Non-standard interactions in future neutrino oscillation experiments

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MAX-PLANCK-GESELLSCHAFT

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in collaboration with M. Lindner, T. Ota, and J. Sato

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Outline

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- "New physics" often leaves low-energy fingerprints in the form of effective, non-standard 4-fermion interactions (*NSI*).
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- Example:

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

$$+ \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\varepsilon}^{m,f}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1-\gamma^5) f\right] + \text{h.c.},$$

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- Lorentz structures different from $(V-A)(V-A)$ are possible, but not considered in this talk.

see e.g. JK Lindner Ota Sato, arxiv:0708:152 for a discussion of NSI with non-$(V-A)(V-A)$ Lorentz structure.

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Standard oscillations

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- CC type NSI: Flavour mixture at source and detector (Grossman PL **B359** (1995) 141)

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta} |\nu_\beta\rangle, \qquad \text{e.g. } \pi^+ \xrightarrow{\varepsilon^s_{\mu e}} \mu^+ \nu_e$$

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- NC type NSI: Extra matter effects in propagation

Wolfenstein PR **D17** (1978) 2369, Valle PL **B199** (1987) 432, Guzzo Masiero Petcov PL **B260** (1991) 154, Roulet PR **D44** (1991) R935, etc.

$$(V_{\mathsf{NSI}})_{\alpha\beta} = \sqrt{2} G_F N_e \varepsilon^m_{\alpha\beta}$$

NSI in oscillation experiments

- Compared to charged lepton flavour violation experiments: Interference between standard and non-standard amplitudes is possible
  $\Rightarrow$ NSI effects suppressed only by $|\varepsilon|$ instead of $|\varepsilon|^2$.
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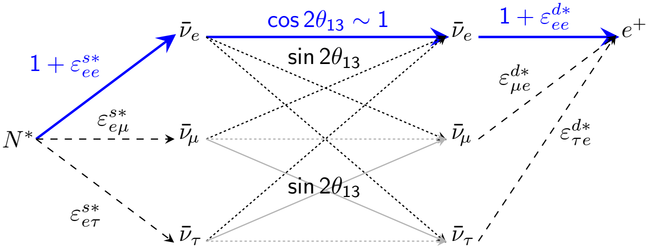
- Possible consequences in oscillation experiments:
  - Poor quality of standard oscillation fit ($\Rightarrow$ Detection of NSI possible)
  - Mismatch between standard fits to different experiments
  - Offset: Consistent, but wrong reconstruction of neutrino mixing parameters

Qualitative arguments



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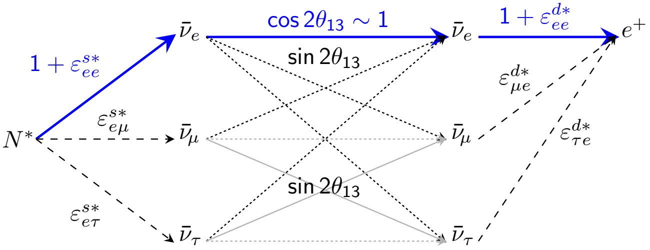

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- NSI production processes: $N^* \xrightarrow{\varepsilon^{s*}_{ee}} \bar\nu_e$ $\quad N^* \xrightarrow{\varepsilon^{s*}_{e\mu}} \bar\nu_\mu$ $\quad N^* \xrightarrow{\varepsilon^{s*}_{e\tau}} \bar\nu_\tau$

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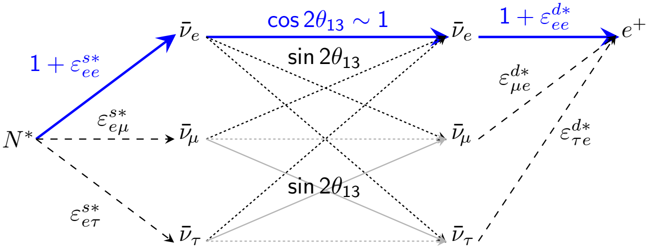

