

Constraining non standard neutrino interactions

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Outline

- Introduction and motivation
- Solar ν analysis NSI with d quark and e
- Laboratory constraints NSI with e
- future perspectives
- Based on:
 1. F. J. Escrihuela, OGM, M.A. Tortola, J.W.F. Valle arXiv:0907.2630
 2. A. Bolaños, OGM, A. Palazzo, M. A. Tortola, J. W. F. Valle PRD **79** 073011 (2009)
 3. J. Barranco, OGM, T.I. Rashba JHEP 0512:021 PRD **76** 073008 (2007)
 4. J. Barranco, OGM, C. A. Moura, J. W. F. Valle PRD **73** 113001 (2006), PRD **77** 093014 (2008)

Motivation

Massive neutrinos are a strong motivation for physics beyond the Standard Model.

$$\begin{bmatrix} M_L & D \\ D^T & M_R \end{bmatrix}$$

Minkowski; Gell-mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic; Schechter, Valle

$$M_{\nu \text{ eff}} = M_L - DM_R^{-1}D^T$$

$$K = (K_L, K_H)$$

Motivation

$$\begin{bmatrix} 0 & D & 0 \\ D^T & 0 & M \\ 0 & M^T & \mu \end{bmatrix}$$

Mohapatra, Valle, PRD **34** 1642 (1986)

$$M_L = DM^{-1}\mu M^{T-1}D^T. \quad (1)$$

$$\mathcal{L} = \frac{ig'}{2 \sin \theta_W} Z_\mu \bar{\nu}_L \gamma_\mu K^\dagger K \nu_L.$$

R_p parity violating SUSY

An example of non-standard neutrino-electron and neutrino quark interactions:

$$\mathcal{L} = \lambda_{ijk} \tilde{e}_R^{k*} (\bar{\nu}_L^i)^c e_L^j + \lambda'_{ijk} \tilde{d}_L^j \bar{d}_R^k \nu_L^i + \dots$$

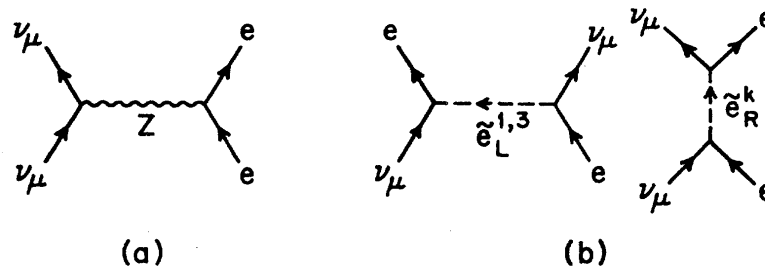
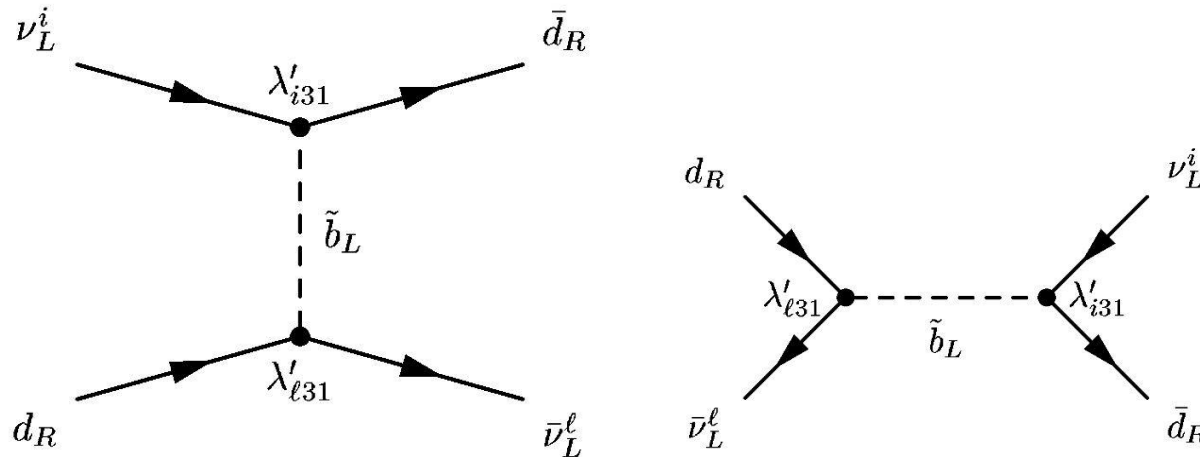


FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R -breaking interactions.

Barger, Giudice & Han'89



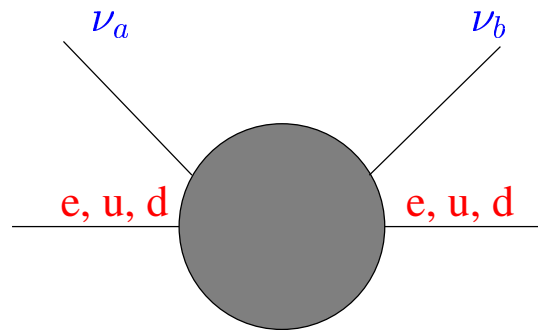
See e.g. Roulet'91, Amanik et al'05

Non Standard Interactions (NSI)

Most extensions of the SM predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (FD or NU) or flavor-changing (FC).

NSI effective Lagrangian:

$$\mathcal{L}_{eff}^{NSI} = - \sum_{\alpha\beta f P} \epsilon_{\alpha\beta}^{fP} 2\sqrt{2}G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta) (\bar{f} \gamma^\rho P f)$$



Here $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$; $P = L, R$; $L = (1 - \gamma_5)/2$; $R = (1 + \gamma_5)/2$

Solar neutrino data

- Solar neutrinos could be sensitive to NSI
- NSI could affect the propagation for d quark and e
- NSI Could also affect detection, especially in SuperKamiokande

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

Oscillations in matter

Wolfenstein 1978, Mikheev & Smirnov 1985

- Neutral currents (NC): exchange of Z_0
- Charge currents (CC): exchange of W_{\pm}

$$V_e = \sqrt{2} G_F \left(N_e - \frac{N_n}{2} \right), \quad V_{\mu} = V_{\tau} = \sqrt{2} G_F \left(-\frac{N_n}{2} \right).$$

Evolution equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_{\mu} \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2} G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_{\mu} \end{pmatrix}.$$

Constant density case

Conversion probability $\nu_e \leftrightarrow \nu_\mu$:

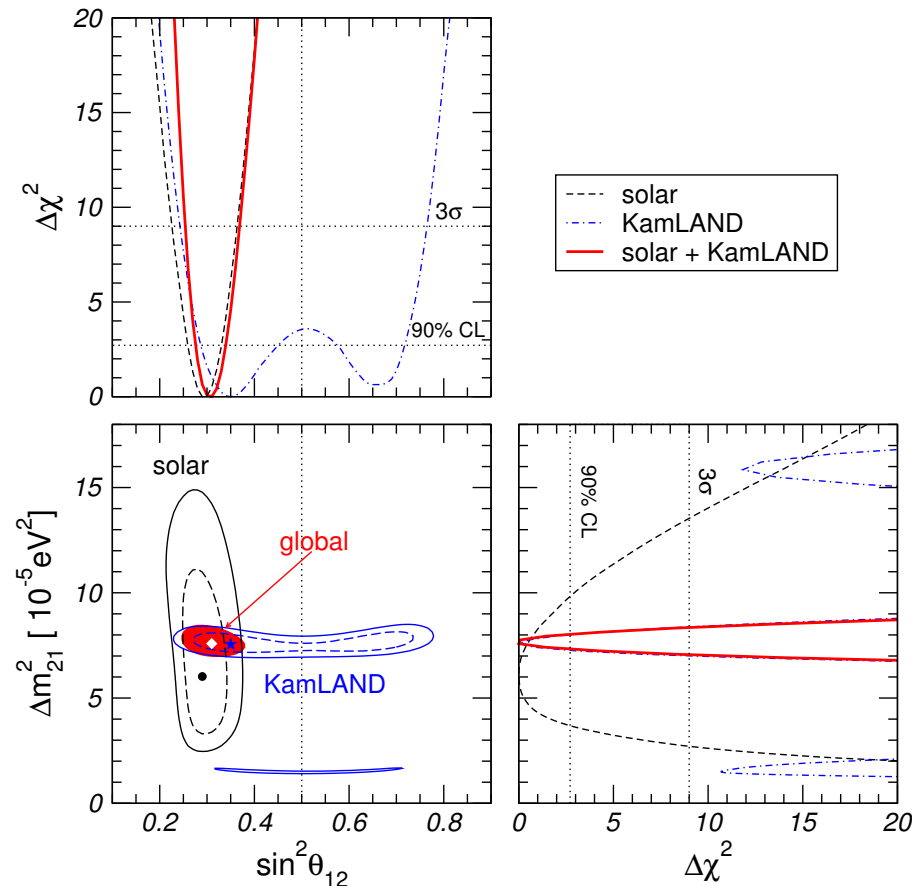
$$P(\nu_e \rightarrow \nu_\mu; L) = \sin^2 2\theta_m \sin^2 \left(\pi \frac{L}{l_m} \right),$$

