Constraining neutrino properties with low energy experiments

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Abstract

It is shown that coherent neutrino scattering off nuclei may be very sensitive to non-standard interactions of neutrinos with quarks and might set better constraints than those expected from future neutrino factory experiments.

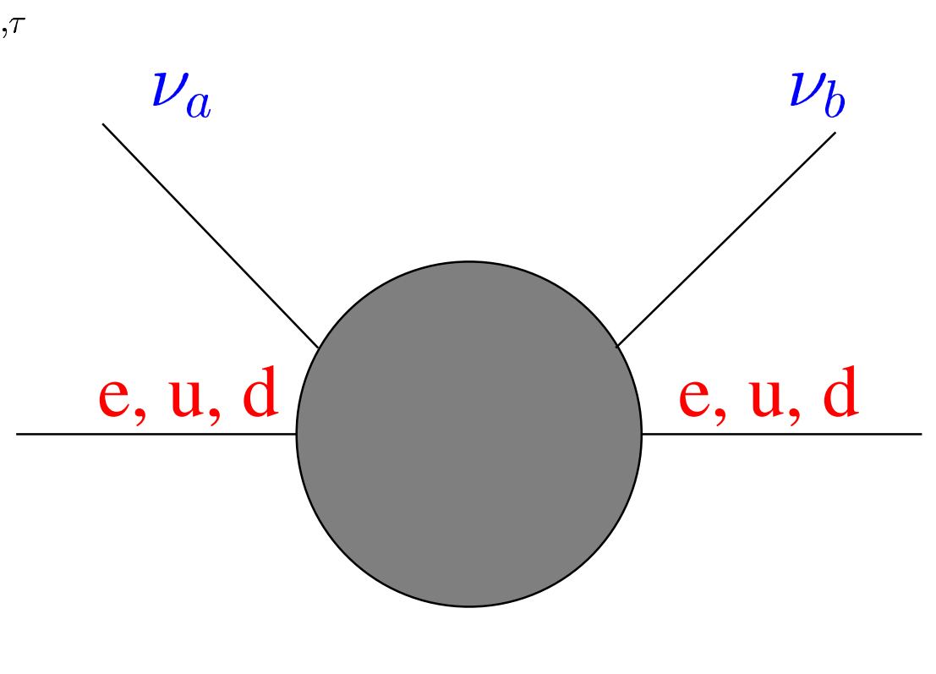
We study and compare the sensitivities of future low energy neutrino experiments to extra neutral gauge bosons, leptoquarks and R-parity breaking interactions. We found that the expected sensitivity for most of the future low energy experimental setups is better than the present constraints.

We have obtained a new limit on the electron neutrino effective charge radius from a new evaluation of the weak mixing angle by a combined fit of all electron-(anti)neutrino electron elastic scattering measurements.

ν 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)

