Standard and Non-standard Neutrino Oscillations at Daya Bay

(Based on arXiv:1412.1064)

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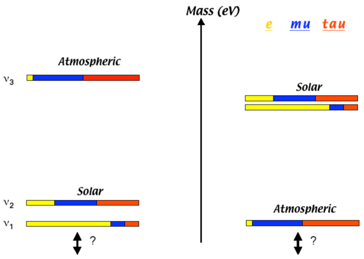
In coll. with S. Agarwalla, P. Bagchi and M. Tórtola

3ν mixing

$$|\nu_\alpha\rangle = \sum_k V^*_{\alpha k} |\nu_k\rangle$$

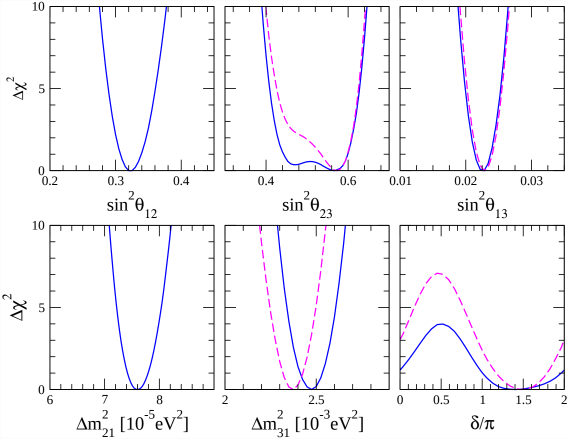
$$V = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \overbrace{\underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Reactor}}}^{\text{Atm.+Solar Interf.}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$

- $P_{\nu_\alpha \to \nu_\beta}(\vec{\lambda}, \rho; L, E) = \left| \langle \nu_\beta | e^{-i\mathcal{H}(x)L} | \nu_\alpha \rangle \right|^2$
  $\vec{\lambda} = (\theta_{ij}, \delta, \Delta m^2_{21}, \Delta m^2_{31})$
  $\rho(x)$ is the medium matter density.
- Neutrino oscillations are sensitive to $\Delta m^2_{jk} \equiv m^2_j - m^2_k$



Global Fit

D.V.Forero, Tórtola & Valle (PRD **90**(2014)) arxiv:1405.7540



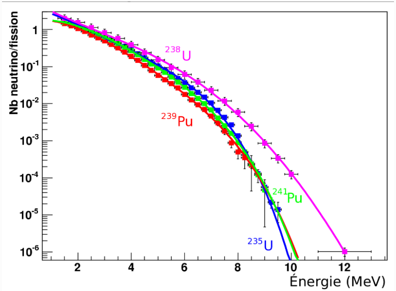
parameter	bf$\pm$ 1σ	
Δm^2_{21} [10^{-5}eV^2]	$7.60^{+0.19}_{-0.18}$	2.4%
$\|\Delta m^2_{31}\|$[10^{-3}eV^2]	$2.48^{+0.05}_{-0.07}$	2.4%
IH	$2.38^{+0.05}_{-0.06}$	
$\sin^2\theta_{12}/10^{-1}$	3.23 ± 0.16	5.0%
$\sin^2\theta_{13}/10^{-2}$	2.26 ± 0.12	5.3%
IH	2.29 ± 0.12	5.2%
$\sin^2\theta_{23}/10^{-1}$	$5.67^{+0.32}_{-1.24}$	7.4%
IH	$5.73^{+0.25}_{-0.39}$	6.9%
δ/π	$1.41^{+0.55}_{-0.40}$	
IH	1.48 ± 0.31	

Production, propagation and detection

Production:

β decay of fission fractions 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))

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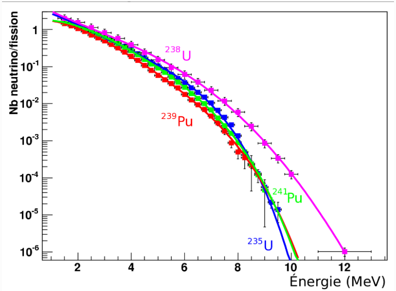

