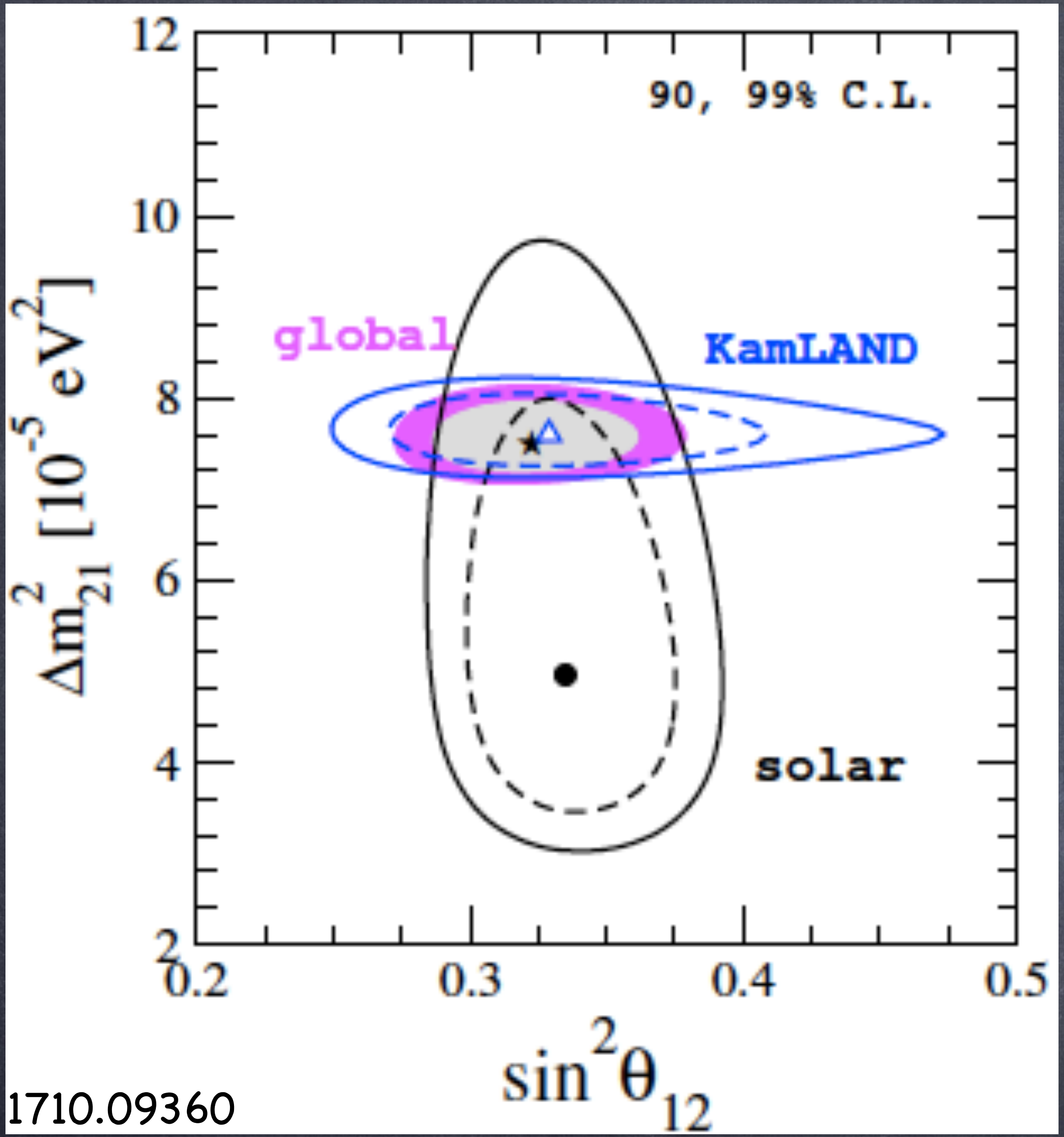
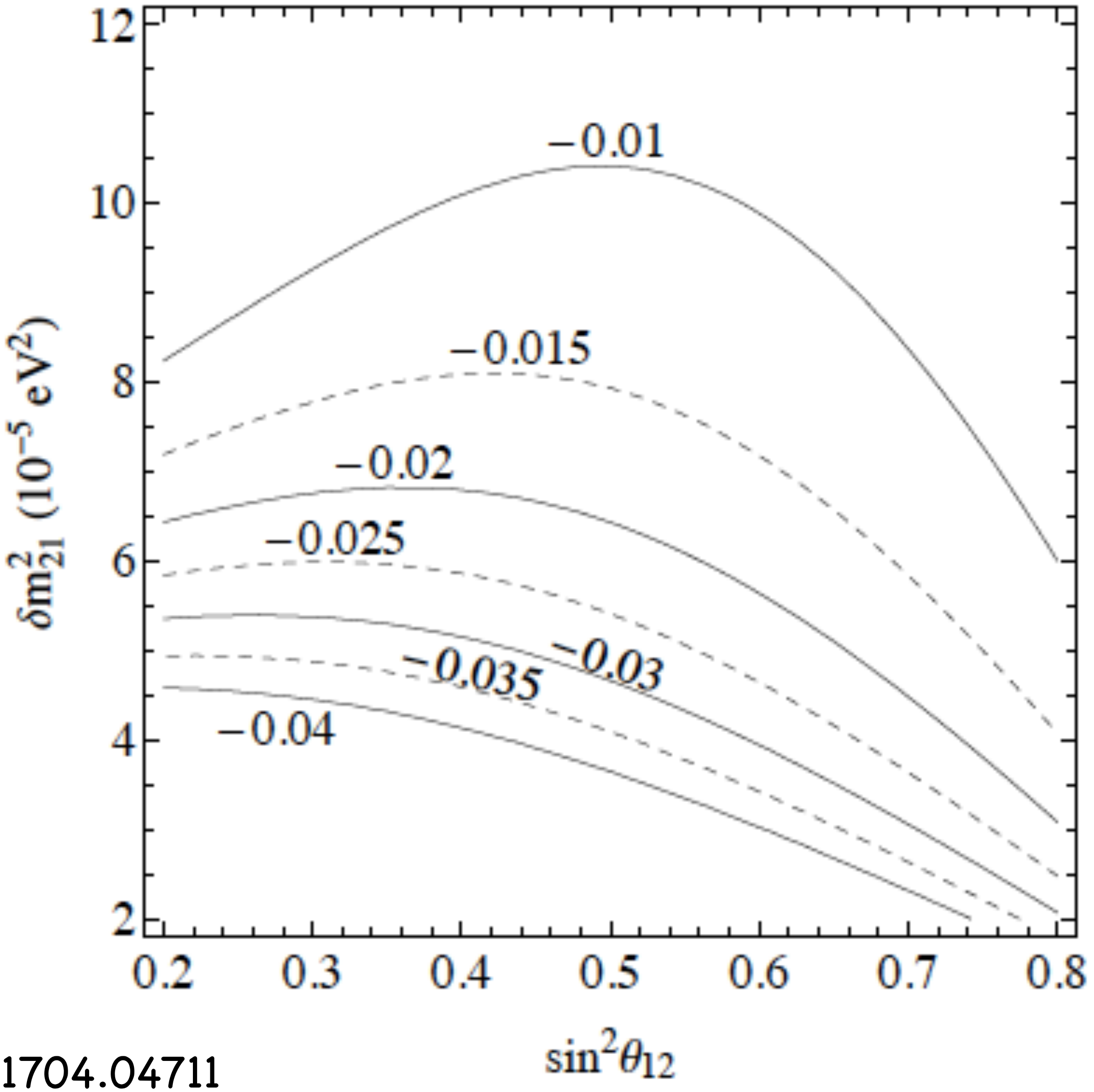
General neutrino interactions

Possible tension in standard oscillation picture



1710.09360



1704.04711

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

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

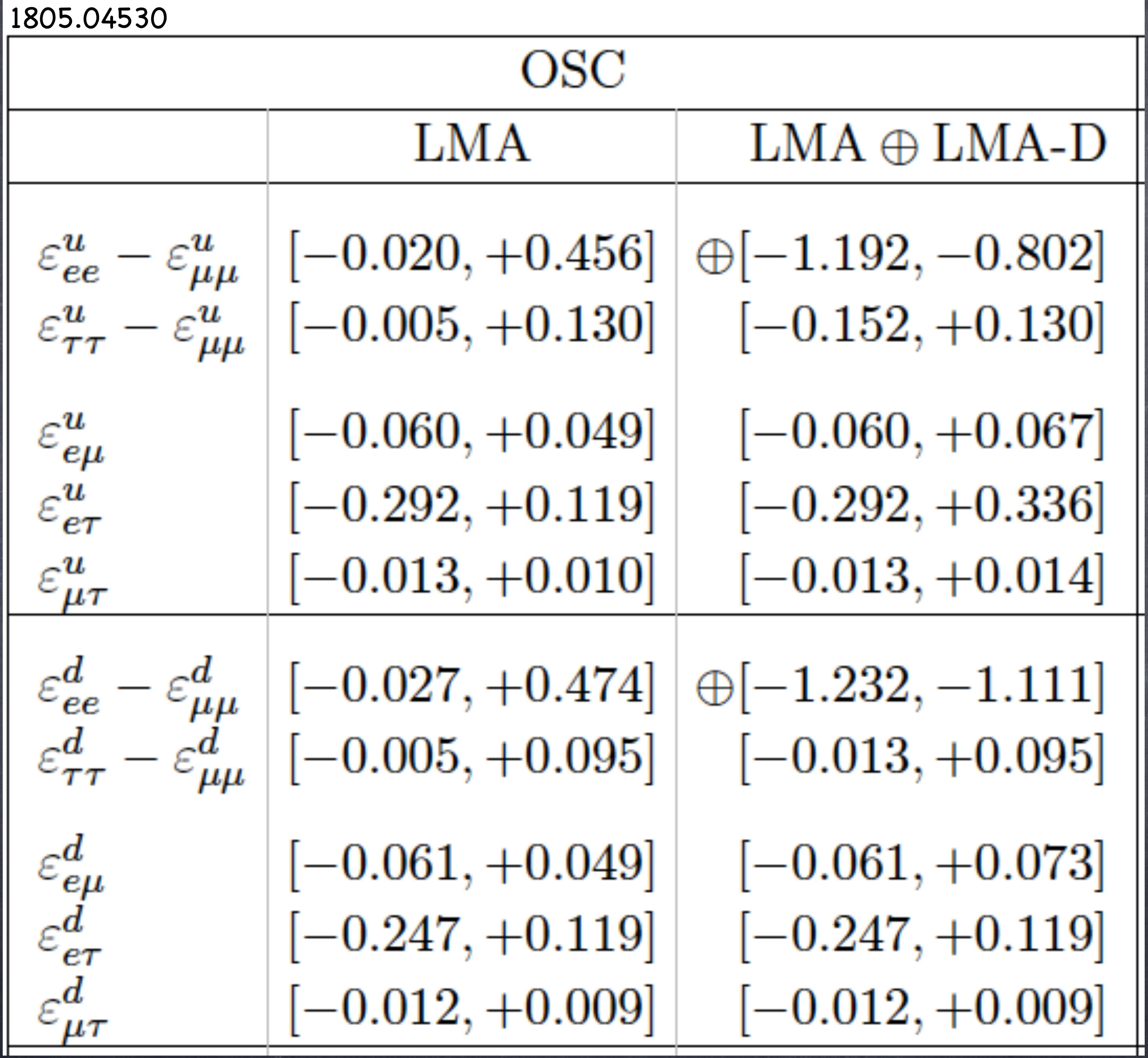
$$\alpha,\beta = e,\mu,\tau, \quad C = L, R, \quad \mathfrak{f} = u, d, e$$