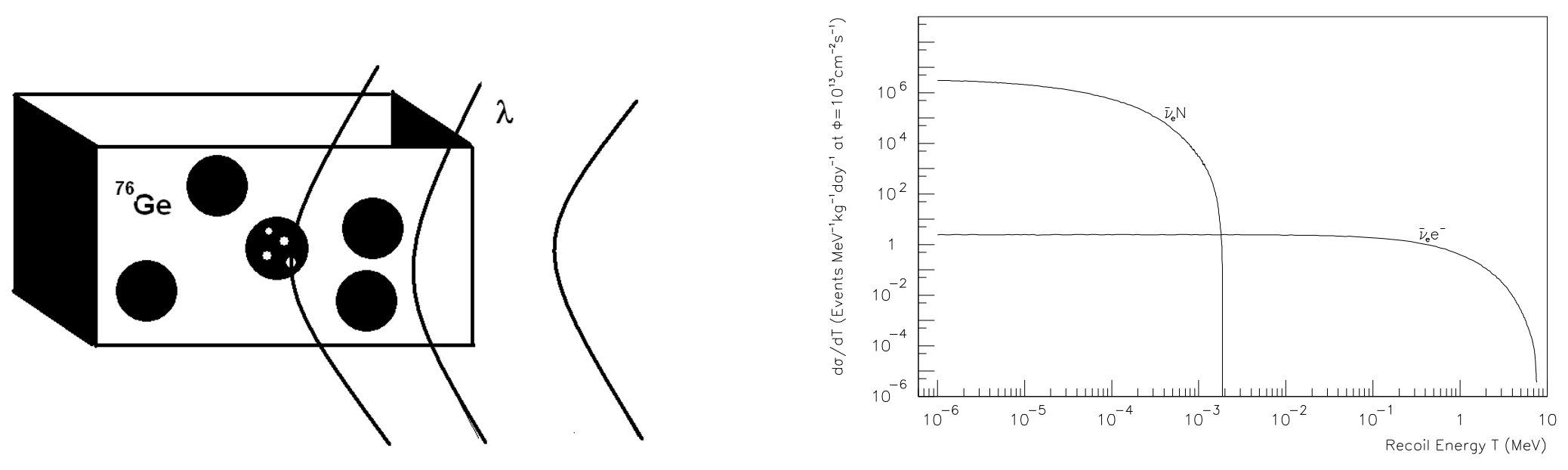
$$\mathcal{L}^{NSI}_{\nu f} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{f=e,u,d\\ \alpha,\beta=e,\mu,\tau}} \left[\bar\nu_\alpha\gamma^\mu(1-\gamma^5)\nu_\beta\right]\left(\varepsilon^{fL}_{\alpha\beta}\left[\bar f\gamma_\mu(1-\gamma^5)f\right]+\varepsilon^{fR}_{\alpha\beta}\left[\bar f\gamma_\mu(1+\gamma^5)f\right]\right)$$



Coherent νN scattering

- 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: TEXONO, CLEAR …and other proposals
- Experimentally difficult: very low energy threshold

figure by H.Wong



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

$$\begin{aligned} G_V &= \left[\left(g_V^p+2\varepsilon^{uV}_{ee}+\varepsilon^{dV}_{ee}\right)Z+\left(g_V^n+\varepsilon^{uV}_{ee}+2\varepsilon^{dV}_{ee}\right)N\right]F^V_{nucl}(Q^2)\\ G_A &= \left[\left(g_A^p+2\varepsilon^{uA}_{ee}+\varepsilon^{dA}_{ee}\right)(Z_+-Z_-)+\left(g_A^n+\varepsilon^{uA}_{ee}+2\varepsilon^{dA}_{ee}\right)(N_+-N_-)\right]F^A_{nucl}(Q^2)\end{aligned}$$