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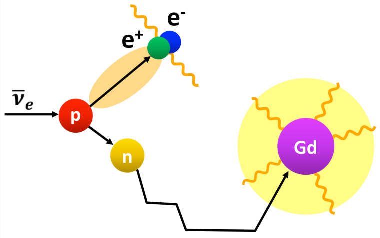
Detection:

Through inverse β decay

$\bar{\nu}_e + p \rightarrow n + e^+$

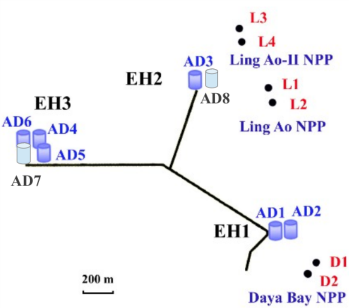


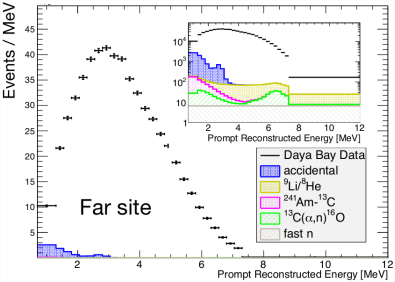
$$N(E,t) = \frac{N_p\,\epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f\rangle} \times \langle\sigma_f\rangle$$

$$\sum_k f_k \int_0^\infty dE\, \Phi_k(E)\, \sigma_{IBD}(E) P_{ee}(E,L)$$

Neutrino propagation $\rightarrow P_{ee}(E,L)$

Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$

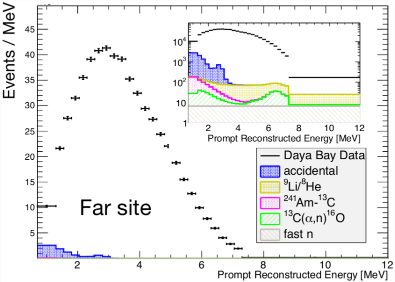


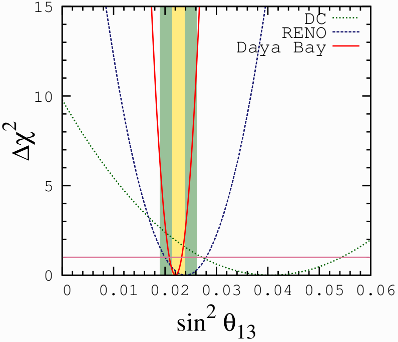


$$\frac{N_F}{N_N} = \frac{N_{p,F}}{N_{p,N}} \times \frac{\epsilon_F}{\epsilon_N} \times \frac{L_N^2}{L_F^2} \times \frac{\int \Phi(E)\sigma(E)P_{ee}(E,L_F)}{\int \Phi(E)\sigma(E)P_{ee}(E,L_N)}$$

Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$

Chao Zhang @neutrino2014

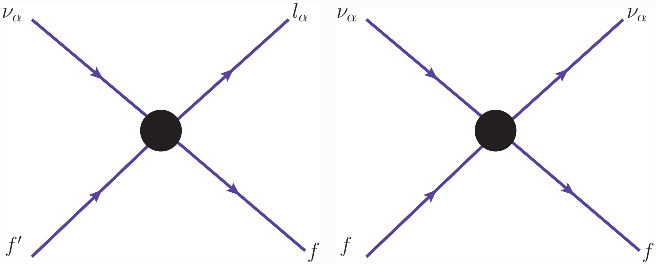




$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + a_{\text{norm}} + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d} + \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right)$$

Free normalization analysis!

Beyond standard ν oscillations: NSI

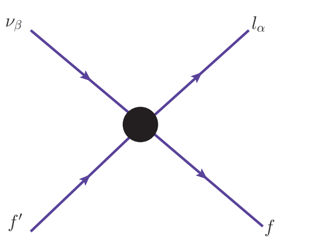


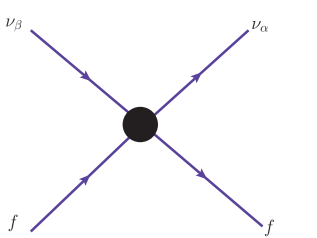
- Neutrino masses imply physics BSM.
- New neutrino interactions are expected in SM extensions
- The exchange of new heavy particles could leave a low energy 'fingerprint' in the form of NSI.
- It is worthy to quantify the 'amount' of NSI allowed by the new data.