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

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 $N_u = N_d = 3N_e$

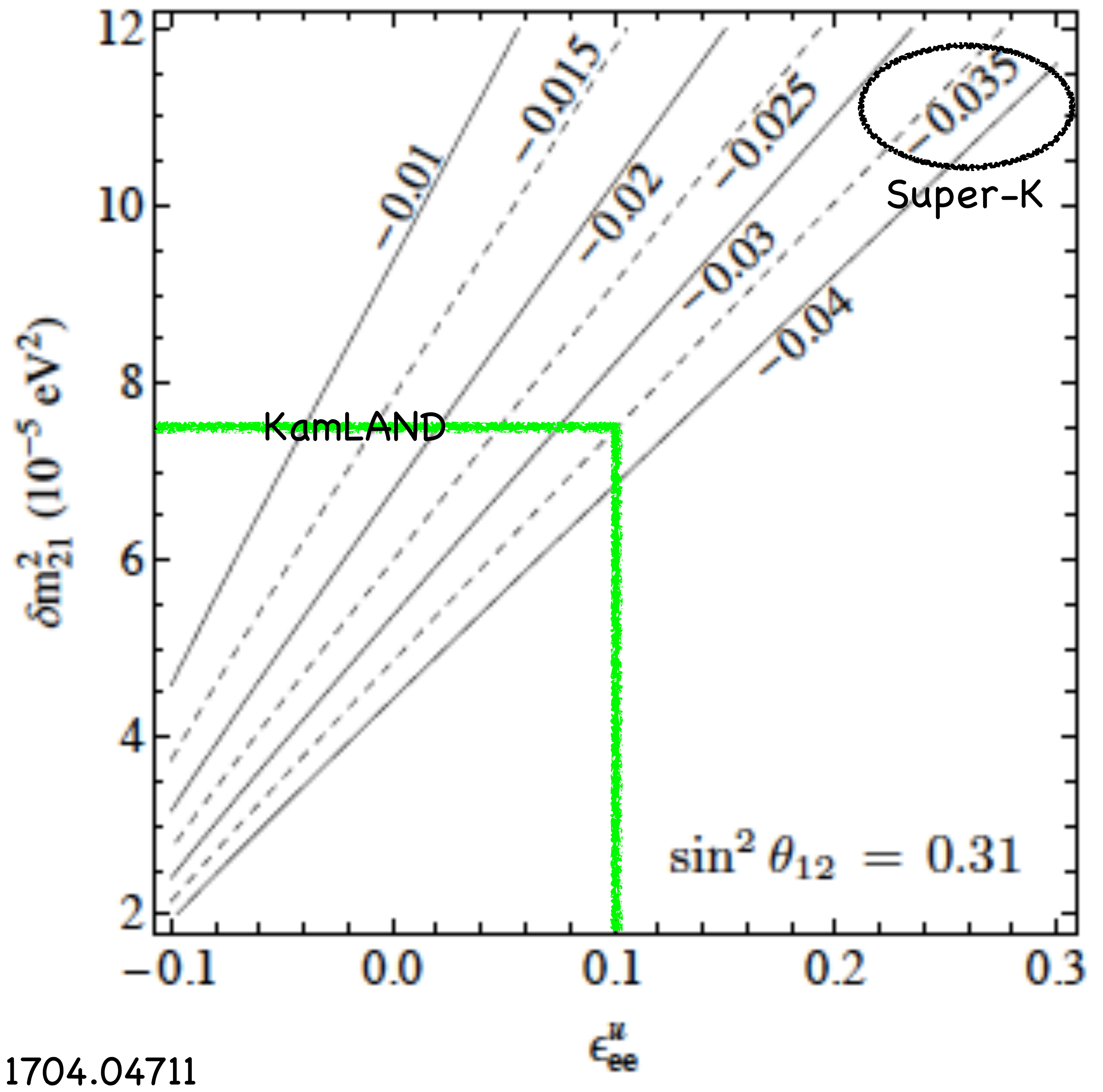


1805.04530

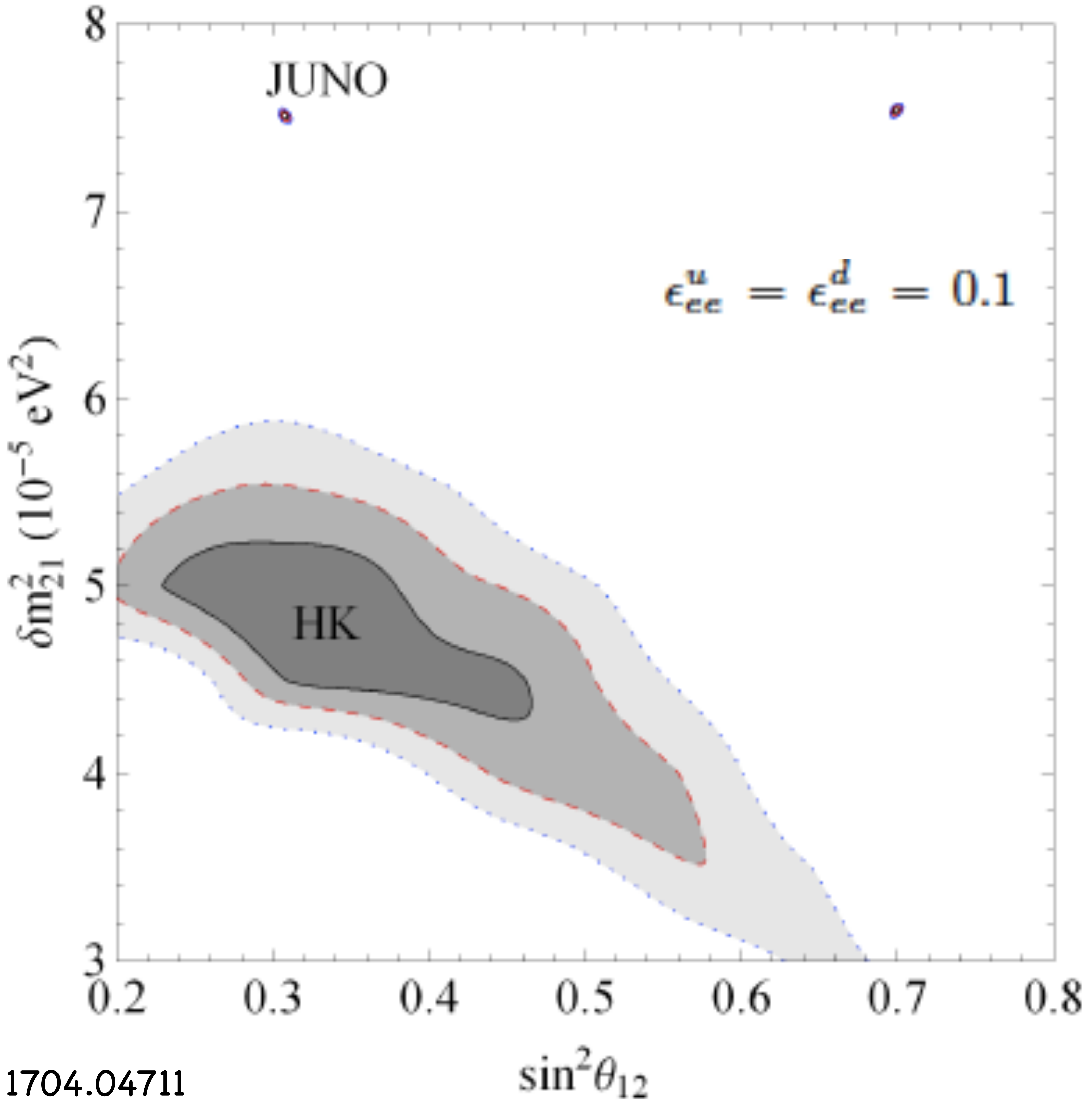
	OSC	
	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$

