Standard and non-standard neutrino physics at reactor experiments

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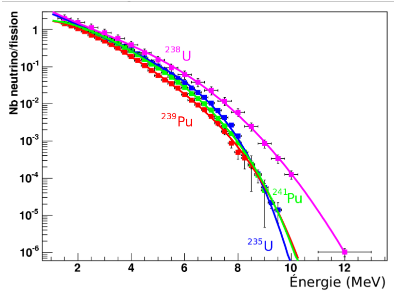
Outline

$\bar{\nu}_e$ production and detection @ current reactor exps.

Production: β decay of
$k =^{235}$ U, ^{239}Pu, ^{241}Pu and ^{238}U

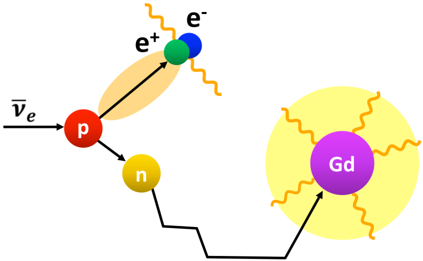


Flux parametrizations: $\Phi_k(E)$

P. Huber (PRC **84**(2011))

T. Mueller *et al.* (PRC **83**(2011))

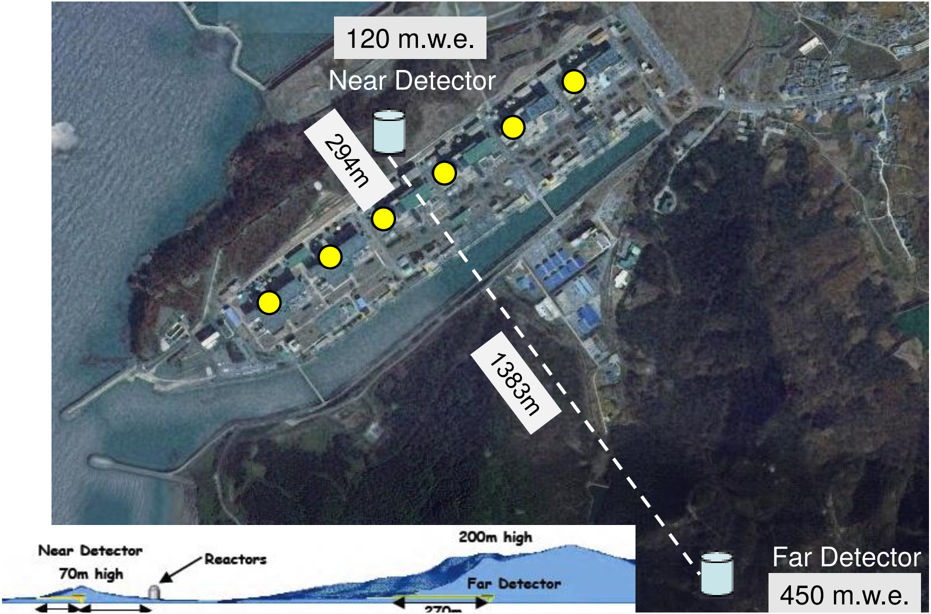
Detection: Inverse β decay,
$\bar{\nu}_e + p \to n + e^+$



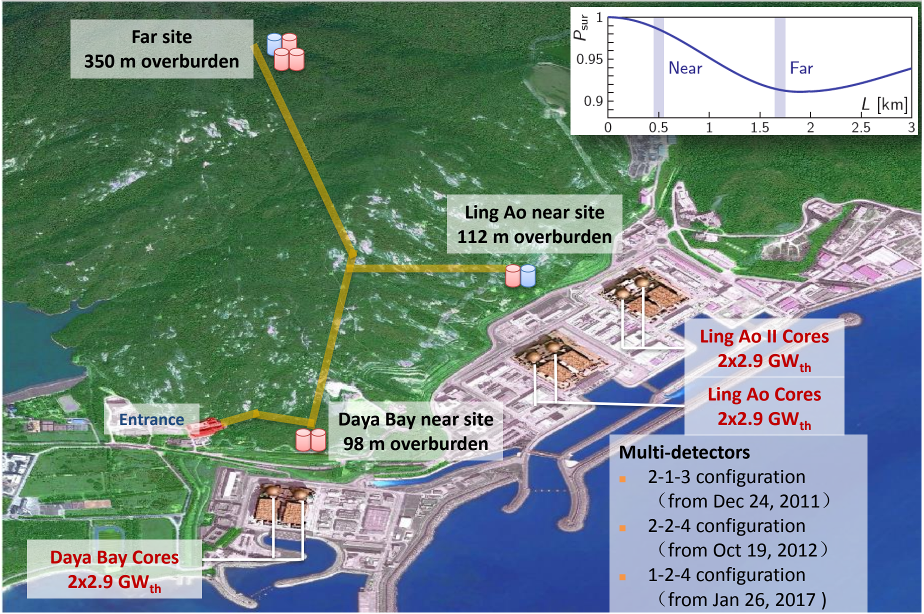
Coincidence signals: Prompt e^+-annihilation and delayed ($\sim$ 30μs) n-capture.

