New neutrino interactions

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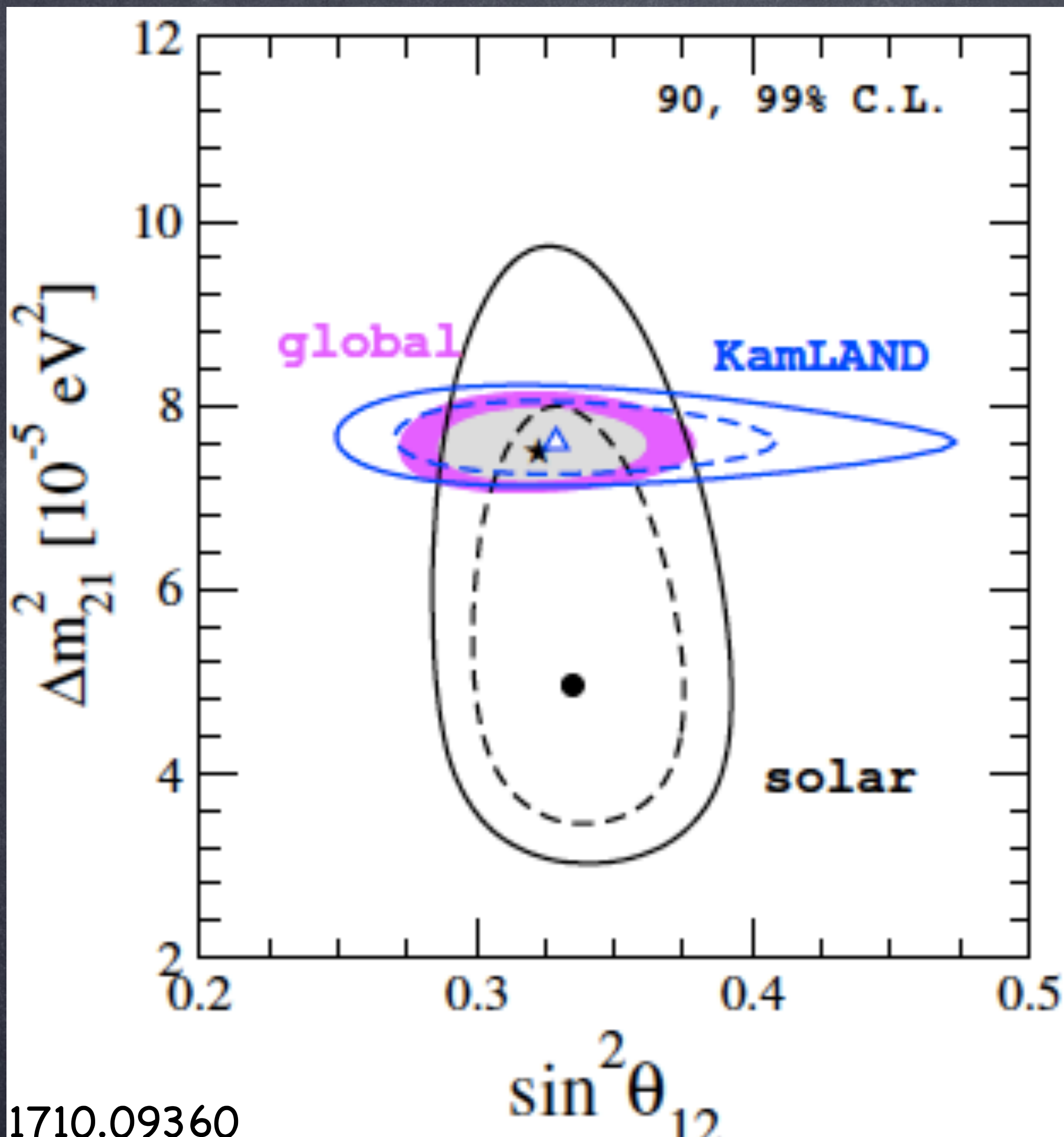
Possible tension in standard oscillation picture



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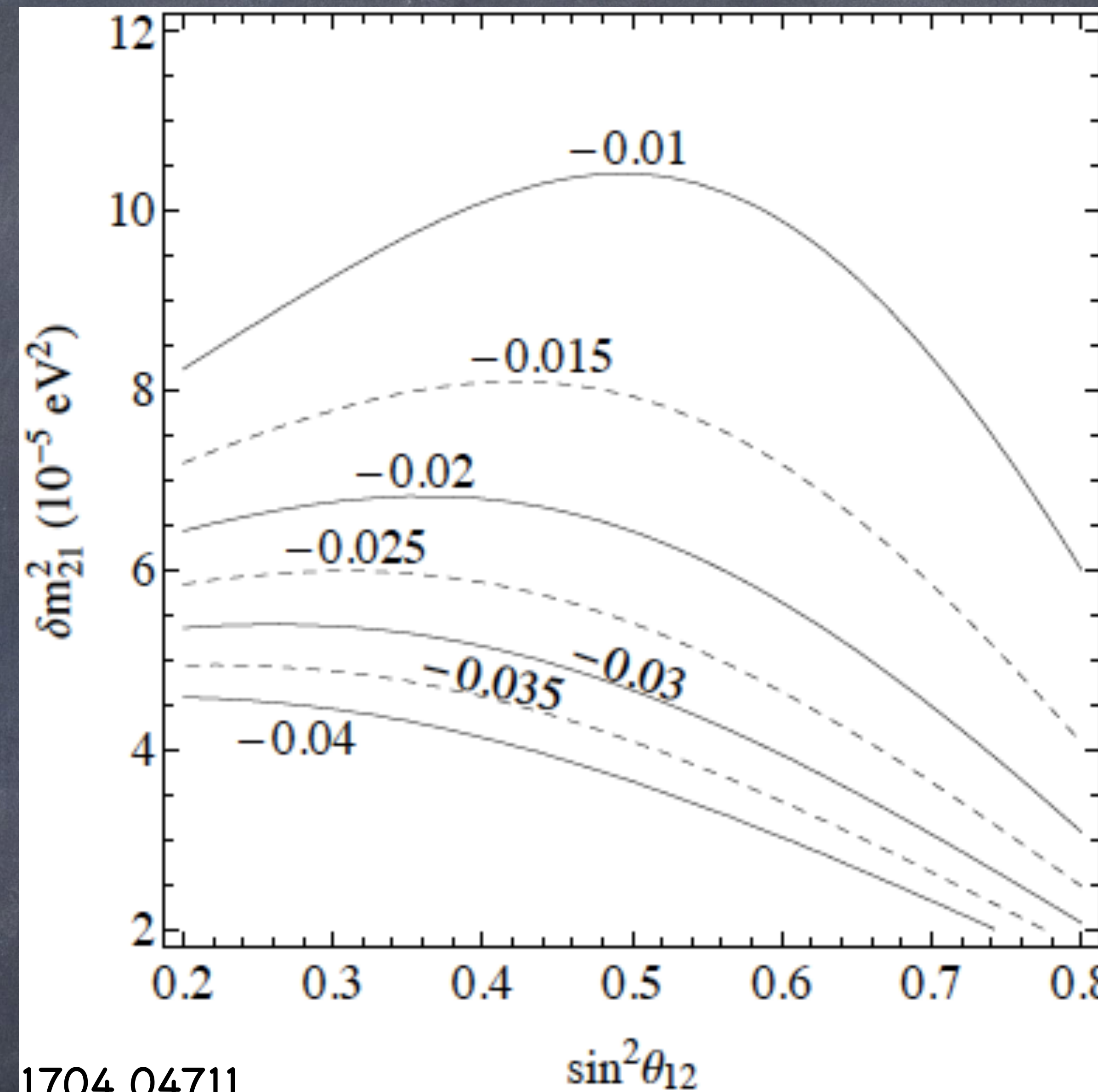

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Discrepancy in mass-squared difference driven by Super-K's day-night asymmetry measurement:

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

Nonstandard interactions in matter

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,\mathfrak{f},C} \epsilon^{\mathfrak{f}C}_{\alpha\beta} \left[\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta\right] \left[\overline{\mathfrak{f}} \gamma_\rho P_C \mathfrak{f}\right]$$

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

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

Vector interaction relevant for propagation:

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

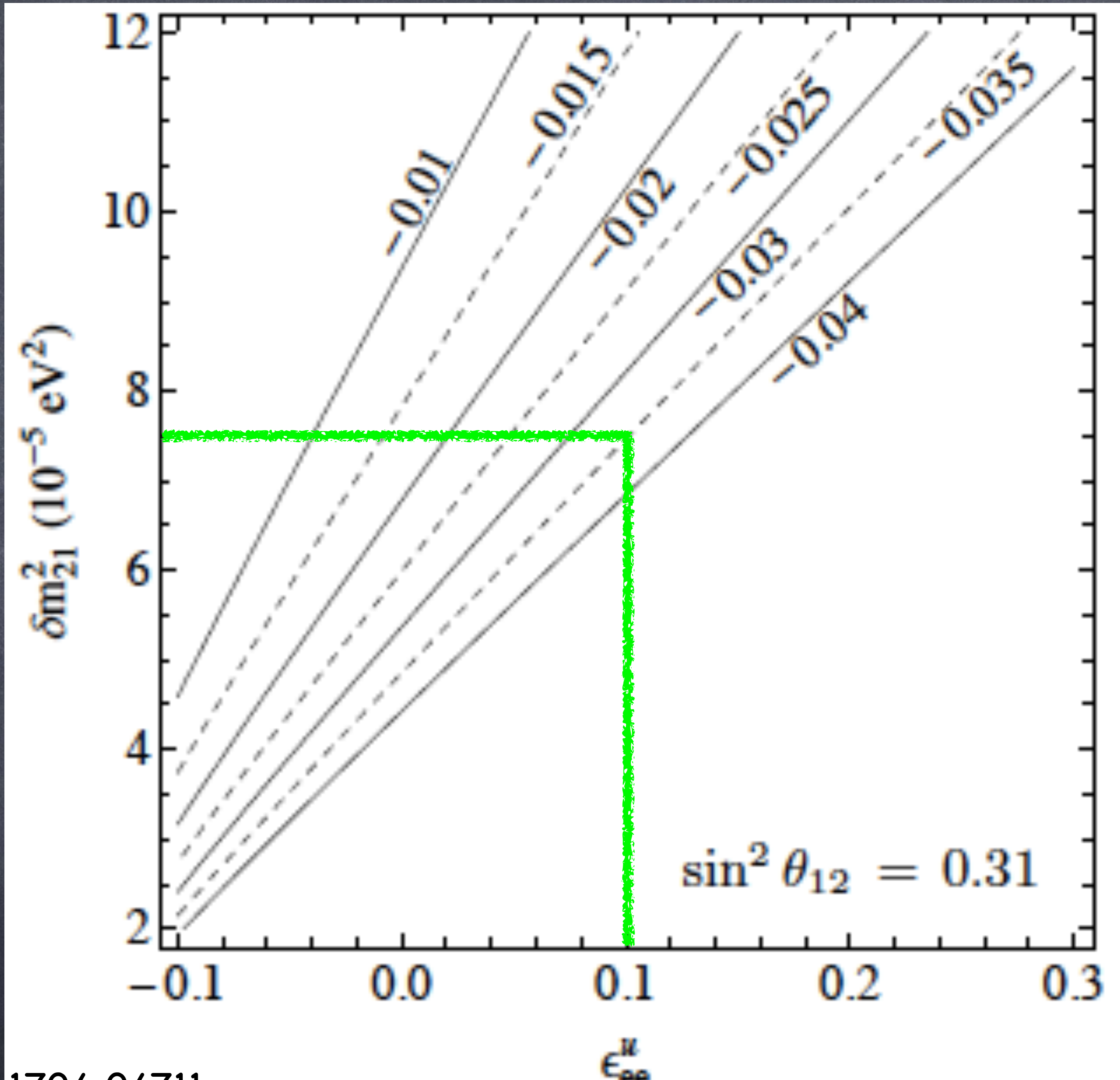
On earth $N_u = N_d = 3N_e$

1805.04530

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

Matter effects if NSI violate lepton universality or/and flavor

Iso-day-night asymmetry contours



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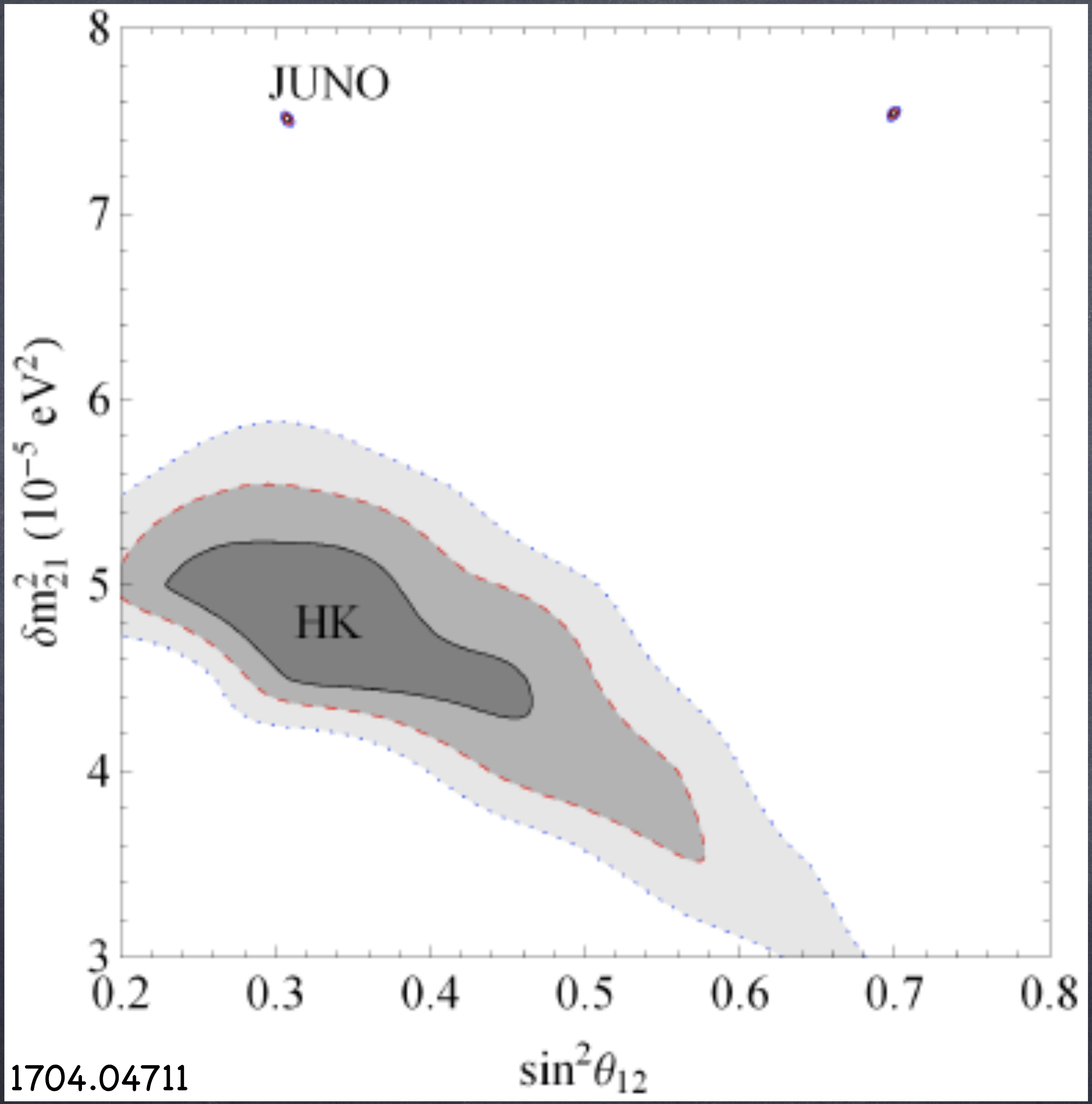
$$\epsilon^u_{ee} = \epsilon^d_{ee} \sim 0.1$$



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·10^7s)	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 $\epsilon_{ee} = 0$

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

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

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

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

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

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

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

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

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

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

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

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

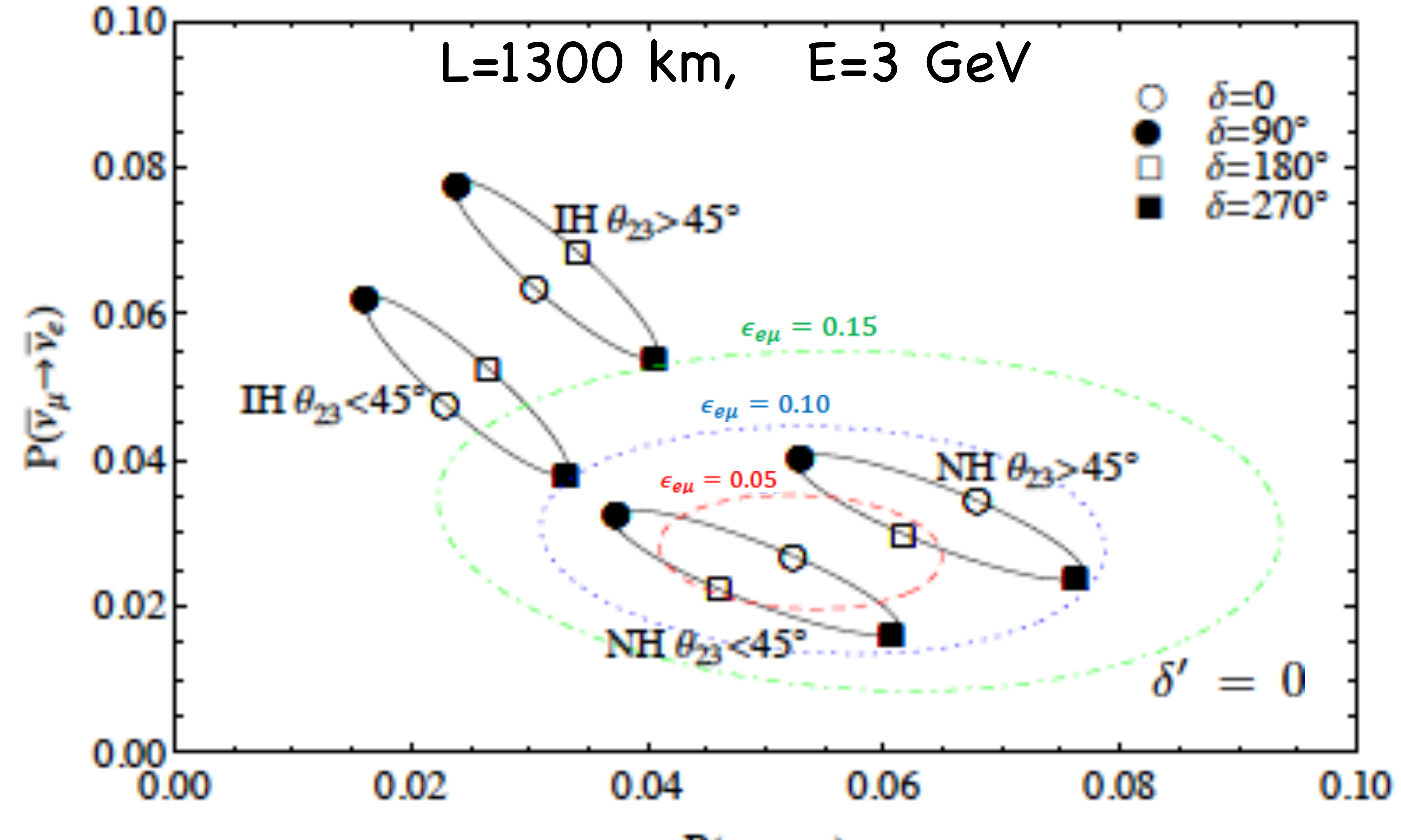
  $\delta \to -\delta, \quad \phi_{\alpha\beta} \to -\phi_{\alpha\beta}$

- NH → IH

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

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

Liao



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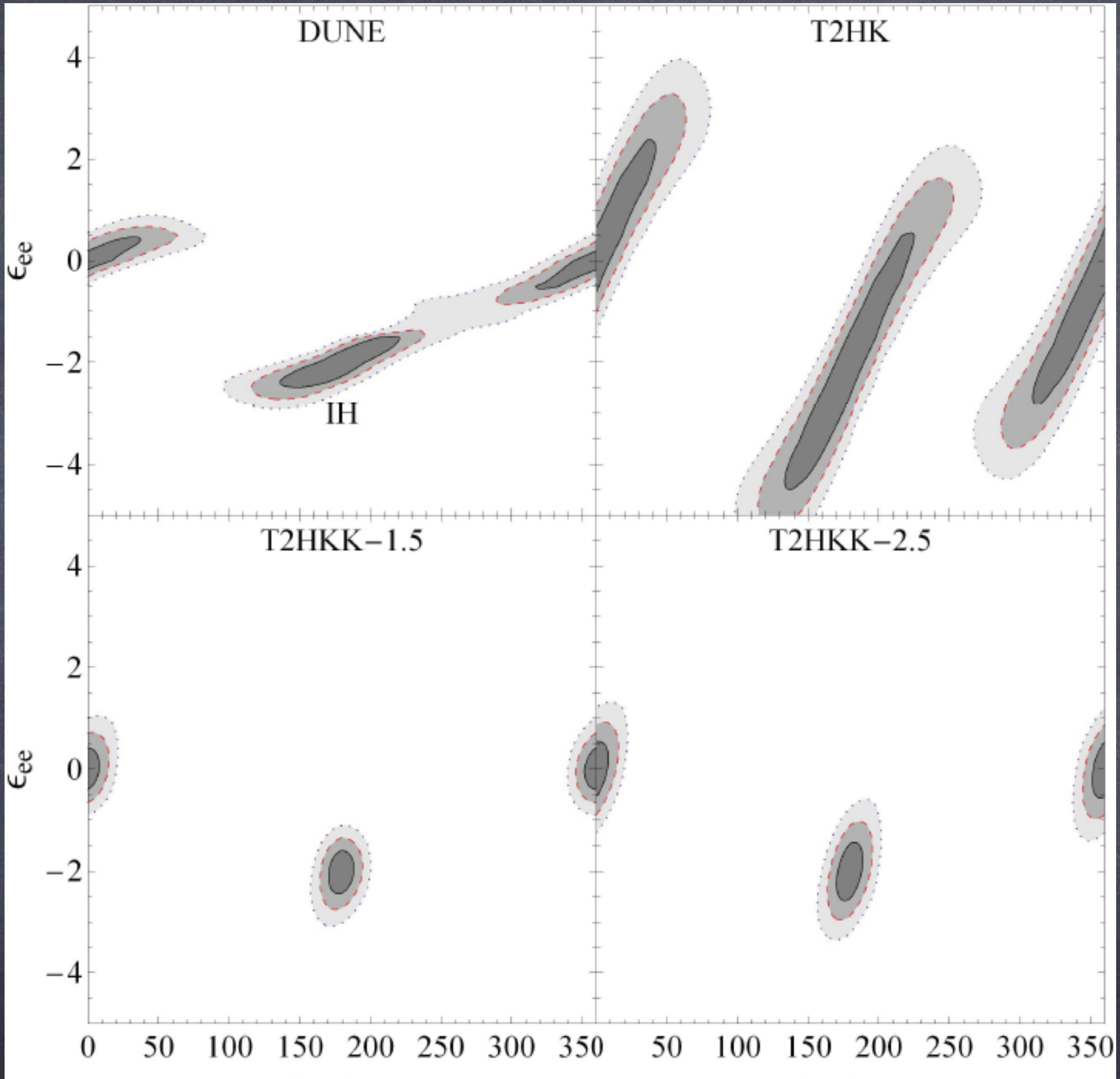
$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$
$$\overline{P}^{SM}(\delta) = \overline{P}^{NSI}(\delta', \epsilon, \phi)$$