Mixing angle in matter

$$\sin^2 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E} \right)^2 \sin^2 2\theta}{\left(\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e \right)^2 + \left(\frac{\Delta m^2}{2E} \right)^2 \sin^2 2\theta}$$

Resonance $\sqrt{2} G_F N_e = \frac{\Delta m^2}{2E} \cos 2\theta$

Δm_{21}^2 and $\sin^2 \theta_{12}$



$$\sin^2 \theta_{12} = 0.304^{+0.022}_{-0.016}, \quad \Delta m_{21}^2 = 7.65^{+0.23}_{-0.20} \times 10^{-5} \text{ eV}^2$$

Schwetz, Tortola, Valle New J. Phys. **10** 113011,2008

Solar ν Oscillations and NSI with quarks

$$H_{\text{NSI}} = \sqrt{2}G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}.$$

with

$$\varepsilon = -\sin \theta_{23} \varepsilon_{e\tau}^{fV} \quad \varepsilon' = \sin^2 \theta_{23} \varepsilon_{\tau\tau}^{fV} - \varepsilon_{ee}^{fV}$$

and

$$\varepsilon_{\tau\tau}^{fV} = \varepsilon_{\tau\tau}^{fL} + \varepsilon_{\tau\tau}^{fR}$$

Non Standard Interactions

$$H_{\text{NSI}} = \sqrt{2}G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}.$$

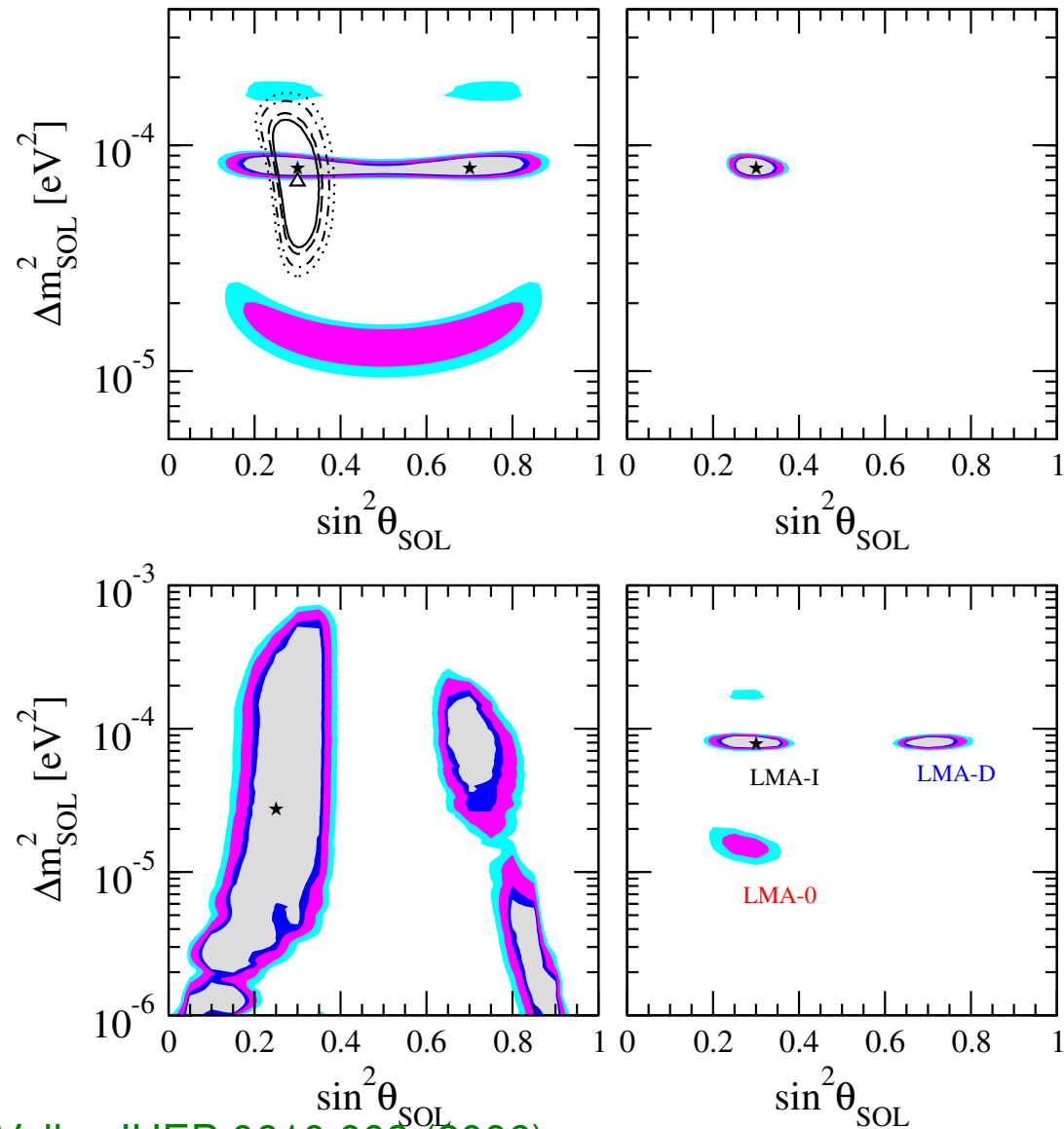
Mixing angle in matter + NSI

$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2}G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}G_F N_e + \sqrt{2}G_F \varepsilon' N_d}.$$

Resonance $\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}G_F N_e + \sqrt{2}G_F \varepsilon' N_d = 0.$