For $\sim$ 1km baseline, $\bar{\nu}_e$s propagate to FD practically in Vacuum!

RENO Experimental Set-up



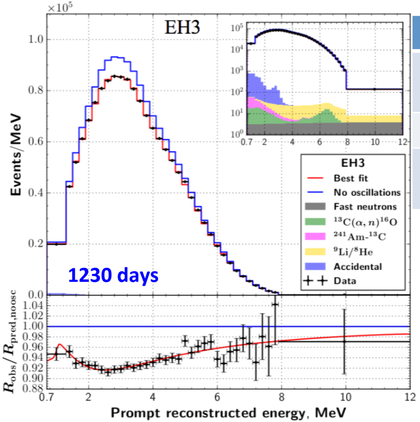
The Daya Bay Experiment



Multi-detectors

- 2-1-3 configuration (from Dec 24, 2011)
- 2-2-4 configuration (from Oct 19, 2012)
- 1-2-4 configuration (from Jan 26, 2017)

Summary of IBD candidates

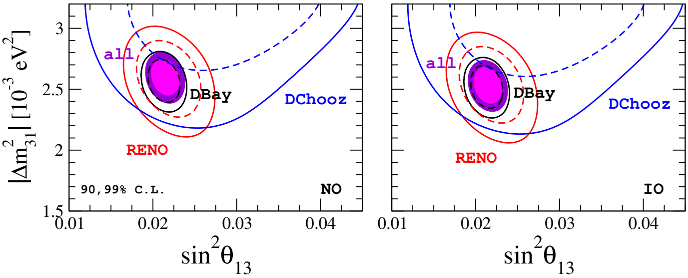


	EH1	EH2	EH3
IBD candidates	1,203,969	1,033,209	308,150
B/S ratio	1.8±0.2%	1.5±0.2%	2.0±0.2%
IBD rate (day^{-1})	1058.5	998.2	285.2

- **Over 2.5M (300K) IBD candidates in total (the far site)!**
- **≤ 2% backgrounds**
- ^{9}Li/^{8}He has the largest uncertainty on B/S ratio: 0.1% ~ 0.15%

6-AD: 217 days (Dec/2011 – Jul/2012)
8-AD: 1013 days (Oct/2012 – Jul/2015)

P.F deSalas, DVF, Ternes, Tórtola & Valle (PLB **782** (2018)) arxiv:1708.01186



$\sin^2\theta_{13} = (2.160^{+0.083}_{-0.069}) \times 10^{-2}$ (global)

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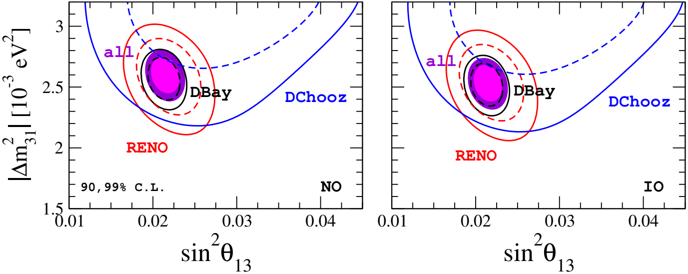

