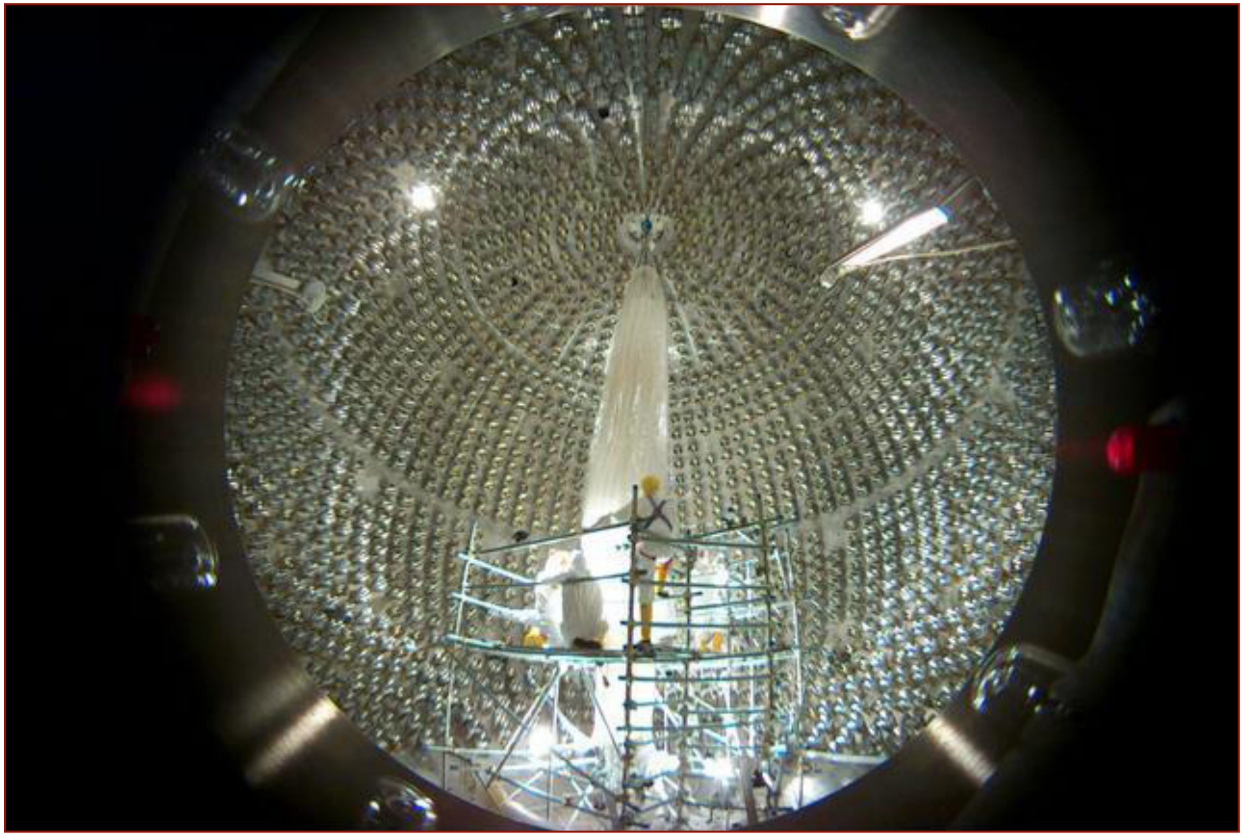
Non-Standard Interactions in Borexino and Daya Bay

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

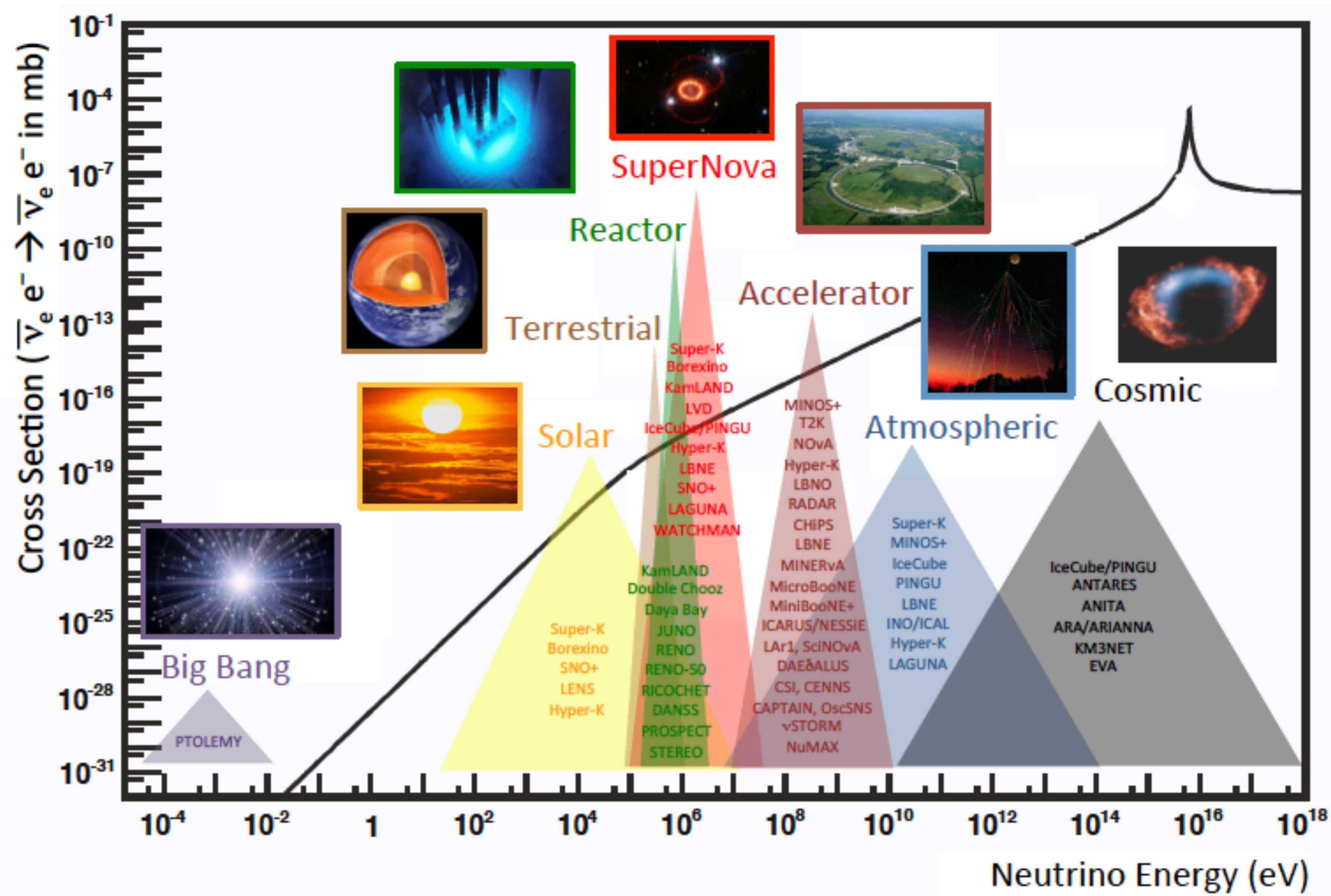
Many Congratulations to the entire Borexino Collaboration



First real time measurement of low energy solar neutrinos

10th Anniversary of Borexino's continuous data-taking

Neutrinos are omnipresent: Friends across 23 orders of magnitude



J. L. Hewett et al., arXiv:1310.4340v1, Snowmass 2013 Neutrino Working Group

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 ν_αe 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:

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

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

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

- Later in 2002, Raghavan, together with Berezhiani and Rossi, discussed the role of Borexino in placing constraints on the flavor diagonal NSIs via measuring 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, after 15 years, with more than 252.3 ton.years of Borexino data, it is now possible to actually place the constraints on these NSI parameters

- For more illuminating discussions on NSIs in solar neutrinos, see the latest review by Maltoni and Smirnov, arXiv:1507.05287v4 [hep-ph]

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

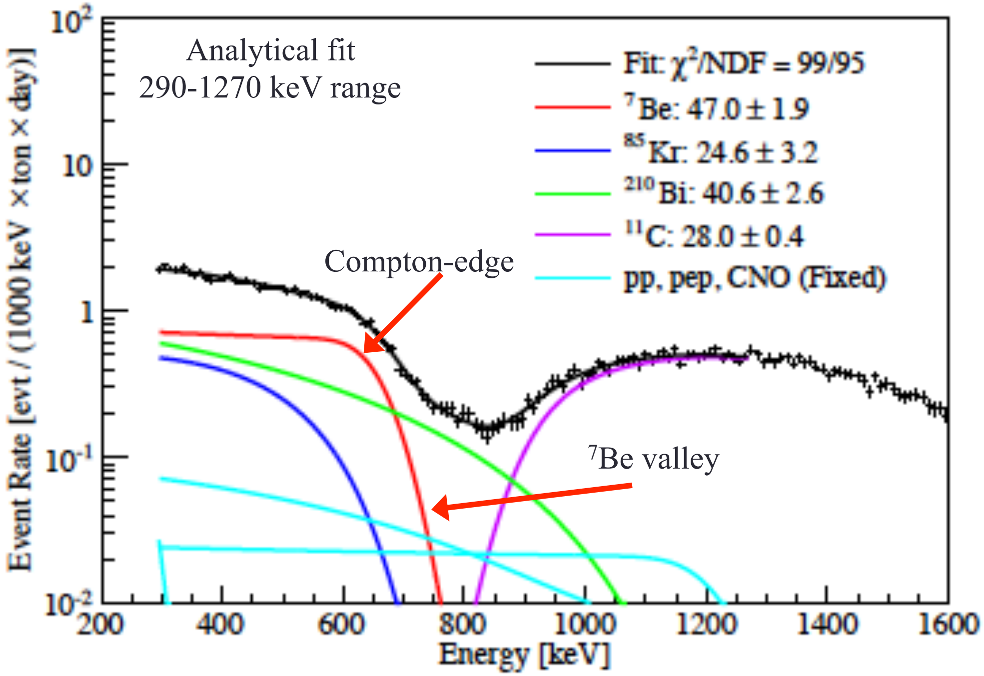
- CHARM-II experiment places strong constraints on $\varepsilon_{\mu L}$ and $\varepsilon_{\mu R}$

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



Phase-I

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

^{7}Be	$46.0\pm1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$
^{85}Kr	$31.2\pm1.7(\text{stat})\pm4.7(\text{syst})$
^{210}Bi	$41.0\pm1.5(\text{stat})\pm2.3(\text{syst})$
^{11}C	$28.5\pm0.2(\text{stat})\pm0.7(\text{syst})$

Phys.Rev.Lett. 107 (2011) 141302

^{7}Be Signal Events

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 : due to small air leak into the scintillator while filling the detector

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

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

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

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

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

$$^{85}\text{Kr} \ :\ 30.4 \pm 5.3(\text{stat}) \pm 1.3(\text{syst})\ \text{counts}/(\text{day} \cdot 100\,\text{tons})$$ $\sim \pm 18\%$ uncertainty

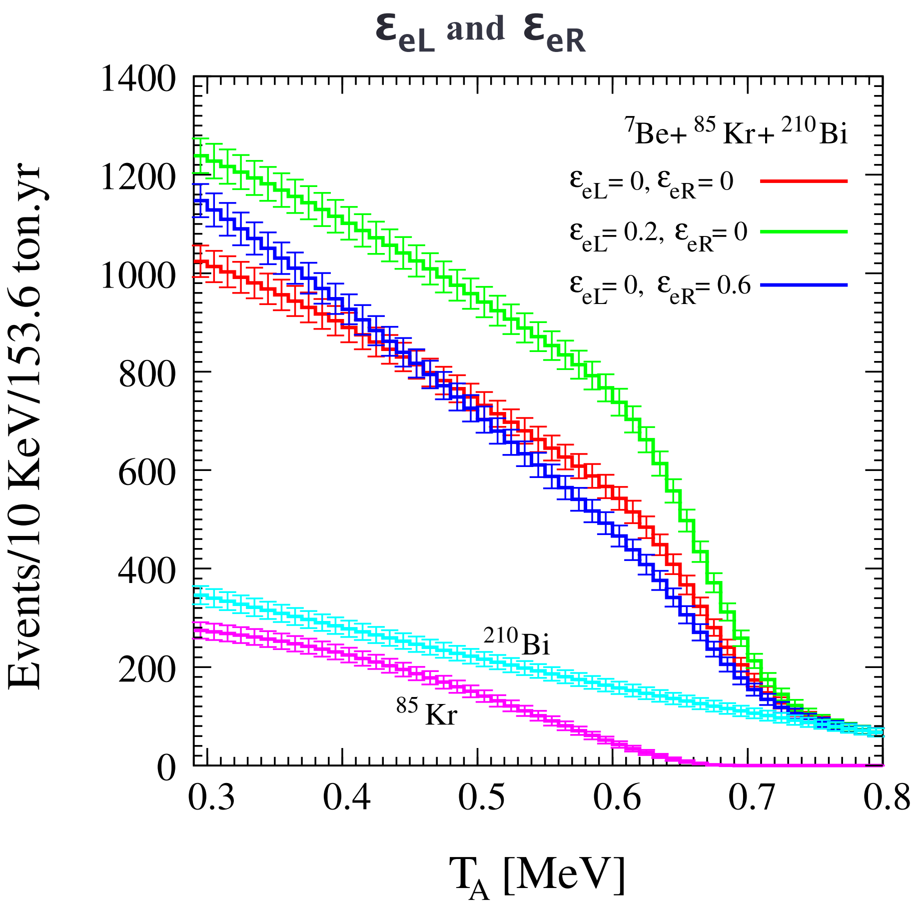
- Another background is ^{210}Bi, a pure β-emitter produced at the end of ^{222}Rn decay chain

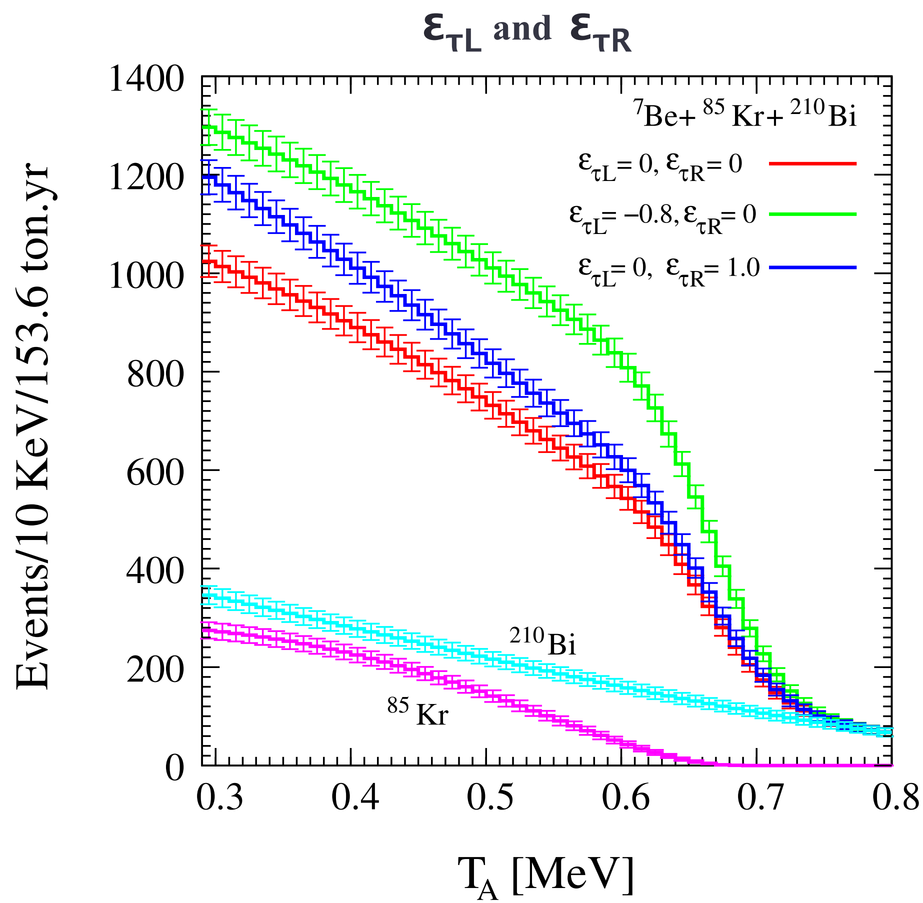
$$^{210}\text{Bi} \longrightarrow {}^{210}\text{Po} + e^- + \overline{\nu}_e \qquad (Q = 1.161\ \text{MeV},\ t^{1/2} = 5.012\ \text{days},\ 100\%)$$

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

Event Spectrum with NSI (Phase-I)

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

Method of Analysis

- Our analysis is based on the 153.6 ton.years of Borexino data in the reconstructed recoil electron energy range of 0.29 MeV < T_A < 0.8 MeV, divided in 10 keV bins

- No. of measured counts in ith-bin be N_i^{exp} and its theoretical value $N_i^{\text{th}}(\vec{\lambda})$

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

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

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

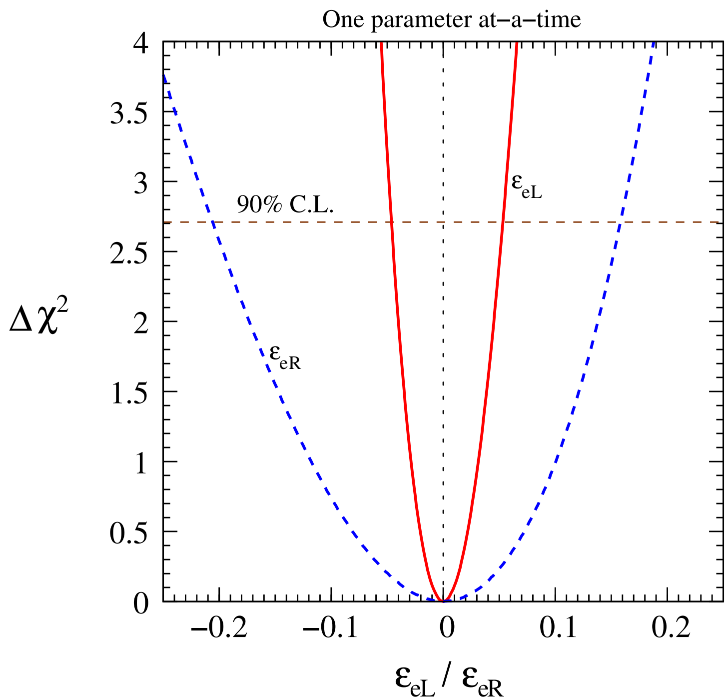
No prior constraint is imposed on ΔN_{Bi}, which will be left for the fit to determine.

