Nonstandard interactions at long-baseline neutrino experiments

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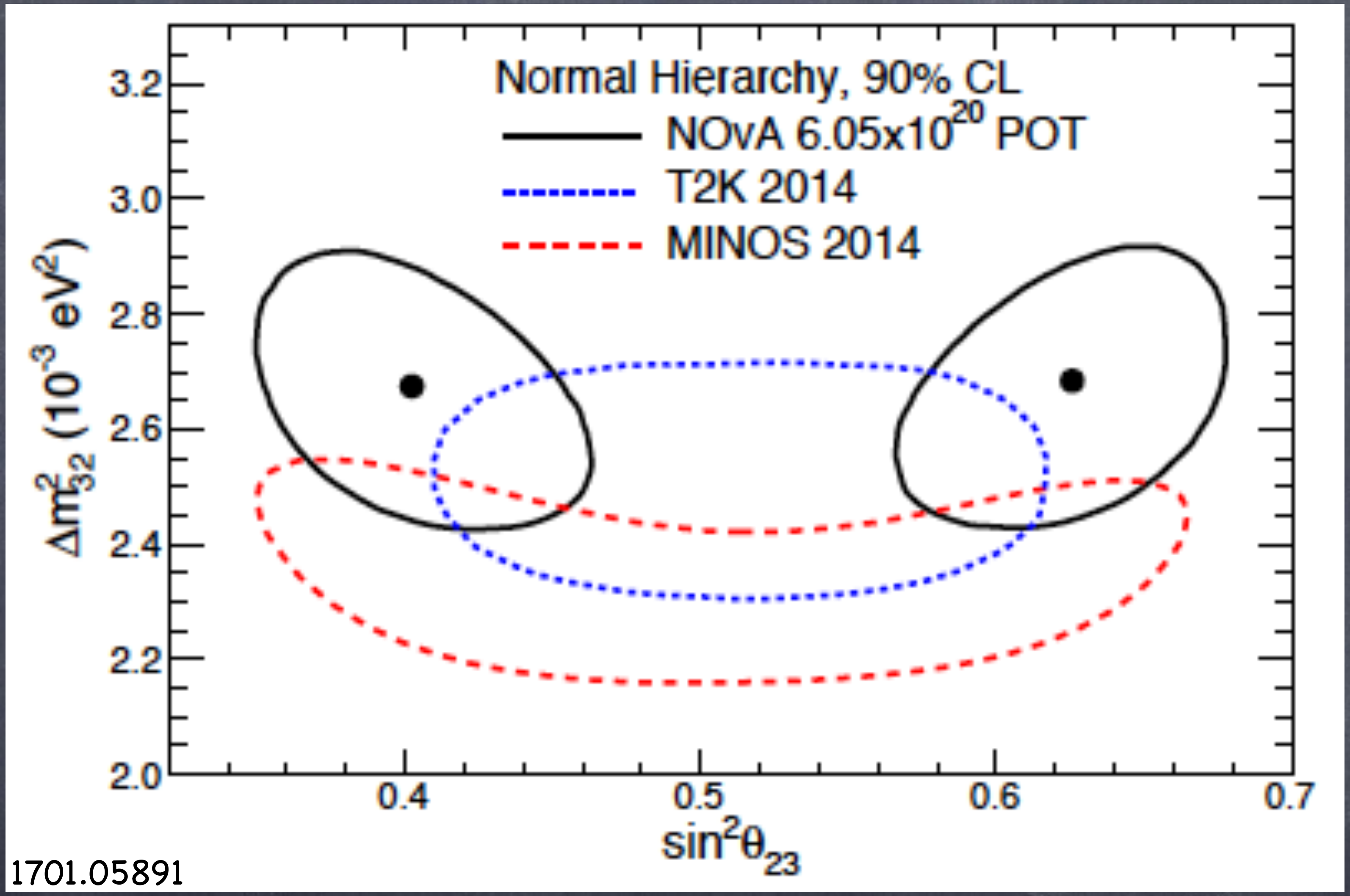
with Liao and Whisnant
(1601.00927, 1609.01786, 1612.01443)

Possible tension in standard oscillation picture



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

Nonstandard interactions in matter

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

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

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

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

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

$$\frac{\Delta m^2}{\Delta m_{32}^2} = \sqrt{(\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2 + |\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}$$

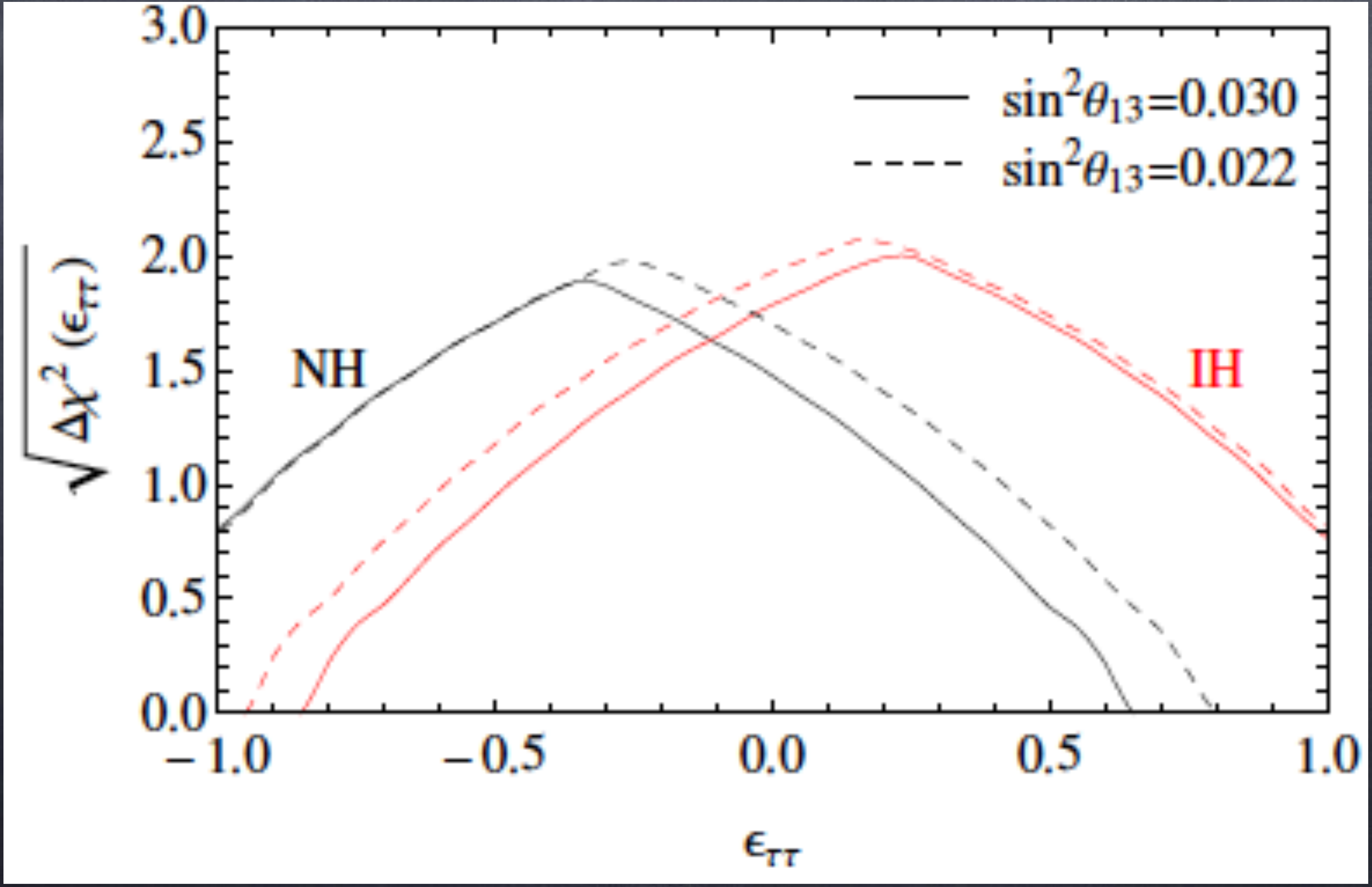
$$\sin^2 2\theta = \left(1 + \frac{(\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2}{|\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}\right)^{-1} . \quad \hat{A} = A/\Delta m_{32}^2$$

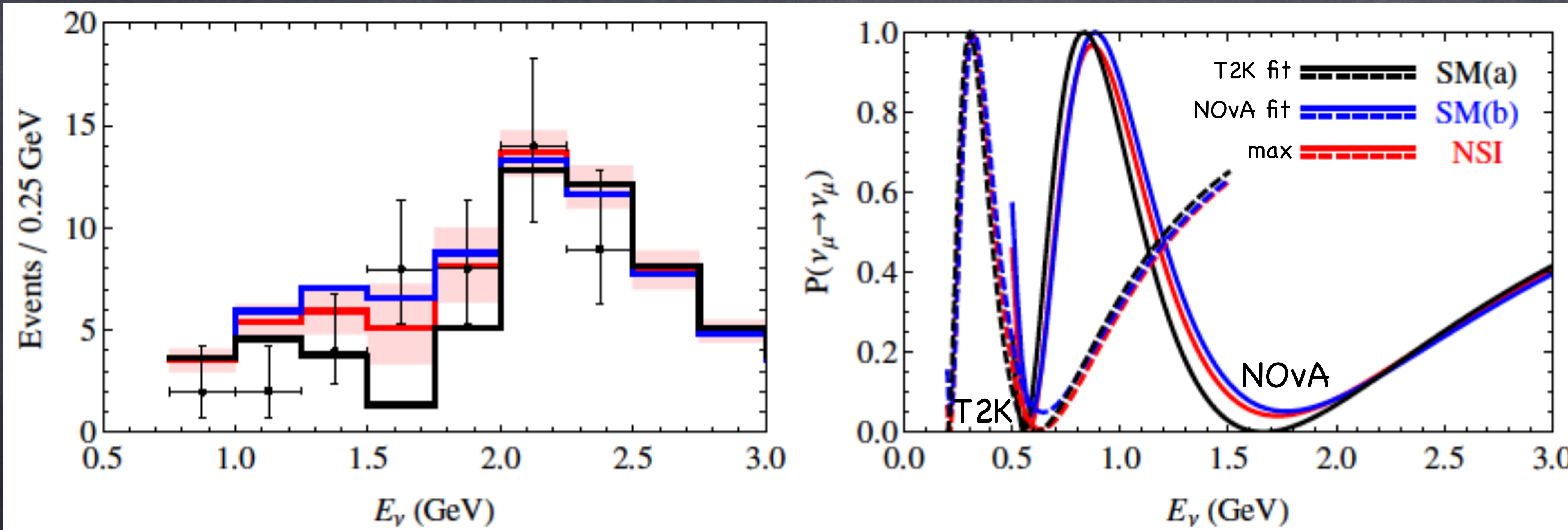
- For maximal mixing, NSI can generate nonmaximal mixing with a much larger effect in NOvA than T2K

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

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

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





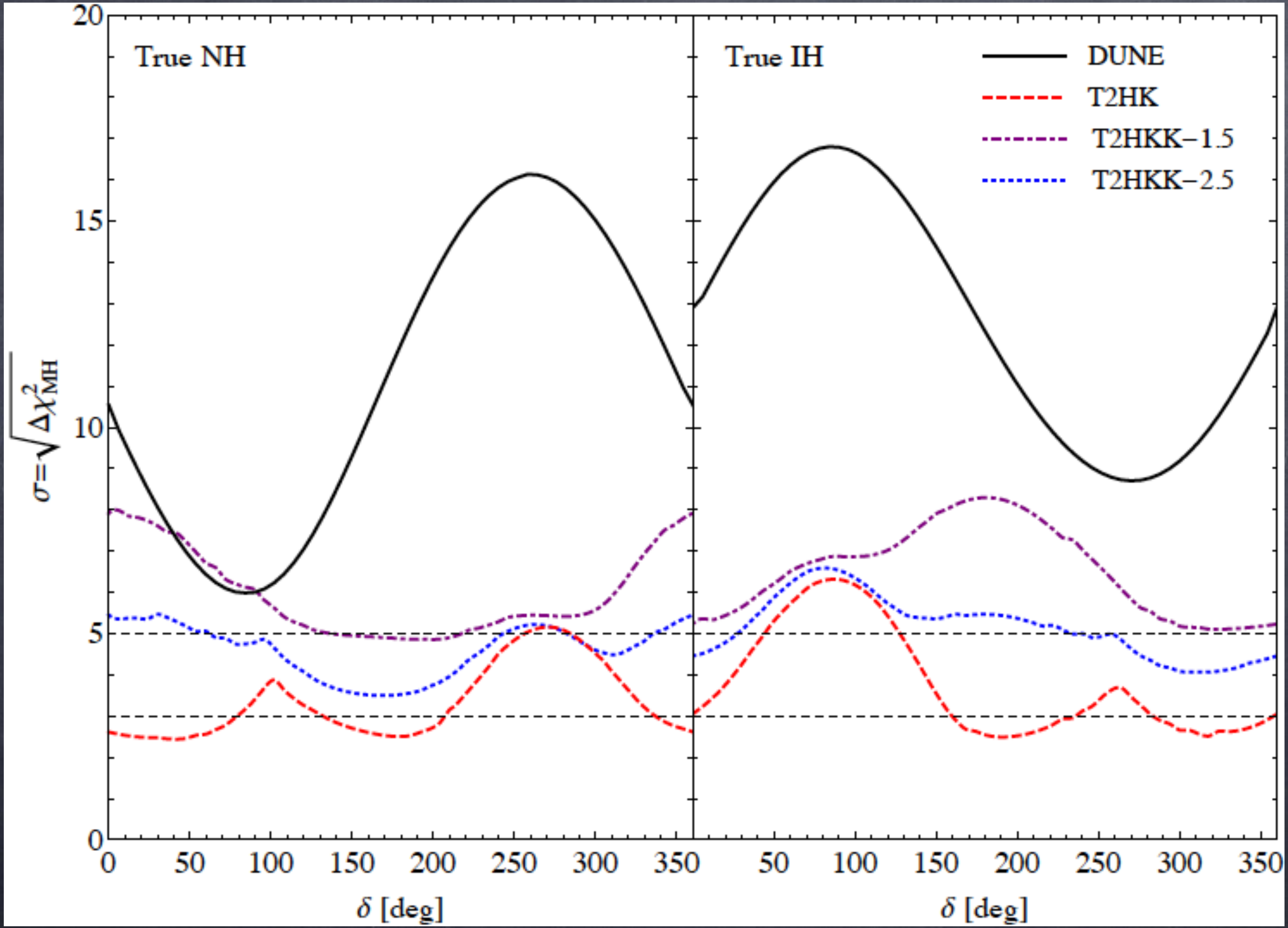
To fit their data, NOvA required nonmaximal mixing and a larger mass-squared difference than T2K