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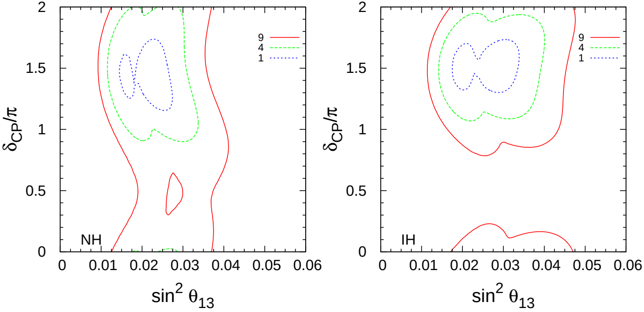
LBL-only



More info in https://globalfit.astroparticles.es/

Outline

Motivating the NSI

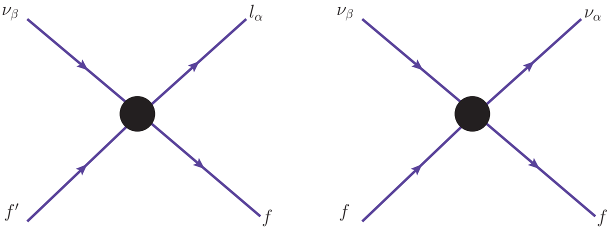
- Neutrino masses imply physics BSM.
- New neutrino interactions are expected in SM extensions
- The exchange of new heavy particles could leave a low energy ‘fingerprint’ in the form of NSI.
- NSI provide a model independent framework to include ‘NP’.
- It is worthy to quantify the ‘amount’ of NSI allowed by the neutrino oscillation data.

The pheno approach to the NSI

Effective four-fermion operators

L. Wolfenstein (PRD **17**(1978)), J.W.F Valle (PLB **199**(1987))

M.M Guzzo *et al.* (PLB **260**(1991)), E. Roulet (PRD **44**(1991))



$$\mathcal{L}_{V\pm A} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{S(D),f,f',V\pm A} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1 \pm \gamma^5) f\right]$$

$$+ \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1 \pm \gamma^5) f\right] + \text{h.c.},$$

Also, see J. Kopp *et al.* (PRD **77**(2008)) for a discussion of other Lorentz structures for the NSI, not distinguishable with current reactor and accelerators.

Outline

Analysis framework

- $\tilde{\varepsilon}^{m,f,V\pm A}_{\alpha\beta} \to 0$ and $\tilde{\varepsilon}^{S(D),u,d,V\pm A}_{e\beta} \to \varepsilon^{S(D)}_{e\beta}$
- $|\bar{\nu}^s_\alpha\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma}|\bar{\nu}_\gamma\rangle$ (l_α produced). $|\bar{\nu}^d_\beta\rangle = |\bar{\nu}_\beta\rangle + \sum_\gamma \varepsilon^{d*}_{\gamma\beta}|\bar{\nu}_\gamma\rangle$ (l_β detected)
- ε^s & ε^d are general complex matrices!
- detection (inv. β-decay) Vs production (β-decay) $\varepsilon^s_{e\alpha} = \varepsilon^{d*}_{\alpha e} \equiv \varepsilon_\alpha = |\varepsilon_\alpha| e^{i\phi_\alpha}$
- The effective oscillation probability is given by:

$$P^{eff.}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq 1 + \overbrace{4|\varepsilon_e|\cos\phi_e}^{\text{'zero distance term'}} - 4\left[\sin\theta_{13} + s_{23}|\varepsilon_\mu|\cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau|\cos(\delta - \phi_\tau)\right]^2 \sin^2\Delta_{31} + \mathcal{O}(\varepsilon)^2$$

Also, notice the 'δ', 'θ_{23}' dependence!

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Also, notice the 'δ', 'θ_{23}' dependence!

Analysis details: One parameter at a time, $\theta_{23} = \pi/4$, and NH.

- I. $\varepsilon_e \neq 0$, II. $\varepsilon_{\mu,\tau} \neq 0$, and Flavour Universal, III. $\varepsilon_{e,\mu,\tau} \equiv \varepsilon$.
- $S_d\left(1 + a_{\text{norm}} + \sum_r \omega^d_r \alpha_r + \xi_d\right) + (1 + \beta_d)B_d$ & $\chi^2 += \sum_k (\eta_k/\sigma_k)^2$ for each η_k.

see Agarwalla, Bagchi, DVF, Tórtola (JHEP **1517** (2015)) for more analysis details

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Here, 'preliminary' results for shape analysis of 1230 days of Daya Bay data.

