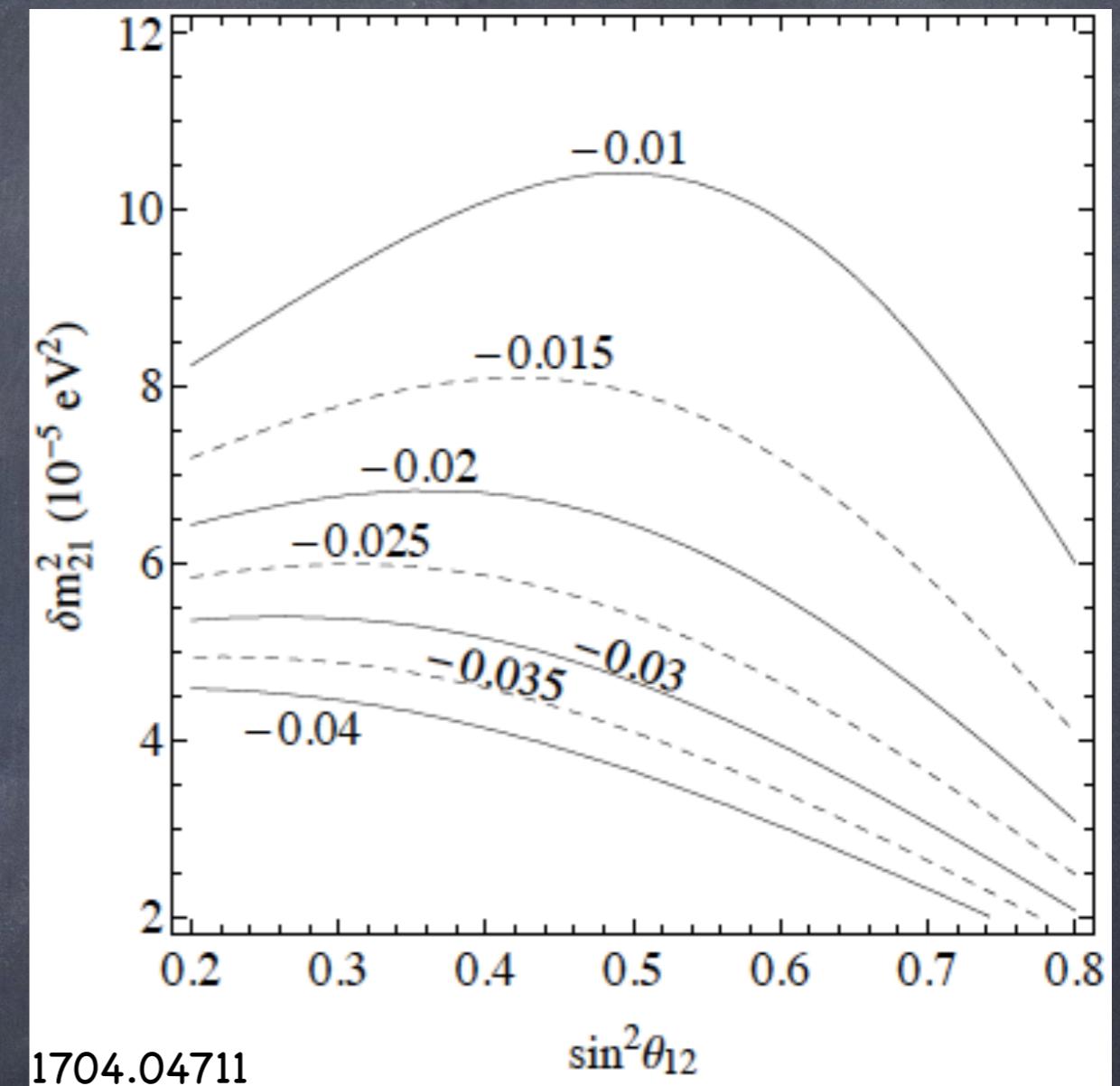
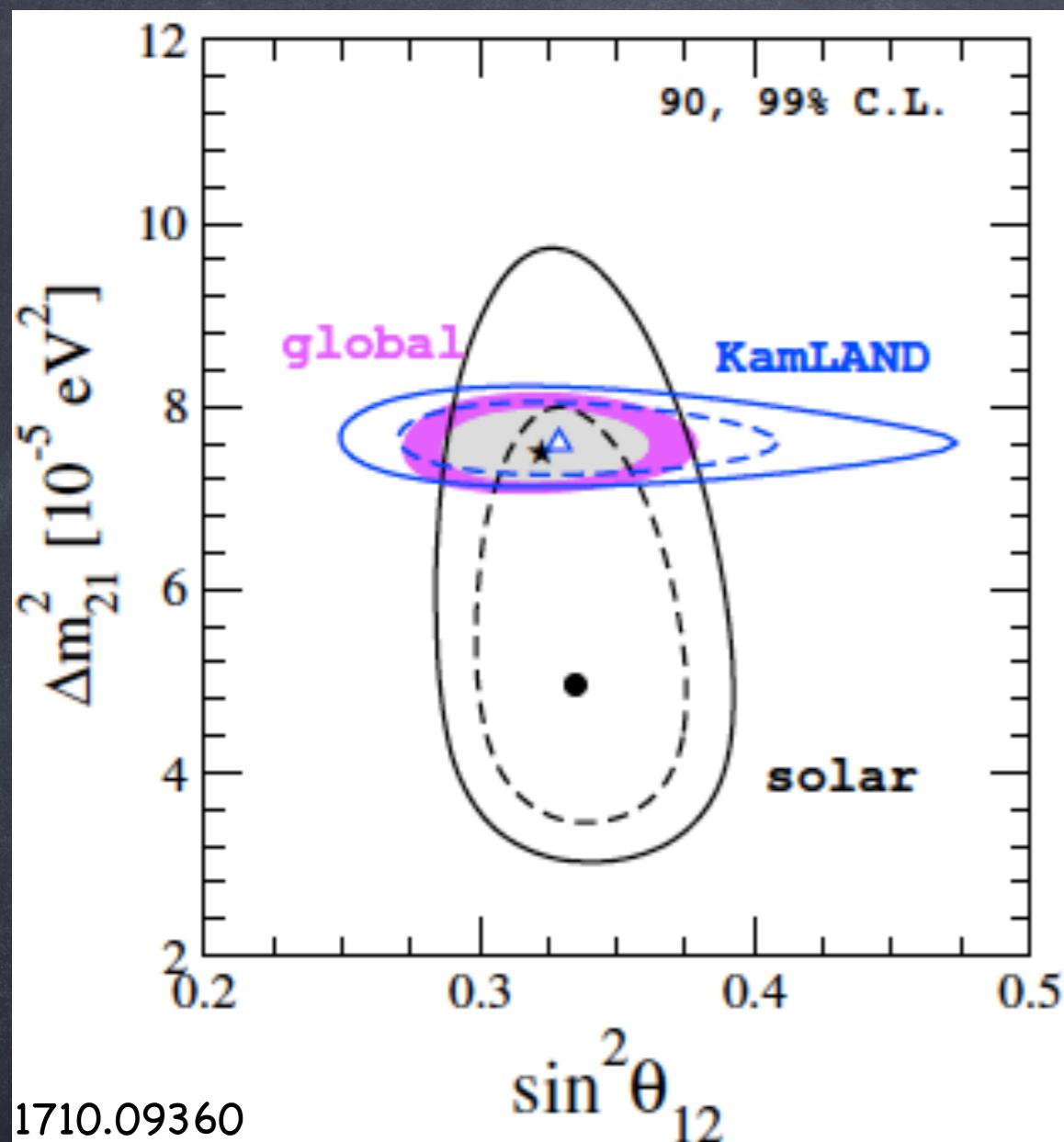


Nonstandard neutrino interactions

Possible tension in standard oscillation picture



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

$$2 \frac{\phi_D - \phi_N}{\phi_D + \phi_N} = -0.033 \pm 0.01 \pm 0.005$$

Nonstandard interactions in matter

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{\alpha, \beta, \mathfrak{f}, C} \epsilon_{\alpha\beta}^{\mathfrak{f}C} [\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta] [\mathfrak{f} \gamma_\rho P_C \mathfrak{f}]$$

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

$$V = 2\sqrt{2}G_F N_e E \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

Vector interaction relevant for propagation:

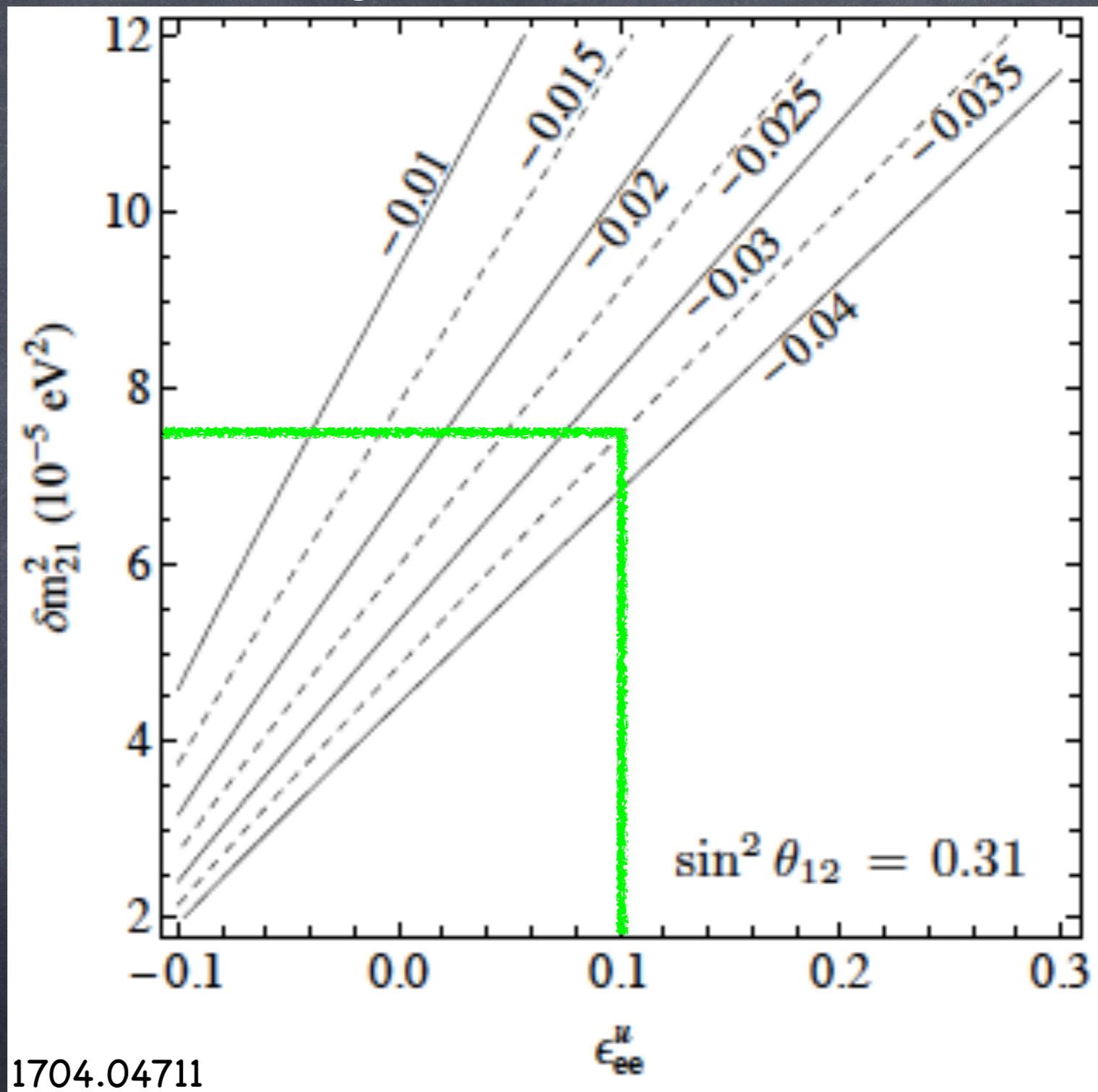
$$\epsilon_{\alpha\beta}^{\mathfrak{f}} \equiv \epsilon_{\alpha\beta}^{\mathfrak{f}L} + \epsilon_{\alpha\beta}^{\mathfrak{f}R} \implies \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f}} \epsilon_{\alpha\beta}^{\mathfrak{f}} \frac{N_{\mathfrak{f}}}{N_e}$$