Could also fit with maximal mixing and NSI

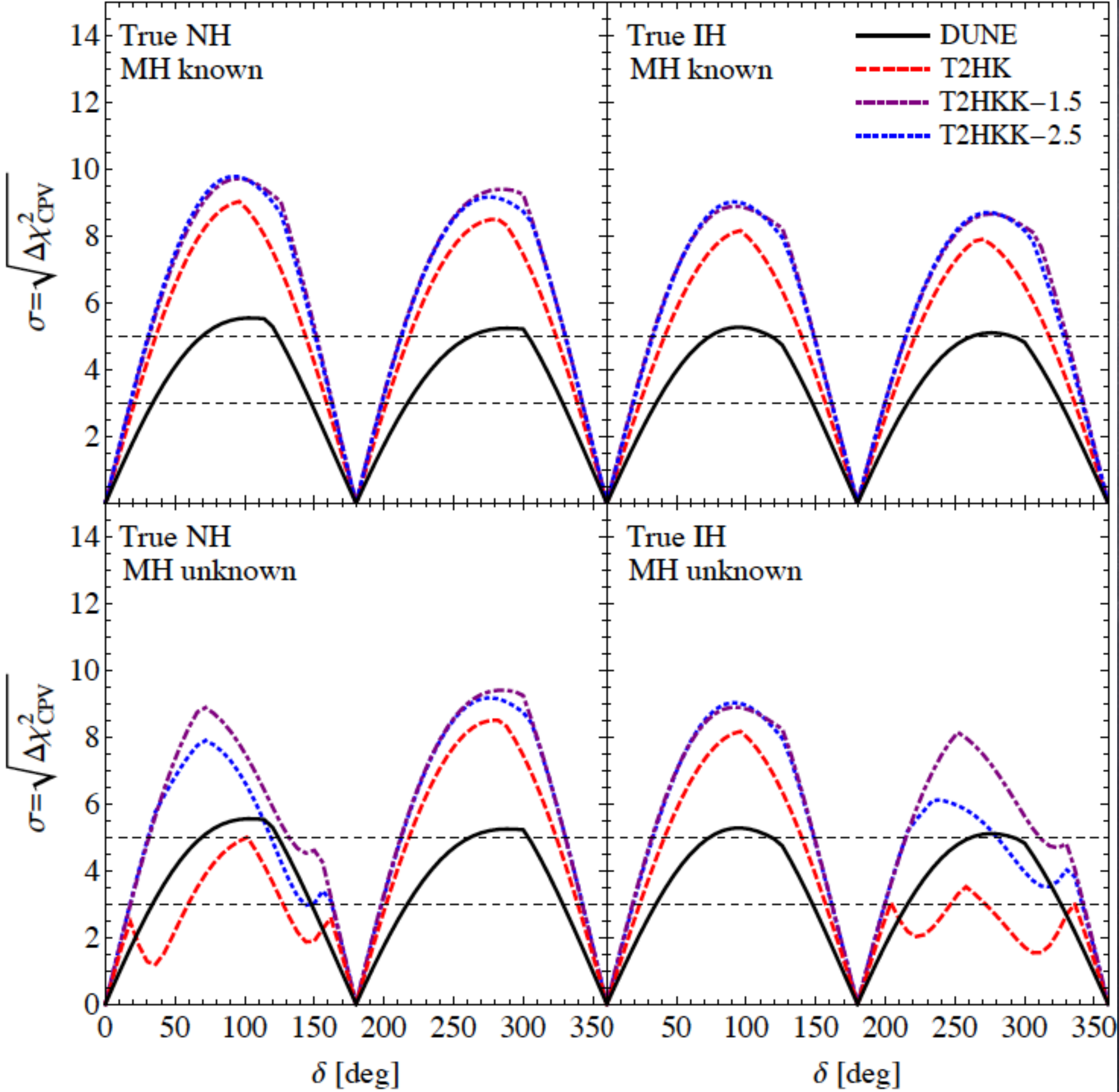
Future experiments

Experiment	$\frac{L(\text{km})}{E_{\text{peak}}(\text{GeV})}$	$\nu + \bar{\nu}$ Exposure (kt·MW·10^7s)	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.



True NH
True IH
DUNE
T2HK
T2HKK−1.5
T2HKK−2.5
$\sigma=\sqrt{\Delta\chi^2_{\rm MH}}$
δ [deg]
0
5
10
15
20
0
50
100
150
200
250
300
350


True NH
MH known
True IH
MH known
DUNE
T2HK
T2HKK−1.5
T2HKK−2.5
True NH
MH unknown
True IH
MH unknown
$\sigma=\sqrt{\Delta\chi^2_{CPV}}$
δ [deg]

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 $\epsilon_{ee}=0$

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

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

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

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

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

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

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

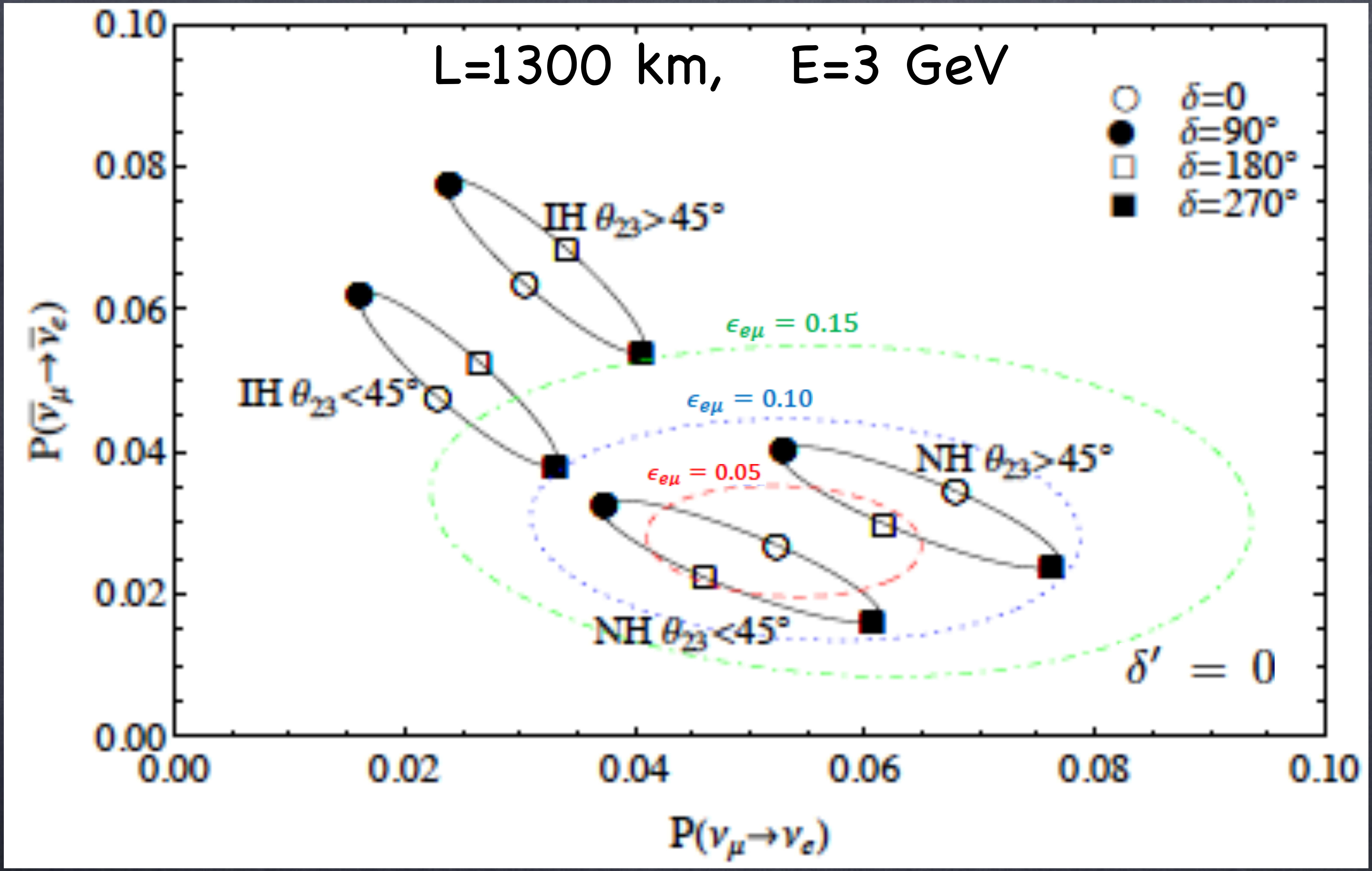
$$x \equiv 2s_{13}s_{23}\,,\quad y \equiv 2r s_{12}c_{12}c_{23}\,,\quad r = |\delta m_{21}^2/\delta m_{31}^2|\,,$$

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

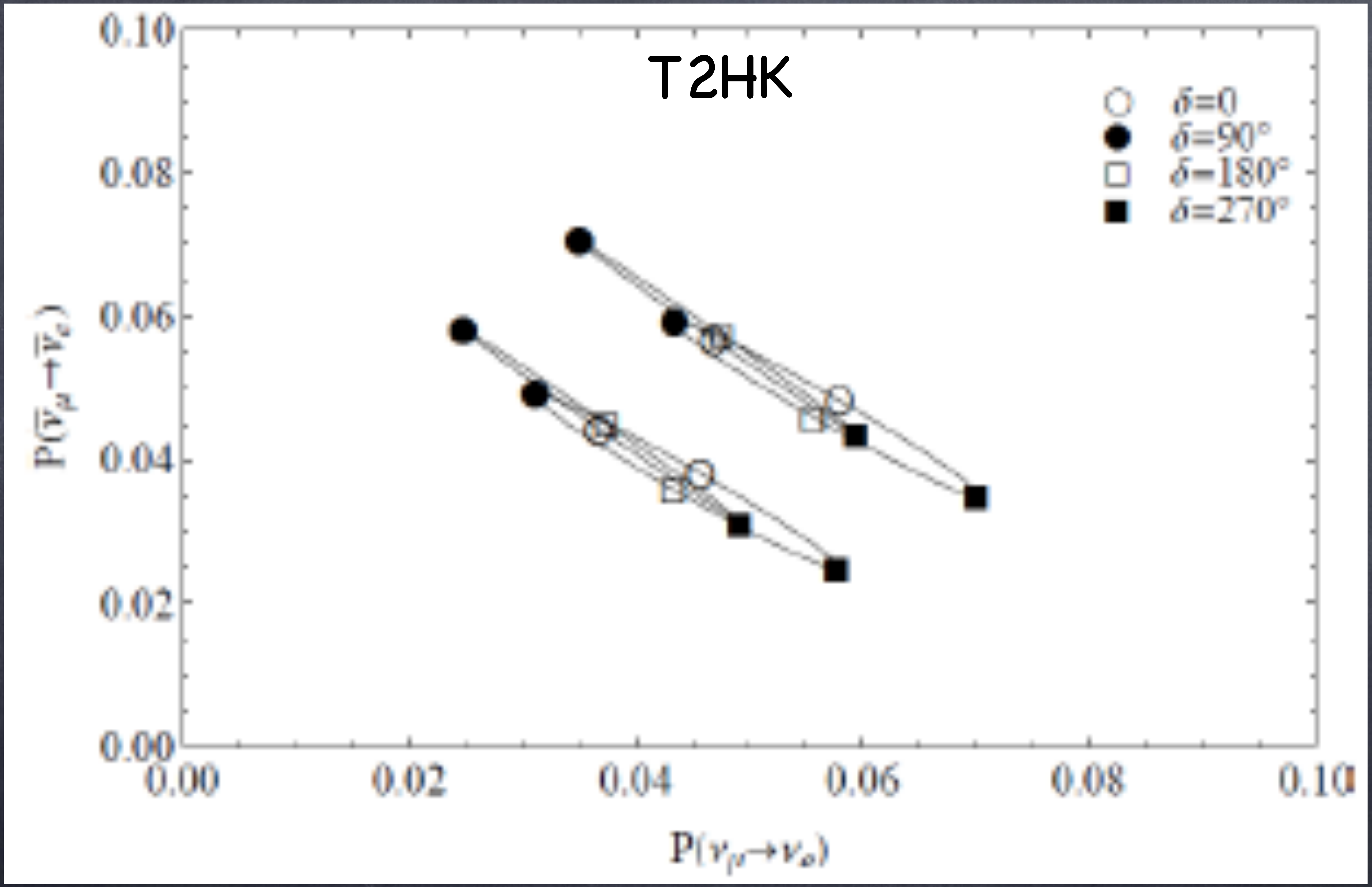
$$\Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|,\quad \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|$$