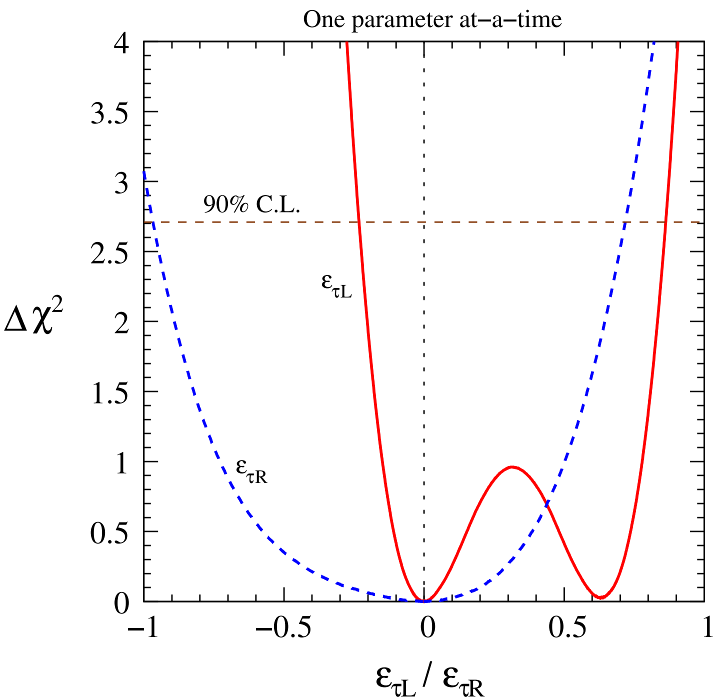
- We reconstruct experimental counts from the fits provided by Borexino as a sum of ^{7}Be, ^{85}Kr, and ^{210}Bi events

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

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

One NSI parameter at-a-time limits (Phase-I)





Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

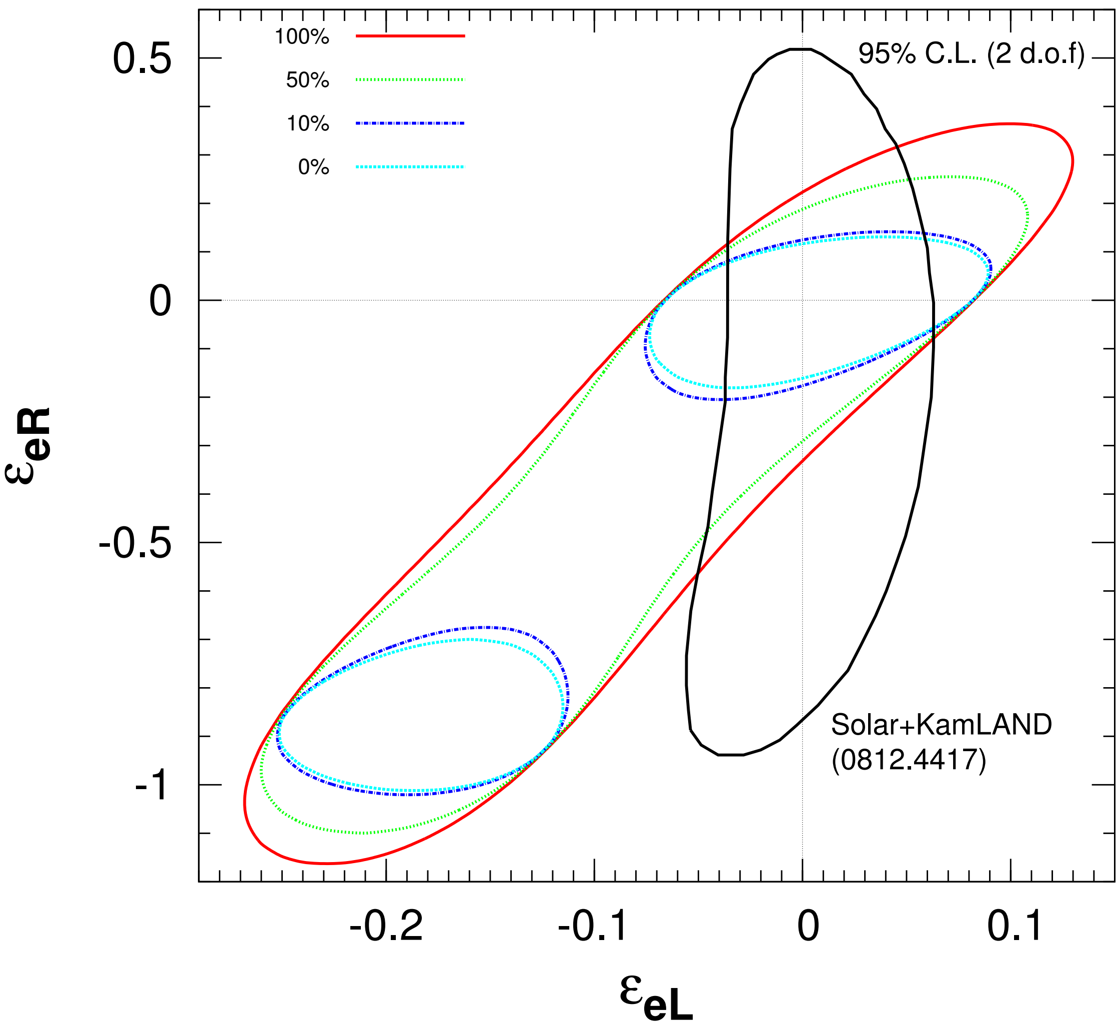
	ε_{eL}	ε_{eR}	$\varepsilon_{\tau L}$	$\varepsilon_{\tau R}$
This work	[−0.046, 0.053]	[−0.206, 0.157]	[−0.231, 0.866]	[−0.976, 0.726]
Global limits [18]	[−0.03, 0.08]	[0.004, 0.151]	[−0.5, 0.2]	[−0.3, 0.4]

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

Constraints in the $\varepsilon_{eL} - \varepsilon_{eR}$ plane (Phase-I)



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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

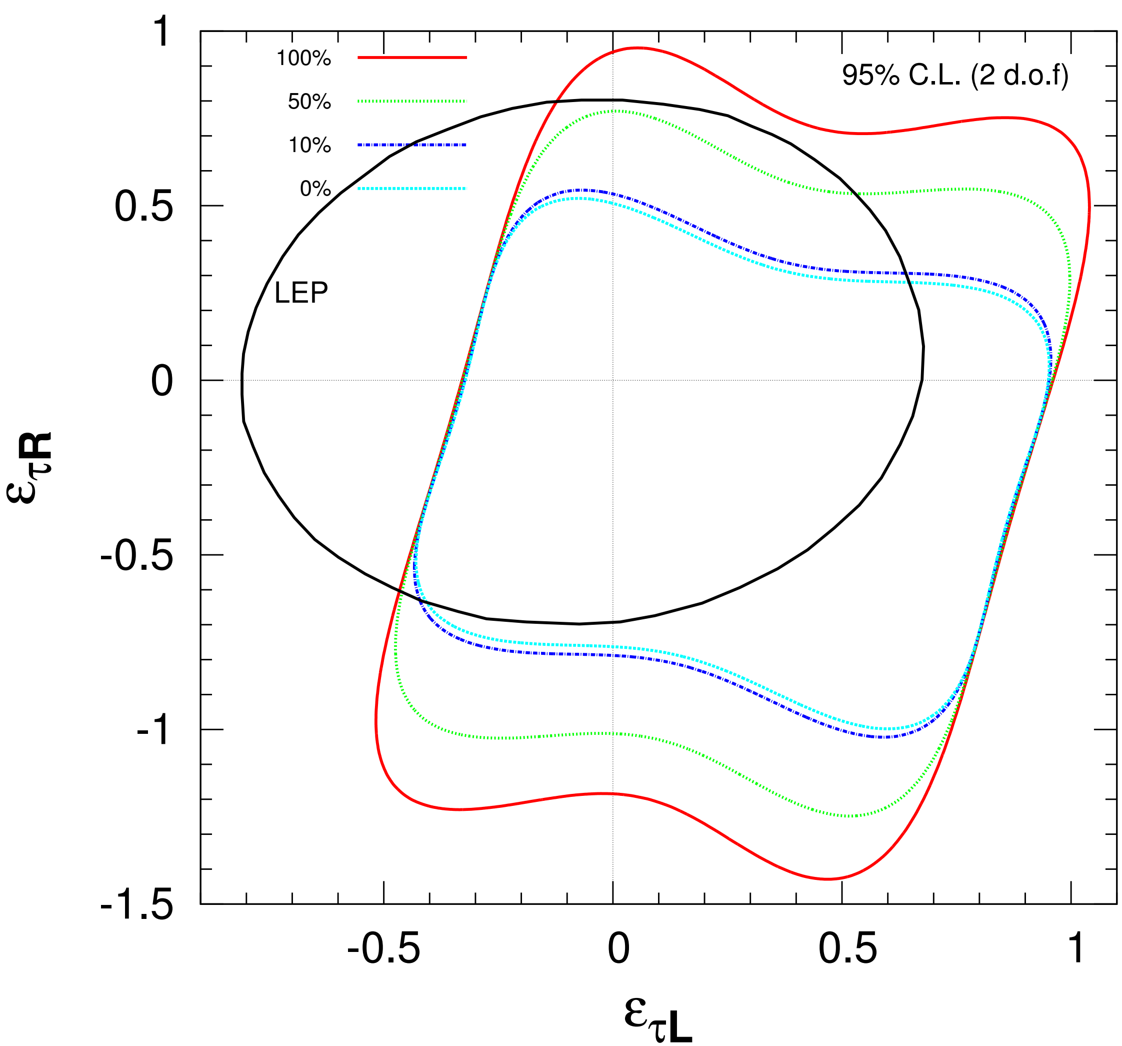
The area outside each contour is excluded

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

Compared with combined Solar+KamLAND bound taken from:

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

Constraints in the $\varepsilon_{\tau L} - \varepsilon_{\tau R}$ plane (Phase-I)



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 assumptions on the amount of ^{85}Kr background

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

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

First Simultaneous Precision Spectroscopy of pp, ^{7}Be, and pep Solar Neutrinos with Borexino Phase-II

Borexino Collaboration, arXiv:1707.09279v1

December, 2011 to May, 2016: 1291.51 days × 71.3 tons = 252.3 ton.years
Exposure is 1.6 times in Phase-II as compared to Phase-I

Phase-II

Best Estimates [counts/(day.100 tons)]

^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9

As compared to Phase-I

^{85}Kr is reduced by ~ 78%
^{210}Bi is reduced by ~ 57%
Big Milestone Achieved!

