ν oscillation experiments & nonstandard ν interactions

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Plan of this talk

1. Introduction

2. New Physics in ν sector

3. Non oscillation experiments to constrain NSI

4. Conclusions

1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

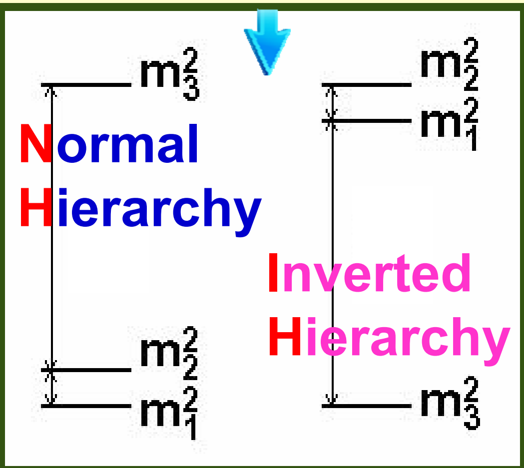
All 3 mixing angles have been measured

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} eV^2$

ν_{atm}, K2K,T2K,MINOS,Nova (accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} eV^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS+Nova → $\theta_{13} \cong \pi / 20$

Both hierarchy patterns are allowed



Next task is to measure

sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

Proposed experiments

- T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV
- T2HKK(JP+KR, JPARC-->HK+Korea) L=295km+1100km, 0.5GeV<E<1.5GeV
- DUNE (US, FNAL-->Homestake, SD), E~2GeV, L=1300km

$$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$$

These experiments are expected to measure

sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

Motivation for research on New Physics

High precision measurements of ν oscillation in future experiments can be also used to probe **physics beyond SM** by looking at deviation from SM+m_ν (just like B factories).

→ Research on **New Physics** is important.

2. New Physics in ν sector

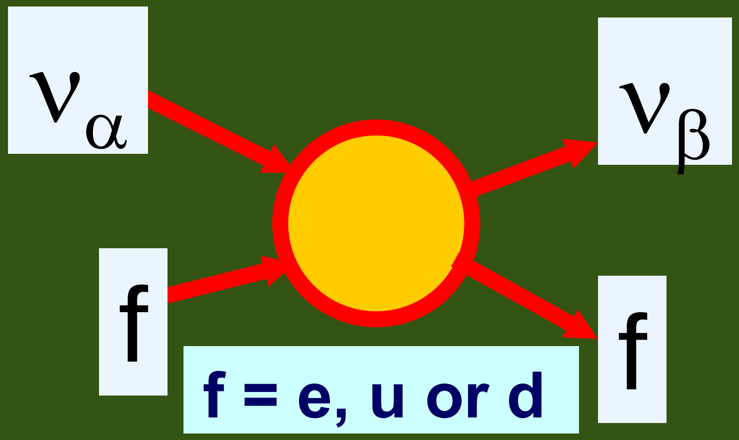
2.1 Popular New Physics discussed in ν phenomenology

Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
Light sterile ν	Maybe	O(10%)
NSI in propagation	Maybe	e-τ: O(100%) Others: O(1%)

NSI: discussed in this talk

2.2. NonStandard Interaction in propagation

Phenomenological New Physics considered here: Flavor-dependent 4-fermi neutral current Non Standard Interactions:



$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\,\epsilon_{\alpha\beta}^{ff'P} G_F \left(\overline{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L}\right)\ \left(\overline{f}_P \gamma^\mu f'_P\right)$$

P = R, L = $(1\pm\gamma_5)/2$

Modification of matter effect in ν propagation

We are interested in coherent ν scatterings: f' = f

$$\epsilon_{\alpha\beta}^{fP} \equiv \epsilon_{\alpha\beta}^{ffP}$$

In ν oscillation, the axial vector part does not contribute to the matter effect:

$$\mathcal{L}_{\rm eff}^{\rm NSI} = -2\sqrt{2}\,G_F \sum_{f,\alpha,\beta} \left(\overline{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L}\right) \overline{f}\left(\epsilon_{\alpha\beta}^{fV} + \gamma_5 \epsilon_{\alpha\beta}^{fA}\right)\gamma^\mu f$$

(Proof) Because the static fermions (f=e,u,d) are nonrelativistic, they satisfy the following:

$$< \bar\psi\gamma_\mu\psi > = \begin{cases} (\phi^\dagger, 0^T)\begin{pmatrix}\phi\\0\end{pmatrix} = \phi^\dagger\phi & (\text{if } \mu=0)\\ (\phi^\dagger, 0^T)\begin{pmatrix}0 & \sigma_j\\ -\sigma_j & 0\end{pmatrix}\begin{pmatrix}\phi\\0\end{pmatrix} = 0 & (\text{if } \mu=j)\end{cases}$$

$$< \bar\psi\gamma_\mu\gamma_5\psi > = \begin{cases} (\phi^\dagger, 0^T)\begin{pmatrix}0 & \mathbf{1}\\ \mathbf{1} & 0\end{pmatrix}\begin{pmatrix}\phi\\0\end{pmatrix} = 0 & (\text{if } \mu=0)\\ (\phi^\dagger, 0^T)\begin{pmatrix}i\sigma_j & 0\\ 0 & i\sigma_j\end{pmatrix}\begin{pmatrix}\phi\\0\end{pmatrix} = i\phi^\dagger\sigma_j\phi \to 0 & \\ \quad (\text{after averaging over the space}) & (\text{if } \mu=j)\end{cases}$$

(QED)

Thus we use the following notation:

$$\epsilon^{f}_{\alpha\beta} = \epsilon^{fV}_{\alpha\beta} \equiv \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

On Earth, #(p)≒#(n), and the density of each fermion satisfies N_e:N_u:N_d= 1:3:3, so we define

$$\epsilon_{\alpha\beta} \equiv \epsilon^{eV}_{\alpha\beta} + 3\epsilon^{uV}_{\alpha\beta} + 3\epsilon^{dV}_{\alpha\beta}$$

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U\,\mathrm{diag}\left(E_1, E_2, E_3\right) U^{-1} + A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

NP

$$A \equiv \sqrt{2} G_F N_e$$

$$N_e \equiv \text{electron density}$$

NB1 Constraints on $\varepsilon_{\alpha\beta}$ from non-oscillation experiments (LSND, CHARM, LEP etc.)

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

Biggio et al., JHEP 0908, 090 (2009)

Constraints are weak for e, τ ($\leftarrow$no ν_e, ν_τ beam)

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4\times 10^0 & |\epsilon_{e\mu}| \lesssim 3\times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3\times 10^0 \\ & |\epsilon_{\mu\mu}| \lesssim 7\times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2\times 10^1 \end{pmatrix}$$

Constraints are strong for μ ($\leftarrow$ ν_μ beam)

These bounds on $\varepsilon_{\alpha\beta}$ are estimated by

$$\epsilon_{\alpha\beta} \simeq \sqrt{\left(\epsilon^e_{\alpha\beta}\right)^2 + \left(3\epsilon^u_{\alpha\beta}\right)^2 + \left(3\epsilon^d_{\alpha\beta}\right)^2}$$

NB2 Observation of matter effect needs large L

ν oscillation in matter (in two flavor toy case)

$$P(\nu_\mu \to \nu_e) = \left(\frac{\Delta E}{\Delta \tilde{E}}\right)^2 \sin^2 2\theta \sin^2\left(\frac{\Delta \tilde{E} L}{2}\right)$$

$$\Delta E \equiv \Delta m^2 / 2E$$

$$\Delta \tilde{E} \equiv \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2\right]^{1/2}$$

$$A \equiv \sqrt{2} G_F n_e(x)$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

A～1/2000km

Matter effect becomes most conspicuous if $\Delta EL \sim AL \sim O(1)$ is satisfied
→L > O(1000km)

2.3 Possible experimental Indications for NP

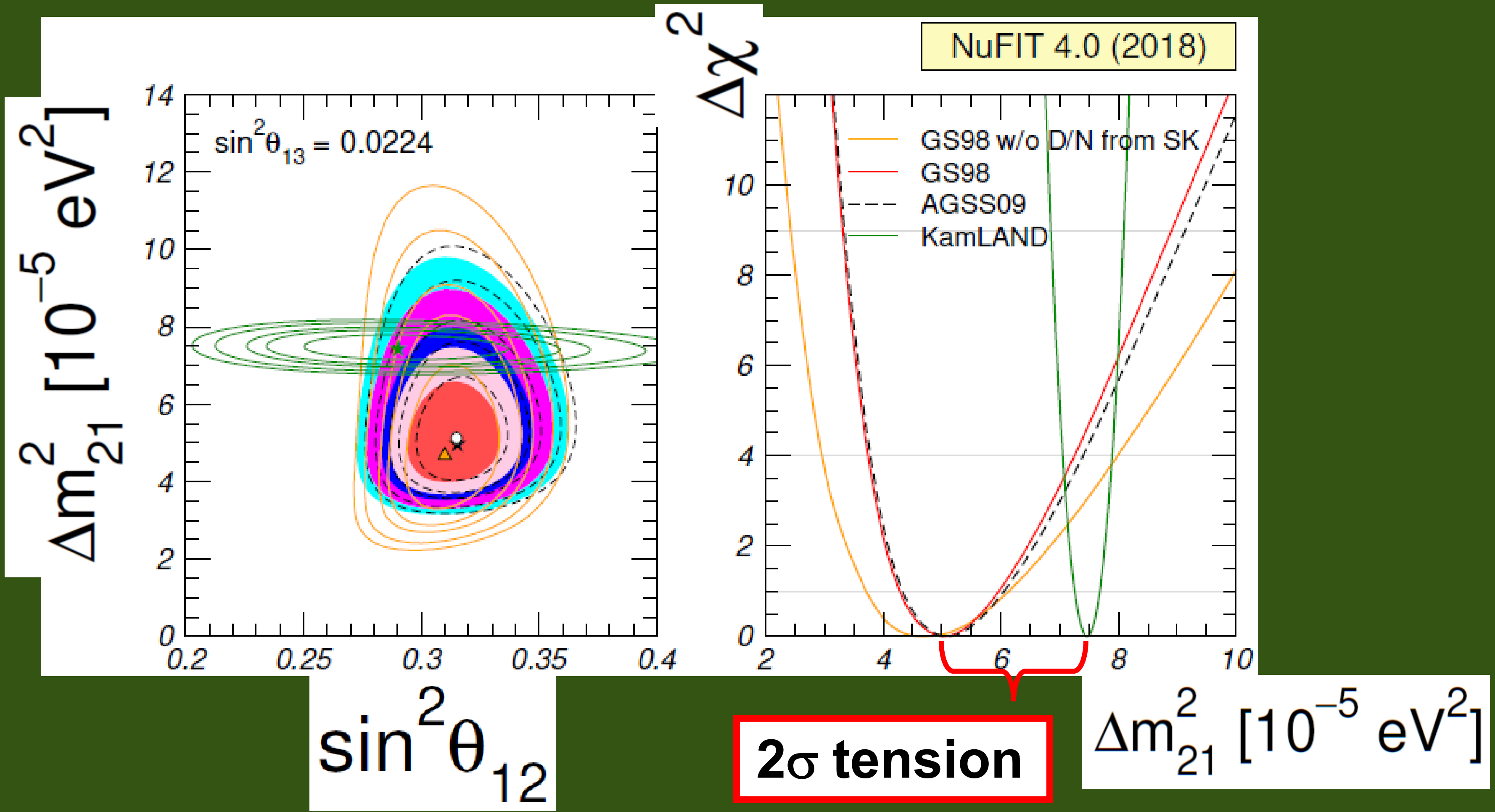
We have had some possible tensions among the data within the standard oscillation scenario:

- ν_{solar} - KamLAND: Δm^2_{21} → NSI or sterile ν w/ Δm^2_{41} =O(10^{-5}) eV^2
- LSND-MiniBooNE anomaly, Reactor anomaly, Gallium anomaly → sterile ν w/ Δm^2_{41} =O(1) eV^2

NSI: discussed in this talk (← relevant to accelerator ν)

sterile ν : not discussed in this talk

Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)



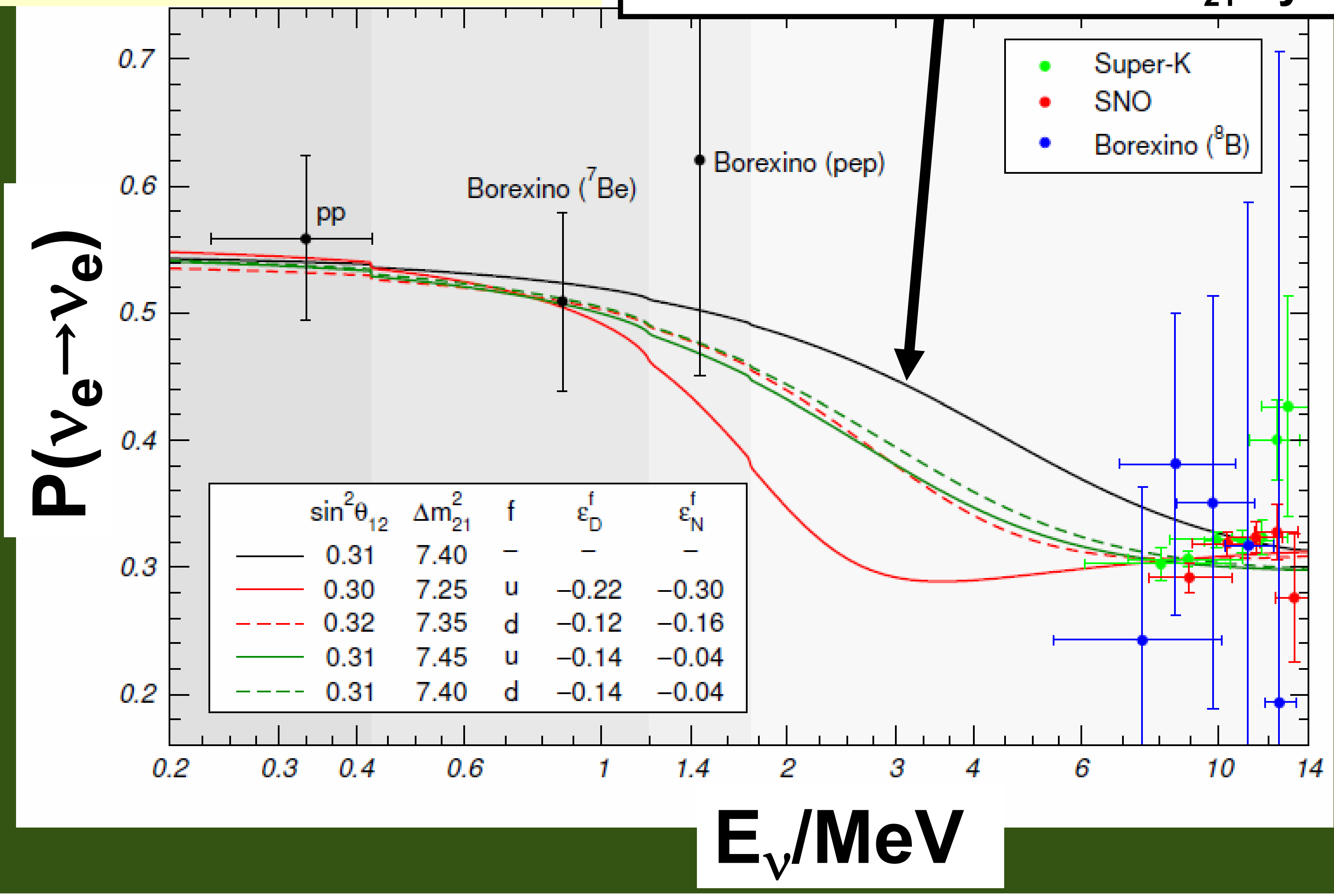
Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz, arXiv:1811.05487v1 [hep-ph]

Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO

As the threshold energy of SK & SNO decreases, they observe little upturn

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

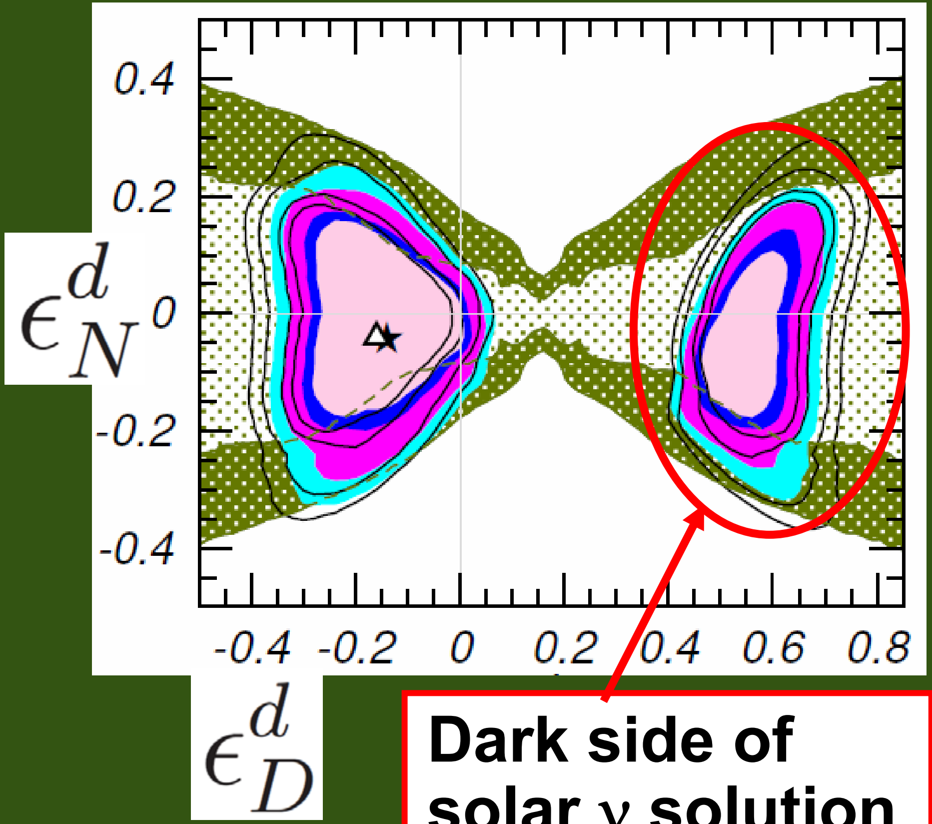
Standard scenario w/ Δm^2_{21} by KamLAND



	$\sin^2\theta_{12}$	Δm^2_{21}	f	ε^f_D	ε^f_N
black solid	0.31	7.40	–	–	–
red solid	0.30	7.25	u	−0.22	−0.30
red dashed	0.32	7.35	d	−0.12	−0.16
green solid	0.31	7.45	u	−0.14	−0.04
green dashed	0.31	7.40	d	−0.14	−0.04

Tension between solar ν & KamLAND can be solved by NSI

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



Dark side of solar ν solution ($\pi/4<\theta_{12}<\pi/2$)

Best fit value of global fit

$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

The values of these best fit points correspond roughly to

$$\varepsilon_{ee} \sim 1, \ |\varepsilon_{e\tau}| \sim 0.1$$

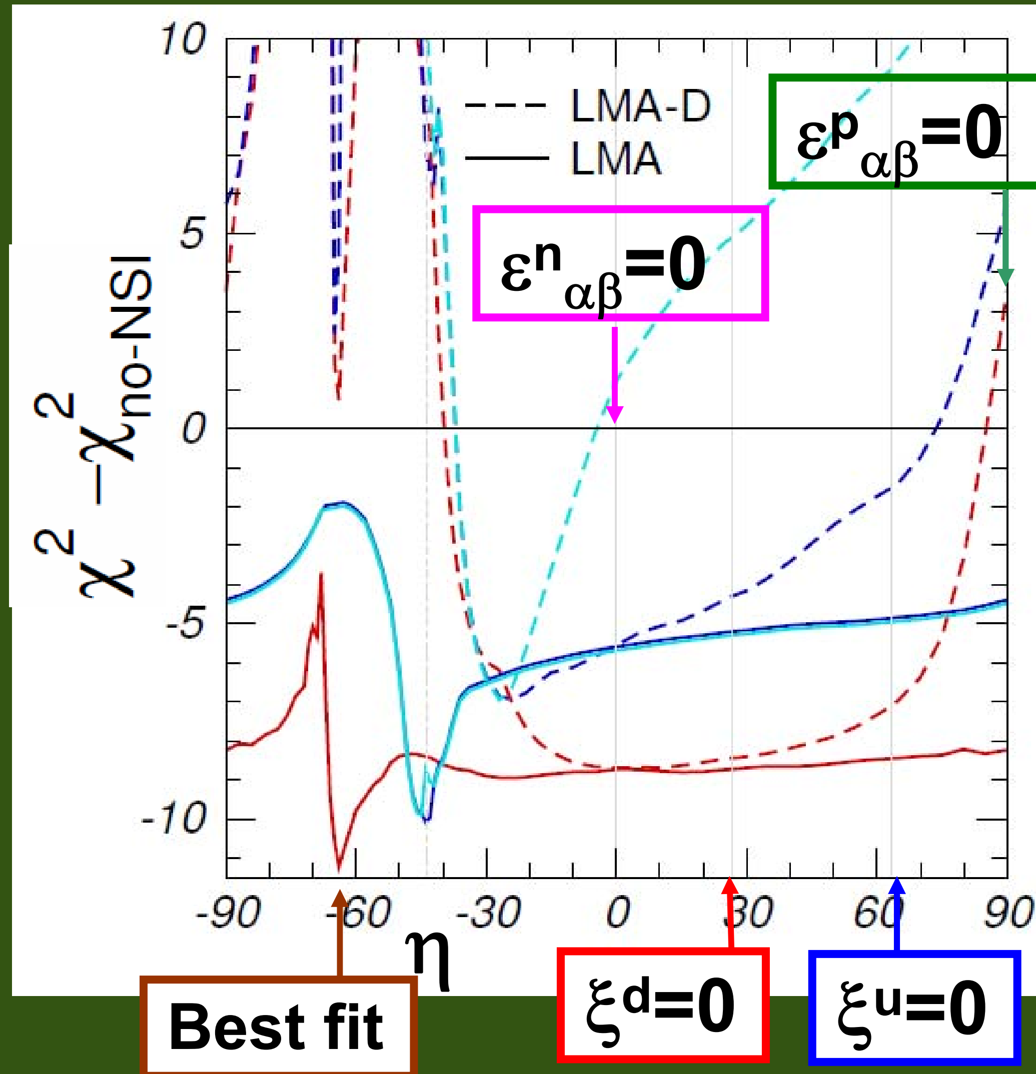
In the earlier analysis, either $\varepsilon^u=0$ or $\varepsilon^d=0$ was assumed

Best fit (η=-64°) is a mixture of ξ^u and ξ^d:

$$\varepsilon^f_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta} = \varepsilon^\eta_{\alpha\beta}\,\xi^f$$

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta)$$

$$\xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)$$



In the most recent analysis, general mixture of ε^u and ε^d is assumed while still assuming $\varepsilon^e=0$

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, arXiv:1805.04530v1 [hep-ph]

2.4 Parameter degeneracy in the presence of NSI

Bakhti, Farzan, JHEP 1407 (2014) 064;
Coloma, Schwetz, PRD94 (2016) 055005

There is **exact** symmetry in $P(\nu_\alpha \to \nu_\beta)$ under

$$H = U \mathcal{E} U^{-1} + \mathcal{A} \;\to\; -H^* = -[U^* \mathcal{E} (U^*)^{-1} + \mathcal{A}^*]$$

$\Delta m^2_{j1} \to -\Delta m^2_{j1}$
$\delta \to -\delta$, $\arg(\varepsilon_{\alpha\beta}) \to -\arg(\varepsilon_{\alpha\beta})$
$\delta_{\alpha e}\delta_{\beta e} + \varepsilon_{\alpha\beta} \to -\delta_{\alpha e}\delta_{\beta e} - \varepsilon_{\alpha\beta}^*$

※ Solar term is usually defined as $\Delta m^2_{21} > 0$:
$(\Delta m^2_{21} < 0,\ 0 < \theta_{12} < \pi/4)$
$\to$
$(\Delta m^2_{21} > 0,\ \pi/4 < \theta_{12} < \pi/2)$

$$A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \to -A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

In the simplest case,
(A) $\varepsilon_{ee} = 0$, other $\varepsilon_{\alpha\beta} = 0$, $\delta=-\pi/2$ (std, NH)
(B) $\varepsilon_{ee} = -2$, other $\varepsilon_{\alpha\beta} = 0$, $\delta=+\pi/2$ (NSI, IH)
cannot be distinguished from ANY oscillation experiment, once we assume the presence of NSI.

→ We have to use other experiments to constrain $\varepsilon_{\alpha\beta}$.

3. Non oscillation experiments to constrain $\varepsilon_{\alpha\beta}$

We are mainly interested in the vector part and e, τ sector $\varepsilon_{\alpha\beta}^V$ (α, β = e, τ), in particular ε_{ee}^V, because the μ sector have already strong constraints.

3.1 CHARM experiment

3.2 LSND experiment

3.3 COHERENT experiment

3.4 ν-d scatterings

3.1 CHARM experiment

J. Dorenbosch et al., Phys.Lett.B180('86)303

Davidson et al., JHEP 0303:011,2003

$$R^e = \frac{\sigma(\nu_e N \to \nu X) + \sigma(\bar{\nu}_e N \to \bar{\nu} X)}{\sigma(\nu_e N \to e X) + \sigma(\bar{\nu}_e N \to \bar{e} X)}$$

$$= (\tilde{g}_{Le})^2 + (\tilde{g}_{Re})^2 = 0.406 \pm 0.140$$

$$(\tilde{g}_{Le})^2 = (g_L^u + \varepsilon_{ee}^{uL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{uL}|^2 + (g_L^d + \varepsilon_{ee}^{dL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{dL}|^2$$

$$(\tilde{g}_{Re})^2 = (g_R^u + \varepsilon_{ee}^{uR})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{uR}|^2 + (g_L^d + \varepsilon_{ee}^{dR})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{dR}|^2$$

Assuming only ee component $\varepsilon_{ee}^V \neq 0$,

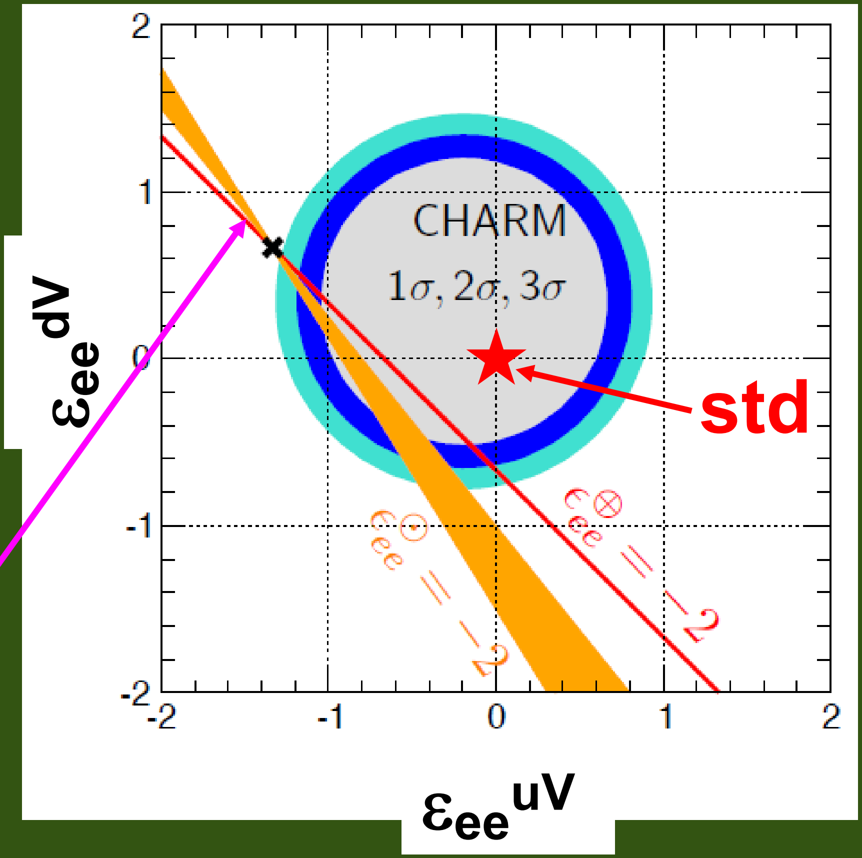
$$0.176 < (0.3493 + \varepsilon_{ee}^{uL})^2 + (-0.4269 + \varepsilon_{ee}^{dL})^2 + (-0.1551 + \varepsilon_{ee}^{uR})^2 + (0.0775 + \varepsilon_{ee}^{dR})^2 < 0.636$$

$$\varepsilon_{\alpha\beta}^R = \varepsilon_{\alpha\beta}^V + \varepsilon_{\alpha\beta}^A, \quad \varepsilon_{\alpha\beta}^L = \varepsilon_{\alpha\beta}^V - \varepsilon_{\alpha\beta}^A$$

CHARM experiment (cont'd)

Assuming only vector component $\varepsilon_{ee}^{fV} \neq 0$ ($\varepsilon_{ee}^{fA}=0$), we get a constraint.