NSI in SBL reactor experiments

J.W.F Valle (PLB **199**(1987))

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





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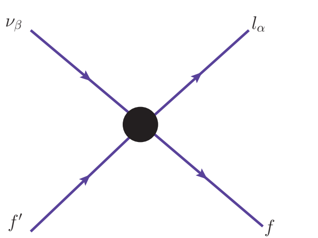

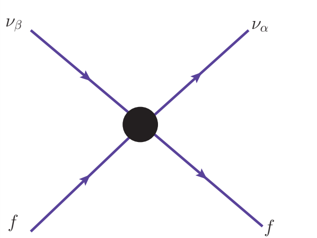

J. Kopp *et al.* (PRD **77**(2008)) arxiv:0705.2595

- Production (Detection) $\Longleftrightarrow$ $\beta(\beta^{-1})$-decay process.
- At the quark level $u \Longleftrightarrow d$.
- NC matter effects in neutrino propagation can be neglected, so only CC part is present in ν production and detection.

$$\tilde{\varepsilon}^{m,f,V\pm A}_{\alpha\beta} \rightarrow 0 \quad \text{and} \quad \tilde{\varepsilon}^{S(D),u,d,V\pm A}_{e\beta} \rightarrow \varepsilon^{S(D)}_{e\beta}$$

Oscillation analysis with NSI

- $\varepsilon^{s}_{e\alpha} = \varepsilon^{d*}_{\alpha e} \equiv \varepsilon_\alpha = |\varepsilon_\alpha| e^{i\phi_\alpha}$
- $|\bar{\nu}^{s}_{\alpha}\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma} |\bar{\nu}_\gamma\rangle$
- The effective oscillation probability is given by:

$$P^{eff.}_{\bar{\nu}^{s}_{e} \to \bar{\nu}^{d}_{e}} \simeq 1 - 4\tilde{s}^2_{13} \sin^2 \Delta_{31}$$

$$\boxed{s^2_{13} \to \tilde{s}^2_{13} = s^2_{13} + f(\theta_{ij}, \delta; |\varepsilon_\alpha|, \phi_\alpha)}$$

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One parameter at time:
I. $\varepsilon_e \neq 0$
II. $\varepsilon_{\mu,\tau} \neq 0, \theta_{23} = \pi/4$

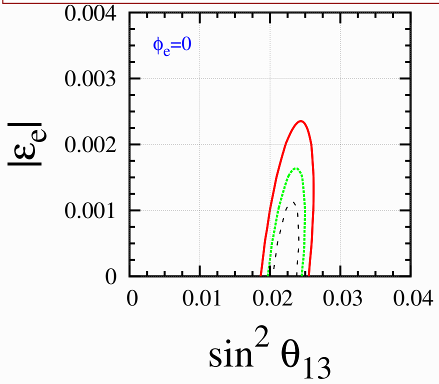
Flavour Universal
III. $\varepsilon_{e,\mu,\tau} \equiv \varepsilon, \theta_{23} = \pi/4$

- Initially, let us assume $a_{\text{norm}} = 0$ in the analysis.

