Resolving CP Violation by Standard and Nonstandard Interactions in Neutrino Oscillation

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with
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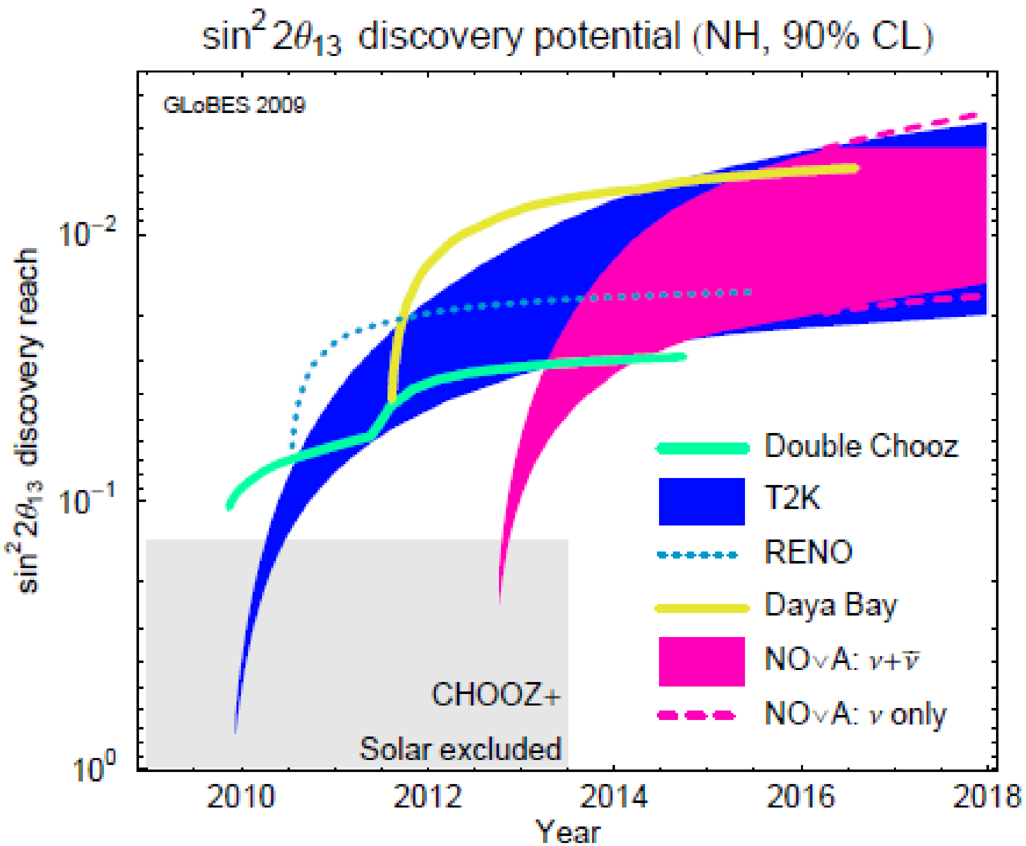
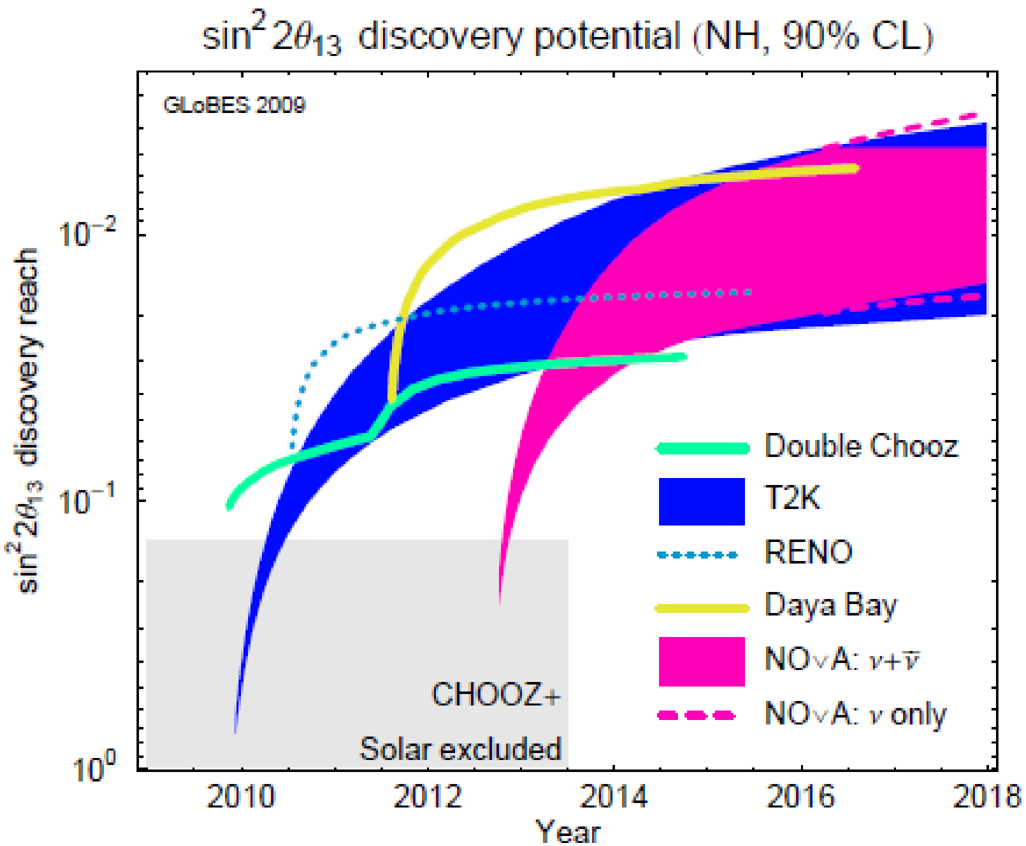
arXiv:0904.3360

