Non-standard interaction effects for θ_{13} at reactor neutrino experiments

Partikeldagarna

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Contents:

- Neutrino oscillations and non-standard interactions
- NSIs at sources and detectors
- Mimicking effects on θ_{13}

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Lepton flavor mixing

Weak interaction eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

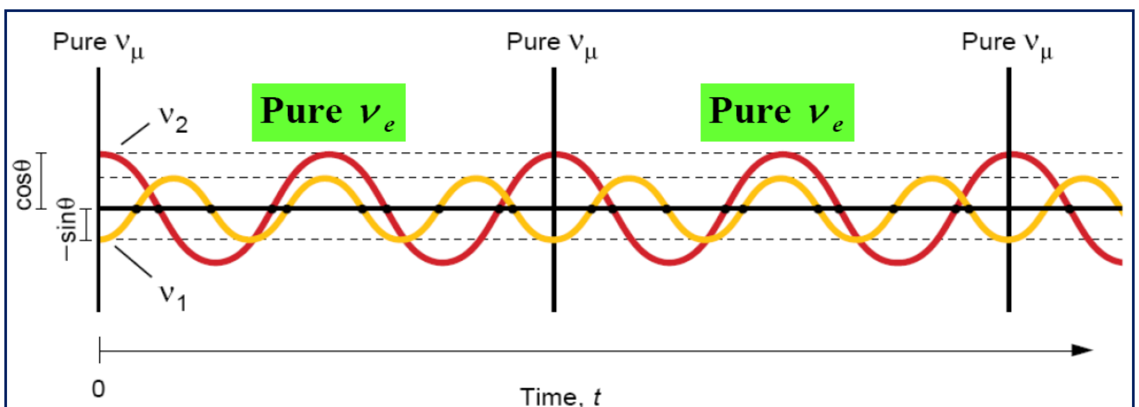
Standard Parametrization

Majorana CP violating phases

$$V_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ \sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Dirac CP violating phase

δ



There are now strong evidences that neutrinos are massive and lepton flavors are mixed. Since in the Standard Model neutrinos are massless particles, the SM must be extended by adding neutrino masses.

Neutrino oscillation parameters

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Schwetz, Tortola, Valle, 08

Unknowns:

1. θ_{13}
2. Sign of Δm_{31}^2
3. Dirac or Majorana ?
4. Absolute masses
5. Leptonic CP violation?
6. Sterile neutrino?

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Experimental steps:

- Improve present measurements of solar and atmospheric parameters.
- Discover the last mixing angle θ_{13} (Daya Bay, Double Chooz)
- CP violating phase (δ) in the future Long baseline experiments (ν-Factory, β-beam).

New physics for neutrino oscillations

- unitarity violation $UU^\dagger \neq 1$

Combined analysis of neutrino oscillations, W and Z decays, rare LFV modes and lepton universality tests. (Antusch, et al., 06)

Natural consequence in seesaw models

$$|VV^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \times 10^{-5} & < 1.6 \times 10^{-2} \\ < 7.0 \times 10^{-5} & 0.995 \pm 0.005 & < 1.02 \times 10^{-2} \\ < 1.6 \times 10^{-2} & < 1.02 \times 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

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- non-standard interactions at neutrino sources

$$\pi^+ \to \mu^+ + \nu_e, \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_\mu, \quad n \to p + e^- + \overline{\nu}_\mu$$

(standard: $\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e, \quad n \to p + e^- + \overline{\nu}_e$)

- non-standard interactions at neutrino detectors

$\nu_e + n \to p + \mu^-$ (standard: $\nu_\mu + n \to p + \mu^-$)

These effects can be measured even for L=0 (near detector $P_{\mu e}$ (L=0) ≠ 0)

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- non-standard interactions with matter during propagation

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\,\varepsilon_{\alpha\beta}^{fP} G_F (\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\overline{f}\gamma^\mu P f)$$

Constraint by experiments with neutrinos and charged leptons. (Davidson, et al., 03; M. Blennow, coming soon)

$$\begin{bmatrix} -0.9 < \varepsilon_{ee} < 0.75 & |\varepsilon_{e\mu}| \lesssim 3.8 \times 10^{-4} & |\varepsilon_{e\tau}| \lesssim 0.25 \\ & -0.05 < \varepsilon_{\mu\mu} < 0.08 & |\varepsilon_{\mu\tau}| \lesssim 0.25 \\ & & |\varepsilon_{\tau\tau}| \lesssim 0.4 \end{bmatrix}$$

Neutrino oscillation with NSIs

- The neutrino states produced in the source and observed in the detector are the superpositions of pure orthonormal flavor states.

