Low energy neutrino experiments sensitivity to physics beyond the Standard Model

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with

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Outline

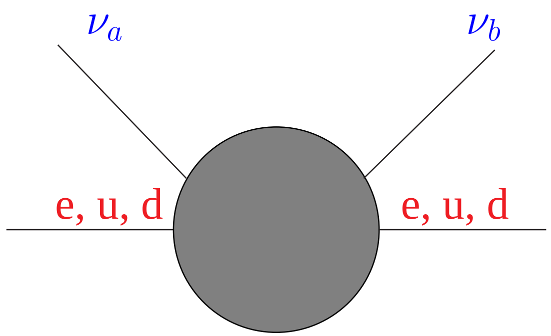
- Motivations
- Non-standard contributions to ν-N coherent scattering
- Experimental sensitivity
- Sensitivity to specific NSI scenarios:
  Z', leptoquark and R-parity breaking SUSY
- Summary

Non Standard Interactions (NSI)

Most extensions of the SM, in particular neutrino mass theories, predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (NU – non-universal) or flavor-changing (FC).

NSI effective Lagragian form:

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



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

Non Standard Interactions (NSI)

Non-standard neutral current neutrino interactions may arise:

- from a non trivial non-unitary lepton mixing matrix
  Schechter & Valle'80
- in models where neutrino masses are "calculable" from radiative corrections Zee'80, Babu'88
- in SUSY models with broken R-parity
  see review by Hirsch & Valle [hep-ph/0405015] and refs therein
- in unified SUSY models as a renormalization effect
  Hall, Kostelecky & Raby'86
- . . . some other models, like left-right models, etc . . .

Predictions:

In most models NSI contributions are expected to be small, e.g. being supressed by the smallness of neutrino masses, however in some models NSI is not strongly restricted or supressed

Example: $R\!\!\!/_p$ parity violating SUSY

Non-standard neutrino-electron and neutrino quark interactions:

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

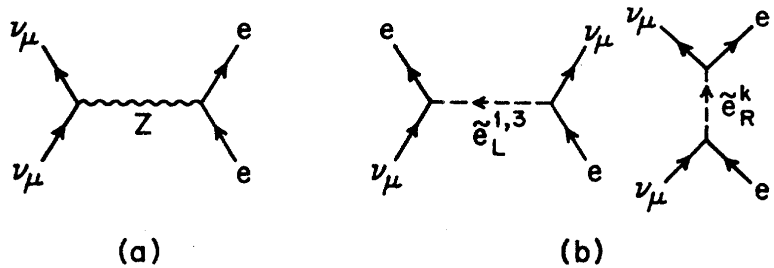
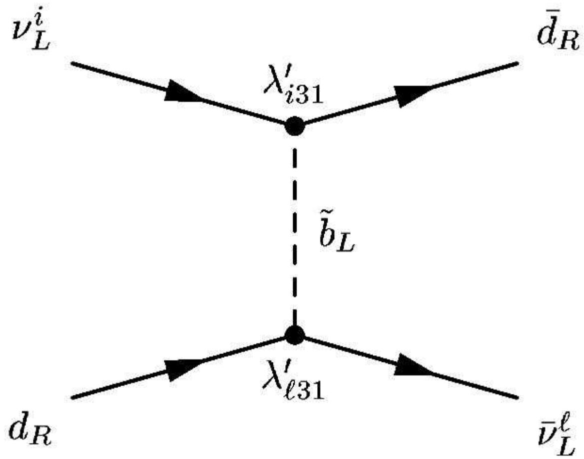
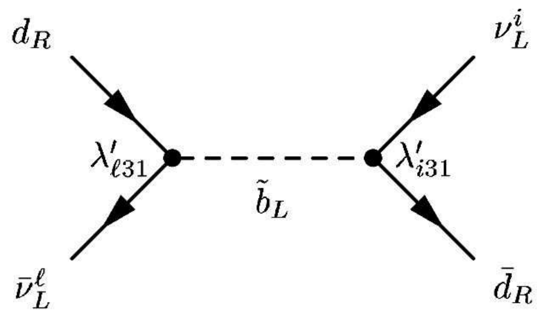


FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

Barger, Giudice & Han'89





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

Applications

- neutrino oscillations in matter: solar, atmospheric, supernovae

  . . . , Guzzo et al'91, Fornengo et al'02, Friedland et al'04'05, Miranda et al'04

- supernovae explosion

  Freedman et al'77, Fuller et al'87'88, Amanik et al'04'06, Esteban-Pretel et al'07

- ν scattering experiments . . . , Barger et al'91, Davidson et al'03

- LEP (ILC) Berezhiani & Rossi'02, Davidson et al'03

- . . .

