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Nonstandard neutrino interactions and low energy experiments

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Outline

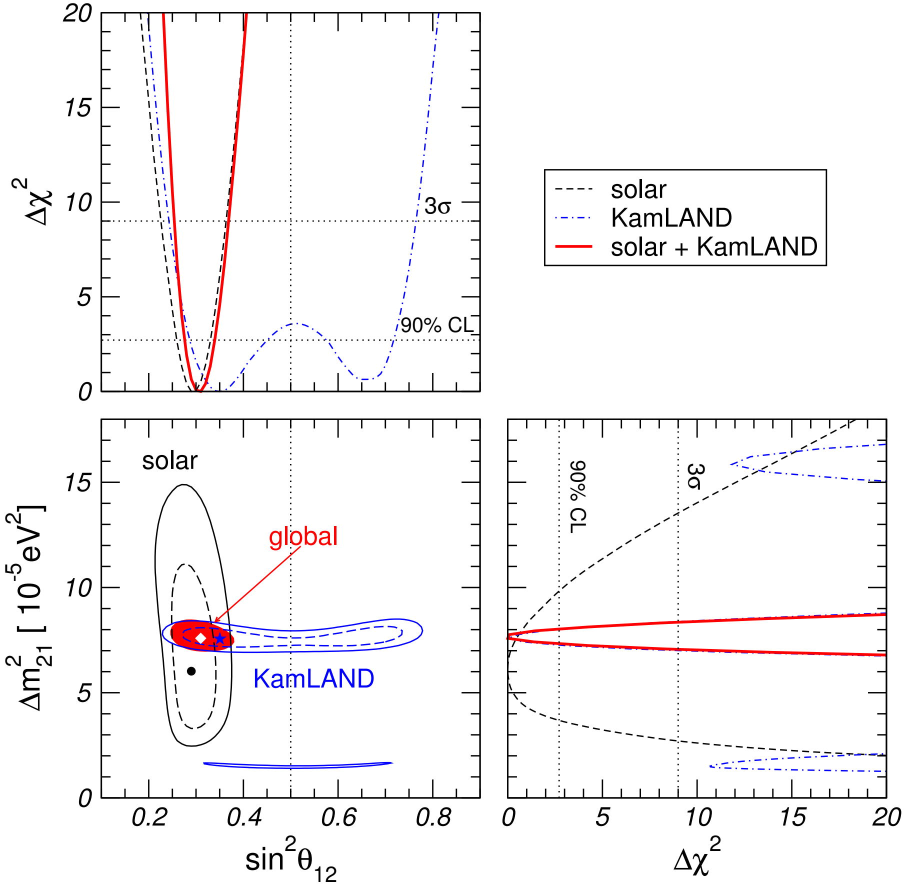
- Introduction and motivation
- Nonstandard ν Interaction with d quark,
  solar ν analysis
- Nonstandard ν Interaction with d quark,
  ν-N coherent scattering
- Nonstandard ν Interaction with electrons
- Based on:
  1. O.G. Miranda, M.A. Tortola, J.W.F. Valle JHEP 0610:008 (2006)
  2. J. Barranco, O.G. Miranda, T.I. Rashba JHEP 0512:021 PRD **76** 073008 (2007)
  3. J. Barranco, O.G. Miranda, C. A. Moura, J. W. F. Valle PRD **73** 113001 (2006), PRD **77** 093014 (2008)

Motivation

There are many experiments confirming that the neutrinos are massive particles

- Solar neutrinos (Davis, SAGE-GALLEX-GNO, SK, SNO, Borexino ...)
- Atmospheric neutrinos (Superkamiokande)
- Reactor neutrinos (KamLAND)
- Accelerator neutrinos (K2K, Minos)

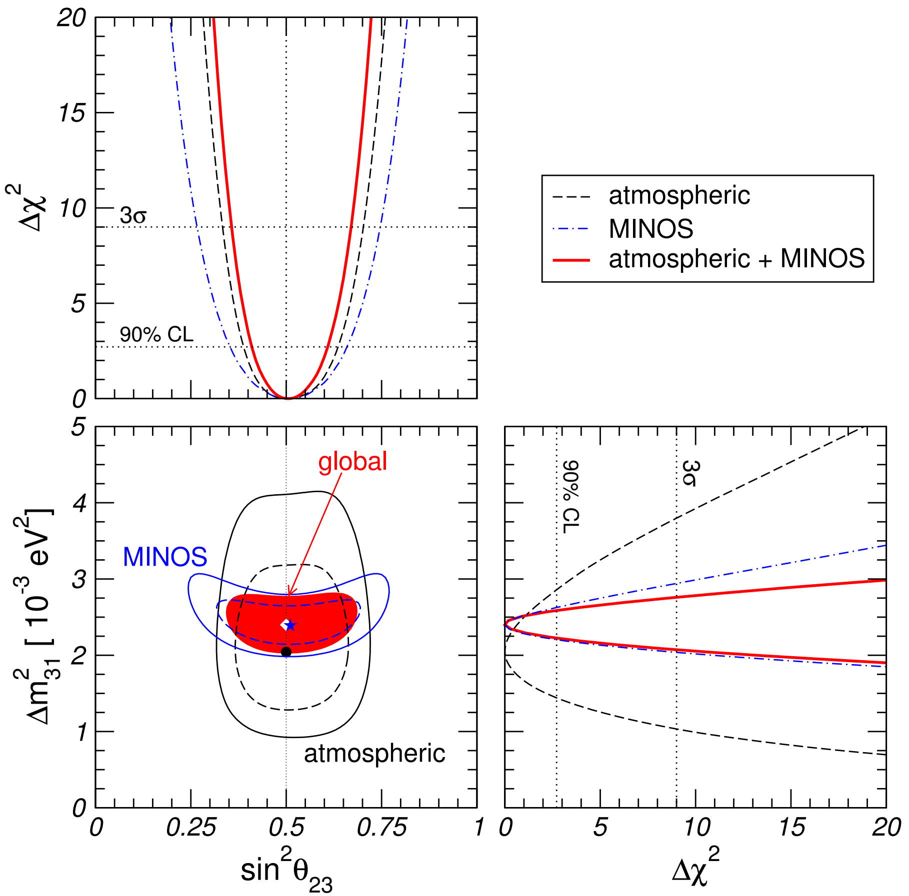
Δm^2_{21} **and** $\sin^2\theta_{12}$



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

Schwetz, Tortola, Valle arXiv:0808.2016

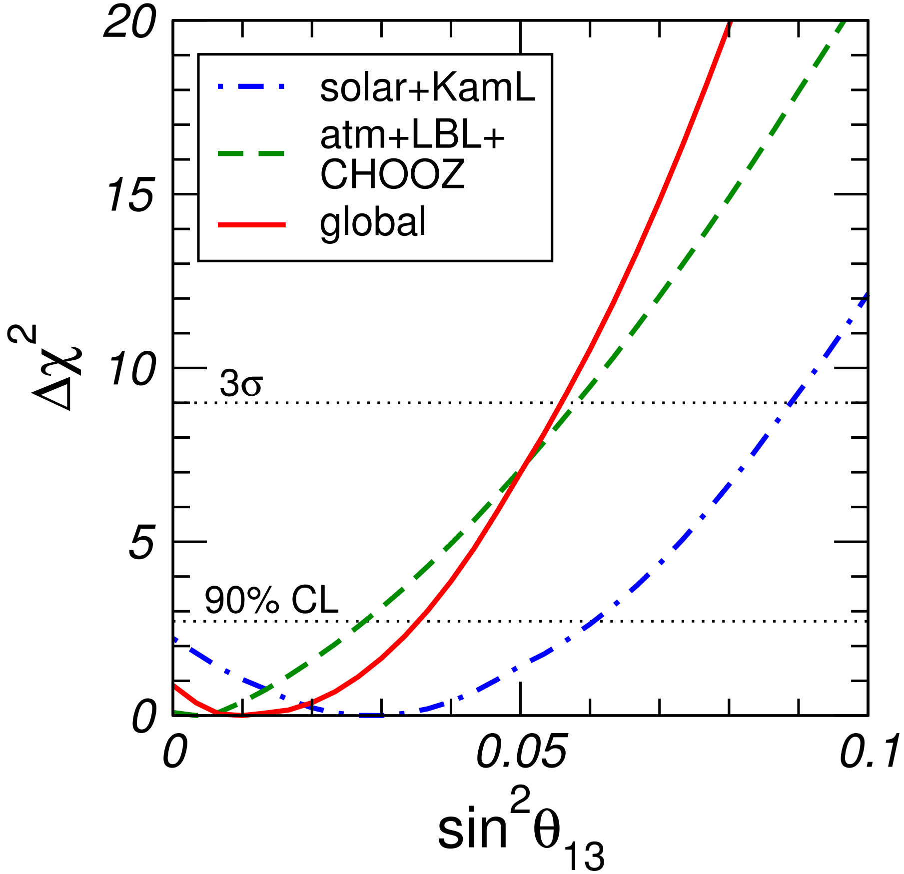
Δm^2_{31} and $\sin^2\theta_{23}$



$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}, \qquad \Delta m^2_{31} = 2.4^{+0.12}_{-0.11} \times 10^{-3}\ \text{eV}^{\,2}$$

Schwetz, Tortola, Valle arXiv:0808.2016

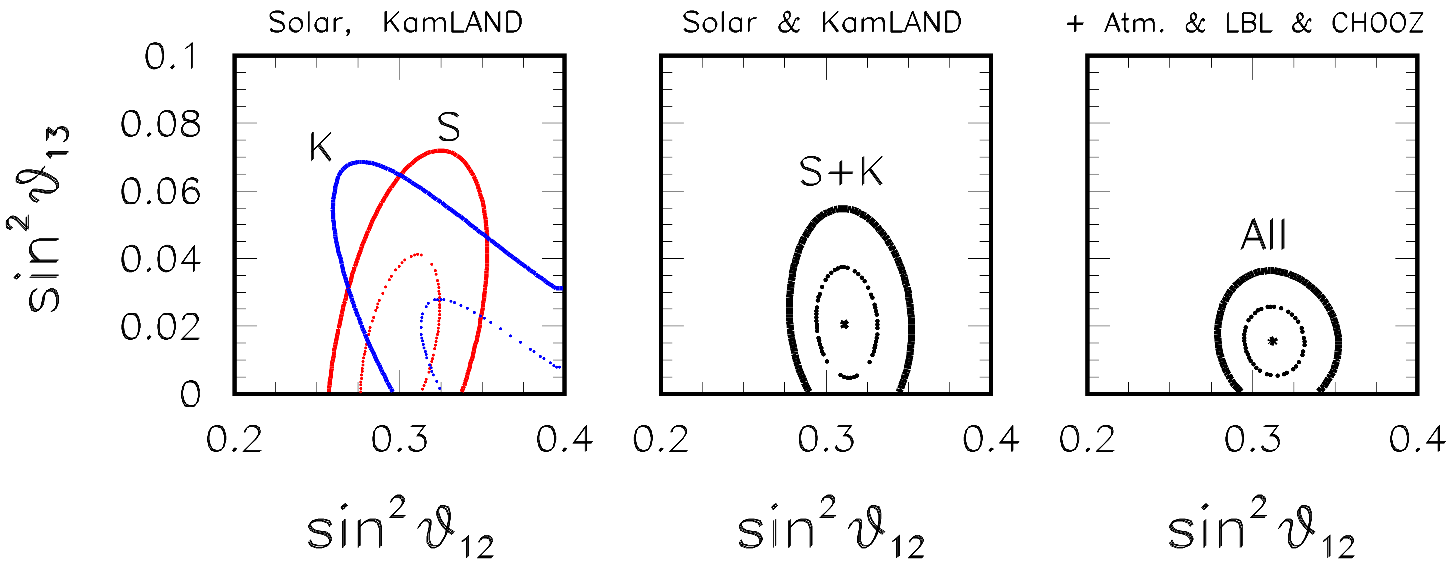
$\sin^2\theta_{13}$



$$\sin^2\theta_{13} = 0.01^{+0.016}_{-0.011}$$

Schwetz, Tortola, Valle arXiv:0808.2016

$\sin^2 \theta_{13}$



$\sin^2 \theta_{13} = 0.016 \pm 0.01$

Fogli, Lisi, Marrone, Palazzo, Rotunno, PRL **101** 141801 (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

$$M_{\nu\,\mathrm{eff}} = M_L \, - \, D M_R^{-1} D^T$$

$$K = (K_L, K_H)$$

Motivation

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

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

$$M_L = DM^{-1}\mu {M^T}^{-1} D^T \,. \tag{1}$$

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

$\not{R}_p$ parity violating SUSY

Non-standard neutrino-electron and neutrino quark interactions:

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

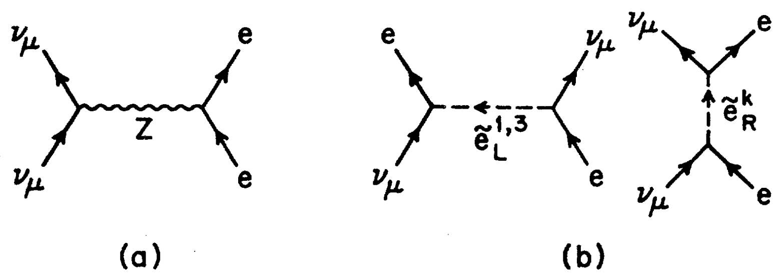
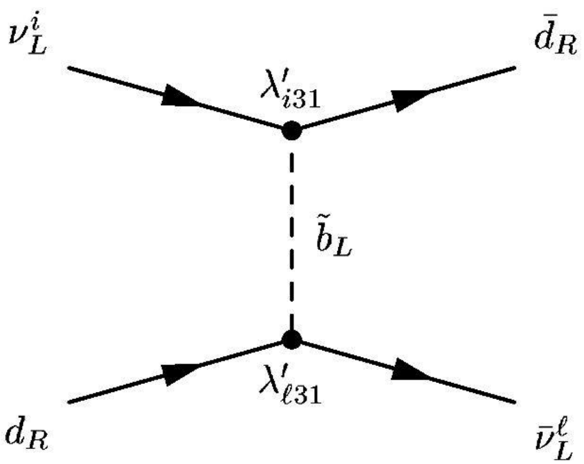
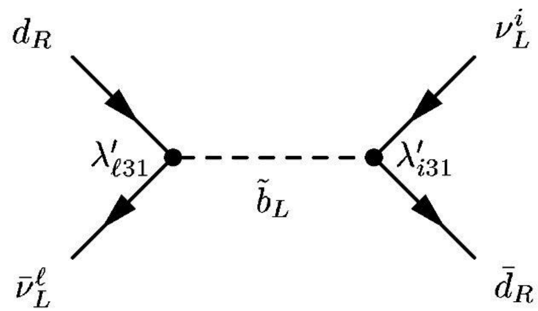


FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

Barger, Giudice & Han'89





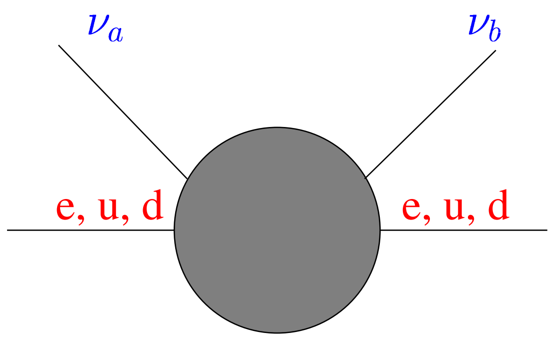
See e.g. Roulet'91, Amanik et al'05

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 Lagragian form:

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



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

Bounds on FD NSI ν-q couplings from Davidson et al'03

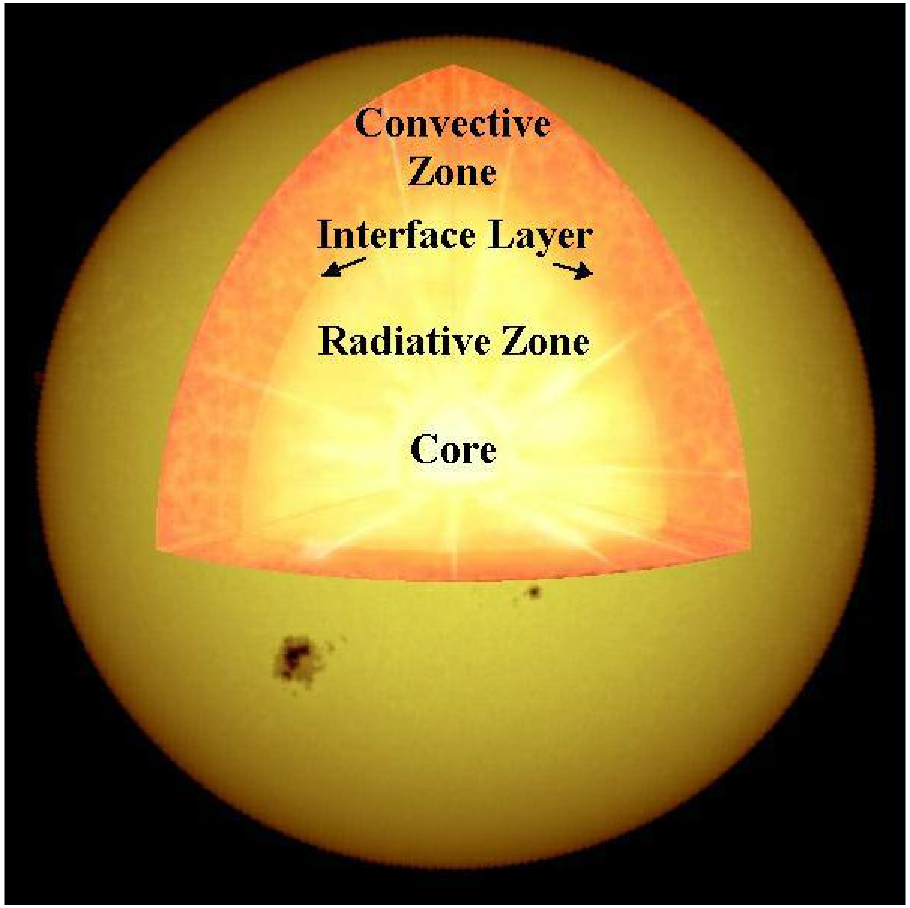
vertex	current limits	future limit
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_\tau\gamma_\rho L\nu_\tau)$	$\lvert\varepsilon^{uL}_{\tau\tau}\rvert < 1.4$ $\lvert\varepsilon^{uR}_{\tau\tau}\rvert < 3$ $(\Gamma_{inv})^{*)}$	$-0.3 < \varepsilon^{uL}_{\tau\tau} < 0.25$ $-0.25 < \varepsilon^{uR}_{\tau\tau} < 0.3$ KamLAND and SNO/SK
$(\bar{d}\gamma^\rho Ld)(\bar{\nu}_\tau\gamma_\rho L\nu_\tau)$	$\lvert\varepsilon^{dL}_{\tau\tau}\rvert < 1.1$ $\lvert\varepsilon^{dR}_{\tau\tau}\rvert < 6$ $(\Gamma_{inv})^{*)}$	$-0.25 < \varepsilon^{dL}_{\tau\tau} < 0.3$ $-0.3 < \varepsilon^{dR}_{\tau\tau} < 0.25$ KamLAND and SNO/SK
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_\mu\gamma_\rho L\nu_\mu)$	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$ NuTeV	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.001$ $\lvert\varepsilon^{uR}_{\mu\mu}\rvert < 0.002$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\mu\gamma_\rho L\nu_\mu)$	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$ NuTeV	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.0009$ $\lvert\varepsilon^{dR}_{\mu\mu}\rvert < 0.005$ s^2_W in DIS at νFactory
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_e\gamma_\rho L\nu_e)$	$-1 < \varepsilon^{uL}_{ee} < 0.3$ $-0.4 < \varepsilon^{uR}_{ee} < 0.7$ CHARM	$\lvert\varepsilon^{uL}_{ee}\rvert < 0.001$ $\lvert\varepsilon^{uR}_{ee}\rvert < 0.002$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_e\gamma_\rho L\nu_e)$	$-0.3 < \varepsilon^{dL}_{ee} < 0.3$ $-0.6 < \varepsilon^{dR}_{ee} < 0.5$ CHARM	$\lvert\varepsilon^{dL}_{ee}\rvert < 0.0009$ $\lvert\varepsilon^{dR}_{ee}\rvert < 0.005$ s^2_W in DIS at νFactory

Bounds on FC NSI ν-q couplings from Davidson et al'03

vertex	current limits	future limit
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\tau \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\tau \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{uP}_{\mu e}\rvert < 7.7 \times 10^{-4}$ $(\mathrm{Ti}\mu \to \mathrm{Ti}e)^{*)}$	
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{dP}_{\mu e}\rvert < 7.7 \times 10^{-4}$ $(\mathrm{Ti}\mu \to \mathrm{Ti}e)^{*)}$	
$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\tau \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.5$ CHARM	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\tau \gamma_\rho L \nu_e)$	$\lvert\varepsilon^{dP}_{\tau e}\rvert < 0.5$ CHARM	$\lvert\varepsilon^{dP}_{\tau e}\rvert < 0.03$ s^2_W in DIS at νFactory

- All these bounds are derived taking one parameter at a time!
- NSI couplings with ν_μ are already strongly restricted

Solar Neutrinos



Oscillations in matter

Wolfenstein 1978

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

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

Evolution equation

$$i \frac{d}{dt} \left(\begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right) = \left(\begin{array}{cc} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{array} \right) \left(\begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right) .$$

Constant density case

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

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

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

Wolfenstein 1978, Mikheev & Smirnov 1985

Oscillations and NSI

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

with

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

and

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

Non Standard Interactions

$$H_{\rm NSI} = \sqrt{2} G_F N_f \left(\begin{array}{cc} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{array} \right).$$