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

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

Normalization factors

$$N_\alpha^s = \sqrt{\left[\left(\mathbb{1}+\varepsilon^s\right)\left(\mathbb{1}+\varepsilon^{s\dagger}\right)\right]_{\alpha\alpha}}$$

$$N_\beta^d = \sqrt{\left[\left(\mathbb{1}+\varepsilon^{d\dagger}\right)\left(\mathbb{1}+\varepsilon^d\right)\right]_{\beta\beta}}$$

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- Effective Hamiltonian in matter

$$V_{CC} = \sqrt{2} G_F N_e$$

$$\begin{aligned}\hat{H} &= H_0 + H_m + H_{\rm NSI} \\ &= \frac{1}{2E} U \mathrm{diag}(m_1^2, m_2^2, m_3^2) U^\dagger + \mathrm{diag}(V_{CC}, 0, 0) + V_{CC}\varepsilon^m\end{aligned}$$

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$$\langle\nu^d_\beta| = \frac{1}{N^d_\beta}\left(\langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta}\langle\nu_\alpha|\right)$$

Normalization factors

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$$N^d_\beta = \sqrt{\left[(\mathbb{1}+\varepsilon^{d\dagger})\left(\mathbb{1}+\varepsilon^{d}\right)\right]_{\beta\beta}}$$

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- Effective mixing matrix and mass squared eigenvalues in matter.

$$\hat{H} = \frac{1}{2E}\hat{U}{\rm diag}\left(\hat{m}_1^2, \hat{m}_2^2, \hat{m}_3^2\right)\hat{U}^\dagger$$

For reactor neutrinos, $H_0 \gg H_m$ & $H_{\rm NSI} \rightarrow \hat{U} \simeq U,\ \hat{m}_i \simeq m_i$

Neutrino oscillation with NSIs

- Amplitude for the process $\nu_\alpha^s \to \nu_\beta^d$

$$A_{\alpha\beta} = \sum_i \hat{U}^*_{\alpha i} \hat{U}_{\beta i} \mathrm{e}^{-\mathrm{i}\frac{\hat{m}_i^2 L}{2E}}$$

$$\begin{aligned}\mathcal{A}_{\alpha\beta}(L) &= \frac{1}{N_\alpha^s N_\beta^d} \langle \nu_\beta^d | \mathrm{e}^{-\mathrm{i}\hat{H}L} | \nu_\alpha^s \rangle = \frac{1}{N_\alpha^s N_\beta^d} (\mathbb{1} + \varepsilon^d)_{\rho\beta} A_{\gamma\rho} (\mathbb{1} + \varepsilon^s)_{\alpha\gamma} \\ &= \frac{1}{N_\alpha^s N_\beta^d} \left[(\mathbb{1} + \varepsilon^d)^T A^T (\mathbb{1} + \varepsilon^s)^T \right]_{\beta\alpha} = \frac{1}{N_\alpha^s N_\beta^d} \left[A + \varepsilon^s A + A\varepsilon^d + \varepsilon^s A \varepsilon^d \right]_{\alpha\beta}\end{aligned}$$

- Oscillation probability

$$\begin{aligned}P(\nu_\alpha^s \to \nu_\beta^d) &= |\mathcal{A}_{\alpha\beta}(L)|^2 \\ &= \sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*} - 4 \sum_{i>j} \mathrm{Re}(\mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}) \sin^2 \frac{\Delta \hat{m}_{ij}^2 L}{4E} \\ &\quad + 2 \sum_{i>j} \mathrm{Im}(\mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}) \sin \frac{\Delta \hat{m}_{ij}^2 L}{2E} \; .\end{aligned}$$

$$\mathcal{J}_{\alpha\beta}^i = \frac{\hat{U}^*_{\alpha i} \hat{U}_{\beta i} + \sum_\gamma \varepsilon^s_{\alpha\gamma} \hat{U}^*_{\gamma i} \hat{U}_{\beta i} + \sum_\gamma \varepsilon^d_{\gamma\beta} \hat{U}^*_{\alpha i} \hat{U}_{\gamma i} + \sum_{\gamma,\rho} \varepsilon^s_{\alpha\gamma} \varepsilon^d_{\rho\beta} \hat{U}^*_{\gamma i} \hat{U}_{\rho i}}{N_\alpha^s N_\beta^d}$$