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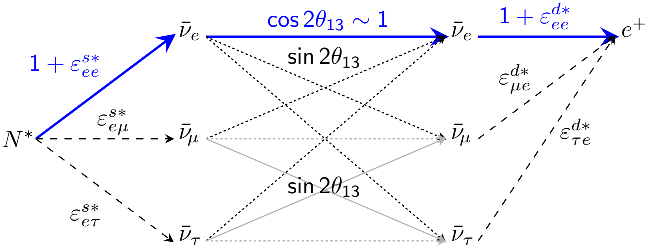

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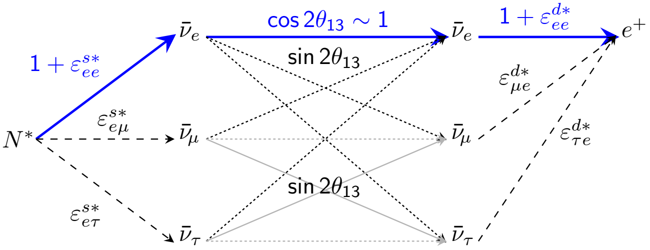

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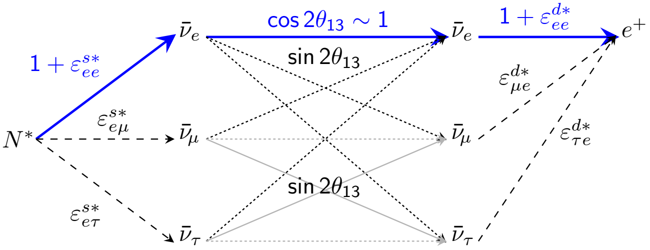
- $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$ oscillations are suppressed by θ_{13}.
- Assume only one ε parameter is sizeable

Qualitative arguments



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$N^* \xrightarrow{\varepsilon^{s*}_{e\mu}} \bar\nu_\mu \xrightarrow{\sin\theta_{13}} \bar\nu_e \to e^+$	$\mathcal{O}(\varepsilon \sin\theta_{13})$	
$N^* \xrightarrow{\varepsilon^{s*}_{e\tau}} \bar\nu_\tau \xrightarrow{\sin\theta_{13}} \bar\nu_e \to e^+$	$\mathcal{O}(\varepsilon \sin\theta_{13})$	
$N^* \to \bar\nu_e \xrightarrow{\sin\theta_{13}} \bar\nu_\mu \xrightarrow{\varepsilon^{d*}_{\mu e}} e^+$	$\mathcal{O}(\varepsilon \sin\theta_{13})$	
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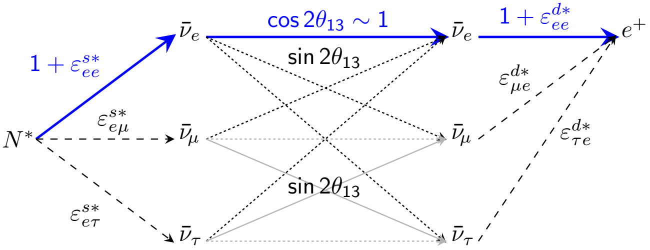

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$N^* \xrightarrow{\varepsilon^{s*}_{e\mu}} \bar{\nu}_\mu \xrightarrow{\sin\theta_{13}} \bar{\nu}_e \rightarrow e^+$ $\quad \mathcal{O}(\varepsilon \sin\theta_{13})$

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$N^* \rightarrow \bar{\nu}_e \xrightarrow{\sin\theta_{13}} \bar{\nu}_\mu \xrightarrow{\varepsilon^{d*}_{\mu e}} e^+$ $\quad \mathcal{O}(\varepsilon \sin\theta_{13})$

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Example: Approximate expression for $P_{\nu_\mu^s \to \nu_e^d}$