- $P_{\mu e} \to \bar{P}_{\mu e}$
  $\hat{A} \to -\hat{A}\ (f \to \bar{f})$,
  $\delta \to -\delta,\quad \phi_{\alpha\beta} \to -\phi_{\alpha\beta}$
- NH → IH
  $\Delta \to -\Delta,\ y \to -y$
  $\hat{A} \to -\hat{A}\ (f \leftrightarrow -\bar{f},\ \text{and}\ g \to -g)$

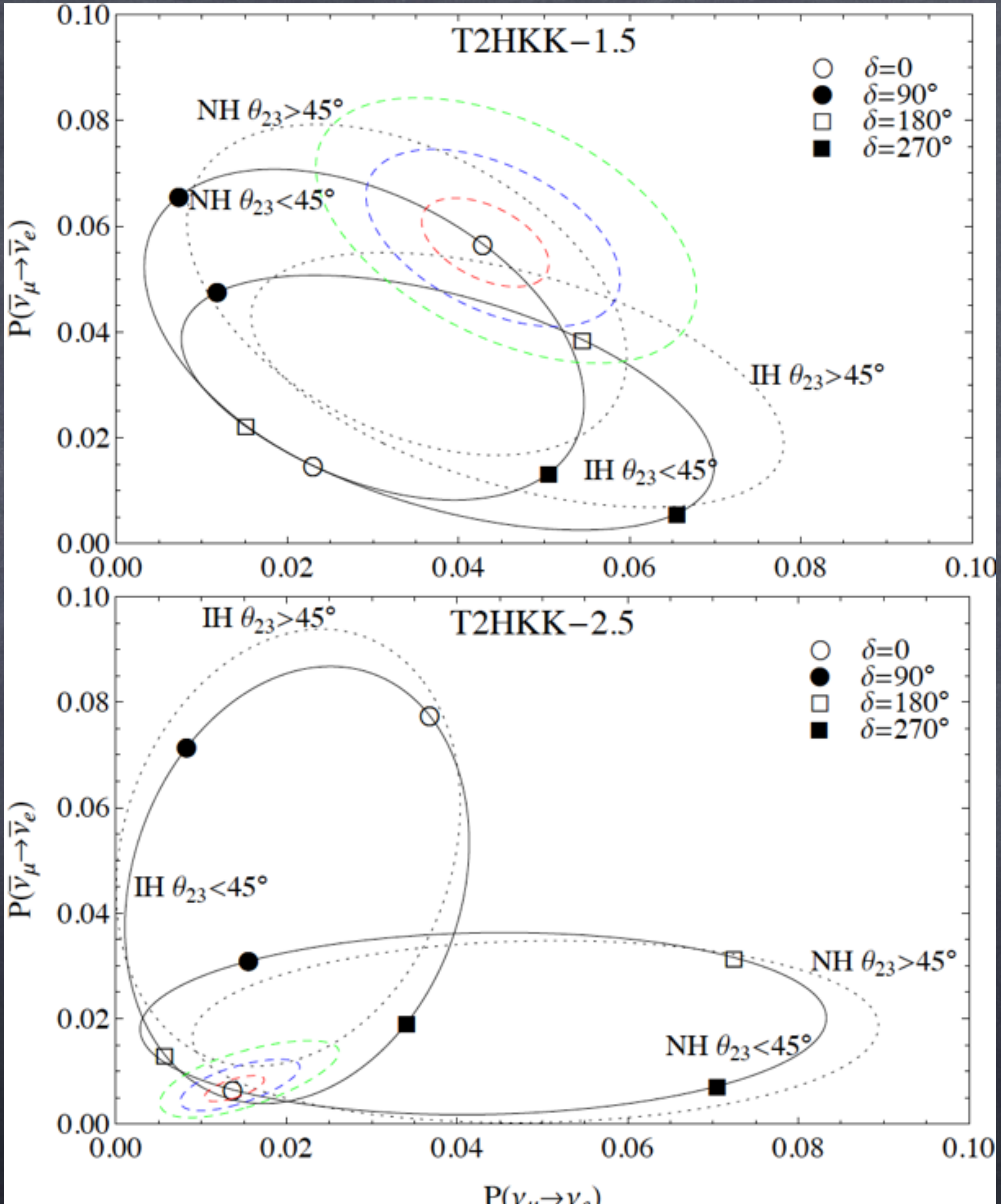
Liao



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



T2HK
δ=0
δ=90°
δ=180°
δ=270°
0.00
0.02
0.04
0.06
0.08
0.10
P($\nu_\mu \to \nu_e$)
P($\bar\nu_\mu \to \bar\nu_e$)



T2HKK−1.5
δ=0
δ=90°
δ=180°
δ=270°
NH θ23>45°
NH θ23<45°
IH θ23>45°
IH θ23<45°
P(ν̄μ→ν̄e)
0.00
0.02
0.04
0.06
0.08
0.10
T2HKK−2.5
IH θ23>45°
IH θ23<45°
NH θ23>45°
NH θ23<45°
P(νμ→νe)

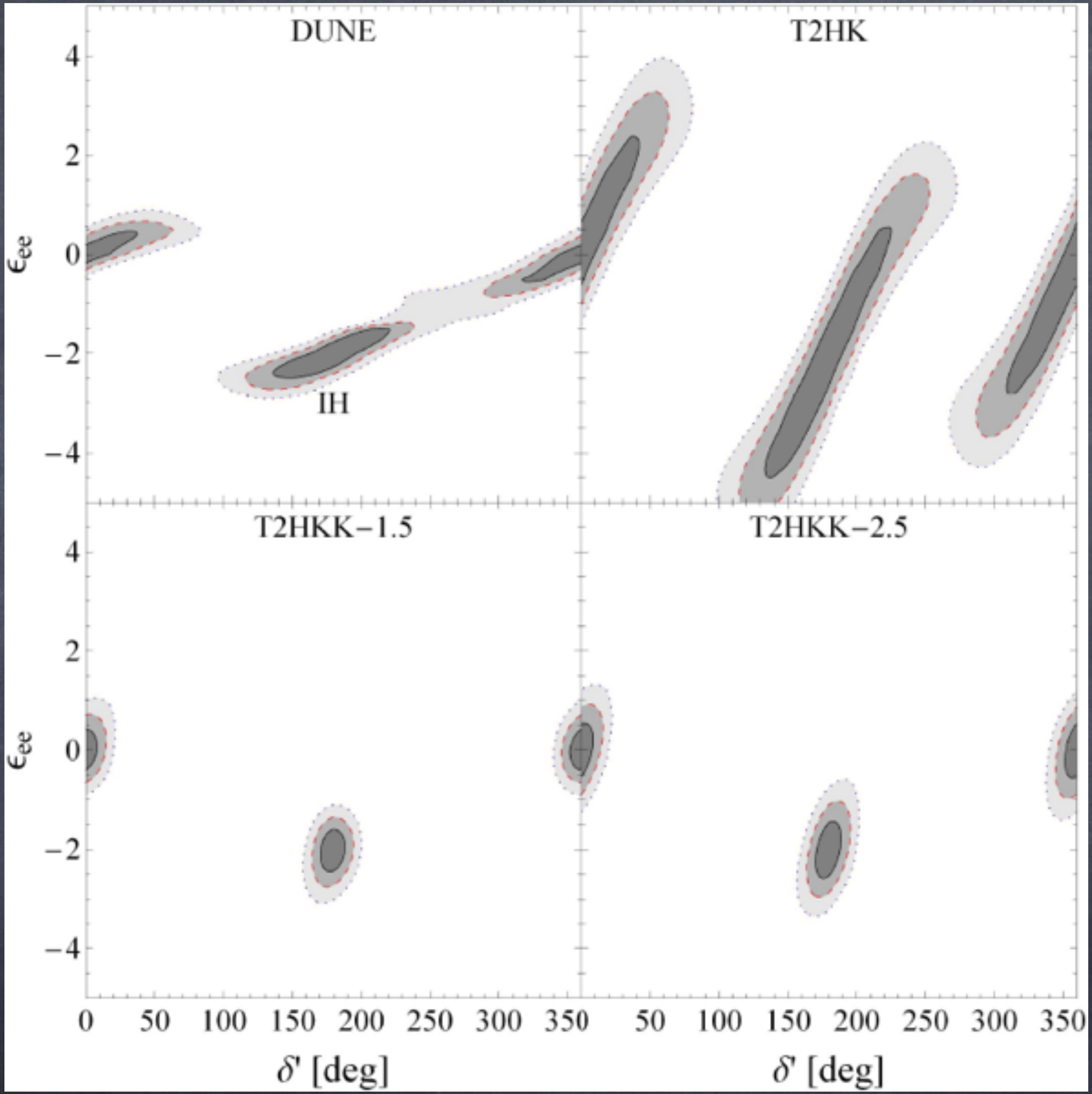
$$\sin^2\theta_{13} = 0.023 \pm 0.002$$
$$\sin^2\theta_{12} = (0.305 \pm 0.015) \oplus (0.70 \pm 0.017)$$
$$\sin^2\theta_{23} = 0.43^{+0.08}_{-0.03}, \;\; \delta = 0$$
$$\delta m^2_{21} = (7.48 \pm 0.21) \times 10^{-5} \text{ eV}^2$$
$$|\delta m^2_{31}| = (2.43 \pm 0.08) \times 10^{-3} \text{ eV}^2$$