On earth $N_u = N_d = 3N_e$

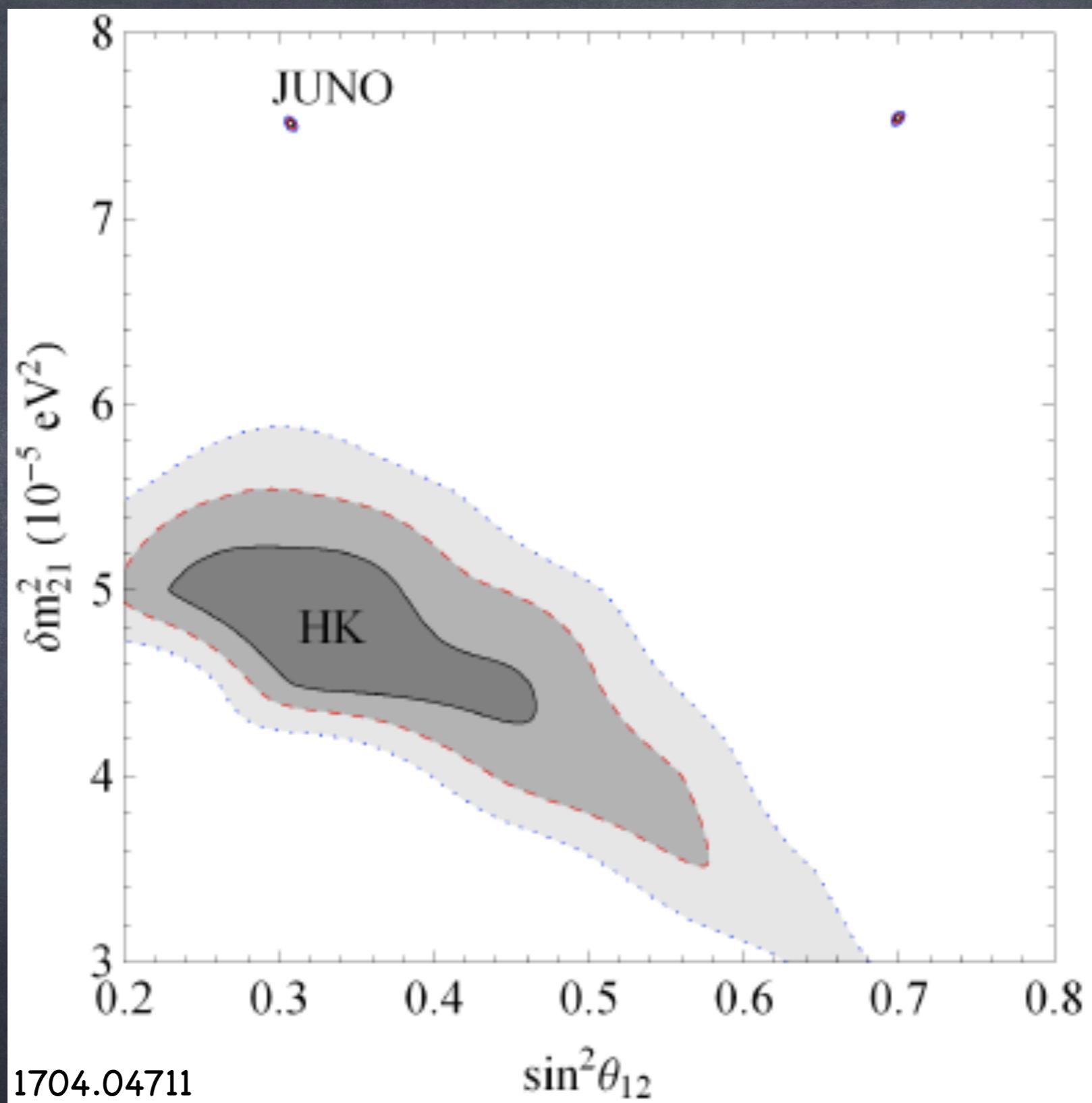
OSC		
	LMA	LMA \oplus LMA-D
$\varepsilon_{ee}^u - \varepsilon_{\mu\mu}^u$	$[-0.020, +0.456]$	$\oplus [-1.192, -0.802]$
$\varepsilon_{\tau\tau}^u - \varepsilon_{\mu\mu}^u$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon_{e\mu}^u$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon_{e\tau}^u$	$[-0.292,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

Matter effects if NSI violate lepton universality or/and flavor

Iso-day-night asymmetry contours



$$\epsilon_{ee}^u = \epsilon_{ee}^d \sim 0.1$$



Hyper-K and JUNO can detect NSI

Future LBL experiments

Experiment	$\frac{L(\text{km})}{E_{\text{peak}}(\text{GeV})}$	$\nu + \bar{\nu}$ Exposure (kt·MW· 10^7 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^{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 = 1.76×10^7 s; for HyperK, 1 yr = 1.0×10^7 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 $\epsilon_{ee} = 0$

1st 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 → $+yg[c_{23}^2 g \cos \phi_{e\mu} + s_{23}^2 f \cos(\Delta - \phi_{e\mu})]\}$

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

← 1st order due to $\epsilon_{e\tau}$

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

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

← 2nd order corrections

$$+ 8\hat{A}^2 fgs_{23}c_{23} \{c_{23} \cos \Delta [s_{23}(\epsilon_{e\mu}^2 - \epsilon_{e\tau}^2) + 2c_{23}\epsilon_{e\mu}\epsilon_{e\tau} \cos(\phi_{e\mu} - \phi_{e\tau})] \\ - \epsilon_{e\mu}\epsilon_{e\tau} \cos(\Delta - \phi_{e\mu} + \phi_{e\tau})\} + \mathcal{O}(s_{13}^2 \epsilon, s_{13} \epsilon^2, \epsilon^3),$$

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

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

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

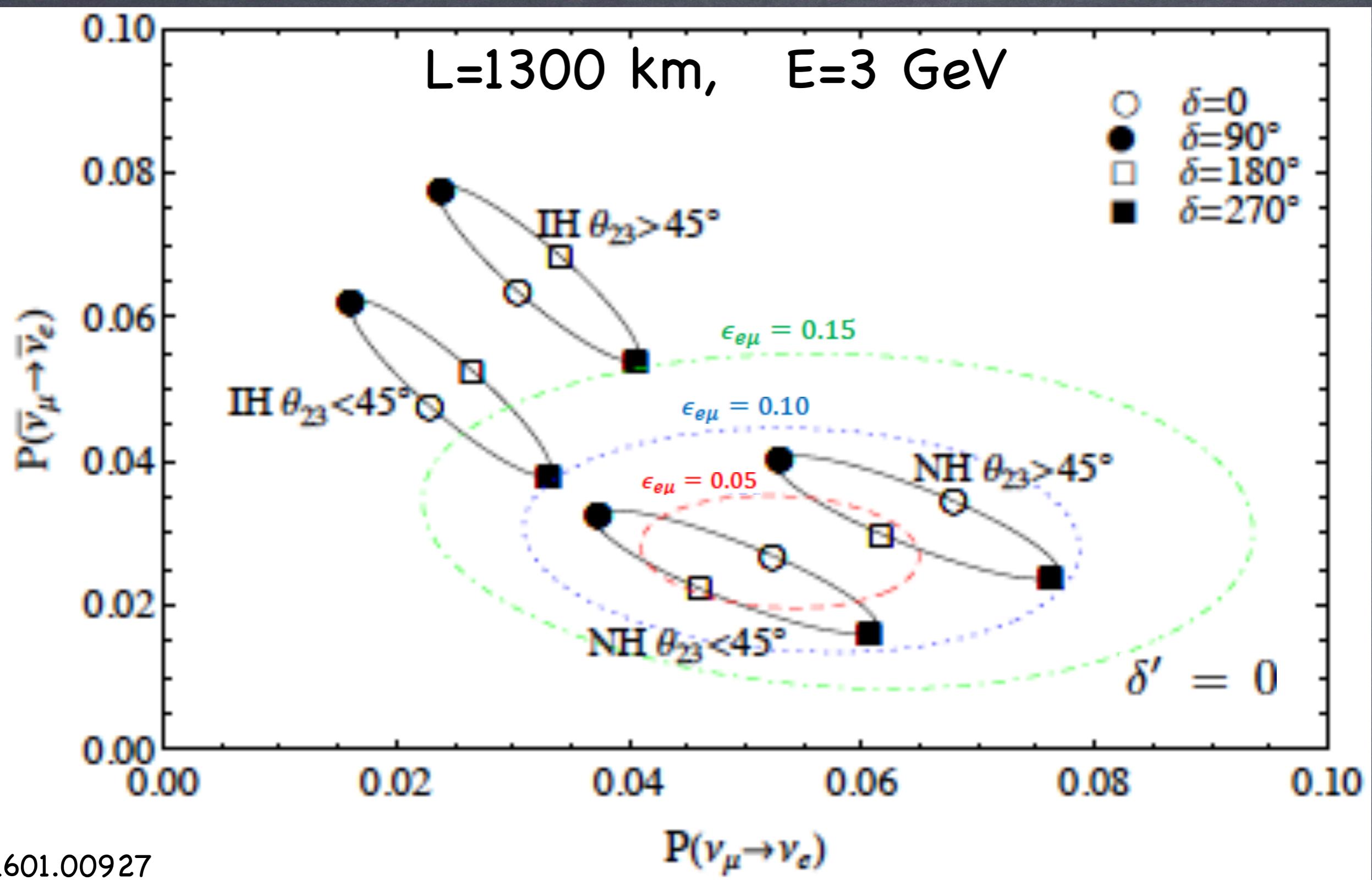
$$f, \bar{f} \equiv \frac{\sin[\Delta(1 \mp \hat{A}(1 + \epsilon_{ee}))]}{(1 \mp \hat{A}(1 + \epsilon_{ee}))}, \quad g \equiv \frac{\sin(\hat{A}(1 + \epsilon_{ee})\Delta)}{\hat{A}(1 + \epsilon_{ee})}, \quad \delta \rightarrow -\delta, \quad \phi_{\alpha\beta} \rightarrow -\phi_{\alpha\beta}$$