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- Oscillation probability

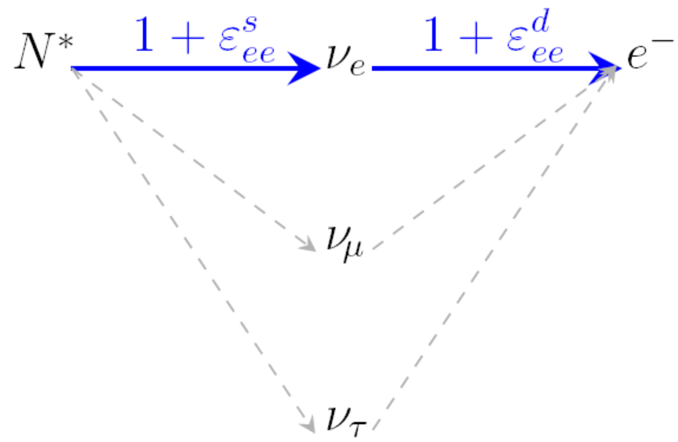
Zero-distance effects

$$\begin{aligned}P(\nu_\alpha^s \to \nu_\beta^d) &= |\mathcal{A}_{\alpha\beta}(L)|^2 \\ &= \sum_{i,j} \mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin^2 \frac{\Delta \hat{m}^2_{ij} L}{4E} \\ &\quad + 2 \sum_{i>j} \mathrm{Im}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin \frac{\Delta \hat{m}^2_{ij} L}{2E} \,.\end{aligned}$$

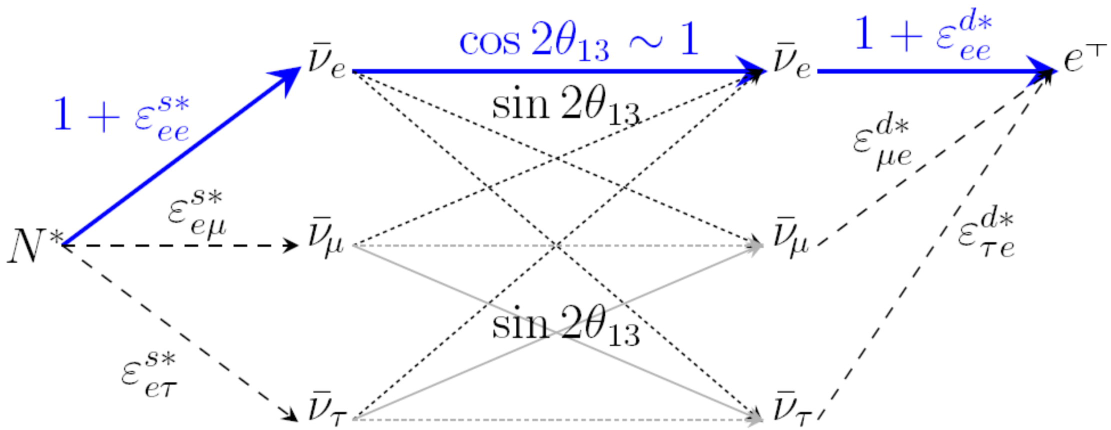
$$\mathcal{J}^i_{\alpha\beta} = \frac{\hat{U}^*_{\alpha i} \hat{U}_{\beta i} + \sum_\gamma \varepsilon^s_{\alpha\gamma} \hat{U}^*_{\gamma i} \hat{U}_{\beta i} + \sum_\gamma \varepsilon^d_{\gamma\beta} \hat{U}^*_{\alpha i} \hat{U}_{\gamma i} + \sum_{\gamma,\rho} \varepsilon^s_{\alpha\gamma} \varepsilon^d_{\rho\beta} \hat{U}^*_{\gamma i} \hat{U}_{\rho i}}{N_\alpha^s N_\beta^d}$$

NSIs at reactor neutrino experiments

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



Far detector



Near detector (zero-distance effect: an enhancement of total neutrino flux)

- Only V±A type of NSIs are involved at the source and detector.
- Average energy E≈3 MeV → matter effects are irrelevant.
- $\varepsilon^s = \varepsilon^{d\dagger}$ ($\varepsilon^s < 0.1$, $\varepsilon^d < 0.2$ from universality in lepton decay)

Short baseline experiments (Daya Bay & D-Chooz)

- Oscillation probability

$$P(\bar{\nu}_e^s \to \bar{\nu}_e^d) \simeq 1 - \sin^2 2\tilde{\theta}_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