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$$
\begin{aligned}
P^{\text{mat}}_{\nu_\mu^s \to \nu_e^d} &= 4\tilde{s}_{13}^2 s_{23}^2 \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E} \\
&+ \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right)^2 c_{23}^2 s_{2\times 12}^2 \left(\frac{\Delta m_{31}^2}{a_{\text{CC}}}\right)^2 \sin^2 \frac{a_{\text{CC}} L}{4E} \\
&- \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \tilde{s}_{13} s_{2\times 12} s_{2\times 23} \cos\delta_{\text{CP}} \frac{\Delta m_{31}^2}{a_{\text{CC}}} \left[\sin^2 \frac{a_{\text{CC}} L}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}\right] \\
&- \frac{1}{2} \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \tilde{s}_{13} s_{2\times 12} s_{2\times 23} \sin\delta_{\text{CP}} \frac{\Delta m_{31}^2}{a_{\text{CC}}} \left[\sin \frac{a_{\text{CC}} L}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{2E}\right] \\
&- 4|\epsilon_{\mu e}^s| \tilde{s}_{13} s_{23} \cos(\phi_{\mu e}^s + \delta_{\text{CP}}) \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E} \\
&- 2|\epsilon_{\mu e}^s| \tilde{s}_{13} s_{23} \sin(\phi_{\mu e}^s + \delta_{\text{CP}}) \sin \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{2E} \\
&+ 4|\epsilon_{\mu e}^d| \tilde{s}_{13} s_{23} \cos(\phi_{\mu e}^d + \delta_{\text{CP}}) \left[c_{23}^2 \sin^2 \frac{a_{\text{CC}} L}{4E} - c_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{23}^2 \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}\right] \\
&+ 2|\epsilon_{\mu e}^d| \tilde{s}_{13} s_{23} \sin(\phi_{\mu e}^d + \delta_{\text{CP}}) \left[c_{23}^2 \sin \frac{a_{\text{CC}} L}{2E} - c_{23}^2 \sin \frac{\Delta m_{31}^2 L}{2E} - s_{23}^2 \sin \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{2E}\right] \\
&- 4|\epsilon_{\tau e}^d| \tilde{s}_{13} s_{23}^2 c_{23} \cos(\phi_{\tau e}^d + \delta_{\text{CP}}) \left[\sin^2 \frac{a_{\text{CC}} L}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} - \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}\right] \\
&- 2|\epsilon_{\tau e}^d| \tilde{s}_{13} s_{23}^2 c_{23} \sin(\phi_{\tau e}^d + \delta_{\text{CP}}) \left[\sin \frac{a_{\text{CC}} L}{2E} - \sin \frac{\Delta m_{31}^2 L}{2E} + \sin \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{2E}\right]
\end{aligned}
$$

Example: Approximate expression for $P_{\nu_\mu^s \to \nu_e^d}$

$$- 4|\epsilon^m_{e\mu}|\tilde{s}_{13} s_{23} c_{23}^2 \cos(\phi^m_{e\mu} + \delta_{\text{CP}}) \left[\sin^2 \frac{a_{\text{CC}} L}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}\right]$$

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$$+ 8|\epsilon^m_{e\mu}|\tilde{s}_{13} s_{23}^3 \cos(\phi^m_{e\mu} + \delta_{\text{CP}}) \frac{a_{\text{CC}}}{\Delta m_{31}^2 - a_{\text{CC}}} \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}$$

$$+ 4|\epsilon^m_{e\tau}|\tilde{s}_{13} s_{23}^2 c_{23} \cos(\phi^m_{e\tau} + \delta_{\text{CP}}) \left[\sin^2 \frac{a_{\text{CC}} L}{4E} - \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \frac{(\Delta m_{31}^2 - a_{\text{CC}})L}{4E}\right]$$

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$$+ 2|\epsilon^s_{\mu e}| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times 12} c_{23} \cos \phi^s_{\mu e} \frac{\Delta m_{31}^2}{a_{\text{CC}}} \sin^2 \frac{a_{\text{CC}} L}{4E}$$

$$- |\epsilon^s_{\mu e}| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times 12} c_{23} \sin \phi^s_{\mu e} \frac{\Delta m_{31}^2}{a_{\text{CC}}} \sin \frac{a_{\text{CC}} L}{2E}$$

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&+ \mathcal{O}\left(\left[\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right]^3\right) + \mathcal{O}\left(\left[\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right]^2 s_{13}\right) + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}} s^2_{13}\right) + \mathcal{O}(s^3_{13}) \\
&+ \mathcal{O}\left(\varepsilon\left[\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right]^2\right) + \mathcal{O}\left(\varepsilon s_{13}\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right) + \mathcal{O}(\varepsilon s^2_{13}) + \mathcal{O}(\varepsilon^2).
\end{aligned}
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Numerical simulation techniques