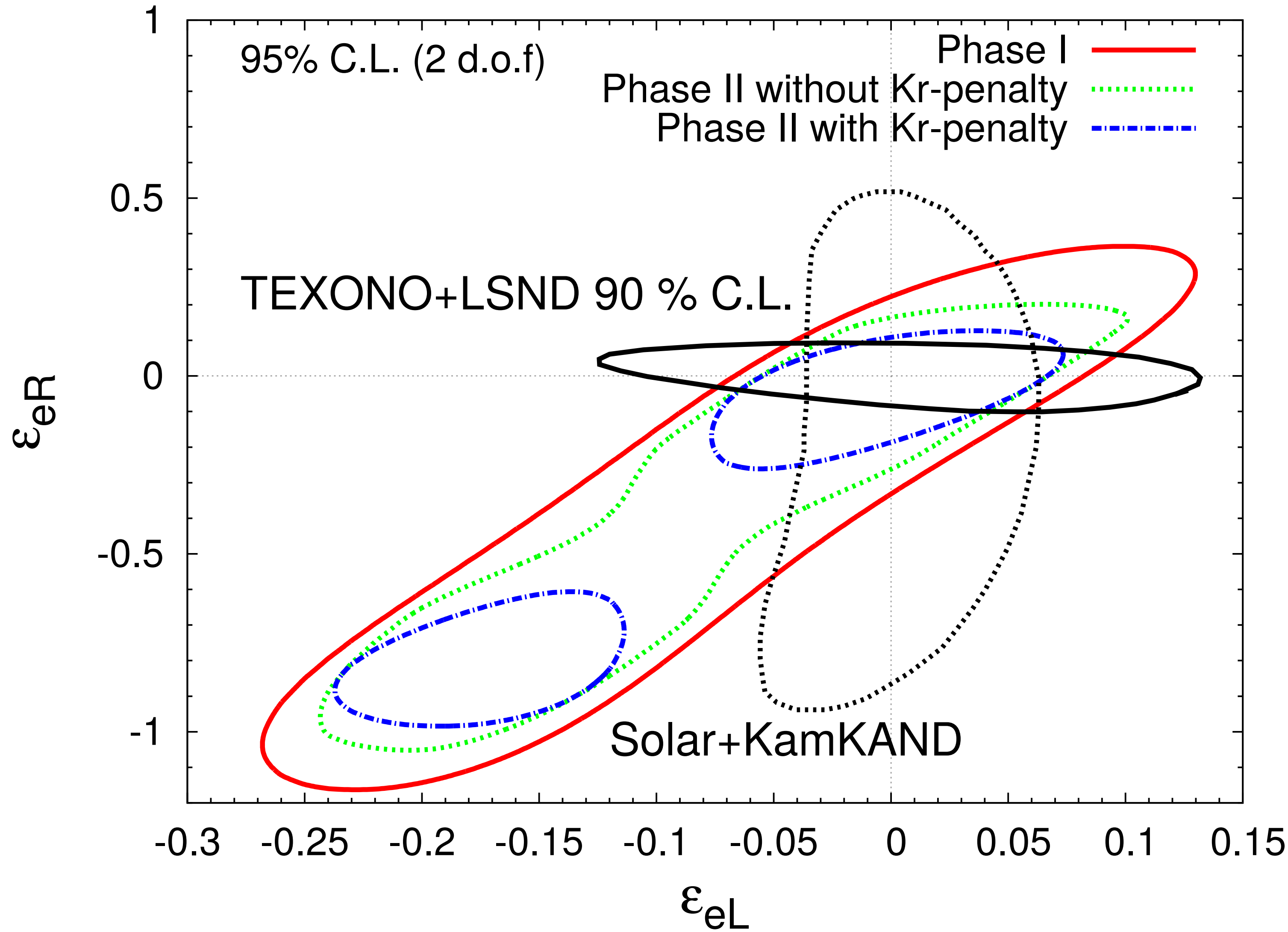
See the talk by Barbara Caccianiga

According to B16 (GS98)-HZ: 6% Uncertainty on 7Be Flux

See the talk by Aldo Serenelli

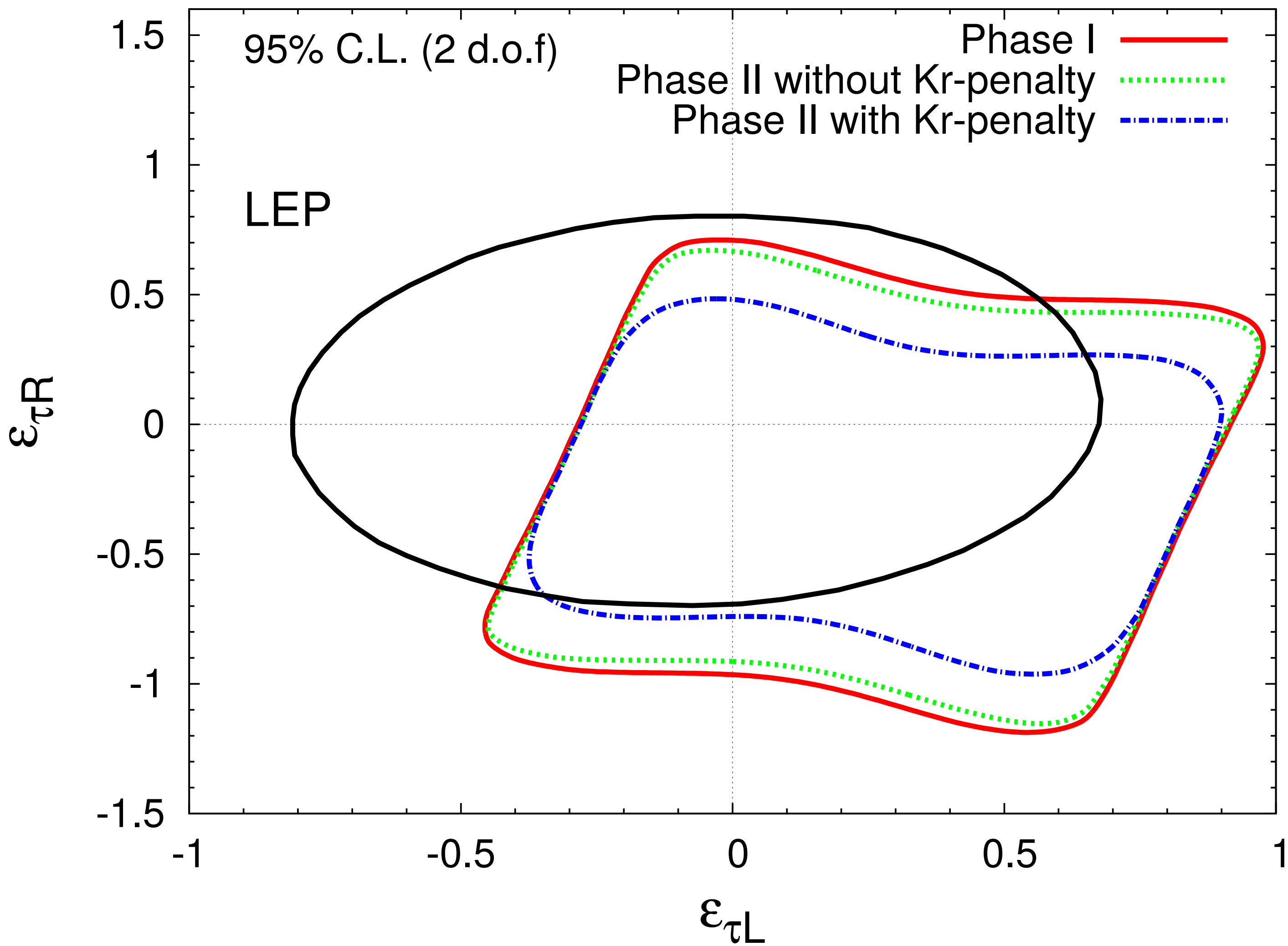
New Constraints on NSI using Phase-II data
See the poster by Andrey Formozov for Preliminary Results

Preliminary Results using Borexino Phase-II Data

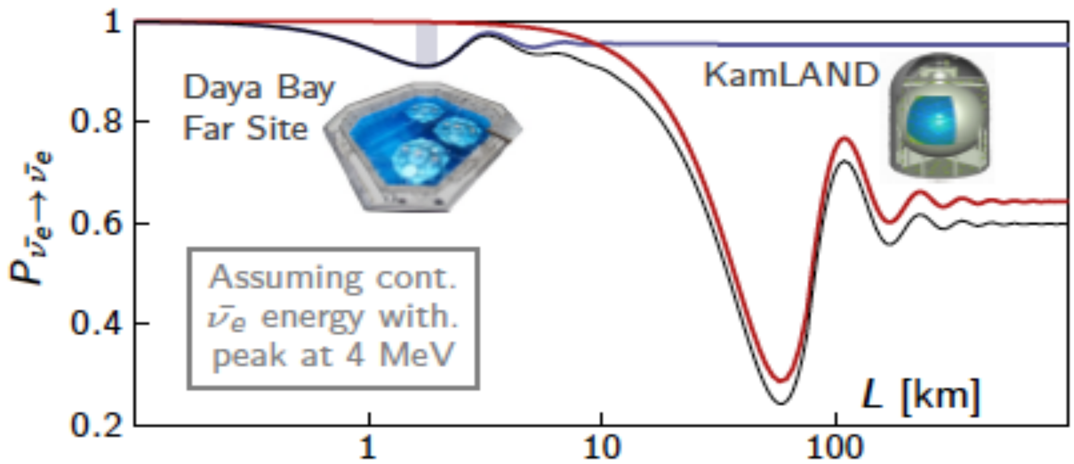


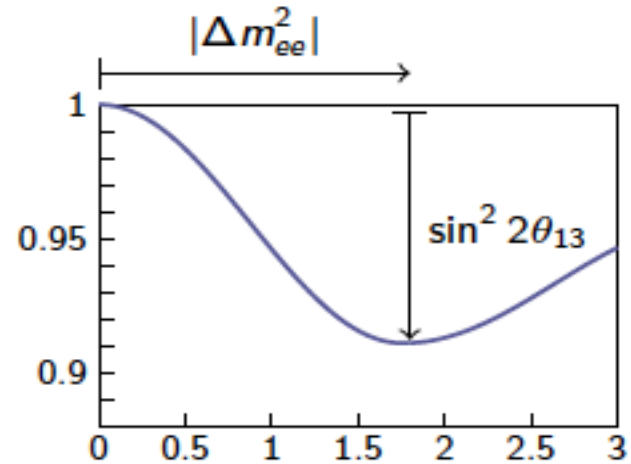
Work in Progress with the Borexino Collaboration

Preliminary Results using Borexino Phase-II Data



Work in Progress with the Borexino Collaboration





θ_{13} measured by seeing the deficit of reactor anti-neutrinos at ~ 2 km

θ_{13} governs overall size of electron anti-neutrino deficit

Effective mass-squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

$$P_{\bar{\nu_e}\to\bar{\nu_e}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12}\cos^4 2\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$

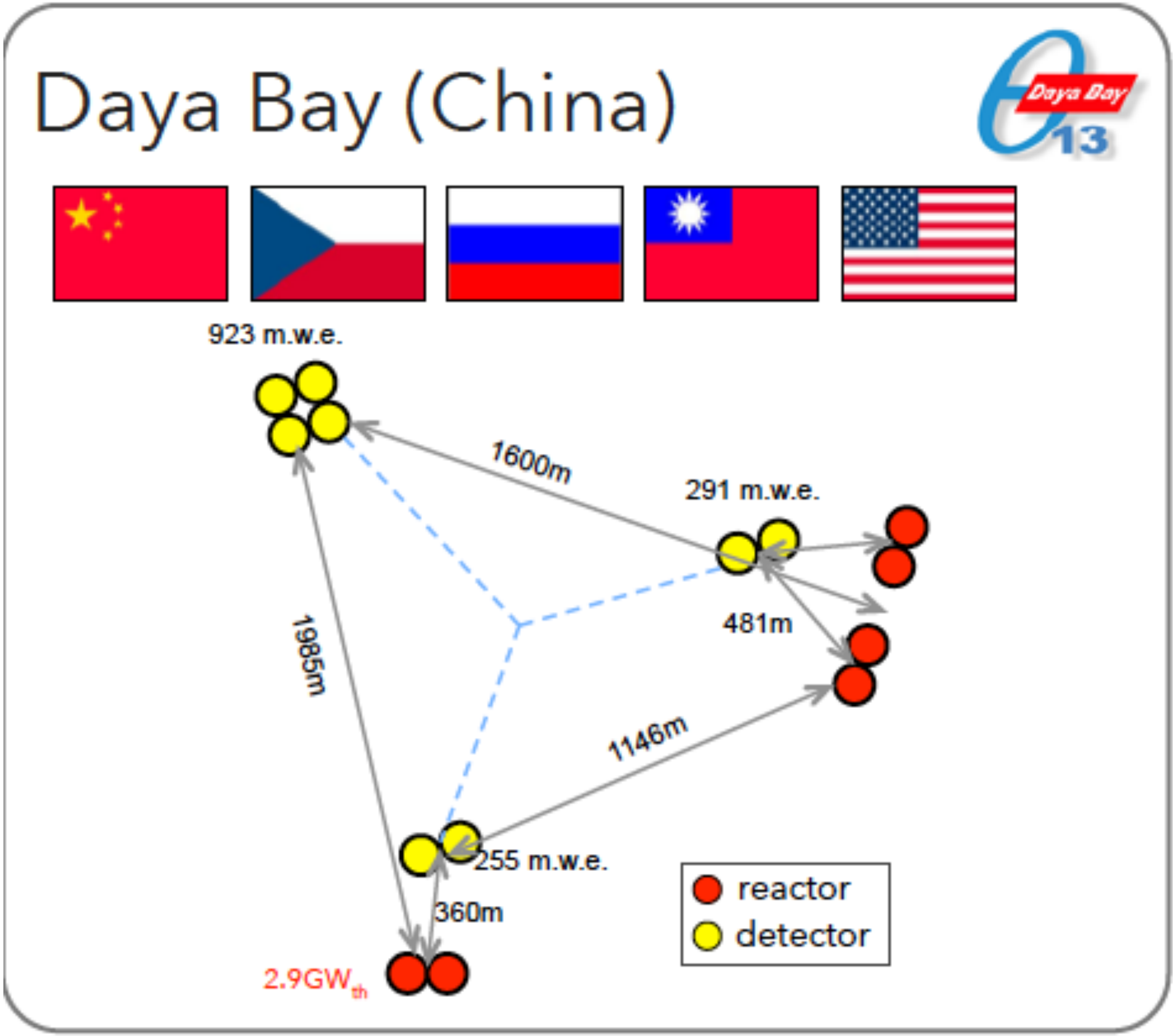
Short Baseline — Long Baseline

$$\sin^2(\Delta m^2_{ee}\tfrac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\tfrac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\tfrac{L}{4E})$$

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21\times 10^{-5}\mathrm{eV}^2$$

+: Normal Hierarchy
−: Inverted Hierarchy

Hierarchy discrimination requires ~ 2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$



Daya Bay Plan:

Go Strong,
Go Big,
Go Deep

To date:

More than 2.5 million IBD events

See the talk by Jun Cao

Two Interesting Questions

How robust are the measurements of the Daya Bay if there are NSIs in production and detection?

Can Daya Bay constrain these NSIs if they are not present in Nature?

Neutrino Non-Standard Interactions

In the low energy regime, these new interactions may be parameterized in the form of effective four-fermion Lagrangian:

$$\mathcal{L}_{\text{CC-NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{s\,d,ff'} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1 \pm \gamma^5) f\right]$$

s = source (β-decay), d = detector (Inverse β-decay)
α = charged lepton flavor (e^+ for IBD)
β = neutrino flavor (e, μ, or τ)
f and f' = light SM fermions (u & d quarks)
$\varepsilon_{\alpha\beta}^{s\,d,ff'}$ = strength of CC-NSI

90% C.L.

$$|\varepsilon_{e\alpha}^{ud,V}| < 0.041\,, \quad |\varepsilon_{e\mu}^{ud,L}| < 0.026\,, \quad |\varepsilon_{e\mu}^{ud,R}| < 0.037$$

$$\varepsilon_{\alpha\beta}^{ff',V} = \varepsilon_{\alpha\beta}^{ff',L} + \varepsilon_{\alpha\beta}^{ff',R}$$

Unitarity constraints on CKM matrix and non-observation ν oscillations in NOMAD

Biggio, Blennow, Fernandez-Martinez, JHEP 0908 (2009) 090
See also, Davidson, Pena-Garay, Rius, Santamaria, JHEP 0303 (2003) 011

Special case of NSI

Considering only the NSI parameters $|\varepsilon_e|$ and ϕ_e which are associated with $\bar{\nu}_e$

"zero-distance" effect

$$P^{\text{NSI-e}}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq P^{\text{SM}}_{\bar{\nu}_e \to \bar{\nu}_e} + 4|\varepsilon_e|\cos\phi_e + 4|\varepsilon_e|^2 + 2|\varepsilon_e|^2 \cos 2\phi_e$$

$$\tilde{s}^2_{13} \approx s^2_{13} - \frac{|\varepsilon_e|\cos\phi_e}{\sin^2 \Delta_{31}}$$

Considering only the NSI parameters $|\varepsilon_\mu|$ and ϕ_μ which are associated with $\bar{\nu}_\mu$

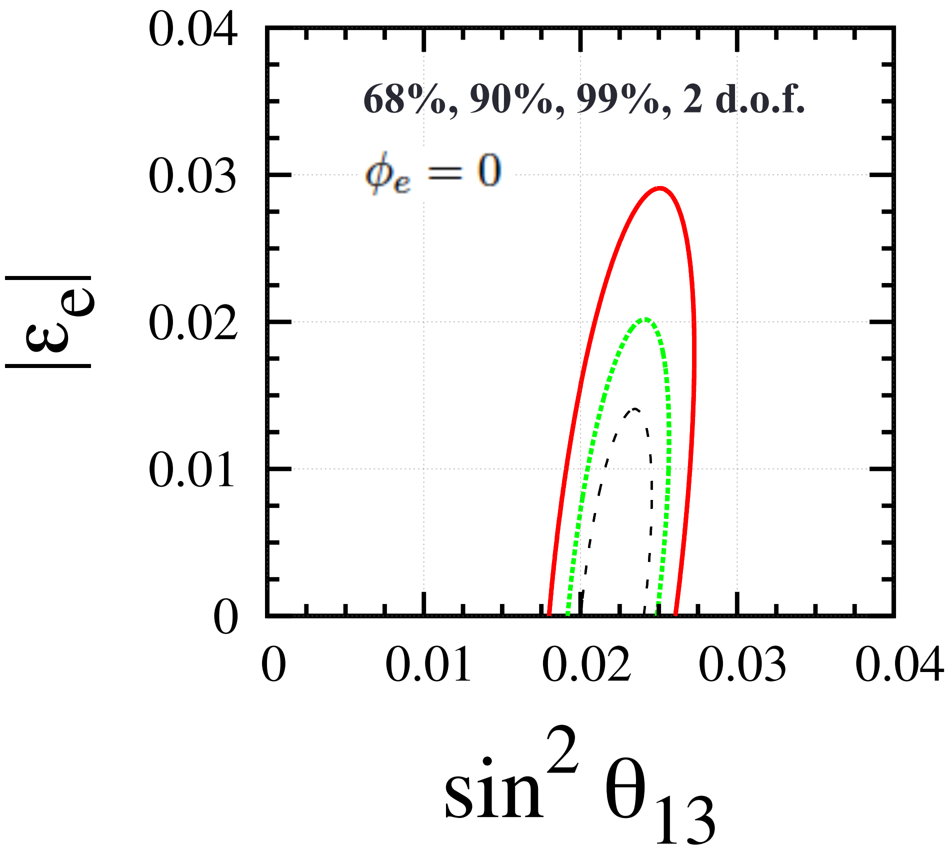
$$P^{\text{NSI-}\mu}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq P^{\text{SM}}_{\bar{\nu}_e \to \bar{\nu}_e} + 2|\varepsilon_\mu|^2 - 4\{s^2_{23}|\varepsilon_\mu|^2 + 2 s_{13} s_{23} |\varepsilon_\mu| \cos(\delta - \phi_\mu)\} \sin^2 \Delta_{31}$$

$$\tilde{s}^2_{13} \approx s^2_{13} + 2 s_{13} s_{23} |\varepsilon_\mu| \cos(\delta - \phi_\mu)$$

Agarwalla, Bagchi, Forero, Tortola, arXiv:1412.1064 [hep-ph]

Comparing NSI bounds from 621 & 1230 days of Daya Bay Run

621 days, rate

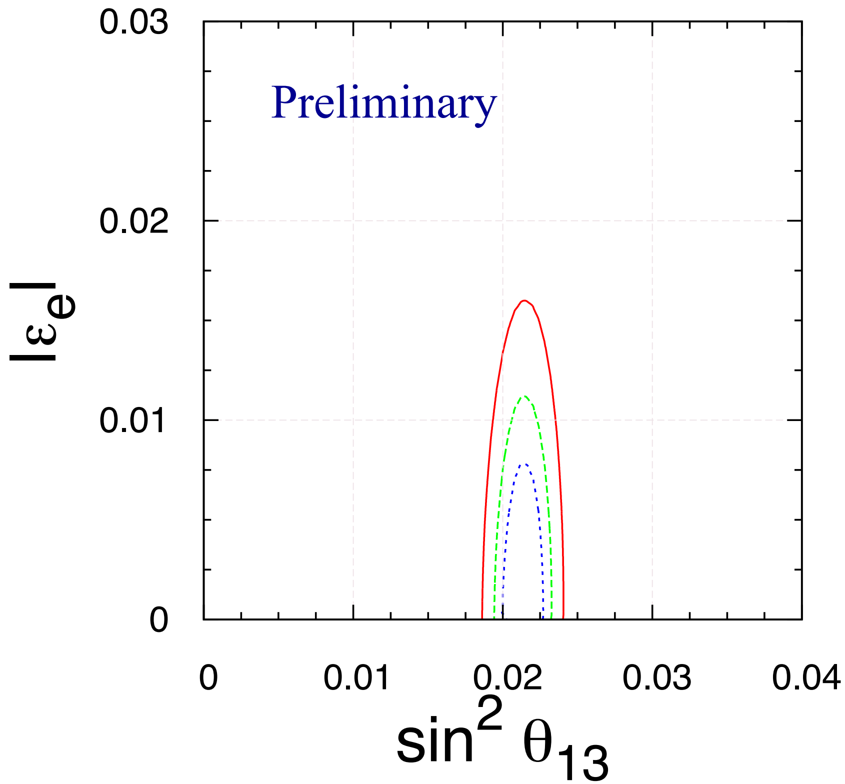


5% uncertainty on flux

$|\varepsilon_e| \leq 0.015$ (90% C.L., 1 d.o.f.)