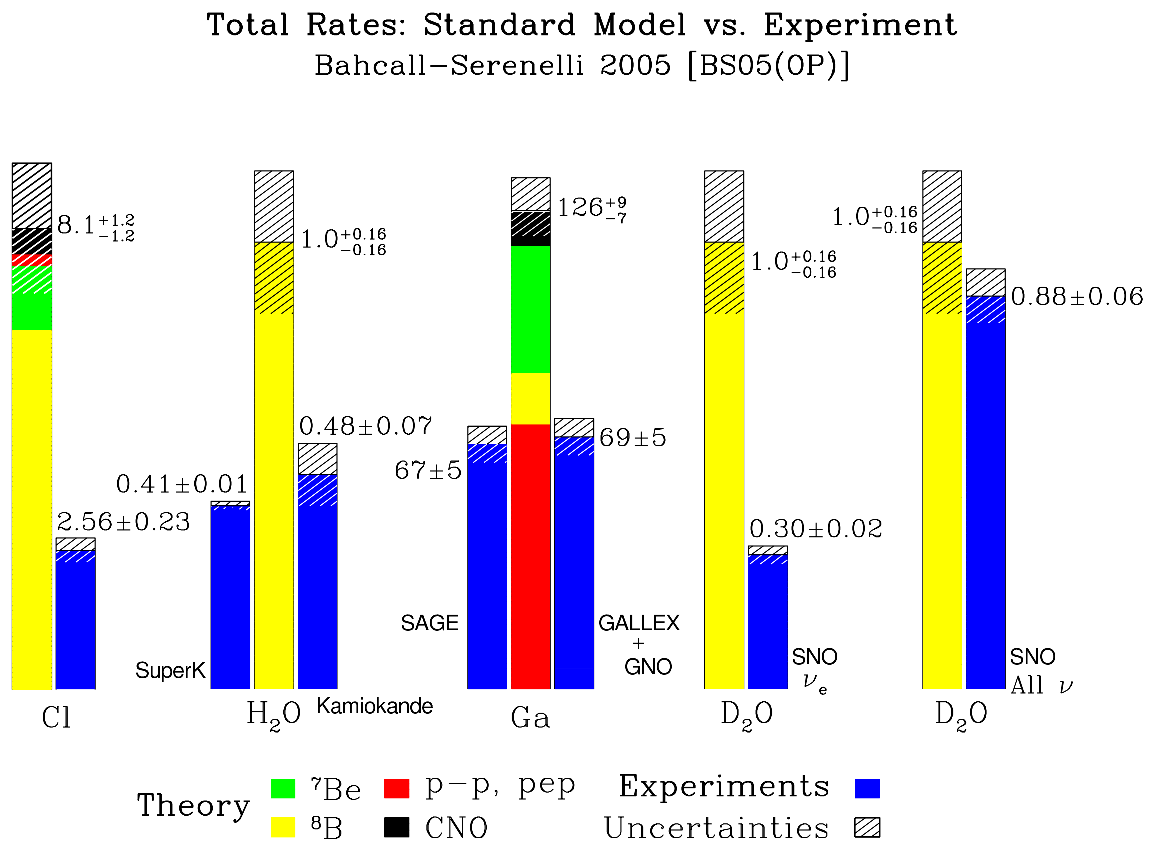
Mixing angle in matter + NSI

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

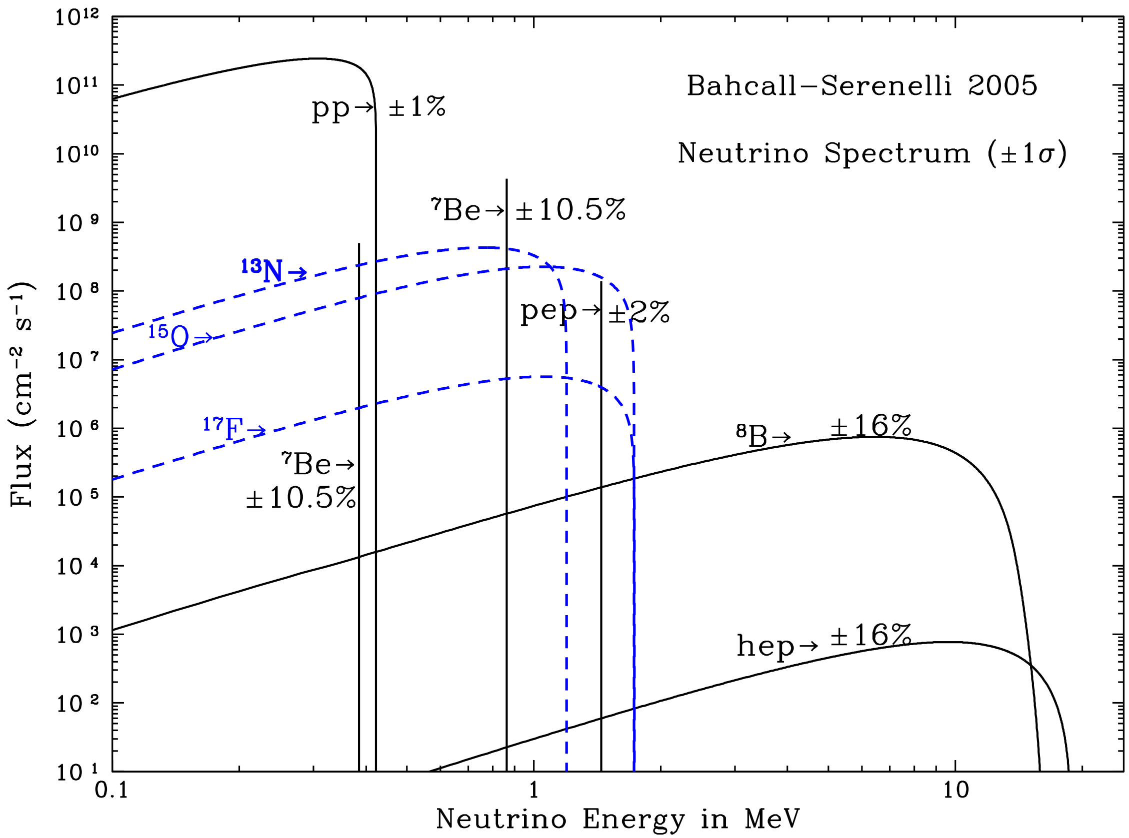
Resonance $$\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F\, \varepsilon'\, N_d = 0\,.$$

