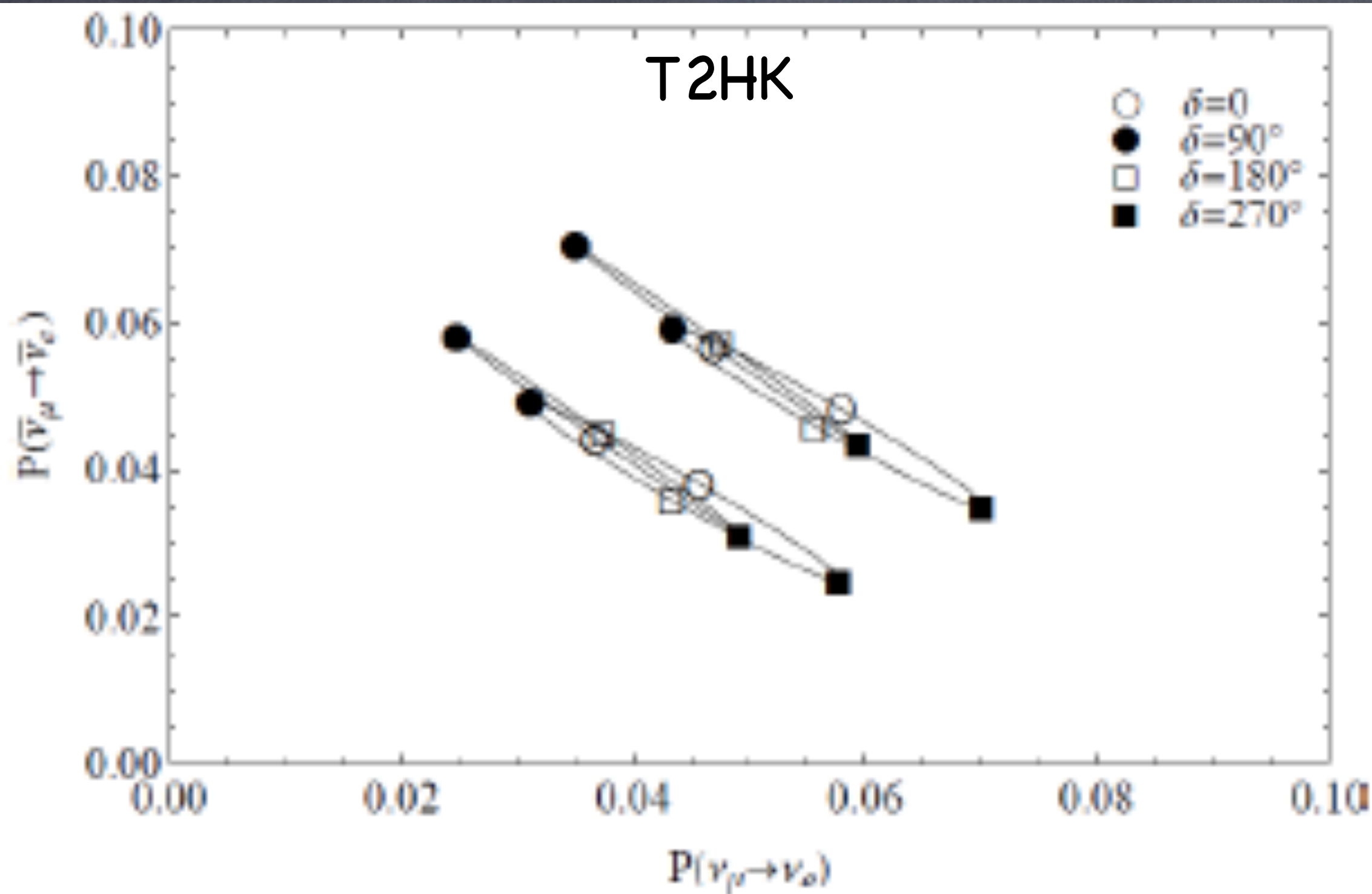




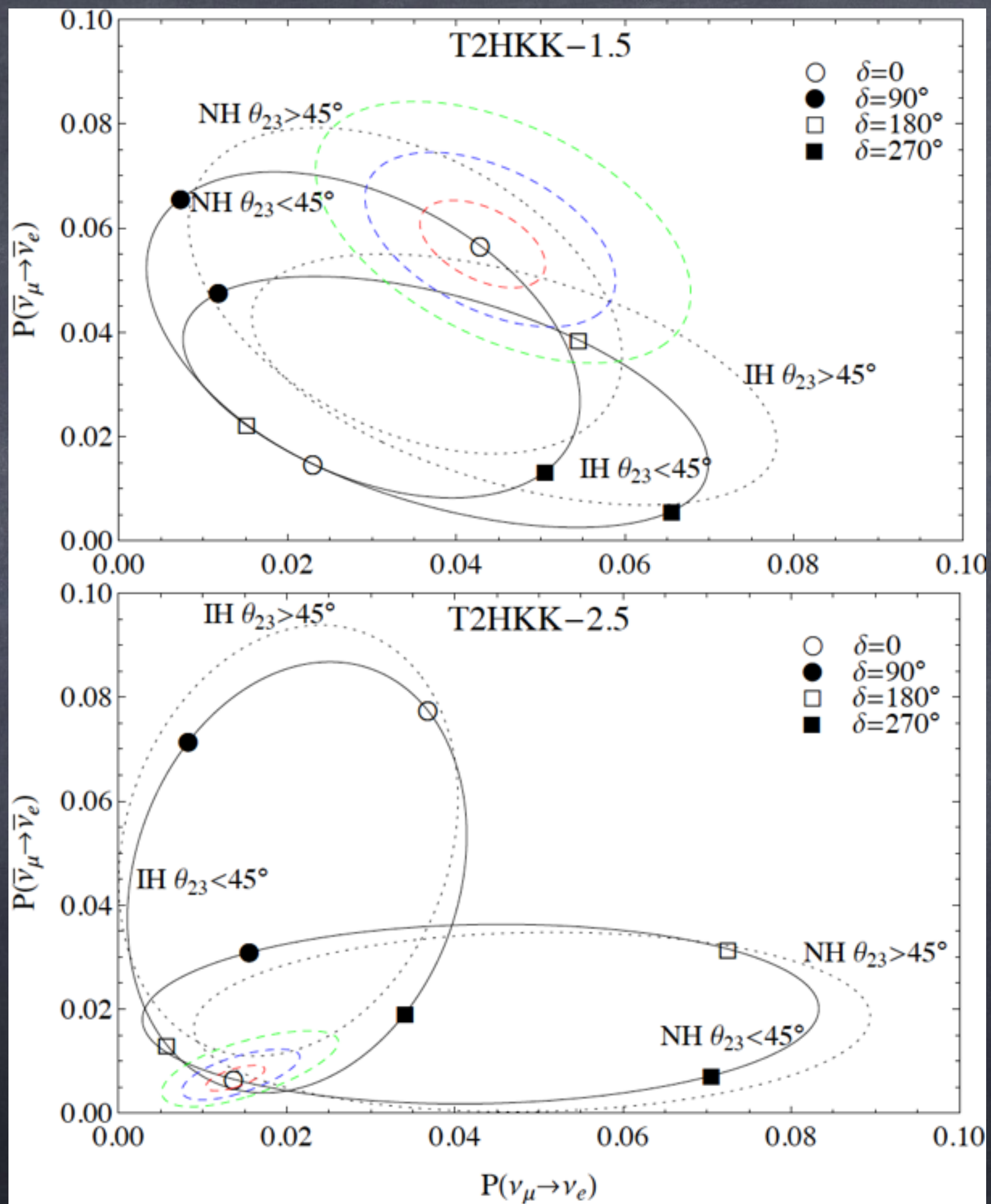
$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$