Current bounds

CC-like NSI

Biggio, *et al.* (JHEP **090**(2009))

Bounds extracted from:

- V^{ud} determination: From Kaon decays $\rightarrow$ V^{us} (and asumming CKM unitarity) compared with the derivation from beta decays (affected by NSI).
- Universality tests: Ratios $\pi \rightarrow e(\mu)\nu$ and $\tau \rightarrow \pi\nu$ decay rates modified by quark CC-like NSI.
- Non-observation of flavor change at NOMAD ('zero distance effect'). Channels $\nu_\mu \rightarrow \nu_e$ ($|\varepsilon^{ud\,A}_{\mu e}|$, $|\varepsilon^{ud\,L(R)}_{e\mu}|$), $\nu_e \rightarrow \nu_\tau$ ($|\varepsilon^{ud}_{\tau e}|$), and $\nu_\mu \rightarrow \nu_\tau$ ($|\varepsilon^{ud\,A}_{\mu\tau}|$, $|\varepsilon^{ud\,L(R)}_{\tau\mu}|$).

Assuming only one parameter at a time (90% C.L. for 1 d.o.f):

$$\mathcal{X} = \begin{bmatrix} V & L(R) & V \\ A & A & A \\ L(R) & L(R) & A \end{bmatrix}, \; |\varepsilon^{ud\,\mathcal{X}_{ij}}_{\alpha\beta}| < \begin{bmatrix} \boxed{0.041} & \underline{0.026(0.037)} & \underline{0.041} \\ 0.026 & 0.078 & 0.013 \\ 0.087(0.12) & 0.013(0.018) & 0.13 \end{bmatrix}$$

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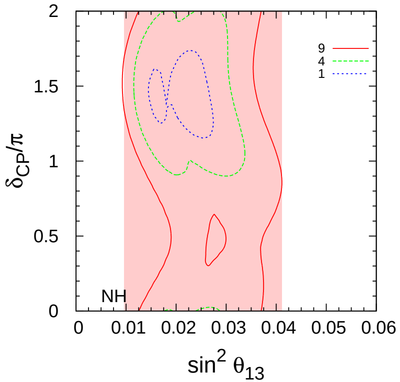
We improved the limit on $|\varepsilon^{ud}_{ee}| < 0.02$ NSI coupling, total-rate analysis of Daya Bay

see Agarwalla, Bagchi, DVF, Tórtola (JHEP **1517**(2015)) for details

Outline

Results for the ‘ε_{ee}’ coupling

Showing s_{13}^2 from LBL-only in vertical bands



$$0.0096 \leq \sin^2\theta_{13} \leq 0.0411 \ (3\sigma)$$

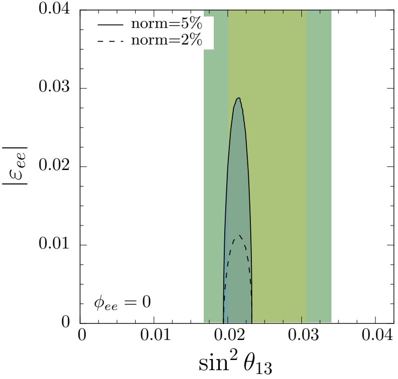
$$\boxed{0.0201 \leq \sin^2\theta_{13} \leq 0.0306 \ (1\sigma)}$$

Results for the ‘ε_{ee}’ coupling

Showing s^2_{13} from LBL-only in vertical bands

Contours at 90% of C.L for 2 d.o.f.

Band: 90% (1σ) of C.L for 1 d.o.f, green(yellow).