One NSI parameter



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

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

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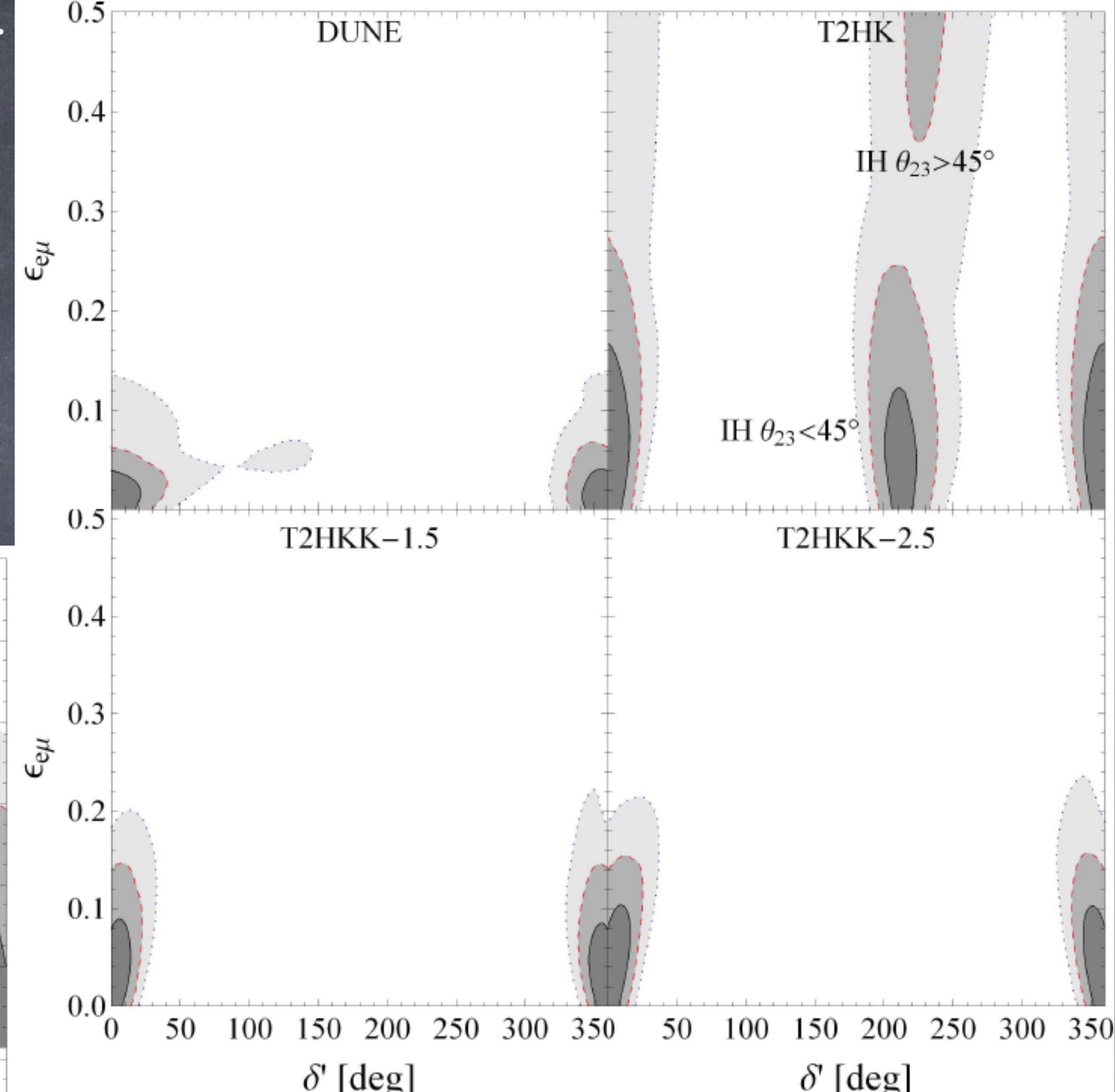
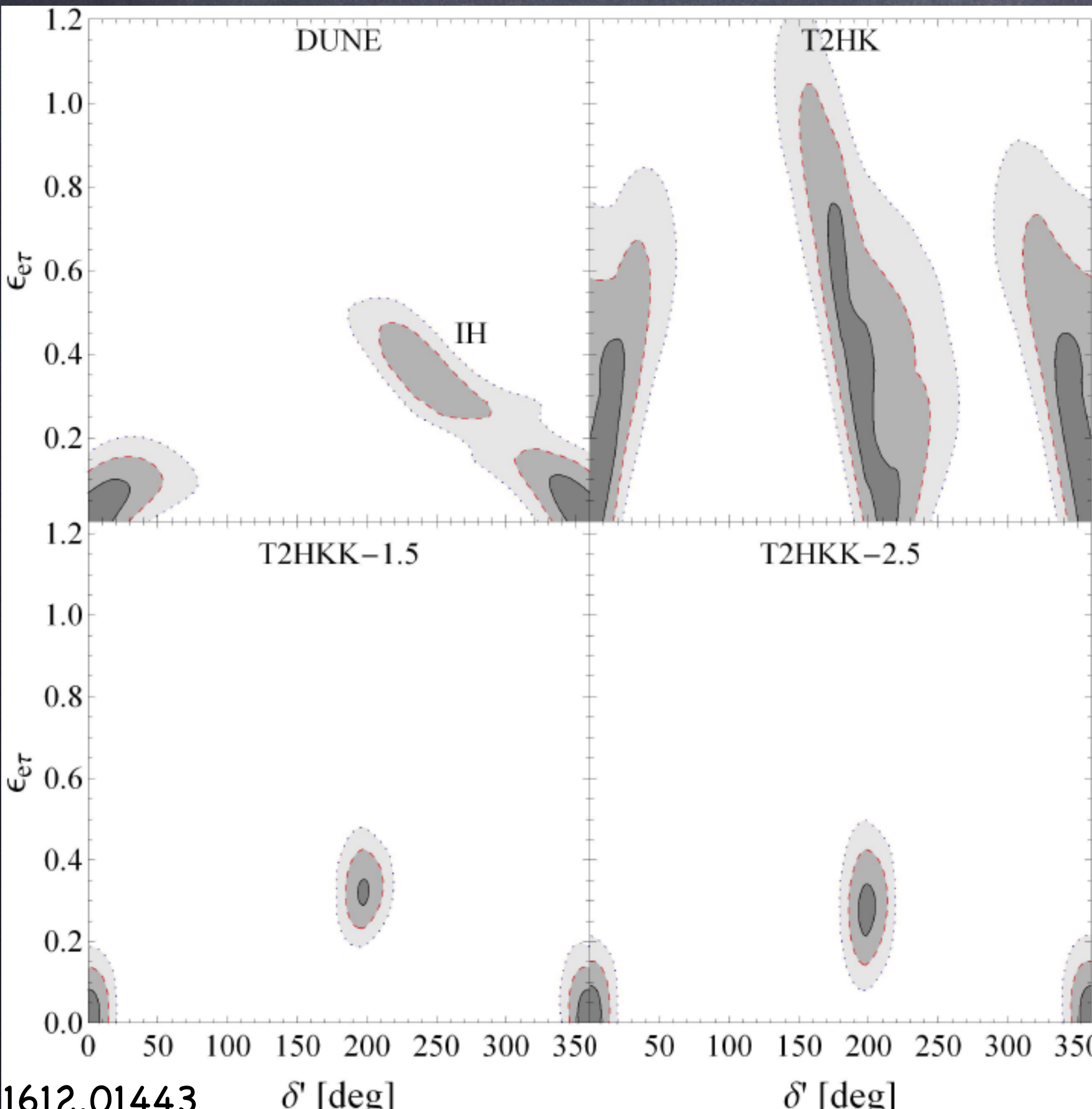
Mass hierarchy resolved at DUNE and T2HKK





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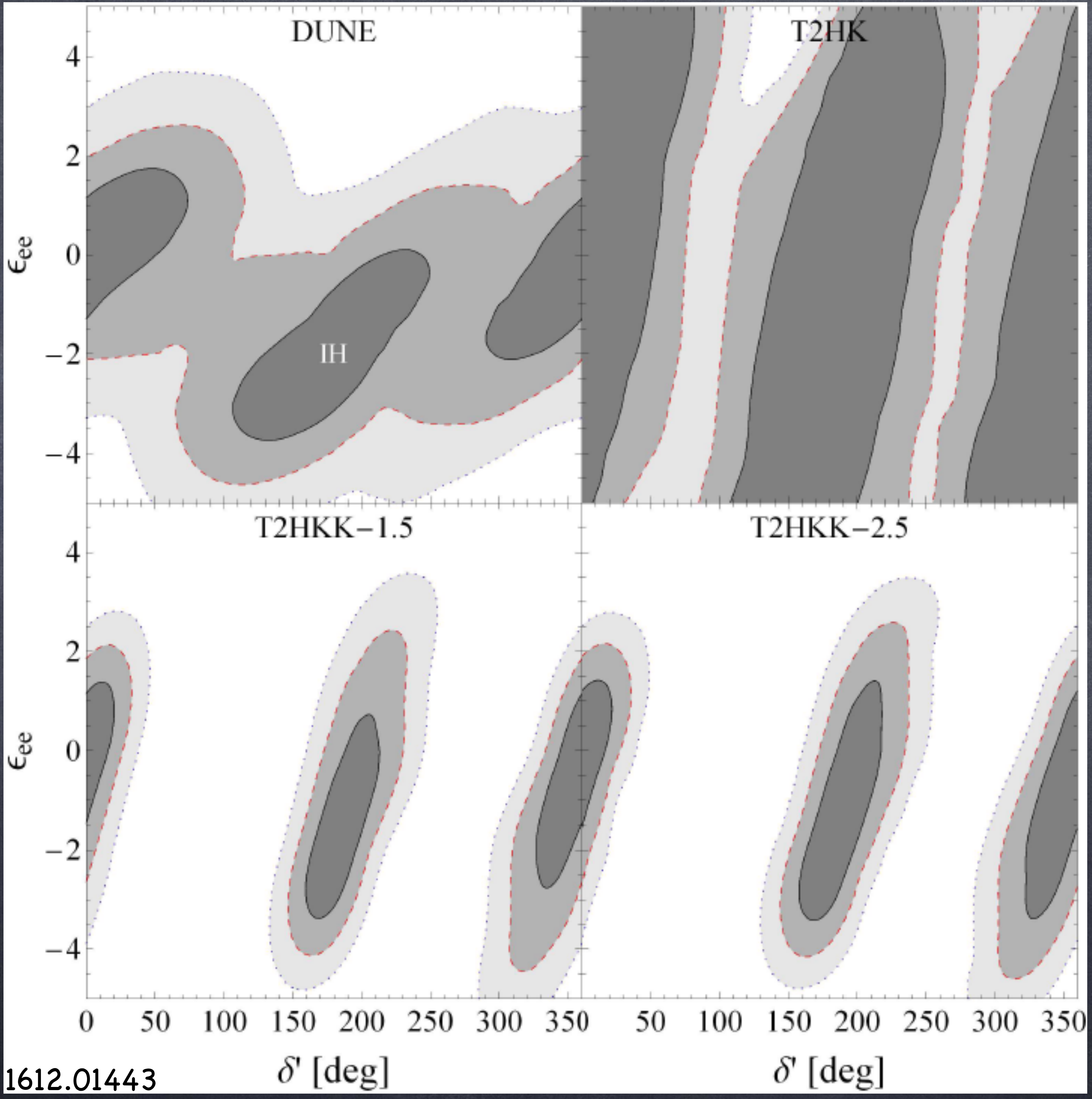
Hierarchy not resolved
Wrong determination of the CP phase possible

3 NSI parameters



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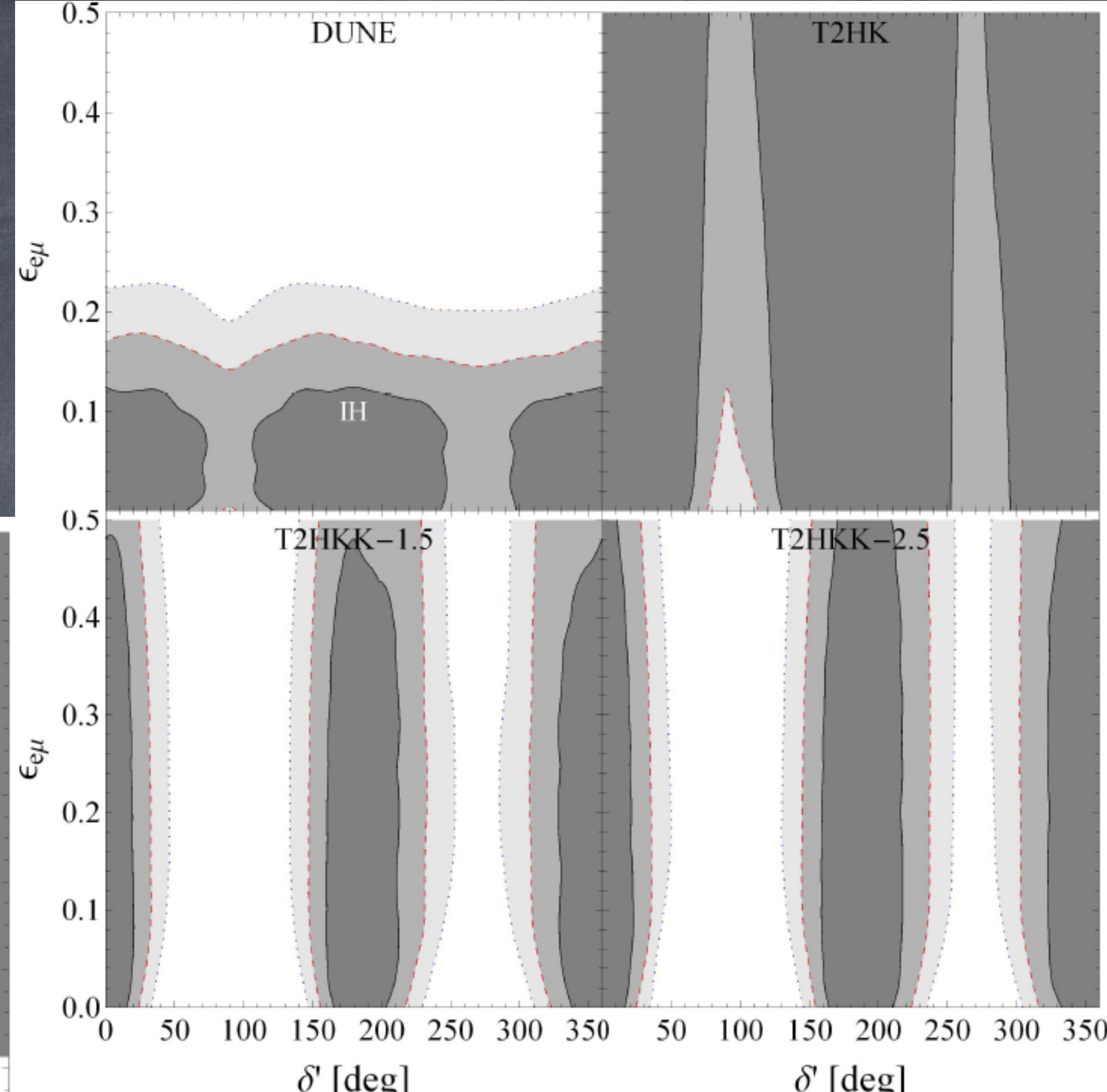
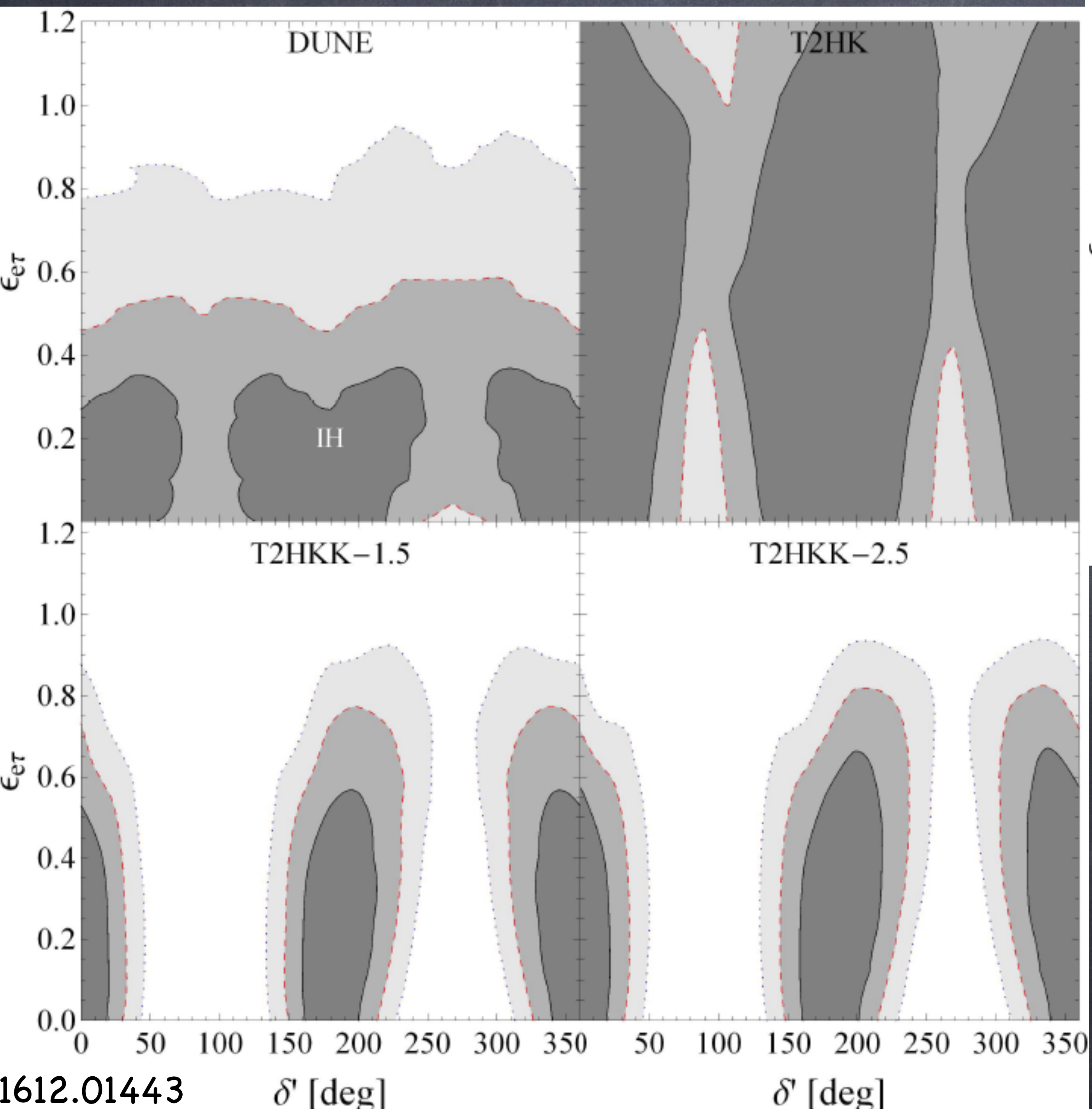
Constraint on $\epsilon_{e\mu}$ much weaker at T2HK and T2HKK