Solar ν oscillations and NSI

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

with,

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

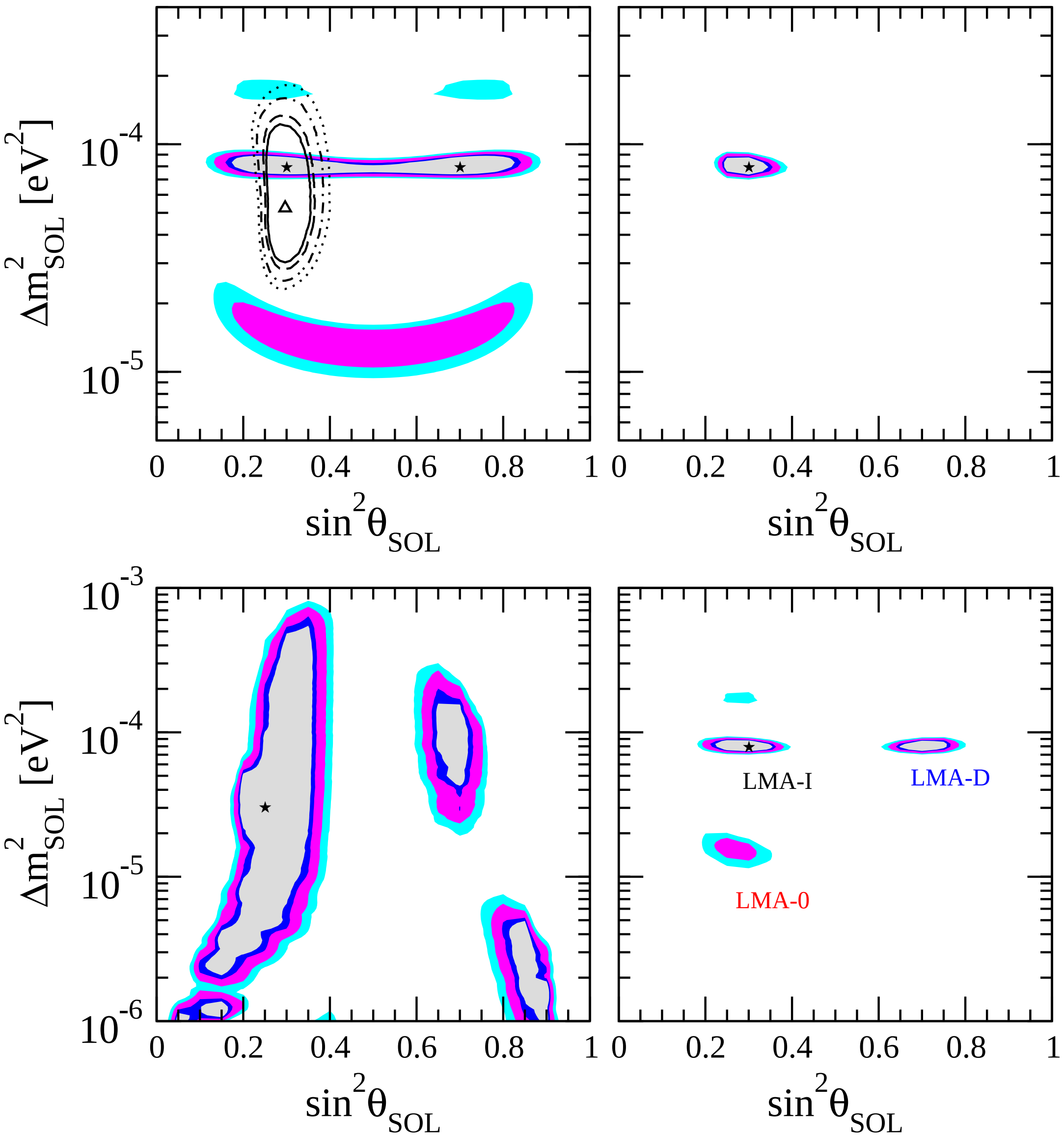
and

$$\varepsilon^{fV}_{\tau\tau} = \varepsilon^{fL}_{\tau\tau} + \varepsilon^{fR}_{\tau\tau}$$

Note:

ν oscillations are sensitive mainly to vector couplings because matter is not polarized.