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

T2HK







$$\sin^2\theta_{13}=0.023\pm0.002$$

$$\sin^2\theta_{12}=(0.305\pm0.015)\oplus(0.70\pm0.017)$$

$$\sin^2\theta_{23}=0.43^{+0.08}_{-0.03}, \quad \delta=0$$

$$\delta m_{21}^2=(7.48\pm0.21)\times10^{-5} \text{ eV}^2$$

$$|\delta m_{31}^2|=(2.43\pm0.08)\times10^{-3} \text{ eV}^2$$

1307.3092

$$-5.0 < \epsilon_{ee} < 5.0$$

$$0 < \epsilon_{e\mu} < 0.5$$

$$0 < \epsilon_{e\tau} < 1.2$$

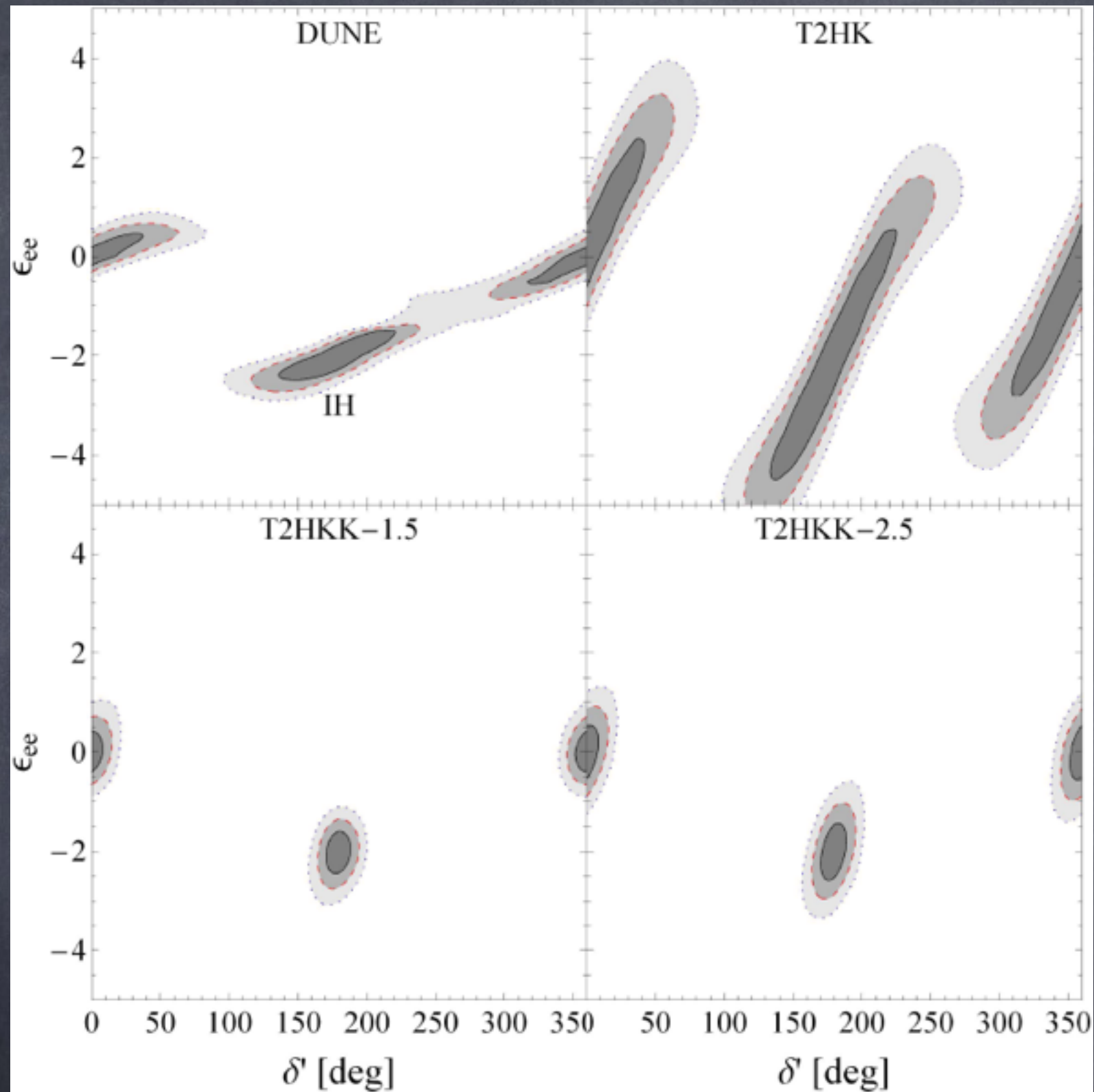
$$0 < \epsilon_{\mu\tau} < 0.1$$

$$-0.6 < \epsilon_{\tau\tau} < 0.6$$

Marginalize over NSI phases and mass hierarchy



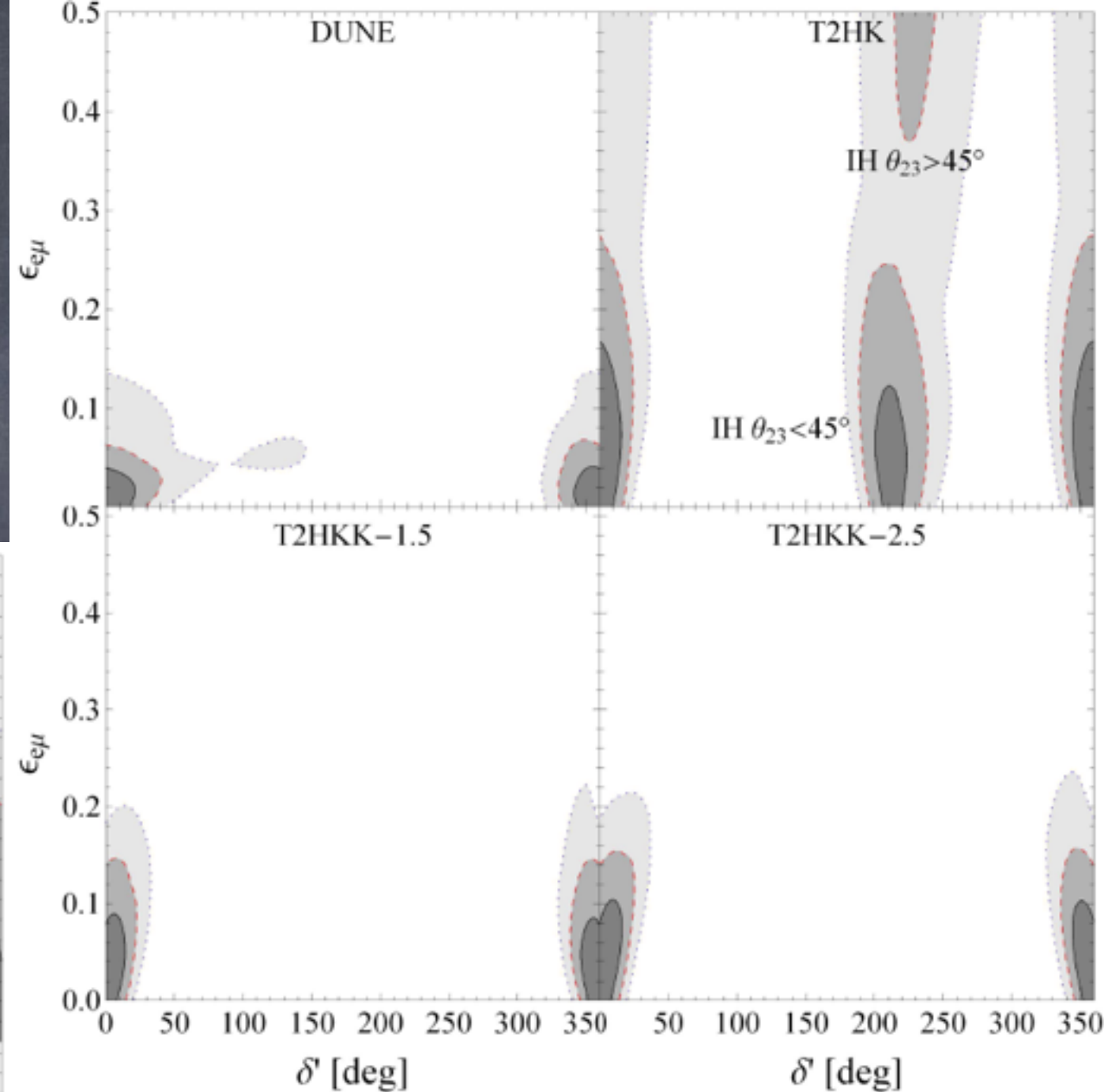
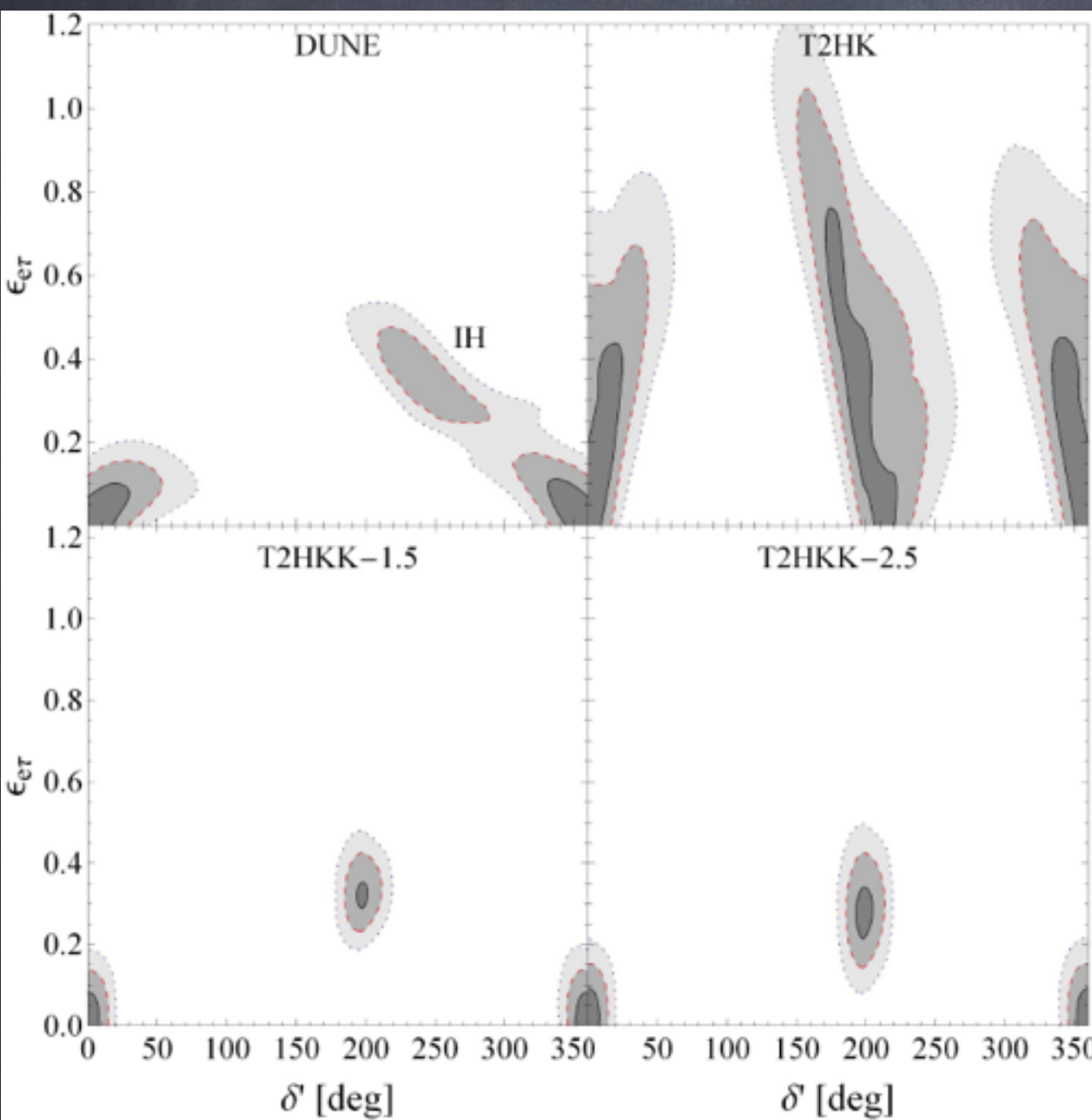
# One NSI parameter



$$\delta m_{31}^2 \rightarrow -\delta m_{32}^2, \quad \theta_{12} \rightarrow 90^\circ - \theta_{12}, \quad \delta \rightarrow 180^\circ - \delta$$