- All simulations have been performed with GLoBES 3.0

  Huber Lindner Winter Comput. Phys. Commun. **167** (2005) 195,

  Huber JK Lindner Rolinec Winter Comput. Phys. Commun. **177** (2007) 432

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NSI-induced mismatches and offsets

$P_{\bar{\nu}_e^s \to \bar{\nu}_e^d}$ (reactor) and $P_{\nu_\mu^s \to \nu_e^d}$ (superbeam) are affected differently by NSI
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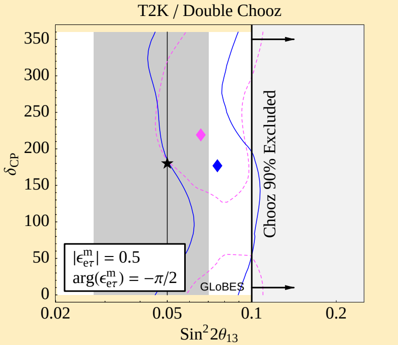

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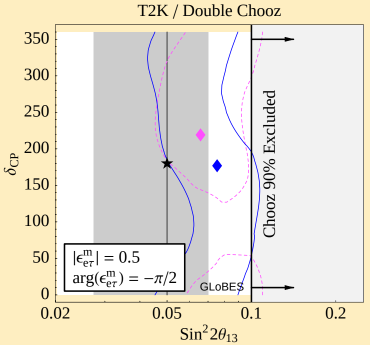
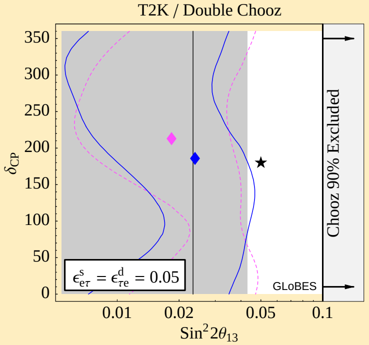


Offset



A more systematic approach

- Choose random values for the NSI parameters $\varepsilon^s_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$, $\varepsilon^m_{\alpha\beta}$ ($|\varepsilon|$ distributed logarithmically, $\texttt{arg}(\varepsilon)$ distributed linearly)

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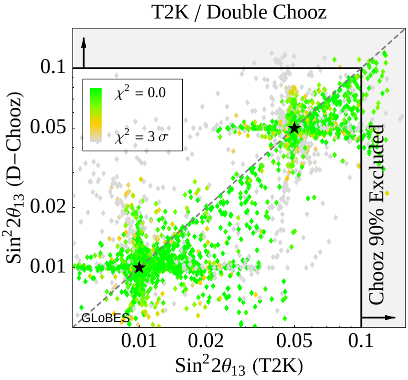
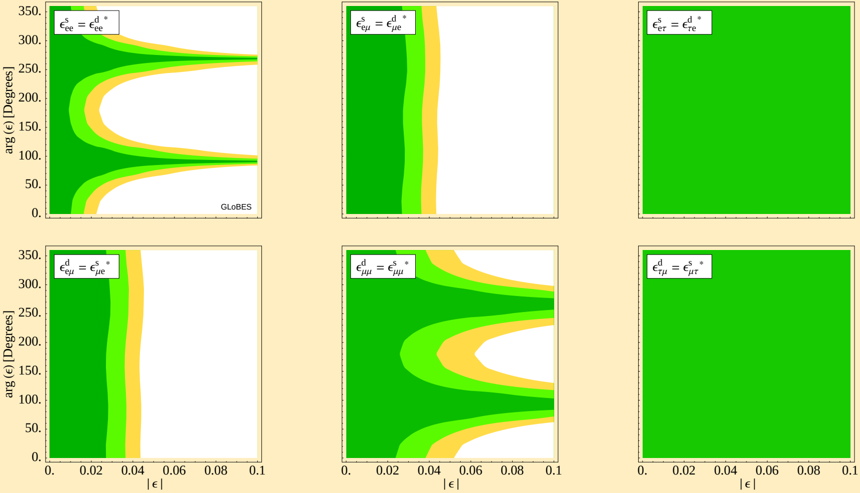


Discovery reach of combined T2K/D-Chooz analysis

NSI in source and detector (current bound $\sim$ 0.1)