New matter effects if NSI violate lepton universality or/and flavor

Iso-day-night asymmetry contours



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



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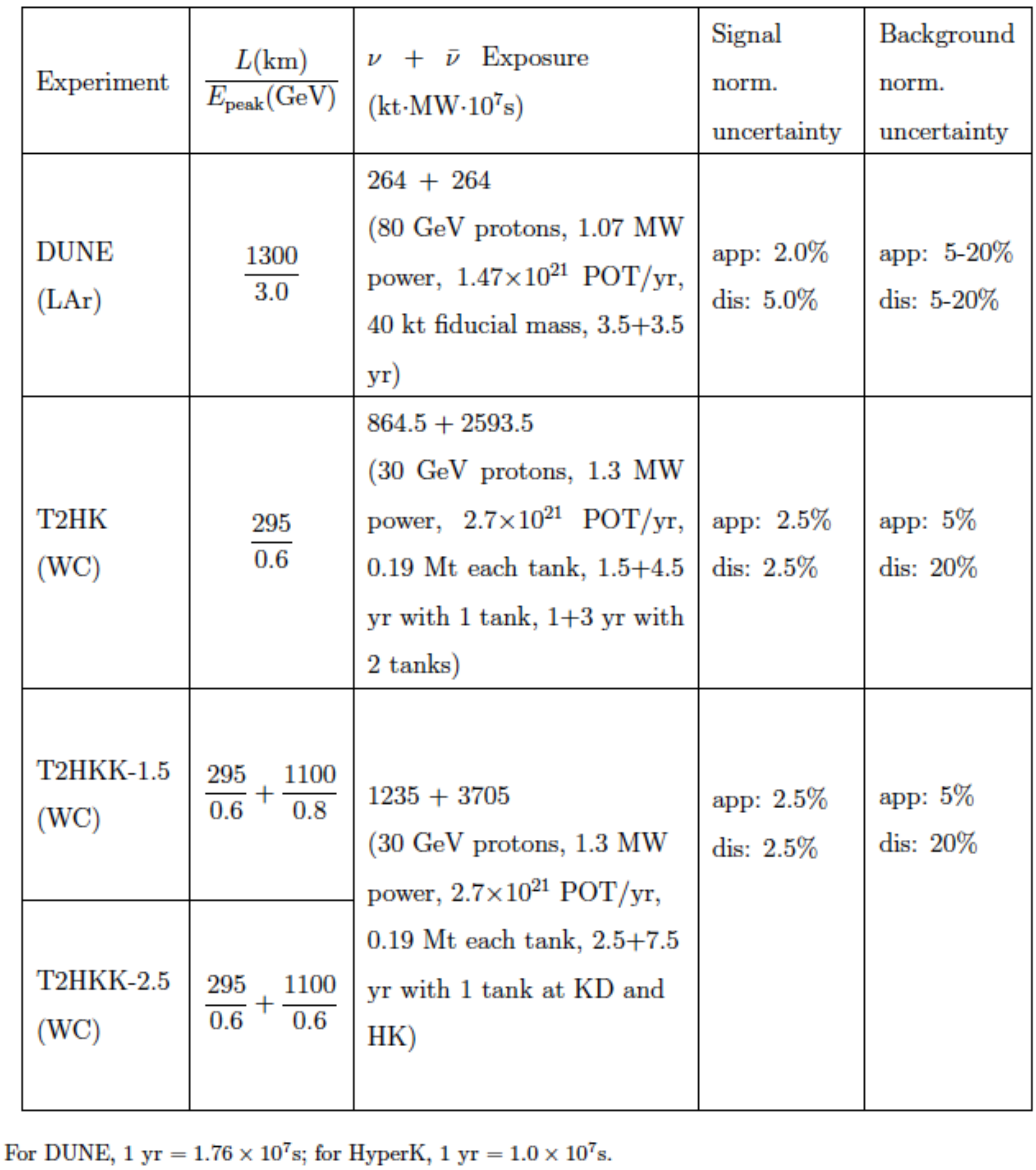
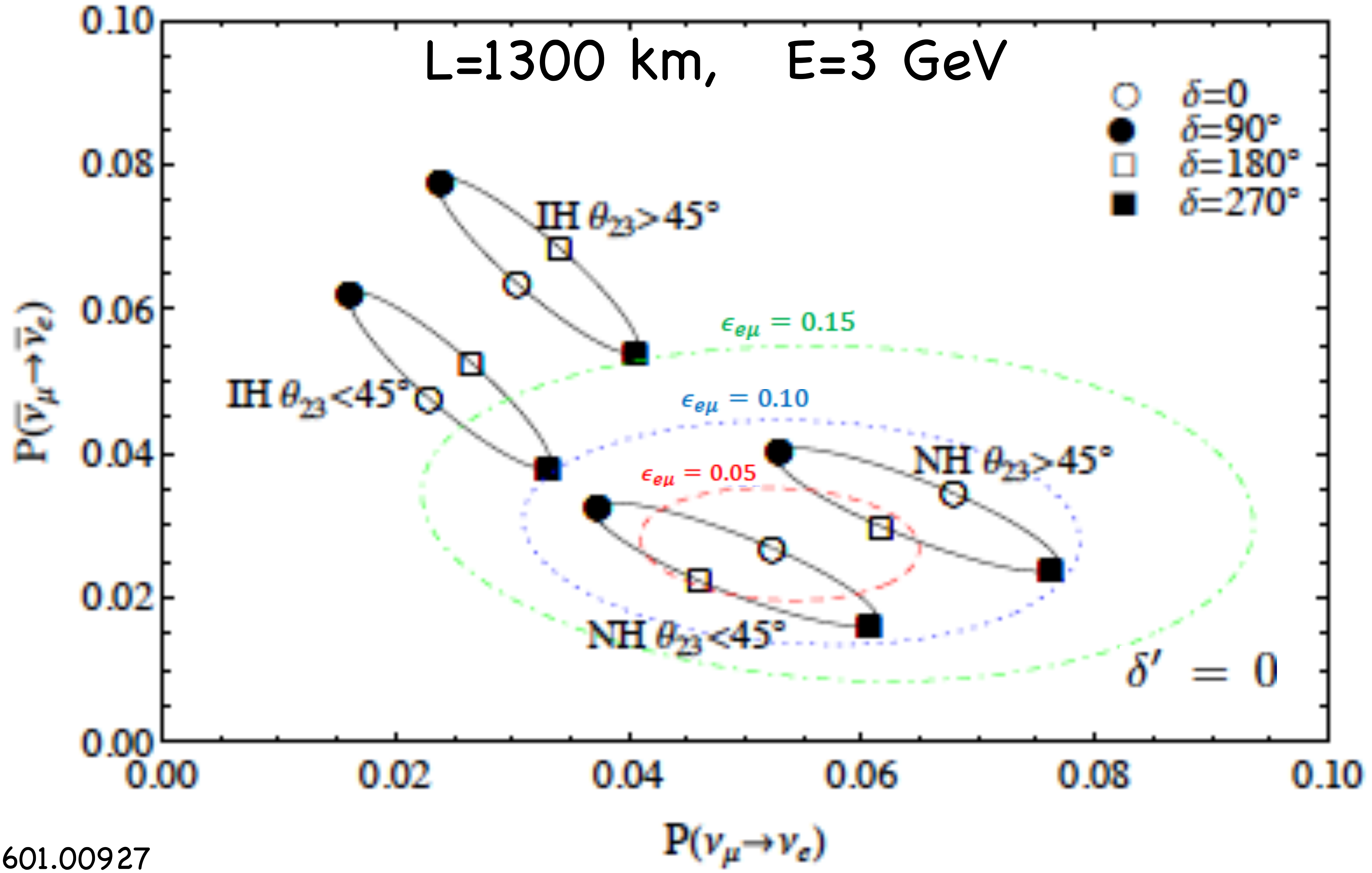
Hyper-K and JUNO can detect NSI

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.



1601.00927

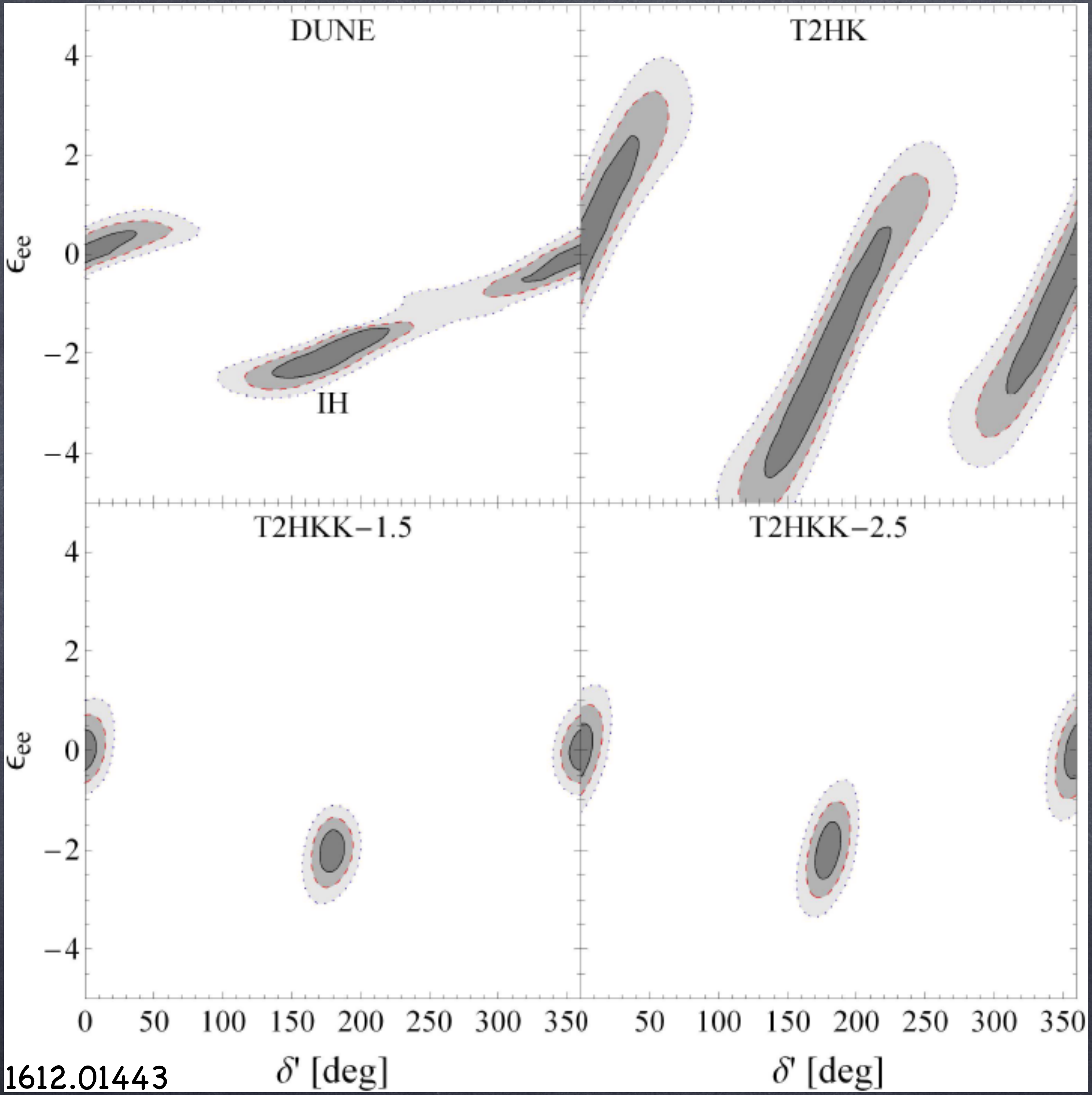
$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$

