"Probing New Physics* in Low Energy Solar Neutrino Oscillation Data"

Amir Khan, Sun Yat-Sen University, China
Douglas McKay, University of Kansas, USA

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中山大學
SUN YAT-SEN UNIVERSITY

*Nonstandard Neutrino Interactions
** Preliminary

Content

- An short introduction to solar neutrinos
- Motivations for this work
- Formalism for the Nonstandard Interactions for solar neutrinos
- Calculated probabilities and cross sections with NSIs
- Application to the current results of solar experiments, e.g. Borexino
- Results and Analysis.
- Future prospects for the proposed experiments
- Summary & Conclusions

Solar Spectrum (review)

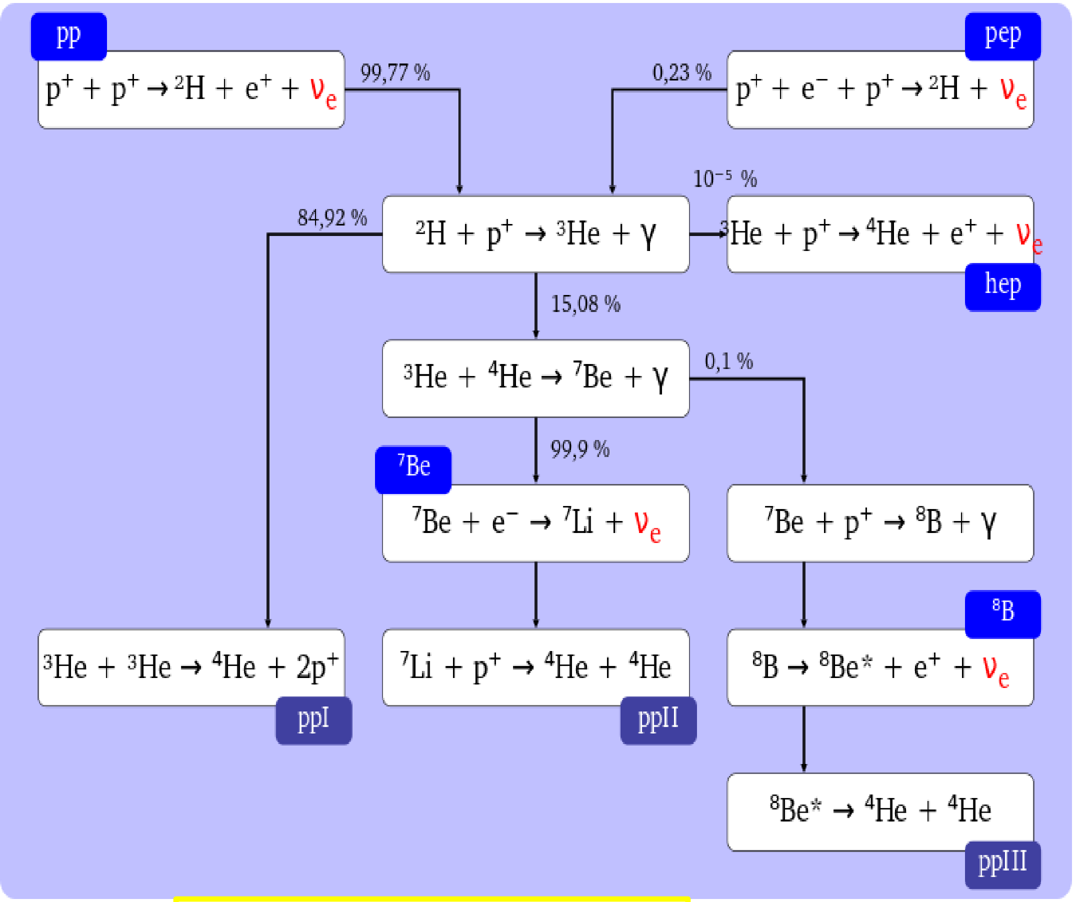
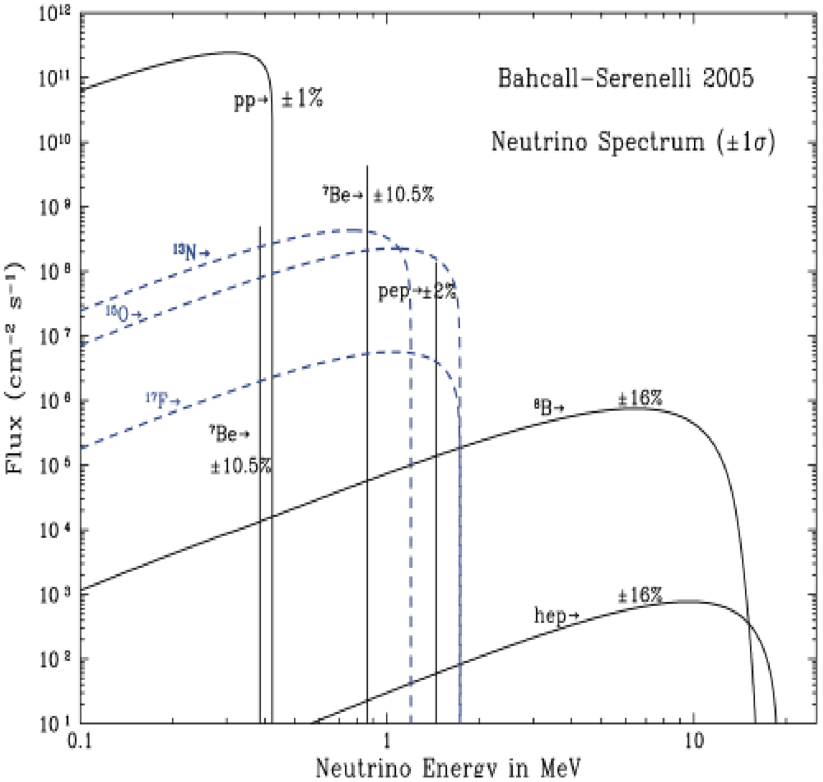


Figure from Wikipedia

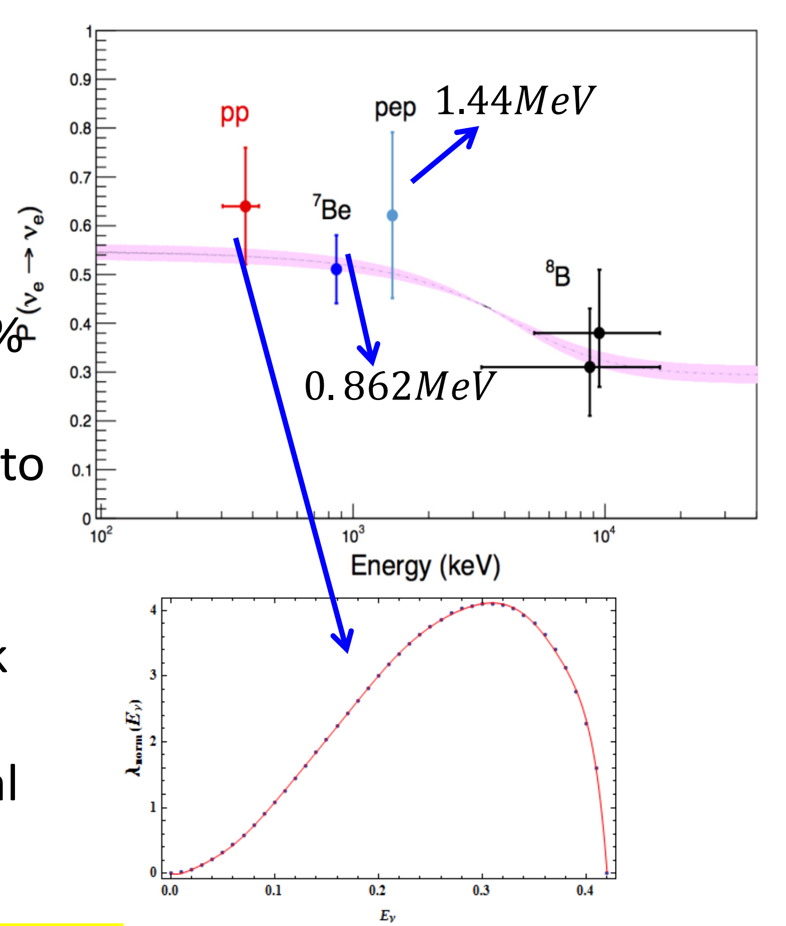


Some facts about Solar neutrinos

- Solar neutrinos have a long history:
  First discovery and creation of "*Solar neutrino problem (SNP)*".
  Homestake experiment(1970).
- SNP :1/3 discrepancy between Standard Solar Model and observations
- Confirmation: Kamiokande(1980s), GNO/GALLEX, SAGE and Super-Kamiokande (1990s)
- Solved in 2002 in SNO experiment ($^{8}B\ \upsilon_s$) due to Neutrino Oscillations (32 years!)
- Solar neutrinos of energy range: sub-MeV to several MeVs (low energies~ difficult detection)
- Complementary to the reactor neutrinos (Same energy range≈(0-10MeV), Reactor: $n \to p + e^- + \bar{\upsilon}_e$, Solar:$p \to n + e^+ + \upsilon_e$ disappearance experiments, similar detector detection techniques.....)
- Before Borexino their fluxes were known only indirectly by the radio-chemical experiments

Motivations for this work

- First time the real-time measurement of the pp[1], ^{7}Be[2] and pep[3] are possible at Borexino
- pp, ^{7}Be and pep are dominated by vacuum oscillations.
- We do take into account small corrections from the LMA-MSW solution (< 2% for pp, <4% for ^{7}Be and <8% for pep)
- Based on the above facts, it's the best source to probe the NSI effects at the Sun and detector and can ignore NSIs at propagation at Sun.
- In addition, its also ideal to estimate the weak mixing angle in the lowest energy regime to date, which o.w. is not possible in the artificial neutrino sources.