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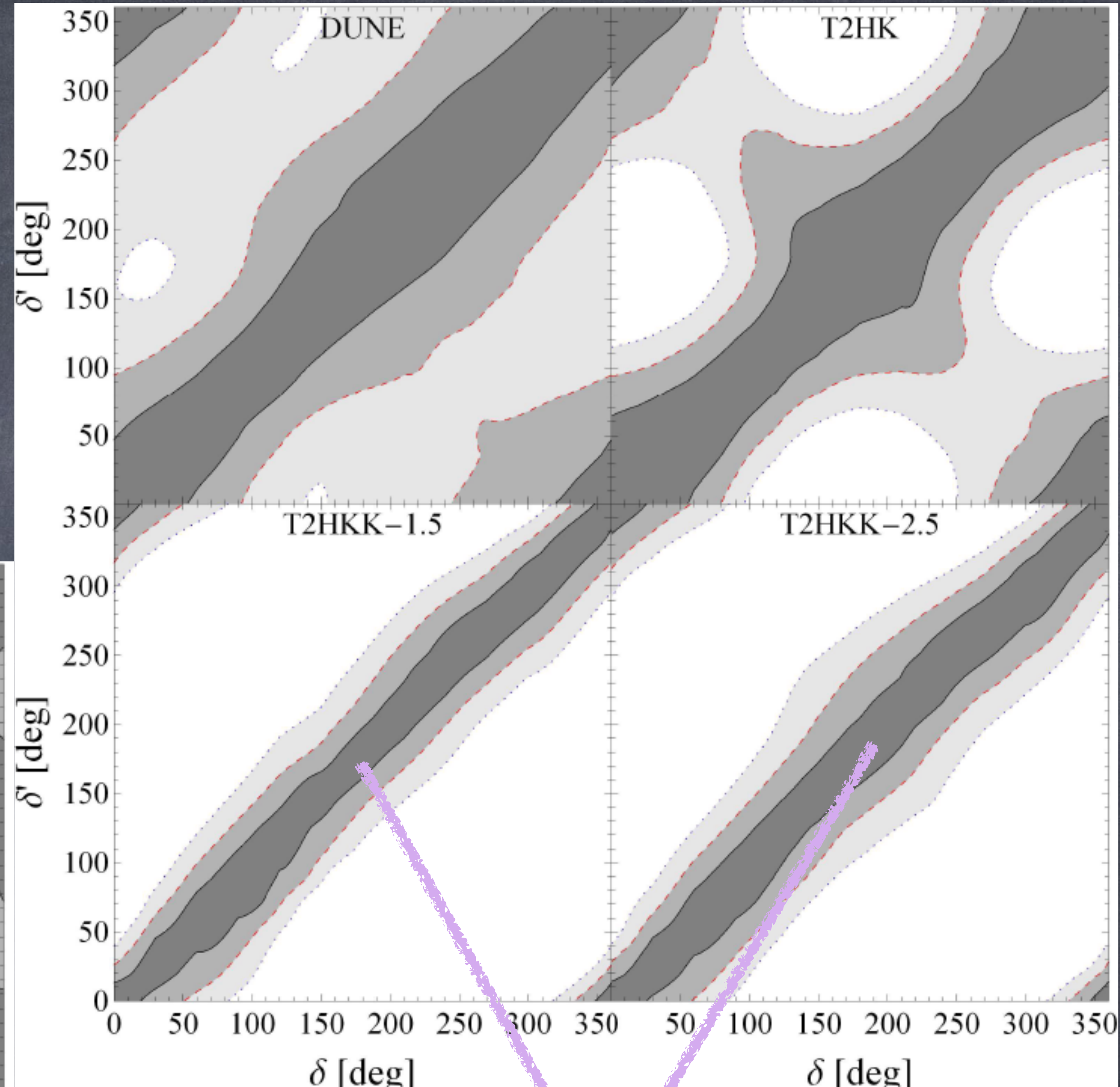
$$\epsilon_{e\mu} = \tan\theta_{23}\epsilon_{e\tau}$$