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

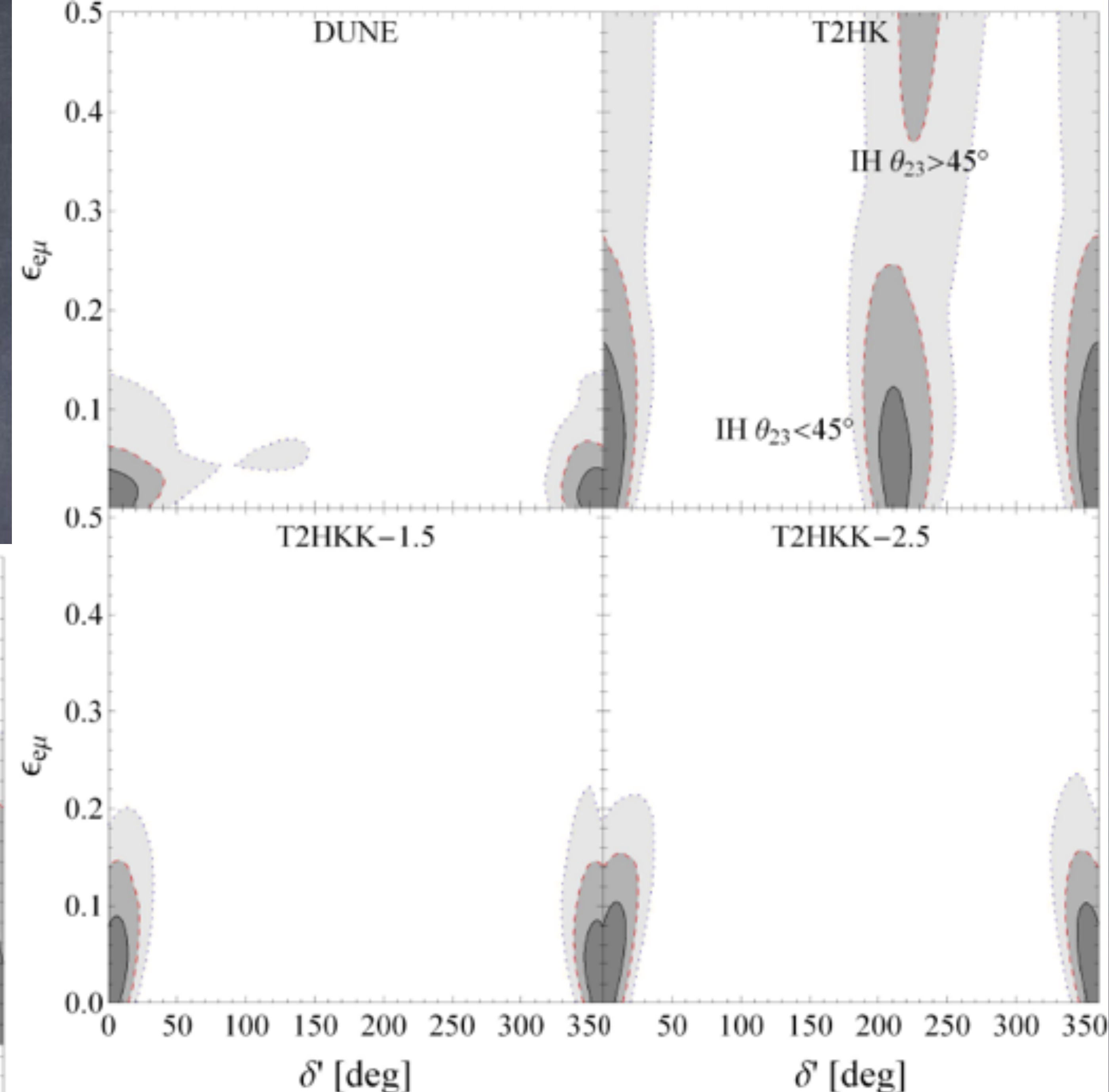


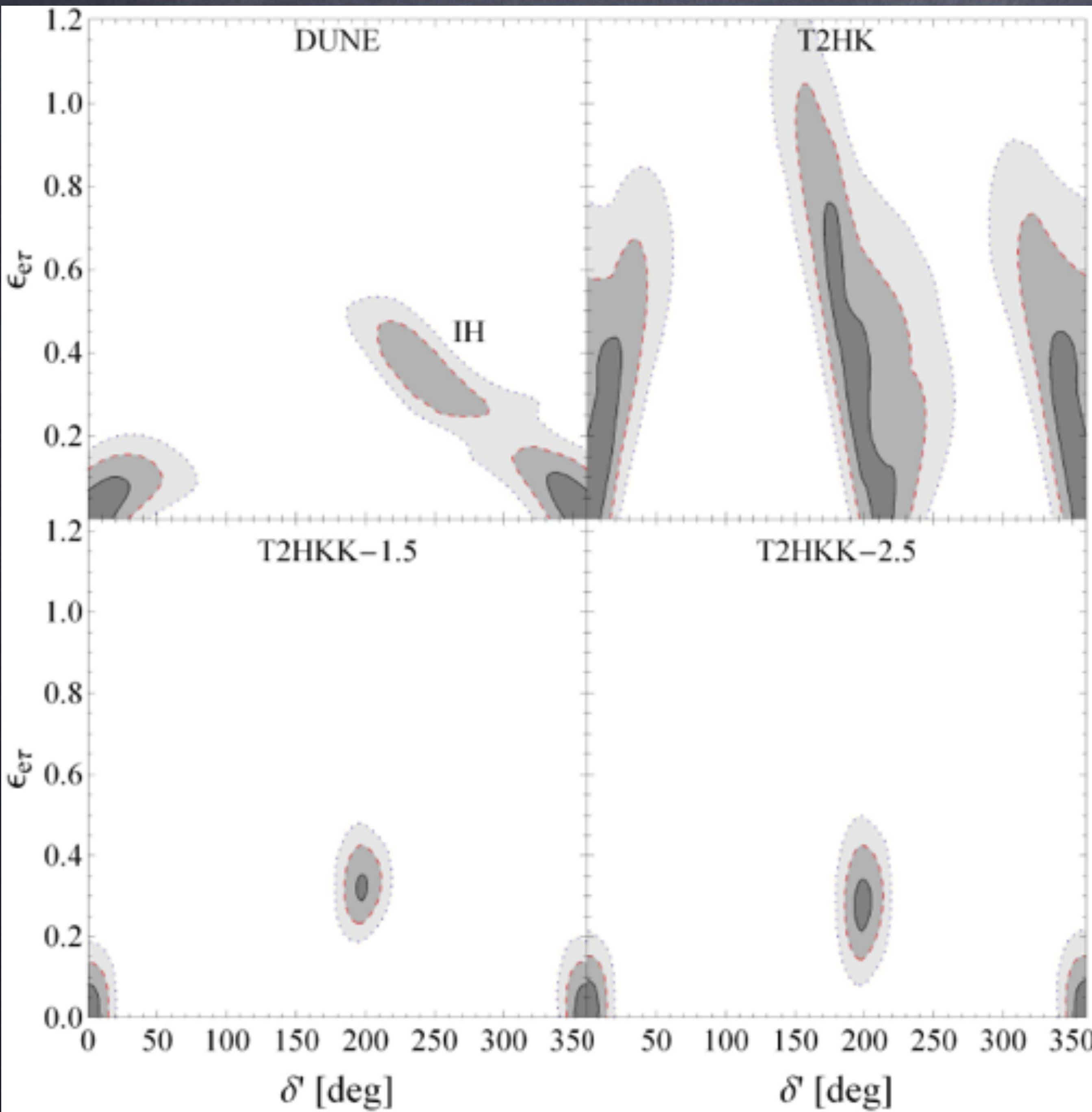
$$\delta m^2_{31} \to -\delta m^2_{32}, \quad \theta_{12} \to 90^\circ - \theta_{12}, \quad \delta \to 180^\circ - \delta$$

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

1604.05772

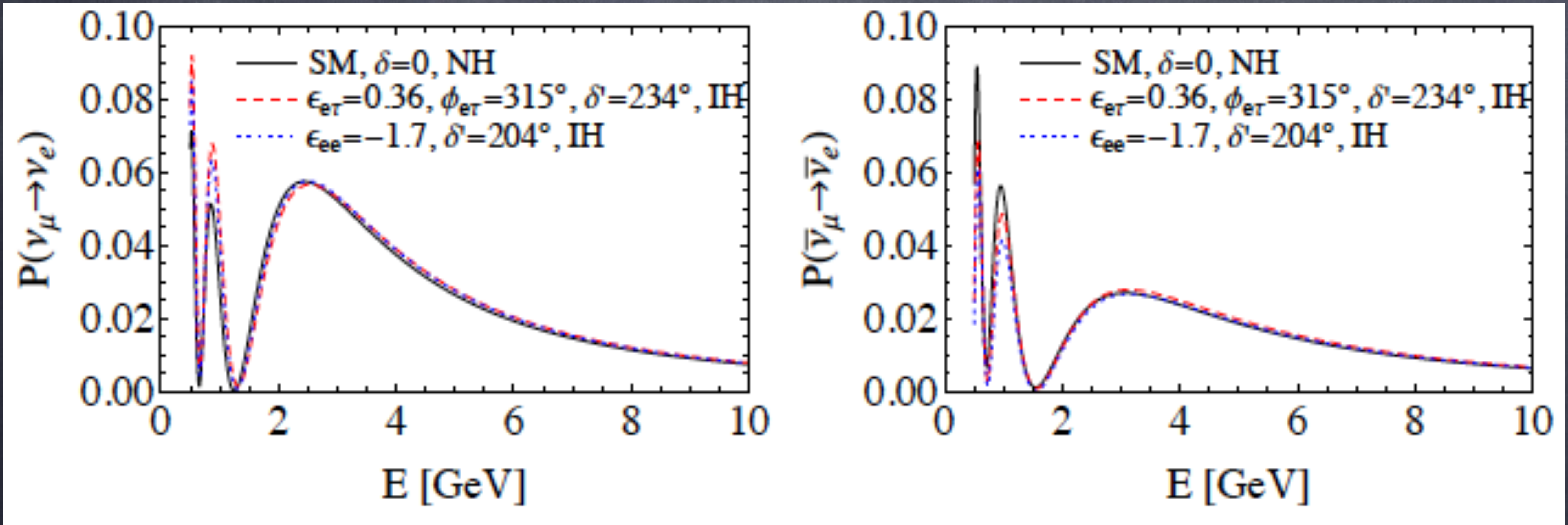
Mass hierarchy resolved at DUNE and T2HKK