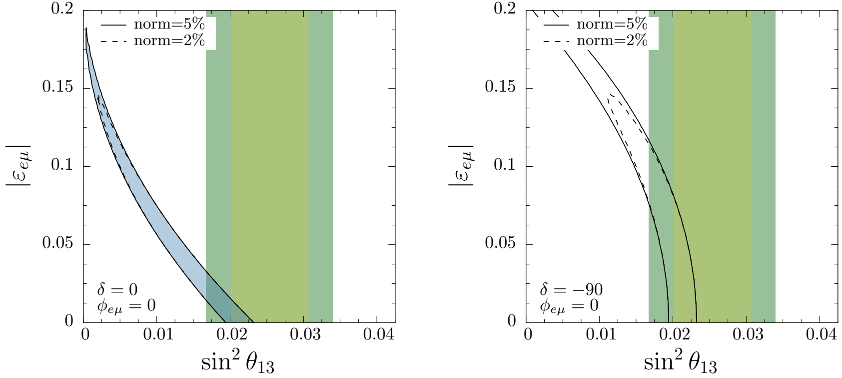


$$\tilde{s}^2_{13} \approx s^2_{13} - \frac{|\varepsilon_{ee}|\cos\phi_{ee}}{\sin^2\Delta_{31}}$$

Results for the '$\varepsilon_{e(\mu,\tau)}$' case

Showing s^2_{13} from LBL-only in vertical bands

Contours at 90% of C.L for 2 d.o.f.   Band: 90% (1σ) of C.L for 1 d.o.f, green(yellow).



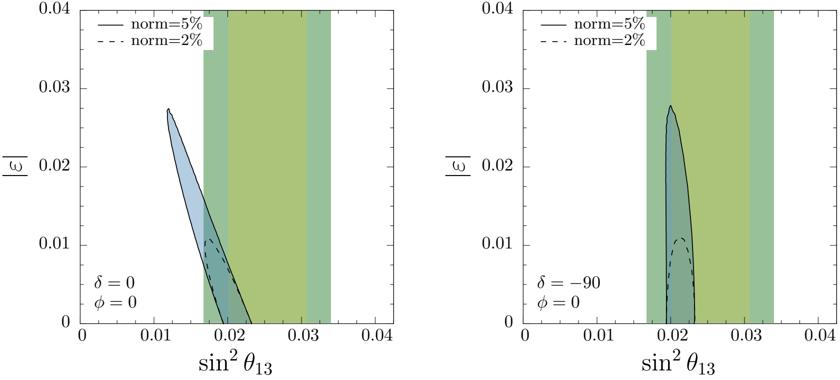
$$\tilde{s}^2_{13} \approx s^2_{13} + 2 s_{13} s_{23} |\varepsilon_{e(\mu,\tau)}| \cos\left(\delta - \phi_{e(\mu,\tau)}\right)$$

Cancellations when $\cos\left(\delta - \phi_{e(\mu,\tau)}\right) = 0$, higher order ε terms important!

Results for the ‘FU’ case

Showing s_{13}^2 from LBL-only in vertical bands

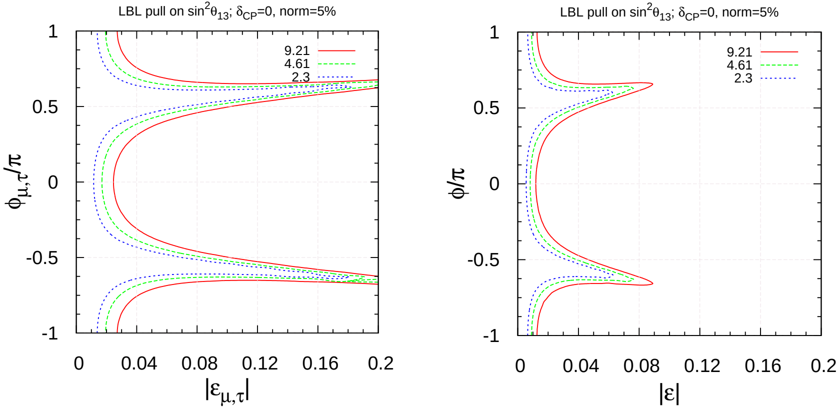
Contours at 90% of C.L for 2 d.o.f. Band: 90% (1σ) of C.L for 1 d.o.f, green(yellow).



$$\tilde{s}_{13}^2 \approx s_{13}^2 - |\varepsilon| \left[\frac{\cos\phi}{\sin^2\Delta_{31}} - 4 s_{13} s_{23} \cos(\delta - \phi) \right]$$

Including the LBL measurement of $\sin^2\theta_{13}$

$$0.0201 \leq \sin^2\theta_{13} \leq 0.0306\ (1\sigma)$$



Cancellations when $\cos(\delta - \phi_{\mu,\tau}) = 0$, higher order ε terms important!