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

• NH → IH

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

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

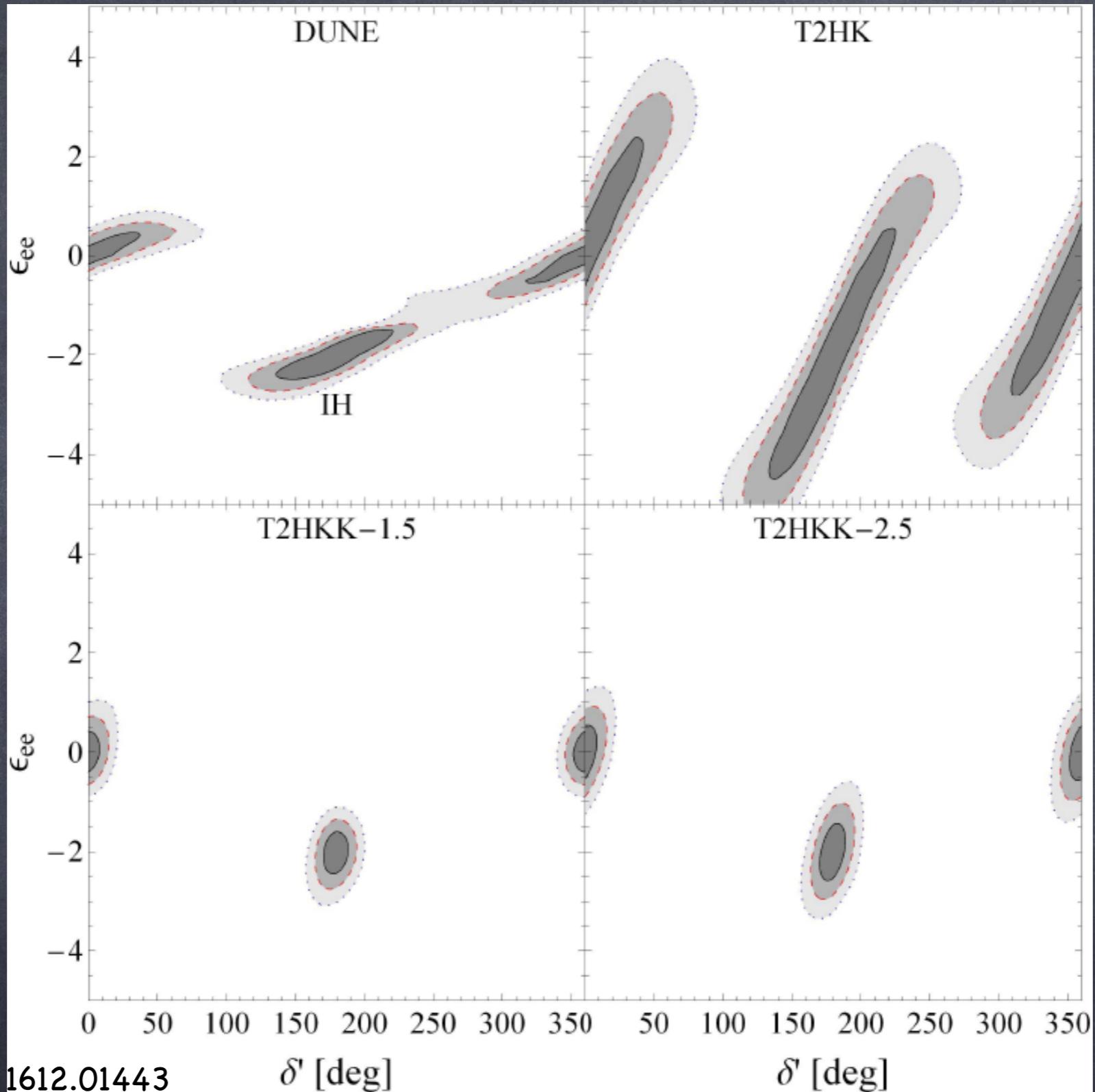


1601.00927

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

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

One NSI parameter

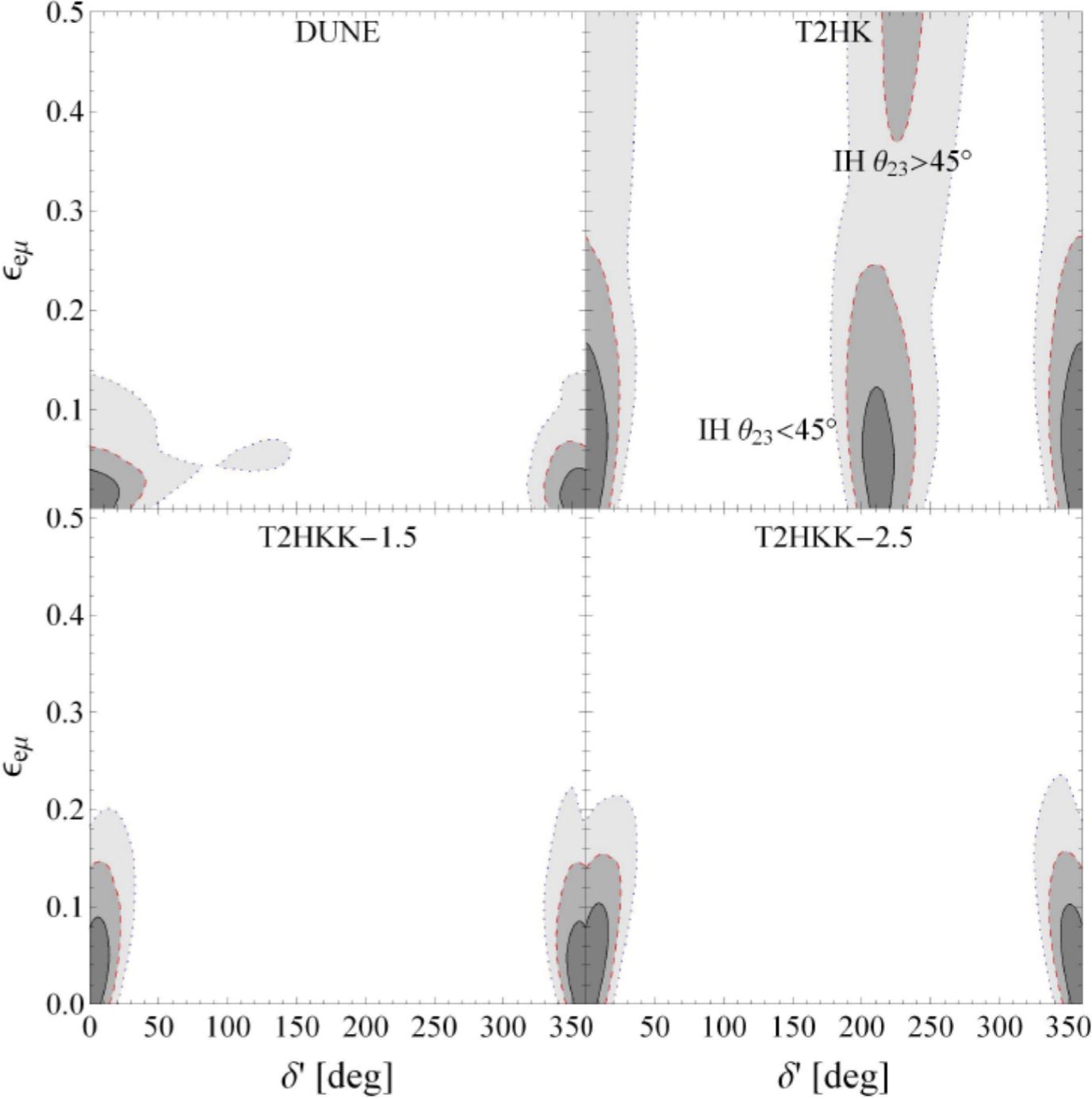
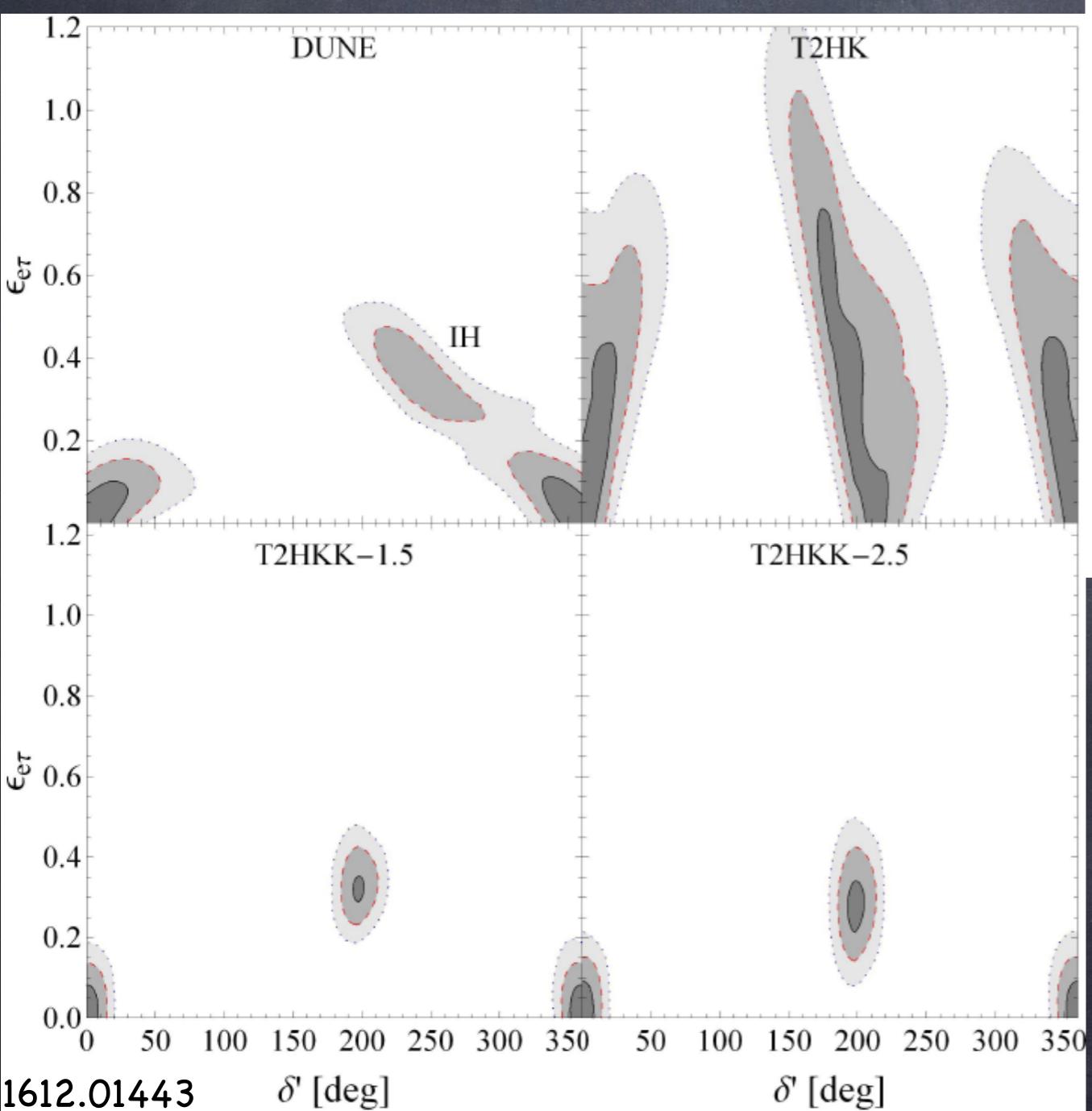


$$\delta m_{31}^2 \rightarrow -\delta m_{32}^2, \quad \theta_{12} \rightarrow 90^\circ - \theta_{12}, \quad \delta \rightarrow 180^\circ - \delta$$