However this constraint is not strong enough to exclude the dark side: $\varepsilon_{ee}^{\oplus}=3\varepsilon_{ee}^{uV}+3\varepsilon_{ee}^{dV}=-2$



Coloma, Schwetz, PRD94 (2016) 055005

3.2 LSND experiment

Davidson et al., JHEP 0303:011,2003

$$\sigma(\nu_e e \to \nu e) = \frac{2G_F^2 m_e E_\nu}{\pi}\left[(1+g_L^e+\varepsilon_{ee}^{eL})^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eL}|^2 + \frac{1}{3}(g_R^e+\varepsilon_{ee}^{eR})^2 + \frac{1}{3}\sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eR}|^2\right]$$

$g_L^e = -0.2718$ $\quad g_R^e = 0.2326$

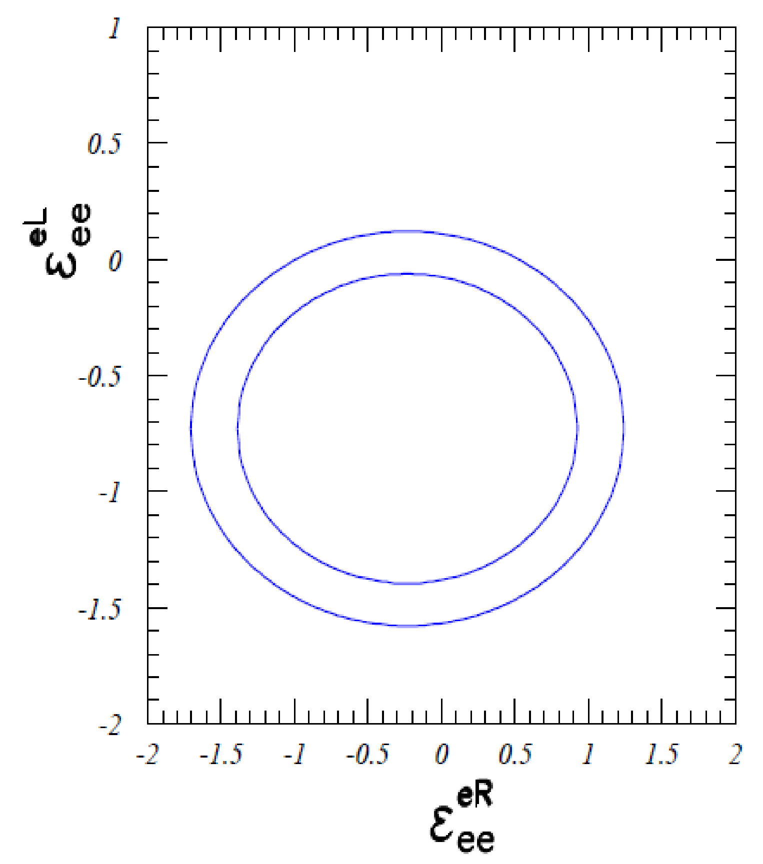
$$\sigma(\nu_e e \to \nu e) = (1.17 \pm 0.17)\frac{G_F^2 m_e E_\nu}{\pi}$$

L.B. Auerbach et al., PRD 63 ('01) 112001

Assuming only ee component $\varepsilon_{ee}^V \neq 0$, we get a constraint

$\varepsilon_{\alpha\beta}^R = \varepsilon_{\alpha\beta}^V + \varepsilon_{\alpha\beta}^A$

$\varepsilon_{\alpha\beta}^L = \varepsilon_{\alpha\beta}^V - \varepsilon_{\alpha\beta}^A$



3.3 COHERENT experiment

D. Akimovet al., 1708.01294 [nucl-ex]

Coherent scattering $\sigma(\nu + A \to \nu + A) \propto A^2$

Freedman, PRD9 ('74) 1389

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left\{(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - \left(G_V^2 - G_A^2\right)\frac{MT}{E_\nu^2}\right\}$$

Barranco, Miranda,Rashba JHEP 0512 (2005) 021

$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right)Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right)N\right]F_{nucl}^V(Q^2)$$

$$G_A = \left[\left(g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA}\right)(Z_+ - Z_-) + \left(g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA}\right)(N_+ - N_-)\right] \times F_{nucl}^A(Q^2)$$

$Z_\pm$ = #(p) spin up/down

$N_\pm$ = #(n) spin up/down

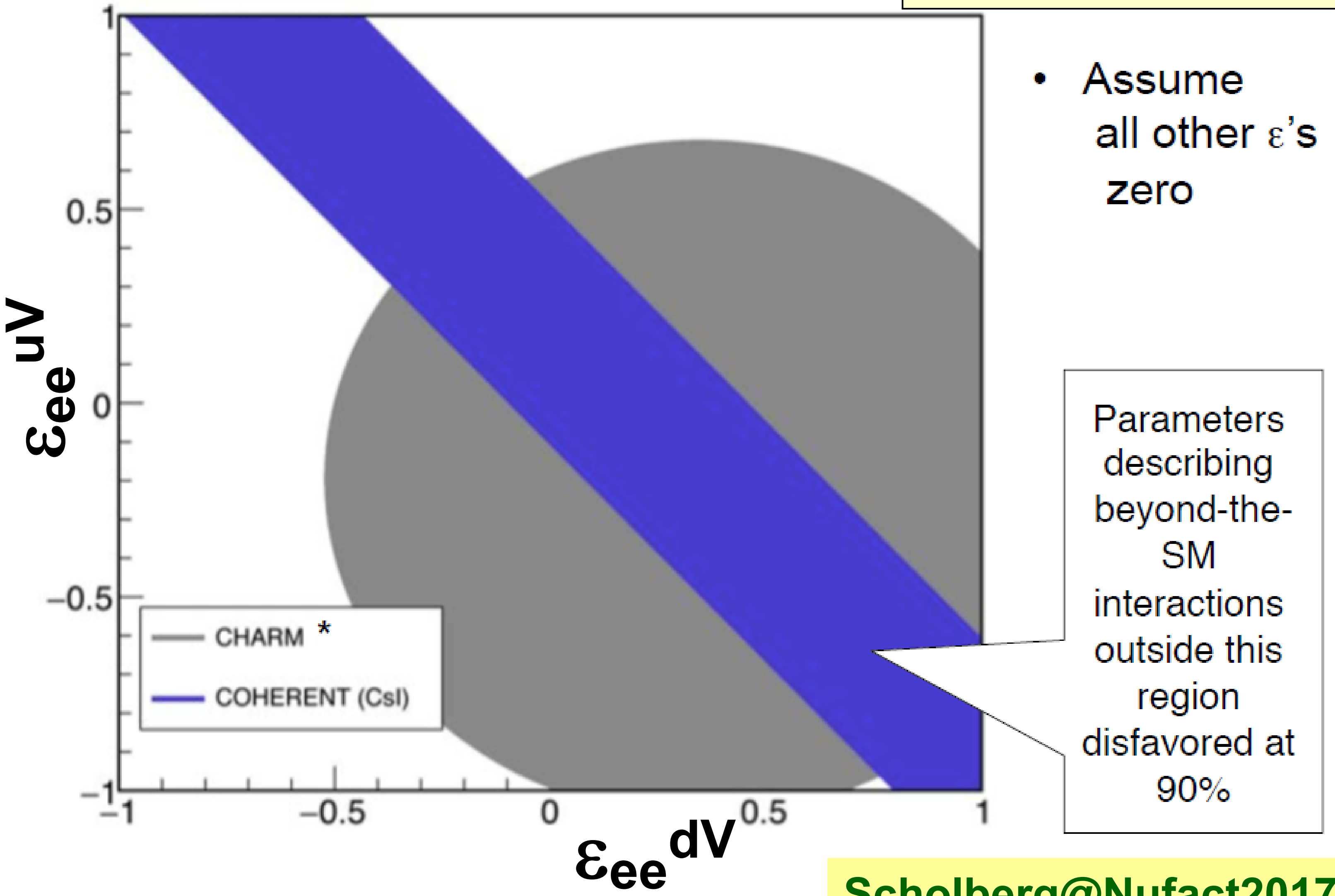
Nice feature: $Z_+ = Z_-$, $N_+ = N_-$

-> No contribution from the axial part ε_{ee}^{fA}

COHERENT experiment (cont'd)

The dark side
$\varepsilon_{ee}^{\oplus} = 3\varepsilon_{ee}^{uV} + 3\varepsilon_{ee}^{dV} = -2$
is excluded at 3σ

Neutrino non-standard interaction results for current CsI data set:



- Assume all other ε's zero

*CHARM constraints apply only to heavy mediators

Scholberg@Nufact2017

3.4 ν-d scatterings at SNO

SNO detects the three interactions:

ES $\nu_e + e^- \rightarrow \nu_e + e^-$

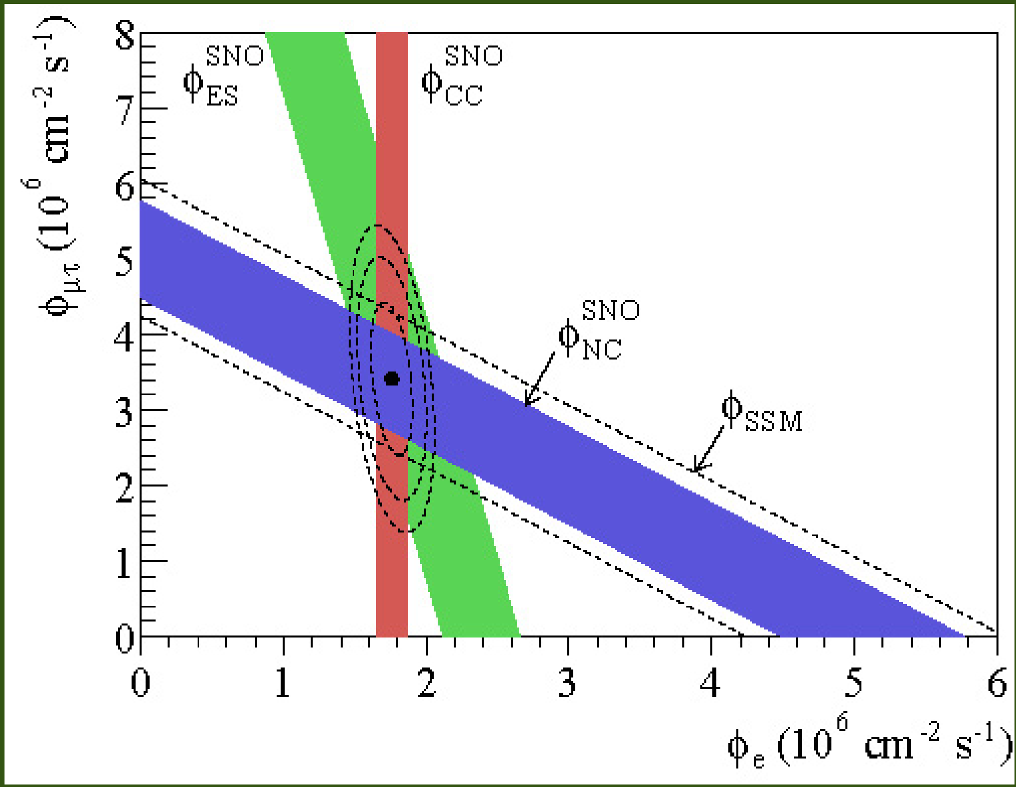
for all ν_x $(x = e, \mu, \tau)$

CC $\nu_e + d \rightarrow p + p + e^-$

only for ν_e

NC $\nu_x + d \rightarrow p + n + \nu_x$

for all ν_x $(x = e, \mu, \tau)$



Q.R. Ahmad et al., PRL 89 ('02) 011301

ν-d scatterings (cont'd)

$$[CC] = f_B \langle P_{ee}(\varepsilon'^V, \varepsilon^V) \rangle_{CC}$$

$$f_B = \frac{\Phi_{^8B}}{\Phi_{^8B}^{SSM}}$$

NC is sensitive only to $\varepsilon_{\alpha\alpha}^{fA}$

$$[NC] \sim f_B(1 + 2\varepsilon^A)$$

$$\varepsilon^A \sim \sum_{\alpha=e,\mu,\tau} \langle P_{e\alpha} \rangle_{NC} (\varepsilon_{\alpha\alpha}^{uA} - \varepsilon_{\alpha\alpha}^{dA})$$

$\varepsilon^A = 0$
if $\varepsilon_{\alpha\alpha}^{uA} = \varepsilon_{\alpha\alpha}^{dA}$

$$[ES] = \frac{2G_F^2 m_e E_\nu}{\pi} \left[(1 + g_L^e + \varepsilon_{ee}^{eL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eL}|^2 + \frac{1}{3}(g_R^e + \varepsilon_{ee}^{eR})^2 + \frac{1}{3} \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eR}|^2 \right]$$

ES is sensitive to ε_{ee}^{eV} -> Analysis becomes complicated

➡ **This is the reason why the case w/ $\varepsilon_{ee}^{eV} \neq 0$ has not been analyzed yet.**

ν-d scatterings (cont'd)

Thus we do not get information on $\varepsilon_{ee}^{fV} \neq 0$ from ν-d scatterings.

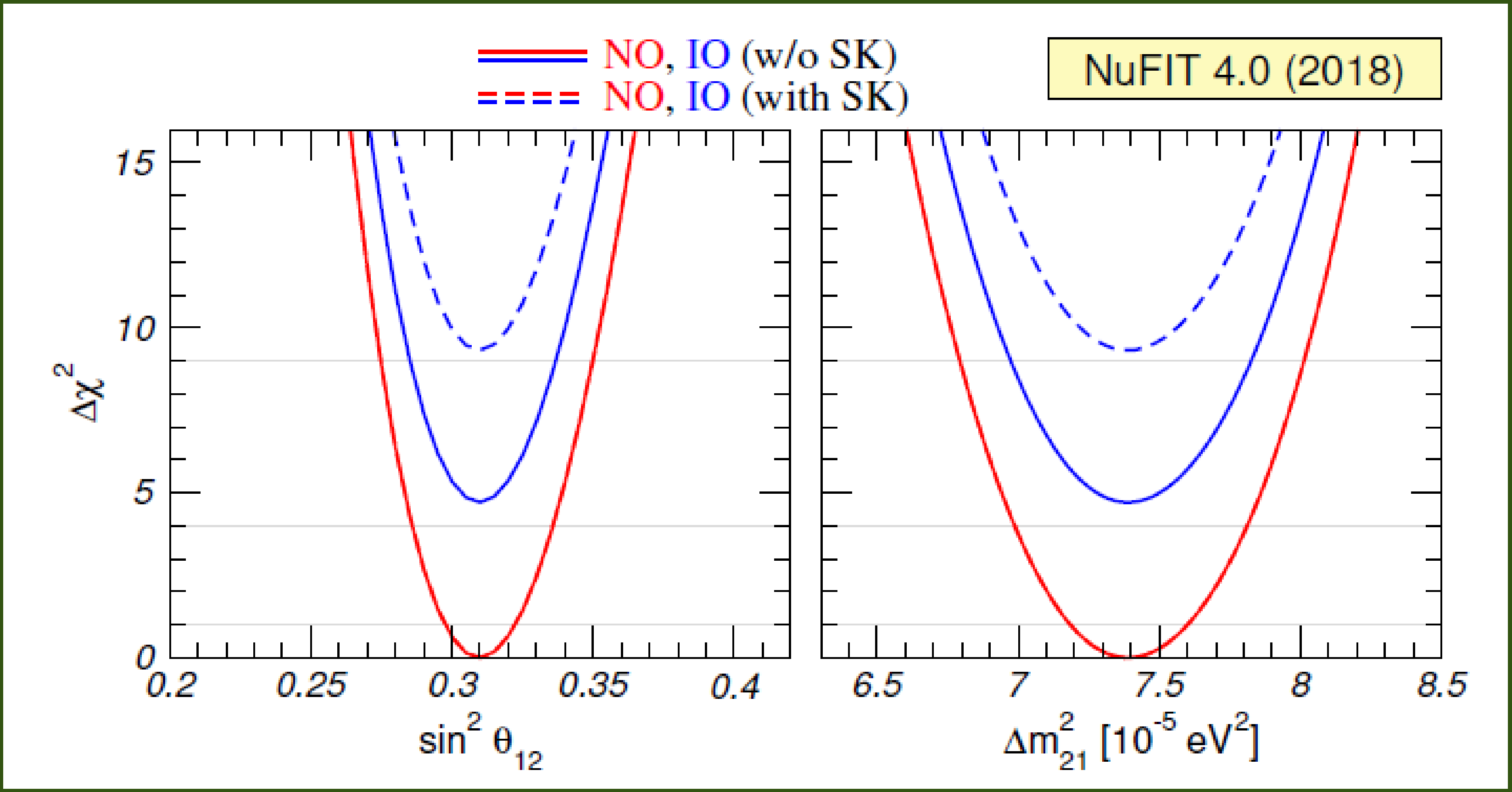
A problem for nuclear physicists

- **Is there any reaction (other than the coherent scattering n+A->n+A) which gives a strong constraint on ε_{ee}^{fV} (instead of ε_{ee}^{fA}) for f = e,u,d?**

