New Physics Searches with ^{7}Be Solar Neutrinos

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Played a significant role in the Borexino experiment & the initiator & driving force behind our work

Constraining Non-Standard Interactions of the Neutrino with Borexino:

Agarwalla, Lombardi and Takeuchi

arXiv:1207.3492v1 [hep-ph]

Non-Standard Interactions (NSIs) of the Neutrino

- Various extensions of the Standard Model, such as L-R symmetric models and SUSY models with RPV, predict NSIs of the ν with other fermions

- These NSIs are generated via the exchange of new massive particles and at low-energies can be described by effective four fermion operators

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F\, \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

Wolfenstein, Grossman, Guzzo, Berezhiani-Rossi, Davidson, Berger et al.,

- $\varepsilon_{\alpha\beta}^{ff'C}$: dimensionless number, parameterizes the strength of NSI

- $\epsilon_{\alpha\beta} \propto \frac{m_W^2}{m_X^2}$: If New Physics scale ~ 1 (10) TeV, $\varepsilon_{\alpha\beta} \sim 10^{-2}$ (10^{-4})

Non-renormalizable & not gauge invariant, break $SU(2)_L$ gauge symmetry explicitly

- In $\nu_\alpha e$ elastic scattering with flavor diagonal NSI parameters we can write

$$\varepsilon_{\alpha L} \equiv \varepsilon_{\alpha\alpha}^{eeL}\,, \qquad \varepsilon_{\alpha R} \equiv \varepsilon_{\alpha\alpha}^{eeR}\,, \qquad \alpha = e, \mu \text{ or } \tau$$

Neutrino-Electron Elastic Scattering

- Described at low energies by the effective four fermion interaction:

$$\mathcal{L}_{\rm SM} = -2\sqrt{2}\, G_F (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha) \Big[g_{\alpha L} (\bar{e}\gamma_\mu P_L e) + g_{\alpha R} (\bar{e}\gamma_\mu P_R e) \Big]$$

At tree level, $g_{e/\mu/\tau R} = \sin^2\theta_W$, $g_{eL} = \sin^2\theta_W + ½$ (W, Z) & $g_{\mu/\tau L} = \sin^2\theta_W - ½$ (only Z)

- Presence of flavor-diagonal NSIs, $\varepsilon_{\alpha L/R}$, will shift the coupling constants

$$g_{\alpha L} \to \tilde{g}_{\alpha L} = g_{\alpha L} + \varepsilon_{\alpha L}\,, \qquad g_{\alpha R} \to \tilde{g}_{\alpha R} = g_{\alpha R} + \varepsilon_{\alpha R}$$

- Differential cross section for neutrino-electron scattering can be written as

$$\frac{d\tilde{\sigma}_{\nu_\alpha}(E_{\nu_\alpha}, T)}{dT} = \frac{2G_F^2 m_e}{\pi} \left[\tilde{g}_{\alpha L}^2 + \tilde{g}_{\alpha R}^2 \left(1 - \frac{T}{E_{\nu_\alpha}}\right)^2 - \tilde{g}_{\alpha L}\tilde{g}_{\alpha R} \frac{m_e T}{E_{\nu_\alpha}^2} \right]$$

P. Vogel and J. Engel, Phys.Rev.D39 (1989) 3378

E_{ν_α} = Incoming neutrino energy and T = kinetic energy of the recoil electron

$$0 \le T \le T_{\rm max} = \frac{E_{\nu_\alpha}}{1 + m_e/2E_{\nu_\alpha}}$$

For 0.862 MeV neutrino, T_{max} = 0.665 MeV

Testing NSI @ Borexino

- First suggested by Z. Berezhiani and A. Rossi in 1995 that Borexino can play a vital role in disentangling the Neutrino NSI when Borexino was a proposal

Z. Berezhiani and A. Rossi, Phys.Rev.D51 (1995) 5229

- Later in 2002, Raghavan, together with Berezhiani and Rossi, discussed the potential of the Borexino detector in placing constraints on the flavor diagonal NSI parameters via the measurement of the electron recoil spectrum

Z. Berezhiani, R. Raghavan and A. Rossi, Nucl.Phys.B638 (2002) 62

- In this publication, they argued that due to the mono-energetic nature of the ^{7}Be solar neutrinos, Borexino would be able to place stronger constraints on ε_{eR} and $\varepsilon_{\tau R}$ compared to SK and SNO where they observe ^{8}B neutrinos with a continuous energy spectrum

- Today, a decade later, with more than 153.6 ton.years of data of Borexino, it is now possible to actually extract the constraints on these NSI parameters

Bounds on NSI from other neutrino experiments

- Bounds given using the solar ν experiments like SK, SNO, and KamLAND

Davidson, Pena-Garay, Rius, Santamaria, JHEP 0303 (2003) 011
Barranco, Miranda, Moura, Valle, Phys.Rev.D73 (2006) 113001
Bolonas, Miranda, Palazzo, Tortola, Valle, Phys.Rev.D79 (2009) 113012

- Bounds from LEP+(LSND+CHARM II)+(Irvine+Rovno+MUNU)