Solar + KamLAND without and with NSI



Miranda, Tortola, Valle, hep-ph/0406280

Current bounds on NSI couplings

Bounds on NSI couplings come from

- ν-scattering experiments: LSND, CHARM, NuTeV, MUNU, MINOS

  Barger et al'91, Davidson et al'03, Barranco et al'05
  Friedland et al'06

- $e^- e^+ \to \nu\bar{\nu}\gamma$ measured at LEP

  Berezhiani & Rossi'02

- analysis of atmospheric neutrino data

  Fornengo et al'02, Friedland et al'04'05

- lepton flavor violating interactions, appeared at loop level from NSI, like μ capture by nuclei

  Davidson et al'03

- Invisible Z-boson decay width including loop corrections due to NSI

  Davidson et al'03

Current bounds on NU 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

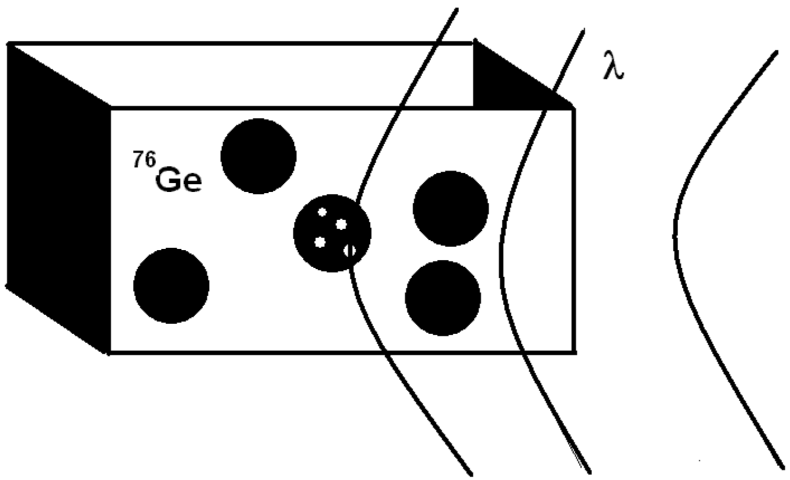
Current bounds on FC NSI ν-q couplings from Davidson et al'03

vertex	current limits	future limit
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_\tau\gamma_\rho L\nu_\mu)$	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{uP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\tau\gamma_\rho L\nu_\mu)$	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.05$ NuTeV	$\lvert\varepsilon^{dP}_{\tau\mu}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_\mu\gamma_\rho L\nu_e)$	$\lvert\varepsilon^{uP}_{\mu e}\rvert < 7.7\times 10^{-4}$ $(\mathrm{Ti}\mu\to\mathrm{Ti}e)^{*)}$	
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\mu\gamma_\rho L\nu_e)$	$\lvert\varepsilon^{dP}_{\mu e}\rvert < 7.7\times 10^{-4}$ $(\mathrm{Ti}\mu\to\mathrm{Ti}e)^{*)}$	
$(\bar{u}\gamma^\rho Pu)(\bar{\nu}_\tau\gamma_\rho L\nu_e)$	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.5$ CHARM	$\lvert\varepsilon^{uP}_{\tau e}\rvert < 0.03$ s^2_W in DIS at νFactory
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\tau\gamma_\rho L\nu_e)$	$\lvert\varepsilon^{dP}_{\tau e}\rvert < 0.5$ 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
- See Davidson et al'03 [hep-ph/0302093] for NSI neutrino-electron couplings bounds

