Non-standard neutrino interactions in reactor and superbeam experiments

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Preface

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- If they will be consistent with each other, is the standard oscillation interpretation rigid?

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In this talk

We take a model independent (effective interaction) approach to interpret the future results — Non-standard interaction (NSI)

Outline

1. Introduction
   - NSI in source and detection
   - NSI in propagation
2. Numerical study
   - Mismatch and Offset: two examples
   - Systematic study: which NSI does what
   - Discovery reach
3. Summary

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Introduction — NSIs

- NSI — Flavour violating interactions with neutrinos parametrized as four-Fermi interactions:
- They can affect the neutrino source, propagation, and detection

Standard oscillation

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle \right|^2$$

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With NSIs

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta^d | \mathrm{e}^{-\mathrm{i}(H+V_{\mathrm{NSI}})L} | \nu_\alpha^s \rangle \right|^2$$

- CC type NSI — flavour mixture states at source and detector
  Grossmann PLB**359** (1995) 141.

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \qquad \text{e.g., } \pi^+ \xrightarrow{\epsilon_{\mu e}^s} \mu^+ \nu_e$$

$$\langle\nu_\alpha^d| = \langle\nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon_{\gamma\alpha}^d \langle\nu_\gamma|, \qquad \text{e.g., } \nu_\tau N \xrightarrow{\epsilon_{\tau e}^d} e^- X$$

- NC type NSI — extra matter effect in propagation
  Wolfenstein PRD**17** (1978) 2369. Valle PLB**1999** (1987) 432. Guzzo Masiero Petcov PLB**260** (1991) 154. Roulet PRD**44** (1991) R935. etc.

$$(V_{\mathrm{NSI}})_{\beta\alpha} = \sqrt{2} G_F N_e \epsilon_{\beta\alpha}^m$$

NSI associated with electron, $\epsilon^s_{e\alpha}$ and $\epsilon^d_{\alpha e}$

- $\epsilon^s_{e\alpha}$ and $\epsilon^d_{\alpha e}$ affect
  - Reactor — source and detection,
  - Accelerator — ν_e detection

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  - Reactor — source and detection,
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- The source and detection states are defined as

$$|\bar{\nu}_e\rangle = |\bar{\nu}_e\rangle + \epsilon^{s*}_{e\alpha}|\bar{\nu}_\alpha\rangle$$

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- We introduce only NSIs with the $(V-A)(V-A)$ structure

$$\mathcal{L}_{\mathrm{NSI}} = 2\sqrt{2}G_F\tilde{\epsilon}_{e\alpha}(\bar{\nu}_\alpha\gamma^\rho \mathrm{P}_L e)(\bar{d}\gamma_\rho \mathrm{P}_L u) + \mathrm{H.c.},$$

This NSI effects take the same energy dependence as the standard interactions: $\epsilon^s_{e\alpha}$ and $\epsilon^d_{\alpha e}$ — energy constant parameters.

$\epsilon^s_{e\alpha}$ in source and $\epsilon^d_{\alpha e}$ in detector are correlated

$$\epsilon^s_{e\alpha} = (\epsilon^d_{\alpha e})^* = \tilde{\epsilon}_{e\alpha}.$$

NSI associated with muon, $\epsilon^s_{\mu\alpha}$ and $\epsilon^d_{\alpha\mu}$

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  - Accelerator — source (π decay) and ν_μ detection

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$$|\nu^s_\mu\rangle = |\nu_\mu\rangle + \epsilon^s_{\mu\alpha}|\nu_\alpha\rangle, \qquad \langle\nu^d_\mu| = \langle\nu_\mu| + \epsilon^d_{\alpha\mu}\langle\nu_\alpha|$$

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- We assume only the $(V-A)(V-A)$ type NSI which is the same as the electron associated NSI case.
  The other cases are also examined in our paper.

$$\mathcal{L}_{\rm NSI} = 2\sqrt{2}G_F\tilde{\epsilon}_{\mu\alpha}(\bar{\nu}_\alpha\gamma^\rho \mathrm{P}_L\mu)(\bar{d}\gamma_\rho \mathrm{P}_L u) + \mathrm{H.c.},$$

$\epsilon^s_{\mu\alpha}$ in source and $\epsilon^d_{\alpha\mu}$ in detector are correlated

$$\epsilon^s_{\mu\alpha} = (\epsilon^d_{\alpha\mu})^* = \tilde{\epsilon}_{\mu\alpha}.$$

NSI in propagtion, $\epsilon^m_{\alpha\beta}$

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  - Accelerator — neutrino propagation

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- Standard oscillation Hamiltonian

$$(H_{\mathrm{SO}})_{\beta\alpha} = \frac{1}{2E} U_{\beta i} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger_{i\alpha} + \begin{pmatrix} \sqrt{2} G_F N_e & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

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- When we introduce

$$\mathcal{L}_{\mathrm{NSI}} = 2\sqrt{2} G_F \epsilon^m_{\beta\alpha} (\bar{\nu}_\beta \gamma^\rho \mathrm{P}_L \nu_\alpha)(\bar{e}\gamma_\rho \mathrm{P}_L e) + \mathrm{H.c.},$$