Barranco, Miranda, Moura, Valle, Phys.Rev.D77 (2008) 093014

- Constraints from atmospheric neutrinos

Friedland, Lunardini and Maltoni, Phys.Rev.D70 (2004) 111301

- Bounds using the data from MINOS

Friedland and Lunardini, Phys.Rev.D74 (2006) 033012

- New bounds from the TEXONO reactor experiments

TEXONO Collaboration, Phys.Rev.D82 (2010) 033004

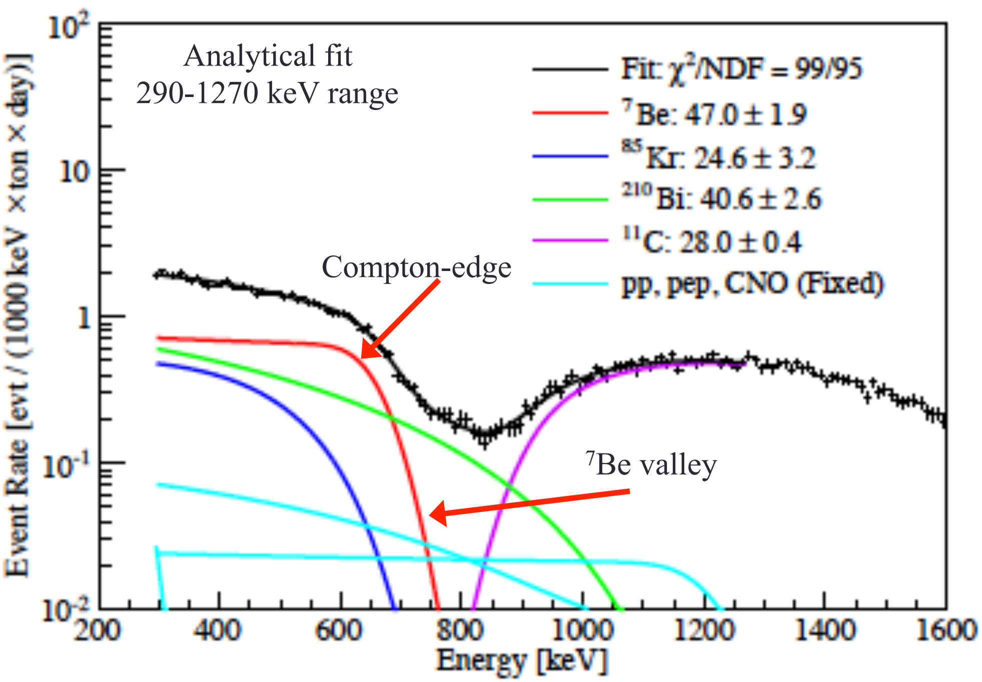
- CHARM-II experiment places strong constraints on $\varepsilon_{\mu L}$ and $\varepsilon_{\mu R}$

CHARM-II Collaboration, Phys.Lett.B335 (1994) 246

$$|\varepsilon_{\mu L/R}| < 0.03 \text{ (at 90\% C.L.)}$$

The Borexino Experiment

- Real-time solar ν detector to observe 0.862 MeV mono-energetic ^{7}Be solar ν
- Fiducial volume consisting of the central 100 tons of Liquid Scintillator (C_9H_{12})
- Detection via scintillation light from the recoil electrons, spreading isotropically
- Very low energy threshold, excellent position reconstruction & energy resolution
- 16-05-2007 – 08-05-2010 : 740.7 live days of data, 153.6 ton.years of exposure



Average Fit Results [counts/(day.100 tons)]

^{7}Be	$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$
^{85}Kr	$31.2 \pm 1.7(\text{stat}) \pm 4.7(\text{syst})$
^{210}Bi	$41.0 \pm 1.5(\text{stat}) \pm 2.3(\text{syst})$
^{11}C	$28.5 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$

Phys.Rev.Lett. 107 (2011) 141302

The number of recoil electrons from 0.862 MeV (89.6%) ^{7}Be solar neutrino flux, detected in the energy bin $T_1 < T_A < T_2$ per unit time is given by

$$\frac{dN(T_1,T_2)}{dt} = \left[N_e \Phi^{0.862}_{^7\mathrm{Be}} P_{ee}\right] \int_{T_1}^{T_2} \frac{d\overline{\sigma}_{\nu_e}(T_A)}{dT_A}\, dT_A + \left[N_e \Phi^{0.862}_{^7\mathrm{Be}} (1-P_{ee}) c^2_{23}\right] \int_{T_1}^{T_2} \frac{d\overline{\sigma}_{\nu_\mu}(T_A)}{dT_A}\, dT_A + \left[N_e \Phi^{0.862}_{^7\mathrm{Be}} (1-P_{ee}) s^2_{23}\right] \int_{T_1}^{T_2} \frac{d\overline{\sigma}_{\nu_\tau}(T_A)}{dT_A}\, dT_A$$

where $\frac{d\overline{\sigma}_{\nu_\alpha}(T_A)}{dT_A} = \int_0^{T_{\max}} R(T_A,T)\, \frac{d\tilde{\sigma}_{\nu_\alpha}(T)}{dT}\, dT$ and $R(T_A,T) = \frac{1}{\sqrt{2\pi}\,\sigma(T)} \exp\left[-\frac{(T_A-T)^2}{2[\sigma(T)]^2}\right]$ with $\sigma(T) = \sigma_0 \left(\frac{T}{\mathrm{MeV}}\right)^{1/2}$ $\sigma_0 = 50\,\mathrm{keV}$

Superposition of all 3 flavors due to vacuum oscillations, MSW effect neglected below 1 MeV

$P_{ee} \approx 1 - \frac{1}{2}\sin^2(2\theta_{12})$ $P_{ee} = 0.57 \pm 0.01$ maximal mixing, $\sin^2\theta_{23} = 0.5$

Due to limited event-position resolution, an uncertainty of $^{+0.5}_{-1.3}\,\%$ in fiducial volume, affecting N_e

$\Phi^{0.862}_{^7\mathrm{Be}} = 4.48\,(1 \pm 0.07) \times 10^9\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 7% uncertainty in ^{7}Be flux (GS98 model)

Serenelli, Haxton, Pena-Garay, Astrophys.J. 743 (2011) 24

Beta-decay Backgrounds in Borexino

- In Borexino, it is impossible to distinguish between electrons from $\nu_\alpha e$ scattering and those from beta-decay of radioactive nuclei
- ^{85}Kr is there due to small air leak into the scintillator while filling the detector

$$^{85}\mathrm{Kr} \longrightarrow {}^{85}\mathrm{Rb} + e^- + \overline{\nu}_e \qquad (Q = 0.687\ \mathrm{MeV},\ t^{1/2} = 10.756\ \mathrm{years},\ 99.57\%)$$

- An independent measurement of ^{85}Kr background from the decay (0.43%)

$$^{85}\mathrm{Kr} \longrightarrow {}^{85\mathrm{m}}\mathrm{Rb} + e^- + \overline{\nu}_e \qquad (Q = 0.173\ \mathrm{MeV})$$

$$^{85\mathrm{m}}\mathrm{Rb} \longrightarrow {}^{85}\mathrm{Rb} + \gamma \qquad (Q = 0.514\ \mathrm{MeV},\ t^{1/2} = 10^{-6}\ \mathrm{s})$$