Future Neutrino Oscillation Experiment



Huber Lindner Schwetz Winter
arXiv:0907.1896

Future Neutrino Oscillation Experiment



Huber Lindner Schwetz Winter
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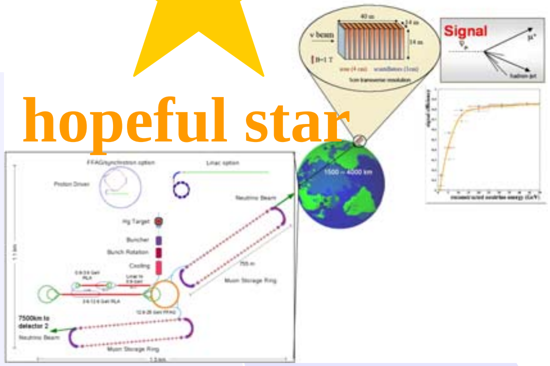
hopeful star



Neutrino Factory

precise measurement of lepton flavor mixing

Motivation

Future "precision measurement" experiments have potential for New Physics Search

in this talk
we concentrate on Non-Standard neutrino Interaction (NSI)

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

Wolfenstein '78, Guzzo-Masiero-Petcov '91
Grossman '95 …

Setup and Scope

- Neutrino Factory

10^{21}useful μ (E_{μ}=50GeV) decay/year

→ 4+4 years for neutrino and anti-neutrino

golden channel ($\nu_e \to \nu_\mu$) only

2 detectors at 3000km and 7000km

propagation (matter effect) NSI only

$\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ with their complex phase ($\varepsilon=|\varepsilon|e^{i\phi}$)

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$\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ with their complex phase ($\varepsilon=|\varepsilon|e^{i\phi}$) and the target region $|e|$:10^{-4}-10^{-2}

Neutrino Factory with Two Detectors

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E}$$
$$a \equiv \sqrt{2} G_F n_e$$
$$X = s^2_{23} \left(\frac{a}{\Delta_{31} - a} \right)^2 \sin^2 \frac{\Delta_{31} - a}{2} L$$
$$Z = c^2_{23} \sin^2 \frac{aL}{2}$$

$$P(\nu_e \to \nu_\mu) = 4 \left| e^{-i\delta} s_{13} \frac{\Delta_{31}}{a} \sqrt{X} + e^{-i\frac{\Delta_{31} L}{2}} c_{12} s_{12} \frac{\Delta_{21}}{a} \sqrt{Z} \right|^2$$

Importance of interference term (δ dependence) **L=3000~4000km**

Probability is simple at Magic Baseline (aL/2=π → **L~7200km**)

Setup and Scope

- Neutrino Factory

10^{21}useful μ (E_μ=50GeV) decay/year

→ 4+4 years for neutrino and anti-neutrino

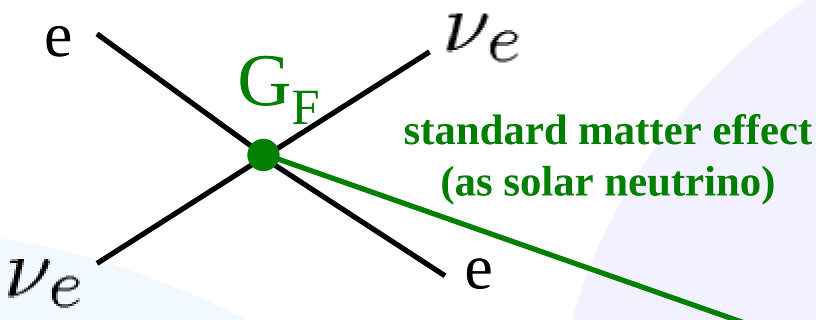
golden channel ($\nu_e \rightarrow \nu_\mu$) only