1. G, Bellini et al, (Borexino Collaboration) , Nature 512, 383, (2014)
2. G, Bellini et al, (Borexino Collaboration) , Phys. Rev. Lett. **107**, 141302 , (2011)
3. G, Bellini et al, (Borexino Collaboration) , Phys. Rev. Lett. **108**, 051302, (2012)

The Effective Interaction Lagrangian

Sun

Source

$$\mathcal{L}^s = \mathcal{L}^s{}_{NU} + \mathcal{L}^s{}_{FC}$$

$$\mathcal{L}^l = \mathcal{L}^l{}_{NU} + \mathcal{L}^l{}_{FC}$$

Detector

LS

$$\mathcal{L}^s{}_{NU} = -2\sqrt{2}G_F \sum_{a,\alpha} (1 + \varepsilon^{udL}_{\alpha\alpha}) \left(\bar{l}_\alpha \gamma_\lambda P_L U_{\alpha a} \upsilon_a\right) \left(\bar{d}\gamma^\lambda P_L u\right)^\dagger + h.c$$

$$\mathcal{L}^s{}_{FC} = -2\sqrt{2}G_F \sum_{a,\alpha\neq\beta} \varepsilon^{udL}_{\alpha\beta} \left(\bar{l}_\alpha \gamma_\lambda P_L U_{\beta a} \upsilon_a\right) \left(\bar{d}\gamma^\lambda P_L u\right)^\dagger + h.c$$

$$\mathcal{L}^l{}_{NU} = -2\sqrt{2}G_F \sum_{a,\alpha} \left(\bar{e}\gamma_\lambda (\tilde{g}_{\alpha R} P_R + (\tilde{g}_{\alpha L} + 1) P_L) e\right) \left(\bar{\upsilon}_\alpha \gamma^\lambda P_L \upsilon_\alpha\right)$$

$$\mathcal{L}^l{}_{FC} = -2\sqrt{2}G_F \sum_{a,\alpha\neq\beta} \varepsilon^{eP}_{\alpha\beta} \left(\bar{e}\gamma_\lambda P e\right) \left(\bar{\upsilon}_\alpha \gamma^\lambda P_L \upsilon_\beta\right)$$

$$\tilde{g}_{\alpha R} \equiv \sin^2\theta_W + \varepsilon^{eR}_{\alpha\alpha} \quad and \quad \tilde{g}_{\alpha L} \equiv \sin^2\theta_W - \frac{1}{2} + \varepsilon^{eL}_{\alpha\alpha}$$

G_F ≡Fermi Constant (a & α,β are mass and flavor indices, respectively)

$\varepsilon^{udL}_{\alpha\alpha}, \varepsilon^{udL}_{\alpha\beta}$ ≡ Semileptonic flavor conserving and flavor violating NSIs at source

$\varepsilon^{eR}_{\alpha\alpha}, \varepsilon^{eL}_{\alpha\alpha}, \varepsilon^{eR}_{\alpha\beta}, \varepsilon^{eL}_{\alpha\beta}$ ≡ Lepton flavor conserving and flavor violating NSIs at detector

NSIs at the Source (Sun)

Oscillation probability: (general)

$$P^{NSI}_{\alpha\beta} = |[(1+\varepsilon^{udL})UXU^{\dagger}]_{\alpha\beta}|^2$$

$U \equiv$ PMNS (Leptonic mixing matrix),

$X \equiv diag(1, \exp(-i2\pi L/L^{osc}_{21}), \exp(-i2\pi L/L^{osc}_{31}))$, ……..(Oscillation phase matrix)

$L^{osc}_{ab} \equiv 4\pi E/(m_a^2 - m_b^2)$ ……….(Oscillation length)

Average oscillation probability: (Average over an oscillation length)

$$< P >^{NSI}_{ee} = (1 + 2Re\varepsilon^{udL}_{ee} + |\varepsilon^{udL}_{ee}|^2) < P >^{SMM}_{ee} - (\cos\theta_{23}\,\varepsilon_-)\cos^3\theta_{13}\sin 2\theta_{12}\cos 2\theta_{12} + (\cos\theta_{23}\,\varepsilon_+)(\frac{1}{2}\cos^2\theta_{13}\sin 2\theta_{13}\sin^2 2\theta_{12} - \sin 2\theta_{13}\cos 2\theta_{13}),$$

where,

$$< P >^{SMM}_{ee} = (\cos\theta_{12}\cos\theta_{13})^4 + (\sin\theta_{12}\cos\theta_{13})^4 + (\sin\theta_{13})^4$$

$$\cos\theta_{23}\,\varepsilon_+ \equiv |\varepsilon^{udL}_{e\mu}|\cos(\phi_{e\mu} + \delta_{CP})\sin\theta_{23} + |\varepsilon^{udL}_{e\tau}|\cos(\phi_{e\tau} + \delta_{CP})\cos\theta_{23}$$

$$\cos\theta_{23}\,\varepsilon_- \equiv |\varepsilon^{udL}_{e\mu}|\cos\phi_{e\mu}\cos\theta_{23} - |\varepsilon^{udL}_{e\tau}|\cos(\phi_{e\tau})\sin\theta_{23}$$

No energy dependence!

Khan,McKay&Tahir, PhysRevD.88.113006 (2013)

NSIs at the Solar Detector

$\upsilon_e e$ – Cross section, $\upsilon_e e \rightarrow \upsilon_\alpha e$, $\alpha = e, \mu, \tau$

Khan,McKay&Tahir Phys Rev D.90.053008 (2014)

Amir Khan , Phys Rev D.93.093019 (2016)

$$[\sigma(\upsilon_e e)]_{SM+NSI} = \frac{2G_F^2 m_e}{\pi} T_{max}[(\tilde{g}_{eL}+1)^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eL}|^2 + ((\tilde{g}_{eR})^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eR}|^2)(1 - \frac{T_{max}}{E_\upsilon} + \frac{1}{3}(\frac{T_{max}}{E_\upsilon})^2)) - (\tilde{g}_{eL}+1)\tilde{g}_{eR} + \sum_{\alpha\neq e} Re[(\varepsilon_{\alpha e}^{eL})^* \varepsilon_{\alpha e}^{eR}]) \frac{m_e T_{max}}{2E_\upsilon^2}]$$

$$|\varepsilon_{\alpha e}^{eL}||\varepsilon_{\alpha e}^{eR}|\cos(\phi_{\alpha e}^{eL} - \phi_{\alpha e}^{eR})$$

$\upsilon_{\mu,\tau} e$ – Cross sections, $\upsilon_{\mu,\tau} e \rightarrow \upsilon_\alpha e$, $\alpha = e, \mu, \tau$

Detector NSI phases

$$[\sigma(\upsilon_{\mu,\tau} e)]_{SM+NSI} = \frac{2G_F^2 m_e}{\pi} T_{max}[(\tilde{g}_{\mu,\tau L})^2 + \sum_{\alpha\neq\mu,\tau}|\varepsilon_{\alpha\mu,\tau}^{eL}|^2 + ((\tilde{g}_{\mu,\tau R})^2 + \sum_{\alpha\neq\mu,\tau}|\varepsilon_{\alpha\mu,\tau}^{eR}|^2)(1 - \frac{T_{max}}{E_\upsilon} + \frac{1}{3}(\frac{T_{max}}{E_\upsilon})^2) - (\tilde{g}_{\mu,\tau L}\tilde{g}_{\mu,\tau R} + \sum_{\alpha\neq\mu,\tau} Re[(\varepsilon_{\alpha\mu,\tau}^{eL})^* \varepsilon_{\alpha\mu,\tau}^{eR}]) \frac{m_e T_{max}}{2E_\upsilon^2}]$$

$$|\varepsilon_{\alpha\mu,\tau}^{eL}||\varepsilon_{\alpha\mu,\tau}^{eR}|\cos(\phi_{\alpha\mu,\tau}^{eL} - \phi_{\alpha\mu,\tau}^{eR})$$

$T_{max} \equiv E_\upsilon/(1 + m_e/2E_\upsilon)$........(Recoiled Electron Energy)

$0 < E_\upsilon < 0.420\ MeV$ (pp-spectrum) $E_\upsilon = 0.862 MeV$ & $1.44 MeV$ (^{7}Be & pep-spectra)

The observable (Event Rates)

Expected counts of pp, ^{7}Be and pep at Borexino Detector

$$R_\upsilon = N_e \int_0^{E_{max}} dE_\upsilon \phi(E_\upsilon)\left([\sigma(\upsilon_e e)]_{SM+NSI} < P >_{ee}^{NSI} + \left[\sigma\left(\upsilon_{\mu,\tau} e\right)\right]_{SM+NSI}[1 - < P >_{ee}^{NSI}]\right)$$

Defined on the last two slides!

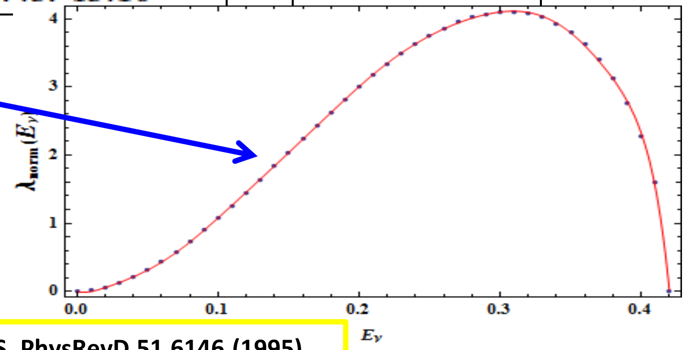
$N_e \equiv$ Target Electron $= 3.307 \times 10^{31}$

(for 100t of liquid scintillator at Borexino)

$$\phi_{pp}(E_\upsilon) \equiv \phi_{pp} \times {d\lambda(E_\upsilon)}/{dE_\upsilon}$$

$${d\lambda(E_\upsilon)}/{dE_\upsilon}|_{fit} \equiv \sum_1^{11} a_n (E_\upsilon)^n$$

a_1	-6.21914	a_5	$-6.82779.10^6$	a_9	$-1.39822.10^9$
a_2	835.245	a_6	$5.06675.10^7$	a_{10}	$1.49676.10^9$
a_3	-28352.1	a_7	$-2.41275.10^8$	a_{11}	$-6.91255.10^{11}$
a_4	573193	a_8	$7.3743.10^8$	—	—



BKS, PhysRevD.51.6146 (1995)

$\phi_{pp} \equiv 5.98 \times 10^{10} cm^{-2} s^{-1}$ ....(pp Flux)

$\phi_{^7Be} \equiv 5.00 \times 10^{9} cm^{-2} s^{-1}$ ....(^7Be Flux)

$\phi_{pep} \equiv 1.44 \times 10^{8} cm^{-2} s^{-1}$ ....(pep Flux)

The Statistical Model

$$\chi^2 = \sum_i \left(\frac{R_i^{exp} - R_i^{obs}}{\Delta_i^{stat}} \right)^2 \qquad i = pp, {}^7Be, pep$$

R_i^{exp} ≡Expected no. of events (cpd per 100 tons) including the LMA-MSW effects

Δ_i^{stat} ≡ The observed statistical uncertainty at Borexino for $pp, {}^7Be, pep$

R_{pp}^{obs} ≡$144 \pm 13(stat)$ ±10(sys) (cpd per 100 tons)

$R_{7Be}^{obs} \equiv 46 \pm 1.5(stat)$ ±1.55(sys) (………… //…………)

$R_{pep}^{obs} \equiv 3.1 \pm 0.6(stat)$ ±0.3(sys) (………… //…………)

Analysis Method

- For the SM fit, we set all NSI parameters to zero and fit the weak mixing angle to Borexino data of pp, ^{7}Be and pep spectra.