- Delayed coincidence measurements of β and γ from the above decay chain has yielded

$$^{85}\mathrm{Kr}\ :\ 30.4 \pm 5.3(\mathrm{stat}) \pm 1.3(\mathrm{syst})\ \mathrm{counts}/(\mathrm{day} \cdot 100\,\mathrm{tons})$$

~ ±18% uncertainty

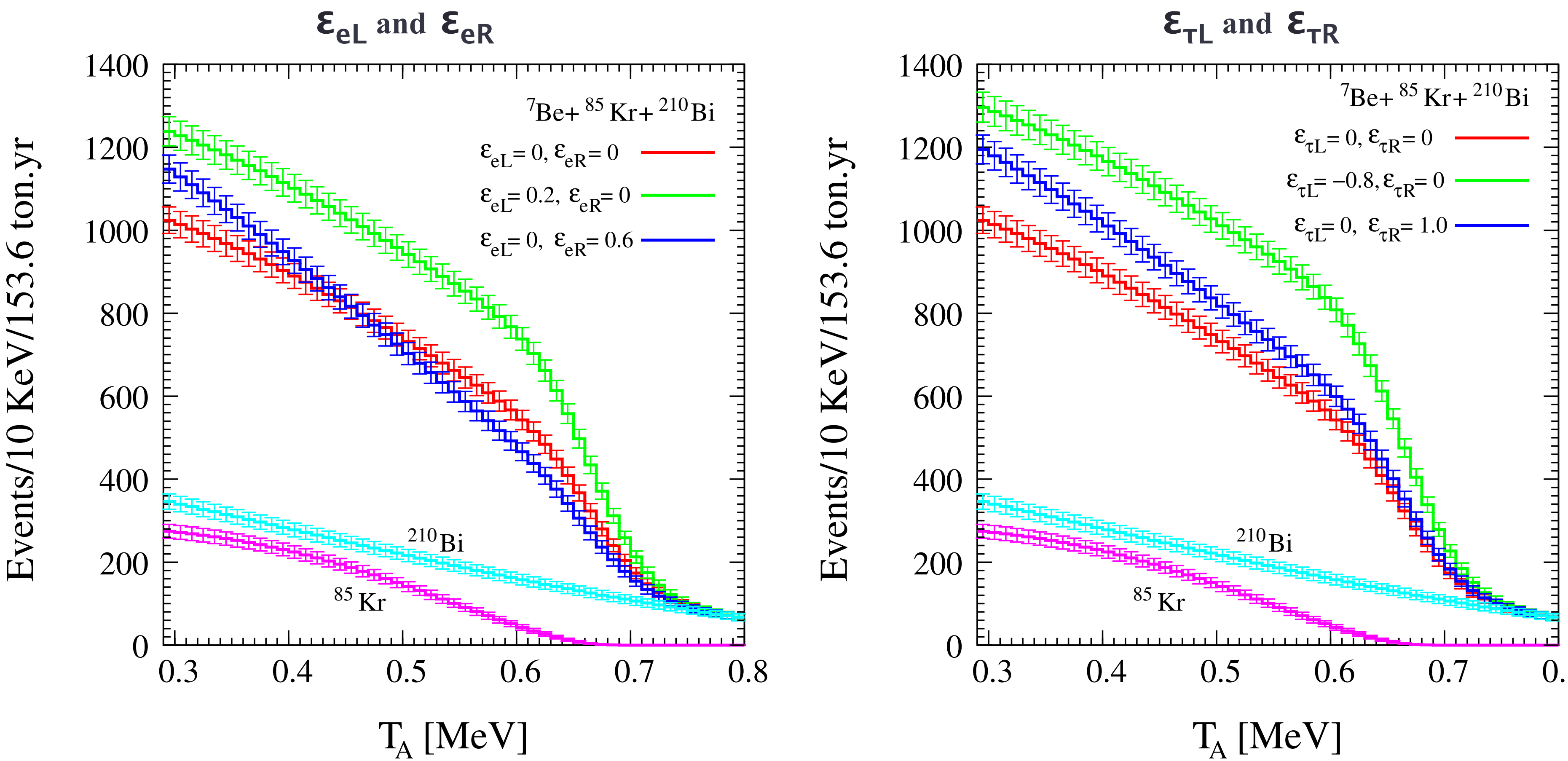
- Another background is ^{210}Bi, a pure β-emitter produced at the end of ^{222}Rn decay chain

$$^{210}\mathrm{Bi} \longrightarrow {}^{210}\mathrm{Po} + e^- + \overline{\nu}_e \qquad (Q = 1.161\ \mathrm{MeV},\ t^{1/2} = 5.012\ \mathrm{days},\ 100\%)$$

- There is no reliable independent measurement of ^{210}Bi. We keep it free in the fit