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

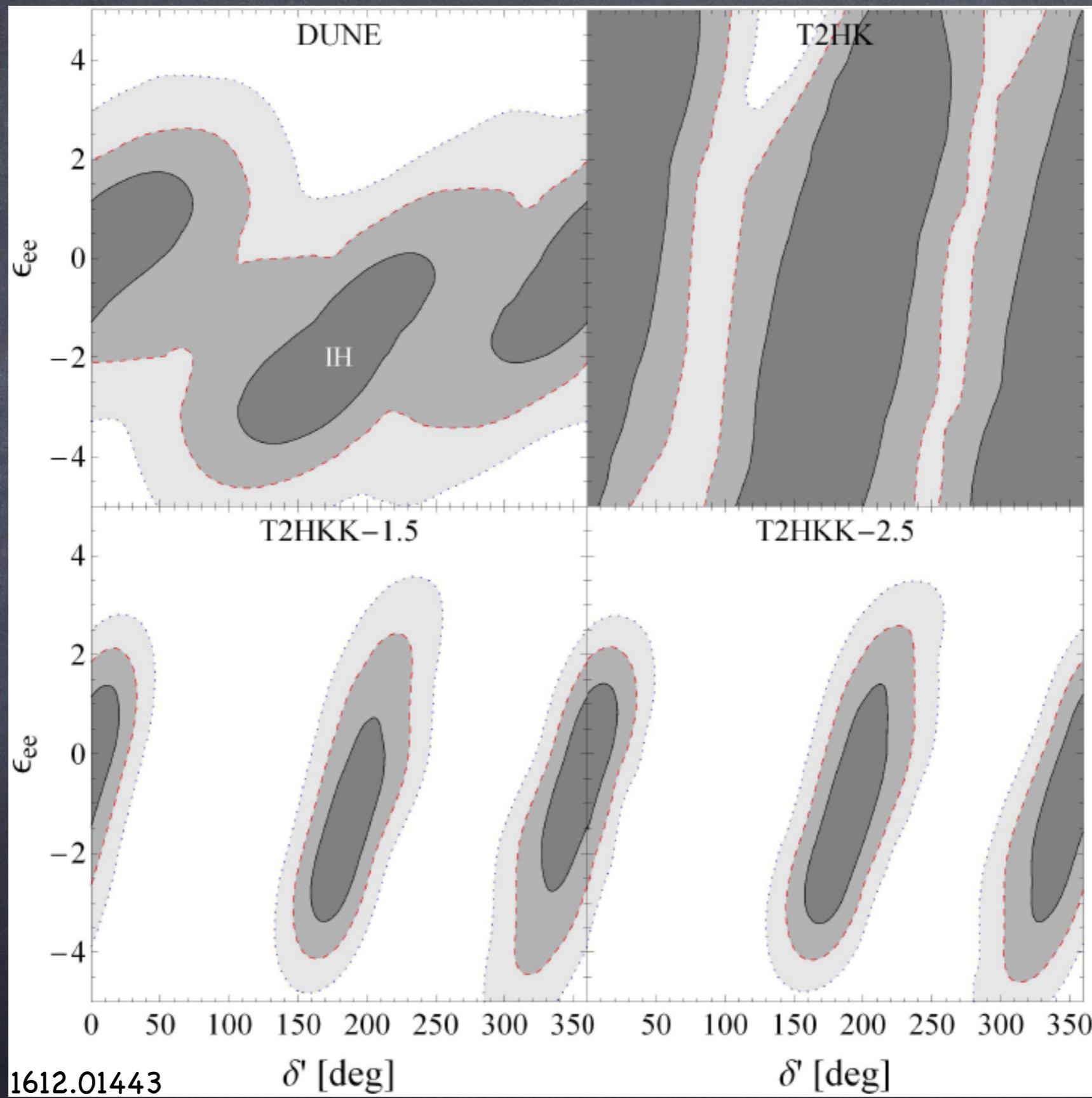
1604.05772

Mass hierarchy resolved at DUNE and T2HKK

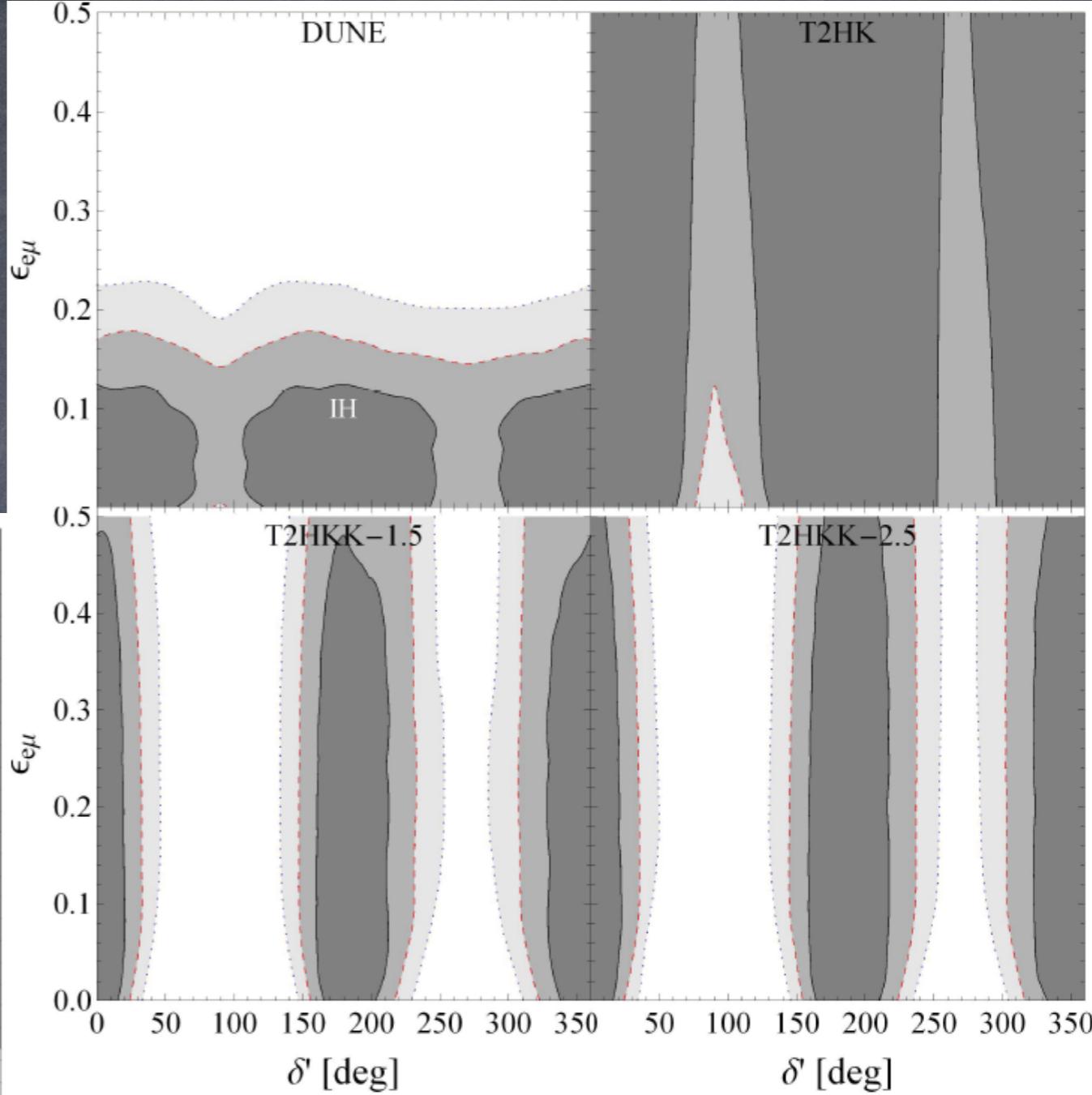
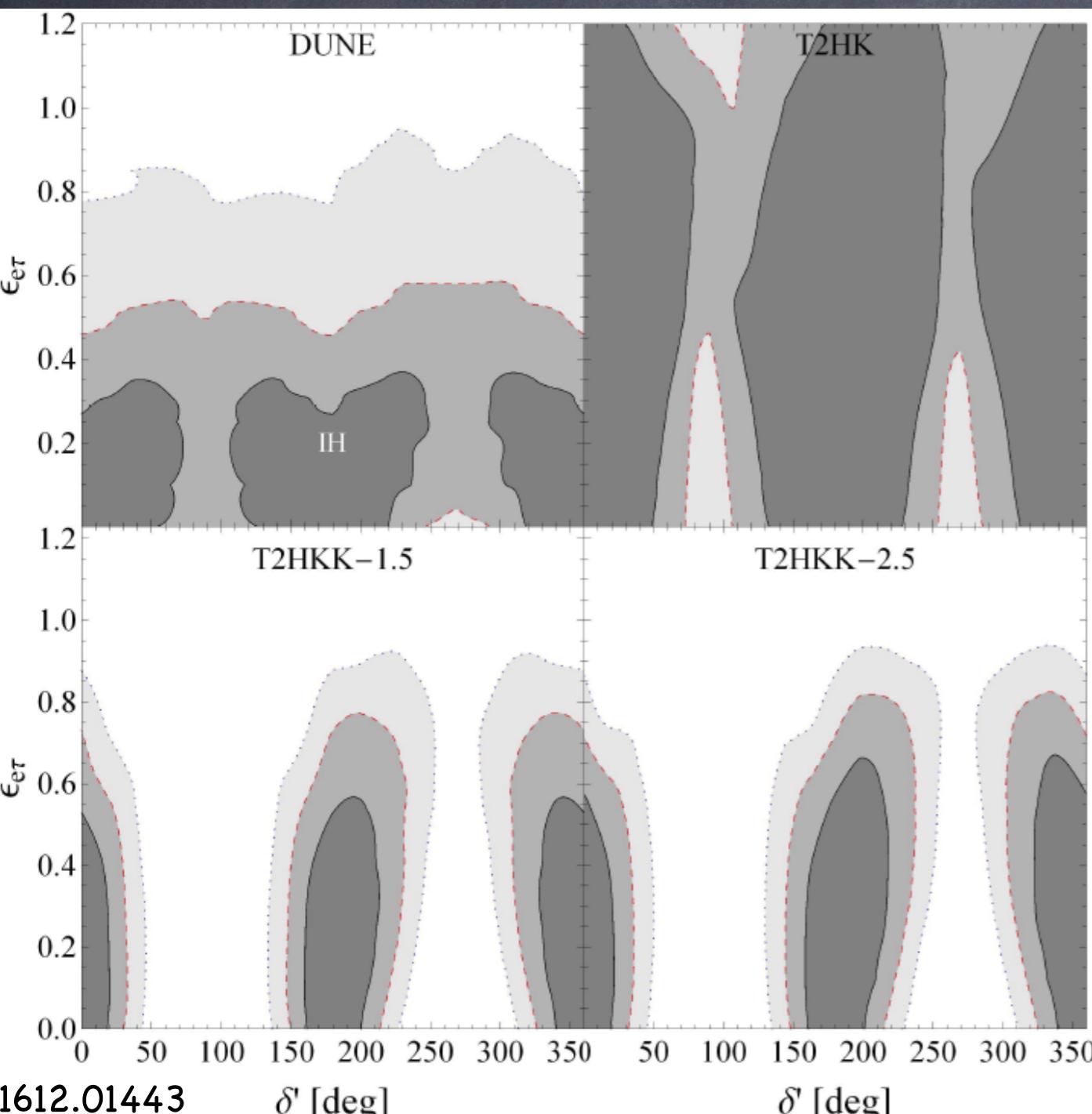