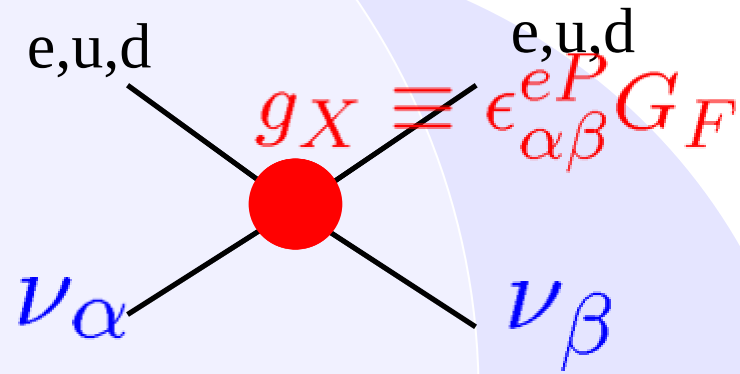
2 magnetized detectors (50 kt) at 3000km and 7000km

Focus on propagation (matter effect) NSI

$\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ with their complex phase ($\varepsilon=|\varepsilon|e^{i\phi}$) and the target region $|e|$:10^{-4}-10^{-2}

Non-Standard Interaction (propagation)





$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0&0&0\\ 0&\Delta m^2_{21}&0\\ 0&0&\Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee}&\varepsilon_{e\mu}&\varepsilon_{e\tau}\\ \varepsilon^*_{e\mu}&\varepsilon_{\mu\mu}&\varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau}&\varepsilon^*_{\mu\tau}&\varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Bound : < O(10^{-2}-10^{-3})

Biggio Blennow Fernandez-Martinez
JHEP 0903:139,2009 and arXiv:0907.0097

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Contribution to Oscillation Probability of NSI

perturbation formula

small parameters:

$$O(\epsilon) \sim \sin\theta_{13} \sim \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{\Delta m^2_{21}}{2Ea} \sim \varepsilon_{\alpha\beta}$$

$$\begin{aligned}
&P(\nu_e \to \nu_\mu; \varepsilon_{e\mu}, \varepsilon_{e\tau}) \\
&= 4\left| c_{12}s_{12}c_{23}\frac{\Delta m^2_{21}}{a}\sin\left(\frac{aL}{4E}\right)e^{-i\Delta_{31}} + s_{13}s_{23}e^{-i\delta}\frac{\Delta m^2_{31}}{a}\left(\frac{a}{\Delta m^2_{31}-a}\right)\sin\left(\frac{\Delta m^2_{31}-a}{4E}L\right)\right. \\
&\quad + \varepsilon_{e\mu}\left[c^2_{23}\sin\left(\frac{aL}{4E}\right)e^{-i\Delta_{31}} + s^2_{23}\left(\frac{a}{\Delta m^2_{31}-a}\right)\sin\left(\frac{\Delta m^2_{31}-a}{4E}L\right)\right] \\
&\quad \left. - c_{23}s_{23}\varepsilon_{e\tau}\left[\sin\left(\frac{aL}{4E}\right)e^{-i\Delta_{31}} - \left(\frac{a}{\Delta m^2_{31}-a}\right)\sin\left(\frac{\Delta m^2_{31}-a}{4E}L\right)\right]\right|^2,
\end{aligned}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij},\ \text{and}\ \Delta_{31} \equiv \frac{\Delta m^2_{31}L}{4E}$$