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

Appearance probabilities depend on

ϵ_{ee} , $\epsilon_{e\mu}$, $\epsilon_{e\tau}$, $\phi_{e\mu}$, $\phi_{e\tau}$

Generalized mass hierarchy degeneracy



1612.01443

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

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

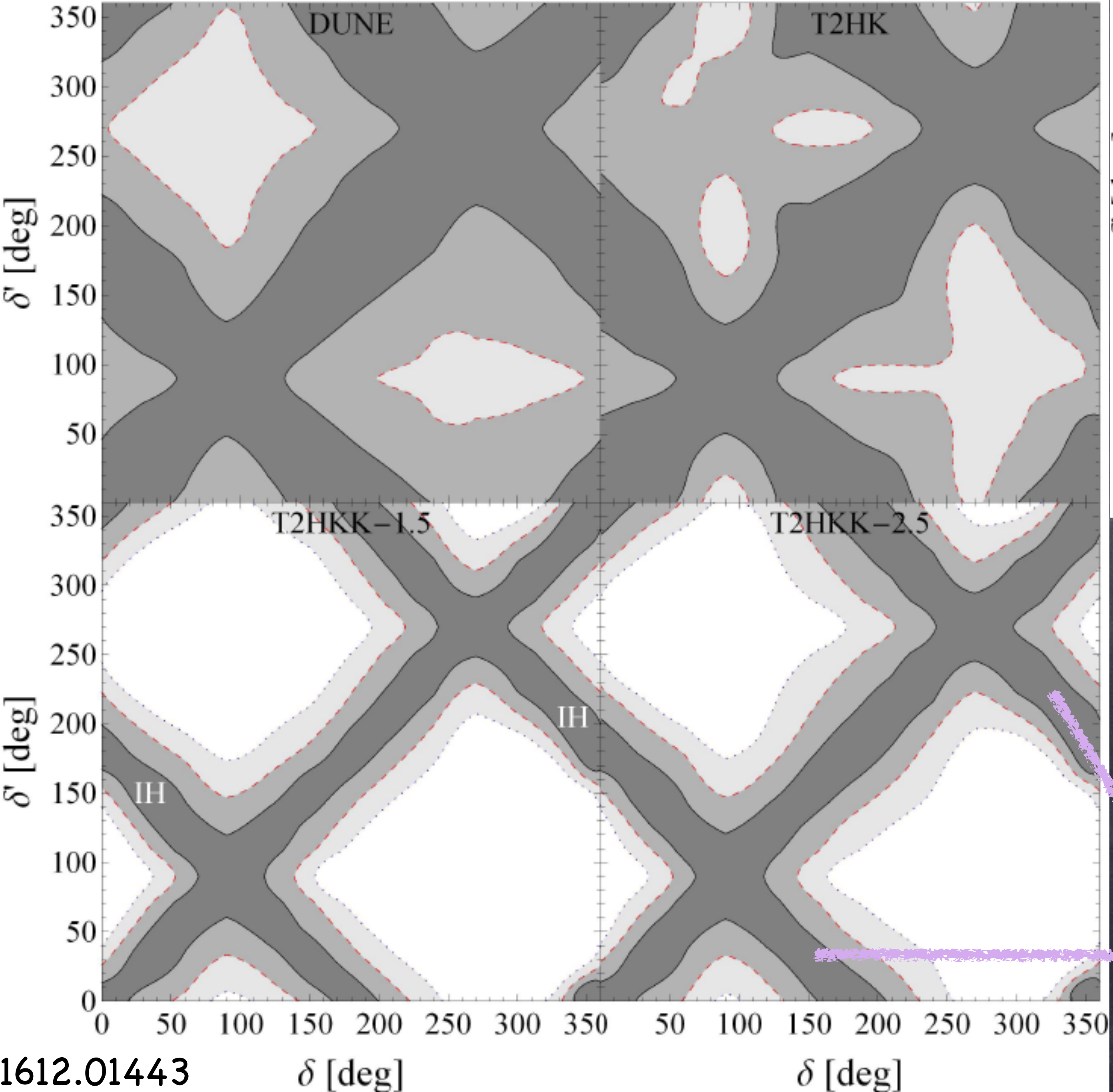
1604.05772

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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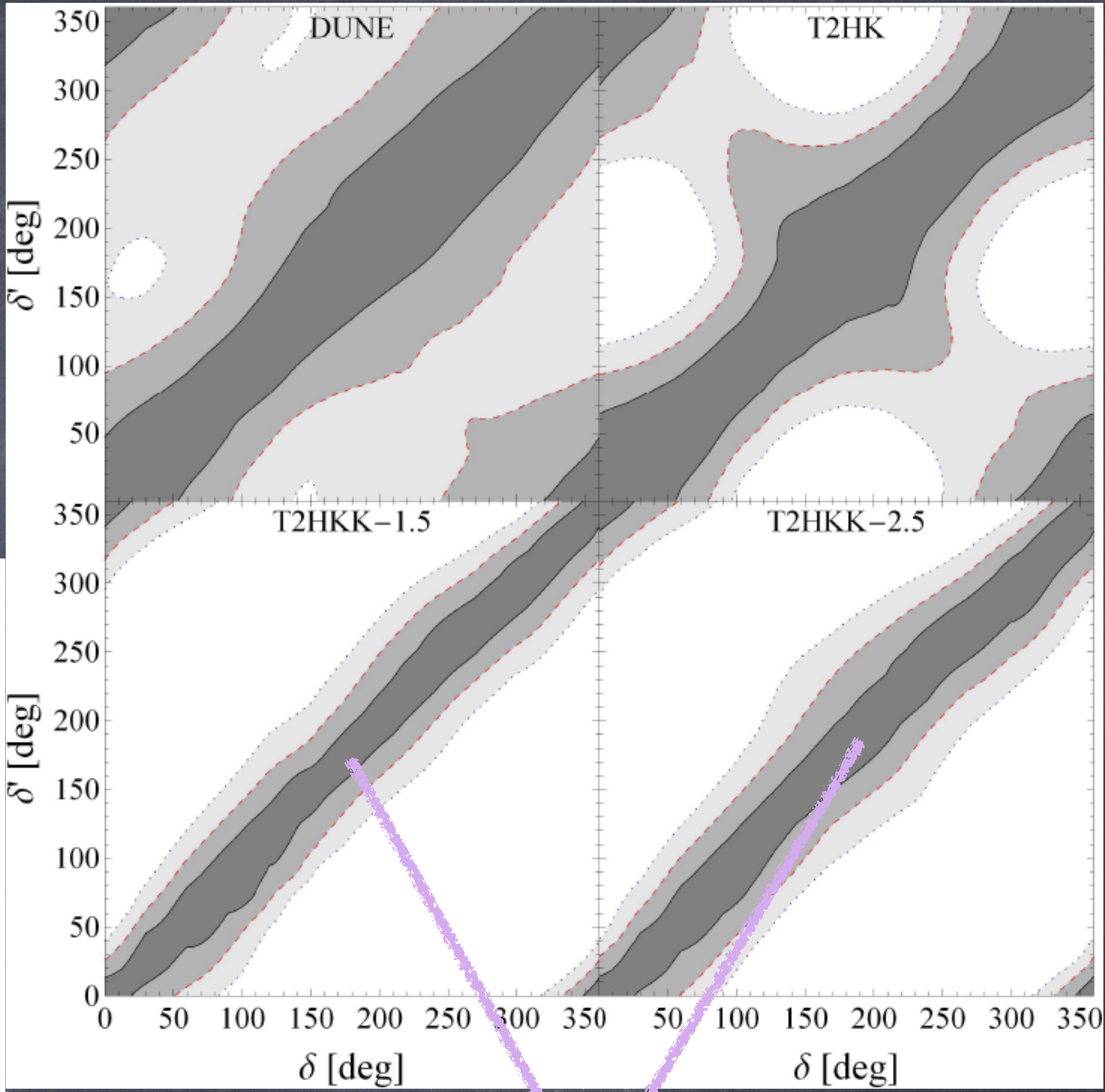