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

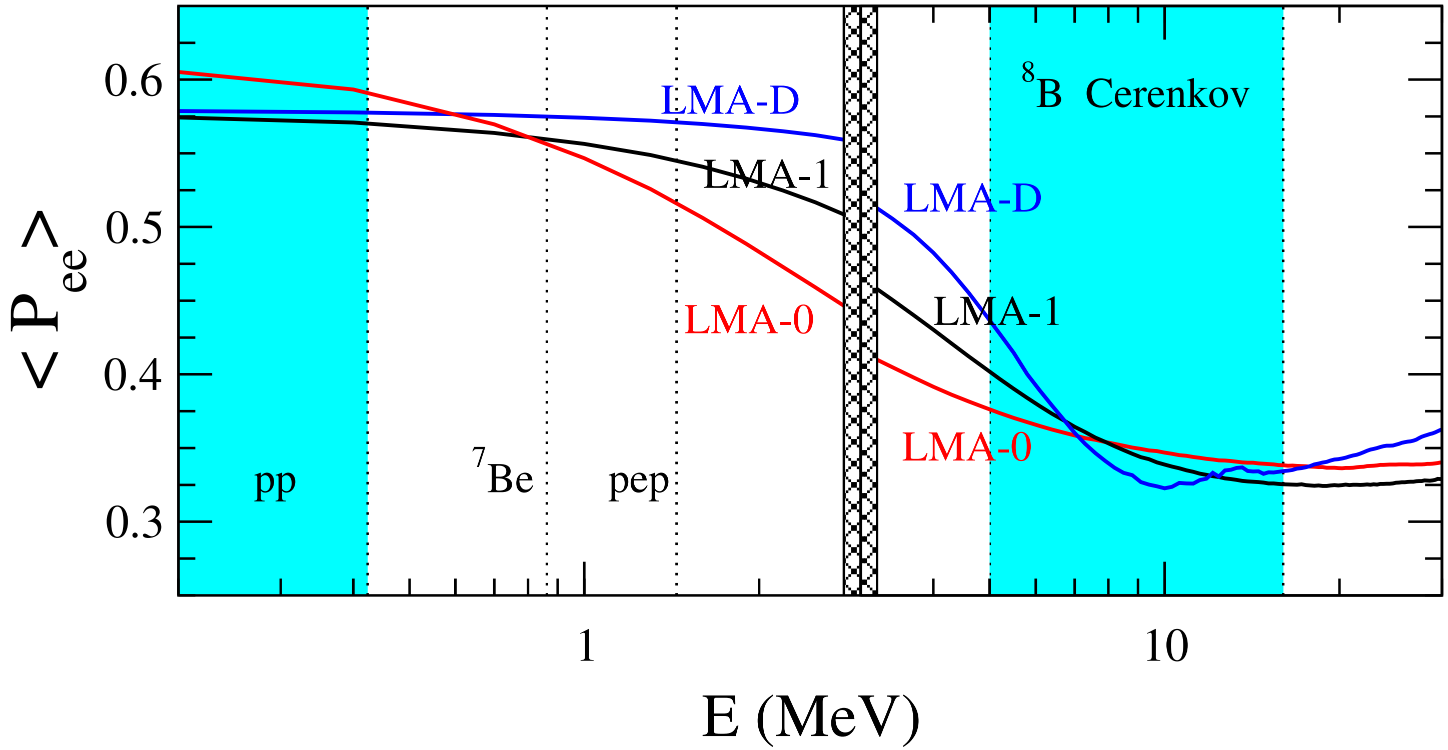
Solar Neutrinos



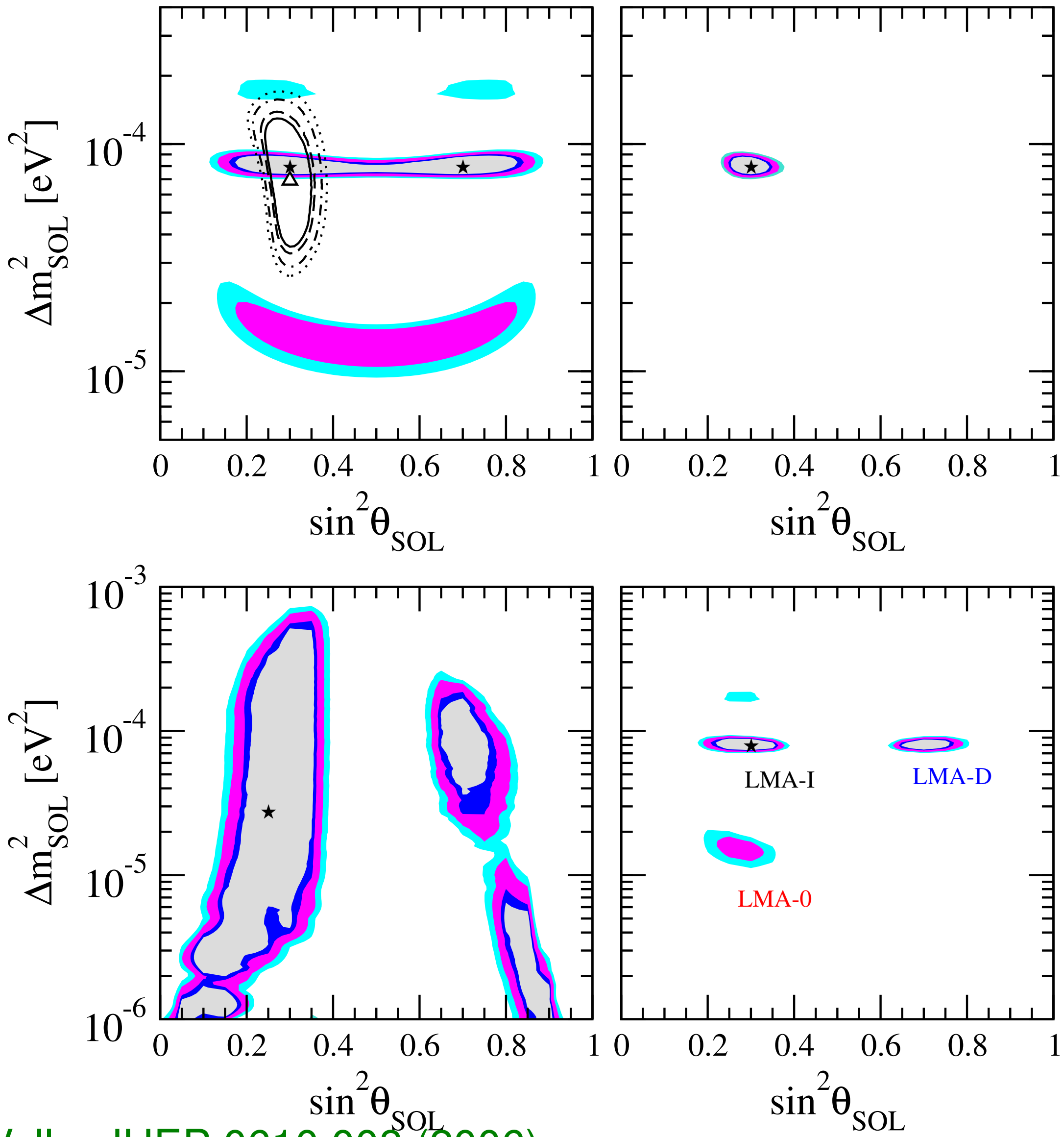
Solar Neutrinos



Solar Neutrinos

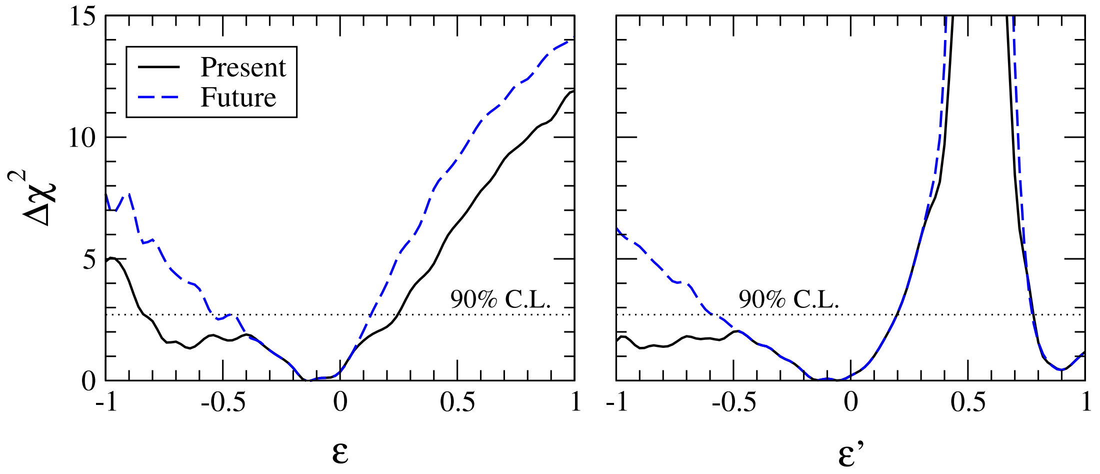


Solar + KamLAND without and with NSI

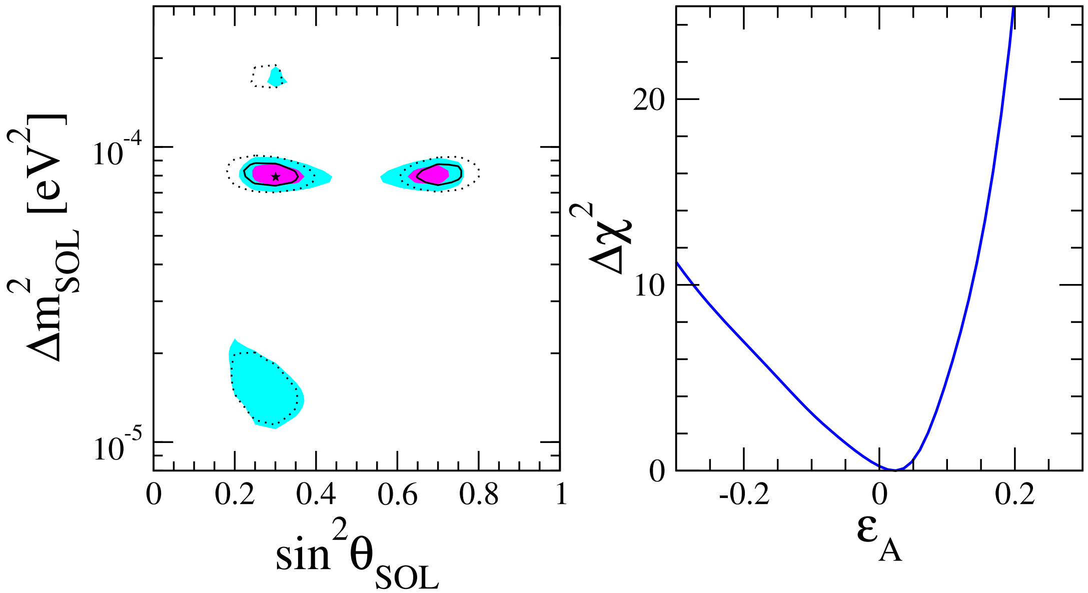


Miranda, Tortola, Valle, JHEP 0610:008 (2006)

NSI constraints from Solar + Kamland



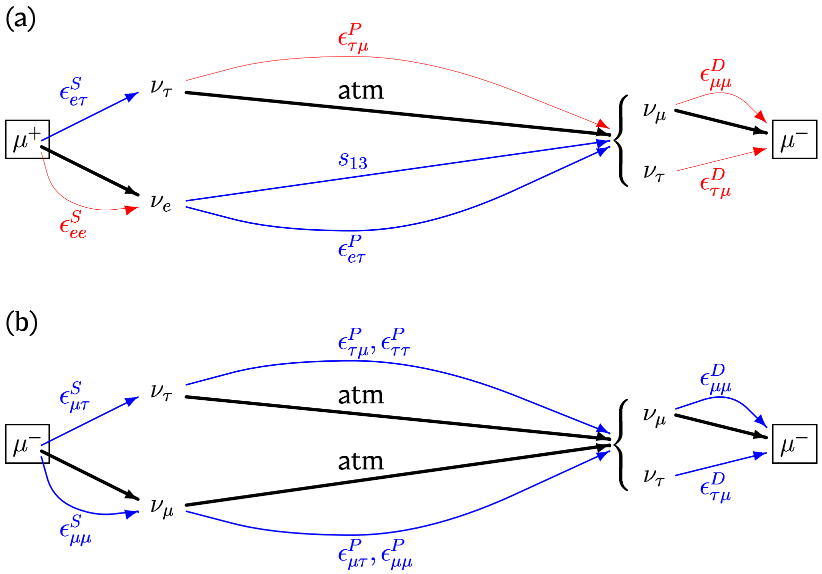
NSI constraints from Solar + Kamland



Confusion problem for θ_{13}

$$\mathcal{R}_{e\mu} \approx A\, s_{13}^2 + B\, s_{13}\epsilon_P + C\, \epsilon_P^2 + D\, \epsilon_P\epsilon_S + E\, \epsilon_S^2 + F\, s_{13}\epsilon_S$$

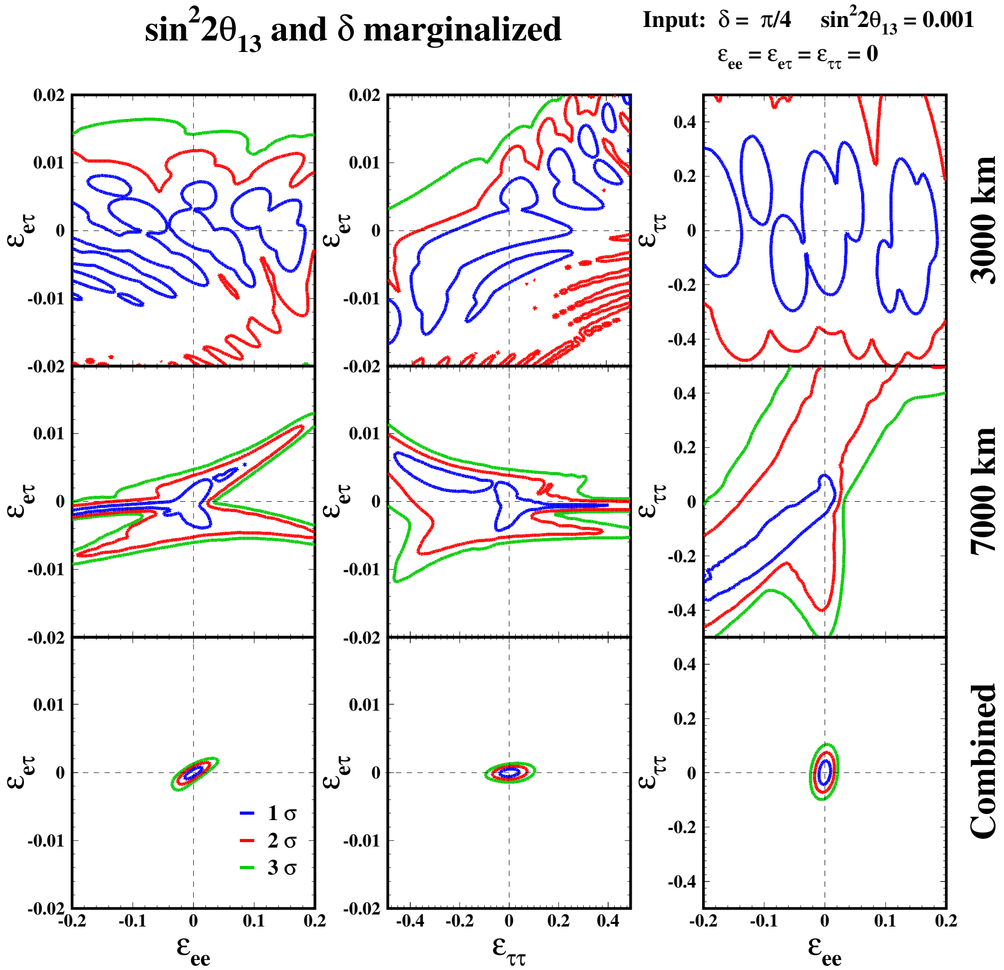
$$\epsilon_S \equiv \epsilon_{e\tau}^S\,, \qquad \epsilon_P \equiv \epsilon_{e\tau}^P\,.$$



Huber, Schwetz, Valle, PRD **66** 013006 '02.

Perspectives

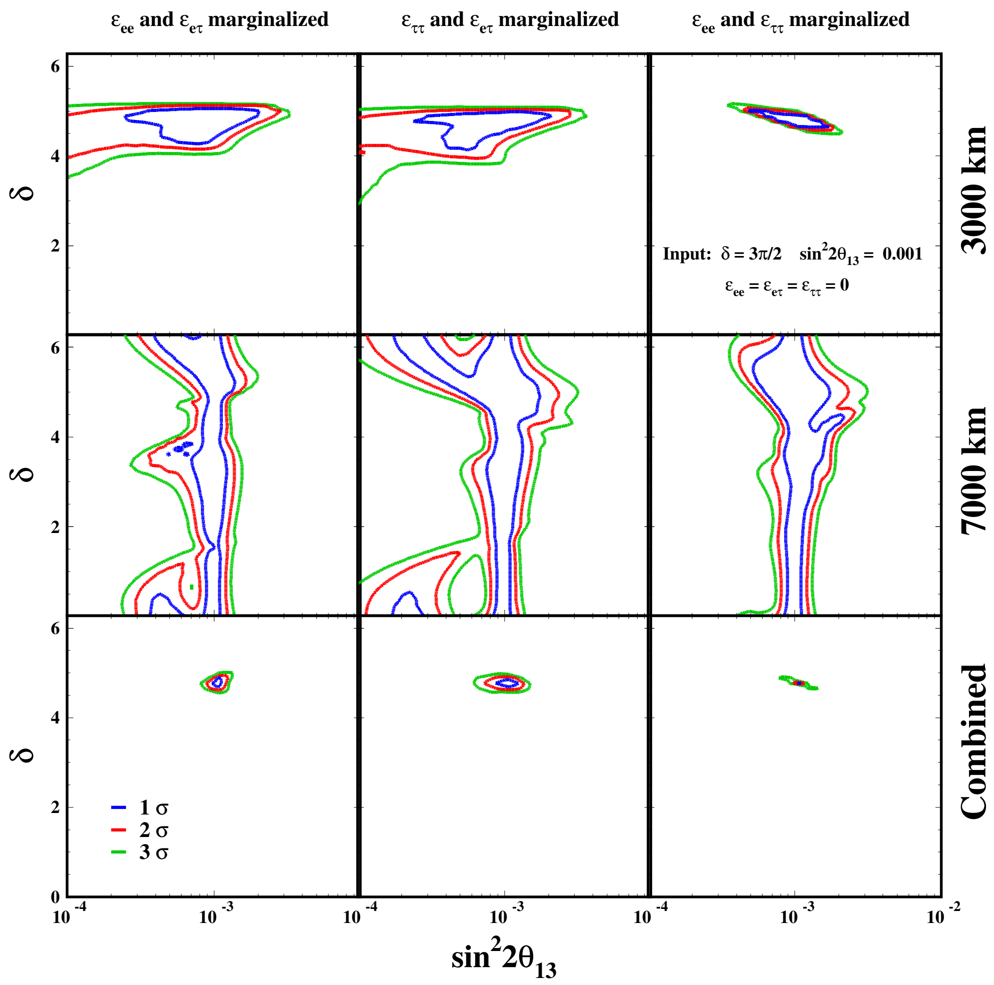
Neutrino factory + two different neutrino detectors