- Effective mixing angle

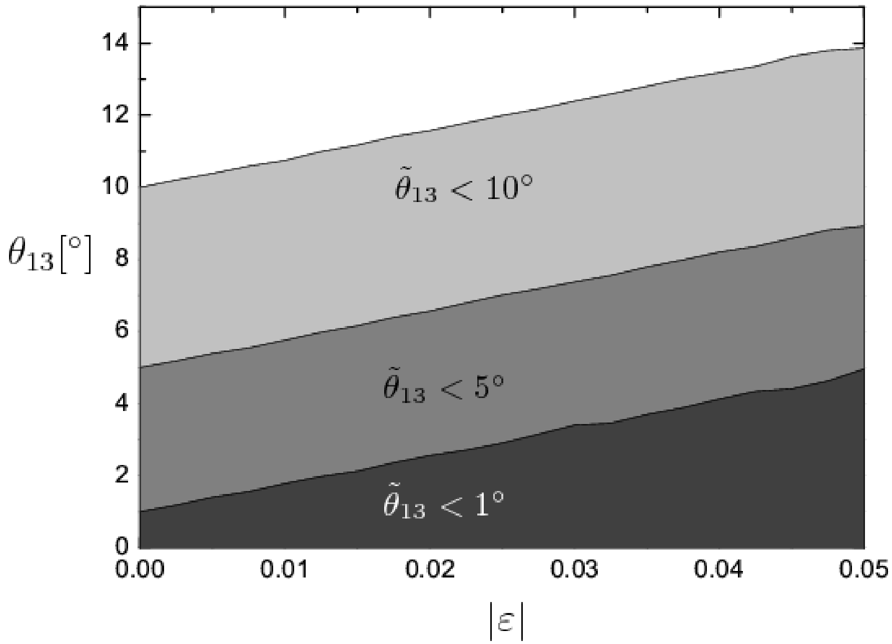
$$\tilde{s}_{13}^2 = s_{13}^2 + 2 s_{13} \left[s_{23} \cos(\delta - \phi_{e\mu}) |\varepsilon_{e\mu}| + c_{23} \cos(\delta - \phi_{e\tau}) |\varepsilon_{e\tau}| \right]$$
$$+ s_{23}^2 |\varepsilon_{e\mu}|^2 + c_{23}^2 |\varepsilon_{e\tau}|^2 + 2 |\varepsilon_{e\mu}| |\varepsilon_{e\tau}| s_{23} c_{23} \cos(\phi_{e\mu} - \phi_{e\tau}) + \mathcal{O}(\varepsilon^3, \varepsilon s_{13}^2)$$

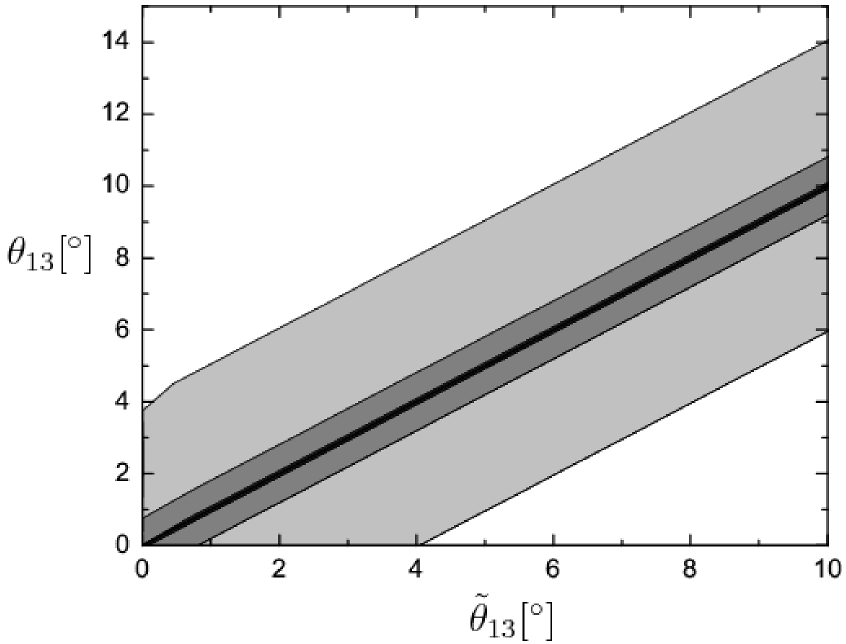
- Only $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ are involved
- Invariant with respect to the exchange $\varepsilon_{e\mu} \leftrightarrow \varepsilon_{e\tau}$
- A minimum exists at the position

$$s_{13}\big|_{\min} = -s_{23} \cos(\delta - \phi_{e\mu}) |\varepsilon_{e\mu}| - c_{23} \cos(\delta - \phi_{e\tau}) |\varepsilon_{e\tau}|$$