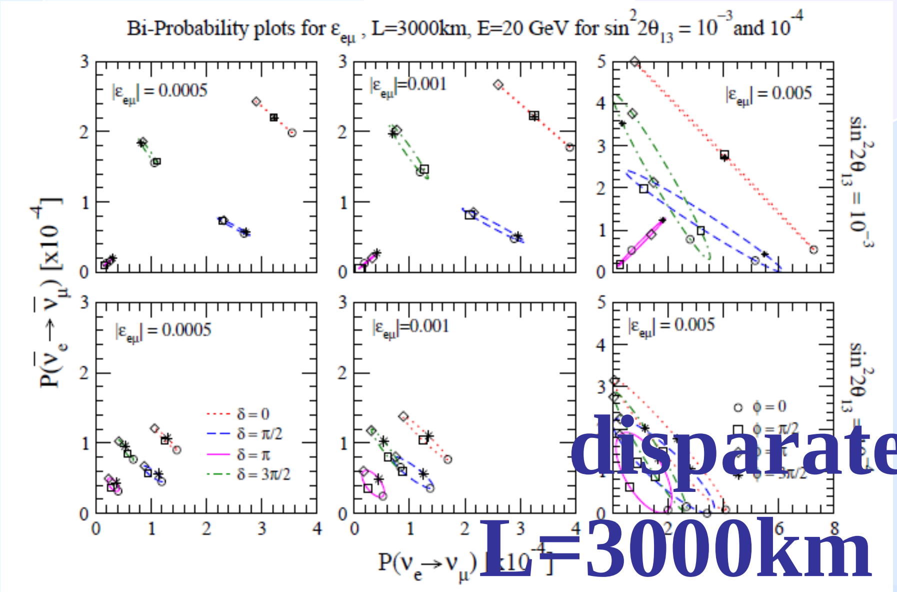
Neutrino Factory with Two Detectors

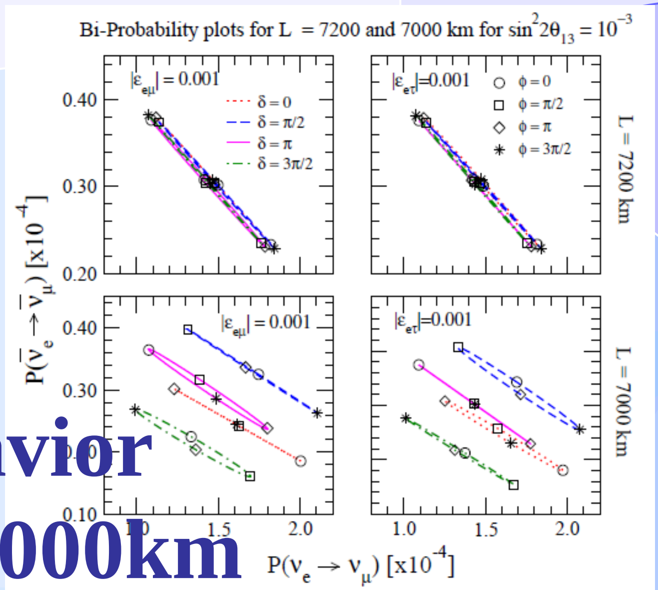
$$P(\nu_e \to \nu_\mu) = 4\left| e^{-i\delta} s_{13} \frac{\Delta_{31}}{a} \sqrt{X} + e^{-i\frac{\Delta_{31}L}{2}} c_{12} s_{12} \frac{\Delta_{21}}{a} \sqrt{Z} \right|^2$$

Kikuchi Minakata S.U.
JHEP 0903:114,2009

$$e^{-i\delta} s_{13} \frac{\Delta_{31}}{a} + s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau}$$

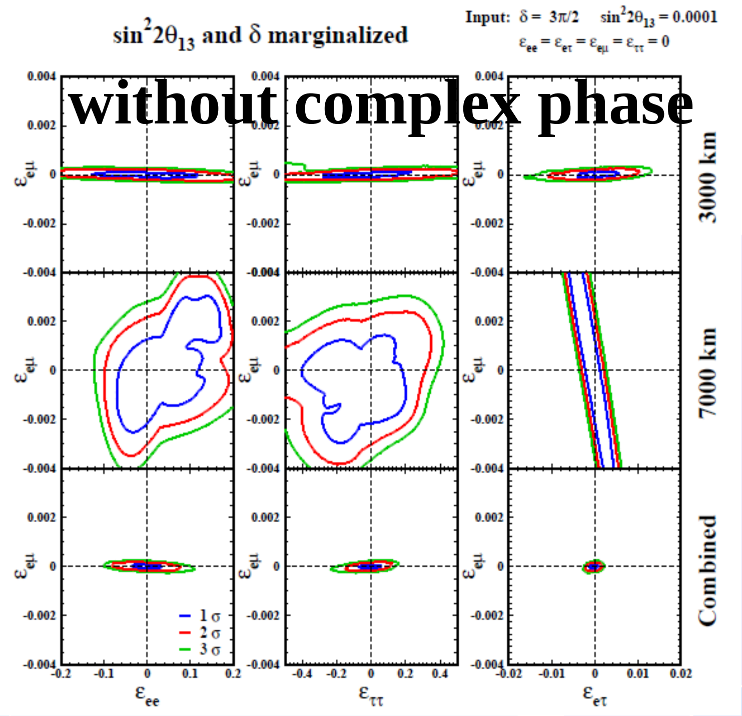
$$c_{12} s_{12} \frac{\Delta_{21}}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}$$



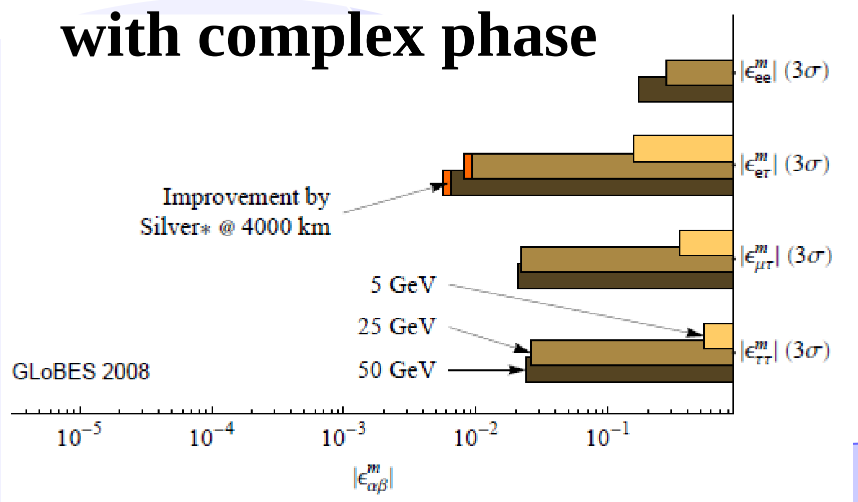


disparate behavior
L=3000km and 7000km

Probing NSI by Neutrino Factory



Cipriano-Ribeiro et.al
JHEP 0712:002,2007



Kopp Ota Winter
Phys.Rev.D78:053007,2008.