The total Hamiltonian becomes

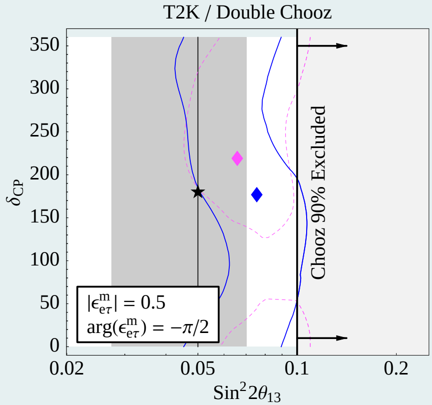
$$H = H_{\mathrm{SO}} + \sqrt{2} G_F N_e \epsilon^m_{\beta\alpha}$$

Outline

Examples: Mismatch

If NSI $\epsilon^m_{e\tau} = 0.5e^{-i\pi}$ exists, what will reactor and accelerator see?

True values — $\sin^2 2\theta_{13} = 0.05$ and $\delta_{CP} = \pi$.

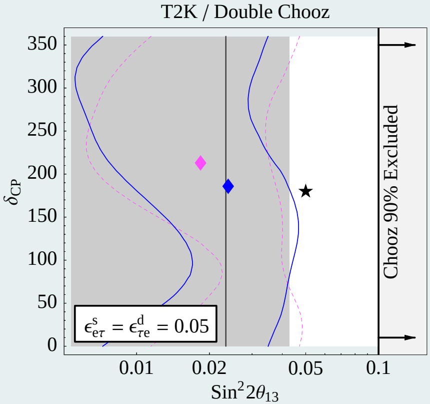


Best-fit point of reactor is located away from that of accelerator — *Mismatch*

Examples: Offset

If $\epsilon^{s}_{e\tau} = (\epsilon^{d}_{\tau e})^{*} = 0.05$

True values — $\sin^2 2\theta_{13} = 0.05$ and $\delta_{\rm CP} = \pi$.



The results are consistent but the true parameter point is excluded — *Common offset*

Systematic study: Before showing plots...

The plots in the next slides indicate —

How the best fit values of θ_{13} change if there is a NSI with

- $|\epsilon| =$0-0.1 (for source and detector), $|\epsilon| =$0-0.7 (for matter),
- $\arg[\epsilon] =$0-2π.

Bounds

- ϵ^m: NSIs in matter

  LFV processes through loop diagrams constrain them

  Davidson Peña-Garay Ruis Santamaria JHEP **03** (2003) 011

  $\rightarrow$ $\boxed{\epsilon^m_{e\tau} \lesssim 0.7}$ This is the only relevant NSI in matter.

  $\epsilon^m_{e\mu} < 5 \cdot 10^{-4} \rightarrow$ irrelevant in superbeam experiments.

  $\epsilon^m_{\mu\tau}$ does not affect the θ_{13} determination.

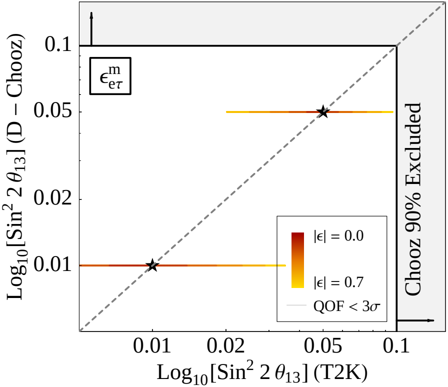
  $\epsilon^m_{\alpha\alpha}$ only gives sub-dominant effects.

- $\epsilon^{s,d}$: NSIs in source and detection:

  $\epsilon^s_{\mu e}$ and $\epsilon^d_{\mu e}$ are constrained at 0.09 PDG. The others are, at least, bound from lepton universality at the same level. $\rightarrow$ $\boxed{\epsilon^s, \epsilon^d \lesssim 0.1}$.

Systematic study: NSI in matter

- How the best fit values of θ_{13} change if there is a NSI with
  - $|\epsilon^m_{e\tau}|$ =0-0.7, $\arg[\epsilon]$ =0-2π.