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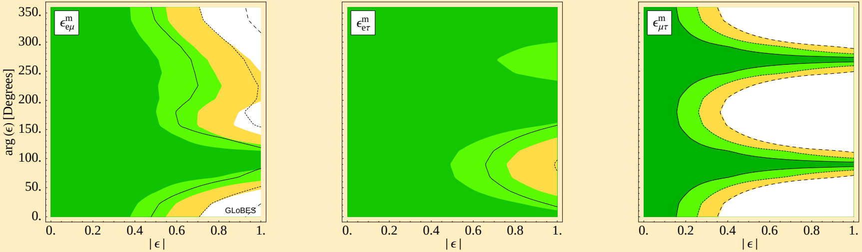
NSI in propagation



- Current bounds: $|\varepsilon^m_{e\mu}| \lesssim 5 \times 10^{-4}$, $|\varepsilon^m_{e\tau}| \lesssim 0.7$, $|\varepsilon^m_{\mu\tau}| \lesssim 0.1$

  Davidson Pena-Garay Rius Santamaria JHEP **03** (2003) 011

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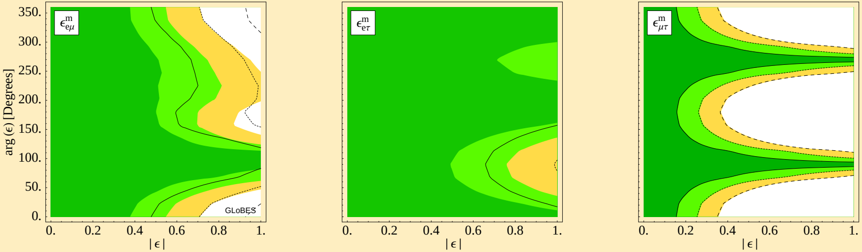

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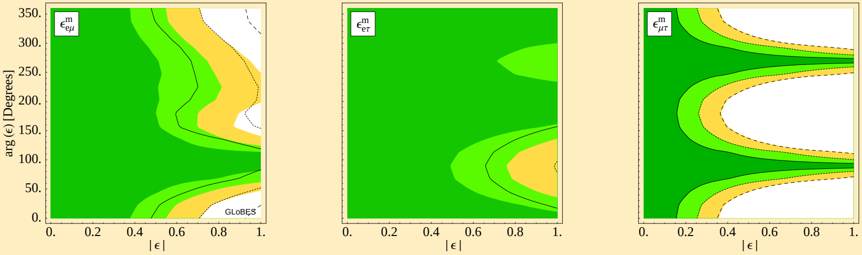

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- Optimal discovery reach requires reactor, superbeam, and near detectors

Outline

Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

- Discovery reach for $\varepsilon^m_{e\mu}$: Minimum value of $|\varepsilon^m_{e\mu}|$ which can no longer be fitted with $\varepsilon^m_{e\mu} = 0$ at a given C.L.

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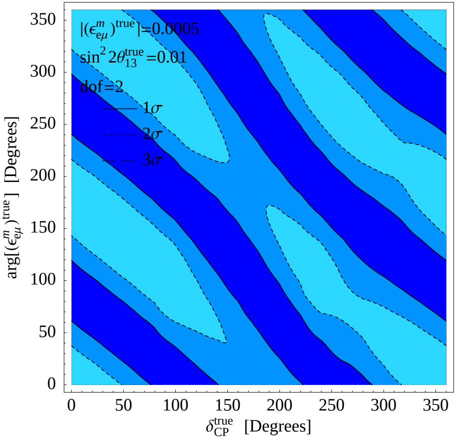
Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

- $|\varepsilon^m_{e\mu}| = 0.5 \times 10^{-3}$
- $|\varepsilon^m_{e\mu}|$ too small



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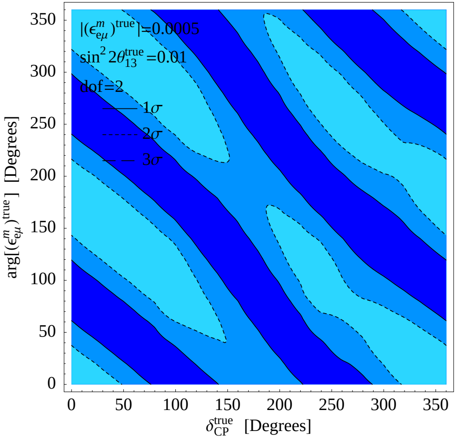
  $\downarrow$

  χ^2 of standard oscillation fit is below 3σ for all true values of δ_{CP} and $\arg \varepsilon_{e\mu}^m$.



