Resolving Standard and Nonstandard CP Violation in Neutrino Oscillations

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(by A.M.Gago *et al.*, arXiv:0904.3360)

Motivations

- Neutrino Masses and Mixings seem to be well established
- Standard Model is extremely successful
- Natural to address Non-Standard Interactions (NSI) via higher dimensional operators
- If New Physics scale $\Lambda \sim 1$ TeV (LHC):
  $|\varepsilon_{\alpha\beta}| \sim (M_W/\Lambda)^2 \simeq 10^{-2}$ (dim-6)
  $|\varepsilon_{\alpha\beta}| \sim (M_W/\Lambda)^4 \simeq 10^{-4}$ (dim-8)
- Many constraints exist in the literature
  If $|\varepsilon_{\alpha\beta}| \lesssim 10^{-2} \rightarrow \nu$-factory
- NSI can produce new sources of CP Violation (CPV)
- Can SI CPV be disentangled from NSI CPV?

[S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, JHEP **0303**, 011 (2003); S. Antusch, J. P. Baumann and E. Fernandez-Martinez, Nucl. Phys. B **810**, 369 (2009); C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0903**, 139 (2009)]

Scope of this Work

- NSI effects may exist in ν production, detection and propagation in matter
- NSI $\rightarrow$ many new/unknown parameters (very complex)
- We deal here with effects in propagation only
- We study a single NSI parameter $\varepsilon \equiv (|\varepsilon|, \phi)$ at a time
- We investigate the target region $10^{-4} \lesssim \varepsilon_{\alpha\beta} \lesssim 10^{-2}$
- We use a *standard setup* for the ν-factory experiment
- We investigate in this context:
  - the discovery potential to NSI
  - the discovery potential to NSI induced CPV
  - the impact of NSI on the discovery of standard CPV
  - the impact of NSI on the discovery of ν mass hierarchy?

Setup and Assumptions

- ν-Factory: 10^{21} useful μ-decays/year w/ $E_\mu = 50\,\mathrm{GeV}$
- 2 *identical* magnetized detectors of 50 kton (fiducial mass); at 3000 km and 7000 km
- 4 years ν + 4 years $\bar{\nu}$
- consider only *golden channels*: $\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$
- fixed: $\sin^2\theta_{12} = 0.31$, $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2, $\sin^2\theta_{23} = 0.5$ and $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ eV^2
- vary: $\sin^2 2\theta_{13}$, δ, mass hierarchy, $\varepsilon = (|\varepsilon|, \phi)$
- detector efficiency 70%; $\sigma_{\mathrm{sys}} = 2.5\%$
- background fraction (NC + right sign μ) 5×10^{-6}; $\sigma_{\mathrm{BG}} = 20\%$

[A. Bandyopadhyay *et al.* (ISS Physics Working Group), arXiv:0710.4947; T. Abe *et al.* (ISS Physics Working Group), arXiv:0712.4129]

χ^2- Analysis

$$\chi^2 \equiv \min_{\theta_{13},\delta,\varepsilon} \sum_{i=1}^{3}\sum_{j=1}^{2}\sum_{k=1}^{2} \frac{\left[N_{i,j,k}^{\text{obs}} - N_{i,j,k}^{\text{theo}}(\theta_{13},\delta,\varepsilon,\text{hierarchy})\right]^2}{N_{i,j,k}^{\text{obs}} + (\sigma_{\text{sys}} N_{i,j,k}^{\text{obs}})^2 + (\sigma_{\text{BG}} N_{i,j,k}^{\text{BG}})^2}$$

- 3 E_ν bins: 4-8 GeV, 8-20 GeV and 20-50 GeV (ν)
  4-15 GeV, 15-25 GeV and 25-50 GeV ($\bar{\nu}$)
- 2 baselines: 3000 km, 7000 km
- 2 mode: neutrinos, antineutrinos

[N. Cipriano, H. Minakata, H. Nunokawa, S. Uchinami and RZF, JHEP **0712**, 002 (2007)]

Neutrino Evolution in Matter with NSI

Consider

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

$$P = P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$$

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

where: $\varepsilon_{\alpha\beta} \equiv \sum_{f,P} \frac{n_f}{n_e}\varepsilon_{\alpha\beta}^{fP}$ $\qquad a = 2\sqrt{2}\,G_F\,n_e\,E_\nu$