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

Perspectives

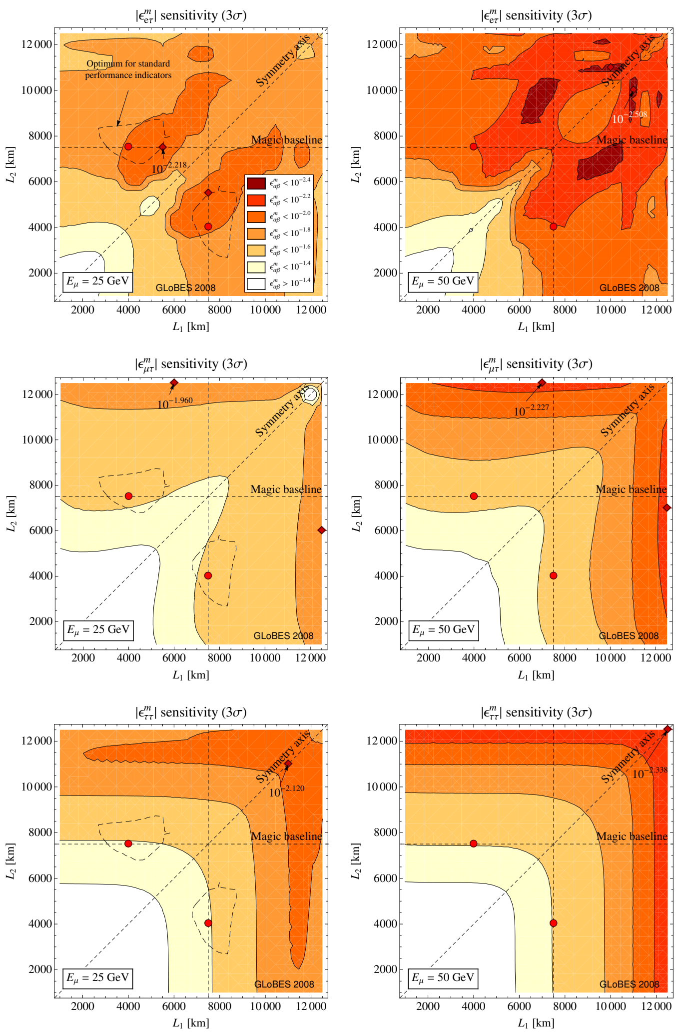
Neutrino factory + two different neutrino detectors



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

Perspectives

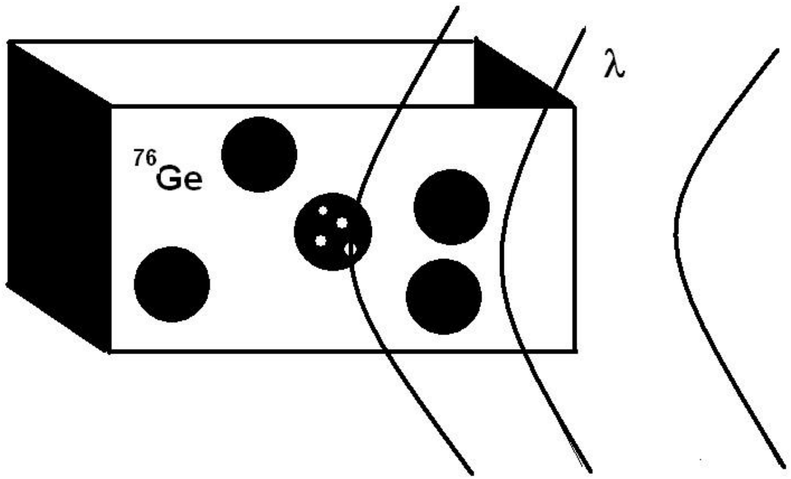
Neutrino factory + two different neutrino detectors



Kopp, Ota, Winter, arXiv:0804.2261

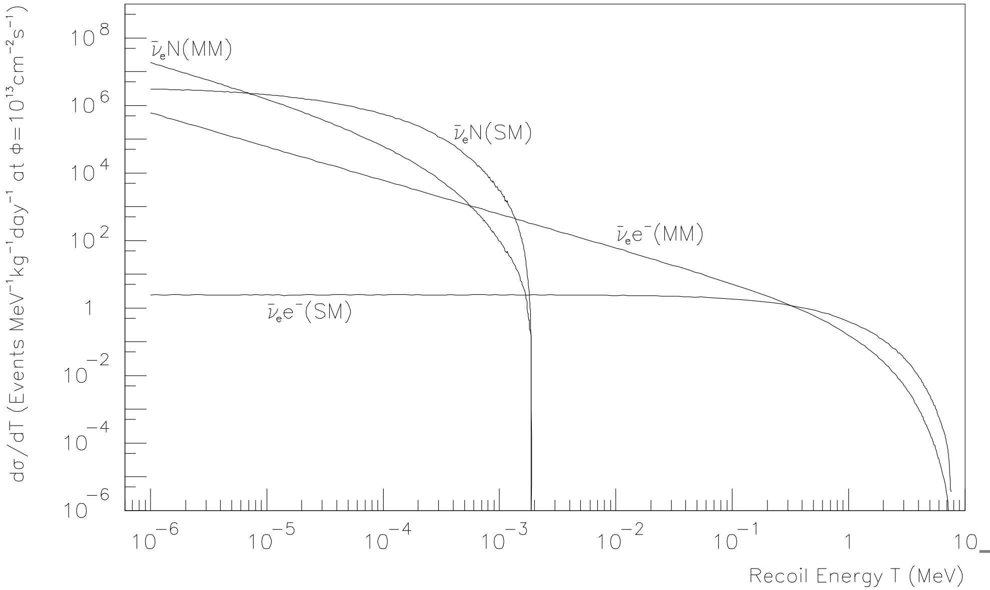
NSI with d, u quark, Coherent $\nu - N$ scattering

- Coherent scattering if the momentum transfer, Q, is small, $QR < 1$ (R is radius of nucleus): $\Longrightarrow$ ν-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
- 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
- Low-energy beta beam with a Xe detector A. Bueno et. al. Phys. Rev. D **74** (2006) 033010.



Neutrino-nuclei interaction

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

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

$$f_{\alpha\alpha}^{uL} = \rho_{\nu N}^{NC} \left(\frac{1}{2} - \frac{2}{3}\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{uL} + \varepsilon_{\alpha\alpha}^{uL}$$

$$f_{\alpha\alpha}^{dL} = \rho_{\nu N}^{NC} \left(-\frac{1}{2} + \frac{1}{3}\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{dL} + \varepsilon_{\alpha\alpha}^{dL}$$

$$f_{\alpha\alpha}^{uR} = \rho_{\nu N}^{NC} \left(-\frac{2}{3}\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{uR} + \varepsilon_{\alpha\alpha}^{uR}$$

$$f_{\alpha\alpha}^{dR} = \rho_{\nu N}^{NC} \left(\frac{1}{3}\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \lambda^{dR} + \varepsilon_{\alpha\alpha}^{dR}$$

ν-N coherent scattering

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

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

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

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

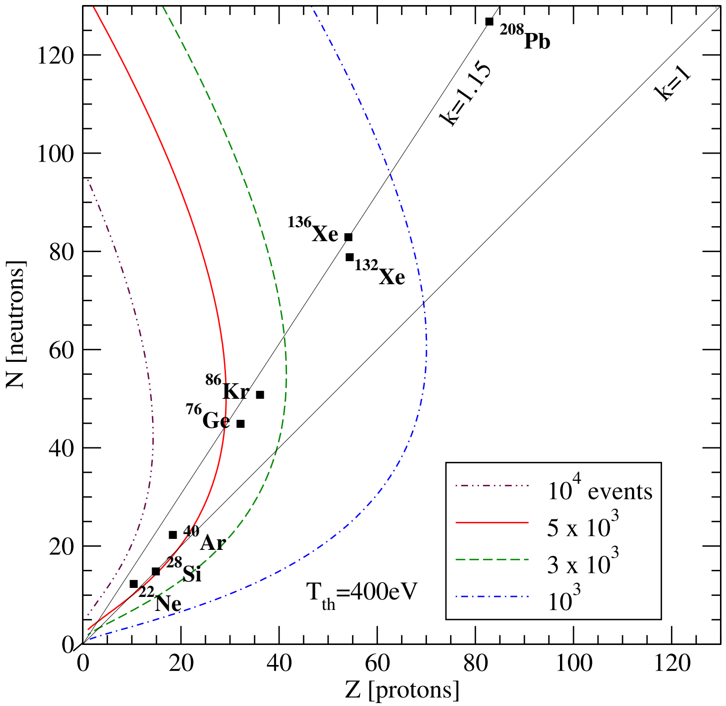
- Axial couplings contribution is zero or can be neglected
- Coherent enhancement of cross section
- Degeneracy in determination of NSI parameters

Resolving the degeneracy

$$\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 = \left[Zg_V^p + Ng_V^n\right]^2$$

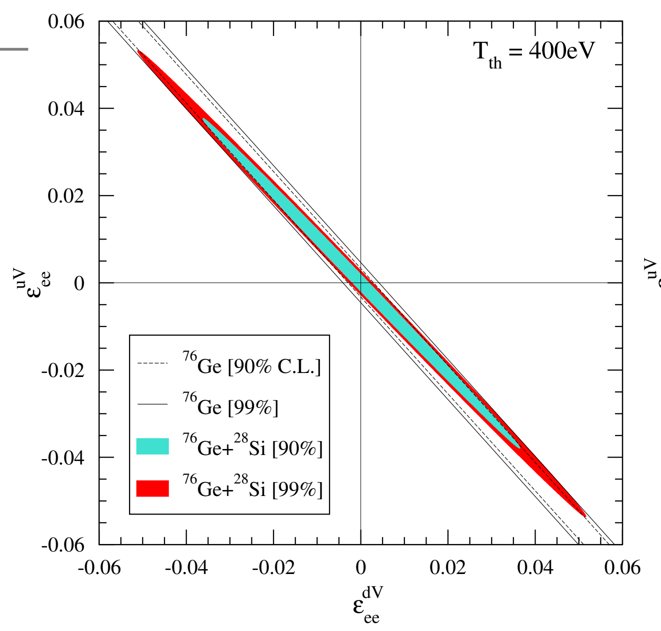
$$\varepsilon_{ee}^{uV}(A+Z) + \varepsilon_{ee}^{dV}(A+N) = \text{const}\,.$$