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

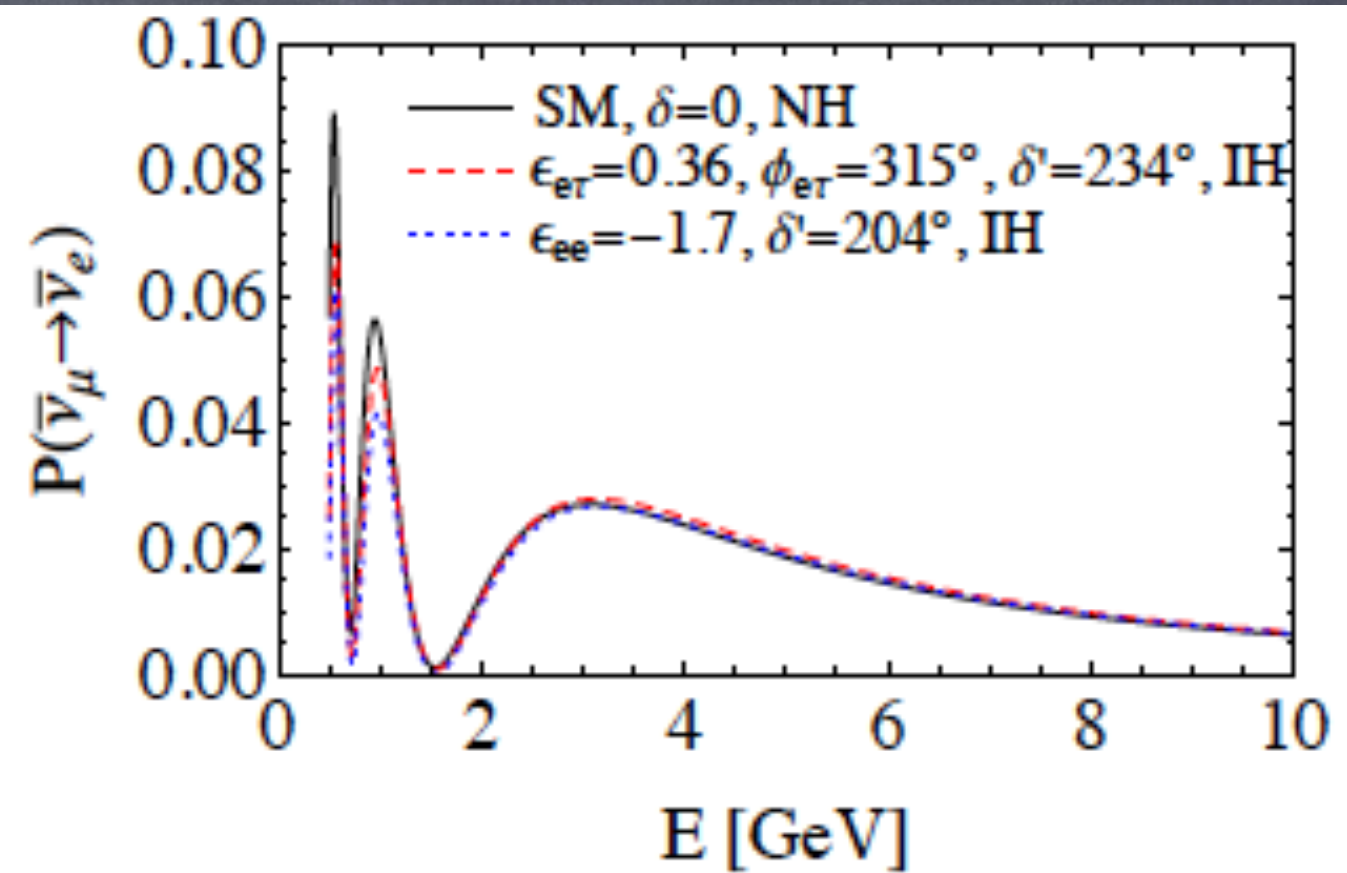
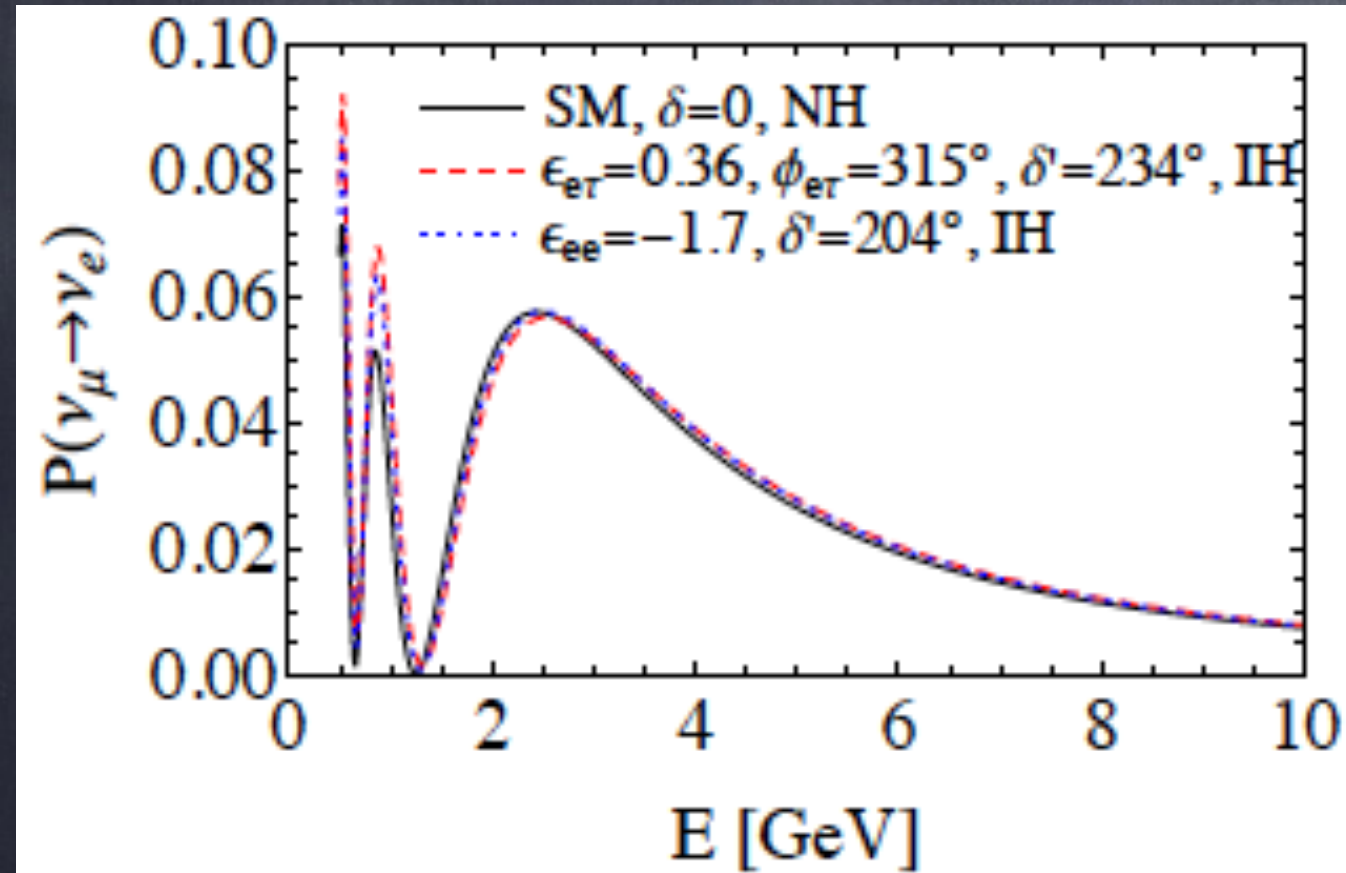
# Mass hierarchy resolved at DUNE and T2HKK