- CP violating phases enter the oscillation probability explicitly

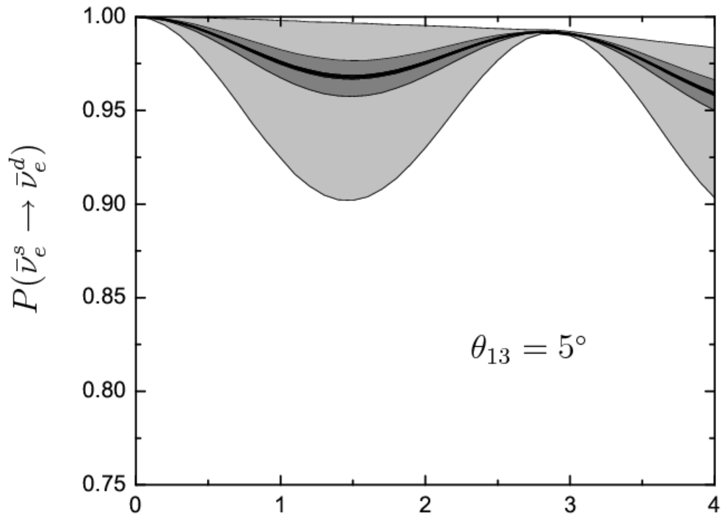
Short baseline experiments (Daya Bay & D-Chooz)

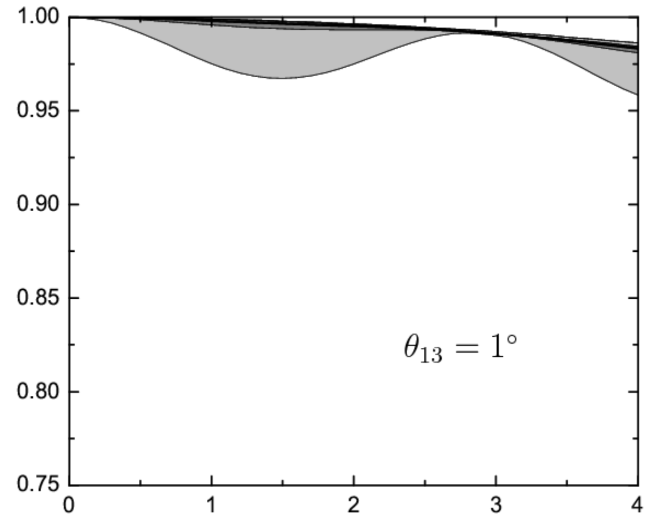


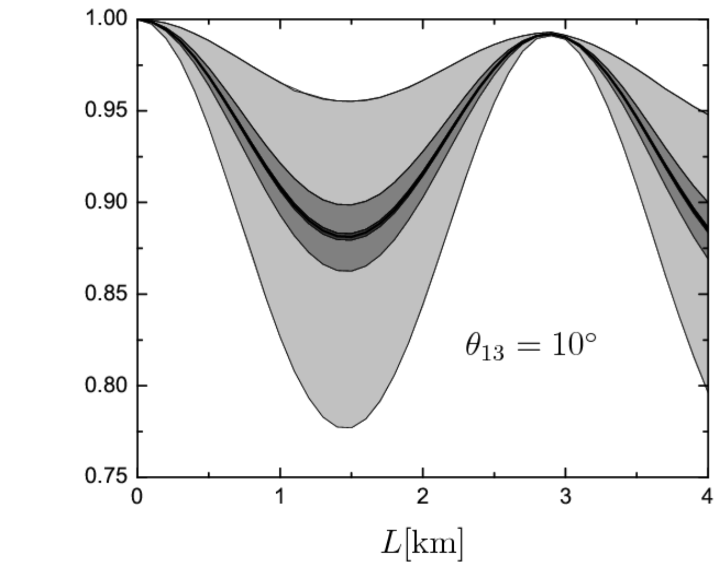


- $\theta_{13} < 14^o$, which is larger than the Chooz bound 10^o
- In despite a very small θ_{13} , a sizable effective mixing angle can be gained due to the mimicking effects.
- Even if the effective mixing angle is too small to be measured in a reactor experiment, a discovery search of a non-vanishing θ_{13} may still be carried out at future neutrino factories.