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

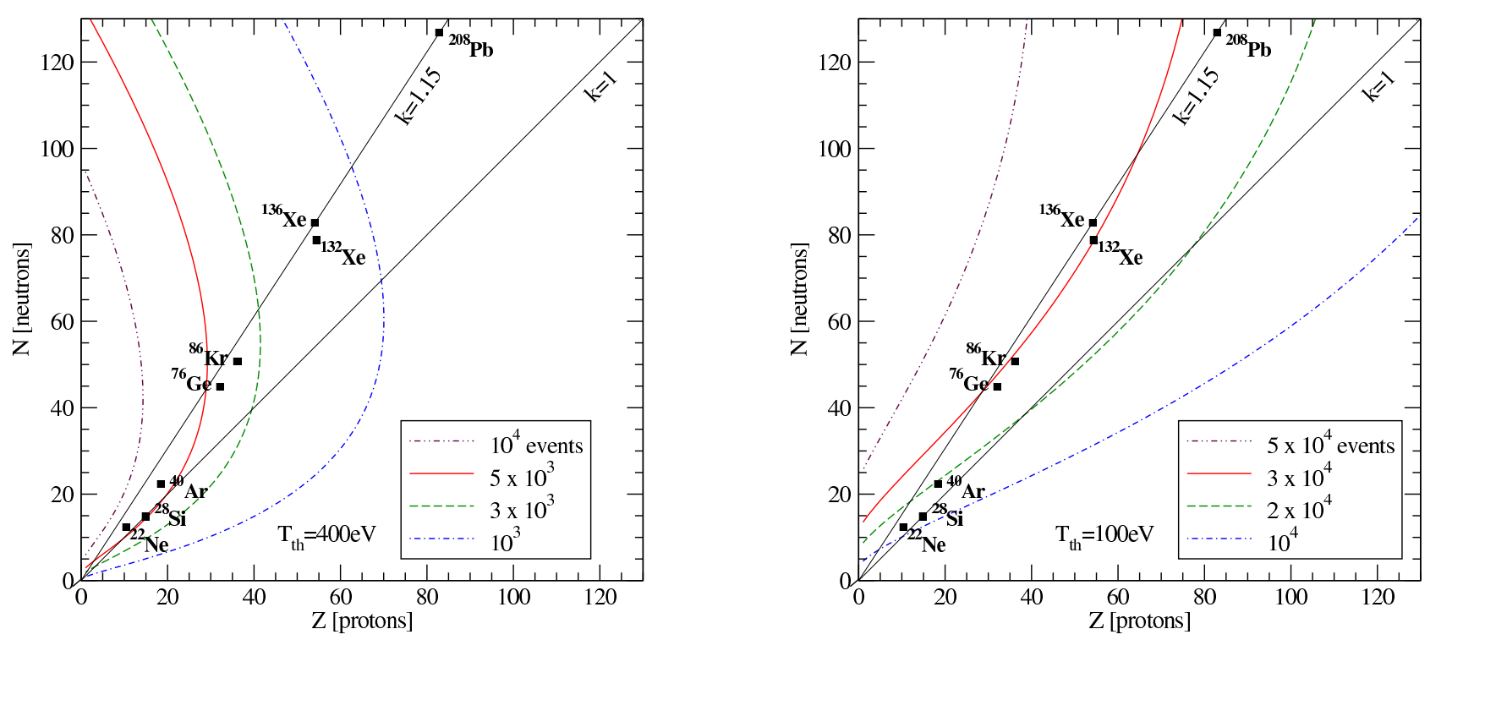
- Axial couplings contribution is zero (for even-even nuclei) or can be neglected
- Degeneracy in determination of NSI parameters

