



(Non)standard oscillations at current facilities

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# Outline

- 1 Introduction
- 2 The pheno approach to the NSI
  - CC-Like NSI pheno approach
  - What are the current limits?
  - NC-Like NSI pheno approach
- 3 Where the CC-like NSI can be probed?
  - Example I, results
- 4 Where the NC-like NSI can be probed?
  - Example II, results

Within the Standard Model, and in ordinary matter:

$$V_{\alpha\beta} = \left( \begin{array}{ccc|ccc} \begin{array}{c} \nu_e \rightarrow \nu_e \\ \text{Z} \\ \text{p, n, e} \end{array} & 0 & 0 & \begin{array}{c} \nu_e \rightarrow \nu_e \\ \text{W} \\ \text{e} \end{array} & 0 & 0 \\ 0 & \begin{array}{c} \nu_\mu \rightarrow \nu_\mu \\ \text{Z} \\ \text{p, n, e} \end{array} & 0 & 0 & 0 & 0 \\ 0 & 0 & \begin{array}{c} \nu_\tau \rightarrow \nu_\tau \\ \text{Z} \\ \text{p, n, e} \end{array} & 0 & 0 & 0 \end{array} \right)_{\text{NC}} + \left( \begin{array}{ccc|ccc} \begin{array}{c} \nu_e \rightarrow \nu_e \\ \text{W} \\ \text{e} \end{array} & 0 & 0 & \begin{array}{c} \nu_e \rightarrow \nu_e \\ \text{W} \\ \text{e} \end{array} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right)_{\text{CC}}$$

↑  
proportional to unity  
and unobservable

↑  
observable in  $\nu_e$   
oscillations

Relevant term is the  $\nu_e - \nu_{\mu, \tau}$  energy difference:  $V_{CC} \approx$

(No analogous for  $\mu, \tau$ , which are absent in ordinary matter)



# Oscillation Channels

## $\bar{\nu}_e$ Disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) + \text{solar term}$$

## $\nu_e$ Appearance from a $\nu_\mu$ -beam

Cervera *et al.* (NPB **579** (2000))

Akhmedov *et al.* (JHEP **004** (2004))

Nunokawa *et al.* (Prog.Part.Nucl.Phys **60** (2008))

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\approx |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{solar}}}|^2 \\ &= P_{\text{atm}} + \underbrace{2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{solar}}}\cos(\Delta_{32} + \delta)}_{P_{\sin\delta} + P_{\cos\delta}} + P_{\text{solar}} \end{aligned}$$

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

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

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

## $\nu_\mu$ Disappearance

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

# Oscillation Channels

## $\bar{\nu}_e$ Disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) + \text{solar term}$$

~ 1 km Reactors.

## $\nu_e$ Appearance from a $\nu_\mu$ -beam

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

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

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

T2K and NOvA.

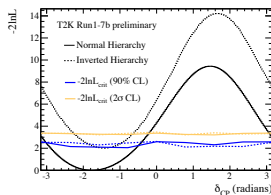
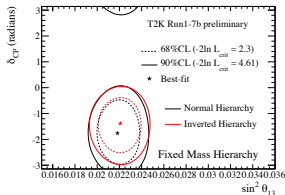
# More importantly ...

## $\theta_{13}$ and $\delta_{cp}$

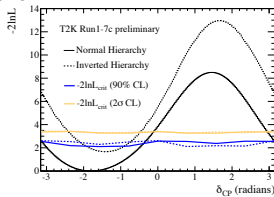
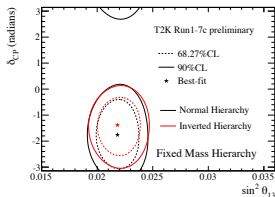
K. Iwamoto @ ICHEP 2016

- T2K result with reactor constraint ( $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ )

### Neutrino 2016



### ICHEP 2016



Neutrino 2016:  $\delta_{cp} = [-3.02, -0.49](NH), [-1.87, -0.98](IH)$  at 90% CL

ICHEP 2016:  $\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74](IH)$  at 90% CL