- Only the accelerator exp. is affected by the NSI in matter — *mismatch*

Systematic study: NSI in source and detector

- How the best fit values of θ_{13} change if there is a NSI with
  - $|\epsilon^{s,d}|$ =0-0.1,
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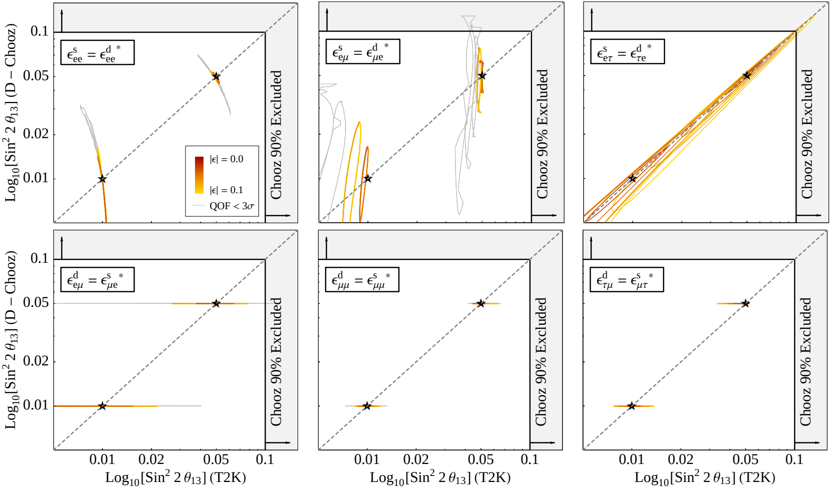
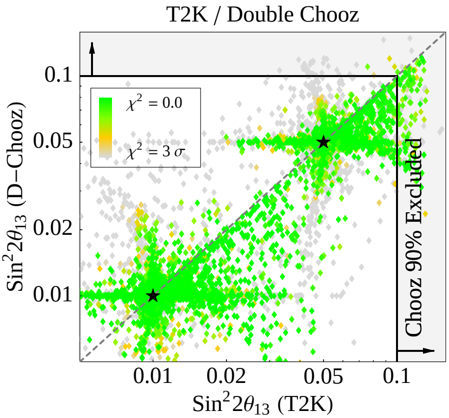


Systematic study: scatter plot

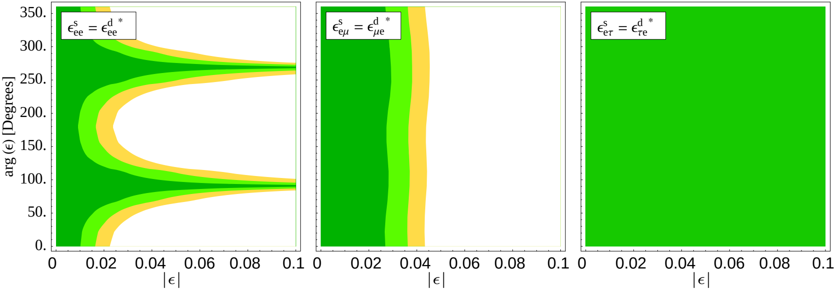
- How the best fit values of θ_{13} change if there are NSIs



- We introduce some random combinations of the NSI parameters.

Systematic study: Discovery reach

- Discovery reach — if $\chi^2 > 3\sigma$ after marginalizing all the standard oscillation parameters, we can discover a NSI.



- The discovery reach strongly depends on the argument of the epsilon parameters.

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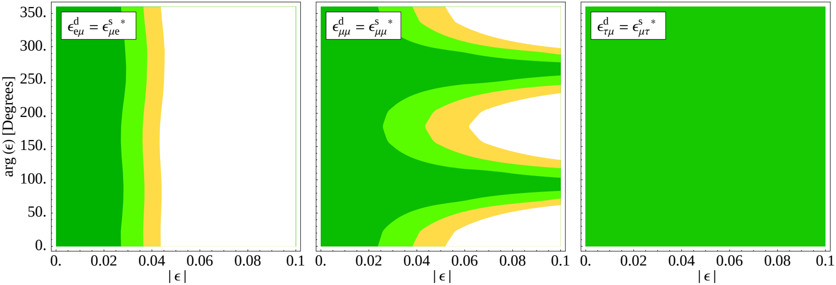

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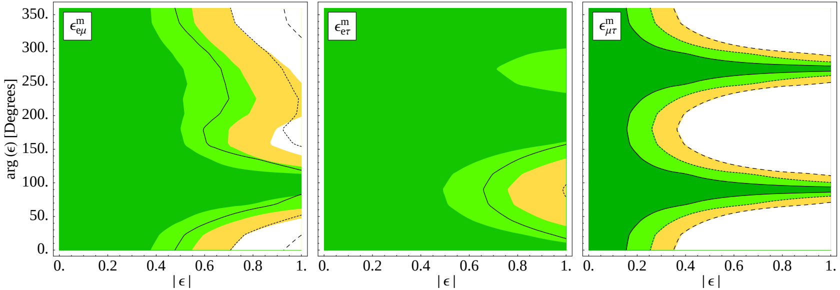

- The discovery reach strongly depends on the argument of the epsilon parameters.

Outline

Summary

- We study the effects of NSIs in forthcoming experiments —

Reactor and *accelerator*

Mismatch — The two experiments yield a tension.
We will feel the existence of something non-standard.
— realized by e.g., $\epsilon^{m}_{e\tau}$.

Offset — The two experiments coincide with each other and are consistent with the standard oscillation hypothesis but the true parameter region is excluded.
— realized by e.g., $\epsilon^{s}_{e\tau} = (\epsilon^{d}_{\tau e})^{*} (= \tilde{\epsilon}_{e\tau})$.

- The two experiments are not redundant — They will give important information for standard and non-standard neutrino physics.