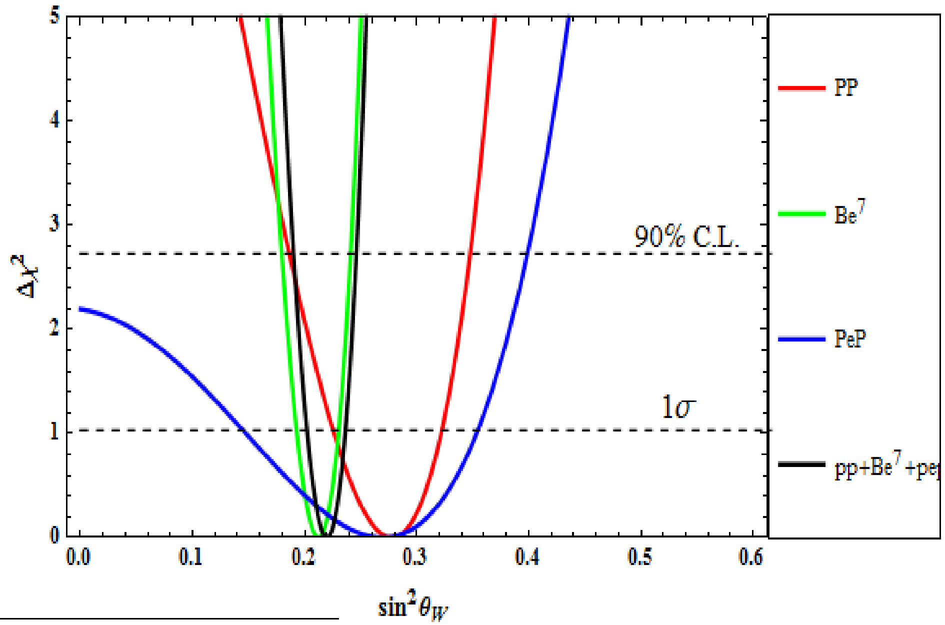
- For all NSI parameter fits, we perform two parameters space analysis, while set all the other parameters to zero, in the order Source-Only, Detector-Only and then Source vs. Detector. the two.

- For the whole NSIs analysis we assume the PDG-14 values of all the standard parameters to calculate the expected rates.

- All the two parameter regions are taken 68%, 90% and 95% C.L.

- The bounds are extracted in all of the above three cases at the 90%C.L.

The SM Fit: Lowest energy value to-date



Spectrum	Weak Mixing Angle
pp	0.28404±0.04796
^{7}Be	0.21873± 0.01862
pep	0.27654±0.10342
combined	0.22627±0.01702

~8% precision

This work

$\sin^2\theta_W = 0.249 \pm 0.020$ ← **Amir Khan , Phys. Rev. D 93, 093019 (2016)**

$\sin^2\theta_W = 0.254 \pm 0.024$ ← **J.F. Valle et al Physics Letters B. 76, 450 (2016)**

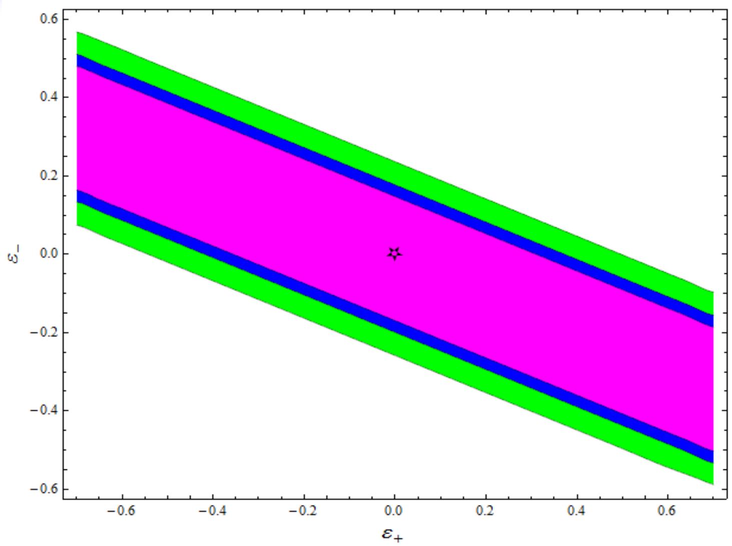
$\sin^2\theta_W = 0.2354 \pm 0.0015$

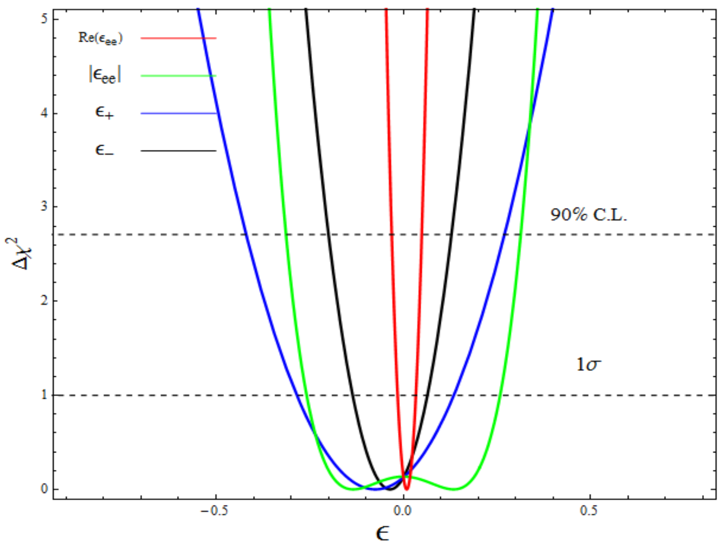
From parity violation measurement in ^{133}Cs at 2.4Mev.

$\sin^2\theta_W = 0.23126 \pm 0.00005$

PDG value (MS bar scheme)

Borexino Data: Source-Only NSIs





Bounds Comparison

NSI Para.	$\Re[\varepsilon_{ee}]$	$\|\varepsilon_{ee}\|$	ϵ_+	ϵ_-
Best Fits	0.009	0.13	−0.07	−0.04
Bounds	[-0.03, 0.05]	[-0.31,0.31]	[-0.41,0.27]	[-0.20,0.13]

This work at 90% C.L.

Table 4. Constraints on the detection NSI couplings at 90% of neutrinos with quarks

NSI parameters	Bounds	Ref.
ε^{dL}_{ee}	$(-0.3, 0.3)$	[40]
ε^{dR}_{ee}	$(-0.6, 0.5)$	[40]
$\varepsilon^{dL}_{\mu\mu}$	$(-0.005, 0.005)$	[69]
$\varepsilon^{dR}_{\mu\mu}$	$(-0.042, 0.025)$	[69]
$\varepsilon^{dL}_{\mu e}$	$(-0.023, 0.023)$	[69]
$\varepsilon^{dR}_{\mu e}$	$(-0.036, 0.036)$	[69]
$\varepsilon^{dL}_{e\tau}$	$(-0.5, 0.5)$	[40]
$\varepsilon^{dR}_{e\tau}$	$(-0.5, 0.5)$	[40]
$\varepsilon^{dL}_{\mu\tau}$	$(-0.023, 0.023)$	[69]
$\varepsilon^{dR}_{\mu\tau}$	$(-0.036, 0.036)$	[69]

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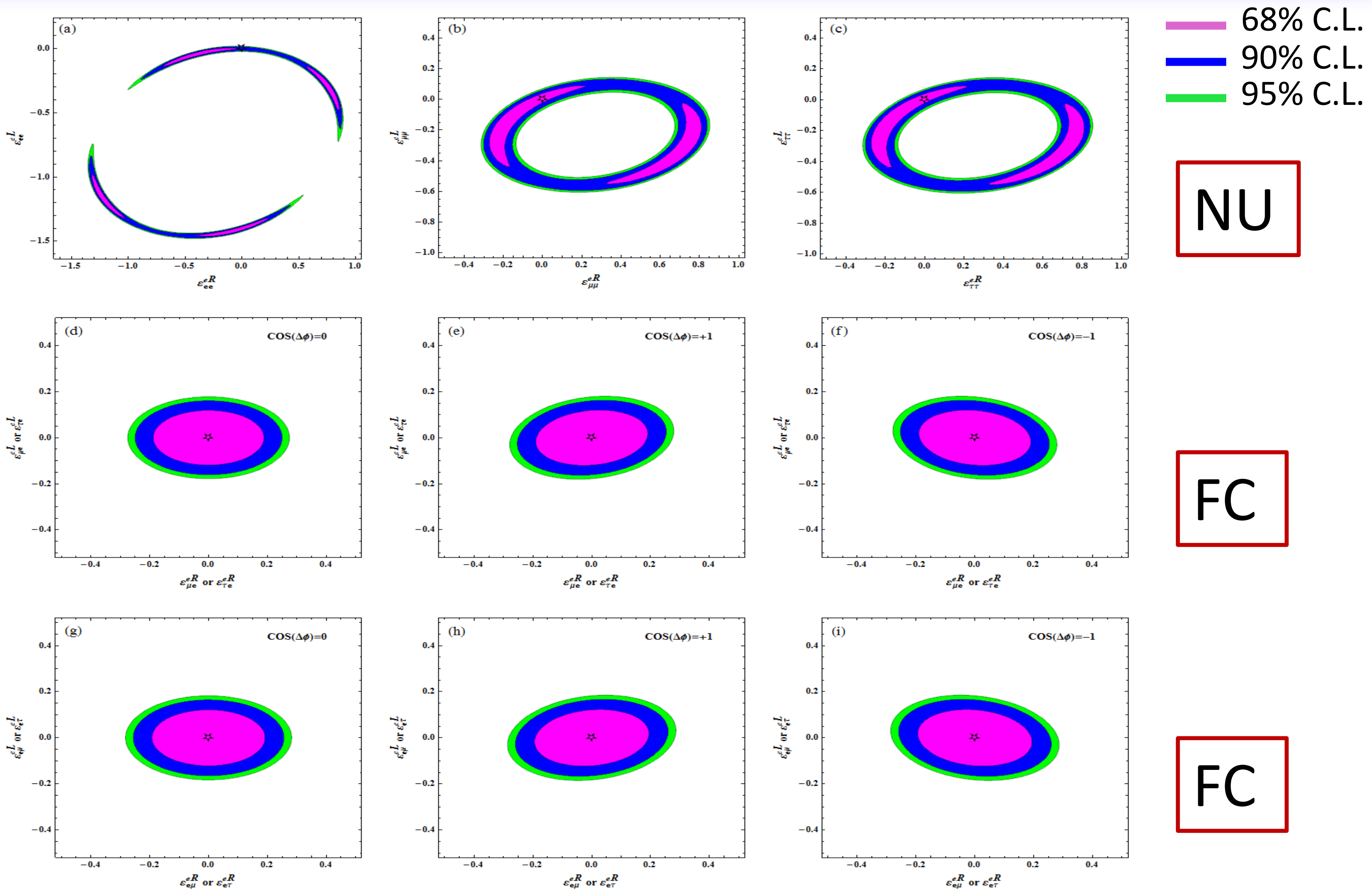
Borexino Data: Detector-Only NSIs



Detector-Only NSI Bounds @90% C.L.