Short baseline experiments (Daya Bay & D-Chooz)







Mimicking oscillation effects

- Oscillation probabilities for different θ_{13} .
- The shadings correspond $\varepsilon<0.05$, $\varepsilon<0.01$ and $\varepsilon<0.001$, respectively.

Medium baseline experiments (KamLAND)

- Oscillation probability

$$P(\bar{\nu}_e^s \to \bar{\nu}_e^d) \simeq 1 - \sin^2 2\tilde{\theta}_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

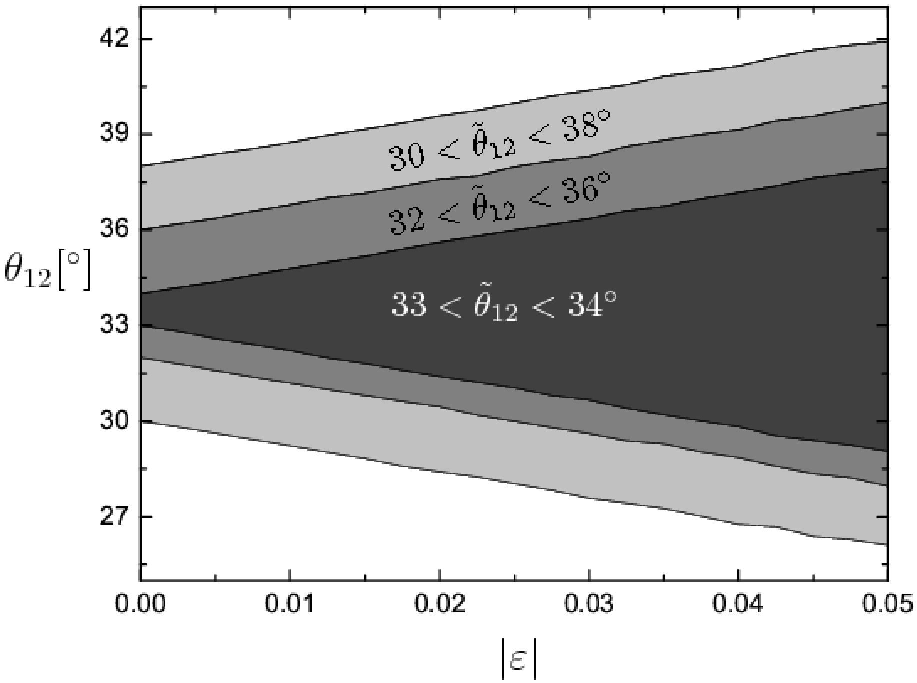
- To improve the accuracy of current measurement, a baseline length ~ 50 km (the first minimum related with $\Delta m_{21}{}^2$) should be taken for next generation experiments.

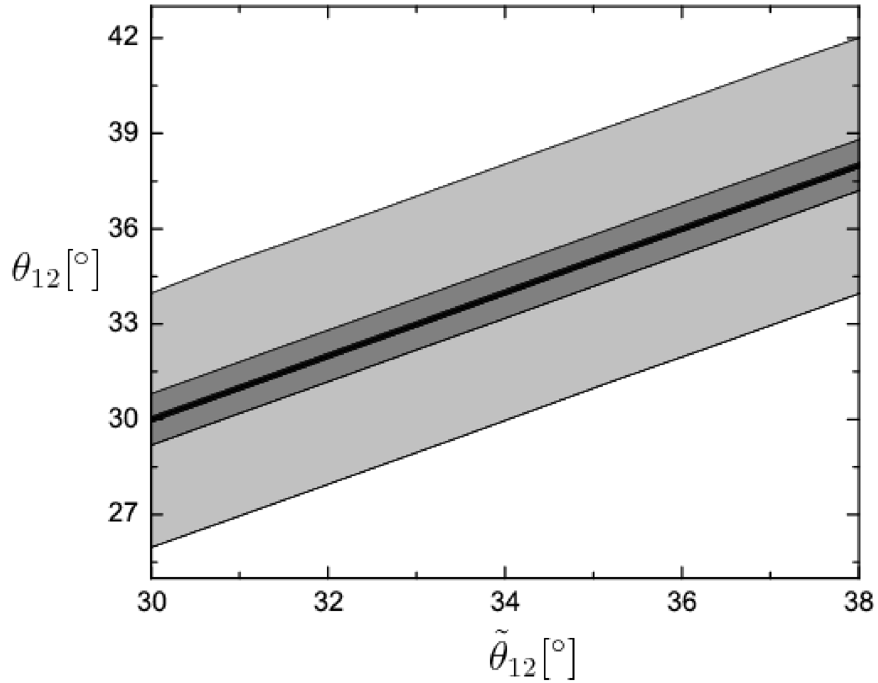
- Effective mixing angle

$$\tilde{s}_{12}^2 = s_{12}^2 + 2 s_{12} c_{12} \left[c_{23} \cos(\phi_{e\mu}) |\varepsilon_{e\mu}| - s_{23} \cos(\phi_{e\tau}) |\varepsilon_{e\tau}| \right] + \mathcal{O}(\varepsilon s_{13}, s_{13}^2)$$