Golden Channel Probability with NSI

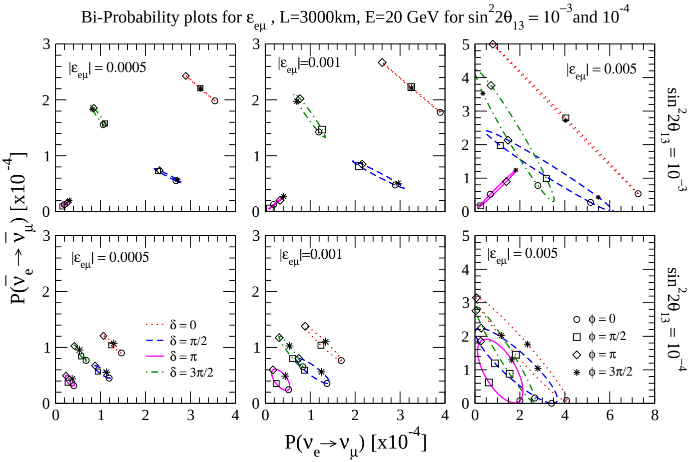
If $\epsilon \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \sin\theta_{13} \sim |\varepsilon_{e\alpha}| << \frac{a}{\Delta m^2_{31}} \sim 1$ then Perturbative Expansion leads to

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

where $c_{ij} \equiv \cos\theta_{ij}$ $\quad s_{ij} \equiv \sin\theta_{ij}$ $\quad \Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$

[T. Kikuchi, H. Minakata and S. Uchinami, JHEP **0903**, 114 (2009)]

Behavior at 3000 km



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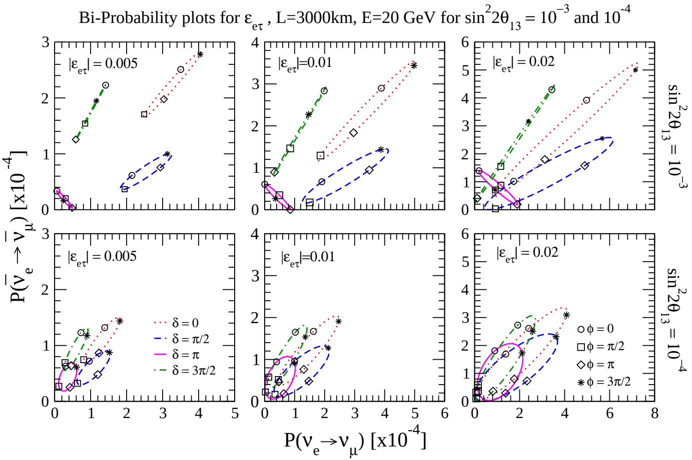
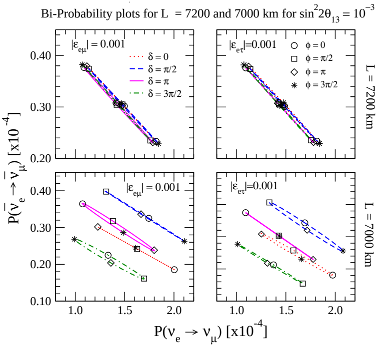


Behavior at 7000 km

$$\mathbf{L}_{\rm magic} = \frac{4\pi \mathbf{E}_\nu}{\mathbf{a}} \approx \mathbf{7200} \left(\frac{\rho}{4.5 {\rm g/cm^3}} \right) \ {\rm km}$$

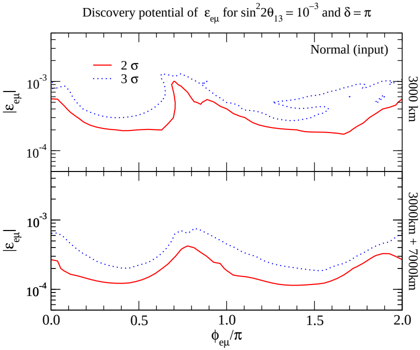
$$P(\nu_e \to \nu_\mu; \varepsilon_{e\mu}) = 4 s_{23}^2 s_{13}^2 \left(\frac{\Delta m_{31}^2}{a - \Delta m_{31}^2} \right)^2 \sin^2 \left(\frac{\Delta m_{31}^2}{4E} L \right)$$