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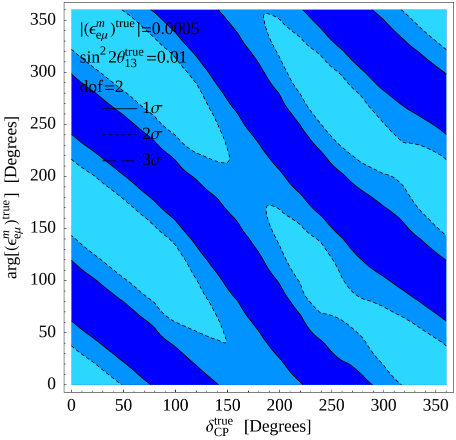
  No chance for discovery



Discovery reach for $\varepsilon_{e\mu}^m$ in a neutrino factory

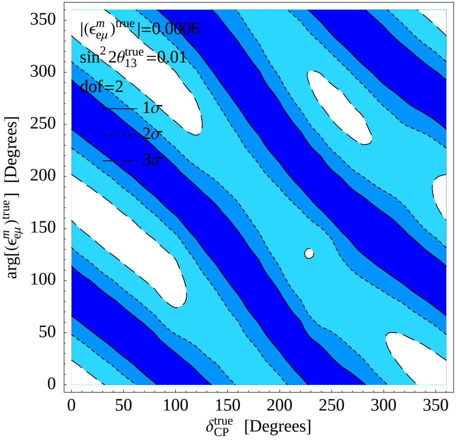
- $|\varepsilon_{e\mu}^m| = 0.6 \times 10^{-3}$
- $|\varepsilon_{e\mu}^m|$ becomes larger

  $\downarrow$

  For some combinations of δ_{CP} and $\arg \varepsilon_{e\mu}^m$, the standard oscillation fit becomes worse than 3σ (white islands appear).

  $\downarrow$

  Discovery possible for favorable phase combinations



Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

- $|\varepsilon^m_{e\mu}| = 1 \times 10^{-3}$
- $|\varepsilon^m_{e\mu}|$ becomes larger

$\downarrow$

For some combinations of δ_{CP} and $\arg \varepsilon^m_{e\mu}$, the standard oscillation fit becomes worse than 3σ (white islands appear).

$\downarrow$

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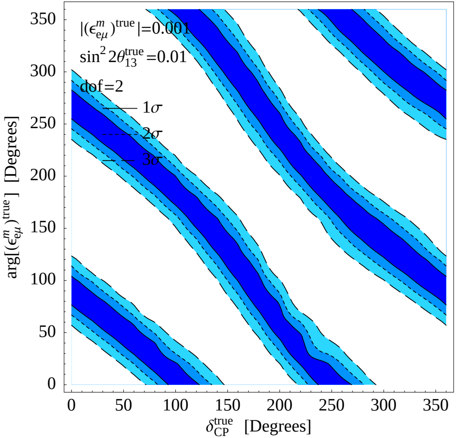

Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

- $|\varepsilon^m_{e\mu}| = 2 \times 10^{-3}$
- $|\varepsilon^m_{e\mu}|$ becomes larger

  $\downarrow$

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  $\downarrow$

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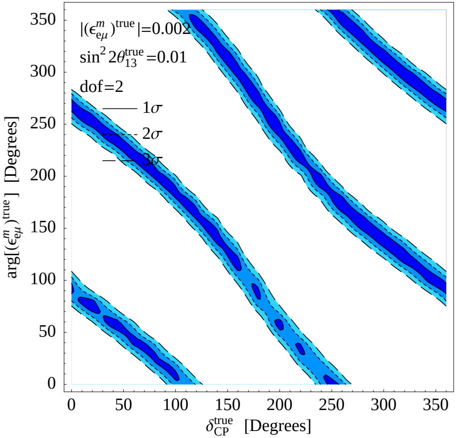

Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

- $|\varepsilon^m_{e\mu}| = 4 \times 10^{-3}$
- $|\varepsilon^m_{e\mu}|$ becomes larger

  $\downarrow$

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  $\downarrow$

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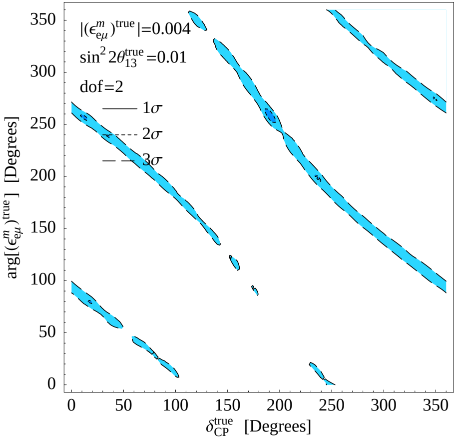


Discovery reach for $\varepsilon^m_{e\mu}$ in a neutrino factory

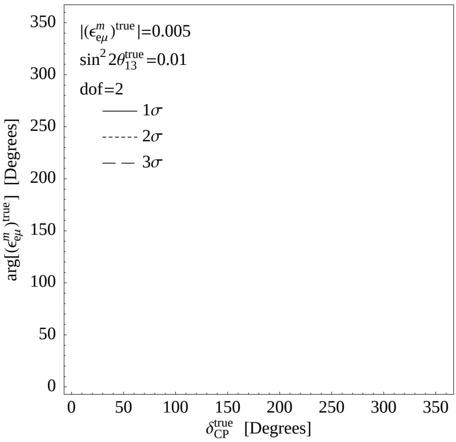
- $|\varepsilon^m_{e\mu}| = 5 \times 10^{-3}$
- $|\varepsilon^m_{e\mu}|$ is large enough

  $\downarrow$

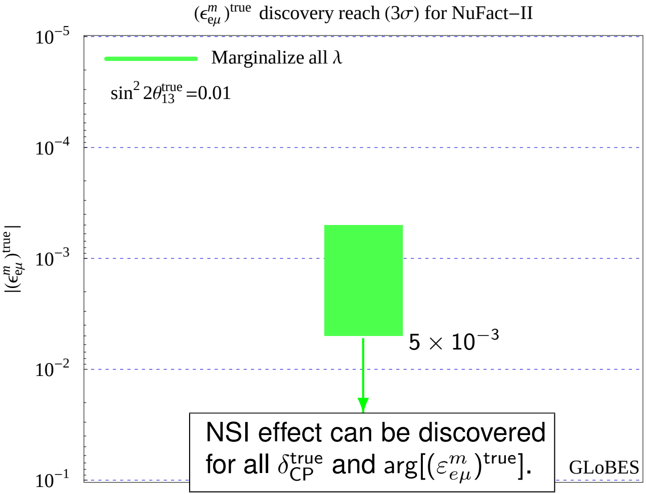
  χ^2 of standard oscillation fit exceeds 3σ in the whole parameter plane.

  $\downarrow$

  Discovery is possible for any phase combination



Summary of the discovery reach for $\varepsilon^m_{e\mu}$



NSI effect can be discovered for all $\delta_{CP}^{\text{true}}$ and $\arg[(\varepsilon^m_{e\mu})^{\text{true}}]$.

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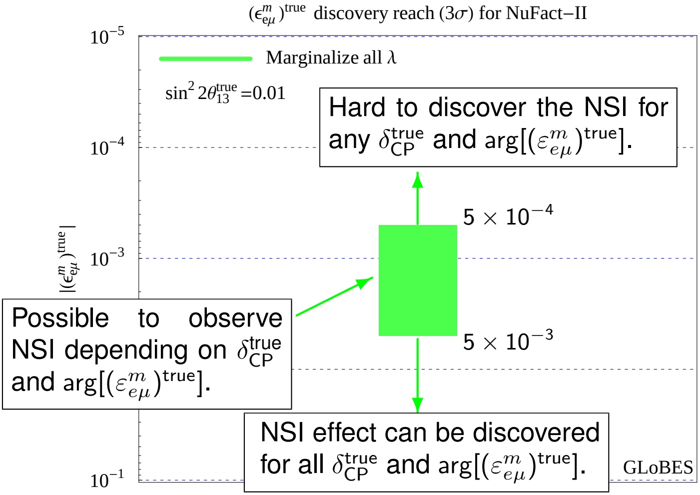