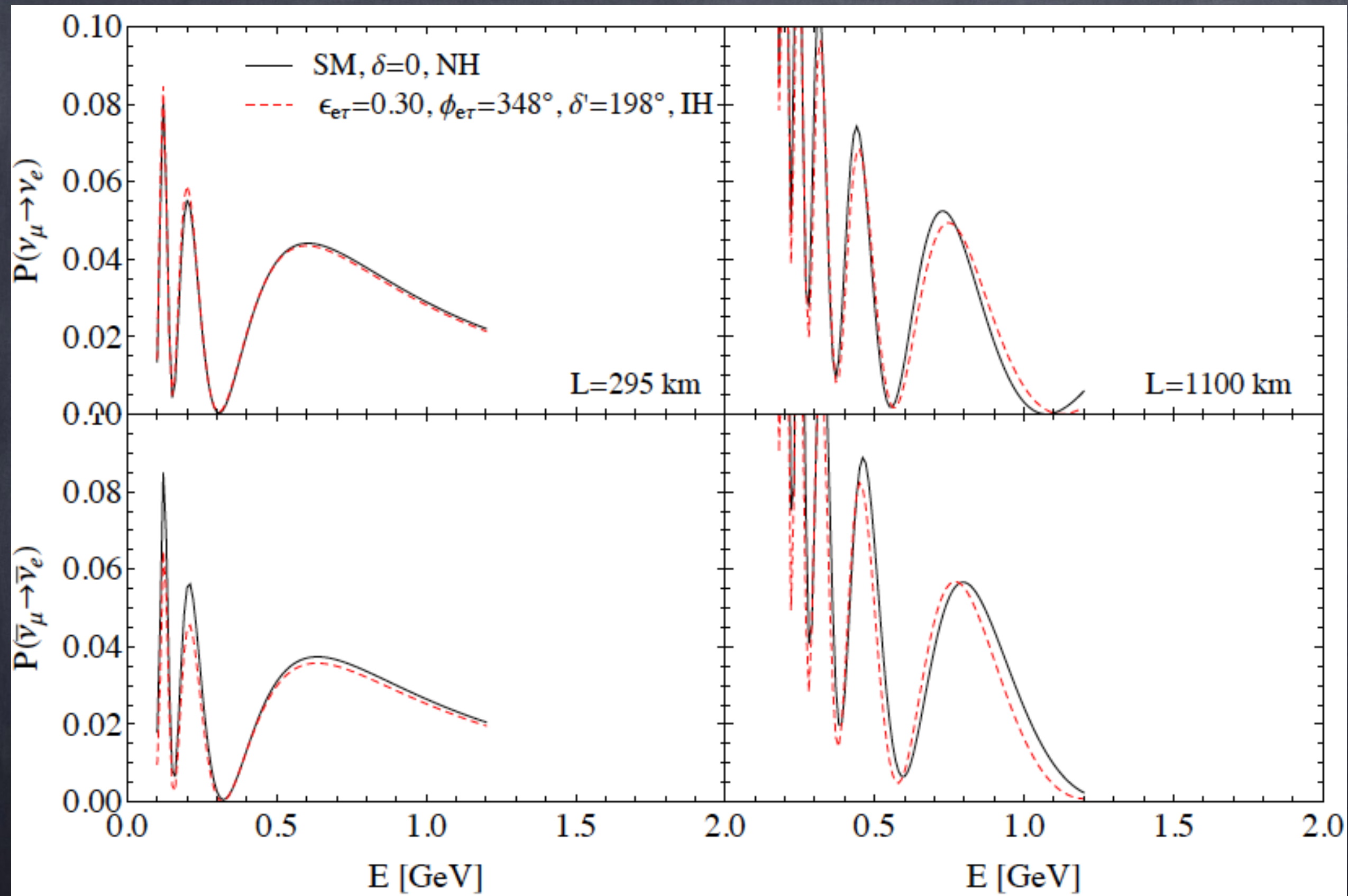


Hierarchy not resolved  
Wrong determination of the CP  
phase possible



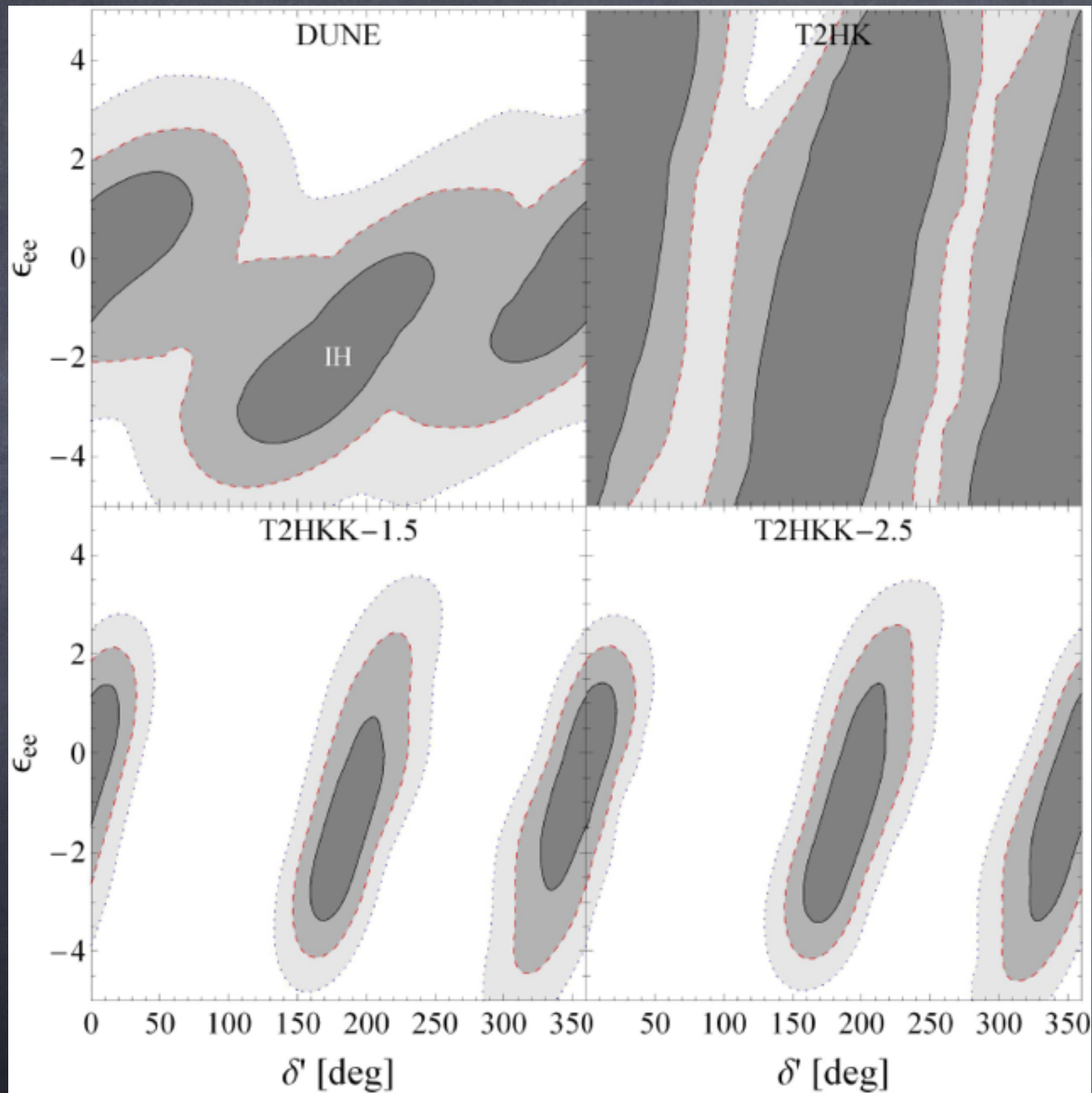
$L=1300$  km



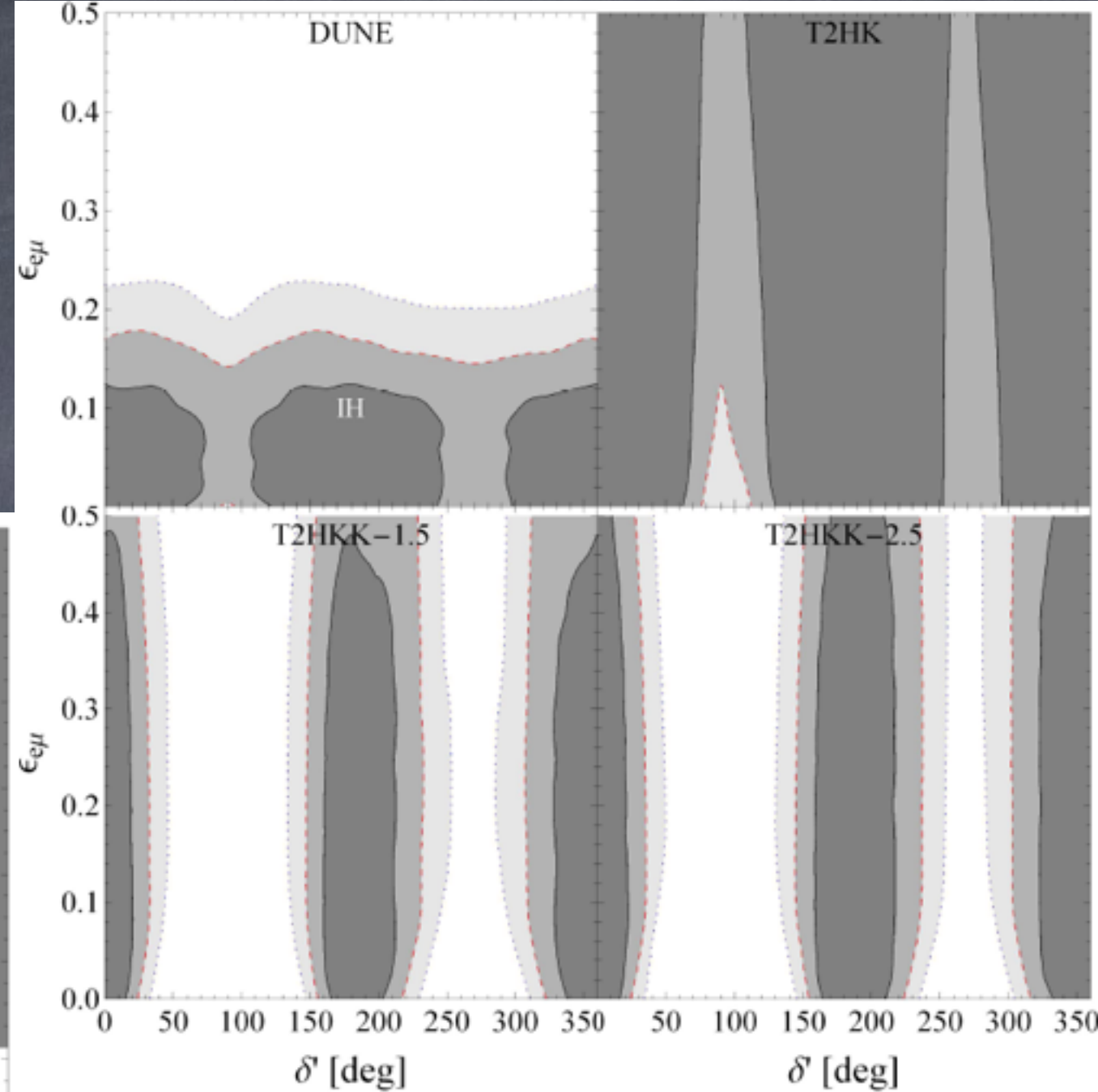
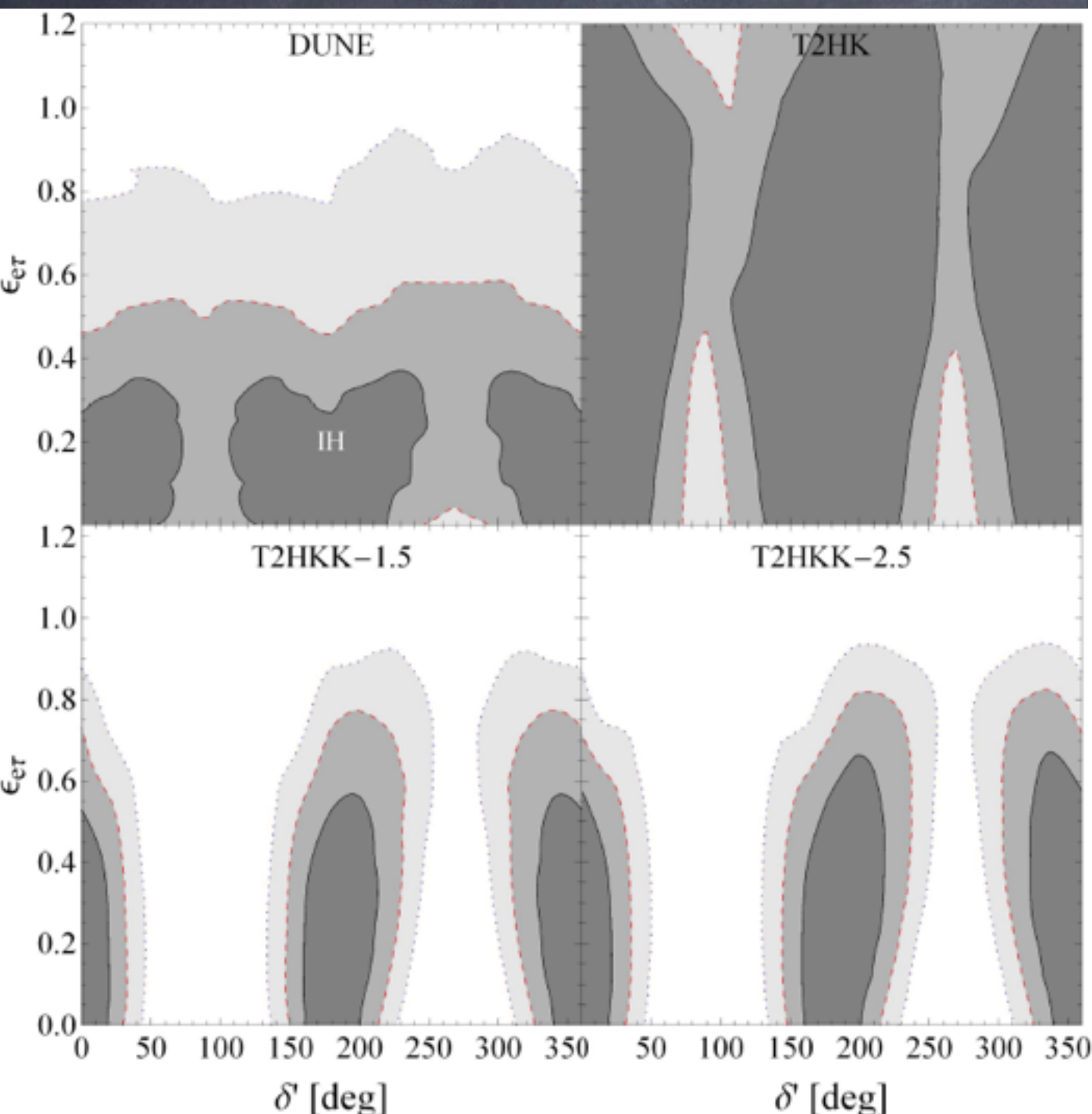