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- NC-Like NSI pheno approach

## 3 Where the CC-like NSI can be probed?

- Example I, results

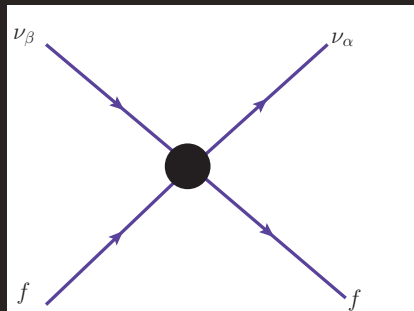
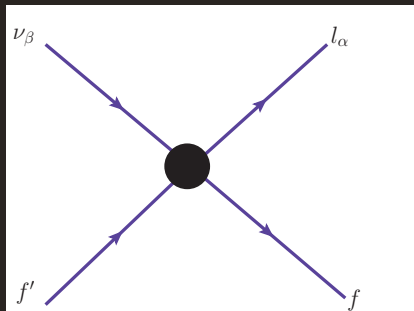
## 4 Where the NC-like NSI can be probed?

- Example II, results

# The pheno approach to the NSI

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))



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

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

Also, see J. Kopp *et al.* (PRD **77** (2008)).



# CC-like NSI pheno approach

Redefining the neutrino states

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

$$|\bar{\nu}_\alpha^s\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon_{\alpha\gamma}^{s*} |\bar{\nu}_\gamma\rangle$$
$$\langle\bar{\nu}_\beta^d| = \langle\bar{\nu}_\beta| + \sum_\eta \varepsilon_{\eta\beta}^{d*} \langle\bar{\nu}_\eta|$$

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

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

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

$$P_{\bar{\nu}_\alpha^s \rightarrow \bar{\nu}_\beta^d} = |\langle\bar{\nu}_\beta^d| \exp(-i\mathcal{H}L) |\bar{\nu}_\alpha^s\rangle|^2.$$

# Current bounds

CC-like NSI

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

Bounds extracted from:

- $V^{ud}$  determination: From Kaon decays  $\rightarrow V^{us}$  (and assuming CKM unitarity) compared with the derivation from beta decays (affected by NSI). [\*NSI quark dominated].
- **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  $\nu_\mu \rightarrow \nu_e$  ( $|\varepsilon_{\mu e}^{ud A}|$ ,  $|\varepsilon_{e\mu}^{ud L(R)}|$ ),  $\nu_e \rightarrow \nu_\tau$  ( $|\varepsilon_{\tau e}^{ud}|$ ), and  $\nu_\mu \rightarrow \nu_\tau$  ( $|\varepsilon_{\mu\tau}^{ud A}|$ ,  $|\varepsilon_{\tau\mu}^{ud L(R)}|$ ). [\*low (high)  $E$  limit].

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

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

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

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

$$|\varepsilon_{\alpha\beta}^{ud} \chi_{ij}| \sim 1\%$$

# NC-Like NSI pheno approach

Generalizing the effective matter potential

The general matter interaction Hamiltonian can be written as

$$H_{\text{int}} = V \begin{pmatrix} 1 + \varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ (\varepsilon_{e\mu}^m)^* & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ (\varepsilon_{e\tau}^m)^* & (\varepsilon_{\mu\tau}^m)^* & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

with  $V = \sqrt{2} G_F N_e$ , and:

$$\varepsilon_{\alpha\beta}^m = \sum_{f=e,u,d} \left\langle \frac{Y_f}{Y_e} \right\rangle \varepsilon_{\alpha\beta}^f = \varepsilon_{\alpha\beta}^e + Y_u \varepsilon_{\alpha\beta}^u + Y_d \varepsilon_{\alpha\beta}^d$$

How many new degrees of freedom do we have now 'in the game'?