NSI parameters	1-parameter	1-parameter	2-parameters	2-parameters
a	$\varepsilon_{ee}^{eL} \in [-0.017, 0.027]$	$\varepsilon_{ee}^{eR} \in [-0.33, 0.25]$	$\varepsilon_{ee}^{eL} \in [-0.55, 0.02]$	$\varepsilon_{ee}^{eR} \in [-0.80, 0.90]$
b	$\varepsilon_{\mu\mu}^{eL} \in [-0.06, 0.04]$	$\varepsilon_{\mu\mu}^{eR} \in [-0.10, 0.12]$	$\varepsilon_{\mu\mu}^{eL} \in [-0.61, 0.15]$	$\varepsilon_{\mu\mu}^{eR} \in [-0.33, 0.86]$
c	$\varepsilon_{\tau\tau}^{eL} \in [-0.06, 0.04]$	$\varepsilon_{\tau\tau}^{eR} \in [-0.10, 0.12]$	$\varepsilon_{\tau\tau}^{eL} \in [-0.61, 0.15]$	$\varepsilon_{\tau\tau}^{eR} \in [-0.33, 0.86]$
d	$\varepsilon_{\mu e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\mu e}^{eR} \in [-0.304, 0.304]$	$\varepsilon_{\mu e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\mu e}^{eR} \in [-0.304, -0.304]$
e	$\varepsilon_{\mu e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\mu e}^{eR} \in [-0.30, 0.30]$	$\varepsilon_{\mu e}^{eL} \in [-0.304, 0.304]$	$\varepsilon_{\mu e}^{eR} \in [-0.312, 0.312]$
f	$\varepsilon_{\mu e}^{eL} \in [-0.197, 0.197]$	$\varepsilon_{\mu e}^{eR} \in [-0.30, 0.30]$	$\varepsilon_{\mu e}^{eL} \in [-0.204, 0.204]$	$\varepsilon_{\mu e}^{eR} \in [-0.312, 0.312]$
g	$\varepsilon_{\tau e}^{eL} \in [-0.192, 0.192]$	$\varepsilon_{\tau e}^{eR} \in [-0.30, 0.30]$	$\varepsilon_{\tau e}^{eL} \in [-0.192, 0.192]$	$\varepsilon_{\tau e}^{eR} \in [-0.30, 0.30]$
h	$\varepsilon_{\tau e}^{eL} \in [-0.192, 0.192]$	$\varepsilon_{\tau e}^{eR} \in [-0.30, 0.30]$	$\varepsilon_{\tau e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\tau e}^{eR} \in [-0.305, 0.305]$
i	$\varepsilon_{\tau e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\tau e}^{eR} \in [-0.30, 0.30]$	$\varepsilon_{\tau e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{\tau e}^{eR} \in [-0.305, 0.305]$

This work

Bounds Comparison

Table 3. Constraints on the detection NSI couplings at 90% C L. for the interaction of neutrinos with electrons

	one parameter		two parameter	
ε_{ee}^{eL}	$(-0.021, 0.052)$ [60]		$(-0.02, 0.09)$ [68]	$(-0.036, 0.063)$ [60]
ε_{ee}^{eR}	$(-0.07, 0.08)$ [114]	$(-0.08, 0.09)$ [115]	$(-0.11, 0.05)$ [68]	$(-0.10, 0.09)$ [115]
$\varepsilon_{\mu\mu}^{eL}$	$(-0.03, 0.03)$ [40]	$(-0.03, 0.03)$ [54]		$(-0.033, 0.055)$ [54]
$\varepsilon_{\mu\mu}^{eR}$	$(-0.03, 0.03)$ [40]	$(-0.03, 0.03)$ [54]		$(-0.040, 0.053)$ [54]
$\varepsilon_{\tau\tau}^{eL}$	$(-0.16, 0.11)$ [60]	$(-0.46, 0.24)$ [54]	$(-0.51, 0.34)$ [68]	$(-0.16, 0.11)$ [60]
$\varepsilon_{\tau\tau}^{eR}$		$(-0.25, 0.43)$ [54]	$(-0.35, 0.50)$ [68]	$(-0.4, 0.6)$ [54]
$\varepsilon_{e\mu}^{eL}$		$(-0.13, 0.13)$ [54]	$(-0.53, 0.53)$ [33]	
$\varepsilon_{e\mu}^{eR}$	$(-0.19, 0.19)$ [114]	$(-0.13, 0.13)$ [54]	$(-0.53, 0.53)$ [33]	
$\varepsilon_{e\tau}^{eL}$	$(-0.4, 0.4)$ [40]	$(-0.33, 0.33)$ [54]	$(-0.53, 0.53)$ [33]	
$\varepsilon_{e\tau}^{eR}$	$(-0.28, -0.05)$ and	$(0.05, 0.28)$ [54]	$(-0.53, 0.53)$ [33]	
	$(-0.19, 0.19)$ [114]			
$\varepsilon_{\mu\tau}^{eL}$	$(-0.1, 0.1)$ [40]	$(-0.1, 0.1)$ [54]	$(-0.53, 0.53)$ [33]	
$\varepsilon_{\mu\tau}^{eR}$	$(-0.1, 0.1)$ [40]	$(-0.1, 0.1)$ [54]	$(-0.53, 0.53)$ [33]	

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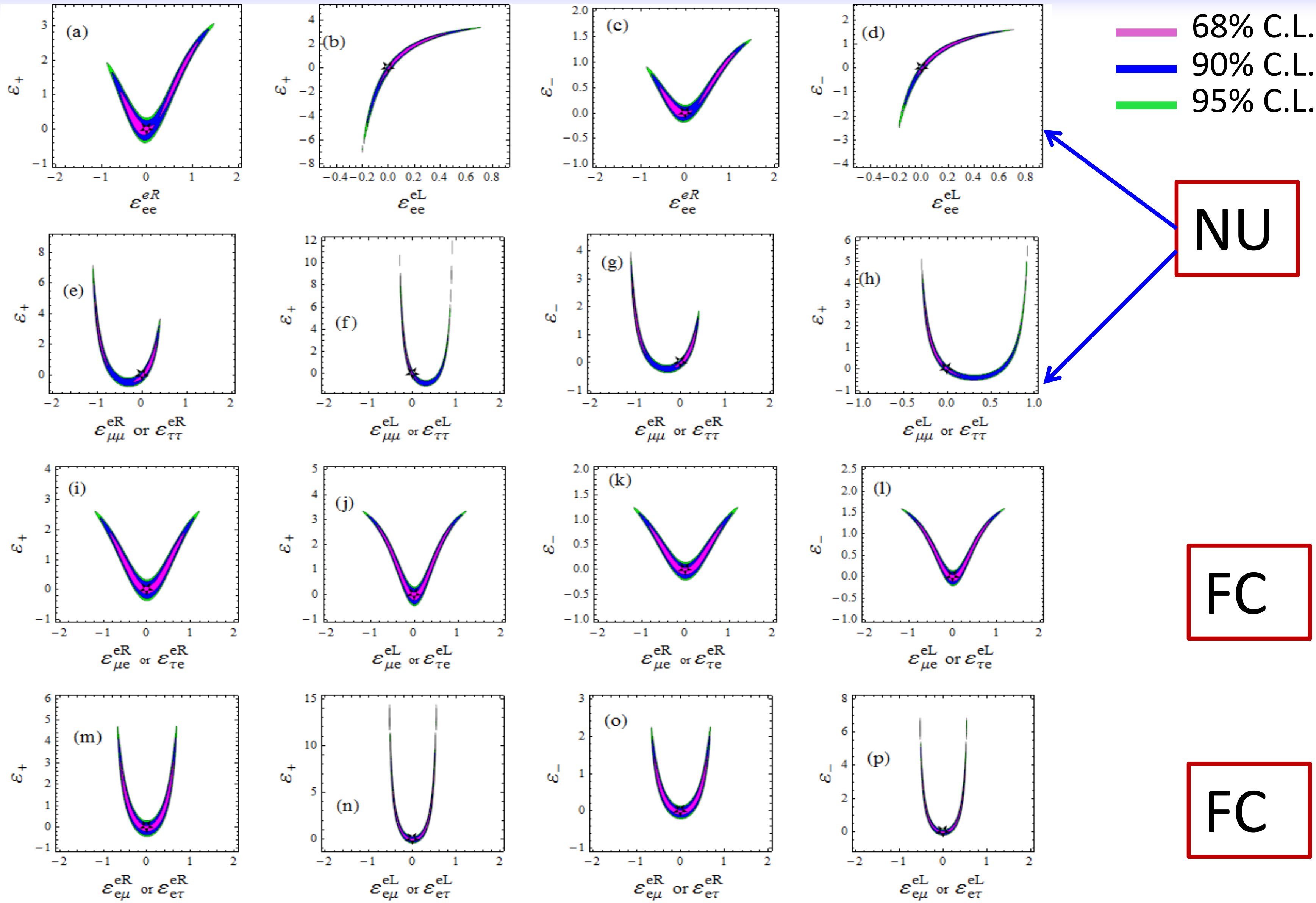
Borexino Data: Source vs. Det. NSIs



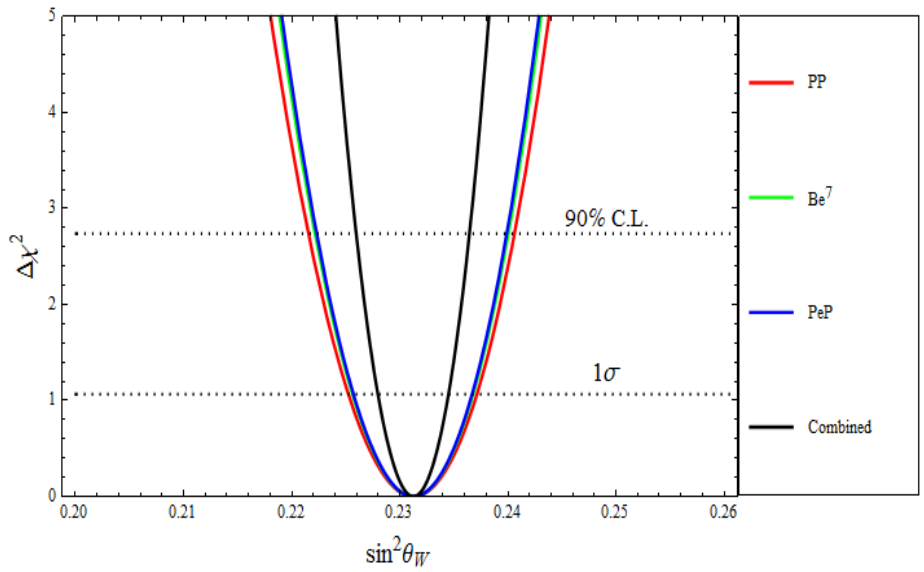
Source vs. Det. NSI Bounds @90% C.L.