Hierarchy not resolved
Wrong determination of the CP phase possible

3 NSI parameters



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



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

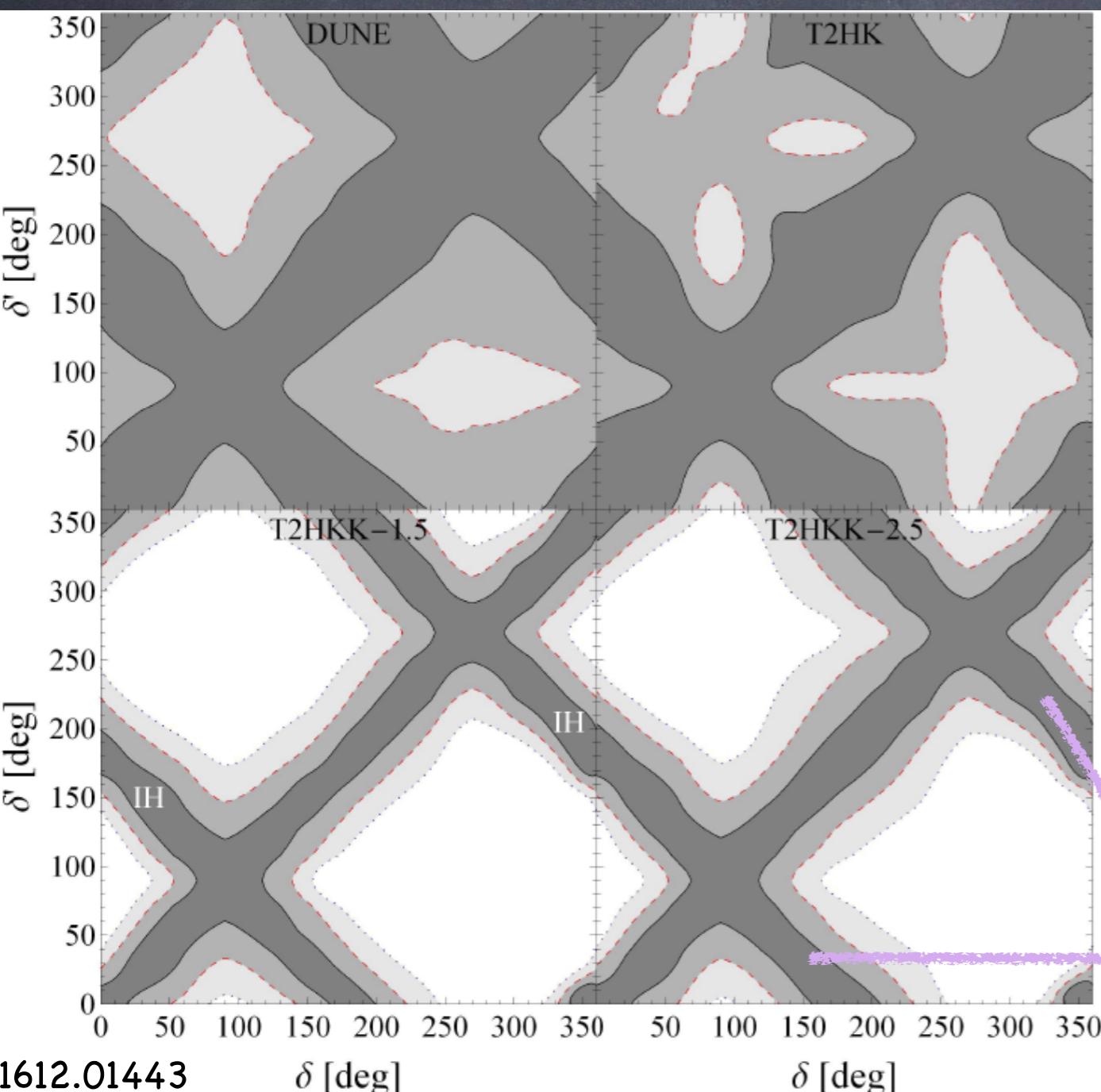
Degeneracy between NSI
parameters unbroken at T2HK and
T2HKK because of the lower energy
J-PARC beam

CP sensitivity

MH known

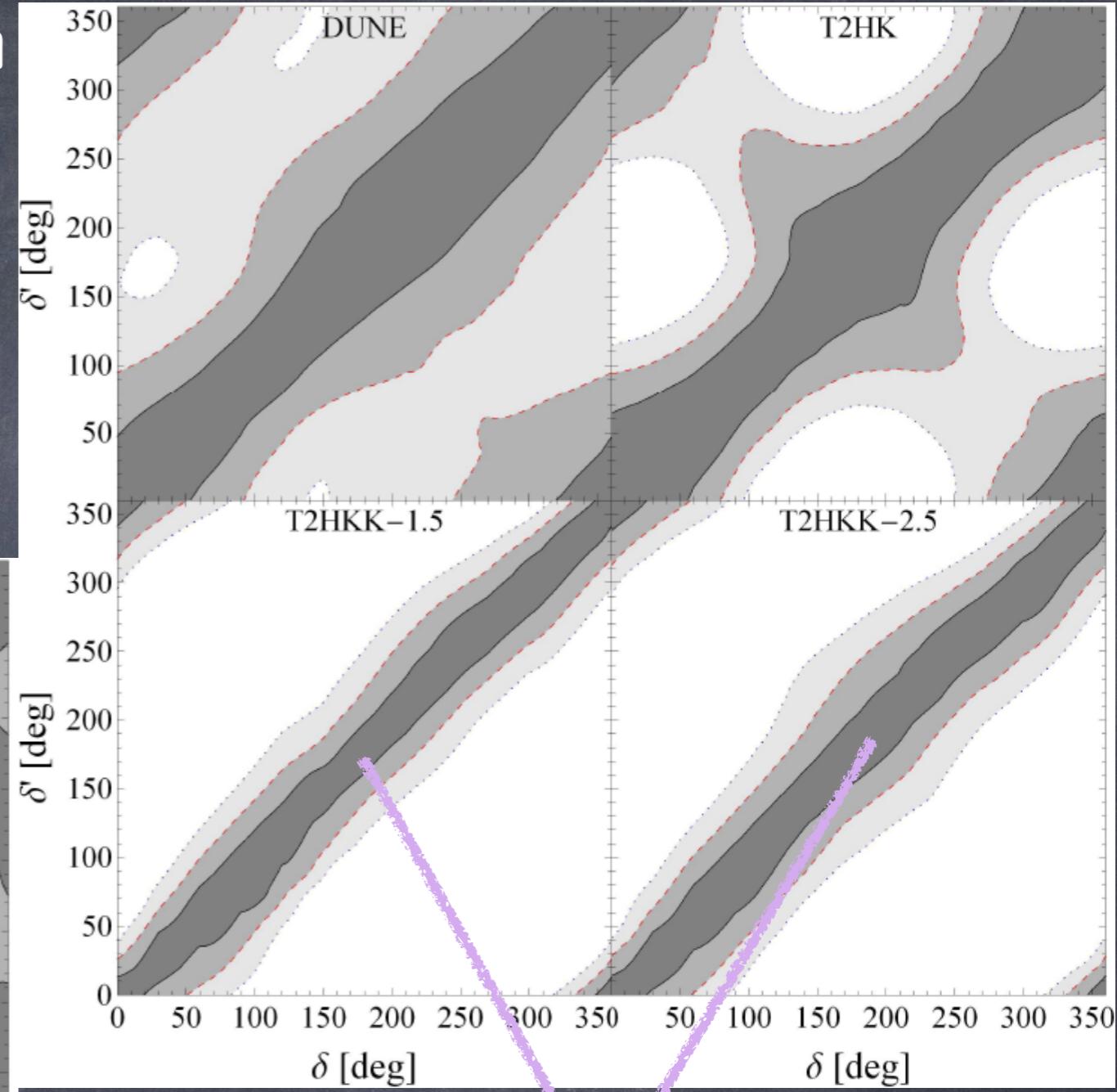
T2HKK better than DUNE for CP; is the only expt. that can measure the CP phase if MH is unknown

MH unknown



1612.01443

δ [deg]



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

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

Sterile neutrino NSI

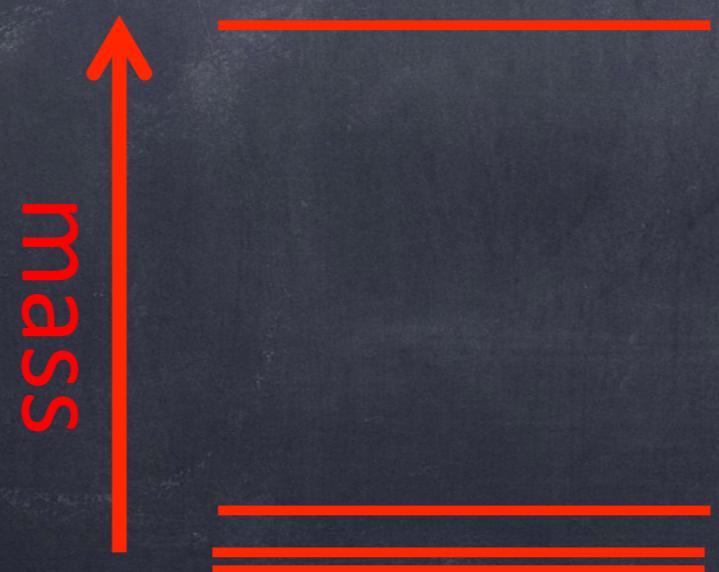
LSND

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Baseline: 30 m

Maximum energy: 53 MeV

$$L/E \sim 1 \text{ km/GeV} \implies \Delta m^2 \sim 1 \text{ eV}^2$$



MiniBooNE

$$\nu_\mu \rightarrow \nu_e \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Baseline: 500 m

Average energy: 800 MeV

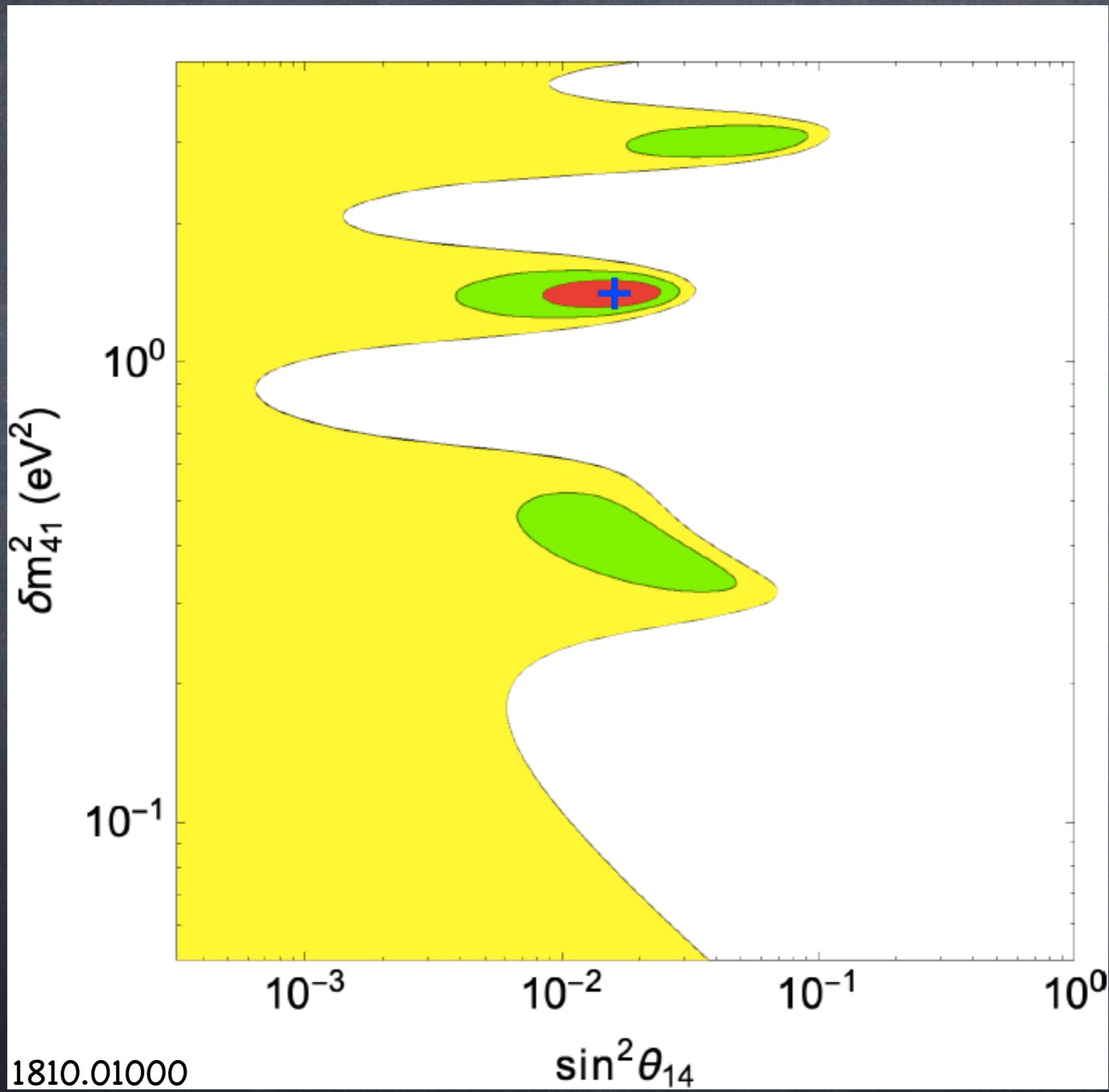
$$L/E \sim 1 \text{ km/GeV} \implies \Delta m^2 \sim 1 \text{ eV}^2$$