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

CP sensitivity

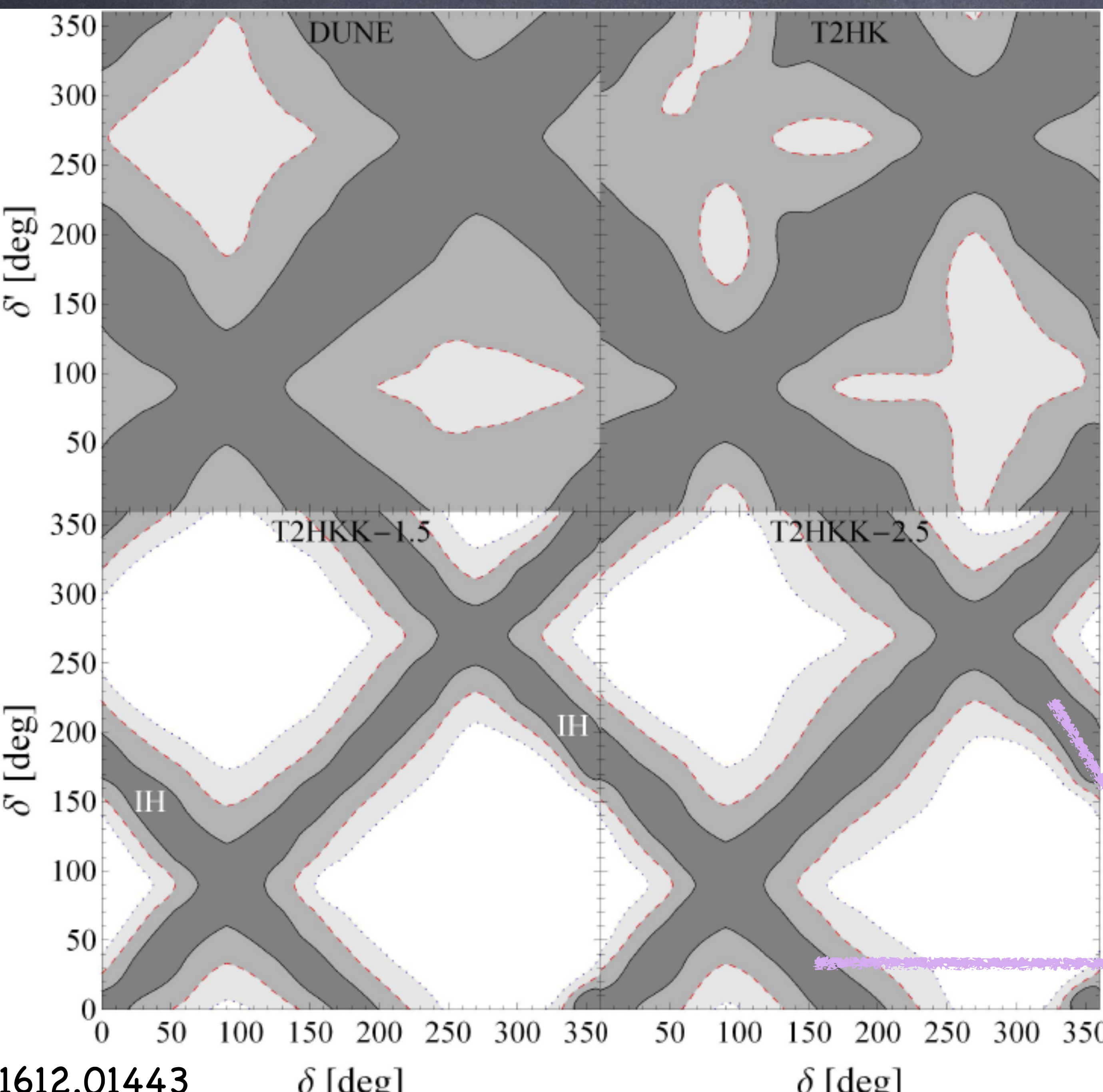
MH known

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



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

MH unknown



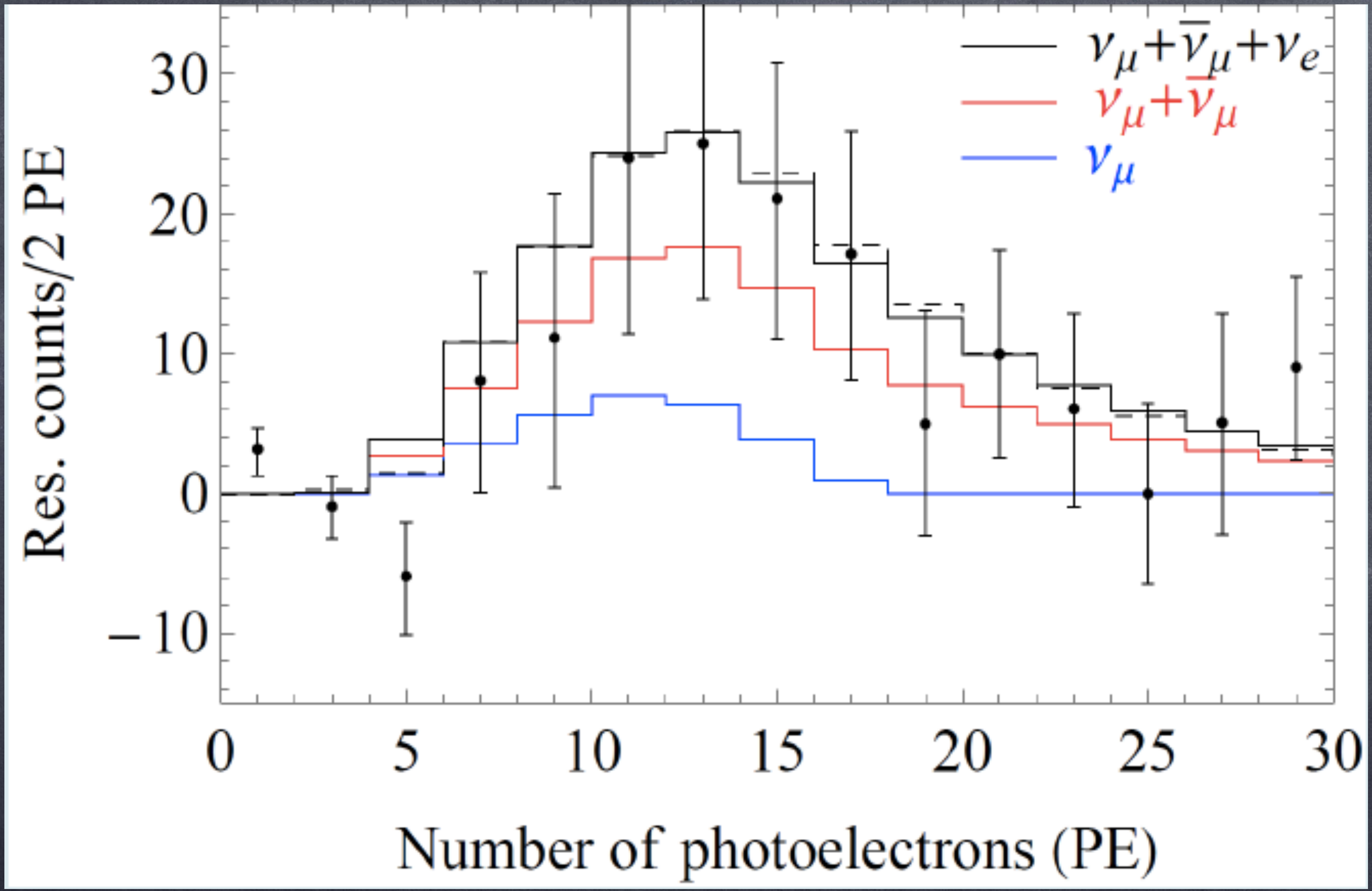
IH and $\delta' = 180 - \delta$

1612.01443

COHERENT

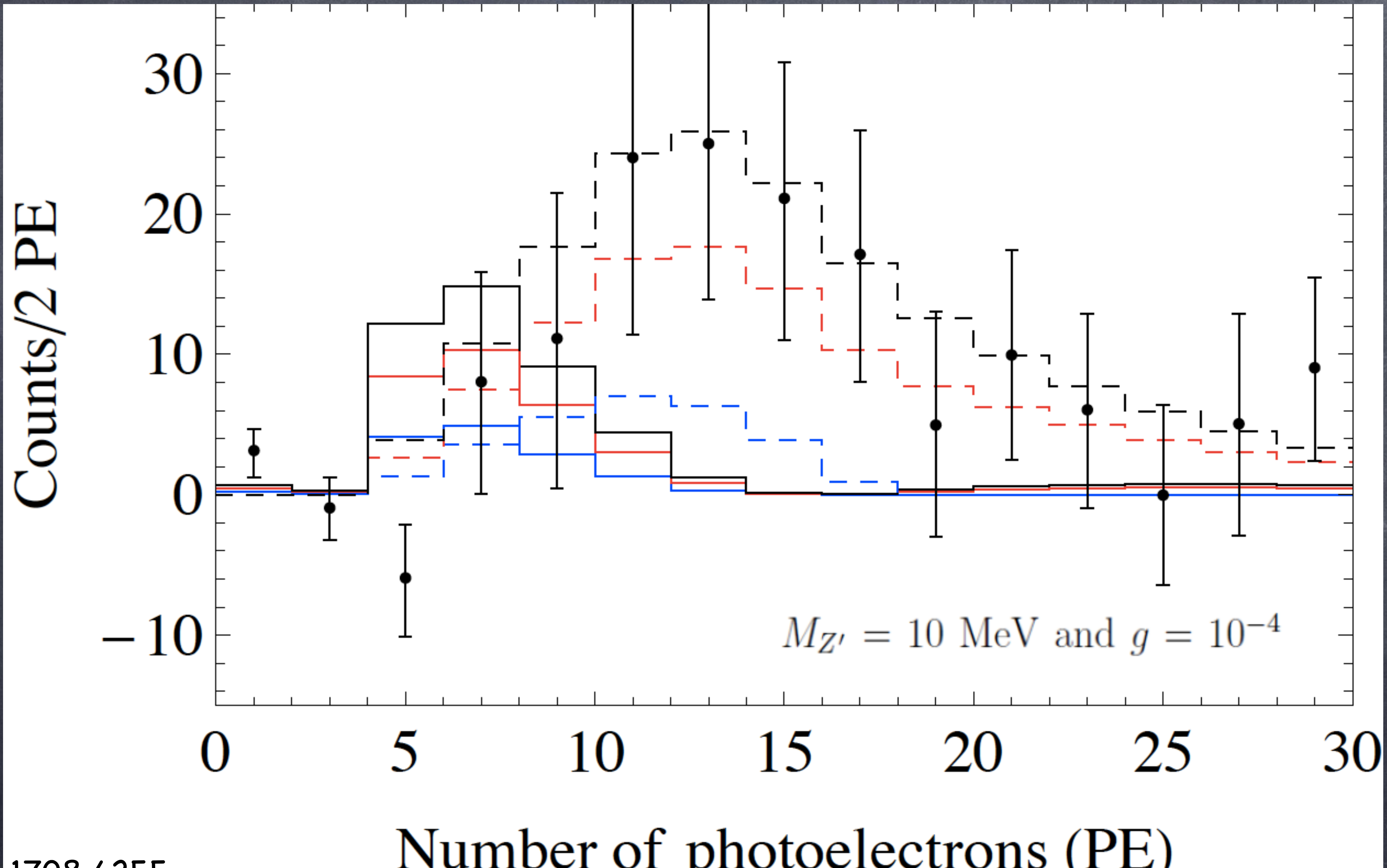
- Has seen CEvNS on 14.6 kg of CsI at 6.7 sigma
- Data are consistent with SM at 1.5 sigma
- Can probe NSI under contact approximation provided mediator is heavier than momentum transfer, 50 MeV
- Spectrum constrains coupling for any mediator mass
- Sensitive only to spin-independent interactions

Standard Model spectrum



$$Q^2_{\alpha,\mathrm{SM}} = \left(Z g_p^V + N g_n^V\right)^2 \qquad g_n^V = -\frac{1}{2} \simeq -10 g_p^V$$

Light vector mediator: $\mathcal{L}_{\rm NSI} = -g\left(\bar{\nu}\gamma^\rho\nu + \bar{\mu}\gamma^\rho\mu + \bar{u}\gamma^\rho u + \bar{d}\gamma^\rho d\right) Z'_\rho$



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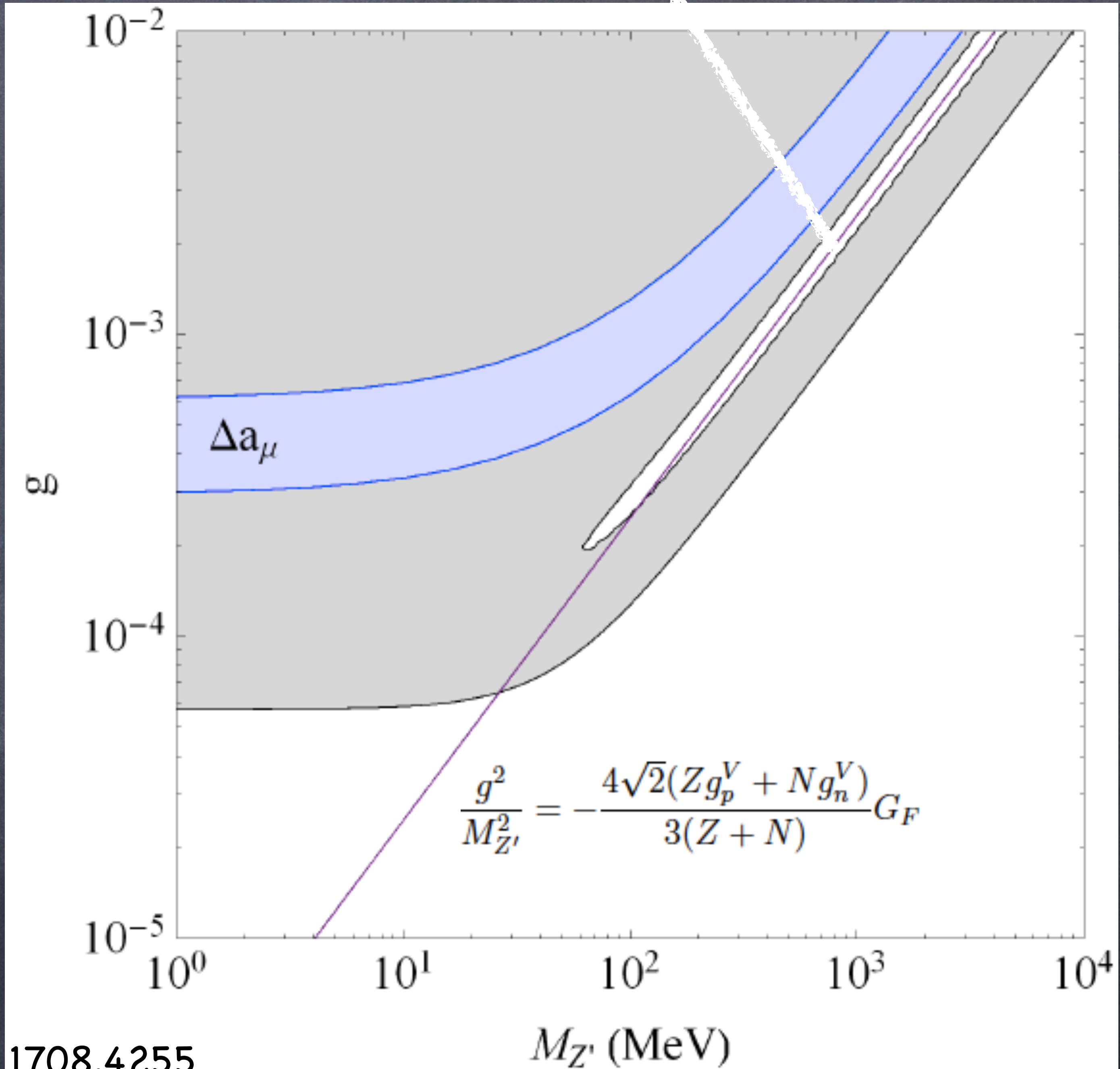
$$Q^2_{\alpha,\rm NSI} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$

$$\epsilon_{eff} \propto \frac{g^2}{2ME_r + M_{Z'}^2}$$

- For heavy mediator, data sensitive to g/M_Z'
- For light mediator, sensitivity to g only. NSI matter effect due to forward scattering depends on g/M_Z', so constraint does not apply to matter NSI arising from light mediator
- Spectral information breaks degeneracy for light mediator

$$Q_{\alpha,\mathrm{NSI}} = -Q_{\alpha,\mathrm{SM}}$$



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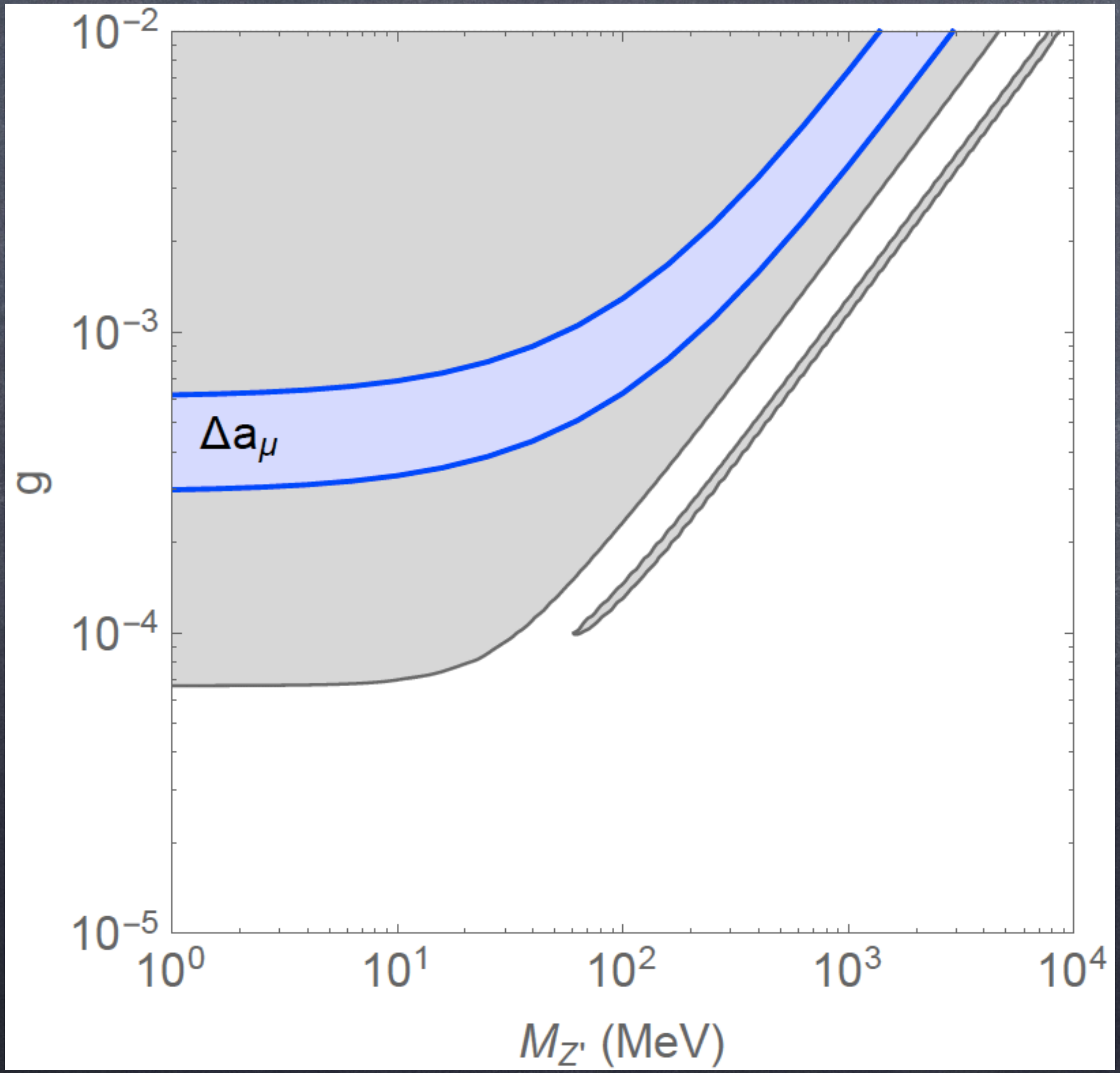
Introduce lepton non-universality to have matter effects

$$\mathcal{L}_{\rm NSI} = -g\left(\bar{\nu}\gamma^\rho\nu + \bar{\mu}\gamma^\rho\mu + \bar{u}\gamma^\rho u + \bar{d}\gamma^\rho d\right) Z'_\rho$$