Degeneracies

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

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

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



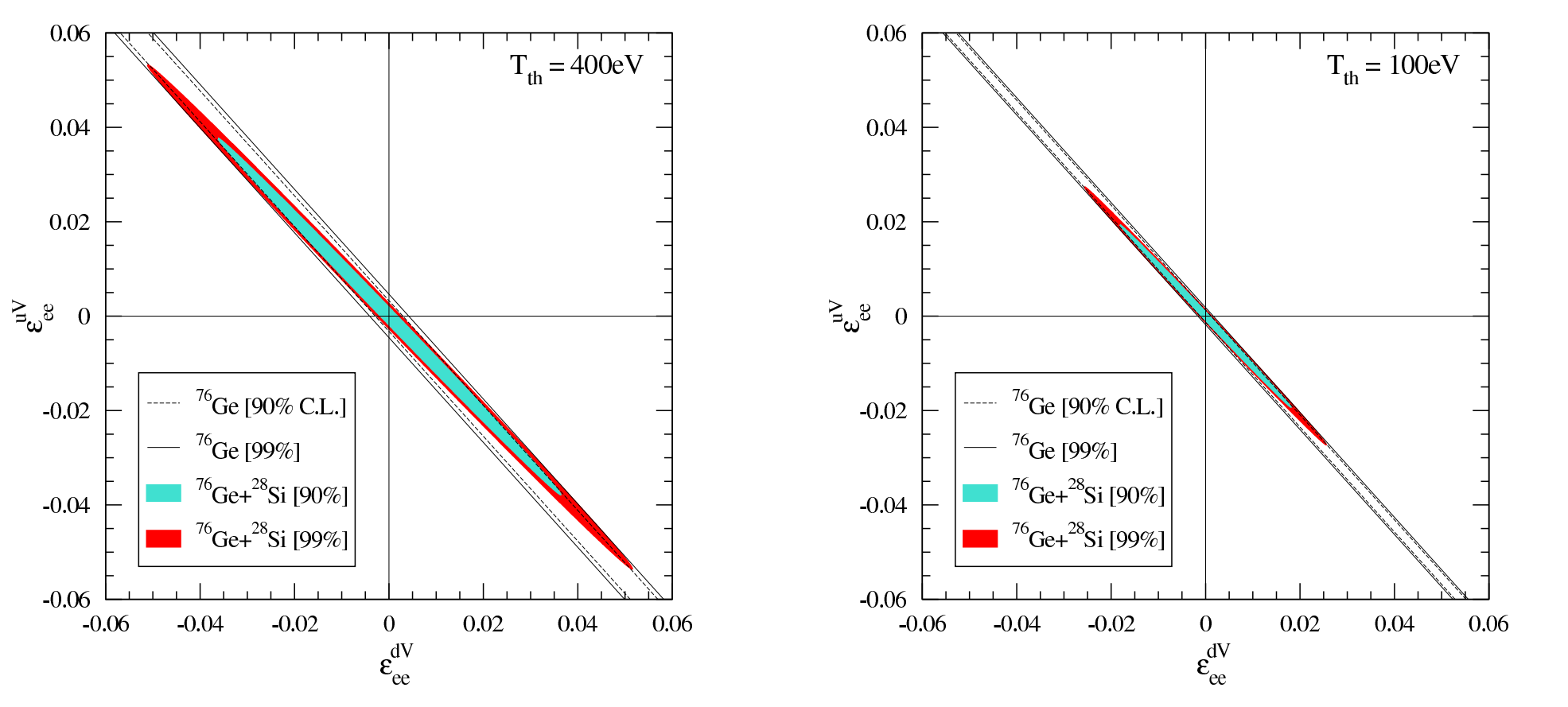
Coherent scatt exp-s

- TEXONO: see poster by Henry Wong, "Sub-keV Neutrino and Dark Matter Physics with Ultra-Low-Energy Germanium Detector",
- CLEAR: see poster by Kate Scholberg, "Prospects for a Low Threshold Neutrino Experiment at the SNS",
- Micropatterned gaseous detectors: see talk by Juan Collar, "Coherent neutrino scattering",
- NOSTOS, spherical TPC detector, 10 ton of Xenon, astro-ph/0511470,
- beta-beams with low energy threshold detector: Bueno et al, PRD'06,
- more ideas in the past: superconducting detector (Drukier & Stodolsky'84), acoustic (Krauss'91), cryogenic (Oberauer'02).