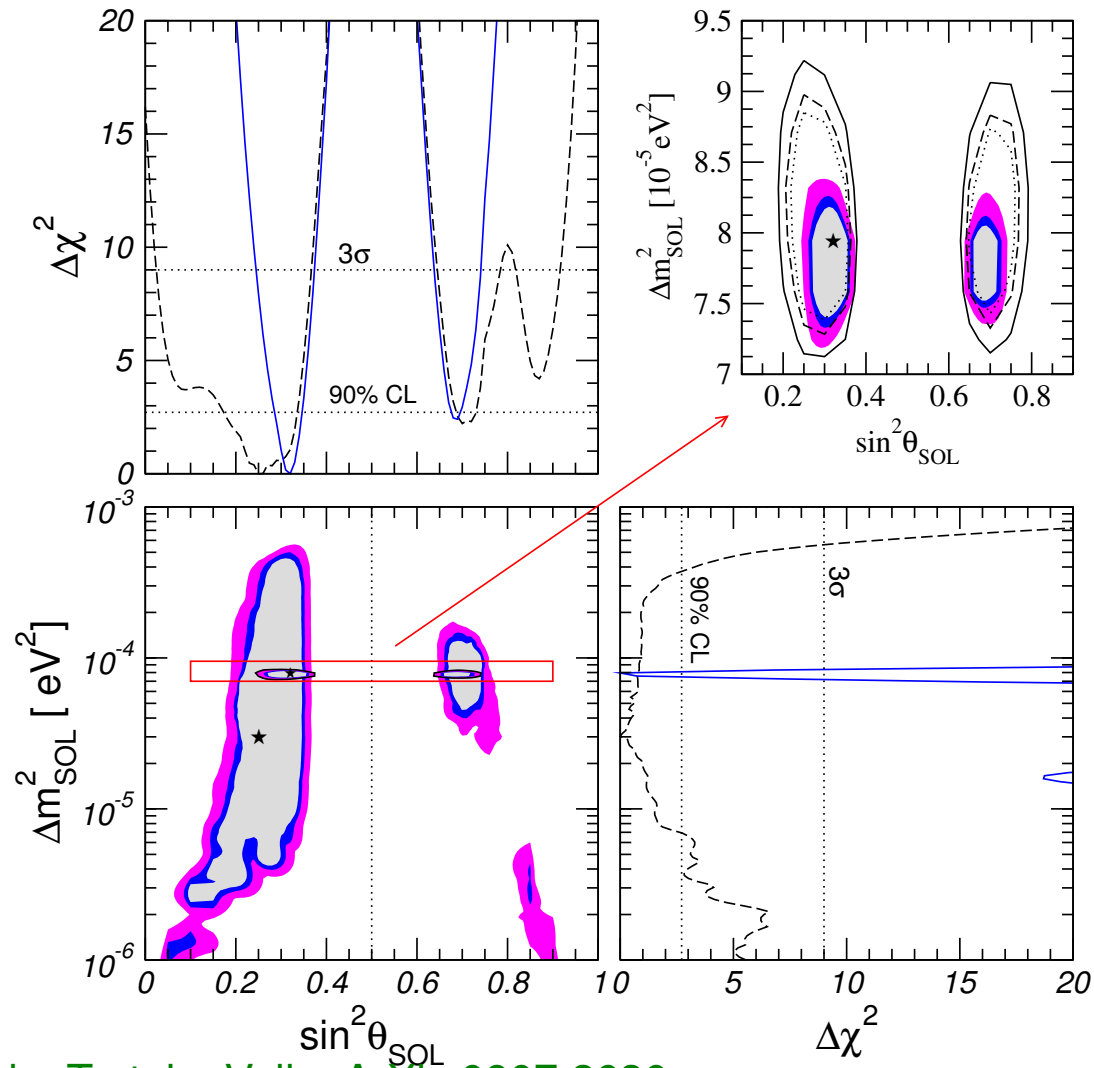
$$\varepsilon' > \frac{N_e}{N_d}$$

Solar + KamLAND without and with NSI - d



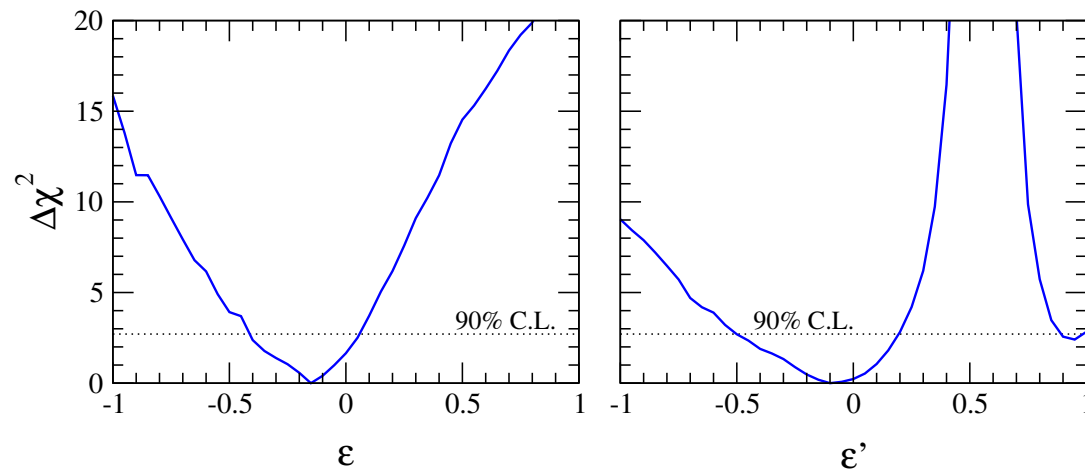
Miranda, Tortola, Valle, JHEP 0610:008 (2006)

Solar + KamLAND without and with NSI - d



Escrivuela, Miranda, Tortola, Valle, ArXiv:0907.2630

NSI-d constraints from Solar + Kamland



NSI-d constraints for ν_e

$$R^e = \frac{\sigma(\nu_e N \rightarrow \nu X) + \sigma(\bar{\nu}_e N \rightarrow \bar{\nu} X)}{\sigma(\nu_e N \rightarrow e X) + \sigma(\bar{\nu}_e N \rightarrow \bar{e} X)} = (\tilde{g}_{Le}) + (\tilde{g}_{Re})$$

Constraints from CHARM II experiment

ε_{ee}^L	$-0.3 < \varepsilon_{ee}^L < 0.3$
ε_{ee}^R	$-0.6 < \varepsilon_{ee}^R < 0.5$
$\varepsilon_{e\mu}^L$	$ \varepsilon_{e\mu}^L < 0.5$
$\varepsilon_{e\mu}^R$	$ \varepsilon_{e\mu}^R < 0.5$
$\varepsilon_{e\tau}^L$	$ \varepsilon_{e\tau}^L < 0.5$
$\varepsilon_{e\tau}^R$	$ \varepsilon_{e\tau}^R < 0.5$

CHARM II Collaboration, P. Vilain et. al. Phys. Lett. **B335** 246 (1994)

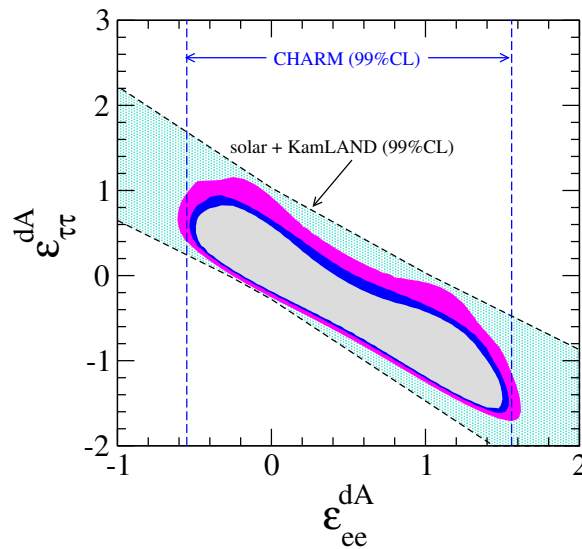
Davidson, Peña-Garay, Rius, Santamaria JHEP 0303:011 (2003) hep-ph/0302093

NSI-d constraints for ν_e

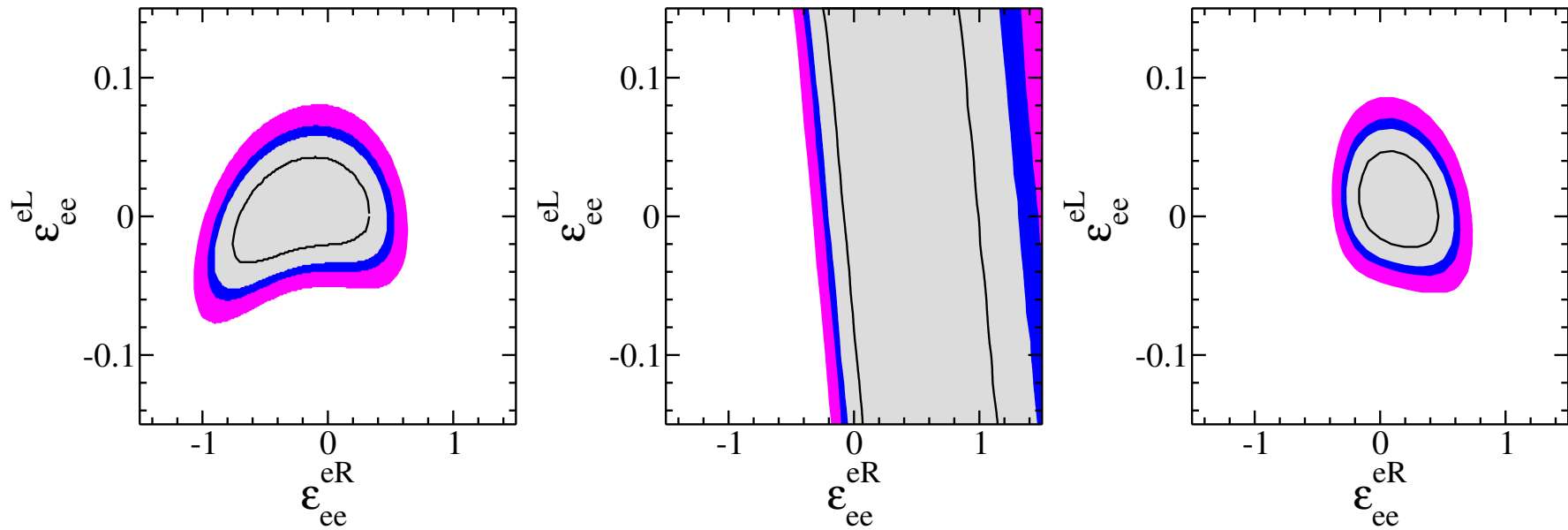
$$\nu + d \rightarrow \nu + p + n$$

SNO NC is proportional to g_A^2

$$\epsilon_A = - \sum_{\alpha=e,\mu,\tau} \langle P_{e\alpha} \rangle_{NC} \epsilon_{\alpha\alpha}^{dA},$$