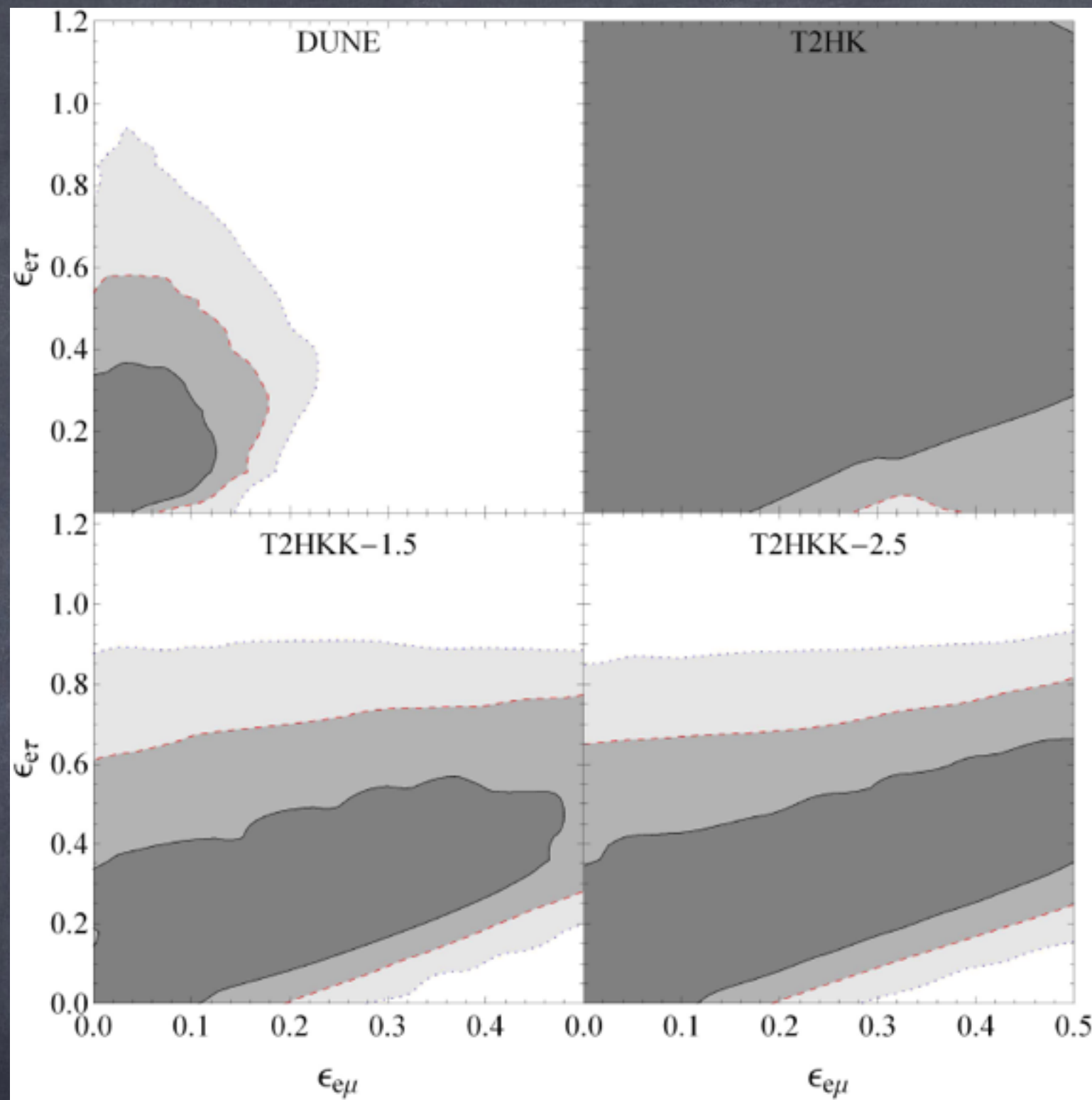
### 3 NSI parameters



Constraint on  $e\mu$  NSI much weaker at T2HK and T2HKK



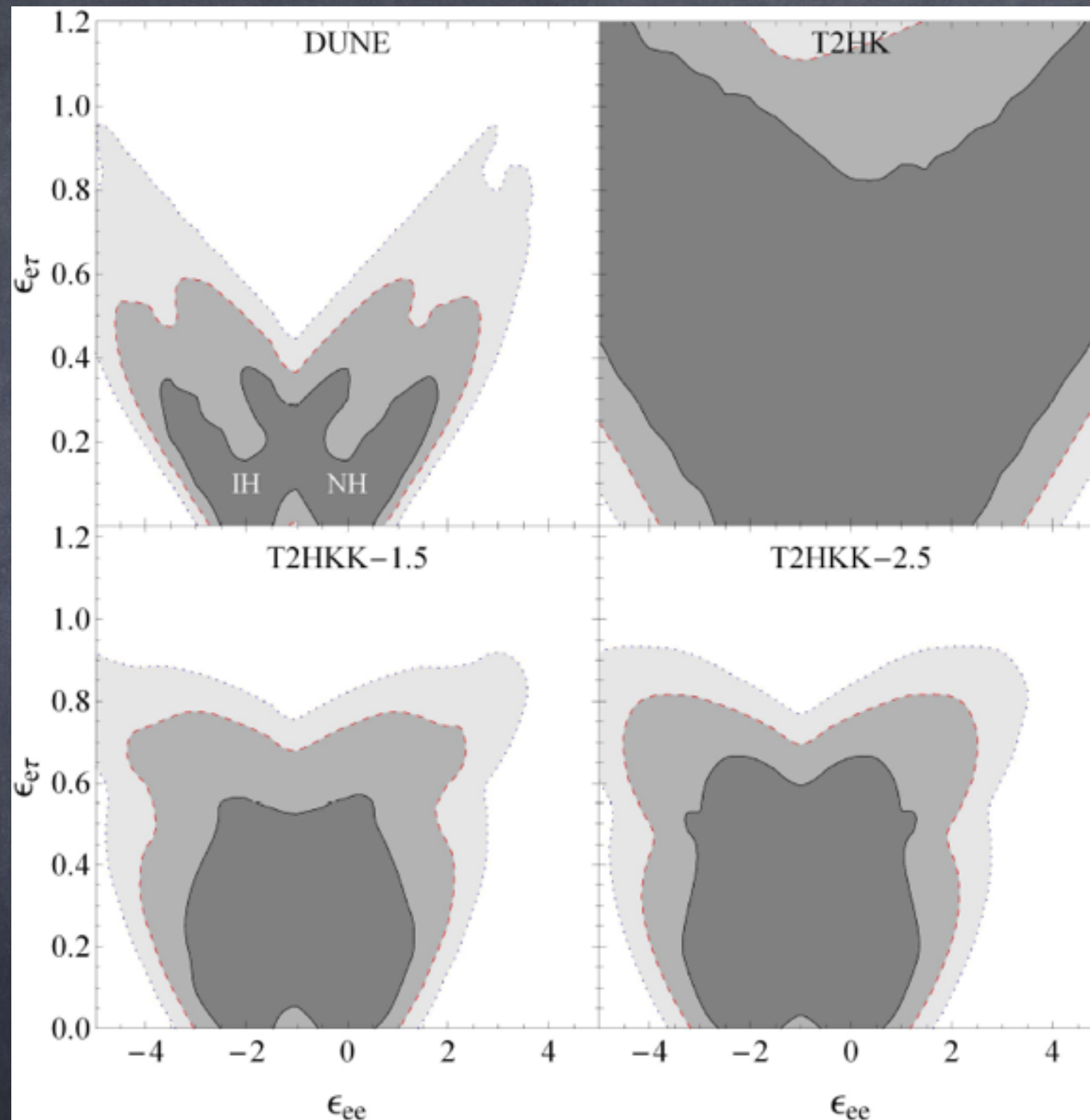




Because of the lower energy J-PARC beam, the difference between SM and NSI appearance probabilities are suppressed at T2HK and T2HKK for

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

# Correlations between $\epsilon_{ee}$ and $\epsilon_{e\tau}$



Symmetry around  $-1$  is because the vertex of the V-shaped NH region is at  $0$  and the vertex of the V-shaped IH region is at  $-2$