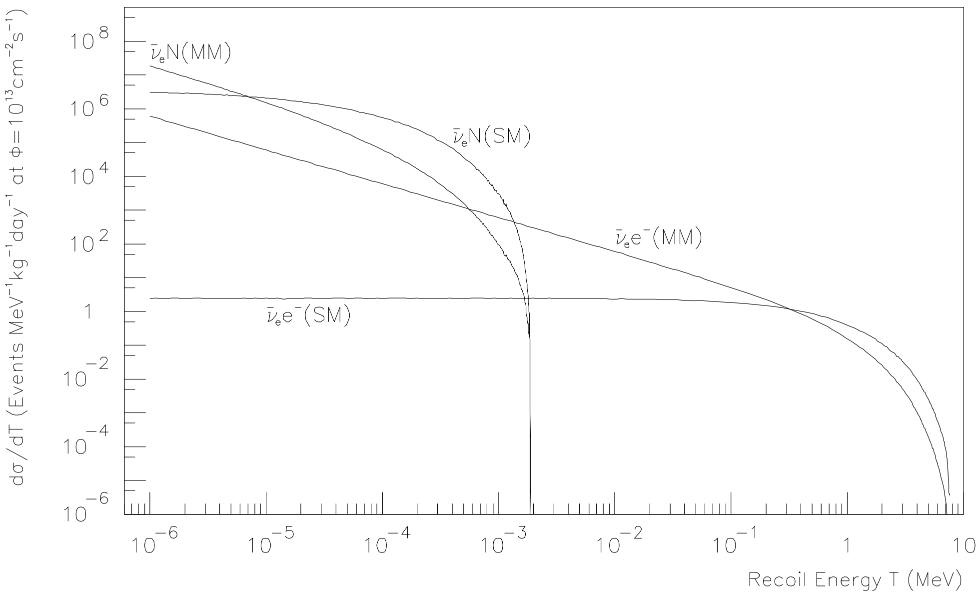
Coherent neutrino scattering off nuclei

- Good statistics due to quadratic coherent enhancement
- Sensitivity to ν-quark couplings
- 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
- Well satisfied for most neutrino sources like supernovae, solar, reactor and artificial neutrino sources
- Planned experiments to measure coherent ν-N scattering: NOSTOS, TEXONO
  . . . and many proposals
- Experimentally difficult: very low energy threshold



Proposed experiments to measure coherent ν-N scattering

- TEXONO: 1kg of germanium, reactor neutrinos — hep-ex/0511001
- NOSTOS: spherical TPC detector, 10 ton of Xenon — astro-ph/0511470
- Stopped-pion neutrino beam and kg-to-ton mass detector — hep-ex/0511042
- more ideas in the past,
  - superconducting detector (Drukier & Stodolsky'84)
  - acoustic (Krauss'91)
  - cryogenic (Oberauer'02)



Neutrino-nuclei interaction

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

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

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

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

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

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

ν-N coherent scattering

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

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

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

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

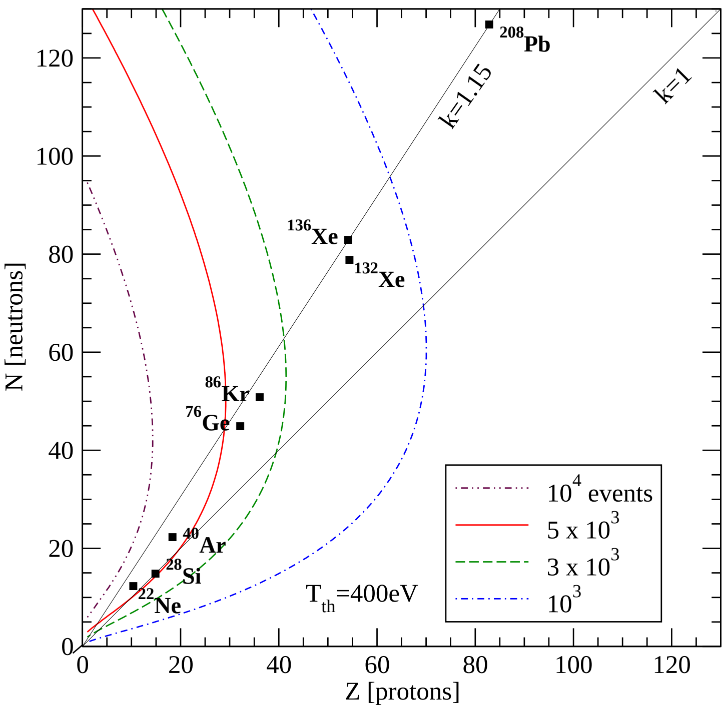
- Axial couplings contribution is zero or can be neglected
- Coherent enhancement of cross section
- Degeneracy in determination of NSI parameters