Fig. No.	1-parameter	1-parameter	2-parameters	2-parameters
a	$\varepsilon_{ee}^{eR} \in [-0.300, 0.200]$	$\varepsilon_{+} \in [-0.3, 0.3]$	$\varepsilon_{ee}^{eR} \in [-0.8, 1.4]$	$\varepsilon_{+} \in [-0.4, 2.9]$
b	$\varepsilon_{ee}^{eL} \in [-0.012, 0.022]$	$\varepsilon_{+} \in [-0.4, 0.2]$	$\varepsilon_{ee}^{eL} \in [-0.18, 0.63]$	$\varepsilon_{+} \in [-5, 3.3]$
c	$\varepsilon_{ee}^{eR} \in [-0.300, 0.200]$	$\varepsilon_{-} \in [-0.16, 0.12]$	$\varepsilon_{ee}^{eR} \in [-0.8, 1.4]$	$\varepsilon_{-} \in [-0.15, 1.4]$
d	$\varepsilon_{ee}^{eL} \in [-0.020, 0.020]$	$\varepsilon_{-} \in [-0.15, 0.12]$	$\varepsilon_{ee}^{eL} \in [-0.17, 0.65]$	$\varepsilon_{-} \in [-1.8, 1.6]$
e	$\varepsilon_{\mu\mu}^{eR}$ or $\varepsilon_{\tau\tau}^{eR} \in [-0.08, 0.11]$	$\varepsilon_{-} \in [-0.4, 0.22]$	$\varepsilon_{\mu\mu}^{eR}$ or $\varepsilon_{\tau\tau}^{eR} \in [-1.1, 0.4]$	$\varepsilon_{+} \in [-0.7, 6.4]$
f	$\varepsilon_{\mu\mu}^{eL}$ or $\varepsilon_{\tau\tau}^{eL} \in [-0.05, 0.03]$	$\varepsilon_{+} \in [-0.4, 0.2]$	$\varepsilon_{\mu\mu}^{eL}$ or $\varepsilon_{\tau\tau}^{eL} \in [-0.4, 0.9]$	$\varepsilon_{+} \in [-1.2, 9]$
g	$\varepsilon_{\mu\mu}^{eR}$ or $\varepsilon_{\tau\tau}^{eR} \in [-0.1, 0.1]$	$\varepsilon_{-} \in [-0.15, 0.1]$	$\varepsilon_{\mu\mu}^{eR}$ or $\varepsilon_{\tau\tau}^{eR} \in [-1.2, 0.4]$	$\varepsilon_{-} \in [-0.4, 3.8]$
h	$\varepsilon_{\mu\mu}^{eL}$ or $\varepsilon_{\tau\tau}^{eL} \in [-0.05, 0.05]$	$\varepsilon_{+} \in [-0.1, 0.1]$	$\varepsilon_{\mu\mu}^{eL}$ or $\varepsilon_{\tau\tau}^{eL} \in [-0.3, 0.9]$	$\varepsilon_{+} \in [-0.5, 4.4]$
i	$\varepsilon_{\mu e}^{eR}$ or $\varepsilon_{\tau e}^{eR} \in [-0.28, 0.25]$	$\varepsilon_{+} \in [-0.3, 0.28]$	$\varepsilon_{\mu e}^{eR}$ or $\varepsilon_{\tau e}^{eR} \in [-1.1, 1.1]$	$\varepsilon_{+} \in [-0.3, 2.4]$
j	$\varepsilon_{\mu e}^{eL}$or$\varepsilon_{\tau e}^{eL} \in [-0.20, 0.20]$	$\varepsilon_{+} \in [-0.34, 0.22]$	$\varepsilon_{\mu e}^{eL}$or$\varepsilon_{\tau e}^{eL} \in [-1.1, 1.1]$	$\varepsilon_{+} \in [-0.4, 3.2]$
k	$\varepsilon_{\mu e}^{eR}$ or $\varepsilon_{\tau e}^{eR} \in [-0.27, 0.27]$	$\varepsilon_{-} \in [-0.2, 0.1]$	$\varepsilon_{\mu e}^{eR}$ or $\varepsilon_{\tau e}^{eR} \in [-0.27, 0.27]$	$\varepsilon_{-} \in [-0.2, 1.1]$
l	$\varepsilon_{\mu e}^{eL}$ or $\varepsilon_{\tau e}^{eL} \in [-0.19, 0.19]$	$\varepsilon_{-} \in [-0.19, 0.12]$	$\varepsilon_{\mu e}^{eL}$ or $\varepsilon_{\tau e}^{eL} \in [-1.1, 1.1]$	$\varepsilon_{-} \in [-0.2, 1.5]$
m	$\varepsilon_{e\mu}^{eR}$ or $\varepsilon_{e\tau}^{eR} \in [-0.25, 0.25]$	$\varepsilon_{+} \in [-0.38, 0.22]$	$\varepsilon_{e\mu}^{eR}$ or $\varepsilon_{e\tau}^{eR} \in [-0.68, 0.68]$	$\varepsilon_{+} \in [-0.42, 4.2]$
n	$\varepsilon_{e\mu}^{eL}$ or $\varepsilon_{e\tau}^{eL} \in [-0.18, 0.18]$	$\varepsilon_{+} \in [-0.4, 0.2]$	$\varepsilon_{e\mu}^{eL}$ or $\varepsilon_{e\tau}^{eL} \in [-0.5, 0.5]$	$\varepsilon_{+} \in [-0.5, 11]$
o	$\varepsilon_{e\mu}^{eR}$ or $\varepsilon_{e\tau}^{eR} \in [-0.3, 0.3]$	$\varepsilon_{-} \in [-0.2, 0.08]$	$\varepsilon_{e\mu}^{eR}$ or $\varepsilon_{e\tau}^{eR} \in [-0.65, 0.65]$	$\varepsilon_{-} \in [-0.2, 2]$
p	$\varepsilon_{e\mu}^{eL}$ or $\varepsilon_{e\tau}^{eL} \in [-0.2, 0.2]$	$\varepsilon_{-} \in [-0.16, 0.14]$	$\varepsilon_{e\mu}^{eL}$ or $\varepsilon_{e\tau}^{eL} \in [-0.52, 0.52]$	$\varepsilon_{-} \in [-0.2, 5.2]$

Future Prospects for 1% rate measurements

- G. Bellini *et al.* Nature **512**, 283 comment on the goals that can be reached with 1% measurements of *pp* rates.
- D. G. Cerdeno et al. “Physics from solar neutrinos in dark matter direct detection experiments”, JHEP **1605**, 118 (2016) aim for the magic 1%.
- J. Beacom *et al.* (The CJPL Collaboration), “Letter of Intent:Jinping Neutrino Experiment”, arXiv:1602.01733 v4 [phys.ins-det] (2016) aims for this level of rate and flux determination.
- JUNO, SNO+, LENA

Future Prospects: SM Fit



precision<2%

$\sin^2\theta_W = 0.2354 \pm 0.0015$

From parity violation measurement in ^{133}Cs at 2.4Mev.

$\sin^2\theta_W = 0.23126 \pm 0.00005$

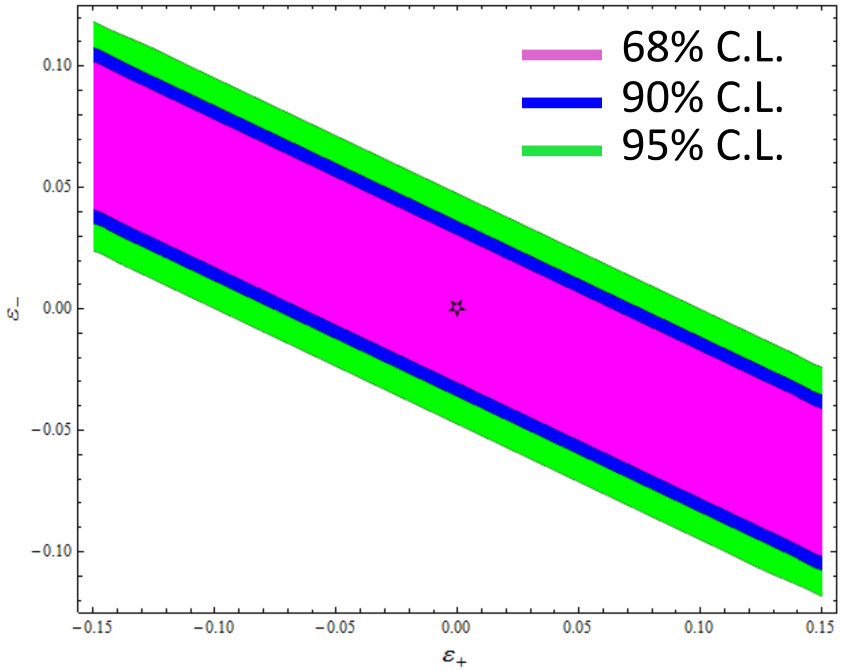
PDG value (MS bar scheme)

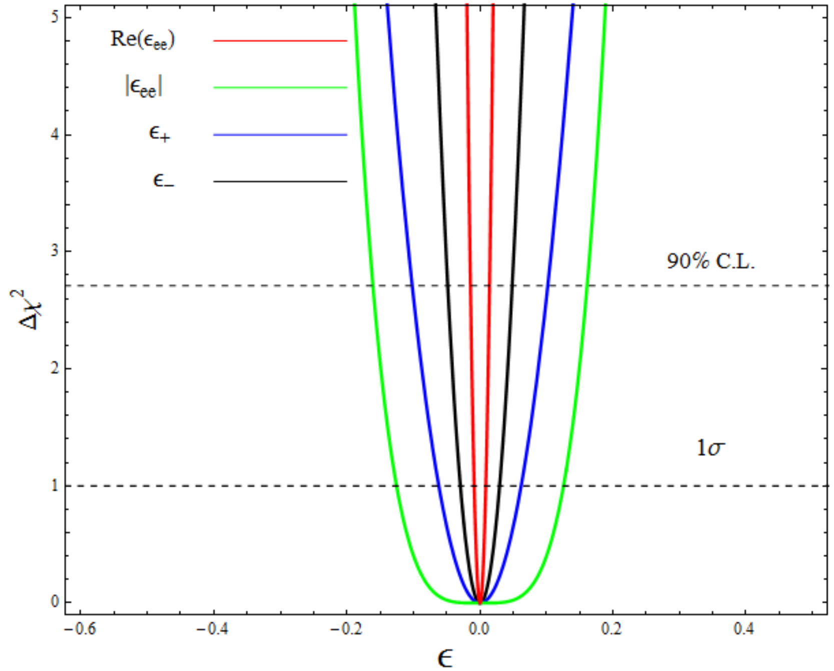
$\sin^2\theta_W = \mathbf{0.23126 \pm 0.00384}$ ← This work