$\delta' = \delta$ always holds when $\epsilon = 0$

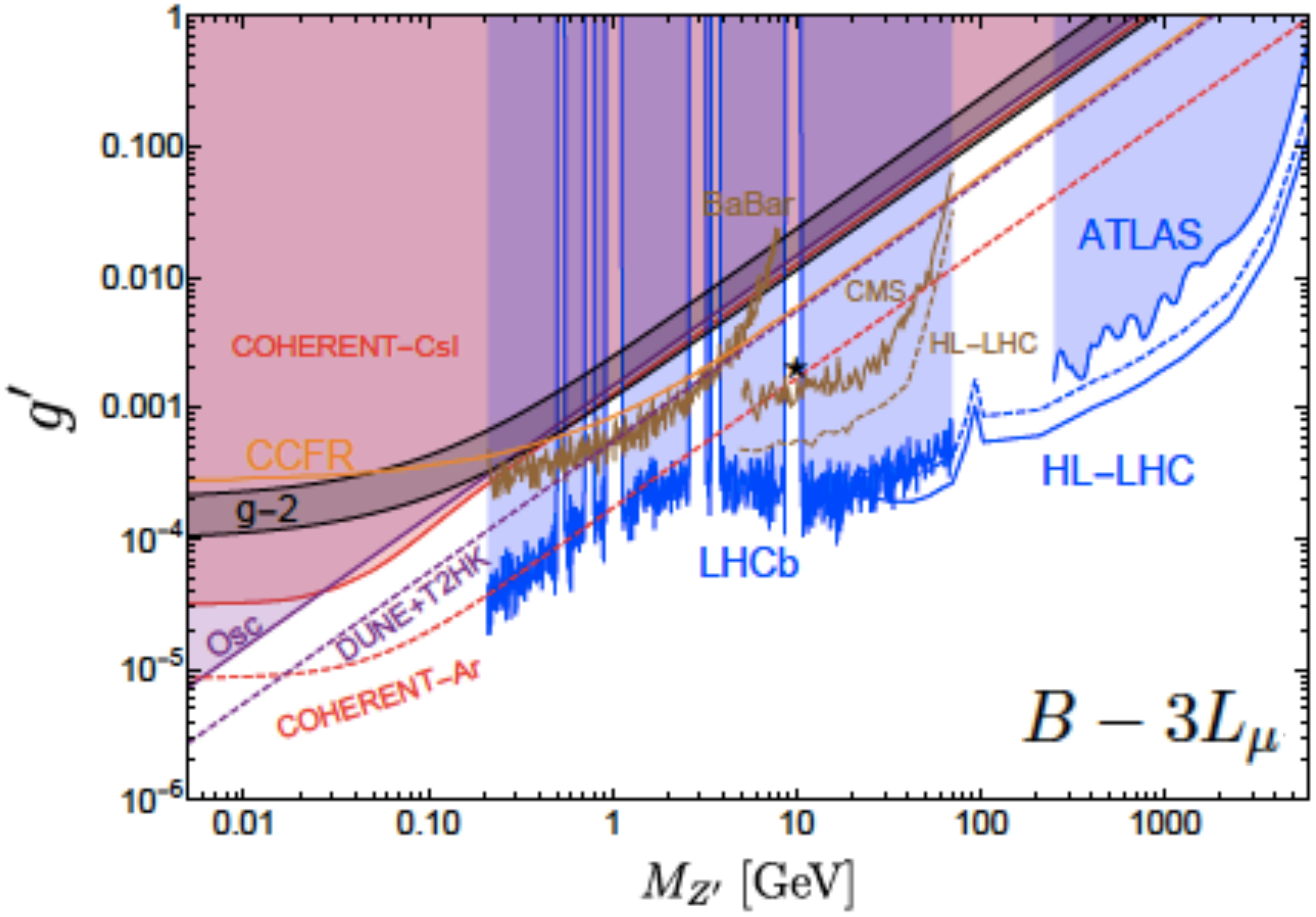
IH and $\delta' = 180 - \delta$

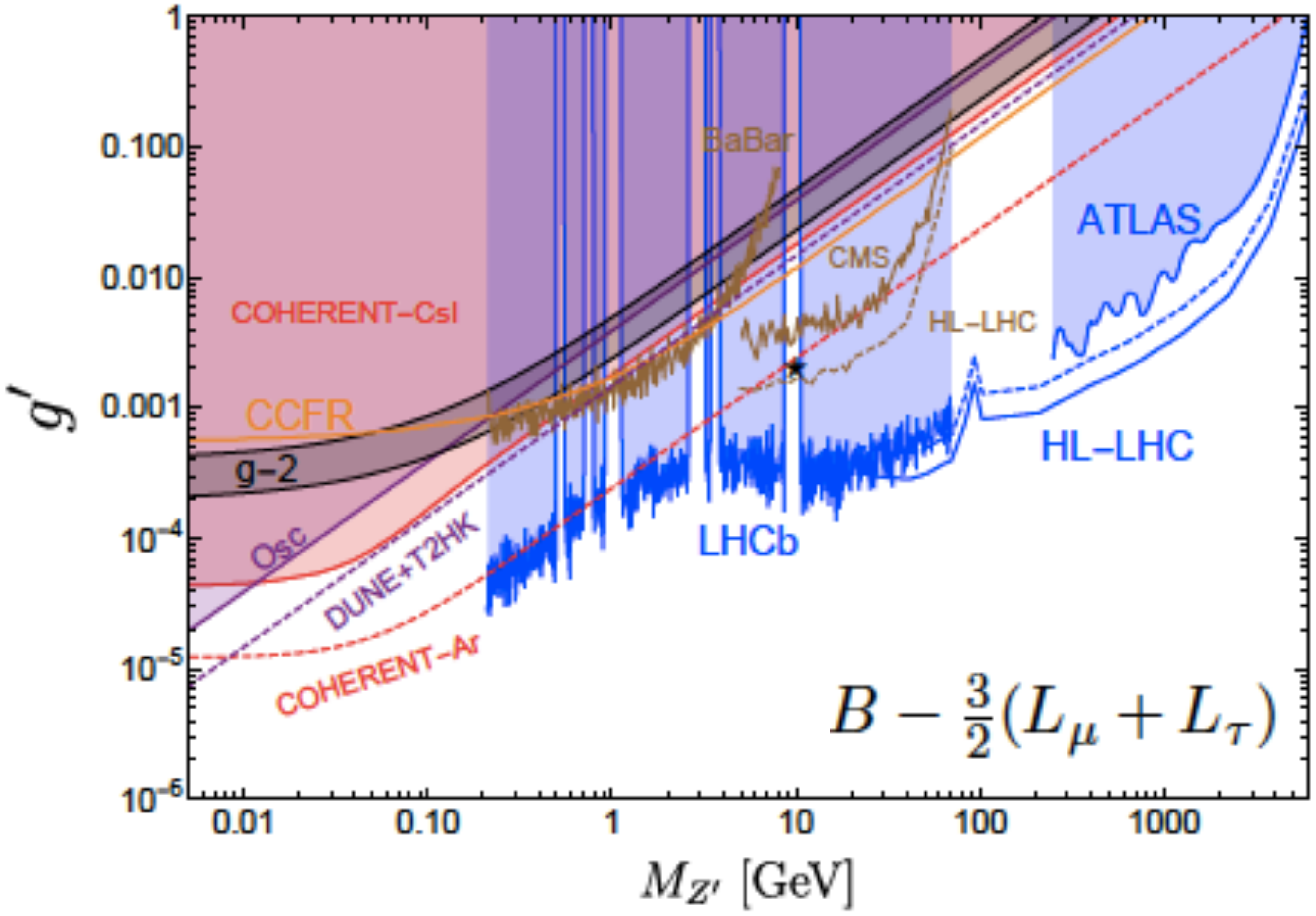
U(1)′ models

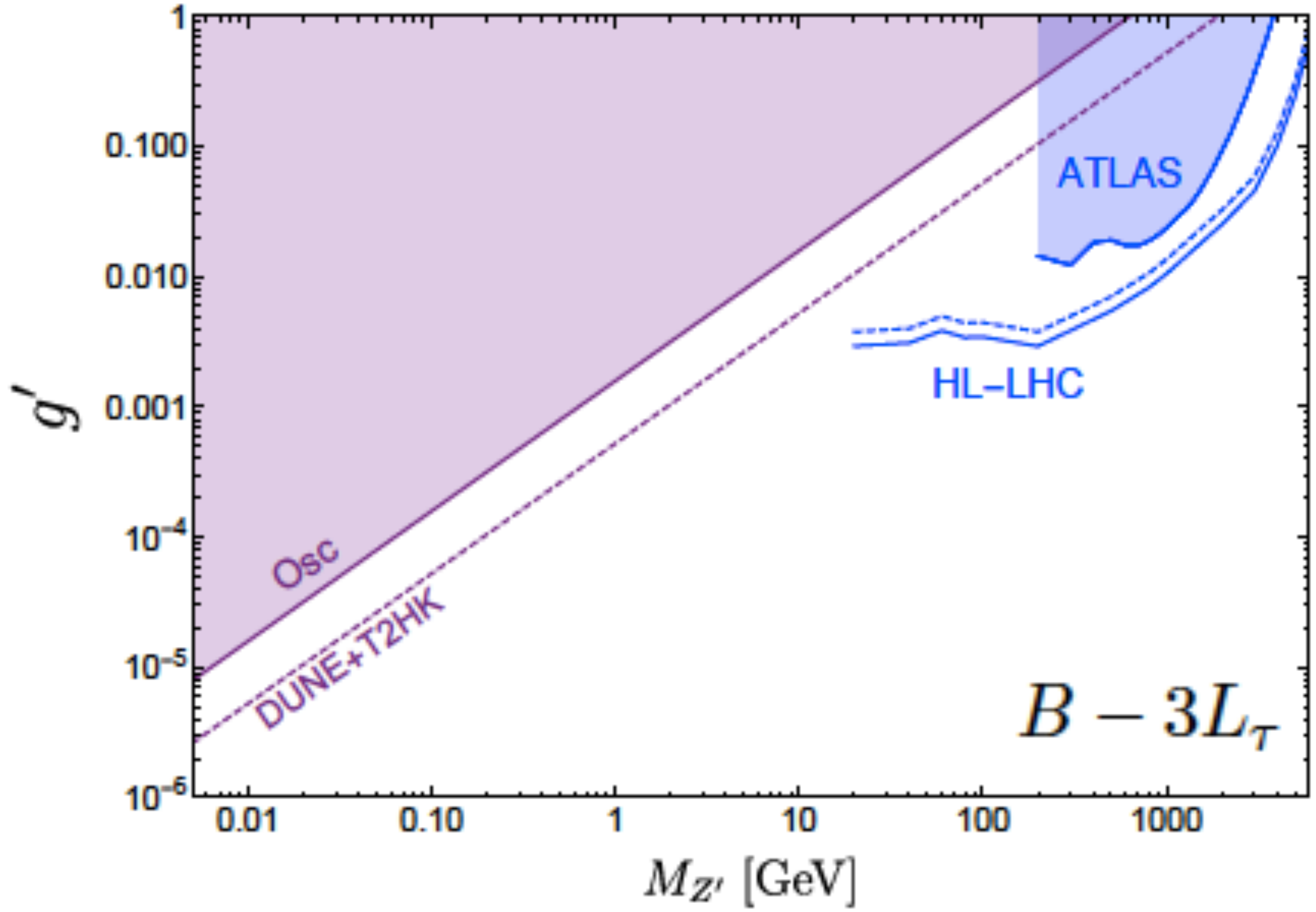
- Anomaly free and UV complete
- Give nonuniversal flavor-conserving NSI
- Give simultaneous couplings to charged leptons
- Can be probed by CEvNS, neutrino oscillations and colliders
- Weak charge of the nucleus relevant for CEvNS:

$$Q_\alpha^2 = \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^u + \epsilon_{\alpha\alpha}^d) + N(g_n^V + \epsilon_{\alpha\alpha}^u + 2\epsilon_{\alpha\alpha}^d)\right]^2$$

$$\epsilon_{\alpha\alpha}^u = \epsilon_{\alpha\alpha}^d = \frac{{g'}^2 Q'_q Q'_\alpha}{\sqrt{2} G_F (2 M E_r + M_{Z'}^2)}$$

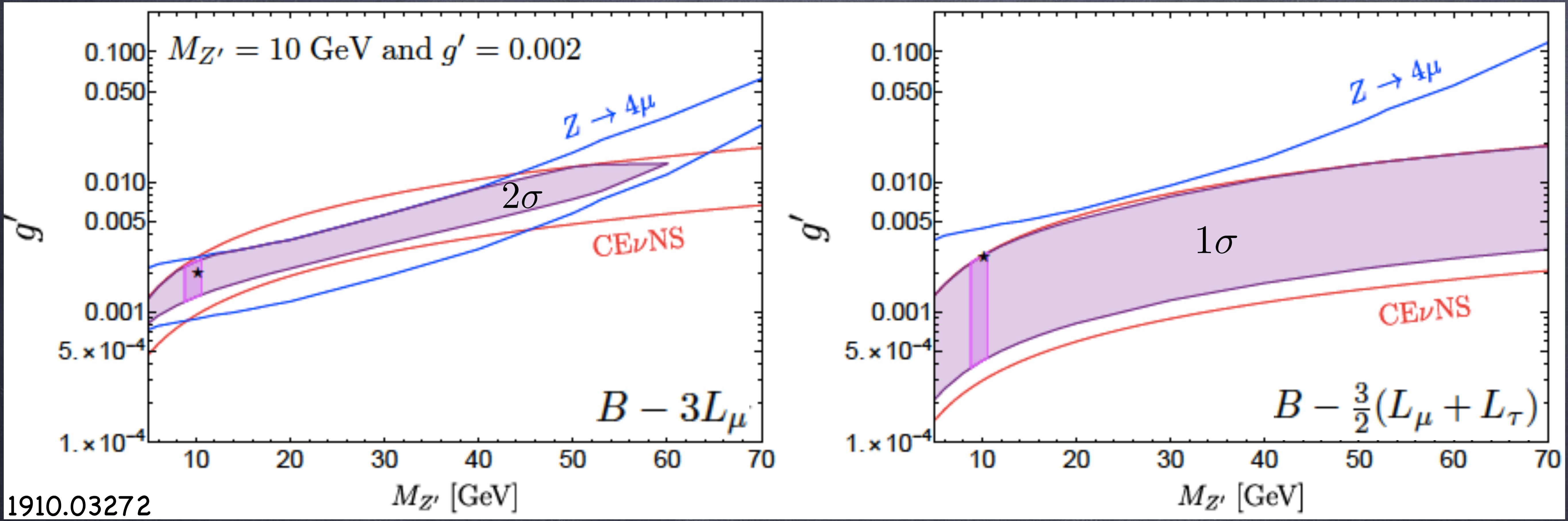

COHERENT-CsI
CCFR
g-2
Osc
DUNE+T2HK
COHERENT-Ar
BaBar
CMS
HL-LHC
LHCb
ATLAS
HL-LHC
$B - 3L_\mu$
g'
$M_{Z'}$ [GeV]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.01
0.10
1
10
100
1000


BaBar
COHERENT-CsI
CCFR
g-2
Osc
DUNE+T2HK
COHERENT-Ar
CMS
HL-LHC
ATLAS
HL-LHC
LHCb
$B - \frac{3}{2}(L_\mu + L_\tau)$
g'
$M_{Z'}$ [GeV]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.01
0.10
1
10
100
1000


ATLAS
HL-LHC
Osc
DUNE+T2HK
$B - 3L_\tau$
g'
$M_{Z'}$ [GeV]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.01
0.10
1
10
100
1000

1910.03272

Joint analysis of future COHERENT LAr and HL-LHC data



1910.03272

Combined data can help limit the Z′ mass from above

General Neutrino Interactions

- GNI describe scalar, pseudoscalar, vector, axial-vector and tensor neutrino-fermion interactions below the weak scale via dimension-6 operators