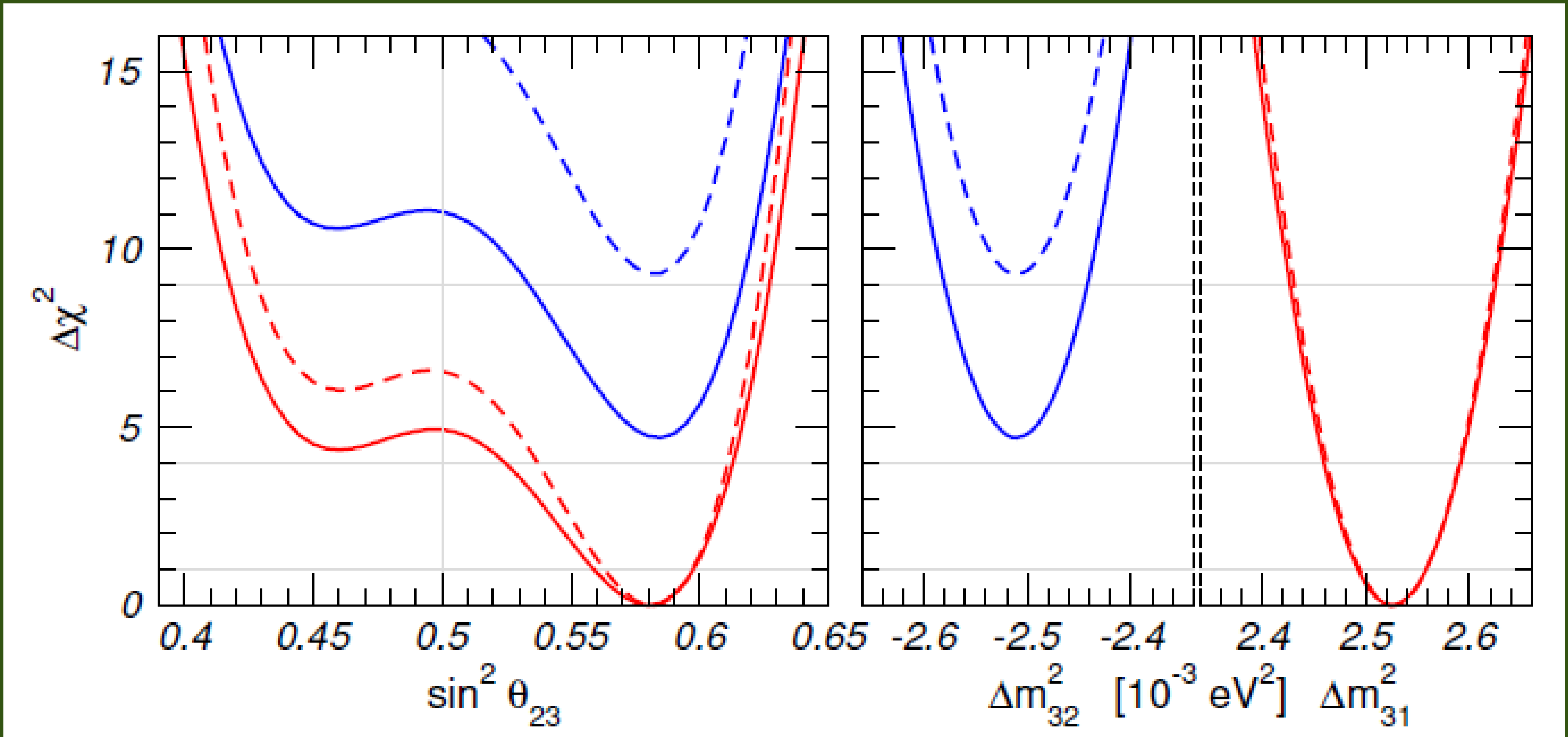
4. Conclusions

- NSI has caught a lot of interests because of (i) the possible NSI solution to the tension between solar ν+KamLAND and (ii) parameter degeneracy in the presence of NSI.
- The COHERENT experiment seems to give the strongest constraint on ε_{ee}^{uV} and ε_{ee}^{dV} .
- It would be interesting if other ν-A reactions can gives constraints on ε_{ee}^{fV} .

Backup slides



Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz, arXiv:1811.05487v1 [hep-ph]



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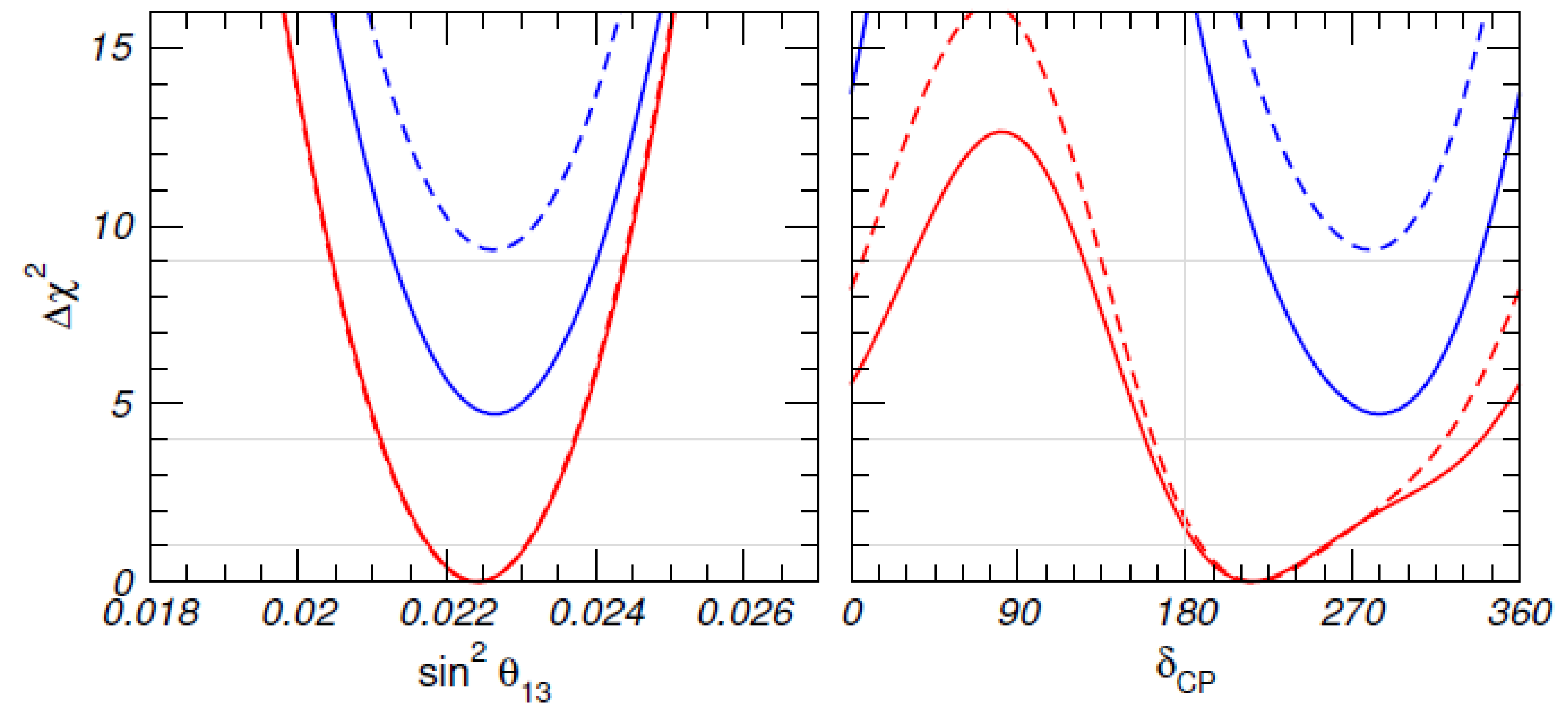

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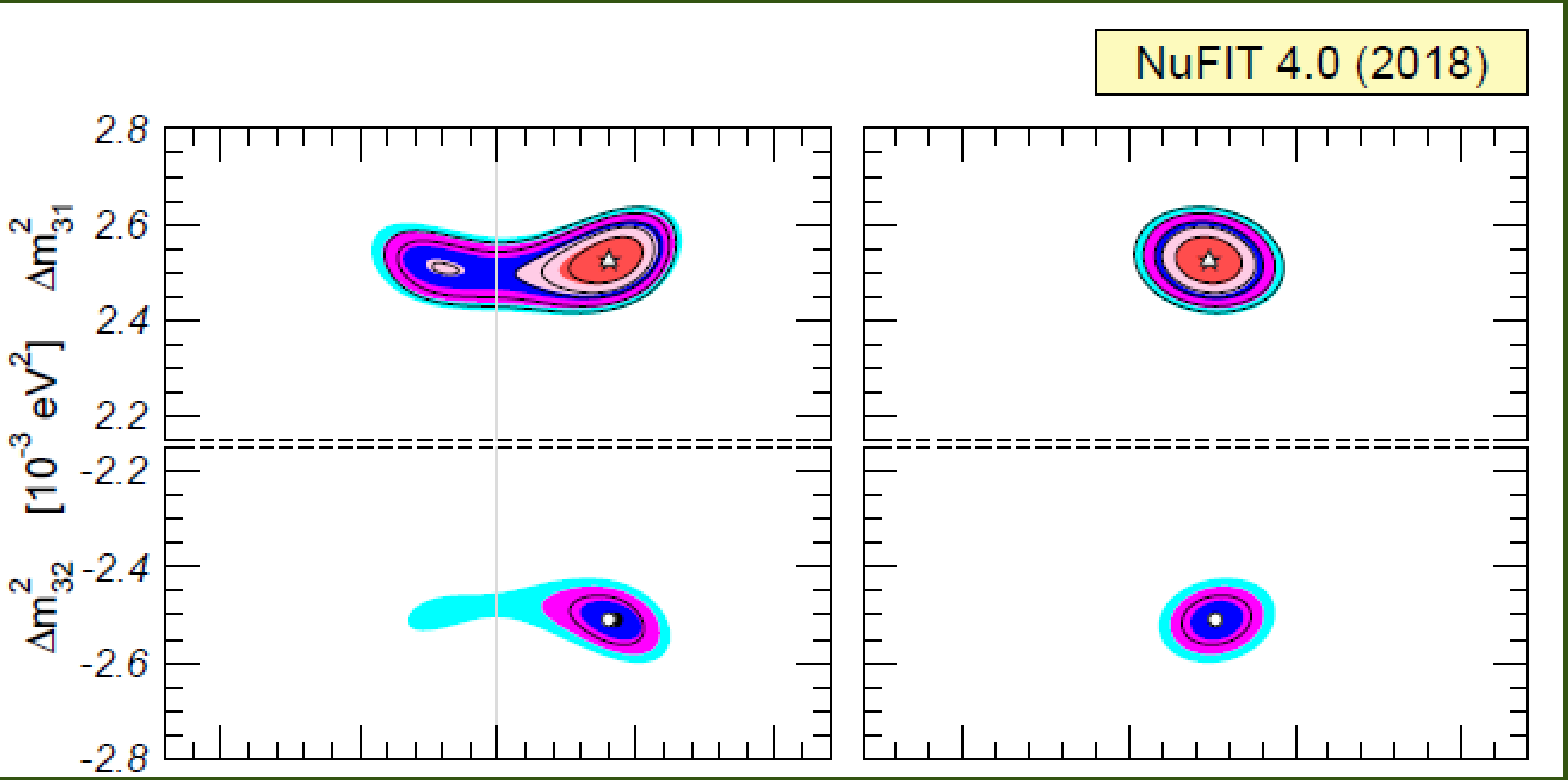

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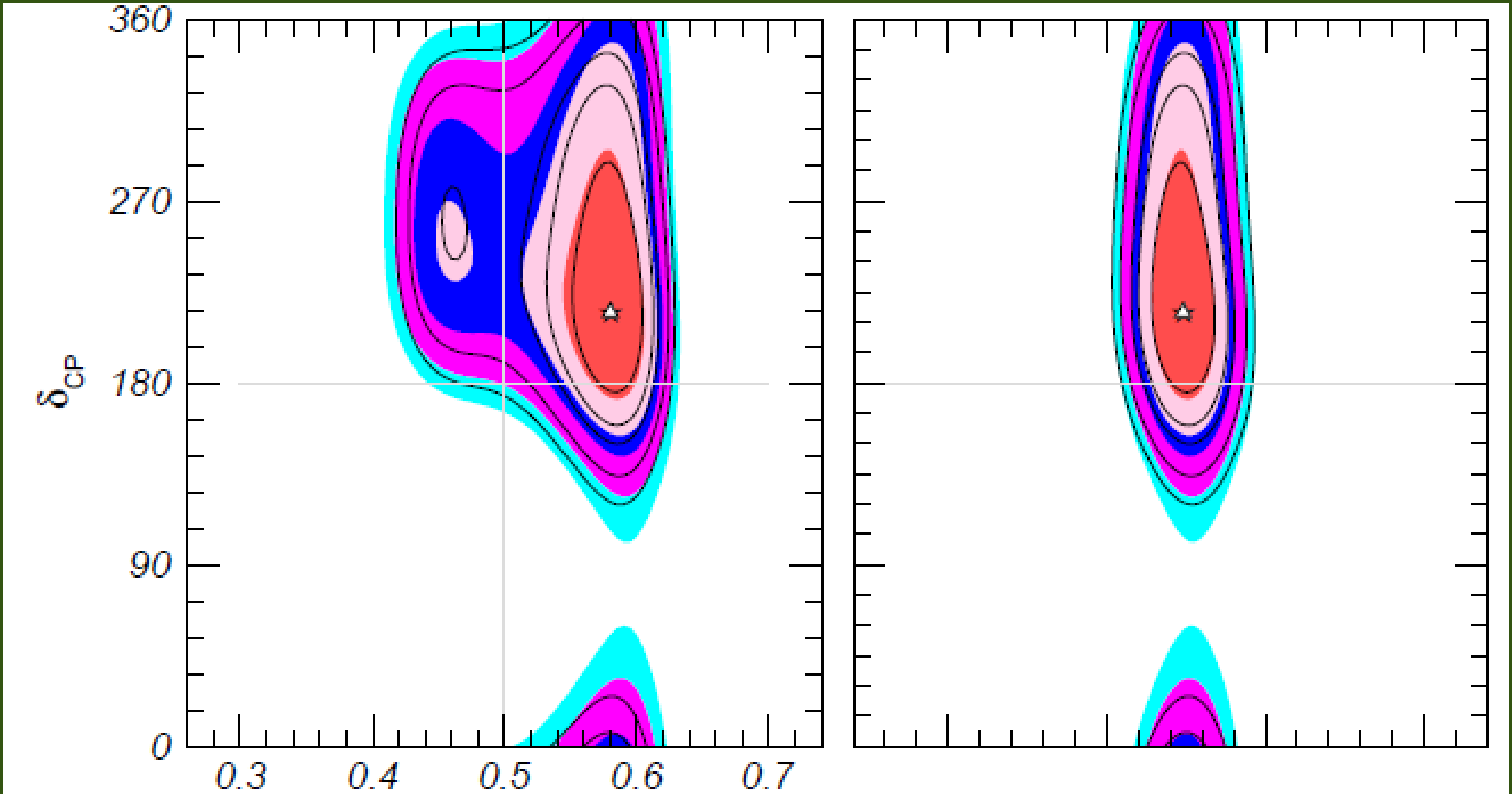