Event Spectrum with NSI

7Be: 14350 events, **85Kr:** 5813 events, **210Bi:** 10057 events

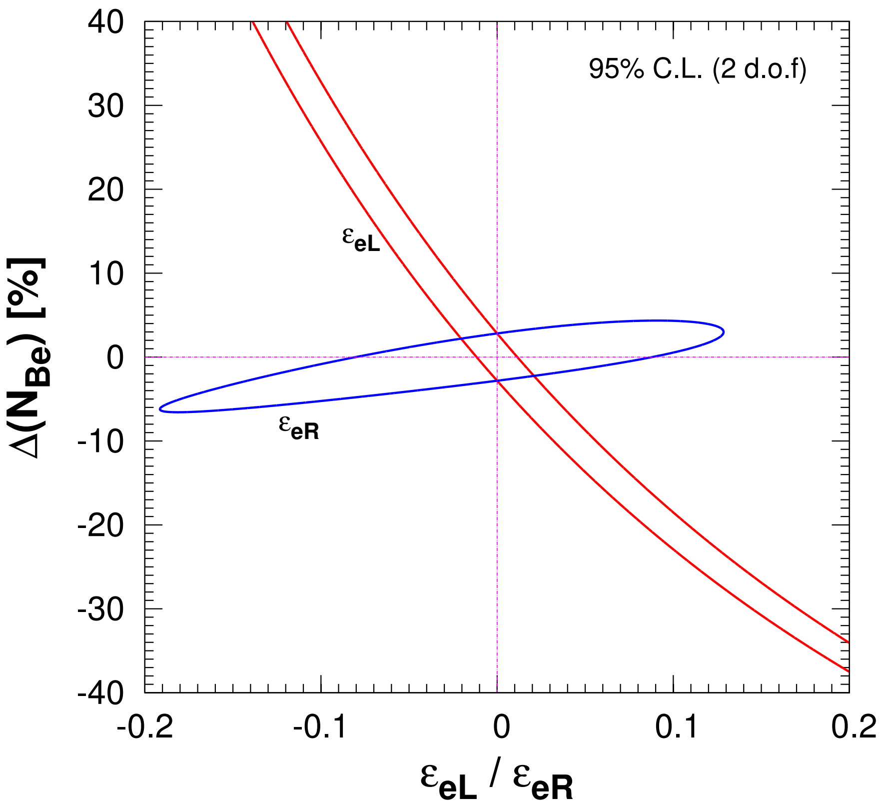


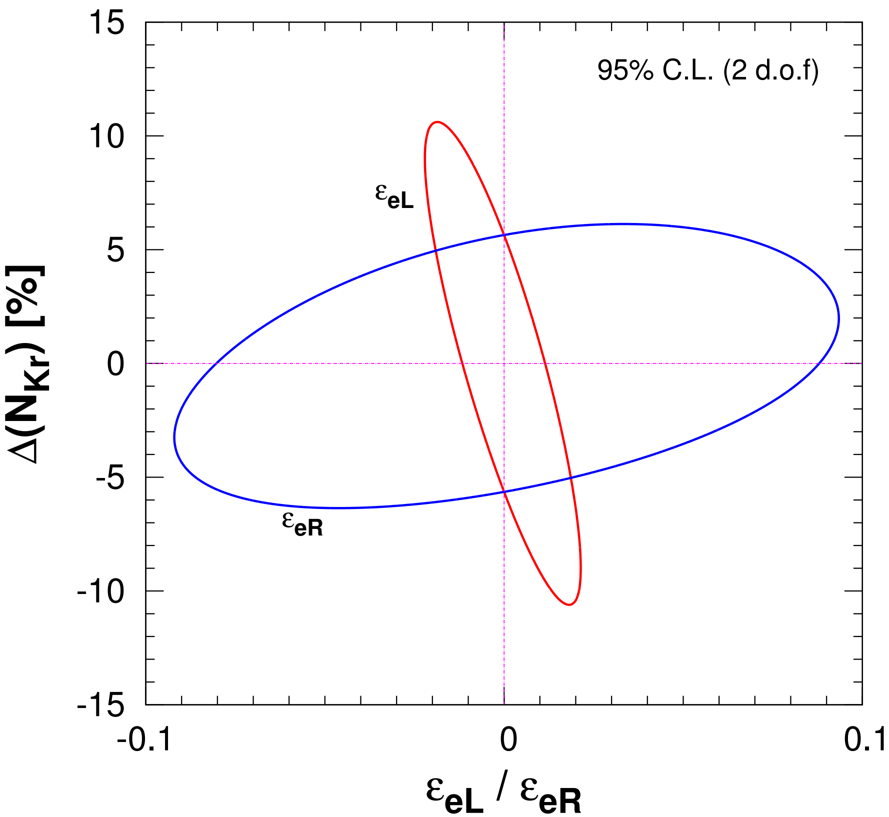
Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

Left-handed couplings affect the overall normalization!

Right-handed couplings affect both shape and normalization!

Possible Correlations





Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

ε_{eL} has strong negative correlation to ΔN_{Be} and ε_{eR} is weakly correlated

Both ε_{eL} and ε_{eR} are weakly correlated with the uncertainty in 85Kr

Method of Analysis

- Our analysis is based on the 153.6 ton.year of Borexino data in the reconstructed recoil electron energy range of 0.29 MeV < T_A < 0.8 MeV, divided in 10 keV bins
- Let the no. of measured counts in the i-th be $N_i^{\rm exp}$ and its theoretical value $N_i^{\rm th}(\vec{\lambda})$

$$\vec{\lambda} = \{\varepsilon_{eL}, \varepsilon_{eR}, \varepsilon_{\tau L}, \varepsilon_{\tau R}, \Delta N_{\rm Be}, \Delta N_{\rm Kr}, \Delta N_{\rm Bi}\}$$

$\Delta N_{\rm Be}$, $\Delta N_{\rm Kr}$ and $\Delta N_{\rm Bi}$ respectively denote the percentage change in the ^{7}Be, ^{85}Kr, and ^{210}Bi event normalizations from their reference values.

$$\chi^2(\vec{\lambda}) = \sum_i \frac{\left[N_i^{\rm exp} - N_i^{\rm th}(\vec{\lambda})\right]^2}{N_i^{\rm exp}} + \left[\frac{\Delta N_{\rm Be}}{7\%}\right]^2 + \left[\frac{\Delta N_{\rm Kr}}{18\%}\right]^2 + \left(\frac{s_{23}^2 - 0.5}{0.055}\right)^2$$