Agarwalla, Bagchi, Forero, Tortola, arXiv:1412.1064 [hep-ph]

1230 days, spectrum

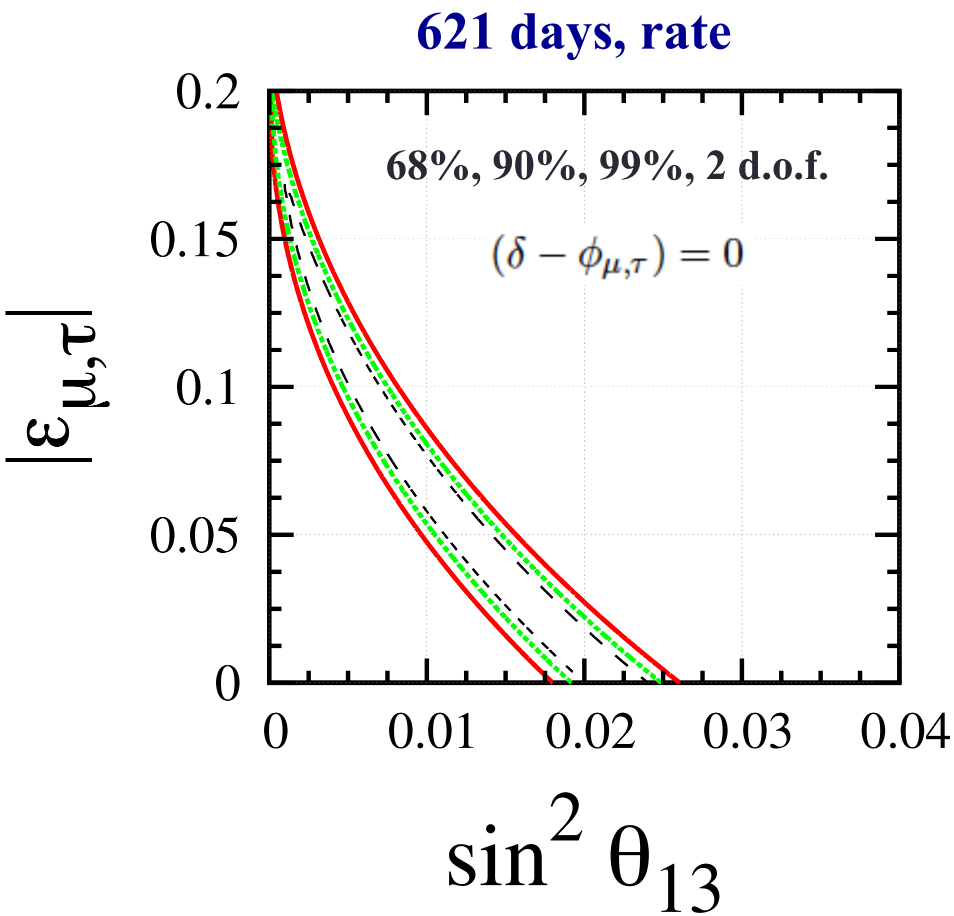


2% uncertainty on flux

$|\varepsilon_e| \leq 0.007$ (90% C.L., 1 d.o.f.)

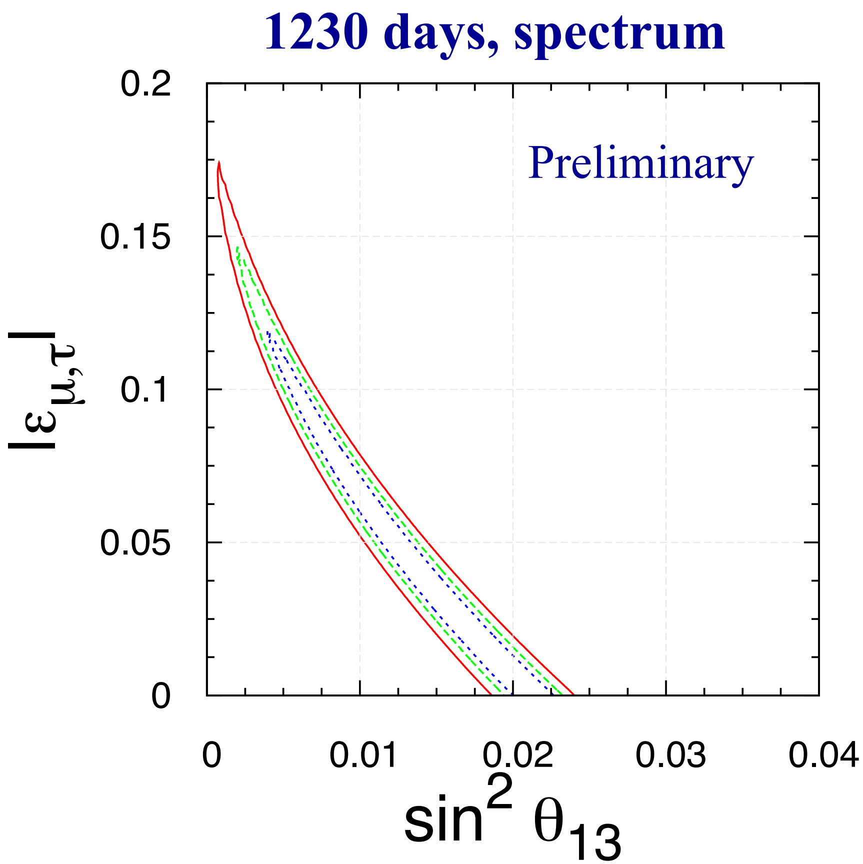
Agarwalla, Forero, Tortola, in progress

Comparing NSI bounds from 621 & 1230 days of Daya Bay Run



5% uncertainty on flux
$|\varepsilon_{\mu,\tau}| \leq 0.176$ (90% C.L., 1 d.o.f.)

Agarwalla, Bagchi, Forero, Tortola, arXiv:1412.1064 [hep-ph]



2% uncertainty on flux
$|\varepsilon_e| \leq 0.12$ (90% C.L., 1 d.o.f.)

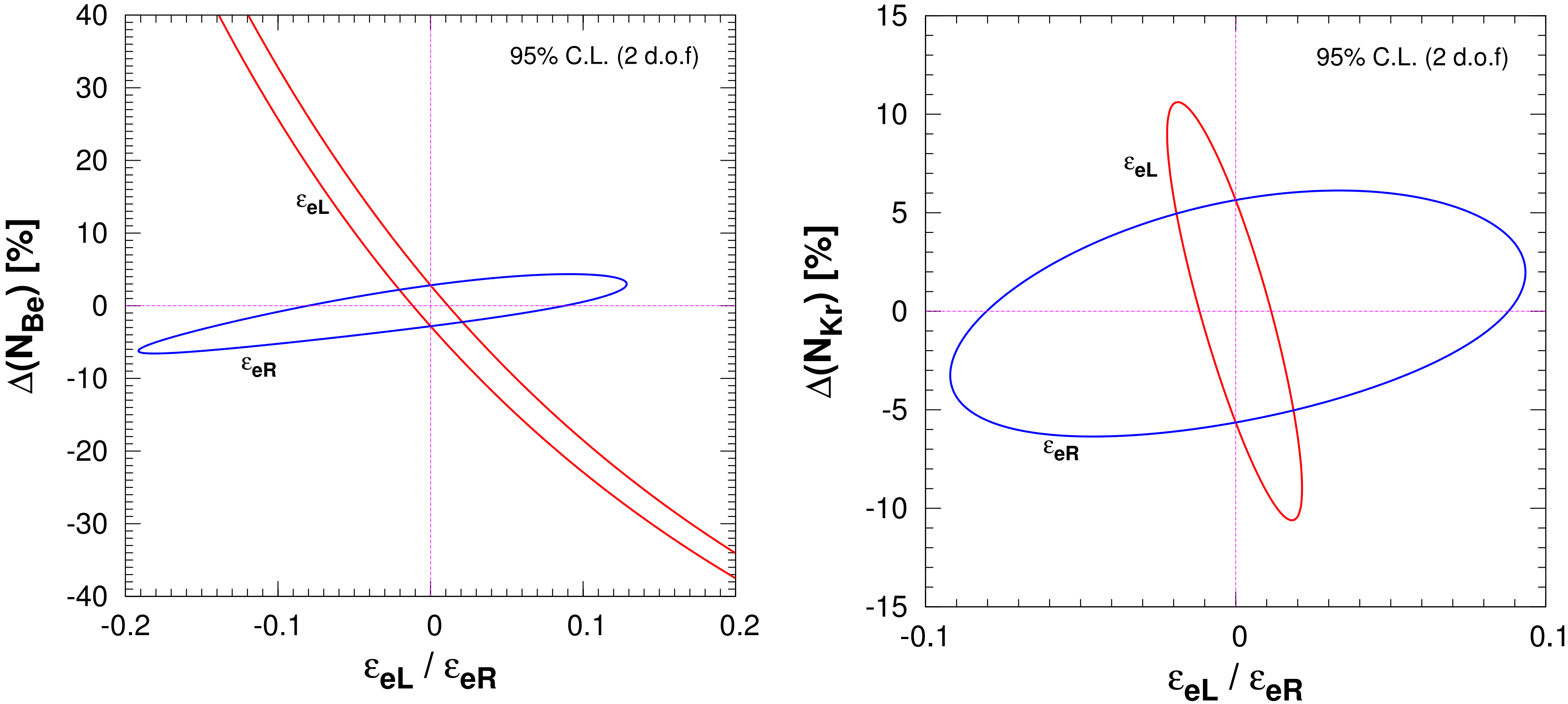
Agarwalla, Forero, Tortola, in progress

Conclusions

- NSIs are well motivated in physics beyond the Standard Model
- Looking for NSIs at Borexino and Daya Bay are complementary to the searches at high energy colliders like ongoing LHC
- Purely leptonic Neutrino-electron scattering is a powerful tool in Borexino to test flavor diagonal non-universal NSI
- Borexino Phase-II data with very low radioactive backgrounds can constrain these NSIs very well with ν_e , complementary to reactor constraints with electron antineutrino
- Huge IBD events in Daya Bay with near & far measurements can also constrain CC-NSIs at production and detection

Thank you!

Possible Correlations

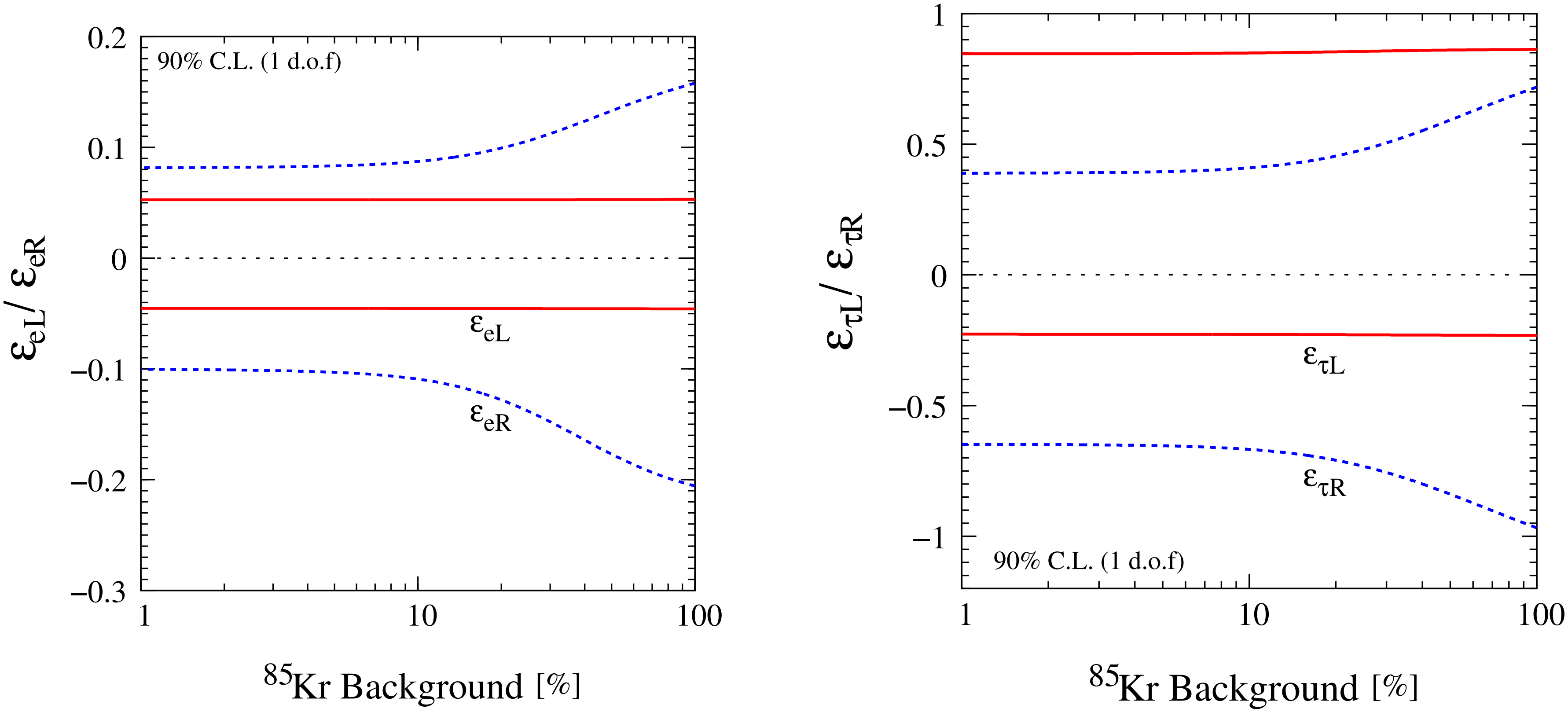


Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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

Future Improvements in Phase II of Borexino



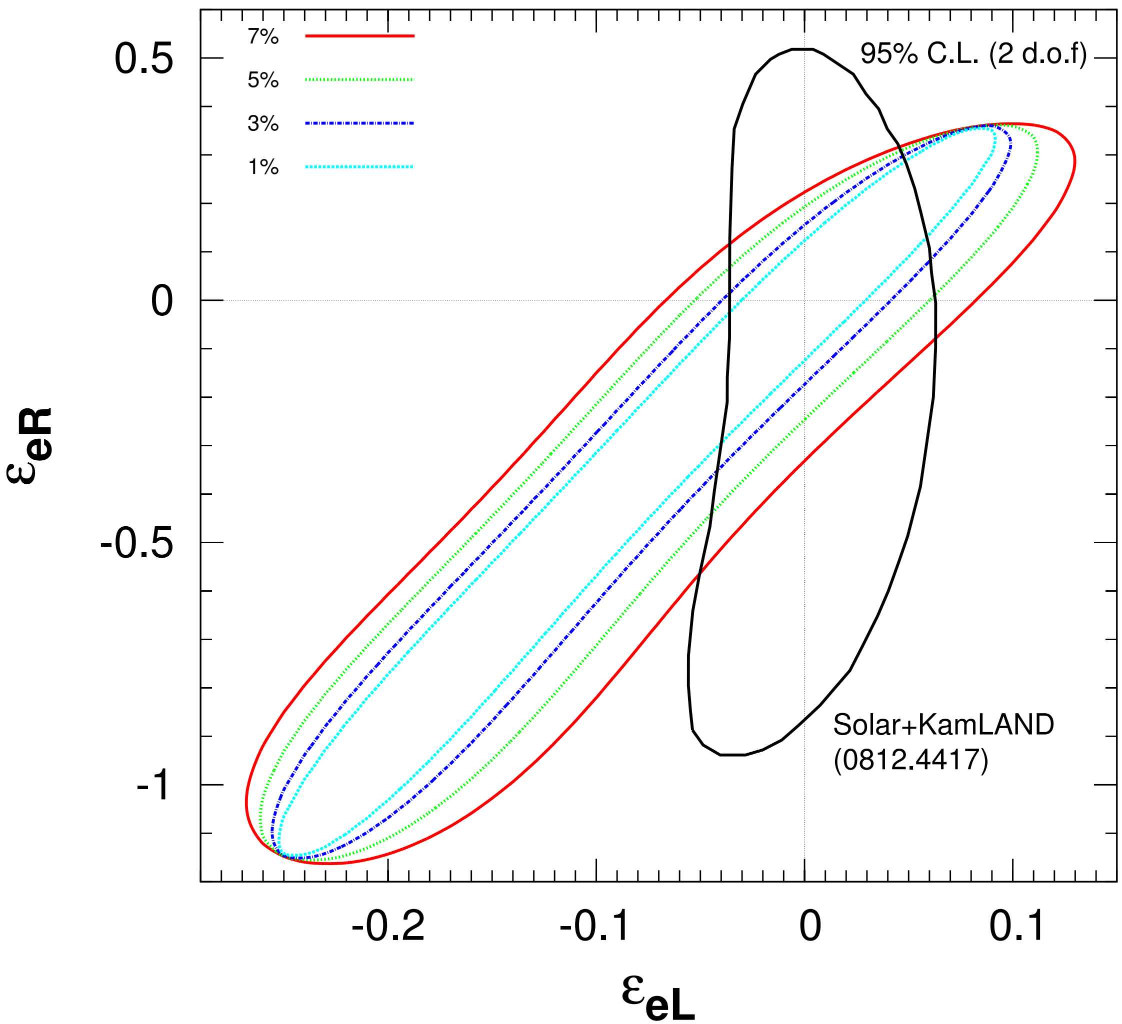
Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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 (Phase-I)