Discovering NSI

$|\varepsilon_{e\mu}|, |\varepsilon_{e\tau}| \sim O(10^{-3}\text{-}10^{-4})$

χ^2-Analysis

$$\chi^2 \equiv \min_{\theta_{13},\delta,\varepsilon,\mathrm{sign}(\Delta m^2_{31})} \sum_{i=1}^{3}\sum_{j=1}^{2}\sum_{k=1}^{2} \frac{\left[N^{\mathrm{obs}}_{i,j,k} - N^{\mathrm{theo}}_{i,j,k}(\theta_{13},\delta,\varepsilon,\mathrm{sign}(\Delta m^2_{31}))\right]^2}{N^{\mathrm{obs}}_{i,j,k} + (\sigma_{\mathrm{sys}} N^{\mathrm{obs}}_{i,j,k})^2 + (\sigma_{\mathrm{BG}} N^{\mathrm{BG}}_{i,j,k})^2}$$

3 energy bin (ν:4-8-20-50 GeV, anti-ν:4-15-25-50 GeV)

σ_{sys}=2.5%, σ_{bg}=20%, BG fraction:$5*10^{-6}$

vary : θ_{13}, δ, mass hierarchy, ε

efficiency:70%

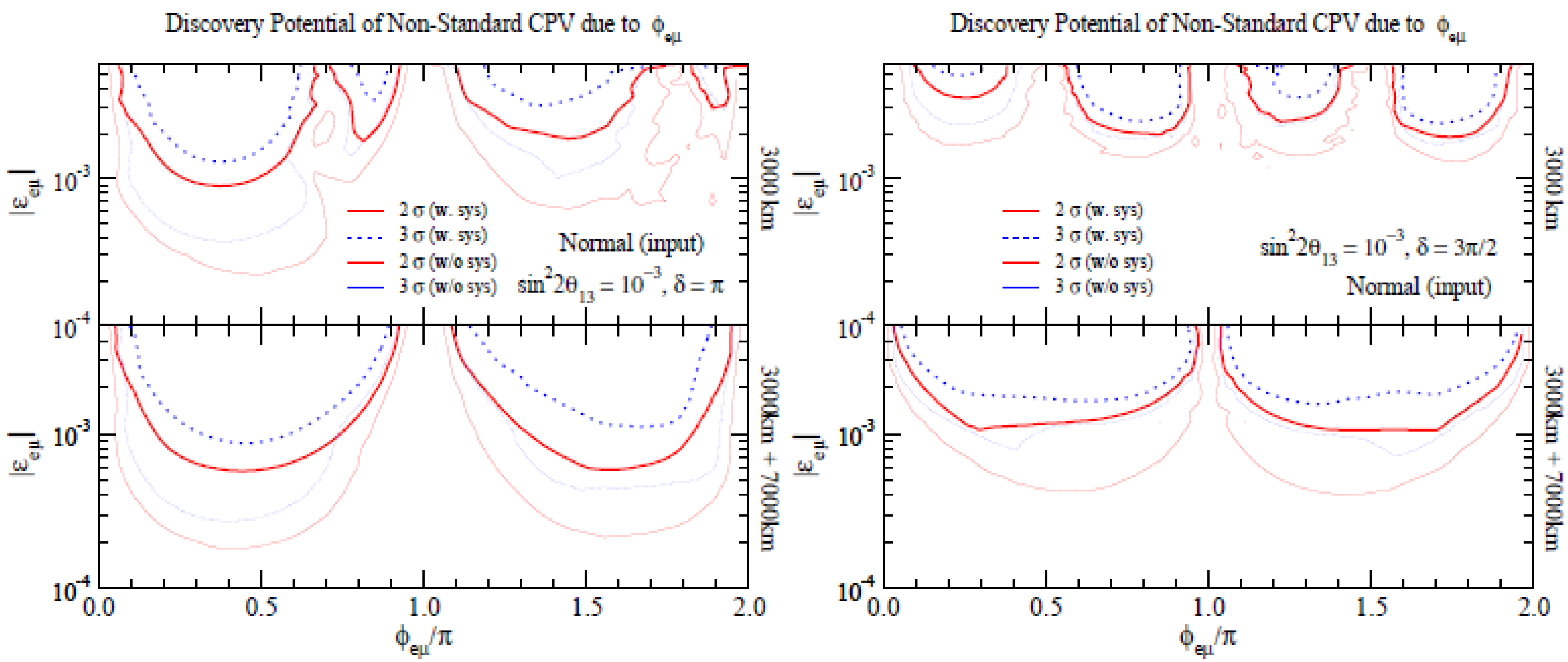
Searching Non-Standard CP-Violation

If NSI have complex phase, it makes another CP violation

Can we discover it?