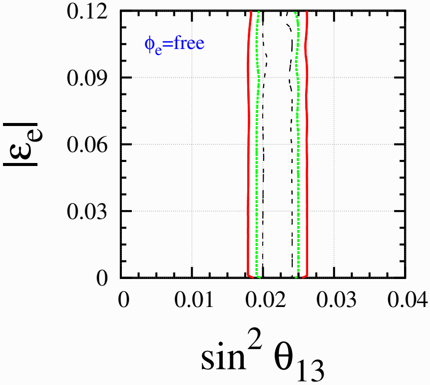
Results for the ε_e case

arXiv:1412.1064

$0.020 \leq \sin^2\theta_{13}^{DYB} \leq 0.024$ @90% C.L ; 1 d.o.f



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



C.L = 68.3, 90, 95%; 2 d.o.f

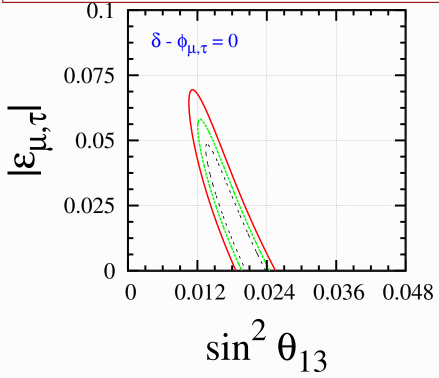
$|\varepsilon_e| \leq 0.0012$ @90% C.L; 1 d.o.f

$0.020 \leq \sin^2\theta_{13} \leq 0.024$

Results for the $\varepsilon_{\mu,\tau}$ case

arXiv:1412.1064

$0.020 \leq \sin^2\theta_{13}^{DYB} \leq 0.024$ @90% C.L; 1 d.o.f



C.L = 68.3, 90, 95%; 2 d.o.f

$\tilde{s}_{13}^2 \approx s_{13}^2 + 2s_{13}s_{23}|\varepsilon_{\mu,\tau}|$

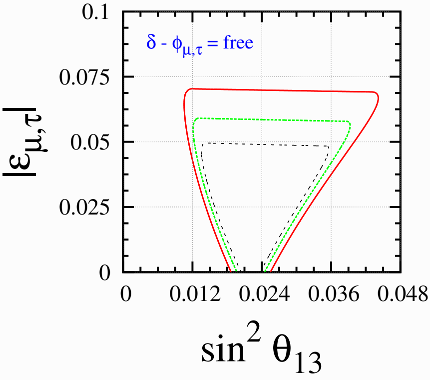
$|\varepsilon_{\mu,\tau}| \leq 0.051$ @90% C.L; 1 d.o.f

$0.013 \leq \sin^2\theta_{13} \leq 0.024$

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

$|\varepsilon_{\mu,\tau}| \leq 0.052$ @90% C.L; 1 d.o.f

$0.013 \leq \sin^2\theta_{13} \leq 0.036$



Absolute flux normalization

- Reactor flux uncertainties in the absolute normalization in reactor experiments can be $\sim 3\%$ P. Huber(PRC **84**(2011)) or slightly bigger $\sim 4\%$ A. C. Hayes *et al.* (PRL **112**(2014)) .
- Other sys. uncertainties can affect the absolute normalization in the event calculation.

Absolute flux normalization

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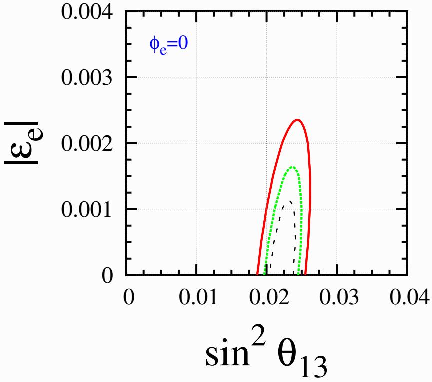
- Other sys. uncertainties can affect the absolute normalization in the event calculation.
- Let us assume conservatively $\sigma_a = 5\%$:

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + a_{\text{norm}} + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d} + \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right) + \left(\frac{a_{\text{norm}}}{\sigma_a}\right)^2$$