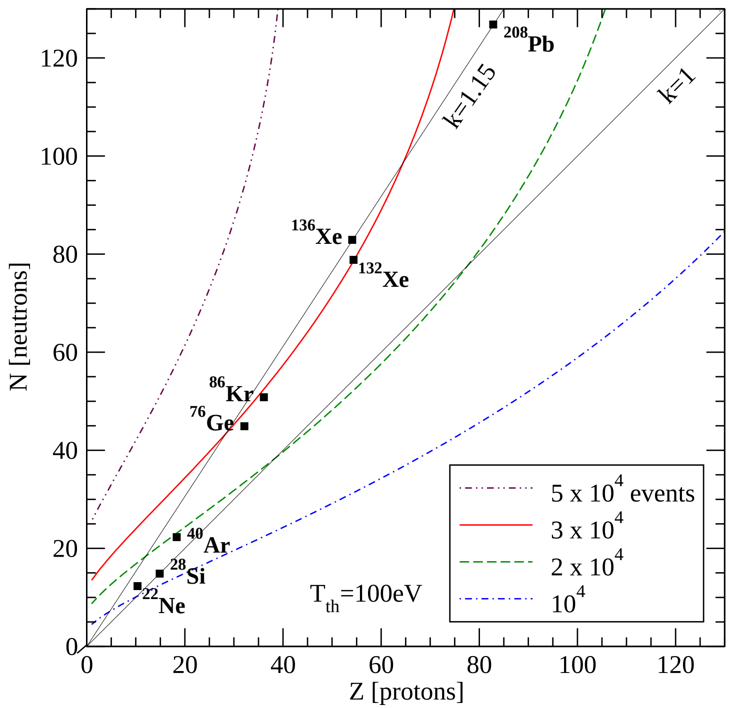
Resolving degeneracy

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

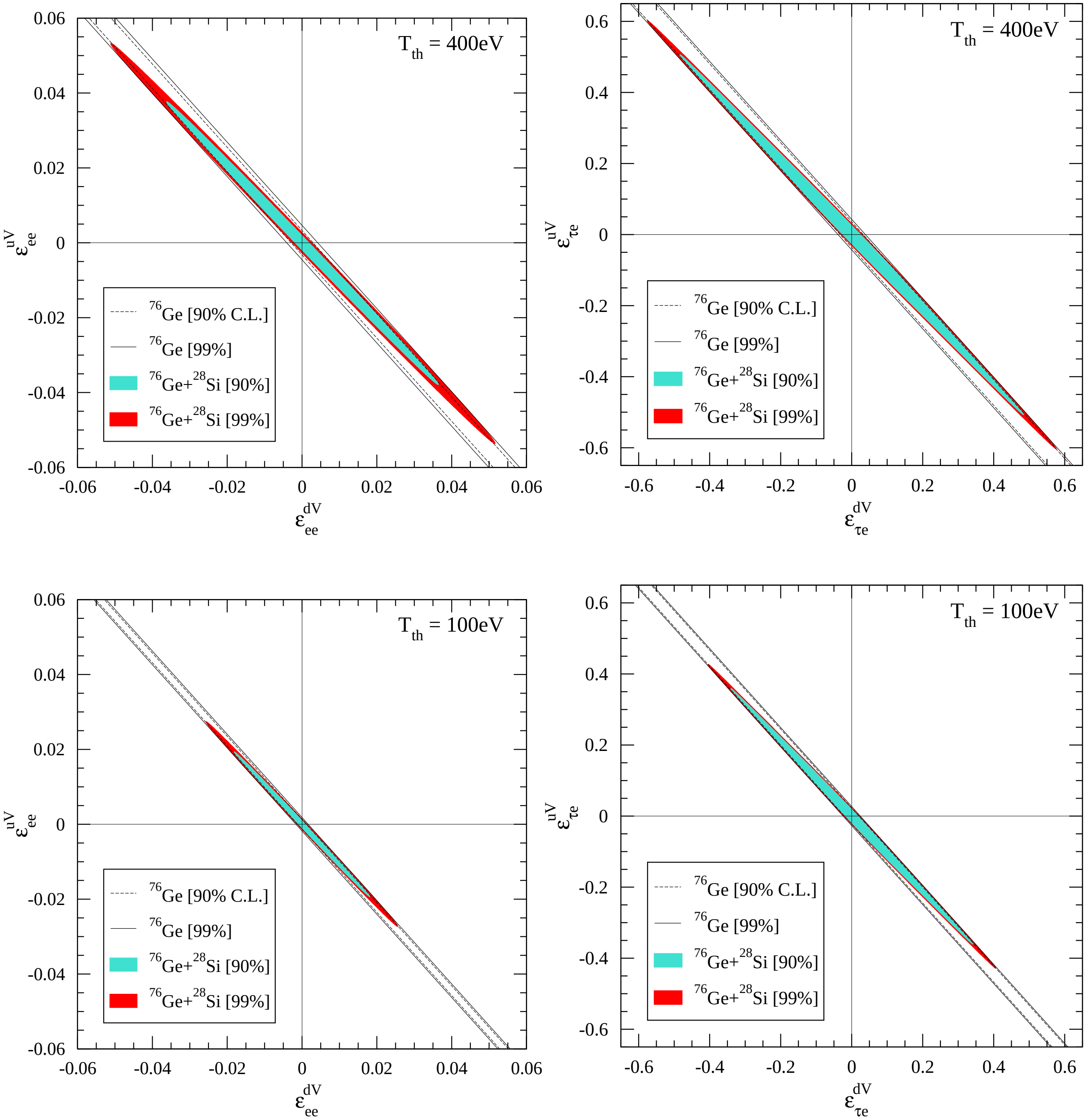
$$\varepsilon_{ee}^{uV}(A+Z) + \varepsilon_{ee}^{dV}(A+N) = \text{const}\,.$$