Searching Non-Standard CP-Violation

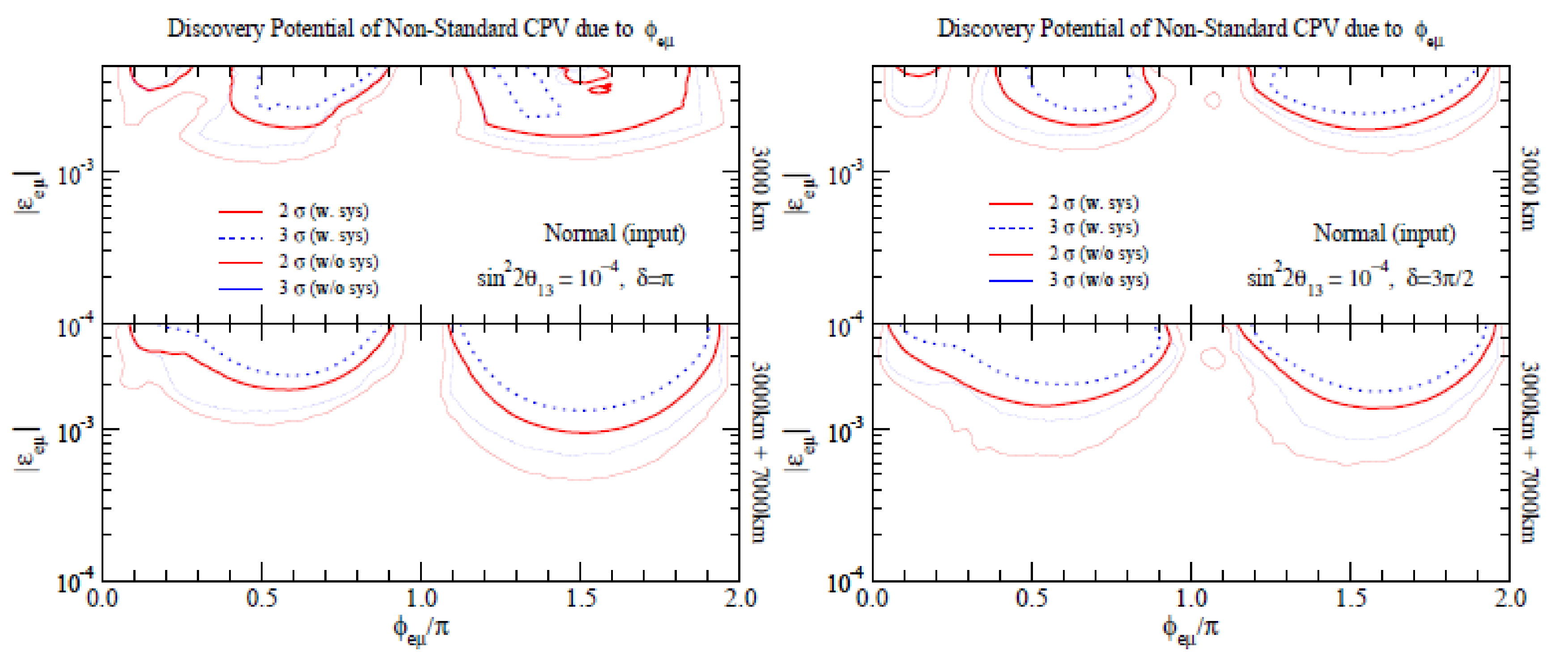
$$\chi^2(\phi_{e\mu}=0, \pi) - \chi^2(\text{input}) > 2\ (3)\ \sigma$$