- Only $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ are involved → reactor experiments are not sensitive to ε_{ee}
- Since the magnitude of θ_{12} is more sizable compared to θ_{13}, NSI effects cannot mimic an effective mixing angle with a vanishing θ_{12} . However, NSIs may significantly modify the observed effective mixing angle.

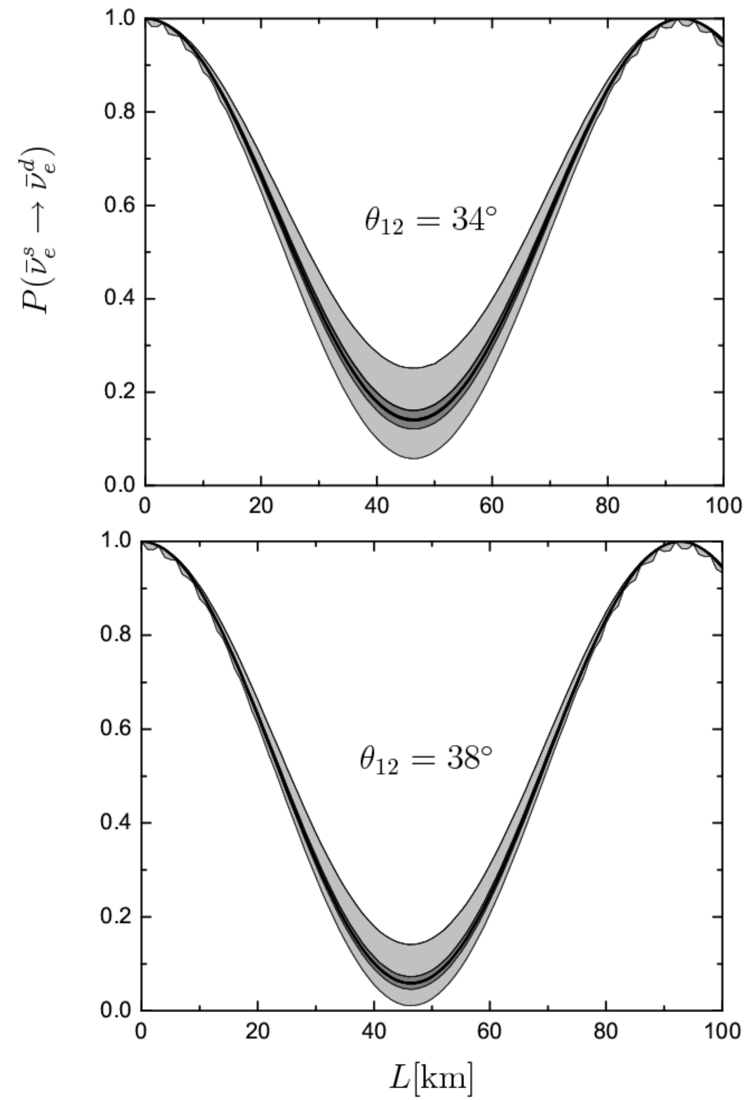
Medium baseline experiments (KamLAND)

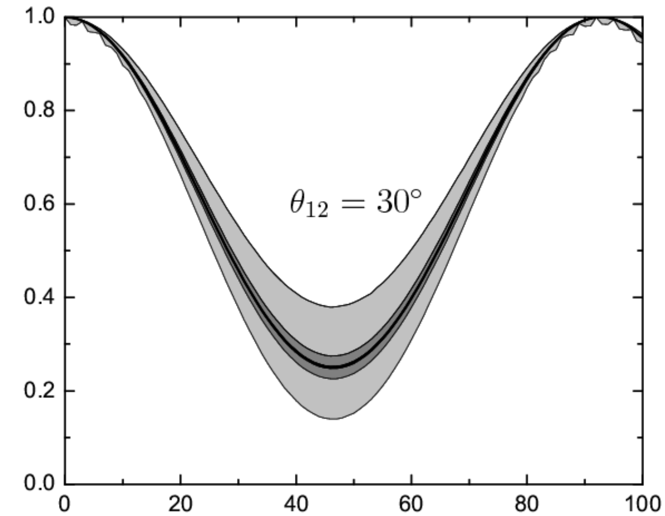




- The true value of θ_{12} may be remarkably different from the measured one, i.e., there exists a degeneracy in θ_{12}
- $26^\circ < \theta_{12} < 42^\circ$, which is close to the bi-maximal mixing for its upper bound and deviates much from the tri-bimaximal mixing for its lower bound.