Future sensitivity

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

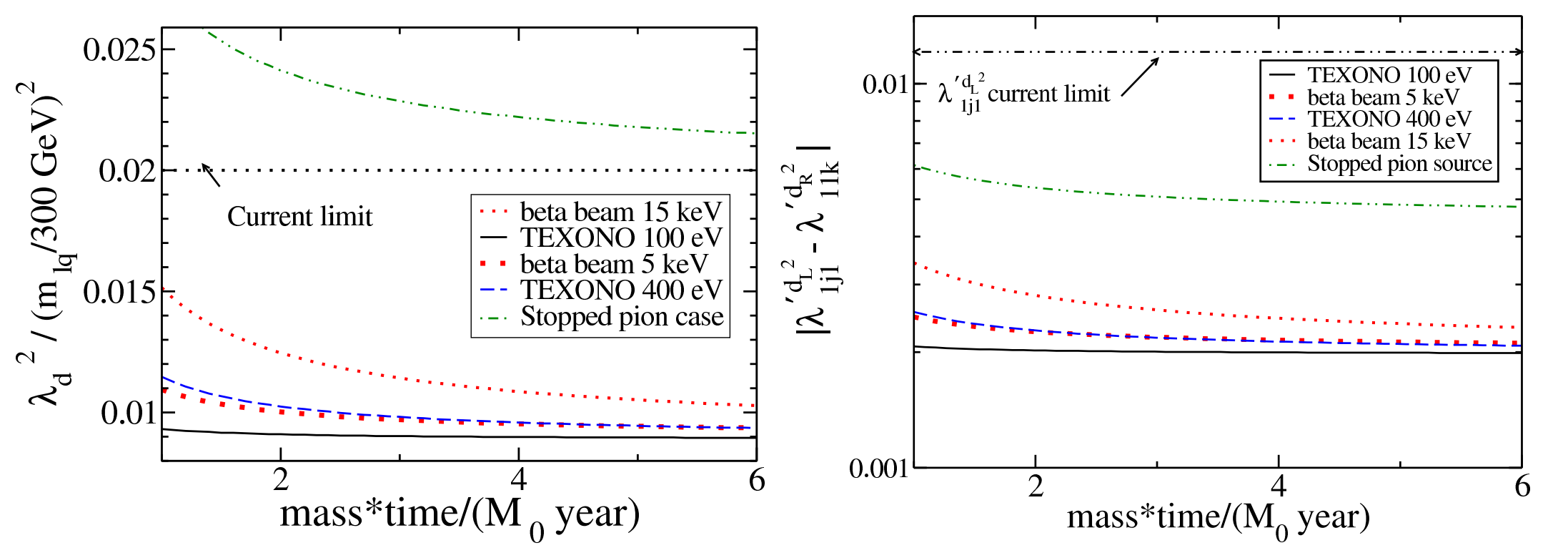
	Present Limits	ν Factory	^{76}Ge $_{T_{th}=400eV}$ (^{76}Ge $_{T_{th}=100eV}$)	^{76}Ge+^{28}Si $_{T_{th}=400eV}$ (^{76}Ge+^{28}Si $_{T_{th}=100eV}$)
ε^{dV}_{ee}	$-0.5<\varepsilon^{dV}_{ee}<1.2$	$\lvert\varepsilon^{dV}_{ee}\rvert<0.002$	$\lvert\varepsilon^{dV}_{ee}\rvert<0.003$ $(\lvert\varepsilon^{dV}_{ee}\rvert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



The allowed regions of non-universal NSI parameters ε^{uV}_{ee} and ε^{dV}_{ee} are shown at 90 and 99% C.L. for combined data from two detectors of ^{28}Si and ^{76}Ge (colored regions) and only for ^{76}Ge (solid and dashed lines). It was assumed 1 kg mass and 1 year of data taking for both detectors, only statistical errors are taken into account. The results presented for two values of threshold, $T_{th}=400$ eV (left) and 100 eV (right panel).