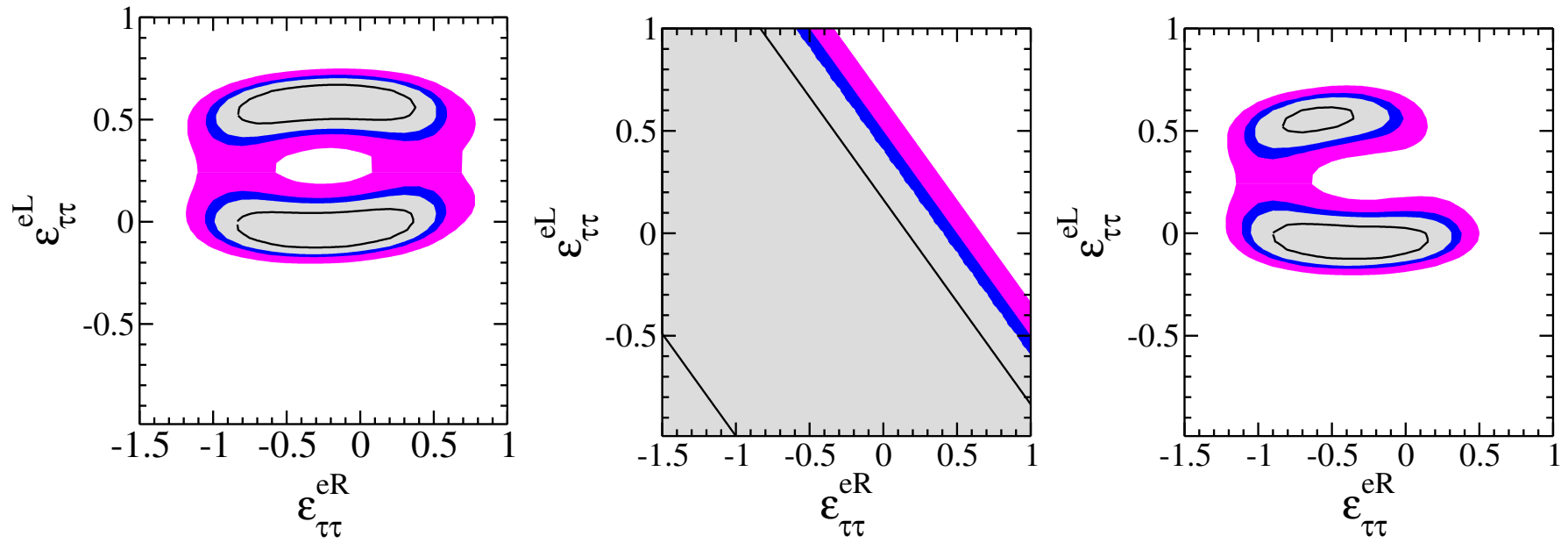


Solar neutrino data and NSI-e



Bolaños, Miranda, Palazzo, Tortola, Valle PRD 79 113012 2009

Solar neutrino data and NSI-e

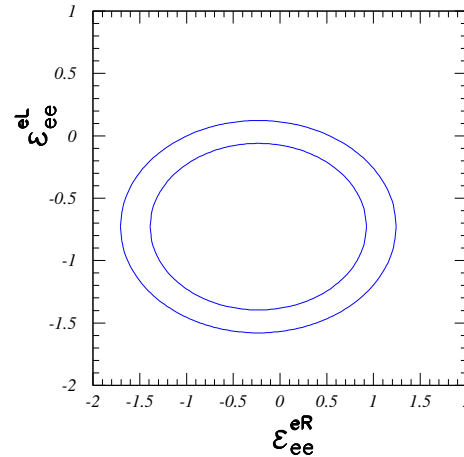


Bolaños, Miranda, Palazzo, Tortola, Valle PRD 79 113012 2009

NSI-e Laboratory constraints

- Laboratory experiments:
 1. Reactor neutrinos
 2. LEP data ($e^+e^- \rightarrow \nu\bar{\nu}\text{gamma}$)
 3. CHARM

The $\nu_e e$ interaction



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

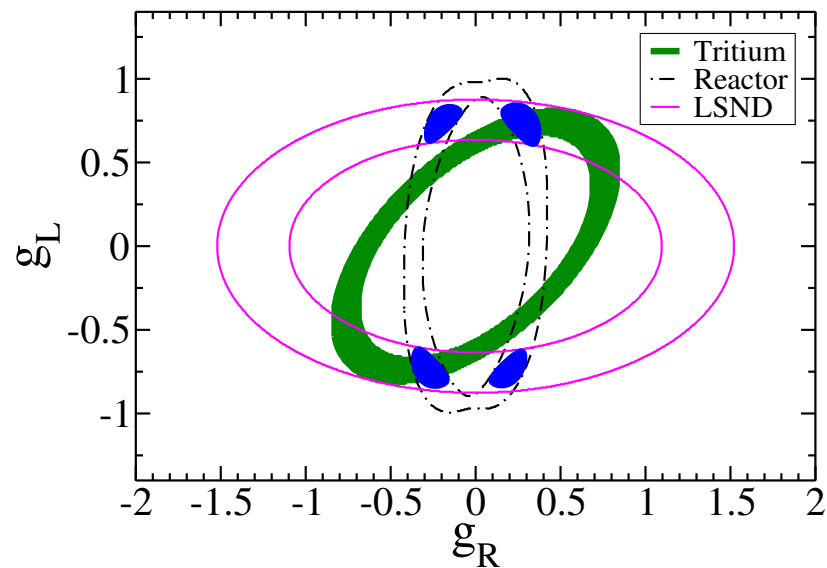
- Davidson, Peña-Garay, Rius, Santamaria JHEP 0303:011 (2003) hep-ph/0302093:

$$-0.07 < \varepsilon_{ee}^{eL} < 0.1 \quad -1.0 < \varepsilon_{ee}^{eR} < 0.50 \text{ at } 90 \% \text{ C L}$$

- Berezhiani, Raghavan, Rossi PLB 535 207 (2002)

The $\nu_e e$ interaction

Experiment	Energy (MeV)	events	measurement
LSND $\nu_e e$	10-50	191	$\sigma = [10.1 \pm 1.5] \times E_{\nu_e} (\text{MeV}) \times 10^{-45} \text{cm}^2$
Irvine $\bar{\nu}_e - e$	1.5 - 3.0	381	$\sigma = [0.86 \pm 0.25] \times \sigma_{V-A}$
Irvine $\bar{\nu}_e - e$	3.0 - 4.5	77	$\sigma = [1.7 \pm 0.44] \times \sigma_{V-A}$
Rovno $\bar{\nu}_e - e$	0.6 - 2.0	41	$\sigma = (1.26 \pm 0.62) \times 10^{-44} \text{cm}^2/\text{fission}$
MUNU $\bar{\nu}_e - e$	0.7 - 2.0	68	$1.07 \pm 0.34 \text{ events day}^{-1}$



The $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ interaction

$$\sigma_{\text{LEP}}^{\text{theo}}(s) = \int dx \int dc_\gamma H(x, s_\gamma; s) \sigma_0^{\text{theo}}(\hat{s}),$$

$$H(x, s_\gamma; s) = \frac{2\alpha}{\pi x s_\gamma} \left[\left(1 - \frac{x}{2}\right)^2 + \frac{x^2 c_\gamma^2}{4} \right],$$

$$\begin{aligned} \sigma_0^{\text{SM}}(s) = & \frac{N_\nu G_F^2}{6\pi} M_Z^4 (g_R^2 + g_L^2) \frac{s}{[(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2]} \\ & + \frac{G_F^2}{\pi} M_W^2 \left\{ \frac{s + 2M_W^2}{2s} - \frac{M_W^2}{s} \left(\frac{s + M_W^2}{s} \right) \log \left(\frac{s + M_W^2}{M_W^2} \right) \right. \\ & \left. - \frac{g_L M_Z^2 (s - M_Z^2)}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \left[\frac{(s + M_W^2)^2}{s^2} \log \left(\frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} - \frac{3}{2} \right] \right\}, \end{aligned}$$