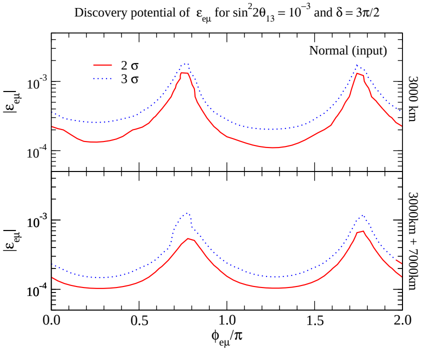
$$+ \quad \frac{4 a s_{23}^3}{(a - \Delta m_{31}^2)^2} \left[2 \Delta m_{31}^2 s_{13} |\varepsilon_{e\mu}| \cos(\delta + \phi_{e\mu}) + s_{23} a |\varepsilon_{e\mu}|^2 \right] \sin^2 \left(\frac{\Delta m_{31}^2}{4E} L \right)$$



Revealing $\varepsilon_{e\mu} = |\varepsilon_{e\mu}|\, e^{i\phi_{e\mu}}$

$\chi^2_{\rm min}(\varepsilon = 0) - \chi^2_{\rm min}(\text{true value of } \varepsilon \text{ and } \phi) > 4(9)$ (1 DOF)





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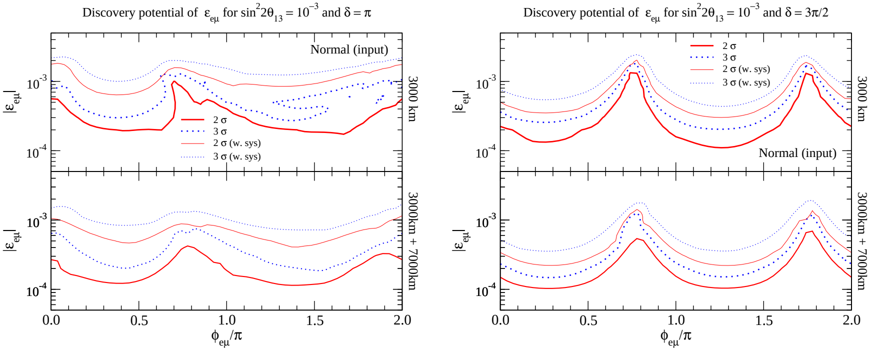

Revealing $\varepsilon_{e\tau} = |\varepsilon_{e\tau}| \, e^{i\phi_{e\tau}}$

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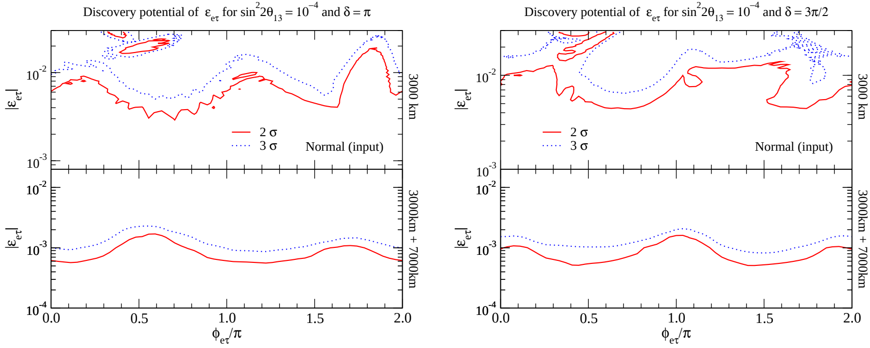

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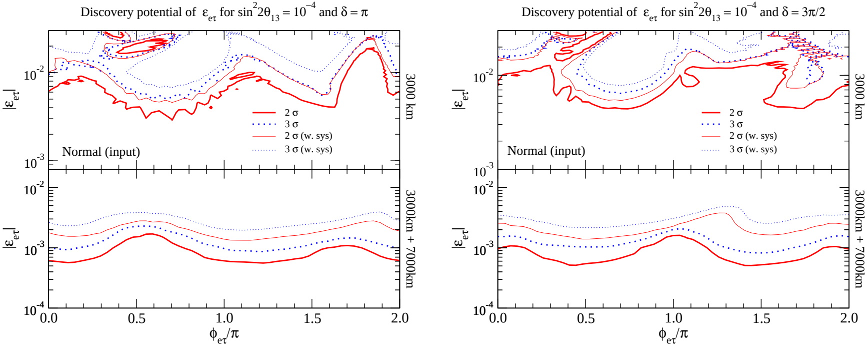