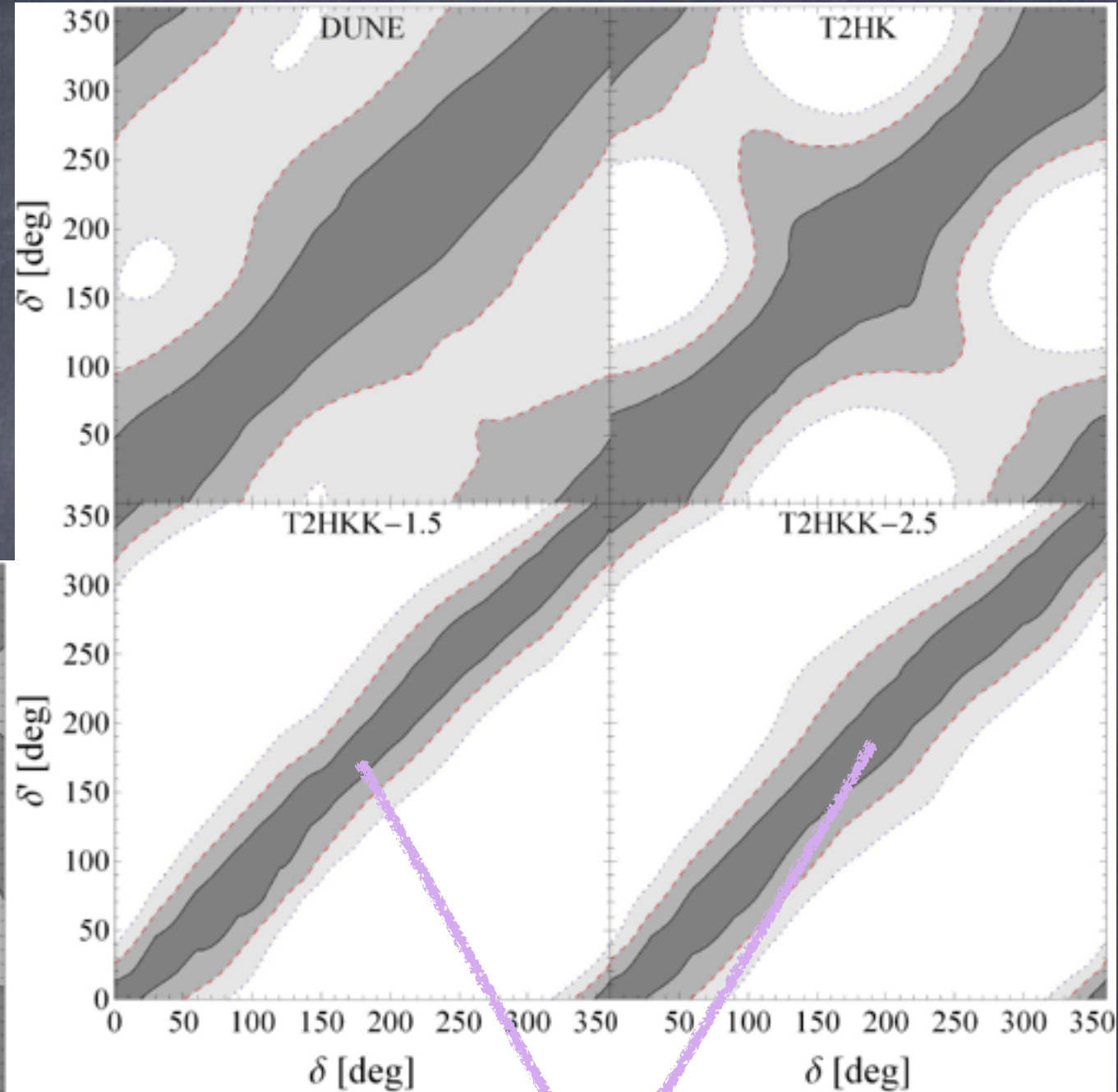
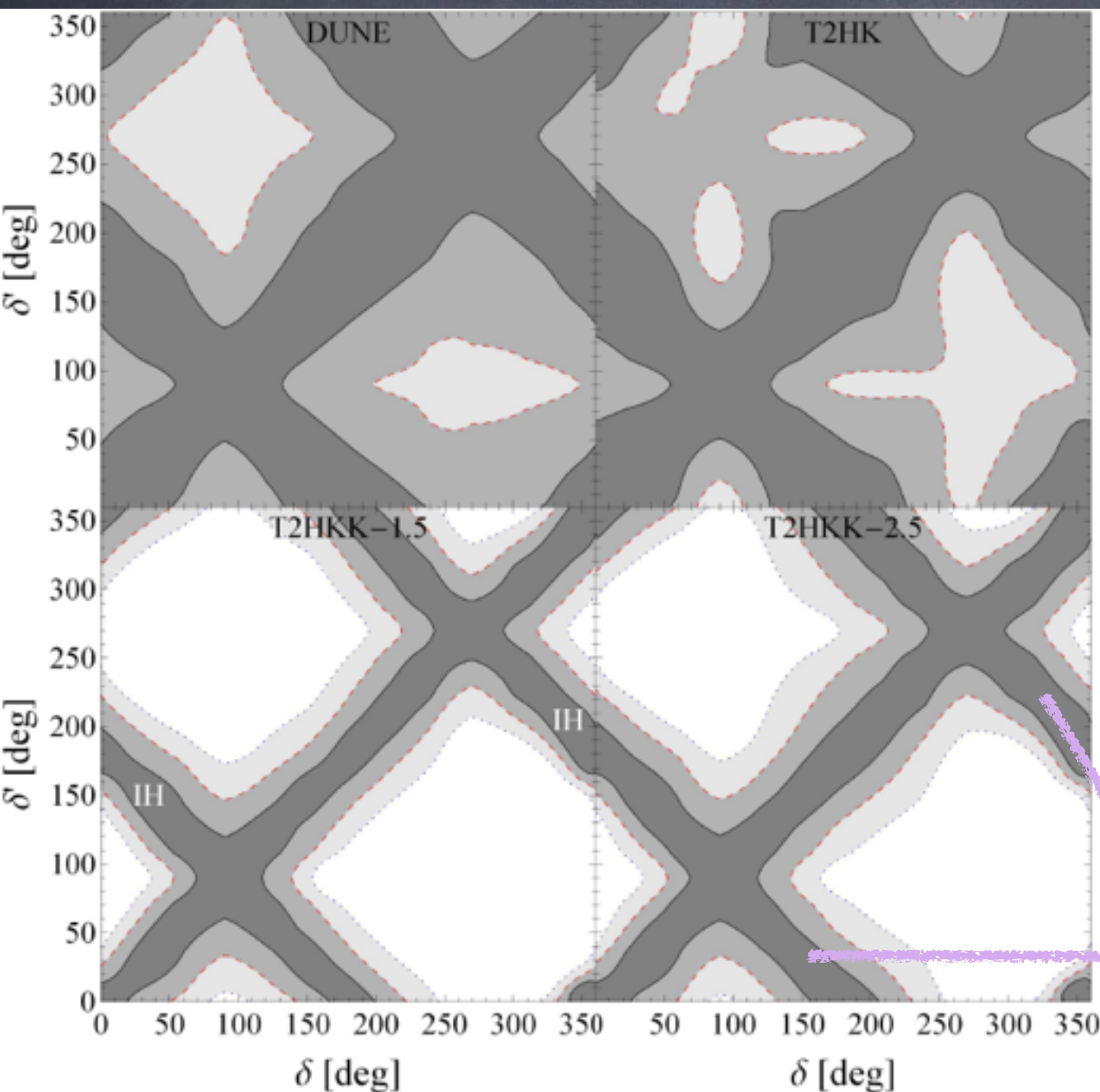


CP sensitivity

MH known

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

MH unknown



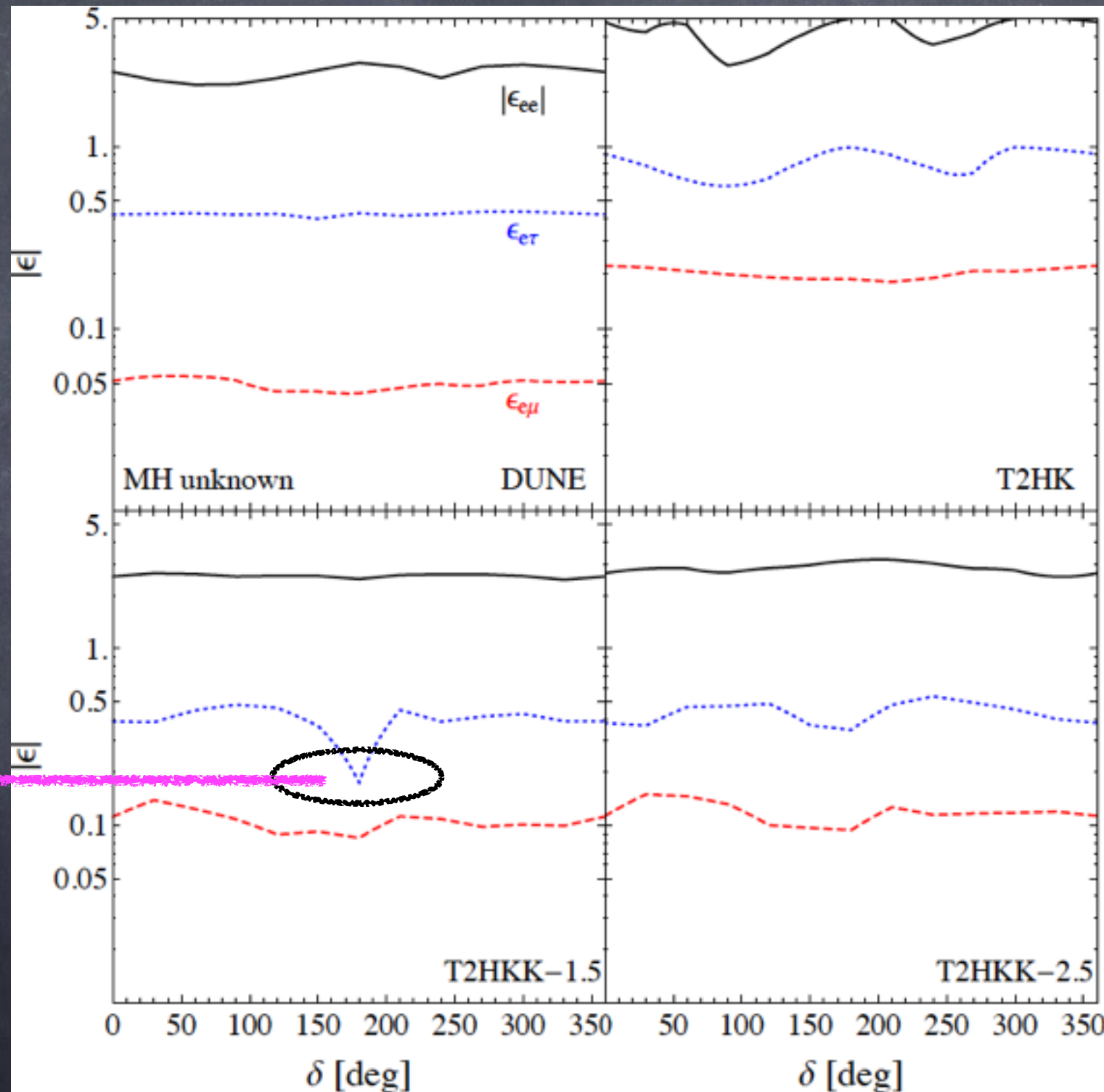
$\delta' = \delta$  holds when  $\epsilon = 0$