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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

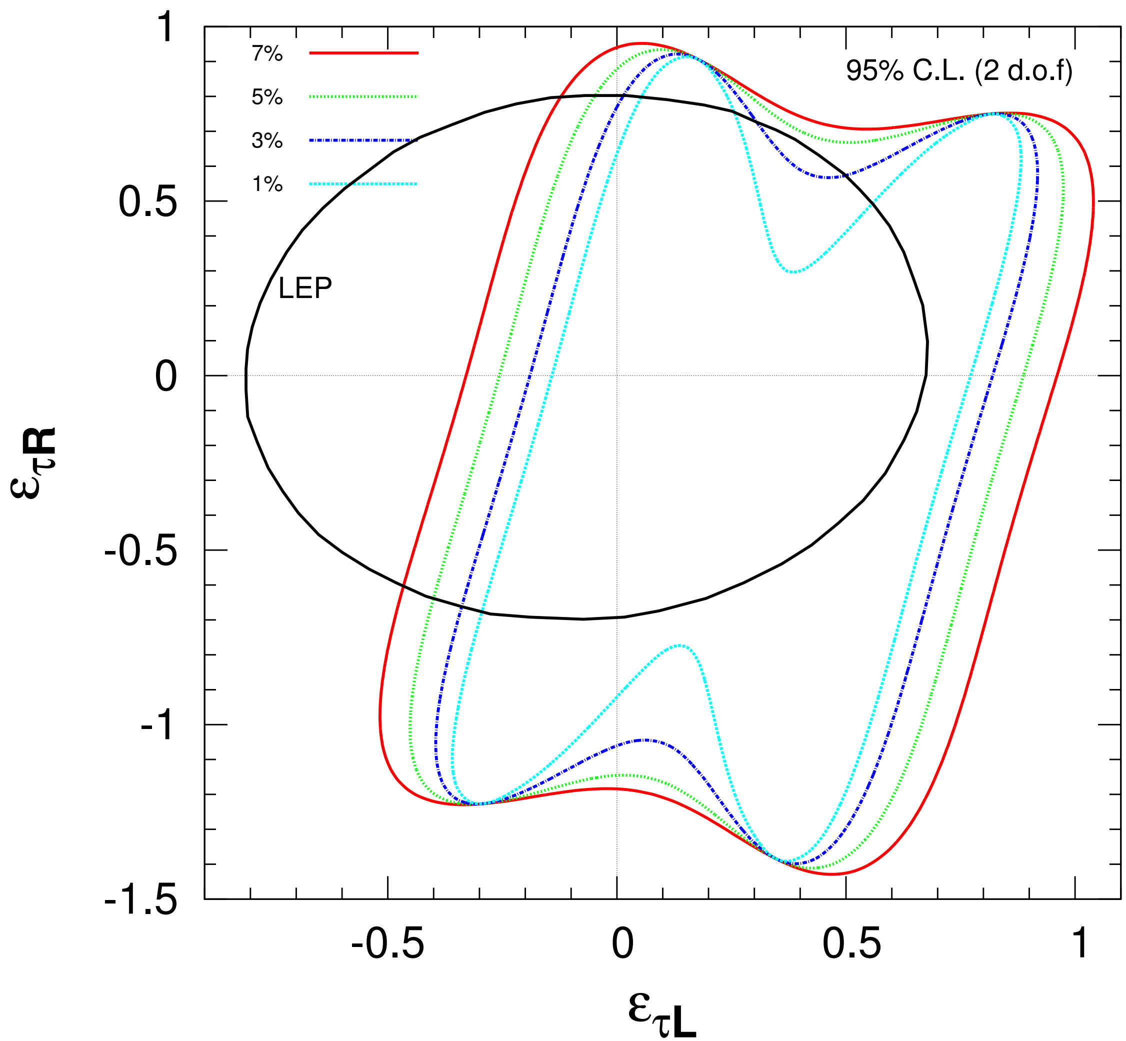
The area outside each contour is excluded

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

Constraints in the $\varepsilon_{\tau L} - \varepsilon_{\tau R}$ plane (Phase-I)



Agarwalla, Lombardi, Takeuchi, arXiv:1207.3492

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

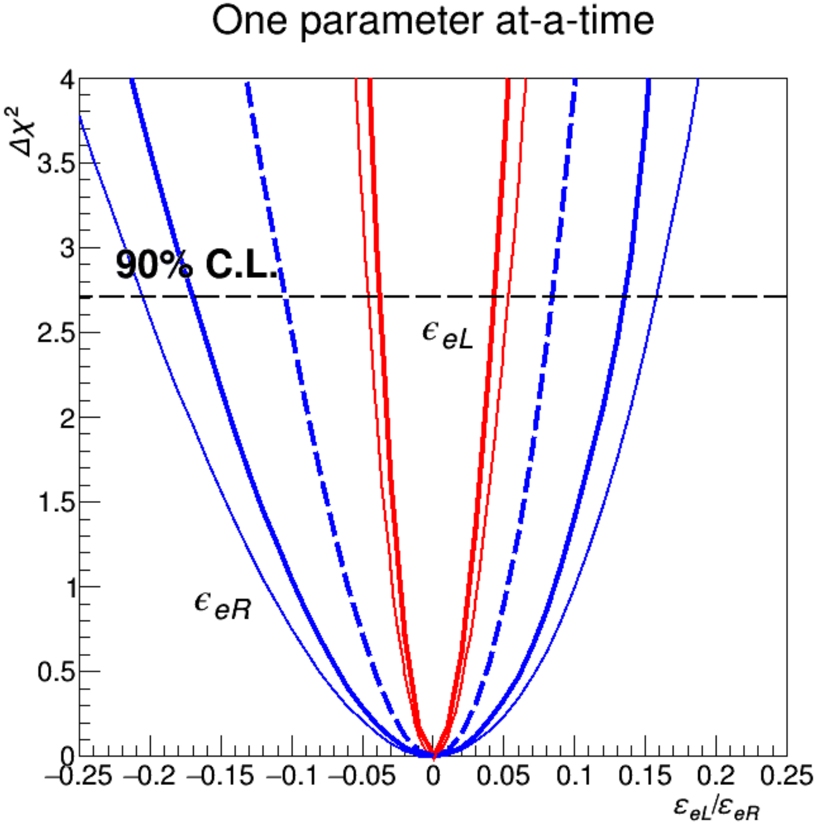
The area outside each contour is excluded

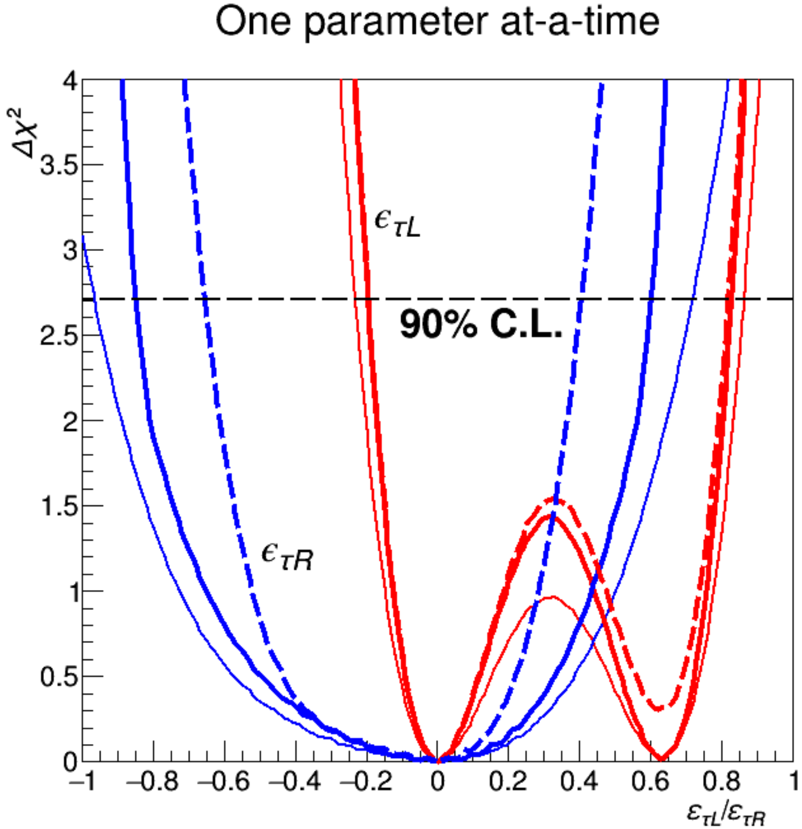
Several curves shown for different uncertainty levels in ^{7}Be signal normalization

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

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

Preliminary Results using Borexino Phase-II Data





Limits obtained Phase II **no** Kr-penalty		Phase II Kr-penalty	Analysis Phase I Kr-penalty JHEP 2012(12), p.79
ε_{eR}	[-0.196, 0.139]	**[-0.127, 0.073]**	[-0.206, 0.158]
ε_{eL}	[-0.043, 0.051]	[−0.044, 0.050]	[−0.046, 0.053]
$\varepsilon_{\tau R}$	[-0.844, 0.598]	**[−0.615, 0.364]**	[−0.976, 0.726]
$\varepsilon_{\tau L}$	[-0.224, 0.856]	[−0.224, 0.830]	[−0.231, 0.866]

Work in Progress with the Borexino Collaboration

Crucial Issues in Reactor Experiment and Possible Solutions

- **Problem: Statistics**

  Solution: Powerful Reactors (17.6 GW_{th}) and Large Detectors (80 ton at Far Site)

- **Problem: Reactor-related uncertainty**

  Solution: Far/Near relative measurement

- **Problem: Detector-related uncertainty**

  Solution: Multiple functional identical detectors (4 Near + 4 Far)

- **Problem: Background**

  Solution: Deep underground (860 m.w.e. at far site)

Key Features of three Reactor Experiments

Experiment	Double Chooz	Daya Bay	RENO
# of reactors (total power)	2 (9.4 GW)	3 (17.4 GW)	6 (16.8 GW)
Reactor configuration	2	3	6 inline
Detector configuration	1 near + 1 far	2 near + 1 far	1 near + 1 far
Baseline [m]	(400, 1050)	(364, 480, 1912)	(290, 1380)
Overburden [m.w.e.]	(120, 300)	(280, 300, 880)	(120, 450)
Target mass [ton]	(8.3, 8.3)	(40, 40, 80)	(16, 16)
Detector geometry	Cylindrical detector (Gd-LS, γ-catcher, buffer)		
Outer shield	0.5m of LS & 0.15 m of steel	2.5m water	1.5m of water
Muon veto system	LS & Scinti-Strip	Water Cerenkov & RPC	Water Cerenkov
Designed sensitivity (90% C.L.)	~0.03	~0.01	~0.02

Daya Bay Strategy: Go strong, big and deep!

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Probing non-standard interactions at Daya Bay

Sanjib Kumar Agarwalla,[a] Partha Bagchi,[a] David V. Forero[b,c] and Mariam Tórtola[b]

[a] *Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*

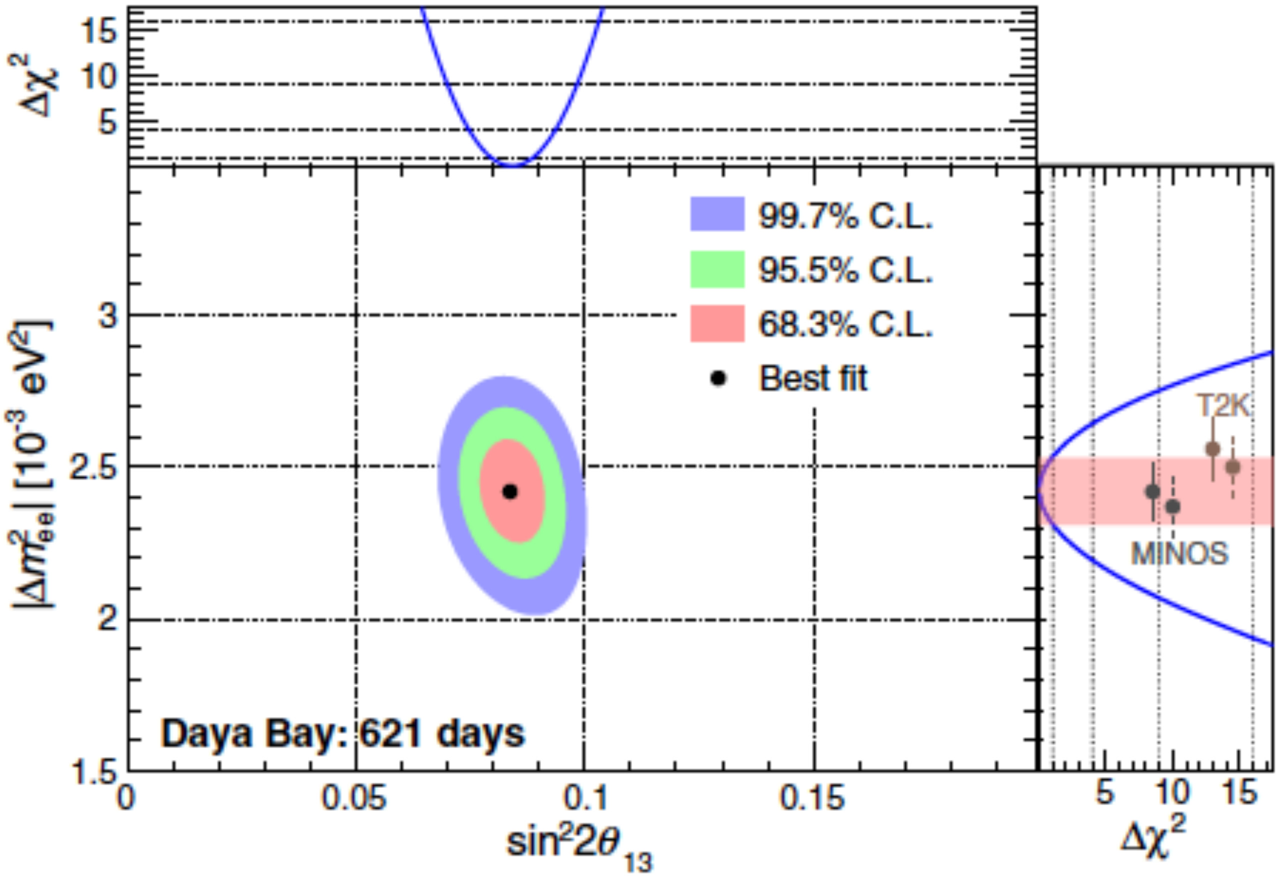
[b] *AHEP Group, Institut de Física Corpuscular — C.S.I.C./Universitat de València, Parc Cientific de Paterna, C/ Catedratico José Beltrán, 2 E-46980 Paterna (València), Spain*

[c] *Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061, U.S.A.*

E-mail: sanjib@iopb.res.in, partha@iopb.res.in, dvanegas@ific.uv.es, mariam@ific.uv.es

JHEP 07 (2015) 060, arXiv: 1412:0804 [hep-ph]
See also, Girardi and Meloni, PRD 90 (2014) 073011
Girardi, Meloni, Petcov, NPB 886 (2014) 31

Latest Oscillation Results from Daya Bay



Daya Bay Collaboration PRL 115, 111802 (2015)

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$

Precision in $\sin^2 2\theta_{13}$ ~ 6%

Precision in $|\Delta m^2_{ee}|$ ~ 4%

Neutrino Non-Standard Interactions

Given the production and detection neutrino processes involved in short-baseline reactor neutrino experiments (β-decay and inverse β-decay), the NSI parameters relevant for these experiments are $\varepsilon^{ud}_{e\alpha}$, i.e., the CC-NSI couplings between up and down quarks, positrons and antineutrinos of flavor α. In the literature we can find the following 90% C.L. bounds on these parameters

$$|\varepsilon^{ud,V}_{e\alpha}| < 0.041\,, \quad |\varepsilon^{ud,L}_{e\mu}| < 0.026\,, \quad |\varepsilon^{ud,R}_{e\mu}| < 0.037$$

$$\varepsilon^{ff',V}_{\alpha\beta} \;=\; \varepsilon^{ff',L}_{\alpha\beta} + \varepsilon^{ff',R}_{\alpha\beta}$$

coming from unitarity constraints on the CKM matrix as well as from the non-observation of neutrino oscillations in the NOMAD experiment.