Searching Non-Standard CP-Violation

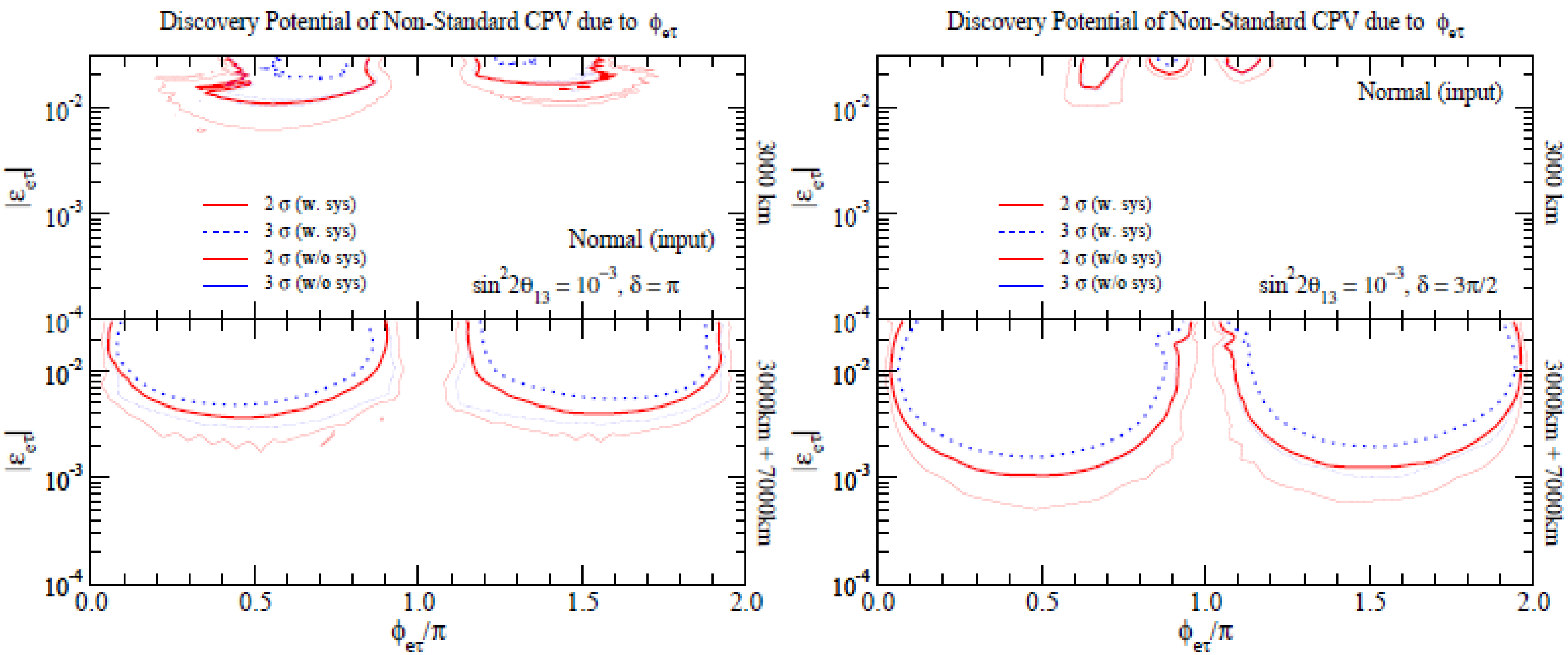
$\chi^2(\phi_{e\mu}=0, \pi) - \chi^2(\text{input}) > 2\ (3)\ \sigma$

small θ_{13} case ($\sin^2 2\theta_{13}=10^{-4}$)