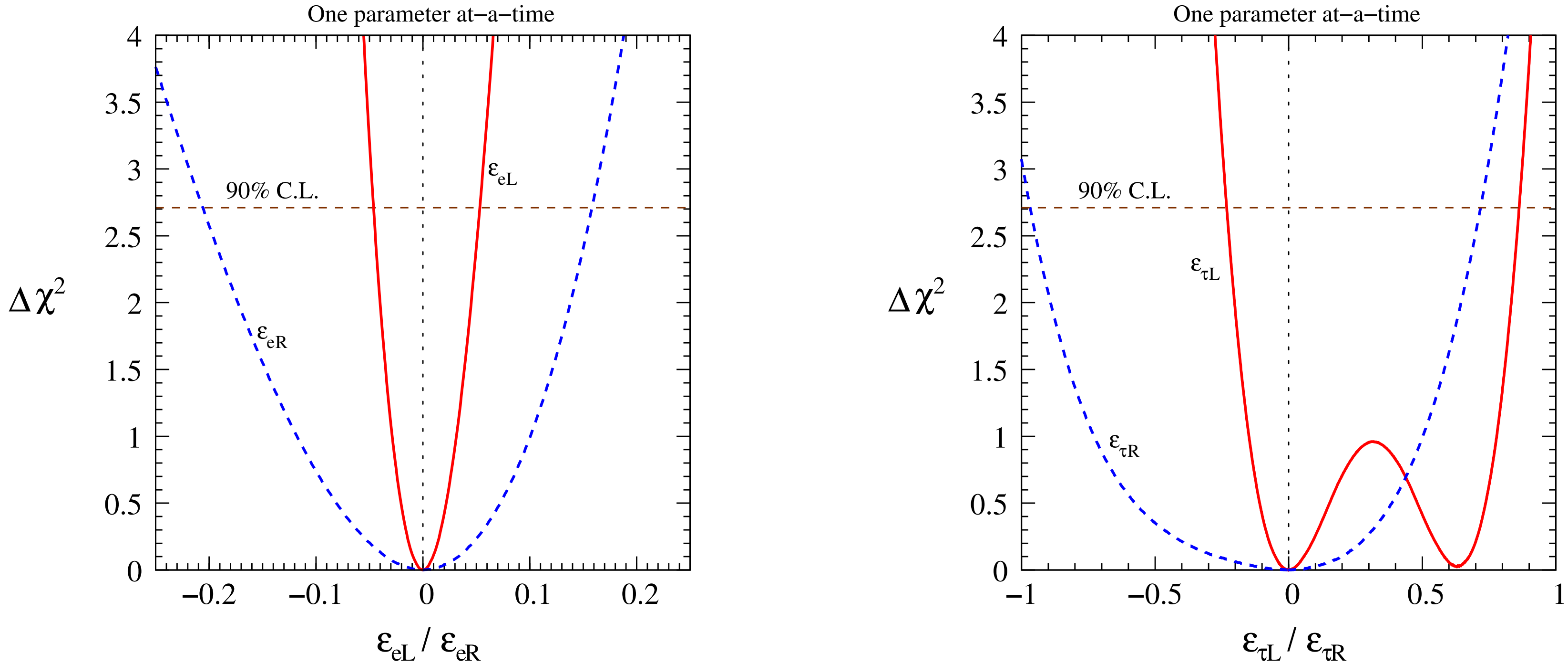
No prior constraint is imposed on $\Delta N_{\rm Bi}$, which will be left for the fit to determine.

- We do not have access to the raw Borexino data, we reconstruct experimental counts from the fits provided by Borexino as a sum of ^{7}Be, ^{85}Kr, and ^{210}Bi events

$N_i^{\rm exp}$ is not equal to $N_i^{\rm th}(\vec{0})$. Thus, the minimal value of χ^2 will be non-zero:

$$\chi^2(\vec{\lambda}) = \chi^2_{\rm min} + \Delta\chi^2(\vec{\lambda})$$

One NSI parameter at-a-time limits



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

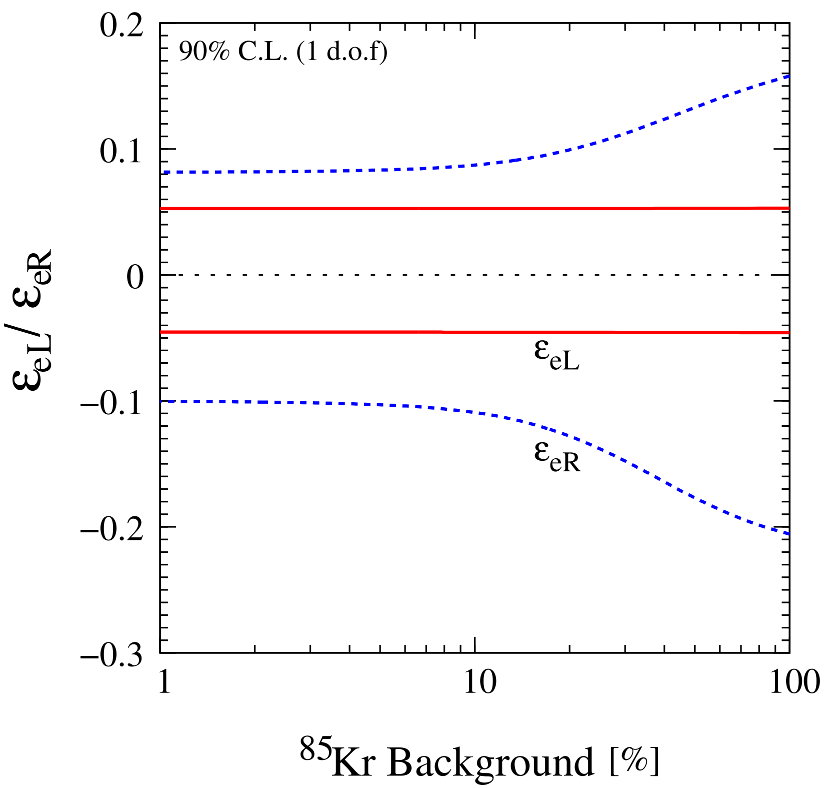
	ε_{eL}	ε_{eR}	$\varepsilon_{\tau L}$	$\varepsilon_{\tau R}$
This work	[−0.046, 0.053]	[−0.206, 0.157]	[−0.231, 0.866]	[−0.976, 0.726]
Global limits [18]	[−0.03, 0.08]	[0.004, 0.151]	[−0.5, 0.2]	[−0.3, 0.4]