$\sin^2\theta_W = 0.249 \pm 0.020$ ← Amir Khan , Phys. Rev. D 93, 093019 (2016)

$\sin^2\theta_W = 0.254 \pm 0.024$ ← J.F. Valle et al Physics Letters B. 76, 450 (2016)

Future Prospects: Source-Only NSIs

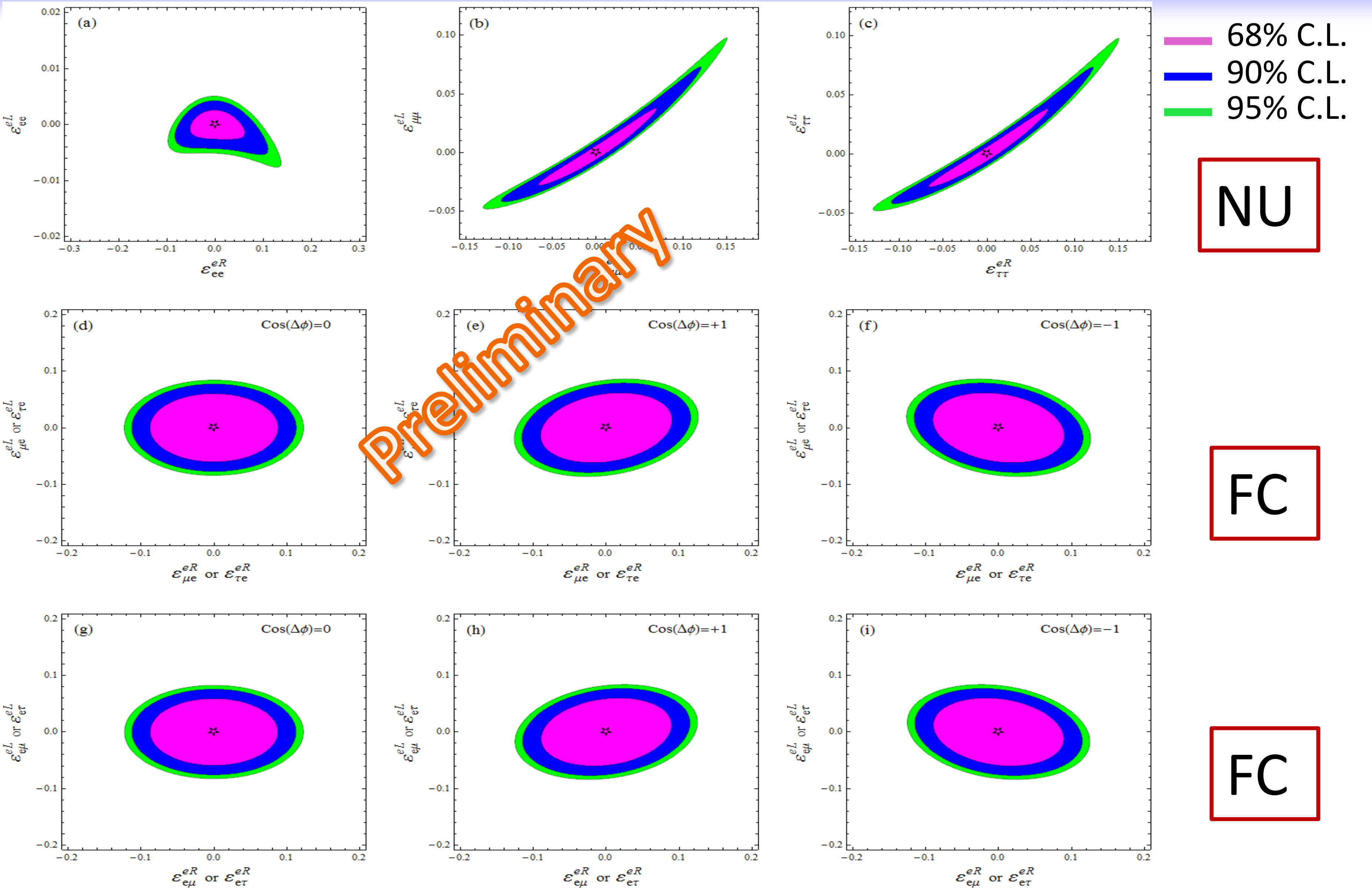




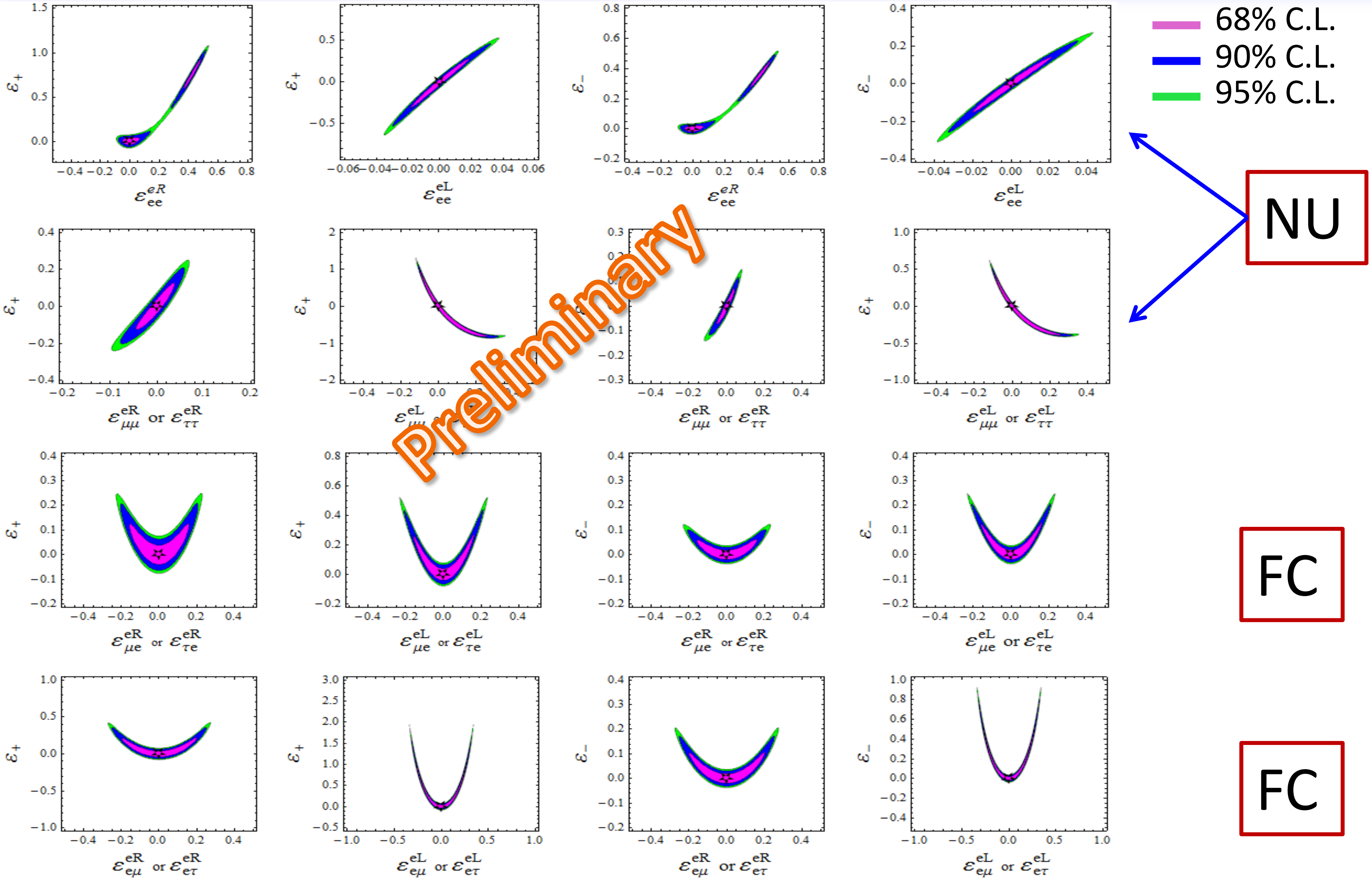
NSI Para.	$\Re[\varepsilon_{ee}]$	$\|\varepsilon_{ee}\|$	ϵ_+	ϵ_-
Best Fits	0.0	1.98722×10^{-8}	-4.44089×10^{-16}	-2.22045×10^{-16}
Bounds	[-0.014, 0.014]	[-0.16, 0.16]	[-0.10, 0.10]	[-0.05, 0.05]

TABLE V: **Future Propects:** 1-parameter source NSI parameter bounds at the 90%C.L.

Future Prospects: Detector-Only NSIs



Future Prospects: Source vs. Det. NSIs



Summary & Conclusion

- The recent real-time measurements of low energy components of the solar spectrum at Borexino have very low LMA-MSW contribution, thus provide a good testing ground for new physics study at source (Sun) and detector.
- We found the best fit value of $\sin^2\theta_W$ at the lowest energy to-date using the Borexino results.
- Constrained the NSI parameters at the production point at Sun and detector using the current data and have future prediction study for the future proposals/planned experiments Borexino(upgrade), CJPL, SNO+, LENA, JUNO etc.
- An improvement in sensitivity to the 1% level will either reveal very small deviations from the SM or reduce possibilities for NSI parameters by factors from 2-3 to more than an order of magnitude
- Our results show the complementarity between solar and reactor data to probes NSI simultaneously (on our To Do List!)

Summary & Conclusion

- As a crucial background in dark matter experiments solar neutrino experiment and theory can anticipate a long future.
- In return, they provide the key to nailing down details of solar structure and dynamics and can play a vital part of progress in resolving neutrino properties.