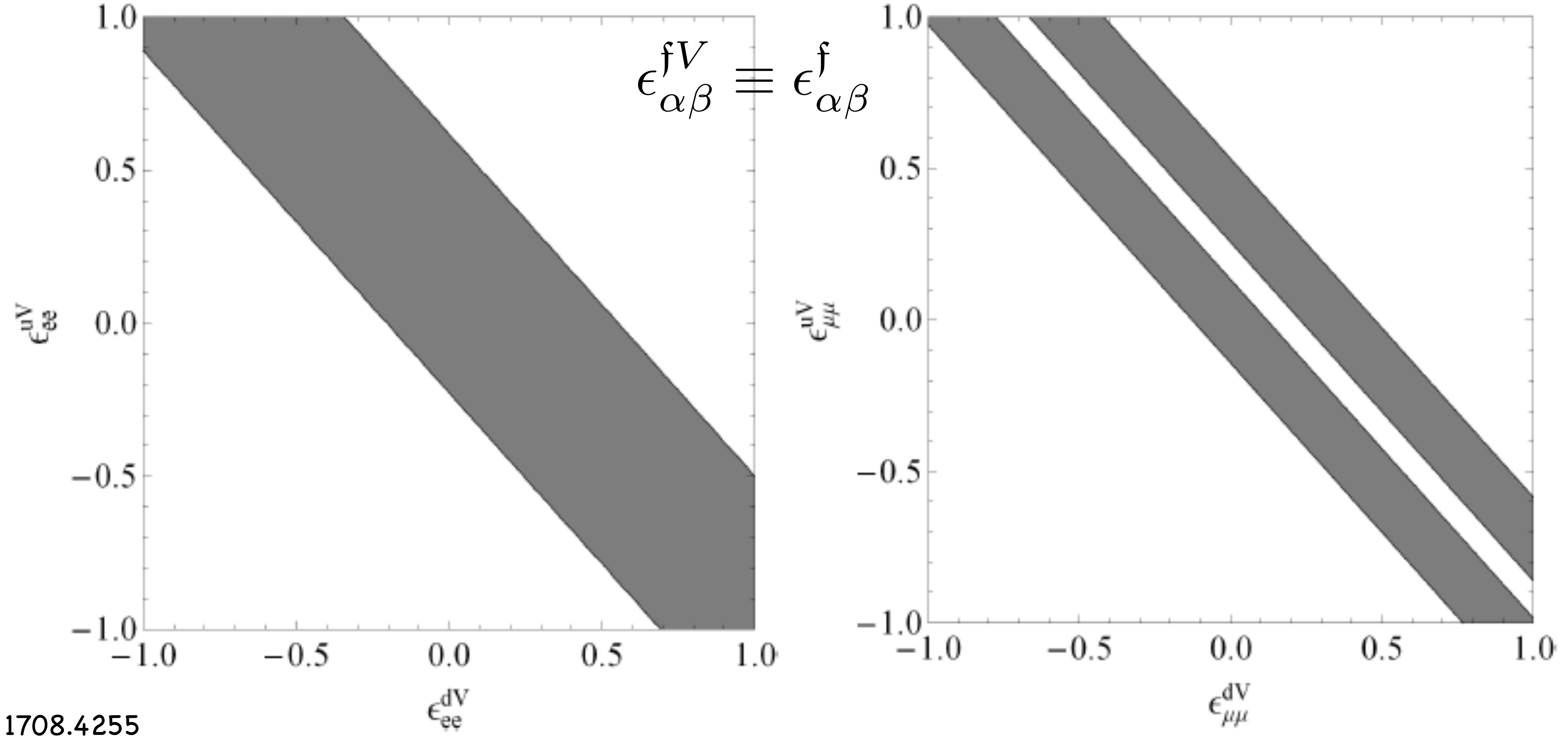
... but no ν_e coupling



Heavy vector mediator: $\mathcal{L}_{\rm NSI} = -\sqrt{2}G_F \sum_{\alpha,\beta,\mathfrak{f}} \epsilon^{\mathfrak{f}}_{\alpha\beta} \left[\overline{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right]\left[\bar{\mathfrak{f}}\gamma_\rho \mathfrak{f}\right]$

$$Q_\alpha^2 = \left[Z(g_p^V + 2\epsilon^u_{\alpha\alpha} + \epsilon^d_{\alpha\alpha}) + N(g_n^V + \epsilon^u_{\alpha\alpha} + 2\epsilon^d_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\epsilon^u_{\alpha\beta} + \epsilon^d_{\alpha\beta}) + N(\epsilon^u_{\alpha\beta} + 2\epsilon^d_{\alpha\beta})\right]^2$$

$$Zg_p^V + Ng_n^V = \pm\left[Z(g_p^V + 2\epsilon^u_{ee} + \epsilon^d_{ee}) + N(g_n^V + \epsilon^u_{ee} + 2\epsilon^d_{ee})\right]$$



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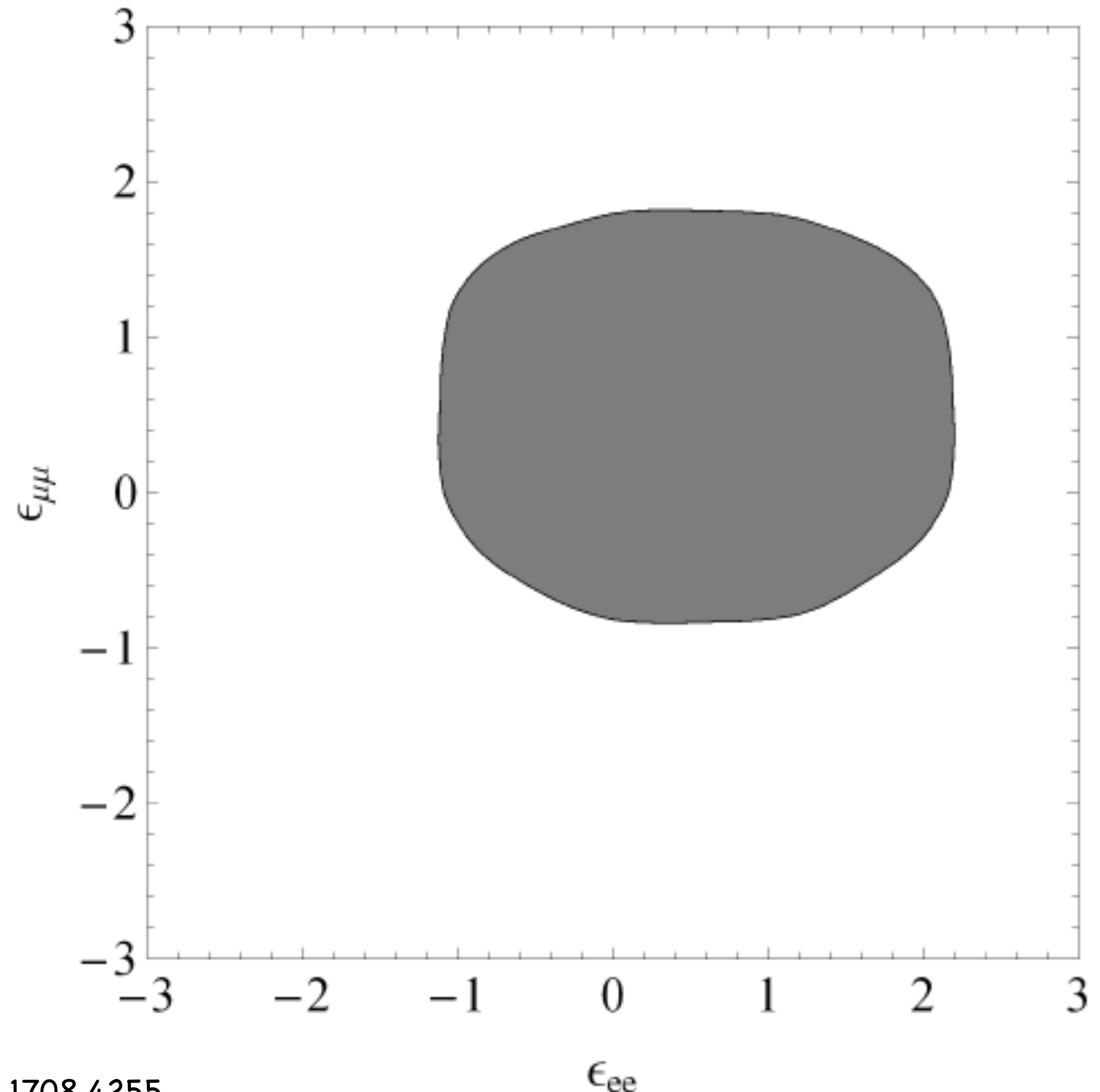
Matter NSI $\epsilon_{\alpha\alpha} \approx 3(\epsilon^u_{\alpha\alpha} + \epsilon^d_{\alpha\alpha})$



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Sterile neutrino NSI

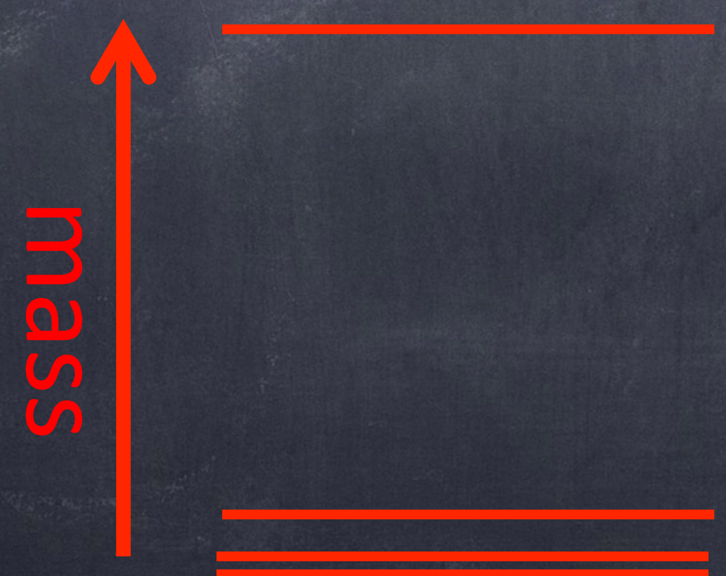
LSND

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

Baseline: 30 m

Maximum energy: 53 MeV

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



MiniBooNE

$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

Baseline: 500 m

Average energy: 800 MeV

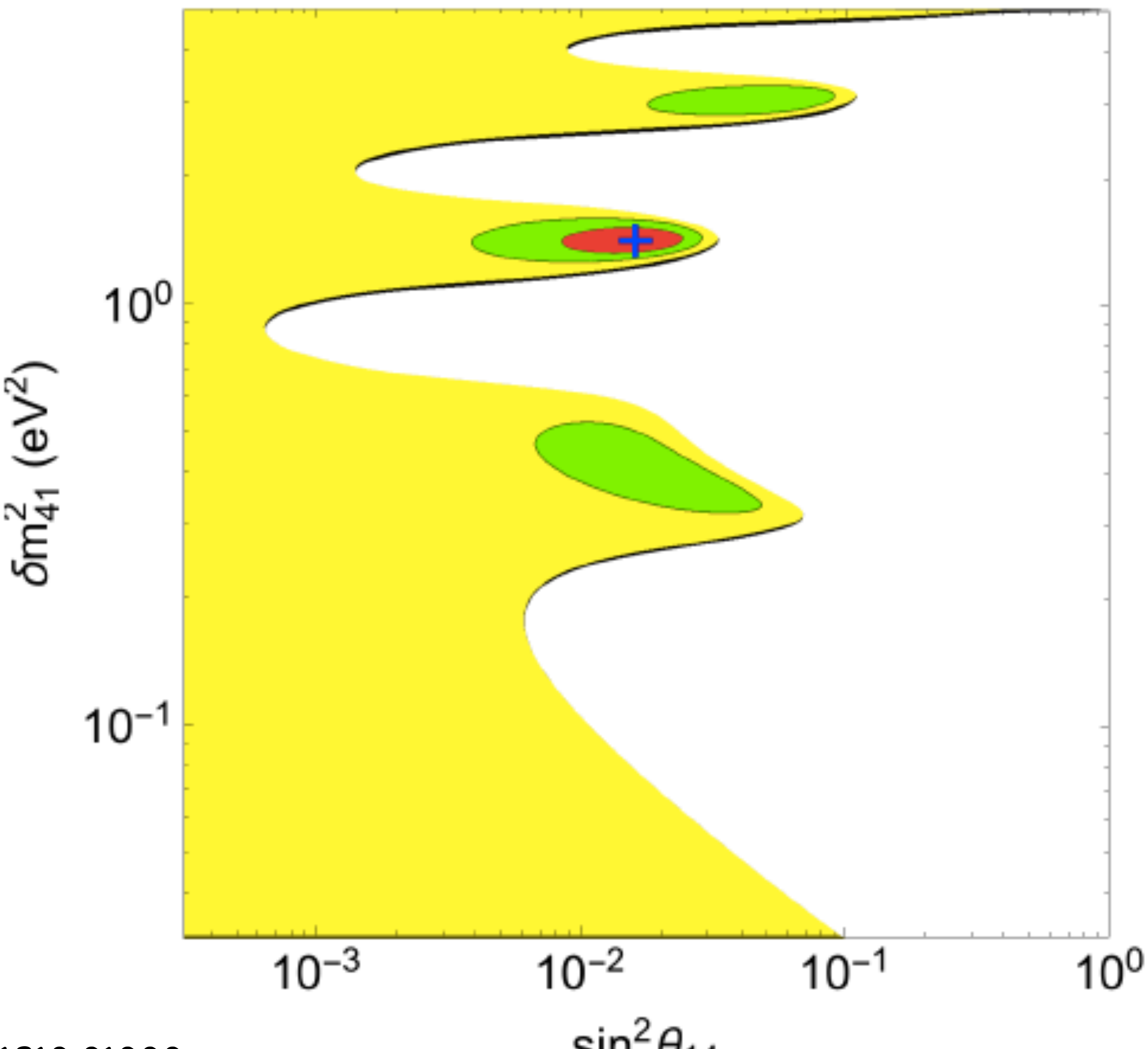
$$L/E \sim 1\ \mathrm{km/GeV} \implies \Delta m^2 \sim 1\,\mathrm{eV}^2$$