Leptoquark and and R-parity broken SUSY

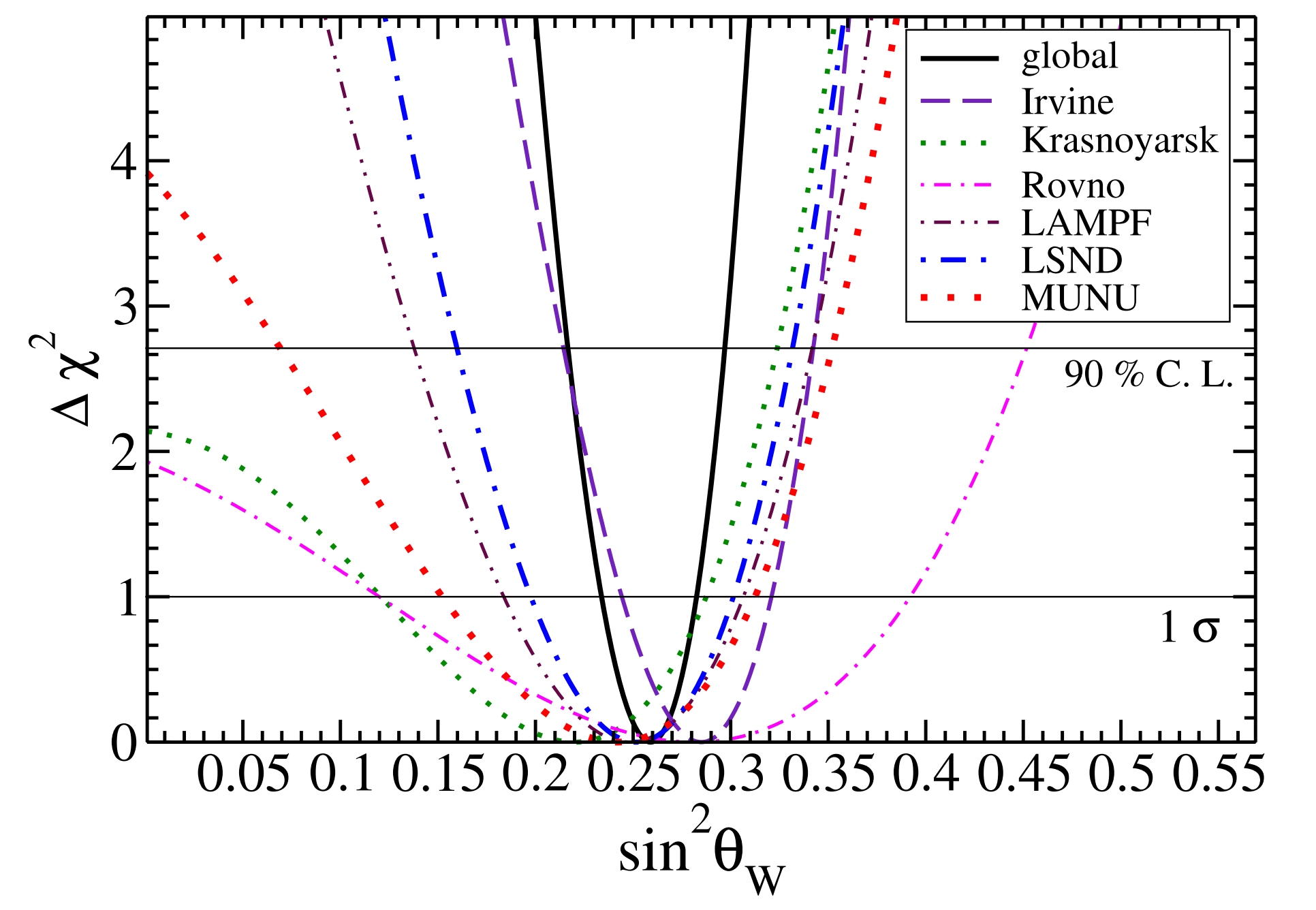
Sensitivity, at 95 % C. L. to a vector leptoquark coupling (left panel) to neutral current R-parity breaking terms (right panel) for different experimental setups. The limit on the coupling λ_d will depend on the leptoquark mass m_{lq} that here is chosen to be 300 GeV in agreement with current literature. The dependence on the size of the detector and time of running is also shown.



ν_e-e scattering data

Experiment	Energy	Events	Measurement, σ	$\sin^2\theta_W$, 90% C.L.	$\langle r^2_{\nu_e}\rangle >$	$\langle r^2_{\nu_e}\rangle <$
LAMPF	7-60	236	$[10.0\pm1.5\pm0.9]E_{\nu_e}\cdot10^{-45}\text{cm}^2$	0.249 ± 0.063	-3.56	5.44
LSND	10-50	191	$[10.1\pm1.5]\cdot E_{\nu_e}\cdot10^{-45}\text{cm}^2$	0.248 ± 0.051	-2.97	4.14
Irvine {	1.5-3.0	381	$[0.86\pm0.25]\cdot\sigma_{V-A}$	} 0.29 ± 0.05	N/A	N/A
	3.0-4.5	77	$[1.7\pm0.44]\cdot\sigma_{V-A}$			
Krasnoyarsk	3.15-5.175	N/A	$[4.5\pm2.4]\cdot10^{-46}\text{cm}^2/\text{fission}$	$0.22^{+0.7}_{-0.8}$	-7.3	7.3
Rovno	0.6-2.0	41	$[1.26\pm0.62]\cdot10^{-44}\text{cm}^2/\text{fission}$	N/A	N/A	N/A
MUNU	0.7-2.0	68	1.07 ± 0.34 events day^{-1}	N/A	N/A	N/A
Global				0.259 ± 0.025	-0.13	3.32