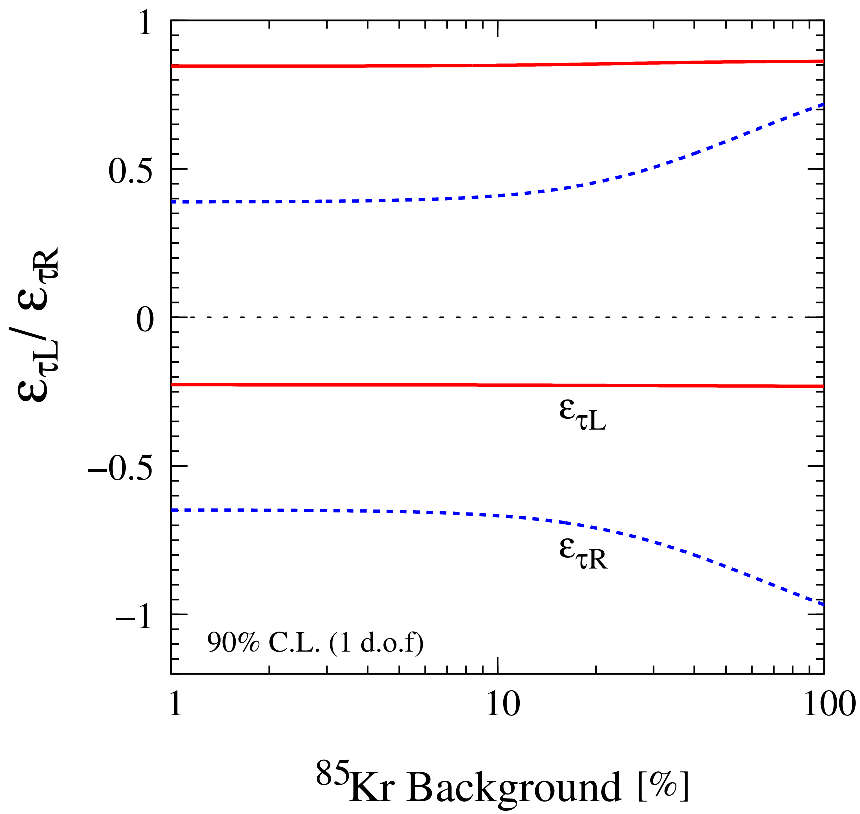
90% C.L. limits based on 153.6 ton.years of Borexino data

Ref.18: Barranco, Miranda, Moura, Valle, Phys.Rev.D77 (2008) 093014

Global limits using LEP, LSND, CHARM II, Reactors (Irvine, Rovno, MUNU) data

Future Improvements in Phase II of Borexino





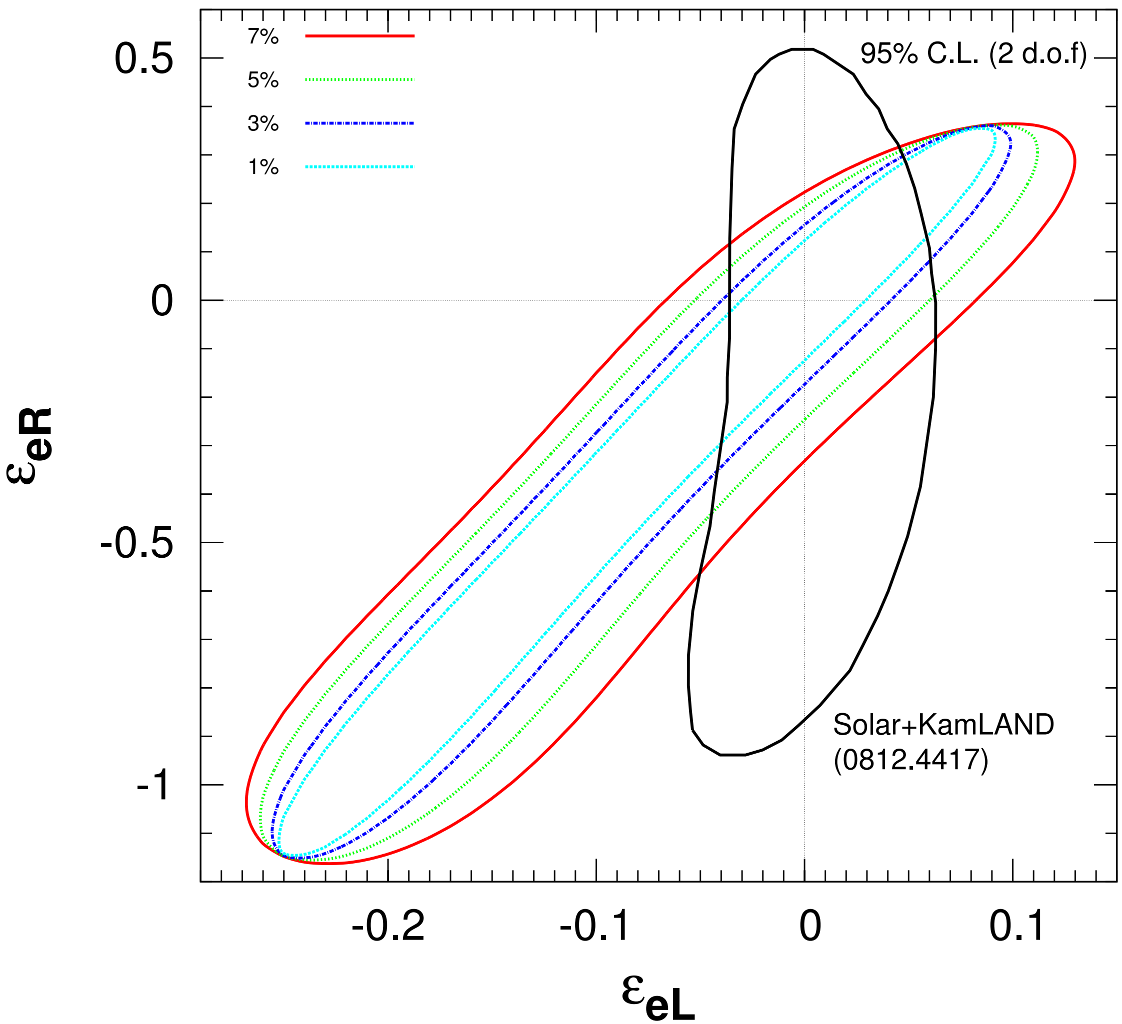
Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

Purification campaigns in Borexino to reduce the radioactive backgrounds. Method of Nitrogen stripping has been quite successful in removing the ^{85}Kr by roughly 90%.

^{85}Kr background mostly changes the slope of the spectrum and affects the RH couplings!

90% reduction in ^{85}Kr, improves the constraints on RH couplings by a factor of ~ 2

Constraints in the $\varepsilon_{eL} - \varepsilon_{eR}$ plane



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

Allowed regions
at 95% C.L. (2 d.o.f)

The area outside each
contour is excluded!

Several curves shown for
different uncertainty levels
in ^{7}Be signal normalization!