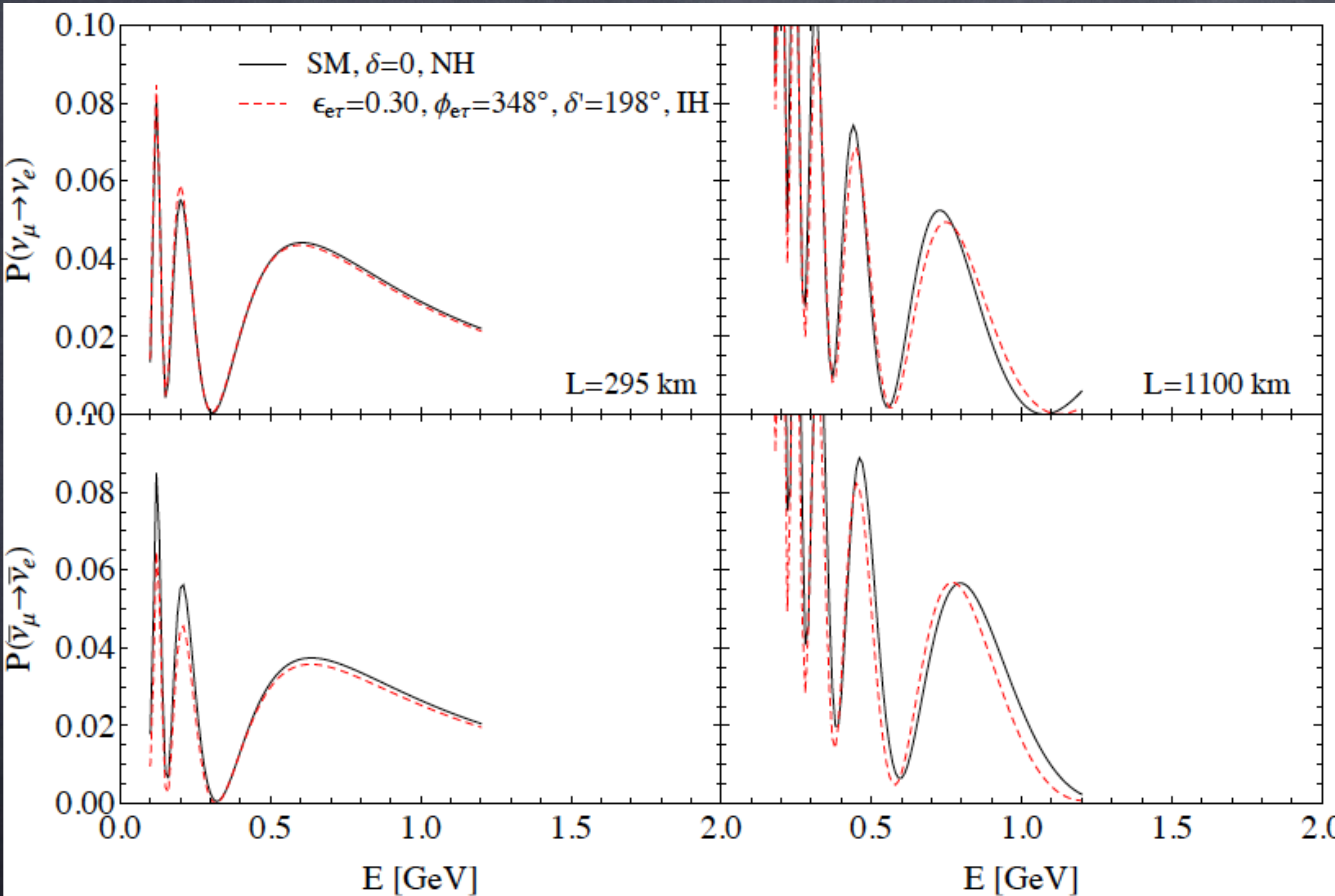


Hierarchy not resolved
Wrong determination of the CP phase possible

L=1300 km

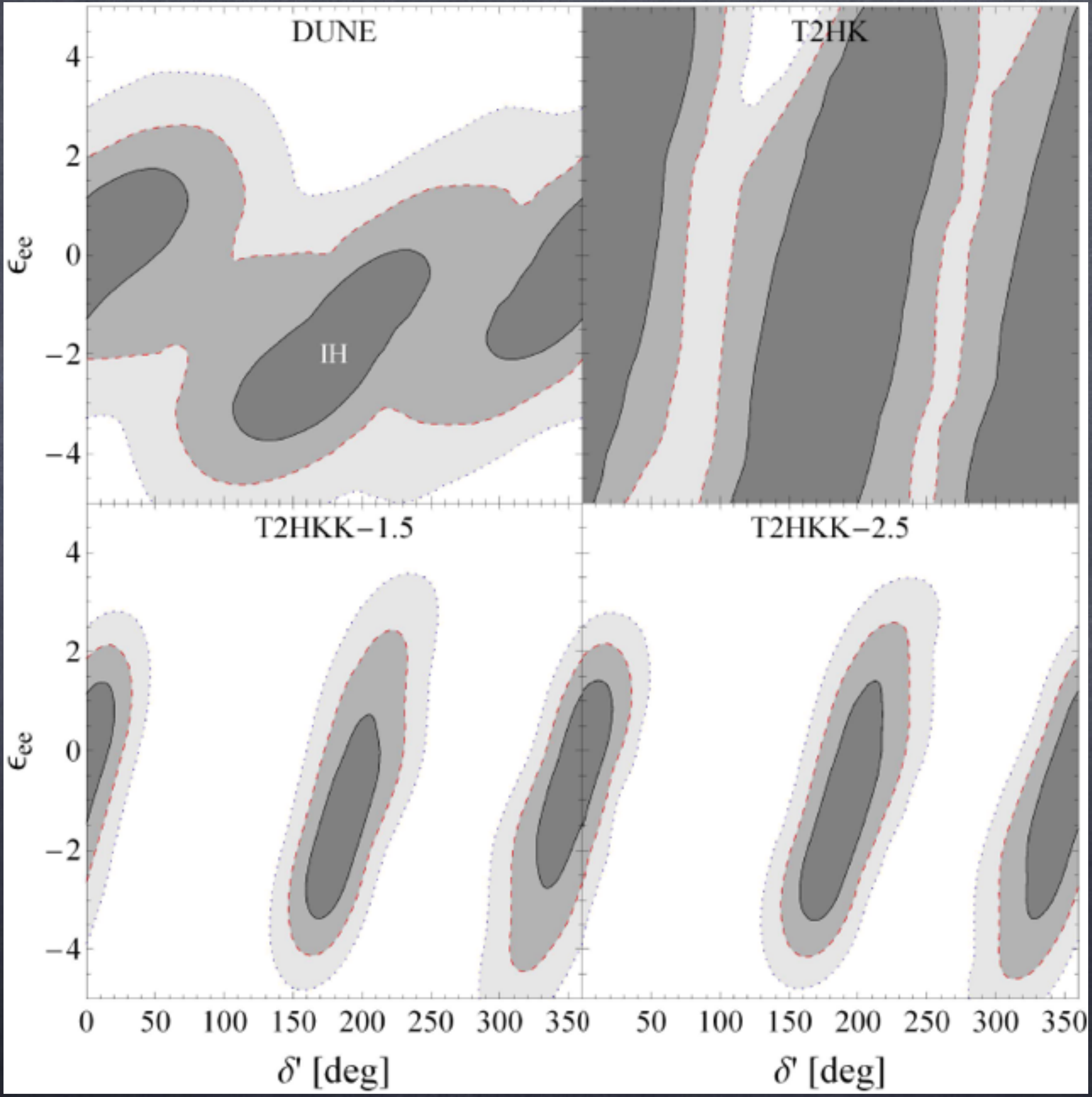


SM, δ=0, NH
$\epsilon_{e\tau}$=0.36, $\phi_{e\tau}$=315°, δ'=234°, IH
ϵ_{ee}=−1.7, δ'=204°, IH
$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
E [GeV]
0.00
0.02
0.04
0.06
0.08
0.10
0
2
4
6
8
10

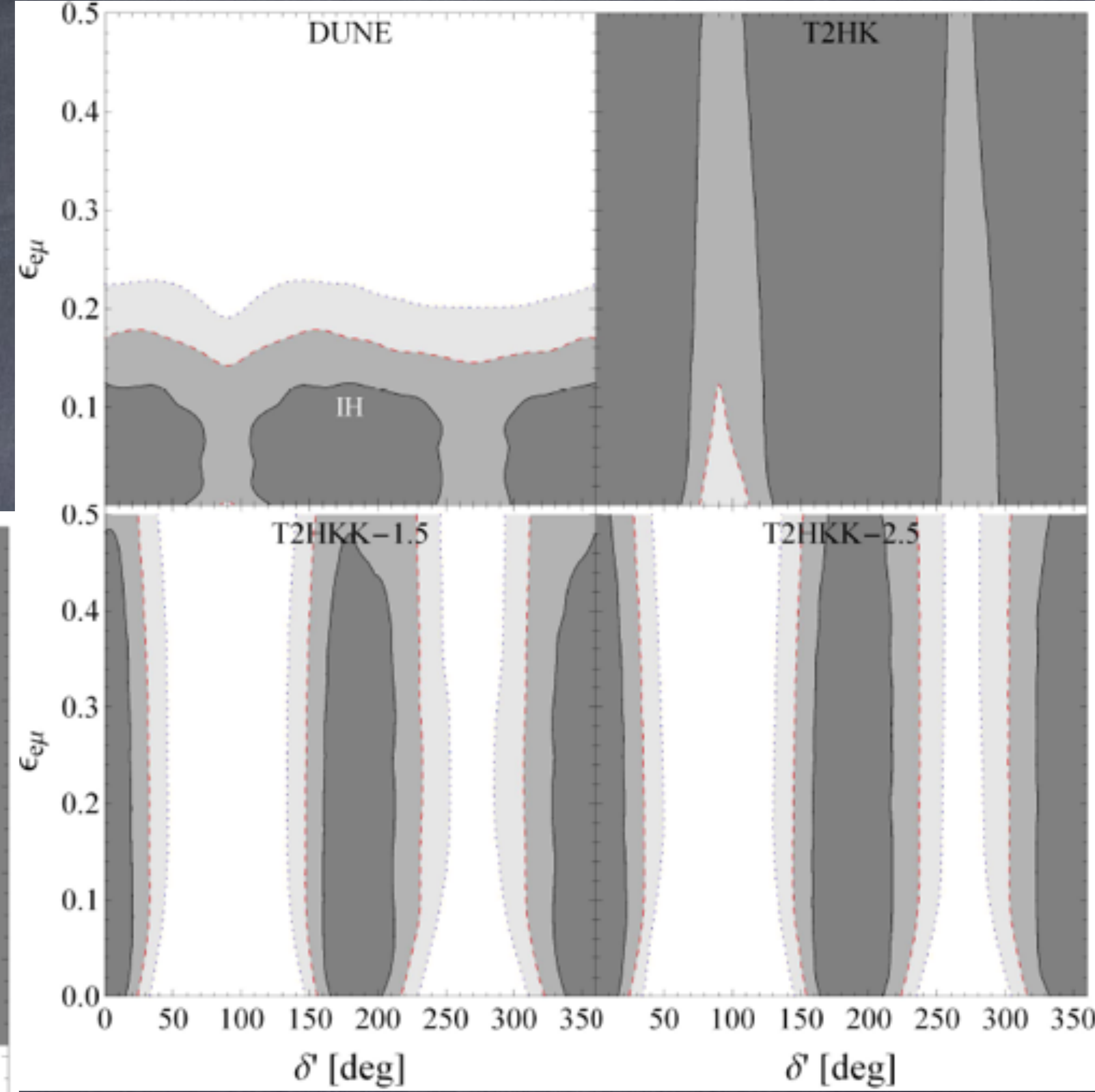


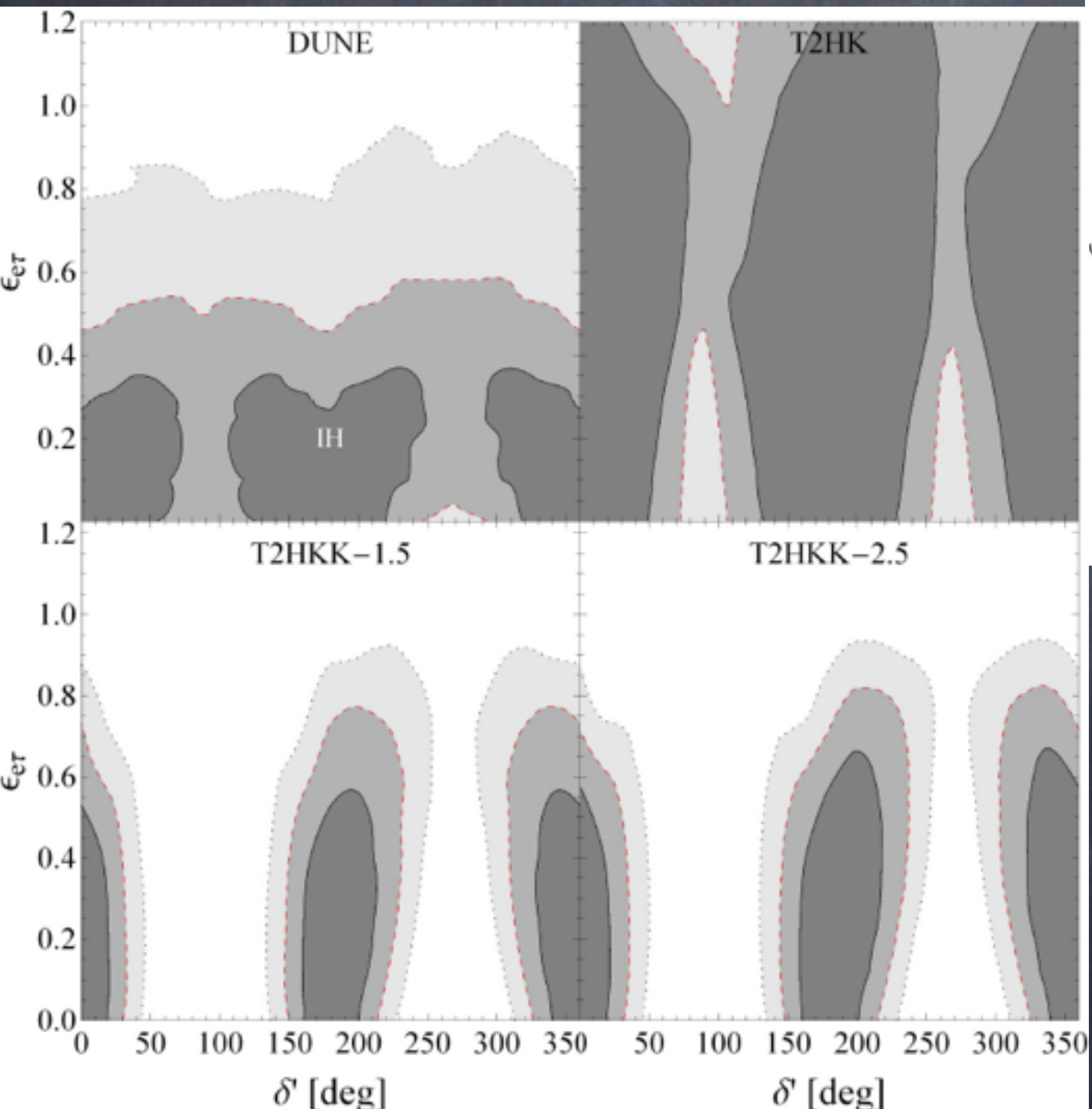
SM, δ=0, NH
$\epsilon_{e\tau}$=0.30, $\phi_{e\tau}$=348°, δ'=198°, IH
$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
L=295 km
L=1100 km
E [GeV]
E [GeV]
0.00
0.02
0.04
0.06
0.08
0.10
0.0
0.5
1.0
1.5
2.0