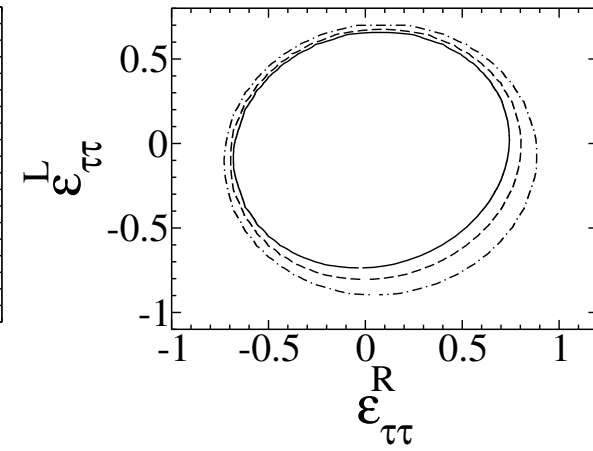
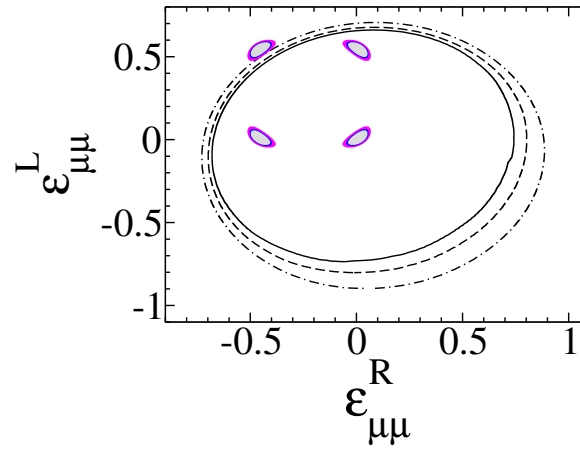
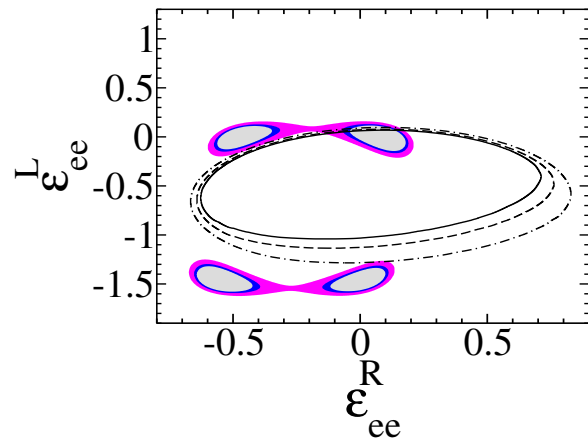
The $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ interaction

$$\begin{aligned}
 \sigma_0^{\text{NU}}(s) &= \sum_{\alpha=e,\mu,\tau} \frac{G_F^2}{6\pi} s \left[(\varepsilon_{\alpha\alpha}^L)^2 + (\varepsilon_{\alpha\alpha}^R)^2 - 2(g_L \varepsilon_{\alpha\alpha}^L + g_R \varepsilon_{\alpha\alpha}^R) \frac{M_Z^2 (s - M_Z^2)}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \right] \\
 &+ \frac{G_F^2}{\pi} \varepsilon_{ee}^L M_W^2 \left[\frac{(s + M_W^2)^2}{s^2} \log \left(\frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} - \frac{3}{2} \right], \\
 \sigma_0^{\text{FC}}(s) &= \sum_{\alpha \neq \beta = e,\mu,\tau} \frac{G_F^2}{6\pi} s \left[(\varepsilon_{\alpha\beta}^L)^2 + (\varepsilon_{\alpha\beta}^R)^2 \right].
 \end{aligned}$$

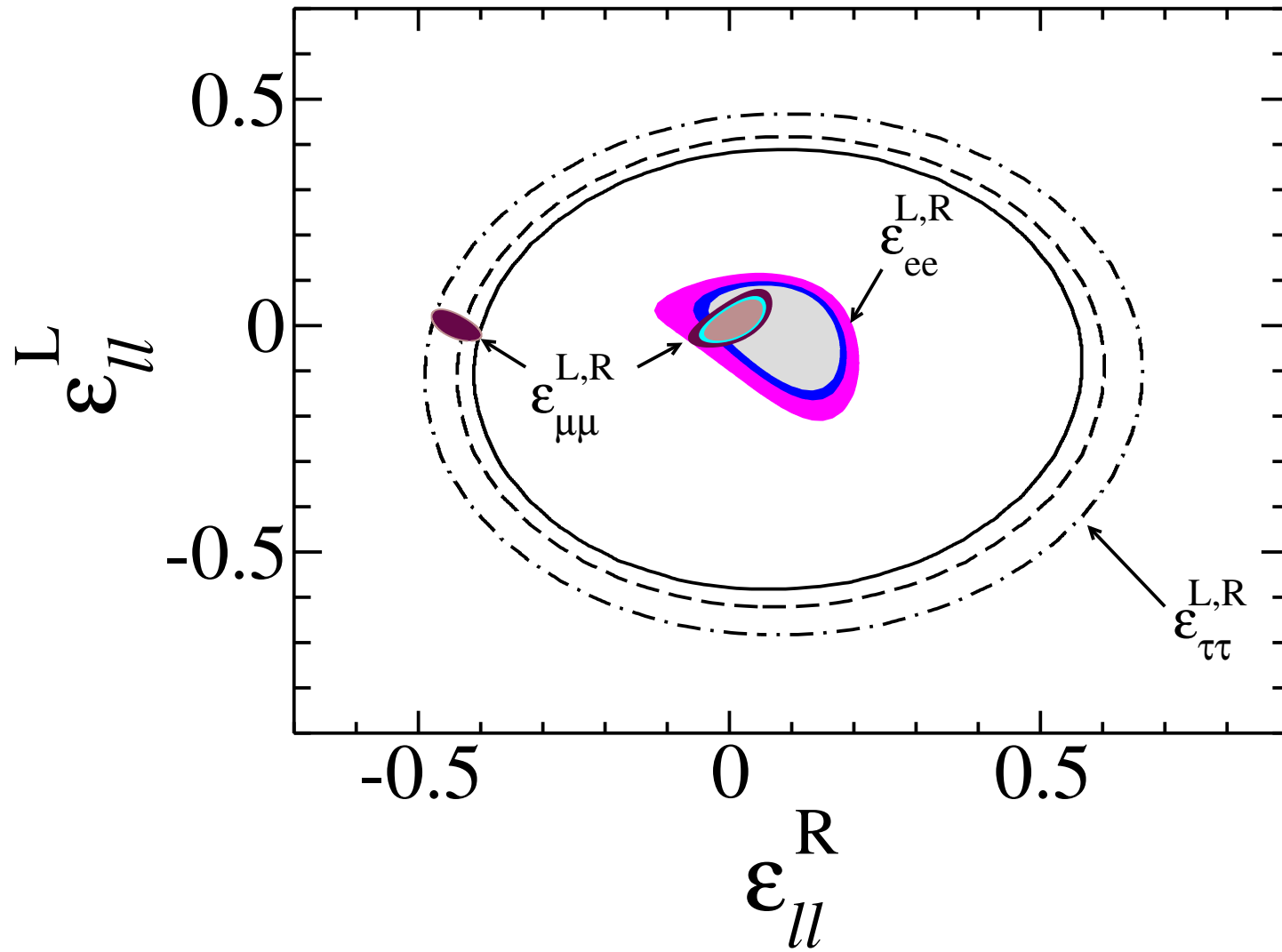
The $\nu_\mu e \rightarrow \nu_\mu e$ interaction

$$\frac{d\sigma_{\text{CHARM}}^{\text{theo}}}{dy} = \frac{2G_F^2 m_e}{\pi} E_\nu \left[\left(\tilde{g}_L^2 + \sum_{\alpha \neq \mu} |\epsilon_{\alpha\mu}^L|^2 \right) + \left(\tilde{g}_R^2 + \sum_{\alpha \neq \mu} |\epsilon_{\alpha\mu}^R|^2 \right) (1-y)^2 \right]$$