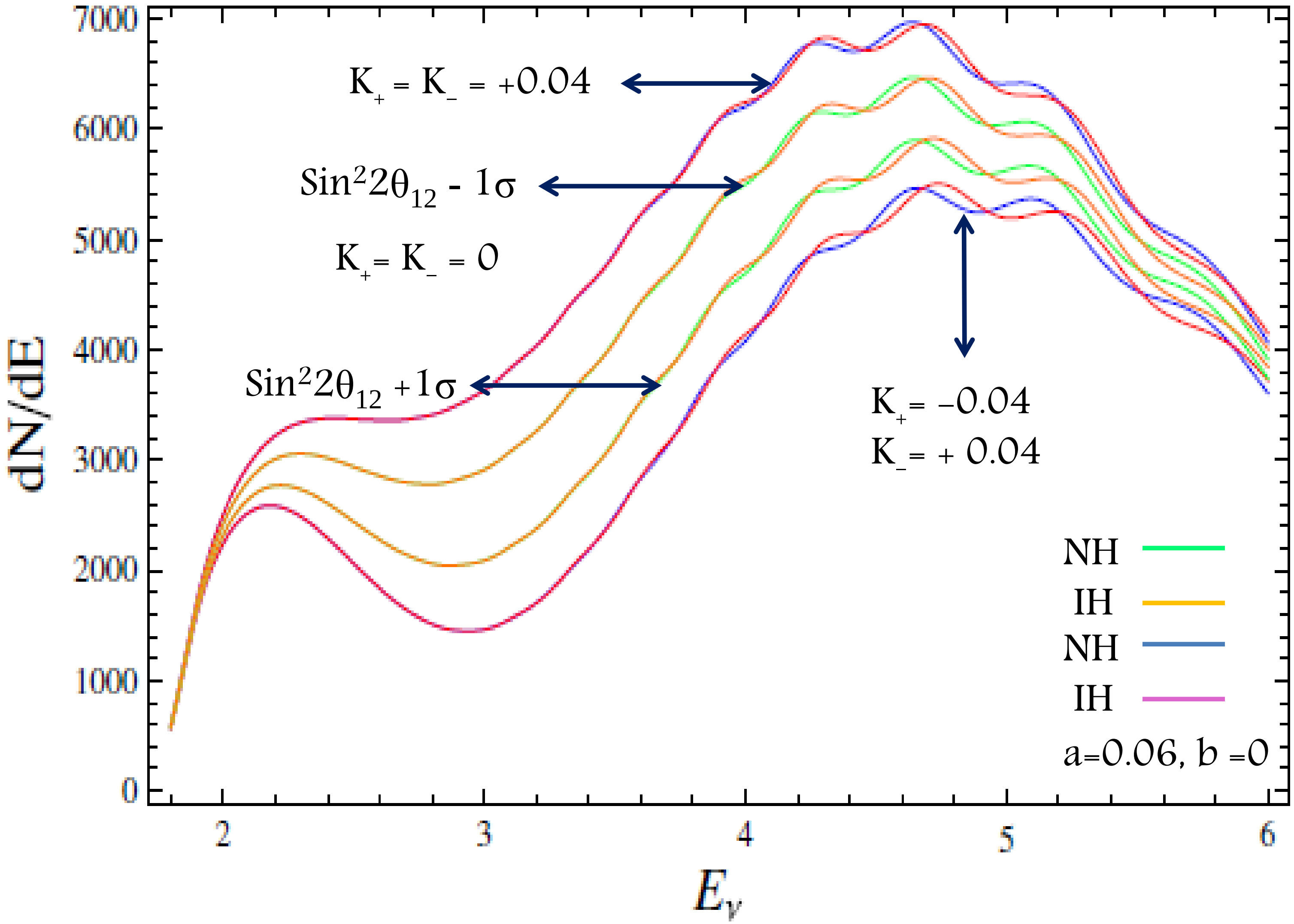
Suggestions from the model experts are welcome!

Thank You All!

Back Ups!

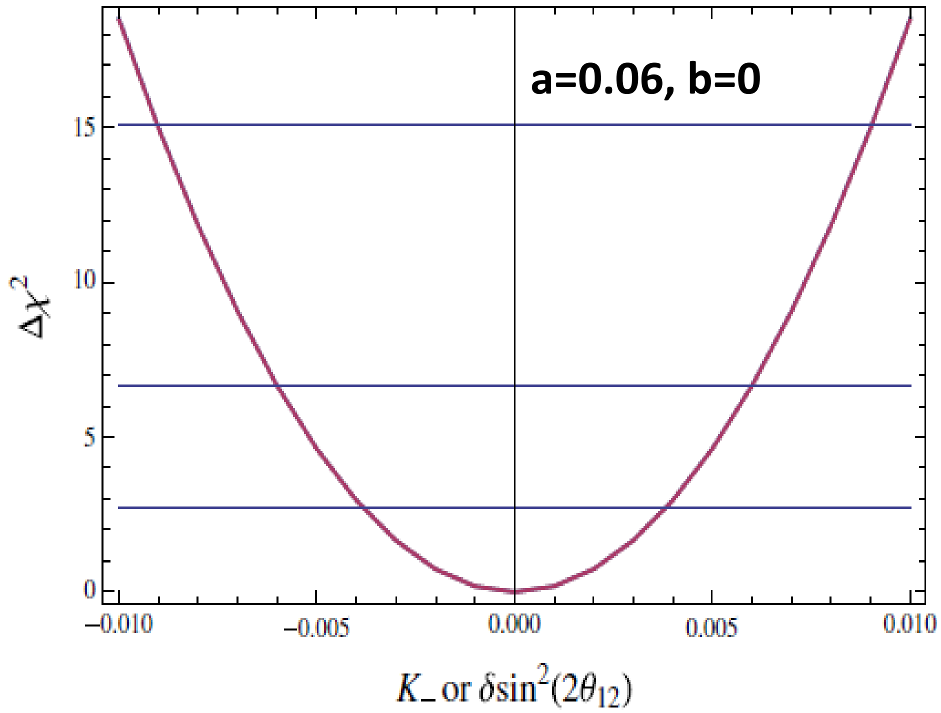
Spectrum Study: Effects of $Sin^2 2\theta_{12}$ Uncertainty

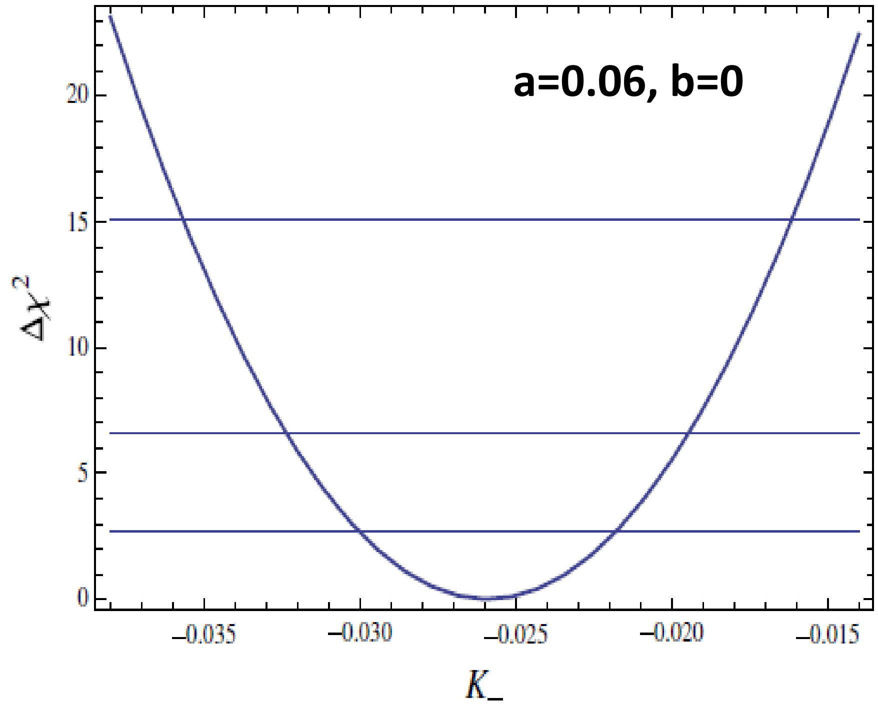
Khan,McKay&Tahir Phys Rev D. 88, 113006 (2013)



I. $\Delta\chi^2$ -Distributions

$\sin^2 2\theta_{12} = 0.857$ | $K_+ = K_- = 0$ | $K_+ = 0, \quad \sin^2 2\theta_{12} = 0.881$





$\sin^2(2\theta_{12})$	0.881	0.873	0.865	0.857	0.849	0.841	0.833
$K_-\|_{min}$	−0.0259	−0.0168	−0.0082	0.0	0.0078	0.0153	0.0225
χ^2_{min}	2×10^{-4}	3×10^{-5}	5×10^{-5}	0.0	2×10^{-5}	2×10^{-5}	8×10^{-5}
Penalty	1.0	0.44	0.11	0.0	0.11	0.44	1.0

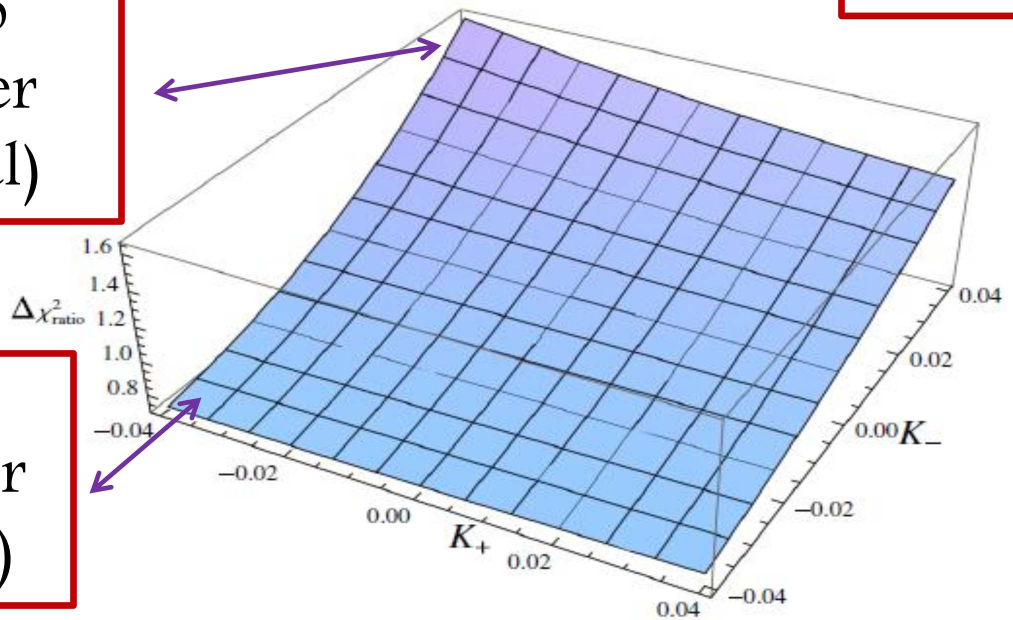
I. Statistical Discrimination of MH

$$\Delta\chi^2_{MH} = \sum_{i=1}^{N} \left[\frac{\frac{dN^{NH}}{dE_\nu} - \frac{dN^{IH}}{dE_\nu}}{\sqrt{\frac{dN^{IH}}{dE_\nu}}} \right]_i (\Delta E_\nu)_i$$