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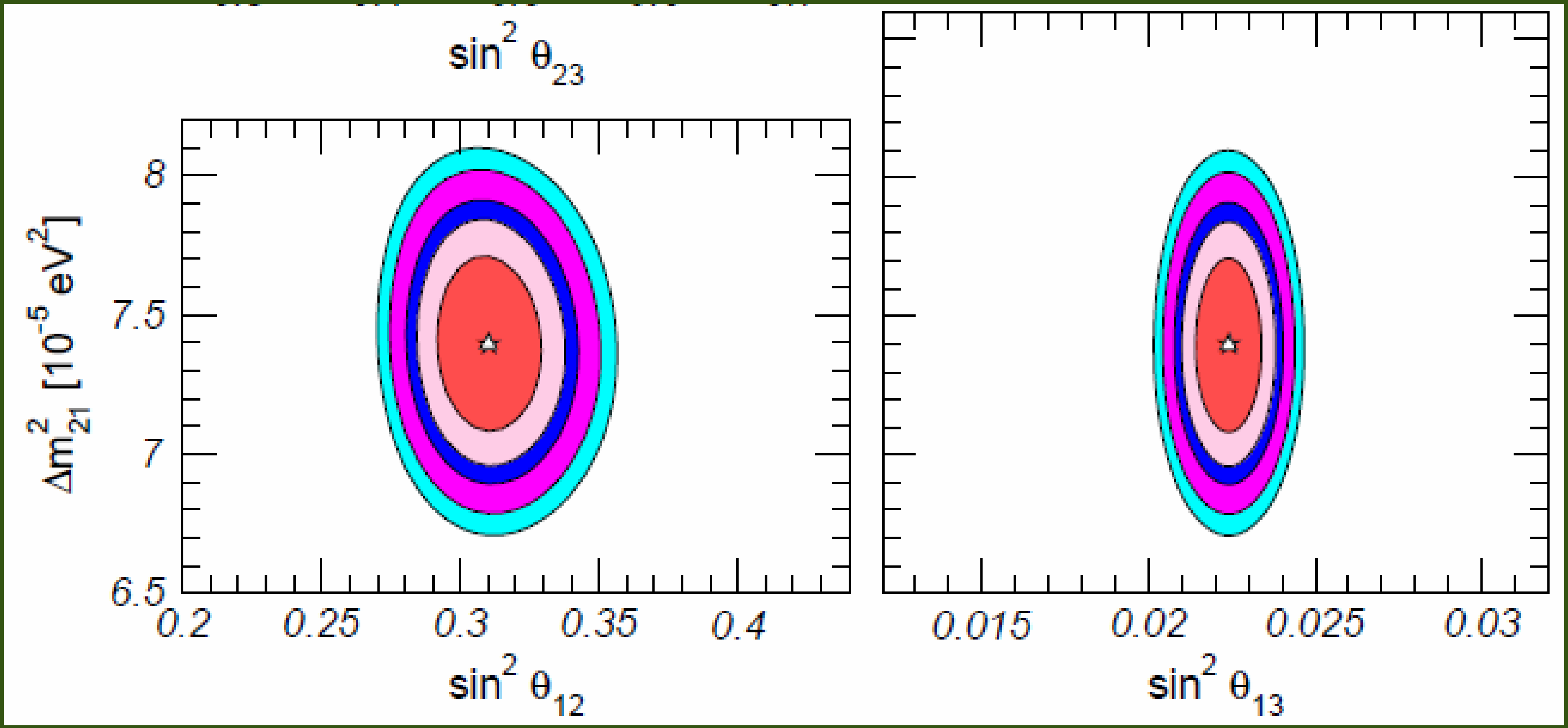

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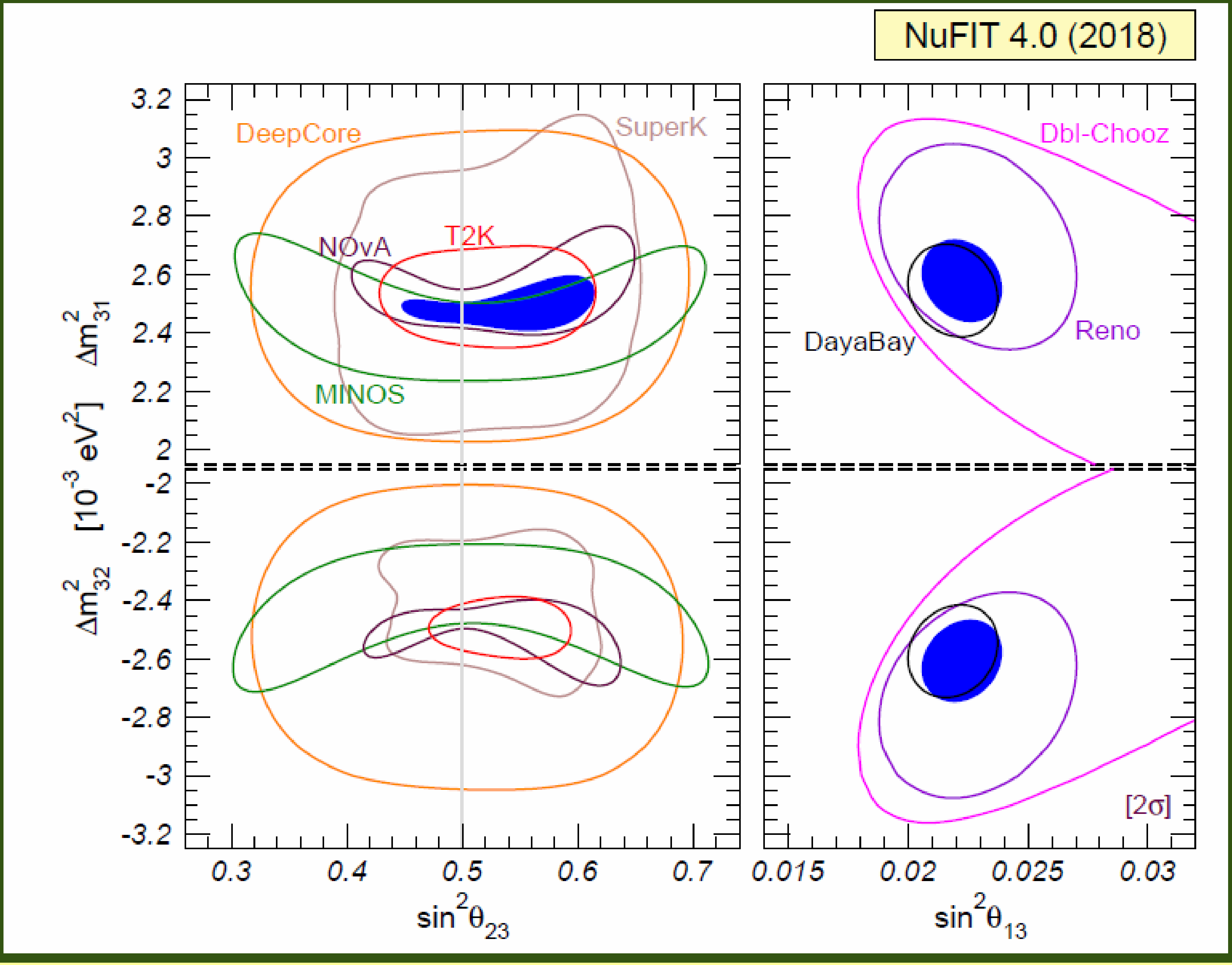

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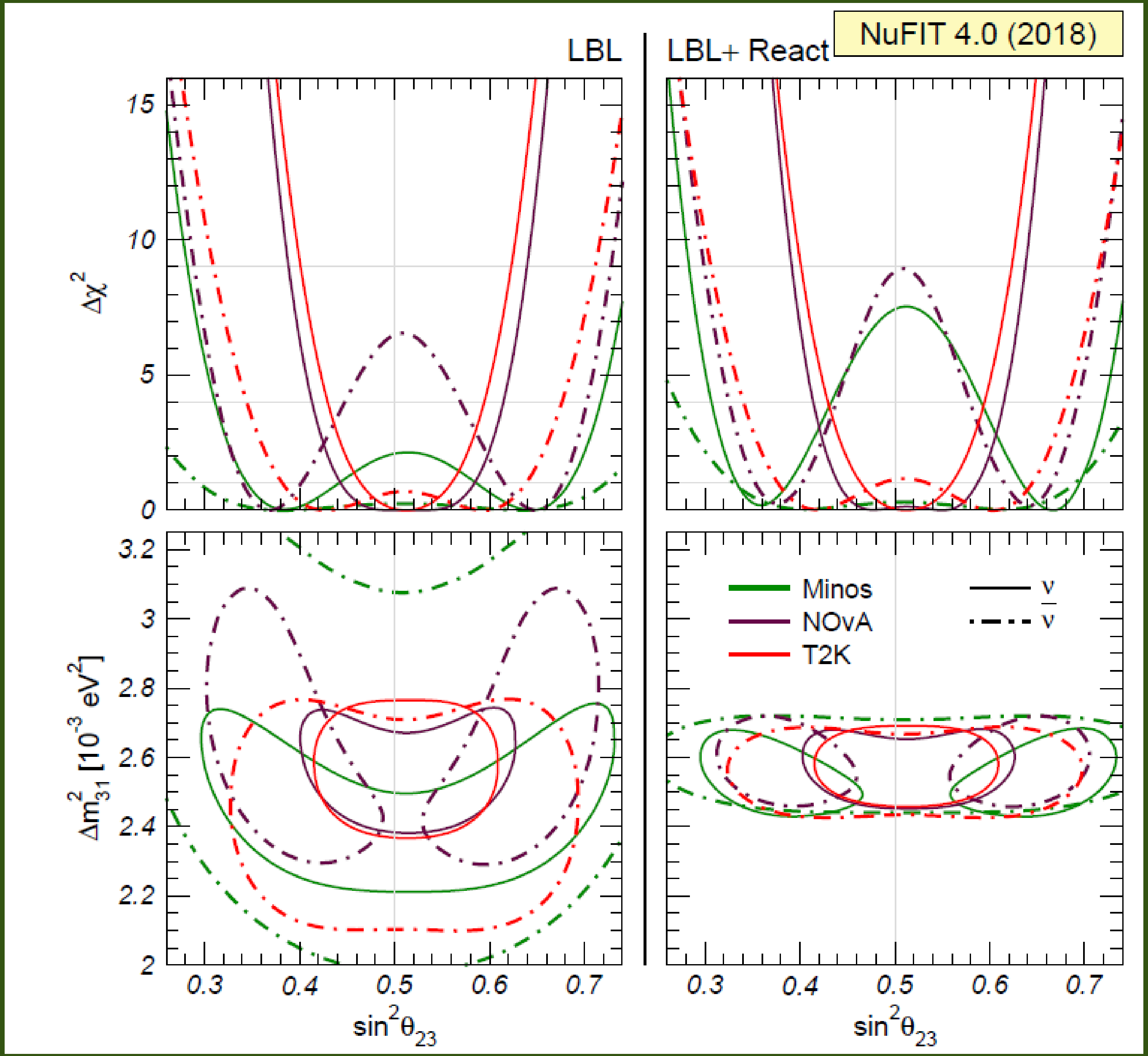
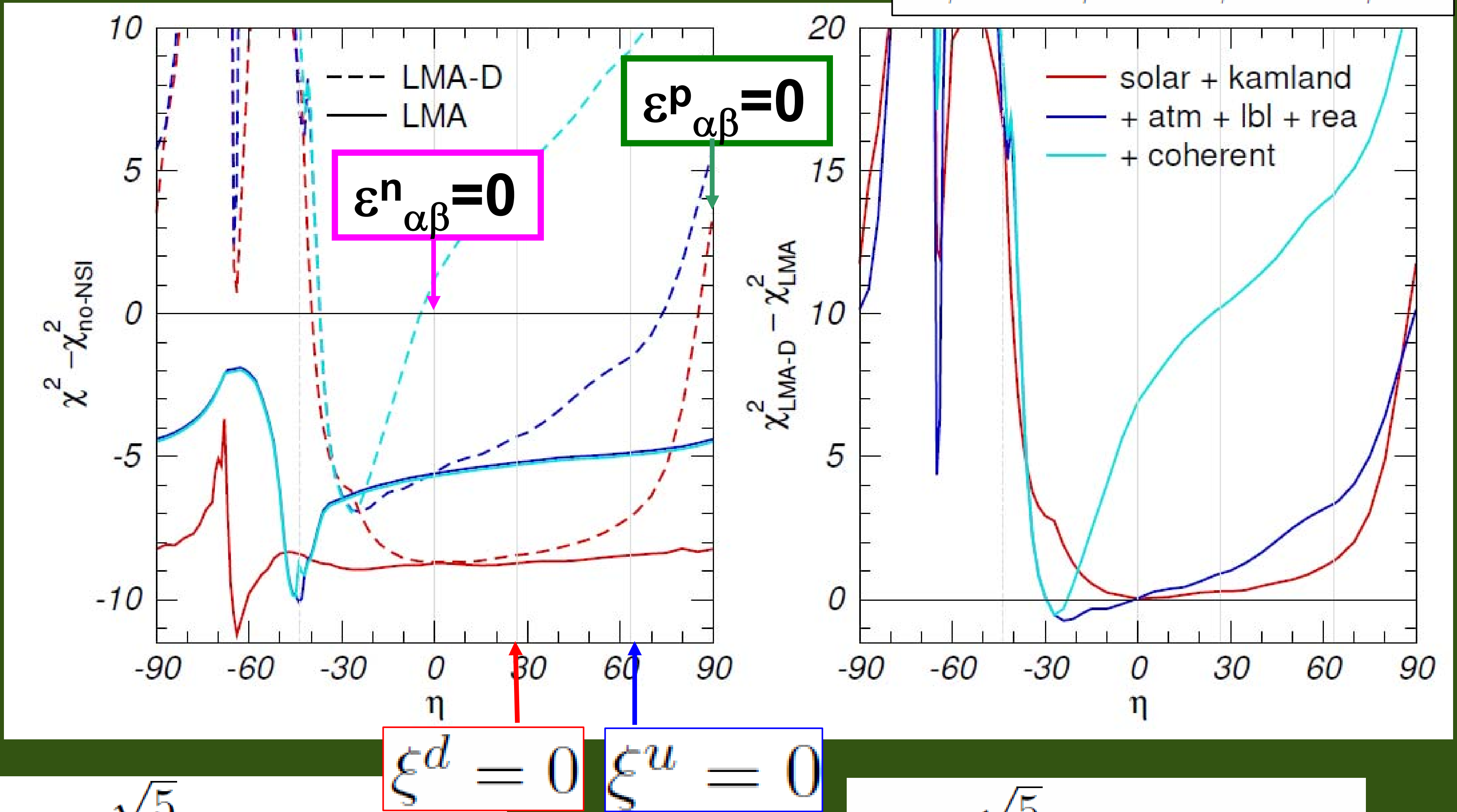


Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz, arXiv:1811.05487v1 [hep-ph]