LSND+MiniBooNE anomaly has 6.1 sigma significance

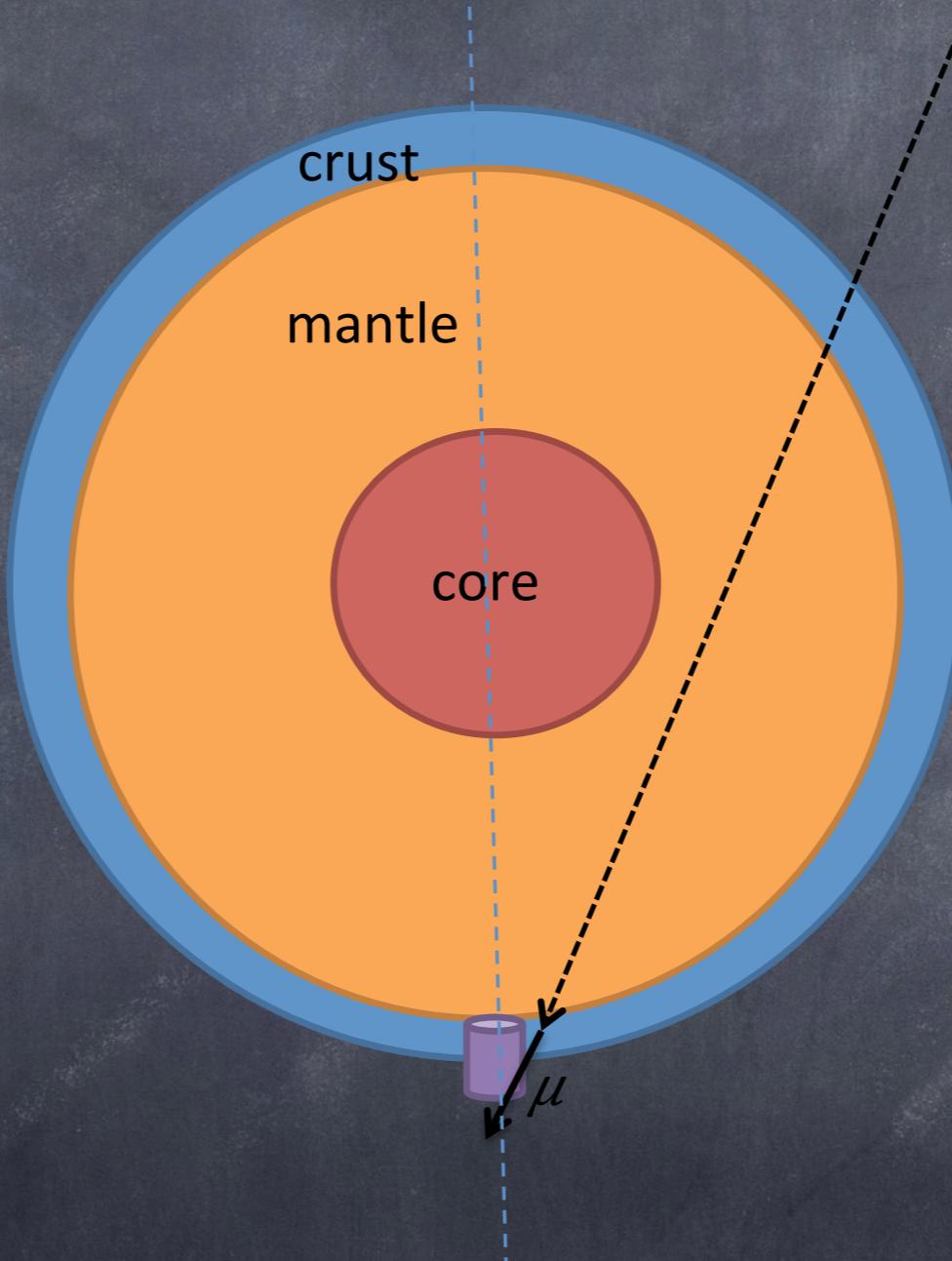
Oscillation amplitude from global analysis:

$$\sin^2 2\theta_{14} \sin^2 \theta_{24} \sim 0.04 \sin^2 \theta_{24}$$

DANSS



IceCube/DeepCore



Focus on (anti)muon neutrino survival probabilities

Resonant 3+1 atmospheric neutrino oscillations

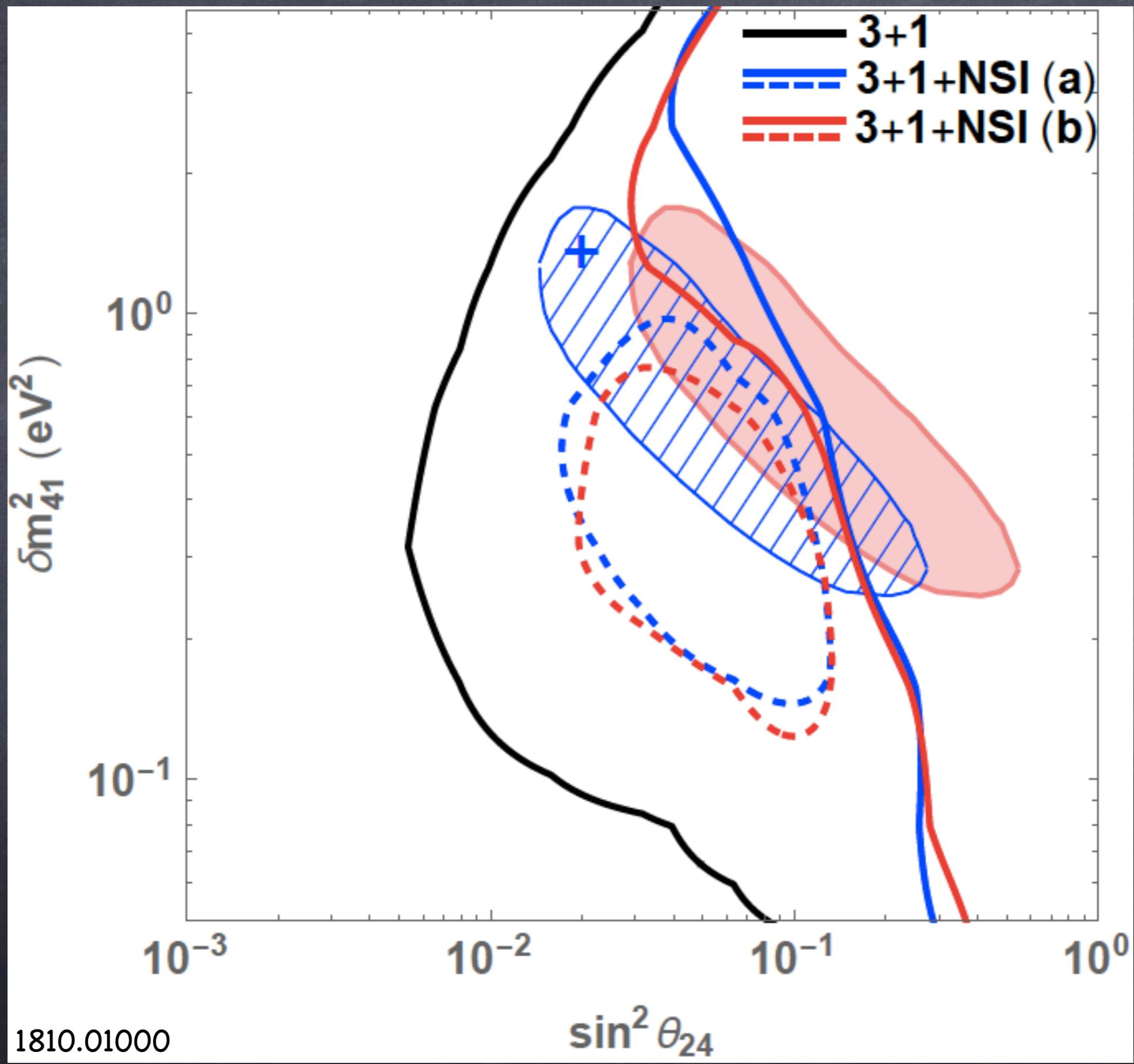
Oscillation maximum in vacuum:

$$\frac{\Delta m^2}{\text{eV}^2} \frac{L}{10^3 \text{ km}} \frac{\text{TeV}}{E} \sim 1$$

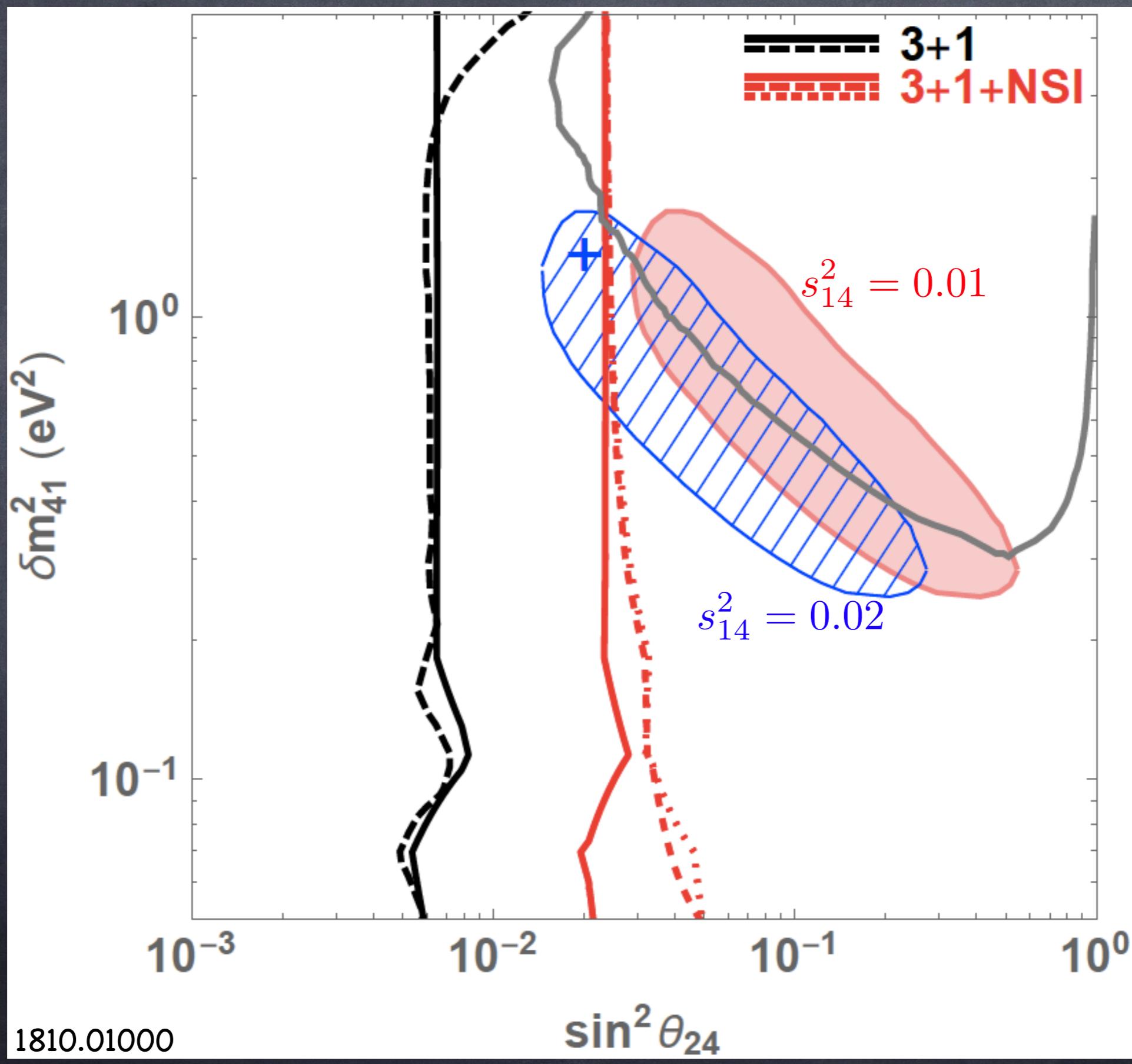
Resonance condition in earth matter:

$$\Delta m_{41}^2 \cos 2\theta_{24} \simeq \mp 1 \text{ eV}^2 \frac{E}{5 \text{ TeV}}$$

Resonance occurs in antineutrino channel



MINOS/MINOS+



NSI to the rescue?