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

# Sensitivity to NSI as a function of CP

One nonzero NSI parameter

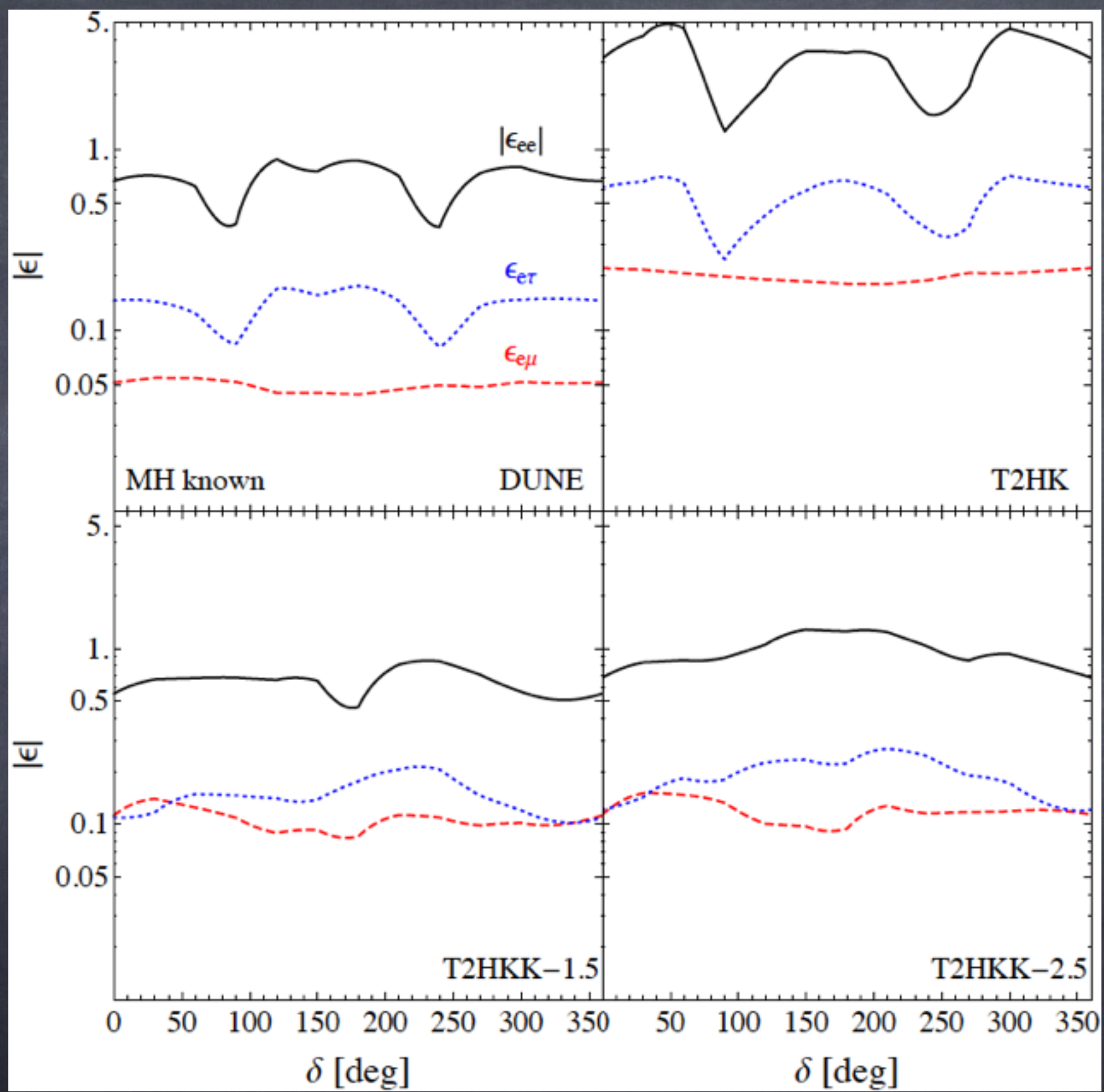
95.4% CL



IH not allowed  
at 95.4% CL

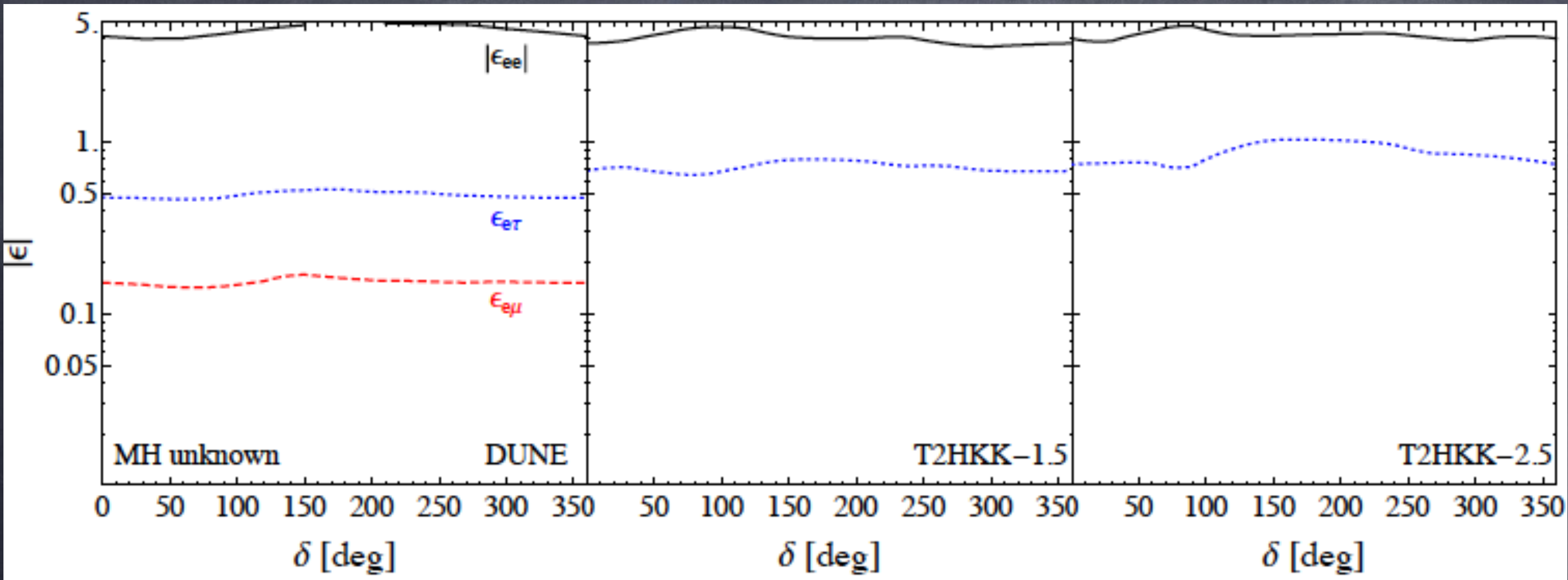
$|\epsilon_{ee}| > 2$  because of the generalized hierarchy degeneracy





### 3 NSI parameters

NH



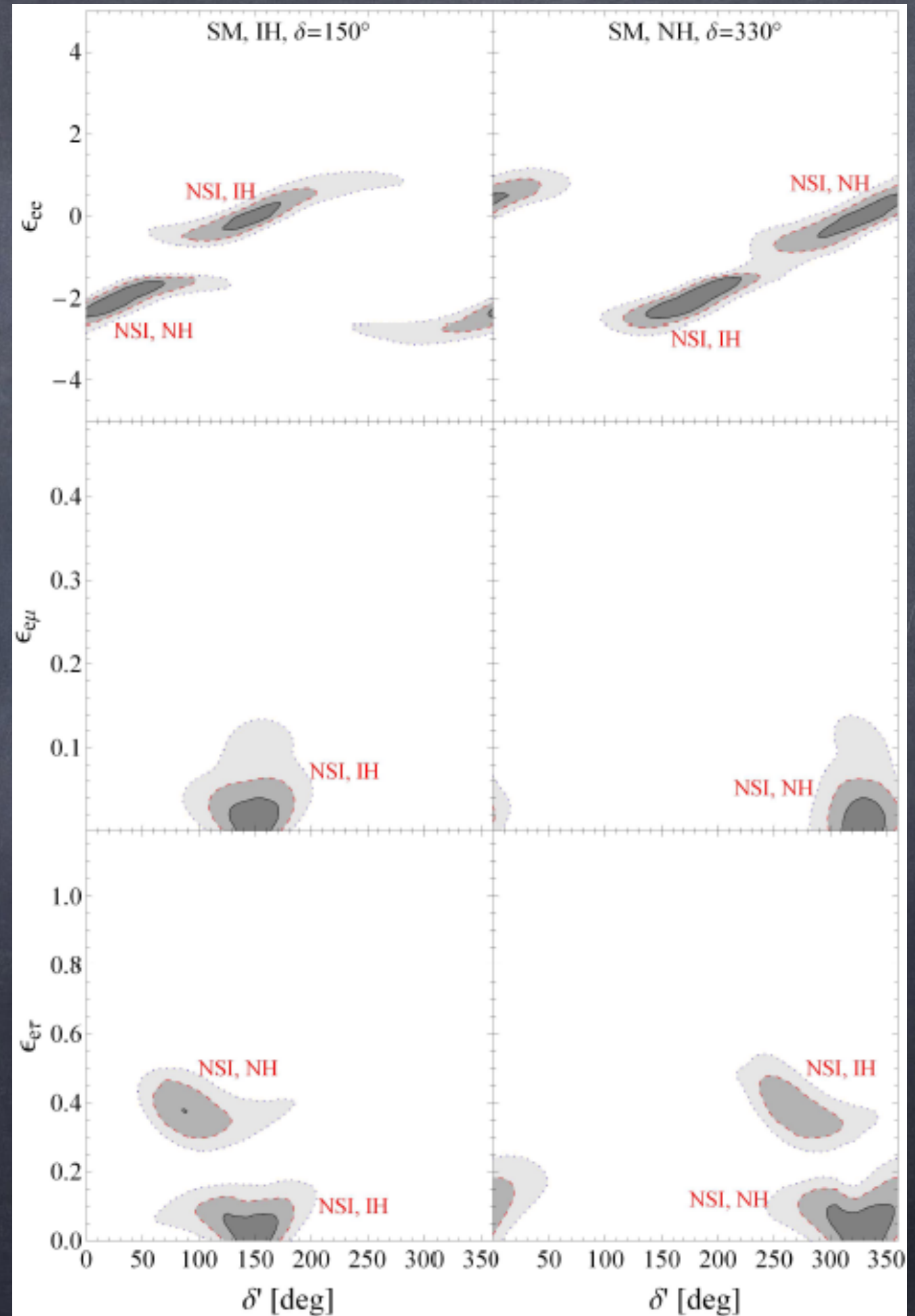
All T2HK, and T2HKK  $e\mu$  sensitivities outside the range of scan