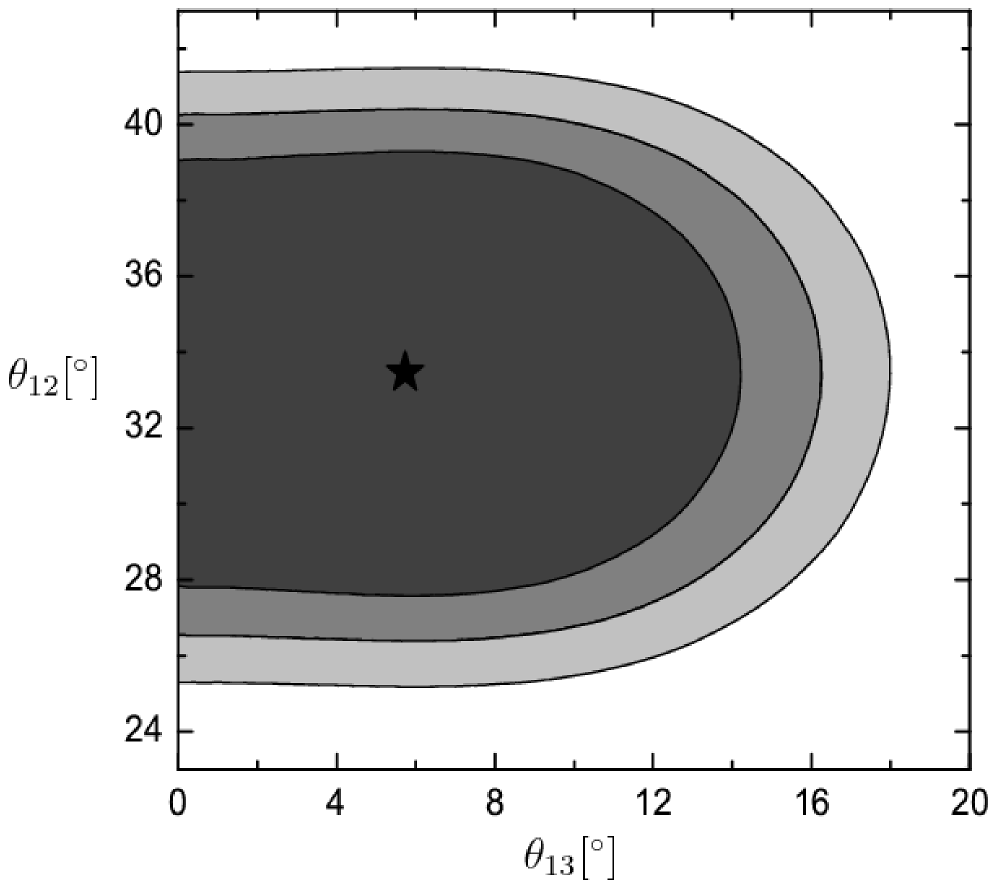
Medium baseline experiments (KamLAND)





- Oscillation probabilities in a medium baseline experiment.
- The shadings correspond $\varepsilon<0.05$, $\varepsilon<0.01$ and $\varepsilon<0.001$, respectively.
- The oscillation behaviors around $L\approx0$ are mainly induced by Δm_{31}^2 and θ_{13}

Correlations between θ_{13} and θ_{12}



- The true value of θ_{12} may achieve the range of Cabibbo angle.

Some hints on the quark-lepton complementary?

Conclusions

- Mixing angles measured in reactor neutrino experiments could be dramatically modified by NSIs at sources and detectors.
- The mimicking effects induced by NSIs play a very important role in short baseline experiments, especially in the case of a tiny θ_{13}. Even for a vanishing θ_{13}, the forthcoming Double Chooz and Daya Bay experiments could still perform a discovery search of an oscillation phenomenon.
- From the phenomenological point of view, two different and complementary oscillation experiments (e.g. reactor and neutrino factory) are needed in order to constrain corresponding NSIs.

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Thank you