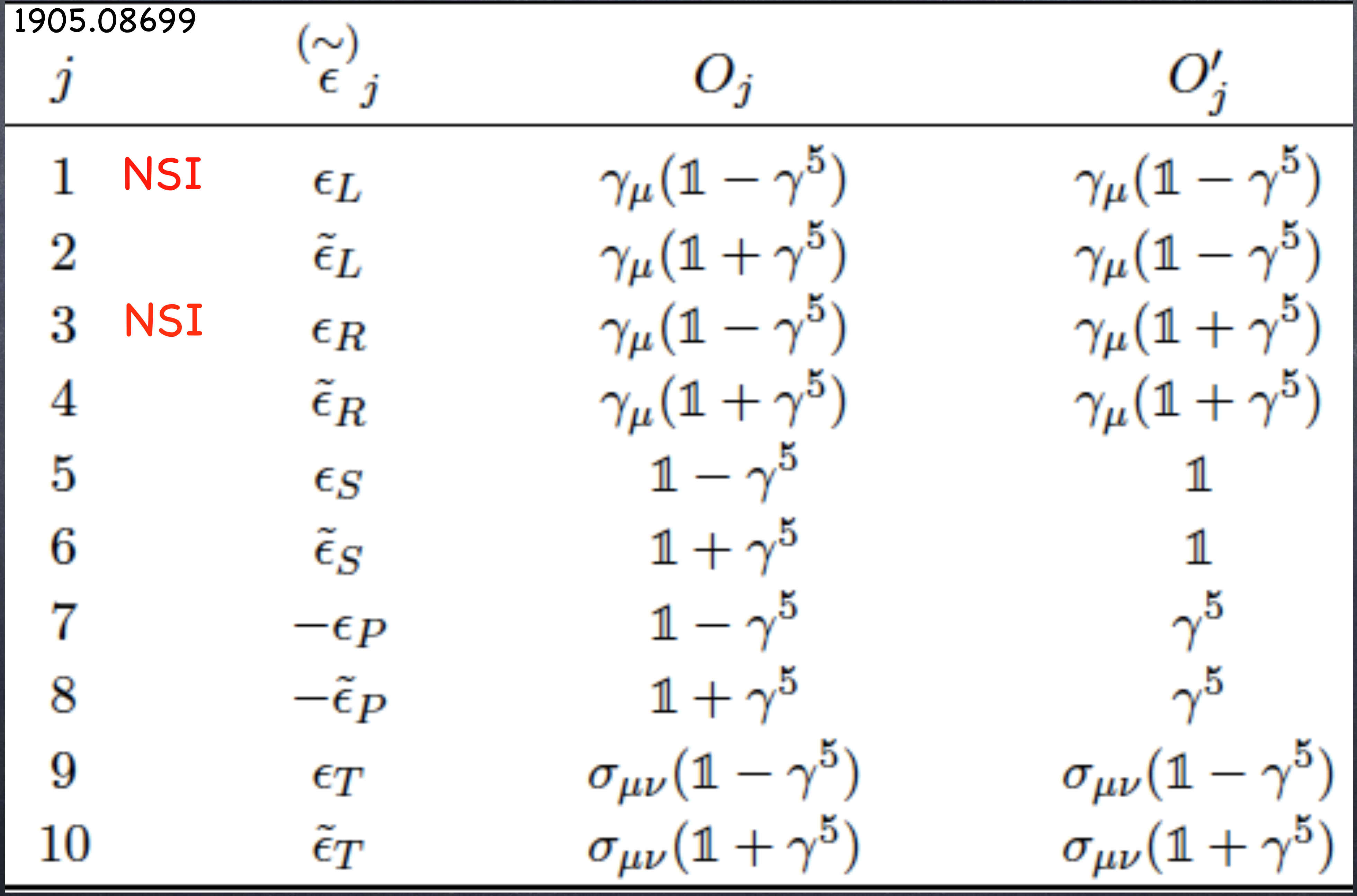
- GNI include LH and light RH singlet neutrinos

- NSI (vector-like interactions of LH neutrinos) are a subset of GNI

- GNI are the subset of neutrino interactions of Low-energy Neutrino EFT (which respects SU(3)_C x U(1)_Q below the electroweak scale)

$$\mathcal{L}^{\rm NC}_{\rm LNEFT} \supset -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} (\overset{(\sim)}{\epsilon}_{j,f})^{\alpha\beta\gamma\delta} (\bar{\nu}_\alpha O_j \nu_\beta)(\bar{f}_\gamma O'_j f_\delta)$$

$$\mathcal{L}^{\rm CC}_{\rm LNEFT} \supset -\frac{G_F V^*_{\delta\gamma}}{\sqrt{2}} \sum_{j=1}^{10} (\overset{(\sim)}{\epsilon}_{j,du})^{\alpha\beta\gamma\delta} (\bar{\nu}_\alpha O_j \ell_\beta)(\bar{d}_\gamma O'_j u_\delta) + \text{h.c.}$$



1905.08699

j		$\overset{(\sim)}{\epsilon}_j$	O_j	O'_j
1	NSI	ϵ_L	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma_\mu(\mathbb{1}-\gamma^5)$
2		$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma_\mu(\mathbb{1}-\gamma^5)$
3	NSI	ϵ_R	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma_\mu(\mathbb{1}+\gamma^5)$
4		$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma_\mu(\mathbb{1}+\gamma^5)$
5		ϵ_S	$\mathbb{1}-\gamma^5$	$\mathbb{1}$
6		$\tilde{\epsilon}_S$	$\mathbb{1}+\gamma^5$	$\mathbb{1}$
7		$-\epsilon_P$	$\mathbb{1}-\gamma^5$	γ^5
8		$-\tilde{\epsilon}_P$	$\mathbb{1}+\gamma^5$	γ^5
9		ϵ_T	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$
10		$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$

Only NSI involve only LH neutrinos

Standard Model Neutrino EFT

- Most GNI do not arise as a low-energy limit of SMEFT

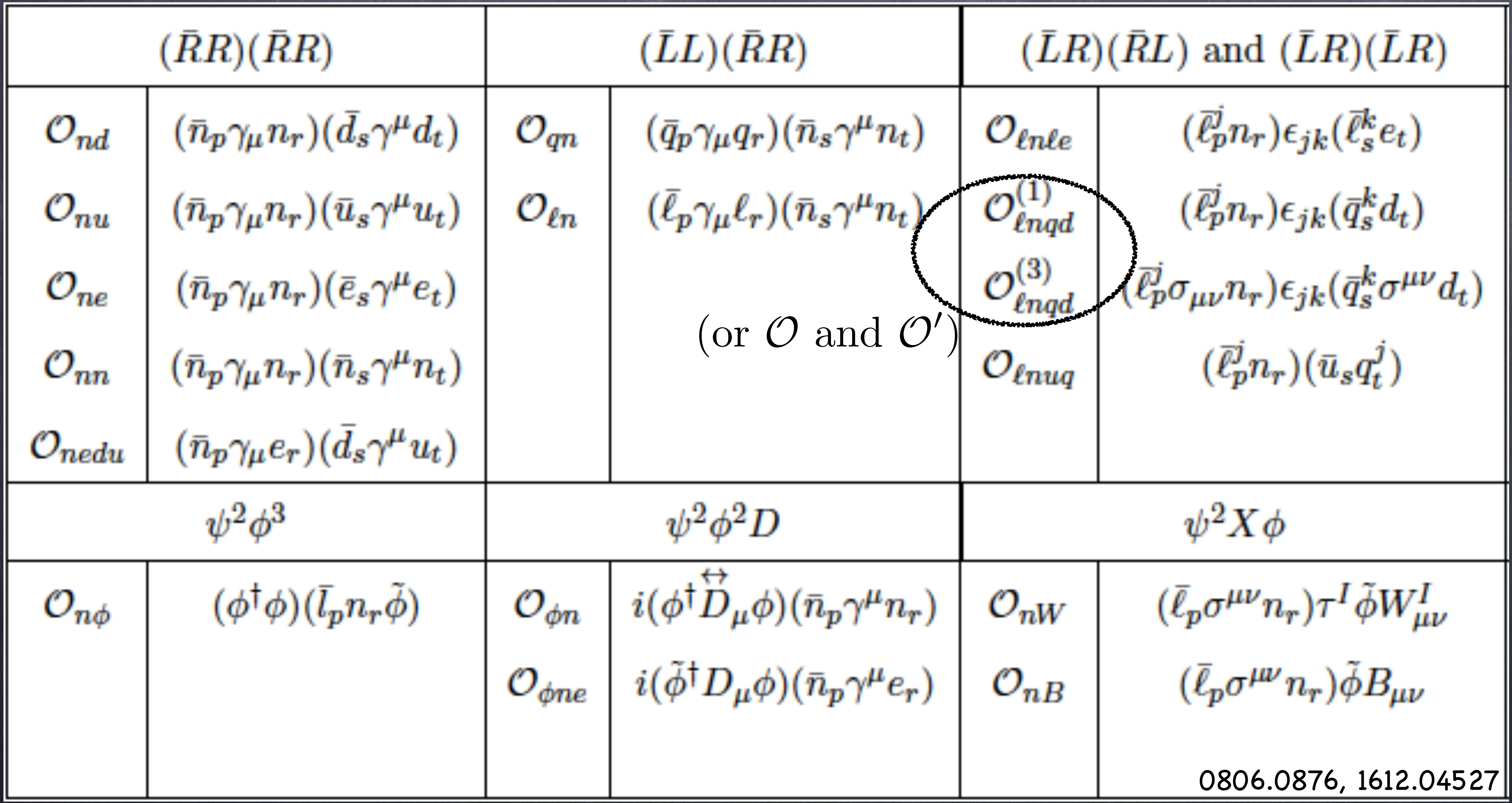
- Motivated by neutrino oscillations, natural to extend SMEFT with RH neutrinos (SMNEFT)

- Describes physics above the weak scale. Operators respect the full SM gauge symmetry with RHN+SM field content

- In general, SMNEFT and LNEFT are independent EFTs above and below the weak scale

- If there are no other new O(10) GeV particles, can match SMNEFT and LNEFT at the weak scale

SMNEFT operators including RH neutrinos



$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$\mathcal{O}_{nd}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qn}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}_{\ell n\ell e}$	$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{\ell}^k_s e_t)$
$\mathcal{O}_{nu}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{\ell n}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{n}_s\gamma^\mu n_t)$	$\mathcal{O}^{(1)}_{\ell nqd}$	$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
$\mathcal{O}_{ne}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{e}_s\gamma^\mu e_t)$			$\mathcal{O}^{(3)}_{\ell nqd}$	$(\bar{\ell}^j_p \sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} d_t)$
$\mathcal{O}_{nn}$	$(\bar{n}_p\gamma_\mu n_r)(\bar{n}_s\gamma^\mu n_t)$			$\mathcal{O}_{\ell nuq}$	$(\bar{\ell}^j_p n_r)(\bar{u}_s q^j_t)$
$\mathcal{O}_{nedu}$	$(\bar{n}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu u_t)$				
$\psi^2\phi^3$		$\psi^2\phi^2 D$		$\psi^2 X\phi$	
$\mathcal{O}_{n\phi}$	$(\phi^\dagger\phi)(\bar{l}_p n_r\tilde{\phi})$	$\mathcal{O}_{\phi n}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{n}_p\gamma^\mu n_r)$	$\mathcal{O}_{nW}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tau^I\tilde{\phi}W^I_{\mu\nu}$
		$\mathcal{O}_{\phi ne}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{n}_p\gamma^\mu e_r)$	$\mathcal{O}_{nB}$	$(\bar{\ell}_p\sigma^{\mu\nu} n_r)\tilde{\phi}B_{\mu\nu}$

(or $\mathcal{O}$ and $\mathcal{O}'$)