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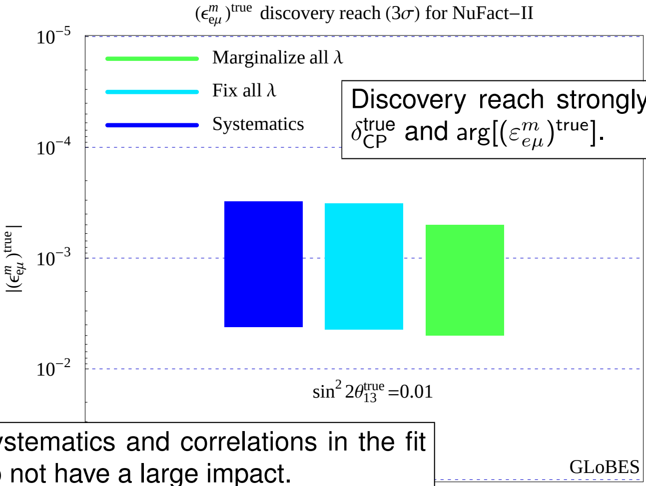
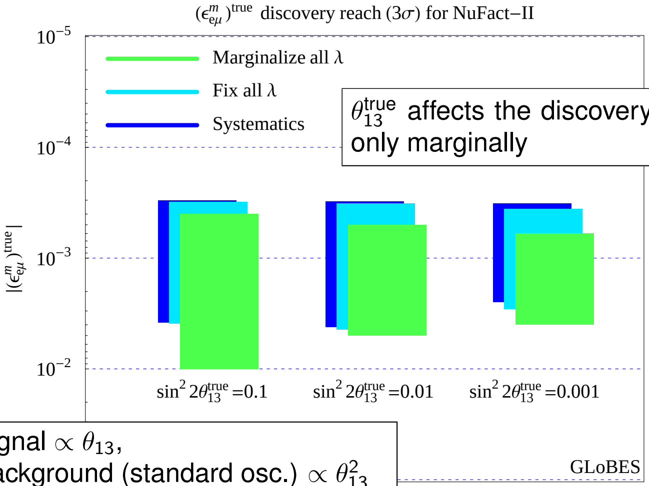


Discovery reach strongly depends on $\delta_{\text{CP}}^{\text{true}}$ and $\arg[(\varepsilon^m_{e\mu})^{\text{true}}]$.

Systematics and correlations in the fit do not have a large impact.

Summary of the discovery reach for $\varepsilon^m_{e\mu}$

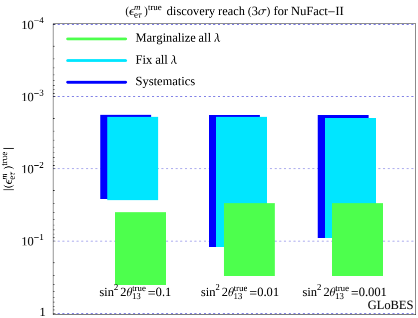


θ_{13}^{true} affects the discovery reach only marginally

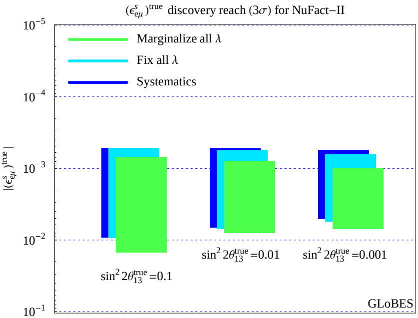
Signal $\propto \theta_{13}$,
Background (standard osc.) $\propto \theta_{13}^2$

Discovery reach for $\varepsilon^m_{e\tau}$ and $\varepsilon^s_{e\mu}$ in a neutrino factory

$\varepsilon^m_{e\tau}$



$\varepsilon^s_{e\mu}$



Outline

Summary and conclusions

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