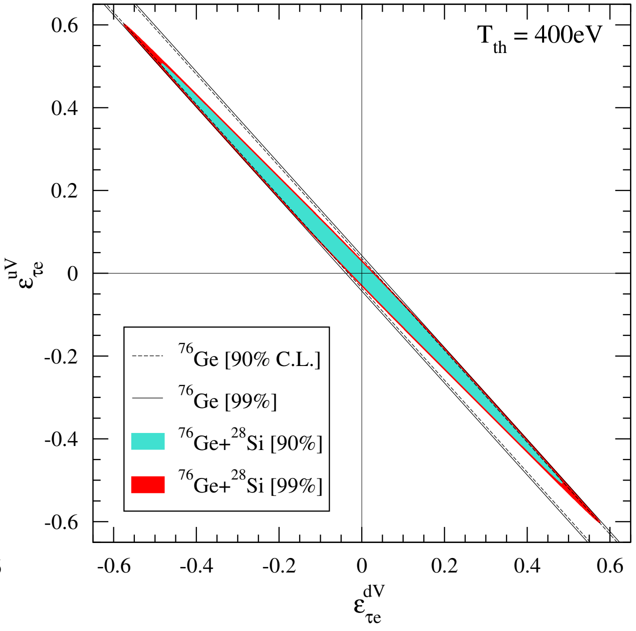
Solution: take two targets with **maximally different** $k = (A+N)/(A+Z)$



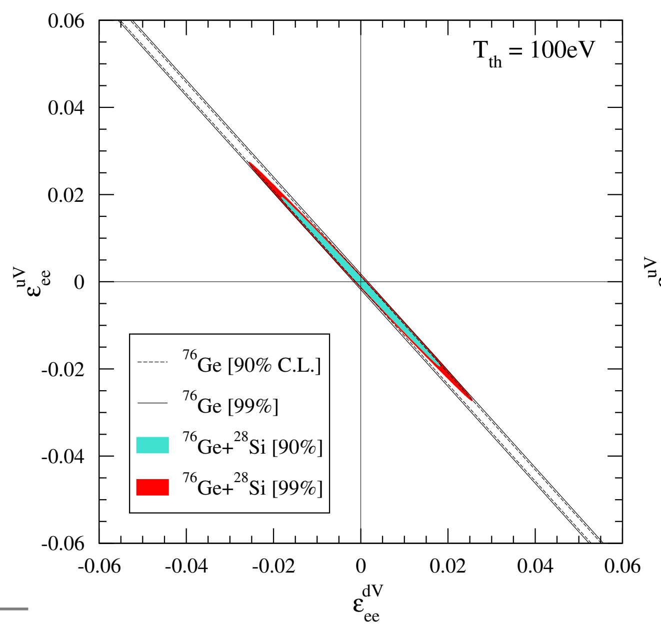
J. Barranco, O.G. Miranda, T.I. Rashba JHEP 0512:021 (2005)

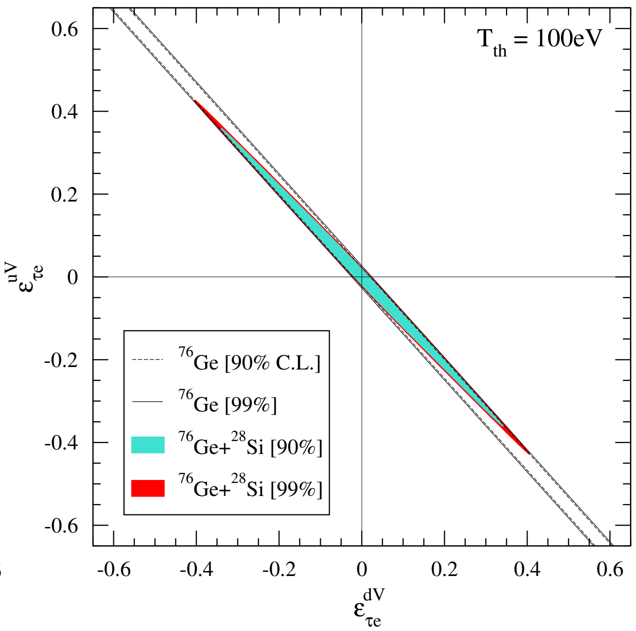
Estimated bounds on NSI from TEXONO-like experiment (Ge+Si)





^{76}Ge+^{28}Si $T_{th}=400eV$
$\lvert\epsilon^{dV}_{ee}\rvert < 0.036$
$\lvert\epsilon^{uV}_{ee}\rvert < 0.038$
$\lvert\epsilon^{dV}_{\tau e}\rvert < 0.48$
$\lvert\epsilon^{uV}_{\tau e}\rvert < 0.50$

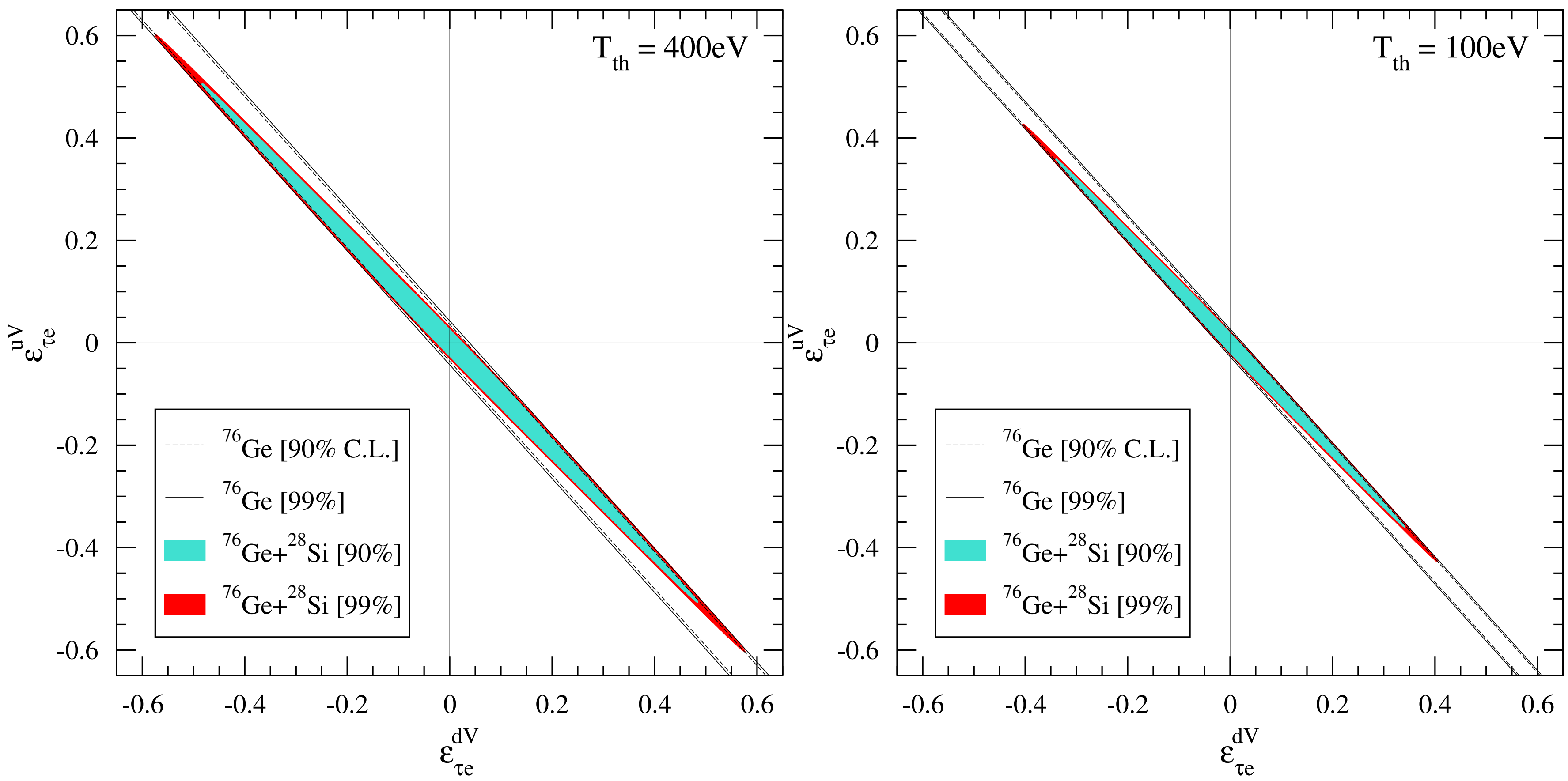




^{76}Ge+^{28}Si $T_{th}=100eV$
$\lvert\epsilon^{dV}_{ee}\rvert < 0.018$
$\lvert\epsilon^{uV}_{ee}\rvert < 0.019$
$\lvert\epsilon^{dV}_{\tau e}\rvert < 0.34$
$\lvert\epsilon^{uV}_{\tau e}\rvert < 0.37$