Laboratory constraints



Laboratory constraints



NSI-e constraints

	Solar analysis	Laboratory analysis	Previous limits
ε_{ee}^L	$-0.036 < \varepsilon_{ee}^L < 0.063$	$-0.14 < \varepsilon_{ee}^L < 0.09$	$-0.05 < \varepsilon_{ee}^L < 0.1$
ε_{ee}^R	$-0.27 < \varepsilon_{ee}^R < 0.59$	$-0.03 < \varepsilon_{ee}^R < 0.18$	$0.04 < \varepsilon_{ee}^R < 0.14$
$\varepsilon_{\mu\mu}^L$		$-0.033 < \varepsilon_{\mu\mu}^L < 0.055$	$ \varepsilon_{\mu\mu}^L < 0.03$
$\varepsilon_{\mu\mu}^R$		$-0.040 < \varepsilon_{\mu\mu}^R < 0.053$	$ \varepsilon_{\mu\mu}^R < 0.03$
$\varepsilon_{\tau\tau}^L$	$-0.16 < \varepsilon_{\tau\tau}^L < 0.11$	$-0.6 < \varepsilon_{\tau\tau}^L < 0.4$	$ \varepsilon_{\tau\tau}^L < 0.5$
$\varepsilon_{\tau\tau}^R$	$-1.05 < \varepsilon_{\tau\tau}^R < 0.31$	$-0.4 < \varepsilon_{\tau\tau}^R < 0.6$	$ \varepsilon_{\tau\tau}^R < 0.5$

Bolaños, Miranda, Palazzo, Tortola, Valle PRD 79 113012 2009

Barranco, Miranda, Moura, Valle PRD 77 093014 '08

Davidson, Peña-Garay, Rius, Santamaria JHEP 0303:011 (2003) hep-ph/0302093

NSI-e constraints

Laboratory analysis

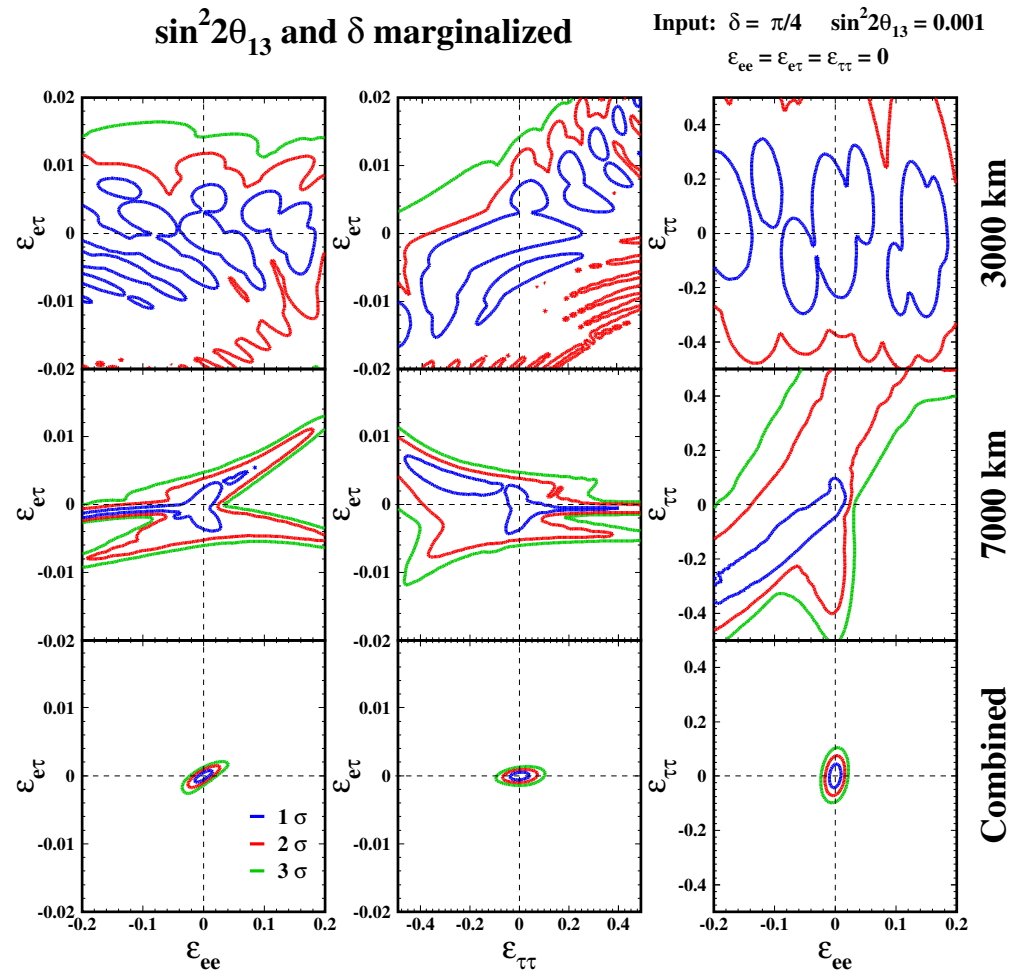
$\varepsilon_{e\mu}^L$	$ \varepsilon_{e\mu}^L < 0.13$
$\varepsilon_{e\mu}^R$	$ \varepsilon_{e\mu}^R < 0.13$
$\varepsilon_{e\tau}^L$	$ \varepsilon_{e\tau}^L < 0.4$
$\varepsilon_{e\tau}^R$	$ \varepsilon_{e\tau}^R < 0.27$
$\varepsilon_{\mu\tau}^L$	$ \varepsilon_{\mu\tau}^L < 0.1$
$\varepsilon_{\mu\tau}^R$	$ \varepsilon_{\mu\tau}^R < 0.1$

Barranco, Miranda, Moura, Valle PRD 77 093014 '08

Davidson, Peña-Garay, Rius, Santamaria JHEP 0303:011 (2003) hep-ph/0302093

Future perspectives

Neutrino factory + two different neutrino detectors

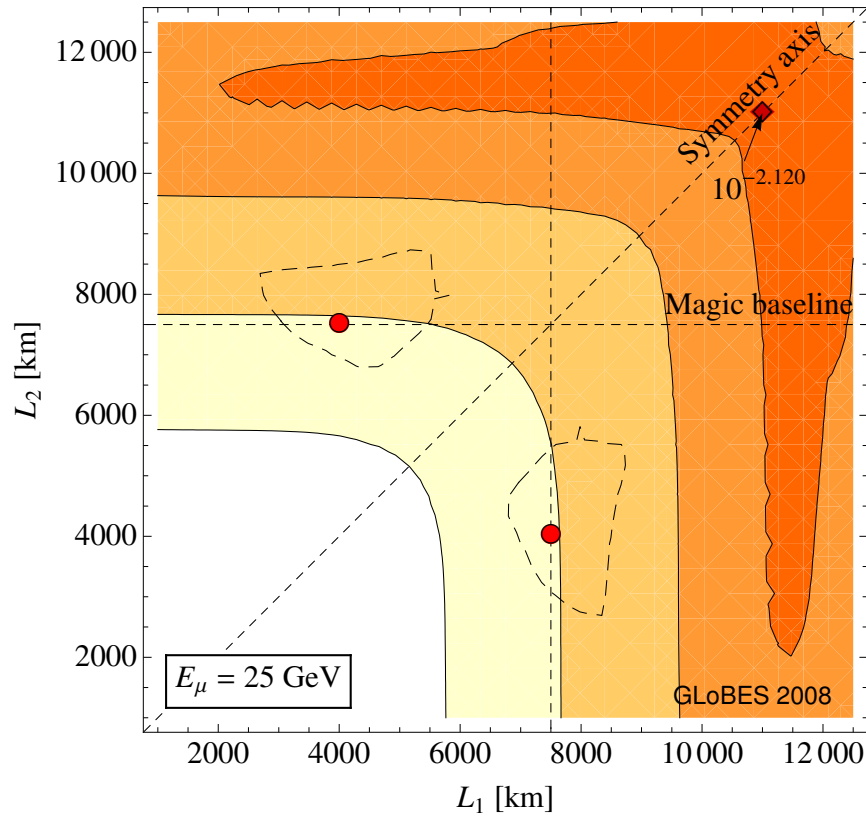


Ribeiro, Minakata, Nunokawa, S. Uchinami, R. Zukanovich-Funchal JHEP 0712:002,2007.