Best fit (η=-64°) is a mixture of ξ^u and ξ^d:

$$\varepsilon^f_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\,\xi^f$$



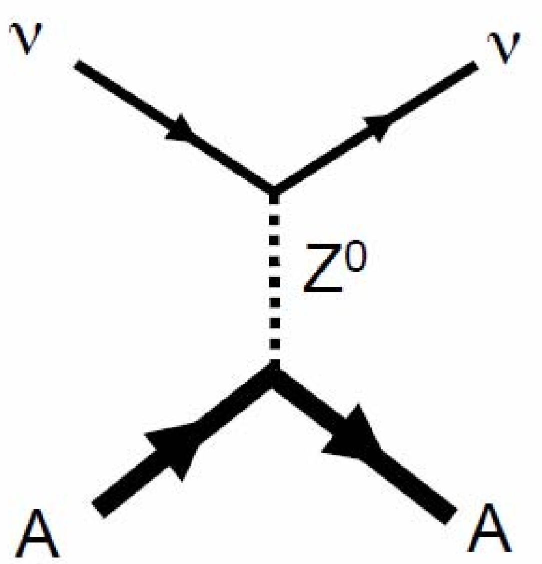
$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta)$$

$$\xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)$$

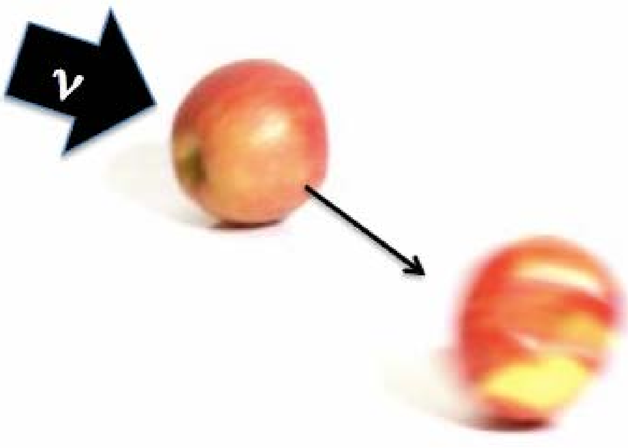
Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, arXiv:1805.04530v1 [hep-ph]

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

$$\frac{d\sigma}{d\Omega} \sim A^2 |f(\mathrm{k}', \mathrm{k})|^2$$

Momentum transfer $\mathrm{Q} = \mathrm{k}' - \mathrm{k}$

For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn]

The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

G_V, G_A: SM weak parameters

vector $G_V = g_V^p Z + g_V^n N,$ ← dominates

axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ + N_-)$ ← small for most nuclei, zero for spin-zero

$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = 0.4955$$
$$g_A^n = -0.5121.$$

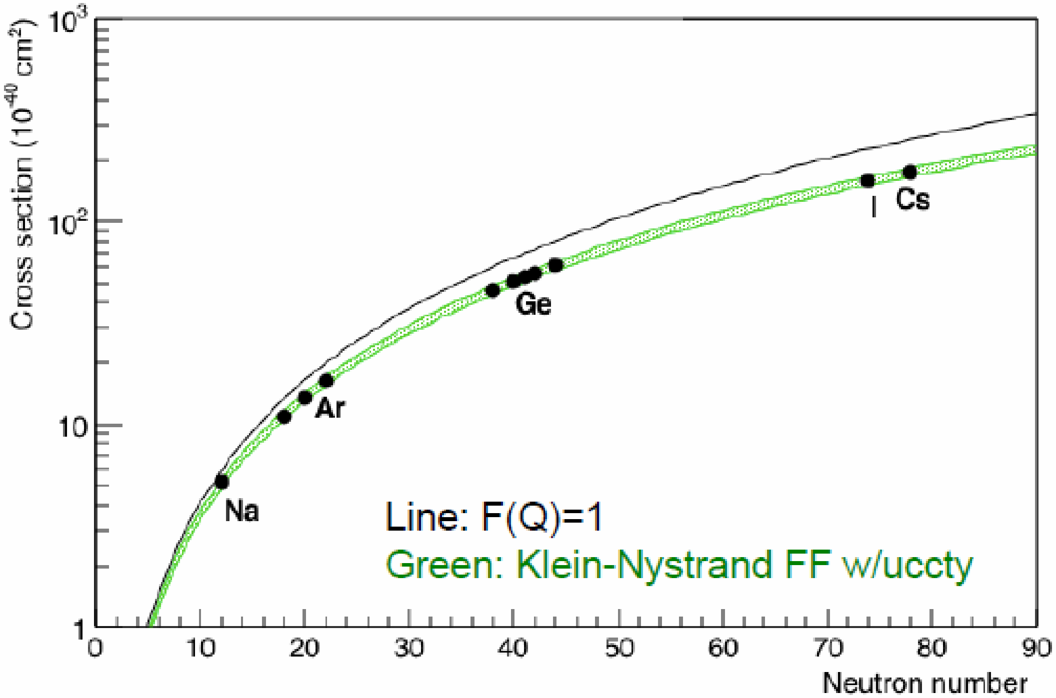
For T<<E_ν, neglecting axial terms:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

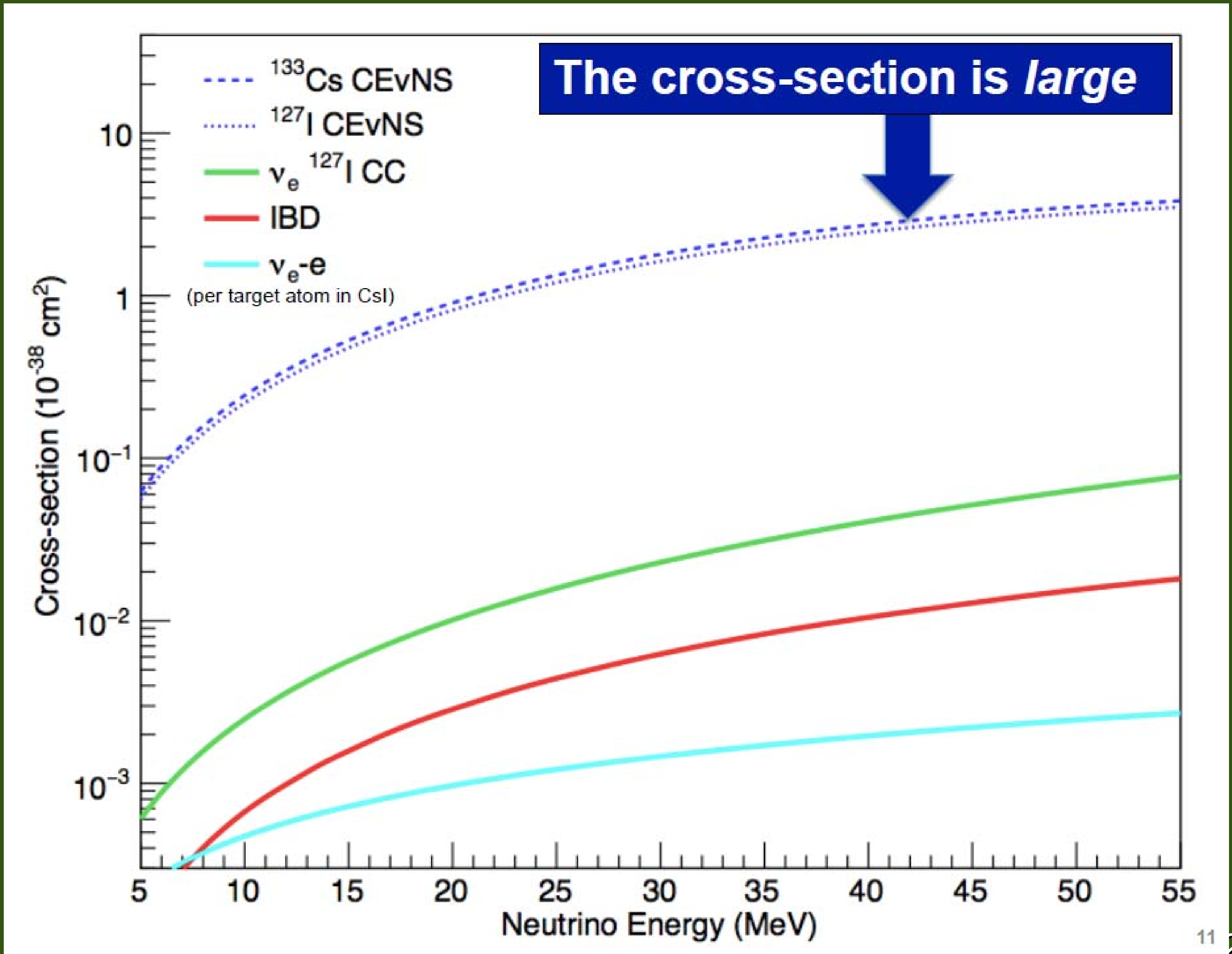
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$: weak nuclear charge