Compared with combined
solar+KamLAND bound
taken from:

Bolonas, Miranda, Palazzo, Tortola, Valle, Phys.Rev.D79 (2009) 113012

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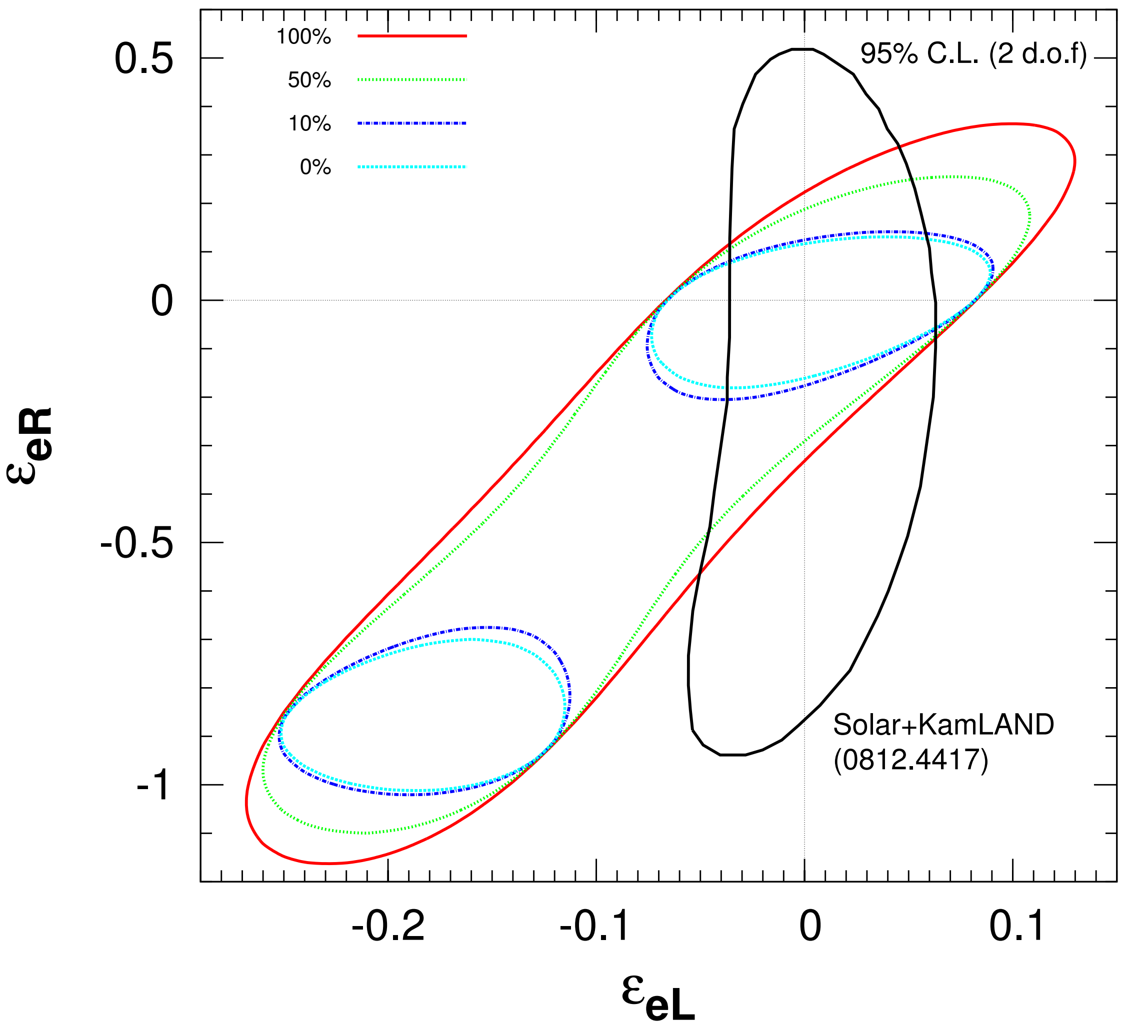

Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

Allowed regions at 95% C.L. (2 d.o.f)!

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Several curves shown for different assumptions on the amount of ^{85}Kr background!

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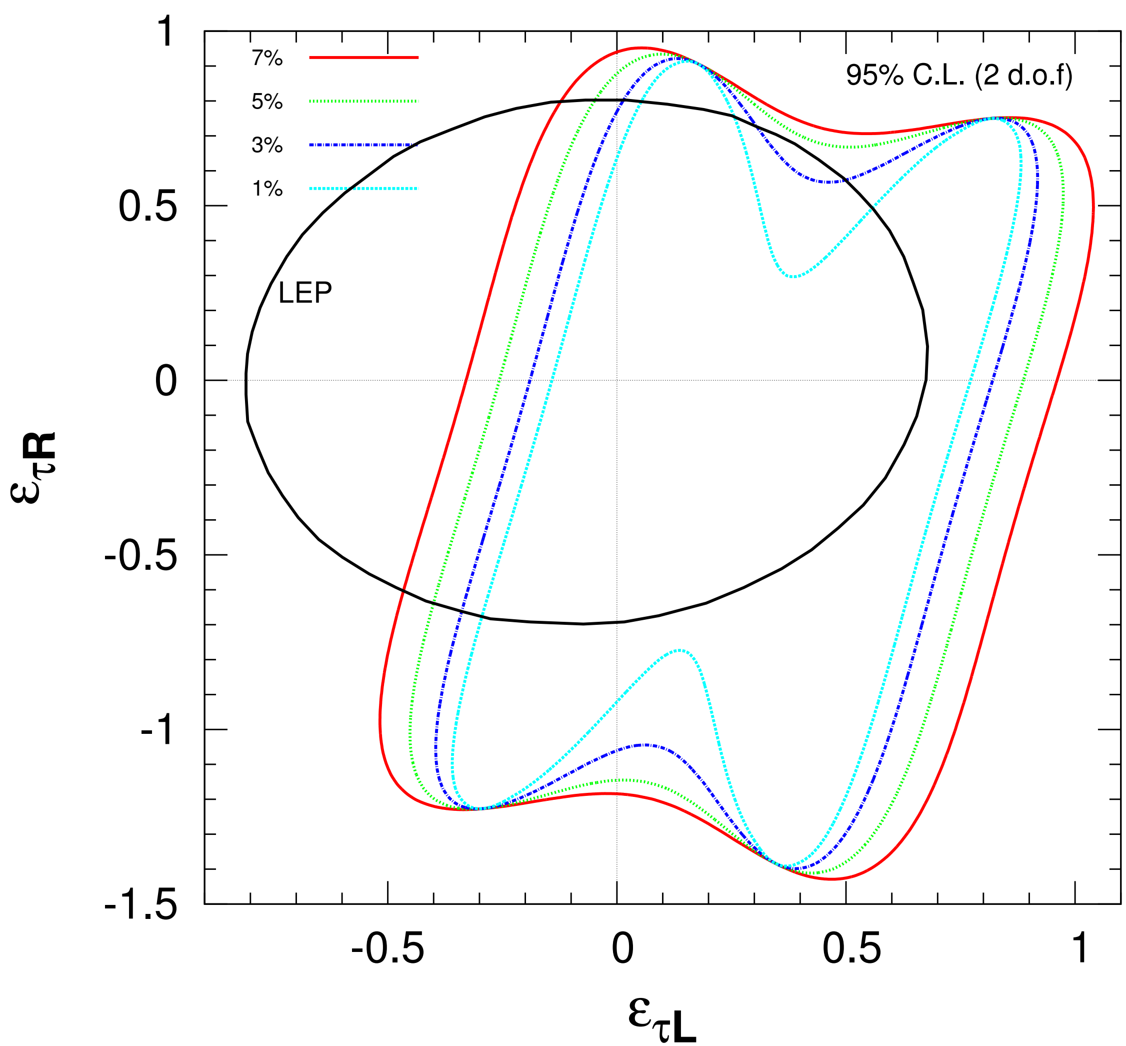
Bolonas, Miranda, Palazzo, Tortola, Valle, Phys.Rev.D79 (2009) 113012