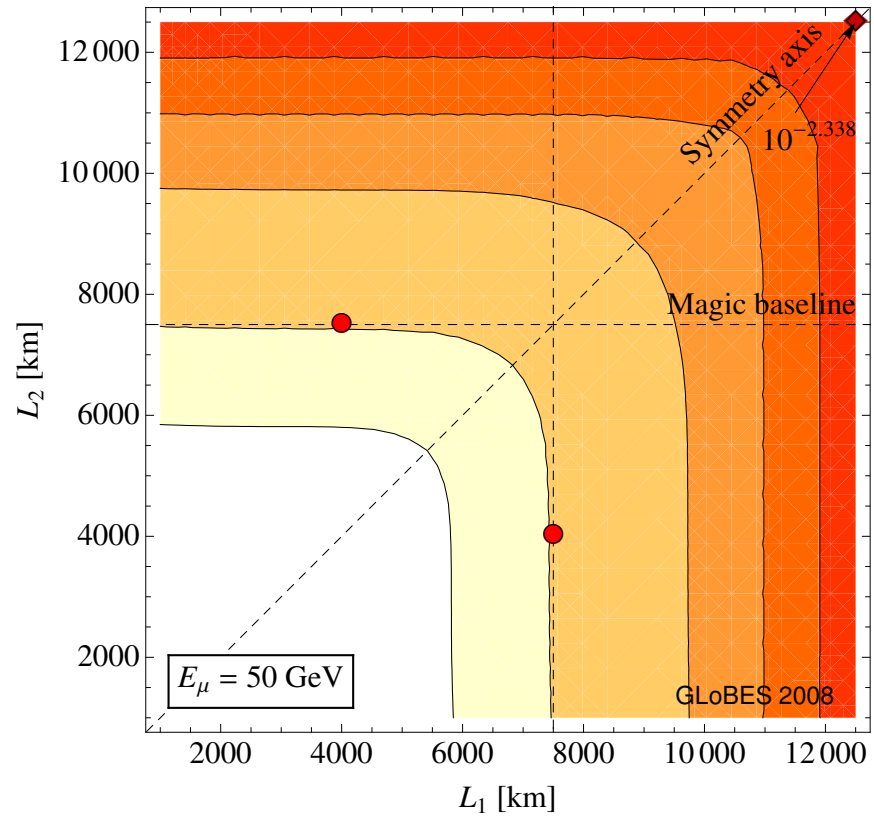
Future Perspectives

Neutrino factory + two different neutrino detectors

$|\epsilon_{\tau\tau}^m|$ sensitivity (3σ)



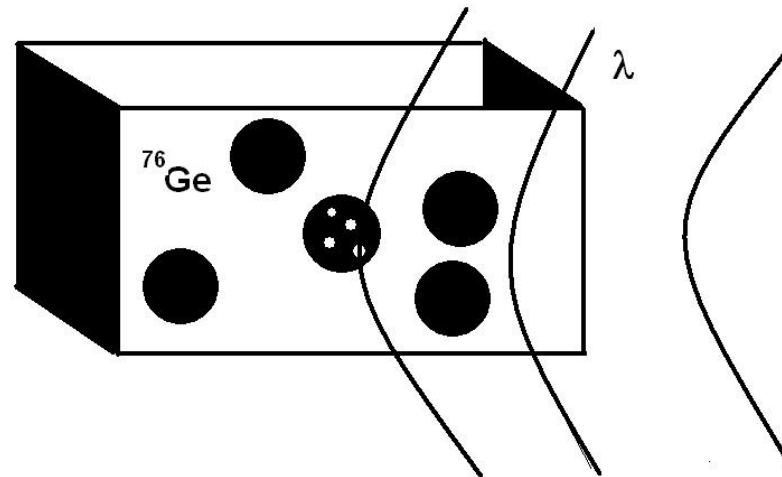
$|\epsilon_{\tau\tau}^m|$ sensitivity (3σ)



Kopp, Ota, Winter, PRD 78 053007 '08

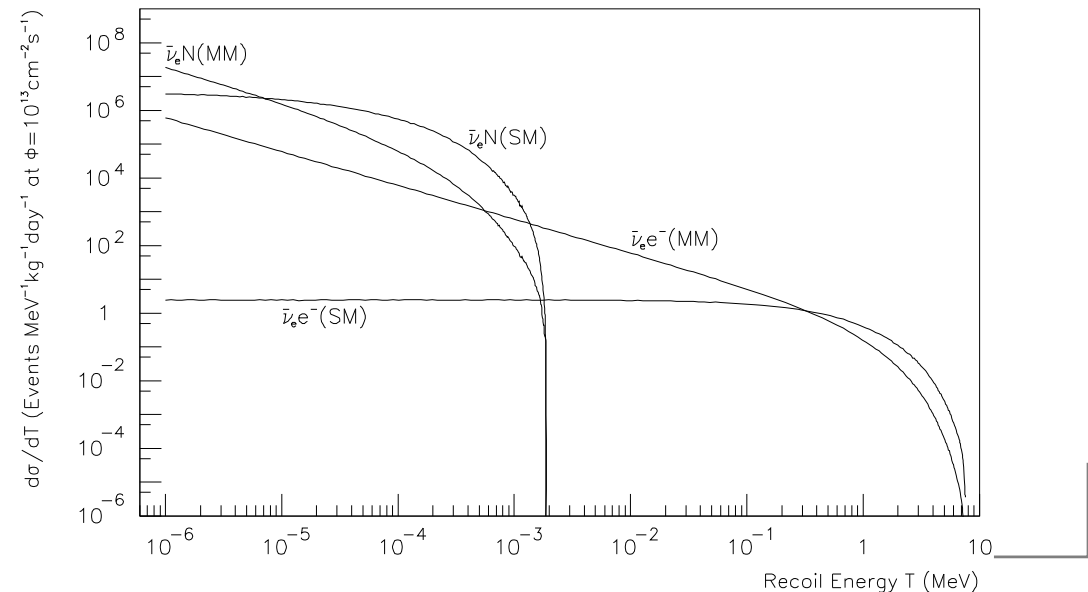
NSI with d, u quark, Coherent $\nu - N$ scattering

- Coherent scattering if the momentum transfer, Q , is small, $QR < 1$ (R is radius of nucleus): $\implies \nu$ -s **doesn't "see" structure of nucleus!**
- For **most of nuclei**: $1/R \sim 25 - 150$ MeV
- Planned experiments to measure coherent ν - N scattering: NOSTOS, TEXONO ... and many proposals
- Experimentally difficult: very low energy threshold
- **Good statistics** due to quadratic coherent enhancement
- Sensitivity to **ν -quark couplings**



Proposed experiments to measure coherent ν - N scattering

- TEXONO: 1kg of germanium, reactor neutrinos [J. Phys. Conf. Ser. 39 266 \(2006\) hep-ex/0511001](#)
- Large-Mass Ultra-Low Noise Germanium Detectors [P.S. Barbeau, J. I. Collar, O. Tench JCAP 0709:009 \(2007\)](#)
- NOSTOS: spherical TPC detector, 10 ton of Xenon [Phys. Atom. Nucl. 70 140 \(2007\) astro-ph/0511470](#)
- Stopped-pion neutrino beam and kg-to-ton mass detector [K. Scholberg, Phys. Rev. D 73 \(2006\) 033005](#)