# Current bounds

NC-like NSI

Gonzalez-Garcia and Maltoni (JHEP **152** (2013) )

From a global fit, using only neutrino oscillation data, the 90% of C.L bounds for the LMA solution are:

$$\varepsilon_{\alpha\beta} - \varepsilon_{\mu\mu} \Big|_{f=d(u)} \in \begin{bmatrix} [0.02(0.00), 0.51] & [-0.09, 0.04] & [-0.14, 0.14] \\ \times & 0 & [-0.01, 0.01] \\ \times & \times & [-0.01, 0.03] \end{bmatrix}$$

Thus, for instance, one of the **less constrained** and non-diagonal NSI coupling is  $\varepsilon_{e\tau}^m \sim \mathcal{O}(1)$ .

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Constraints on  $\varepsilon_{\alpha\beta}^{f=e}$  also come from ' $\nu$ - $e$ ' scattering (not cover them here), see for instance table III in Ref:

Miranda and Nunokawa (NJP 17 (2015))

# Outline

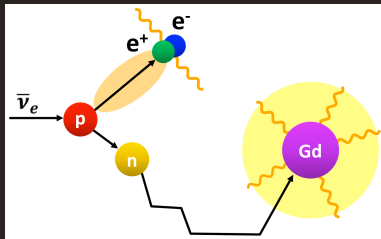
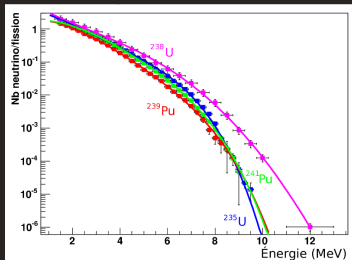
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# Reactor $\bar{\nu}_e$ production and detection

**Production:**  $\beta$  decay of

$k = {}^{235}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu}$  and  ${}^{238}\text{U}$

**Detection:** Inverse  $\beta$  decay,



Flux parametrizations:  $\Phi_k(E)$

P. Huber (PRC 84 (2011))

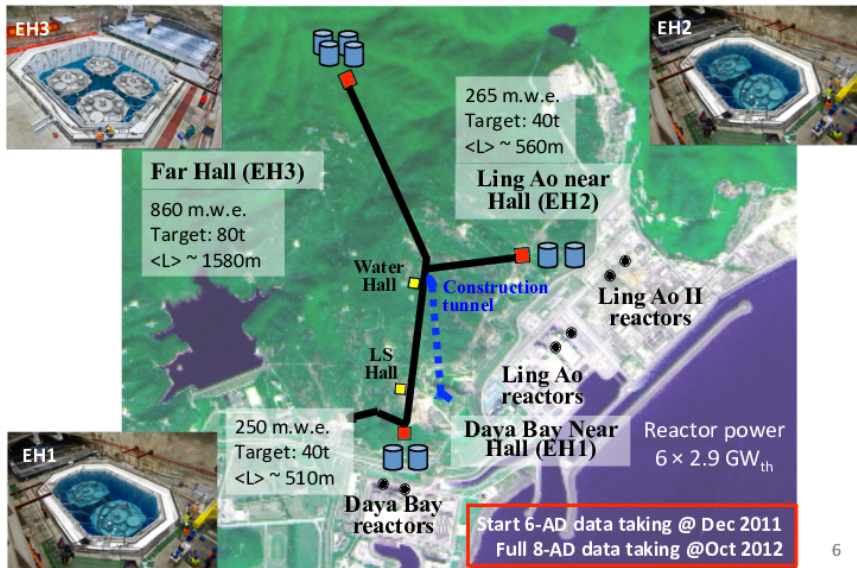
T. Mueller *et al.* (PRC 83 (2011))

Coincidence signals: Prompt  $e^+$ -annihilation and delayed  $n$ -capture.