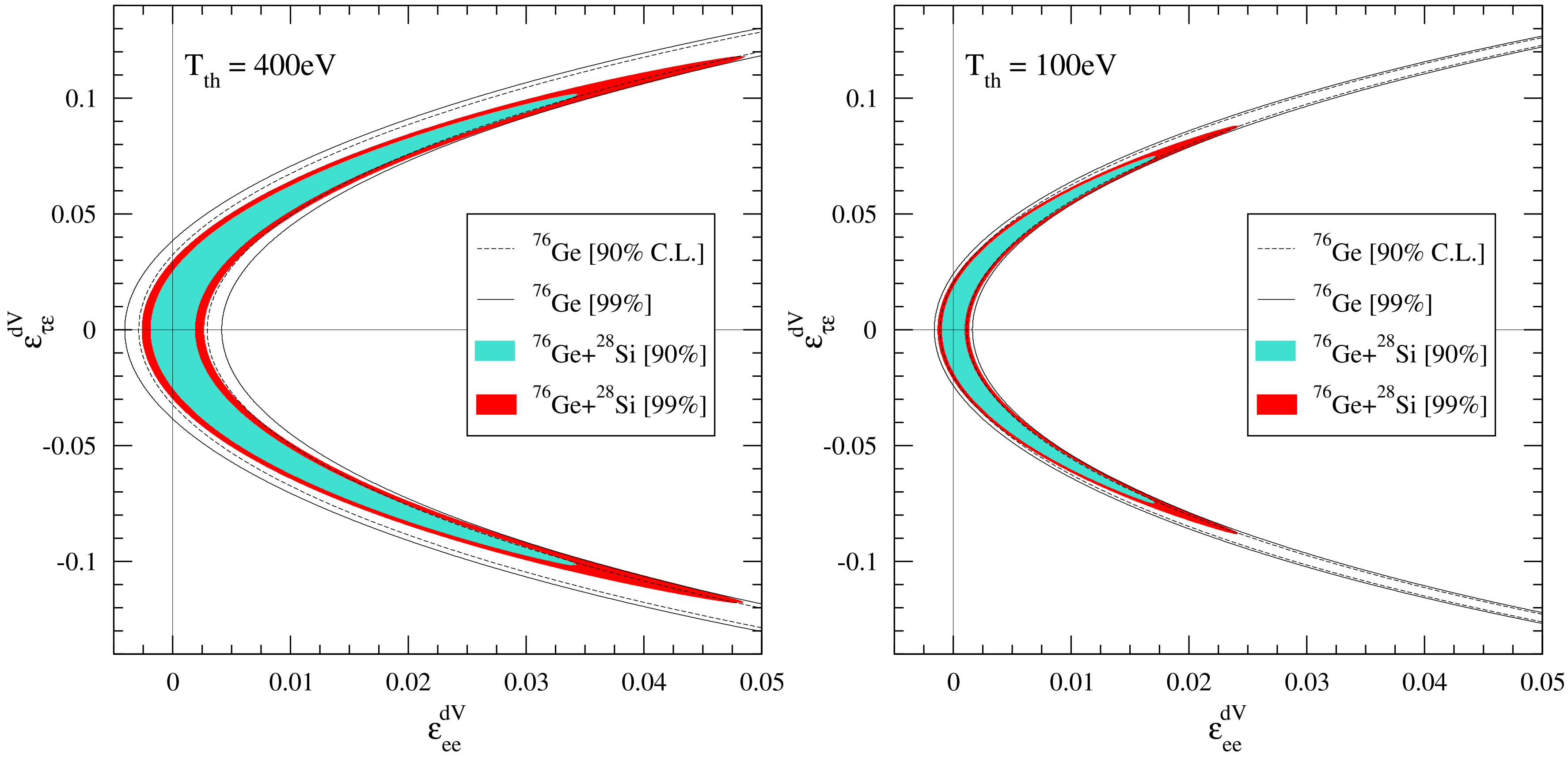
Flavor changing NSI

$$\varepsilon_{\tau e}^{uV} \; vs \; \varepsilon_{\tau e}^{dV}$$



NSI with d-quark only

$\varepsilon_{\tau e}^{dV}$ versus ε_{ee}^{dV}



Present and future bounds on NSI

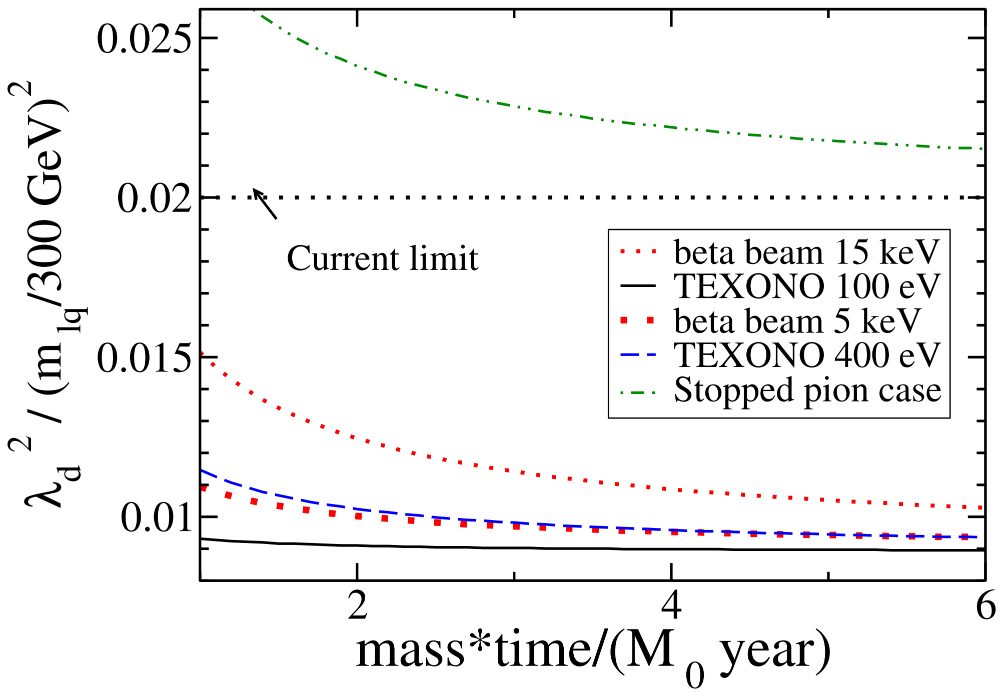
One parameter analysis to compare coherent scattering sensitivity with present bounds and νFactory sensitivity (taken from Davidson et al'03)

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

The leptoquark as an example of NSI

$$\varepsilon^{uV} = \frac{\lambda_u^2}{m_{lq}^2}\frac{\sqrt{2}}{4G_F}, \qquad \varepsilon^{dV} = \frac{\lambda_d^2}{m_{lq}^2}\frac{\sqrt{2}}{4G_F}$$

S. Davidson, D. C. Bailey and B. A. Campbell, Z. Phys. C **61**, 613 (1994)

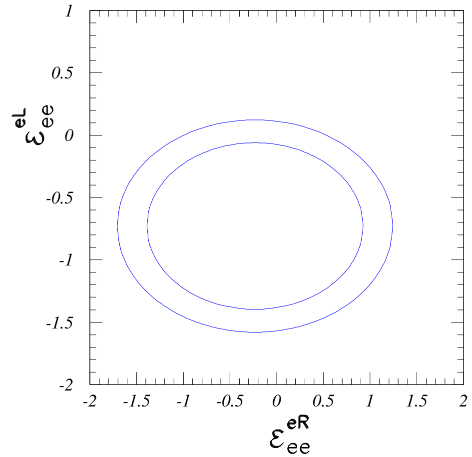


J. Barranco, O.G. Miranda, T.I. Rashba Phys. Rev. **D76** 073008 (2007)

What we have learned up to know

- Current constraints to NSI in the quark sector are relatively weak, but future experiments, including low-energy experiments could improve the present bounds.
- Future constraints could take into account several NSI parameters at a time if different detectors are considered
- NSI constraints can be tranlated in future into competitive constraints to specific models in physics beyond the Standard Model.

The $\nu_e e$ interaction



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

- Davidson, Peña-Garay,Rius,Santamaria JHEP 0303:011 (2003) hep-ph/0302093:
  $-0.07 < \varepsilon_{ee}^{eL} < 0.1 \qquad -1.0 < \varepsilon_{ee}^{eR} < 0.50$ at 90 % C L
- Berezhiani, Raghavan, Rossi PLB **535** 207 (2002) hep-ph/0111138:
  $-0.15 < \varepsilon_{ee}^{eL} < 0.17 \qquad -0.95 < \varepsilon_{ee}^{eR} < 0.50$ at 99 % C L

The $\bar{\nu}_e e$ cross section

In the Standard Model

$$\frac{d\sigma}{dT} = \frac{2G_F m_e}{\pi}[g_L^2 + g_R^2(1-\frac{T}{E_\nu})^2 - g_L g_R \frac{m_e T}{E_\nu^2}]$$

with

$$\begin{aligned} g_L &= \frac{1}{2} + \sin^2\theta_W \\ g_R &= \sin^2\theta_W\,. \end{aligned}$$

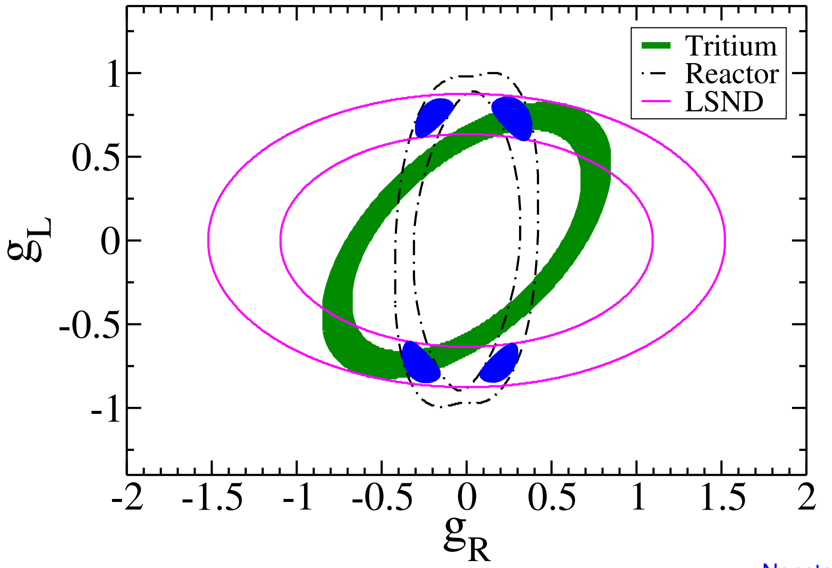
But this is the Eq. of an ellipse with axes 1 and $(1-\frac{T}{E_\nu})$ and rotated an angle

$$\tan 2\theta = \frac{m_e}{(2E_\nu - T)}$$

Barranco, Miranda, Moura, Valle, Phys. Rev. **D73** 113001 (2006)

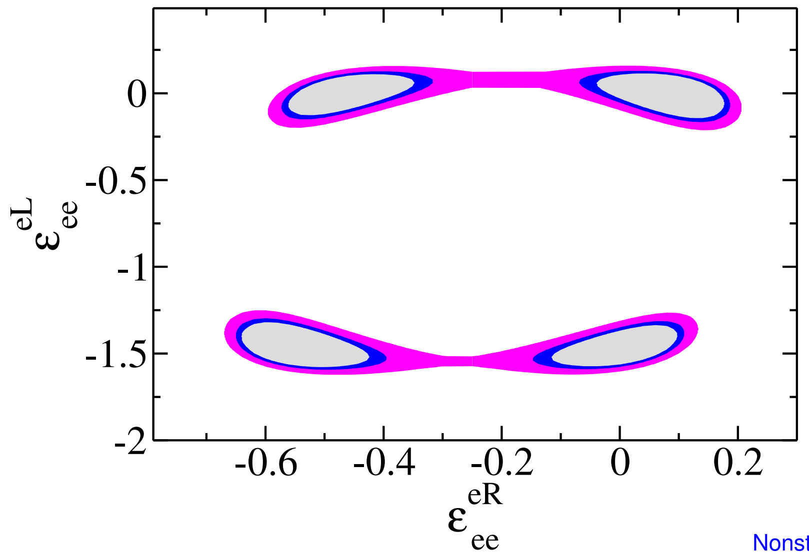
The $\nu_e e$ interaction

Experiment	Energy (MeV)	events	measurement
LSND $\nu_e e$	10-50	191	$\sigma = [10.1 \pm 1.5] \times E_{\nu_e}(\mathrm{MeV}) \times 10^{-45}\mathrm{cm}^2$
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	$\sigma = (1.26 \pm 0.62) \times 10^{-44}\mathrm{cm}^2/\mathrm{fission}$
MUNU $\bar{\nu}_e - e$	0.7 - 2.0	68	1.07 ± 0.34 events day $^{-1}$



The $\nu_e e$ interaction

	Previous Limits	One parameter	Two Parameters	All Parameters
ϵ_{ee}^{eL}	$-0.07 < \epsilon_{ee}^{eL} < 0.11$	$-0.05 < \epsilon_{ee}^{eL} < 0.12$	$-0.13 < \epsilon_{ee}^{eL} < 0.12$	$-1.58 < \epsilon_{ee}^{eL} < 0.12$
ϵ_{ee}^{eR}	$-1.0 < \epsilon_{ee}^{eR} < 0.5$	$-0.04 < \epsilon_{ee}^{eR} < 0.14$	$-0.07 < \epsilon_{ee}^{eR} < 0.15$	$-0.61 < \epsilon_{ee}^{eR} < 0.15$
$\epsilon_{e\tau}^{eL}$	$\|\epsilon_{e\tau}^{eL}\| < 0.4$	$\|\epsilon_{e\tau}^{eL}\| < 0.43$	$\|\epsilon_{e\tau}^{eL}\| < 0.43$	$\|\epsilon_{e\tau}^{eL}\| < 0.85$
$\epsilon_{e\tau}^{eR}$	$\|\epsilon_{e\tau}^{eR}\| < 0.7$	$\|\epsilon_{e\tau}^{eR}\| < 0.27$	$\|\epsilon_{e\tau}^{eR}\| < 0.31$	$\|\epsilon_{e\tau}^{eR}\| < 0.38$



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

$$\sigma^{\text{theo}}_{\text{LEP}}(s) = \int \mathrm{d}x \int \mathrm{d}c_\gamma \; H(x, s_\gamma; s) \; \sigma^{\text{theo}}_0(\hat{s}) \,,$$