$\sin^2\theta_W$ from ν_e-e data



$\Delta\chi^2$ for weak mixing angle obtained from all $\nu_e e$ and $\bar\nu_e e$ elastic scattering experiments (Irvine, Krasnoyarsk, Rovno, LAMPF, LSND, MUNU) are plotted.
The new value of the weak mixing angle in the low energy range (below 100 MeV):

$$\sin^2\theta_W = 0.259\pm0.025$$

This value is 1.45 standard deviations larger than the value of the weak mixing angle obtained from a global fit to electroweak measurements without neutrino-nucleon scattering data, $\sin^2\overline{\theta_W}=0.2227\pm0.00037$ [NuTeV, PRL, **88**, 091802 (2002)]

ν_e charge radius $\langle r^2_{\nu_e}\rangle$

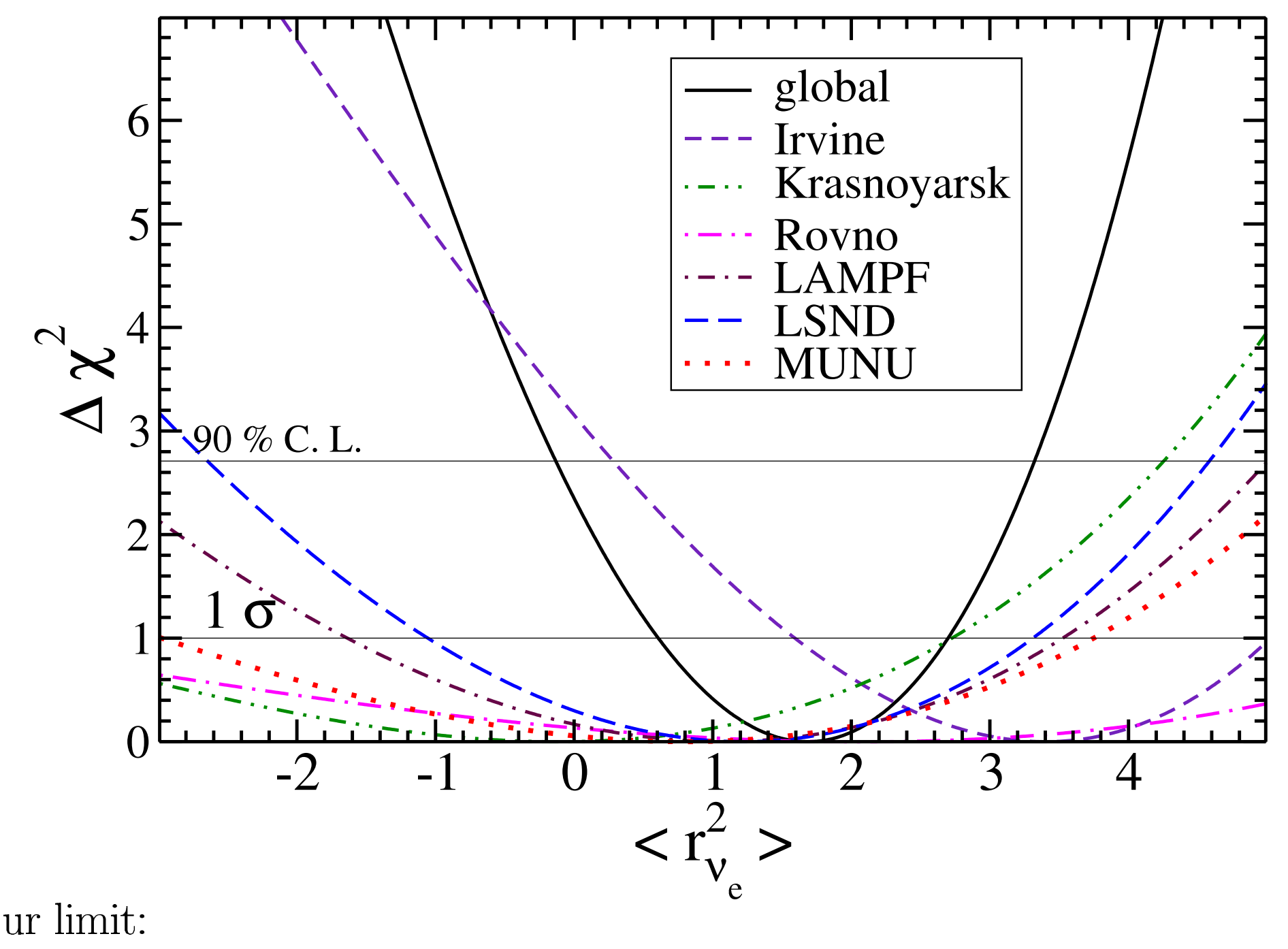
We follow effective approach denoting

$$g_V = 1/2+2\sin^2\theta_W+(2\sqrt{2}\pi\alpha/3G_F)\langle r^2_{\nu_e}\rangle\,,$$

This expression translates into an effective displacement in the value of the weak mixing angle $\sin^2\theta_W=\sin^2\overline{\theta_W}+\delta$ with the radiative correction

$$\delta=(\sqrt{2}\pi\alpha/3G_F)\langle r^2_{\nu_e}\rangle = 2.3796\times10^{30}\ \text{cm}^2\times\langle r^2_{\nu_e}\rangle$$

Besides the standard tree-level amplitude and the $\langle r^2_{\nu_e}\rangle_{SM}$ contribution, one should keep in mind that the full neutrino-electron scattering amplitude in one-loop approximation contains additional terms: the photon-Z mixing term and the box diagrams involving W and Z bosons. Therefore, in a single process experiment like the one considered in our paper, one cannot separate and measure different contributions. Potentially this can be done by combining data from several neutrino-electron and neutrino-neutrino scattering processes.