Revealing $\phi_{e\mu} \neq 0, \pi$

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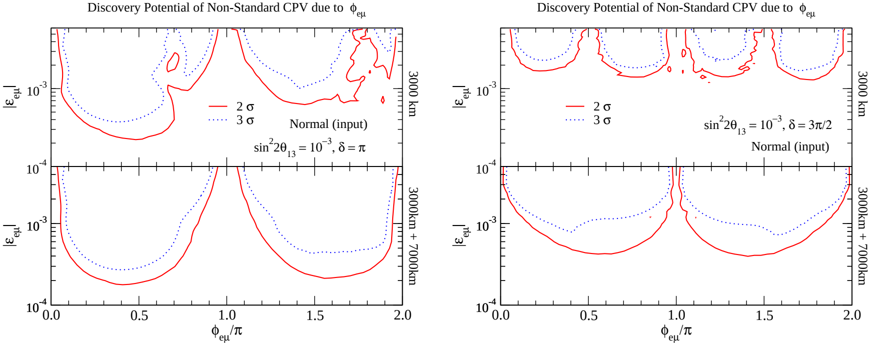

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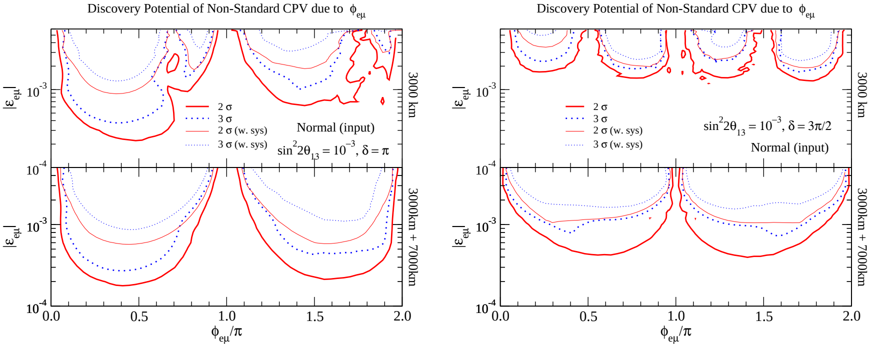

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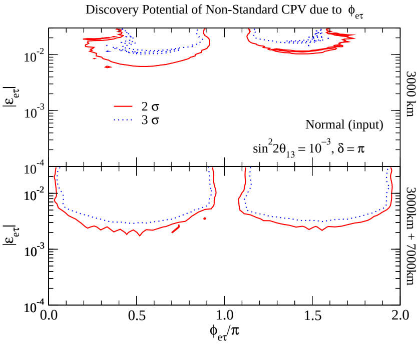

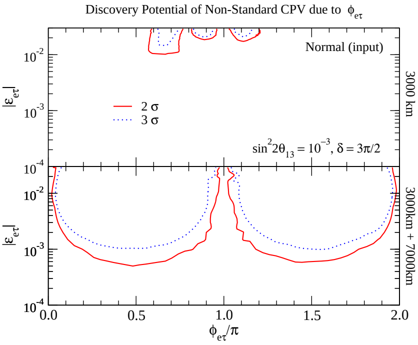

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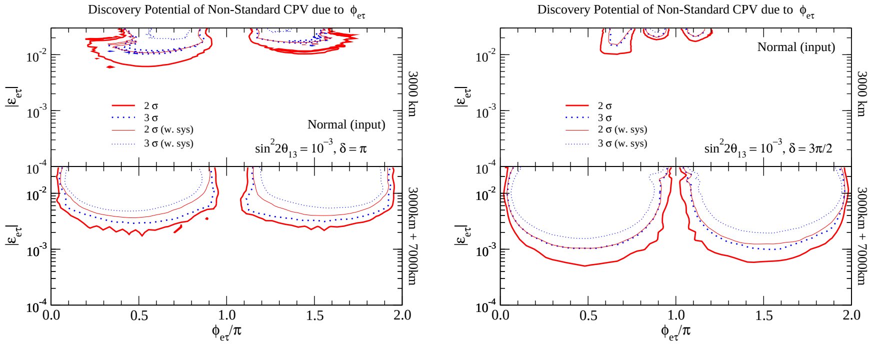