$0.020 \leq \sin^2\theta_{13}^{DYB} \leq 0.024$

arXiv:1412.1064



C.L $=$ 68.3, 90, 95%; 2 d.o.f

$a_{norm} = 0$

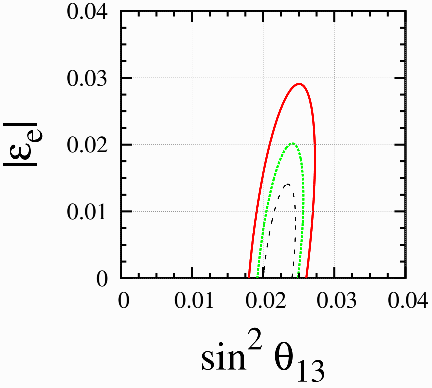
$|\varepsilon_e| \leq 0.0012$ @90% C.L

$0.020 \leq \sin^2\theta_{13} \leq 0.024$

$\sigma_a = 5\%$

$|\varepsilon_e| \leq 0.015$ @90% C.L

$0.020 \leq \sin^2\theta_{13} \leq 0.025$



Summary

- The reactor mixing angle has been measured within a $\sim 5\%$ 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.
- In presence of NSI the determination of θ_{13} is modified (the robustness is lost). Constraints on the NSI couplings were calculated. Those constraints strongly depend on the assumptions on the absolute flux normalization.

THANK YOU

Back up

Oscillation Channels

$\bar{\nu}_e$ Disappearance

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

ν_e Appearance from a ν_μ-beam Cervera *et al.* (NPB **579** (2000))

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{\rm atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2$$
$$= P_{\rm atm} + \underbrace{2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\cos(\Delta_{32}+\delta)}_{P_{\sin\delta}+P_{\cos\delta}} + P_{\rm sol}$$

$$\sqrt{P_{\rm atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31},$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

with $a \equiv V_{CC}/2$ and $\Delta_{ij} \equiv (\Delta m^2_{ij} L)/(4E)$

ν_μ Disappearance

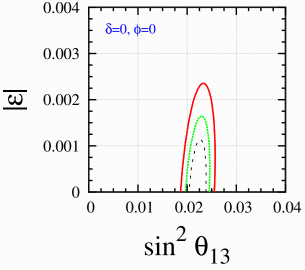
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\Delta_{32} - \sin^2 2\theta_{13}\sin^2\theta_{23} \sin^2\Delta_{31}$$

Results for the FU case

$0.020 \leq \sin^2 \theta_{13}^{DYB} \leq 0.024 \quad @90\%\ \text{C.L; 1 d.o.f}$

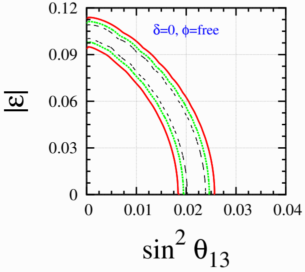
$\varepsilon_{e,\mu,\tau} \equiv \varepsilon, \theta_{23} = \pi/4$

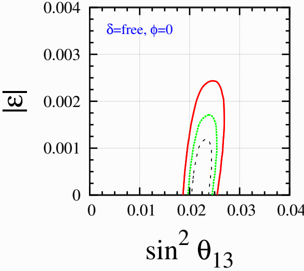
$$\tilde{s}_{13}^2 = s_{13}^2 - |\varepsilon| \left[\frac{\cos\phi}{\sin^2 \Delta_{31}} - 4 s_{13} s_{23} \cos(\delta - \phi) \right]$$



$|\varepsilon| \leq 0.110$ @90% C.L

$\sin^2 \theta_{13} \leq 0.024$





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$|\varepsilon| \leq 0.0013$ @90% C.L

$0.020 \leq \sin^2 \theta_{13} \leq 0.025$

Flavor neutrino states with NSI

A 'new' state $|\nu_\beta\rangle$ can appear with the usual state $|\nu_\alpha\rangle$ in a CC weak process together with l_α. That flavor 'admixture' is incorporated to the anti-neutrino flavor states:

$$|\bar{\nu}^s_\alpha\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma}|\bar{\nu}_\gamma\rangle$$

$$\langle\bar{\nu}^d_\beta| = \langle\bar{\nu}_\beta| + \sum_\eta \varepsilon^{d*}_{\eta\beta}\langle\bar{\nu}_\eta|$$

where the standard flavor states are related to mass eigenstates by:

$$|\bar{\nu}_\alpha\rangle = \sum_k V_{\alpha k}|\bar{\nu}_k\rangle$$

The anti-neutrino transition probability for the new states is:

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

Complete second order NSI probability

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

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