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





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



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

$$|\epsilon_{ee}^{dV}| < 0.036$$
$$|\epsilon_{ee}^{uV}| < 0.038$$
$$|\epsilon_{\tau e}^{dV}| < 0.48$$
$$|\epsilon_{\tau e}^{uV}| < 0.50$$

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

$$|\epsilon_{ee}^{dV}| < 0.018$$
$$|\epsilon_{ee}^{uV}| < 0.019$$
$$|\epsilon_{\tau e}^{dV}| < 0.34$$
$$|\epsilon_{\tau e}^{uV}| < 0.37$$

Present and future bounds on NSI

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

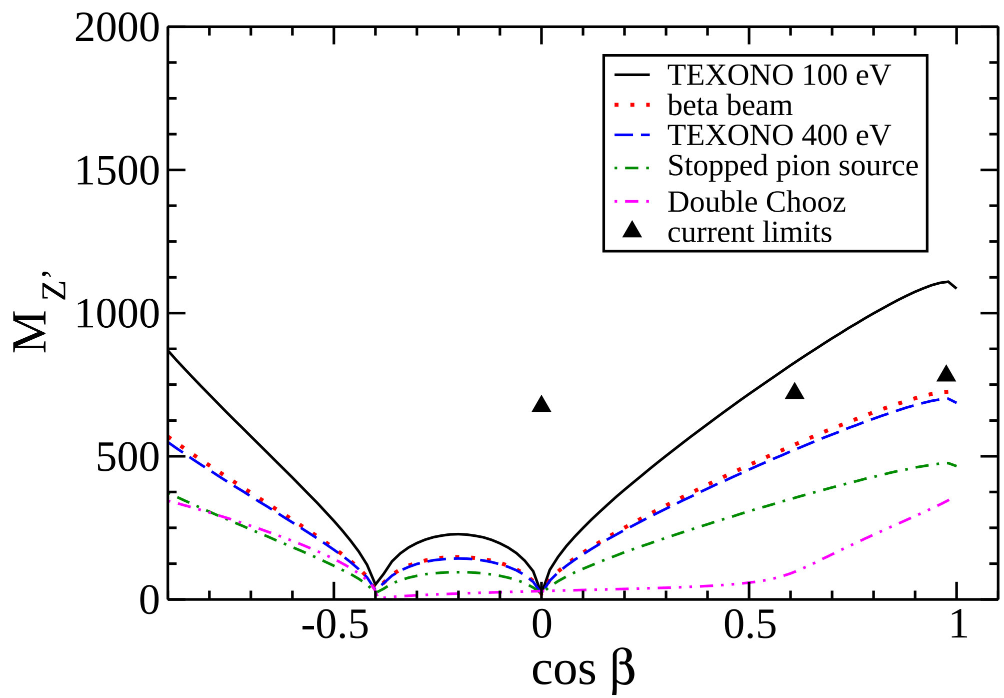
	Present Limits	ν Factory	^{76}Ge $T_{th}=400eV$ (^{76}Ge $T_{th}=100eV$)	^{76}Ge+^{28}Si $T_{th}=400eV$ (^{76}Ge+^{28}Si $T_{th}=100eV$)
ϵ_{ee}^{dV}	$-0.5 < \epsilon_{ee}^{dV} < 1.2$	$\lvert\epsilon_{ee}^{dV}\rvert < 0.002$	$\lvert\epsilon_{ee}^{dV}\rvert < 0.003$ ($\lvert\epsilon_{ee}^{dV}\rvert < 0.001$)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