ν - N coherent scattering

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

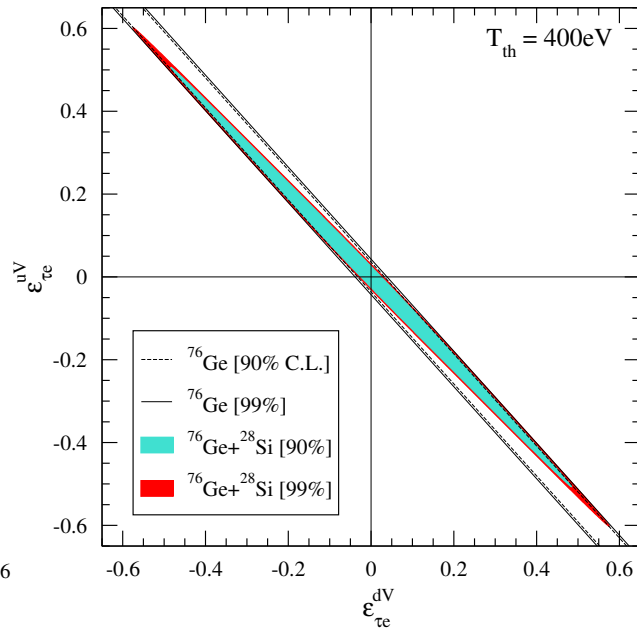
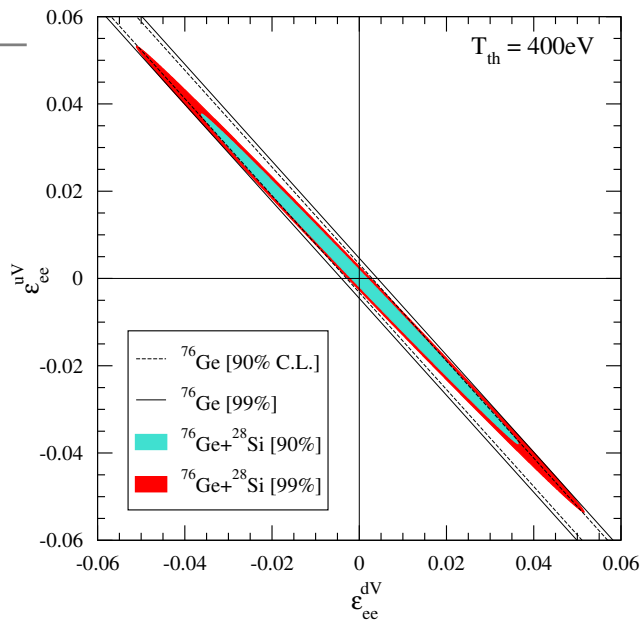
$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV} \right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV} \right) N \right] F_{nucl}^V(Q^2)$$

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

$$\begin{aligned} \frac{d\sigma}{dT}(E_\nu, T) &= \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \times \\ &\times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \right. \\ &\left. + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\} \end{aligned}$$

- Axial couplings contribution is zero or can be neglected
- Coherent enhancement of cross section
- Degeneracy in determination of NSI parameters

Estimated bounds on NSI from TEXONO-like experiment (Ge+Si)



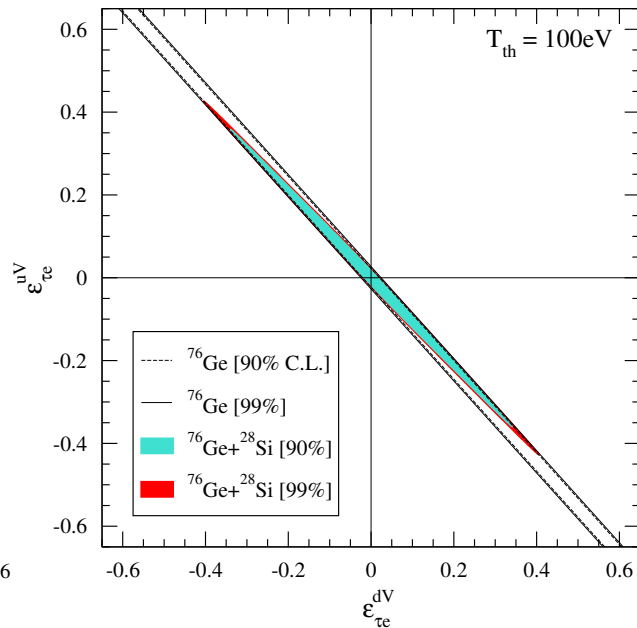
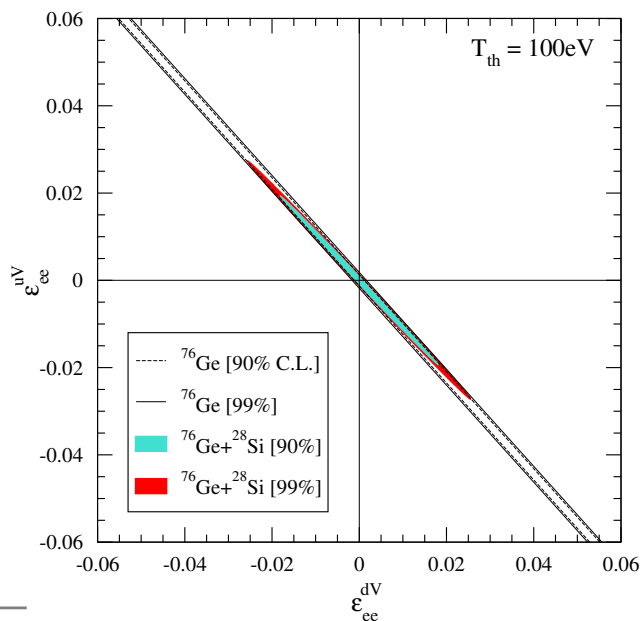
$^{76}\text{Ge}+^{28}\text{Si}$ $T_{th}=400\text{eV}$

$$|\epsilon_{ee}^{dV}| < 0.036$$

$$|\epsilon_{ee}^{uV}| < 0.038$$

$$|\epsilon_{\tau e}^{dV}| < 0.48$$

$$|\epsilon_{\tau e}^{uV}| < 0.50$$



$^{76}\text{Ge}+^{28}\text{Si}$ $T_{th}=100\text{eV}$

$$|\epsilon_{ee}^{dV}| < 0.018$$

$$|\epsilon_{ee}^{uV}| < 0.019$$

$$|\epsilon_{\tau e}^{dV}| < 0.34$$

$$|\epsilon_{\tau e}^{uV}| < 0.37$$

Present and future bounds on NSI

One parameter analysis to compare coherent scattering sensitivity with present bounds and ν Factory sensitivity (taken from Davidson et al'03)

	Present Limits	ν Factory	^{76}Ge $T_{th}=400\text{eV}$ (^{76}Ge $T_{th}=100\text{eV}$)	$^{76}\text{Ge}+^{28}\text{Si}$ $T_{th}=400\text{eV}$ ($^{76}\text{Ge}+^{28}\text{Si}$ $T_{th}=100\text{eV}$)
ϵ_{ee}^{dV}	$-0.5 < \epsilon_{ee}^{dV} < 1.2$	$ \epsilon_{ee}^{dV} < 0.002$	$ \epsilon_{ee}^{dV} < 0.003$ ($ \epsilon_{ee}^{dV} < 0.001$)	$ \epsilon_{ee}^{dV} < 0.002$ ($ \epsilon_{ee}^{dV} < 0.001$)
$\epsilon_{\tau e}^{dV}$	$ \epsilon_{\tau e}^{dV} < 0.78$	$ \epsilon_{\tau e}^{dV} < 0.06$	$ \epsilon_{\tau e}^{dV} < 0.032$ ($ \epsilon_{\tau e}^{dV} < 0.020$)	$ \epsilon_{\tau e}^{dV} < 0.024$ ($ \epsilon_{\tau e}^{dV} < 0.017$)
ϵ_{ee}^{uV}	$-1.0 < \epsilon_{ee}^{uV} < 0.61$	$ \epsilon_{ee}^{uV} < 0.002$	$ \epsilon_{ee}^{uV} < 0.003$ ($ \epsilon_{ee}^{uV} < 0.001$)	$ \epsilon_{ee}^{uV} < 0.002$ ($ \epsilon_{ee}^{uV} < 0.001$)
$\epsilon_{\tau e}^{uV}$	$ \epsilon_{\tau e}^{uV} < 0.78$	$ \epsilon_{\tau e}^{uV} < 0.06$	$ \epsilon_{\tau e}^{uV} < 0.036$ ($ \epsilon_{\tau e}^{uV} < 0.023$)	$ \epsilon_{\tau e}^{uV} < 0.023$ ($ \epsilon_{\tau e}^{uV} < 0.018$)

Conclusions

- NSI arise naturally in many models of physics beyond the SM and may be important in oscillation experiments.
- For big values of NSI the solar neutrino oscillation parameters can change drastically.
- Current and future neutrino experiments will be able to give stronger constraints on these parameters and perhaps could give a hint on the physics underlying neutrino masses.