$\sin^2\theta_W = 0.231$,
so protons unimportant

$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$

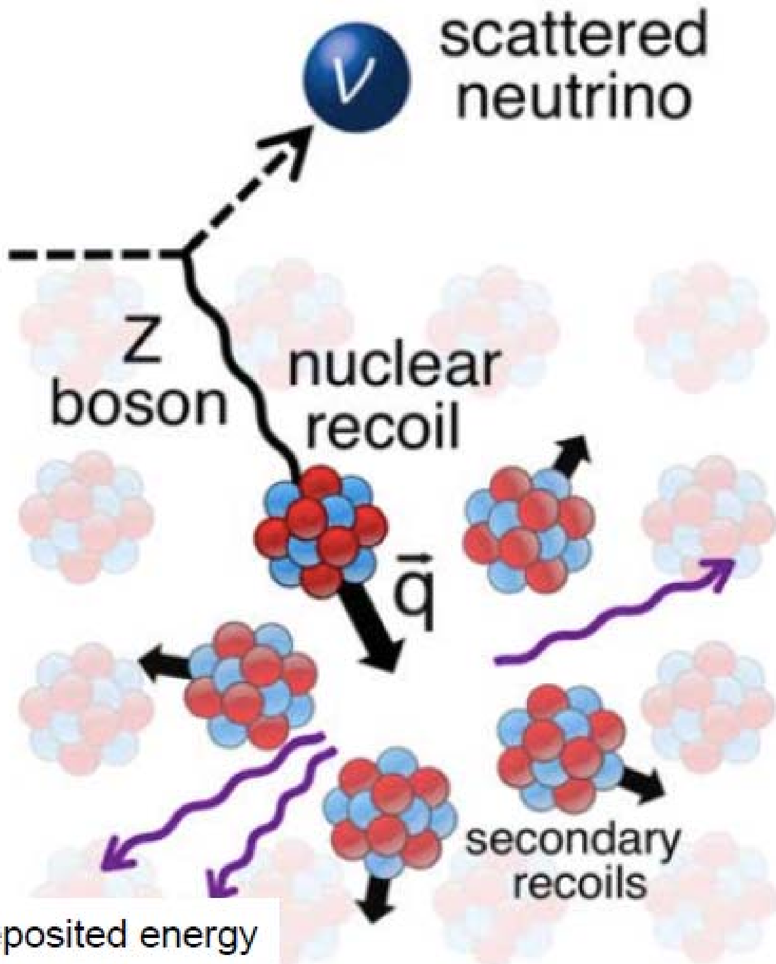


Scholberg@Nufact2017



The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

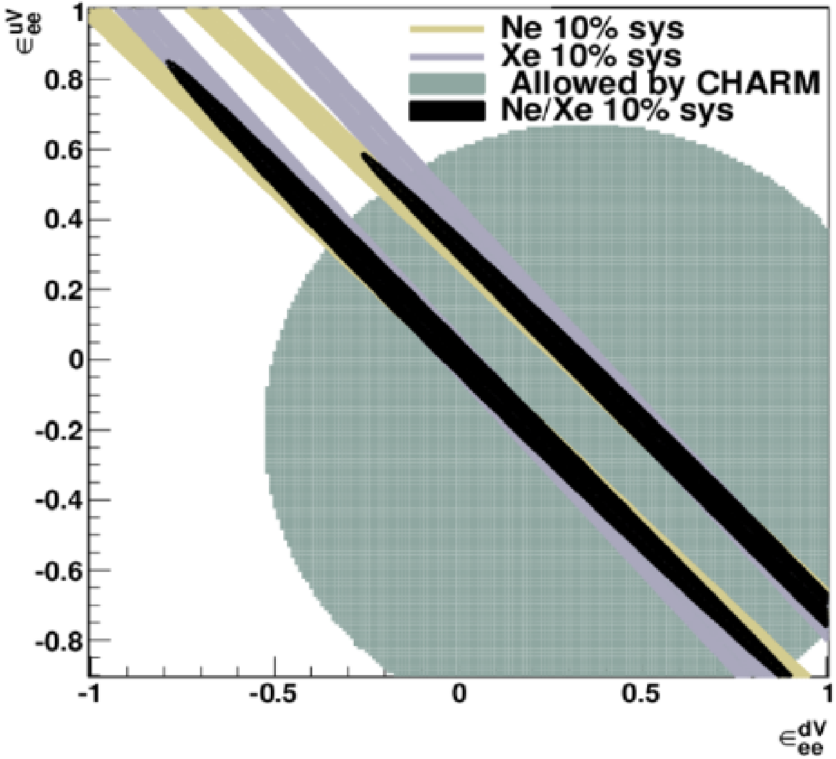


➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

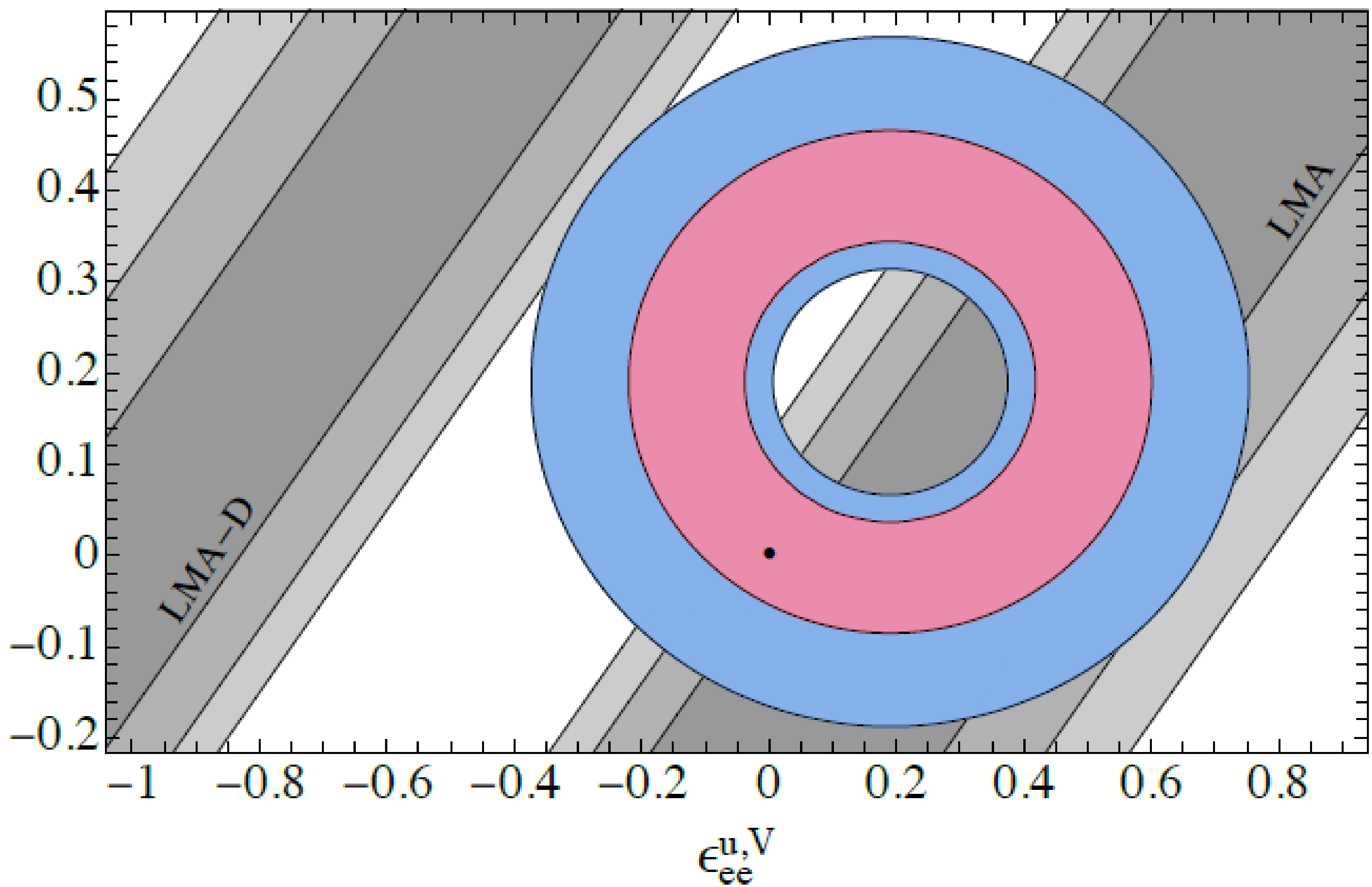


If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

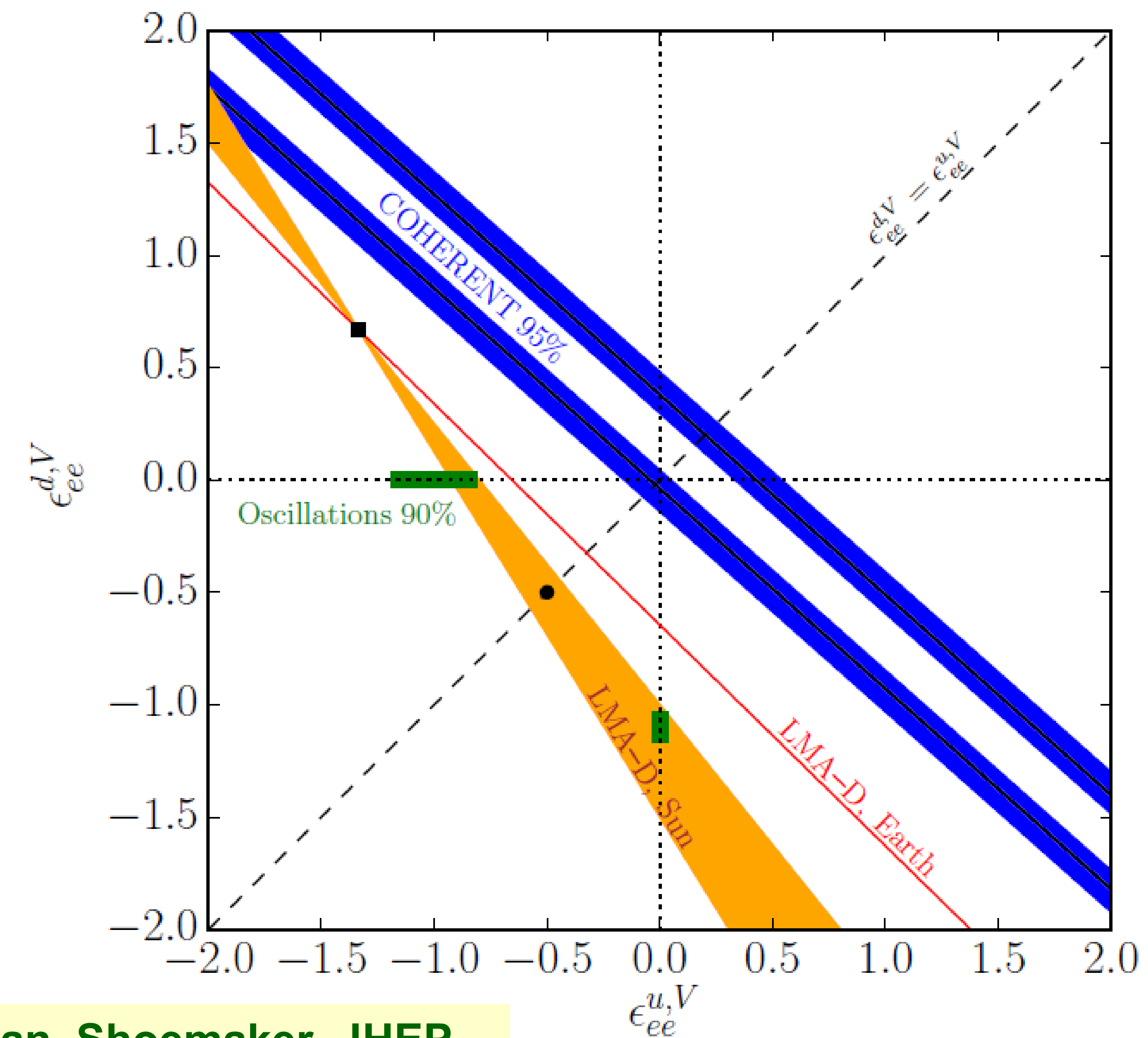
J. Barranco et al., JHEP 0512 (2005), K. Scholberg, PRD73, 033005 (2006), 021

Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

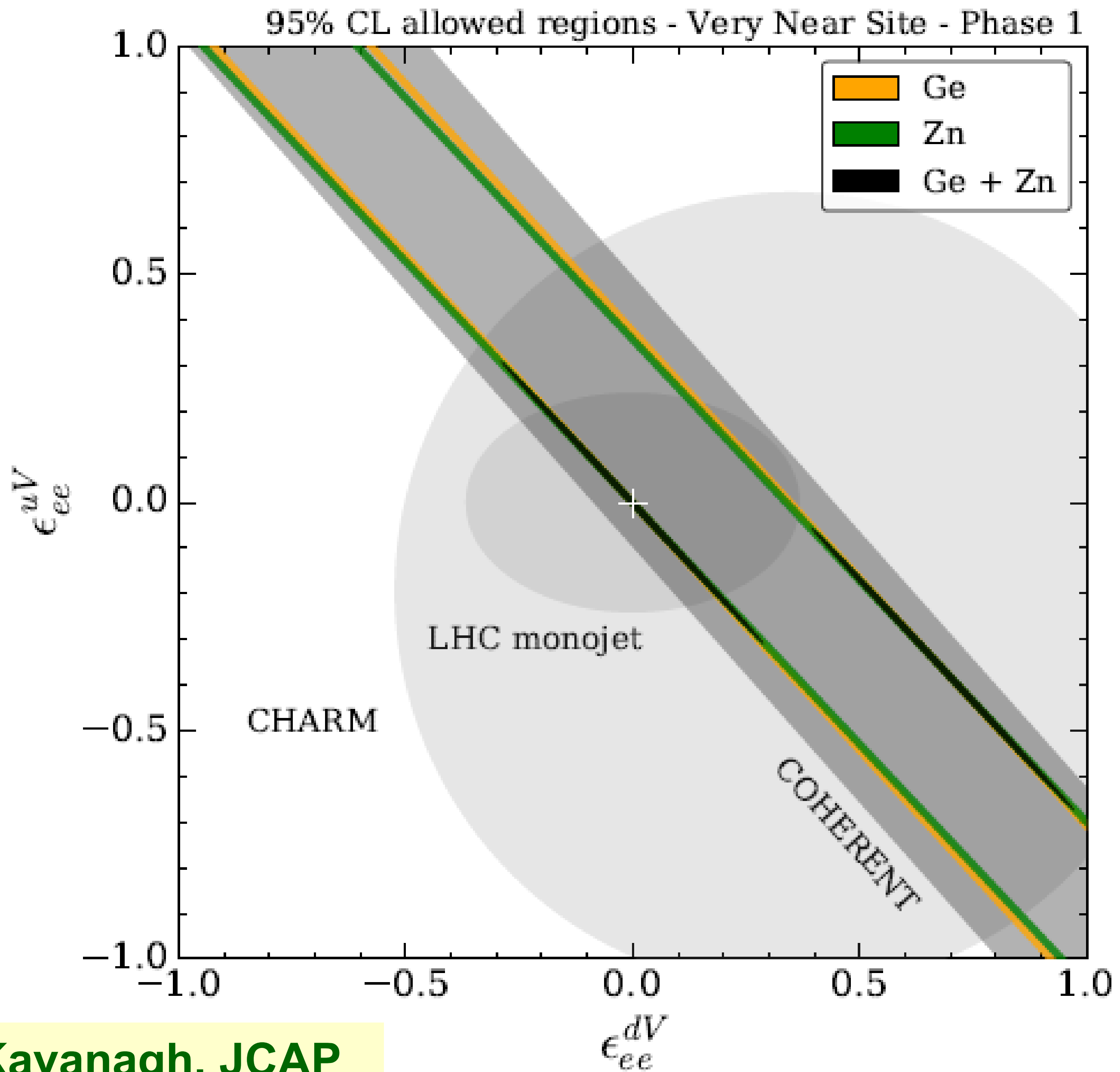
More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf



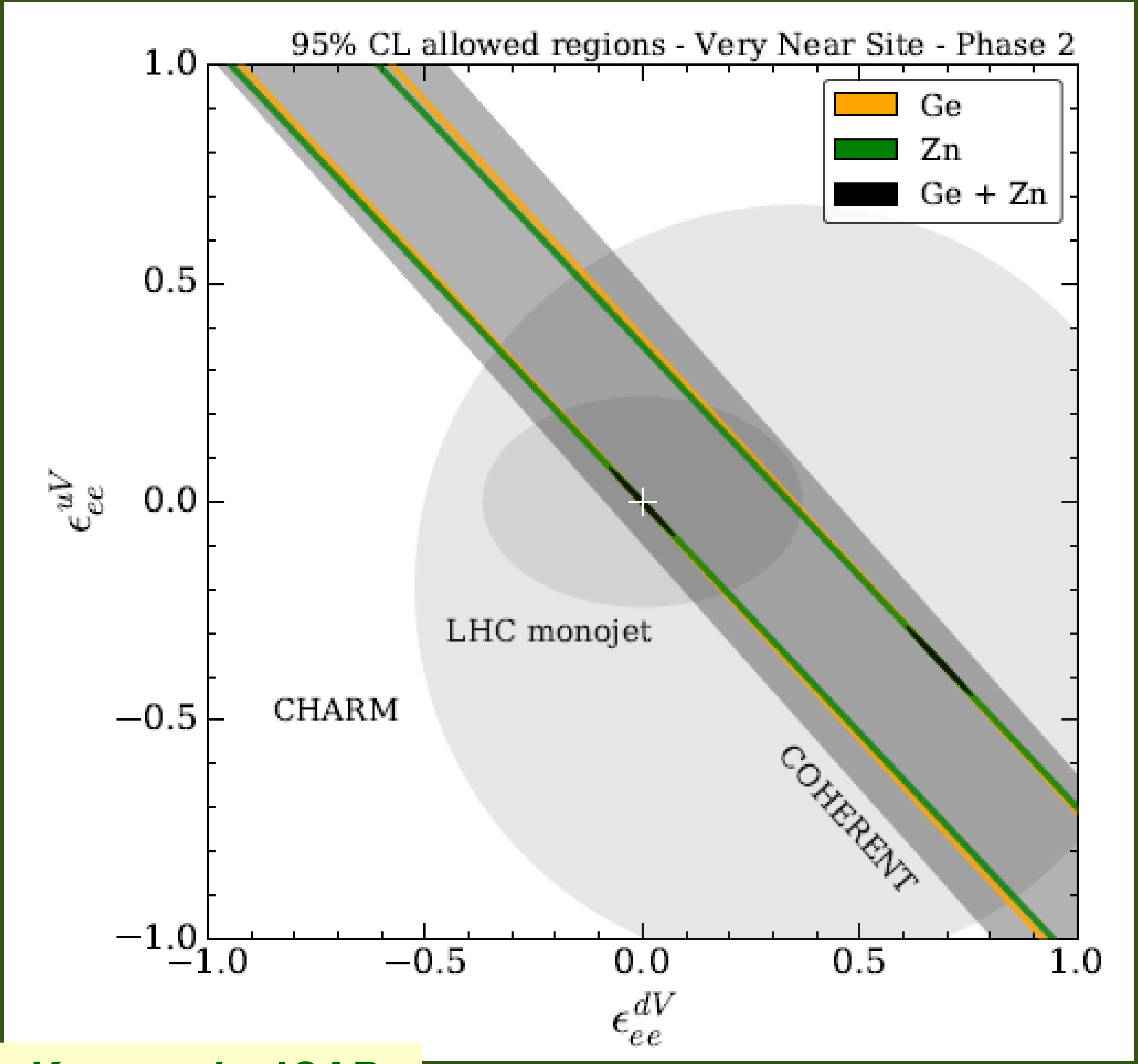
Coloma, Gonzalez-Garcia, Maltoni, Schwetz, Phys.Rev. D96 (2017) no.11, 115007



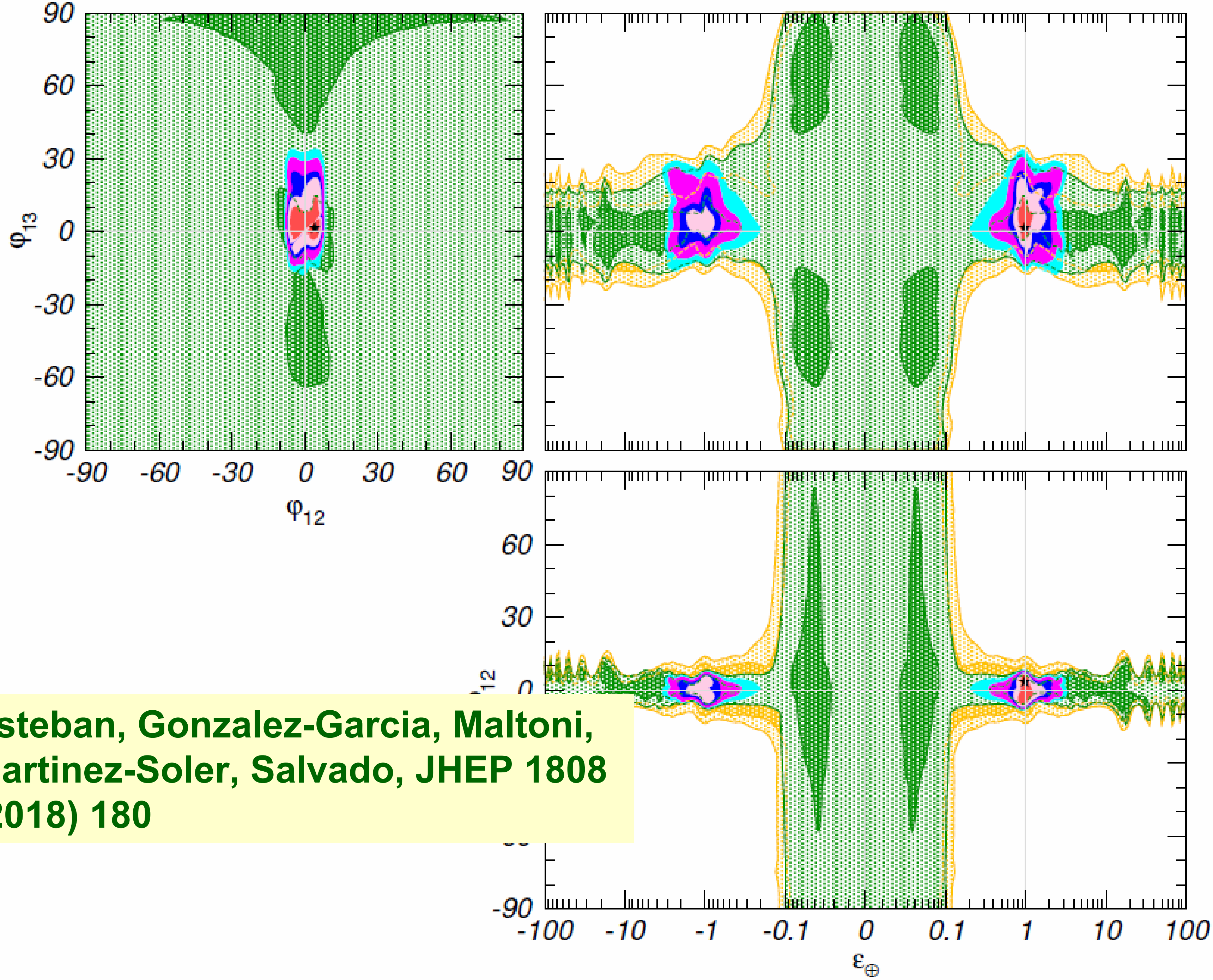
Denton, Farzan, Shoemaker, JHEP 1807 (2018) 037