Biggio, Blennow, Fernandez-Martinez, JHEP 0908 (2009) 090
See also, Davidson, Pena-Garay, Rius, Santamaria, JHEP 0303 (2003) 011

Re-define the neutrino flavor states in the presence of NSI

For the initial (at source) and final (at detector) neutrino flavor states:

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left(|\nu_\alpha\rangle + \sum_\gamma \varepsilon^s_{\alpha\gamma}|\nu_\gamma\rangle\right), \quad \langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left(\langle\nu_\beta| + \sum_\eta \varepsilon^d_{\eta\beta}\langle\nu_\eta|\right),$$

while the redefinition of the antineutrino flavor states is given by:

$$|\bar{\nu}_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left(|\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma}|\bar{\nu}_\gamma\rangle\right), \quad \langle\bar{\nu}_\beta^d| = \frac{1}{N_\beta^d}\left(\langle\bar{\nu}_\beta| + \sum_\eta \varepsilon^{d*}_{\eta\beta}\langle\bar{\nu}_\eta|\right).$$

The normalization factors required to obtain an orthonormal basis can be expressed as:

$$N_\alpha^s = \sqrt{[(1+\varepsilon^s)(1+\varepsilon^{s\dagger})]_{\alpha\alpha}}, \quad N_\beta^d = \sqrt{[(1+\varepsilon^{d\dagger})(1+\varepsilon^d)]_{\beta\beta}}$$

the neutrino mixing between flavor and mass eigenstates is given by

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle, \quad |\bar{\nu}_\alpha\rangle = \sum_k U_{\alpha k}|\bar{\nu}_k\rangle$$

Leitner, Malinsky, Roskovec, Zhang, JHEP 1112 (2011) 001

Normalization of the Neutrino States

The correct normalization of the neutrino states in presence of NSI is a very important point, required to obtain a total neutrino transition probability normalized to 1. However, one has to consider that when dealing with a non-orthonormal neutrino basis, the normalization of neutrino states will affect not only the neutrino survival probability but also the calculation of the produced neutrino fluxes and detection cross sections. In this case, as shown in Ref. [68], all the normalization terms coming from N^s_α and N^d_β will cancel while convoluting the neutrino oscillation probabilities, cross sections, and neutrino fluxes to estimate the number of events in a given experiment such as Daya Bay.

Ref: 68 Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP 0610 (2006) 084

Consider the following effective redefinition of neutrino and anti-neutrino states:

$$|\nu^s_\alpha\rangle_{\text{eff}} = |\nu_\alpha\rangle + \sum_\gamma \varepsilon^s_{\alpha\gamma}|\nu_\gamma\rangle, \quad \langle\nu^d_\beta|_{\text{eff}} = \langle\nu_\beta| + \sum_\eta \varepsilon^d_{\eta\beta}\langle\nu_\eta|$$

$$|\bar{\nu}^s_\alpha\rangle_{\text{eff}} = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma}|\bar{\nu}_\gamma\rangle, \quad \langle\bar{\nu}^d_\beta|_{\text{eff}} = \langle\bar{\nu}_\beta| + \sum_\eta \varepsilon^{d*}_{\eta\beta}\langle\bar{\nu}_\eta|$$

Effective anti-neutrino survival probability

$$P_{\bar{\nu}^s_\alpha \to \bar{\nu}^d_\beta} = |\langle \bar{\nu}^d_\beta| \exp(-i\, H\, L) |\bar{\nu}^s_\alpha\rangle|^2.$$

$$P_{\bar{\nu}^s_\alpha \to \bar{\nu}^d_\beta} = \sum_{j,k} Y^j_{\alpha\beta} Y^{k*}_{\alpha\beta} - 4 \sum_{j>k} \mathcal{R}\{Y^j_{\alpha\beta} Y^{k*}_{\alpha\beta}\} \sin^2\left(\frac{\Delta m^2_{jk} L}{4E}\right) + 2 \sum_{j>k} \mathcal{I}\{Y^j_{\alpha\beta} Y^{k*}_{\alpha\beta}\} \sin\left(\frac{\Delta m^2_{jk} L}{2E}\right),$$

where $\Delta m^2_{jk} = m^2_j - m^2_k$. In the case of standard oscillations, $Y^j_{\alpha\beta}$ is defined as:

$$Y^j_{\alpha\beta} \equiv U^*_{\beta j} U_{\alpha j}$$

In the presence of NSI, according to the re-definition of neutrino states

$$Y^j_{\alpha\beta} \equiv U^*_{\beta j} U_{\alpha j} + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma} U^*_{\beta j} U_{\gamma j} + \sum_\eta \varepsilon^{d*}_{\eta\beta} U^*_{\eta j} U_{\alpha j} + \sum_{\gamma,\eta} \varepsilon^{s*}_{\alpha\gamma} \varepsilon^{d*}_{\eta\beta} U^*_{\eta j} U_{\gamma j}$$

We adopt the following parameterization for the NSI couplings

$$\varepsilon^s_{e\gamma} \equiv |\varepsilon^s_{e\gamma}|\, e^{i\phi^s_{e\gamma}} \quad \text{and} \quad \varepsilon^d_{\eta e} \equiv |\varepsilon^d_{\eta e}|\, e^{i\phi^d_{\eta e}}$$

Effective anti-neutrino survival probability

$$P_{\bar{\nu}_e^s \to \bar{\nu}_e^d} = P^{\rm SM}_{\bar{\nu}_e \to \bar{\nu}_e} + P^{\rm NSI}_{\text{non-osc}} + P^{\rm NSI}_{\text{osc-atm}} + P^{\rm NSI}_{\text{osc-solar}}$$
$$+ \mathcal{O}\left[\varepsilon^3, s_{13}^3, \varepsilon^2 s_{13}, \varepsilon s_{13}^2, \varepsilon s_{13}\left(\frac{\Delta m^2_{21} L}{2E}\right), \varepsilon\left(\frac{\Delta m^2_{21} L}{2E}\right)^2, s_{13}^2\left(\frac{\Delta m^2_{21} L}{2E}\right)\right]$$

where the Standard Model (SM) contribution is given by

$$P^{\rm SM}_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\left(c_{12}^2 \sin^2\Delta_{31} + s_{12}^2 \sin^2\Delta_{32}\right) - c_{13}^4 \sin^2 2\theta_{12} \sin^2\Delta_{21}$$

with $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, and $\Delta_{ij} = \Delta m^2_{ij} L/4E$

$$P^{\rm NSI}_{\text{non-osc}} = 2\left(|\varepsilon^d_{ee}|\cos\phi^d_{ee} + |\varepsilon^s_{ee}|\cos\phi^s_{ee}\right) + |\varepsilon^d_{ee}|^2 + |\varepsilon^s_{ee}|^2 + 2|\varepsilon^d_{ee}||\varepsilon^s_{ee}|\cos(\phi^d_{ee} - \phi^s_{ee})$$

$$+ 2|\varepsilon^d_{ee}||\varepsilon^s_{ee}|\cos(\phi^d_{ee} + \phi^s_{ee}) + 2|\varepsilon^s_{e\mu}||\varepsilon^d_{\mu e}|\cos(\phi^s_{e\mu} + \phi^d_{\mu e}) + 2|\varepsilon^s_{e\tau}||\varepsilon^d_{\tau e}|\cos(\phi^s_{e\tau} + \phi^d_{\tau e})$$

Continued….

Effective anti-neutrino survival probability

$$
\begin{aligned}
P^{\rm NSI}_{\rm osc\text{-}atm} &= 2\Big\{ s_{13}s_{23}\left[|\varepsilon^s_{e\mu}|\sin(\delta-\phi^s_{e\mu}) - |\varepsilon^d_{\mu e}|\sin(\delta+\phi^d_{\mu e})\right] \\
&+\ s_{13}c_{23}\left[|\varepsilon^s_{e\tau}|\sin(\delta-\phi^s_{e\tau}) - |\varepsilon^d_{\tau e}|\sin(\delta+\phi^d_{\tau e})\right] \\
&-\ s_{23}c_{23}\left[|\varepsilon^s_{e\mu}||\varepsilon^d_{\tau e}|\sin(\phi^s_{e\mu}+\phi^d_{\tau e}) + |\varepsilon^s_{e\tau}||\varepsilon^d_{\mu e}|\sin(\phi^s_{e\tau}+\phi^d_{\mu e})\right] \\
&-\ c^2_{23}|\varepsilon^s_{e\tau}||\varepsilon^d_{\tau e}|\sin(\phi^s_{e\tau}+\phi^d_{\tau e}) - s^2_{23}|\varepsilon^s_{e\mu}||\varepsilon^d_{\mu e}|\sin(\phi^s_{e\mu}+\phi^d_{\mu e})\Big\}\sin\left(2\Delta_{31}\right) \\
&-\ 4\Big\{ s_{13}s_{23}\left[|\varepsilon^s_{e\mu}|\cos(\delta-\phi^s_{e\mu}) + |\varepsilon^d_{\mu e}|\cos(\delta+\phi^d_{\mu e})\right] \\
&+\ s_{13}c_{23}\left[|\varepsilon^s_{e\tau}|\cos(\delta-\phi^s_{e\tau}) + |\varepsilon^d_{\tau e}|\cos(\delta+\phi^d_{\tau e})\right] \\
&+\ s_{23}c_{23}\left[|\varepsilon^s_{e\mu}||\varepsilon^d_{\tau e}|\cos(\phi^s_{e\mu}+\phi^d_{\tau e}) + |\varepsilon^s_{e\tau}||\varepsilon^d_{\mu e}|\cos(\phi^s_{e\tau}+\phi^d_{\mu e})\right] \\
&+\ c^2_{23}|\varepsilon^s_{e\tau}||\varepsilon^d_{\tau e}|\cos(\phi^s_{e\tau}+\phi^d_{\tau e}) + s^2_{23}|\varepsilon^s_{e\mu}||\varepsilon^d_{\mu e}|\cos(\phi^s_{e\mu}+\phi^d_{\mu e})\Big\}\sin^2\left(\Delta_{31}\right), \\
P^{\rm NSI}_{\rm osc\text{-}solar} &= 2\sin 2\theta_{12}\Delta_{21}\ \Big\{-c_{23}(|\varepsilon^s_{e\mu}|\sin\phi^s_{e\mu} + |\varepsilon^d_{\mu e}|\sin\phi^d_{\mu e}) \\
&+\ s_{23}(|\varepsilon^s_{e\tau}|\sin\phi^s_{e\tau} + |\varepsilon^d_{\tau e}|\sin\phi^d_{\tau e})\Big\}.
\end{aligned}
$$

Special case of NSI

Likewise the mechanisms responsible for production (via beta-decay) and detection (via inverse beta-decay) of reactor anti-neutrinos are just inverse of each other, this is also true for the associated NSIs: $\varepsilon^s_{e\gamma} = \varepsilon^{d*}_{\gamma e}$

It allows us to write: $\varepsilon^s_\gamma = \varepsilon^{d*}_\gamma \equiv |\varepsilon_\gamma| \mathrm{e}^{\mathrm{i}\phi_\gamma}$ (dropping the universal e index).
Now the effective survival probability takes the form:

$$
\begin{aligned}
P_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq\ & \underbrace{1 - \sin^2 2\theta_{13} \left(c^2_{12} \sin^2 \Delta_{31} + s^2_{12} \sin^2 \Delta_{32}\right) - c^4_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}}_{\text{Standard Model terms}} \\
& + \underbrace{4|\varepsilon_e| \cos\phi_e + 4|\varepsilon_e|^2 + 2|\varepsilon_e|^2 \cos 2\phi_e + 2|\varepsilon_\mu|^2 + 2|\varepsilon_\tau|^2}_{\text{non-oscillatory NSI terms}} \\
& - \underbrace{4\{s^2_{23}|\varepsilon_\mu|^2 + c^2_{23}|\varepsilon_\tau|^2 + 2 s_{23} c_{23} |\varepsilon_\mu||\varepsilon_\tau| \cos(\phi_\mu - \phi_\tau)\} \sin^2 \Delta_{31}}_{\text{oscillatory NSI terms}} \\
& - \underbrace{4\{2 s_{13} [s_{23} |\varepsilon_\mu| \cos(\delta - \phi_\mu) + c_{23} |\varepsilon_\tau| \cos(\delta - \phi_\tau)]\} \sin^2 \Delta_{31}}_{\text{oscillatory NSI terms}} .
\end{aligned}
$$

(keeping the terms up-to the second order in small quantities)

Special case of NSI

Lepton number conserving *universal* NSI parameters which do not depend on flavor. In this case, we have $|\varepsilon_e| = |\varepsilon_\mu| = |\varepsilon_\tau| = |\varepsilon|$ and $\phi_e = \phi_\mu = \phi_\tau = \phi$ and the probability in Eq. (2.17) takes the form:

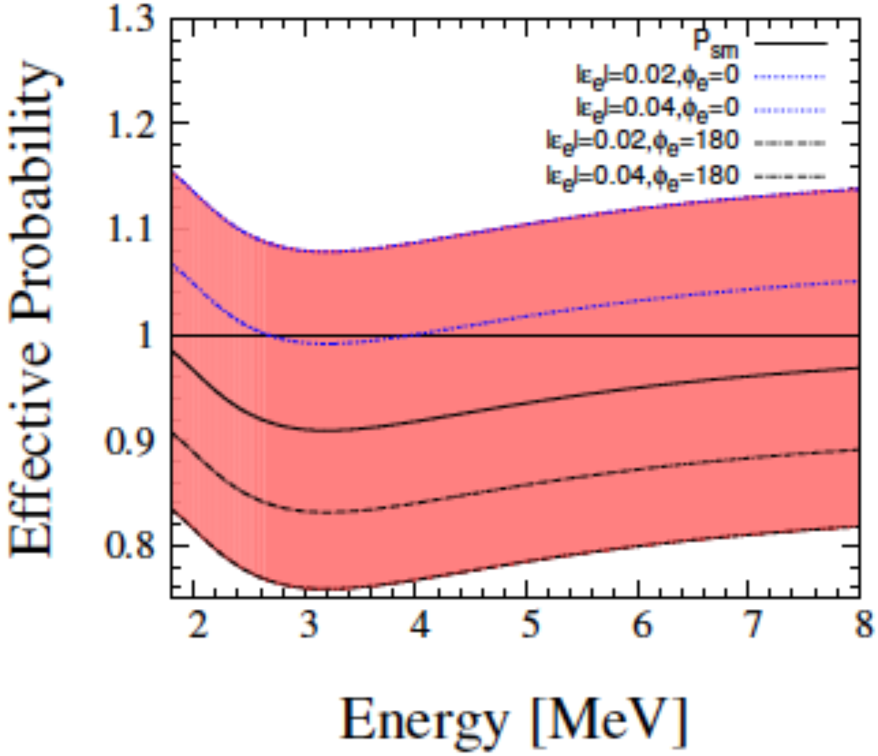
$$P^{\text{NSI-}\alpha}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq P^{\text{SM}}_{\bar{\nu}_e \to \bar{\nu}_e} + 4|\varepsilon|\cos\phi + 2|\varepsilon|^2 (4 + \cos 2\phi) - 4\{|\varepsilon|^2 + 2 s_{23} c_{23} |\varepsilon|^2 + 2 s_{13} |\varepsilon| \cos(\delta - \phi)(s_{23} + c_{23})\} \sin^2 \Delta_{31} . \quad (2.24)$$