Our limit:

$$-0.13\times10^{-32}\text{cm}^2<\langle r^2_{\nu_e}\rangle<3.32\times10^{-32}\text{cm}^2\quad\text{at 90\% C.L.,}$$

$$\langle r^2_{\nu_e}\rangle = 1.69^{+1.01}_{-1.09}\times10^{-32}\text{cm}^2\quad\text{for }1\sigma\text{ deviation}$$

PDG limit (based on LSND only): "a more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering"

$$-2.07\times10^{-32}\text{cm}^2<\langle r^2_{\nu_e}\rangle<4.14\times10^{-32}\text{cm}^2\quad\text{at 90\% C.L.,}$$

Theoretical SM prediction (Bernabeu et al, PRD, 2000):

$$\langle r^2_{\nu_e}\rangle_{SM}=\langle r^2_{\nu_i}\rangle_{SM}=\frac{G_F}{4\sqrt{2}\pi^2}\left[3-2\log\left(\frac{m_i^2}{m_W^2}\right)\right]\approx0.4\times10^{-32}\ \text{cm}^2\,.$$

Summary

- Neutrino coherent scattering off nuclei has a lot of potential to make precision tests of new physics, not only in the case of a non-zero neutrino magnetic moment as had already been studied in the literature, but also to test non-standard neutrino interactions.
- The weak mixing angle with 10% precision at energies below 100 MeV from (anti)neutrino electron scattering off electrons was recently obtained. To get this result the combined set of all available data from accelerator (LSND and LAMPF) and reactor (Irvine, Rovno, Krasnoyarsk and MUNU) experiments was used. This analysis was also applied to set a new limit to the electron neutrino effective charge radius squared which improves previous bounds.
- Future reactor experiments with the estimated precision of $\delta(\sin^2\theta_W)\sim1\%$ will be able to find a strong evidence for theoretically predicted electron neutrino effective charge radius.