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



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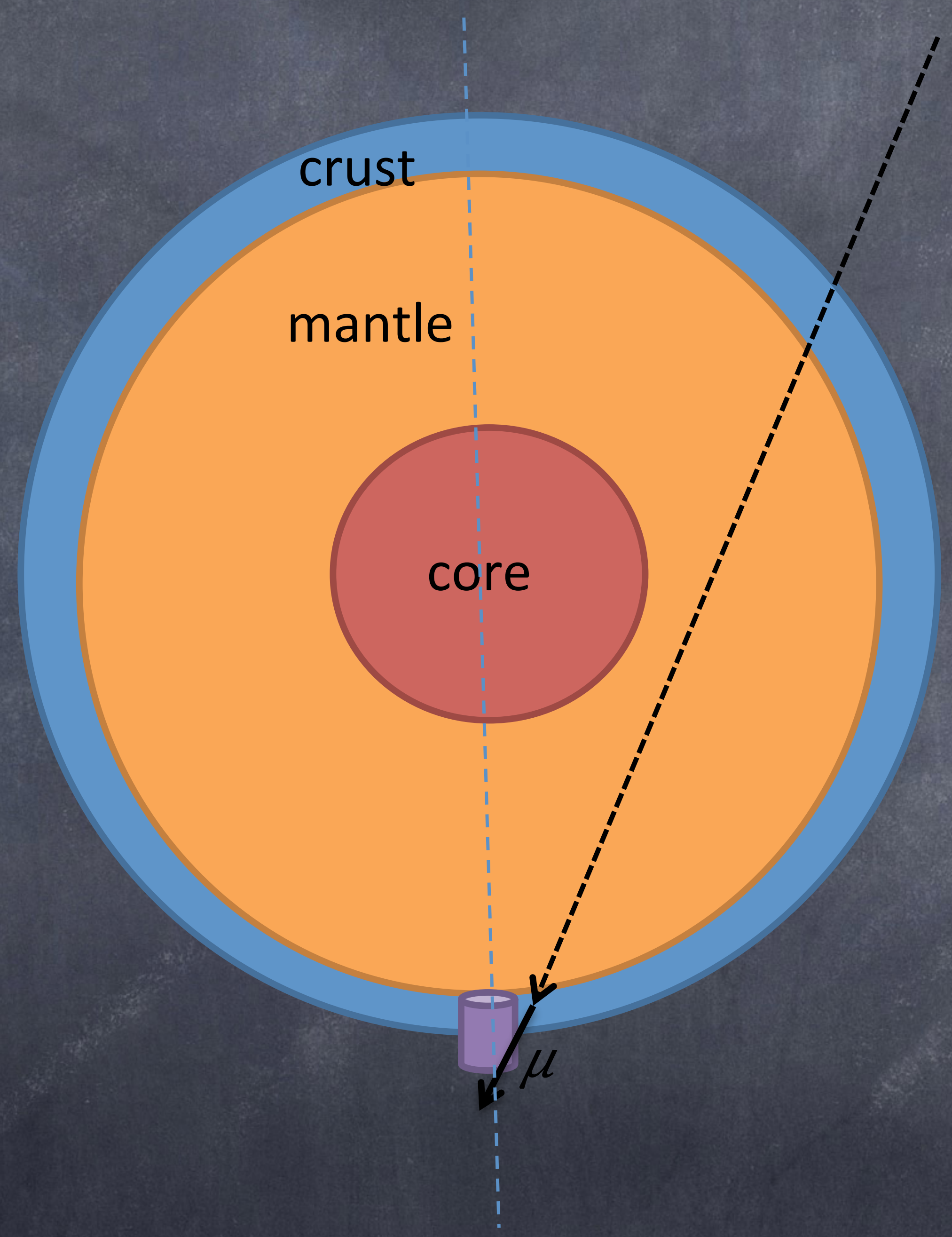
IceCube/DeepCore



Focus on (anti)muon neutrino survival probabilities

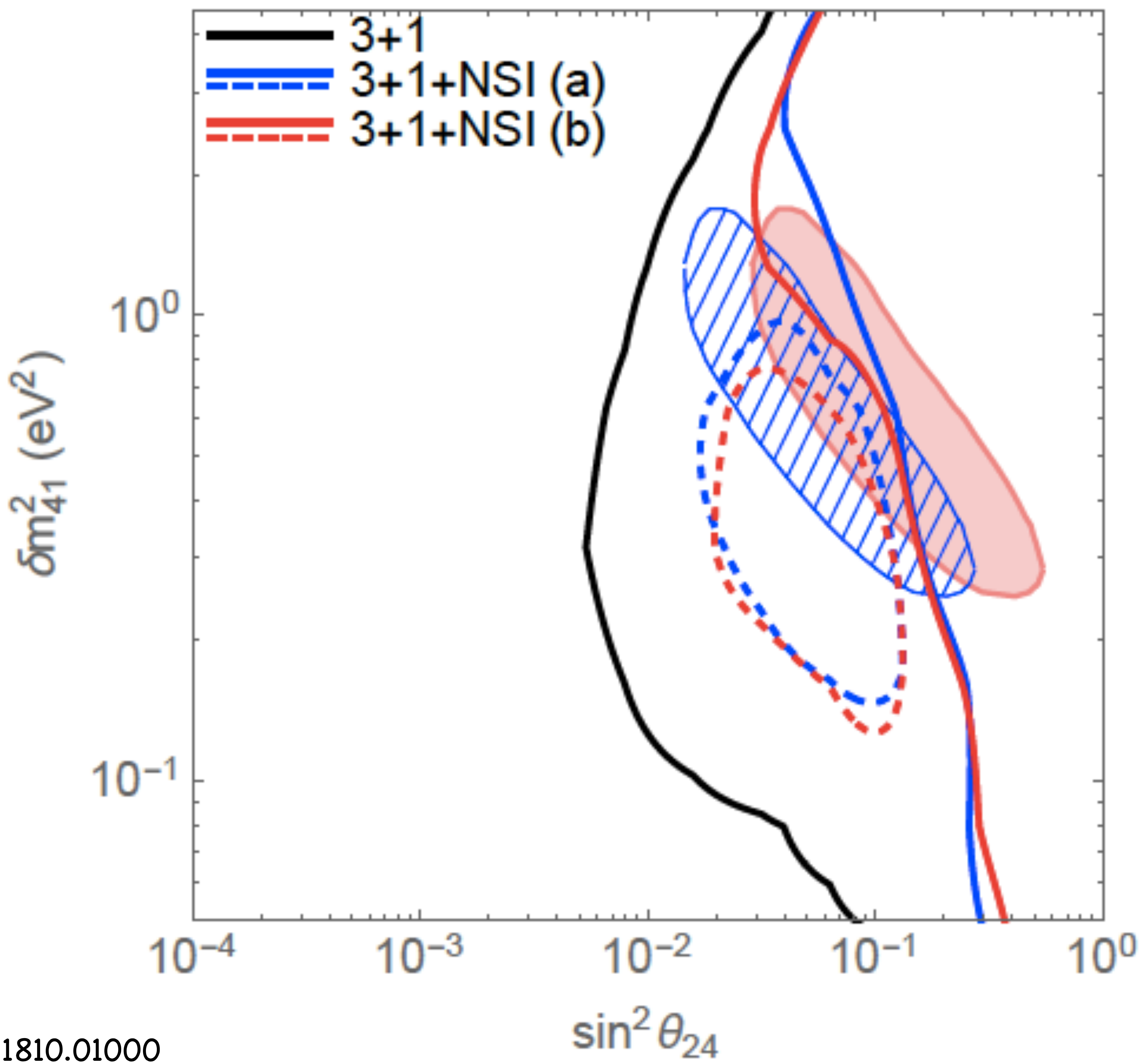
Resonant 3+1 atmospheric neutrino oscillations

Oscillation maximum in vacuum: $\frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{10^3\ \mathrm{km}} \frac{\mathrm{TeV}}{E} \sim 1$

Resonance condition in earth matter:

$$\Delta m^2_{41} \cos 2\theta_{24} \simeq \mp 1\ \mathrm{eV}^2\ \frac{E}{5\ \mathrm{TeV}}$$

Resonance occurs in antineutrino channel


3+1
3+1+NSI (a)
3+1+NSI (b)
10^0
10^{-1}
δm^2_{41} (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2\theta_{24}$

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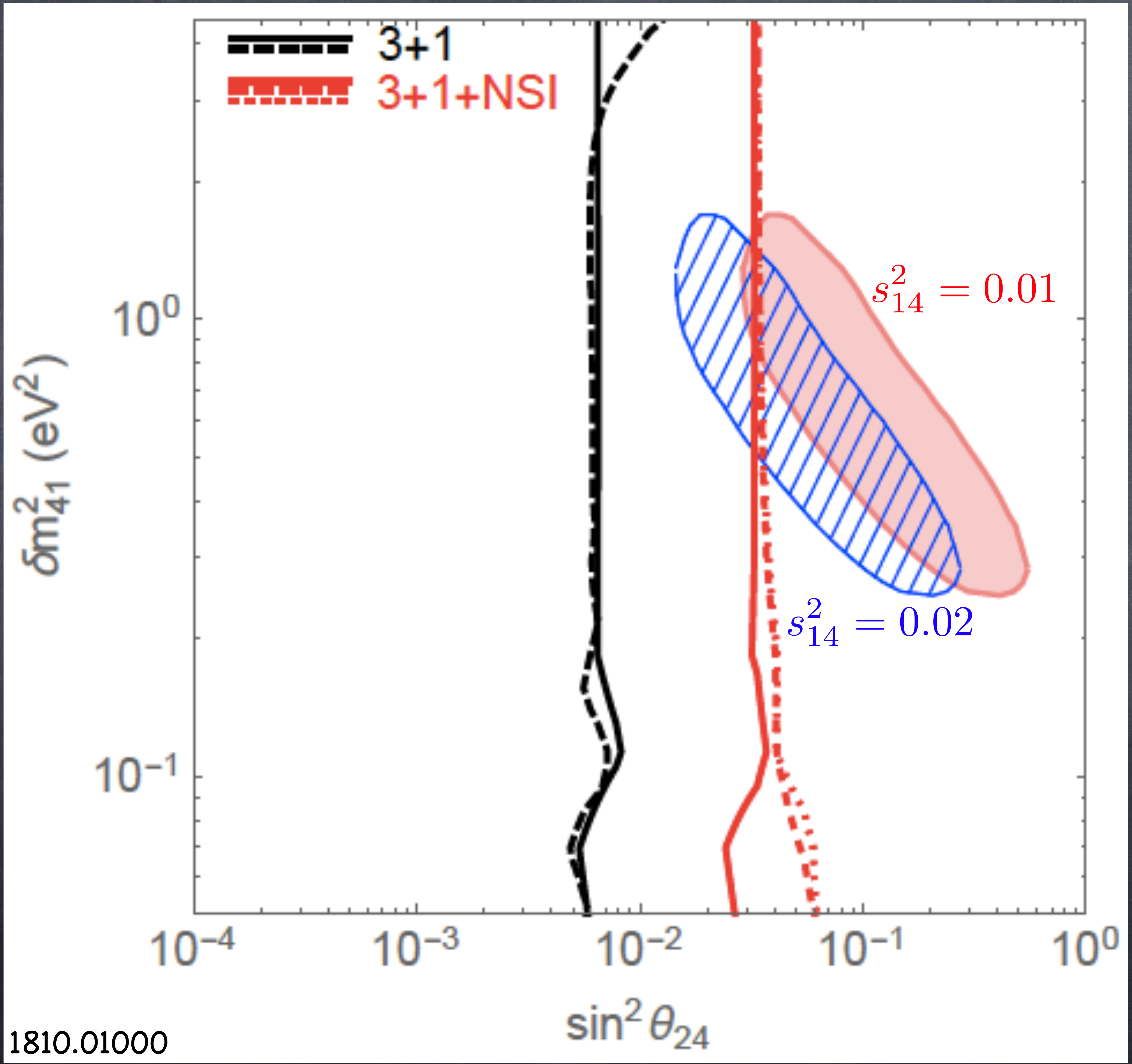
MINOS/MINOS+