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

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

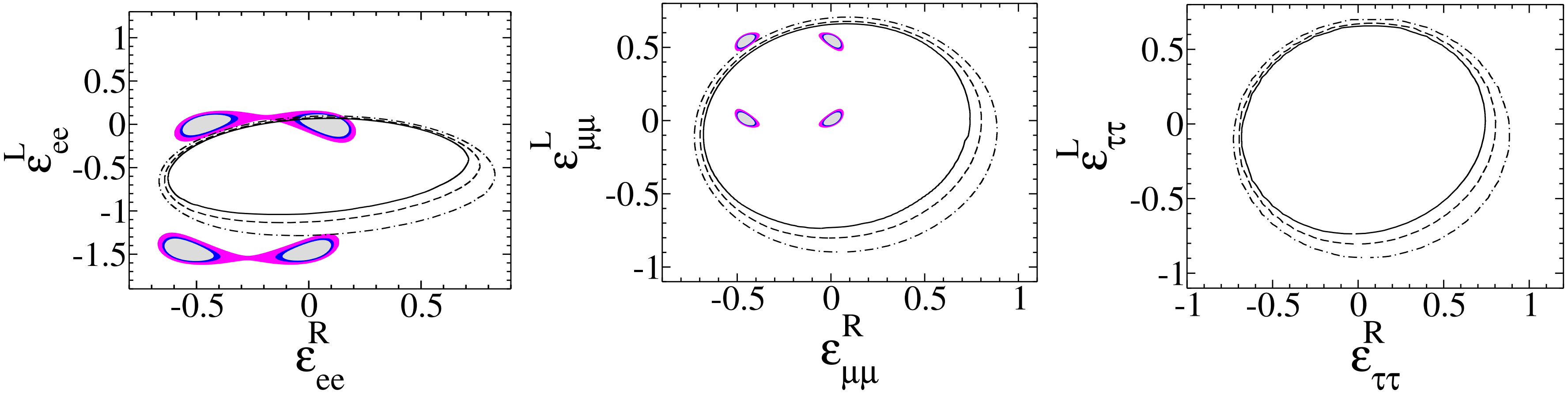
The $e^+e^- \to \nu\bar{\nu}\gamma$ interaction

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

The $\nu_\mu e \to \nu_\mu e$ interaction

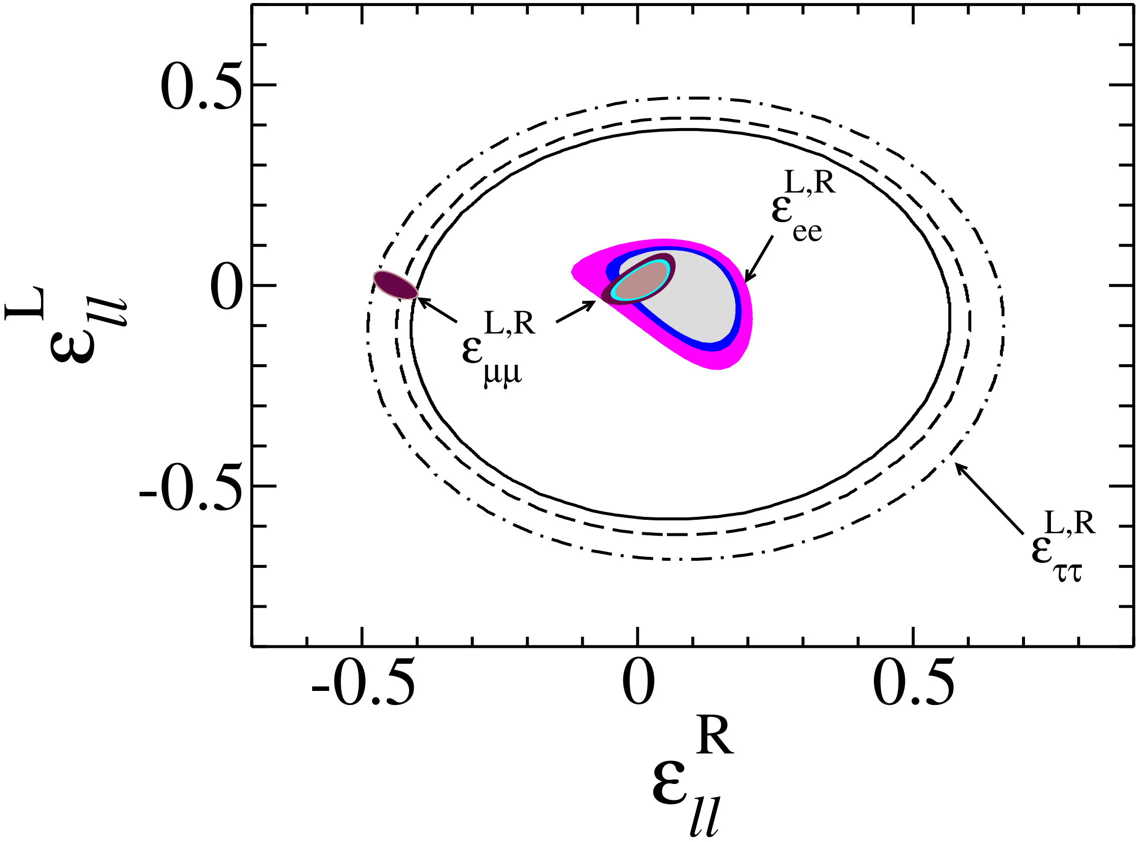
$$\frac{\mathrm{d}\sigma^{\mathrm{theo}}_{\mathrm{CHARM}}}{\mathrm{d}y} = \frac{2G_F^2 m_e}{\pi} E_\nu \left[\left(\tilde{g}_L^2 + \sum_{\alpha \neq \mu} |\varepsilon^L_{\alpha\mu}|^2 \right) + \left(\tilde{g}_R^2 + \sum_{\alpha \neq \mu} |\varepsilon^R_{\alpha\mu}|^2 \right) (1-y)^2 \right]$$

The χ^2 analysis



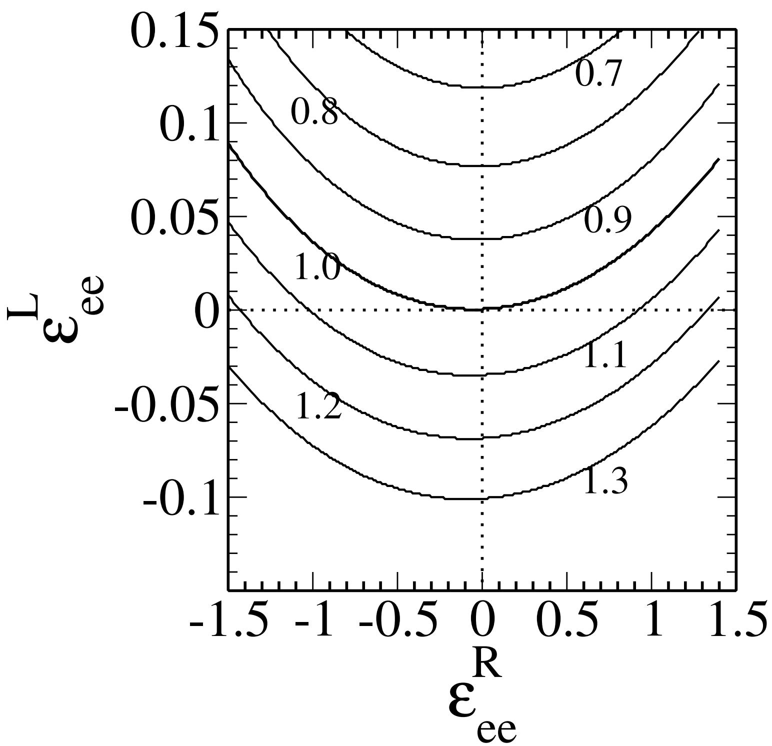
	90% C.L. Allowed Region	One parameter	Previous limits
ε^L_{ee}	$-0.14 < \varepsilon^L_{ee} < 0.09$	$-0.03 < \varepsilon^L_{ee} < 0.08$	$-0.05 < \varepsilon^L_{ee} < 0.1$
ε^R_{ee}	$-0.03 < \varepsilon^R_{ee} < 0.18$	$0.004 < \varepsilon^R_{ee} < 0.15$	$0.04 < \varepsilon^R_{ee} < 0.14$
$\varepsilon^L_{\mu\mu}$	$-0.033 < \varepsilon^L_{\mu\mu} < 0.055$	$\lvert\varepsilon^L_{\mu\mu}\rvert < 0.03$	$\lvert\varepsilon^L_{\mu\mu}\rvert < 0.03$
$\varepsilon^R_{\mu\mu}$	$-0.040 < \varepsilon^R_{\mu\mu} < 0.053$	$\lvert\varepsilon^R_{\mu\mu}\rvert < 0.03$	$\lvert\varepsilon^R_{\mu\mu}\rvert < 0.03$
$\varepsilon^L_{\tau\tau}$	$-0.6 < \varepsilon^L_{\tau\tau} < 0.4$	$-0.5 < \varepsilon^L_{\tau\tau} < 0.2$	$\lvert\varepsilon^L_{\tau\tau}\rvert < 0.5$
$\varepsilon^R_{\tau\tau}$	$-0.4 < \varepsilon^R_{\tau\tau} < 0.6$	$-0.3 < \varepsilon^R_{\tau\tau} < 0.4$	$\lvert\varepsilon^R_{\tau\tau}\rvert < 0.5$

The χ^2 analysis



Perpectives

- Solar neutrinos could be sensitive to NSI with electrons
- NSI could affect the propagation
- NSI Could also affect detection, especially in SuperKamiokande

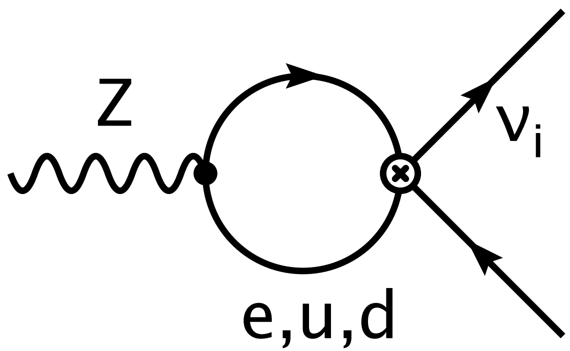


Conclusions

- NSI arise naturally in many models of physics beyond the SM and may be important in oscillation experiments.
- Low energy neutrino experiments can improve the constraints to NSI with similar sensitivity that ν-Factories of LBL.
- Low energy neutrino experiments can give constraints that are independent of the oscillation parameters.

Constraints on NSI from one loop effects

- On general grounds we expect that interactions in which the ν_α are replaced by the corresponding leptons will be generated by one loop diagrams with virtual W's or Z's .
- Effective interactions, however, are nonrenormalizable and, therefore, a precise prescription has to be given in order to estimate these corrections.
- Our If these are originated from a more complete theory at scales $\Lambda \gg m_W$ which is renormalizable (or perhaps finite) and in which observables can be computed in terms of a few parameters.



Solar ν oscillations and NSI

$$P(\nu_e \to \nu_e) = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right],$$

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}\, E G_F (N_e - \varepsilon' N_d)}{[\Delta m^2]_{matter}},$$

where

$$[\Delta m^2]^2_{matter} = \left[\Delta m^2 \cos 2\theta - 2\sqrt{2}\, E G_F (N_e - \varepsilon' N_d)\right]^2$$

$$+ \left[\Delta m^2 \sin 2\theta + 4\sqrt{2}\, \varepsilon\, E G_F N_d\right]^2$$