Extra heavy neutral gauge boson Z'

See Gonzalez-Garcia & Valle'90

$$\varepsilon_{ee}^{uL} = \varepsilon_{ee}^{dL} = -\varepsilon_{ee}^{uR} = -4\gamma \sin^2\theta_W \rho_{\nu N}^{NC} \left(\frac{c_\beta}{\sqrt{24}} - \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6}\sqrt{\frac{5}{8}}\right)$$

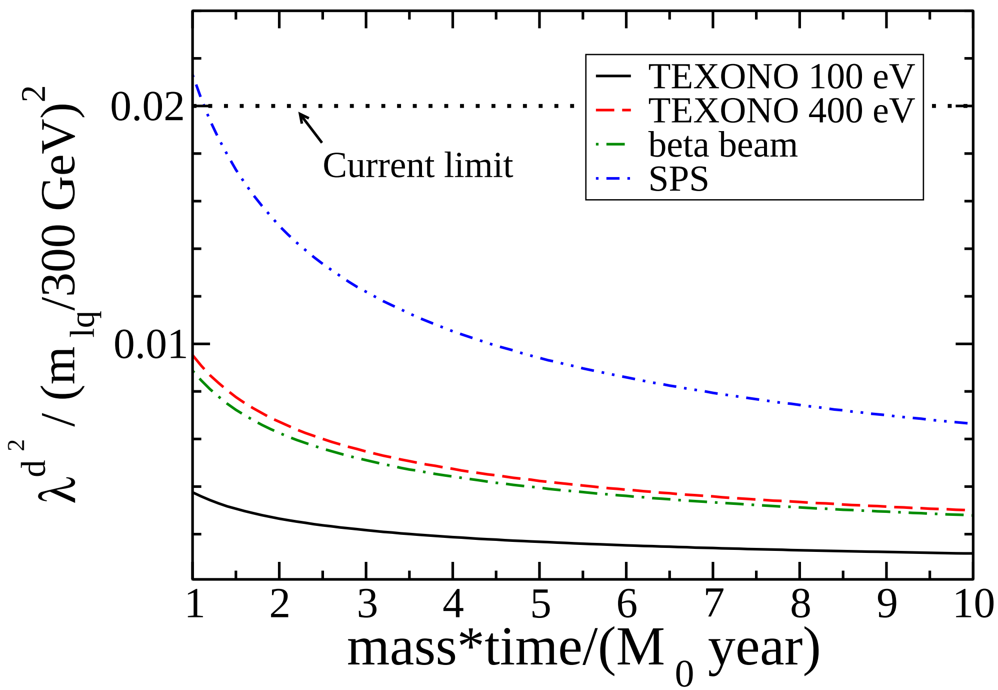
$$\varepsilon_{ee}^{dR} = -8\gamma \sin^2\theta_W \rho_{\nu N}^{NC} \left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6}\sqrt{\frac{5}{8}}\right)^2, \quad \gamma = (M_Z/M_{Z'})^2$$