- Model independent bounds from neutrino oscillation data allow large diagonal NSI parameters with $O(1)$ differences between them
- COHERENT bounds obtained using contact approx don't apply for mediators lighter than 50 MeV

3+1 oscillations with CC and NC NSI

$$\tilde{P}(\nu_\alpha^S \rightarrow \nu_\beta^D) = \left| \left[(1 + \epsilon^D)^T e^{-iH_L} (1 + \epsilon^S)^T \right]_{\beta\alpha} \right|^2$$

$$H = \frac{1}{2E} \left[V \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 & 0 \\ 0 & 0 & \delta m_{31}^2 & 0 \\ 0 & 0 & 0 & \delta m_{41}^2 \end{pmatrix} V^\dagger + V_m \right]$$

$$V_m = 2\sqrt{2}G_F N_e E \begin{pmatrix} 1 + \epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m & \epsilon_{es}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m & \epsilon_{\mu s}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m & \epsilon_{\tau s}^m \\ \epsilon_{es}^{m*} & \epsilon_{\mu s}^{m*} & \epsilon_{\tau s}^{m*} & \kappa + \epsilon_{ss}^m \end{pmatrix}$$

$$\kappa = \frac{N_n}{2N_e} \simeq 0.5$$

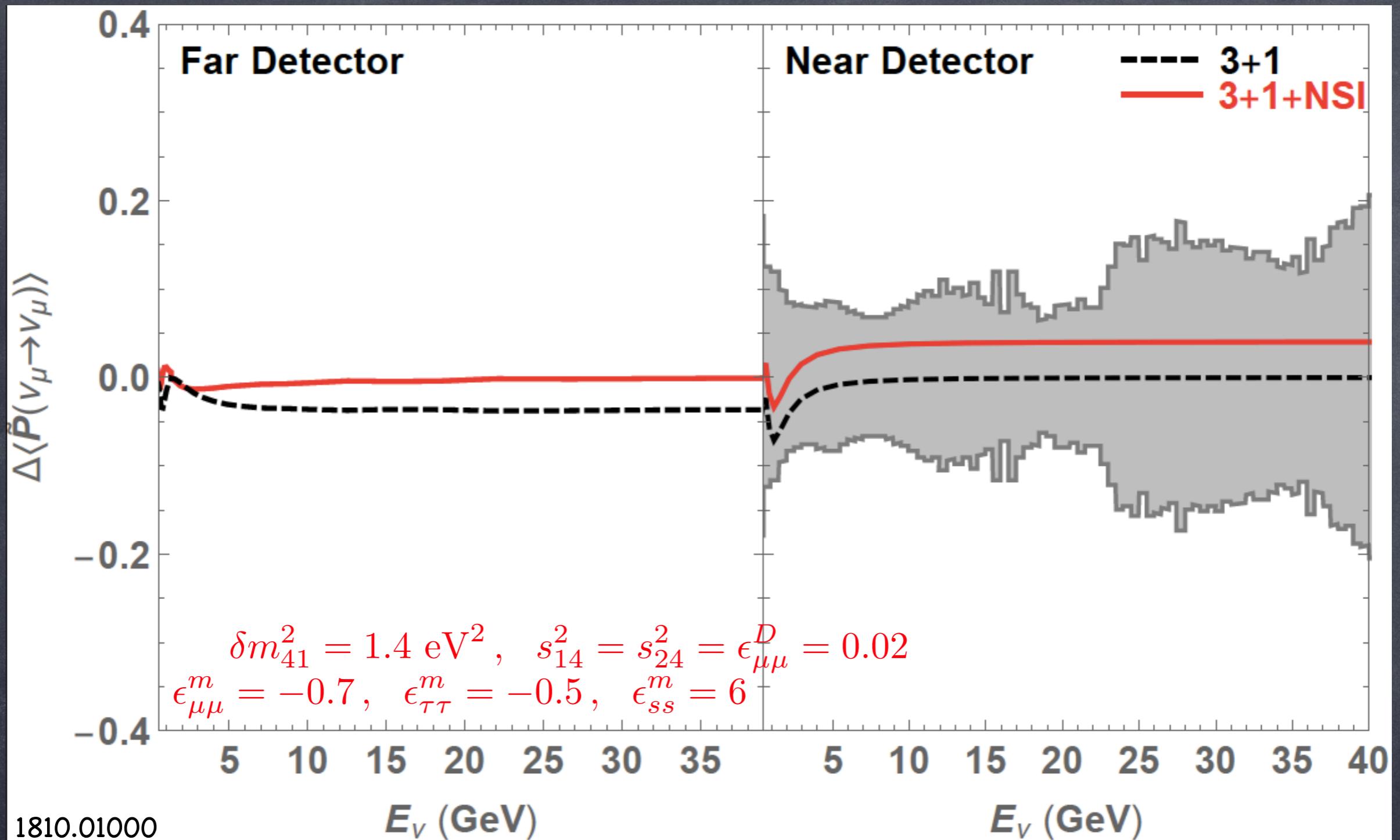
Try hard to use Occam's razor!

- Vector-like CC interaction contributes NSI at detector, but not at pion source

- Only nonzero CC NSI parameter is $\epsilon_{\mu\mu}^D = 2\epsilon_{\mu\mu}^{udL}$

$$\left(\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{ff'C} [\bar{\nu}_\beta \gamma^\rho P_L \ell_\alpha] [\bar{f}' \gamma_\rho P_C f] \right)$$

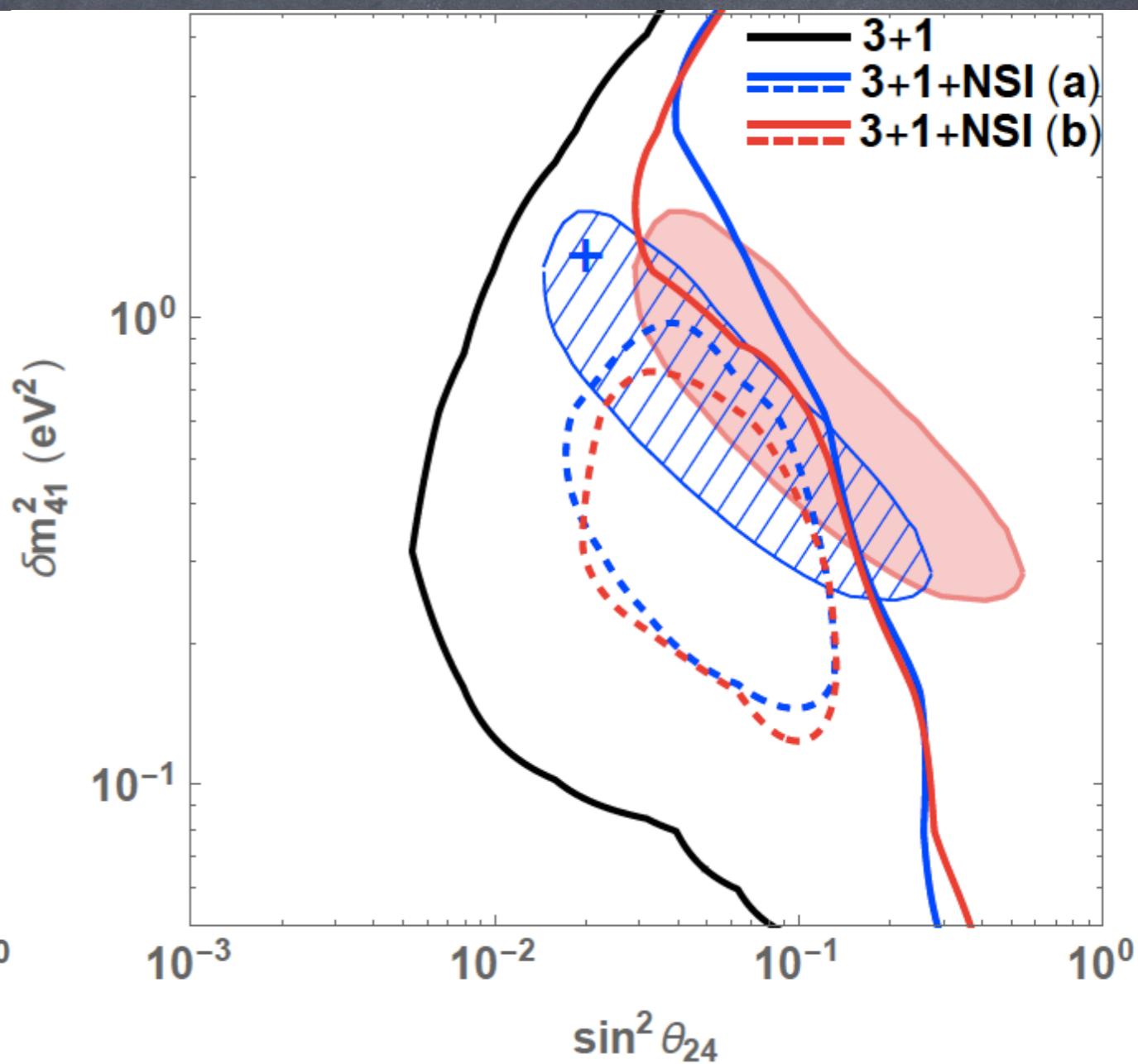
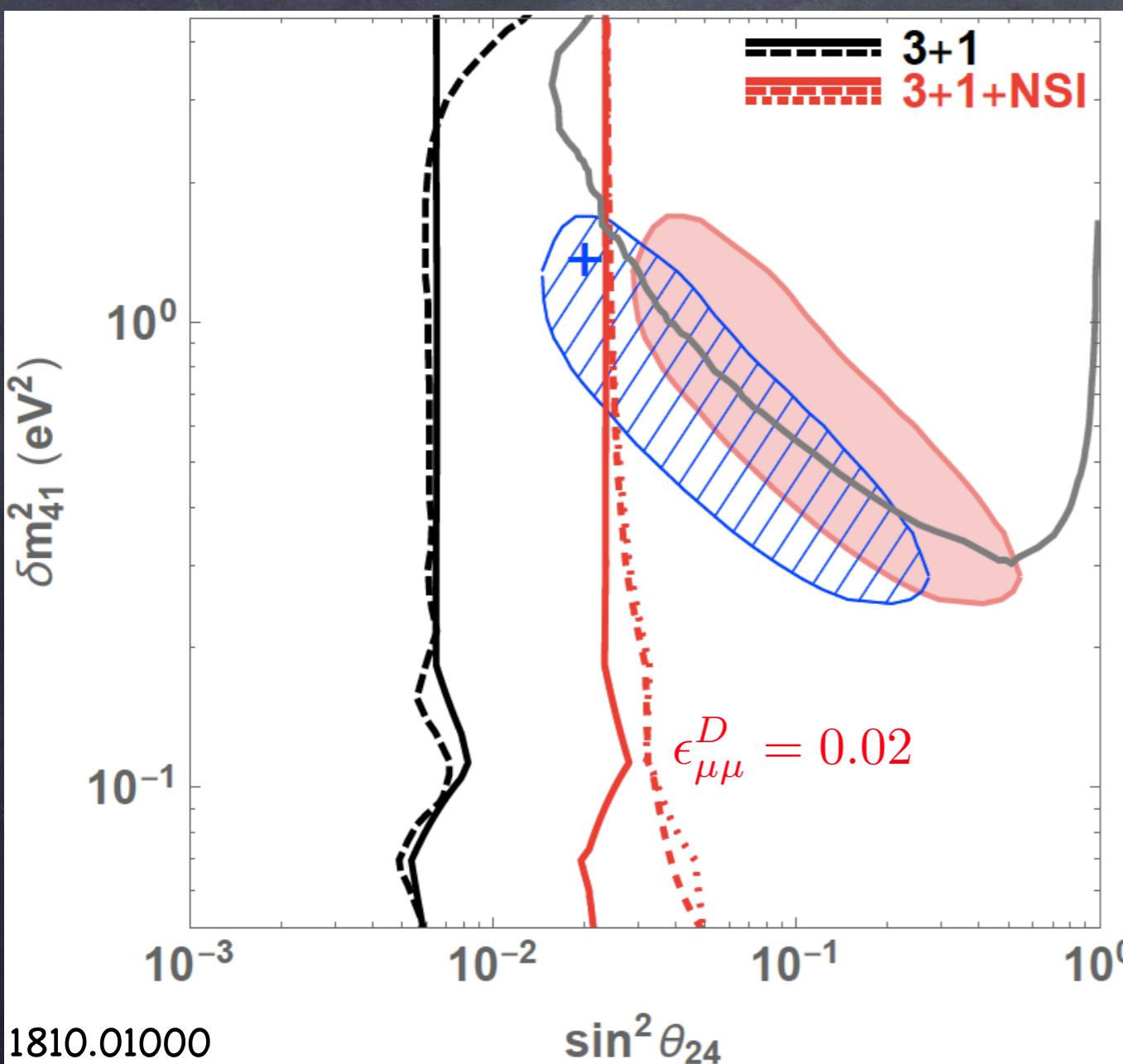
- Nonzero NC NSI parameters: $\epsilon_{\mu\mu}^m$, $\epsilon_{\tau\tau}^m$, ϵ_{ss}^m