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



# Daya Bay Experimental Setup



# Analysis details

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

Our setup:

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

$$P_{\bar{\nu}_e^s \rightarrow \bar{\nu}_e^d}^{\text{eff.}} \simeq 1 + \overbrace{4|\varepsilon_e| \cos\phi_e}^{\text{'zero distance term'}} - 4[\sin\theta_{13} + s_{23}|\varepsilon_\mu| \cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau| \cos(\delta - \phi_\tau)]^2 \sin^2 \Delta_{31} + \mathcal{O}(\varepsilon)^2$$

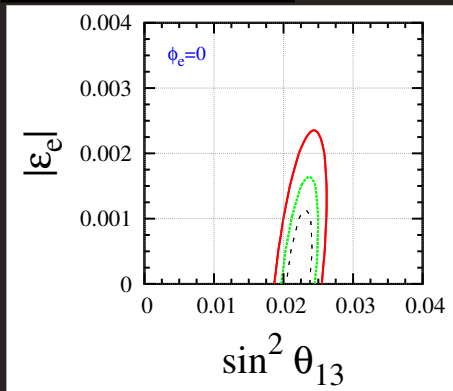
- Ours is a total rate analysis.

# Results for the $\varepsilon_e$ case

Agarwalla, Bagchi, DVF, Tórtola

(JHEP **060** (2015))

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



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

$$a_{\text{norm}} = 0$$

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

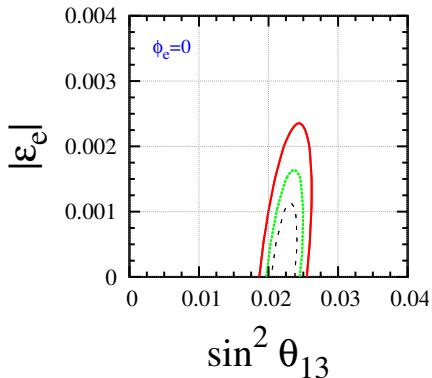
$$0.020 \leq \sin^2 \theta_{13} \leq 0.024$$

# Results for the $\varepsilon_e$ case

Agarwalla, Bagchi, DVF, Tórtola

(JHEP 060 (2015))

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



$$\sigma_a = 5\%$$

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

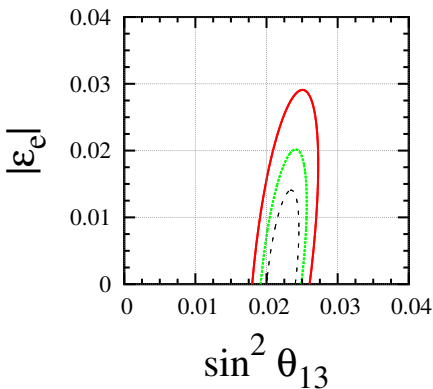
$$0.020 \leq \sin^2 \theta_{13} \leq 0.025$$

$$\text{C.L.} = 68.3, 90, 95\%; 2 \text{ d.o.f.}$$

$$a_{\text{norm}} = 0$$

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

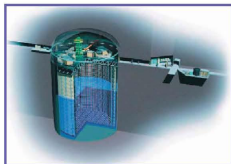
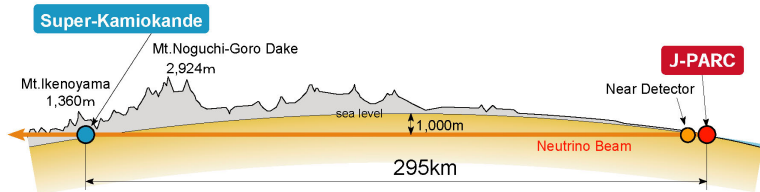
$$0.020 \leq \sin^2 \theta_{13} \leq 0.024$$