3+1
3+1+NSI
$s^2_{14} = 0.01$
$s^2_{14} = 0.02$
10^0
10^{-1}
δm^2_{41} (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2\theta_{24}$
1810.01000

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

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

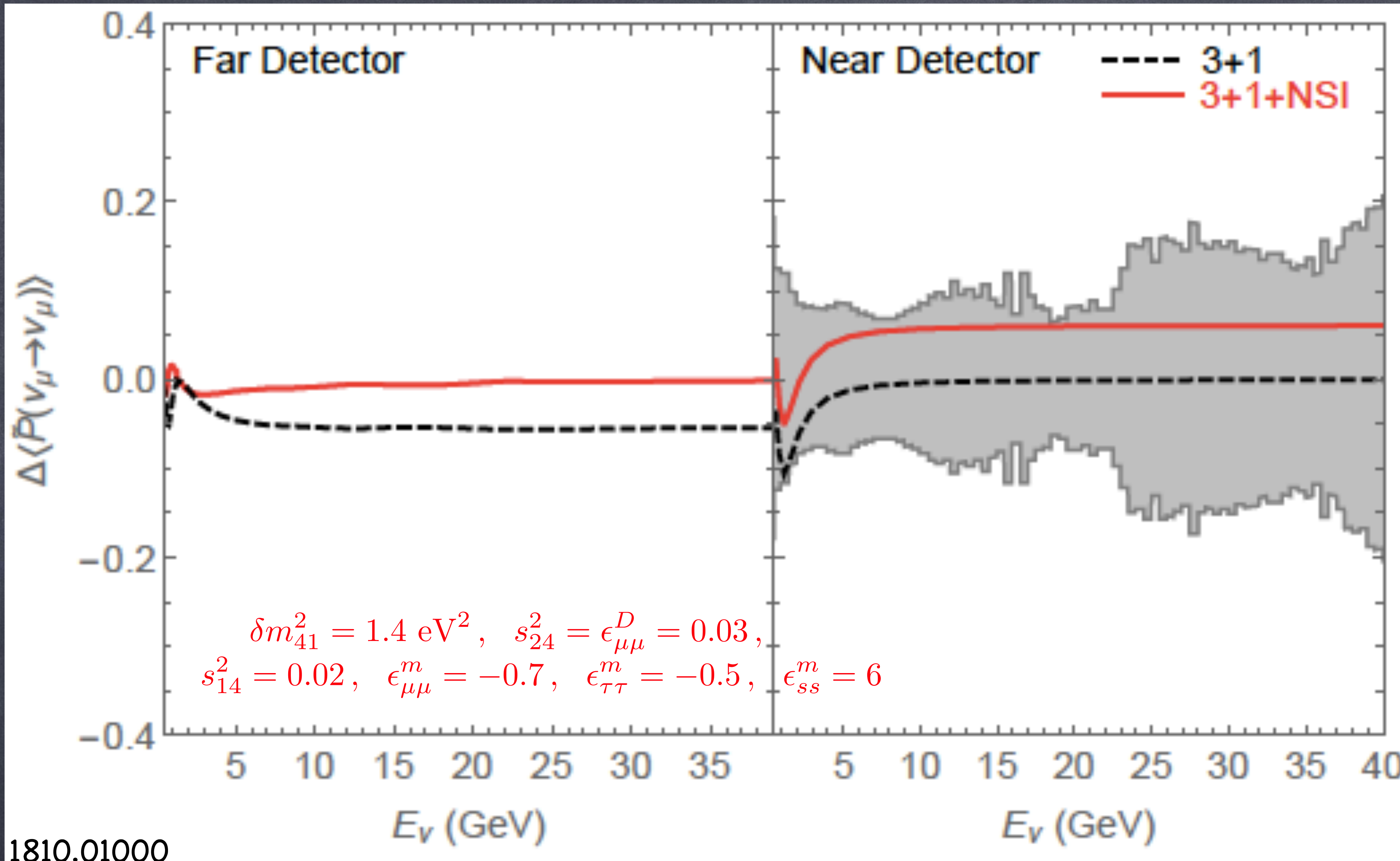
$$H = \frac{1}{2E} \left[V \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 & 0 \\ 0 & 0 & \delta m_{31}^2 & 0 \\ 0 & 0 & 0 & \delta m_{41}^2 \end{pmatrix} V^\dagger + V_{\rm m} \right]$$

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

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

Try hard to use Occam's razor!

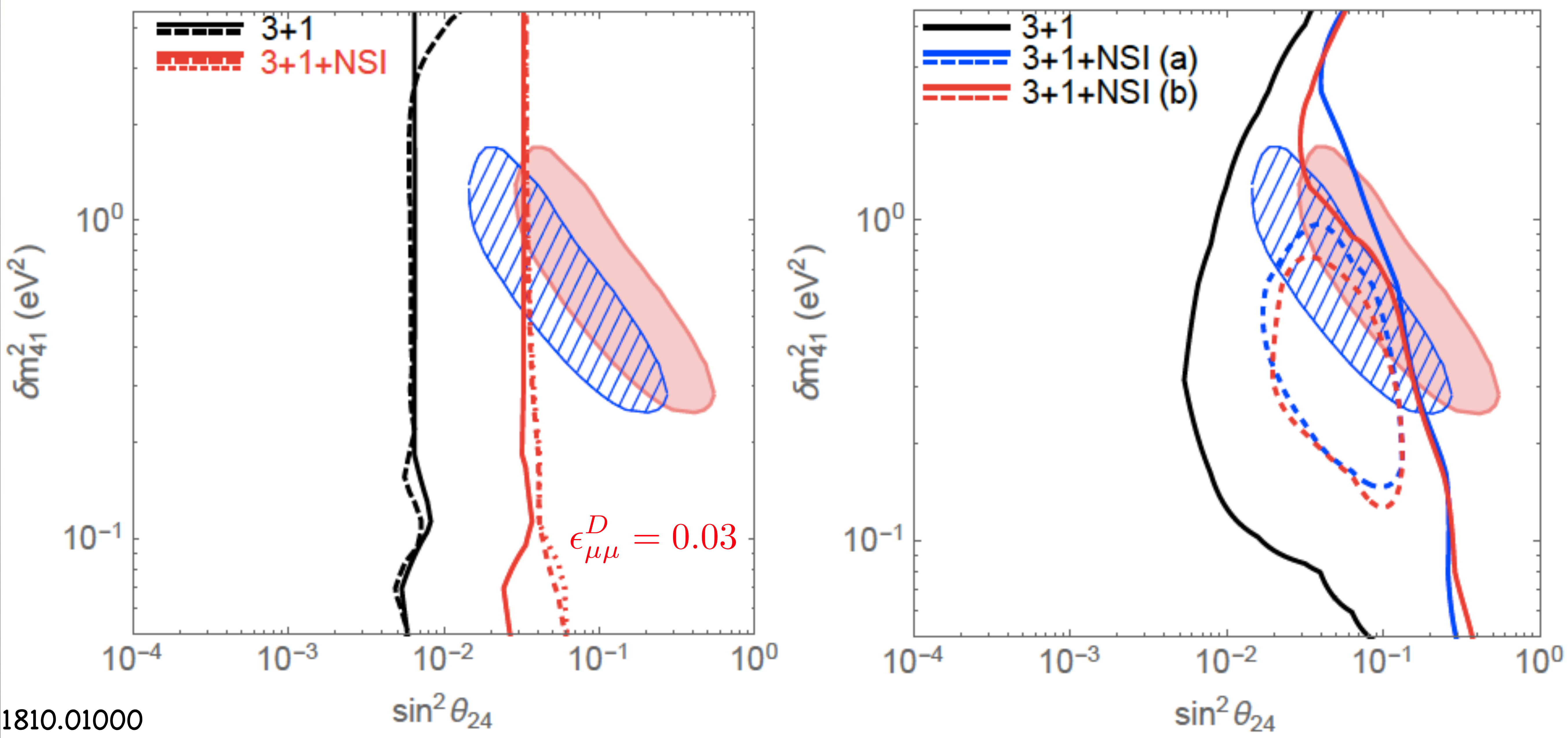
- Vector-like CC interaction contributes NSI at detector, but not at pion source
- Only nonzero CC NSI parameter is $\epsilon^{D}_{\mu\mu} = 2\epsilon^{udL}_{\mu\mu}$
- Nonzero NC NSI parameters: $\epsilon^{m}_{\mu\mu}$, $\epsilon^{m}_{\tau\tau}$, ϵ^{m}_{ss}



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

$$\epsilon^D_{\mu\mu} \simeq s^2_{24}$$

$$\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau} \simeq s^2_{24}(\epsilon^m_{\mu\mu} - \epsilon^m_{ss} - \kappa)$$



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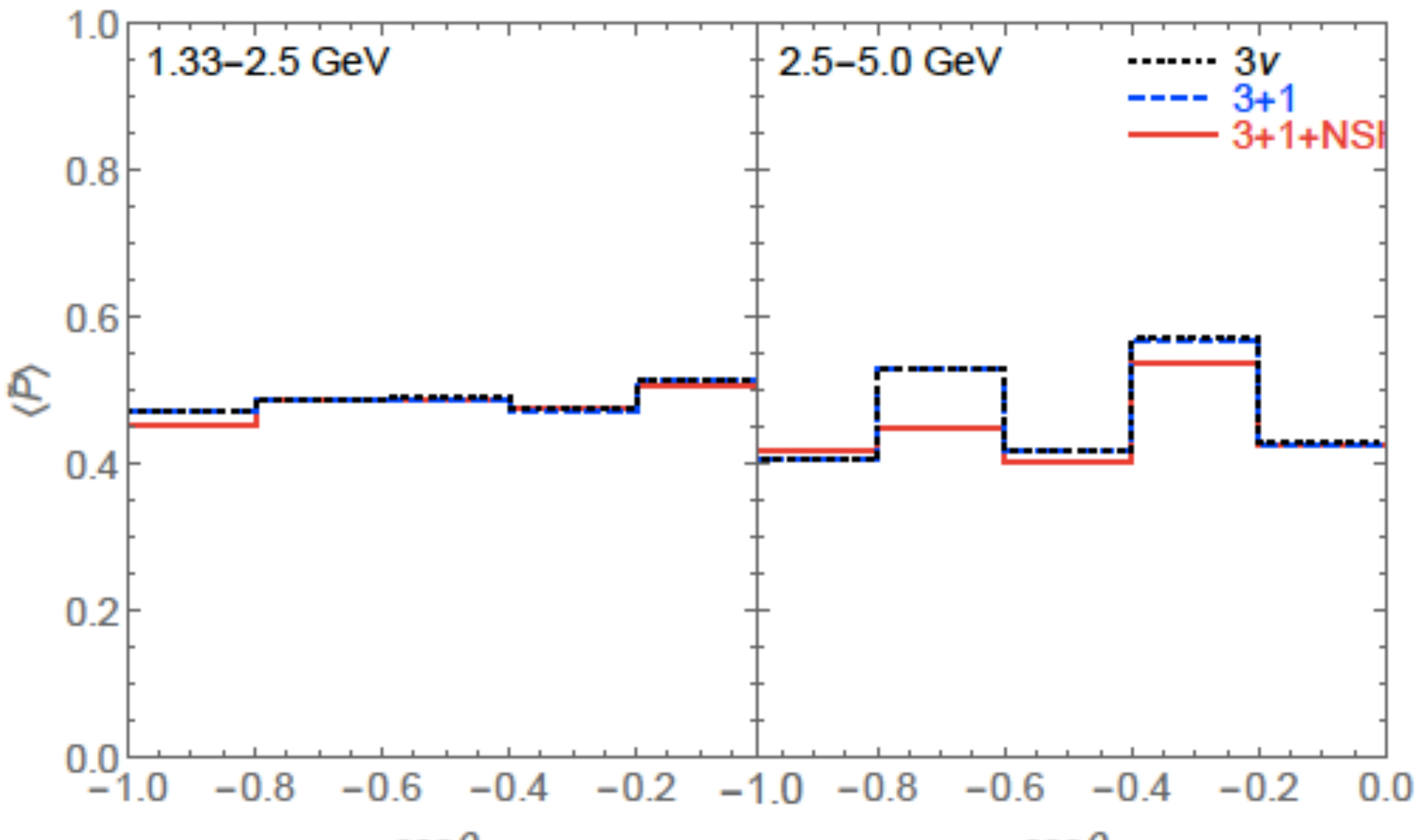
$$(a) \quad |\epsilon^m_{\tau\tau}| < 6\,, \quad |\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau}| < 0.5$$

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

Super-Kamiokande



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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

- COHERENT bounds on matter NSI parameters obtained using contact approx don't apply for mediators lighter than 50 MeV

- For heavy mediators, COHERENT places meaningful constraints on effective NSI parameters for propagation in Earth

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