0806.0876, 1612.04527

Relate WCs of LNEFT at GeV to WCs of SMNEFT at TeV

TeV

SMNEFT

RGEs:
2010.12109
2103.04441

Match WCs at EW scale: $\epsilon(M_Z) = f(C(M_Z))$

LNEFT

RGEs:
2010.12109

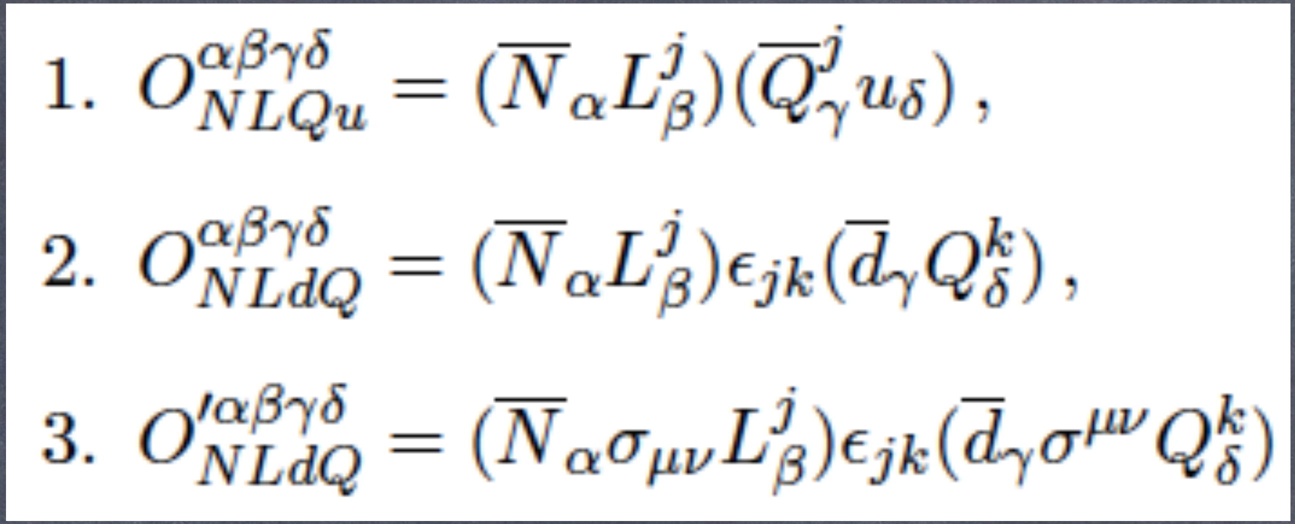
GeV

Some consequences of operator matching and RGE

- Lepton flavor violating NSI strongly constrained by charged LFV
- NC interactions of neutrinos with up-type and down-type quarks are generally different; often assumed to be equal in NSI phenomenology
- Operator mixing due to RG evolution produces degeneracies in the WCs
- RG evolution of SMNEFT operators induces NC and CC GNI

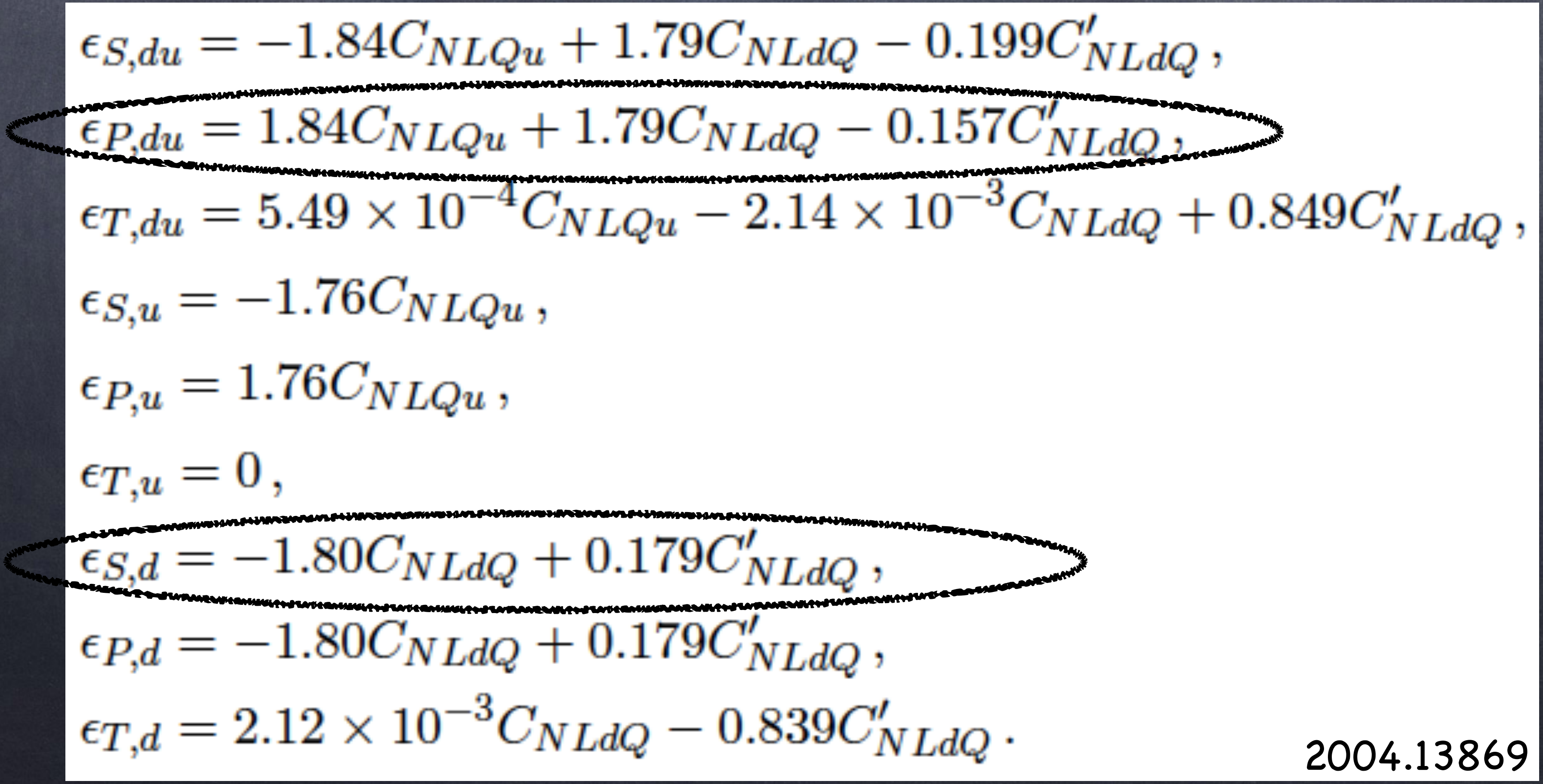
Scalar and tensor neutrino interactions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + 2\sqrt{2}G_F[C_{NLdQ}O_{NLdQ} + C_{NLQu}O_{NLQu} + C'_{NLdQ}O'_{NLdQ}]$$



1. $O^{\alpha\beta\gamma\delta}_{NLQu} = (\overline{N}_\alpha L^j_\beta)(\overline{Q}^j_\gamma u_\delta)\,,$
2. $O^{\alpha\beta\gamma\delta}_{NLdQ} = (\overline{N}_\alpha L^j_\beta)\epsilon_{jk}(\overline{d}_\gamma Q^k_\delta)\,,$
3. $O'^{\alpha\beta\gamma\delta}_{NLdQ} = (\overline{N}_\alpha \sigma_{\mu\nu} L^j_\beta)\epsilon_{jk}(\overline{d}_\gamma \sigma^{\mu\nu} Q^k_\delta)$

GNI WCs at 2 GeV are related to SMNEFT WCs at 1 TeV by



$$\epsilon_{S,du} = -1.84C_{NLQu} + 1.79C_{NLdQ} - 0.199C'_{NLdQ}\,,$$
$$\epsilon_{P,du} = 1.84C_{NLQu} + 1.79C_{NLdQ} - 0.157C'_{NLdQ}\,,$$
$$\epsilon_{T,du} = 5.49\times 10^{-4}C_{NLQu} - 2.14\times 10^{-3}C_{NLdQ} + 0.849C'_{NLdQ}\,,$$
$$\epsilon_{S,u} = -1.76C_{NLQu}\,,$$
$$\epsilon_{P,u} = 1.76C_{NLQu}\,,$$
$$\epsilon_{T,u} = 0\,,$$
$$\epsilon_{S,d} = -1.80C_{NLdQ} + 0.179C'_{NLdQ}\,,$$
$$\epsilon_{P,d} = -1.80C_{NLdQ} + 0.179C'_{NLdQ}\,,$$
$$\epsilon_{T,d} = 2.12\times 10^{-3}C_{NLdQ} - 0.839C'_{NLdQ}\,.$$

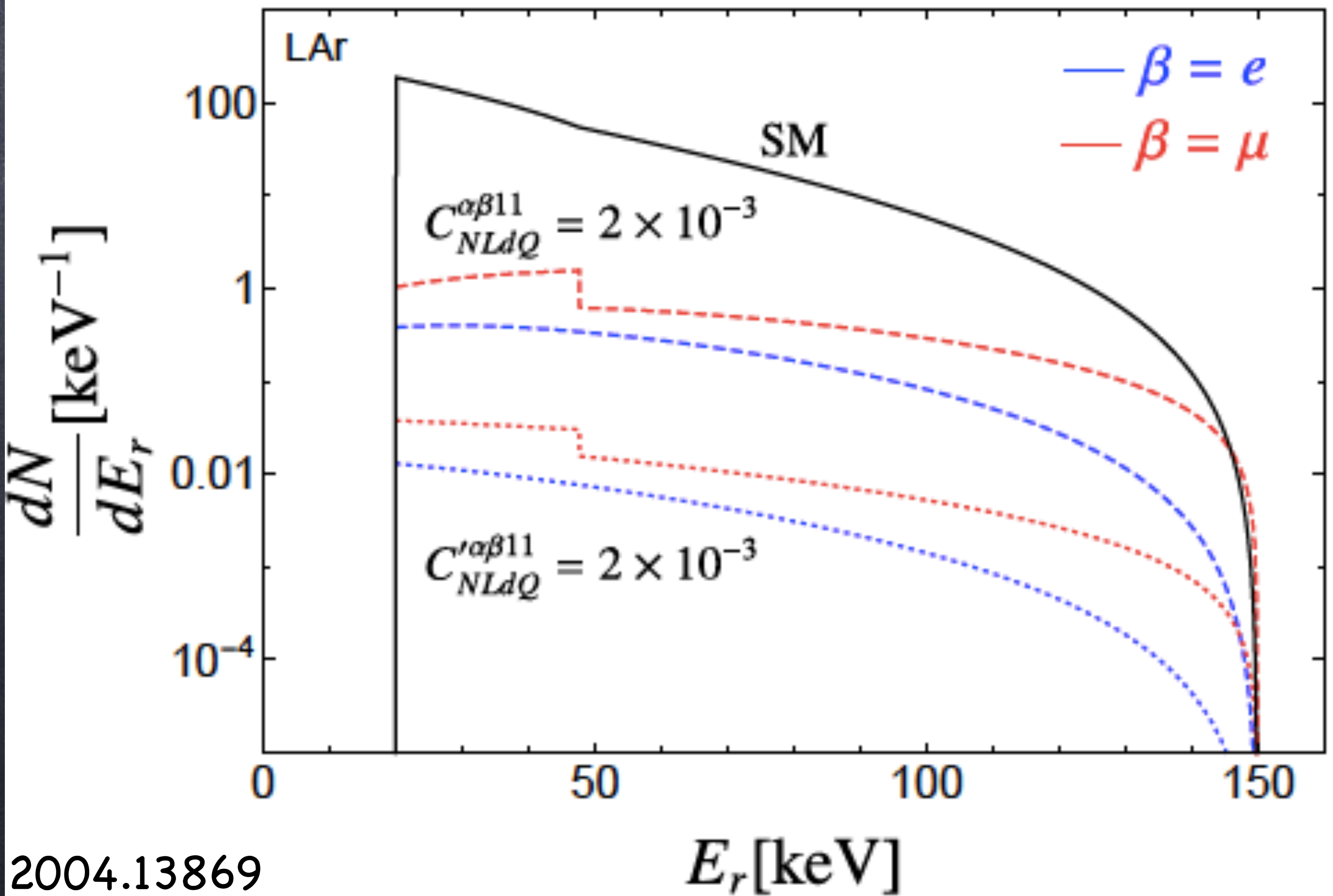
2004.13869

Constraints

- Sensitivity of low-energy probes suffers from degeneracies in the SMNEFT WCs due to RGE
- Helicity suppression is lifted in pseudoscalar meson decay