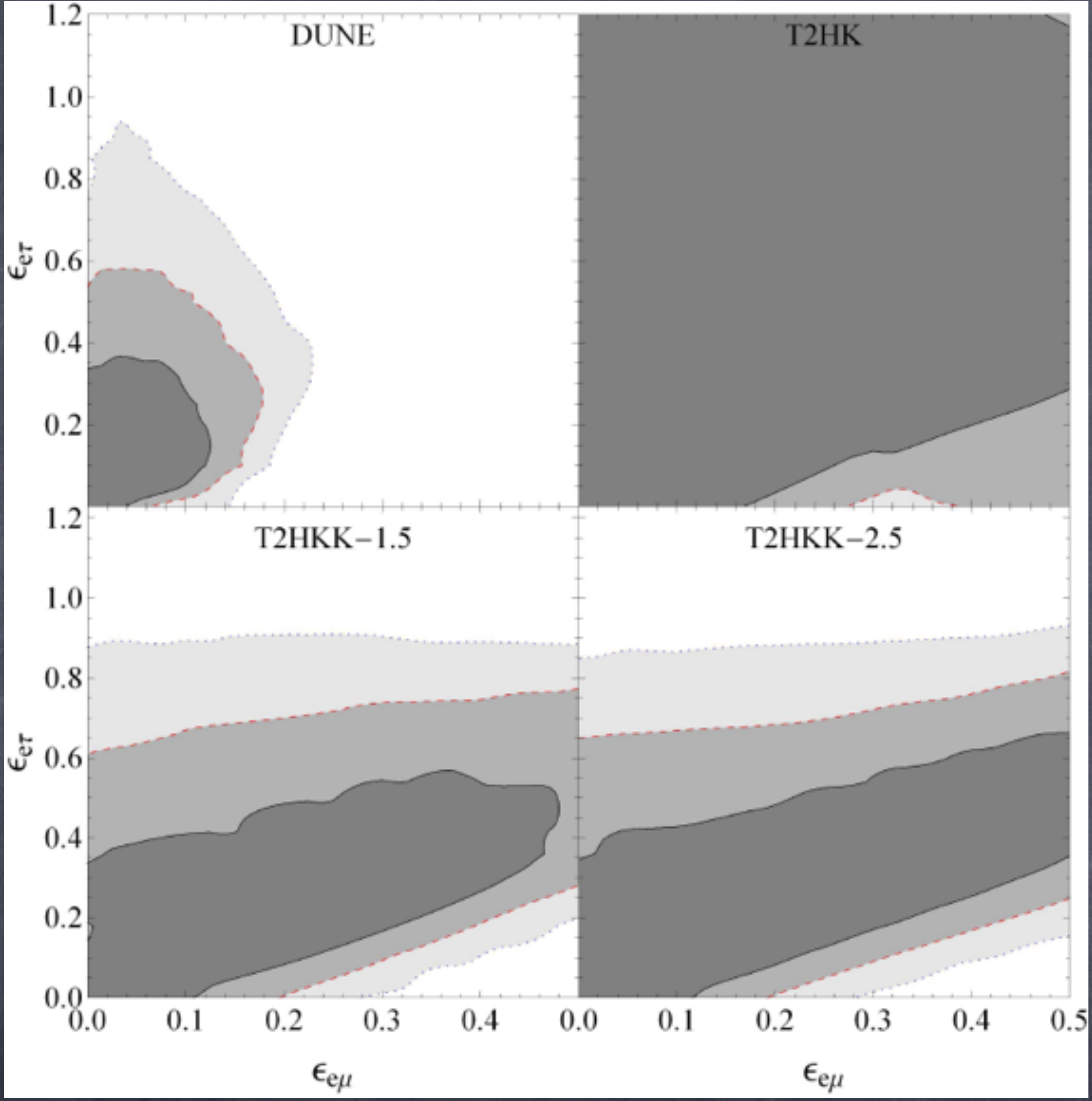
3 NSI parameters



Constraint on e\mu NSI much weaker at T2K and T2HKK



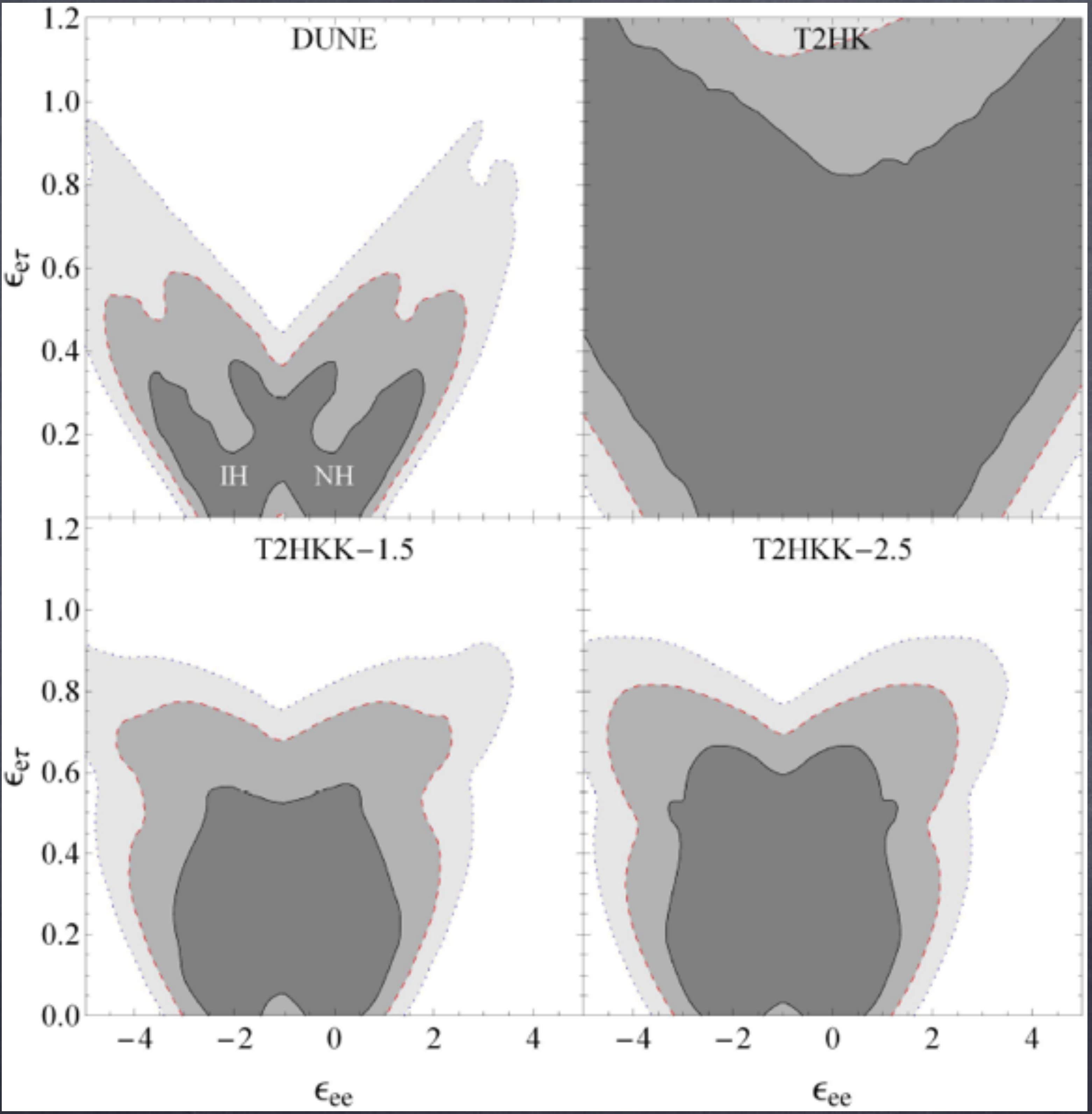




Because of the lower energy J-PARC beam, the difference between SM and NSI appearance probabilities are suppressed at T2K and T2HKK for