Leptoquark

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

See Davidson et al'94



In some models leptoquark can be light

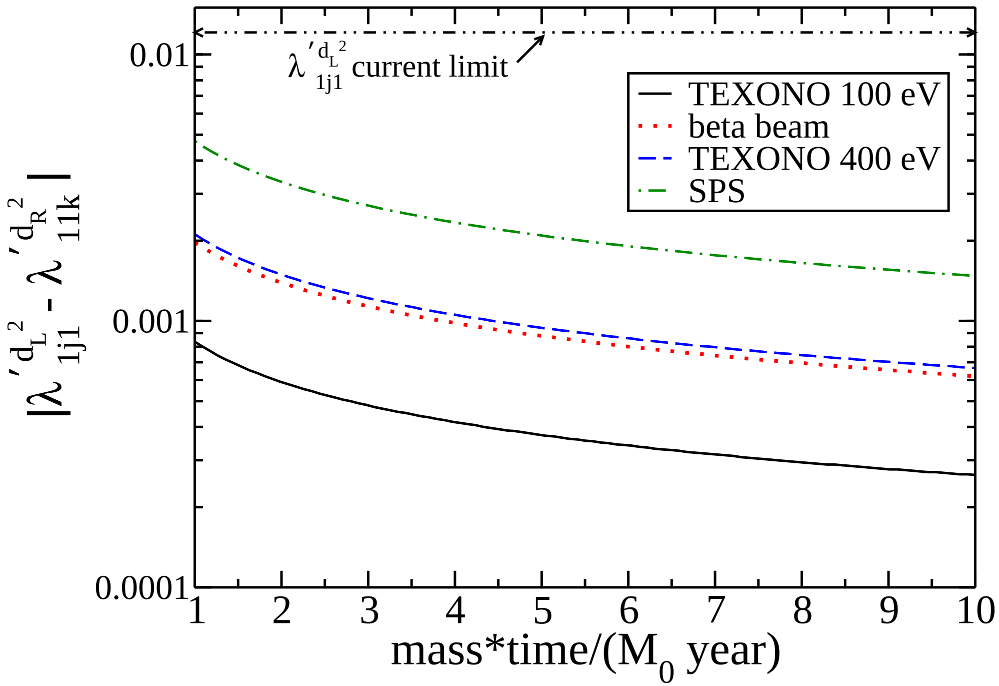
See Dorsner et al'05

SUSY with broken R-parity

R-parity violating MSSM (imposing baryon number conservation) with a superpotential that contains the following L- violating terms:

See Barger et al'89

$$\lambda_{ijk} L_L^i L_L^j \bar{E}_R^k, \quad \lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k$$



Conclusions

- Non-standard interactions in the neutrino sector are predicted in models beyond the SM and can be rather large
- NSI can play significant role in astrophysical environments
- Coherent neutrino scattering off nuclei gives a new sensitive probe to ν-quark vector couplings
- Degeneracy in determination of NSI parameters can be successfully resolved by taking two different targets
- Estimated sesnitivity to NSI couplings is comparable and better than those expected from future ν-Factory

neutrino-nuclei scattering

	^{76}Ge+^{28}Si $_{T_{th}=400eV}$	^{76}Ge+^{28}Si $_{T_{th}=100eV}$
ϵ_{ee}^{dV}	$\|\epsilon_{ee}^{dV}\| < 0.036$	$\|\epsilon_{ee}^{dV}\| < 0.018$
ϵ_{ee}^{uV}	$\|\epsilon_{ee}^{uV}\| < 0.038$	$\|\epsilon_{ee}^{uV}\| < 0.019$
$\epsilon_{\tau e}^{dV}$	$\|\epsilon_{\tau e}^{dV}\| < 0.48$	$\|\epsilon_{\tau e}^{dV}\| < 0.34$
$\epsilon_{\tau e}^{uV}$	$\|\epsilon_{\tau e}^{uV}\| < 0.50$	$\|\epsilon_{\tau e}^{uV}\| < 0.37$
ϵ_{ee}^{dV}	$-0.002 < \epsilon_{ee}^{dV} < 0.034$	$-0.0009 < \epsilon_{ee}^{dV} < 0.016$
$\epsilon_{\tau e}^{dV}$	$\|\epsilon_{\tau e}^{dV}\| < 0.1$	$\|\epsilon_{\tau e}^{dV}\| < 0.074$

NSI with d-quark only

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