3+1+NSI survival prob at FD same as 3-neutrino case if

$$\epsilon_{\mu\mu}^D \simeq s_{24}^2$$

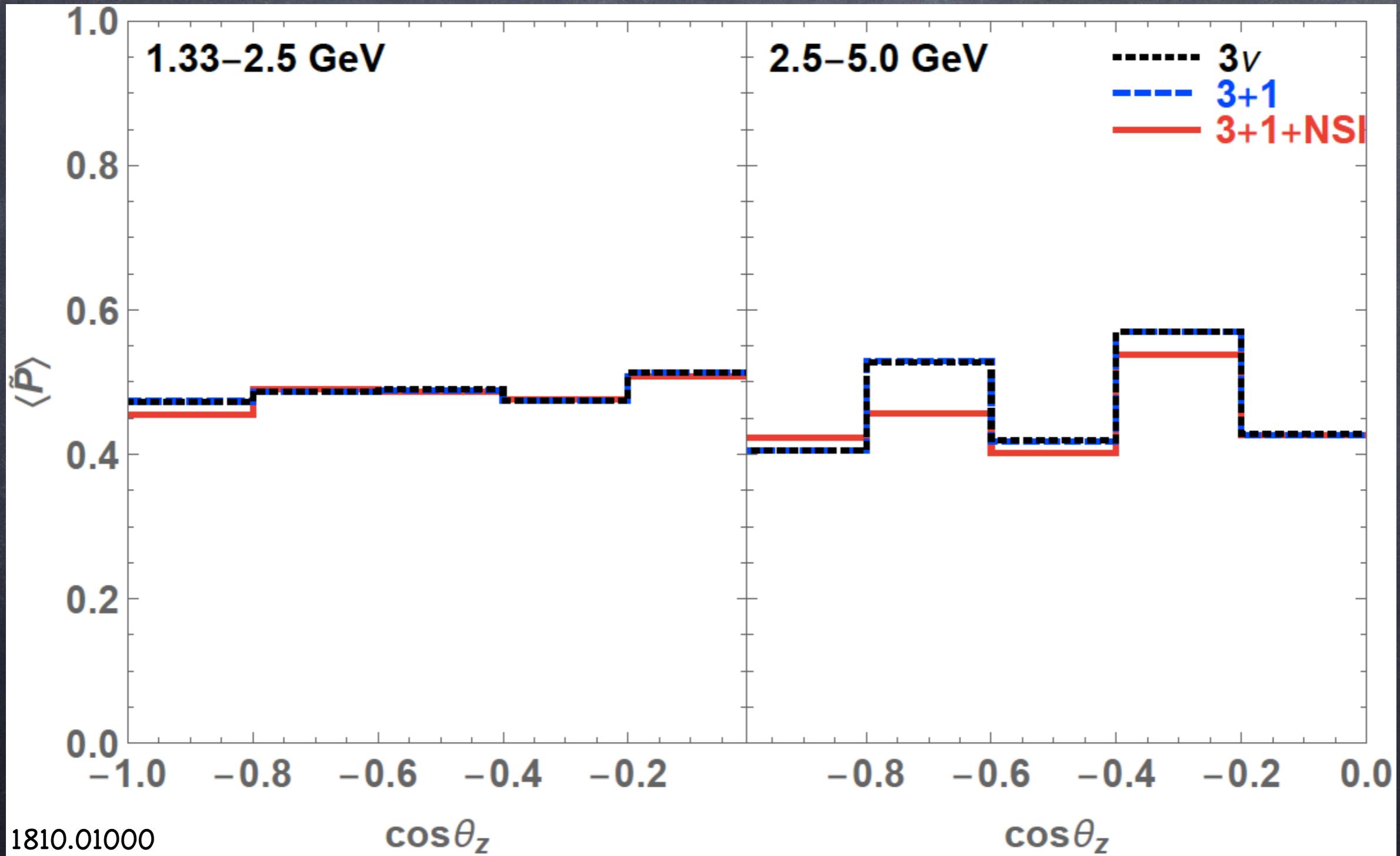
$$\epsilon_{\mu\mu}^m - \epsilon_{\tau\tau}^m \simeq s_{24}^2 (\epsilon_{\mu\mu}^m - \epsilon_{ss}^m - \kappa)$$



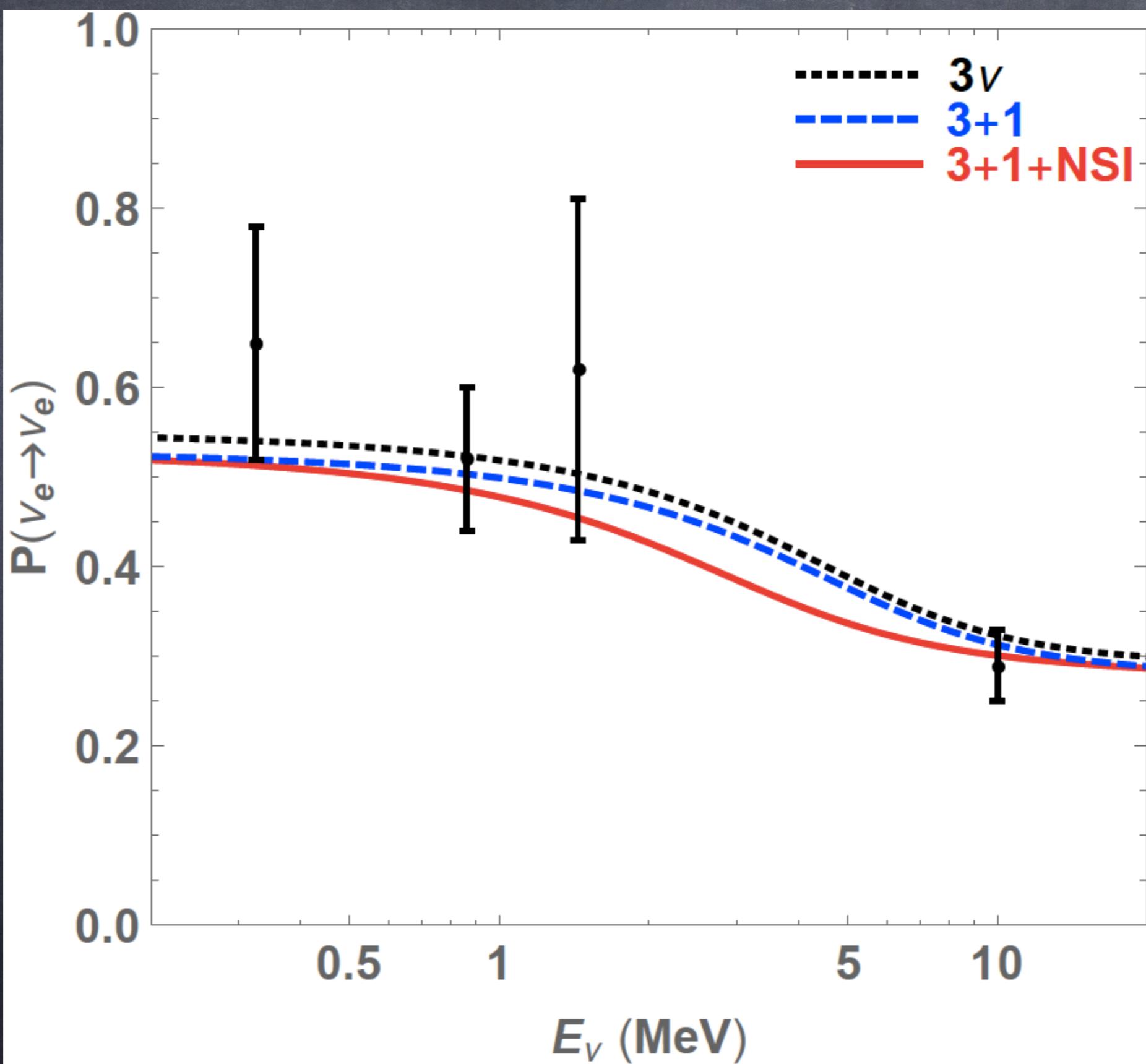
(a) $|\epsilon_{\tau\tau}^m| < 6, \quad |\epsilon_{\mu\mu}^m - \epsilon_{\tau\tau}^m| < 0.5$

(b) $|\epsilon_{ss}^m| < 6, \quad |\epsilon_{\tau\tau}^m| < 0.5, \quad |\epsilon_{\mu\mu}^m - \epsilon_{\tau\tau}^m| < 0.5$

Super-Kamiokande



Solar neutrinos



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 in the presence of NSI
- LSND/MiniBooNE is consistent with IceCube/DeepCore and MINOS/MINOS+ in a (3+1)+NSI model with CC and NC NSI