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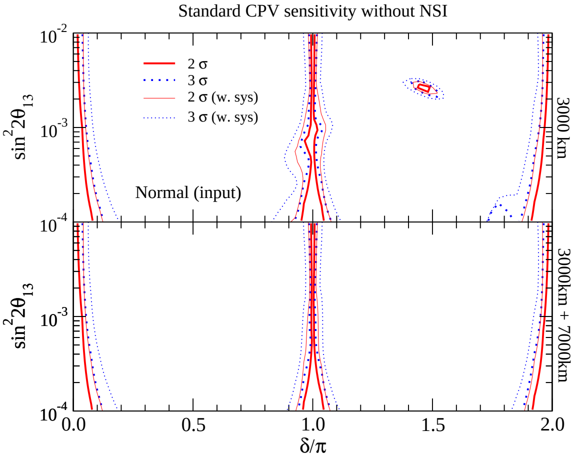

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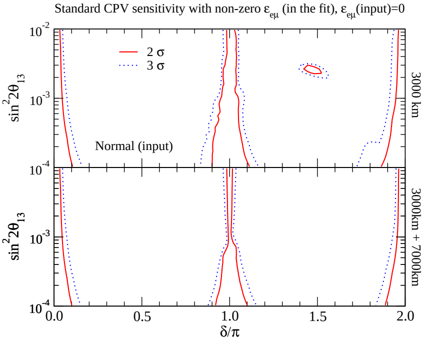

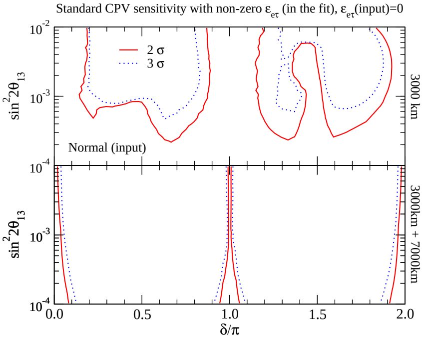

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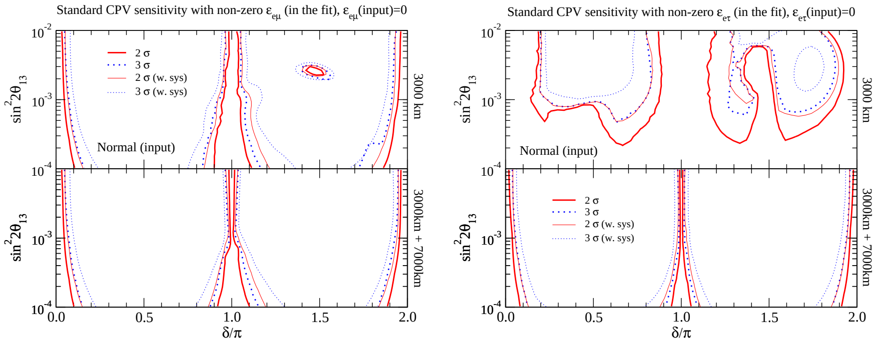
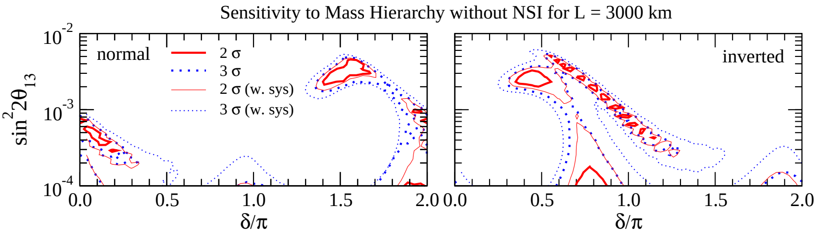