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# T2K Experiment



**Super-Kamiokande**  
(ICRR, Univ. Tokyo)



**J-PARC Main Ring**  
(KEK-JAEA, Tokai)



# NOvA

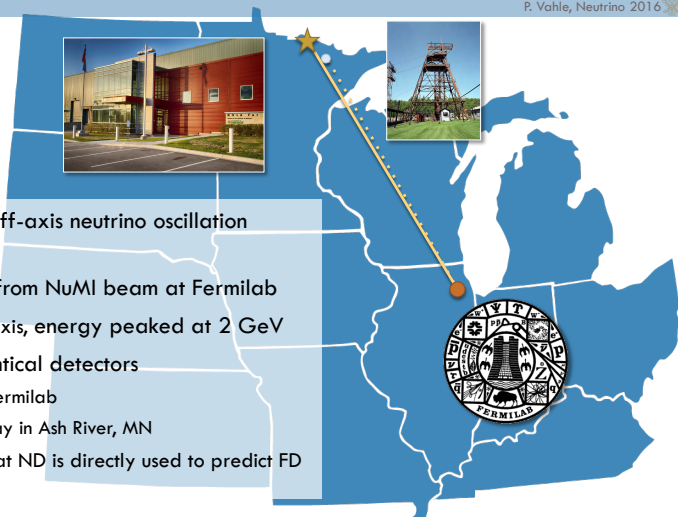
2



P. Vahle, Neutrino 2016



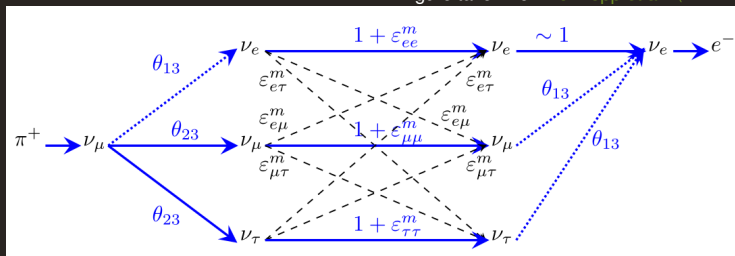
- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD



# Analysis details

(Anti)neutrino appearance

Figure taken from: [J. Kopp et al. \(PRD 77 \(2008\)\)](#)

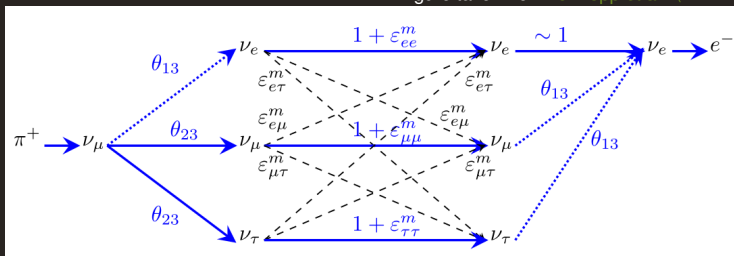




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(Anti)neutrino appearance

Figure taken from: [J. Kopp et al. \(PRD 77 \(2008\)\)](#)

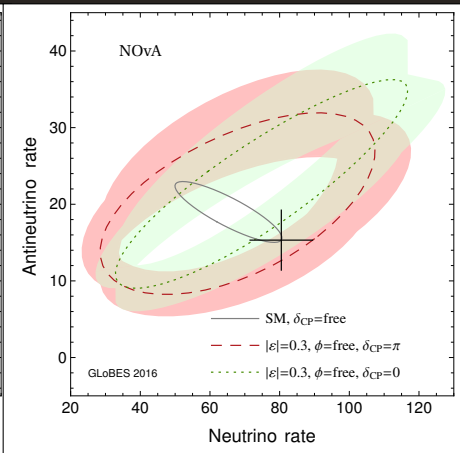
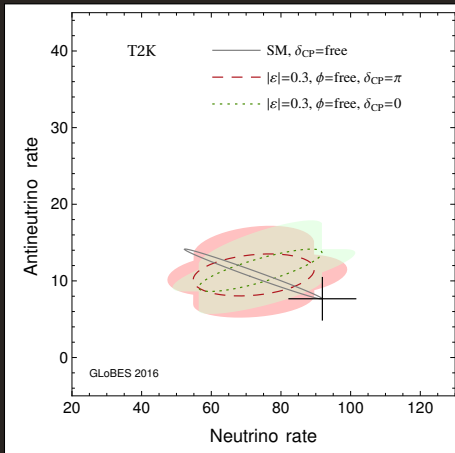


- We considered only the (Anti)neutrino appearance channel.
- Only the off-diagonal NSI parameter  $\varepsilon_{e\tau}^m \equiv |\varepsilon| \exp(i\phi) \neq 0$ .
- We simulated true neutrino events including NSI and we compare them to the test SM events in both T2K (scaled 5 yrs) and NOvA ( $3\nu+3\bar{\nu}$ ).