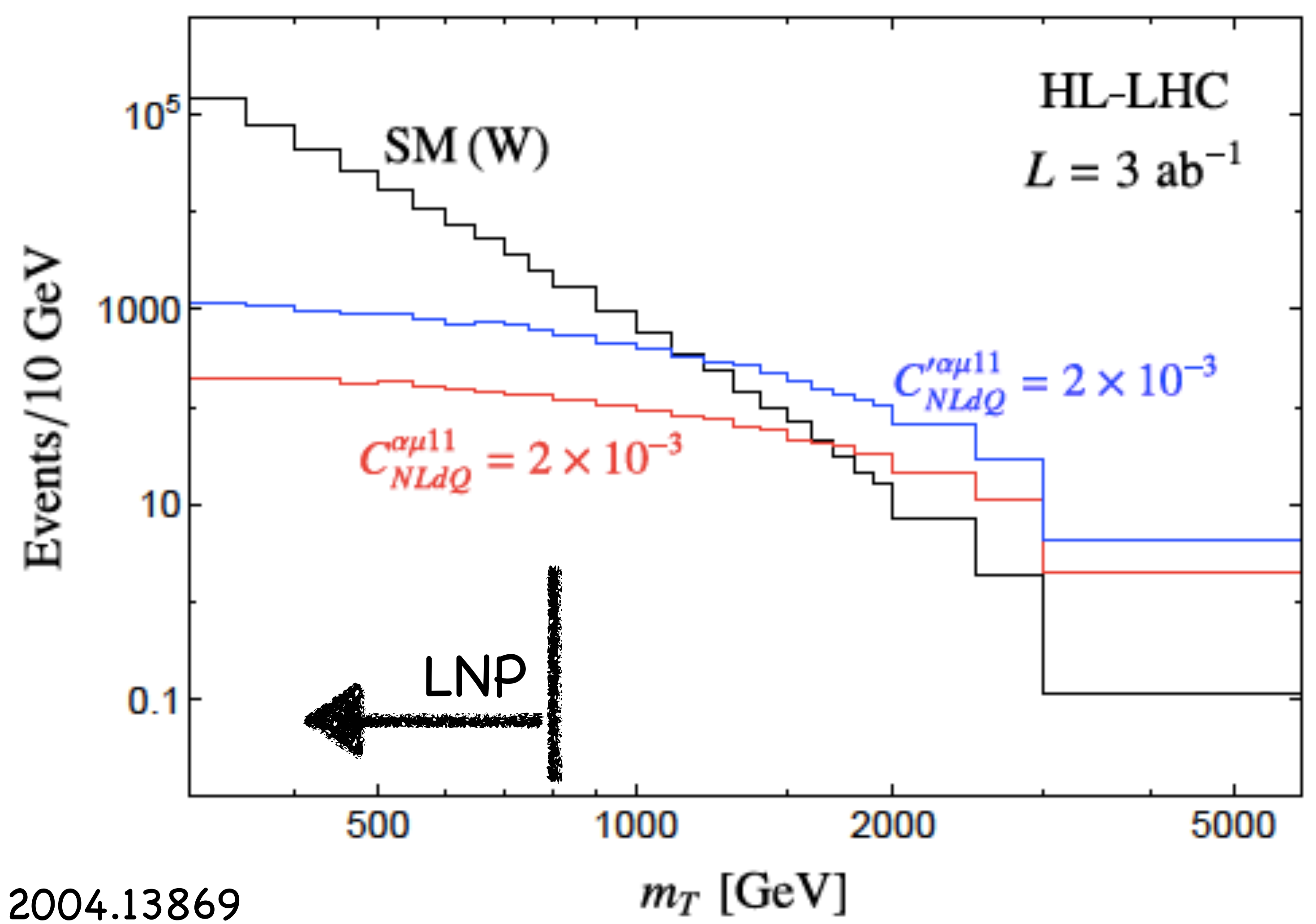
$$\Gamma_{\mathrm{GNI,p}}(P \to \ell_\beta \nu_\alpha) \propto (\epsilon^{\alpha\beta 11}_{P,du})^2 \frac{m_\pi^4}{(m_u + m_d)^2}$$

- Future COHERENT LAr data will be much more sensitive to the scalar operators than the tensor operator



2004.13869

- At LHC, the signal is the DY process, $pp \to \ell\nu + X$
- Transverse mass distribution in charged lepton+missing E_T searches directly constrain the SMNEFT WCs
- To ensure validity of EFT, need to differentiate between low-scale (1 TeV) new physics (LNP) and high-scale (>> 1 TeV) new physics (HNP)



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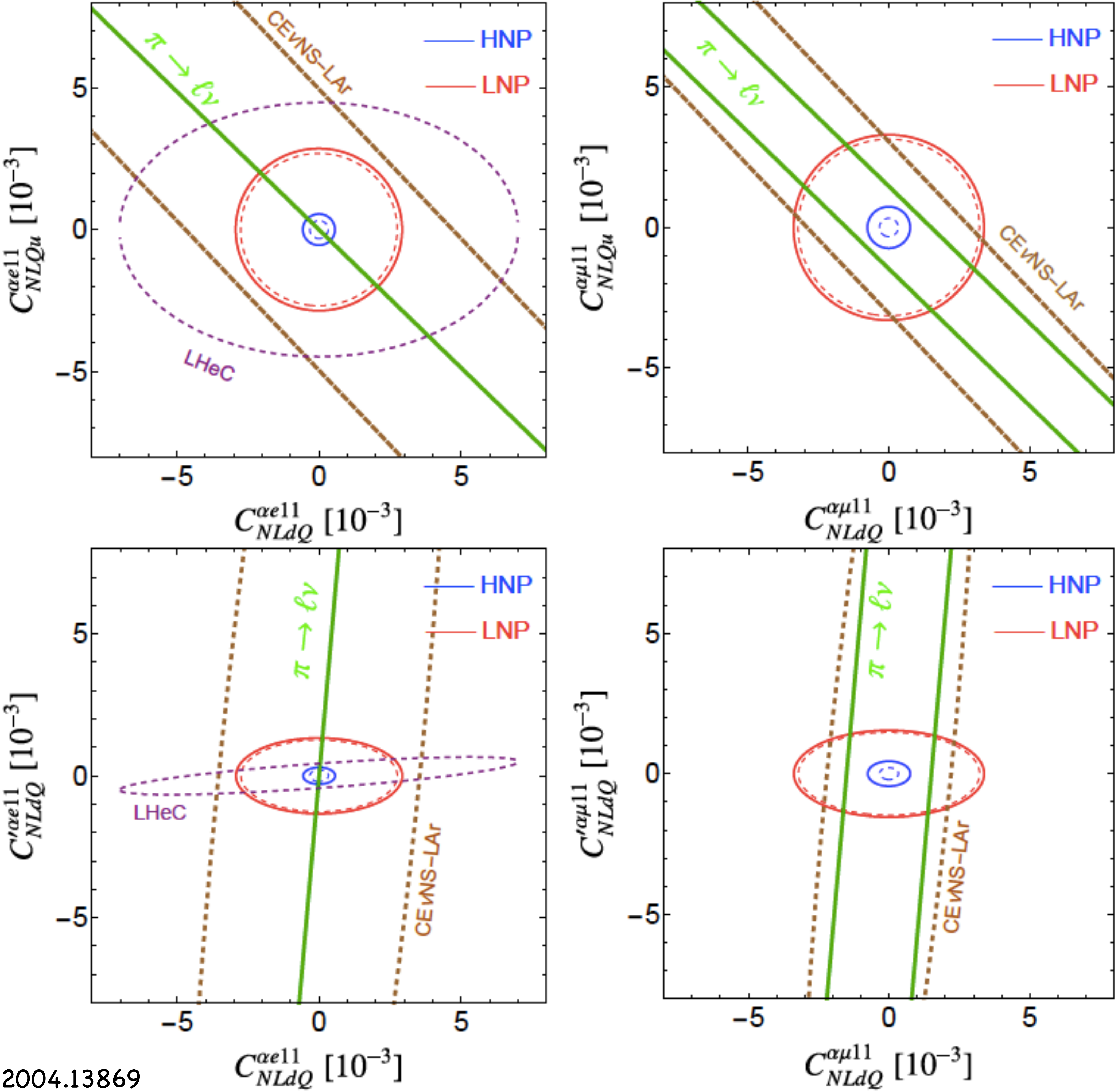
HNP
LNP
$\pi \to \ell\nu$
CEνNS-LAr
LHeC
$C^{\alpha e11}_{NLQu}$ [10^{-3}]
$C^{\alpha e11}_{NLdQ}$ [10^{-3}]
$C^{\alpha\mu11}_{NLQu}$ [10^{-3}]
$C^{\alpha\mu11}_{NLdQ}$ [10^{-3}]
$C'^{\alpha e11}_{NLdQ}$ [10^{-3}]
$C'^{\alpha\mu11}_{NLdQ}$ [10^{-3}]
−5
0
5

2004.13869

Bird's-eye view summary

- In precision era of neutrino physics, need to test SM neutrino interactions and try to discover new interactions
- New interactions may have consequences for mass hierarchy, CP measurements at DUNE, T2HK, JUNO ...
- NSI describe new matter effects, but need broader framework to go beyond vector-like interactions
- Motivated by neutrino oscillations, GNI and SMNEFT include RH neutrinos

- GNI allows for all possible interaction structures, most of which arise from SMNEFT

- Use of GNI and SMNEFT puts phenomenological analyses on a theoretically sound footing

- Allows to harness the significant complementarity between neutrino scattering, oscillation, collider and CEvNS data to study new neutrino interactions