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

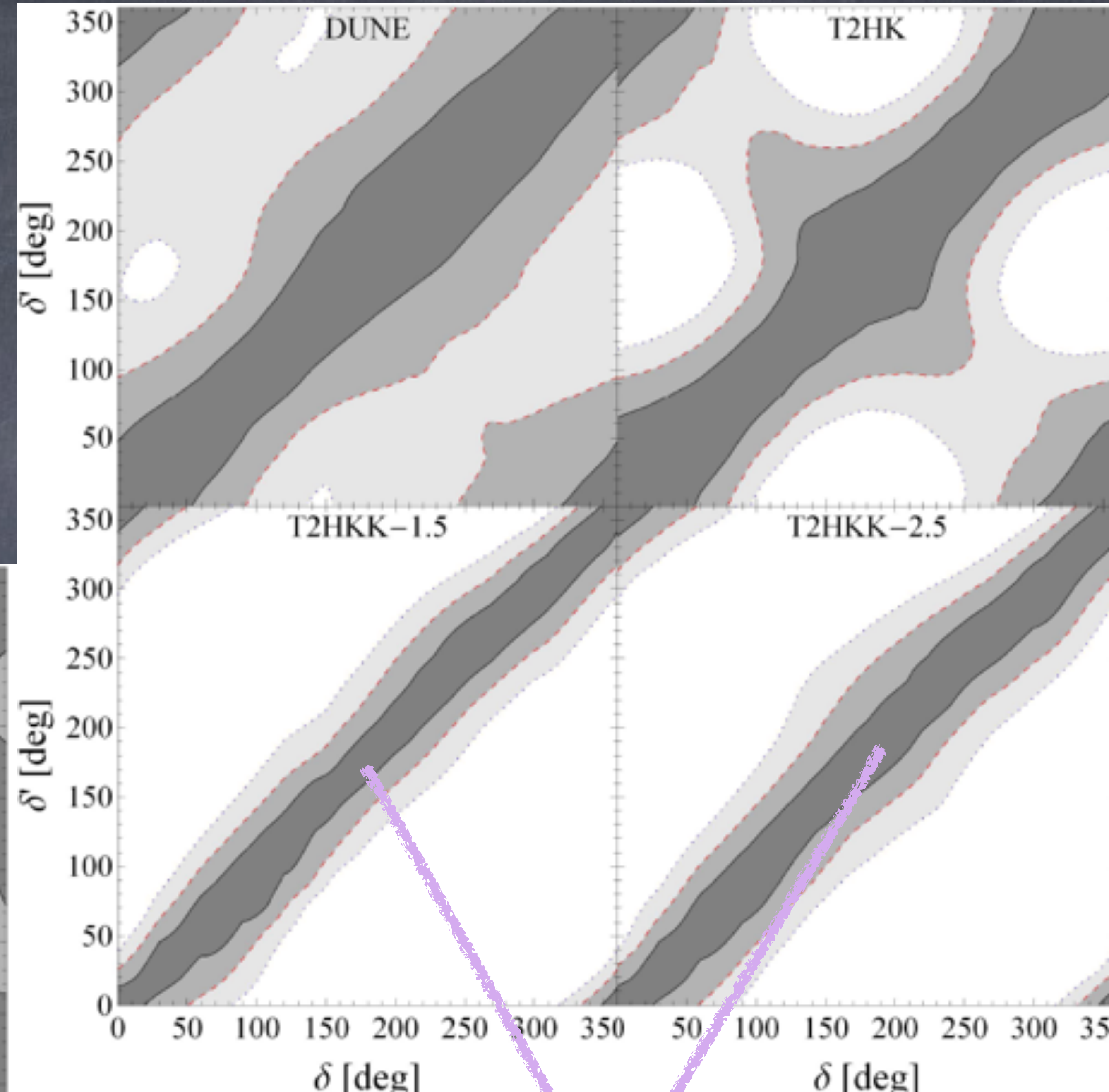
Correlations between ee and e\tau



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

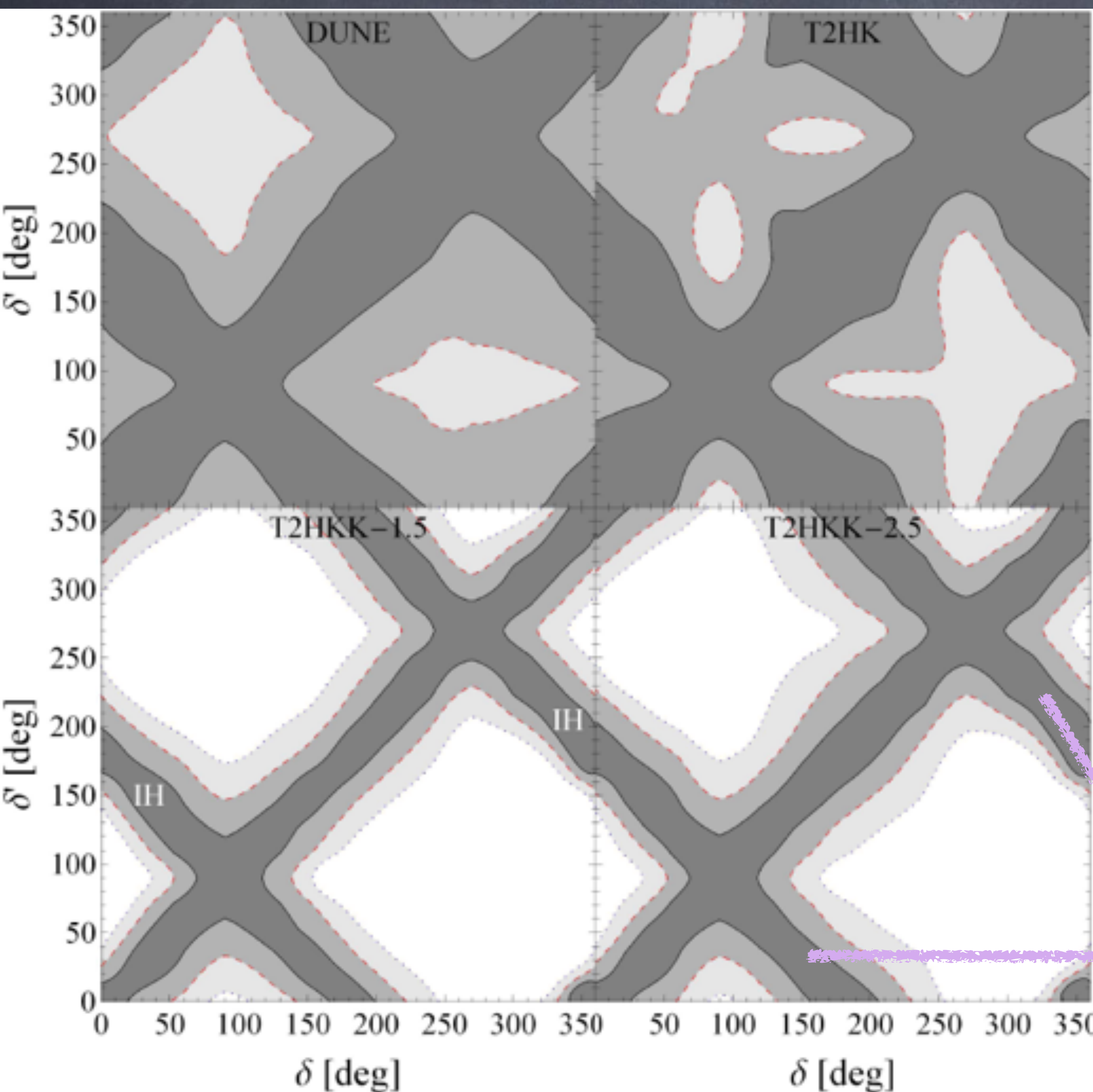
CP sensitivity

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 $\epsilon = 0$

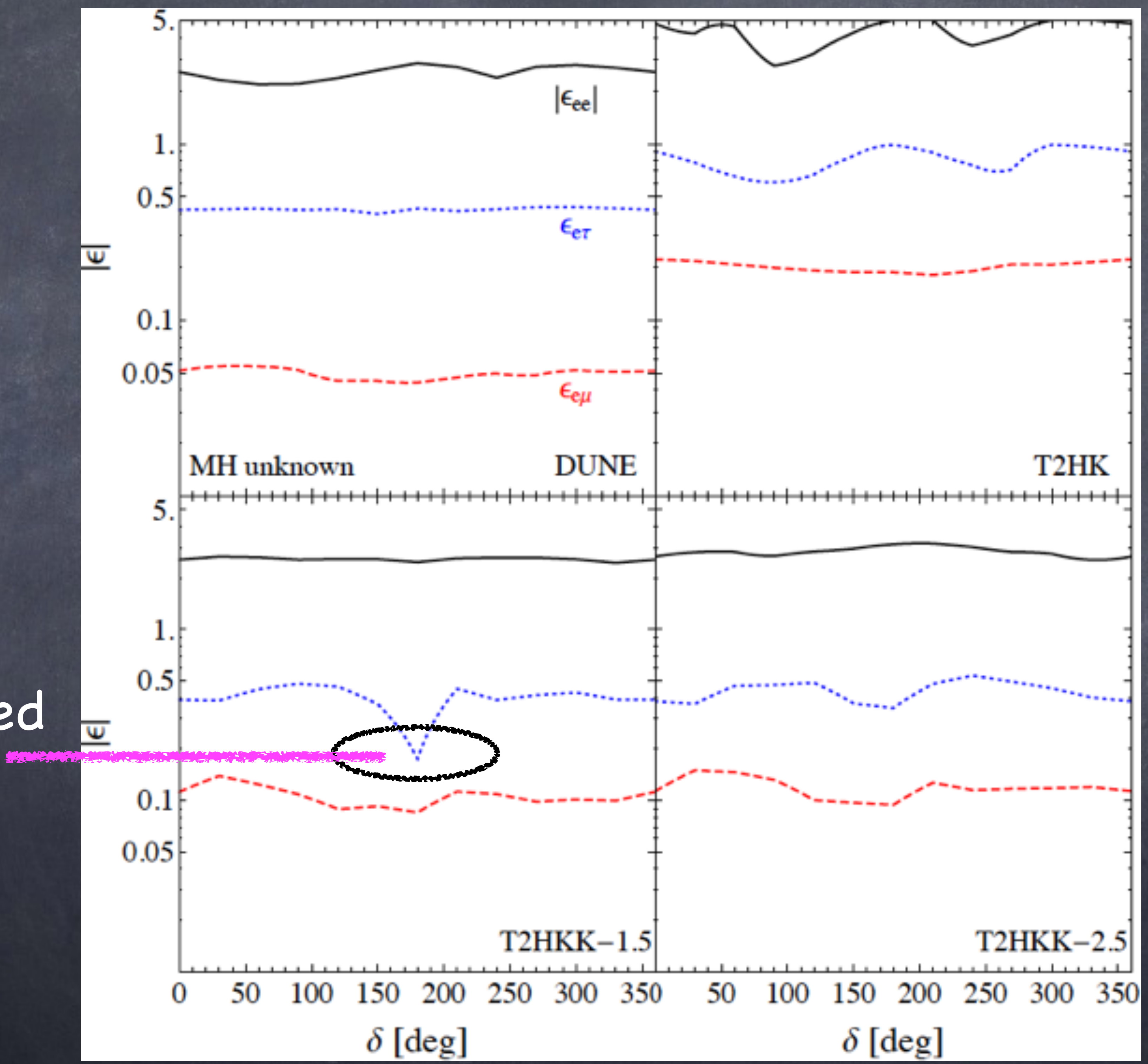
IH and $\delta' = 180 - \delta$

Sensitivity to NSI as a function of CP

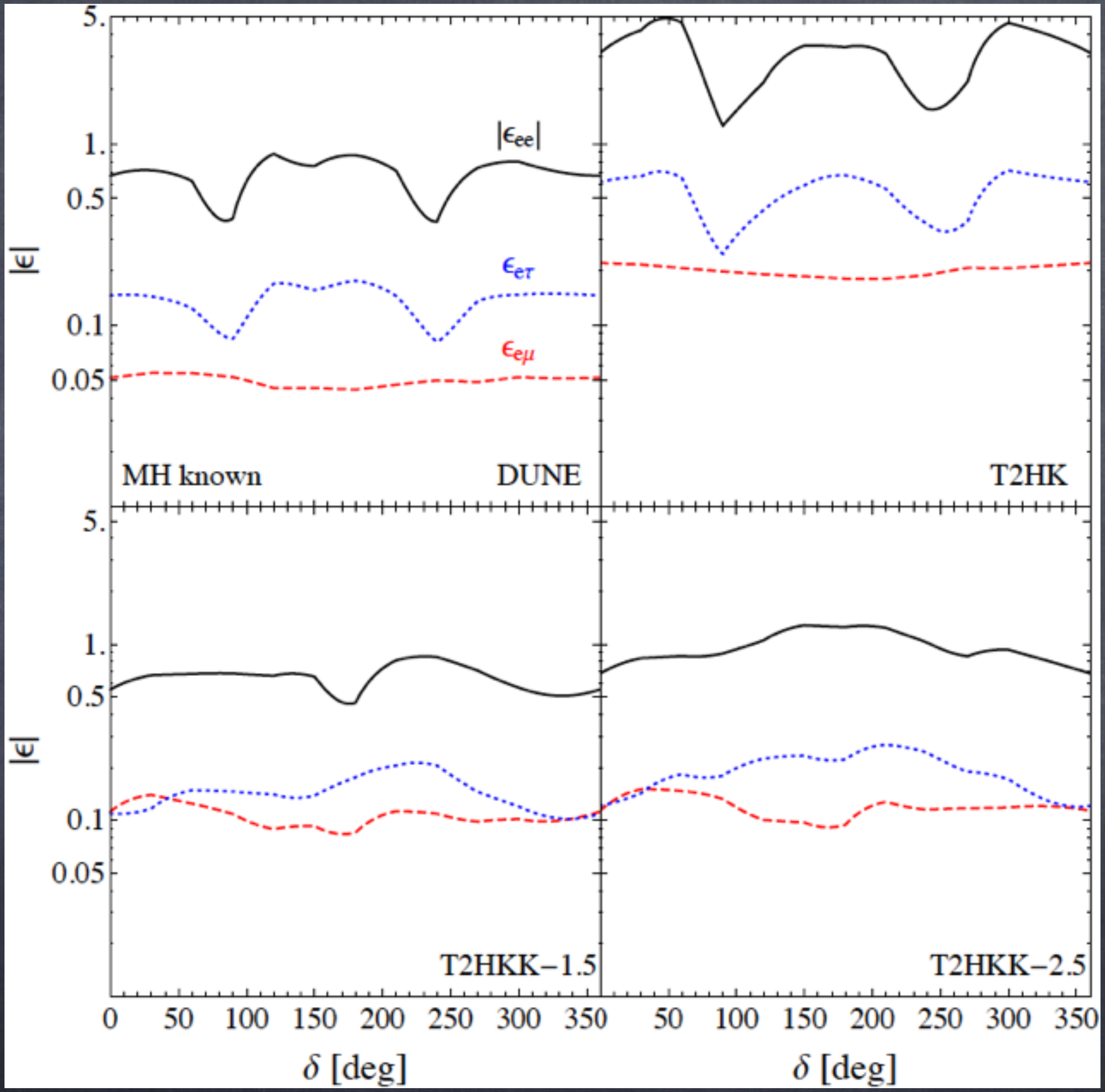
One nonzero NSI parameter

95.4% CL

IH not allowed at 95.4% CL



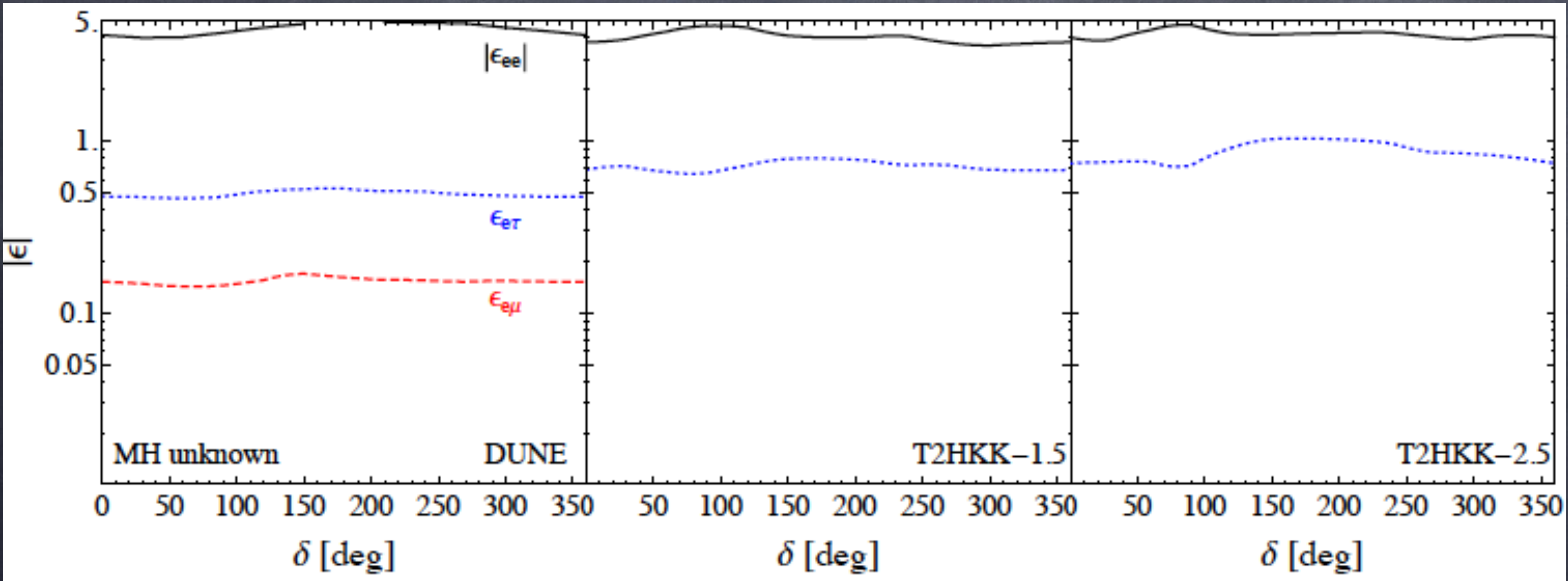
|ee| > 2 because of the generalized hierarchy degeneracy



|ϵee|
ϵeτ
ϵeμ
|ϵ|
MH known
DUNE
T2HK
T2HKK−1.5
T2HKK−2.5
δ [deg]
5.
1.
0.5
0.1
0.05
0
50
100
150
200
250
300
350