# Results

## Bi-rate plots

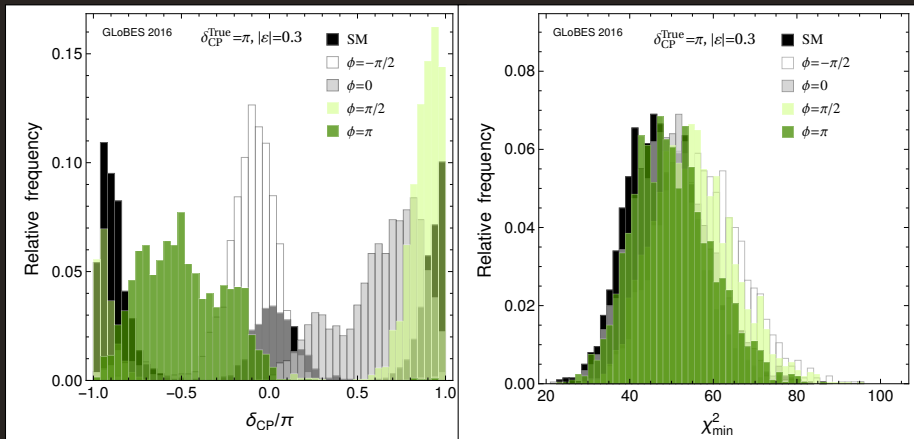
DVF and Huber (PRL 117 (2016))



# Results

## Histograms

DVF and Huber (PRL 117 (2016))

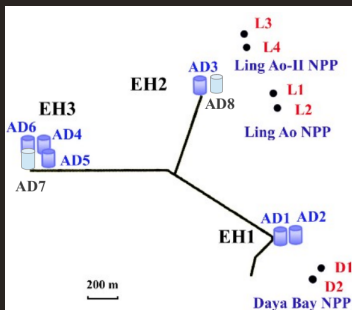


# Summary

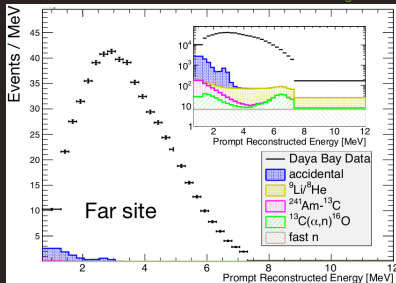
- A pheno approach to the NSI has been discussed leaving out the ‘model building’ treatment to generate sizable NSI indicated by the pheno studies.
- NSI phenomenology with current neutrino oscillation experiments was presented. Two cases were shown, one for CC-like NSI and the other for NC-like NSI. Another study of NC-like NSI was presented by Prof. **O. Yasuda**.
- Multidetector reactor neutrino experiments offer a clean probe of CC-like NSI. The  $\theta_{13}$  determination is robust under CC-like NSI while the value of the NSI constraint is limited by our current knowledge of the (total normalization) reactor neutrino fluxes.
- Thanks to ‘parameter degeneracies’ (after including NC-like NSI in the  $3\nu$ -framework) if the current prefer value for  $\delta_{\text{CP}}^{\text{True}} \sim -\pi/2$  were established, with current facilities, we can not disentangle whether the origin of the CP violation comes from the usual Dirac CP violating phase or from the NSI couplings (even with  $\phi = \pi$ ).

THANK YOU

# Daya Bay $\bar{\nu}_e \rightarrow \bar{\nu}_e$



Chao Zhang @neutrino2014



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

$$\chi^2 = \sum_{d=1}^8 \frac{[M_d - T_d (1 + a_{\text{norm}} + \sum_r \omega_r^d \alpha_r + \xi_d) + \beta_d]^2}{M_d + B_d} + \sum_{r=1}^6 \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^8 \left( \frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2} \right) + \left( \frac{a_{\text{norm}}}{\sigma_a} \right)^2$$

Constrained normalization analysis!  $\sigma_a \sim 5\%$ .