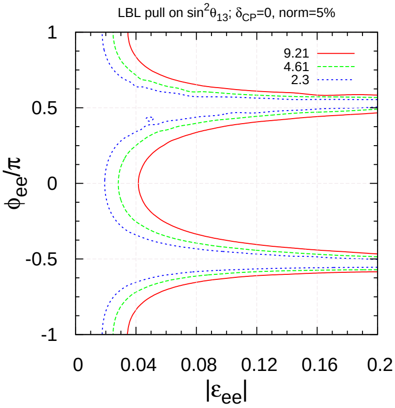
Including the LBL measurement of $\sin^2\theta_{13}$

Daya Bay Vs RENO

$$0.0201 \leq \sin^2\theta_{13} \leq 0.0306 \; (1\sigma)$$

Daya Bay, 1230 days

RENO, 1500 days



Cancellations when $\cos\phi_{ee} = 0$, higher order ε terms important!

Work in progress: Updating RENO results with the latest data, $\sim$ 2200 days.

Outline

Summary

- The reactor mixing angle has been measured within a $\sim 4\%$ precision mainly thanks to Daya Bay.
- Taking advantage of the Daya Bay data other beyond standard oscillation scenarios can be probed. In particular, CC-like NSI have been tested.
- Multidetector reactor neutrino experiments offer a clean probe of CC-like NSI. The θ_{13} determination is in general NOT robust under CC-like NSI (due to the effect of the phases) while the value of the NSI constrains is limited by our current knowledge of the 'absolute normalization of reactor neutrino fluxes'. New physis might be 'entangled' with syst. errors.
- By using the LBL result for the reactor mixing angle as an input, constrains on the '$\varepsilon_{e(\mu,\tau)}$' and 'FU' couplings substantially improved.

THANK YOU

Thanks to FAPESP for financial support under 2017/01749-6

Thanks to the organizers for the invitation and for the partial financial aid.

Back up

Complete second order NSI probability

Assuming $\varepsilon^s_{e\alpha} = \varepsilon^{d*}_{\alpha e}$

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

Normalization of the NSI states

The new neutrino favor states, in presence of NSI are normalized as:

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left(|\nu_\alpha\rangle + \sum_\gamma \varepsilon_{\alpha\gamma}^s|\nu_\gamma\rangle\right) \ ,$$

$$\langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left(\langle\nu_\beta| + \sum_\eta \varepsilon_{\eta\beta}^d\langle\nu_\eta|\right) \ ,$$

where the normalization factors are given by:

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

To see the normalization effect in the probability, we can compute the oscillation probability at zero distance:

$$P_{\nu_\alpha^s\to\nu_\beta^d}(L=0) = \left|\langle\nu_\beta^d|\nu_\alpha^s\rangle\right|^2 = \left|\frac{\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^s + \varepsilon_{\alpha\beta}^d + \sum_\gamma \varepsilon_{\alpha\gamma}^s\varepsilon_{\gamma\beta}^d}{N_\alpha^s N_\beta^d}\right|^2 .$$

For $\varepsilon_{\alpha\gamma}^s = \varepsilon_{\gamma\alpha}^{d*} = |\varepsilon_{\alpha\gamma}|\exp(i\phi_{\alpha\gamma})$ we find the oscillation amplitude is given by:

$$A_{\alpha\beta}(L=0) = \frac{\delta_{\alpha\beta} + 2\mathcal{R}(|\varepsilon_{\alpha\beta}|\exp i\phi_{\alpha\beta}) + \sum_\gamma |\varepsilon_{\alpha\gamma}||\varepsilon_{\beta\gamma}|\exp[i(\phi_{\alpha\gamma}-\phi_{\beta\gamma})]}{\sqrt{1+2\mathcal{R}(|\varepsilon_{\alpha\alpha}|\exp i\phi_{\alpha\alpha}) + \sum_\gamma|\varepsilon_{\alpha\gamma}|^2}\sqrt{1+2\mathcal{R}(|\varepsilon_{\beta\beta}|\exp i\phi_{\beta\beta}) + \sum_\gamma|\varepsilon_{\beta\gamma}|^2}}$$
$$\neq 0 \ .$$