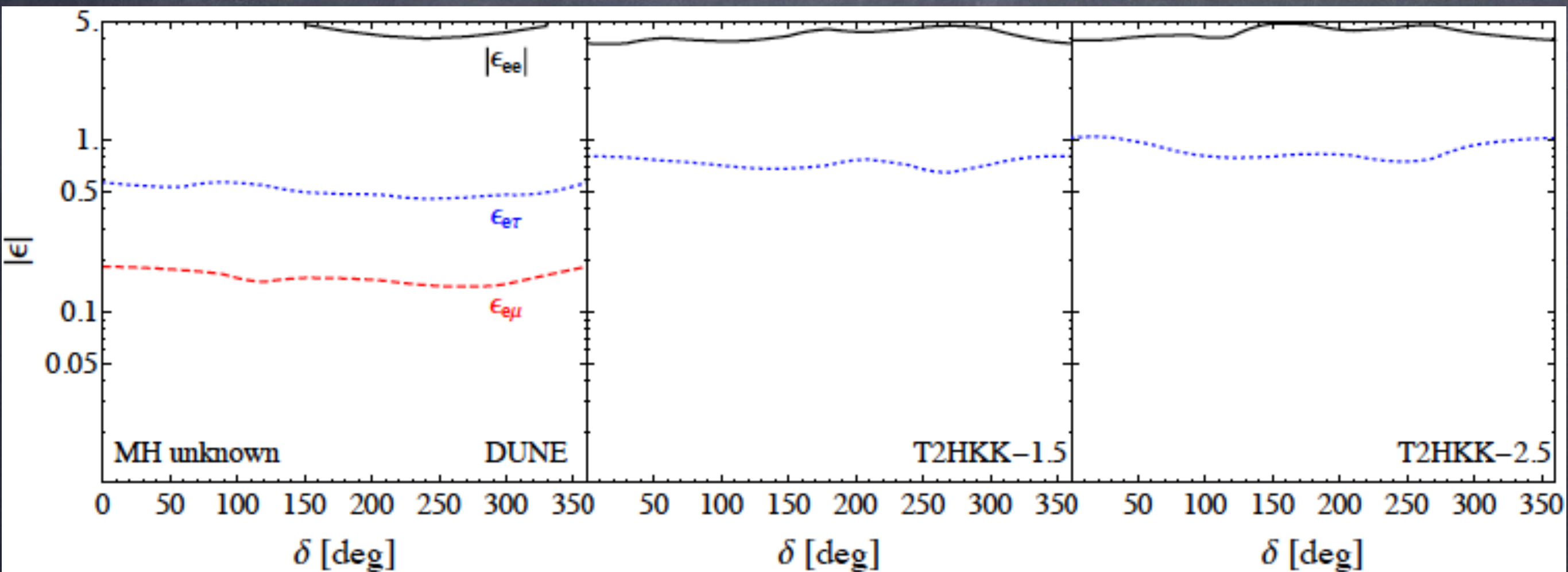
# Sensitivity to NSI similar for both mass hierarchies

Regions are similar under

$$\delta' \rightarrow \delta' + 180^\circ$$

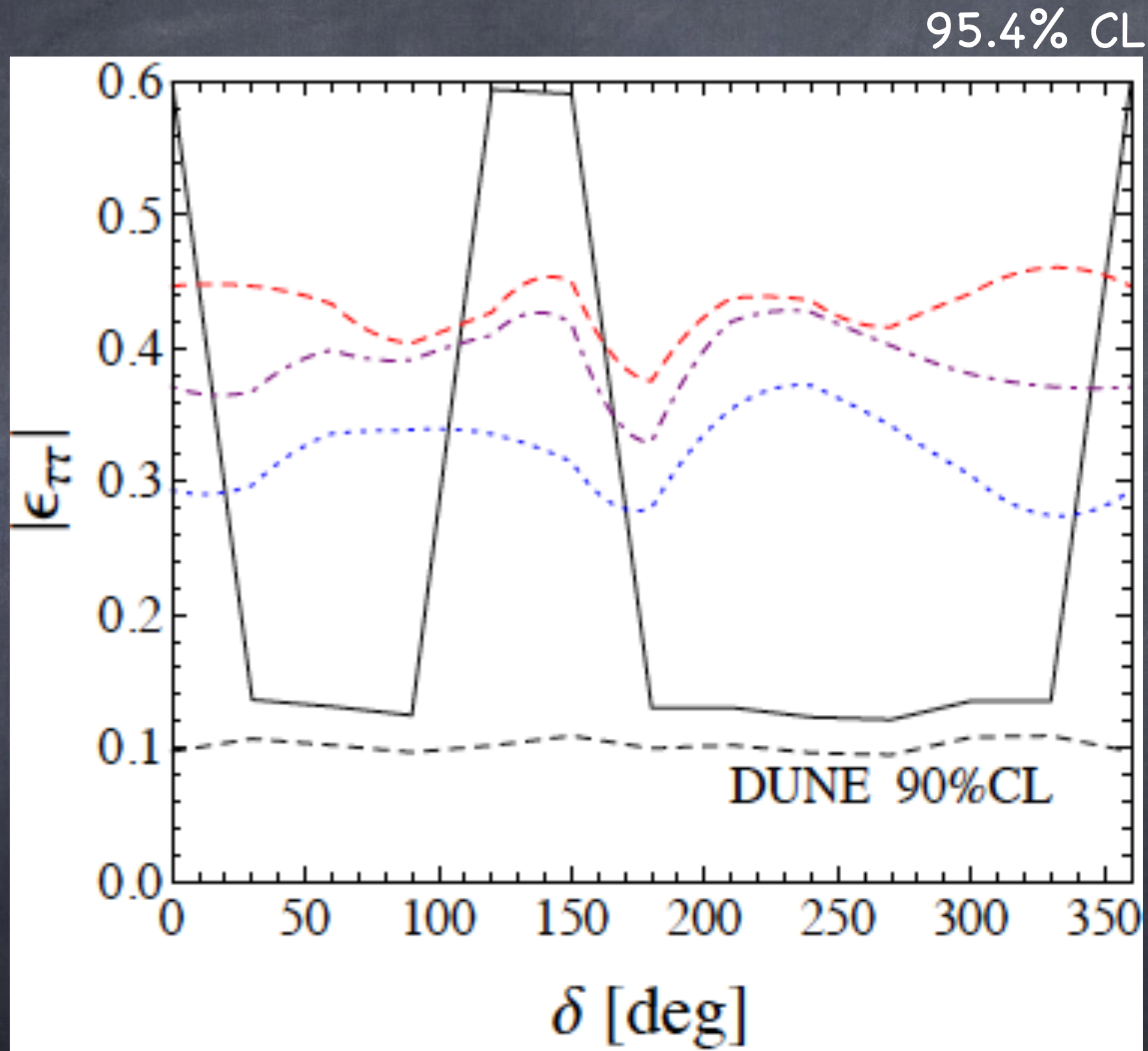


IH

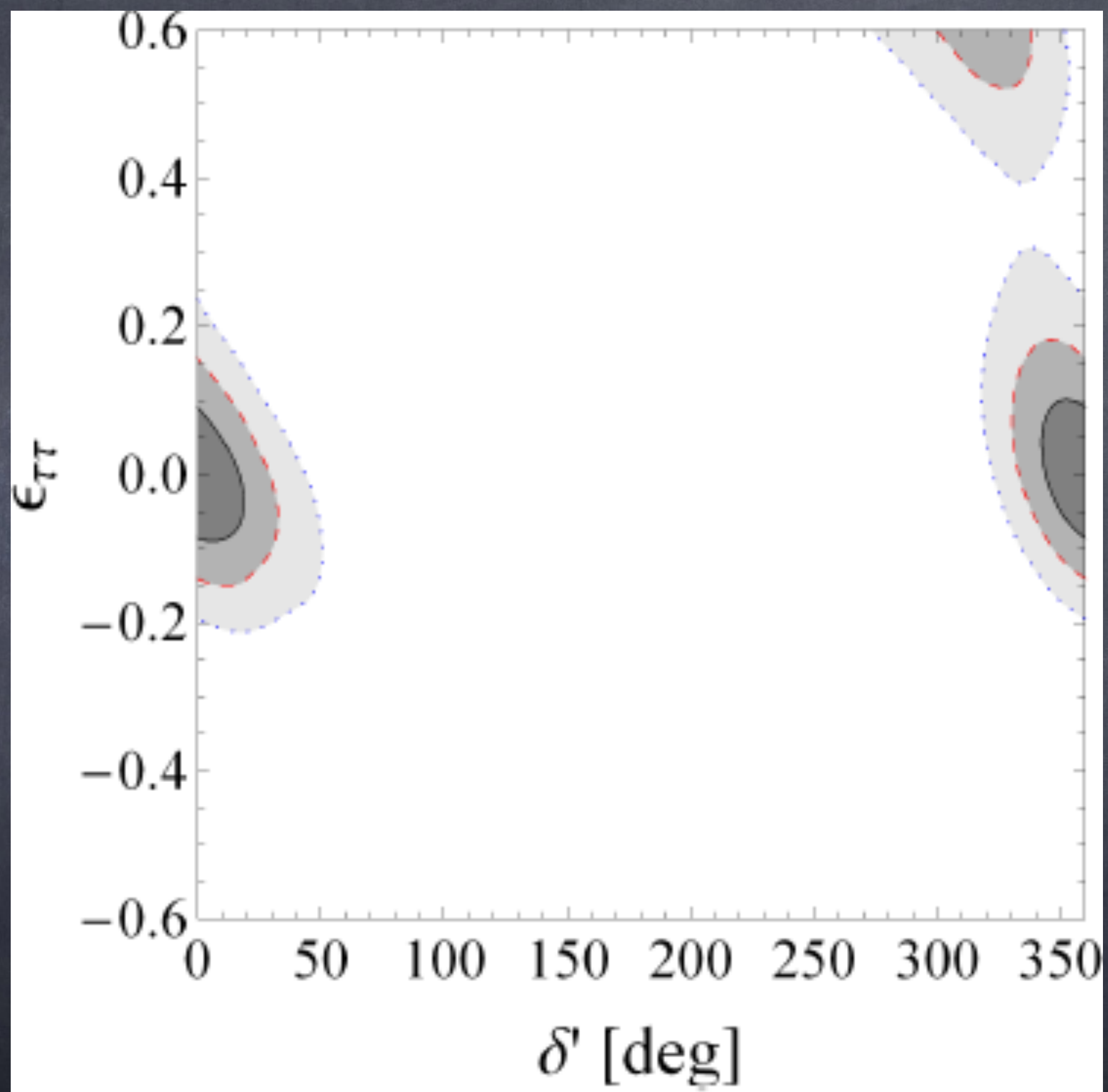




# Disappearance channels



$\mu$ / $\tau$  sensitivity for all experiments outside the range of scan





# Summary

- NOvA's exclusion of maximal mixing may be a hint of NSI
- Degeneracies between SM and NSI parameters, and between NSI parameters strongly affect sensitivities
- If  $\epsilon$  NSI parameter is  $O(1)$ , impossible to determine hierarchy at LBL experiments
- DUNE has best sensitivity to NSI
- T2HK has best sensitivity to CP phase in the presence of NSI
- Sensitivity to NSI same for both mass hierarchies at LBL expts