3 NSI parameters

NH

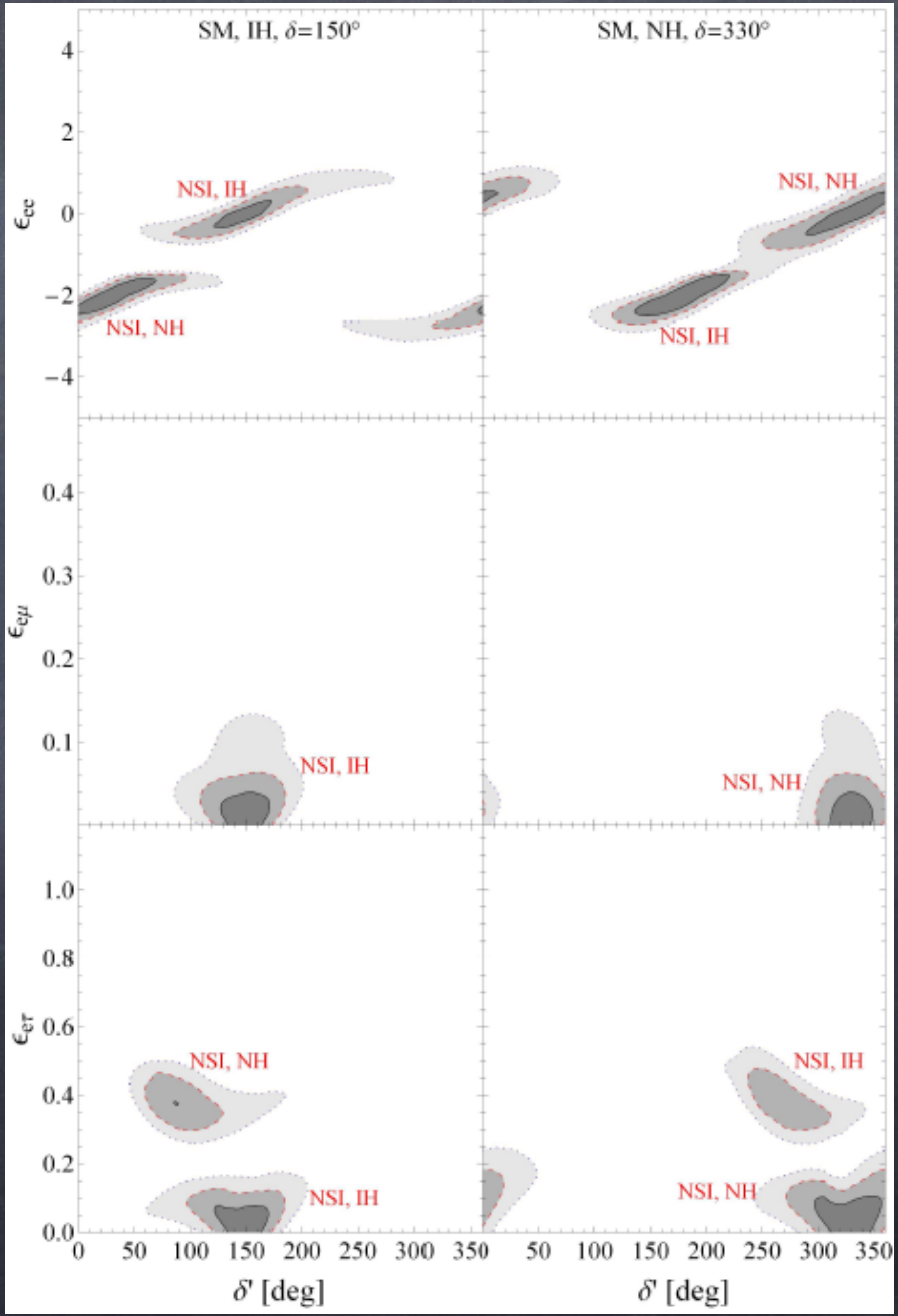


All T2HK, and T2HKK e\mu sensitivities outside the range of scan

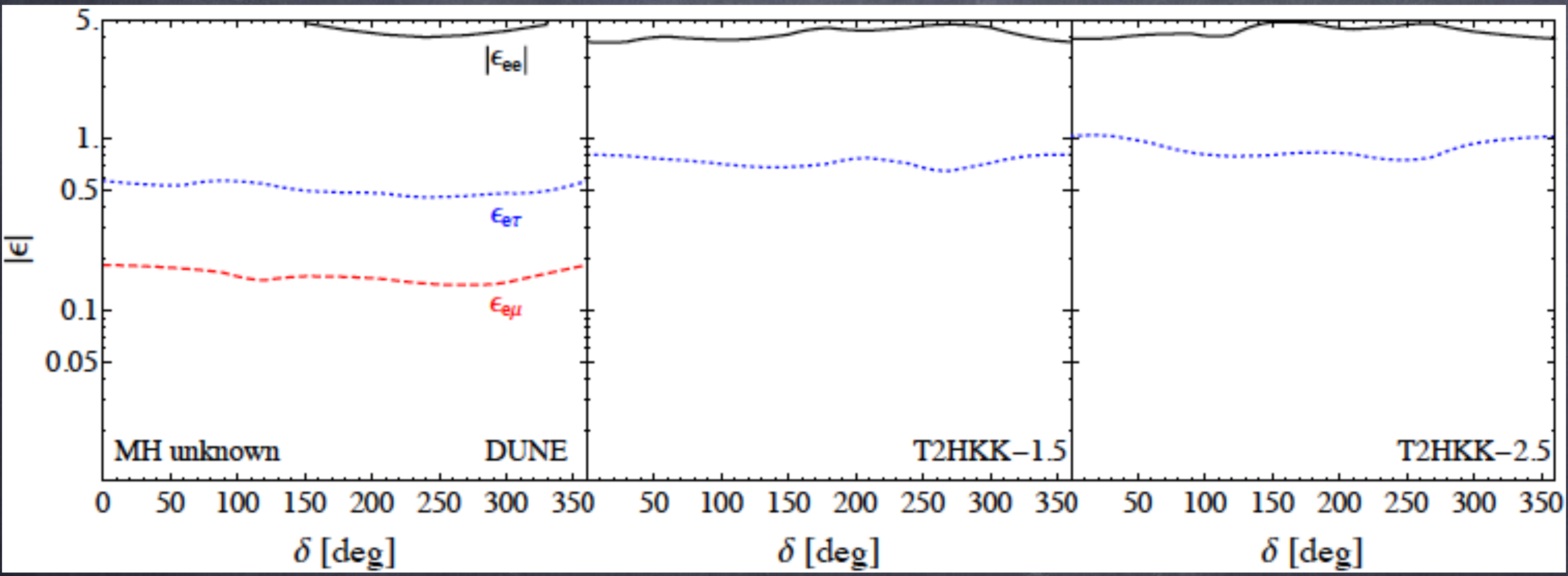
Sensitivity to NSI similar for both mass hierarchies

Regions are similar under

$$\delta' \rightarrow \delta' + 180°$$



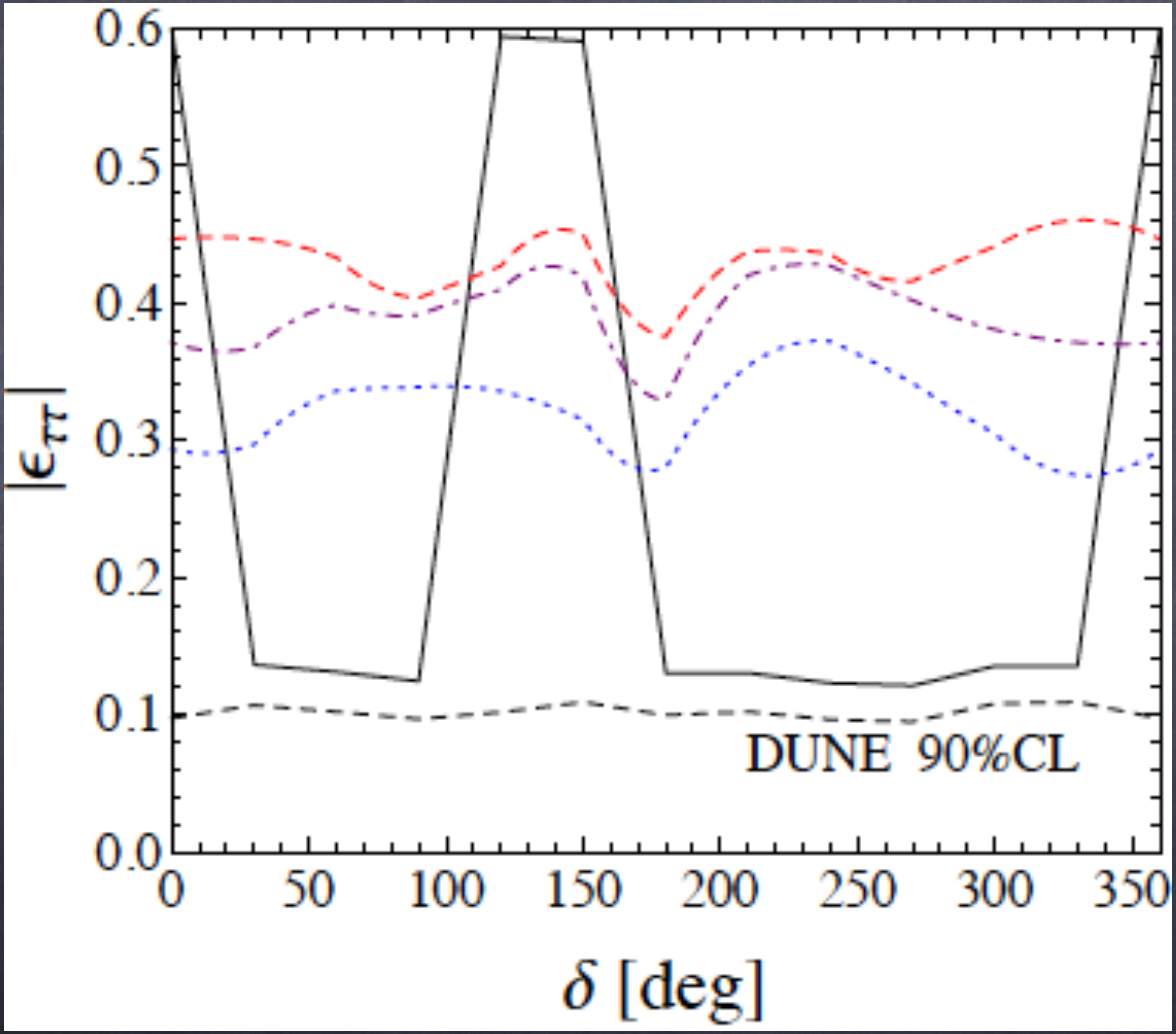
IH



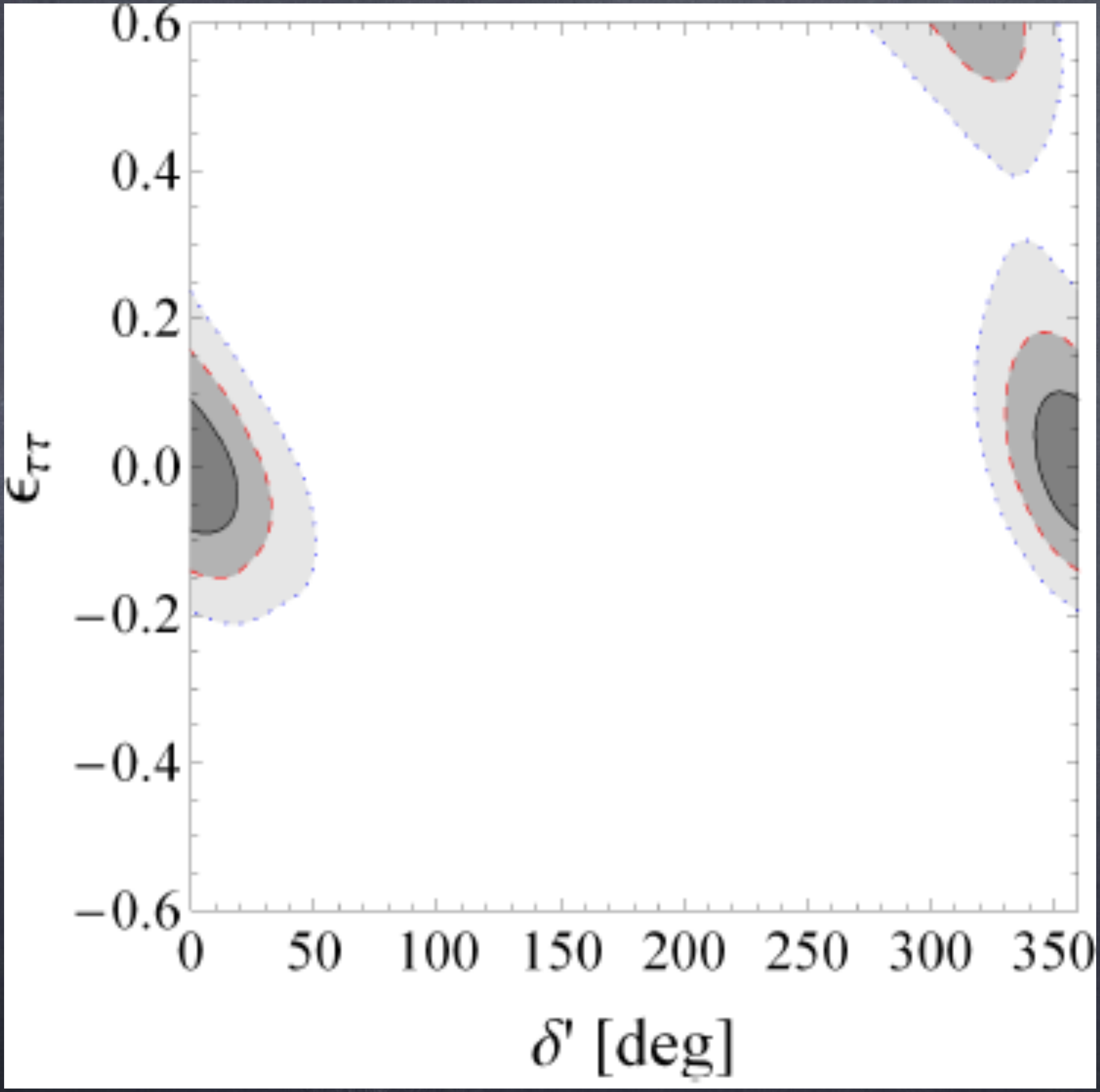
5.
1.
0.5
0.1
0.05
$|\epsilon|$
$|\epsilon_{ee}|$
$\epsilon_{e\tau}$
$\epsilon_{e\mu}$
MH unknown
DUNE
T2HKK−1.5
T2HKK−2.5
0 50 100 150 200 250 300 350
δ [deg]

Disappearance channels

95.4% CL



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



0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
$\epsilon_{\tau\tau}$
0
50
100
150
200
250
300
350
δ' [deg]

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 ee NSI parameter is O(1), impossible to determine hierarchy at LBL experiments
- DUNE has best sensitivity to NSI
- T2HKK has best sensitivity to CP phase in the presence of NSI
- Sensitivity to NSI same for both mass hierarchies at LBL expts