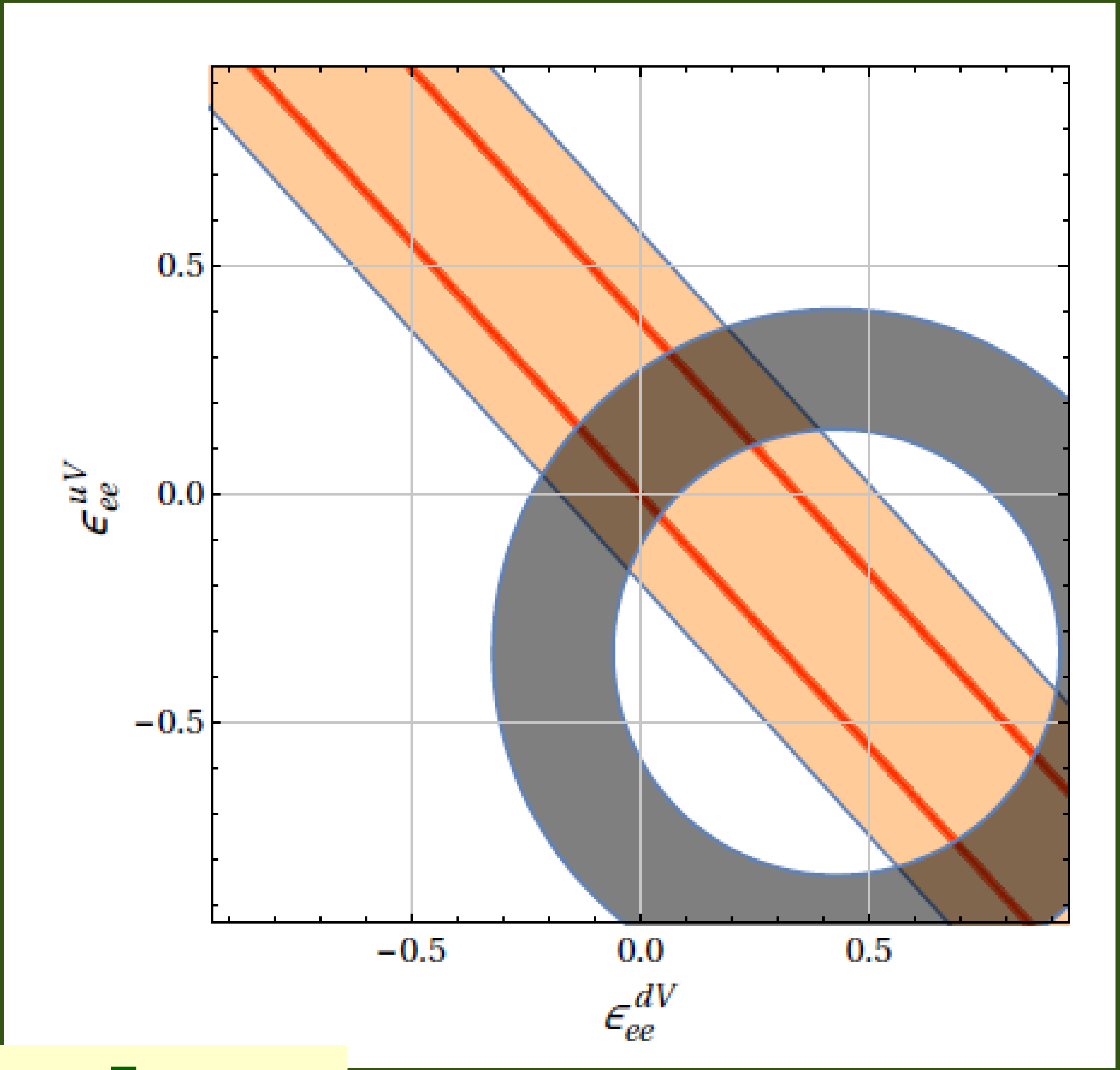
Billard, Johnston, Kavanagh, JCAP 1811 (2018) no.11, 016



Billard, Johnston, Kavanagh, JCAP 1811 (2018) no.11, 016

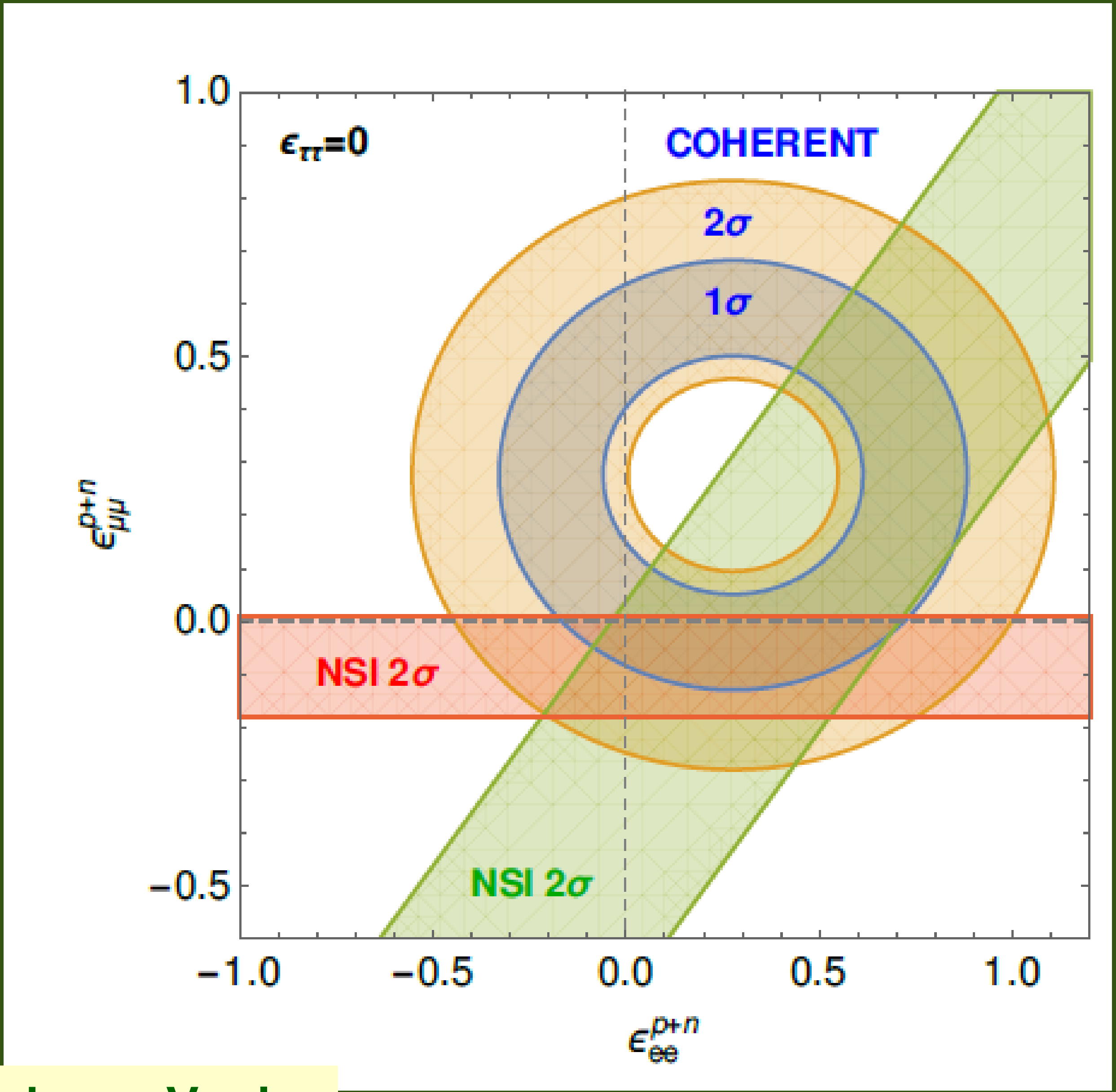


Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 1808 (2018) 180



Altmannshofer, Tammaro, Zupan,

e-Print: arXiv:1812.02778 [hep-ph]



**Heeck, Lindner, Rodejohann, Vogl,
e-Print: arXiv:1812.04067 [hep-ph]**

- Direct constraints　　Davidson et al.

ex. $$\sigma(\nu_e e \to \nu e) = \frac{2G_F^2 m_e E_\nu}{\pi}\Big\{(0.73 + \epsilon_{ee}^{eP_L})^2 + \sum_{\alpha\neq e}(\epsilon_{\alpha e}^{eP_L})^2 + \frac{1}{3}(0.23 + \epsilon_{ee}^{eP_R})^2 + \frac{1}{3}\sum_{\alpha\neq e}(\epsilon_{\alpha e}^{eP_R})^2\Big\}$$

LSND: $$\sigma(\nu_e e \to \nu e) = (1.17 \pm 0.17)\frac{G_F^2 m_e E_\nu}{\pi}$$

$$\Downarrow$$

$$90\%\mathrm{CL}(1.6\sigma\mathrm{CL})$$

$$-0.07 < \epsilon_{ee}^{eP_L} < 0.11 \qquad -1 < \epsilon_{ee}^{eP_R} < 0.5$$

$$|\epsilon_{\mu e}^{eP_L}|,\ |\epsilon_{\tau e}^{eP_L}| < 0.4 \qquad |\epsilon_{\mu e}^{eP_R}|,\ |\epsilon_{\tau e}^{eP_R}| < 0.7$$

LSND $\nu_e e \to \nu e$

LEP $e^+ e^- \to \nu \overline{\nu} \gamma$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{e} \gamma^\rho P_L e)$$

$$\begin{pmatrix} -0.07 < \epsilon^{eP_L}_{ee} < 0.11 & |\epsilon^{eP_L}_{e\mu}| < 0.4 & |\epsilon^{eP_L}_{e\tau}| < 0.4 \\ & -0.025 < \epsilon^{eP_L}_{\mu\mu} < 0.03 & |\epsilon^{eP_L}_{\mu\tau}| < 0.1 \\ & & -0.6 < \epsilon^{eP}_{\tau\tau} < 0.4 \end{pmatrix}$$

CHARM II $\nu_\mu e \to \nu e$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{e} \gamma^\rho P_R e)$$

$$\begin{pmatrix} -1 < \epsilon^{eP_R}_{ee} < 0.5 & |\epsilon^{eP_L}_{e\mu}| < 0.7 & |\epsilon^{eP_L}_{e\tau}| < 0.4 \\ & -0.027 < \epsilon^{eP_L}_{\mu\mu} < 0.03 & |\epsilon^{eP_L}_{\mu\tau}| < 0.1 \\ & & -0.4 < \epsilon^{eP}_{\tau\tau} < 0.6 \end{pmatrix}$$

CHARM $\nu_e q \to \nu q$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{u}\gamma^\rho P_L u)$$

$$\begin{pmatrix} -1 < \epsilon^{uP_L}_{ee} < 0.3 & |\epsilon^{uP_L}_{e\mu}| < 0.5 & |\epsilon^{uP_L}_{e\tau}| < 0.5 \\ & |\epsilon^{uP_L}_{\mu\mu}| < 0.003 & |\epsilon^{uP_L}_{\mu\tau}| < 0.05 \\ & & ? \end{pmatrix}$$

NuTeV $\nu_e q \to \nu q$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{u}\gamma^\rho P_R u)$$

$$\begin{pmatrix} -0.4 < \epsilon^{uP_R}_{ee} < 0.7 & |\epsilon^{uP_R}_{e\mu}| < 0.5 & |\epsilon^{uP_R}_{e\tau}| < 0.5 \\ & -0.008 < \epsilon^{uP_R}_{\mu\mu} < 0.003 & |\epsilon^{uP_R}_{\mu\tau}| < 0.05 \\ & & ? \end{pmatrix}$$

CHARM $\nu_e q \to \nu q$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{d}\gamma^\rho P_L d)$$

$$\begin{pmatrix} |\epsilon^{dP_L}_{ee}| < 0.3 & |\epsilon^{dP_L}_{e\mu}| < 0.5 & |\epsilon^{dP_L}_{e\tau}| < 0.5 \\ & |\epsilon^{dP_L}_{\mu\mu}| < 0.003 & |\epsilon^{dP_L}_{\mu\tau}| < 0.05 \\ & & ? \end{pmatrix}$$

NuTeV $\nu_e q \to \nu q$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{d}\gamma^\rho P_R d)$$

$$\begin{pmatrix} -0.6 < \epsilon^{dP_R}_{ee} < 0.5 & |\epsilon^{dP_R}_{e\mu}| < 0.5 & |\epsilon^{dP_R}_{e\tau}| < 0.5 \\ & -0.008 < \epsilon^{dP_R}_{\mu\mu} < 0.015 & |\epsilon^{dP_R}_{\mu\tau}| < 0.05 \\ & & ? \end{pmatrix}$$

● NSI for solar ν: (ε_D, ε_N) reduced from $\varepsilon_{\alpha\beta}$

In solar ν analysis, $\Delta m_{31}^2 \to \infty$, H → H^{eff}

To a good approximation, the oscillation probability is described by 2 mass eigenstates and 2 parameters (ε_D, ε_N) :

$$H^{\text{eff}} = \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} c_{13}^2 A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

$\varepsilon_{\alpha\beta}$ & (ε_D, ε_N) are related in a complicated way

$$\epsilon_D^f = -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) + c_{13} s_{13} \mathrm{Re}\left[e^{i\delta_{\mathrm{CP}}}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right)\right] - \left(1 + s_{13}^2\right) c_{23} s_{23}\,\mathrm{Re}\left[\epsilon_{\mu\tau}^f\right]$$

$$\epsilon_N^f = c_{13}\left(c_{23}\,\epsilon_{e\mu}^f - s_{23}\,\epsilon_{e\tau}^f\right) + s_{13}\, e^{-i\delta_{\mathrm{CP}}}\left[s_{23}^2\,\epsilon_{\mu\tau}^f - c_{23}^2\,\epsilon_{\mu\tau}^{f*} + c_{23} s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$

f = e, u or d