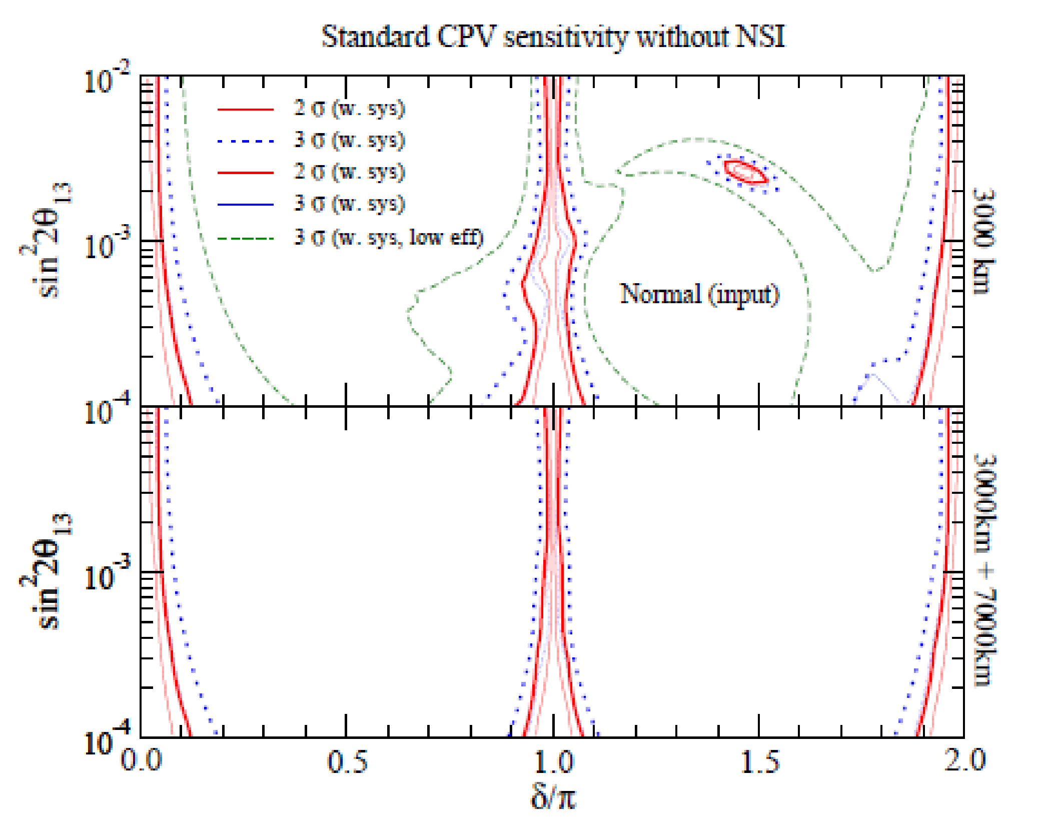
Searching Non-Standard CP-Violation

$\chi^2(\phi_{e\tau}=0, \pi) - \chi^2(\text{input}) > 2\ (3)\ \sigma$



Searching Standard CP-Violation

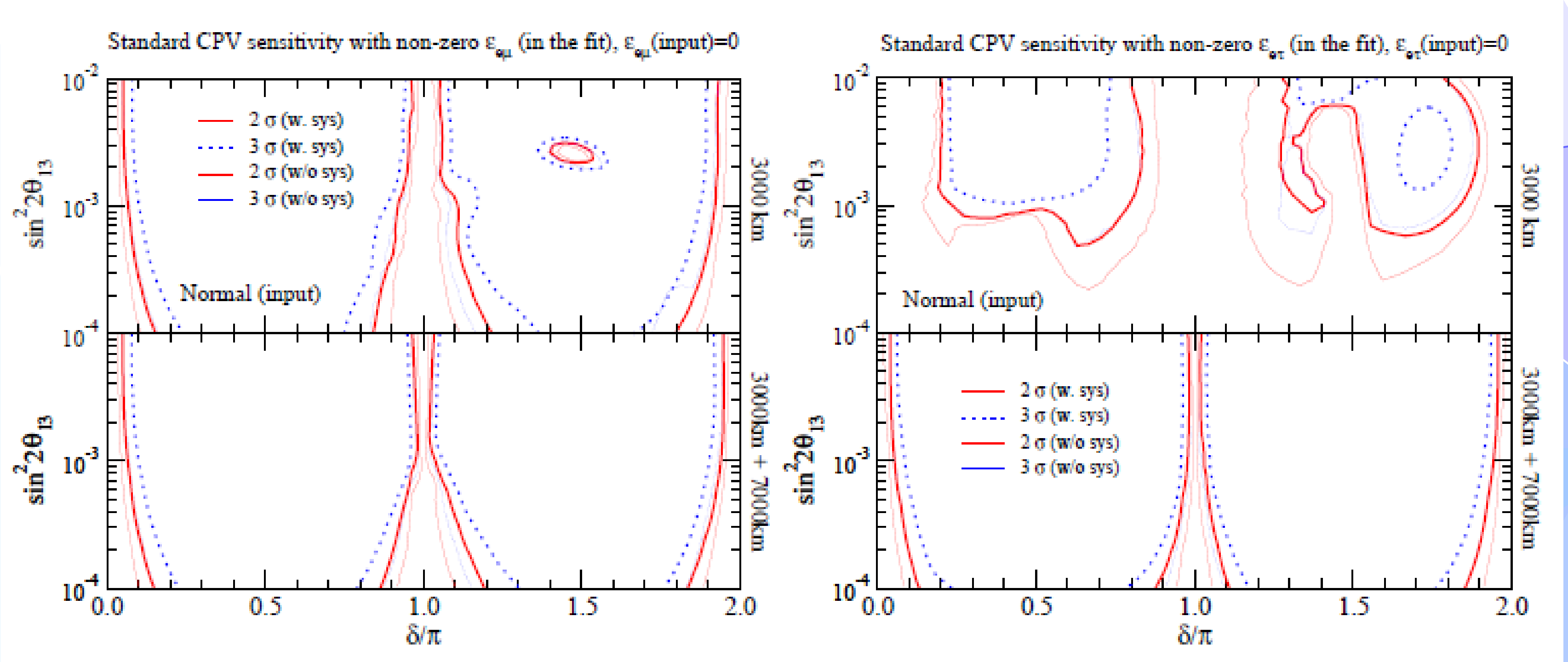
$$\chi^2(\delta=0, \pi) - \chi^2(\text{input}) > 2\ (3)\ \sigma$$



Searching Standard CP-Violation with NSI

$\chi^2(\delta=0, \pi) - \chi^2(\text{input}) > 2\ (3)\ \sigma$

take account of possible existence of NSI



Summary

- Neutrino Factory have powerful potential to discover Non-Standard Interaction

→ $|\varepsilon_{e\mu}| \sim 10^{-3}\text{-}10^{-4}$, $|\varepsilon_{e\tau}| \sim 10^{-3}$

- we can discover non-standard CP Violation

if $0.1 < \phi_{e\mu}/\pi < 0.9$ with $|\varepsilon_{e\mu}| >$ a few $\times 10^{-3}$

if $0.1 < \phi_{e\tau}/\pi < 0.9$ with $|\varepsilon_{e\tau}| > 10^{-2}\text{-}10^{-3}$

two detector combination (L=3000km and 7000km) is important