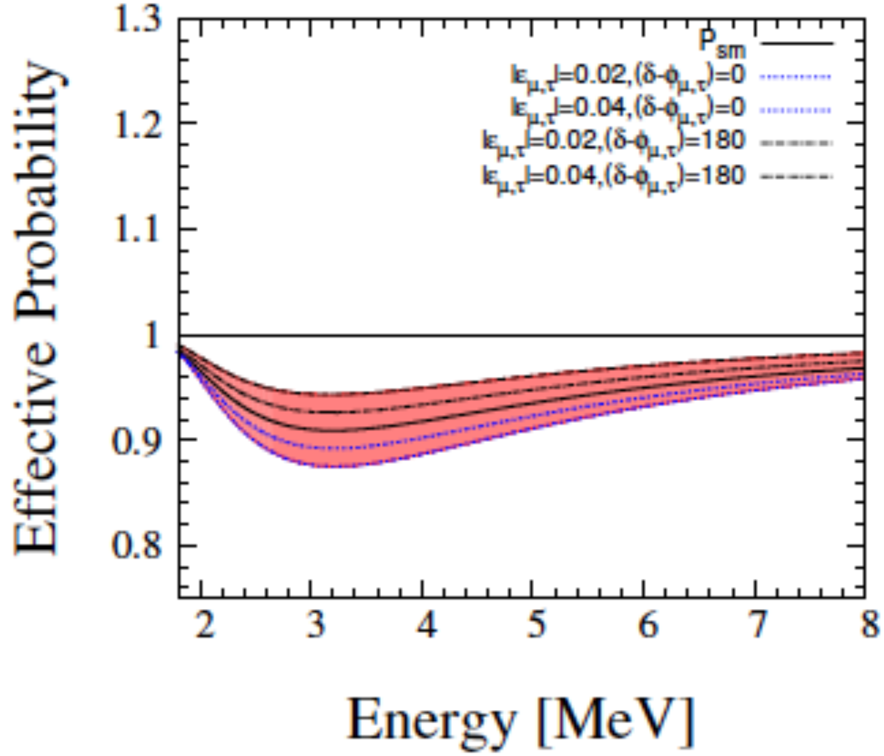
In this case, the effective mixing angle in the presence of oscillatory and non-oscillatory NSI terms will be given by:

$$\tilde{s}^2_{13} \approx s^2_{13} - |\varepsilon| \left[\frac{\cos\phi}{\sin^2 \Delta_{31}} - 2 s_{13} (s_{23} + c_{23}) \cos(\delta - \phi) \right] . \quad (2.25)$$

Parameter	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\Delta m^2_{21}(\text{eV}^2)$	$\Delta m^2_{31}(\text{eV}^2)$	δ
Value	0.32	0.5	0.023	7.6×10^{-5}	2.55×10^{-3}	$0 - 2\pi$

Effective probability for the electron and muon/tau-NSI couplings



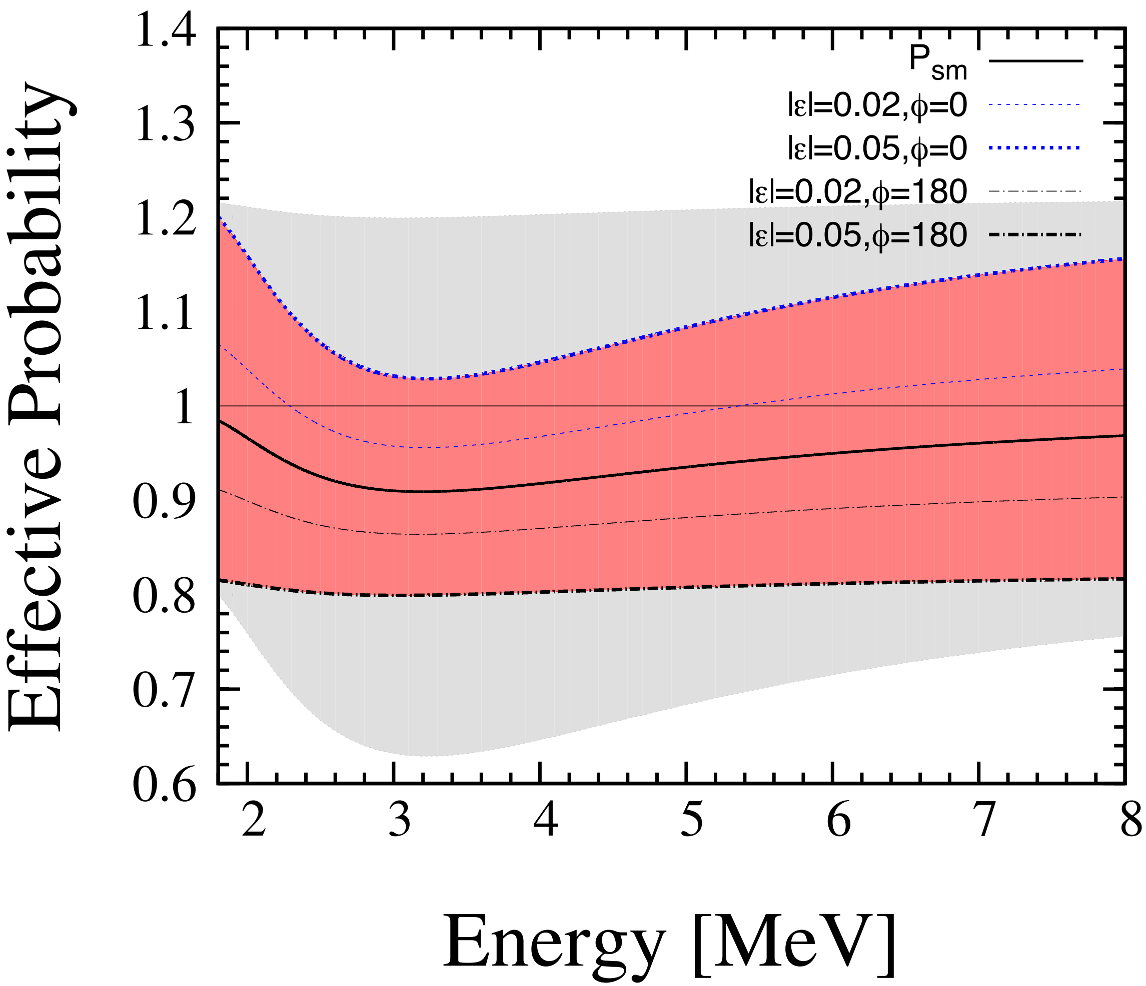


L = 1.58 km

Band is due to
$|\epsilon_e|$ in the range [0, 0.04]
ϕ_e in the range [-π to +π]

Band is due to
$|\epsilon_{\mu,\tau}|$ in the range [0, 0.04]
δ-$\phi_{\mu,\tau}$ in the range [-π to +π]

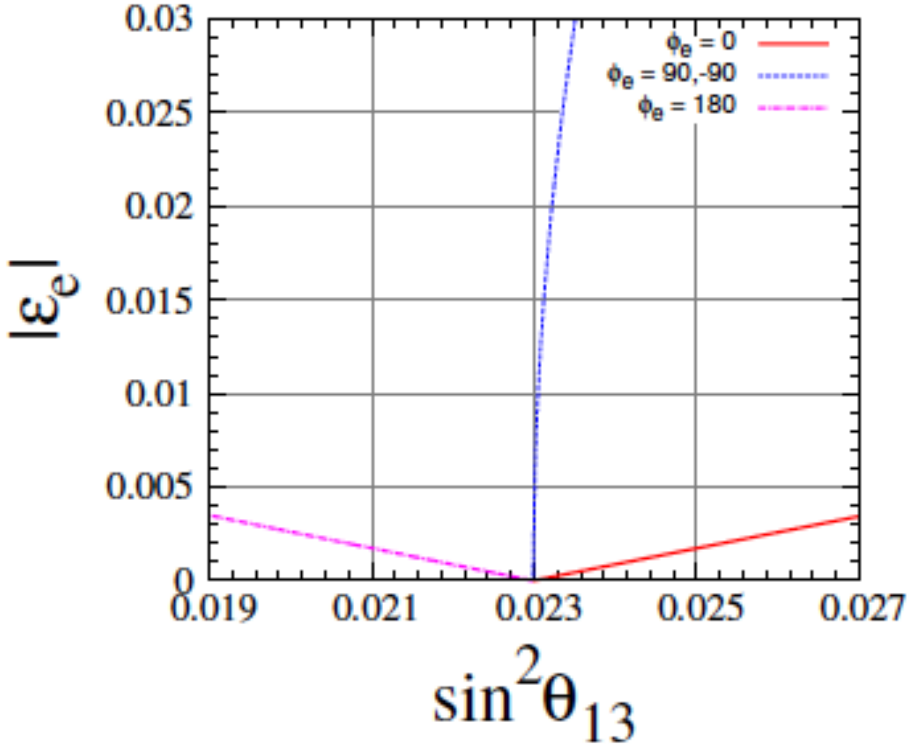
Effective Probability for the flavor-universal NSI case

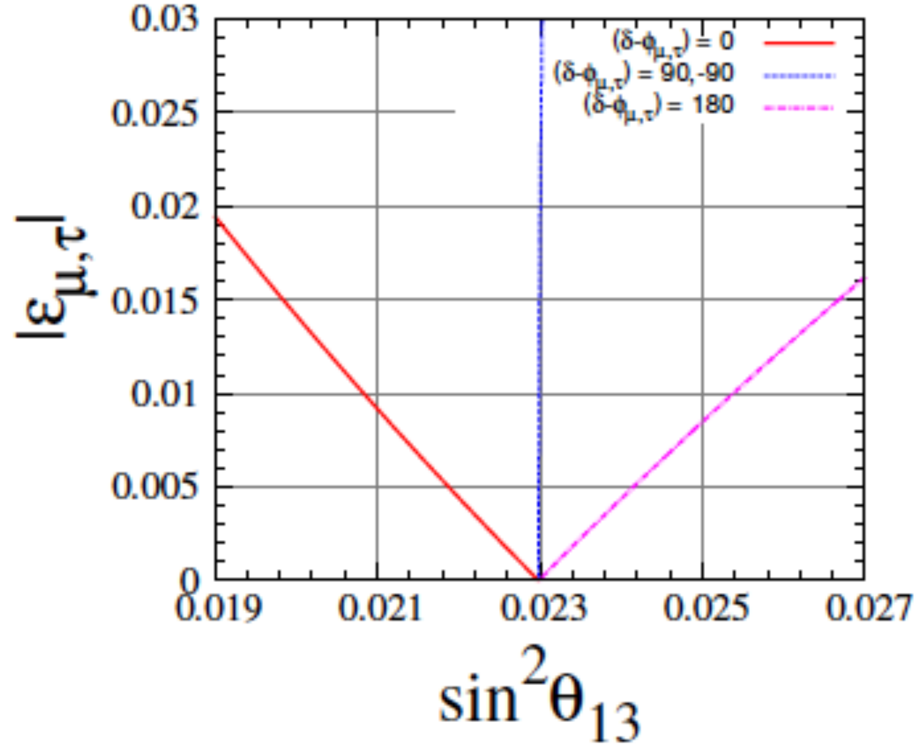


Dark salmon region:
|ε| in the range [0, 0.05]
ϕ in the range [-π to +π]

Light grey region:
along with |ε| & ϕ, vary
δ in the range [-π to +π]

Correlations between NSI parameters and θ_{13}: iso-probability plots

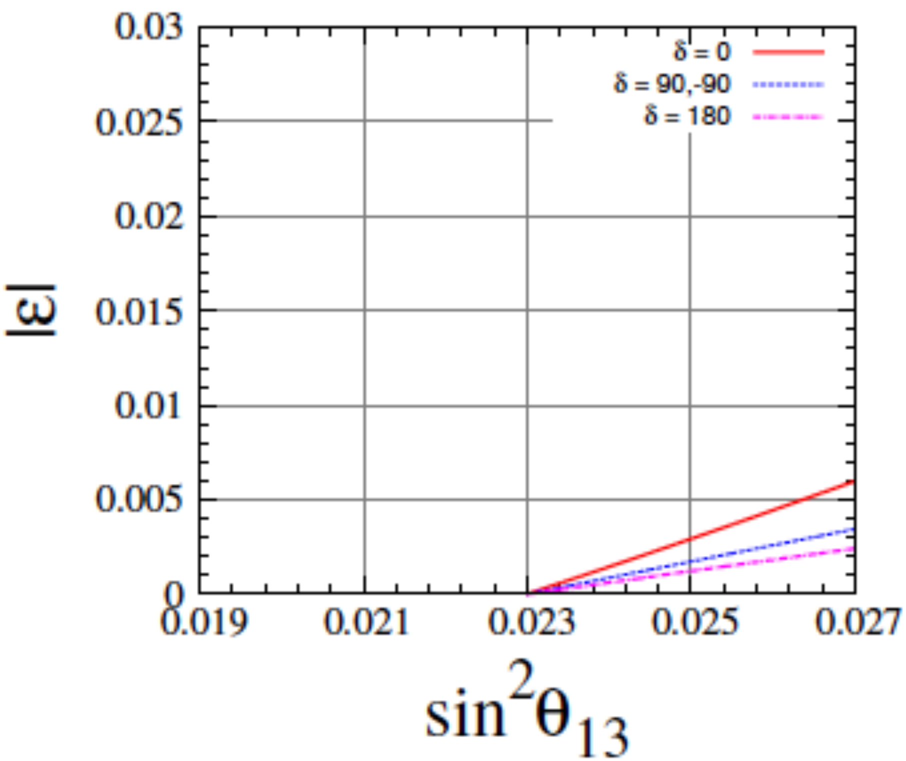


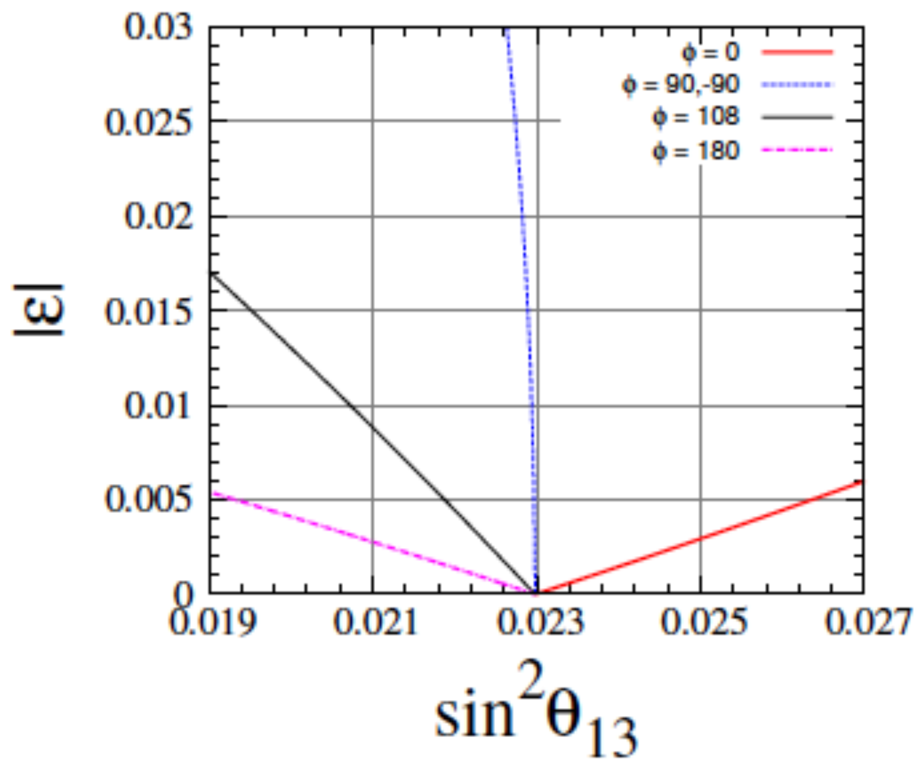


Best-fit:
$\sin^2\theta_{13} = 0.023$, $|\varepsilon_e| = 0$

Best-fit:
$\sin^2\theta_{13} = 0.023$, $|\varepsilon_{\mu,\tau}| = 0$

Correlation between $\sin^2\theta_{13}$ & $|\varepsilon|$ for the flavor-universal NSI case





Best-fit:
$\sin^2\theta_{13} = 0.023$, $|\varepsilon| = 0$
($\phi = 0^o$ in the fit)

Best-fit:
$\sin^2\theta_{13} = 0.023$, $|\varepsilon| = 0$
($\delta = 0^o$ in the fit)

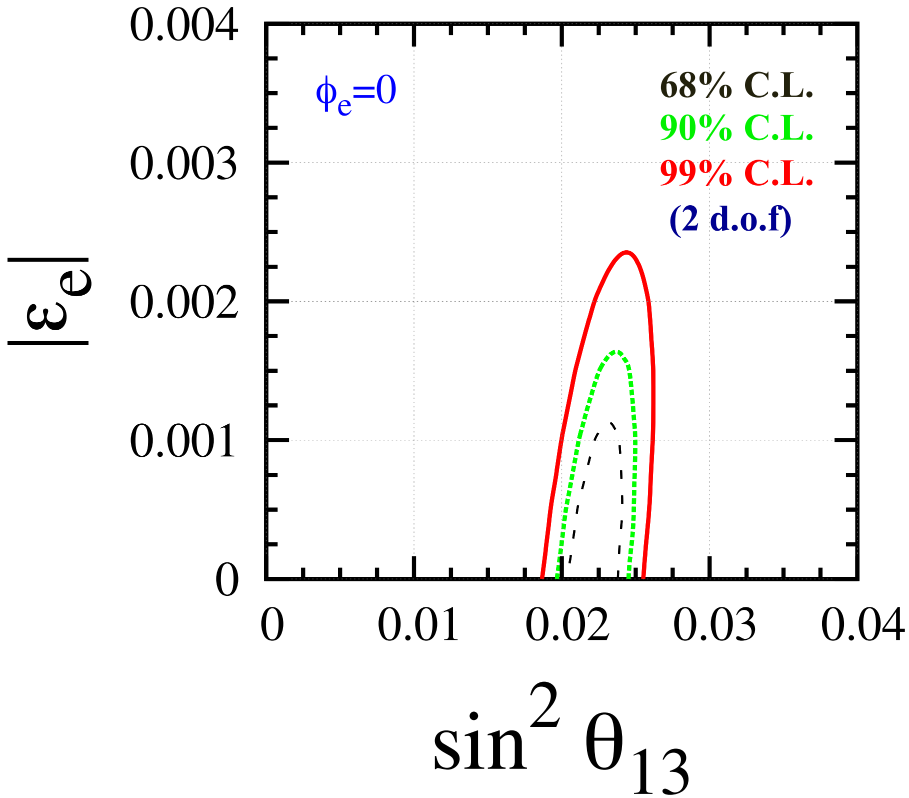
No. of IBD events due to all the reactors at the d-th detector:

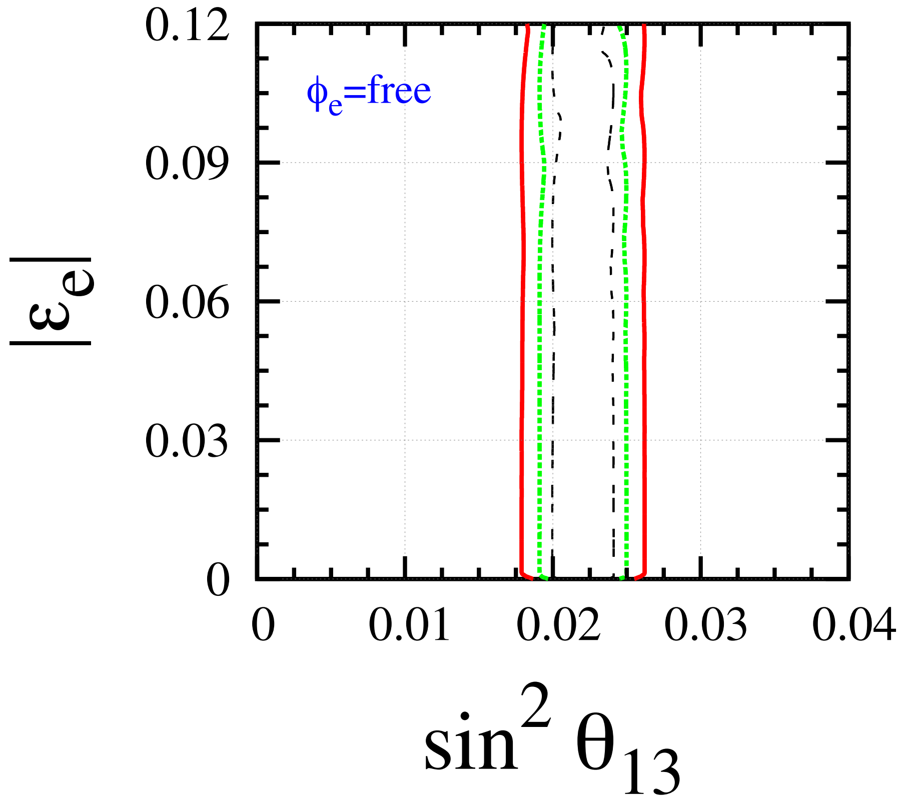
$$T_d = \sum_r T_{rd} = \\ = \sum_r \epsilon_d \frac{N_p}{4\pi L_{rd}^2} \frac{P_{th}^r}{\sum_k f_k \langle E_k \rangle} \sum_k f_k \int_0^\infty dE \, \Phi_k(E) \, \sigma_{IBD}(E) P_{ee}(E, L_{rd})$$

N_p = number of free protons in the target detector
P_{th}^r = reactor thermal power
ϵ_d = efficiency of the detector
$\langle E_k \rangle$ = energy release per fission for a given isotope k
f_k = fission fraction of k-th isotope
P_{ee} = survival probability
L_{rd} = distance from the r-th reactor to the d-th detector
$\Phi_k(E)$ = anti-neutrino flux prediction
$\sigma_{\rm IBD}(E_\nu)$ = inverse beta-decay cross-section

Constraints on electron-NSI couplings

621 days





$|\varepsilon_e| \leq 1.2 \times 10^{-3} \quad (90\%\,\text{C.L.})$

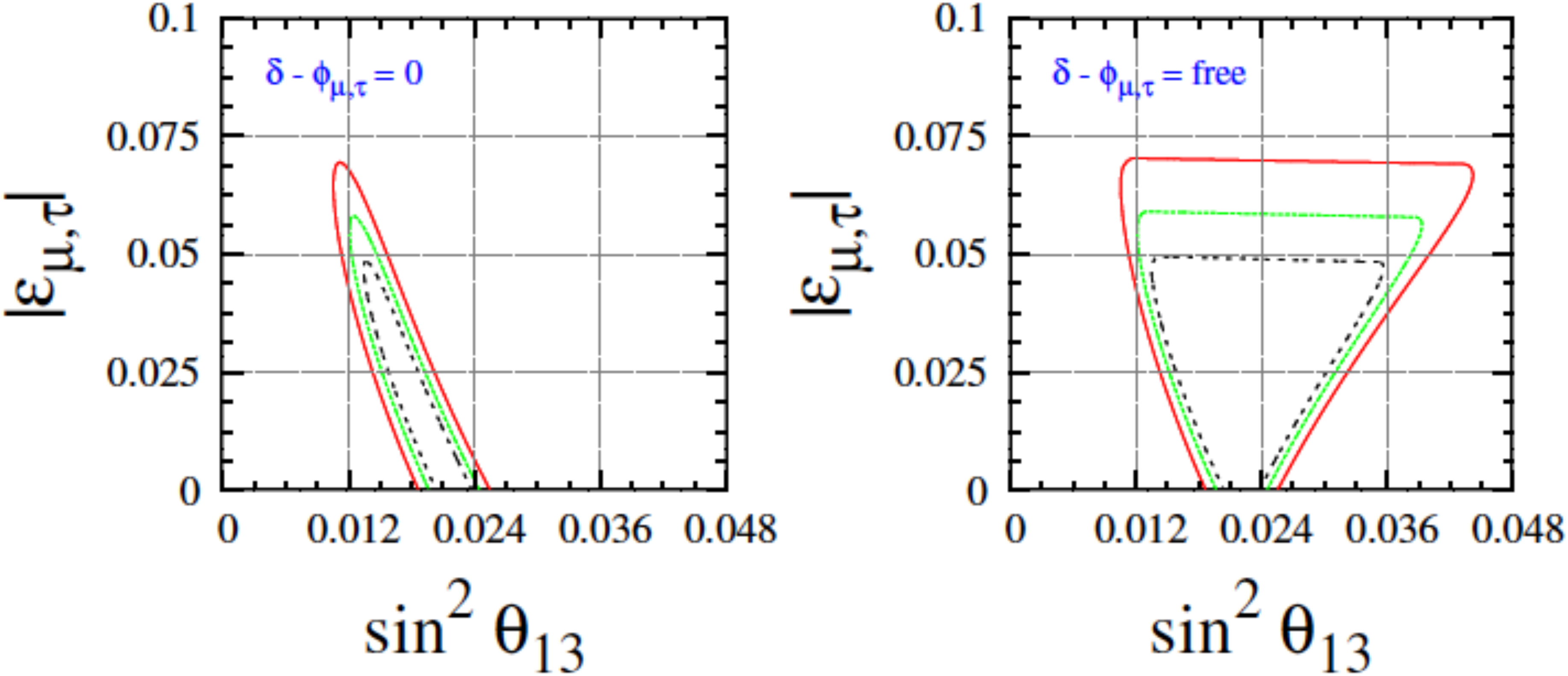
$|\varepsilon_e|$ unbound

(One order of magnitude better bound)

Allowed range for θ_{13} : $0.020 \leq \sin^2\theta_{13} \leq 0.024 \quad (90\%\,\text{C.L.})$

Constraints on muon/tau-NSI couplings

621 days



$|\varepsilon_{\mu,\tau}| \leq 5.1 \times 10^{-2}$ (90% C.L.) $|\varepsilon_{\mu,\tau}| \leq 5.2 \times 10^{-2}$ (90% C.L.)

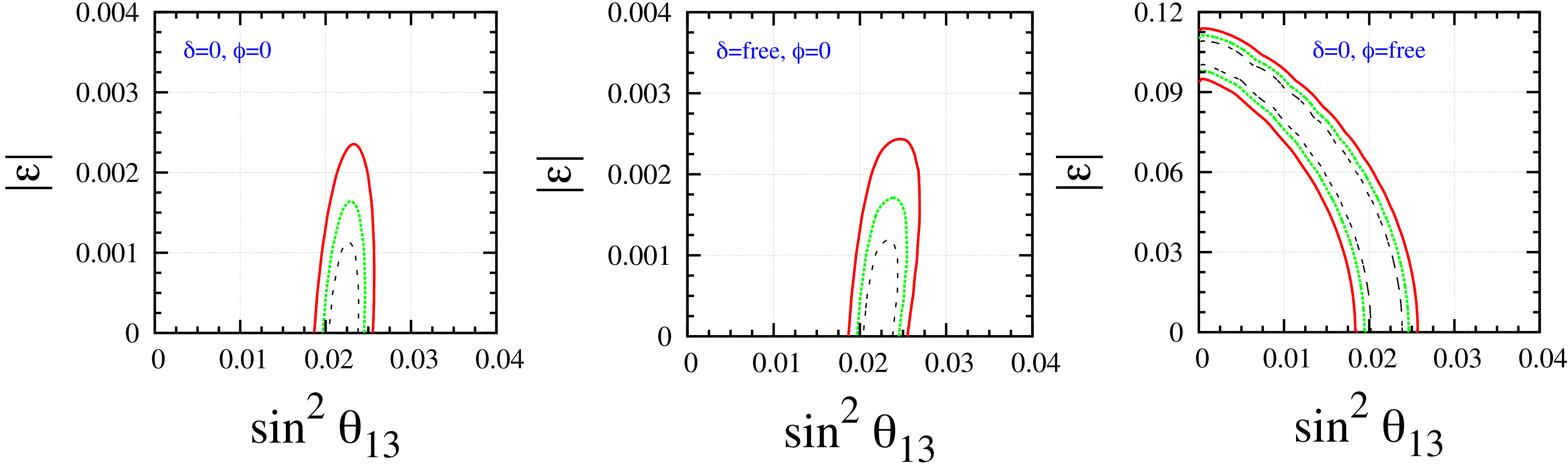
(Comparable to the present bound)

$0.013 \leq \sin^2\theta_{13} \leq 0.024$ (90% C.L.) $0.013 \leq \sin^2\theta_{13} \leq 0.036$ (90% C.L.)

Allowed range for θ_{13}

Constraints for the flavor-universal NSI case

621 days



$$|\varepsilon_e| = |\varepsilon_\mu| = |\varepsilon_\tau| = |\varepsilon| \text{ and } \phi_e = \phi_\mu = \phi_\tau = \phi$$

$\lvert\varepsilon\rvert \leq 1.2 \times 10^{-3}$	$\lvert\varepsilon\rvert \leq 1.3 \times 10^{-3}$	$\lvert\varepsilon\rvert \leq 1.1 \times 10^{-1}$
$0.020 \leq \sin^2\theta_{13} \leq 0.024$	$0.020 \leq \sin^2\theta_{13} \leq 0.025$	$\sin^2\theta_{13} \leq 0.024$

All the quoted bounds are at 90% C.L. (1 d.o.f)

New Constraints on NSI from Daya Bay

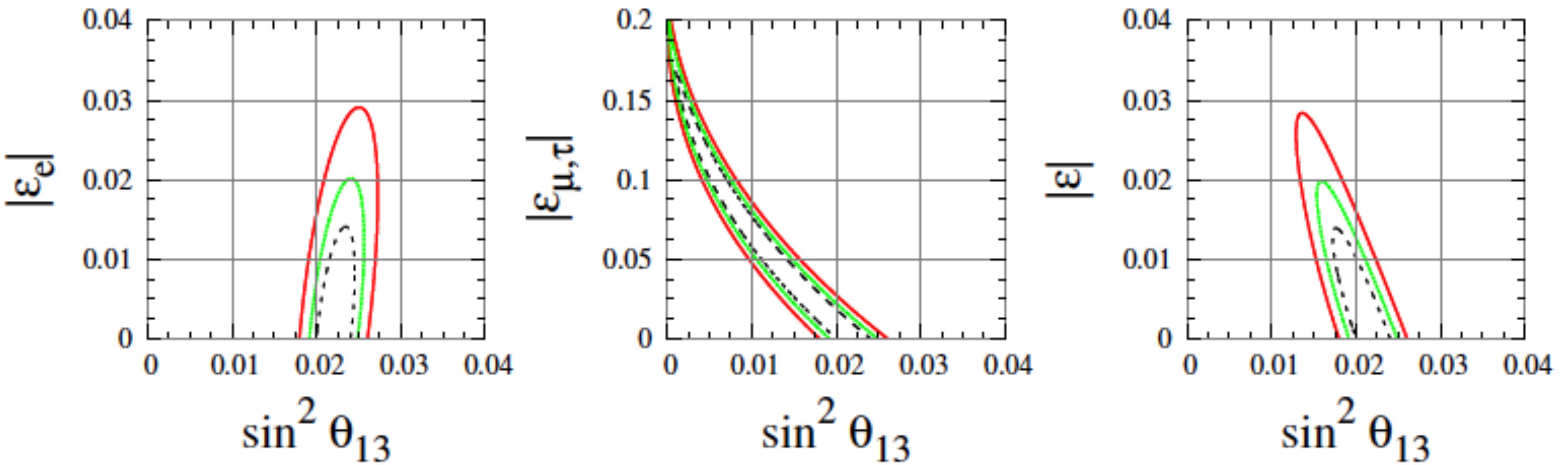
621 days

phases	$\sin^2\theta_{13}$	$\lvert\varepsilon\rvert$
electron-type NSI coupling		
$\phi_e = 0$	$0.020 \leq \sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon_e\rvert \leq 0.0012$
ϕ_e free	$0.020 \leq \sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon_e\rvert$ unbound
muon or tau-type NSI couplings		
$(\delta - \phi_{\mu,\tau}) = 0$	$0.013 \leq \sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.051$
$(\delta - \phi_{\mu,\tau})$ free	$0.013 \leq \sin^2\theta_{13} \leq 0.036$	$\lvert\varepsilon_{\mu,\tau}\rvert \leq 0.052$
universal NSI couplings		
$\delta = \phi = 0$	$0.020 \leq \sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon\rvert \leq 0.0012$
δ free, $\phi = 0$	$0.020 \leq \sin^2\theta_{13} \leq 0.025$	$\lvert\varepsilon\rvert \leq 0.0013$
$\delta = 0$, ϕ free	$\sin^2\theta_{13} \leq 0.024$	$\lvert\varepsilon\rvert \leq 0.110$

90% C.L. bounds (1 d.o.f.) without considering any uncertainty in the normalization of reactor event rates

New Constraints on NSI with 5% uncertainty on normalization

621 days



Case	$\sin^2\theta_{13}$	$\lvert\varepsilon\rvert$
$\phi_e = 0$	$0.020 \le \sin^2\theta_{13} \le 0.025$	$\lvert\varepsilon_e\rvert \le 0.015$
$(\delta - \phi_{\mu,\tau}) = 0$	$\sin^2\theta_{13} \le 0.024$	$\lvert\varepsilon_{\mu,\tau}\rvert \le 0.176$
$\delta = \phi = 0$	$0.017 \le \sin^2\theta_{13} \le 0.024$	$\lvert\varepsilon\rvert \le 0.015$

90% C.L. bounds (1 d.o.f.) with a 5% uncertainty on the total event rate

Comparing NSI bounds from 217 and 621 days of Daya Bay

621 days

Daya Bay data	$\sin^2\theta_{13}$	$\lvert\varepsilon\rvert$
electron-type NSI parameters		
Current (621 days)	$0.020 \le \sin^2\theta_{13} \le 0.024$	$\lvert\varepsilon_e\rvert \le 0.0012$
Previous (217 days)	$0.019 \le \sin^2\theta_{13} \le 0.027$	$\lvert\varepsilon_e\rvert \le 0.0024$
muon or tau-type NSI parameters		
Current (621 days)	$0.013 \le \sin^2\theta_{13} \le 0.024$	$\lvert\varepsilon_{\mu,\tau}\rvert \le 0.051$
Previous (217 days)	$0.011 \le \sin^2\theta_{13} \le 0.026$	$\lvert\varepsilon_{\mu,\tau}\rvert \le 0.070$
universal NSI parameters		
Current (621 days)	$0.020 \le \sin^2\theta_{13} \le 0.024$	$\lvert\varepsilon\rvert \le 0.0012$
Previous (217 days)	$0.019 \le \sin^2\theta_{13} \le 0.026$	$\lvert\varepsilon\rvert \le 0.0024$

Comparing NSI bounds from 217 and 621 days of Daya Bay