Revealing the Neutrino Mass Hierarchy

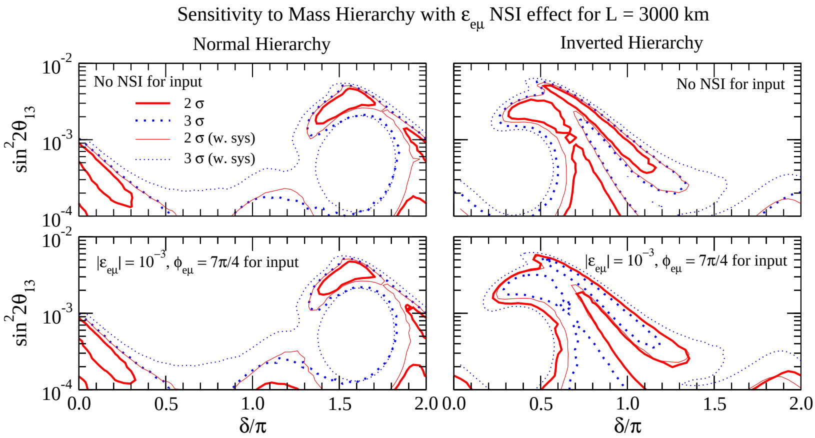
$\chi^2_{\rm min}$(opposite hierarchy) $-$ $\chi^2_{\rm min}$(input hierarchy) $> 4(9)$ (1 DOF)



3000+7000 km $\rightarrow$ hierarchy solved in the whole plane

Revealing the Neutrino Mass Hierarchy

$\chi^2_{\rm min}(\text{opposite hierarchy}) - \chi^2_{\rm min}(\text{input hierarchy}) > 4(9)$ (1 DOF)



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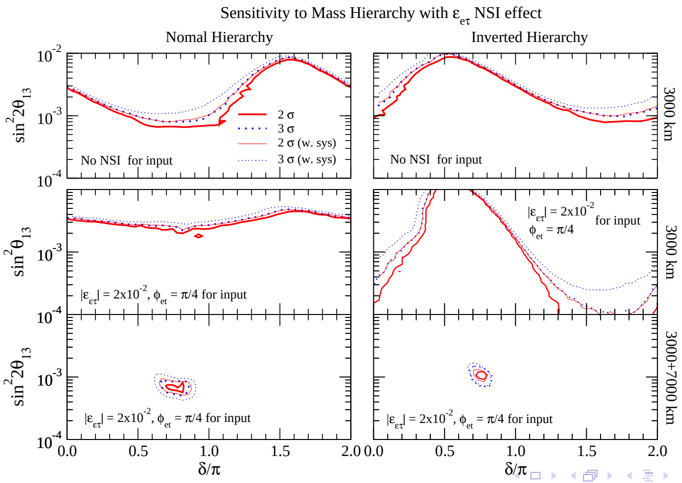

Conclusions

- a single detector at 3000 km can discover NSI down to $|\varepsilon_{e\mu}| \sim 10^{-3} - 10^{-4}$
- synergy between detectors leads to similar sensitivity in the $|\varepsilon_{e\tau}|$ system

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- synergy between detectors leads to similar sensitivity in the $|\varepsilon_{e\tau}|$ system
- if $0.1 \lesssim \phi_{e\mu}/\pi \lesssim 0.9$ or $1.1 \lesssim \phi_{e\mu}/\pi \lesssim 1.9$ non-standard CPV can be discovered down to $|\varepsilon_{e\mu}| \sim (2 - 10) \times 10^{-4}$ (depending on $\sin^2 2\theta_{13}$ and δ) at 3 σ CL (for both mass hierarchies) - here 2 detectors help
- if $0.1 \lesssim \phi_{e\tau}/\pi \lesssim 0.9$ or $1.1 \lesssim \phi_{e\tau}/\pi \lesssim 1.9$ non-standard CPV can be discovered down to $|\varepsilon_{e\tau}| \sim (5 - 20) \times 10^{-4}$ at 3 σ CL (for both mass hierarchies) - here synergy of 2 detectors is crucial

Conclusions

- NSI will not aggravate much the potential discovery of standard CPV. For the $\varepsilon_{e\tau}$ system the 7000 km detector is important

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- NSI will not aggravate much the potential discovery of standard CPV. For the $\varepsilon_{e\tau}$ system the 7000 km detector is important
- For $\varepsilon_{e\mu} \neq 0$ with the help of the far detector can distinguish the mass hierarchy for all values of δ if $\sin^2 2\theta_{13} \gtrsim 10^{-4}$
- For $\varepsilon_{e\tau} \neq 0$ the power of the combination of 2 detectors allows the mass hierarchy to be determined in almost the whole parameter space of δ and θ_{13} considered in this work (except for a small region if $|\varepsilon_{e\tau}|$ is rather large)