Constraints in the $\varepsilon_{\tau L} - \varepsilon_{\tau R}$ plane



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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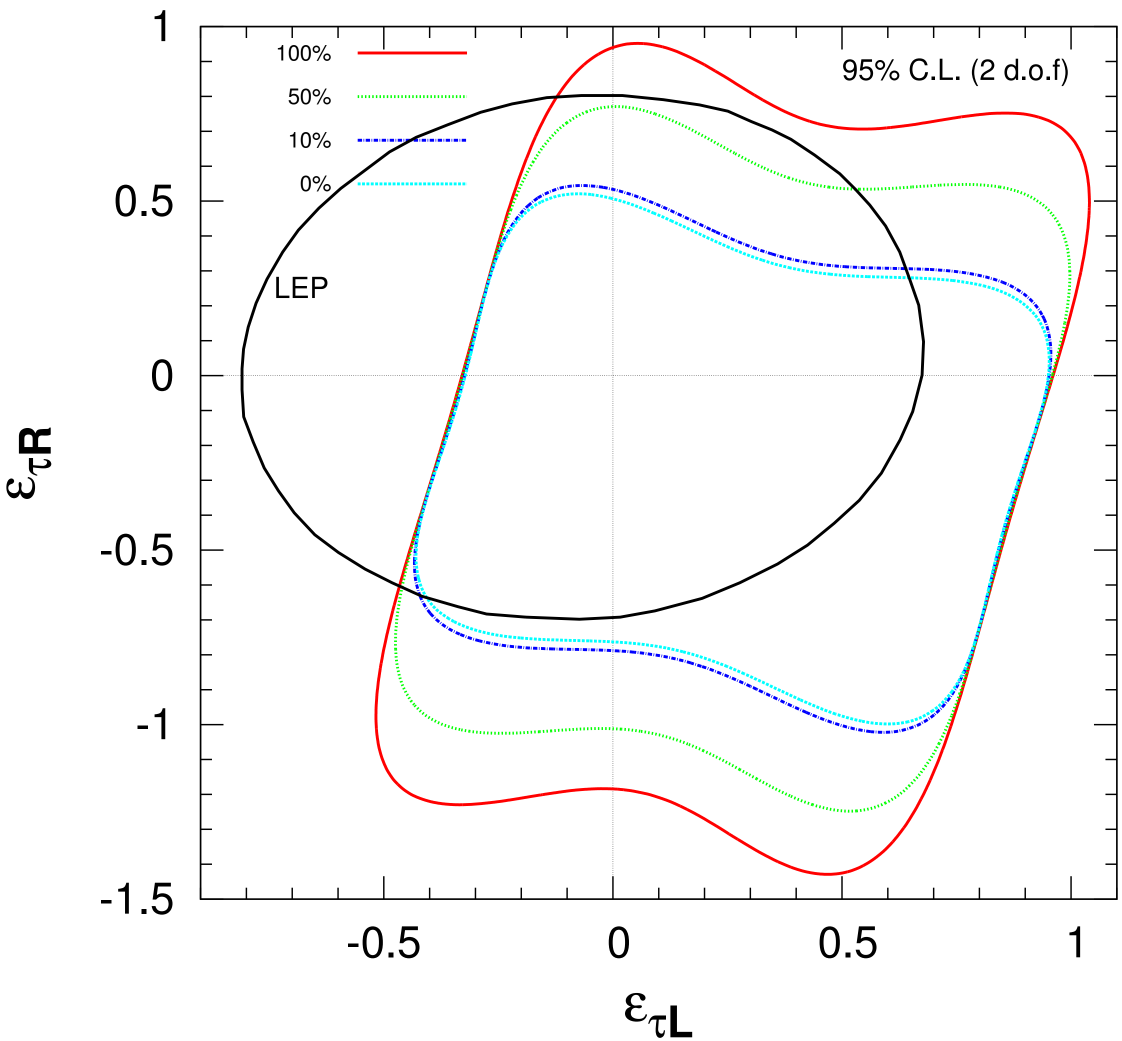
Compared with bound based on the LEP 'neutrino counting' data taken from:

Barranco, Miranda, Moura, Valle, Phys.Rev.D77 (2008) 093014



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Conclusions

- Neutrino-electron scattering process is a powerful tool in low energy neutrino experiments to test flavor diagonal non-universal NSI

- First real-time spectroscopic measurement of low energy monochromatic ^{7}Be solar neutrinos in Borexino has enabled us to put tight constraints on these NSI parameters

- Extreme low level of radioactive background is mandatory to perform these measurements and Borexino is an excellent example for this

- These new physics searches at low energy neutrino experiments are complementary to the efforts being made at higher energies using colliders like ongoing LHC

In future, we have bright chances to probe NSI further along this direction using LENS (dream of Prof. Raghavan), SNO+, LENA

Thank you!