Model=NH with Ks
Data= IH without Ks

a=0.06, b=0

Sensitivity to MH is greater (P_{32} maximal)



Sensitivity to MH is smaller (P_{32} minimal)

Landscape of the Ratio: $\chi^2_{NSI} / \chi^2_{SMM}$

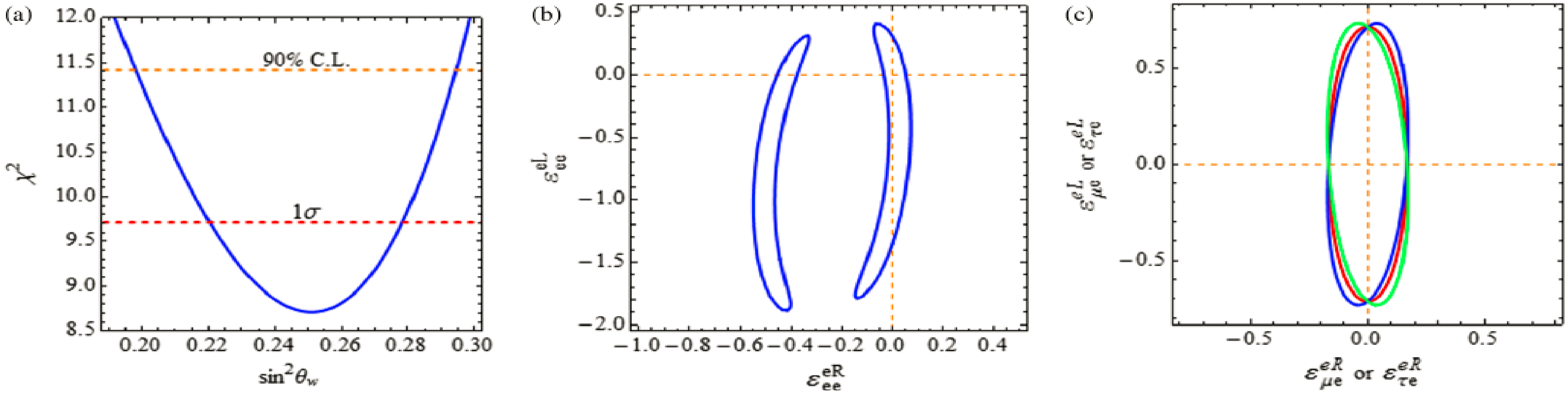
II. The Leptonic Case

@ 90% C.L.

Khan,McKay&Tahir PhysRevD.90.053008 (2014)

$-0.15 < \varepsilon^{eR}_{ee} < 0.08$
$-1.79 < \varepsilon^{eL}_{ee} < 0.41$

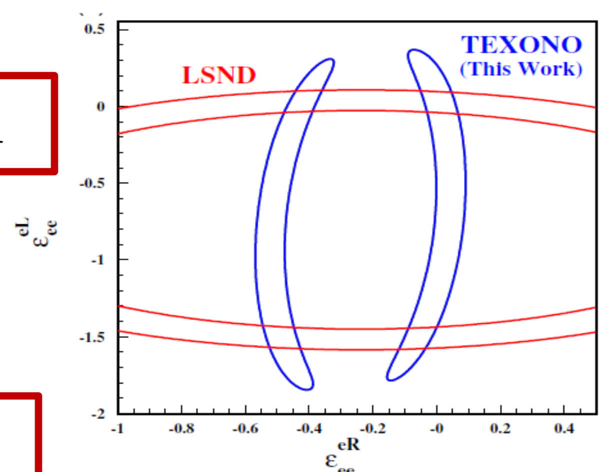
$-0.18 < \varepsilon^{eR}_{\alpha e} < 0.18$
$-0.76 < \varepsilon^{eL}_{\alpha e} < 0.76$

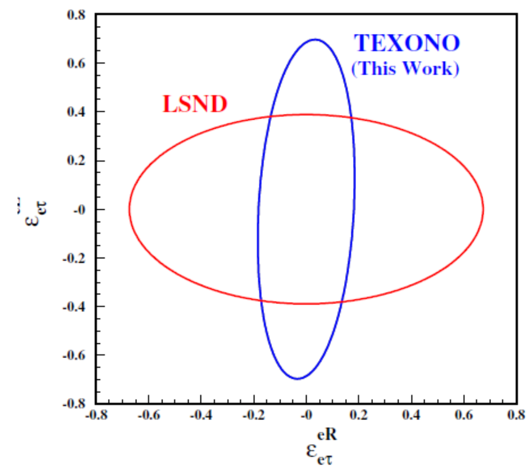


$\sin^2\theta_W = 0.251 \pm 0.031$

TEXONO Result

$\sin^2\theta_W = 0.251 \pm 0.031$





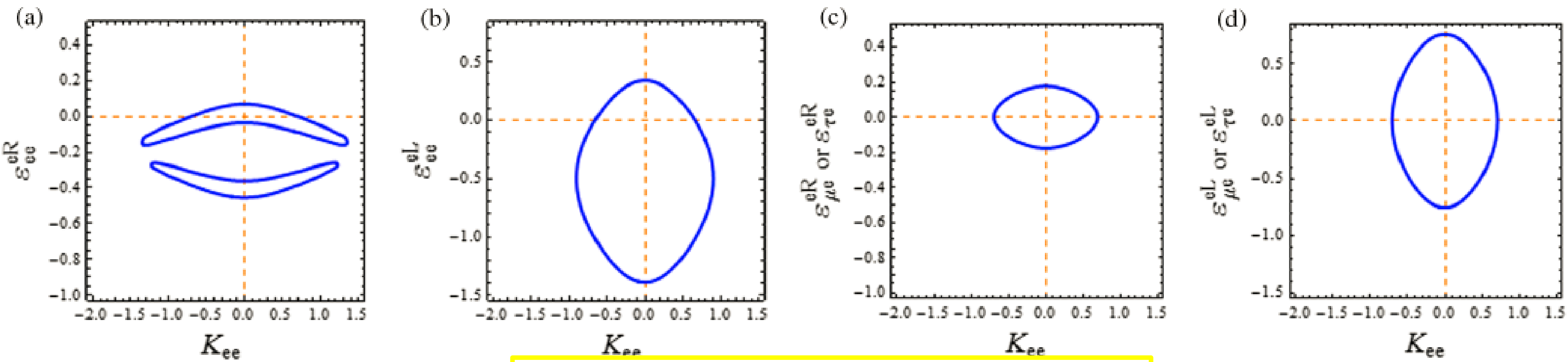
$-0.14 < \varepsilon^{eR}_{ee} < 0.08$
$-1.53 < \varepsilon^{eL}_{ee} < 0.38$

$-0.19 < \varepsilon^{eR}_{\alpha e} < 0.19$
$-0.84 < \varepsilon^{eL}_{\alpha e} < 0.84$

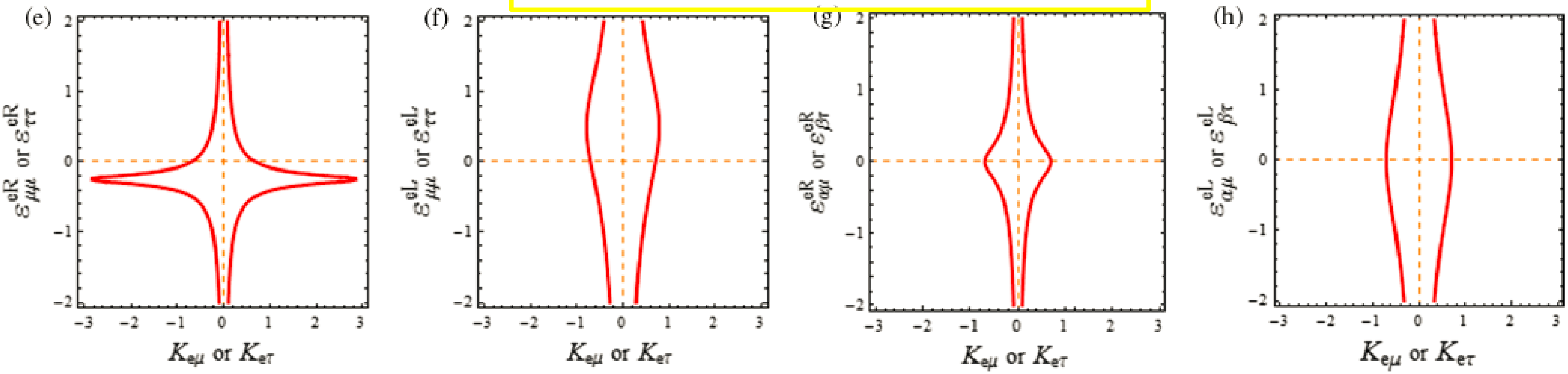
II: Interplay: SL & Leptonic NSIs

@ 90% C.L.

$-1.35 < ImK_{ee} < 1.35$ $-0.17 < \varepsilon^{eR}_{ee} < 0.07$	$-0.90 < ImK_{ee} < 0.90$ $-1.4 < \varepsilon^{eL}_{ee} < 0.34$	$-0.72 < ImK_{ee} < 0.72$ $-0.18 < \varepsilon^{eR}_{\alpha e} < 0.18$	$-0.72 < ImK_{ee} < 0.72$ $-0.76 < \varepsilon^{eL}_{\alpha e} < 0.76$



Khan,McKay&Tahir PhysRevD.90.053008 (2014)



$-0.72 < ImK_{e\,\alpha} < 0.72$	$-0.72 < ImK_{e\,\alpha} < 0.72$	$-0.72 < ImK_{e\,\alpha} < 0.72$	$-0.72 < ImK_{e\,\alpha} < 0.72$

$\varepsilon^{eR}_{\mu\mu}$, $\varepsilon^{eR}_{\tau\tau}$ $\varepsilon^{eL}_{\mu\mu}$ $\varepsilon^{eL}_{\tau\tau}$, $\varepsilon^{eR}_{\alpha\mu}$, $\varepsilon^{eR}_{\beta\tau}$, $\varepsilon^{eL}_{\alpha\mu}$, $\varepsilon^{eL}_{\beta\tau}$ are unbounded